# Why did video screens get slimmer?

A study of the role of Intellectual Property in the commercial development of organic light-emitting diodes

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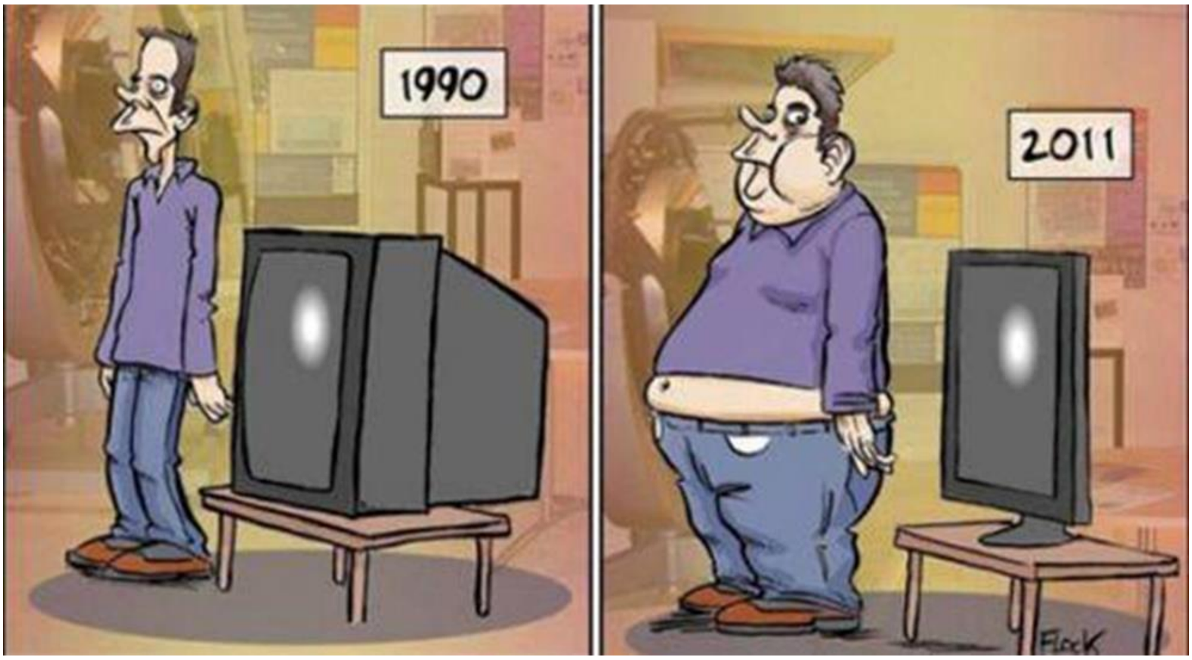
Submitted in partial fulfilment of the requirements of the degree of Doctor of Philosophy

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I would like to give all the glory and honour to the Almighty God, for not only inspiring me to do this but for providing the grace, provision, favour, wisdom, strength and resilience I needed to start and to finish well.

Special thanks goes to my PhD supervisors: Prof. Spyros Maniatis and Prof. Roger Cullis for constantly helping me to see the beauty in the vision and for showing me the multifaceted victor in me. Roger, thank you for always being an email's length away, and for the many evenings you helped me burn the midnight oil, even to the final hour. Hajime, the student that became an invaluable teacher, thank you.

Grateful thanks also goes to my family that always supported me and put up with a shell of a person, especially over the last year of this project. Zaabu, thank you for your patience, time and support. My friends and spiritual family, thank you for your prayers.

May God richly reward you all.

## Abstract

This research project consists of a critical analysis of the role of intellectual property amongst other factors in the successful commercial development at the Cavendish Laboratory of optoelectronic light emitting diode display devices based on novel organic semiconductor materials. It begins by giving the background to the quantum mechanical properties upon which the technology is based, followed by a discussion of the path of innovation, describing the interaction between the different socioeconomic factors that influence this path. It then draws an analogy with the development of an analogous technology - inorganic semiconductors - to signpost the factors that may affect the developmental history of the technology. This is followed by an analysis of a chronology derived initially from patents downloaded from the World Patents Database of the European Patent Office to showcase the technology's development steps, and to study the patenting strategy of Cambridge Display Technology (CDT) - the company that was set up to commercialise the novel technology - through a patent trends analysis. From that, the major socioeconomic factors critical to the technology's development are analysed, followed by a test and extension of an existing Black Box mathematical model for studying the dynamics of innovation that is based on the interaction of those factors. Finally, through a patent citation analysis, CDT's commercial strategy for the technology is shown as being based on its patents portfolio to build an extensive licensing programme that pooled major academic, industry and commercial partners for the furtherance of the technology. This later evolved into a new ecosystem for the innovation, of which CDT occupied a central and indispensable position.

# Table of Contents

## List of Figures

# List of Tables

# Glossary of Acronyms

| | |
|---|---|
| AMOLED | Active Matric OLED |
| AP-OLEDs | All-Printed OLEDs |
| a-Si | Amorphous Silicon |
| BJT | Bipolar Junction Transistor |
| CDT | Cambridge Display Technology |
| CE | Cambridge Enterprise |
| CES | Consumer Electronics Show |
| CMOS | Complementary Metal-Oxide-Semiconductor |
| CPC | Cooperative Patent Classification |
| CRIL | Cambridge Research Innovation Limited |
| CRT | Cathode Ray Tube |
| DG-FET | Dual-Gate FET |
| EPC | European Patent Convention |
| EPO | European Patent Office |
| EPSRC | Engineering and Physical Science Research Council |
| ESS | Energy Storage System |
| EWG | Electron-Withdrawing Group |
| FET | Field-Effect Transistor |
| FPD | Flat Panel Display |
| HDTV | High Definition Television |
| HOMO level | Highest Occupied Molecular Orbital |
| IJP | Inkjet Printing |
| ILED | Inorganic LED |
| IP | Intellectual Property |
| IPC | International Patent Classification |
| IPRs | Intellectual Property Rights |
| ITO | Indium Tin Oxide |
| LC | Liquid-Crystalline |
| LCD | Liquid Crystal Display |
| LED | Light Emitting Diode |
| LTPS | Low-Temperature Polysilicon |
| LUMO level | Lowest Unoccupied Molecular Orbital |
| MEH-PPV | Poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] |
| NPN structure | *n*-type:*p*-type:*n*-type polymer sandwich |
| NRDC | National Research Development Corporation |
| OLED | Organic Light Emitting Diode |
| OTFT | Organic TFT |
| OVPD | Organic Vapour Phase Deposition |
| PADT | Post-Alloy Diffused Transistor |
| PCT | Patent Cooperation Treaty |
| PF | Polyfluorene |
| PMOLED | Passive Matrix OLED |
| PNP structure | *p*-type:*n*-type:*p*-type polymer sandwich |
| POLED | Polymer OLED |
| PPV | Polyphenylenevinylene |
| PTA | Patent Trends Analysis |
| PTFE | Polytetrafluoroethylene |
| QD-LED | Quantum-Dot LED |
| RGB | Red, Green and Blue |
| SMOLED | Small Molecule OLED |

| | |
|---|---|
| TFEU | Treaty on the Functioning of the European Union |
| TFT | Thin Film Transistor |
| TMA | Total Matrix Addressing Technology |
| TOLED | Transparent OLED |
| UDC | Universal Display Corporation |
| UKIPO | UK Intellectual Property Office |
| USPTO | US Patent and Trademark Office |
| VTE | Vacuum Thermal Evaporation |
| WIPO | World Intellectual Property Office |

# 0.0 Thesis Preamble

This thesis consists of a critical analysis of the role of intellectual property amongst other factors in the successful commercial development at the Cavendish Laboratory (University of Cambridge) of optoelectronic light emitting diode display devices based on novel organic semiconductor materials. This technology will be collectively referred to as OLEDs - organic light emitting diodes - of which there are two types: small molecule OLEDs (SMOLEDs) and polymer OLEDs (POLEDs). In many ways, SMOLEDs and POLEDs are very closely related so the thesis addresses the technology as a whole with the denotation 'OLEDs'. When the discussion goes beneath the surface, a distinction will be made between the two technologies.

The thesis' objective is to demonstrate how IP, among other factors, has affected the commercial development of POLEDs technology by using the IP portfolio owned by Cambridge Display Technology (CDT) as a case study; CDT was spun out of the University of Cambridge to commercialise the invention. The patents examined are those considered by the author to be central to the birth of the technology; this analysis looks at the quantum mechanical evolution of the technology alongside a comment on the legal validity and commercial significance of each invention. These factors are pooled from extant patent data (because the nature of the invention at issue here is technological and patents are technology development indicators), published commercial data and expert knowledge of the invention lifecycle based on industry experts, all embellished with technical papers, relevant specialist books, journals and other suitable secondary material.

Notably, as more players and thus competitors are entering the OLED market, work has become increasingly secretive (also due to the existence of IP) so the figures reported are those that are published and might not necessarily reflect the current state of being. Further, CDT along the way acquires further IP related either to improvements of the POLED invention or related technologies that complement its development; an analysis of this IP is outside the thesis' objective. This research is important because it looks at the success of an invention on a global perspective; examining several factors that are likely to affect its commercial success - from molecular issues such as the limitations or enablement of physics and science behind the invention to the availability of finances, collaborations, the need for a ready market for the invention, other enabling or disabling factors such as government intervention, the existence of an outside socioeconomic stimulus that catapults or stifles continued development, right down to consumer reception or lack thereof of one's invention. It also examines the role of the support or lack thereof of other players in the industry and very vitally points out the indispensable nature of multi-disciplinary collaborations to achieving maximum benefit from the invention. The factors are examined at a surface level. The author is by no means purporting to provide an authority on social or economic issues but an analysis sufficient to warrant their later inclusion into a novel model for innovation dynamics.

Once all the factors are examined in detail, they are treated as parameters of a mathematical model - the Black Box model - to illustrate their relative contribution to the innovation journey. The point is to prove, or otherwise, whether innovation follows a similar path irrespective of industry, and thus confirm or revise an extant model that was proposed to measure the dynamics of innovation. We live in a fast-paced generation that is laced with technological innovation; understanding the relationship between innovation, economics and society will place innovators in an elevated position to better our society. An analysis of the relative contribution of each factor informs an inventor of the path they are likely to embark on, so as to anticipate where the likely hurdles or victories may lie and otherwise be better prepared for the journey from conception to market. An enhanced understanding of the innovation process, in other words, allows for predictability of its future course.

For OLEDs, my hypotheses and anticipated results are based on an analogy with the development of inorganic semiconductors, in particular, the transistor. As such, I postulate that OLED market entry will have been made feasible by market substitution of an extant technology, such as Liquid Crystal Displays (LCD); this success will be driven by OLED and complementary technological developments. Interestingly, IP - in particular patents and trade marks - will influence the course of this commercial development, providing the basis for whom the major players will become. The subsequent global and multidisciplinary OLED ecosystem will speed up the technology's uptake and other factors such as timing and finance will limit how fast and how far the technology develops.

Of note, the factors examined are not exhaustive - they are expounded as reasonably as possible to the type of technology the author deals with. They so far apply to two analogous technologies: organic and inorganic semiconductors. In the near future, the study is likely to be extended for different types of technologies as well as industries such as finance, pharmaceutical, agricultural and HR; essentially inventions owned by the British Technology Group (formerly National Research Development Corporation - NRDC), the principle organisation in the UK that licensed and commercialised publicly funded developments in the UK.

As such, the main research questions are sevenfold: (1) to chart the technical developmental history of POLED technology with the starting point as inorganic semiconductor development; (2) to narrow down and analyse the socioeconomic factors that played a major role in the commercial development of the technology; (3) to identify the relative contribution played by IP in the context of those factors; (4) to use a patent trends analysis to gain insight into CDT's patenting strategies; (5) to paint a picture of the overall innovation's dynamics by understanding the extent of the interaction among the aforementioned factors; (6) to analyse the strength of individual patents in CDT's patent portfolio; and (7) to showcase how CDT has used its IP as a valuable commercial tool to further its success in the OLED value chain.

The overarching hypotheses are fivefold: (1) that by analogy with the development of the transistor, initial conditions (discovery of new materials, topological manipulation of device structures and the presence of a precursor market) will be dominant in deciding the success of the OLED invention at the offset; (2) this being complemented by the resource base provided by multi-disciplinary collaborations and the effect of intellectual property monopoly rights to (3) interestingly culminate into a licensing programme that will place CDT at the centre of the OLED value chain; (4) a confirmation of the importance of IP, in particular specific patents, in CDT's business strategy in a bottom-up manner to mirror the finding of top-down economic studies about CDT's commercial success; and (5) quite surprisingly, as a development towards the tail end of the research, a quantitative confirmation of the hierarchical value of individual patents in CDT's patent portfolio that will be provided by a patent citation analysis. These hypotheses will be expounded upon, in context, in sections 2.4 and 4.11.

Due to the nature of the study, in that it is multidisciplinary, the research questions, hypotheses and methodologies are not in the typical format expected of a law PhD but are rather interwoven and flow in and out of several chapters. However, as a general guideline, the first research question is addressed by chapters 3 and 5, the second by chapters 5 and 6, the third by chapters 5, 6 and 7, the fourth by chapter 5, the fifth by chapters 6 and 7, the sixth and seventh by chapter 7.

Accordingly, chapter 1 firstly gives a brief chemistry/physics tutorial to set the context of the technology that will be discussed. This is important for those without a scientific background and to hone the topic of discussion for those with one. Chapter 2 is a review of innovation dynamics which gives a brief background to some of the socioeconomic factors that have been anticipated to have a greater effect on the development of OLEDs - again, this list is by no means exhaustive. Chapter 3 is review of the analogous inorganic semiconductor technology. This analysis is based on a previous study of that technology's innovation dynamics and is anticipated to signpost the OLED development journey, achieving similar milestones and encountering similar challenges. From this, the major socioeconomic factors to focus on will be drawn. Chapter 4 then sets out the patent analysis methodology of how the research will be undertaken based on patent data. Chapter 5, grounded on the methodology, chronologically analyses the fundamental OLED patent data from conception in 1989 to October 2012 (the start of this project) based on patent specifications from the key inventors at the Cavendish Laboratory. Chapter 6 discusses the relative contribution of the major factors - technological, regulatory including intellectual property law, market related, societal and incidental - that affected the development of OLED technology, interwoven with the environment for innovation does not happen in isolation. Finally, chapter 7 analyses the identified factors in light of the Black Box model, makes some observations about the commercial development of the technology, and originally, a justification of the technology's anticipated continued success based on an analysis of patent citation data. From time to time, the reader will be referred to appendices that contain all the raw data onto which the thesis analyses are based.

# 1.0 Genesis

## 1.1 Introduction

In his presidential address to the Newcomen International Society for Engineering and Technology, Dr. John Russell outlined milestones in the development of organic carbon compounds (Russell, 2011; speech in appendix 10). These ranged from Bakelite, the first durable plastics material, via polyethylene and nylon, to conjugate polymer semiconductors which are currently being developed at the Cavendish Laboratory of Cambridge University by the optoelectronics group led by Professor Sir Richard Friend FRS. Sir Richard kindly agreed for me to document and analyse the factors, particularly the intellectual property, which resulted in the commercial success achieved by his team. The spreadsheet in appendix 1, containing raw data extracted from the European Patent Office (EPO) World Patents database lists information on patents naming Richard Friend as inventor and gives a chronological record of some 53 patents which outline the historical progress of this development from its conception in 1989 to 2012, the start of this project. It also reveals the names of co-inventors and commercial partners who participated in this work, provides international patent classifications for the subject area of all patent applications in this technological field and will provide a starting point for a relevant patent trends analysis (Cullis, 2011).

This study is concerned with the inter-relationship between law and technology. More specifically, the role of IP in the commercial development of organic light-emitting semiconductor polymer materials and devices, first discovered at the Cavendish Laboratory of the University of Cambridge by Sir Richard and his colleagues. A comparison with a study of the development of inorganic semiconductors (Cullis, 2008) will identify similarities and differences with a model of innovation dynamics developed previously (Cullis, 2007). It is envisioned that this will contribute to the understanding of the dynamics of innovation, stated by Rosa Maria Ballardini of HANKEN-Swedish School of Economics and Business Administration to be one of the most relevant topics of our global economy (Ballardini, 2008). A chronology derived initially from patents downloaded from the EPO database will be developed and analysed. The information will be expanded by secondary sources such as studying technical papers, and the resulting data will be utilised as a foundation for a case study setting out the economic development of the innovation, with particular emphasis on the role played by IP. A patent trends analysis will be performed to shed light on the patenting strategy of the Cambridge team. An existing model of innovation dynamics will then be tested to showcase the interdependence of other socioeconomic factors in the innovation's developmental path on IP, and finally, a patent citation analysis to determine the importance of individual patents in this IP portfolio.

At the outset however, it is essential to understand the physical and chemical principles underlying the technology in order to identify the inventive step introduced in the respective patent specifications. This chapter will trace the historical hypothesis of basic elements as building blocks of matter by the ancient Greeks and its development by medieval alchemists, leading to modern physicists' and chemists' quantum mechanical theories of the structure and properties of atoms and chemical compounds. In particular, it will focus on the behaviour of electrons and present these concepts with reference to the element carbon, highlighting some of the useful properties of complex carbon compounds such as organic copolymer semiconductors, based on their nature, properties and commercial utility. Particular emphasis will be placed on the underlying working principles of the technology that is the subject of this thesis - Organic Light Emitting Diode (OLED) devices - devices that use thin films of carbon-based semiconductor polymers to emit light in response to an electric current.

## 1.2 The Ancient Elements

In examining the route followed by innovation, or the progress of anything in life really, it is desirable to look back to the very beginning. Just as a house needs to be built brick by brick, an innovation is usually arrived at step by step. The ancient Greek philosophers, having observed the natural phases of matter believed that the root of all existing matter, the simplest essential part of life was encompassed in what classically they called the four elements; earth, wind, fire and water (Strathern, 2001). They believed these four elements were indestructible and unchangeable and combined with one another to produce different structures.

## 1.3 The Medieval Alchemists

This notion was developed during the Middle Ages by medieval alchemists who hypothesised that the four classical elements could be described in terms of four basic qualities: fire which was both hot and dry; earth which was cold and dry; water which was cold and moist; and air (wind) which was hot and moist (Thurlow, 1998). They believed that every metal was a combination of these four qualities and reasoned that they could change one metal into another by rearranging these qualities. They were particularly renowned for their attempts to change inexpensive base metals like lead into gold or silver and from this we get the apocryphal stories of the Philosopher's Stone, which could be used to alter the base metal. Nevertheless, their ideology, experiments and discovered chemical elements gave rise to modern scientific theories which became the standard dogma for modern chemistry.

Thanks to methods developed by the alchemists, scientists went on to identify several elements. An element is a substance that cannot be chemically broken down into simpler substances and is thus a primary constituent of matter (Thurlow, 1998 at p30). Elements comprise of units of matter called atoms, and are generally identified by the mass of those atoms - their atomic mass. The first discovered elements included hydrogen, oxygen carbon, silver, copper, iron, and zinc (Thurlow, 1998). Hydrogen and oxygen were particularly important in the development of modern chemistry. As time passed, more and more elements having different chemical properties were isolated and it became difficult to explain their individual properties as well as to establish relationships between them. Scientists used various classifications at different times to arrange all known elements. Johann Dobereiner introduced the concept of triad, where he arranged elements in groups of three, in increasing order of their atomic mass but this was not applicable to all elements (McDonald, 1965). John Newland proposed a law of octaves based on musical notes, in which he arranged the elements in increasing order of their atomic mass (Bryson, 2004). He observed a periodicity in the elements when he found that the first and eighth elements were similar in their physical and chemical properties. This arrangement however had its limitations, as did several other classifications proposed at the time (Ragai, 1992).

## 1.4 The Periodic Table

Several years later, when the four qualities of the classical elements became known as four states of matter, that is solid, liquid, gas and plasma, the elements were grouped into one of those three states, with the exception of plasma. In the mid-nineteenth century, a Russian chemist, Dmitri Mendeleev realised that the physical and chemical properties were related to their atomic mass and arranged the elements in what is today known as the periodic table (Mendeleev, 1889). In this arrangement he noticed similarities in the chemical properties of groups of elements: alkali metals - sodium, potassium, rubidium and caesium; alkaline earths - calcium, magnesium and mercury; non-ionic diamond-lattice-forming carbon, silicon and grey tin; the chalcogenides - oxygen, sulphur, selenium and tellurium; the halogens - fluorine, chlorine, bromine, iodine and the inert gases helium, argon, neon, krypton and xenon. He left gaps in this periodic table for elements that were later discovered, such as germanium and radon (Emsley, 2001).

## 1.5 Atomic Theory

In continuing to appraise Mendeleev's work critically, several scientists attempted to explain the properties of the elements in the table to support their periodic arrangement. Notably, in 1913, Niels Bohr proposed a model for an atom, the basic unit of an element, based on quantum mechanics (Bohr, 1913). The Bohr model had an atom consisting of a relatively heavy, positively charged nucleus orbited by negatively charged electrons, like a miniature solar system. He compared the nucleus to a central sun and the electrons to the planets orbiting the sun, with electrical charge replacing gravitation as the attractive force; see illustration in figure 1.1.

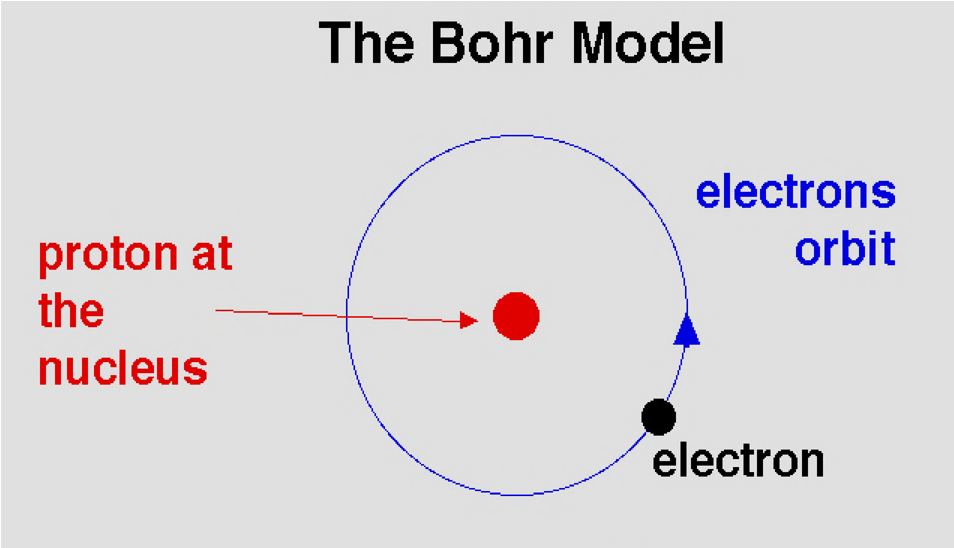



***Figure 1.1: Bohr's atomic model of the hydrogen atom (Source: George Mason University, 2012)***

Bohr's original model was based on the premise that any planetary orbit was possible with an appropriate amount of kinetic energy acting to prevent the planet from being pulled into the sun by gravity. Initially, he postulated that electrons would orbit the nucleus (containing subatomic particles called neutrons and protons) in orbits of a set size and energy, with the lowest energy found in the smallest orbit. However, in the case of charged electrons attracted to a charged nucleus, moving electrons would emit electromagnetic radiation, gradually lose energy and spiral into the nucleus (Bohr, 1913).

Since this did not accord with the situation observed empirically, Bohr postulated that there was a number of stationary orbits in which an electron could be bound without releasing radiation, and that as it moved from one orbit to another in which it either had lower or higher energy, it either emitted or absorbed radiation (or electromagnetic energy) of a particular frequency. Therefore, an electron starting at a given distance away from the nucleus will pass into successive stable orbits as it moves towards the nucleus, giving off radiation as it transits between orbits, until it reaches the orbit nearest to the nucleus, whereupon the atom is said to be in the ground state. A complementary phenomenon would occur if the electron moved in the opposite direction and away from the nucleus, except this time, radiation would be absorbed as it moved to an orbit in which it had higher energy. The electromagnetic energy could be in the form of a packet of light, known as a photon, and this forms the basis for electroluminescence which will be discussed later in this chapter.

The arrangement of electrons around the nuclei of atoms is such that the permitted energy levels or shells are filled in succession. An increase in electron count (and complementary nuclear charge) is manifest as a different element with different characteristic chemical and physical properties. According to the Royal Society of Chemistry, there are currently 118 known and approved elements (Royal Society of Chemistry). The innermost shell which is of lowest energy takes a maximum of two electrons. When that shell is filled, a new shell begins to form outside it and is filled in a similar way. There are four shells in total; the first and innermost takes a maximum of 2 electrons, the second 8, the third 18 and the fourth and outermost 32. All elements with the same number of completed electron shells, that is, 2, 8, 18 or 32, are arranged in the same row of the periodic table (called periods), and elements with the same number of electrons in the incomplete outer shells are arranged in the same columns (called groups). This logical arrangement, shown in figure 1.2 for the first 20 elements, was pioneered by Mendeleev's work.

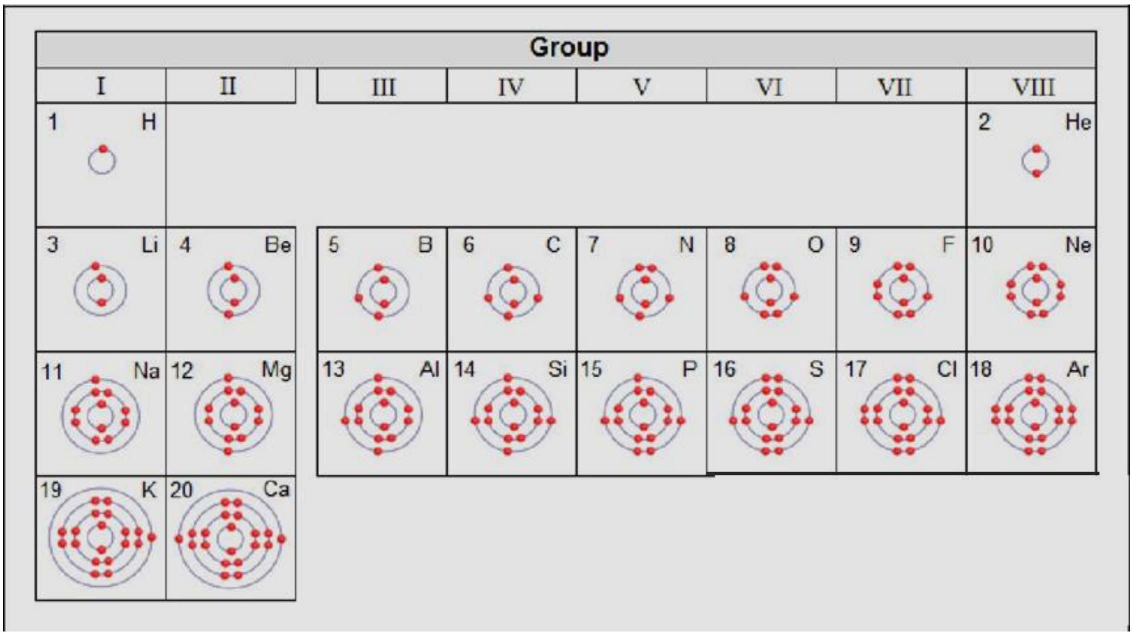



***Figure 1.2: A schematic of the periodic table, showing the arrangement of electrons in the first 20 elements (Source: elabschool, 2012)***

Since electrons are negatively charged and are attracted to the nucleus because of its positive charge, binding energy, that is, the amount of energy needed to detach electron from this attractive force, varies from atom to atom. Moreover, where there is more than one electron in an orbit, electrostatic repulsion between the electrons comes into play. Binding energy therefore decreases as the atom becomes bigger and contains more electrons.

Atoms also have a tendency to combine with other atoms and how easily they do this depends on the number of outer shell electrons (so-called valence electrons) that may be involved in forming chemical bonds with one or more atoms. This came to be known as the theory of valency (Petrucci, Harwood and Herring, 2002). Inert elements, those with full shells, have a zero valency. All other elements have valencies from 1 to 8. Further, two common types of valency exist; electrovalency and covalency, as shown in figure 1.3. Atoms in electrovalent compounds combine following the complete transfer of electrons from one to another so as to produce two oppositely charged ions that are held together by electrostatic attraction (Kossel, 1916). These compounds are referred to as ionic. On the other hand, atoms in covalent compounds combine due to the sharing of two electrons, each pair constituting a single directed valency bond (Lovegrove et. al., 2014). Sometimes, four or six electrons are equally shared, forming a double or triple bond respectively. The elements in such compounds are neutral and the compound is said to be non-ionic. In cases where the shared electrons are donated by one atom, a special type of a covalent bond, called a coordinate link, is formed (Partington, 1949).

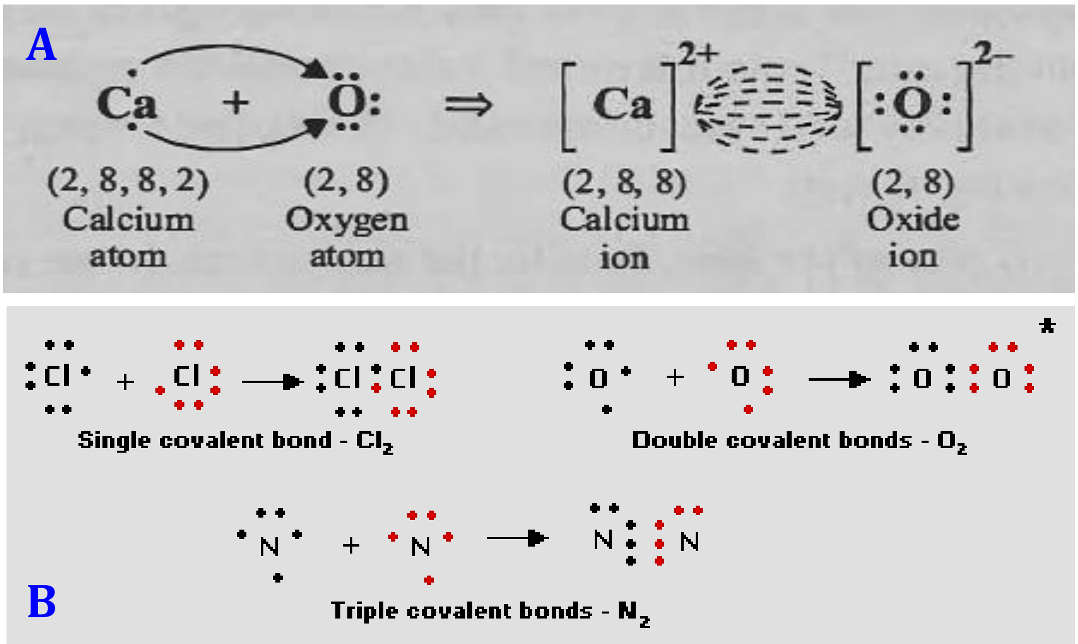



***Figure 1.3: (a) Illustration of electrovalent bonding. (b) Formation of a single, double and triple covalent bonds (Source: Lovegrove et. al., 2014; Chemistry-Assignment, 2013)***

The theory of valency and Bohr's atomic model led to a greater understanding of how subatomic particles such as electrons, protons and neutrons interact; this developed into a field of physics that mathematically describes the motion and interaction between these particles - referred to as quantum mechanics (Orchin et. al., 2005). Subsequent research by other scientists both proved and quantified the existence of permitted orbits aka orbitals - now defined as the size, shape and orientation of the region in space available to an electron - and further, that a maximum of two electrons can occupy an orbital but only if their spins are opposite so that they repel each other as little as possible.

Spin is a quantum mechanical property that describes a subatomic particle in terms of an angular momentum and an orbital momentum. The former describes movement of the particle to be similar to that of a gyroscope - constant movement in the x y and z axes, unless disturbed by an external force - while the latter describes its movement within the orbit. In very simplistic terms, electrons were found to have their own continuous and individual spins, in addition to orbiting a nucleus. The spin produces a magnetic field in two specific directions, denoted by either an upward arrow (positive) or a downward arrow (negative) (Orchin et. al., 2005).

The logic is then that if two electrons have the same spins, their magnetic fields will repel each other and they cannot exist in the same orbital. However, if the spins are opposite, they cancel each other out and are then able to occupy the same orbital. Accordingly, a single electron is placed in all orbitals of equal energy (degenerate energy) before a second electron is placed in any one of them. Consequently, Bohr's model implies that only certain electron orbits are permitted and valency theory states that the valency of an atom is equal to the number of unpaired electrons in the outer shell, which can then pair with electrons of opposite spins from other atoms (Partington, 1949).

In addition to behaving like particles that have momentum, electrons were found to have wave-like properties; existing as standing waves and never in a single point of location (Orchin et. al., 2005). The wave patterns of different elements were studied and classified according to whether they appeared sharp (*s*), principal (*p*), diffused (*d*), or fundamental to those produced by hydrogen (*f*). Orbitals are now known to exist as: symmetrically spherical *s* orbitals, three lobed *p* orbitals that are perpendicular to one another, five *d* orbitals and seven *f* orbitals, as shown in figure 1.4:

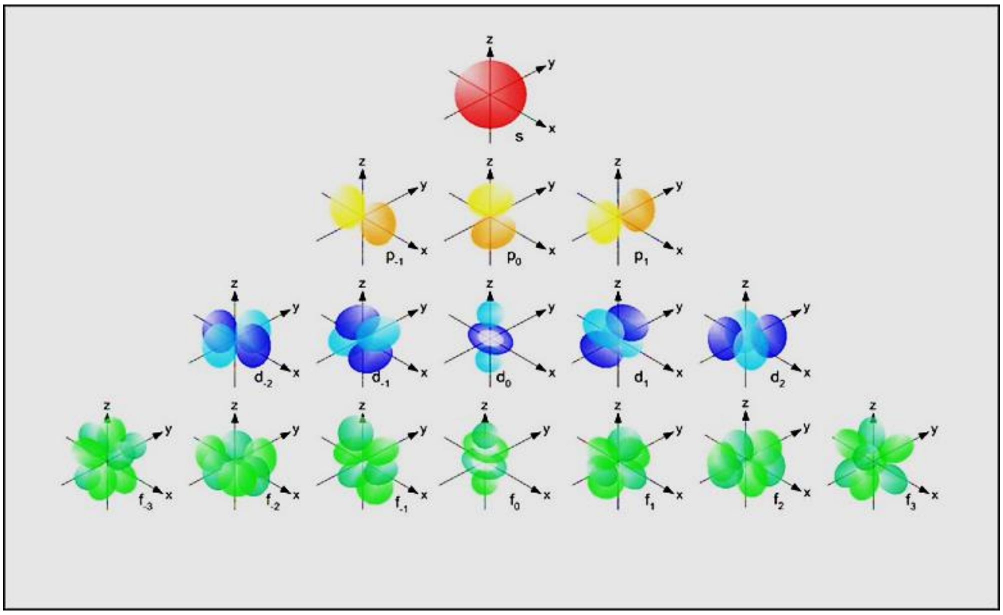


***Figure 1.4: A schematic of the four different types of orbitals shown in different planes (Source: Libre Texts, n.d.)***

Furthermore, orbitals within the same atom can mix to form new hybrid orbitals (Brown et al., 2013). This often helps to provide a uniform energy level and to provide suitable axes of symmetry for incoming bonding orbitals. As shown in figure 1.5, the hybrids' names and geometries are based on the atomic orbitals that are involved in the hybridisation. Sometimes the lobes of parallel atomic orbitals in close proximity may overlap so that the electrons in the orbitals are free to move around in an "orbital cloud"; they are said to be delocalised/detached from their parent atoms and are thus shared amongst more than two atoms in a molecule. These are called π atoms and the electrons are said to be located in π-orbitals, as in figure 1.10 (Orchin et. al., 2005).

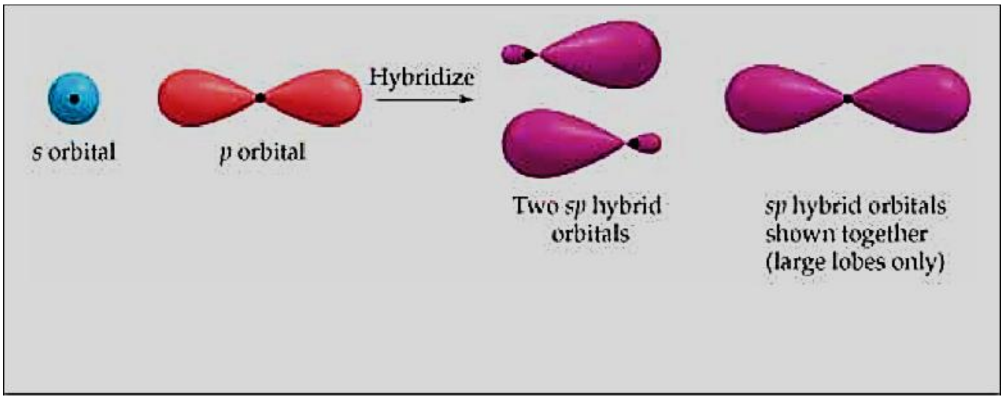



***Figure 1.5: Diagram demonstrating the formation of an sp orbital (Source: Brown et al., 2013, at p310)***

## 1.6 Valence Theory and Semiconductors

The valence electrons (electrons in the outer shell) in an isolated atom can only exist in one of the allowed orbitals or energy levels. When two atoms interact, however, these energy levels are disrupted and spread in the form of bands, several of which exist (Kakani and Bhandari, 2011). The bands are illustrated in figure 1.6. Valence bands are formed by a series of energy levels containing valence electrons. This band is of maximum energy; as such, the electrons cannot conduct electricity since they cannot gain energy from an external electric field. In contrast, the conduction band is partially filled with electrons and may also be referred to as an empty band of minimum energy. The electrons here can gain energy from an external electric field, are free to move within a solid and as a result, conduct electricity. The energy gap between the conduction and valence bands is called the forbidden energy gap or the energy band gap. This gap contains no free electrons. Its magnitude is dependent on the nature of the substance, and decreases with increasing temperature (Kakani and Bhandari, 2011 at p7).

Some materials such as the elements germanium and silicon have free electrical charge carriers within this energy gap and conduct electricity imperfectly. These elements are known as semiconductors. In addition to other properties that will be described shortly, their electrical conductivity can be manipulated under certain conditions. Semiconductors can either be organic or inorganic; the former include the element carbon, whilst the latter are not carbon-based (ignoring its crystalline isotope diamond) but are made up of the other Group 6 elements, grey tin, germanium and silicon or III-V crystalline compound such as gallium arsenide or indium antimonide (Morris, 2004).

As de-localised π-orbitals form a bond, they split into bonding and anti-bonding energy levels, and semiconducting properties emerge as this delocalisation extends (Doust, 2011). The former is referred to as the HOMO level (highest occupied molecular orbital) while the latter is the LUMO level (lowest unoccupied molecular orbital). The HOMO and LUMO levels in organic semiconductors are tantamount to the top of the valence band and the bottom of the conduction band in inorganic semiconductors respectively. We shall severally use these terms since we are particularly dealing with the former technology.

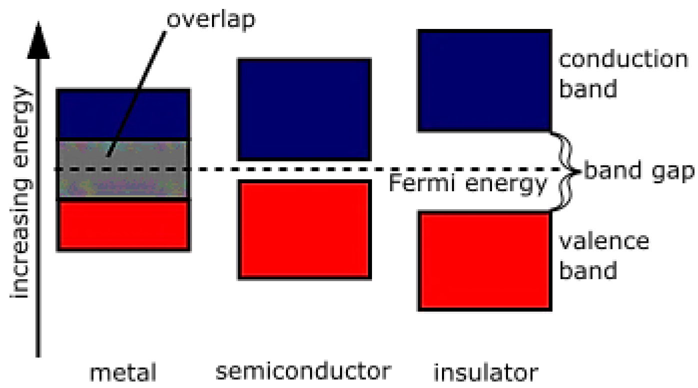



***Figure 1.6: An illustration of the valence and conduction band of a semiconductor in comparison to those of a metal and an insulator (Source: Semiconductors 2014)***

Accordingly, semiconductor materials have a band gap between that of a conductor and insulator. At absolute zero temperature (0°), the conduction band of a semiconductor is completely empty and it behaves like an insulator.

As the temperature increases, the valence electrons gain enough thermal energy to migrate to the conduction band, leaving behind a deficiency of electrons in the valence band referred to as a hole (Kakani and Bhandari, 2011). This leaves a net positive charge at the location. Just like electrons, holes are charge carriers. The number of charge carriers freed by thermal vibration depends on the width of the semiconductor band gap - so at room temperature, there is a small number of charge carriers, resulting in low conductivity but at higher temperatures, more charge carriers are generated and thus an increase in conductivity.

Figure 1.7 illustrates the movement of a hole in a semiconductor material. Electrons have a greater mobility than holes. Holes behave as if they are positively charged particles which are heavier than electrons and thus less mobile. They are also considered as seats of virtual positive charge, having a magnitude of charge equal to that of an electron.

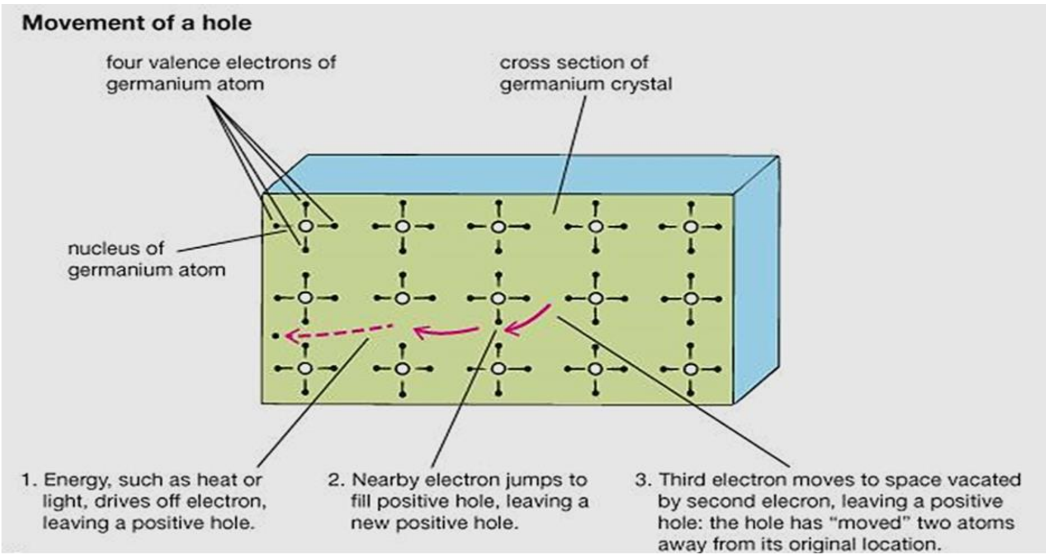



***Figure 1.7: Diagram showing the movement of a hole in a semiconductor (germanium) wafer (Source: Riordan, 2014)***

Further, crystalline inorganic semiconductors can either be intrinsic or extrinsic. Pure semiconductors are intrinsic semiconductors. They have four electrons in the outermost orbit of atoms and the atoms in the crystal are held together by covalent bonds. The crystals have an equal number of negative charge carriers (electrons) and positive charge carriers (holes), so their intrinsic electrical conductivity is relatively poor. However, the kinetic energy of atoms in the crystalline lattice at a temperature above absolute zero raises some electrons to a higher energy level, creating holes. These thermally generated current carriers; free electrons and holes in both the covalent and valence bands act as charge carriers, giving the semiconductor slightly better conductivity (Kakani and Bhandari, 2011).

Extrinsic elemental semiconductors are impure semiconductors - in other words, pure semiconductors whose electrical conductivity has been improved by addition of impurities that improve their conductivity. These impurities introduce extrinsic conductivity. The process is called doping - where foreign elements are added to the semiconductor to occupy the position of a tetravalent semiconductor element in the crystalline lattice (see figure 1.8). Dopants may either be pentavalent elements (5 valence electrons) that donate an extra electron e.g. arsenic, phosphorus and antimony (As, P, Sb) or trivalent elements (3 valence electrons) that accept an electron/create a hole e.g. indium, aluminium, boron and gallium (In, Al, B, Ga). This results in relatively high conductivity. Group 4 semiconductors such as silicon and germanium, which are the subject of this study, are doped in this way; other semiconductors have different dopants and we shall not be concerned with this. The more abundant charge carriers, which are primarily responsible for current transport in a piece of semiconductor, are called majority carriers. Likewise, the less abundant are the minority charge carriers.

Doped elemental semiconductors are classified as *n*-type and *p*-type semiconductors. *N*-type semiconductors result from pentavalent dopants and so have electrons as the majority charge carriers, are electrically neutral (not negatively charged) and have a donor energy level which lies just below the conduction band. *P*-type semiconductors result from trivalent dopants so have holes as the majority charge carriers, are also electrically neutral (not positively charged) and have an acceptor energy level which lies just above the valence band (see figure 1.8).

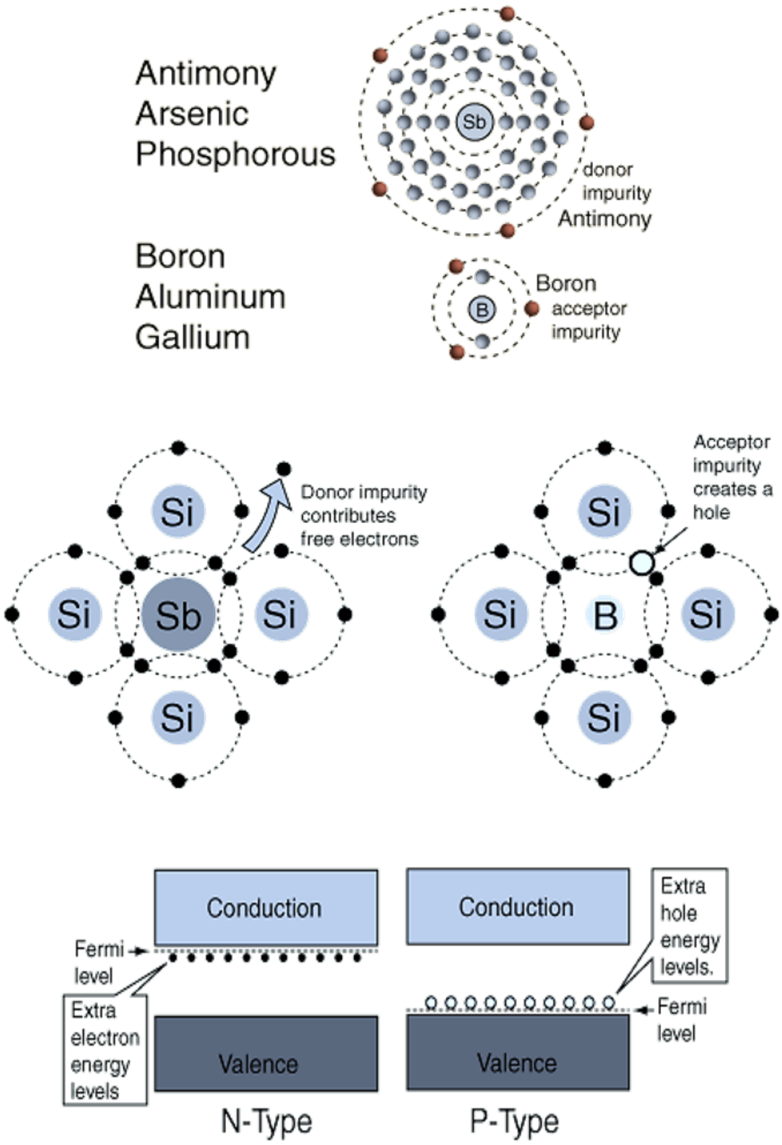



***Figure 1.8: Showing different dopant elements for group 4 semiconductors and their valence electrons, their addition into the tetravalent silicon crystal lattice and the subsequent effect on the conduction and valence bands of the semiconductor (Source: Nave, n.d.)***

## 1.7 Carbon Allotropes

So to sum up, I will explore the quantum mechanical basis of these concepts for the semiconducting properties of conjugated organic copolymers as this is directly relevant to the technology on which this research is based; complex carbon based polymers. As a basic building block of every plant, animal and life as we know it, carbon is a very important element and is one of the few elements that occur in nature in its native form. It exists in several forms, called allotropes that have different structures, of which the best known are graphite, diamond, buckminsterfullerene (fullerene) and amorphous carbon or soot (Bonchev and Rouvray, 1999).

The carbon atom has four electrons in its outer electron shell, which allows it to form four covalent bonds. Two of these come from the spherical *s*-orbital and two from the lobed *p*-orbitals. However, when bonding, four new hybrid $sp^3$ orbitals are formed from the initial *s* orbital and all three *p* orbitals, and each takes up one of these electrons. These orbitals have lobes pointing to the corners of an imaginary tetrahedron. Upon repetition in a giant lattice, this tetrahedral bonding network builds up the rigid structure shown in figure 1.9 in which atoms cannot move, making diamond the hardest substance known to man.

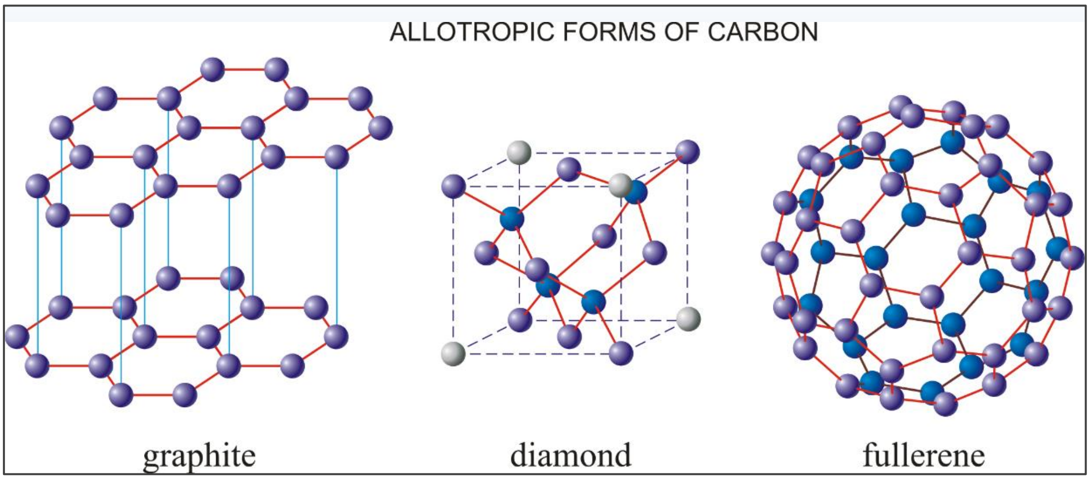



***Figure 1.9: The macromolecular structures of graphite, diamond and buckminsterfullerene. The purple and blue balls represent carbon atoms in the fore and backgrounds respectively, white balls: hydrogen atoms, red lines: strong C-C covalent bonds, blue lines: weak Van der Waals interactions (Source: Generalic, 2015)***

In conjugated molecules (molecules containing double or triple bonds each separated from the other by a single bond) like graphite and buckminsterfullerene, the hybridisation is incomplete. This produces three $sp^2$ hybrid orbitals with lobes directed towards the corners of an equilateral triangle, to the three neighbouring atoms in the plane, and a lone 2*p* orbital with its axis perpendicular to the molecular plane. Three of the four carbon electrons enter the $sp^2$ hybrids and pair off, each with an electron from a corresponding neighbouring atom. They are called σ-electrons. The last electron is in the *p*-orbital and is called a π-electron. The π-electrons are relatively easily detached and give rise to the conduction properties of the compounds.

In what are known as cyclic molecules, the *sp*$^2$ hybrid atomic orbitals lead to the formation of a hexagonal carbon ring: the three-lobed hybrid orbitals overlap to form six carbon-carbon sigma bonds in the ring, as well as the bonds with six hydrogen atoms. The six *p* orbitals at right angles to the plane of the ring pair off to form the three double bonds or π bonds. These electrons are free to move within this cloud so that they are no longer local to one atom but are "delocalised". This mobility enables graphite to conduct electricity whereas diamond, in which the electrons are tightly bound by a multitude of strong covalent bonds, cannot.

The honeycomb pattern of graphite layers with the π-electrons protruding at right angles from the plane of the graphite layer is shown in figure 1.10. These π-electrons form weaker bonds, called Van der Waals bonds, with π-electrons in the opposite parallel layer of graphite. Because of their closeness, the *p* orbitals merge to form a continuous electron cloud that extends the entire surface of the graphite layer. The bonding power of this cloud of electrons is insufficient to prevent the honeycomb layers of the graphite slipping past one another when an external force is applied (Bonchev and Rouvray, 1999). This is what makes graphite soft and malleable.

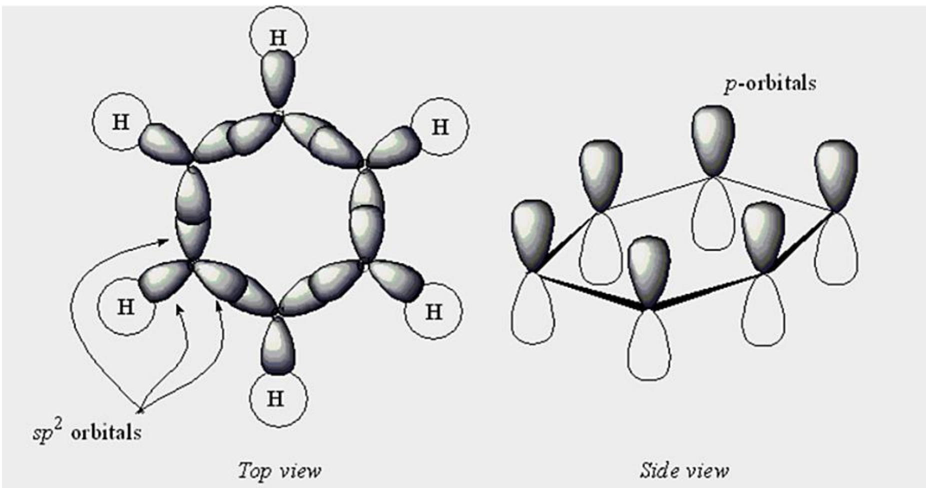



***Figure 1.10: Bonding of electrons in graphite structures (Source: Boudreaux, 2014)***

Another interesting carbon allotrope is buckminsterfullerene ($C_{60}$). It was first fabricated by Harry Kroto and co-workers at Sussex University in 1985 (Aldersey-Williams, 1995). It has a cage-like structure shown in figure 1.9 above, which resembles a football, made up of twenty hexagons and twelve pentagons with a carbon atom at the vertices of each polygon and a bond along each polygon edge. The molecule has many potentially useful applications as a nanostructure in medicine, chemistry and industry. This is because it is extremely stable; can withstand high temperatures and pressures; the exposed surface can react with other species while maintaining the spherical shape; and the hollow structure can entrap other elements or molecules that do not react with it (Aldersey-Williams, 1995).

Almost all organic chemistry is attributed to the geometries that stem from the nature of the carbon bonding in diamond and graphite. Many organic compounds kink and branch at roughly tetrahedral angles like fragments of diamond whilst others have the planarity of graphite. Some combine aspects of the two geometries within a single molecule and whilst there are other structural possibilities, these two arrangements represent the two dominant paradigms for carbon architecture. Nanostructures on the other hand tend to take the cage-like structure of buckminsterfullerene.

## 1.8 Organic Copolymer Semiconductors

The carbon allotropes are of limited practical use in their pure state so more complex macromolecules have been synthesised from commercially important polymers to combine the properties of two or more of these carbon structures. Polymers of different composition have different electrical properties due to the positions of the electrons and holes in the structures of the molecule. Excited electrons usually release their energy as photons or light. This property has led to pioneering research into electroluminescent semiconducting compounds - compounds that emit light in response to electric charge transfer.

The research which is the subject of this thesis was based on one such electroluminescent semiconductor material. The starting point was the electronic properties of graphite, based on the delocalised π-electrons in the electron cloud. The graphite structure was manipulated by cleaving a graphite-structured sheet into a phenylene vinylene repeating motif; this is essentially a conducting rigid rod polymer (see figure 1.11). The $sp^2$ hybrid orbitals still formed the three characteristic bonds between adjacent carbons along the backbone, and the π-electrons were still capable of being disturbed to give interesting electronic properties by pairing up with other π-electrons to form alternating carbon-carbon double bonds.

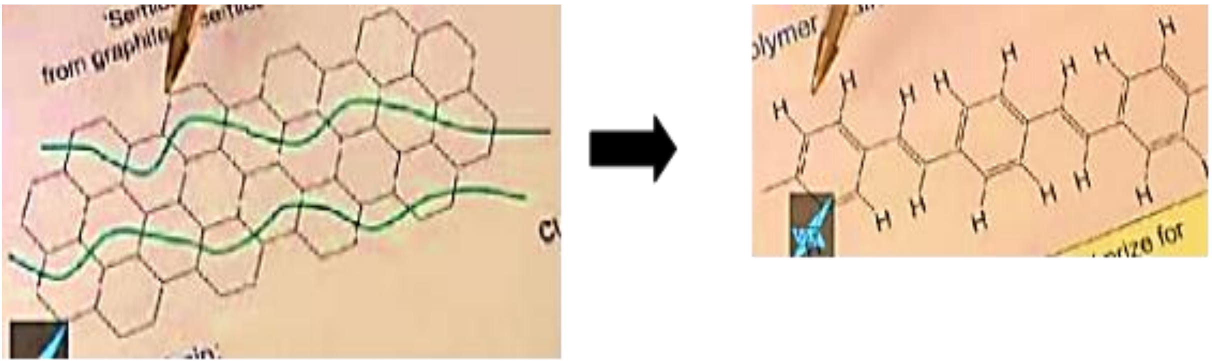


***Figure 1.11: Cleavage of the graphite-based structure, showing the points of cleavage as a green line, to produce a phenylenevinylene repeating unit (Source: Friend, 2004-2005)***

Following a multidisciplinary collaboration between Sir Richard Friend (Physics, University of Cambridge), Andrew Holmes (Chemistry, University of Cambridge), and Jim Feast (Chemistry, University of Durham), it was realised that by making up a polymer chain with slightly different repeat units, as opposed to the conventional way of having the same repeat units, the electrical behaviour of certain polymers could be manipulated (Friend, 2004-2005, also see appendix 9 for the full transcript of the interview). So, starting with the phenylene vinylene chain, the repeat units in the polymer were interchanged by adding, for example, dialkoxy phenylene in place of the phenylene. It was found that in such copolymers, if the building blocks were randomly linked along the chain as opposed to being placed in well-defined blocks, the result was an average of the properties of the two building blocks. The consequence of this discovery was that it formed the basis for the design of commercially important devices.

The boundaries between the different compounds or semiconductor materials are known as heterojunctions, and because the two semiconductor materials are dissimilar, they have unequal band energy gaps, a situation which may occur with inorganic semiconductors, for example when gallium arsenide is grown epitaxially on a substrate of germanium, which has a dimensionally similar crystal structure. This is advantageous because the HOMO and LUMO levels of one polymer molecule can be juxtaposed with those of another polymer molecule so that the effect is to make all of the energy levels lower in energy. Usefully, this can create a certain size of offset in the positions of the conduction and valence band edges. Matching offsets are essential to overcome the strong attraction between the hole and the electron so this determines which materials have to be mixed.

Moreover, there are different types of heterojunctions: type I, type II and type III. As illustrated in figure 1.12, in type I, the LUMO and HOMO levels of one material lie within or are straddled by the LUMO-HOMO energy band gap of the second material while in type II, the LUMO-HOMO levels of the two materials are staggered so that the energy band gaps of both materials cross each (PCT/GB99/00741, p3). It then follows that an electron-hole pair at the heterojunction will arrange itself so that the electron sits in the lowest LUMO level while the hole sits in the highest HOMO level. Accordingly, for any given pair, both the electron and hole will be present on the same side of the heterojunction in type I (and thus within the same material) whilst they will be separated in type II (and thus in two different materials). As a consequence, light-emission is expected in type I but not in type II. In type III, the band gaps of the materials do not overlap but this category is not relevant to the study.

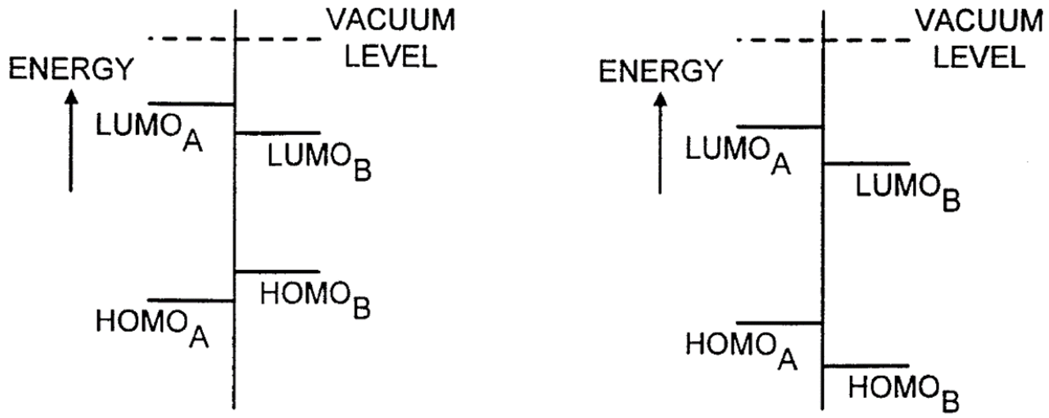



***Figure 1.12: An illustration of the two types of heterojunctions in two different materials A & B - type I on the left and type II on the right (Source: PCT/GB99/00741)***

On a practical level within a device, if a potential difference is applied across the junction by anode and cathode electrodes so that the anode is positive with respect to the cathode, the energy subsequently absorbed can excite an electron to move to the LUMO level, leaving behind a hole in the HOMO level. In essence, as electrons flow from the cathode to the anode, electrons are injected into the LUMO levels and withdrawn from the HOMO levels - or synonymously, holes are injected therein - (Zissis and Bertoldi, 2014 at p6). If that electron is adjacent to the heterojunction, it can traverse that junction to enter a lower energy state of the other semiconductor material while the hole, which behaves like a bubble, floats up to the conduction band (now newly vacated by the electron) to occupy a lower energy state. See figure 1.13 for an illustration.

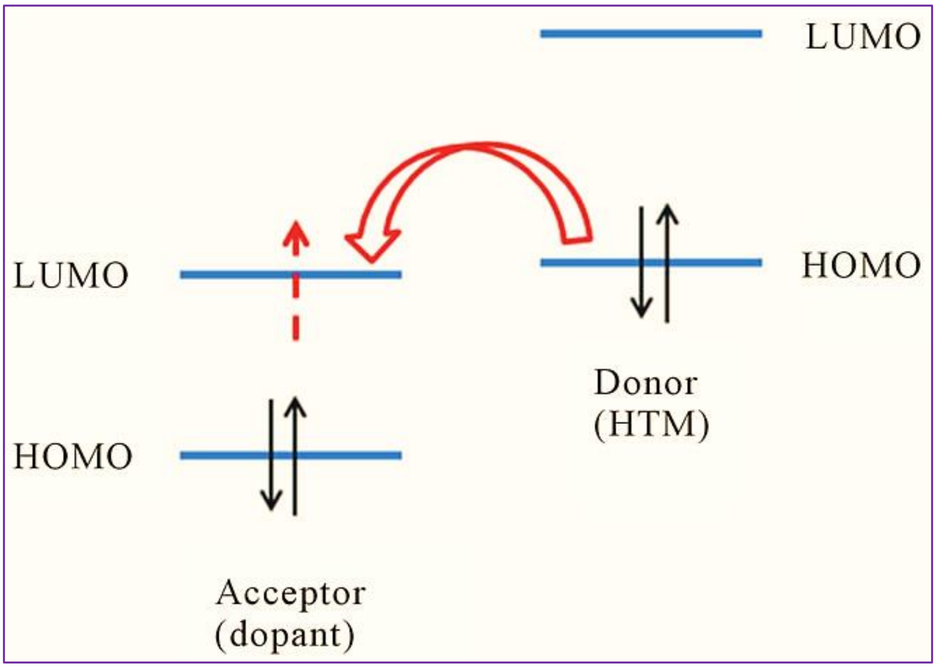



***Figure 1.13: A juxtaposition of the LUMO/HOMO levels of two semiconductor materials (one a dopant) showing the difference in energy levels at a heterojunction and illustrating the movement of an electron form one material to another following excitation (Source: Padmaperuma, 2012).***

Accordingly, the LUMO levels of one material act as electron acceptors while the HOMO levels of the other act as hole acceptors. The end result is that the electrons in one material are separated from their holes. Devices containing heterojunctions can thus be stimulated to generate radiation by application of a voltage between appropriately positioned electrodes.

Moreover, these mobile electrons and holes within a semiconductor polymer can also be drawn towards each other by electrostatic forces; they pair up and recombine forming a bound state termed as an exciton (see figure 1.14(a)).

Excitons are further distinguished as either singlet or triplet, with a statistical ratio of 1:3 of the likelihood of occurrence (Doust, 2011; Zissis and Bertoldi, 2014; Kappaun, Slugovc and List, 2008). In the former, the spins of the LUMO and HOMO electrons match so that they can sit in the same orbital (note, the hole forming the exciton would be in the orbital that is being populated) and in the latter, the spins of the electrons do not match so the electrons cannot occupy the same orbital (see figure 1.14 (b)).

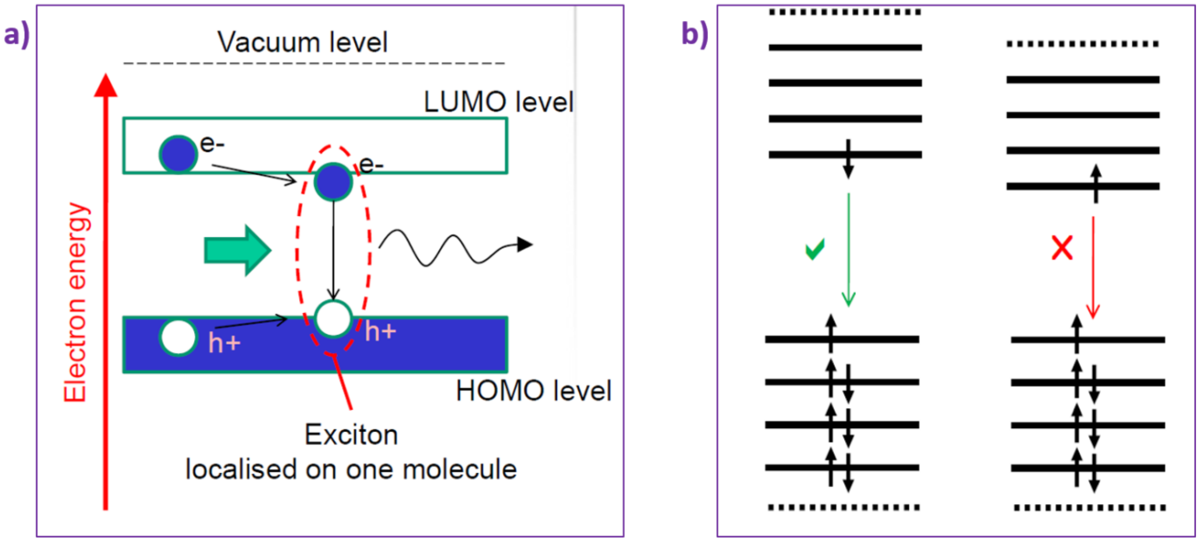



***Figure 1.14: a) Illustrating the formation of an exciton with electron represented as blue coloured circles and white coloured circles for holes. The wavy arrow represents emitted light on formation of an exciton; b) showing the spins of the singlet and triplet excitons. Electron pairs in an energy level are represented by black arrow and the coloured arrows show and allowed or disallowed coupling (Source: Doust, 2011)***

Excitons eventually decay and this is what results in an emission of radiation, usually light with a frequency in the visible spectrum. The frequency and thus colour of emitted light depends on the band gap of the semiconductor material, that is to say, the energy difference between the HOMO and LUMO levels (Zissis and Bertoldi, 2014). Only occurring 25% of the time, singlet excitons decay much faster and their transition is called fluorescence; they have a short lifetime and are only about 25% efficient. Triplet excitons occur 75% of the time and their transition, called phosphorescence, is much slower so they have a longer lifetime as they can be manipulated to achieve an efficiency of 100% (Mikhnenko, 2012; Kappaun et al., 2008). The lifetime issue will be discussed in later chapters. This creates the distinction between fluorescent and phosphorescent materials. Notably, singlet excitons occur in both types of materials.

The foregoing describes the theory underlying OLED devices (see figure 1.15). The simplified device comprises a flat glass substrate pre-coated with a thin layer of a transparent conductor such as indium-tin oxide (the anode), a layer of an organic semiconductor polymer, and finally, a layer of metal (the cathode). The polymer layer usually comprises a conductive layer (closest to the anode) and an emissive layer (where excitons decay to produce light). The device is connected to an external circuit via two electrodes above and below the substrate. The external circuit drives electrons out of the cathode metal into unfilled energy levels in the polymer, and because of the presence of heterojunctions, the electrons are able to migrate from one polymer chain to the next within the layer as there is enough three-dimensional contact. Simultaneously, holes are driven in from the anode as electrons are being extracted. As already explained, excitons are generated and the end product is illumination.

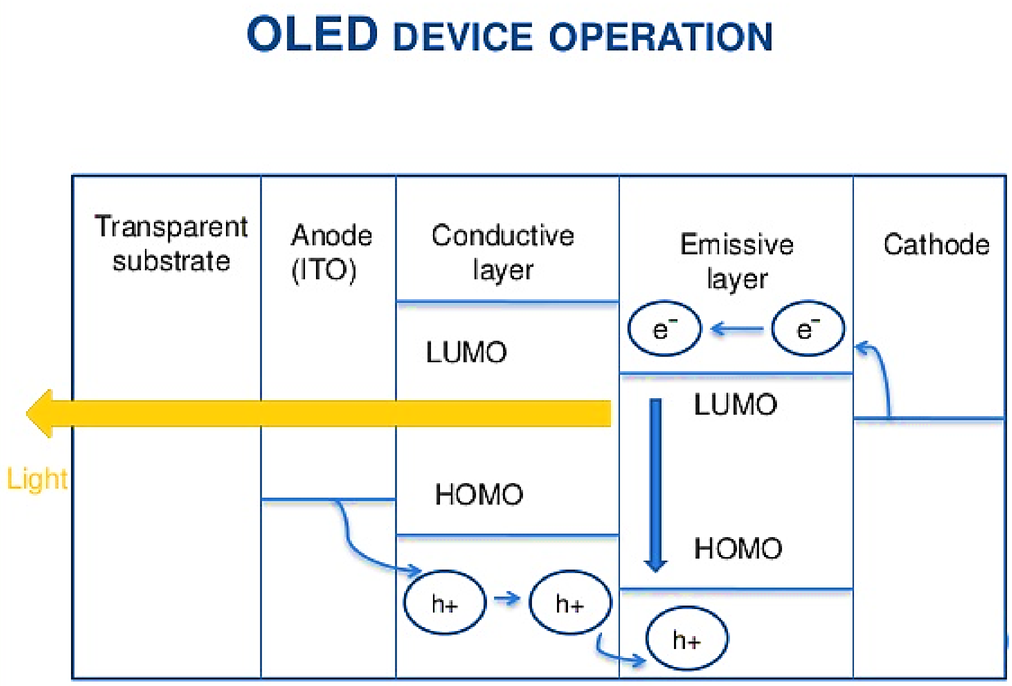



***Figure 1.15: Illustrating the technology behind an OLED device (Source: Liza, 2013)***

On the practical side, these principles have been employed in making display technologies. Amongst these are: mobile displays utilised in mobile phones, e-readers, notepads or laptops, and desktop flat panel displays used in consumer and professional television apparatus. The reader may look to appendix 8 for the background on display technologies. Arrays of OLEDs can be patterned with different arrangements of electrodes to permit manipulation of an individual pixel (that is the smallest controllable element of a picture represented on a screen). This work was commenced in 1989 when Jeremy Burroughs, discovered serendipitously, that a high enough electrical current passing through a certain polymer semiconductor caused the material to produce a bright green light emission (Friend, 2010). We will discuss this further in chapter 5.

Finally, this thesis is fundamentally based on fluorescent POLED technology although CDT eventually branched out into phosphorescent POLED research. In context, figure 1.16 shows OLED technology in line with extant display technologies, along with the key companies that deal/have dealt with and owned the fundamental IP in the technology.

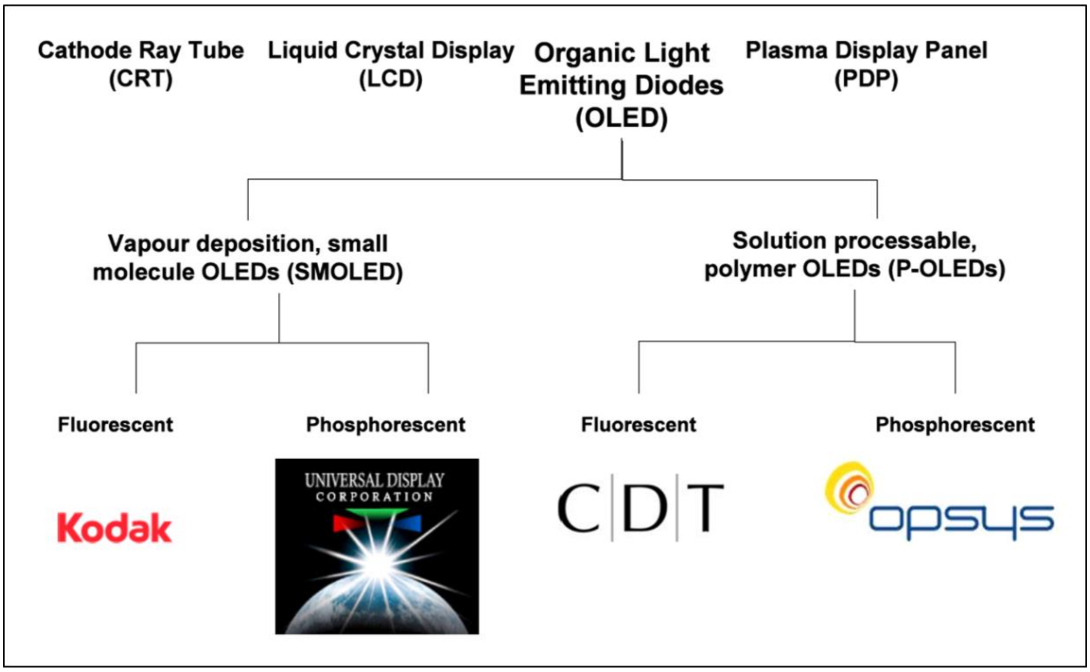



***Figure 1.16: The relative position of OLED materials, in particular fluorescent POLED materials discovered at Cambridge and commercialised by CDT, in context with other display technologies. (Source: Minshall et al., 2007, p229)***

## 1.9 Conclusion

This chapter has explored the historical background of the basic elements of matter, through their discovery and classification by ancient philosophers and alchemists, and how modern day scientists have built opon these principles to explain the behaviour of complex compounds. Using carbon allotropes as an example, it has culminated in an explanation of the nature and properties of organic copolymer semiconductors, in particular, OLEDs. Emphasis was placed on the working principles of heterojunctions, whose manipulation has been employed in numerous useful commercial applications in electronic devices as we will discuss in successive chapters.

# 2.0 The Dynamics of Innovation

## 2.1 Introduction

Having explored the physical and chemical principles underlying POLED devices, this chapter aims to paint a socioeconomic picture of the technology, and innovation in general. This will firstly be done through an innovation dynamics review of the factors that influence the proliferation of an innovation, to show that the process of innovation is not an isolated event (this chapter), and secondly, through a technology survey of an analogous technology - inorganic semiconductors - in the next chapter. The innovation dynamics study aims to provide a holistic picture of the path of innovation, showing how the different socioeconomic factors interact to influence the path an invention takes from the conception to market and beyond. The discussion culminates in an analogy between technology development and biological evolution. The main factors anticipated to affect POLED development are highlighted.

## 2.2 The Nature of Innovation

The usual pattern of development in science is through a series of successful paradigm shifts, which create different and better technologies. Thomas Kuhn, a physicist, historian and philosopher of science who coined the term 'paradigm' explained a paradigm shift as a fundamental change in the basic concepts or practices of a scientific disciplines (Kuhn, 1970 at p10-11). For example, artificial lighting was first provided by candles and tallow dips. These were superseded by the gas flame, the gas mantle, and following the introduction of reliable electricity supplies, the carbon filament lamp which was itself successively replaced by the more efficient fluorescent tube, and in recent times by light-emitting diodes (LEDs) (Cullis, 2007 at p561; Tonzani, 2009). In communications, the semaphore and signal fire were superseded by the electric telegraph, the telephone, wireless radio, television and fibre optic cables, each advance permitting more rapid transmission of data (Cullis, 2008). In the display of moving optical images, OLED devices are slowly replacing flat panel displays such as LCDs and plasma displays, which themselves replaced cathode ray tubes (CRT), film projectors and moving mechanical arrangements of mirrors.

Kuhn concluded that the series of revolutions/paradigms through which science progresses themselves have a structure, to quote: (1) normal science; (2) puzzle-solving; (3) paradigm; (4) anomaly; (5) crisis; and (6) revolution (Kuhn, 2012 at px-xi). In other words, somewhere in between the workings of day to day scientific research and attempts to solve extant puzzles to fill knowledge gaps (or find novel solutions), an invention/paradigm arises which creates an anomaly (uncharted scientific territory); this leads to a crisis whose resolution would come in the form of a new paradigm that then initiates the next revolution.

Science is the pursuit of knowledge for its own sake, the objective being discovery. Technology is the translation of that knowledge into everyday products and services that can be used to improve human life. Since technology is the application of science, Kuhn's deductions as to scientific revolutions can be extended to apply to technological advances. Indeed, several scholars conclude that technology, just like science, develops through two main stages: continuous change that progresses along a particular technological trajectory, until a radical change (new paradigm) affects the course of that trajectory (Dosi, 1982 at p152; Mackenzie and Wajcman, 1999 at p13; von Tunzelmann et al., 2008). Dosi in particular asserts that these technological trajectories are often a set of interrelated and ubiquitous solutions to problems associated with research and development, each solution having a distinct bearing on the market (at pp.151-157). Some solutions are likely to lead to a radical innovation, changing the trajectory of the technology and thus significantly affecting the market, while other solutions that are not as radical keep the technology in its trajectory, barely affecting the market. These changes are more incremental than what Kuhn deduced for scientific paradigms.

Although extremely useful, these scientific/technological resolutions oftentimes create disruptive change (Kuhn, 1970 at p66; Bower and Christensen, 1995). Because of the change in paradigm, they are likely to create a new network of players and to feed a new market, eventually disrupting established markets, key players as well as products. This for example would include the introduction of electricity as a source of lighting in a market dominated by gas lighting, or the invention of the automobile when bicycles are the primary mode of transportation.

Accordingly, paradigm shifts are typically incommensurable although they may be explained by drawing an analogy, particularly between similar technologies or events (Kuhn, 1970 at p103). Throughout this study, it should become evident that POLED technology, which itself was initiated by a revolution comprising the discovery of organic electroluminescent semiconductor materials, is a revolution that is currently at the crisis stage - where current research is centred around finding solutions to the technology's shortcomings. Those solutions will consequently spark off other revolutions, and the cycle continues. The disruptive nature of the technology should also become evident.

Further, new ideas are generally conceived in several ways: (i) randomly or as a result of an epiphany; (ii) "blindly" or by the so-called "King Saul effect", where the search for a particular solution leads to a completely new opportunity; or (iii) systematically, where methodological improvements are made to particular techniques (Mokyr, 1990 at p277; Taton, 1957; Cullis, 2007 at p69-79). Cullis also mentions "sailing ship" conception, which is where the introduction of a new technology, material, concept, method etc. accelerates developments in another technology, albeit sometimes across different time eras (Cullis, 2007 at p98-99). Once ideas are conceived, they are typically discontinuous and follow a sequence, but steady progress is frequently inhibited by the need for some enabling process or event (Jewkes, 1968 at p100). Some authors majorly attributed this enabling process to economic factors (Wyatt, 1986) but over the years several other factors have shared the stage, including the discovery of a suitable material or method for construction of a device; market structures that may or may not influence further investment into research and development; the role played by the inventor(s); knowledge dissemination; IP policy such as patent monopolies; the influence of cartels; loss of continuity in extant technologies; or indeed external stimuli such as, war that encourages government or military funding into new technologies or those complementary to extant ones to enhance defence systems, or urbanisation that may blow investment in a particular direction (Schumpeter, 1950; Jewkes, 1968; Schmookler, 1966; Kingston, 1977; Korres, Marmaras and Tsobanoglou, 2004; Maine and Garnsey, 2006; Cullis, 2007).

Additionally, the hierarchical structure of these factors varies according to the type or industry of the innovation, with at least one factor determining the extent of the profit earned by the innovator and the others playing the part of negative or positive modifiers (Cullis, 2007 at p8). The discovery of a new fabrication technique for example might drive a certain innovative device; availability of resources (say financial, personnel, manufacturing infrastructure etc.) will positively influence the device's commercial journey but if there is a lack of a market for it, it can only go so far before it either has to be modified or be put back on the shelf to become a teaching tool. On the other hand, if the market is available, then innovation costs are easily recovered. In other scenarios, the use of the device could be stifled by the existence of IP rights that would be infringed by its use; be subject to a government secrecy order for matters of national security; or even be introduced on the market at a less than optimal time because either the consumer isn't ready or educated about it or there is already an easier understood and more affordable product. Innovation thus does not take a straightforward path and understanding its dynamics so as to reveal alternative courses of action is crucial to innovators, investors and researchers alike.

The economist Joseph Schumpeter proposed that innovation happens in two dynamic phases. The first, disruptive and characterised by frequent paradigm changes, and once the technology has settled down, the second, in which the dominant paradigm which emerges from the first phase is continuously improved (Schumpeter, 1950 in Part II). He also asserted that economic change revolves around innovation, entrepreneurial activities and market power. Changes which happen during the first phase would provide a market advantage and create a temporary monopoly which, in turn, would provide a further incentive to innovate as well as enable recovery of innovation costs (Schumpeter, 1950 at p98-102). However, competition from imitators would soon deplete these abnormal profits, making way for a dominant paradigm to emerge. Moreover, whilst the process of innovation (the first phase) may itself be cheap or free, making the innovation commercially feasible (the second phase) is not. The latter costs therefore determine the commercial returns, the subsequent investment in its improvement, and in turn, how it later evolves. Eventually, more important secondary inventions which yield larger returns arise from exposure to technical and economic factors rather than as a consequence of principal inventions (Usher, 1920 at p274).

Other researchers have proposed several patterns that innovation follows but the most typical is discontinuous. Like Schumpeter, most agree or at least recognise that the innovation process comprises: (i) periods when radical concepts are developed; and (ii) periods of development, imitation or commercialisation of the dominant concept (Jewkes, 1968; Schmookler, 1966; Utterback and Abernathy, 1975; Nelson, 1995; Breschi, Malerba and Orsenigo, 2000; Korres, Marmaras and Tsobanoglou, 2004; Godin, 2008; Fontana et al., 2012; Aghion et al., 2014). Most believe this discontinuity results from several factors including the emergence of new markets, new technologies, political rules, evolving business models, unexpected events such as terrorism, natural disasters etc., and that the innovator has to manage this discontinuity in order to stay in the game (Mann, 2006).

Notably, a paradigm can in the midst of this discontinuity acquire a dominant position (or a long lifetime) that may limit future developments. This is most exemplified by so called legacy systems that are common in computing where modern computers have to use the architecture imposed by the Intel processor, granting the paradigm initiator a dominant position (Ungson and Trudel, 1998 at p112 & 189). Gordon Moore, the founder of Intel, epitomised legacy systems in his quote: "*Don Estridge, the man responsible for the IBM PC, really defined compatibility for us. Before that compatibility pretty much meant recompiling software. The Intel architecture carries some warts, some wrinkles that we'd rather not have. It would be nice to throw it away and start with a clean sheet of paper. But with all that installed software, that's not something we can do.*" (Cullis, 2007 at p203, also see pages 112 and 188). There are several reasons why this may be, including the fact that they meet consumer needs and are performance and cost effective. The technology under study here is showing the seedling to such a system.

## 2.3 The Biological Analogue

Like technological change, biological evolution consists of sharp transitions separated by periods of continuous adaptation to the environment. Over the past two decades, the two have often been compared because of this discontinuous nature. This analogy has a long venerable history. Several researchers have examined its potentialities and came to a similar conclusion; that although it may be limited because the parallels are incomplete, it is nevertheless useful for modelling the innovation process (Nelson and Winter, 1982; De Bresson, 1987; Mokyr, 1990; Basalla, 1988; Hull, 1988; Maynard Smith, 1972; Ruse, 1986; Gould, 1987; Arthur, 1989; Solé et al., 2012). They also agree that both develop sequentially in time, with some form of selection process at each stage enabling the best ideas to survive. Mokyr summarised the similarity in the following terms:

> *"Like mutations, new ideas represent deviations from the displayed characteristics, and are subjected to a variety of tests of their performance against the environment. Like mutations, most are stillborn or do not survive infancy. Of the few that do, a number of ideas are actually reproduced, that is, are transferred to other specimens. Natural selection may well operate through changes in gene frequencies without mutation, simply by more adaptive species dominating the processes of Mendelian inheritance. Yet the stationary state in which a single superior species dominates the environment may not ever be observed. By the time the new species has replaced the old one, new mutations may have occurred creating an even more successful form. …………………Technological change follows a similar dynamic. At any given time, we observe a best-practice (most up to date) technique, as well as an average-practice technique reflecting older practices still extant. For a one-shot innovation, the competitive process will, under certain circumstances, eventually eliminate the obsolete technologies, and produce uniformity in production methods. But if novel techniques are continuously 'born,' no single best-practice technique will ever dominate the industry"* (Mokyr, 1990 at p277-278)

Further, Goldschmidt distinguished between macro-mutations; great changes that create new species, and micro-mutations; continuous and cumulative changes within a species (Goldschmidt, 1960 in Parts III & IV). Calling to mind Schumpeter's two phases of innovation and drawing an analogy to Goldschmidt, the technological analogue would be the concept of a primary innovation or macro-invention; one responsible for a major paradigm shift (phase 1), and of a secondary innovation or micro-invention; one that extends the dominant technology (phase 2) (Cullis, 2007 at p21; Mokyr, 1990 at p289-297).

The main criticism of this analogy is that biological adaptation is passive, unintentional and usually within the same or closely related species while in technology, ideas are often transferred between individuals faced by a common problem, usually from unrelated disciplines (Sahal, 1981 and Basalla, 1988).

Arguably, innovation would therefore be more adaptive than if it were purely random (Mokyr, 1990 and Cavalli-Sforza and Feldman, 1981). Biological advances such as genetic modification that have permitted the transfer of DNA across unrelated species have gone some way in counteracting this criticism (Cullis, 2007 at p22).

Another criticism is that biological evolution can be modelled in two major ways: gradualism and punctuated equilibrium (Darwin, 1871 at pp119-120; Eldregde and Gould, 1972 at pp.82-115; Dawkins, 1996 in chapter 9 pp.224-252). Gradualism states that changes and thus variation amongst species happens over a gradual period of time, as a result of slow and incremental changes that are not normally visible from one generation to the next. The second model, punctuated equilibrium, is predominantly characterised by stability, with species changing very little for millions of years; however, this pace is "punctuated" by sharp bursts of change that introduce new species. Even though the two biological models have differing and distinct results, technological change bears similarity to both.

Nevertheless, the analogy between biological evolution and technological progress suggests some convenient hypotheses to test when modelling the innovation process. Quite usefully, the similarities and differences between evolution and technological change are summarised in table 2.1 below. For example, the path that both will take depends on the resistance to change (Mayr, 1988 at p424). Both are constrained by the environment, because the further the move away from the norm, the greater the costs as the existing cohesion has to be broken. For success therefore, the invention must be feasible both technically and economically, and have no direct equivalent - so that it is born into a sympathetic environment as it were (Mokyr, 1990 at p291). The path dependency of evolution is also emphasised, stating that possible developments are determined by the starting point (Nelson and Winter 1982 at p142). The same concluded that intermediate steps are of no significance as several options are available; what is important is the start and end point.

## Comparing Technological and Biological Evolution

### Similarities in biological and technological evolution

Consider the following parallels in biological and technological evolution:

| Biological evolution | Technological evolution |
|---|---|
| Occasional appearance of mutations | Occasional appearance of new ideas |
| Same mutations repeated in different organisms, in different time and places | Same ideas repeat themselves in different systems, in different times and places |
| Increasing probability of mutations along with deterioration of the environment or other conditions | Increasing probability of generating new ideas and concepts along with increasing number of problems in existing systems (deterioration of conditions or the appearance of threats) |
| Natural selection of the most appropriate organisms based on environmental conditions | Selection of the best technical solutions by the market |
| "Fight for survival" as a driving force of evolution | The fight for market share as a driving force of evolution |
| Selection of successful organisms rather than successful mutations | Selection of successful systems rather than partial concepts |
| Selection according to the following basic factors:<br>• Functional efficiency of an organism<br>• Reproductive efficiency | Selection according to the following basic factors:<br>• Functional efficiency of a technical system<br>• Reproductive efficiency |
| Expansion of biological species into all possible ecological niches | Expansion of technical systems into all possible ecological niches |
| Evolution of evolutionary mechanisms | Evolution of evolutionary mechanisms |

### Differences in biological and technological evolution

Consider the following parallels in biological and technological evolution:

| Biological evolution | Technological evolution |
|---|---|
| A biological system (organism) reproduces itself | A technological system does not reproduce itself |
| Species preservation at the expense of preserving information stored in the genes of every organism | Technical system preservation at the expense of storing information outside of the system (drawings, descriptions, etc.) |
| Generation of mutation caused by occasional mistakes in the "reading" of genes | Generation of changes caused by:<br>• Occasional mistakes<br>• Purposeful activities of engineers |
| Selection via elimination or removal of the reproduction function from the worst samples | Selection via:<br>• Elimination or removal of the reproduction function from the worst samples<br>• Choosing the best samples for reproduction |
| Narrow acceptable range of environmental parameters (pressure, temperature, radiation, components, etc.) | Wide and continuously increasing range of acceptable environmental parameters |
| Strong restrictions on acceptable materials | No restriction on utilized materials |
| Near impossibility of transferring "solutions" between remote species | Ability to transfer solutions between remote technological systems |

***Table 2.1: A tabulation of the parallels between biological and technological evolution (Source: Ideation International 2005)***

Another example is that the future path of the innovation/biological evolution is determined by economic choices; each affecting the subsequent one (Arthur, 1989 at p117 & 128). Selection occurs at every step of the evolution. Previously unsuccessful routes may not be retraced, leading to a binary-decision nature - in essence, a choice between two alternatives: doing something or not - or "branched character" of the selection process that gives rise to innovation patterns resembling biological phylogenetic trees (Schumpeter, 1934 at p6; Basalla, 1988 at p190; Mokyr, 1990 at p285; Cullis, 2007 at p21; Solé et al., 2012 at p9-10).

Interestingly, evolution does not always ensure "*survival of the fittest*" in the strictest sense. Often, geographical isolation has the effect of subjecting different populations to different selection pressures (Mokyr, 1990 at p278), with the result that weak species can coexist alongside stronger ones. This alludes to the notion of either effectively competing to come out on top or successfully collaborating with others to stay in the game. In technology, different techniques can similarly coexist if the less efficient possesses property rights to a specific resource that enables it to avoid direct competition with the more efficient one. This is where innovation interacts with intellectual property rights such as patents. By definition, a patent is a right granted by the State to an innovator to exclude others from commercially exploiting his invention for a limited period of time, in exchange for disclosure of the invention (Gader-Shafran, 2006). Individual innovators or Small-Medium-Enterprises that do not have the resources multinational corporations have may well stay ahead of the competition by using a vital patent as leverage. This concept will become evident throughout the discussions in this thesis.

Ecosystem is another conceptual term that has also been borrowed from biology (Nelson and Winter, 1982; Jackson, 2011; Oh et. al., 2016). In biology, an ecosystem defines a specific geographical area comprising a community of living organisms and their physical environment interacting to create a stable environment (Allaby, 2015). For example, animals, birds, microorganisms, trees etc. in a rainforest interacting with each other as well as the sun, climate, soil, water, air etc. The glue that holds them together is the transference of energy from one to another to facilitate growth and survival. Biological ecosystems are known to be controlled by both internal (e.g. soil, animal predators, rain) and external (e.g. hunters, tree fellers etc.) factors.

Similarly, an innovation ecosystem has come to be known as the diverse nature and number of participants and resources required to take the innovation through from the petri dish to the shelf. This would include the resources (materials, equipment, facilities, finances etc.) and personnel from involved institutions (academic and industry and in between). In other words, the interaction between the fundamental research and the commercial sector (Jackson, 2011). The glue here is the facilitation of technology development and innovation (at p2). Although cautiously approached and now widely adopted by the industry (Oh et. al., 2016), the analogy has proved a useful way to study the innovation process.

Timing is also important. Barzel states that it determines the date at which an innovation is socially optimal, in other words, when the maximum profits can be achieved by the innovator; when the best contribution to society can be made; and when the market conditions are favourable (Barzel, 1968 at p348). However, if the basic knowledge used by an innovator is free, he is likely to introduce the innovation when it becomes beneficial rather than when the profit would be maximised. In any event, his profits are affected by the actions of potential competitors, the market structure and whether the innovation is adopted immediately or gradually by both the industry and consumers (Mann, 2006). Intel Corporation, the world's leader in making silicon chips, used innovation adoption delay to control the profits of its competitors whilst amplifying its own (Cullis, 2008 at p61-62). Upon introduction of its chips on the market, it took advantage of the temporary monopoly - the response time monopoly - it had to charge higher prices for the product whilst its potential competitors were taking time to both understand and adopt the new technology, and before they could subsequently put imitating products on the market to create a price war. This period is what is crucial for an innovator to recover his innovation rent.

Further, inventions are solutions to problems. Oftentimes, the group of people that face the problem are far removed from those that have the solution, and for the invention to have maximum usability, or at the very least be realised, these two groups of people have to cross paths at the right time (Cullis, 2007 at p19). Such as was the case when the German blacksmith and goldsmith, Johannes Gutenberg, joined forces with wine makers in the 1450's to develop the printing press, which then made it possible to make copies of a bible (and eventually other works which were copied by hand) so that everyone in the village could afford the luxury of having a bible as opposed to gathering at the village church for one to be read out to them corporately. In contrast, the efforts of Julius Lilienfeld, one of the first scientists to propose a three-electrode transistor structure, failed because the semiconductor materials he needed were developed years later (Cullis, 2007 at p268) - this will be developed in context in chapter 3. Accordingly, an invention only has a limited window when the conditions are favourable.

All in all, innovation is not an isolated event; it does not happen in a vacuum. It requires the interaction of several factors that often need to coordinate to optimise profitability. In a study of "*inventions that changed the world economy*", namely, the developments of the incandescent filament lamp; wireless communication and the thermionic valve; the transistor; the microprocessor and the memory chip; and personal computers and software, Cullis summarised the process of innovation in the quote below:

> *"A roulette wheel is a deterministic system in which the ultimate resting place of a ball depends precisely on the physical parameters of its initial trajectory and those of the motion of the wheel. However, the financial returns are influenced by many other factors, such as the personality of the gambler, the management policy of the casino and the regulatory regime under which it operates, together with the success of a liaison with Lady Luck……….*
>
> *Likewise, the economic rent of engineering innovation is governed, inter alia, by the laws of physics, chemical properties of materials, the timing of inventions and the stimulus and countervailing action provided by intellectual property monopolies, competition laws and direct regulation, all leavened by the unpredictable advent of serendipity." Cullis, 2007 at px*

## 2.4 Commercialising an Invention

So what then happens when several of the previously discussed socioeconomic factors have lined up and a new and useful invention has successfully arisen? The innovator/company has to figure out how to derive value from its innovation (Teece, 1986). In effect: (1) to create value by converting it into a resource that aids further R&D and development of the end products; (2) to appropriate that value by profitably commercialising those products in the marketplace; all the while, (3) effectively managing competitors who would usually want a slice of the pie. This would in turn facilitate company growth and expansion.

Different innovators/companies adopt diverse strategies to commercialise new technologies (Lubik, Garnsey and Minshall, 2013 at table 1). In technology at least, some may choose to focus on developing their innovation and license the resultant IP rights to other incumbent companies to commercialise. Others may choose to develop, manufacture and license. Others may sell or license right off the bat. Within that context, some may choose to focus on niche markets to avoid competitors, others may target mainstream markets. The route taken depends on several factors, including the company vision, availability of resources, facilities/infrastructure, personnel, knowledge, maturity of the technology, access to the consumer market, etc.

The adopted strategy will interact with the environment so at some point, it will be affected or influenced by others in the innovation's ecosystem. This introduces the concept of intellectual property which grants the innovator the right to inhibit from doing something with their invention, absent their permission. Effectively managing a company's IP will not only signal to others in the ecosystem within which their fence boundaries lie and thus avoid trespass (in the form of infringement), it will also attract potential collaborators and investors, adding value to the company (Brant and Lohse, 2013). This is especially beneficial to small-medium companies that rely on collaborations to bring in requisite resources, expertise, infrastructure, exposure and access to the consumer market. Given the extent of knowledge sharing, effectively managing IP is crucial to these relationships.

This IP can be in the form of (1) registered rights e.g. patents, trade marks or registered designs; (2) unregistered rights or complementary strategies e.g. know-how, trade secrets or confidential information; or (3) a combination of (1) and (2). The first category consists of exclusive rights for a limited period of time, granted by specific governmental offices on adherence to specific criteria provided for by law; it can thus be enforced in courts, albeit on a jurisdictional level as the rights are territorial. The second is an expansive group of strategies (see Brant and Lohse, 2013 at p13-14) but we will focus on the above mentioned which are provided for in IP case-law. The IP types focussed will be discussed in detail as and when the need arises.

### 2.4.1 My Hypotheses

CDT was established in 1992 shortly after the discovery of POLED technology, with the objective of drawing commercial value from the technology. An early decision was to file patents to protect the core of the technology. My hypothesis is that in addition to other socioeconomic factors, IP has made a significant contribution to the commercial development of POLED technology.

CDT has been the subject of a handful of top-down economic studies. Seldon, Probert and Minshall (2005) described the growth of CDT through its IP and technology strategies, and its partnerships up until 2005. Maine and Garnsey (2006) in looking at the market strategies adopted by advanced materials ventures proposed a model that highlighted the challenges they faced in getting their technology to market, and tested it on two case studies, including CDT. Minshall, Seldon and Probert (2007) analysed CDT's success with a particular emphasis on open innovation - drawing on the role of collaborations between start-ups and established firms - to comment on the commercialisation of university IP, and of disruptive technologies. Lubik (2008 & 2010) aimed at understanding how sixty-seven UK university advanced material spinouts created value in getting their innovations to market, based on how their business models evolved in response to their respective environments. And finally, Lubik et al. (2013) extended this by focussing on market selection strategies, in particular, those that mitigated the risk of potentially detrimental partner dependence that has been the death of many a venture.

They all agreed that the company's commercial success to a certain degree was tied to its IP. They came to this conclusion through a high level economics analytical viewpoint, looking at how CDT fared in its ecosystem, how its technology was matched to the market route chosen and how the selection of both academic and commercial partners helped it to establish a central position for itself in the POLED value chain.

Although those studies all agree that IP does play an important role in the commercialisation of CDT's technology, they did not consider it in detail, that is, from a patent to patent level. Further, none considered at all or in detail, the role played by other factors that affect innovation, namely, the effect of the technological developments (material improvements, device fabrication processes and complementary technologies); government/military involvement; the effect of timing; or the personalities of the inventors for example. These are the gaps that this thesis will fill, to paint a holistic picture of the technology's commercial development.

I postulate that I will, however, confirm this importance of IP by a bottom-up or molecule-market approach. I will firstly analyse the influence of individual patents to create a hierarchy of the different innovation steps to the invention as it stands today; a patent trends analysis will also draw some conclusions to the company's patenting strategy. This will show whether it mirrors the findings in the 'economic' case studies. Secondly, it will paint a picture of the dynamics of the innovation and test the identified factors through a novel model for innovation dynamics whose development was based on an analogous technology - inorganic semiconductors. Thirdly, the importance of IP will be illustrated through a patent citation analysis that has for years been taken as proxy for determining the value of individual patents within a portfolio. I anticipate that this will point to CDT's commercial success being significantly hinged to the success or failure of its IP, more specifically, certain patents.

## 2.5 Conclusion

The objective of this thesis is to document the dynamic process surrounding the commercial development of POLED devices. The path and nature of the innovation will be charted from conception to market, documenting both the internal and external factors that controlled its ecosystem. Right off the bat, the factors expected to play a role will be grouped in five broad themes: (1) technology development; (2) market; (3) regulation; (4) external stimuli; and (5) timing. The narrative is that when an invention is introduced, the market will react to it; the invention may be clear cut or more often a combination of several scientific advancements into a workable concept, in the form of a new material, a device fabrication method or an enabling or complementary technology. The market may respond classically in a demand-supply manner, particularly if the invention was introduced at a socially optimal time. Here the author intends to focus on the profits of the inventor in addition to how his competitors respond to the new dynamic; do they collaborate or compete? And as a result, is there generation or redirection of finances to match the new market dominant? Does the demand or lack thereof affect company R&D, corporate strategy, investment decisions, commercial behaviour, personnel mobility etc.? Of course this new 'furore' has to be regulated so everybody behaves. This may be achieved by establishment of IP (and in particular, a subsequent licensing programme) or adherence to competition law provisions. Do external stimuli play a part? Are there any other positive or negative enablers? And last but not least, the all-important role of timing; the effect of everything happening at right time or otherwise. Of course most of these factors are cyclic and may occur within the timeline in any order. These groups of factors are anticipated as the author expects they will oscillate between a combination of the patent analysis and the exploration of the analogous technology, supplemented by other secondary sources of information such as specialist journals and books on the technology and CDT company information and inventor interviews available in the public domain.

# 3.0 Technology Survey

## 3.1 Introduction

Having considered the socioeconomic factors that influence innovation, I will chart the developmental history of one of the major inventions in inorganic semiconductors, specifically, the transistor, postulating that this is the antecedent to the technology on which this thesis rests. The technology review will draw on prior art from fundamentally relevant patent specifications. In addition to other primary and secondary sources, the review will largely focus on an earlier study of the transistor, whose conclusion was cognisant of Schumpeter's two-phase structure of innovation (Cullis, 2004 at p305, 329 & 335). From this same research, several of the socioeconomic factors discussed in chapter 2 were examined, culminating into the development of the model for innovation dynamics that will be discussed later on in this thesis. The objective of this review is, firstly, to put into context and exemplify the economic theories in the preceding chapter, and secondly, because drawing an analogy with some of the signposts in the development of inorganic semiconductors will provide a useful starting point for studying organic semiconductors.

## 3.2 Technological Background to the Transistor

At face value, the transistor sounds like an improbable physics artefact. In reality, it is the backbone of modern technology, found in numerous everyday applications such as computers, televisions, radios, mobile phones, cameras and in almost everything electrical in our homes, hospitals, national defence systems, aircraft and so on. In its simplest form, a transistor is a miniature electronic component that can serve as either an amplifier or a switch, and considered as *the "nerve cell" of the Information Age* (Riordan, Hoddeson and Herring, 1999 at pS336). It is made from semiconductor material and its electrical properties can be manipulated as earlier explained in section 1.6 of chapter 1, adding impurities to the semiconductor lattice to create *n*-type and *p*-type regions. In that section, we discussed that *n*-type materials are those to which impurities containing surplus valence electrons can be added so that electrons flow in them more naturally while impurities containing fewer valence electrons are added to *p*-type materials to create the effect of positive charge carriers.

In early bipolar transistors, such as the one shown in figure 3.1, layers of *n*-type and *p*-type semiconductor are sandwiched together and connected to an electrical circuit:

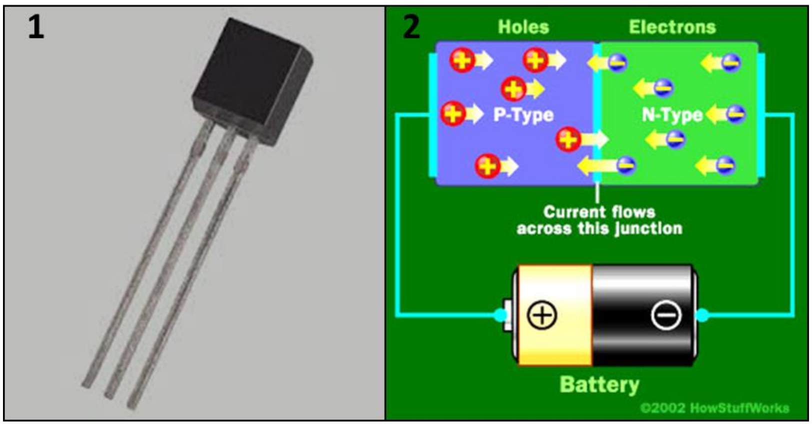



***Figure 3.1: (1) A depiction of a simple present-day transistor and (2) A schematic illustration of what happens at a junction when a silicon sandwich is connected to an electrical circuit (Source: Renewable Energy UK, 2014; HowStuffWorks)***

The bipolar transistor is controlled by electrical current flows across the junctions between the two types of semiconductor material. In essence, when a potential difference of the correct polarity is applied, charge carriers will flow across the junction from the n-type region to the p-type region and out through the circuit, but if the voltage is reversed, there is no current flow. A transistor can work as an amplifier, where a small electric current controls a much bigger current. It is used in mobile phones, televisions, radios, and signal processors like computers, cameras, electrocardiograms, hearing aids, pace makers etc. It can also work as a switch, where a tiny current through one part of the transistor causes a larger current to flow through another part of the transistor, as is the case in computer chips, which contain many millions of transistors.

Over the years, the fabrication of transistors has migrated from germanium to other semiconductor materials with more desirable electrical characteristics, such as silicon which has a stable oxide that protects the surface of the device from contaminants. Different applications in numerous electronic devices have been achieved simply by what type and how many different layers of semiconductor material are combined. Before transistors, electronic equipment was big, inefficient, unreliable and expensive. With its simplicity, longer life, significantly lower power consumption and size, devices utilising the transistor are now smaller and can easily be mass produced. This has made many everyday electrical devices cheaper and easily accessible by virtually everyone. But as the historical chronology set out in Appendix 2 and Sewagudde (2011) will illustrate, the road it followed was not straightforward.

The novelty requirement for patentability inhibits prior disclosure of an invention to the public before the date of application for a patent (Patents Act 1977, section 1.1). Therefore, in order to create an historical chronology of the evolution of an invention, a framework may be built using published patents which chart the emergence of new technologies. To that end, patents relevant to inorganic semiconductors can be downloaded from the EPO database. This is a comprehensive listing of most of the patent applications and grants by patent offices around the world.

Cullis performed one such study (Cullis, 1966). He listed all, mainly inorganic, significant semiconductor device inventions made during the fifteen years following the discovery of the transistor effect at Bell Laboratories in December 1947 which created an explosion of inventive activity with frequent paradigm changes (the "Schumpeter A-phase"). This period of fifteen years was chosen because the device fabrication technology settled down (the "Schumpeter B-phase") with development of silicon planar technology and epitaxial deposition of crystalline layers at Bell Laboratories, Texas Instruments and Fairchild Semiconductor Corporation around 1960. Cullis' initial search revealed some 1040 published patents (appendix 7 of Cullis, 2004). He then created a phylogenetic tree by categorising those inventions based on how far removed each development was from the first transistor (the initial point contact transistor which will be discussed shortly) and the value of each contribution to the development of the art. An analysis of these patents prepared for a presentation to the Surrey Retired Members Branch of the Institution of Engineering and Technology is set out in Appendix 2.

## 3.3 The History of the Development of the Transistor

Prior to the invention of the transistor, it was known at the turn of the 20$^{th}$ century, among other things, that the conductivity of semiconductors could be affected by temperature (Faraday, 1839 at p122) and light, leading to the first conversion of light into electricity (Braun, 1982 at p15). As such, semiconductors were commonly applied in detection devices.

In the early 1890s wireless telegraphy signals were detected by a “coherer”. This was essentially a glass tube containing two electrodes spaced by a loose iron filing that would ‘cohere’ when a radio signal was applied, to allow flow of current; this current would in turn activate a bell or a recorder of some sort to symbolise reception of a radio communication (see figure 3.2). Although this was unreliable or inefficient, it provided the foundation for the discovery of the crystal detector - in particular, made of silicon carbide and galena lead sulphide crystals with a metallic “cat’s whisker” contact (US755840; US837616; US879067) - and the point contact transistor which will be discussed shortly.

In parallel, the thermionic valve invented by Lee de Forest in 1906, was used to amplify wireless signals; this came to be known as the audion. The essence was a three electrode (triode) vacuum tube containing a heated filament cathode that generated electrons thermionically, or when it became very hot (see figure 3.2). It was also an inefficient amplifier; amongst other things, the wires in the vacuum tube were not durable, the heat produced by the filament aged adjacent electronic components, cathode efficiency decreased with time and the vacuum tube was large and impractical for military applications (Cullis, 2004 chapter 5).

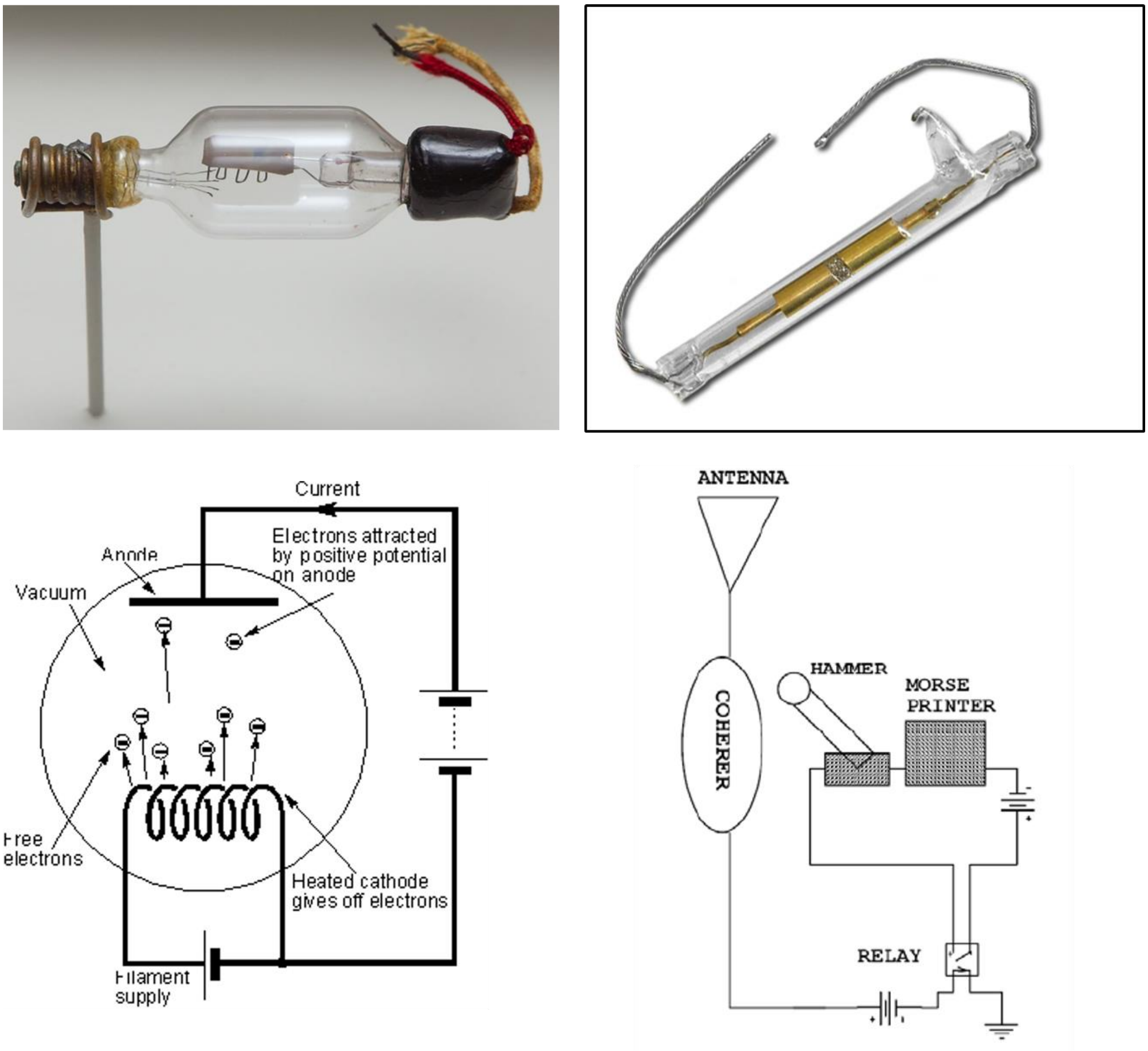



***Figure 3.2: A depiction of de Forest's audion (top left) and its working principal (bottom left), and an exemplar coherer (top right) and its working principal exemplified in a connection to a Morse printer to generate messages in Morse code (Sources: Maxwell, 2006; Radio-Electronics, 2016; Navone Engineering, 2016 and Aggarwal, 2015)***

At the end of the nineteenth century, much telegraphy research was concerned with building effective wireless signal detectors (Fritz, 1883; US879061; US879062; US879117; Pierce, 1907) in an attempt to circumvent the shortcomings of the coherer and the thermionic valve. These two major innovation drivers, fuelled by the need of the military for better radar detectors in the 1930s World War era largely drove the innovation of the transistor (Riordan, Hoddeson and Herring, 1999; Lojek, 2002; Riordan, 2004; Morris, 2004 at p701; Cullis, 2007 at p45-48). As will become clear, the transistor was a suitable solution; it was robust, tiny, consumed one thousandth of the power and its incorporation into devices could exploit already established technologies.

Julius Lilienfeld was one of the first to attempt to make a semiconductor amplifier. He proposed several structures for a three-electrode device in the late-1920s (US1745175; US1611653; US1877140). He wanted to build a solid-state amplifier device to replace thermionic valves, the standard at the time in wireless telegraphy practice. The fundamental concept was to make an amplifying device by controlling the flow of current between the two terminals of a semiconductor through an intermediate terminal which responds to electrostatic changes, heat, magnetic movement etc. to change the resistance of the material and thus affect the subsequent current flowing (US1745175; US1900018; US1877140). An example of his proposal is shown in figure 3.3:

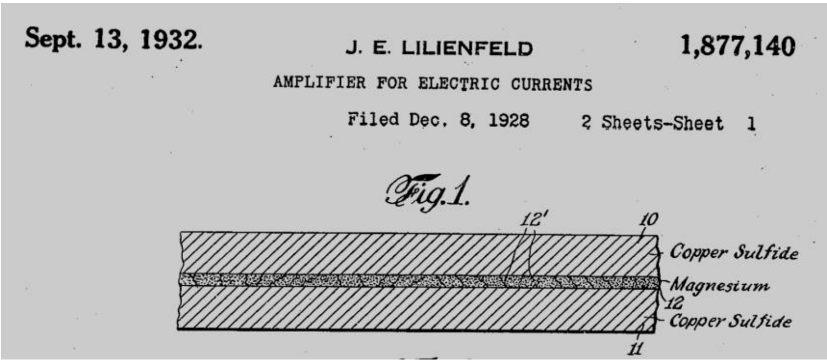



***Figure 3.3: An exemplary vertical section of one of four of Lilienfeld's proposed amplifiers using copper sulphide as the semiconductor and magnesium as the intermediate terminal. He proposed to attach an electrical contact to each of the layers to build the amplifier (Source: US1877140)***

Lilienfeld's efforts however failed because the polycrystalline cuprous sulphide semiconductor material available at the time did not support minority charge carriers (see chapter 1, section 1.6 for background). Nevertheless, his device topographies were the precursors of subsequent *npn* bipolar junction transistors (BJTs) and field-effect transistors (FETs). The former were current-controlled and used both electrons and holes to conduct electricity while the latter were voltage-controlled and used either electrons or holes for conduction.

At this point, it is relevant to introduce some basic principles of a three-electrode transistor or BJTs. They usually have three electrical contacts: an emitter, a collector and a base. The first two are usually connected to either ends of a region of a semiconductor wafer; the emitter provides the charge carriers which then diffuse across the base region to reach the collector. The base is the region or means which controls the current. These three contacts will be denoted by the letters E, C and B in some subsequent diagrams. The detail of an FET will not be discussed further in this chapter; the BJT initially became the dominant paradigm and will be the focus of the proceeding dialogue.

After Lilienfeld, Pohl and Hilsch in 1938 constructed a solid-state analogue of a three-electrode vacuum tube amplifier device (US841386) although it was not commercially viable because it would not work at a sufficiently high frequency to amplify any useful signal (Hilsch and Pohl, 1938). In the years that followed, several attempts were made to solve Lilienfeld's problem or at least, to conceive a viable alternative. Work at Purdue University in connection with the second World War was concerned with improving semiconductor materials by either doping semiconductors or creating alloys thereof (US2801376; US2745046; US2615966; US2637770) to fabricate devices which were used as detectors in radar receivers. Later, a team of experts in disparate technologies at Bell Laboratories investigating the fundamental atomic basis of semiconductors initially tried to control the current flowing in a semiconductor by generating an electric current from electrodes applied to the surface of a semiconductor (germanium) wafer - the so-called FET, but experienced similar difficulties as previous researchers, obtaining lower than expected signal magnitudes (Shockley, 1976 at p602; US2438110; US2441590; US2485069; US2469569; US2503837). Neither the Purdue nor the Bell Laboratory researchers actually investigated Lilienfeld's work although they needed to solve the problem that had prevented his success.

In 1946, John Bardeen, a physicist in the Bell Laboratories team proposed that the reduced gain of an FET could be explained as a result of what he called "surface states"; local fields created by the hanging bonds resulting from the crystalline nature of the semiconductor, that prevented an externally applied field from penetrating the semiconductor body (Shockley, 1976 at p605). With his colleague, Walter Brattain, they set out to prove this theory. They took current measurements using two pointed metallic probes pressed against the surface of the germanium wafer; these acted as an emitter and collector. Serendipitously, they discovered that a small current flowing between one electrode and the wafer controlled a much larger current between the two electrodes, hence producing amplification (Shockley, 1976 at p610-611;

Brattain, 1976 at p10). They conceived the first viable transistor in 1947, which came to be known as the "point contact transistor" (Bardeen, 1956; US2617865; US2438110; US2441590). Figure 3.4 illustrates this in a circuit:

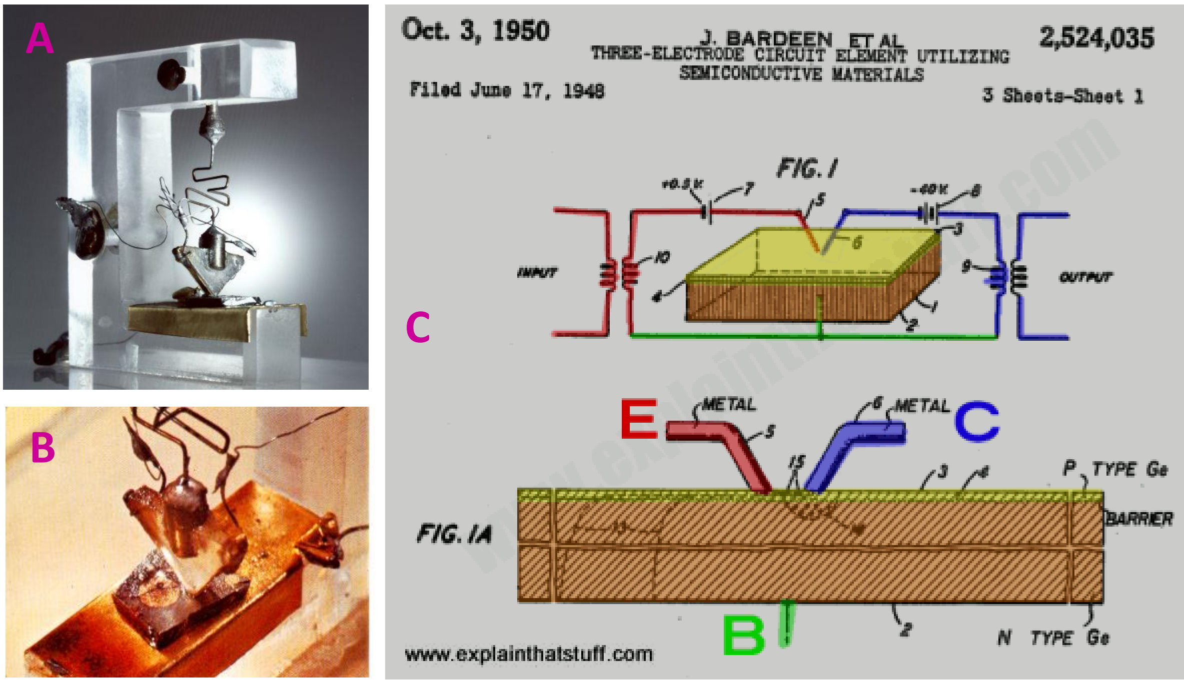



***Figure 3.4: (a) and (b) Bell Laboratories' point contact transistor publicity photos (c) a circuit diagram illustrating the principle of the point contact transistor. E, C, and B respectively represent the emitter, collector and base, and the yellow strip represents the "surface states" (Source: Computer History Museum, 2016 and US2524035, artwork courtesy of US Patent and Trademark Office)***

In parallel, the team leader, William Shockley, was looking at the theoretical basis of semiconductors. He proposed that if a single germanium crystal was made by sandwiching one narrow region having one extrinsic/doped type of conductivity (*n*-type or *p*-type) between two regions of the opposite conductivity, the current flowing to an electrode connected to the central region would have a direct link to the current flowing between the two outer regions, and this could provide the source of amplification (Shockley, 1976 at p602 & 614; US2569347; US2623102). This he called the "junction transistor". Figure 3.5 shows a simplified version of his proposal:

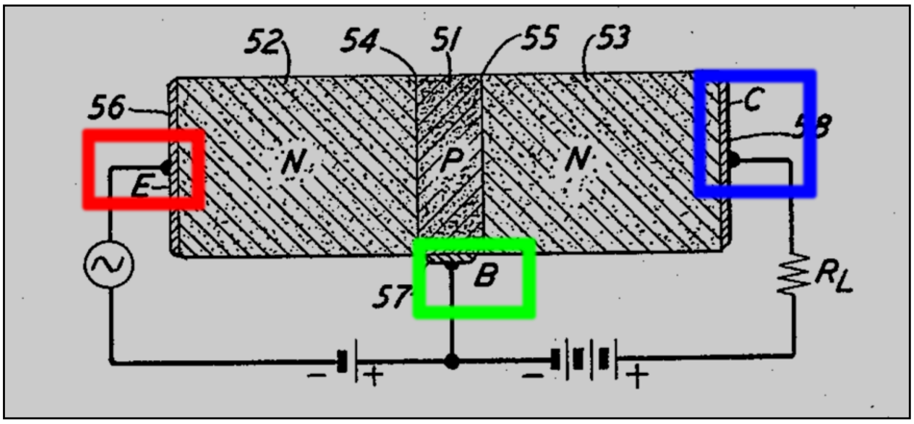



***Figure 3.5: Shockley's bipolar junction transistor showing an n-p-n semiconductor wafer with illustrative circuit connections. E, B and C respectively denote the emitter, the base and the collector (Source: US2569347)***

Shockley's theory was not put to a workable device for several reasons, including the fact that at the time, it was not possible to build crystals of that complexity and there was not enough semiconductor material to experiment with. The years immediately following Bardeen's and Shockley's discoveries were filled with improvements to the point contact transistor (US2524034; US2586597; US2524035; US2673311; US2626985; US2661448; etc.) and attempts to mimic bipolar junction structure using point contact electrodes (US2691750). At the same time, improvements to the FET were taking place but they were not widely adopted and so remained mere theoretical proposals (US2648805; US2618690).

Contributory to the success at Bell were several techniques specific to material processing that provided the basis for the subsequent successful device fabrication. Notably, the materials scientists developed a key method for preparing the semiconductor slices (US2606405), methods of depositing photoconductive semiconductor layers or their alloys onto a ceramic support (US2556991, US2556711) and a method of neutralising the effect of surface states by using a drop of an electrolyte (a liquid or gel containing ions) on the surface of a semiconductor) (Shockley, 1976 at p607-610). They largely focused their efforts on growing, purifying and refining large single and poly crystals of doped germanium using known and new techniques (Pfann, 1952; US2576267; US2739088; US2701216; US2750541). Joint efforts of metallurgists, material scientists, chemists and physicists yielded highly polished and purified germanium wafers that made the junction transistor a reality.

Further developments and modifications in fabrication methods in the industry made it possible to grow crystals with structures such as those earlier proposed by Shockley, the first being predominantly *n*-type with a thin layer of *p*-type material in the middle (an NPN structure). This was used to build the first BJT, the "grown junction transistor" (US2728034). The end result was a practical realisation of Shockley's theoretical proposal except the semiconductor wafer was obtained by growing a single semiconductor crystal with dopants added to the melt during the growth process. PNP grown-junction transistors were also made by the same method.

An improvement of the grown junction transistor was the "alloyed junction transistor", which stemmed from the search for a solution to the problem of making contact with the active regions of the germanium crystal (US3005132; US2999195; and US2733390). Many of the metals tried either formed brittle alloys with germanium or in some way affected the intrinsic electrical properties of germanium. The end result was a transistor with pellets of indium metal alloyed to opposite sides of a germanium wafer as shown in figure 3.6; these acted as the emitter and collector:

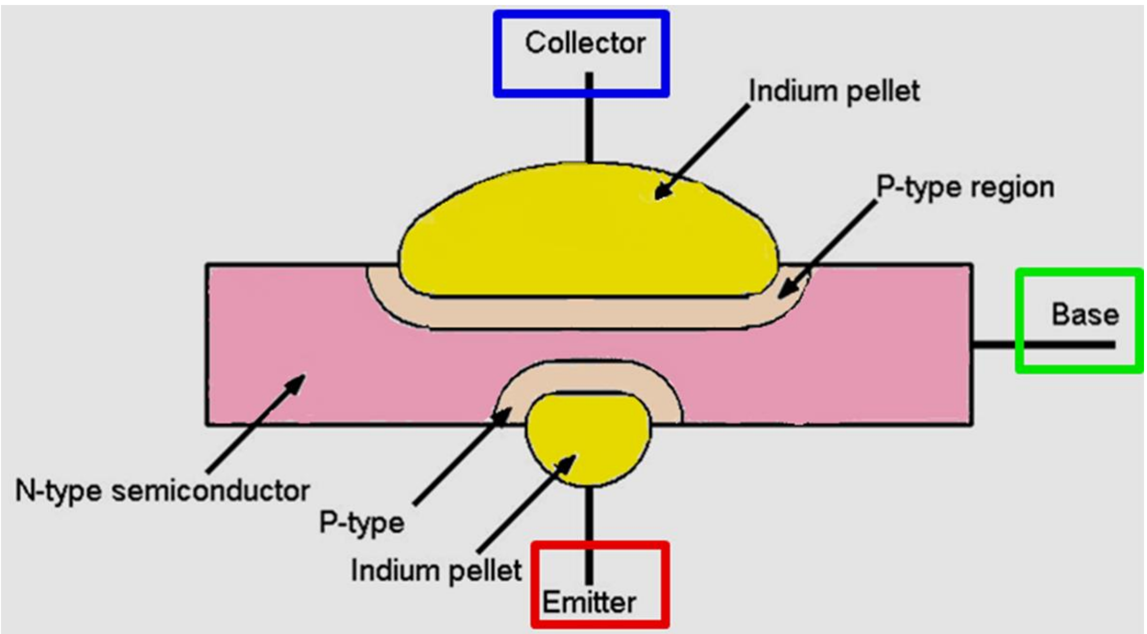



***Figure 3.6: Alloyed junction transistor showing yellow indium pellets alloyed to the semiconductor wafer (p-type in brown and n-type in pink), and the base, emitter and collector in green, red and blue respectively (Source: US3005132)***

Several modifications were made to overcome the shortcomings of the alloyed junction transistor, most notably: (1) alloying the indium emitter with gallium to improve its electrical properties, as pure indium did not produce an efficient emitter; and (2) development of the "post-alloy diffused transistor" (PADT) (US2663830; US2754455; US3160797). The PADT in simplistic terms, replaced the alloy with a thin layer of *n*-type semiconductor, followed by another thin layer of *p*-type semiconductor (Keihner, 1956; US3160799). This way, the bulk, thick semiconductor crystal became the collector (instead of the base), providing advantageous mechanical strength that was absent in its predecessor. The base was diffused on top of this, followed by two alloy beads; one *p*-type and one *n*-type, one becoming part of the base while the other became part of the emitter (shown in figure 3.7). The end result was donor and acceptor materials with advantageously complementary properties (Cullis, 2008 at p256).

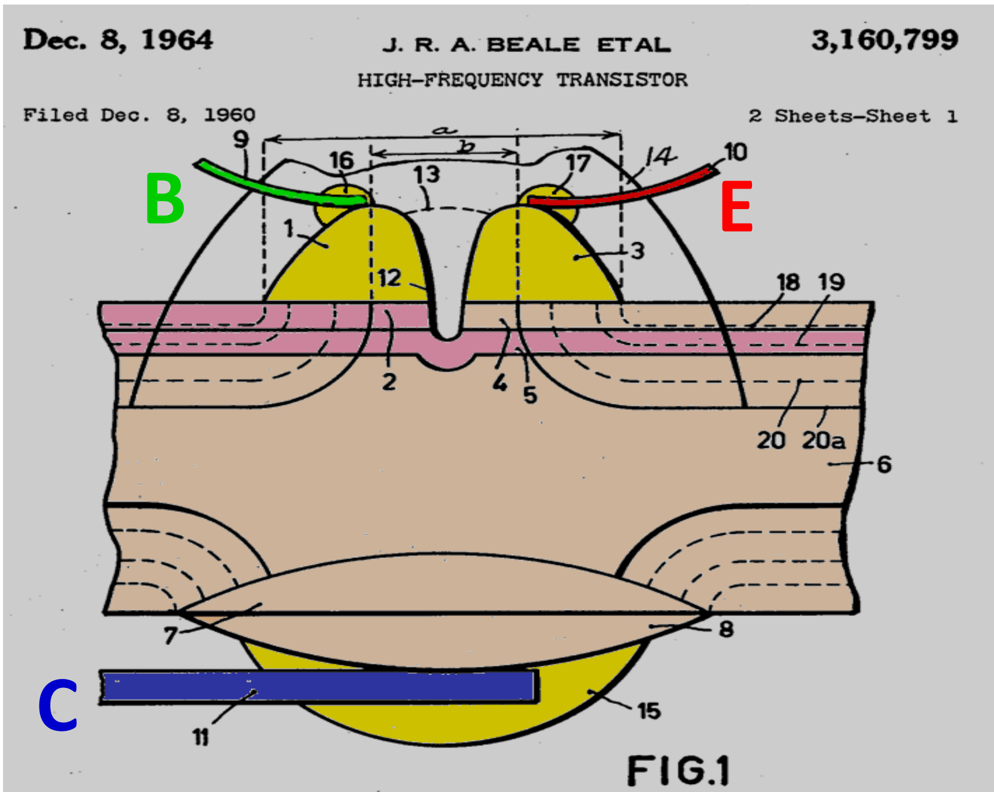



***Figure 3.7: An illustration of the PADT transistor showing the p-type semiconductor regions in brown (where regions 4, 7 and 8 fused with different proportions of other metals such as indium, gallium, lead or aluminium), n-type regions in pink, the indium alloys in yellow and connections to the base in lime green, the emitter in red and the collector in blue (Source: US3160799)***

The "double-diffused mesa transistor" was the first viable silicon-based transistor. Silicon, being in the same group of the periodic table as germanium, was long passed over as an alternative for building transistor devices due to difficulties arising from its metallurgical properties in comparison to those of germanium (Cullis, 2004 at p326). The first double-diffused silicon transistor was fabricated at Bell Laboratories in 1954 following the discovery that a layer of silicon dioxide easily grew on and protected the surface of a silicon wafer from impurities; the technique later came to be known as oxide masking (US2804405). This however was not pursued at the time for commercial reasons (Computer History Museum, 2007).

Shortly afterwards, Gordon Teal, a former member of the Bell Laboratories team and subsequently at Texas Instruments, established silicon technology at his latter employer - developing new fabrication techniques specifically suited for silicon to build the first viable silicon transistor (Riordan, 2004, Teal, 1954). One of these was a technique called epitaxy - a method for forming single crystal thin films - which he co-developed at Bell Labs with Howard Christensen (Cullis, 2008 at p256 and Cullis, 2004). They used an etched silicon dioxide layer to diffuse impurities selectively into predetermined regions of the slice, in other words, masking specific regions of the wafer surface and etching away the remainder. This created localised and flat-topped *n*-type regions similar the topography of flat-topped mountains (mesas) found in Mexico (see figure 3.8).

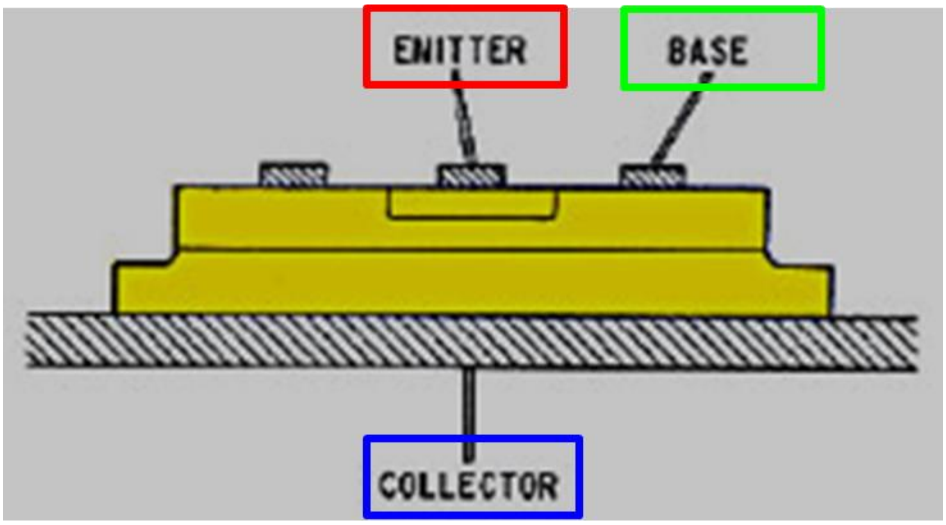



***Figure 3.8: The double-diffused mesa transistor showing the E, C and B electrodes, the semiconductor wafer in yellow and the mesas cut out of the top silicon dioxide layer in dashed black line squares (Source: http://spectrum.ieee.org/image/47335)***

The "double-diffused planar transistor" (see figure 3.9) was an improvement on the mesa transistor and resulted from a realisation by Jean Hoerni at Fairchild Semiconductor that leaving the silicon dioxide layer in place after impurities have been diffused into the wafer at the desired points actually made the transistor more stable (US3025589; US3064167). This overcame the problem of surface contamination that had caused several earlier transistor topographies to fail. Planar transistors were so named because the resulting device had a flat structure. In addition, Hoerni harnessed the phenomenon of "deathnium" that had caused early transistors to fail due to iron contamination of the semiconductor in the alloying furnaces. Deathnium was earlier explained by Shockley as an imperfection in the semiconductor crystal which resulted in deep quantum mechanical energy traps that reduced the lifetime of both electrons and holes (Shockley, 1956 at p347). Hoerni deliberately created these deep traps by diffusing gold into the wafer, enhancing the "switch-off" performance of the transistor to optimise its use in computer logic circuits (US3184347).

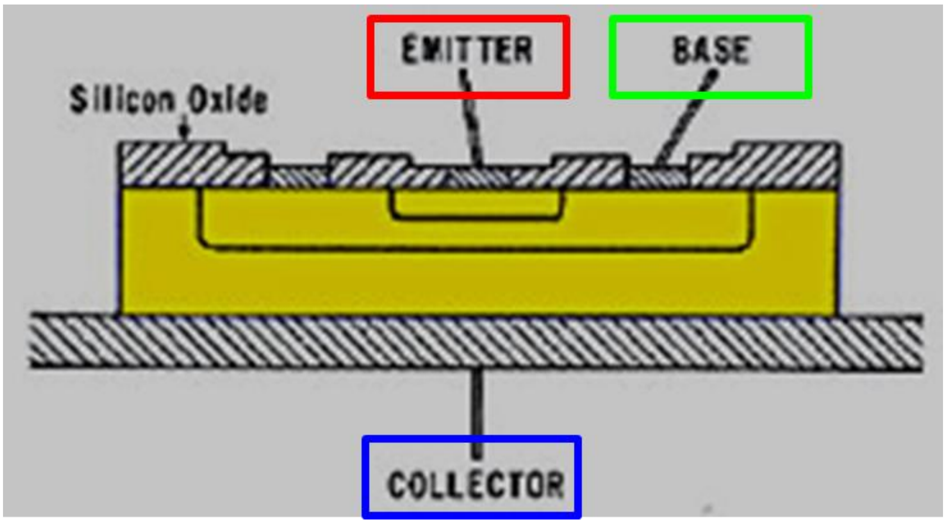



***Figure 3.9: The double-diffused planar transistor showing the E, C and B electrodes, the semiconductor wafer in yellow, the mesas cut out of the top silicon dioxide layer in dashed black line squares and the pre-existing silicon layer still in place (Source: http://spectrum.ieee.org/image/47335)***

Another improvement in fabrication methods was a process known as epitaxial growth; the addition of a layer of semiconductor deposited by decomposition of its halide or other volatile compounds to the surface of the semiconductor, by which the layer extended the crystal lattice structure. The method was pioneered by Teal and Christensen at Bell Laboratories (US2556711; US2692839). The advantage was that the proportion of the impurity dopant halide added could be used to control the dopant concentration of the semiconductor - failure to do this had previously led to the downfall of the first silicon double-diffused mesa and planar transistors (Cullis, 2004 at p316-317; Riordan, Hoddeson and Herring, 1999). The resultant transistor in which the product semiconductor wafer was used was named the "epitaxial transistor", and is illustrated in figure 3.10:

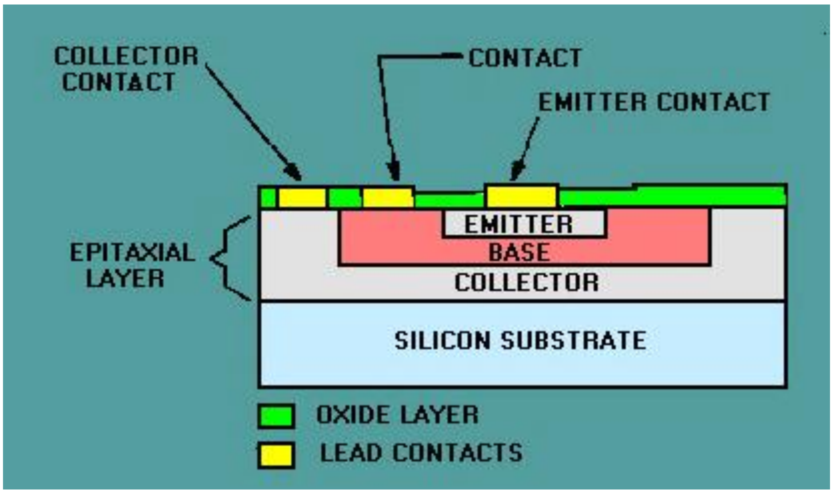



***Figure 3.10: The epitaxial transistor showing the three electrode contacts as part of the epitaxial layer and the silicon dioxide layer in place (Source: Integrated Publishing Inc., n.d.)***

By 1958, Jack Kilby at Texas Instruments proposed that electronic components could be formed in a single solid block, and built the first functional integrated circuit (US3138743; Morris, 1990). In essence, he built all the different parts of an electronic circuit onto a single germanium chip, connecting them with gold wires. Independently, Robert Noyce at Fairchild Semiconductor (a break-away company formed by former employees of Shockley Transistor Corporation) using Hoerni's work as a starting point also built an integrated circuit onto a silicon block (US2981877). Figure 3.11 illustrates their circuits:

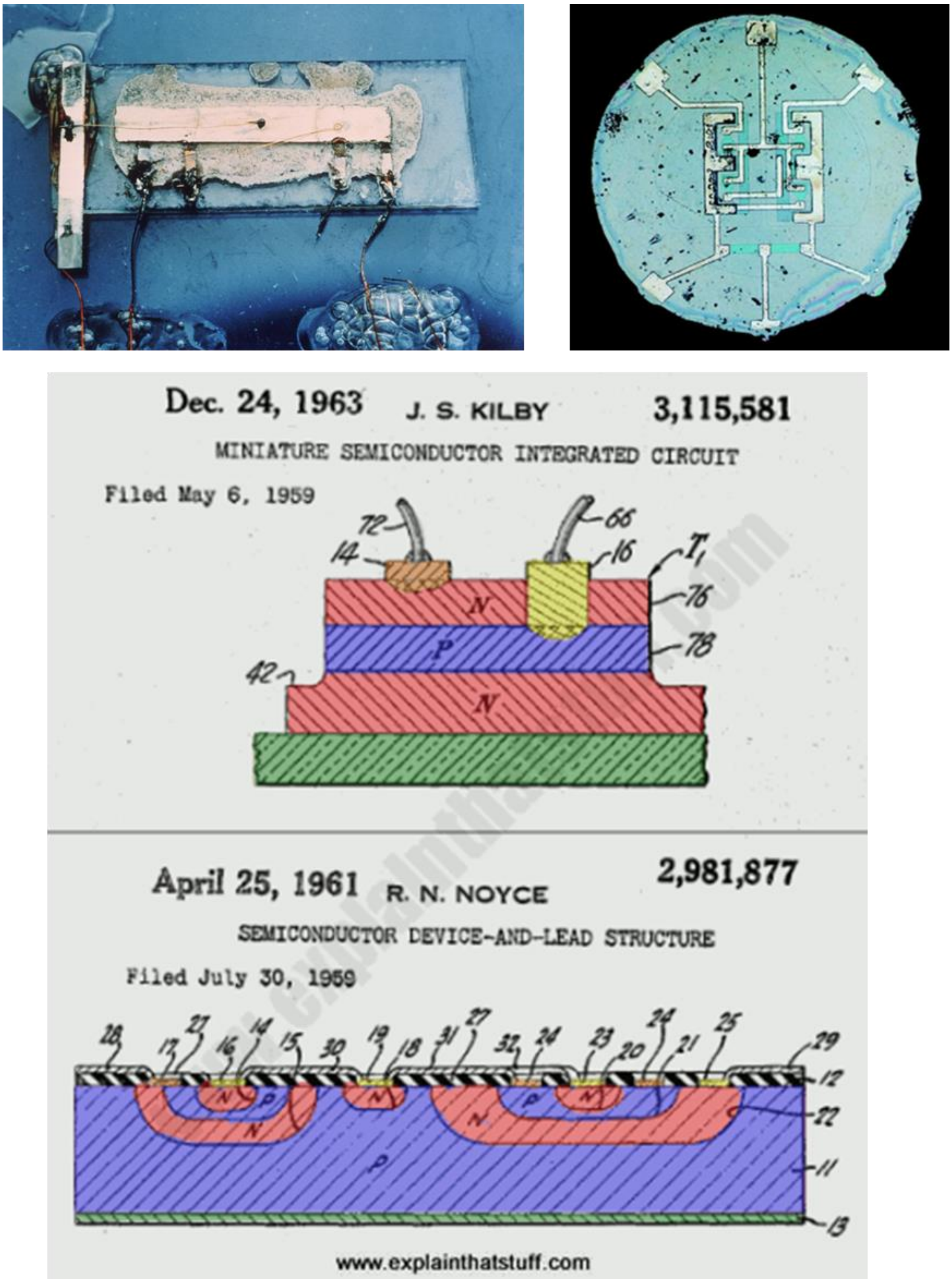



***Figure 3.11: Illustrations of Kilby's and Noyce's integrated circuits (top left and right respectively) with similarities colour coded: the doped semiconductor wafer shown in purple and pink, and the emitter, base and collector in orange, yellow and green respectively (Source: Lojek, 2002 at p231 & p234 and Woodford, 2013)***

Due to the similarity between the two circuit topographies, Texas Instruments and Fairchild Semiconductor unsurprisingly fought over the patent rights in the invention and after much contention, agreed to share the rights. Similarly, Kilby and Noyce jointly shared the Nobel Prize in Physics in 2000 for the "*most important and far-reaching technology developed in the 20$^{th}$ century*" (Woodford, 2013). In the years that followed, the semiconductor industry was awash with improvements to techniques used in building integrated circuits (US3234440; US3206670; US3137796 to mention a few) and their complexity greatly increased (US3304469, US3325652; US3320485; US3312879). This introduced a new era; the Schumpeterian B-phase.

## 3.4 Discussion

Albeit condensed, the history above clearly illustrates that the invention of the transistor was not an isolated event. It confirmed Kuhn's assertion (Kuhn, 1970) that the usual pattern of development in science is through a series of successful paradigm shifts that either create different and better technologies or solve previously encountered problems. In the time frame considered for this survey, there were 143 paradigm shifts which constituted: (1) observations or postulations of new phenomenon; (2) new materials or processing methods; (3) new or altered devices with improved or different characteristics; or (4) alternative constructions or topologies for existing devices (see Appendix 3).

One such paradigm was Faraday's discovery in 1833; this was the first documented experimental observation of what we now call semiconductors, when he realised that silver sulphide was affected by temperature in an opposite manner to what was expected of metals. This was followed at the turn of the century by investigations of different semiconducting materials for use as wireless detectors. From this resulted the invention of the transistor, itself followed by a flurry of research into semiconductor properties - marked by the 1040 patents filed in the first fifteen years alone - and into the possible applications of semiconductors as replacements for thermionic valve devices. A multitude of other patents were filed for their use in other fields.

In 1874, Braun found that current flowed freely in one direction when he probed a semiconductor crystal with a sharp metal point (Braun and MacDonald, 1982). This phenomenon was the basis for detection of current using a point-contact but found no useful application until the advent of radio in the early 1900s where new materials and processing methods meant it was possible to apply it in “cat’s whisker” crystal radio detectors (Pierce, 1907; US879061; US755840).

By the late-1920s, Lilienfeld had proposed three-electrode semiconductor amplifying devices and although these failed because he lacked suitable materials and resources at the time, his proposed device topographies were realised practically several decades later in the construction of viable FETs.

One of the biggest stimuli to innovate was the unexpected event that was World War II (1939-1945). Work on semiconductor materials processing for military applications at Purdue University provided the materials Lilienfeld and previous researchers lacked. These materials, in addition to an excellent research culture and a generously funded multidisciplinary team of exceptional skilled researchers that developed several techniques specific to material processing provided the platform for the successful invention of the first viable transistor at Bell Laboratories in 1947 (Cullis, 2004 at p330). They initially experimented with field effect transistors, experiencing similar difficulties as their predecessors but with the realisation of the possible existence of “surface states”, went on to conceive the point contact transistor. The latter led to a “sailing ship” effect, where 96 patents were filed in relation to improvements to this transistor in the 15 years following its supercession (see Appendix 3 - highlighted in purple).

Point contact transistors suffered considerable defects so efforts were directed to the more stable grown junction transistor similar to that which had earlier been proposed by Shockley in 1951 but had not come to practical realisation at the time until it was possible to build complex semiconductor crystals with uniform characteristics using new crystal-growing techniques. Of the alternatives which were far more efficient, the alloyed junction was universally adopted by the industry, PADTs were only made by Philips, and the rest of the industry made double diffused mesa transistors (Cullis, 2008).

When it was discovered that silicon could produce an oxide coating and operate at much higher temperatures than germanium, there was a shift towards silicon technology. This was followed by two significant advances that greatly increased the performance of the transistor. The first was the ability to control junction depth by high temperature diffusion which led to better performance at high frequencies, and the second, oxide masking during the diffusion process which electrically stabilised the surface of the semiconductor wafer. As such, it was possible to construct flat, planar devices; the double-diffused mesa and planar transistors. This planar approach made transistors more stable, reliable and much cheaper to produce because they could be encapsulated in plastic (Morris, 2004 at p702-703).

By the early 1960s, the combination of planar technology and epitaxial growth made it possible to construct integrated circuits, marking the transition from the Schumpeterian A-phase to the B-phase. The circuits were initially relatively simple but grew in complexity as skills in these techniques improved. Since all the circuits in the single block were fabricated simultaneously, there was minimal variation in the characteristics of the device before they were formed into “chips”, and hence increased reliability. As a consequence of Moore’s Law, which states that the number of transistors in an integrated circuit doubles approximately every two years (Moore, 1965), integrated circuits today can contain millions of transistors.

Fitting is Arthur. C. Clarke’s quote from *The View from Serendip*, that: “*Some electronic components are now so small that more time is spent looking for them than using them.*” (Clarke, 2011)

It is clear that the A-phase was discontinuous and frequent paradigm changes were the order of the day, punctuated by periods where radical concepts were proposed and periods of development, imitation or commercialisations of the dominant concept. The planar epitaxial silicon integrated circuit then emerged as the dominant paradigm, symbolising the B-phase.

In addition to the high-calibre of inventors involved, the success of this innovation can greatly be attributed to the physical properties of the materials that were harnessed to produce advantageous device topographies, as well as fabrication techniques that made this possible (Cullis, 2004 at p305). However, several of the socioeconomic factors discussed in chapter 2 can also be seen in play. For example, the conception of ideas was often systematic, where methodological improvements were made to particular techniques to overcome a specific problem (999 out of the 1040 patents or 96%). A few were conceived by the "King Saul effect". Notably, the search for a solution to the issue of "deathnium" turned out to be what was needed to make faster switching transistors. Similarly, the perceived problem that was the formation of the silicon dioxide layer, instead provided the support for interconnections required to make the integrated circuit functional.

Once ideas were conceived, their discontinuous nature was evident, with steady progress frequently prevented by the need for a suitable material or process. Discontinuity resulted from several factors, including new fabrication methods, and unexpected events such as wartime research which produced suitable semiconductor materials that catapulted the invention of the transistor. Innovators managed this discontinuity through their economic choices; the industry was growing at 30% per annum so they often abandoned technologies that did not work and rapidly adopted those that did (Cullis, 2008). At the same time, the economic growth of the industry at the time (the period of the Industrial Revolution) afforded them the luxury of revisiting previously abandoned ideas as and when the enabling materials or techniques for their viability became evident. Moreover, some players often either possessed or could easily obtain the skills and equipment necessary to innovate; those that could not were knocked out of the ring.

Timing also played a significant role. Shockley and Lilienfeld's ideas were not initially reduced to practice because they were postulated ahead of their time. In contrast, viable silicon transistors were mass produced after WWII, when the US government was heavily investing in the semiconductor industry because of their military potential and the space programme. At that time, the innovation was socially optimal; maximum profits were possible, the best contribution to society was made through improvements to radar technology that aided the war, and the market conditions were favourable. So the innovation thrived.

As Mokyr observed in drawing an analogy between technological change and biological evolution (Mokyr, 1990), some ideas, did not survive infancy or were bright ideas, such as the surface barrier transistor that failed because it was electrically and physically fragile, and required high maintenance machinery for fabrication (167 out of the 1040 patents or 16%). Of the few that did, some were reproduced, albeit several decades later, and others eventually faced the wall as uniformity was created in material processing and device fabrication methods. In the same vein, drawing an analogy to macro and micro mutations, it can be said that the point contact transistor which was responsible for a major paradigm shift could be classed as a macro invention, while vapour diffusion and oxide masking could be classed as micro inventions since they extended the dominant technology - the integrated circuit.

The interaction with IP rights is also evident. Several of the key stages in this development were conceived at major US corporations that had a culture of thoroughly protecting the IP generated through patents. Furthermore, Bell Laboratories could not directly exploit the transistor by making and selling the devices because of US anti-trust law restrictions that had arisen following the invention of the telephone. A licensing programme was therefore introduced and resulted into subsequent transfer of know-how to the licensees (Cullis, 2004 at p330-335). This also provided a unique opportunity to consider competition law from the conception stages of the invention. Moreover, technological know-how was transferred following the emergence of several technology start-ups, the movement of personnel seeking new opportunities, and the camaraderie amongst the semiconductor community in what came to be known as the "Silicon Valley Effect" (Hyde, 2015). This could have facilitated the adoption of new and superior techniques, rendering average-practice techniques obsolete.

Furthermore, from the chronology in Appendix 3, we can deduce from the 143 paradigm shifts considered (highlighted in yellow) that they are roughly 2-3 years apart. It is reasonable to assume that because of the nature of the technology and the industry, the time in between paradigm shifts was spent making improvements as well as filing patents. On average, it takes about 2-3 years for a patent to be granted, and the patent proprietor can only sue infringers after the patent has been granted (Patents Act 1977, section 60). Given that the turnover of innovative technology was every 3-4 years, it can be argued that the most useful patents were the 'major ones'; those mentioned above that covered the transistor and the integrated circuit, most likely to be owned by the major players. Of the 1040 patents, 167 belonged to Bell Laboratories, 89 to Texas Instruments and 26 to Fairchild Semiconductors. The smaller players that owned the 'smaller' patents, usually regarding improvements to the major paradigms, would see no need to sue for infringement as the technology would have moved on by the time they achieve the desired result. As a consequence, this in addition to the US anti-trust law restrictions would have influenced the licensing programme already mentioned. I would anticipate that this pattern will be repeated in the development of organic semiconductors.

## 3.5 Conclusion

From a commercial and research perspective, both the innovation dynamics analysis (chapter 2) and the technology survey (chapter 3) have demonstrated that holistically, the path of innovation requires the interaction of several factors that often need to coordinate in time to optimise profitability. The financial returns rest heavily on the laws of science, available resources, materials, skills, research culture, timing and the interaction with IP. The aforementioned surveys have shown that this is certainly the case for inorganic semiconductor technology. I postulate that it will apply to other forms of innovation, or at least, similar ones such as organic semiconductors. The aim is to perform a similar survey for POLED technology to ascertain whether the same factors apply and to what extent they have affected the development of the technology. The next chapter will outline the methodology as regards to how the patent search will be performed and how the data will be used to meet that objective.

# 4.0 Patent Analysis Methodology and Related Hypotheses

## 4.1 Introduction

Having surveyed the development of inorganic semiconductors in the previous chapter, the next step is to perform a similar study for organic semiconductors on the assumption that the technologies are analogous. This will permit us to identify the determinants of latter's success and their relationship to the socioeconomic factors described previously. This chapter will set out the patent analysis methodology for how the working data will be derived from the EPO database, and how it will be sorted and evaluated. It will give a rationale for carrying out a Patent Trends Analysis to make some general conclusions about the patent data obtained. From this, some hypotheses about the development of the technology on the basis of chapter 3 conclusions and in light of the socioeconomic factors that are expected to play a major role will be drawn.

## 4.2 Justification of the Methodology

Technology is crucial to the success of modern corporations and they develop technology strategies such as protecting new technology through patents to, among other things: (a) attract investors; (b) increase market share through exclusivity; (c) attract revenue through licences; and (d) build a defensive portfolio. Patents are therefore indicators of technology; they provide quantitative information on technology development, since it is usually the first time an invention is made public. Patents also assist with investment decisions and corporate strategic planning (Cullis, 2011).

When searching for patent documents, a **subject matter** search indicates all patents existing in a particular field, and since patent databases are continuously updated, new developments are listed shortly after they are realised. **Bibliographic information**, found at the beginning of a patent document and in official registers, reveals some key points: (a) inventors, patent proprietors, licensees or third party assignees; (b) indicates whether or not the patent is in force and for how long or whether it has expired; (c) the territories in which protection was or may be obtained; and (d) and the subject area to which it relates. If patent office searches or examinations have been carried out, details of related patents and literature cited, as well as those used in third-party oppositions to grant or cited by the applicant, are indicated, usually at the end of the specification.

Additionally, the **patent specification** typically contains detailed information of new techniques, products and processes in each industry. From it, the breadth of the monopoly awarded to a patentee can be inferred from a set of granted claims - this is a summary of what the patentee purports to have invented and is typically found towards the end of the patent specification document. The patent specification is the document that details the invention - it is initially called a patent application, and once the monopoly has been granted, a patent. Patent legislation requires descriptive disclosures of the inventions in the specification so patent literature often contains information not available anywhere else. Moreover, most territories, including the UK, have a legal requirement of novelty, meaning that an invention cannot be disclosed elsewhere either orally or in writing until a patent application has been filed (Patents Act 1977, section 2). Therefore, patent applications, which are published 18 months after the priority date (the date of filing of the patent application) often provide the earliest indication of a new development.

Furthermore and to mention a few, previous researchers have utilised this methodology to study the development of inventions: Schmookler, an economist who pioneered the use of patent statistics in a detailed study of the development of the chemistry, electronics, and machine construction industries (Schmookler, 1966), Cullis, who studied the path of innovation in the electrical, electronics and communications engineering industries (Cullis, 2007), Katila, a doctoral researcher who concluded that patent data was a useful way to measure innovation performance in the biotechnology sector (Katila, 2000), and surveys into the use of patent data to measure technological change (Griliches, 1990; Archibugi and Pianta, 1996; Basberg, 1987; Yoon and Lee, 2012).

It is apparent from the foregoing that patents can reveal sufficient data about an invention and are a good, if not the best place to start in order to map its historical development. Logically, therefore, the methodology described below has been selected to map the chronological development of POLED materials and devices.

## 4.3 Patentability

A patent is a right granted to an inventor by a government to exclude others from the economic exploitation of his invention for a specified period of time, in exchange for disclosing the details of that invention to the public. It is granted for an invention, which may be a product or a process, that is new (not previously disclosed to the public in an enabling manner), not obvious to a person skilled in the art (that is to say, having an inventive step), capable of industrial applicability and not excluded subject matter (Patents Act 1977, section 1). For the purposes of this thesis, we shall only concern ourselves with the first two patentability criteria, novelty and inventive step.

When a patent application is received by a patent office, it undergoes a preliminary search and examination, publication at the 18-month mark, and a substantive examination before grant (Patents Act 1977, sections 16-18). Once it is granted, and subject to the payment of annual renewal fees, it is in force for a period of 20 years from the date of filing of the application or the priority date (Patents Act 1977, sections 25). Under certain circumstances, the term can be extended by *sui generis* rights. After 20 years, the patent expires and the invention becomes available for the public to make free use of it.

The exclusive rights of a patent proprietor include: (1) the right to stop others from making, disposing of, offering to dispose of, using or importing, keeping whether for disposal or otherwise, a patented product; (2) using or offering for use, a patented process; or (3) disposing of, offering to dispose of, using, importing or keeping any product obtained directly by means of a patented process, without their consent (Patents Act 1977, section 60). The exception to this provision are licensees and third parties who have obtained consent to use the invention from the proprietor through licences or development agreements. The thesis will heavily focus on this group.

Further, patents are territorial and therefore validly enforceable for the countries in which protection has been granted. Although different countries have different laws that govern their patent systems, there is a degree of harmonisation in patent law. This enables filing and acquisition of a regional or international application or patent via the European Patent Convention (EPC), administered by the EPO, and the Patent Cooperation Treaty (PCT), administered by the World Intellectual Property Office (WIPO). On consideration of several factor such as budgetary and economic needs, the type of product/process to be patented, the geographical area within which the manufacture of the end products is likely to take place and where the main market exists, a patent applicant can apply for a patent via the national (e.g. UK), regional (e.g. EPC) or international (PCT) routes.

This is additionally enabled by the priority principle provided for in the Paris Convention, which allows an applicant who has filed a first application in a Contracting State to file a subsequent patent application in any other Contracting State for the same invention within a period of 12 months (Paris Convention 1883, Article 4). The later filed application is regarded as having the same filing date (now called the priority date) as the first application. Advantageously, the priority application is not affected by any events that happened within that 12-month period, such as novelty destroying prior art that may have been published during that time. This thesis will heavily centre on priority filings, US and PCT applications.

## 4.4 Methodology

Based on the methodology used to chart the evolution of inorganic semiconductor technology set out in chapter 3, it is proposed to use the EPO International patents database to build a chronology of the development of POLED technology. The primary source of information on the incidence of new inventions relating to the POLED technology will be the comprehensive listing of patent applications and grants from 1836 to October 2012 by patent offices around the world. This is available on the EPO database via the Espacenet search engine (Espacenet).

Light-emitting organic polymers were first observed in the Cavendish Laboratory at Cambridge University in 1989. When the weight of their commercial importance was evident, a spin-out, CDT was formed in 1992 to aid the commercialisation of that and subsequent discoveries. The polymers have since been used to develop POLEDs and the patents surrounding its protection has since grown extremely rapidly. There are several patent databases available worldwide from which to obtain patent application and granted patents. A quick search on the EPO database using the tag "organic semiconductors" reveals 3,378 patents and applications, while that under the tag "organic polymer light emitting devices" produces 519 general hits: both data pools are too large for the timeframe of this study (Espacenet).

I narrowed down this search by focussing on those filed by CDT as it pioneered the technology, and in 2002 won the MacRobert Award for it; this is the leading prize recognising UK innovation in engineering (Royal Academy of Engineering, 2016). The innovation was also nominated for the EPO Invention of the Year in 2006 (EPO, 2006). Several other awards won for the technology and by its individual inventors will be discussed in detail in chapter 6. An Espacenet search further revealed 1,979 patents owned by CDT; this was not inclusive of those patents CDT may have filed under shell companies or those related to the technology it may have assigned.

To obtain a manageable patent pool for analysis in the available time frame, I chose to look at patents that included the key inventors who made the discovery: Jeremy Burroughes, Sir Richard Friend and Donal Bradley. An iterative search revealed more than 300 organic semiconductor patents and applications owned by CDT and naming either all or combinations of those inventors in addition to other CDT inventors (Espacenet). A decision was made to focus the search on those that named Sir Richard Friend as inventor; in addition to numerous awards (University of Cambridge, 2016), he was knighted in 2003 for services to physics (The London Gazette, 2003) and he is also the world's most cited physicist (Minshall et al., 2007 p234). A search by his name should reveal a good chronology of key patents in POLED development, sufficient to meet the objective of the study.

To perform the search, three separate facilities are available: (1) smart search (2) advanced search and (3) classification search.

### 4.4.1 The Smart Search

This is the simplest of all, with a single field of search and requires the entry of key words such as inventor or applicant names, numbers, dates, keywords and classes in any order and without any specificity. These keywords may be linked by Boolean operators such as AND, OR and NOT. The database then recognises these terms using fuzzy logic to produce a basic response. Particularly useful search fields are company and inventor names, subject matter, country of origin, and date of filing. So the entry of keywords "*Cambridge Display Technology*" would be interpreted as a search for patents in the name of Cambridge [AND] Display [AND] Technology. This would retrieve patents assigned to CDT. Keywords "*Richard*" and "*Friend*" would be recognised as the names of an inventor and/or assignee and would thus retrieve patents naming Richard Friend as inventor. The search would be iterated for Richard Friend's laboratory contributors and collaborators until a saturation point is reached (where no new patents are found).

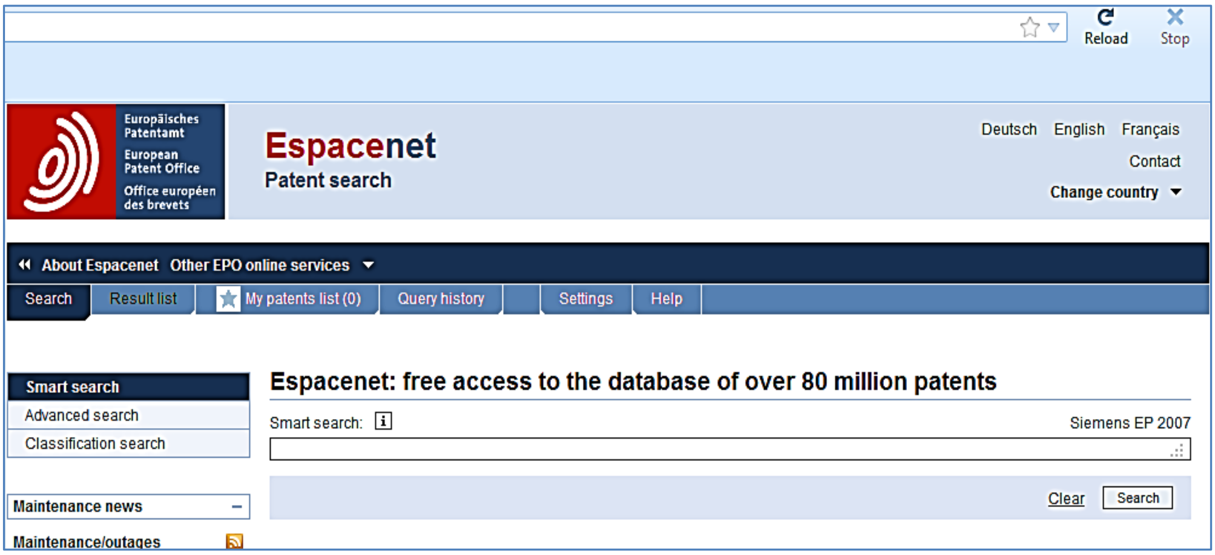



***Figure 4.1: A screenshot of a smart search menu from Espacenet.***

### 4.4.2 The Advanced Search

This permits entry of keywords by category as shown in figure 4.2. It is not necessary to enter keywords in all categories. This search provides fewer hits, but more relevant results than the Smart Search and may indeed be used to verify the results obtained from the Smart Search.

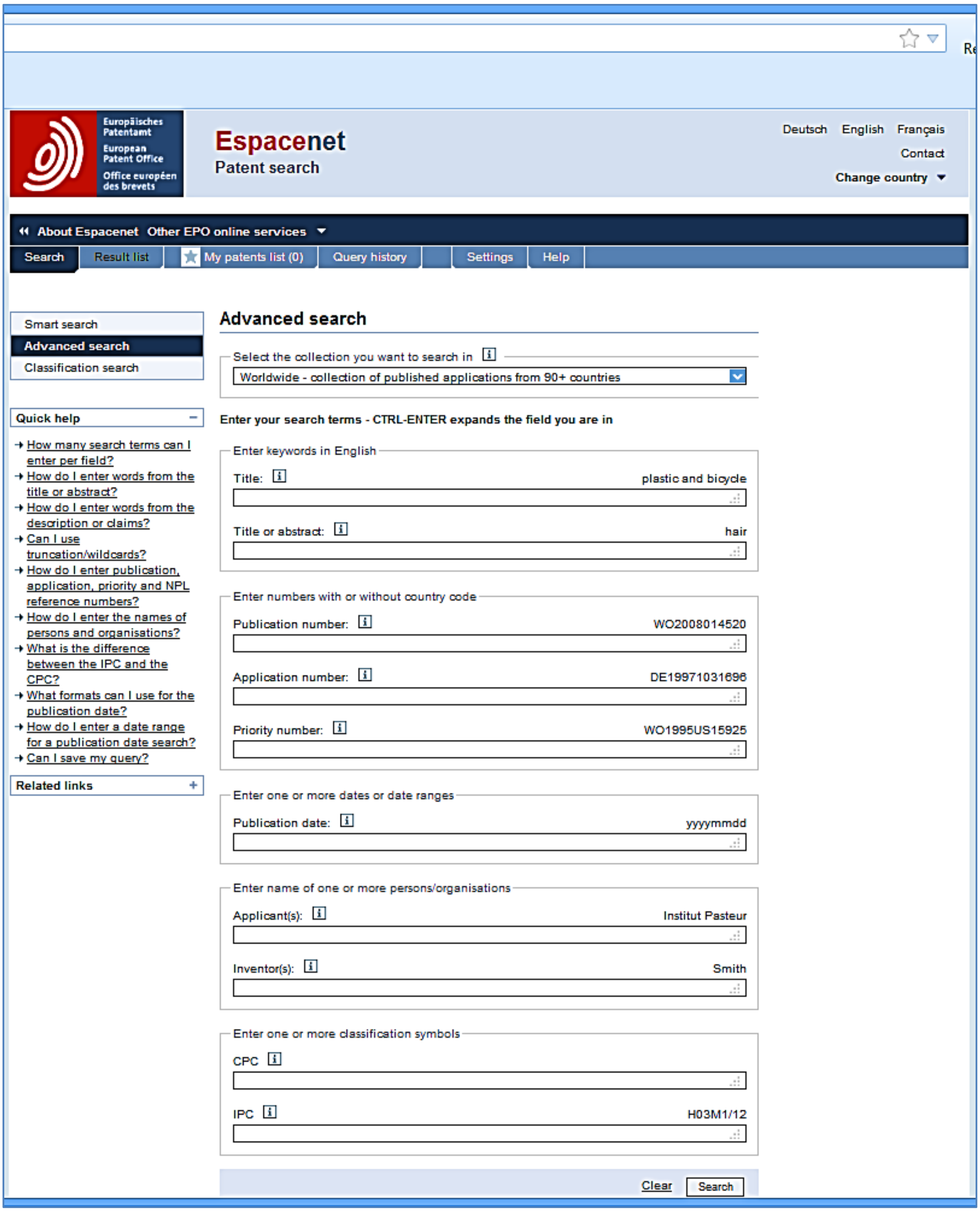



***Figure 4.2: A screenshot of the Espacenet Advanced Search menu.***

### 4.4.3 Classification Search

This is a high precision search based on an hierarchical set of symbols from a thesaurus. When patents are examined and entered on the EPO database, their subject matter is analysed by a search examiner and allocated to specific classes and sub-classes in the technology-based International Patent Classification (IPC) and a Cooperative Patent Classification (CPC) maintained by WIPO; these codes are found on the bibliographic page of the patent specification. The latter [CPC] is a more detailed and a joint US and EP version based on the former [IPC]. The nomenclature used is of a thesaurus-like format (see figure 4.3). It is possible to retrieve all patents having content of a specific technical subject matter by a classification search since these codes are used by all patent offices around the world. The classifications are updated regularly to accommodate the emergence of new technologies. The advantage is that one can obtain all the patent documents (and in some cases, non-patent data) related to a particular technical field (denoted by the codes) and thus easily chart the development of a technology. As the codes are standardised worldwide, this search is not prone to language or phraseological variations (WIPO). A detailed WIPO guide on how to carry out this search and a breakdown of the different codes is available on their website.

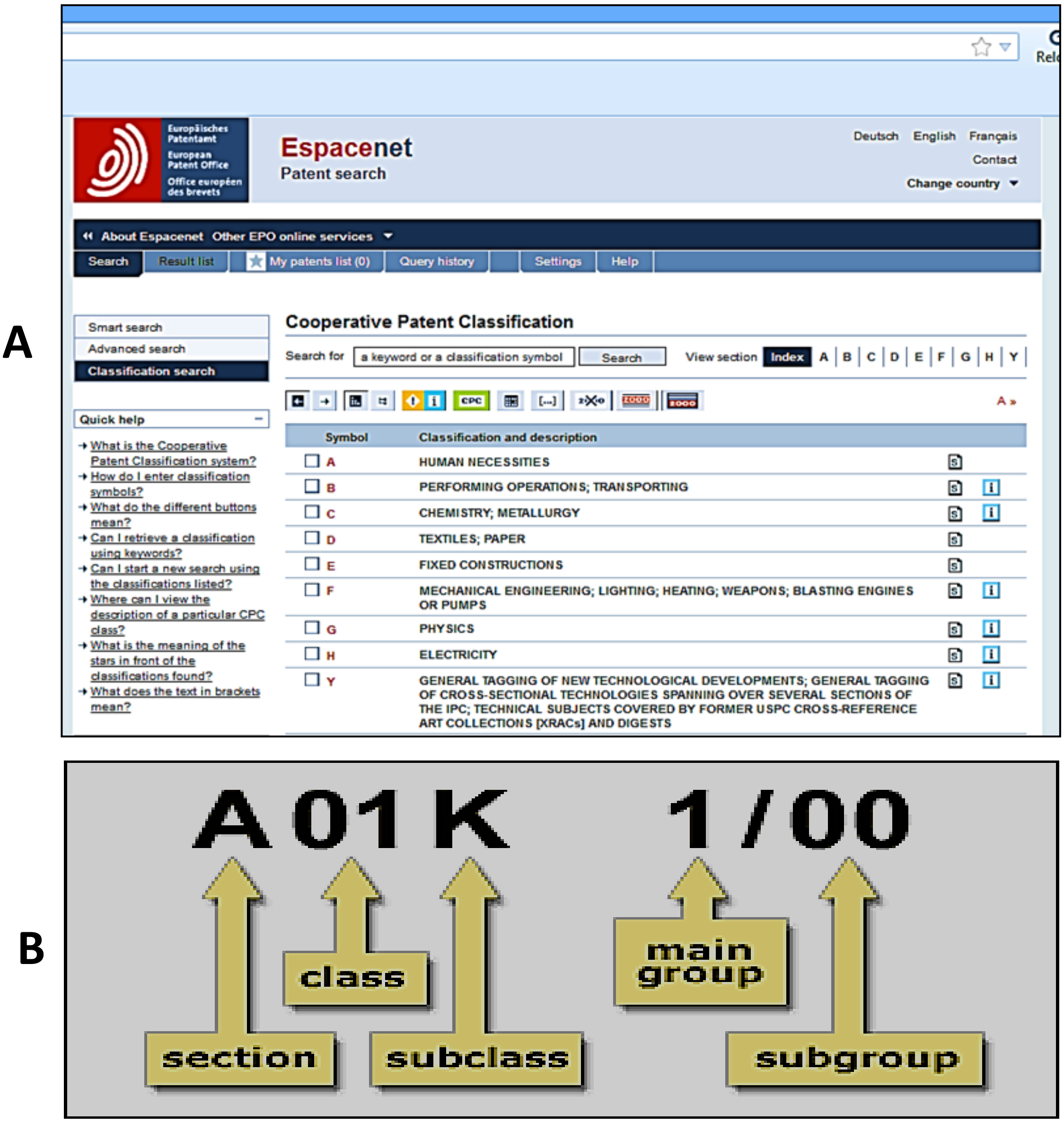



*Figure 4.3: (a) A screenshot of a classification search menu from Espacenet (b) an exemplary IPC with the various letters and numbers defined.*

## 4.5 Obtaining Copies of Patent Specifications and Bibliographic Information

It is also possible to download PDF copies of most actual patent specifications since the majority of recently published patents are sent by IP offices around the world for storage on the EPO database. Once any one of the searches described has been performed and a list of patents is provided, a selection of any one will reveal the patent data in a manner similar to figure 4.4. The left hand column enables selection of different sections of the patent specification and in addition, links to the legal status and the patent family data. Navigating via the "original document" tab enables one to download a PDF of the specification in its entirety. The bibliographic data give comprehensive information about the patent, including priority date, priority number, title, inventor(s), publication number publication date, name of applicant (assignee), an abstract for search purposes, a drawing, IPCs and CPCs. Copies of the cited patents and literature in the various level patent office searches and examinations can also be obtained.


***Figure 4.4: An Espacenet screenshot of a single patent selection.***

## 4.6 How to Interpret Patent Specifications

An array of useful information can be gleaned from a patent specification once it has been downloaded from Espacenet. As already mentioned, the first page typically contains the bibliographic information; this includes details as to the type of patent application (national, regional or international), priority data, filing and application numbers and dates, inventors, applicant/patent proprietor (and thus reveals licensees or third party assignees), the territories in which protection was or may be obtained, an indication of the technical field by way of a title, and an abstract. The description then sets the scene for the relevance of the invention by exploring relevant prior art and highlighting a particular problem in the prior art subject matter that the invention aims to solve. Following this is a detailed teaching of the invention, exemplified by several features and sometimes aided by figures or tables. The invention is then summarised in a set of claims of the invention; these determine the scope of monopoly awarded to the patent proprietor if the patent were to be granted.

Patent claims are classified as either independent or dependent (UKIPO Code of Practice for Patent Applicants and Patent Agents, 2010 at p5). Independent claims stand alone and are directed to the essential features of the invention. By virtue of their title, dependent claims rely on other claims, and concern specific and non-essential features of the invention. For example, an independent claim could be "*claim 1 - a table having only four legs*" while a dependent claim could be "*claim 2 - the table of claim 1, comprising at least one leg made of wood*" or "*claim 3 - the table of claim 2, having a substantial part of the table covered in leather*". A dependent claim therefore provides a broader interpretation of the claim upon which it is dependent. A further example in the context of the technology of this thesis could be taken from the second patent in the list to be analysed, PCT/GB91/01421, wherein the first independent claim is:

1. *A method of forming in a semiconductive conjugated polymer at least first and second regions having different optical properties, the method comprising: forming a layer of a precursor polymer and permitting the first region to come into contact with a reactant and heat while permitting the second region to come into contact with a lower concentration of the reactant, the reactant affecting the conversion conditions of the precursor polymer in such a way as to control the optical properties of at least the*

*first region so that the optical properties of the first region are different from those of the second region.*

Whereas the first three dependent claims state:

2. *A method as claimed in claim 1, wherein the precursor polymer comprises a poly (arylene-l, 2-ethanediyl) polymer, at least some of the ethane groups of which include a modifier group whose susceptibility to elimination is increased in the presence of the reactant.*
3. *A method as claimed in claim 2, wherein the reactant is an acid.*
4. *A method as claimed in claim 2 or claim 3, wherein the modifier group is substantially stable to heat in the absence of the reactant.*

Typically, patent applications contain a mixture of one or more of each type of claim, although dependent claims are usually the most prevalent. There are several advantages and disadvantages to the types of claims and how many of each are included in a patent application, and the strategies employed vary according to the prosecuting patent attorney. A discussion on this is outside the thesis objective; it is sufficient for the reader to have a basic awareness of the types of claims that will be encountered in the patent data to be analysed in order to understand the conclusions that will be made as to the validity and strength of the patents.

If the patent application has been searched or examined by the relevant patent office, an official search report is usually provided at the end of the specification. This cites prior art (granted patents, patent applications and other literature) the Patent Examiner deemed to be relevant (or linked) to the subject matter of the invention. The Examiner provides an idea of the citation's content by using nine category codes. The most occurring categories are A, X and Y and a focus on these is sufficient to meet the objectives of this research.

Code A indicates that the cited document merely contains background information related to the technical field of the invention. X and Y codes indicate documents that might be useful to the Examiner in making the decision to reject or partially reject a particular claim(s). The invention could be deemed to lack novelty or inventive step when the cited document is read on its own (X code) or to lack an inventive step if the cited document is read in combination with another document (Y code). As such, the search report greatly affects the time taken for the patent to be granted (as the applicant is given opportunity to address the Examiner's reservations) and additionally eludes to the strength and breadth of the resultant monopoly if granted. Notably, a query on or rejection of certain claims does not automatically bury the application; the applicant may amend or rely on the remaining claims to obtain their monopoly.

## 4.7 Data Processing

Once all the patents granted to Richard Friend and other laboratory contributors are obtained and tabulated chronologically in a sensible format, the next step will be to carry out a micro assessment of the patents. This will involve sorting the data by their course of development so as to create the skeletons of phylogenetic trees of their derivation from the selected milestone patents. The data manipulation will be as follows:

1. Based on an initial assessment of the technology, milestone patents will be selected from the chronology and studied. This is done on a patent by patent basis and involves comparing the granted claims to those of the very first applicable conception of organic semiconductors, to pick out those that either introduced a new paradigm or led to a "sailing ship" effect - that is, where the introduction of a new technology, material, concept, method etc. accelerates developments in an existing technology.

2. A Microsoft Word table will be created with columns for priority date (the date of initial filing), priority numbers, invention title, the international application numbers, a summary of the main claim of the patent - the inventive step highlighted, and finally the category (as below) given to the invention, to symbolise its significance. These data will be sorted by date to create a chronology.

3. The invention categories will be according to the following definitions:

| Category | Number |
|---|---|
| Observation or postulation of new phenomenon | 1 |
| New material or processing method | 2 |
| New or altered device with improved or different characteristics | 3 |
| Alternative construction or topology for existing device | 4 |
| Testing or measuring method | 5 |
| Speculations | 6 |
| Non-workable | 7 |
| Paradigm shift | |
| Technological cul de sac | |
| "Sailing ship" effect | |

4. A summary of each invention category will provide the narrative for the developmental history of the technology in chapter 5.

Moreover, patent data does not distinguish between inventions that make a significant contribution to the art and those that are mere fruitless proposals. For this, supplementary secondary data is required. The secondary sources of information will include a video interview with the principal inventor, Sir Richard Friend, available online (Friend, 2004-2005). Information from technical papers obtainable from the usual university library sources, and the library and archive of the Institution of Engineering and Technology which contains relevant specialist books and journals, presentations at seminars, trade magazines, technology reviews, market studies, annual reports etc. will be used to balance the possibly prejudiced viewpoint of the inventors.

With the collection of data from both the primary and secondary sources, footnotes and references will be followed up until they begin consistently to refer back to each other, or until it is reasonable to believe that all the key sources and materials have been identified. The data (analysed in chapter 5) will then set the foundation for the narrative of the economic development of the technology that forms chapter 6.

## 4.8 Patent Trends Analysis

The next part of the process will involve carrying out a patent trends analysis (PTA). By definition, this is a quantitative study of trends in a given group of patents, over a particular period of time. It is usually commissioned on a large scale by companies who want to manage R&D decision-making. PTAs are generally used in four significant business applications: (a) to track and analyse competitors' activities; (b) to monitor and assess changes in technology, including the emergence of new participants; (c) to evaluate the current state of an industry so as to invest in new ventures and; (d) to manage technology portfolios through licenses, technology sales or joint ventures (Acs and Audretsch, 1989; Bigwood, 1996; Basberg, 1987; Daim et al., 2006; Cullis, 2011). Since patents are technology indicators, they provide quantitative information on technology development and company R&D.

Some researchers have also submitted that a PTA can be used to determine the level of maturity of a technology, of whether it is emerging, growing, mature or declining (Campbell, 1982; Bigwood, 1996). Based on the number of patents filed per year, they conclude that those stages are respectively characterised by sporadic, accelerated, steady and decreasing patenting activity. This will reveal whether the level of POLED patenting activity - perhaps coupled to its presence or lack thereof on the market - will correspond to how mature the technology is.

### 4.8.1 Patent Indicators

Battelle points to five useful statistical parameters for quantifying a PTA from patent data: (1) activity (2) dominance (3) company characteristics (4) patent portfolio, and (5) specific company activity (Battelle, 1987). Identifying these indicators will highlight some of the socioeconomic factors discussed in chapter 2 which should be considered in looking at the economic development of the technology - discussed in detail in chapter 6. Several of these indicators will also be discussed in chapter 7.

- **Activity** - the number of patents, companies, and inventors in a given technical area indicate the level of interest and effort in a particular technology.
- **Dominance** - market leaders are usually the proprietors of dominant patents; patents obtained earlier on in the development of a technology that are severally cited in the majority of later patents. The proprietors of the later patents frequently become licensees.
- **Company characteristics** - an holistic picture of companies' patenting behaviour can be painted from the number of patents, inventors, active

years, new inventors in last three years, average age of patents, average number of countries and citation rate.

- **Patent portfolio -** effectively auditing the patent holdings of a company.
- **Specific company activity -** the percentage of patents and inventors from specific company indicates their activity in a particular technological area.

### 4.8.2 Validation of the Methodology

The PTA is validated by two tests. The first, **retrospective evaluation** is where it is determined whether patent disclosures precede market developments. This is a reasonable assumption, given the legal requirement of novelty for patentability, companies would usually first file patents before a product is put on the market to deter competitors.

The second validation is **speculations from recent trends,** to determine whether patents could be used to forecast innovations in the market. Several researchers have concluded that patent analysis can be a useful tool to forecast emerging technologies (Bigwood, 1996; Liu and Shyu, 1997; Abraham and Morita, 2001; Daim et al., 2006; Jun and Lee, 2012). Although the semantics vary based on which type of industry was studied, the general consensus is that firstly, the expense and time-intensive nature of the patent process points to both a financial and technical impact of an invention; although the former is not always guaranteed as some inventions are not commercially viable, the latter certainly always encourages more innovation. Secondly, that the launch of a new product on the market is almost always preceded by a plethora of patent applications filed in the year(s) preceding the launch, and even of complementary technologies. Studying the patents surrounding a particular technology before it is launched on the market is thus a very valid way to chart its developmental history.

Moreover, a study of the connection between newly-launched products and patenting behaviour showed that 50% of the time, product launch (for short life cycle products) was preceded by one or more patents issuing at least one year prior to the launch. The launch of products with a longer life cycle is usually preceded by many patents (Battelle, 1987).

### 4.8.3 Conducting a PTA Study

The relevant patents have already been obtained and categorised. For the PTA, the time frame is limited to recent years and all relevant patents are significant. In a series of iterations, key companies will be identified and patent trend indicators looked for. Particular attention will be paid to changes from past trends to recent behaviour, highly cited patents, and percentage of activity in a particular area of technology in comparison to other areas.

### 4.8.4 Limitations of a PTA

There are some limitations to this method (detailed in Bigwood, 1996 at p38-39) but because of the relatively smaller scale of this study, not all will come into play. The ones envisioned to play a part will include the fact that although the electronics industry has a fairly high propensity to patent in comparison to other industries, not all IP is patented so inventions that are kept as trade secrets are not included in the PTA. Further, not all patents are useful or lead to commercial success. A PTA does not identify which players are commercialising a technology, especially by way of a trade secret or through a licence, as again, this information tends to be confidential. Moreover, interpretation of the patent indicators based on purely "compositional" patents is difficult. Accordingly, even though the PTA identifies sensitive areas, other data sources and judgement are required for interpretation and corroboration. These data will duly be derived from the sources described in section 4.5.

## 4.9 Caveats of Overall Methodology

Whilst the methodology will provide the required data for the analysis, classification and searching of patent literature is an imprecise art. Pre-publication delays, usually of eighteen months or more, may occur to applications that relate to national security or on which a Secrecy Order is imposed, where there is an opposition to grant or even due to patent office administrative delays. It is therefore always possible that a vital item of prior art may not be found in a search. In addition, the invention category codes will be allocated based on a subjective value judgement of the invention according to the author's understanding of the technology, supplemented by the aforementioned sources. In any event, the data are to the highest commendable accuracy having been sourced from the EPO database and from specialist books. The methodology applied is tried, tested, and highly reviewed (Griliches, 1990; Bigwood, 1996) so should yield the required data to meet the objectives of the study.

## 4.10 Comparison to the Black Box

The narrative constructed from the data analysed (chapter 5) and the patent indicators will reveal the socioeconomic factors that affected the development of the technology. The relative contribution of each of the aforementioned factors will to be considered (chapter 6). Finally, those factors will be used to test the existing model of innovation dynamics - the Black Box mathematical model of the process of invention as detailed in Cullis, 2007, chapters 12 and 13 (chapter 7). The detail of the workings of the model will be explained then. I propose to use, test and confirm this model.

## 4.11 Hypotheses

The findings in chapter 3, lead to some hypotheses. By analogy with the development of the transistor, I postulate that initial conditions will determine which of the socio-deterministic factors will be dominant in deciding the success of this invention. Due to the similarity to transistor technology, I expect the discovery of new materials, topological manipulation of device structures and the presence of a precursor market to be of primary significance. I anticipate that multi-disciplinary collaborations will bring complementary skills that should improve efficiency. The effect of intellectual property rights such as patents and also trademarks could influence the course of the commercial development. If so, it may or may not lead to a licensing programme. It will be interesting to see whether other factors such as Haitz's Law, which is analogous to Moore's Law for inorganic semiconductors (Moore, 1995), or indeed other external stimuli will limit the technological development.

A significant difference from the development of the transistor is that the electronics industry in the period of 1940-1965 was predominantly parochial whereas it is now organised on a global basis (Cullis, 2008 at p285). As a subsidiary matter, I consider that a technology-based *sui generis* IP right analogous to semiconductor mask protection rights may not emerge and play a significant part, reason being that political lobbying by dominant US manufacturers largely influenced the development of the transistor whereas OLED technology is led by manufacturers from other countries where political lobbying for commercial advantage is not so overt. Other minor considerations like the effect of individually-owned versus corporation-owned inventions, the research culture of the key players and the role or effect of competition law will be given some thought if they emerge. Finances are of course always an issue.

## 4.12 Conclusion

The methodology will be utilised to search and download all patents relevant to POLED technology. On the outset, a time limit in terms of years will not be set as the technology is fairly just about past the infancy stage so all available patent data at this point will be significant. Bearing the caveats in mind, the data generated will be utilised to build a narrative of the development of POLEDs which will constitute chapter 5.

# 5.0 Data Analysis

## 5.1 Introduction

Having outlined the methodology in the previous chapter, the next step is to employ it to obtain the relevant data. On the outset, a time limit in terms of years will not be set - the technology is only 27 years old (1989 to present) so all available patent data at this point is significant. With the data, a survey for organic semiconductors similar to that detailed in chapter three for inorganic semiconductors will be performed. Both technologies are concerned with electronic devices fabricated from semiconductor materials so it is fair to assume that similar socio-economic factors will apply. Factors relevant to the inorganic semiconductors' commercial success and their relationship to the previously described socioeconomic factors in chapter two will be identified. This chapter proceeds with a short introduction to energy storage devices and a brief history of the discovery of OLED technology. It then mentions how the working data derived from the EPO database was sorted and evaluated before flowing into a narrative of the technology's developmental history based on the acquired patents. It concludes with some general remarks about the patent data based on a Patent Trends Analysis.

## 5.2 Energy Storage Systems

Before we delve into the developmental history, it is imperative to highlight the basics of energy storage devices. Every device around us runs on some form of power and contains an energy storage system (ESS) that provides this power. These ESSs directly or indirectly store different types of energy, such as mechanical, thermal, electrical, magnetic energy etc., on a short or long-term basis, and release it in the same or a different form as and when it is required. Depending on their makeup, they differ in energy storage size, efficiency, capabilities and limitations (Kularatna, 2014, pp.2-26). ESSs are very important in almost every sector of industry, in particular, the transport, communications and lighting industries.

Depending on the state of matter in which the energy is stored, ESSs primarily exist in two forms: solid state and fluid state. We will focus on solid state devices as POLEDs fall in this category. It is worth mentioning that solid state devices typically have a common structure: a layer or more of some form of solid material, in which the energy is stored, sandwiched between two electrodes: a cathode which injects electrons when a current flows through the device, and an anode that inversely removes electrons or essentially adds holes (see chapter 1, section 1.6 for quantum physics background). The electric current passing from the cathode to the anode causes the material to transform and/or release the stored energy, in this case, electrochemical energy stored by OLEDs is released as light. The movement of energy is usually via charge carriers (electrons and holes) moving between the electrodes and the active polymer layers. Electrodes exist in a number of different forms, namely a wire, a plate, or a rod, etc. The cathode is most commonly made of metals, such as copper, zinc, silver or lead, but can also be made of a non-metallic substance like graphite that conducts electricity (Mertens, 2016). The anode is usually made of indium tin oxide (ITO), if a transparent conductive layer is required. The types of electrodes used determine how efficiently electricity is delivered to the material.

The specific group of ESSs we will deal with are polymer optoelectronic devices. Several types of these devices will be mentioned in this chapter. Notably, these will be organic light-emissive devices (OLEDs) based on both small molecules and polymers, photovoltaic devices (PVs), photodetectors, field-effect transistors (FETs) and thin-film transistors (TFTs). All typically comprise semiconductor layer(s) between electrodes. Although closely related and often grouped together, all these devices work in differing ways and brief details of each will be provided. OLEDs are however the subject of this thesis and will be the main focus of the discussion.

Most modern OLEDs contain two layers of solid material: an emissive layer; which transports electrons from the cathode and is responsible for the emission of light, and a conductive layer; which transports holes from the anode. As explained in chapter 1, electroluminescence occurs where mobile electrons moving through a semiconductor material encounter holes extant in the material, forming hole-electron pairs which subsequently decay radiatively to emit photons (or packets of light). In particular, photons are emitted at heterojunctions (see chapter 1, section 1.8 for background).

Figure 5.1 shows that the whole structure is normally supported by a substrate, a layer of an appropriate material such as plastic, glass or foil, onto which the assembled layers are deposited. In an OLED, the structure generally comprises four main parts: (1) a substrate; (2) a backplane consisting of additional electronics that control the pixels - the basic units of the display image; (3) a frontplane that comprises the layers of the organic materials from which the light is emitted, the cathode and the anode; and (4) a barrier that protects the device from the ambience.

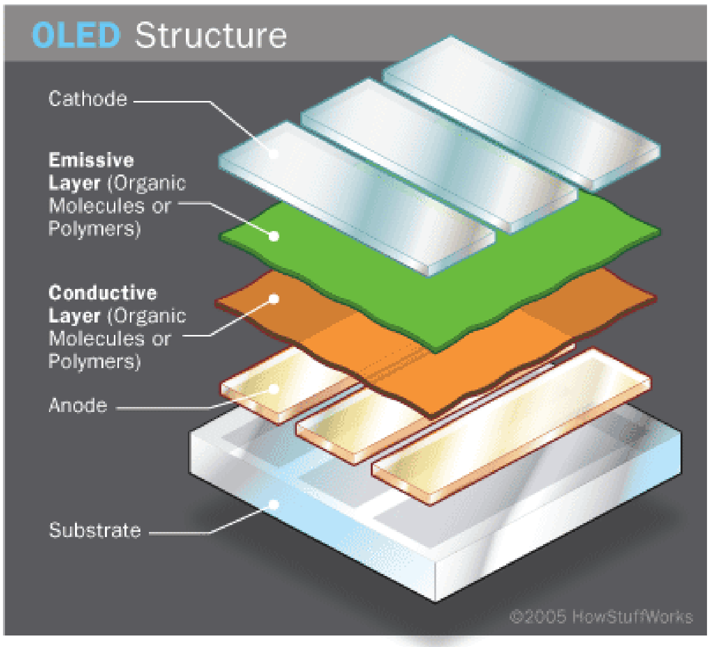



***Figure 5.1: An illustration of the general structure of an OLED device (Source: HowStuffWorks)***

The efficiency of ESSs such as OLEDs largely depends on the properties and relative arrangement of the materials used in the emissive and conductive layers, and how the layers are deposited onto the substrate. Arguably, the latter forms the biggest and most sensitive part of manufacturing OLEDs, particularly because the materials are prepared in solution, and deposited as thin films.

In contrast, in PVs, light incident on the polymer material causes coupling, followed by dissociation of charge carrier pairs and their migration to respective electrodes subsequently to provide a potential difference between the electrodes. Photodetectors operate in a similar manner to PVs, except they are usually connected to another device so that the resultant current flowing in that device is a direct measure of the intensity of incident light falling on the photodetector. The details of their workings are not necessary for this discussion but the reader may refer to **PCT/IB95/01042, PCT/GB02/01723**, **PCT/GB2004/001696** and **PCT/GB2004/002078** for these should they require it.

The structure of FETs differs from that of OLEDs, PVs and photodetectors. They are three-terminal devices that function particularly to control the conductivity of one type of charge carrier in a semiconductor material, termed as "the channel" (**PCT/GB2004/003452** and **PCT/GB2004/002078**). FETs comprise a source contact through which the carriers enter the channel; a drain contact through which the carriers leave and a gate contact which regulates the channel's conductivity. The source and drain contacts are separated by a semiconductor layer, which is itself spaced from the gate contact by an insulating layer called the gate dielectric. The contacts are interchangeably referred to as electrodes. In essence, FETs operate by application of a voltage to either all or some of the three electrodes, which voltage then causes an increase or decrease of a specific charge carrier concentration in a particular part of the semiconductor layer, affecting the characteristics of the resultant light. FETs operate in two modes: n-channel (if there is an increase in electrons in the semiconductor layer) or p-channel (if there is an increase in holes). Further, a type of FET called a phototransistor has a transparent gate electrode which permits light/photons to pass through the gate and the gate dielectric layer and into the semiconductor layer (**PCT/GB04/02054**). Here, the photon can produce electron-hole pairs which eventually dissociate and affect the current flowing between the source and drain electrodes. In yet another type of FET, the TFT, each pixel of a display panel is controlled by its own transistor but the device physics is otherwise similar.

In general, the properties of these devices are largely controlled by the chemical structure of the polymer; the nature of the main chain units and the side chains of the polymer. To that end, several of the improvements to such devices involved finding novel compositions of these polymers, and suitable polymer deposition and device fabrication methods that maintain the integrity of the polymers.

Several methods for achieving these improvements exist. Spin coating, which is one of the traditional polymer deposition methods, typically involves placing a small puddle of a fluid polymer onto the centre of a substrate and spinning the substrate at high speed until the polymer forms a thin film around it (Scriven, 1988). The main issue here is repeatability as the final thickness of the film - which greatly affects its performance in a device - largely depends on both the intrinsic properties of the polymer, such as its viscosity, and the spin process parameters. Dip coating involves dipping the substrate into a solution of the liquid polymer and withdrawing it at a controlled speed. As with spin coating, the final thickness of the film is at the mercy of the polymer nature as well as the withdrawal speed and technique, and once again, repeatability is an issue. Other methods such as vacuum thermal evaporation (VTE), organic vapour phase deposition (OVPD) and inkjet printing are also employed (Mertens, 2016). VTE is a very expensive and rather inefficient method that involves gently evaporating the organic molecules in a vacuum, followed by condensation onto cooled substrates as thin films. OVPD is less expensive and more efficient, and involves a low-pressure hot-walled reactor chamber in which a carrier gas transports evaporated organic molecules. The molecules then condense into thin films onto cooled substrates. Finally, the cheapest and most useful, because it is most controllable, inkjet printing utilises inkjet technology to spray organic molecules onto substrates so that they can be sprayed onto large surfaces such as electronic billboards. We will also encounter several other methods throughout this chapter.

On this basis, the development of optoelectronic devices, and in particular, POLED technology, is largely centred around improvements in existing materials, manufacture of novel materials and optimisation of polymer deposition and device fabrication methods. This is characteristic of the Schumpeterian B-phase discussed in chapter 2. As regards the numerous advantages of the properties of organic semiconductors over other materials, they have proved particularly useful in the construction of ESSs. The existence of HOMO and LUMO levels in semiconductors (see chapter 1, section 1.6 for background) and how easily they can be manipulated at *p-n* and hetero junctions has made them a very popular material with which to manufacture ESSs, in particular, those whose function is to generate light. The journey to this end was an interesting one.

## 5.3 Introduction to OLED Technology

As we have discussed, OLEDs generally use flat sandwiches of semiconductor materials to create light, and they exist in two different types: small molecules (SMOLEDs) and polymers or long chains of organic molecules (POLEDs). The former were discovered at Kodak Chemical in 1979 by Ching Tang and Steven Van Slyke who observed that light was produced when current was sent through small molecular carbon materials - diamine and hydroxyquinoline aluminium (Tang and Van Slyke, 1987). This was the first discovery of organic electroluminescent materials. They built the first SMOLED device in 1987 using the VTE deposition method.

POLEDs, which are the subject of this research, were discovered in 1989 by Jeremy Burroughes, Sir Richard Friend and Donal Bradley at Cambridge University's Cavendish Laboratory (Doust, 2011). They discovered that the polymer polyphenylenevinylene (PPV) emitted yellow-green light when an electric current was passed through it. The first working display device was manufactured in 1991 and the initially low device efficiencies stimulated further research into different types of polymers. To date, and as we will see throughout the succeeding discussion in this chapter, several types of suitable polymers suitable for use in light emitting devices exist, including PPV, polyfluorene (PF) and polyacetylene and its derivatives.

POLEDS can generally be formulated to generate specific colours of light and have properties that are compatible with both the intended application as well as the process for deposition. Given the obvious commercial potential of such polymers, CDT was formed at the University of Cambridge in 1992 to commercialise POLED technology, especially in the manufacture of displays with better intrinsic characteristics (CDT). The story started with the simple polymer PPV being employed in simple OLED devices such as that in figure 5.1 above. Over the years, research has led to novel and more complex polymers, used in increasingly more complex devices as well as other analogous applications, all the while aided by increasingly more complex methods of polymer deposition and device fabrication. This thesis focuses on those efforts. To that end, I have downloaded all the patent applications relating to this technology filed by CDT, from the conception of the polymers to the start of this project.

## 5.4 Data Acquisition

An EPO patent smart search revealed 53 patents naming Richard Friend as inventor, and other CDT laboratory contributors. Excel spreadsheets of these patents are found in appendix 1 and the bibliographic data for individual patents is found in appendix 5 - from this, inventors' names and details, companies collaborated with, designated states that indicate the possible size of the patent family and abstracts and the search reports can be obtained. This also indicates the names of co-inventors and commercial partners who participated in this work, and provides international patent classifications for the subject area of all patent applications in this technological field. The latter will provide a starting point for a relevant patent trends analysis (Cullis, 2011). The main claims of each patent (claim 1) can be found in appendix 4.

The patents were sorted by their phylogeny (categories) so as to create the skeletons of the phylogenetic trees from the selected milestone patents. In the first instance, the inventions and their significance will be analysed on a patent-by-patent basis to showcase the evolution of each branch of the phylogenetic trees.

## 5.5 Data Analysis

For full comprehension of this section, it is imperative that the reader brings to mind the background already outlined in chapter 1, sections 1.4 - 1.8 and in the preceding sections 5.2 and 5.3. We shall now turn to the patent list in appendix 4. The patents will be described below in chronological order of filing/priority date - this is the same manner in which they are listed in the appendix.

The first patent, **GB8909011** (resultant **PCT/GB90/00584**), was filed in 1989 and followed the discovery that an injection of charge carriers into conjugated semiconductor polymers could cause them to electroluminesce. At the time of that invention, it was common to produce energy storage devices comprising a layer of electrolyte (solids that conduct electricity by the passage of ions) sandwiched between two polymer electrodes (**GB8329906**). The electrodes acted as electronic conductors and the electrolytes as ionic conductors, and it was known to dope the polymer with ions from the electrolyte. However, the devices' efficiency was greatly reduced by relatively low diffusion rates of the dopant ions from the electrolytes into the electrode. **GB8329906,** filed in 1983 by Sir Richard Friend under a British Petroleum research contract had actually addressed this shortcoming by producing thin films of intimately and continuously mixed electrode and electrolyte materials throughout the composite to overcome the ion diffusion issue by decreasing the distance the ions had to travel. The first patent, **PCT/GB90/00584**, solved the diffusion problem in a different way. A thin dense layer of PPV (figure 5.2) was straddled by two charge injecting contact layers: two thin layers of aluminium, or aluminium and gold/indium oxide, or indeed any other suitable material. The PPV layer was made to have "*a sufficiently low concentration of extrinsic charge carriers*", so that when an electric current was applied, the contact layers were polarised so that the second contact layer was positive relative to the first. The result was a flow of positive charge carriers from the first contact layer into the PPV layer and a flow of negative charge carriers from the second contact layer into the PPV layer. The resultant electron-hole pairs within the polymer layer decayed radiatively to produce light. The PPV polymer was made to carry different substituent groups depending on the type of light that was desired. Arrangement of the layers in this way solved several of the problems encountered in earlier devices, such as poor reliability and the setbacks related to the deposition of both the organic semiconductor and electrode layers but also made it possible to make larger displays than what was earlier possible. This was the first description of a polymer OLED.

FIG. 2

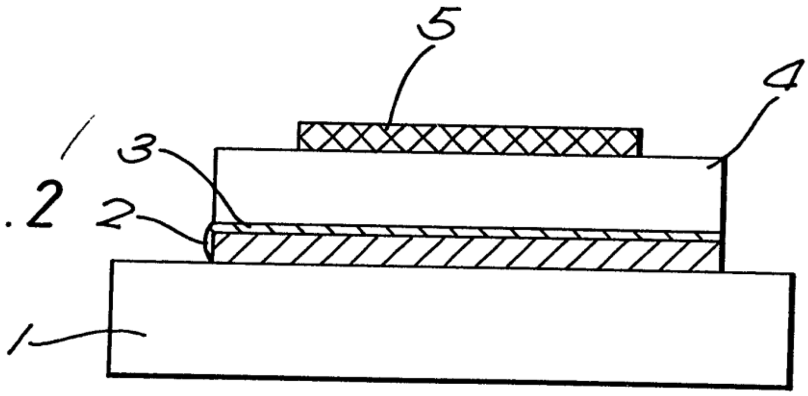



***Figure 5.2: A diagram of an electroluminescent device showing the supporting substrate 1 e.g. glass (1); first charge injecting contact layer (2); thin surface oxide layer formed by (2) that constitutes the electron injecting layer (3); semiconductor layer/PPV film (4); and the second charge injecting contact layer that constitutes the hole injecting layer (5) (Source: PCT/GB90/00584)***

To allow for continuous charge injection into the semiconductor layer, the team then went on to devise a method for forming continuous films of patterned semiconductive polymers having different regions of different characteristics. This was the subject of a third patent, **GB9018698** filed in 1990, in particular, resultant applications **PCT/GB91/01420** and **PCT/GB91/01421**. Previous devices utilised polymer films that had the same quantum characteristics throughout the continuous film, and although this may have been advantageous to a certain extent, its drawbacks needed to be overcome to advance the technology. It is not useful to mention the details of the product and/or method but rather the end result; a semiconductive polymer that had at least two regions, typically adjacent to one another, having different optical properties. This was achieved by using copolymers that consisted of at least two chemically different monomers that inherently had different bandgaps, mixed in predetermined ratios so as to manipulate the overall bandgap of the resultant copolymer. In layman terms, monomers are the building blocks for polymers, and because of the chemical composition of each region of the polymer, each region had the capability of emitting light at a different wavelength, and thus a different colour (see figure 5.3 below). To that end, the optical properties, and indeed, how efficiently the polymer was able to produce light in the different regions, could be tailored during the formation process by varying the semiconductor bandgap (or the positionings of the HOMO and LUMO orbitals), to control the emitted colour. The official searches revealed no prior art which destroyed the novelty or inventive step.

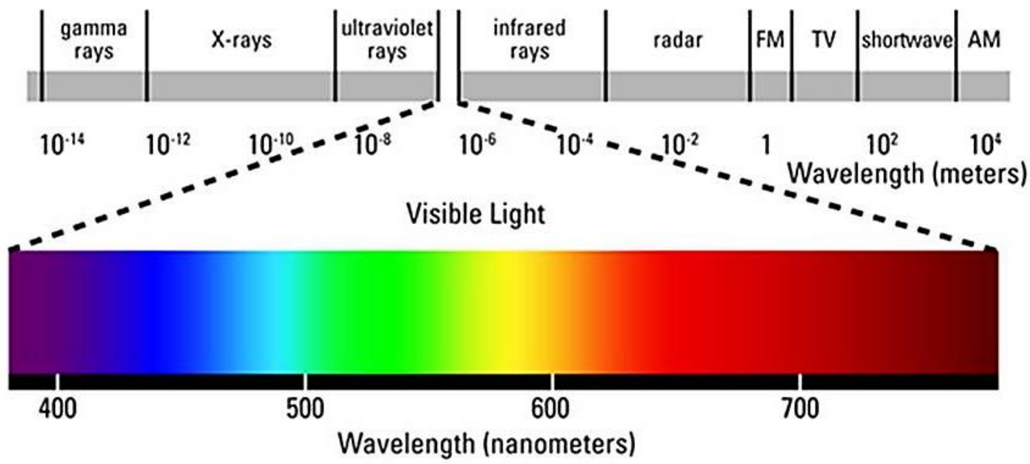



***Figure 5.3: A diagram of the visible light region of the electromagnetic spectrum showing each colour corresponding to a different wavelength (Source: McCann, 2013)***

Conjugated polymers are usually difficult to get into solution so that they can be deposited onto substrates in such methods as spin-coating or dip-coating. To improve their solubility, the polymers were commonly prepared from precursors in which flexible side-groups were attached to the main polymer chain to reduce conformational restrictions that contributed to insolubility. The precursors would subsequently be converted to the polymers using thermal decomposition or other alternative methods. The common setback with all these methods was that the semiconductor polymers were usually chemically disordered, forming coils and the like, during the soluble phases of their preparation, and the resultant conformational imperfections significantly affected their electrical and optical properties. The inventors, Sir Richard Friend and his co-workers in 1992 solved this problem in **PCT/GB93/00131** by making conjugated polymers, and a method of producing such, particularly conjugated poly(arylenevinylene) polymers (essentially substituted or unsubstituted PPV polymers) that could directly be prepared from their precursors in solution, to the effect that this improved their electronic properties. Once again, it is not necessary to delve into the chemical detail of the methodology but the gist of it was that, while the polymer was in solution and without decomposing it, they were able to introduce specific chemical groups into the polymer chain to add the optimal percentage of unsaturation (single bonds) required to minimise the amount of disorder of the chain as well as keeping the polymer soluble. The end result was a highly ordered polymer that had better electronic properties than those produced in the previous way.

Six months later, the inventors filed **PCT/GB93/01573** and **PCT/GB93/01574** which utilised such conjugated polymers in electroluminescent devices. This time more than one layer of the films of polymers was sandwiched between the electrodes; all were PPV derivatives but with at least one soluble to charge carriers and the other insoluble, and all polymers had differing band gaps so as simultaneously to emit light at predetermined wavelengths, i.e., selected to emit a broader spectrum of colours than a single layer device. Also in the sandwich was a hole injecting layer such as ITO at the anode and an electron injecting layer such as calcium at the cathode. One of the arrangements is shown in figure 5.4 in which, from bottom to top; the ITO layer coats the glass substrate; followed by a suitable PPV copolymer layer (in this case, poly (arylenevinylene) that helped with the transportation of holes from the ITO layer to the emission zone; the zone comprising first the insoluble polymer (PPV) and the soluble polymer (MEH-PPV); and finally, the calcium layer before the cathode. One of the main advantages of this arrangement, and similar embodiments of this invention, was that the insoluble polymer layer acted as a barrier to protect the soluble polymer layer from holes/mobile ions released by the ITO layer. Another advantage was that all three semiconductors layers emitted light of different colours. Further embodiments exploited other advantages of using multiple layers over single layer devices, such as mechanical rigidity and stability at high temperatures.

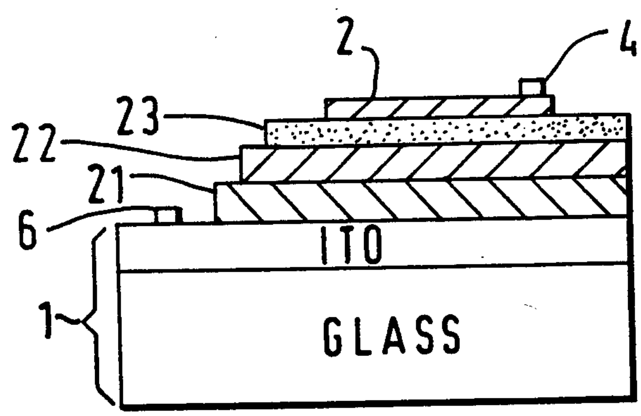



***Figure 5.4: A diagram of an electroluminescent device showing the glass substrate with the ITO anode (1); calcium cathode (2); negative contact (4); positive contact (6); PPV copolymer layer (21); precursor to PPV to form the insoluble polymer layer (22); and the soluble MEH-PPV polymer layer (23) (Source: PCT/GB93/01573)***

The production of blue light had always been a challenge. Several molecular compounds had earlier been investigated and observed to produce blue light but the quality had not been up to par given the extensive processing that in particular, blue light-emitting compounds had to undergo. The invention that followed, **PCT/GB93/02586** filed in 1992, was the result of the inventors "chemically tuning" the emitter layer to produce blue light. The layer arrangement was as in the aforementioned inventions. The novelty lay in chemically adding or blending a chromophoric molecule such as stilbene or distyrylbenzene as a side chain to a polymer matrix of a suitable conjugated polymer. Stilbene and distyrylbenzene are ring hydrocarbons that can be "programmed" by the addition of certain chemical entities to emit radiation in the region of 400nm to 500nm, in other words, blue light. This was the first use of dyes in electroluminescent devices.

Next, without damaging either device, the inventors fabricated a device with "two independently operable electroluminescent structures one on top of the other". This was the subject of **PCT/GB94/01840** filed in 1993. In simplified terms, they placed an MEH-PPV layer straddled by two contact layers of calcium and gold, from top to bottom respectively, over a PPV layer straddled by two contact layers of calcium and ITO, also from top to bottom respectively. At the top of that sandwich was an aluminium layer to reduce the device's sensitivity to contamination and at the bottom, the substrate. See figure 5.5 for illustration:

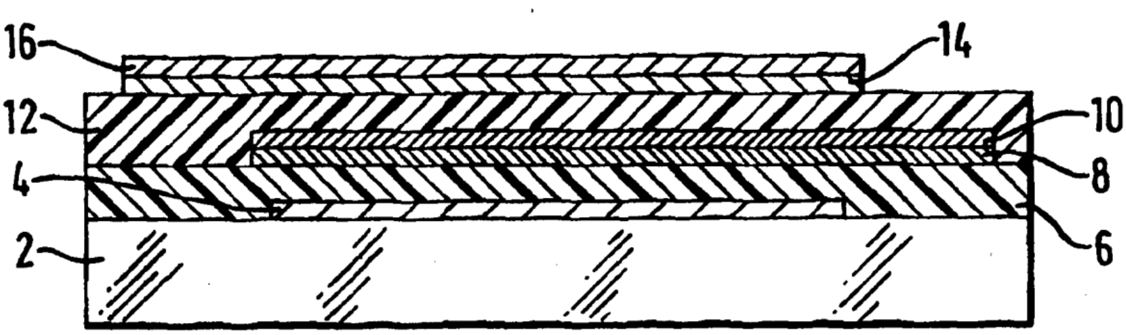



***Figure 5.5: A diagram of an electroluminescent device showing the first and second contact layers (4 & 8) for the first layer of polymer PPV (6) and the first and second contact layers (10 & 14) for the second layer of polymer MEH-PPV (12). Layer 16 of aluminium caps 14 to reduce contamination of the device (Source: PCT/GB94/01840)***

As before, the contact layers were to inject charge carriers of opposite polarities into the polymer/emitter layers following the application of an electric field. The device was innovatively fabricated in such a way that the contact layers could share electrodes - the result was that either one of the emitter layers could be activated at any one time to emit its predetermined colour, or both layers could simultaneously be activated to produce a colour resulting from the combined emission. Further, the materials used were either transparent or semi-transparent so that the colours could easily be viewed. This was the first device in which the colour of the emitted light could be controlled after device fabrication; previously, colour was predetermined by the band-gap of the choice of polymer used in the device, for example, green for PPV or red-orange for MEH-PPV.

Moreover, the efficiency and quality of light emission depends on the formation of singlet or triplet excitons, in other words, the formation of the electron-hole pairs (see chapter 1, section 1.8 for background). It follows therefore that improved injection of electrons into the polymer will increase the chances of formation of singlet exciton pairs. From the above inventions, this can clearly been seen in the use of metals like calcium and aluminium at the cathode to inject electrons into the polymer layers. These metals' utility is however limited by their sensitivity to air and moisture. To achieve this objective alternatively, and as illustrated by the aforementioned inventions, several contact layers may be conveniently employed. In **PCT/GB94/01118**, the inventors discovered that addition of an electron-withdrawing group (EWG) to the polymer would improve device efficiency by a range of 0.1 - 0.4%, which in the context of device physics is a significant increase. Suitable EWGs such as nitrile or carboxyl groups would effectively increase the affinity of the polymer for electrons, by drawing electrons away from the cathode and into the polymer. Additionally, solubilising groups were also incorporated in the polymer to ease its processability in solution. The addition of both EWGs and solubilising groups was done in such a way that it advantageously altered the optical properties of the polymer, such as adding them to particular groups in the polymer chain to alter the semiconductor band gap and subsequently, the resultant wavelength of the emitted light, in particular, for emission to occur in the infrared region as well as in the blue region. Notably, in all the examples above, emission has been occurring in the visible light region of the spectrum.

By way of reminder, in the internal electric field, electrons migrate from the anode through the semiconductor sandwich and are collected at the cathode. Holes move in the opposite direction. Some of the electrons will pair with holes forming excitons which then decay to release photons. The quantum yield (photons emitted per electron injected) is largely limited by how mobile the electrons are. If a device has a low electron mobility, most of the light produced will be absorbed close to the ITO electrode. The challenge is that electrons injected by the cathode have to travel across the polymer sandwich to be collected at the ITO anode. In so doing, many are either trapped or recombine with holes on their way. Several researchers have tried to overcome this by facilitating exciton decay into separate charges, firstly, by decreasing the thickness of the polymer layer so that the internal field is stronger, the distance to be travelled is shorter and the electron flow is faster, inevitably decreasing the amount of light that will be absorbed by the polymer and secondly, by using multilayers of different semiconductors, forming heterojunctions at which exciton decay is favoured (the background to heterojunctions can be found in chapter 1, section 1.8). The heterojunction interface however needs to be large enough for any efficient and observable difference. In **PCT/IB95/01042,** the inventors approached this problem by sandwiching a photoresponsive layer made up of a polymer blend comprising distinct regions of two types of semiconductors between two electrodes, as in figure 5.6 below, with one semiconductor having a greater electron affinity than the other.

Photoresponsive materials are those that release electrons on absorption of light.

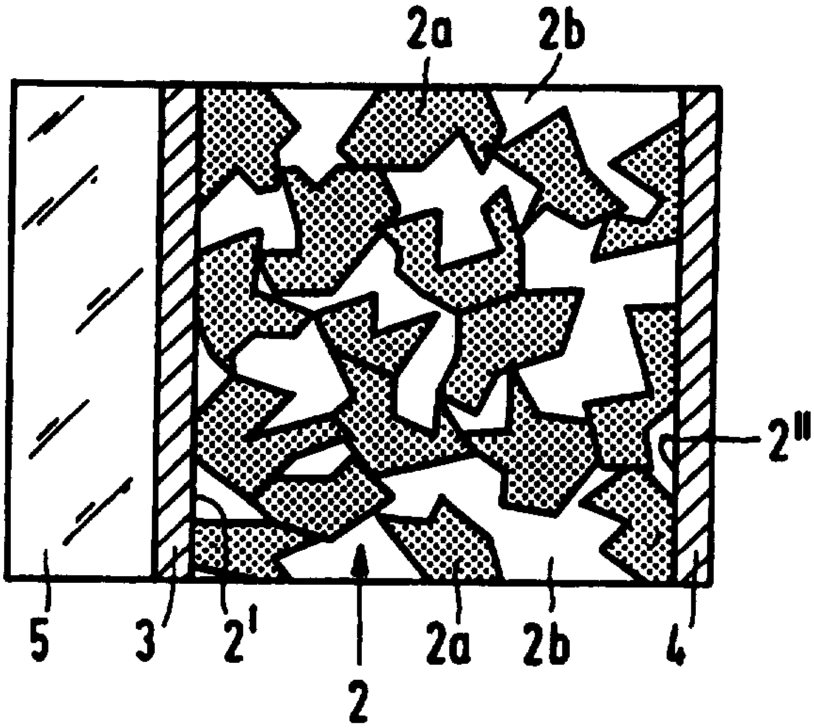



***Figure 5.6: A diagram of an electroluminescent device showing the photoresponsive layer (2) with major surfaces ($2^{I}$ and $2^{II}$), comprising a blend of two semiconductive polymers existing in two distinct phases (2a and 2b). 3, 4 and 5 represent the anode, cathode and substrate respectively (Source: PCT/IB95/01042)***

When either polymer was excited by light, excitons were generated, followed by exciton dissociation. The result was a photocurrent flowing between the electrodes; the electron current travelling predominantly through one semiconductive polymer and holes travelling predominantly through the other semiconductive polymer. The polymers were either both PPV or derivatives thereof, having different substituent groups so as to create the differing electron affinities. The advantage of the blend was that charge was distributed throughout the bulk of the blend because the regions of the polymers formed continuous interpenetrating networks, to the effect that charge carriers within one polymer could travel through that region without having either to cross into the other polymer layer or only need to travel a short distance across the other polymer. This not only improved the amount of light being produced by the device (its quantum efficiency) but also lessened the effect of low electron mobility on the yield. The official search revealed two novelty destroying citations so there is a *prima facie* presumption that the validity of the patent would be questioned.

It has been mentioned that conjugated polymers have a processability problem; namely insolubility and infusibility that arises because of their rigid main chain and strong intermolecular forces between the polymer chains. Several of the foregoing inventions have tried to circumvent this issue by (a) using soluble precursors that are later converted into the rigid conjugated polymer (**PCT/GB93/00131, PCT/GB93/01573**); (b) adding flexible side groups to the fully conjugated polymer to increase solubility (**PCT/GB94/01118, PCT/GB93/00131**); or (c) attaching a chromophore to a flexible polymer chain (**PCT/GB90/00584, PCT/GB91/01421**, **PCT/GB93/02586**). It has also been discussed that the addition of a charge transport polymer layer or blend greatly increases the performance of OLEDs (**PCT/GB90/00584, PCT/GB93/01573, PCT/IB95/01042**). With all this manipulation, the polymers either suffered from structural changes or were likely to be affected by the solvents. The inventors in **PCT/GB95/03043** discovered that cross-linking (either thermally, chemically or photochemically) certain chemical groups to the polymer chain would increase its molecular mass and avoid the aforementioned shortcomings, all the while, and surprisingly, not affecting its desirable semiconductive and luminescent properties. That way, they were able to make several polymers suitable that had an increased morphological stability for use in optical devices, leading to improved device performances. No citations destructive of novelty or inventive step were found in the official search so there is a presumption that the validity of the patent would not be questioned. Several divisional applications of this patent family were also filed.

**PCT/GB96/00923** related to a novel method of manufacturing OLEDs. As previously stated, the most difficult part about manufacturing OLEDs was the deposition of thin layers of polymers onto the substrate. The problem with the previous multilayer devices was that during their manufacture using traditional methods such as spin coating, previously deposited polymer layers would usually redissolve as new layers were being laid down. In some instances where thin layers of soluble precursors were laid onto the substrate and later heat treated to convert them into the insoluble active polymer, previous layers or even the substrates were damaged by the heat, especially where the substrates were flexible plastics prone to heat damage. The inventors devised a way to laminate, either by heat, pressure or by using an adhesive, two self-supporting components. One component was formed by coating a substrate with an organic light emissive polymer, and the second, a different substrate coated with an organic polymer and/or a charge transport material. The organic layers particularly used were PPV or its derivatives, and they were selected to emit light at different wavelengths. They were laminated so that the layers were positioned between the substrates in the finished device, as shown in figure 5.7 below:

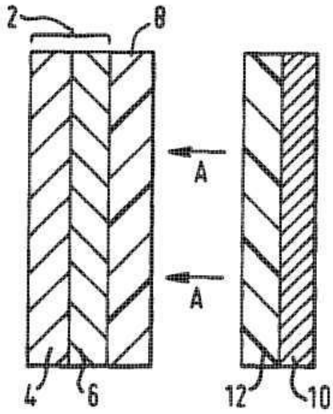



***Figure 5.7: An illustration of the method (arrows A) of laminating two substrates to form an electroluminescent, showing the first substrate (2) consisting of glass or plastic (4) coated with an ITO anode (6) and carrying a polymer for charge transport (8), and the second substrate (10) such as aluminium foil coated with a second polymer - the light-emitting layer (12) (Source: PCT/GB96/00923)***

Usefully, the substrates could directly either be used as an electrode because of the material of which they were made or they were already pre-coated with an electrode; aluminium on one, and glass or a transparent plastic coated with ITO on the other. Advantageously, there was no need for vacuum deposition methods to deposit the metallic electrodes onto the substrates, or concern of redissolution as explained above where multiple layers were added to any one substrate. Once again, no citations destructive of novelty or inventive step were found in the official search so there is a presumption of validity.

**PCT/GB97/01972** related to an invention in which organic semiconductor polymers were applied in radiation sensors such as those that utilised FETs, voltage-controlled transistors mentioned in section 3.3 of chapter 3. In almost all previous sensors, inorganic semiconductor films had been employed, and these exhibited several disadvantages such as insensitivity, and the major one being the production of a transient/instantaneous response as opposed to a cumulative one. This meant that in most devices, the radiative reading could only be taken once, rendering the process expensive. It is not necessary to mention the technical details but the result of it was that a more sensitive radiation sensor was built with at least one layer of an organic semiconductor material, whereby the electrical characteristics of one or more FETs within the device were controlled by how much radiation was incident on and therefore affected the organic layer. One embodiment of the device is shown in figure 5.8.

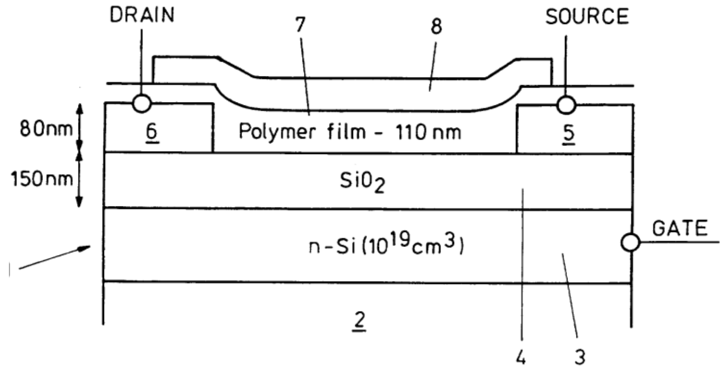



***Figure 5.8: A diagram of a radiation sensor showing the organic semiconductor layer/polymer film (7) between the source (5) and drain (6) regions of an FET. Other layers include the substrate (2), the gate layer (3), the insulating layer (4) and a non-conducting film (8) that encapsulates and protects the device (Source: PCT/GB97/01972)***

Sensitivity was further enhanced by shielding certain portions of the device from radiation, measuring radiation as a function of the photoluminescence of the organic layers, including a photo-oxidising step to alter certain bonds in the polymer and therefore make the radiation induced changes within the polymer layer more permanent, adding a transparent protective layer (such as a silicon dioxide film - $SiO_2$) over the organic material layer to protect it from the destructive effects of air and other impurities, and including a sensitising layer that would generate secondary electrons in the organic layer and increase the measurable response. The obvious economic benefit was that more sensitive sensors that took readings multiple times made the use of these devices much cheaper in the long run. The official search revealed one novelty destroying prior art patent and four which indicated that the invention was obvious but these only destroyed the validity of one specific embodiment. The latter concerned one independent/major claim (out of eight) and the former to several dependent claims (optional features) so the main claims of the invention were unquestioned.

**PCT/GB98/01804** addressed the issue of producing purer colour emissions. In order to obtain a full colour display, previous devices had employed use of an array of pixels that each emitted a primary colour, namely, red, green and blue. The colours were then combined to form the desired colour patterns. However, during the manufacture of display devices, the light-emissive films suffered from etching processes with the result that the resultant colour was not sufficiently pure. In other attempts, a colour conversion medium was added to the device, so that for example blue emission was converted to red or green but the extra processing steps introduced other disadvantages. Moreover, ambient light such as light from the surroundings caused unnecessary photo-degradation (alteration of polymer molecules by photons), photo-conduction (a change in electrical conductivity as a result of light), or in some cases, photoluminescence.

The inventors devised an arrangement such as that illustrated in figure 5.9, in which an organic light-emissive layer had an electrode on one side for injecting charge carriers of one polarity and on the other side, a light filtering layer made of an organic material that had been doped enough to inject charge carriers of a second polarity into the light-emissive layer.

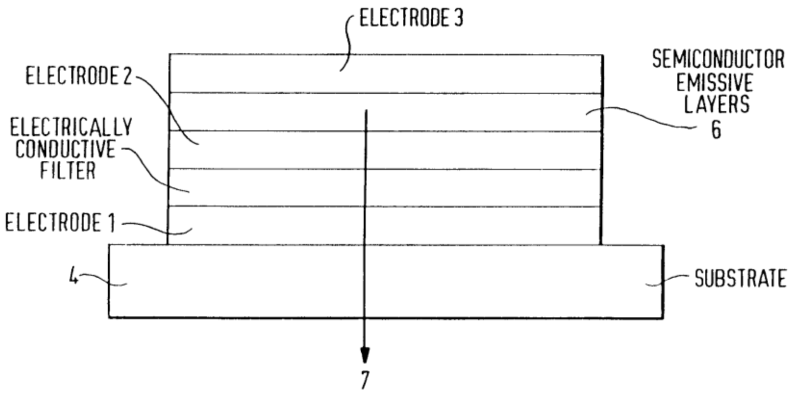



***Figure 5.9: A schematic diagram of the light-emissive device; as indicated by arrow 7, light emitted from the polymer layers (6) passes through the filter layer and leaves the device through the transparent electrode (1) and substrate (4). Electrodes 1 and 3 represent the anode and cathode respectively (Source: PCT/GB98/01804)***

The light filtering layer may itself act as the electrode to provide the second charge carriers or it may be assisted by an additional electrode. The function of the light filtering layer may either be absorptive and/or fluorescent in that: (a) it may either absorb light emitted by the emissive layer and may or may not re-emit it at a different wavelength; (b) may emit light at the same wavelength as the light-emissive layer to amplify the latter's emission; (c) absorb light at wavelengths that would cause the light-emissive layer to emit; (d) absorb ambient light and prevent it from affecting the performance of the light-emissive layer. Additionally, the device may also contain extra charge transport layers, multiple light-emissive and light filtering layers, all arranged in distinct regions, so that the same or different colours are emitted from each region. The electrodes may be ITO on one end and a metal such as calcium, aluminium etc. or alloys of such. Typically, one of the electrodes is transparent to allow for the colours to be viewed. Suitable materials such as PPV may be used for the light-emissive layer. No citations destructive of novelty or inventive step were found in the official search so there is a *prima facie* presumption of validity.

When light is produced in a light-emitting device, it scatters in all directions. The devices we have looked at so far have at least one transparent electrode, usually the anode, in addition to a glass or plastic substrate so that light is viewed from that direction (the viewing direction). The cathode side is usually made of opaque metal that either absorbs or reflects the light back to the anode side. Some light is scattered at slanting angles and is waveguided within the typically planar sandwich of material; some light is trapped within the plane but some of it reaches the edge of the emissive pixel, albeit not contributing to the brightness of the overall light viewed as it travels in a different direction. This obliquely emitted light can cause "cross-talk" between pixels, reducing the contrast between emitting and non-emitting pixels. In **PCT/GB98/02615**, the inventor revealed that this cross-talk issue could be avoided by building devices with multiple light-emissive regions, each region representing a pixel, and spacing the regions apart in a direction perpendicular to the viewing direction, so that each region could guide emitted light towards another emissive region. Several devices with differing configurations were built; some of the embodiments are shown in figure 5.10.

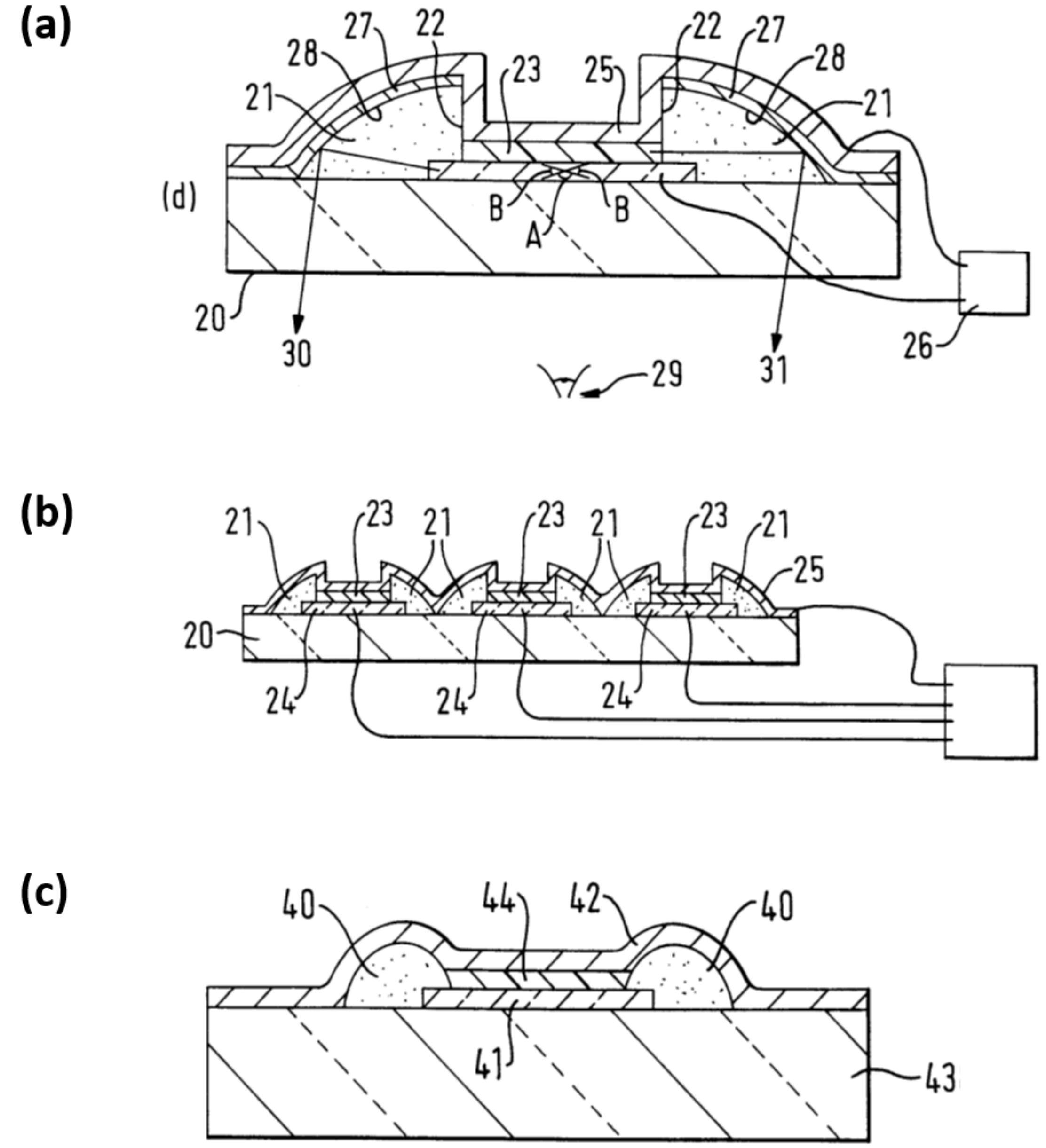



***Figure 5.10: An illustration of some configurations of display devices according to the invention showing the transparent substrate (20), insulating region (21), and its inner walls defining a well (22), light-emissive region (23), anode and cathode (24 & 25 respectively), connected to controlling circuitry (26), light-reflective layer (27) placed over the upper walls (28) of region 21, whose lower side reflects light emitted inside the device (in modes such as 30 & 31) back towards the direction of the viewer (29), the range of angles for light emitted towards the substrate that passes directly out of the device into the viewer (A), and the range of angles for light emitted sideways into the device (B) that is reflected back to the viewer by layer (27). The three different configurations illustrate that in (a) the light-reflective layer (27) coats some of the cathode to increase the amount of light reaching the viewing direction; (b) is an extension of (a) showing multiple light-emissive regions, and; (c) alternatively, the light-emissive anode (41) and the light-emissive layer (44) are deposited within a well specified by walls (40). The glass substrate (43) and cathode (42) also doubles as the light-reflective layer (Source: PCT/GB98/02615)***

A light-absorbent or light-reflective barrier structure was also placed between the regions to redirect light directly emitted towards it or waveguided thereon to the viewing direction. The barrier structure could also advantageously comprise an electrode for injecting charge carriers into the emissive layers and enhance light production. Moreover, the barrier was formed in an electrically insulating manner; either coating the upper surface such as the cathode in a light-reflective role (to absorb then reflect light to the viewing direction or back to the pixel from whence it was emitted), or in a light-absorbent role where it is located between emissive regions. The obvious economic benefit was increased contrast between pixels, especially in multi-pixel devices and ultimately, better displays. One embodiment appeared *prima facie* to be patentable, but that would be vulnerable to a suitably constructed obviousness attack based on the citations against the other embodiments.

Further, the performance of OLED devices greatly depended on the thickness and how well-defined the polymer and other layers in the sandwich were. The layers were usually deposited in order of ITO anode onto the substrate, followed by the organic polymer layers and any interfaces, before finally, the cathode layer. Several of the methods such as spin-coating, evaporation or thermal deposition already described above were employed. To build thin and continuous films, the most popular of those methods at the time was self-assembly. In this, successive polymer layers were prepared from solution and adsorbed onto one another with the help of attractive forces between dissimilar layers (positively and negatively charged layers). The entire device would be fabricated this way. This however involved several dipping and rinsing steps that were very time-consuming and not commercially viable. The inventors in **PCT/GB98/02671** improved the fabrication process; they employed self-assembly to form at least one layer of polymer at an electrode/light-emissive layer interface and completed the rest of the device using any one of the other standard techniques. Economically, this reduced processing time and cost, and enhanced other key performance parameters such as quantum efficiency, maximum achievable brightness and ease and reproducibility of manufacture. The official search revealed no prior art that could bring the validity of the patent into question.

**PCT/GB99/00060** provides a detector and a method for improved radiation monitoring. As already explained, radiation detectors such as those used in health physics and in laboratory equipment suffered from several setbacks, the main and perhaps what made them expensive being that they could only be read once. **PCT/GB97/01972** (already discussed above) and other applications of organic semiconductor materials in radiation detectors specifically focussed on detecting dopants produced as a result of the materials absorbing radiation. They did not consider the numerous other ways in which absorbed radiation affects the materials. This invention concerned measuring/detecting those other effects to build more sensitive radiation detectors. Two layers of material, preferably intimately mixed together, were enclosed in an opaque device. The first material, a conjugated polymer such as polyacetylene or PPV derivatives would absorb directed radiation such as light shone on it, convert it into mobile excited states such as excitons which were free to diffuse throughout the polymer blend. The first material was in contact with a second material such as an onium salt or a dye molecule, which would be activated by the mobile excitations to produce doping species. These dopants affected either the first material or any additional material within the enclosure, providing for means detection through changes in electrical conductivity, optical properties, mobility and concentration of charge carriers or concentrations in unpaired spins. The end result was a more sensitive method of detection whose economic viability was better than previous detectors. No citations destructive of novelty or inventive step were found in the official search so there is a *prima facie* assumption that the validity of the patent would not be questioned.

So far we have seen how colour is easily produced by organic light-emitting materials. The production of greyscale is not so straightforward. In electroluminescent devices that use organic light-emitting materials such as PPV or its derivatives, the organic layer is usually divided into individual pixels arranged in rectangular rows and columns, the pixels being of different sizes and/or in different areas as seen in figure 5.11. The pixels are switched between emitting and non-emitting states by changing the current that flows through them. Usually electrodes are placed at the end of each row or column and are co-ordinately switched on to vary current and thus which pixels (located at the intersections of the rows and columns) light up, as well as how bright they are. Clear images are produced when the brightness of each individual pixel is controlled, to provide what is called greyscale. Additional circuitry such as transistors and capacitors may be included to amplify, rectify or to store electric charge to be used at a later point. The construction of such devices is not without its difficulties, but particularly where organic light-emitting materials are used, the pixels are very sensitive to current in that the same input of current for different organic materials produces widely differing levels of brightness, affecting the consistency of the greyscale. The inventors in **PCT/GB99/00383** solved this problem by including switching devices in the circuitry, each associated with and switching power to a respective pixel, and a driver associated with each switch to cause it to cycle between predetermined power modes (low, intermediate and high) at a frequency that made the associated pixels appear to emit light in a generally continuous manner and at an average brightness. The economic benefit was more stable greyscales which made for clearer display devices. No citations destructive of novelty or inventive step were found in the official search report.

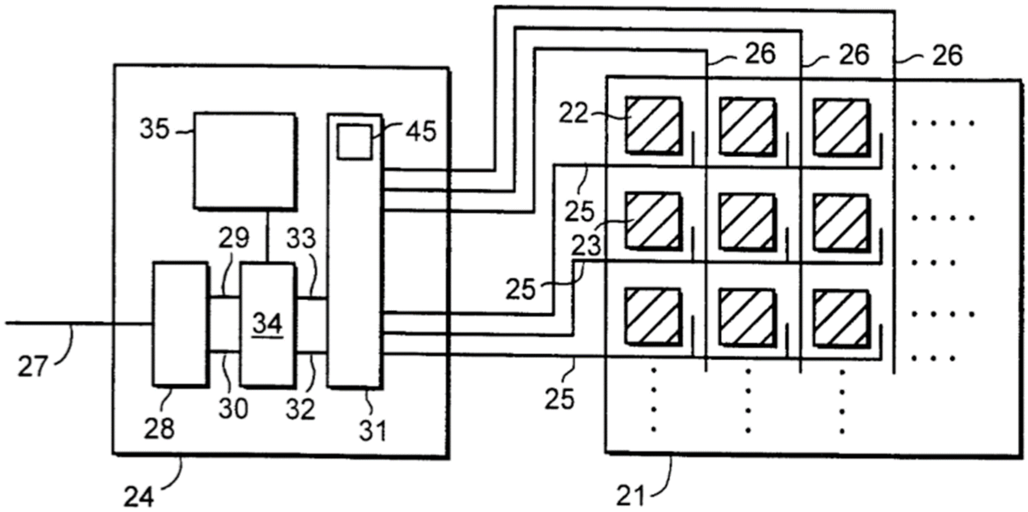



***Figure 5.11: A schematic depiction of an electroluminescent device (21) with multiple pixels, each forming a distinct light-emitting region and arranged in rows and columns (some indicated by numerals 22 & 23), connected to a control device (24). The voltage of each pixel is individually controlled by device 24 via a scan line (25) and a signal line (26). The details of device 24 are not expedient for this discussion but notably, it itself receives instructions at 27 from, say for example, a computer. (Source: PCT/GB99/00383)***

We have also seen that ITO is transparent and usually deposited using such methods as evaporation, as a continuous layer over the entire substrate. This is usually located at the anode, which also generally serves as the viewing direction. The ITO then has to be patterned by etching away unwanted regions to form separate regions that may designate pixels; this additional processing sometimes damages the circuitry, even only at one pixel and cause the entire display to be rejected. This yield problem was also experienced in inorganic semiconductor device fabrication as was discussed in chapter 3. This makes the manufacturing process expensive. The invention that was the subject of **PCT/GB99/00530** filed on the same day as previously discussed **PCT/GB99/00383** solved this problem by using a method in which both the light-emitting layer such as PPV and the ITO layer were deposited using the much more precise ink-jet printing. This way a multi-colour display was formed from multiple pixels all sharing a common substrate, electrodes and all the corresponding circuitry (figure 5.12). Each pixel formed a separate region of organic material. This greatly reduced the margin for error in damaging pixels, making the manufacture much less expensive. Further, the light-emitting regions were separated by banks of insulating material such as silicon dioxide, which additionally insulated the rear of the circuitry. The official search examiners considered that this invention lacked inventive step.

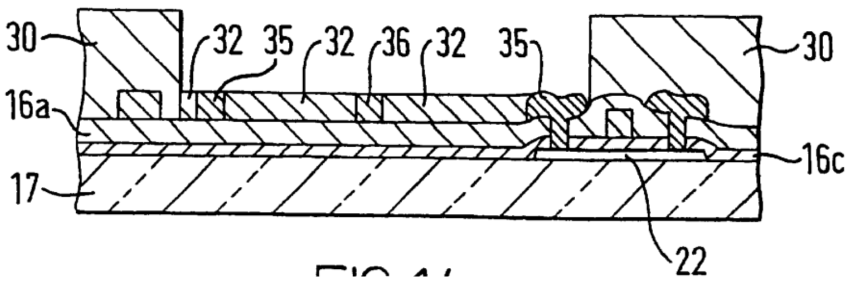



***Figure 5.12: A cross-section of the switching circuitry connected to the pixels (35 & 36) in an electroluminescent device, showing the circuitry generally located to the side of the light-emitting material to prevent it from obscuring the emitted light. The insulating layers (16a & 16c), glass substrate (17), polysilicon base for the transistor (22), banks of insulating material (30) and electrode/conductive layer (32) are also shown (Source: PCT/GB99/00530)***

Further and similarly filed on the same day as **PCT/GB99/00383**, **PCT/GB99/00381** was an improvement of the aforementioned method and device. The device arrangement was the same, comprising multiple regions of the organic material (such as a PPV blend) forming pixels or sub-pixels each controlled by separate blocks of circuitry. The exception was the addition of an opaque layer, that was light-absorbent and/or light-reflective. This layer coated the glass sheet, and was located between the transparent substrate and the circuitry but not as far as between the emissive layers and the substrate so that light from the emissive layers could leave the device and be viewed (see figure

5.13). It therefore framed the emissive regions, in a lattice type configuration. It was made of a treatment resistant metal, an alloy or a metal oxide and was either black, brown or another suitably dark colour. It functioned to: (a) mask light from outside the device from interfering with the circuitry; (b) and in turn that light being reflected back to the viewer, and; (c) absorbing some of the guided light in the glass sheet and preventing it from interfering with the emitted light. This improved the contrast of the emitted light and provided better displays compared to prior art devices (JP 5-107550; JP 9-57862 etc..), in which, although a black material had been added to guard against incident light, it had not specifically been designed to protect the circuitry or deal with the waveguided light. No citations destructive of novelty or inventive step were found in the official search report.

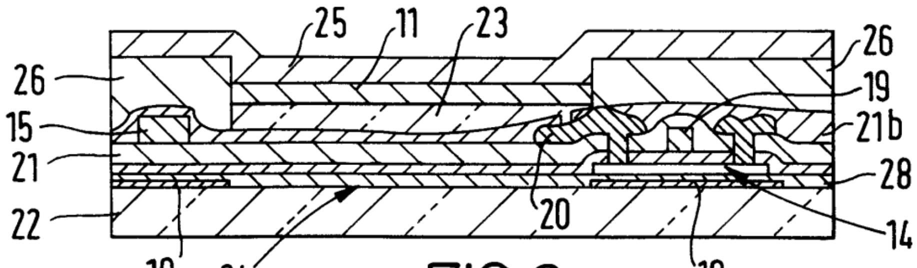


FIG.3

***Figure 5.13: A cross-section of an electroluminescent device showing the substrate (22) separated from the circuitry (14) by an opaque layer (10) which absorbs light. Also shown are the light-emitting material/pixel (11), row electrode that controls the switch mechanism (15), the current transistor (19), the output terminal (20), an inter-layer insulator (21) that reduced chemical reactivity and contamination of layers on either side of it, the anode (23), the hole through which emitted light from (11) could pass and subsequently be viewed (24), the cathode (25), insulating banks (26) and another insulating layer (28). (Source: PCT/GB99/00381)***

Referring to the background of heterojunctions that was discussed in chapter 1 sections 1.6 and 1.8, it was mentioned that light-emission was typically expected at type I heterojunctions and not at type II. The next patent **PCT/GB99/00741** was centred around taking advantage of heterojunctions to overcome the issue with the difficulty particularly to inject holes into, especially, blue emissive polymer layers, that affected resultant light. As such, the inventors devised electroluminescent devices in which the light-emissive polymer layer was straddled by charge injecting layers - one for holes and another for electrons. Further, the polymer itself comprised a mixture of three even dispersed and phase-separated components: one to accept holes and another electrons from the aforementioned charge injecting layers; and the third, to generate light as a result of the combinations of the injected electrons and holes from the other two components (see figure 5.14a). This charge carrier mobility was enhanced by the formation of type II heterojunctions between the three components. A further aspect of the invention introduced charge transport layers between the charge injecting layers and the light-emissive layer, where movement of electrons and holes was aided by the presence of type II heterojunctions between the transport layers and the light-emissive layer (see figure 5.14b). Multiple layers of any of the foregoing layers and components were also employed. The result was a realisation that type II heterojunctions could be both luminescent and non-luminescent, and that their presence in a device could permit it to operate at lower voltages. This greatly improved device efficiency. There were no destructive citations in the search report so there is a presumption of validity of the invention.

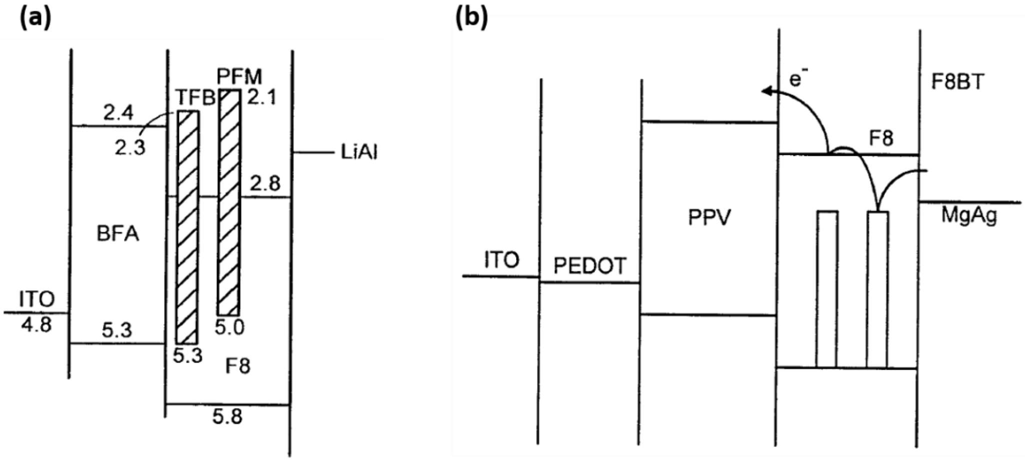



***Figure 5.14: Energy band diagrams for some of the electroluminescent devices according to the invention: (a) the light-emissive layer comprises components F8, TFB and PFM where TFB is the hole acceptor component and PFM is the light-emitting component. The cathode (LiAl), anode (ITO) and hole transport layer (BFA) are also shown. Type II heterojunctions exist at interfaces between BFA/F8, BFA/PFM, TFB/PFM, TFB/F8 and PFM/F8. (b) the light-emissive layer comprises components F8, F8BT and PPV where F8BT/F8 mixture acts as the electron transport layer. PEDOT is the hole transport layer providing an intermediate energy level for holes to migrate from the anode to the HOMO layer of PPV, MgAg the cathode and ITO the anode. An electron (e-) can be seen moving from the cathode, traversing several heterojunctions and occupying LUMO levels of increasing energies to reach the LUMO level of PPV (Source: PCT/GB99/00741, the acronyms represent different types of conjugated polymers found on page 10 of the patent application)***

We have previously discussed FETs that utilised organic materials. However, several of the organic polymers used tended to have a disordered structure, and this in turn decreased the mobility of the electronic charge carriers and hence the amount of current that flowed. Until this point, transistors as good as the silicon transistors discussed in chapter 3 had not yet been made with organic materials. Researchers had attempted to use molecular organic materials in place of polymers. The molecules however had to be deposited on the substrates at high temperatures that, in turn, damaged the substrates - they easily formed cracks and micro-cracks when deposited as films - and were highly sensitive to further processing steps in multilayer devices. Using the general structure of an FET which we have been discussing as the starting point (figure 5.15a), the inventors in **PCT/GB99/01176** built an integrated circuit such as those we discussed in chapter 3 but based of course on organic semiconductor active polymers. Further embodiments of the invention contained either an electro-optical element that either stored or consumed electrical energy, or an additional element that emitted or detected light, such as a multi-layer light-emissive device or a display device. A further addition was an insulating layer made of silicon dioxide or any suitable material with several advantageous roles including at least partially encapsulating the semiconductor layer and/or attraction of residual dopants from the semiconductor layer so that they would not interfere with current flow. The result was as shown in figure 5.15b, a multi-layer device comprising an integrated circuit and a light-emissive device, the FET innovatively functioning to switch the current flow between them. Economically advantageous was that this polymer transistor device was capable of electrical performances comparable to those of inorganic silicon transistors; this had not been previously possible with prior devices whose transistors were based on molecules and suffered from post-processing shortcomings. The official search revealed five novelty destroying prior art patents and six which indicated that the invention was obvious.

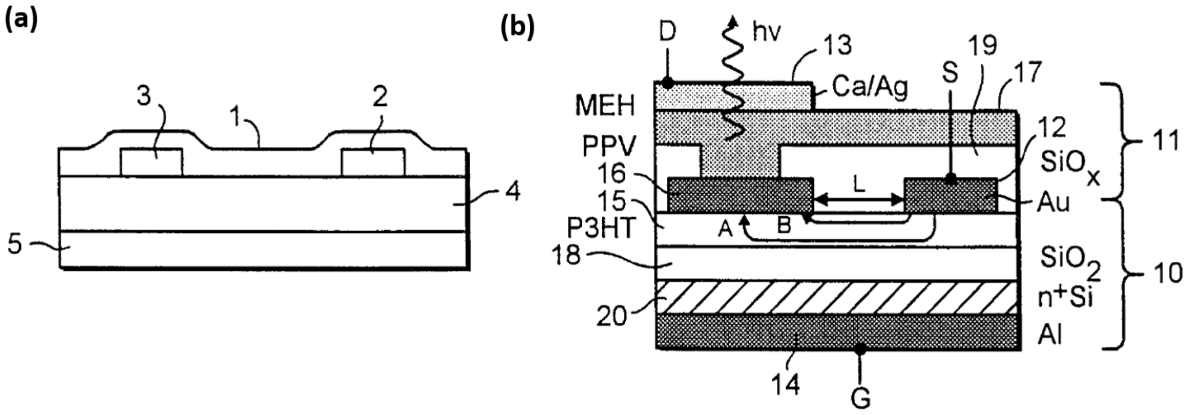



***Figure 5.15: (a) A depiction of the general structure of an FET showing the active polymer layer (1), the drain (2) and source (3) electrodes, an optional insulating layer (4) and the gate electrode (5). (b) A schematic representation of the invention; an integrated circuit (10) and the light-emissive device (11). Voltage contacts D, S and G are connected to the drain (16), source (12) and gate (14) electrodes respectively. The drain also functions as the anode. The cathode (13), semiconductor layer (15), light-emissive layer (17) whose light emission is indicated by the letters hv, and insulating layers of silicon (18, 19 & 20), source-to-drain current flow when the transistor is ON (A), source-to-drain current leakage when the transistor is OFF (B) and the channel length (L) are also shown. (Source: PCT/GB99/01176)***

Power consumption in light-emitting display devices such as those already discussed that have pixels arranged at right angles was usually high. As we have seen, the pixels were normally individually controlled by a controller device connected to the display. Most efforts to reduce power consumption were often directed towards the structure of the devices, each improvement only achieving small incremental effects. In **PCT/GB99/01145**, the inventors devised a suitably battery-powered display control device with a reduced power consumption mode. The device comprised input means for receiving display data; processing means for subsequently processing this data to control the pixels of the display in (1) a normal mode as according to the data, and in (2) a power-saving mode in which certain pixels (either sets or a specific area of the display) were made to operate with reduced power, by reducing their brightness in comparison to the normal mode, and without compromising the overall display pattern; and output means by which the processed data would be transmitted to the pixels. Included in the device operation were means to determine when and for how long to enter or leave the power-saving mode. Moreover, screen “burn-in” occurs when certain features/pixels remain on the display for a prolonged period of time, creating certain heavily used parts; dimming certain pixels in the power-saving mode prevented this.

A further aspect of the invention involved taking advantage of the intensity of natural light falling on the display to control the brightness of the pixels. A photo-detector, either independently, integrated into the display controller, or into the display itself, or indeed a number of them placed around the periphery of the display, was added to measure the intensity of the incident light on the display. The photo-detector(s) communicated with the display controller, which in turn increased the brightness of the display as natural light increased. In the past, the power consumption of the light-emissive device itself would have been increased to counter the negative effects of natural light on viewing clarity. Economically, the efficiency of display devices was enhanced with the reduction in power consumption, especially in larger displays that were particularly affected by ambient light. The official search found prior art which destroyed novelty and inventive step of some of the claims in the patent application.

Nanoparticles, very small particles of sizes 100nm, had by this time been used in polymer layers in devices such as LEDs. In the methods employed in the prior art, the nanoparticles often suffered from agglomeration, forming masses or balls that made it difficult to exploit fully the nanoparticular nature of the polymers. **PCT/GB99/02271** and **PCT/GB99/02263** concerned methods for preparing unaggregated or only weakly aggregated nanoparticles. A solution of nanoparticles in a solvent was formed and then incorporated, in their disaggregated state, into a body of material (such as the organic material that would later be used to fabricate the device). The solvent was then evaporated off leaving a uniform and non-aggregated dispersion of nanoparticles fixed in the material. This way the nanoparticles advantageously influenced the morphology, optical and/or electrical characteristics of the organic material, such as structure, refractive index and/or conductivity. The amount of nanoparticles added could then be tailored to the degree the aforementioned characteristics needed be influenced. The official search found no relevant prior art.

The next invention, the subject of **PCT/GB00/01288** was concerned with a method for doping a conjugated polymer at a controlled, low or intermediate level; a polymer that had so been prepared and a device that included such a material. Previous conventional doping methods had provided a high level of doping that had proved unnecessary and undesirable in that, amongst other disadvantages, the optical properties of the polymers had been affected as the extra sub-groups undesirably absorbed any emitted light. It is not expedient to delve into the detailed methodology but the gist of it was that the amount of doping agent added to the conjugated polymer solution was less than the amount required to form a fully doped conjugated polymer. Economically, this was both simple and cost effective and the resultant polymers had balanced electrical and optical properties. The official search revealed one novelty-destroying prior art. Divisional applications of this patent were also filed to meet the statutory requirement of unity of invention.

Conjugated polymers exhibit liquid-crystalline (LC) phases; this is a state of matter in which they have a preferred orientation in space. In layman terms, because they are crystalline, the molecules in the polymer are randomly distributed in at least one direction to form several shapes including 1D columns, disc-shapes crystals in columnar aggregates (discotic crystals), rigid 2D cores etc. Advantageously, these highly structured phases contributed to high charge carrier mobilities which improved device performances. Methods for inducing these structures were highly experimental especially given the difficulties in solution-processing of organic polymers. In particular, there was no suitable processing technique for preferential alignment of polymer chains in the axis of the plane of the film: these are required to produce linearly polarised light. That was until **PCT/GB00/02404**. The inventors devised a method of aligning the chains of the polymer parallel to each other and within a single axis of alignment whilst bringing the polymer into liquid-crystalline phase. This was achieved by depositing the polymer on top of an alignment layer that was capable of inducing the parallel alignment in the polymer (see figure 5.16). They additionally formed electronic devices such as polymer transistors in this way. Even where the alignment only occurred locally, the improvement in device performance was still significant compared to polymers not ordered this way. Some novelty destroying prior art relevant to some claims was found in the official search report; the validity of the bulk of the claims however was not questioned.

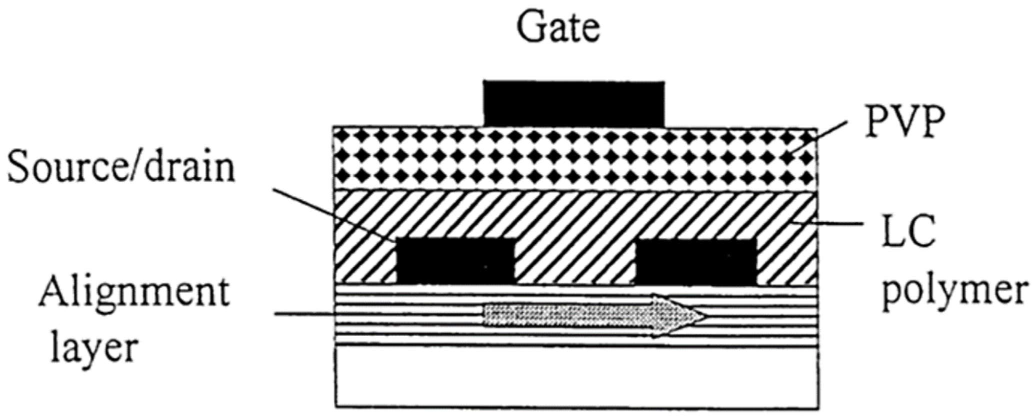



***Figure 5.16: A depiction of a transistor formed by use of an alignment layer coating the substrate and before the polymer layers are laid down so as to influence the alignment of the chains in the latter. The liquid-crystalline polymer (LC polymer) for light emission and the polymer polyvinylphenol (PVP) that provides insulation for the gate region of the transistor are also shown (Source: PCT/GB00/02404)***

A year later, the inventors filed **PCT/GB02/04180** (patent 36 in the list) that disclosed an alternative deposition method to the above mentioned, for disc-shaped molecules in particular. The method was based on template growth of the discotic molecules from solution. It involved the adsorption of the polymer molecules from solution onto a substrate capable of inducing the discotic alignment either (1) by virtue of the atomic or molecular structure of its surface or (2) interaction with the regular topographical features on the substrate. The end result was solid, highly orientated thin films of discotic LCs in which the columns were aligned in the plane of the substrate as seen in figure 5.17, the ideal orientation for most devices such as transistors, in which current flows in the plane of the substrate. Advantageously, it was found that no alignment layer was required if multilayer configurations were desired. The later (4 March 2004) published search report indicated that the invention lacked novelty or inventive step.

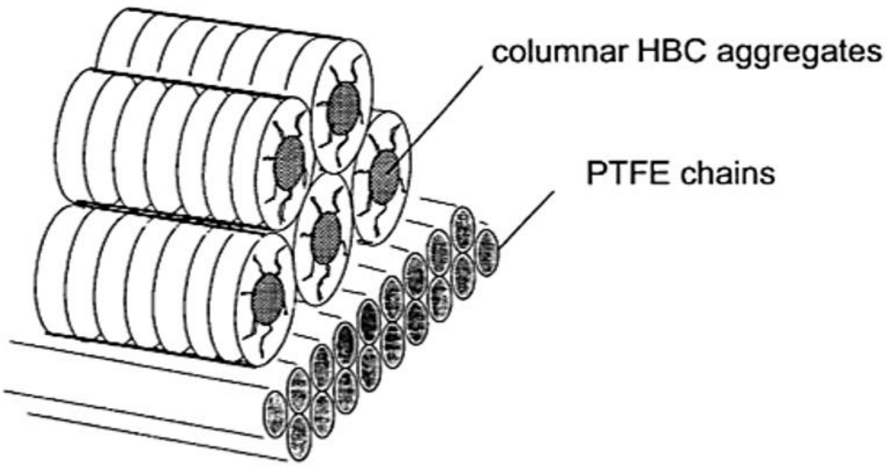



***Figure 5.17: A schematic of the columnar arrangement of the semiconductor active layer (HBC is a family of disc-shaped LC organic molecules) induced by adsorption to a substrate coated with an alignment layer of PTFE (polytetrafluororethylene) (Source: PCT/GB02/04180)***

From the foregoing discussion, it will be apparent that two of the main problems with fabrication of OLEDs are (1) polymers that emit good red, green and blue colours, and (2) how easily they can be fabricated into low-power consuming full-colour displays that are commercially viable. We have seen several researchers employing different approaches to solving these issues: changing the chemical structure of the polymers; copolymerisation; attaching chemical side groups that enhance the polymers' performance; incorporating various dyes to colour-tune the polymers, etc. The next invention, detailed in **PCT/GB00/04594**, concerned a novel type of copolymer that directly showed colour-tuning properties, was easy to solution-process into thin films, was thermally stable and relatively inexpensive to fabricate on an industrial scale. The copolymer comprised fluorene-perylene moieties - both types of conjugated polymers that covered the visible spectrum. The perylene moieties used exhibited superior stability and a high, close to 100% ability to fluoresce a diversity of colours, providing an effective way of fine-tuning the colour emission of the polymers. Innovatively, an end-capping group was added to either ends of the polymer to cap the growth of the polymer and prevent aggregation or formation of residual end-groups which had caused problems in earlier polymers. This invention purported to solve a lot of the problems that other researchers were addressing at the time. If it did, as stated, others would have adopted it as a standard and thus become the start of a Schumpeter B phase. Other aspects of the invention included a kit for synthesising the copolymer, and electroluminescent devices using such copolymers. The official search revealed two citations which questioned the inventive step of this invention.

For cost effectiveness and ease of processing, it is desirable that all the layers in a semiconductor device are deposited from solution. However and commonly, previously deposited layers would dissolve on addition of a new one or sometimes the solvent used to deposit latter layers would 'swell'. In **PCT/GB00/04934** the inventors devised solution-processed devices such as TFTs and methods for forming these in a way that dealt with some of these issues. Innovatively, they deposited each layer in a solvent in which the previously formed layer was substantially insoluble, such as depositing the first layer in a polar solvent and the second layer in a non-polar solvent. Notably, at least one of the layers was formed by ink-jet printing. The advantage of this was evident; polymers layers were deposited in such a way that they had to follow the alignment pattern of the substrate. Traditionally, where the substrates were flexible, a distortion in one layer, especially over large areas, would affect the alignment of subsequent layers and disrupt the underlying pattern. In this method however, the ink-jet printer head could be adjusted locally to match the pattern in the substrate. More accurate underlays were thus produced and devices were ultimately cheaper to produce. The official search revealed two novelty destroying citations.

In the same spirit of solution-processing entire devices, the inventors in **PCT/GB00/04938** further built integrated circuits using inkjet printing, forming at least part of the circuit, such as the deposition of the active semiconductive material onto the substrate or of an insulating layer. The benefits of using IJP have already been discussed. There were several destructive citations in the search report so the validity of the invention would be questioned.

Using similar principles, next filed was **PCT/GB00/04940**, in relation to a method for forming interconnects, particularly connecting two or more devices such as transistors in a multi-layered device - this is reminiscent of the development of the inorganic integrated circuit (discussed in chapter 3). This was achieved by defining a region in which to form the interconnect; using a solvent capable of progressively dissolving the underlying layers to form a hole through the sequence of layers; means of defining the diameter of the hole and of removing the dissolving solvent and dissolved material; and finally, filling the hole with conductive or semiconductive material that thus formed a channel of electrically conductive material extending through the sequence of the layers. Economically, this allowed for circuits to be made compactly so that more components could be put into a device. Prior art detrimental to the novelty, inventiveness and industrial applicability of several of the claims in the patent application was highlighted in the official examination report.

**PCT/GB00/04942** further concerned solution-processed devices and methods for making such, comprising a plurality of regions electrically separated from each other due to the relative repellence of a common mixture, that mixture itself being confined to the substrate by the repulsion. Advantageously, the space between the spaced apart regions could be filled with a conductive or semiconductive polymer to form TFT channels for a transistor. This went a long way in combating the age-old problem of maintaining the integrity of a solution-processed multilayer device, and of producing well-defined electrodes at high resolution. The official search report showed prior art that was detrimental to the novelty of two out of four main claims.

Certain families of modified conjugated semiconductors are desirable for use in transistors and related devices. This includes polymers such are those with chemical groups called thiophenes - electron-rich rings that trap certain charge carriers by their resident impurities. However, they easily trap negative charge carriers and end up acting as p-type semiconductors. Although advantageous, in some cases it caused certain difficulties in device stability and processing. At the time there was a gap in understanding and use of n-type organic semiconductors after this manner; the available options had several shortcomings including difficulty to synthesise or undesirable environmental sensitivity. **PCT/US01/41408** provided a new and useful n-type material, and a method of its preparation, to overcome these problems. The inventors achieved this by fluoroalkylating (adding fluoro- and alkyl side chains) p-type thiophene polymers to convert their conductivity to n-type. This substantially enhanced the volatility, thermal stability and electron affinity of the polymers. Alternatively, n- and p-type materials were used in combination to provide more stability and lower power consuming devices. Several citations in the search report indicated that this invention was obvious.

**PCT/GB01/04376** related to an improved electroluminescent display device, a method for running it and an electronic apparatus. We have already commented that the quality of the images produced by a display device depends on how well the brightness of the individual pixels is controlled to provide different colour variations such as greyscales, and that the better of such devices are those that effect reduced power consumption. One of the popular methods at the time was dividing the pixels into sub-pixels and then separately controlling the sub-pixels; this however presented the inevitable disadvantage of increasing the size of the display panel and subsequently, the number of signals generated. It also reduced the production yield due to the more complex structure having greater propensity to fail tests. The novelty of this invention lay in the fact that the on-period of the pixels in the OLED device was modulated by a separate apparatus to about 20 milliseconds, which modulation was perceived by the human eye as a change in the intensity of the emitted light. For the purposes of the discussion, the details of the method and apparatus are not necessary but to note the resultant advantage of an exceptionally effective switching period between pixels that provided better greyscale capabilities in comparison to the prior art. The search report revealed three novelty destroying citations.

The foregoing inventions have indicated that perhaps the biggest advantage of polymer semiconductors is that they can easily be solution-processed with simple and cheap methods. The difficulty however was in the ability of known patterning technologies to form precise lateral patterns/layers, in particular, in defining the source and drain electrodes of a TFT (as seen in figures 5.7 and 5.16 above). The crux of the matter was usually getting the indentation depth during the creation of these channels to match the thickness of the thin film. In **PCT/GB01/04421**, the inventors devised such devices, and a method of fabrication comprising forcing a microcutting protrusion of a cutting tool into the first layer of the polymer multilayer, to carve out a particular design, as seen in figure 5.18. The indentations/grooves were then filled with conducting polymer electrodes using known methods like IJP. This way, the side walls of the active regions between the source and drain electrodes were accurately defined. The method was also employed to define other parts of the devices, such as interconnects. Devices were thus built with better electrical and structural integrity, offering better commercial advantages. There was one novelty destroying citation.

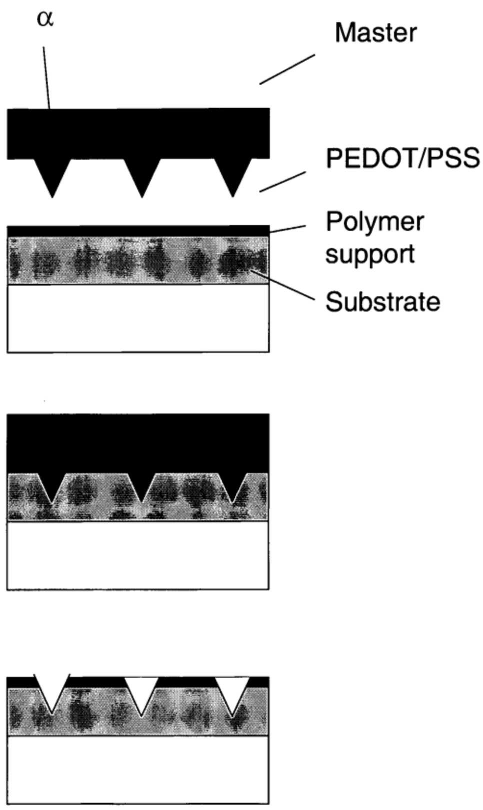



***Figure 5.18: A schematic diagram of an exemplar microcutting process showing the microcutting tool (the Master) making indentations into the polymer layer and the substrate. A soft material layer (PEDOT/PSS) is added before the cutting to aid the Master in adhering to and uniformly penetrating the device layers. a defines the indentation angle (Source: PCT/GB01/04421)***

In **PCT/GB02/01723** the inventors devised light-emissive devices**,** such as photovoltaics and photodetectors, and methods for forming their fabrication, after the general structure we have been discussing but with the added inventiveness that the active layers consisted of fluid polymer blends - similar to those earlier discussed in **PCT/IB95/01042.** The device is shown in figure 5.19. These blends either: (1) caused emitted light to be propagated in a predetermined direction or in a direction parallel to the plane of the polymer blend layer; (2) or contained additional electronic components that guided or modulate emitted light in a predetermined direction; or usefully, (4) charge transport layers that aided in charge carrier mobility. The resultant devices produced clearer light than the prior art. One citation destructive of novelty of only three out of the eleven main claims was found in the official search report.

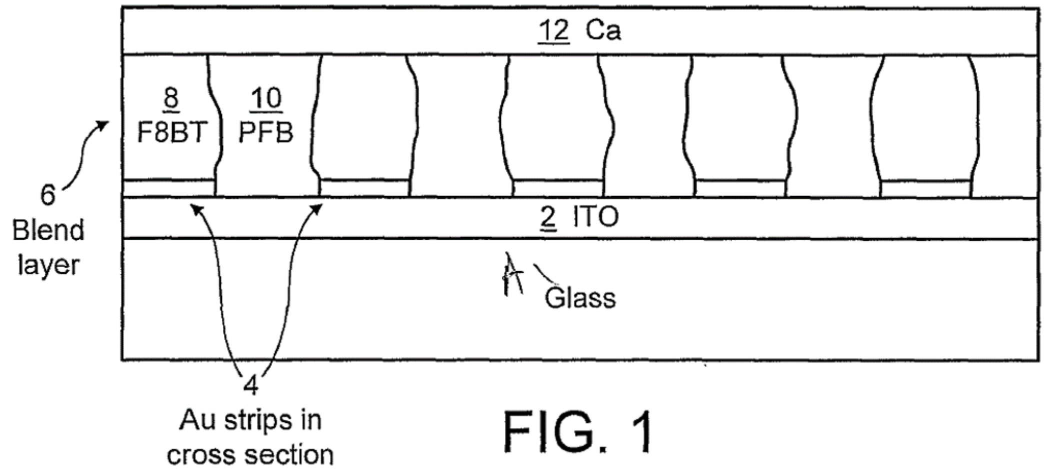



FIG. 1

***Figure 5.19: A schematic cross-sectional view of a light-emissive device highlighting the polymer blend (6) comprising of two phase-separated polymers (8 & 10) straddled by a calcium cathode (12) and an ITO anode (2) coated onto a glass substrate. The gold strips (4) facilitate micro contact between polymer (8) and the anode (2), maintaining the integrity of the polymer blend (Source: PCT/GB02/01723)***

**PCT/GB02/05054** dealt with the problems encountered in the injection of holes by the metallic electrodes of FETs into the active organic semiconductor layer. Metals generally have a much lower work function (the minimum quantity of energy required to remove an electron from the surface of the metal) compared to the HOMO levels of semiconductors so that there is a difficulty in holes being transferred from the metals into the semiconductor. As a result, metal electrode channels get saturated, affecting device efficiency. In building an FET, the inventors included a hole transport layer comprising a layered metal chalcogenide. In other words, the metal electrodes were made in a layer-type structure comprising sheets of metals atoms such as titanium or tin sandwiched between sheets of chalcogenide atoms (these are elements in group 16 of the periodic table - see chapter 1, sections 1.4 & 1.5) such as sulphur or selenium. In addition to having a work function close to the semiconductor HOMO levels and providing more efficient hole transport, the metal chalcogenides were usefully chemically inert in that they did not chemically interact with the interfaces of the organic semiconductor layers which would have reduced the efficiency and lifetime of the FETs. Moreover, the chalcogenides could simply and cheaply be processed into thin films, enabling low cost manufacture of FETs. The invention embodied a process of making the aforementioned and a device so formed. There were no citations of concern in the official search report.

**PCT/GB2003/004753** addressed the major issue encountered with polymers producing emitted blue light; an innate short lifetime (time taken for brightness to halve at a given current) in comparison to red or green light. Researchers have submitted that perhaps the LUMO level of blue polymers isn't deep enough, resulting into a short-lived charged state. It has also been suggested that there exists a greater energy gap between the blue polymer's LUMO and the work function of the cathode in comparison to those of red or green polymers, making it difficult for electrons to be injected into blue light-emitting polymers (paragraph 6 of the US national filing - US2006228576). Several options - the details of which will not be discussed - to assisted electron injection into blue polymers have been explored. The current invention provided a material with a high electron affinity that was able to function as an electron transport layer for the blue, as well as red and green emitting polymers. This was achieved by increasing the electron affinity of known polyfluorenes (multiply fluorinated polymers) by synthesising them with certain electron attracting groups. Improved electron injection into the LUMO levels of blue electroluminescent polymers produced better blue light which made for better full colour displays. The official search found prior art which destroyed the novelty of one of the two main claims and six out of the twenty-two dependent claims.

**PCT/GB2004/001696** related to building more efficient and stable electroluminescent devices such as LEDs, PVs, FETs, and methods for manufacturing such. It innovatively employed at least one of the semiconductor layers in the thin sandwich layer in the form of polymer brushes (see figure 5.20) attached to the surface at least one of the electrodes, and in contact with at least one of the other semiconducting materials in the sandwich. The point was to create a large interaction area between the brushes and the semiconducting layers with which they were in contact, so as to provide a direct transport path for electrons and holes moving from the electrodes to the polymer. This was especially useful because in many of these devices, especially where polymer blends were used, charge carriers used to get trapped by the different components of the blend due to lack of direct transport paths to the electrodes, decreasing charge extraction and therefore quantum efficiency. The resultant devices exhibited current flow of at least 30 times greater than conventional devices. Several citations detrimental to the novelty and inventiveness of a number of claims were revealed in the search report; many detailed dependent claims would however be sustainable.

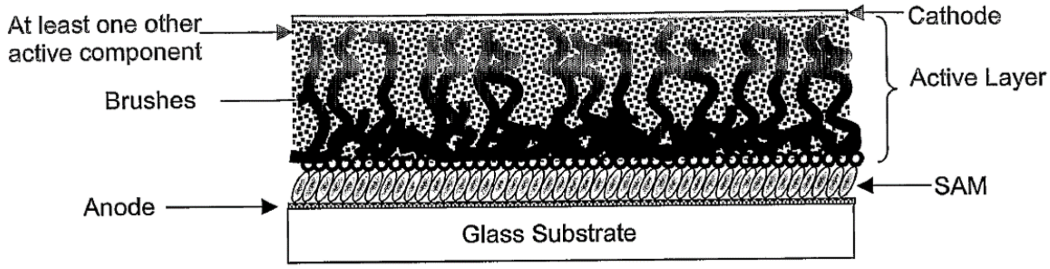



***Figure 5.20: A schematic representation of a device after this invention, showing the semiconductor polymer brushes intercalated with a second semiconductor polymer (the dotted region). The SAM layer (a self-assembled monolayer) and the attached thin layer of thick black circles contain the molecules that initiate the growth of the polymer brushes (Source: PCT/GB2004/001696)***

**PCT/GB2004/002078** related to a method for making a polymer device. We have already discussed the difficulties associated with getting organic polymers into solution so that they could be deposited on the substrate during device manufacture. We also discussed the option of using soluble precursor polymers that subsequently converted into the insoluble polymer after deposition; this limited utility to specific classes of polymers and the additional processing steps themselves introduced some disadvantages. Other researchers used polymers with different solvent solubilities to circumvent the dissolution of later deposited layers: again, this limited the class of useable polymers. Crosslinking then became a popular solution. This is where particular side groups were added to the polymer main chain to form insoluble layers onto which additional polymers layers were deposited. Several approaches existed in the prior art but until the time of this invention, the resultant novel polymers were not suitable for use within devices. The reason for this was that cross-linker groups had to be present in high amounts, which interfered with charge-carrier transport. In **PCT/GB2004/002078**, the inventors discovered that low concentrations of crosslinking groups, either mixed with the semiconductive polymer or part of the main chain or as a side chain, could successfully be used in a semiconductor layer of a device without degrading its performance. So they devised a method to deposit such polymers in device fabrication. Usefully unlimited stacks of multilayers and patterned polymer films could be fabricated post-deposition and then incorporated into the devices. The official search report found some novelty-destroying prior art.

Also based on crosslinking groups and filed on the same day as the previous invention, **PCT/GB2004/02054** related to a new polymer FET. As we have already discussed, FETs typically contain source and drain electrodes separated by a semiconductor layer, the layer being spaced from a gate electrode by the gate dielectric. Fabrication of a defect-free ultrathin gate dielectric layer is one of the greatest challenges in FET device fabrication. It is very important to achieve a high-quality interface with the semiconductor layer that is easy to fabricate on a variety of substrates, resistant to the effects of the environment around it etc. In silicon FETs, silicon dioxide or silicon nitride is used to form such a layer, and forms a near perfect interface with the semiconductive layer, with all the desired properties. The inventors here employed the aforementioned concept of crosslinking to build the gate dielectric of an FET and of a phototransistor. As such, the chemical and mechanical stability attributable to crosslinking produced a more robust gate dielectric polymer that produced charge-carrier mobilities at the interface comparable to those of a silicon transistor. The official search found several prior art that would bring the novelty of several claims into question.

Moreover, conventional methods at the time involved the deposition of the semiconductor and gate dielectric layers in two separate steps. The time delay between depositions exposed the materials to the ambient atmosphere, opening up a host of disadvantages including either bulk trapping of or unnecessary reactions of charge carriers with impurities in the ambience. **PCT/GB2004/003452** concerned a method for forming these layers in a single step, conferring the additional advantage of reduced processing steps. Moreover, the interface between the two layers was protected from the ambience; it was advantageously planar; and its quality and charge mobilities were comparable to the benchmark silicon transistors. Prior art potentially fatal to the novelty and inventive step of some of the claims was disclosed in the official search.

We also discussed that traditional FETs operate in either n-channel or p-channel modes. Traditionally p-channel FETs were easier to fabricate, as polymer materials for n-channel FETs were at the time more limited. **PCT/GB2005/000130** related to a new type of FET that was capable of ambipolar conduction (both modes in the same device), and very interestingly, light emission from a specific channel of the transistor. Until this point, FETs were mostly employed in charge carrier control and not effectively in light-emission. The intricate details are outside the scope of this discussion but notably, the challenge with fabricating ambipolar FETs was that both electrons and holes had to be injected from the same electrode into a single semiconductor layer; the work function of the electrode therefore had to permit both conductivities. As with n-channel FETs, useable polymers for ambipolar FETs were also limited. Moreover, for an ambipolar device to emit light, it has to be capable of moving the position of the recombination zone (where light is produced) in the semiconductor layer to any position along the channel between the source and the drain electrodes by varying the voltage applied to all three electrodes. This movement is dependent on the charge carrier mobilities. This invention comprised the source injecting holes and the drain injecting electrons into the semiconductor layer, and the voltage being biased so as to balance the mobilities of both the electrons and holes and as a result cause the recombination zone to, for example, be confined to the middle of the channel (see figure 5.21). This was aided by the use of electron trapping groups in different regions of the gate dielectric layer so that at certain areas of the gate dielectric/semiconductor interface, electrons were irreversibly trapped and thus immobile while in other regions where electron mobility was needed, they were not. The obvious economic benefit of an ambipolar light-emitting FET was an increased variety of applications. This echoes a type of technology for constructing inorganic semiconductor integrated circuits called CMOS (Complementary metal–oxide–semiconductor) that was pioneered by RCA and Fairchild Semiconductors in 1983 (Fairchild Semiconductor, 1983). The search report revealed no invalidating prior art.

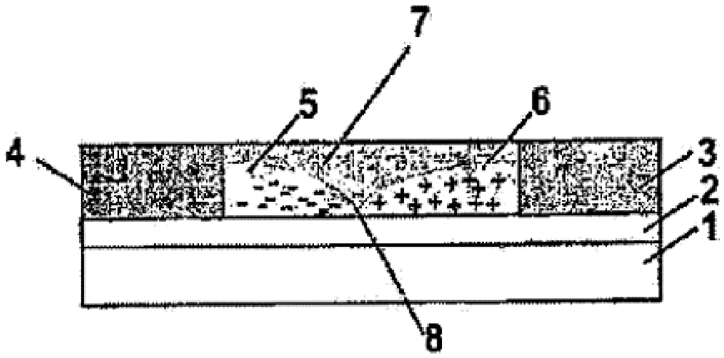



***Figure 5.21: A schematic representation of a general light-emitting FET showing the substrate/gate electrode (1), gate dielectric (2), source electrode (3), drain electrode (4), electron channel (5), hole channel (6), the organic semiconductor layer (7) and the recombination zone (8) (Source: PCT/GB2005/000130)***

**PCT/GB2005/001309** involved organic dual-gate FETs (DG-FETs); four-terminal devices that comprised a pair of source/drain electrodes, a pair of gate electrodes and a pair of gate dielectrics flanking an organic semiconductor channel (see figure 5.22). In essence, two FETs connected in parallel. The present invention sought to introduce the feature of "volume inversion" common in silicon DG-FETs into organic DG-FETs. Volume inversion was a phenomenon in silicon DG-FETs whereby the transistors were turned on when a voltage applied at the gates caused the sign of charge carriers at the interface between the silicon and the electrodes to be inverted - when a negative charge carrier became a positive one and vice versa. Amongst the several advantages of this was an increase in current and operational speed due to the redistribution of charge carriers. Previous organic DG-FETs operated in the regular way, turning on when charge carriers injected from the electrodes accumulated. By having two gate structures flanking the organic semiconductor layer, the conductance of each of the two channels (semiconductor regions) could be influenced by voltage applied to both gates. Further, as the gates were coupled, the operation of one gate influenced or affected the channel next to the other gate. Therefore, the transistor was only switched on (became conducting) when both gates were biased to the "on" state. This opened up possibilities for new applications, considering prior art FETs were switched on when at least one of the gates was in the "on" state. Moreover, compared to single-gate FETs, the two gates in DG-FETs shared the same semiconductor layer so their properties were more easily matched as there was less variation in processing etc., rendering the resultant

FETs of better efficiency. The official search found prior art which destroyed novelty and inventive step of some claims in the patent application.

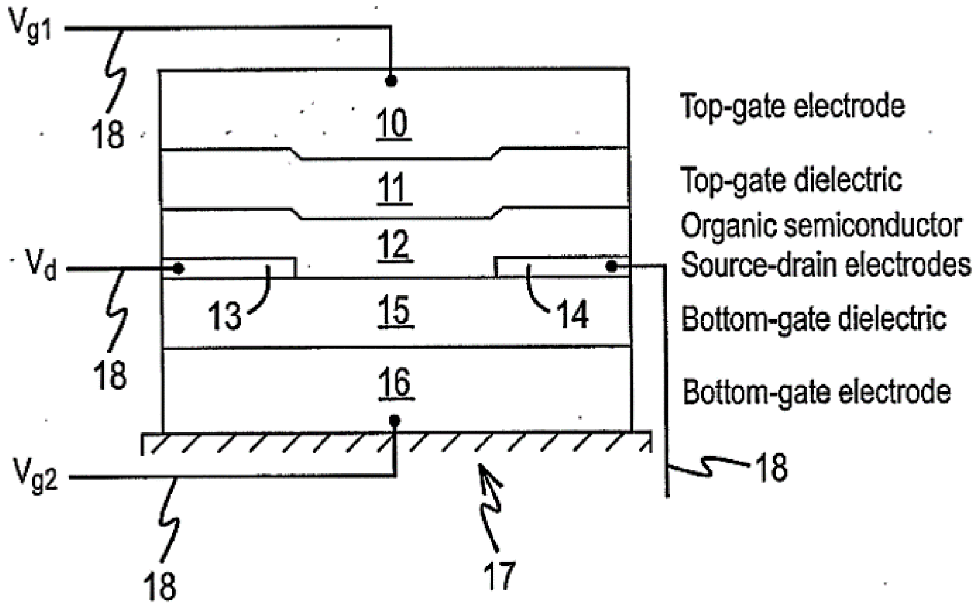



***Figure 5.22: A schematic of a DG-FET showing the organic semiconductor layer (12) flanked by the two FETs: gate electrodes (10 & 16), gate dielectrics (11 & 15) and shared source and drain electrodes (13 & 14 respectively). The substrate (17), the external connections to the electrodes (18) and voltage applications (Vd/gx) are also shown (Source: PCT/GB2005/001309)***

**PCT/GB2007/001245** related to an improved method of deposition, in particular, solution-processing techniques as regards to filling wells; troughs, valleys, regions etc. that define lines/areas in a circuit device or pixels/sub-pixels in a display device. It addressed the difficulties associated with IJP: (i) formation of thin edges when material was deposited into wells with shallow edges, potentially creating a problem of non-uniform film formation; (ii) difficulties in filling corners of wells whose diameter was larger than the size of the inkjet droplet - this was usually overcome by overfilling the well but this slowed down the printing process, and; (iii) shorting; where the hole-injecting layer extended and overlay the semiconductor layer, providing a shorter path at an edge of a well for charge-carriers to move between the cathode and the anode. The solutions to the aforementioned were complex and expensive. The inventors devised a simple and inexpensive way of filling wells/pixels using a stamp. The stamp (see figure 5.23) was made to contact areas of the substrate to decrease the wettability of those areas, and the semiconductive polymer was deposited over areas of the substrate located between the areas of decreased wettability. This ensured accurate positioning of the active polymer material into wells because the differences in wettability in adjacent regions of the substrate prevented the material from flowing over into adjacent regions. Further accuracy and thus device efficiency was ensured by freedom in selection of bank (side walls of the wells) materials based on wettability. Moreover, simple bank and deposited materials could be used. Prior art that was fatal to the novelty and inventive step of some of the claims was revealed in the official search report.

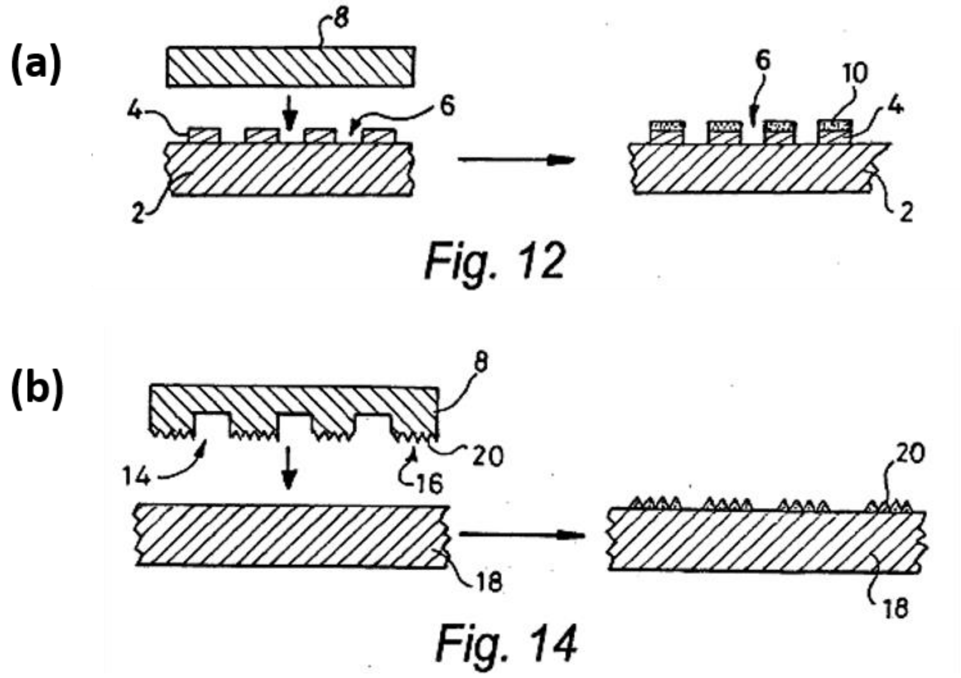



***Figure 5.23: An illustration of the method of manufacture of an electroluminescent device by way of two examples. (a) shows the substrate (2), comprising on the upper side of bank structures (4) that define wells (6), being brought into contact with the stamp (8). The stamp introduces a layer of material (10) onto the surface of the banks that alters the wettability of those areas of the substrate. The active polymer can then be deposited into the wells (6). (b) shows a stamp (8) comprising bank structures (14) with roughened surfaces (16) made of several projections (20). This time the substrate (18) has a flat surface and regions of low wettability are introduced thereon by the roughened surfaces of the bank - the active polymer is deposited between these (Source: PCT/GB2007/001245)***

Casting the mind back to the discussion of heterojunctions in chapter 1, we saw that the selection of appropriate materials is very crucial to the efficiency of heterojunctions in particular applications such as LEDs and PVs. Heterojunctions exist in several shapes: “distributed heterojunctions” or flat/planar ones. The former includes columnar, columnar nanostructures, or modulated heterojunctions (those that vertically vary in composition), and is more desirable than the latter as it creates a larger interface between the two materials in contact so that they are in intimate contact with each other. This importantly provides continuous paths for the charge-carriers to flow between the materials and reach their respective collection electrodes, leading to improved device performance. The fabrication of distributed heterostructures however was not easy; the difficulty was in naturally obtaining a phase-separated mixture of the two polymers to deposit onto the substrate, and post deposition, maintaining those phases throughout the active layer so that charge-carriers were not trapped. In **PCT/GB2008/003965**, the inventors produced a modulated composition by immobilising a polymer onto a substrate by crosslinking and then deposited a second polymer thereon, creating a columnar modulated composition as shown in figure 5.24. A further aspect of the invention was the creation of nanostructured heterostructures and methods of making them. The resultant devices exhibited improved performance to the prior art. Novelty destroying prior art was indicated in the search report.

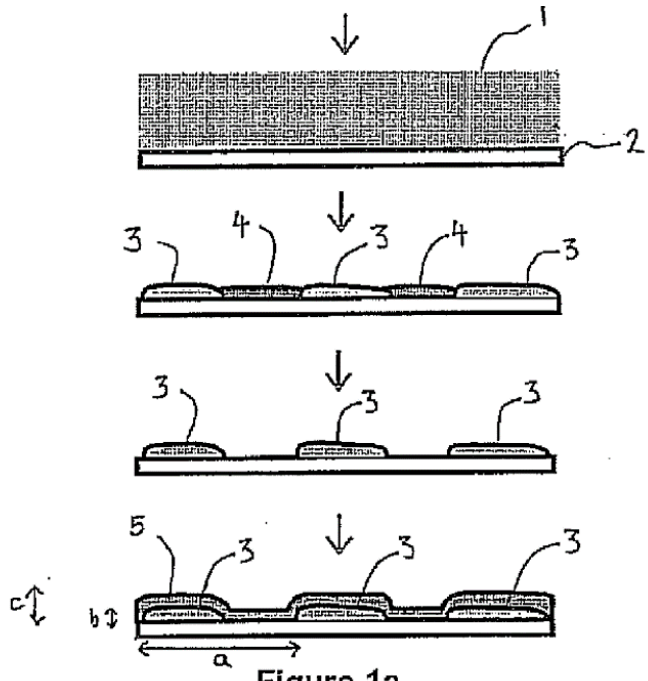



***Figure 5.24: An exemplar illustration of the formation of a nanostructured heterojunction in an electroluminescent device showing a mixture of the first polymer and a phase control material (1) being immobilised onto the substrate (2). Mixture 1 then underwent phase separation into the polymer (3) and the phase control material (4); the latter was selectively removed while the former was immobilised. The second polymer (5) was then deposited. Letters a, b and c refer to the length and width of the structures (Source: PCT/GB2008/003965)***

Metal electrodes have long been problematic in polymer-based electronics; even the more stable gradually degrade due to oxidation. Prior art often employed encapsulated metal electrodes in order for them to operate in ambient conditions. Drawing on the success of metal-oxide semiconductors as charge-carrier transport and injection layers, namely exceptional stability, robustness, resistance to oxidation etc., the inventors in **PCT/EP2009/057637** layered devices with transport and injection layers so that the optical gain due to their presence countered the optical loss due to the metal electrodes. The quantum details are not considered necessary for this discussion. This further improved the electrical and optical performance of LEDs. Although there is one novelty destroying citation which may be fatal to the respective claim, the remaining claims may still be worthwhile.

Solar cells differ slightly from the devices we have been discussing. They are classified as photoresponsive devices; they produce electricity in response to light. They typically include a donor layer, a film of active polymer material that donates electrons when excited by light to a film of acceptor molecules. Both films/layers are sandwiched between electrodes. At the interface of these two films, light-generated exciton pairs dissociate, the electron passes to the donor layer and is collected at the electrode close to that layer, while the hole passes to the acceptor layer and is collected at the other electrode. The mobilities of the electrons/holes need to be high enough for them to reach the electrodes; otherwise the two may get trapped in intermediate layers, recombine, remain in the donor/acceptor layers, or somewhere else in the device, affecting device efficiency. The invention in **PCT/GB2010/050726** sought to provide a new type of species for use in solar cells; modified conjugated polyelectrolytes (CPEs), in other words, active layers either blended with electrolytes or made of polymers that had ion pairs attached to their side chains had previously been proven to have desirable properties as charge-carrier injection layers. The inventors fabricated a solar cell in which the ion pairs in the polymers were preferentially located at, near or towards the donor/acceptor interface. Application of an external voltage then caused dissociation and redistribution of formerly strongly bound and neutral excitons (see figure 5.25), and movement and collection of resultant ions at opposite electrodes. This redistribution of some charge led to better performing devices in comparison to the prior art. The official search revealed some prior art that could bring the validity of some claims into question.

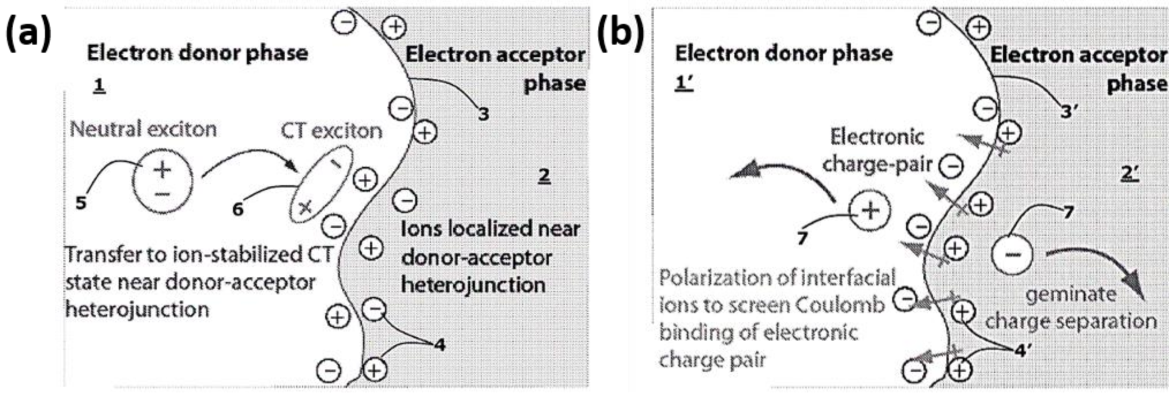



***Figure 5.25: A schematic diagram of the donor/acceptor interfaces/heterojunctions (3) in a solar cell, showing ion pairs (4) located near the heterojunction. In (a), the electron donor (1) contains a neutral exciton (5) that migrates towards the interface (3) and aligns with the ion pairs there to form a stable charge-transfer (CT) state (6) which is long-lived and immobile. In (b), an applied external voltage disrupts the field causing like ions to be located on respective sides of the interface. This leads to dissociation of the CT state (7) and escape of resultant ions to the attraction of opposite charges (Source: PCT/GB2010/050726)***

To enhance the previous invention and others like it containing heterojunctions, the inventors in **PCT/GB2010/051138** solved the issue of charge-carriers getting trapped at the interface because they could not diffuse away from the fast enough. They included an intervening species at the interface. These species comprised materials that altered the energy transfer characteristics of electrons & holes between the donor and acceptor polymers, by say for example, inducing coupling between the charge carriers so that excitons easily moved either to or from interface. This is turn improved the efficiency of charge generation. Two pieces of prior art detrimental to the novelty of the main claims were cited in the search report; many detailed dependent claims would however be sustainable.

Synonymous to finding a solution to the issues previously discussed in **PCT/GB2004/002078** and **PCT/GB04/02054, PCT/SG2010/000454** related to an improved cross-linking moiety. Prior art cross-linkers were typically added in high concentrations; amongst other disadvantages already discussed, this altered the morphological characteristics of the active polymers or even undesirably formed traps for electrons and excitons. Without resorting to discussion of minutiae, the essence of this invention was a strategic addition of specific cross-linking moieties to the active polymer without degrading its properties, creating better performing polymers. Methods for forming electroluminescent devices comprising the cross-linkers were also devised. The prior art search revealed three articles that could potentially prejudice the validity of some claims in the application.

**PCT/GB2011/050038** related to devices built after any of the structures that have been discussed except with active semiconductor layers of a particular thickness, 200-3000nm; this had been found to be the optimal film thickness for efficient hole injection. The resultant devices were easier and cheaper to manufacture than the prior art. Three novelty-destroying citations were indicated in the search report.

CPEs, active semiconductor layers either blended with electrolytes or made of polymers with ion pairs attached to their side chains, were previously introduced in **PCT/GB2010/050726** above as aiding charge-carrier injection layers to counter the issue of low electron/hole mobilities, which led to better performing solar cells. On the flipside, and because they are charged entities, the presence of CPEs in other devices such as OLEDs leads to several complications. These include redistribution of the internal electric field, alteration of the work function of the electrodes or interference with the doping species, which would all negatively affect device performance. The inventors in the next patent, **PCT/GB2011/052503,** provided materials for use optoelectronic devices with the advantages of CPEs and minus the aforementioned complications. These materials were zwitterion moieties - small stable molecules comprising both a positive and negative charge centre, and therefore ultimately charge neutral - covalently bonded to the semiconductor polymer backbone. The polymers comprised one or more zwitterions and could function as charge transport, charge injection or light-emissive layers. Advantageous, this combatted the age old problem of low charge carrier mobilities by attracting electrons/holes as they moved through the polymer sandwich to their respective electrodes but without disrupting the internal electric field. Economically, this would increase device efficiency, and thus performance. A further aspect of the invention was a method of preparing such materials and devices utilising the materials. The official search report revealed some prior art that would bring into question the novelty and inventiveness of some of the main claims of the invention.

Filed in 2012, the final patent in the list **PCT/GB2013/051726**, related to the utilisation of a silicon/organic semiconductor heterojunction in the production of electricity in solar cells. Given the advantages of silicon - high efficiencies, natural abundance, and mature production processes - and those of organic semiconductors as discussed throughout this thesis, it is not surprising that prior art had looked into hybrid heterojunctions. In particular, Avasthi et al. (2011) had fabricated solar cells with such hybrid heterojunctions; the organic polymer they used, poly (3-hexylthiophene), had given them an efficiency of 10.1%. The inventors in this application utilised the organic polymer pentacene instead (see figure 5.26), and were able to achieve "*quantum efficiencies exceeding 60%*". Advantageously, pentacene is capable of generating multiple triplet excitons (see section 1.8 in chapter 1 for background). The device would be fabricated in a similar manner to those already discussed. The obvious commercial benefits of this invention need not be spelt out. However, even though four pieces of prior art potentially detrimental to the validity of several claims were revealed in the search report, several detailed dependent claims would be sustainable. The application is still under prosecution.

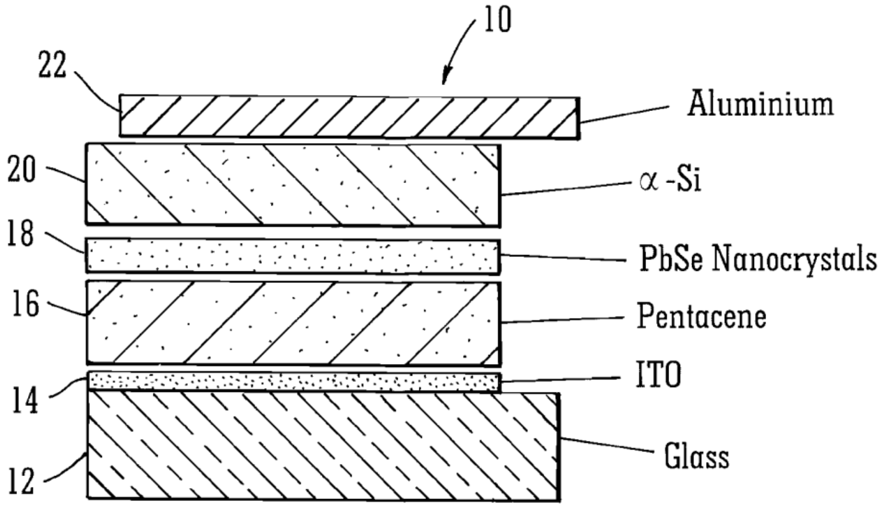



***Figure 5.26: A schematic representation of the photovoltaic device showing the amorphous silicon layer (a-Si) laid over the organic semiconductor layer (pentacene) to form the hybrid heterojunctions. PbSe nanocrystals forming the interlayer between the aforementioned layers serve to protect the pentacene layer during the deposition of silicon. The electrodes and substrate remain as per usual (Source: PCT/GB2013/051726)***

Although several of the official search reports revealed some prior art that was potentially detrimental to the novelty and inventiveness of some of the claims in several patents, the patent prosecution system allows for appeal and correction of such Examiner's objections - some of these would have been overturned or the scope of the claim monopoly narrowed. Further, the bulk of the claims in those particular patents that were not questioned would have been sufficiently detailed to sustain the application. Evidently, CDT went on successfully to file several national patent families from those international patent applications. These were granted and are now maintained as part of its patent portfolio. The valid national patents can be obtained from the Espacenet database.

## 5.6 Patent Trends Analysis

Reference in this section will be made to the patent bibliographical data found in appendix 5 and the Patent Trends Analysis found in appendix 6. From this we can pick out several of the patent indicators discussed in chapter 4: activity, dominance, specific company activity and characteristics, and breadth of the patent portfolio. Several of these patent indicators will be discussed in detail in chapter 6.

For one player, CDT, out of a pot of several players in the OLED industry, the number of patents they alone own indicate the level of interest and effort in this technology. The patent bibliographical data (appendix 5) indicates the breadth of inventors in addition to other players like Cambridge University subsidiaries, Plastic Logic, Seiko Epson, British Petroleum, University of Singapore etc. that CDT collaborated with on the research. CDT is also showcased in a dominant position given its ownership of at least three fundamental patents: **PCT/GB90/00584** (Priority application: **GB8909011**) - use of an organic polymer in a light-emitting device; **PCT/GB91/01421** (Priority application: **GB9018698**) - use of organic copolymers in luminescent devices; and **PCT/GB93/00131** (Priority application: **GB9201240**) - use of conjugated polymers in luminescent devices, on which possibly the whole POLED development stands. CDT itself stated that these particular patents were fundamental to OLED technology (CDT Annual Report, 2006 at p13 & 24). Citation analysis of CDT's patents in chapter 7 will shed more light on this.

CDT's patenting behaviour can also be painted; on average, several priority patents were filed every year - as many as 9 in 1998 and 7 in 1999 - from which international (PCT) and regional (e.g. EP) filings were birthed. Their priority filings were usually GB (93%) and US (7%) - the significance of this will be discussed in chapter 6, in light of CDT's commercial structure. Their patent families indicate global cover. Several Asian jurisdictions like Japan and Korea are present; this is presumably where most of the use and/or manufacturing and assembly of the end product display devices would take place. A large number of European countries also point to where most of the seed research and development would take place. Should a patent dispute arise, filing in multiple territories also permits the concept of forum shopping - having the choice to litigate in the territory that will provide the easiest ride and the most advantageous result (Cameron and Borenstein, 2003). Further, from the year 2000 onwards, patent management was shifted from CDT to the University of Cambridge's technology transfer office, Cambridge Enterprise Limited (formerly, Cambridge University Technical Services Limited) that had more expertise in managing IP so that CDT could focus on their core objective which has always been POLED research.

Inventor turnover is low - 'core' inventors remained fairly constant throughout the examined period: Bradley, Holmes, Kraft, Burn, Brown, Greenham, Pichler and Moratti in the earlier years; Sirringhaus, Ho, Huck and Chua in the latter years; and Friend and Burroughes throughout (see figure 5.27). This was especially vital to keeping know-how, confidential information and specialist expertise in-house. Expectedly, collaborations with other companies and institutions introduced new inventors; this would be useful to pull in extra resources and expertise. Further, given the close relationship between deposition and device fabrication methods to the polymers, it is not surprising that CDT's patent portfolio also includes co-owned patents with pioneers of enabling technologies such as IJP like Seiko Epson (see figure 5.28). Collaborative work is also evident with co-ownership of patents with several other academic institutions and centres of research.

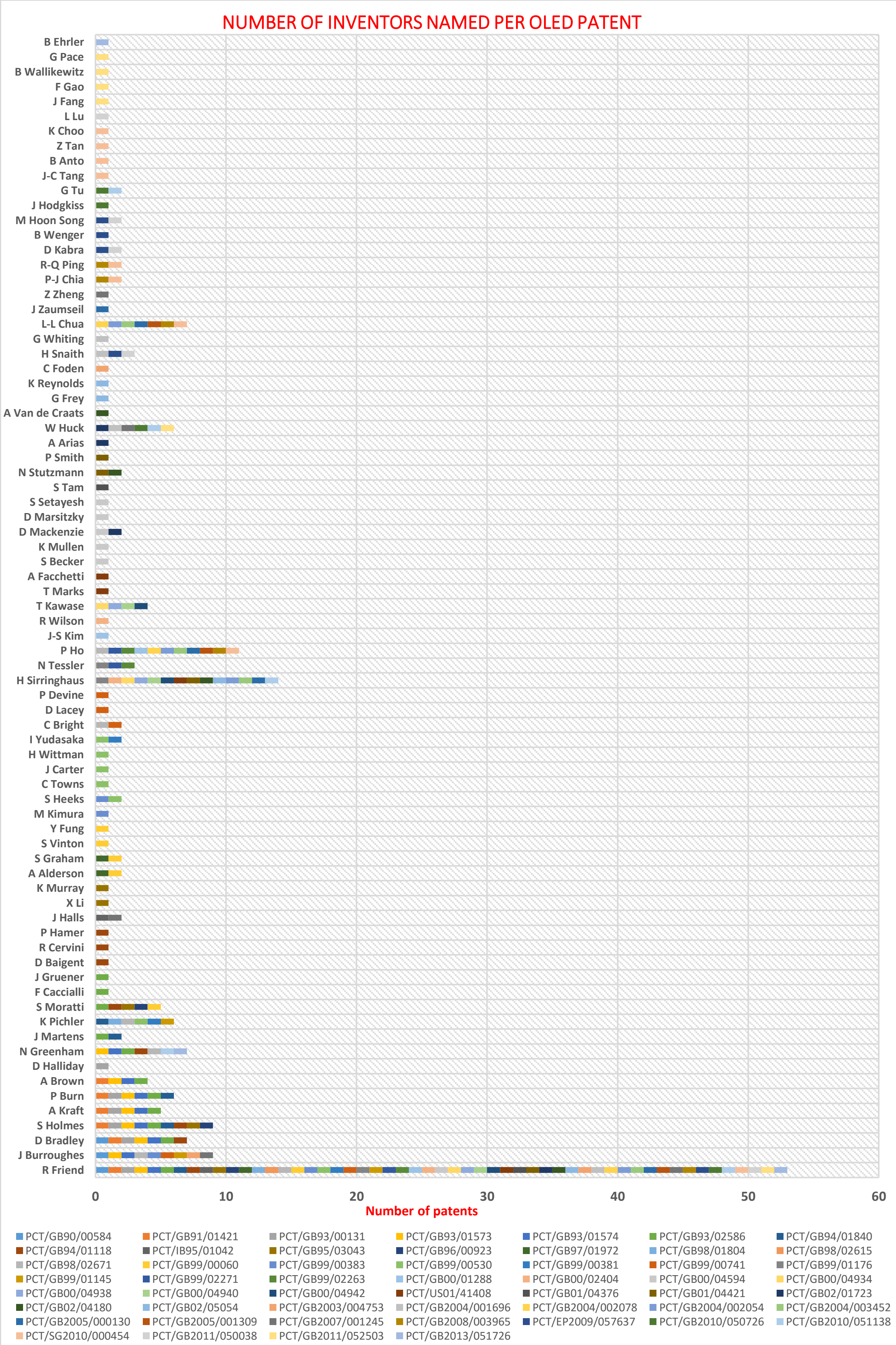



***Figure 5.27:*** *A plot of the number of inventors named per POLED patent filed by CDT for the period between 1989 and 2012 (Source: appendix 6, "inventors by patent" tab)*

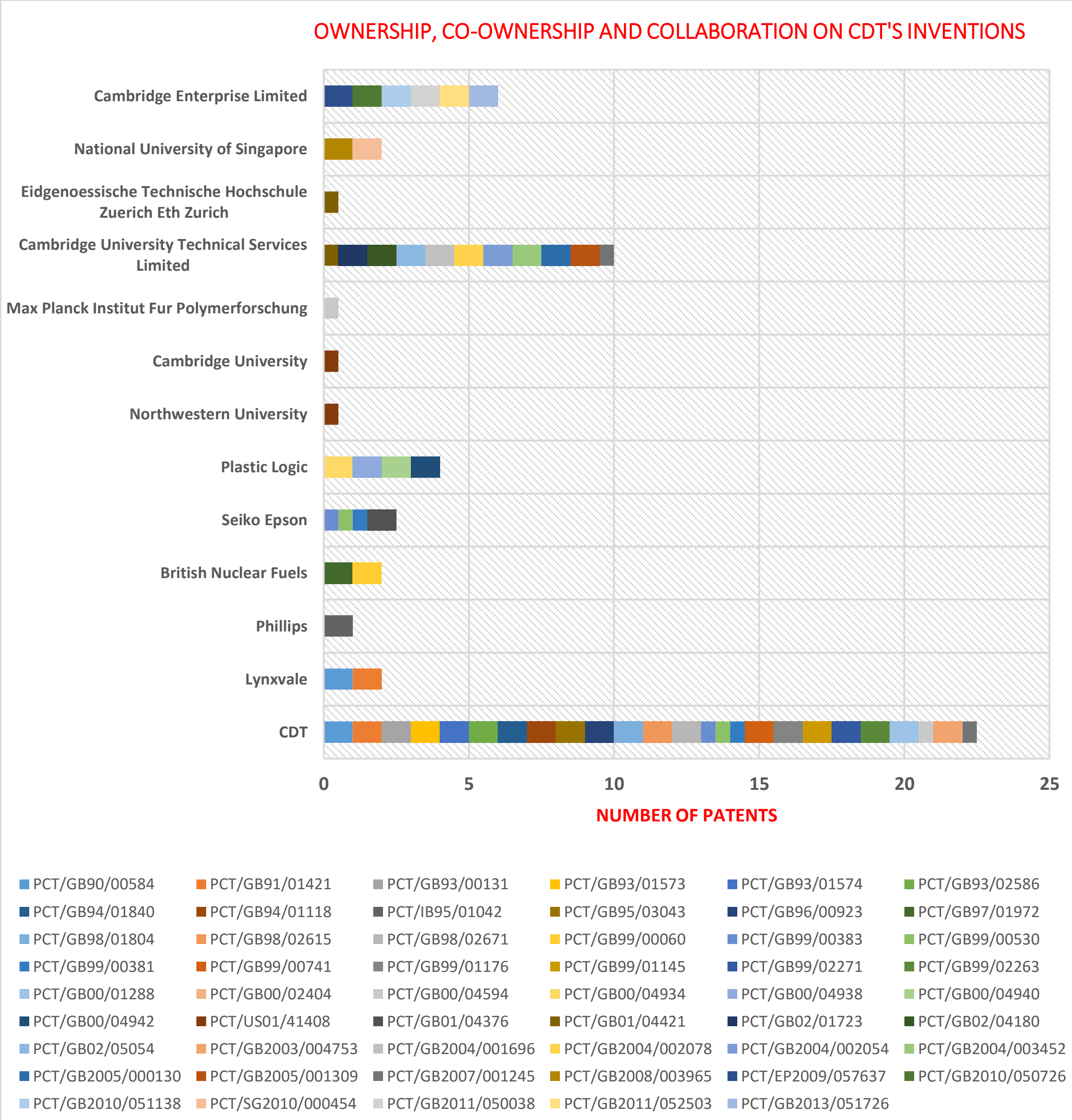



***Figure 5.28: An illustration of ownership and co-ownership of CDT's POLED patents filed between 1989 and 2012 (Source: appendix 6, "patent ownership" tab)***

The increase in the number of patents filed per year points to the different stages of maturity of the technology. From the data analysed, it can be said that there was an average of 2 patents per year between 1989 and 1996 when the technology was emerging; accelerated activity to an average of 4 between 1997 and 2004 that reflects the growth stage, and finally a steady average of 1 patent a year between 2005 and 2012 to symbolise maturation (see figure 5.29). The allocated stages are the author's observation and not necessarily a true reflection of the entire POLED industry. It is important to note that these are only figures based on one company in the POLED industry. The patents were also chosen according to those that name Sir Richard Friend as inventor; the other CDT inventors could have also filed POLED related patents with CDT or with other companies that did not name Sir Richard as inventor.  The EPO records also do not guarantee 100% accuracy so there may well be relevant patents that were not listed on the EPO database.  A definitive answer could be obtained by looking at all POLED related patents in the entire industry, and to extend that from 2012 to the present day; this is outside the scope of this thesis. Also, as mentioned in the methodology, inventions that were kept confidential are not accounted for in either data pool.

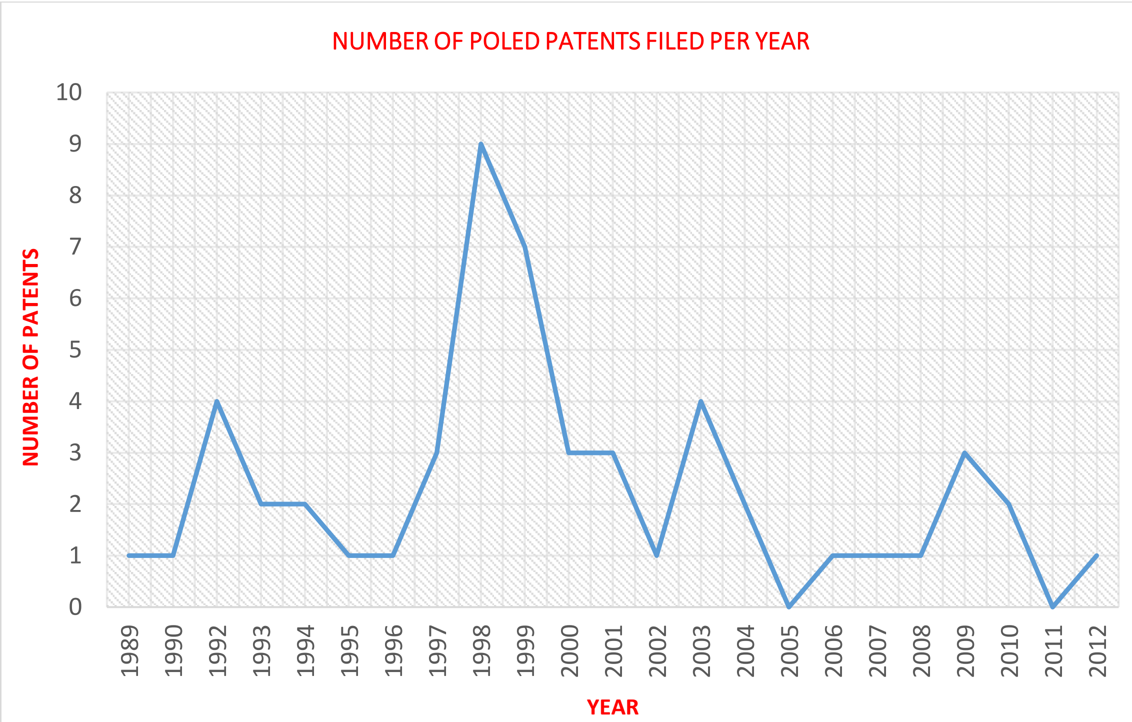



***Figure 5.29: A plot of the number of POLED patents filed by CDT per year between 1989 and 2012 (Source: appendix 6, "patents filed per year" tab)***

## 5.7 Conclusion

It is clear from the foregoing that the development of OLED devices was grounded on cumulative team efforts that led to novel as well as better and more complex polymer materials, matching material deposition and device fabrication methods to bring the best out of said polymers, the end goal being cheaper, more complex and better performing devices, especially comparable to the standard - the silicon-based devices.  This required interaction and collaboration between chemistry (polymers/materials) and physics and engineering (material deposition and device fabrication).  We see several instances where the POLED journey followed the precedent of the development of inorganic semiconductor devices discussed in chapter 3, following the invention of the transistor, and similarly led them to building integrated circuits. This is perhaps what triggered several citations in the official search reports where some claims were found to be obvious.

The conception of the bulk of the developments was systematic, each building onto the previous one, for example, **PCT/GB02/01723** that utilised the earlier principles in **PCT/IB95/01042** or **PCT/GB99/00060** that solved subsidiary problems that had arisen in **PCT/GB97/01972**. Occasionally, some were serendipitous (**PCT/GB94/01840, PCT/GB95/03043**), and others by the so called "King Saul effect" mentioned in chapter 2 (e.g. in **PCT/GB00/04942** in which the inventors set out to find a way of maintaining the integrity of a solution-processed device by creating regions of repulsion so as to prevent newly deposited layers from disrupting previously laid down ones and additionally found that these regions (in which new layers were repelled) could actually be filled with other polymers to create high resolution electrodes). The Reader may also wish to see appendix 4 for a more detailed categorisation of the conception of the inventions. It is also clear from the above that there are several Schumpeter A-phase inventions (e.g. the fundamental patents as identified by CDT, **PCT/GB99/01176, PCT/GB00/04938** etc.) as well as some B-phase inventions (e.g. **PCT/GB00/04594**).

The PTA has also revealed several characteristics about CDT that shine a light into their back room. Several of these will be discussed in chapter 6, particularly to paint a holistic picture of their commercial strategy for the technology. As for the socioeconomic factors that played a major role in the technology's development, the most evident are technological: new materials, better device fabrication methods and enabling technologies such as IJP that utilised the solution-processability of POLEDs. These however would have had to be supported by available finances and multidisciplinary collaborations, both reciprocally aided by actual availability, or semblance thereof, of a consumer market for the resultant devices. IP is also expected to play a major role; the ownership of fundamental patents points to the possibility of the existence of a licensing programme similar to that built by Bell Laboratories, Texas Instruments and Fairchild Semiconductor Corporation discussed in chapter 3.

It will be interesting to see if this, possibly in addition to other factors, holds true in chapter 6.

# 6.0 Factors that Influenced Commercial Development of OLED Technology

## 6.1 Introduction

Having looked at the chronological development of OLED technology in chapter 5, the next step is to examine whether the factors affecting the technology's development we postulated in chapter 4, section 4.9, hold true. From the observations in chapter 5 and the literature, the main factors to be discussed will be grouped in five broad themes: (1) technology development; (2) market; (3) regulation; (4) external stimuli; and (5) timing. We stated that the factors expected to play an important part were likely to at least involve: (1) the technical development of the technology such as the discovery of new materials; topological manipulation of device structures; and parallel development of enabling technologies; (2) regulation of this new technology such as through the establishment and enforcement of intellectual property as innovation progresses; how that IP is leveraged to either hinder or encourage continued innovation; and the effect of resultant competition amongst innovators as well as those selling the technology in the market place; (3) the response of the market to (1) and (2) through creating a precursor market for the new technology; multidisciplinary collaborations to manage competition as well as the prohibitive nature of IP; and the resultant finance from these collaborations that then feeds back into more R&D; (4) the role played by the government/military in the proliferation of the new technology; and (5) the indispensable role played by time. We will examine the relative contribution of each of these factors in this chapter, drawing from our narrative in chapter 5 and the secondary sources mentioned in the methodology (chapter 4, section 4.5). In chapter 7, we will examine these factors in the context of the Black Box model, to test and/or confirm it, before making some general conclusions on the dynamics of this innovation.

## 6.2 Technology Development

### 6.2.1 New Materials

OLED technology was founded on the discovery in 1989 of a polymer material that emitted yellow-green light when it was electrically stimulated. This was a few years after 'small molecule' materials had also been found to be electroluminescent in 1979 (see chapter 5). Naturally, this fuelled a curiosity into light-emitting organic semiconductor materials, with some researchers like CDT looking into POLED materials and others such as Kodak and its licensees into SMOLEDs. Both types of OLEDs have two branches: fluorescent and phosphorescent materials (see figure 6.1). The background to the technology, in particular, the developmental history of fluorescent POLEDs at CDT has already been discussed in chapter 5.

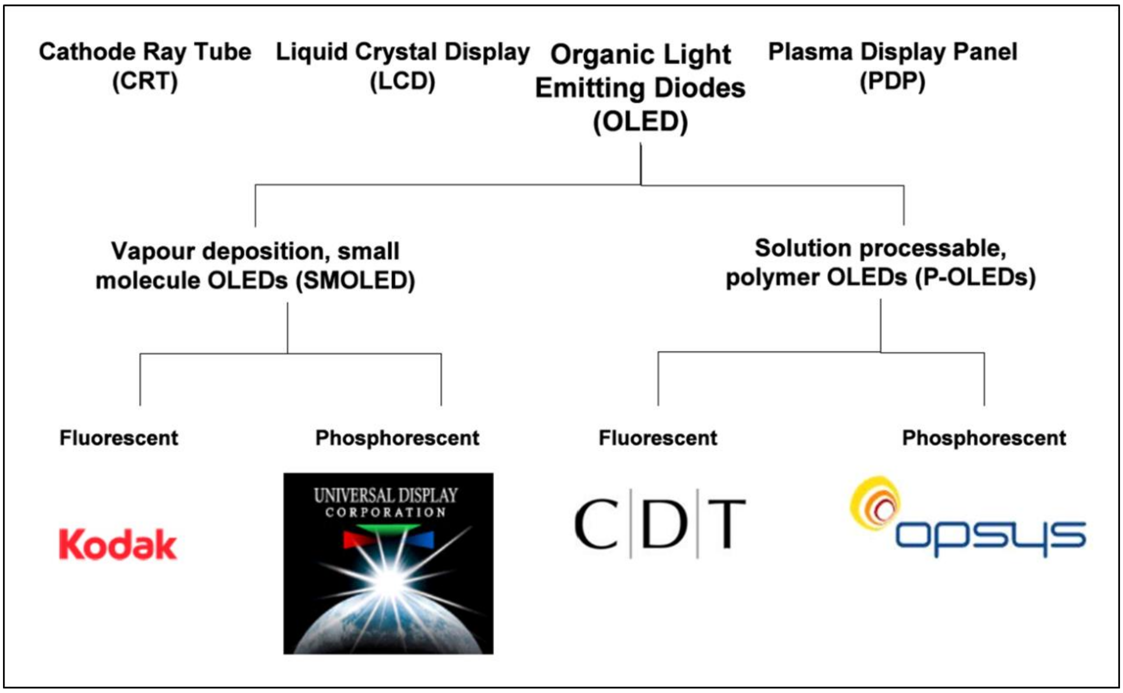



***Figure 6.1: The relative position of OLED materials in context with other electronic display technologies. (Source: Minshall et al., 2007 at p229)***

Although some companies like Kodak, Samsung and Pioneer have for several years had a developing interest in SMOLEDs, the use of POLEDs by CDT was an early informed decision based on their theoretical advantages. SMOLEDs exist in powder form. This limits the diversity of useable deposition methods; expensive vacuum evaporation processes have to be employed. These deposition methods limit the size of the display to relatively small applications

(Chow, 2014). Furthermore, SMOLEDs are rapidly degraded by contact with oxygen and water (making manufacturing both difficult and expensive), have a lower ability to convert electricity into light and do not dissolve well; they aggregate in solution making it difficult to achieve the thin uniform layers required for OLED devices (Borchardt, 2004). Irrespective of these shortcomings, SMOLEDs give a higher-resolution image, high purity and easy fabrication of multilayers by vacuum deposition methods, albeit at a larger cost than POLEDs (Chow, 2014). These advantages make them irrefutably better than POLEDs in small display devices; today they are widely used in many applications, mostly PDAs, cameras and mobile phones (Chow, 2014, Reineke, 2015).

In contrast, P-OLEDs can be placed in solution. This makes the polymer manufacturing processes much simpler, so far as to permit a wide array of common methods including ink-jet techniques and roll-to-roll or continuous production. In turn, this widens the scope of possible applications to include large displays. In addition to CDT, other companies like GE, Konica Minolta and Modistech are currently working on solution based POLEDs in a roll-to-roll context (Young, 2016; Chansin et al., 2016). Most OLED displays on the market today are based on SMOLEDs, perhaps because they have a longer lifetime (half-life - the time taken for the intensity of the light produced by a device to decrease to half its original value) and are more efficient than POLEDs (Fyfe, 2009). However, some prototype POLED displays are available; these are discussed later in section 6.3.2 and 6.4.1. CDT developed the POLED approach and continues to research the materials alongside its licensees. Currently several other companies including Philips, Dow Chemicals and DuPont also joined the race (Borchardt, 2004; Reineke, 2015).

However, being organic (having a high carbon atom content), OLED materials are subject to natural biodegradation, with or without oxygen. Consequently, this affects the lifespan of OLED devices. Therefore, the performance of OLED devices greatly depends on the materials used. Performance in terms of output colour typically depends on neighbouring pixels emitting red, green and blue (RGB). The colours are produced by specific polymer materials which are placed in varying combinations within the device. Moreover, these materials (and hence colours) degrade at different rates, but whilst also gaining brightness with age (Forge and Blackman, 2009). This complicates the device fabrication to include additional electronics to compensate for this loss. This is currently one of the main hurdles the development of this technology has yet to overcome.

Currently available polymers for red and green light easily produce the required lifetime and have acceptable quantum efficiencies (how effectively electrical energy is converted into light) for different electronic applications (Fallahi et al., 2014; Reineke, 2015). CDT has over the years focussed its attention on developing blue materials; they are the most problematic to optimise because they have the largest bandgap (see chapter 1 for an explanation of bandgaps) and are yet very vital to achieving a full colour display.

As we have seen from chapter 5, continuous efforts were employed by CDT into improving the light efficiency, stability and lifetime of available materials. In PCT/GB93/02586 and PCT/GB00/04594, the research group found novel ways to attach dyes and other chemical groups to polymer materials to "chemically tune" POLEDs to produce better blues. We also see the use of light filtering layers (PCT/GB98/01804); of multiple and distinctively spaced light-emissive regions that designated pixels (PCT/GB98/02615); and of polymer blends (PCT/GB02/01723), all to create cleaner blues by removing the negative effects of ambient light as well as obliquely scattered coloured light within the devices. PCT/GB2003/004753 addressed the innate short lifetime of blue light sources by providing a high electron affinity material that improved electron injection into the LUMO levels of blue materials.

These improvements, in addition to improved deposition methods (also discussed in chapter 5 and in the proceeding section 6.2.2) and inventive device structures, have overall increased the lifetime of blue materials from 900 hours in 2005 to 10,000 hours in 2007, 18,000 in 2009, 26,000 hours by 2010, and to an excess of 70,000 hours thereafter (CDT; Young, 2016; Fyfe, 2009). These are experimental figures. As of 2015, commercialised blue materials currently have a lifetime of more than 11,000 hours (CDT). However, the longest lifetime in commercialised blue materials (11,000 hours) is still far behind that of reds (between 200,000 - 350,000 hours) and greens (80,000 - 350,000 hours) and the quantum efficiency stood at 4.7% in 2011 compared to 19-20% for both reds and greens (CDT; Fisher et al., 2011 at p1640). Although significantly lower, it is still a massive improvement from where the story started, and has even contributed significantly towards the commercialisation of POLED devices. CDT aims to transfer these improvements to full manufacturing processes.

Other researchers are taking different approaches to improve blue light lifetime, some incorporating nanoparticles, graphene or other chemical moieties (Fallahi et al., 2014; Shi et al., 2013; Kim et al., 2010; Lee et al., 2016; Fukagawa et al., 2015; Reineke, 2015). Notably, Taiwan's Industrial Technology Research Institute towards the end of 2015 coupled green phosphorescent emitters with metals to emit blue light that reportedly lasts 27 times longer than blue fluorescent light, bringing the current blue lifetime from 11,000 hrs (fluorescent blues) or 20,000 hrs (for phosphorescent blues) to 300,000 hrs (ITRI Today, 2015). These materials are still at prototype level but may be ready for commercialisation within the next 2 years. DuPont and Novaled report lifetimes in the range of 38,000 - 41,000 hours for blues and a milestone 1,000,000 hours for reds and greens (Novaled, n.d.; Nature Photonics, 2009). More recently, one of the highest quantum efficiency for blue fluorescent materials was reported at 21.8% (Sun et al., 2016).

Notably, there are parallel efforts in improving white OLEDs particularly for application in the lighting sector (Zissis and Bertoldi, 2014; Karkazi, 2014; Mertens, 2016 at p27-28). White OLEDs use the aforementioned device structures but contain pixels/materials that emit white light in addition to the conventional RGB; all four types of pixels are arranged in a way that the resultant light is filtered and brighter (see figure 6.2 and Mertens, 2016). This makes it easier and cheaper to manufacture OLEDs. These were initially developed for lighting applications by Kodak but have now crossed into the display industry; LG bought Kodak's OLED assets in 2009 and is currently the leading mass producer of OLED TVs, enabled by this technology (discussed later on). Other researchers including CDT have jumped onto the white light OLED wagon.

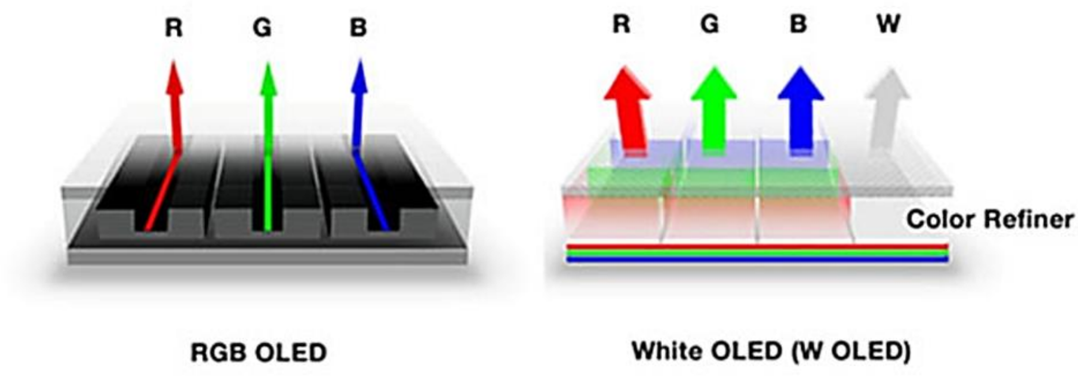



***Figure 6.2: A device structure showing the emission of RGB and white light (Source: LG)***

There are additionally other material issues/improvements that were dealt with in chapter 5, such as the use of nanoparticles (PCT/GB99/02263 and PCT/GB99/02271) to improve morphology, optical and electrical characteristics of the materials. Significant improvements were also made to materials that form the other parts of OLED devices such as the anode and cathode, and the layers that inject/control the charge carriers migrating to/from the emissive layers (PCT/GB94/01118; PCT/GB99/02271; PCT/GB02/05054; PCT/GB2004/002078; PCT/EP2009/057637; PCT/GB2010/050726; Fyfe, 2009).

To echo the purpose of this thesis, we have merely focussed on the blue lifetime issue as it has been a major commercial setback. CDT's CEO Dr David Fyfe commented "*We focused on the blue material since it is vital to providing the full colour capability essential for mainstream display markets such as television and personal computing along with the exploding market for multimedia-enabled cell phones, PDAs and other mobile products. Even though longer lifetimes are still needed, these results are a significant milestone towards the commercialisation of the LEP technology*" (Business Wire, 2003).

This effect on lifespan is very vital to whether OLED technology overtakes LCD, the market leader. LCD TVs currently have a lifetime between 40,000 - 90,000 hours of continuous use (excluding other contributing factors such as environment, brand and type of screen) (Forge and Blackman, 2009). OLED display devices had lower lifetimes in the beginning stages of their development but following cumulative and progressive developments in their materials, they now have lifetimes that are similar or better than that of LCDs. The experimental material lifetimes are significantly higher - double and even triple that of LCDs (OLED Association). In that regard, as long as LCDs continue to use a backlight, which consumes the vast amount of their device power, they will always have an inferior lifetime to OLEDs.

Moreover, the conundrum is that SMOLEDs are better at high-resolution applications like small displays because they are vacuum deposited so the materials performance is higher whilst POLEDs are better suited for large area applications because of their solution processability but this however compromises the materials' performance. The past few years have seen extensive work and application prototypes in both fields. Some technology analysts are of the view that it's immaterial whether SMOLEDs or POLEDs will lead the charge of OLED technology (Borchardt, 2004). When interviewed by CNET as to whether having two methods of developing OLED displays slows down the market, David Fyfe responded "*It's healthy to have two competing OLED technologies, because they both look and feel the same. So it only gives OLED a bigger profile in the market place, and the manufacturers will decide which tech dominates at the end of the day*" (Fyfe, 2002).

Would it be better to develop materials that combine the useful properties of both types of materials? Certainly. Covion Organic Semiconductors back in 2004 developed hybrid materials; doping POLEDs with small molecules (Borchardt, 2004). Using laser technology, Universal Display Corporation innovatively created multi-layered structures containing stripes of both small molecules and polymers (Chin et al., 2003). Some researchers have used oligomers - short-chain polymers whose characteristics are a cross between those of small molecules and those of polymers (Zissis and Bertoldi, 2014 at p8). The results in both instances were OLED devices with better lifetimes and efficiencies in comparison to conventional OLED devices (i.e. those that are solely POLED or SMOLED).

CDT adopted a slightly different approach. After its acquisition of Opsys - an Oxford based company that had extensive expertise in dendrimer OLED technology, it branched into phosphorescent POLEDs research. As already mentioned, CDT had been working with fluorescent POLEDs. Phosphorescent materials are materials that absorb electrical energy and release that energy in the form of light relatively slowly and usually over a couple of hours. They are based on triplet excitons as opposed to fluorescent materials that are based on singlet excitons (see background in chapter 1, section 1.8). They have been shown to have theoretical quantum efficiencies of 100% and long lifetimes, especially where they are attached to transition metals such as platinum, iridium etc. (Baldo et al., 1998; Yersin, 2004; Yang and Neher, 2006; Kappaun et al., 2008; Levermore et al., 2011). As a result, they have been blended into OLED materials to improve device lifetimes (Kappaun et al., 2008). On the other hand, dendrimers are highly-branched solution-processable molecules that can be blended with phosphorescent polymers. The colour emission of the resultant hybrid can precisely be tuned without compromising the other intrinsic characteristics of the polymers (Markham et al., 2004; Xu et al., 2015).

Dr. David Fyfe in 2005 commented that "*the work on phosphorescent emission from dendrimers opens up new possibilities for the application of OLEDs to practical applications and this work complements our work on fluorescent polymer OLEDs, especially as the technologies potentially can be combined in one device without any increase in complexity of the structure*" (Research Excellence Framework, 2014).

The dendrimer approach therefore created a way of combining the high efficiency of SMOLEDs with the advantageous solution processability of POLEDs. At the peak of dendrimer discovery, CDT reported improved colour emission efficiencies and lifetimes: red emitters with a lifetime of 250,000 hours in October 2005, up from 150,000 hours in May 2005 and from 15,000 hours in 2004 (CDT). CDT is currently commercialising these dendrimer materials. Several other researchers have since jumped onto the dendrimer wagon as well (Lo and Burn, 2007; Ko et al., 2010).

Given the foregoing, it seems reasonable to expect a synergy between the two types of OLED materials in the race to continue advancements in finding better materials that will provide better colours and lifetime. Nevertheless, CDT has over the past two decades more than tripled the lifetime of its blue research devices, and in addition to its IPR in POLED materials, still has a firm grounding as a major materials supplier. It has additionally forged major collaborations in the form of joint development agreements or licences (see section 6.3.1 below) with renowned industry material manufacturers such as Dow Chemical, Bayer, Sumitomo, Covion and Novaled, and continues work to better its extant pool. Most importantly, it was bought by Sumitomo Chemical (CDT's former materials licensee, which had also previously bought Dow's POLED business and associated IPRs) and together they formed a joint venture in material development; Sumation (Fyfe, 2009). Despite the fact that longer lifetimes are still required, CDT's results have greatly accentuated the commercialisation of POLED technology, and this will continue to be so as long as innovative materials are being churned out by themselves and the rest of the industry.

### 6.2.2 Device Structures and Fabrication

In addition to discovering new materials (such as in PCT/US01/41408; PCT/GB00/04594; PCT/GB2004/002078), CDT's efforts focussed on improving device performance through topological manipulation of the device structures and, for the obvious commercial reasons, looking into deposition methods that most affected device performance. As we saw from chapter 5 (figure 5.1), the simple structure of an OLED device comprises four main parts: (1) the substrate, usually glass; (2) the backplane aka electronics that control the pixels; (3) the frontplane which comprises the layers of organic materials from which the light is emitted, the cathode and the anode; and (4) the barrier that protects it from the ambience. In conjunction with other researchers, this basic structure has been continuously improved and manipulated over the years to facilitate different applications by creating structures that were more complex, efficient and economically viable. This has permitted the technology to compete at market level.

CDT's earlier patents embodied the advantages of injecting charge carriers into the organic polymer layers to increase the likelihood of formation of electron-hole pairs (and in turn, resultant light), by straddling the emissive layer either with suitably "edited" charge injection layers (PCT/GB90/00584; PCT/GB91/01421; PCT/GB93/01573; PCT/GB93/01574; PCT/GB94/01118; PCT/GB02/05054; PCT/EP2009/057637; PCT/GB2010/050726; PCT/GB2010/051138; PCT/GB2011/052503) or photoresponsive layers that would create favourably spaced heterojunctions (PCT/IB95/01042; PCT/GB2005/000130; PCT/GB2008/003965; PCT/GB2013/051726). This was further accentuated by; (1) the use of polymer blends or multiple light-emissive layers in a single device to increase the efficiency of charge carrier transport (PCT/GB98/02615; PCT/GB02/01723); (2) the combination of multiple layers of polymers as well as charge injection layers into one device (PCT/GB93/01573; PCT/GB93/01574); and (3) the fabrication of devices containing multiple and independently operable electroluminescent devices (PCT/GB94/01840; PCT/GB96/00923; PCT/GB00/04940). Other intrinsic characteristics of the polymer materials were improved through either doping methodologies (such as in PCT/GB00/01288) or use of more experimental technologies such as nanoparticles (PCT/GB99/02263; PCT/GB99/02271).

To address the biggest shortcoming of OLED devices - the production of good blues and purer colours - the inventors either attached several chemical groups to the polymer layers to chemically "tune" them for the desired colour (PCT/GB93/02586; PCT/GB00/04594; PCT/GB2003/004753), employed light-filtering/light-absorbent layers to clean up resultant colour (PCT/GB98/01804; PCT/GB99/00381), or employed additional circuitry such as transistors and capacitors to manipulate individual pixels (PCT/GB99/00383; PCT/GB01/04376). Other improvements in this vein have already been discussed in detail in section 6.2 above.

We additionally discussed the susceptibility of the organic compounds used in OLEDs to biodegradation, in particular, damage by water, moisture and air. As such protection methods against physical damage included the addition of a transparent protective layer (such as a silicon dioxide film) over the organic material layer to shield it from the destructive effects of air and other impurities (PCT/GB97/01972). Also invented were novel methods to deposit the organic layers along with their immediately surrounding layers in a single step (as opposed to multiple steps) so as to eliminate the exposure of those layers to the ambience during deposition (PCT/GB2004/003452). Metal electrodes also degrade due to oxidation, especially where traditional vacuum deposition methods are employed. Layering OLED devices with extra charge-carrier transport and injection layers produced an optical gain which compensated for the optical loss due to the degradation of the electrodes (PCT/EP2009/057637). Moreover, cathodes can nowadays be solubilised and thus fabricated using solution-processable methods such as spin coating and IJP (Forge and Blackman, 2009).

Device sensitivity was improved by the inclusion of radiation monitors (PCT/GB97/01972; PCT/GB99/00060) or insulating layers to remove residual interfering charges (PCT/GB99/01176). Device power consumption was reduced in some cases by the use of either integrated or additional low-power consumption devices such as photo-detectors that took advantage of unwanted natural light to control the brightness of individual pixels (PCT/GB99/01145).

Device lifetimes were greatly favoured by improvements in device fabrication methods. More accurate layers were laid down by: (1) using templates or alignment layers to direct more precise deposition (PCT/GB00/02404; PCT/GB02/04180; PCT/GB01/04421; PCT/GB2007/001245); (2) depositing successive layers in solvents unlikely to affect previously formed layer (PCT/GB00/04934); or (3) mixing traditional with newer methods of deposition such as ink jet printing (PCT/GB98/02671; PCT/GB2004/003452). This not only reduced processing time and cost but also enhanced other key performance parameters such as quantum efficiency, maximum achievable brightness, and ease and reproducibility of manufacture.

Manufacturing costs were lowered by the fact that these layers could be solubilised (PCT/GB93/00131; PCT/GB95/03043 etc.) for easier device fabrication, especially by cheaper, simpler and more precise methods such as inkjet printing (PCT/GB99/00530; PCT/GB99/00381). CDT's expertise in IJP was assisted by its collaboration with Seiko Epson (the pioneers of inkjet printing) which went on to produce the world's first P-OLED print head. The latter brought with it expertise that included ongoing large-scale research projects into printable phosphorescent materials with Universal Display Corporation (UDC) and Mitsubishi Chemical Corporation (Forge and Blackman, 2009). In 2002, CDT further acquired a US printer manufacturer, Litrex Corporation, which was the leader in the development of precision inkjet systems for the electronics industry (CDT; Fyfe, 2009).

Moreover, Toppan Printing, another collaborator of CDT, offered roll-to-roll printing - a cheaper printing alternative that did not compromise the desirable characteristics of the displays, namely good uniformity and resolution (CDT; Fyfe, 2009; Edwards, 2008). This presented the possibility of creating displays on a roll of flexible plastic; flexible plastic substrates greatly widen the scope of possible applications at an even lower manufacturing cost. CDT and Toppan produced the world's first roll printed display at 5.5 inches in 2006 (SID). Continuous progress has since been made to the printing technologies to support the large and highly precise POLED display manufacture that is necessary for cost competitiveness. This chapter mentions several POLED prototypes that have been manufactured this way. Notably, aside from ink jet printing being the current 'best-in-class' printing method, there are other well-established and low-cost manufacturing methods common to the graphics industry such as screen printing, lithography etc. that could be utilised (CDT Annual Report, 2006 at p11).

Furthermore, POLEDs can be manufactured by both IJP and vacuum deposition methods (the only methods employed for SMOLEDs). We will not discuss the latter in detail (see Forge and Blackman, 2009 for interest). We will however note that while these methods offer clear advantages, such as additional purification and more accurately laid down layers (hence the high efficiency with which SMOLEDs operate), they are expensive - as they require a vacuum chamber and highly regulated parameters - and the materials inevitably suffer from thermal stress (Kappaun et al., 2008; Reineke, 2015). Over the years POLED fabrication via cheaper solution-processing methods such as IJP - even with their disadvantages - has far superseded use of vacuum deposition methods (Fyfe, 2009; Forge and Blackman, 2009). There are other solution-based processes of manufacture but we have focused on the printing technology for the purposes of this thesis; it has provided the largest push to commercial viability, especially in the context of large area displays.

Going forward and for easier understanding of subsequent sections, I should mention that OLEDs are classified in several types of structure (Karzazi, 2014; Reineke, 2015). In passive matrix OLEDs (PMOLEDs), strips of cathode are arranged perpendicular to both the organic layer(s) and strips of anode; light is then emitted where the cathode intersects with the anode (the pixel). (PCT/GB99/00383). Usefully, device power consumption is lowered and determined by individually regulated pixels, lit by external circuitry - which disadvantageously consumes more power than the structure itself, to in fact make this the most power hungry OLED structure but yet at less power than LCDs. For efficiency purposes, this type of structure is best for relatively small displays, such as mobile phone displays and MP3 players (Karzazi, 2014; Kunic and Sego, 2012). In an alternative arrangement, active matrix OLEDs (AMOLEDs), the anode layer is connected to a layer of TFTs. Each pixel is therefore switched on and off by a transistor, creating the least power consuming OLED structure (PCT/GB99/00530). This is suitable for large displays such as those in computers, TVs and billboards.

Furthermore, light emitted can either escape on the anode side ("bottom emission") or on the cathode side ("top emission"). For this to happen, the electrodes have to consist of transparent or semi-transparent materials (see figure 6.3). This makes it feasible for applications such as smart cards (Karzazi, 2014). The majority of the structures discussed throughout chapter 5 were of these types: to mention a few, PCT/GB99/00381; PCT/GB94/01840; PCT/GB96/00923; PCT/GB97/01972; PCT/GB98/01804; PCT/GB98/02615, etc. in which the ITO anode was transparent and the usually opaque cathode (made of metal) reflected emitted light back to the anode so that it could be viewed. For technical reasons, CDT was known to focus on top-emitting AMOLEDs (CDT; Fyfe, 2009). Further structures contain all transparent components and so emit light in both directions - these are so called Transparent OLEDs (TOLEDs), and can either be PMOLED or AMOLED. Commercial applications include mirror displays, TVs, and laptops (see figure 6.8, Karzazi, 2014). More recent work, that will be discussed in section 6.2.3, has focussed on foldable/flexible OLEDs, in which the layers are made of flexible materials such as metallic foils of plastics, to expand possible applications to wearable technology, bendable smart phones, curved TVs etc. (See figure 6.16). CDT is also currently exploring printed flexible electronics.

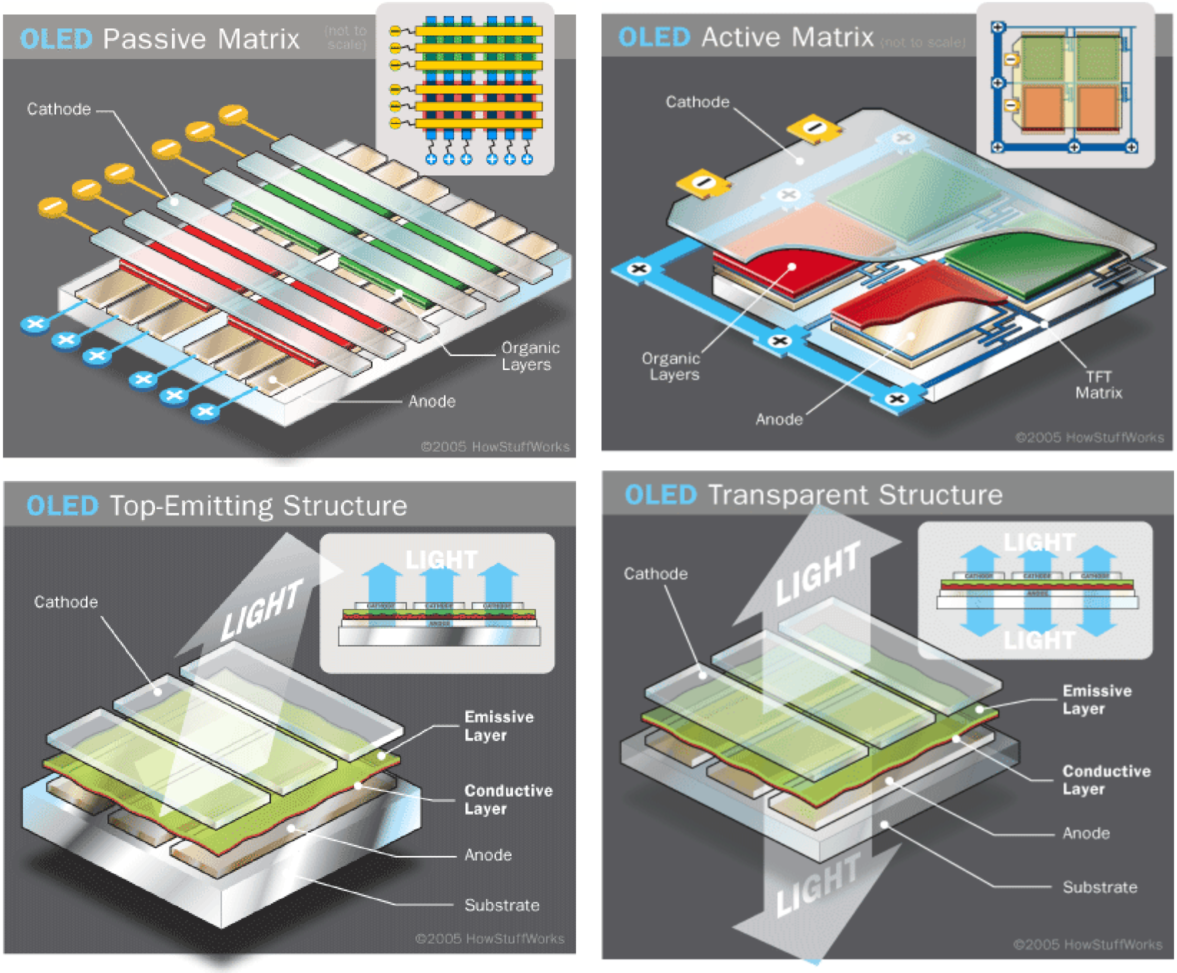



***Figure 6.3: Collage of the some of the different OLED structures (Source: HowStuffWorks)***

The above cumulative efforts made it possible to make complex and highly effective integrated circuits, such as those discussed for inorganic semiconductors in chapter 3, that had better colour capabilities as well as not suffering from post-processing shortcomings (PCT/GB99/01176; PCT/GB00/04938). Device fabrication has come a long way. IJP has and will continue to provide for low-cost device fabrication; however, developments in suitable materials as well as processes need to happen concurrently for maximum benefit.

### 6.2.3 Complementary or Enabling Technologies

There are several pipeline inventions that are likely to enhance the development of OLED technology. Most are still at optimisation level and are therefore confidential. A few of the most publicised will be highlighted. By way of reminder, the OLED panel comprises the substrate; the backplane; (3) the frontplane; and (4) the barrier. Over the years, there have been constant and cumulative improvements to the different layers which in amalgamation make for more efficient OLED devices. It is outside the scope of this thesis to mention but a few of these improvements - enabling technologies/inventions - if only to shine a light on the future of OLEDs.

Most OLED panels have glass substrates because of its uniformity, flat nature to ease material deposition and inherent barrier function; glass is however heavy, thick, rigid and fragile, and thus not a suitable candidate for the 'out-of-the-box' applications we have mentioned throughout this thesis. There has been progress by the leading glass maker, Corning, and Asahi Glass to make thin, flexible and shatterproof glass, even thinner than a human hair (Bourzac, 2016; Das and Harrop, 2016 at p172 & 186) but Mertens (2016) submits that a more viable option is to use plastic or a metal foil. Plastic allows for flexibility that can enable roll-to-roll applications, transparency and ultra-thinness even though caution has to be taken as to the temperatures applied. Roll-to-roll technology has already been applied for mass production of solar cell applications in the US, and other US researchers such as GE Global Research are optimising the technology for OLED lighting (Forges and Blackman, 2009 at p28). Metal gives the advantage of electrical conduction, durability, a great barrier against impurities and the effects of the ambience etc. but has a transparency issue. Samsung and LG have been reported to have started using plastic substrates as of late 2013 (Mertens, 2016 at p14). Continuous advances in these alternative substrates will no doubt expand the pool of possible applications.

Backplanes are one of the more expensive parts of the display - they contain the switching and driving circuitry that controls the pixels. The circuitry is most commonly made from amorphous silicon (a-Si) and low-temperature polysilicon (LTPS). The former is the most common with several advantages but falls short in electronic performance; in addition to other advantages including the ability to anneal the circuitry onto the substrate, the latter is about 100 times electronically better and more suited for driving displays but much more expensive and limited to a particular substrate size (Mertens, 2016 at p14-15). Even though most AMOLED displays use an LTPS backplane, efforts are underway to find a cheaper alternative that will also enable larger substrate sizes. Mertens (2016) details the performance of the most viable alternatives (see Table 6.1): a-Si compensation which addresses the current shortcomings of a-Si backplanes, Oxide TFT which he says "virtually all companies" are currently exploring, and organic TFT in which either small molecule or polymer organic materials are used to produce the TFT (at p15-18, also see Chansin et al., 2016 at p161-175 and Das and Harrop, 2016 for more detail). The background for TFTs was already discussed in chapters 3 and 5.

| | A-Si | LTPS | Oxide-TFT | OTFT |
|---|---|---|---|---|
| Electron mobility ($cm^2/Vs$) *a high-end OLED requires at least 10 $cm^2/Vs$ | 0.5-1 | 30-500 | 1-50 | 0.1-0.5 (target = 10) |
| Process temperature (Celsius) | $350^0$ | $450^0$ | $150^0$ or less | Room temperature |
| Transparency | 20% | 20% | 80% | 80% |
| Substrate choice | Glass | Glass | Glass or plastic | Glass or plastic *can be printed so suitable for flexible OLEDs |
| Cost | Low | High | Medium | ? |
| Status | Needs compensation, no a-Si AMOLEDs in production yet | Mass production for both OLEDs and LCDs | In mass production for small/medium LCDs (Sharp) and large-size OLED TVs (LGD) | R&D, some prototypes *commercially expected within the next few years |

***Table 6.1: A comparison of the current and most viable emerging backplane technologies. *comments are the author's addition (source: Mertens, 2016 at p17-18)***

Further, Total Matrix Addressing technology (TMA) was launched in 2006 by CDT; it is a "*more intelligent approach to passive matrix driving*" that enhances the lifetime of the display panel and reduces power consumption by up to 50% (CDT Annual Report, 2006 at p11, also see section 6.2.2 for the background to the AMOLED/PMOLED driver technologies). Interestingly, TMA applies to displays for both POLED and SMOLED (CDT Annual Report, 2006 at p37). Until that time, small-size displays relied on simple PMOLED drivers while large-size displays were based on more complex and thus more expensive AMOLED systems. TMA allowed for medium-sized displays to be manufactured in a similar low-cost way as small-sized displays, based on PMOLED technologies that were already readily available to many display companies worldwide. Continued development of this technology for large-size displays would have significantly decreased the manufacturing costs but TMA was abandoned (Mertens, 2016 at p26). Other efforts by CDT in developing better drivers continue.

A lot of work has also gone into improving frontplane materials; CDT's and others' research has already been detailed in section 6.2.1. In addition to improvements to the polymers themselves (such as CDT's incorporation of dendrimers), we have discussed work around hybrid materials - those that combine the properties of polymers and small molecules. With each year that goes by, colour lifetime and consequently, device performance get better. The number of available organic materials is now considered too broad to count (Reymond, Blum and van Deursen, 2011). The advantage is that each material introduces different properties and functions, increasing the pool of applications. Reineke (2015) however asserts that this is actually counterproductive given that several parallel efforts going on around the world to optimise these materials are in fact slowing down the process, especially as each material may require a complementary processing technique that will best showcase its capability.

Further, many of the materials (both front and backplane) are increasingly being turned into inks to match the rapid development of printing methods as the preferred method of deposition. Several of the inks for the backplane are based on silicon, for the desirable advantages it provides, including forming a stable oxide on its surface that makes it easier to process (see chapter 3). Organic semiconductor materials are lighter, more flexible, much cheaper and better light emitters than silicon but it is proving beneficial for the organic industry to borrow from the far more advanced inorganic semiconductor industry, particularly in making TFTs (Forge and Blackman, 2009 at p25).

Carbon nanoparticles have also been shown to influence the morphology, optical and/or electrical characteristics of the organic materials advantageously (Forge and Blackman, 2009). They have been incorporated into the polymer layers as we saw in PCT/GB99/02263 and PCT/GB99/02271 in chapter 5 or best case scenario, incorporated into silicon inks. Nanoparticles have further been found to enhance some deposition methods (Ju, Yamagata and Higuchi, 2009) as well the performance of electrodes - especially a graphene nanoparticle electrode (Wu et al., 2010).

Electrodes are most commonly made from indium oxides and metals; despite the former shrinking in abundance and the latter not being transparent, both are not flexible. Indium tin oxide currently holds 93% of the market share of materials used to make electrodes in displays (OLED, LCDs, e-paper etc.) and several other electronic devices but that is encroaching on its availability and driving prices up (Das and Harrop, 2016 at p157-164). One of the most viable alternatives is graphene, a honeycomb-shaped, one-atom-thick, ultra-light, stronger than steel and incredibly flexible allotrope of carbon that has gained tremendous popularity since its discovery in 2004 at the University of Manchester. Graphene is transparent and has unusually advantageous electronic properties and thus a diverse array of applications, including electrodes as shown in figure 6.4.

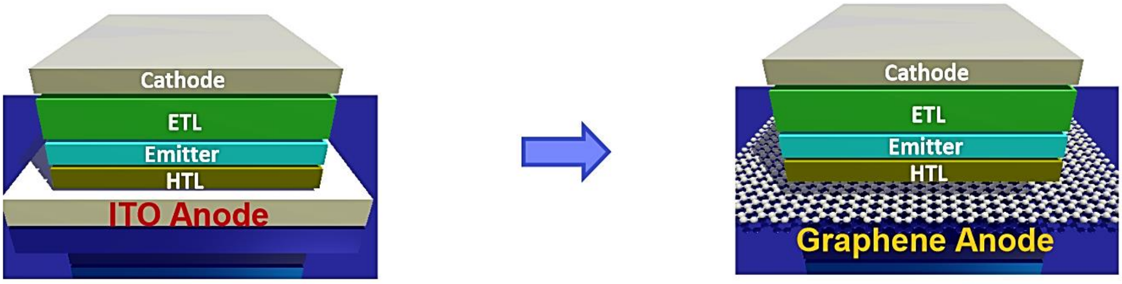



***Figure 6.4: A schematic of an OLED device - conventional type with an ITO/glass anode (left) and a new generation one with a graphene/plastic anode (right) (Source: Li, 2014)***

The European Commission funded a seven EU country-wide project called GLADIATOR (Graphene Layers: Production, Characterisation and Integration) aimed at cost-effectively producing graphene electrodes for numerous applications (FEP 2015). The project coordinator commented in 2015 that "*Graphene is a very interesting material with many possibilities. Because of its opto-electrical properties and its excellent mechanical stability, we expect that the reliability of flexible electronics will be improved many times over*". By 2015, they had proved feasibility of these electrodes for small-area OLEDs; work continues for large area OLEDs, to match graphene's performance to that of indium. Several other researchers and European projects are looking into the same area (Li et al., 2013; Li, 2014; Meyer et al., 2014; Song and Lee, 2014; Cho et al., 2016). Noteworthy emerging alternatives to graphene include silver nanowires, PEDOT:PSS and metal mesh; details of these, other technologies and commercial stages of each are examined in Chansin et al., 2016 at p243-247.

The final layer of the device - the barrier or encapsulation - protects the device, particularly the organic materials, from the effects of oxygen, moisture and from physical harm. The most common seal is glass, for the advantages already mentioned in addition to being transparent, which is important for a seal. For the same aforementioned disadvantages, manufacturers are working on flexible glass as well as plastic options; the latter is however not entirely impermeable to moisture. Several thin-film encapsulation technologies have stood out including inkjet printing (which we have extensively discussed), atomic layer deposition and UDC's UniversalBarrier - for more details see Mertens, 2016 at p19-22; OLED-info and Chansin et al., 2016 at p267-279). Mass-production IJP encapsulation systems have already been sold by Kateeva allegedly to

Samsung; the other two methods are still being evaluated. Sumitomo, UDC, Merck and DuPont sell OLED inks suitable for IJP, and several companies including Panasonic, Sony, BOE and AUO have already showcased prototype printed TVs (Chansin et al., 2016 at p90-102). The last two use CDT/Sumitomo's materials (Chansin et al., 2016 at p223-224). CDT and Sumitomo continue to work with Konica Minolta, Ulvac and Seiko Epson to optimise their IJP systems; their inkjet printed devices are now almost as good as spin-coated ones (CDT). The improvements in these processes will go a long way in achieving cost effective mass production of OLED products.

These developments of OLED technology would lead to further consumer applications. Firstly, the feasibility of flexible devices would expand possible applications to those that are curved, bendable, rolled or conformable, making room for obliquely shaped lighting panels, TVs, electronic paper and other display devices that are foldable/rollable or wearable. Secondly, transparent or even dual-sided OLED panels would allow for applications with see-through monitors such as the ones in figure 6.8. And thirdly, multicolour designs, in the lighting industry for example, panels that could change colour on demand. With regard to these possibilities, the industry is progressively moving towards maturity and expediency which will catapult OLED technology onto the market, if only to satisfy the consumer's thirst for lighter and more portable everyday devices.

A further complementary technology called quantum-dot LEDs (QD-LEDs) was developed in 1994; these are infinitely variable nanometre-sized crystals made from inorganic semiconductor materials that are capable of electroluminescence (Reineke, 2015). In a device arrangement similar to that of OLEDs, QD-LEDs can form the light-emitting layer in place of the organic materials we have been discussing (Coe et al., 2002) or replace the liquid crystal layer in LCDs (QD-LCDs - that will be discussed in section 6.3.2). Sony showcased a 55-inch flat panel QD-LED TV in 2013 but has not yet commercialised it; Apple also started work in 2014 when it acquired a QD-LED start-up called Luxvue (Chansin et al., 2016 at p111-112). Considering they share device architecture, the two technologies share developmental and technical problems - namely production costs and challenges in obtaining good blue emitters - so they are complementary in the sense that what is likely to work for one is likely to work for the other. (Reineke, 2015). This technology is still at infancy.

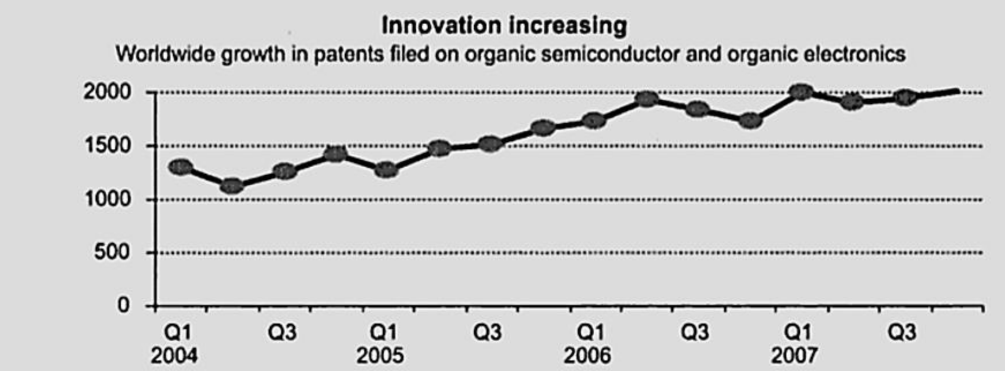
## 6.3 Regulation

### 6.3.1 Intellectual Property; Introduction to CDT's IP

Intellectual property is key to gaining a competitive edge, particularly in a technology-based industry. Not only does it provide revenue through licences and attracting investors, it is key to cementing market share through its inherent exclusivity and the advantages afforded by an established defensive IP portfolio. As Edison and Swan demonstrated in the nineteenth century, patents are indispensable in technology; they highlight R&D investments, success and research direction, and the frequency of patent filings in a particular industry indicates how relevant a new technological advance is. Bearing in mind that POLED technology is less than 30 years old, developments in the technology have grown steadily over the years. By way of indication, a simple search on the WIPO database (PatentScope) reveals 27,985 filed patents and applications tagged 'organic light emitting display' so the interest in this technology is tremendous (WIPO, searched 29th April 2016).

In a report ordered by the House of Commons to examine developments in science, the potential for plastic electronics (including OLED technology) was examined for the UK and the global economy (Innovation, Science and Skills Committee, 2009 at p561-576). The report concluded that there was a steady worldwide grant and filing of organic semiconductor patents for the period of 2004 and 2007 and a total of 16,288 patents and applications filed for the European, US and Far East regions between 2005 and 2007, of which 12,901 related to OLEDs (see figure 6.5 (a) and (b)). OLED IP ownership in Europe was topped by CDT at 133 patents and applications although they were pushed to third place in consideration that Philips filed under different assignees (Philips IP & Standards) bringing their total to 181, and Merck later acquired Covion making their total 174 (see figure 6.5 (c)). Notably, CDT also ranked in the top ten European patents assignees in organic electronics patents - inventions related to transistors, photovoltaics, lasers, sensors etc. (see table 6, page 571 of Innovation, Science and Skills Committee, 2009).

(a)




*Source: cintelliq Ltd ; * Q3-2007 & Q4-2007 forecast, Incl Granted EP & US, applications EP, US, JP & WO*

Source: cintelliq Ltd.

(b)

ORGANIC SEMICONDUCTOR PATENTS—2005-Q1 TO 2007-Q2: DEVICES VS MATERIALS AND PROCESS

| *Priority Region* | | *OLED* | *Organic Electronics* | *Both* | *Total* |
|---|---|---|---|---|---|
| Europe | Materials | 566 | 95 | 189 | 850 |
| | Process | 405 | 235 | 100 | 740 |
| | Both | 162 | 48 | 15 | 225 |
| US | Materials | 739 | 176 | 206 | 1,121 |
| | Process | 757 | 342 | 145 | 1,244 |
| | Both | 330 | 63 | 14 | 407 |
| Far East | Materials | 3,284 | 321 | 358 | 3,963 |
| | Process | 4,260 | 662 | 313 | 5,235 |
| | Both | 2,398 | 71 | 34 | 2,503 |
| **Total** | | **12,901** | **2,013** | **1,374** | **16,288** |

Source: cintelliq Ltd.

(c)

TOP TEN EUROPEAN PATENTS ASSIGNEES—2005-Q1 TO 2007-Q2: OLEDS

| *Assignee* | *Materials* | *Process* | *Both* | *Total* |
|---|---|---|---|---|
| Cambridge Display Technology Ltd | 55 | 60 | 18 | 133 |
| Koninklijke Philips Electronics NV | 29 | 65 | 32 | 126 |
| Merck Patent GmbH | 88 | 6 | | 94 |
| Covion Organic Semiconductors GmbH | 76 | 4 | | 80 |
| Novaled GmbH | 20 | 42 | 9 | 71 |
| Philips Intellectual Property and Standards GmbH ... Koninklijke Philips NV | 15 | 29 | 11 | 55 |
| Thomson Licensing SA | 6 | 20 | 15 | 41 |
| Osram Opto Semiconductors GmbH | 20 | 20 | 1 | 41 |
| Ciba Specialty Chemicals Holding Inc | 39 | | | 39 |
| BASF AG | 34 | 1 | | 35 |
| **Total** | **382** | **247** | **86** | **715** |

Source: cintelliq.

***Figure 6.5: A depiction of organic semiconductor patent filings: (a) worldwide filings for 2004 to 2007; (b) comparison of device and materials and process patents filed between 2005 and 2007 for the European, US and Far East regions; and (c) OLED filings by the top ten European companies - accounting for 64% European OLED patents (Source: Innovation, Science and Skills Committee, 2009 at p568-570)***

CDT has proved that using IP as a weapon is not a skill only reserved for big corporations. At the time of the OLED discovery, Cambridge University did not have the disposable funds to patent the POLED invention. However, having realised how significant their discovery would become in light-emitting displays, Sir Richard Friend, Jeremy Burroughes and Donal Bradley self-funded the filing of the patent for it in 1989 (Priority application: **GB8909011**). By 1994 the patent had been granted in most major territories such as Europe, the United States, China and Japan (WIPO). The technology was still very young and had little commercial value; however, it was important to have a bargaining chip and gain a strong position in the emerging market. The quick thinking paid off; the patent later became fundamental in the POLED field.

When CDT was formed in 1992 to help commercialise the technology, ownership of the patent was transferred to them. Only they had the right to use POLED technology; everyone else had to obtain a licence (CDT). From this, and in addition to two other fundamental patents, they built a network of collaborators with whom they shared technical know-how, transferred technology and gained expertise that would have otherwise been beyond their reach. Most importantly, the majority of these were its competitors in the field; they would usefully keep an eye on their activities through transparency clauses written in their licence agreements.

Given their relatively small size, a strong and comprehensive IP portfolio was critical to their success in the display industry. And so they continued to expand their IP through their internal efforts, granting licences and acquiring other businesses, technologies and assets. They continued to file patent applications in all major jurisdictions including Europe (mainly the UK, France, Germany and the Netherlands), North America and Asia (including Japan, China, Taiwan and South Korea), with the most significant inventions protected in several countries (CDT, 2006). CDT's R&D efforts saw its patent portfolio grow from 13 in 1993 to 140 in 2003 (Maine and Garnsey, 2006 at p387). In 2004, it had 116 granted patents and 238 applications in 162 families (Cambridge Display Technology, Inc., 2004). By 2010, that number had risen to over 560 patents granted worldwide in 280 families.

The strength of this portfolio is demonstrated by the sizeable licensing programme CDT has built up and the growing commercial adoption of the technology over the years. It additionally has exclusive control of other patents and IPRs owned by some of its licensees or companies and institutions with whom it has partnerships - notably, patents from the Universities of Cambridge and Oxford, and Seiko-Epson in respect of IJP manufacture (CDT Annual Report, 2006). For the purposes of this thesis, the author has mentioned this later acquired IP, and indeed other acquired IP mentioned throughout this chapter, to demonstrate the breadth of CDT's IP portfolio but its analysis is outside the scope of the thesis objective. Only core patents by Sir Richard's research group, listed in appendix 1 were analysed in chapter 5.

The chronology in appendix 4 indicates that there are 15 paradigms shifts at an average of 2.6 years apart - for statistical purposes, those that happened in the same year are considered as one. This time period is echoed by the analogous technology - inorganic semiconductors - discussed in chapter 3. From the discussions of the inventions in both chapters 3 and 5, it is clear that the time in between paradigm shifts was spent making improvements to extant inventions as well as filing patents. For example, the fundamental patent PCT/GB90/00584 whose priority application was filed in 1989 saw the application, for the first time, of an organic polymer semiconductor in an electroluminescent device. The two patents that followed PCT/GB91/01421 and PCT/GB93/00131 concerned methods of making the polymers more efficient. The next paradigm shift was 3.3 years later in PCT/GB93/01573 and PCT/GB93/01574 (p1), both filed in 1992 and introducing the idea of using multiple light-emissive layers in a single device. The next shift was a year later in PCT/GB98/01840 which introduced the idea of stacking light-emitting devices into a single device with the added capability of being able to independently operate each device in the stack, and 3 years later in PCT/GB97/01972 in 1996 (p3) when for the first time organic semiconductors were used in transistors. Between those last two shifts, five other patents were filed relating to improved material blue colour emission (PCT/GB93/02586), charge transport properties (PCT/GB94/01118 and PCT/IB95/01042), dealing with the polymer insolubility issues (PCT/GB95/03043) and on alternative constructions of existing devices (PCT/GB96/00923). This pattern - paradigm shift inventions punctuated by improvement inventions, "sailing ship" effect inventions and solutions to specific and usually industry wide problems - continues throughout the data.

Moreover, under the Patents Act 1977, it takes about 2-3 years for a patent to be granted, and patent infringement suits can only be brought after the patent has been granted. From appendix 4, the turnover of innovative technology was roughly every 3-4 years. It can therefore be asserted that the most useful patents were the fundamental ones and those that introduced paradigm shifts as those were the ones on which subsequent technological improvements, and ultimately, the licensing programme were based. It is not possible to ascertain which patents were most licensed as the author is not privy to the company's confidential commercial data but CDT in its financial and annual reports asserts that it had to hasten the establishment of its licensing programme to solidify its IP bargaining chip before its fundamental patents expired in 2010, 2011 and 2015 (CDT Annual Report, 2006 at p13 & 24). Although the other patents it owns would have extended its monopoly well beyond 2015, it stated that its competitive position would not be as certain because the additional patents were not fundamental. However, most fundamental patent licences will have included cross-licensing clauses allowing it freedom to use its partners' IP to further its own. This arrangement, in addition to its other patents and those resulting from these collaborations would have created a patent thicket that would be sufficient to maintain as well as extend its monopoly (the patent thicket is not unlawful in light of CDT's adherence to competition law provisions as explained in section 6.3.1, page 175-176).

Further, because of the successful licensing programme it set up over the years, it has in a way extended that monopoly by having rights in the patents that cover most of the inventions that resulted from improvements to those original inventions, either through its own efforts or those of its licensees and research relationships. Further, grant-back clauses are a standard feature of technology licensing and these require the licensee to disclose and transfer all improvements made, including know-how, in the licensed technology for the duration of the licence (Cameron and Borenstein, 2003); this enabled CDT to keep an eye on its competitors. Would it have had issues with patent infringement? To a very small extent because several of its competitors were licensees. The advantage of being a pioneer of the technology was such that everyone had to come to it to either obtain the necessary licence to apply that technology in their endeavours or attain the prerequisite know-how to further their research. CDT kept quite a tight leash on the technology.

The turnover of innovative technology for inorganic semiconductors was also every 3 - 4 years (see chapter 3). We saw that the most useful patents were the 'major ones' - those that covered the transistor and the integrated circuit, owned by Bell Laboratories, Texas Instruments and Fairchild Semiconductors. In that era, the semiconductor industry had to obtain licences from them to incorporate technology into their devices. Cullis for example states that in 1966, one needed the patents of 14 different companies to fabricate a silicon planar epitaxial switching transistor; at the time, this was the basic building block of computers (Cullis, 1966). Among other things, these licensing programmes were part of the reason companies such as Bell Laboratories succeeded over other companies (see chapter 3). The other players who owned the "smaller" patents - mostly improvements to the major paradigms - usually found no benefit in suing for patent infringement because of the fast turnover; the technology simply would have moved on. And so it seems that CDT had picked a leaf from the predecessor electronic industry giants.

Notably, CDT's patent monopoly may also be prejudiced by several factors that affect the patent system. These may include procedural errors; delays in the legal process, in particular where there are appeals or oppositions to grant; differences in patent law systems, especially as they seek protection in multiple jurisdictions - particularly, the degree of protection granted and delays in the grant of patents by the European and Japanese patent offices; and even everyday administrative matters relating to patent prosecution and maintenance. If the patents are not granted when the potential market is ripe, it may affect CDT's ability to exploit the technology fully or widen its pool of licensees. This is important because the OLED value chain is now global, with most of the early stages in the technology's development such as components and device physics dominated by US and European players whilst several mid-final stages like product assembly and incorporation into commercial products are dominated by Asian companies (see section 6.4.2, Innovation, Science and Skills Committee, 2009). This also explains why their priority filings are largely US and UK applications.

The second most important part of CDT's IP portfolio is know-how/trade secrets/confidential information, especially relating to the manufacturing processes and engineering expertise. The Oxford dictionary defines know-how as practical knowledge, skill or expertise gained during the course of employment. In Faccenda Chicken Ltd v Fowler [1987] 1 Ch 117, the court clarified that this can be classified in three main ways: (1) trivial knowledge that is easily accessible from public sources and is therefore not confidential; (2) information that the employee knows is confidential and uses during the course of employment for his employer's benefit but which nevertheless remains in his head after termination of employment, becoming part of his own knowledge and being free for him to use once he has moved on; and (3) information that is so confidential that, even if he has learned it by heart, outside of his employer, he cannot lawfully use it for anyone else's benefit on termination of that employment. Determining the difference between class 2 and class 3 is not always straight forward and is usually judged based upon what an ordinary honest and intelligent person in those circumstances would perceive as knowledge that is mere know-how and therefore free for him to use on departure from that employment and knowledge that is in the strictest sense confidential to his employer.

Often times, class 3 is the most valuable part of a business; it is kept confidential and gives a company a competitive advantage over its counterparts. Know-how is especially important in rapidly evolving industries such as in technology in which cumulative knowledge is important; as we have already discussed, innovation in these industries usually builds upon what is already extant. However, know-how that is not communicated is relatively worthless so companies commonly use it to complement or supplement their IP portfolios, licensing or selling it to further innovation. Fairchild Semiconductors did this with its silicon planar technology (Cullis, 2007 at p55-59).

By its nature, know-how is fragile and highly susceptible to misappropriation. As such, it is usually protected by non-disclosure agreements and contractual obligations, or common law causes of action for breach of confidence. What is not so easily controlled is the use of such; public policy dictates that an employee is entitled to use and put at the disposal of a new employer all his acquired skill and knowledge gained through previous employment, after all, work experience is usually a major deciding factor in securing a new job (*Ocular Sciences Ltd. v. Aspect Vision Care Ltd.* (1997) RPC 289). The lines however get blurred when deciding between knowledge that is in the strictest sense a trade secret and therefore property of the ex-employer and information that is merely knowledge, skill and experience that an employee acquired in the course of their duties (*United Indigo Chemical Company Ltd. V. Robinson.* (1932). 49(5): RPC 178).

Accordingly, it is difficult for companies to rely on the commercial advantage of know-how on the basis that it will be kept secret because of employee turnover. As such, ex-employees may take with them and put at the disposal of the new employer, albeit sometimes unknowingly, accumulated knowledge that may prejudice their ex-employer. A good example of this was the establishment of the Silicon Valley following the invention of the transistor, integrated circuit and silicon chips, which was largely based on knowledge sharing as a result of the high mobility of employees between different technology start-ups. At that time the speed of technology turnover was realised and IP enforcement in a strict sense was briefly suspended in favour of knowledge sharing to foster innovation (Cullis, 2008). Even though there were subsequent contentions between the different companies as to ownership of this knowledge, this factor went a long way in establishing the Silicon Valley into the world's oldest high-tech community (Hyde, 2015).

Like many other companies, CDT protects its secrets through signed non-disclosure agreements and establishment of fiduciary relationships with their research and commercial partners. These agreements are however not airtight as already explained and may not therefore adequately protect against misappropriation - once the cat is out of the bag, it's out! To CDT's advantage, it has a low level of employee turnover so to a certain extent is more likely to keep its secrets in-house. It is additionally CDT's practice to bind ex-employees by short-term express covenants to protect its know-how to a further extent. It has an average of 120 employees and the UK Companies House has only recorded 38 resignations in 24 years - since the incorporation of CDT in 1992; 27 of these were directors and 6 secretaries - that turnover for the nature of these roles is not unexpected - leaving 5 resignations of core staff (Companies House, Endole). This also reflects its evolving business model, especially around the time it was acquired by Sumitomo. It acknowledges that it may well employ staff that have worked for competing companies as is the norm in this industry;

to the author's knowledge, CDT has so far not been subject to any breach of confidence causes of action by other companies.

In addition to experienced CEOs and directors of spinout companies from industry to drive the business forward, CDT notably employed the core inventors in the POLED discovery in the running of the company. Up until 2000 when he turned his attention to his new spinout (Plastic Logic), Sir Richard Friend ran CDT in the first few years alongside other scientists, and Jeremy Burroughes also joined in 1997 and is now its current Chief Technology Officer (CDT). This keeps the company's focus on the core technological needs from the laboratory upwards to the boardroom.

Moreover, the industries - in which POLED has application - are very competitive and companies need a strong brand to distinguish themselves, gain competitive advantage, and build and retain a loyal customer base. Trade marks are required for this purpose. CDT successfully registered four European Community trade marks: 'CDT is LEP' in 2003; 'CAMBRIDGE DISPLAY TECHNOLOGY' in 2003; 'CDT' in 2005; and P-OLED in 2004, all as word marks for goods and services in Class 9 (Polymer electronics; polymer semiconductors; displays; parts and fittings for all the aforesaid goods), Class 11 (Lighting apparatus and installations; solar cells) and Class 42 (Technical consultancy; research and design of polymer electronics and polymer semiconductors and components comprising polymer electronics and semiconductors and parts and fittings therefor) (TMDB). In 2007, CDT further registered two UK trade marks: a word and a device mark for TMA technology, both in respect of goods and services in Class 9 (UKIPO). TMA stands for Total Matrix Addressing and in layman terms is chip technology that reduces the power consumption of the passive matrix OLED structure discussed in section 6.3. Interestingly, it applies to displays for both POLED and SMOLED technologies. To the author's knowledge, CDT has no registered designs. By virtue of their nature, the author also cannot comment on the status of any unregistered designs or copyright that CDT may own.

Over the years, further research from CDT and its licensees has generated more inventions and hence more IP. CDT believes it now holds the most extensive and significant IP - encompassing patents, trade secrets, know-how and other proprietary material - in the manufacture and use of POLED materials and devices, TMA applications as well as the fundamental patents for their incorporation into POLED displays and other electroluminescent applications (CDT Inc., 2004, CDT Annual Report, 2006). Its portfolio currently covers "*electroluminescent devices; electroluminescent and charge transport materials; manufacturing processes; electrodes/cathodes; device architecture; electronics/drivers; applications for the TMA algorithm; optics; solution processing and ink jet printing; encapsulation; flexible display devices; and photovoltaics, such as solar cells*", mainly surrounding developments in POLED materials, device lifetimes, colour outputs and power efficiencies (CDT Annual Report, 2006). Its business is highly centred on the ability to maintain this portfolio and to extend the protection to all, or at least, most of the territories in which POLED applications might be made or sold.

The patents have by far been the most financially rewarding, but what happens when the monopoly on the fundamental patents expires? Does the licensing programme CDT has set up collapse? Is the technology then available for all to use? Not exactly. Over the years CDT has consistently made improvements to the technology through its internal R&D, that of its licensees and joint development partners. Its patent strategy has always been to protect resultant IP from those efforts, to in a way, extend its monopoly. In addition to completely new inventions, it has also protected combination inventions as well as broadly claimed inventions which have expiration dates ranging from 2017 to 2036. This strategy is indeed not foreign to innovative companies.

Combination inventions are those in which: (1) known and previously patented compounds, each with a different function, are combined in the fabrication of an OLED device and claimed as a new material patent; (2) a known compound is combined with a known process and claimed as a new device patent; or (3) a non-essential physical parameter is highlighted in a known material or device (Joung, 2014). Broadly claimed inventions are self-explanatory.

By their nature, these patents do not usually introduce new technologies or achieve substantial progress in the field. In fact, more often than not, they are merely a disclosure of know-how or a trade secret that researchers in the industry already use. As long as they meet the patenting criteria, a patent will be granted for them. The proprietor can then attempt to require everyone in the industry to acquire a licence to do what they have already been doing! This patent strategy is common to many technology companies who seek to extend their patent monopoly, especially at the point where they have already gained a competitive advantage in their industry by leveraging their IP portfolio.

The strategic extension of an existing temporary monopoly, such as a patent monopoly, by effectively inventing around the core idea protected by a patent, obtaining patents and other proprietary rights for those improvements, and subsequently using that IPRs package to delay or create some sort of barrier for entry for competitors is part of a wider phenomenon termed as evergreening (Granstrand, 2003 at pp.246-251; Rathod, 2010 at p227; Granstrand and Tietze, 2015 at p3). Granstrand and Tietze recently defined it as:

"*IP based evergreening is the business strategy to extend the duration of the effective protection derived or derivable from a portfolio of IPRs in order to increase the appropriability of an innovation or a set of business related innovations or technologies*" at p8.

Evergreening is therefore a combination of business strategy that aims to extend a dominant market position and IP strategy that in a way seeks to extend the legal IPR monopoly, and encompasses patents, know-how, trademarks, usage rights, licence rights as well as any other form of proprietary information. To this end, known business strategies that aim to create entry barriers or delay entry of a competitor onto the market, strengthen one's dominant position through strategic commercial agreements, leverage sales from specific products or technologies etc., can be combined with certain IP management structures. IP strategies include: (1) filing of blocking patents, as will be discussed later on pages 174 & 275 of this thesis, (2) creating a patent thicket as was discussed on page 166 of this thesis and will be expounded upon on pages 175-176, that effectively makes it difficult to navigate around a particular technology, making it necessary for other traders and advantageously, competitors to seek licences from the patent proprietor, (3) follow up patenting of subsequent improvements or different features of the original innovation that are often technically significant but not necessarily economically visible, (4) progressive introduction of successive product generations on the market, where the products are protected by overlapping patented technologies or resources, (5) global patent litigation strategy that deters competitors (6) new and non-obvious applications of the same technology, and (7) filing of substitute patents - potentially competing patents that cover alternative technologies and can be used in parallel without infringing each other (Granstrand, 2003; Rathod, 2010; WIPO Secretariat, 2014; Granstrand and Tietze, 2015). Technologies in this context includes patents, know-how, trade secrets and other proprietary rights.

Granstrand and Tietze exemplify this using a case study of AstraZeneca's blockbuster stomach ulcer drug, Losec (Omeprazol) (at pp.15-19). The drug was introduced on the market in 1988 and quickly became the world's annually bestselling drug for several years, in particular, it was the top selling drug for four consecutive years from 1996 (p15). It had an estimated value of 15-30 billion USD, and accordingly raised AstraZeneca's profile on the market from being part of the top 40 to the sixth largest pharmaceutical company in the world (at p16-17). The drug was protected by two patent families, one for the active substance (filed in 1979) and the other for the formulation (filed in 1987), which provided a monopoly in several territories including Europe and the US. In the language of this thesis, these were fundamental patents.

In addition to consistent generation and protection of IPRs throughout the lifecycle of those patents, the authors in their assessment concluded that at least five different types of evergreening strategies contributed to the success of Losec. These were: (1) a combination of both radical and technically minor improvements to the formulation to improve drug delivery mechanisms, (2) creation of a second generation product with overlapping technologies, (3) an aggressive brand protection strategy around their trade marks that laid a firm foundation for the second generation product, (4) a global litigation strategy that spanned a period of over fifteen years and both delayed and deterred competitors and potential entrants to the market (see figure 8 of the paper), and (5) the use of reverse settlements in which AstraZeneca paid alleged patent infringers to conclude patent infringement lawsuits and avoid further challenges to the validity of its patents (at p19). Notably, these strategies overlapped, interacted with and complemented each other in extending either the patent monopoly, the dominant market position or usually both.

Moreover, evergreening is not unlawful. As long as the legal criteria for obtaining a patent are met, a patent will be granted. And as long as a dominant market position does not offend the provision of the TFEU (and in particular, an advantageous application of the block exemptions as will be discussed on pages 175-177 below, a company cannot be found to act anti-competitively. A combination of both those strategies, in addition to any other helpful legal business methods, is merely a savvy way of doing business. From the discussions in this chapter, it is clear that CDT employed a combination several of the aforementioned IP strategies to increase the lifetime of its patent portfolio, and business methods to accentuate its market dominance. Both have paid off to keep a company of its still relatively small size afloat, and relatively successfully, for such a long time.

The accumulation of patents in a particular field, especially by pioneer or dominant companies is a result of cumulative R&D as well as the freedom afforded by the patent system (*Van Dyk Research Corp. v. Xerox Corp.* (1981). 101 S. Ct. 3029). However, if this is done in a way that bars competitors from exploiting their own inventions - usually by inhibiting them from entering the market because there is an overlap in patent rights and the use of one's patent infringes another's, so called 'blocking patents' - that freedom might be viewed as anticompetitive behaviour and may trigger competition law scrutiny, be seen as predatory or a misuse of the patent system (Barton 2002, Lianos 2008, p52).

Patent law encourages innovation by granting innovators an exclusive right in the form of a patent to control the commercial exploitation of their invention. Given the novelty of their products, patent proprietors tend to have a certain authority on the price of their products on the market, and rightly so, to recover the innovation rents associated with developing the products. This freedom can very easily border on abuse. The patent system however only punishes infringers of this exclusive right; it does not punish the misbehaviour of patent proprietors.

In contrast, competition law (or antitrust law as it is known in the US) seeks to balance the interests in a patent with the impact it has or is likely to have on competition; it controls the extent to which patent monopolies can be exercised by regulating the degree of market power a patent proprietor can have (Lianos

2008, p15-21). In other words, it prohibits misconduct amongst competitors that may harm innovation, to the detriment of consumers. Accordingly, a patent right is not absolute; it can be restricted if it is found to infringe competition law (Lianos 2008, p23).

CDT's commercial agreements are subject to competition law provisions applicable to the UK - the Treaty of Rome, the Treaty on the Functioning of the European Union (TFEU), the Competition Act 1998 etc. as well as US antitrust policy (since they are legally registered in the US). Whilst, of course, it drafts the agreements with due care, there is always a risk that it could fall foul of any of these provisions given its dominant IP position. As far as the EU market is concerned, the deciding factor is whether a company/patent holder is at the time of the alleged abuse '*in a dominant position within the common market or in a substantial part of it*', and how it measures up to the criteria to be considered in the application of Article 102, including its market power, and the effect and necessity of its pricing on competitors (see Article 102 of the TFEU for detail).

On the other hand, technology transfer agreements are vital to ensuring scientific knowledge sharing to further R&D and the development of innovative products and services. The agreements largely concern the sharing of R&D IP in exchange for some sort of benefit for the licensor. They often contain restrictive clauses that for example, prevent the parties from gaining an upper hand over each other or other competitors, or from such acts as collusion (Peeperkorn, 2003; Barazza, 2014 at p186). Consequently, this has potential to affect competition.

Article 101 of the TFEU aims to promote trade in the European Union internal market by regulating agreements between companies to prevent anti-competitive practices such as the creation of cartels between competitors, price-fixing, exclusive dealing etc. However, in the interest of furthering technology licensing, the Technology Transfer Block Exemption regulation of this Article permits certain surprisingly restrictive licensing terms that would otherwise be objectionable. The exemption only applies to contract products; products incorporating or produced with the licensed technology. Guidance on the application of this exemption is provided in Part 3 of the European

Commission's Guidelines (2014/C 89/03) of 28 March 2014. An in-depth analysis of this exemption is outside the scope of this thesis.

Moreover, Article 101 is further mitigated by the Research and Development Block Exemption regulation (EU) No. 1217/2010) of 14 December 2010. This in essence permits companies such as CDT to enter into R&D agreements or joint exploitation arrangements with other companies if their combined market share in the technology field at hand does not exceed 25%, and provided they conform to certain other criteria such as sharing of R&D results and any resulting IP and know-how. This protects it from in-depth anti-competitive assessments of the effect of its R&D activities on competition. The R&D Block Exemption can also be used in conjunction with Part 3 of the European Commission's Guidelines on the applicability of Article 101 of the TFEU to horizontal co-operation agreements (2011/C 11/01) of 14 December 2011 - this governs agreements between companies at the same level of production or distribution in the market.

Even though in-depth analyses of both exemptions are outside the scope of the thesis objective, it is noteworthy that the core of CDT's activities fall within the scope of both - CDT is therefore largely protected from offending Article 101 of the TFEU. Otherwise its agreements that have allowed it to pool patents from different sources to create an overlapping set of patent rights (commonly negatively viewed as a patent thicket) would be frowned upon.

The balance between maintaining the exclusivity of IP and enforcing competition law is not an easy one to strike without prejudicing their inherent rights. Lianos 2008 (at p42-45) submits the doctrine of patent misuse as the key to this dilemma. Patent misuse comes into play where the monopoly of a patent is extended to the prejudice of the underlying public policies in granting the patent in the first place. The doctrine prevents a patent holder from leveraging the monopoly from the patent from one goods market into another in principally two ways: 'tying' arrangements and threats of contributory infringement. The former is where a patent holder 'ties' the grant of a patent licence or the sale of a patented product to the condition that the licensee or purchaser will also obtain other prerequisite resources or requirements from the patentee or other source specified by the patent, specifically where those resources are not covered by the patent (Kobak, 2000, p38-39). The latter is where a patentee asserts contributory infringement liability for those who, without his consent, create and sell products or means that are likely to aid in the infringement of their patented product (Kobak, 2000, p6-8).

Another important area of patent misuse likely to bring CDT under scrutiny are package licences; where multiple patents are simultaneously licensed as a package, irrespective of whether or not the licensee requires the whole bundle (Kobak, 2000, p43-45). This is synonymous to copyright bundles such as the Microsoft browser, Internet Explorer, being bundled with Microsoft Office packages such as Windows. This is not illegal where the bundle is accepted voluntarily but it constitutes patent misuse if the patentee either makes it compulsory or coerces the licensee to take up the package, particularly where there is no relationship between the patents in the bundle. Patent misuse and competition law concepts have over the years attracted a plethora of contention, the details of which are outside the scope of this thesis but the reader may refer to Kobak, 2000 and Lianos, 2008 for more detail should they require it.

Given CDT's expansive IP portfolio and the business model it has adopted (details discussed later in sections 6.6.1 and 6.6.2), it is easy to see how they may easily fall foul of any of the aforementioned behaviour. This would lead to time-consuming and costly litigation that is disruptive to its business and that of its licensees and research partners, not to mention possible invalidation of the patents at issue. Given its "safe haven" in the block exemptions of Article 101 of the TFEU however, the foregoing is not envisioned to be a problem. Indeed, thus far, the author is unaware of such suits on the hand of CDT's technology or its licensees but other major OLED technology licensors in a similar IP position to CDT have been party to such. UDC, for example, which owns almost all of the fundamental phosphorescent OLED materials patents: over 3500 patents and applications worldwide as of December 2014, of which more than 60 patents cover 4 early fundamental phosphorescent OLED inventions (UDC). UDC has built a large licensing network comprising of almost all major OLED manufacturers including Samsung, LG, Panasonic Pioneer, Konica Minolta, Philips and Sony (UDC). Having been subject to antitrust scrutiny in several jurisdictions in Europe and Asia, UDC in 2011 lost one Japanese patent and had two others as well as a European patent in 2013 (which had been challenged by Sumation, Merck and BASF) partially invalidated because the claims in all had been too broad (UDC Annual Report, 2013 at p23-25; UDC Press Release, 2013; Joung, 2014). Over the past three years or so, several of its patents have also been litigated for the same reason.

#### *6.3.1.1 Ownership and Commercial Exploitation of CDT's IP*

In contrast to industry, academic staff and research students often gravitate towards publishing revolutionary papers rather than seek to earn income from an invention. A select few with an entrepreneurial edge participate in spin-out endeavours. The latter was how CDT came to be in existence, after Sir Richard's team realised the future potential of POLED technology. As was the case then and still is, CDT's objective was to establish POLED as a leading technology through its IP portfolio. The company was spun-out of a university research project and the IP at the time was owned by Cambridge University. According to section 39 of the Patents Act 1977, inventions devised by employees of the university during the course of their employment belong to the university. This excludes inventions devised by students who are not employees of the university. The research culture at Cambridge was - and still is - such that the university expected the inventors/academics as well as students to be involved in the commercial exploitation of their inventions (Cambridge Enterprise, 2015). The university's IP rights policy allows the inventors to buy patents back from the university, as long as the university gets 15% of the value of the patent (Statutes and Ordinances of the University of Cambridge, 2015 at p1038-1046). Cambridge Enterprise (CE) - the technology transfer arm of Cambridge University and a free standing not-for-profit company - was set up in 1996 to aid in the commercialisation and revenue sharing of inventions that are not bought back from the university.

Chief amongst what CE does is the identification of ownership. Inventions are team efforts, and most research groups consist of employed academics and post-docs, and non-university employed PhD students or undergrads. In the case of the former, ownership is straightforward according to patent law. The latter are not bound by university employment contracts so the situation is a little hazy. These students usually make substantial use of material resources provided by the university and are often tethered to obligations of their funding

Research Councils. Their contribution to the conception of an invention either solely belongs to them or to the Research Councils that fund them.

It is however not practical to exploit or assign a percentage contribution to an invention, if indeed it can be ascertained. It is more beneficial to deal with the invention as a whole, so the students usually sign agreements authorising CE to exploit their part in the invention. One would imagine that they would do this enthusiastically, if not cognisant of the possibility of financial compensation on successful exploitation of the invention but to welcome the idea of having a patent on their CV. The most viable inventions that come out of Cambridge University are accordingly commercially exploited through CE.

When CDT was formed as a separate entity from University of Cambridge - it acquired IP through three main ways: employee inventions, and extensions of that technology by licensees, and/or through other commercial partnerships. The last two introduced industry and academic researchers that would usually have additional resources and/or expertise in technologies that would enable the success of POLED technology. These categories were bound by agreements that expressly addressed the ownership of IP generated during the course of the partnership.

And so, in line with its objective to establish POLEDs as the leading technology in the flat panel display industry, CDT adopted a bespoke business strategy. It capitalised on its IP position in the industry; manufacturing process and engineering know-how; the commercial collaborations it had in place with leading display manufacturers; and further drove interest in the technology by other industries that would benefit from the advantages of POLED technology, such as the lighting, signage, defence, medical and fashion industries (see sections 6.4.1 and 6.5). Through the Sumation venture (explained later) and its extensive licensing programme (see section 6.3.1.2), it collaborated with players at different levels of the industry to accelerate the development and optimisation of better POLED material lifetimes, efficiencies and manufacturing processes such as inkjet printing, so as to facilitate better adoption of the technology by the industry at large. It continues to foster its formal relationships through licence agreements and technology development agreements, and its informal relationships through non-disclosure agreements and exchange of technical know-how.

CDT now exploits its technology according to its business model - to generate revenues through: (1) lump sum licence fees and recurring royalty payments; (2) technology development and service provision; and (3) sale of products and equipment related to POLED applications (CDT). The first avenue will be expounded in section 6.3.1.2. The second avenue chiefly takes place at CDT's $25million Technology Development Centre - opened in 2002 in Godmanchester near Cambridge - at which commercial scale manufacturing processes and fully functional POLED displays are tested and demonstrated. Over the years, improved POLED materials, fabrication methods, devices (see sections 6.2.1 and 6.2.2) and resultant process and engineering know-how have been sold to licensees and other commercial partners. Further, and as part of some of its licence collaborations, CDT trains its licensees' staff to resolve technology related problems and further provides custom service packages to assist its licensees in incorporating POLED technology into their commercial products (CDT Annual Report, 2006; Minshall et.al., 2007).

Through the third avenue, the products (materials, ink jet printers, polymer inks, display modules, test equipment etc.) and associated know-how of its research and that of its licensees and commercial partners are sold to major industry players. To mention a few, in 2006 inkjet printing systems were sold to the National University of Singapore, and advanced testing equipment (the "Eclipse") for calibrating POLED devices to Merck (EE Times, 2006). In 2003, Inkjet printers jointly developed by CDT and Litrex were sold to Ulvac - a large Japanese semiconductor equipment supplier - along with a 50% equity interest in Litrex. CDT at the time owned Litrex (US developers and suppliers of industrial ink jet printers), had funded them to develop commercial scale ink jet printers for POLEDs and was the exclusive distributor of specialised Litrex printers for POLED applications (CDT Annual Report, 2006; Fyfe, 2009). CDT eventually sold the remaining 50% of its interest in Litrex to Ulvac in November 2005 for $10 million (CDT Annual Report, 2006).

Additionally, as CDT's capacity has grown, it has been able to buy some companies whose IP has further both enlarged and enhanced its portfolio. Such include the acquisition in 2002 of an Oxford University spin-out company, Opsys UK Limited (now CDT Oxford Limited) that owned several patents and know-how related to the use of dendrimers to improve POLEDs materials and to enable solution-processability of phosphorescent materials (CDT, 2006). Analysis of this IP is outside the scope of this thesis. In addition to taking ownership of Opsys' IP, CDT took over management of the commercial and technical developments of Opsys' UK business including facilities and over 25 highly-skilled scientists who were well-versed in dendrimer OLED development. This acquisition expanded CDT's research operations into phosphorescent materials, in addition to the fluorescent materials with which it traditionally worked (see section 6.2.1).

Further, Japan's Toppan Printing, a leader in the global printing industry, which had previously invested in a joint dendrimer development agreement with Opsys transferred that joint work to CDT, and further investment in them (University of Oxford, 2002). In 2006, the two collaborated on roll-printed POLED displays and subsequently produced the world's first-roll printed display at 5.5 inches in 2006 (SID). In the same year, CDT acquired a sizeable patent portfolio relating to new POLED derivatives and applications from Maxdem Inc., which CDT later sold to Sumation (CDT Annual Report, 2006). CDT then acquired the US-based chip design firm, Next Sierra, in 2007 to aid in the speedy marketing of its TMA technology (CDT).

Perhaps the biggest commercial decision CDT made was to collaborate with the Japanese chemical company, Sumitomo Chemical. Sumitomo is a POLED materials supplier and acquired CDT in 2007, after taking licences for their materials and investing in joint development projects with them from as early on as 1998 (CDT). It has since continued to manufacture and sell POLED materials to the display industry through its joint venture called 'Sumation', established in 2005. In addition to providing CDT with working capital and access to their massive IP portfolio, Sumitomo brought with it materials manufacturing expertise, POLED material derivatives and associated IP, links with other major industry players as well as purchased IP, in particular IP related to POLED materials previously owned by another materials giant, Dow Chemicals (CDT Annual Report, 2006 at p47).

In 2008, Sumitomo built a POLED manufacturing process development line in Japan and in 2011, completed a manufacturing facility in Osaka (Sumitomo). It also announced in 2012 plans to enter the OLED lighting market and produce all printed (except electrodes) commercial lighting panels by around 2013 - 2015; it is yet to release these (Mertens, 2016). It started manufacturing touchscreen panels for flat OLED displays in 2012, and for curved displays in 2014 and launched volume production in 2015 (Sumitomo Annual Report, 2015). It demonstrated a flexible display in in 2013 but these have not yet gone commercial (Chansin et al., 2016 at p225). Sumitomo also had collaborated with Panasonic to produce TV materials which Panasonic used for its 56-inch POLED TV panel prototype in 2013 (see section 6.4.1) but Panasonic dropped out of the OLED race at the tail end of 2013 (Mertens, 2016). It has, however, several agreements with other display manufacturers, including UDC (the US's largest phosphorescent OLED technology developer), Kateeva (which specialises in a novel kind of OLED ink-jet deposition) Seiko Epson and AUO so it will be interesting to see how these pan out. IDTechEx submits that Sumitomo annually invests between $5-100million in POLED research, and that at the moment, a greater proportion of the revenue comes from leveraging its materials know-how (as it has the strongest printable OLED materials IP) and selling R&D devices than from commercial sales of its POLED materials (Chansin et al., 2016 at p226).

Further, the bulk of CDT's business model is built on licensing IPRs. The nature of a licence implies that one party (in the current case, CDT) grants permission to another party (its licensee) to use its technology in a way that would have otherwise amounted to an infringement of its IP rights (Patents Act 1977, section 60). That is straightforward. What is not so straightforward and usually the source of contention in licence agreements is the issue of ownership of IP generated during the course of the agreement. It is common legal practice to expressly address this in the licence agreement but the reality is not always as simple. As such, disputes may arise between CDT and its licensees, and lack of a resolution may either adversely affect the commercial agreement in place or lead to litigation. Both would have consequences as to finances, time and effort, and in the worst case, loss of IP rights or of the commercial relationship.

As licence agreements are contracts of sorts, conflicts may arise as to construing the terms in the licence. CDT in 2005 sued its licensee DuPont in a dispute about the timing of royalty payments based on a difference in construction of the relevant clause in the licence agreement; the two very different constructions meant that the payments were a year apart (CDT vs DuPont). DuPont claimed that the term at issue had not been drafted consistently throughout the licence. Applying principles of contract construction, the High Court ruled in favour of DuPont stating their construction made the most commercial sense when the licence was read as a whole. CDT's appeal was subsequently dismissed, and accordingly, they lost a year's worth of royalty payments.

Moreover, CDT's licence agreements usually include "most favoured nation" provisions (CDT Annual Report, 2006). These entitle extant licensees to renegotiate the financial terms of their licences in the event that more favourable financial terms are offered to new licensees under essentially similar terms. This, among other reasons, is likely to happen following patent infringement proceedings where CDT is forced to either renegotiate an existing licence (with the licensee involved in the suit) to account for the resultant adjustments following the litigation or have to offer more 'friendly' licence terms in a bid to attract licensees who may have otherwise been scared off by the complications.

The ubiquitous nature of technology also creates the likelihood that the use of one's patents may either wholly or in part infringe another's patents as more often than not, several 'parts' of a technology may have to be pooled to attain a single workable concept. The matter is further complicated by the issuance of Prohibition or Secrecy Orders that may be imposed in relation to certain inventions, particularly defence-related inventions, wherein some patent applications may be kept secret until the patent is granted and in some instances, indefinitely (see The Invention Secrecy Act 1951, 35 U.S Code Chapter 17; Patents Act 1977, section 23). In certain jurisdictions like the United States, it was not unusual to keep patent applications confidential until the patent was granted, especially those that related to economically significant inventions (Kappos, 2012) - in the UK, this was the case under the 1949 UK Patents Act and its predecessors. Patents or applications could neither be published nor accessed in the US, or even filed outside the US - so called submarine patents (Quinn, 2010). The logic was that they were essentially too innovative to reveal and needed to be kept back for the benefit of the US economy. This was argued in some cases to expedite the patent application prosecution and in others, to stall the process (Quinn, 2012; Kappos, 2012 at p23664), thus affecting the date at which the invention was published. Enforcement of such a right while economically exploiting the invention was a different issue altogether.

By normal patent practice, applications are published 18 months after the filing date but the patent is usually granted about three years after filing - even up to five years or more for some types of patents such as divisionals and continuations, or where the grant is opposed, or due to a backlog at the USPTO. The rationale for the secrecy was that the publication of the application gave competitors time to design around the invention and so prejudice the financial exploitation of the patented invention by the proprietor, usually by beating him to the market (Kappos, 2012 at p23663). US patent law was harmonised in November 2000 to the rest of the world to introduce publication at the 18-month mark but certain 'special' applications are still outside this requirement (USPTO).

Given the advantages of POLED technology, it is feasible to see application in the defence sector (see section 6.5) and indeed economic significance. As such, CDT acknowledged that there was always a risk that third party IPRs could be infringed by the use of its technology especially in commercial products, resulting into patent infringement proceedings for CDT and/or its licensees (CDT Annual Report, 2006 at p22). In addition to being disruptive, loss of such a suit would have significant implications as to finances, time, resources and personnel that would no doubt affect both CDT's and its licensees' businesses. In other scenarios, the licensee may be forced to take a licence from the third party in order to continue using the technology; attempt to redesign its products to avoid liability; and/or discontinue selling or efforts to incorporate the patented technology into its commercial products. This would likely prejudice the commercial agreement it had in place with CDT, in particular, as to royalties, and probably lead the licensee to renegotiate the financial terms of its licence to reflect the extra expenses attributed to the third party, if not terminate it altogether. The outcome, if reduced royalty fees, would likely trigger other CDT current and future licensees to evoke the 'most favoured nation' provision, further prejudicing CDT's financial position. Moreover, the risk to CDT would be an invalidity counterattack on its patents that if lost would lead to loss of the whole or part of its monopoly or render the patents unenforceable. This would of course award its competitors a field day.

#### *6.3.1.2 Licensing Programme*

Patents are treated differently in different industries. From chapter 5, we saw that OLED devices are fabricated by a combining several layers of materials. Each of these materials, deposition methods and device testing equipment may be developed and patented by different companies, so that a licence from each is required in order to test the performance of a device or new material. Such has over the years evolved into an industry-wide dialogue between material manufacturers, component devisers, device manufacturers etc., even though superficially, they are potentially each other's competitors. Moreover, from chapter 3, we saw patents and know-how being shared among competitors through licensing or pooling in the electronic industry, indispensably so because commercial products usually encompass several patented technologies. Accordingly, it is not surprising that the highest revenue earner for CDT is its extensive licensing model, comprising: (a) up-front and milestone licence fees, and (b) royalty payments from the sale of any product incorporating its technology as well as for primary products such as POLED materials before they are even incorporated into commercial products (CDT Annual Report, 2006 at p38).

When CDT was set up in 1992, the idea was to manufacture displays and manage everything in house. After considering the vast financial investment and high risk associated with running such an operation, and the fact that the core patent (**GB8909011** filed in 1989) was due to expire in 2010, it built its business model to take maximum advantage of the discovery and establish a stronghold in the display market before the expiry of its monopoly which was dominated by global players. This was made possible by the bargaining power it possessed as a result of the fundamental IP it owned in POLED technology.

Its CEO at the time, Danny Chapchal, a renowned 'company doctor' reputed for turning small start-ups into successful businesses, said of CDT: "*In my time of building small technology companies into market leaders, I have never come* *across a company with such potential as CDT…….I intend to put CDT and its UK technology where it should be, at the centre of the world stage*" (PR Newswire, n.d.). He revised the business model in 1996 towards licensing any newly acquired technology. That same year CDT granted its first licence to Philips Electronics, followed by Hoechst and Uniax in 1997 and a cross-licensing deal with Hewlett Packard (Maine and Garnsey, 2006 at p387).

CDT initially had very little capital to develop the technology itself. So it sought to raise revenue through establishing technology relationships and equally promoting the adoption of POLED technology by the electronic industry. It did not manufacture or sell display products based on its technology but capitalised on its IP position while it instead concentrated on "*their core strengths of technology development and innovation*" (CDT). By licensing the technology to big name display manufacturer such as Philips, Hewlett-Packard and DuPont, it gained the income it desperately needed through royalties, the credibility of working with the biggest names in the industry - "*tip-toing amongst the elephants*" as David Fyfe, the succeeding CEO later put it - and the right both to cross-license and sub-license its licensees' proprietary technology (Seldon et al., 2005; CDT Inc., 2004; Wild, 2005). The latter went a long way in consolidating IP in the POLED industry. This not only provided it with the necessary leverage it needed to stay in the game but also significantly reduced potential competition between its licensees and itself. In return, the licensees gained access to what was at the time the most novel and innovative technology on the market. This started "the CDT display revolution" as it came to be known (Seldon et al., 2005 at p8).

The potential licence pool and its subsequent income was however greatly reduced by CDT's lack of sufficient process know-how to attract the smaller scale display companies that specialised in manufacturing processes (Seldon et al., 2005). Following new ownership by an American-based venture capital consortium and a reshuffle of its business team, the business model was further revised to provide a 'one-stop solution' for licensees and joint development partners. This was attractively to save companies/potential licensees from multiple licensing agreement negotiations with several parties, a norm in the technology sector in which IP relating to a single product usually has to be consolidated from several proprietors (Wild, 2005; Seldon et al., 2005). The new model involved granting both exclusive and non-exclusive licences to companies at all aspects of the production of displays, categorised in seven ways as shown in figure 6.6: (1) materials; (2) material deposition; (3) device physics; (4) device electronics; (5) manufacturing services; (6) process equipment; and (7) optical enhancements (CDT).

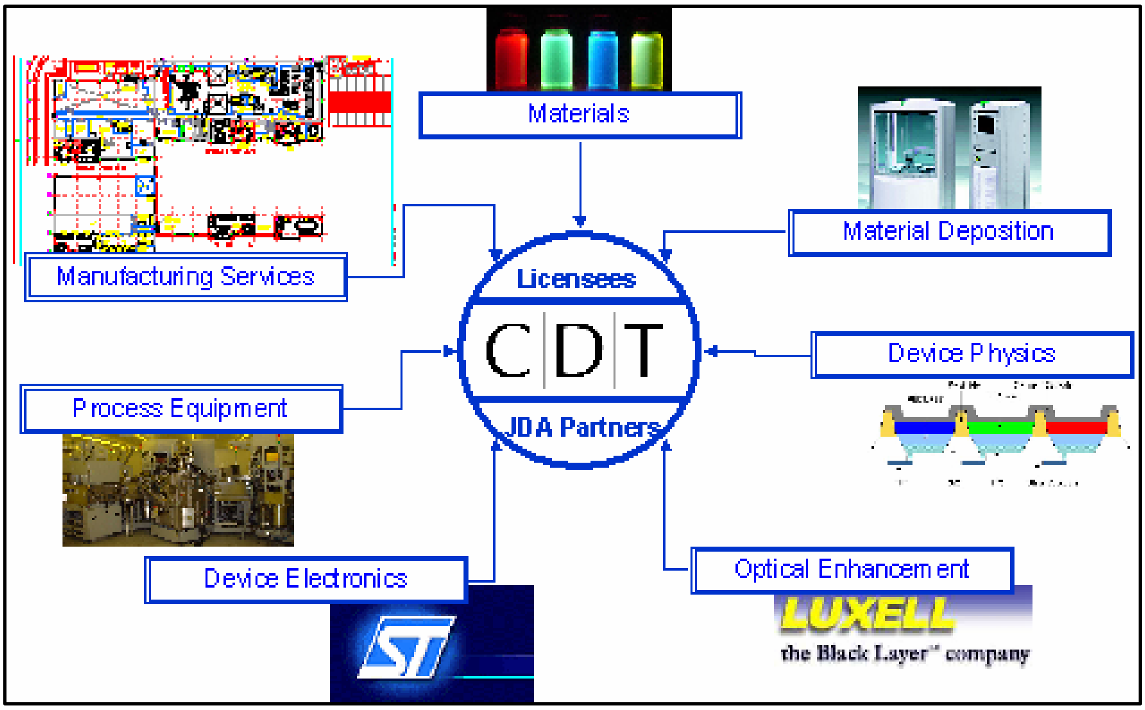



***Figure 6.6: As of 2001, CDT's licensing programme (Source: Seldon et al., 2005 at p9)***

To develop its existing POLED materials for mass production, CDT granted licences to renowned chemical companies such as Dow Chemical, Bayer, Sumitomo, Covion, Novaled and Hoechst. Material deposition mainly involved the development of inkjet printing technologies by CDT, Seiko-Epson and Litrex Corporation. Device physics - the fundamental physics of POLED displays - were handled by CDT and the Cavendish Laboratory at Cambridge University, and device electronics - driver software - by ST Microelectronics, one of the world's largest semiconductor manufacturers, and GDesign, a Hong-Kong-based microchip designer. Tokki Corporation, a leading Japanese developer of display equipment was tasked to provide efficient and low cost process equipment. Luxell Technologies Inc. provided optical enhancements by incorporating its patented 'Black Layer' technology into POLED displays; this contrast enhancing technology greatly increased the performance (including longer colour lifetime and lower power consumption) of POLED technology at a reduced manufacturing cost (Speed Communications, 2001). Cavendish as well as the National Physical Laboratory aided in optical enhancement, and CDT undertook the manufacturing services itself, albeit producing devices for niche markets (Minshall et al., 2007).

As a consequence of this model, each licensee had immediate access to all materials and knowledge required for display production. In addition to CDT's, this encouraged independent development work by the licensee and subsequently catapulted the advance of POLED technology. And with other companies doing all the work, CDT was freed to focus on its own research and on obtaining more licensees. The licensees were further allowed to sub-license the POLED display technology, with different levels of information content being subject to different up-front fees. Moreover, the licences were "living" - they included all current and future CDT patents and subject to adherence to the terms therein, were valid until the expiry of the very last of the patents (CDT Inc., 2004). A few exceptions applied to certain licensees, albeit with an option to negotiate an extension (CDT Inc., 2004 at p58).

Consequently, the licensing programme was greatly selective and highly coveted. CDT often formed informal collaborative relationships with potential licensees the success of which then led to a formal licence agreement (CDT Inc., 2004). As such, they were able to choose partners they believed had something positive to contribute to the technology's development, as summarised in 2002 by Stewart Hough, Vice President of Business development (Seldon et al., 2005 at p11):

*"We have been approached by many potential licensees, but we do not want to overlay too many licensees in any one market segment, so we practise critical selection, and evaluate potential licensees for their ability to drive the market. …we also work closely with players from less obvious industry segments, exploring the possibilities for integrating LEP technology into other industry specific applications. These include players in the paper, food packaging, printing, architectural display and other segments"*

The business model was further revised in 2003 as in figure 6.7 given the high risk of manufacturing in-house: instead CDT focussed on making prototypes for proof-of-concept demonstrations, and developing its technology now to offer 'process packages' as part of its licences.

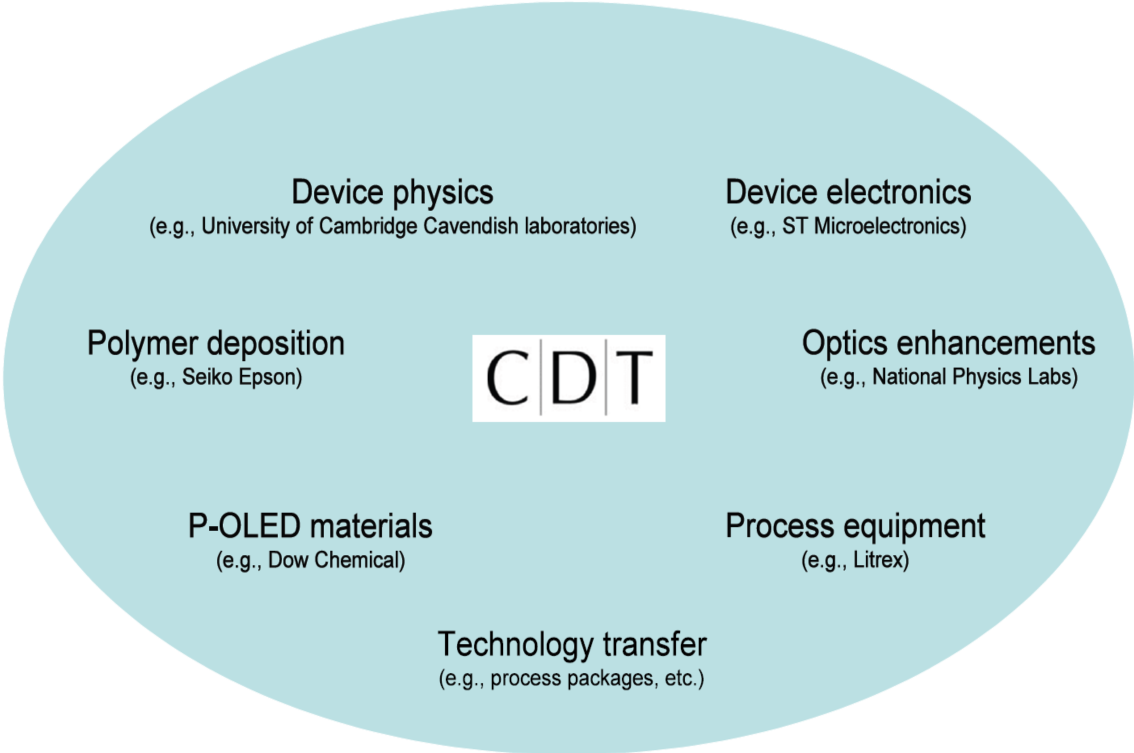



***Figure 6.7: CDT's revised business model as of 2003 (Source: Minshall et al., 2007 at p232)***

By the end of 2004, its financial statement states that CDT had "*set up formal relationships with Philips, Samsung Electronics, Seiko Epson and Thomson Multimedia and informal relationships with Casio Computer, LG Philips and Toshiba Matsushita Displays*" (CDT Inc., 2004). In addition, it had eight licensees for display devices, four licences to material suppliers and two driver circuit licensees (CDT Inc., 2004 at p59-60). It later added Panasonic, MicroEmissive Displays, Georgia-Pacific Chemicals, Eastgate, Kolon Industries etc. (UKIPO Informatics Team, 2015; Lubik et al., 2013). A more exhaustive list of partners was obtained from Lubik (2010 at p181) as is shown here in table 6.2.

| Partner | Partnership area | Partner provides |
|---|---|---|
| Sumitomo Chemical *Now owner* | Materials development | IP, market knowledge, market access, investment |
| Thorn Lighting | Materials and devices | Materials and device architecture |
| University of Durham | Materials and devices | Materials and device architecture |
| University of Cambridge | Materials development | R&D collaborations into underlying technology |
| Seiko-Epson | Materials development and manufacturing | R&D, manufacturing, access to market |
| Plastic Logic (USO) | Materials development | IP, R&D |
| Luxell | Materials development | Complementary innovations: technology integration |
| Litrex | Manufacturing | Printing |
| MicroEmissive Displays (USO) | Manufacturing | Manufacturing trials and product integration |
| H.C. Starck | Materials | Supply of hole transport materials |
| Uniax (USO) | Materials development | Market knowledge, market access, R&D resources |
| Philips | Materials development | Market knowledge, market access, R&D resources |
| Dow | Materials development | Market knowledge, market access, R&D resources |
| Covion | Materials development | Market knowledge, market access, R&D resources |
| Bayer | Materials development | Market knowledge, market access, R&D resources |
| Dai Nippon Printing | Manufacturing | R&D, market access |
| Delta Optoelectronics | Manufacturing | Process development, access to market |
| DuPont | Display devices | Market access |
| OTB Engineering B.V. | Manufacturing | Manufacturing equipment |
| Eastgate | Manufacturing | Access to market |
| Mark IV Electronics | Manufacturing | R&D, access to market |
| Osram Opto Semiconductors | Manufacturing | R&D, access to market |
| Toppan Printing | Manufacturing | Process innovations (high-efficiency patterning), investment, pilot plant |
| ST Micro Electronics | Devices electronics | Complementary innovations (drivers for display performance) |
| Tokki Corporation | Manufacturing | Manufacturing processes and capabilities |
| Samsung Electronics | Manufacturing | Prototypes |
| Thomason Multimedia | Manufacturing | Prototypes |
| Add-Vision *CDT is also an investor* | Equipment | Manufacturing (displays and lighting applications) |
| Silvaco | Manufacturing | Complementary Innovations: Organic Thin Film Transistors (OTFT) |
| Semprius | Manufacturing | Improved performance of backplanes for flat panel displays |
| ANSYS Europe | Software | Complementary Innovations: Software |
| Kolon Industries | Technology Transfer | Market access |
| Opsys (USO) | Technology Transfer | IP |
| ILFORD Imaging Switzerland | Materials | R&D |
| *DTI* | *Funding* | *Government grants* |
| *European Photonics Industry Consortium (EPIC)* | *Industry association* | *Input into industry development* |

***Table 6.2: A list of CDT licensees and joint research partners as of 2010 (Source: Lubik, 2010 table 32)***

It was not surprising that the first POLED products on the market were launched by CDT licensees: Philips (the electric shaver and a mobile phone screen); Delta Optoelectronics and DuPont (both displays for MP3 players); OSRAM Opto Semiconductors (medical devices and several point-of-purchase and promotional items); and Dai Nippon Printing (displays within book covers and posters) (Fyfe and Nicklin, 2004; CDT Inc., 2004).

Additionally, CDT had joint development partnerships and evaluation agreements with several companies: Semprius Inc, Silvaco Data Systems, DuPont (for flexible substrates for large area displays), Seiko-Epson (for IJP and blue lifetime development), Hewlett-Packard (for small area displays), Philips and DELTA (for display applications), Samsung and Thompson Multimedia (for active matrix prototypes), Covion (materials) and Toppan Printing (patterning) (CDT; CDT Inc., 2004; Seldon et al., 2005 at p13). Some of these eventually graduated to full licences.

CDT also sought to encourage the adoption of the technology in other market applications outside the display industry. Of note, they licensed to two of the world's largest lighting companies: Philips and OSRAM Opto Semiconductors. Both companies have since sold OLED lighting applications on the consumer market, albeit several for the premium sector such as hotels and restaurants given the current high price tag of the technology (OSRAM, Philips).

On the academia side, CDT increased its collaboration with universities worldwide, establishing similar IP pipeline licensing agreements with other institutions such as the University of Cambridge, University of Oxford, the University of St. Andrews, Georgia Institute of Technology, the National University of Singapore to commercialise IP arising from research into POLED displays, lighting, and other applications (CDT; CDT Inc., 2004). It owned either solely or jointly some or all of the IP emanating from these joint development programs. CDT also offered "Research Licences"; licences for R&D purposes only, with the end game being to speed a potential licensee to the higher value licences already mentioned (CDT Inc., 2004). As part of the licence, CDT would be expected either to train the potential licensee's staff in certain aspects of the technology or be called upon for specific research advice (Minshall et al., 2007 at p232).

Although the licensing programme only provides cumulative income, its vastness has enabled CDT to raise enough funds to continue its research programme, and the requisite credibility to acquire more licensees. Not to mention the confluence of several global companies' expertise, knowledge and resources, and pooling of their IP for the common goal of developing POLED technology and bringing it to market. It has further established an international status for CDT through links with a strong global supply chain, as well as enhanced its academic and research reputation. Both its business and patenting strategy ensure that CDT will continue to generate IP and thus income for the foreseeable future.

This intricate communication within the industry has accelerated the technology development, so that it has matured commercially at a faster than average rate. OLED devices first appeared in commercial products some ten years after the Cambridge discovery. David Fyfe, when interviewed in 2006 stated that "*part of the problem [was] that perception [had] been skewed by over-enthusiastic early hype, and by the high profile of some of the technically more challenging applications such as wafer thin televisions and fully flexible displays*" (Fyfe, 2006). Notably, the famous polymers polypropylene and PTFE (Teflon), and carbon fibres also took ten years to reach the market. This is still shorter than the equivalent for POLED's main competitor, LCD, which took over twenty years to mature and a total of forty years before it was mass-produced in commercial TVs (Forge et al., 2013 at p76, Kressel, 2007 at p247). Moreover, a study of spinouts, particularly those involved in advanced materials, concluded that it took about a decade or more to develop an innovation fully, and that for the duration of that time, the companies were likely to survive on external funding without getting their innovation into products or co-products on the market (Maine and Garnsey, 2006). CDT seems to have broken this mould with the choice of partnerships it made.

In conclusion, it is clear the CDT had stumbled upon an invention with great commercial potential. However, developing it to a commercial standard was an early challenge given the limited resources available to it as a small university start up. In order to navigate the complex ecosystem that the electronics industry was - dominated by global giants with virtually unlimited resources - it built its business strategy around its fundamental and subsequent IP. The relationships nurtured with these giants aided in the joint development of the technology whilst it both demonstrated the viability and value of its technology at its facility in Cambridge and trained its partners' staff to bypass the technical issues encountered in incorporating the technology into commercial products. The very selective licensing programme gave it access to continuous resources and complementary assets beyond its means, effectively cementing CDT's position in the OLED value chain. Accordingly, CDT and its partners grew together in the knowledge of the technology, troubleshooting and overcoming issues associated with adoption of a potentially disruptive technology - this accelerated the learning curve. It helped that the fundamental patents were "*virtually impossible*" to design around so that it was more expedient for CDT's partners to collaborate with it rather than enforce overlapping/blocking patents (Maine and Garnsey, 2006 at p390). The extension of this monopoly was IP either solely owned by CDT or co-applied for with its partners, further tying it into longstanding relationships that continue to finance CDT's R&D and keep it in a central position in the POLED ecosystem. Even though mass production of POLED commercial products is still a short way off, it is much closer than it would have been had it not been for this business approach.

### 6.3.2 Competition

As a new technology, OLED has to deal with its own teething problems, the main ones being colour lifetime and efficiency; suitable materials to attain and maintain sufficient performance to support the consumer market; optimisation of processing techniques and establishment of a manufacturing infrastructure at a sufficiently low enough cost for display companies to volume produce OLED products and sell them at consumer friendly prices to take advantage of the precursor market the technology has already gained. The details of these challenges were discussed in sections 6.2.1, 6.2.2 and 6.3.1. Those however are not the only growing pains. CDT also has not only to contend with other researchers in POLEDs but with SMOLED researchers, as well as other incumbent technologies such as LCD and plasma displays; and alternative technologies to OLED such as FEDs and SEDs. A reminder of CDT's position in materials line up is shown in figure 6.1. CDT also has to be wary of its conduct in the market place with respect to its competitors, lest it offend competition law and patent misuse provisions. These were already explained in section 6.3.1, and in particular include: Article 101 that prohibits certain restrictive agreements; Article 102 that prohibits the abuse of a dominant position; and the European Commission's Block Exemption Regulation that prohibits organisations from certain business activities, such as particular agreements, in order to create competition (TFEU, 2007).

We have seen from the previous sections that because of ownership of the fundamental IP in fluorescent POLED technology, CDT has established a foothold in that area that is second to none. Its acquisition of Opsys enhanced its ability to make significant steps in POLED development by giving it the resources and IP to expand into the phosphorescent POLED sector. Today, it continues to develop both types of POLEDs successfully with its partners. Most of the major players in the display industry who are bigger and better resourced than CDT, and hence CDT's competitors, actually work with it as licensees, joint development partners or service customers (CDT Annual Report, 2006 at p14 & 20). Through certain clauses in the agreements that govern these relationships, CDT has auditing arrangements and access to accounting details of its licensees/'competitors' - this transparency enables it to monitor their financial and R&D activities so that it is able to anticipate their next move. Even if its fundamental patents expired in 2010, 2011 and 2015, its monopoly is extended through the IP that resulted from those patents as well as several patents co-owned by itself and its commercial partners. In any event, the process and engineering know-how they will have accumulated over the years makes it more expedient for their 'competitors' to collaborate rather than compete. For now, that model works well.

Up to 2005, four companies dominated POLED material development: CDT, Sumitomo, Dow Chemical and Covion (Fyfe, 2009 at p453). As we already saw in section 6.3.1, all the other three were CDT's licensees. Sumitomo bought Dow Chemical's POLED business in late 2005 and CDT in 2007; Covion was bought by Merck in 2005 - leaving two major players in the POLED materials business. Merck continues to compete with Sumation in the supply of POLED materials. Furthermore, DuPont has also been extensively researching phosphorescent POLED materials for the past fifteen years and they currently have impressive lifetimes (DuPont; Mertens, 2016 at p140). It has collaborations with the new generation inkjet equipment maker, Kateeva, and with Dai Nippon Screen (with whom it developed nozzle printing), and licences with some big name display manufacturers including Samsung (Mertens, 2016 at p140). It also in late 2015 opened an OLED materials manufacturing facility (DuPont). Notably, DuPont also has a foot in SMOLED research.

CDT stated that as it has the POLED IP end covered, its major competitors are those who commercialise SMOLED technology (CDT Annual Report, 2006 at p14). CDT's extensive licensing programme and acquisition of several SMEs in the POLED industry has over the years strengthened its position in competing against SMOLEDs. For the longest time, Kodak was CDT's main competitor. In contrast to CDT's purely IP and technology transfer business strategy, Kodak's was based on both licensing and manufacturing, initially jointly with Sanyo - so its licensees were also its manufacturing competitors (Shim, 2002). Being the pioneers of SMOLED technology, Kodak had an impressive SMOLED IP portfolio and products such as digital cameras on the market (CDT Annual Report, 2006 at p14). Kodak sold its OLED assets to LG in 2009 (OLED-info).

Like Kodak, UDC also had a foothold in both displays and lighting phosphorescent SMOLED. It holds one of the largest SMOLED IP portfolios resultant from: (1) collaborations with academic institutions like Princeton University, the University of Michigan and the University of South Carolina; (2) licences to industry giants like Sony, Panasonic, Samsung, Nokia, LG, Pioneer, Philips, Konica Minolta, DuPont etc. who have incorporated the technology into mobile phones, MP3 players, cameras, TVs and other displays on the market; and (3) acquired SMOLED patents from the likes of Motorola and Fuji Film (UDC Annual Report, 2013). In 2009, UDC claimed that "substantially all of the active phosphorescent OLEDs" that were on the market used its technology, based on the fact that it possesses almost all of the fundamental phosphorescent OLED patents with expiry dates ranging from 2017-2020 (UDC Annual Report, 2013 at p17). Chansin et al. (2016) reports that it is currently the sole supplier of such materials for commercial applications (at p239).

Development-wise, POLED technology was a few years behind SMOLEDs but the latter had created the necessary precursor market for OLED technology in general, so that when POLED was offered as an alternative to the technical shortfalls of SMOLED technology, it was easily welcomed by the industry. CDT's Senior Vice-President, Keith Bergelt in 2002 when he was asked whether it was detrimental for SMOLED technology to have arrived on the market before

POLEDs: "*In a way it was good that Kodak got to market first as it created an interest in the [OLED] field that would not otherwise be there*" (Seldon et al., 2005 at p7).

On the consumer front, SMOLED has gained a pretty consistent stage, albeit in small screen displays. Commercially, the technology started to emerge as early as 1996 in Pioneer's car audio system display, mobile phones by Sanyo and cameras by Kodak in 2003 and MP3 players by Sony in 2005 (see section 6.4.1 and Mertens, 2016 at p191-196 and OLED-info, 2016 for a detailed list of devices). Most recently, and more impressive for this technologically savvy generation, Samsung started selling flexible AMOLED displays in the form of a curved smartphone (Samsung Galaxy Round in 2013), a bendable smartphone (Galaxy Edge), bendable wearable technologies in the form of smartwatches (Gear Fit and Galaxy Gear S both in 2014) and several tablets (Samsung Galaxy Note Edge and the Galaxy Tab S in 2014, and the Galaxy TabPro S in 2016 - the biggest OLED tablet by far with a 12 inch display) (Lee, 2014; Mertens, 2016; Chansin et al., 2016 at p106). Noteworthy, these are all made using vacuum processes and are on glass substrates. They also showcased the world's first transparent and mirrored displays at the Retail Asia Expo in June 2015 (see figure 6.8) in combination with their Intel® Real Sense™ technology, a virtual fitting room application intended to revolutionalise the retail shopping experience by enabling customers to "see" themselves virtually wearing retail articles they intend to purchase (Lucas, 2015). There are also 14-inch notebooks with similar displays. Notably, Samsung announced an investment of $3.6 billion in its OLED production between 2015 and 2017 for small - medium sized displays for devices such as smartphones and tablets (Chansin et al., 2016 at p36).


***Figure 6.8: Samsung's 55 inch transparent and mirrored OLED displays (Source: Samsung)***

POLEDs displays first appeared in consumer products in 2002 in the form of a display for a shaver produced by Philips. By 2005, CDT had printed its first OLED display at 14-inches using inkjet printing, and in 2006, jointly with Toppan Printing, the world's first roll-to-roll display. By 2007, Sony had started selling the world's first POLED TVs at 11 inches in Japan - selling 1,300 in one day! (also see section 6.4.1 for earlier prototypes and a more detailed history in OLED-info, 2016). Panasonic in collaboration with Sony unveiled an all-printed 56-inch OLED TV in 2013 intended for mass production but this venture ceased when Panasonic bowed out of the OLED TV race at the end of 2013 (Chansin et al., 2016 at p56).

SMOLED development is still advancing: most recent efforts have been in making the molecules solution-processable. Merck, UDC and DuPont are all involved in this; performance wise, their soluble SMOLEDs still have a way to go but the advances are coming in fast and steady (Mertens, 2016 at p23). This research shows there is potential for SMOLED displays to be applicable to large screen displays but the maturation is still a way off. They are also making strides in their evaporable material lifetimes; DuPont's evaporable green material has an impressive lifetime of a million hours (DuPont).

Having two competing OLED technologies on the market - which essentially deliver the same results to the consumer - only creates a bigger profile for the technology (Fyfe, 2002). It is left to the manufacturers to decide which one dominates but Fyfe (2009 at p455) speaking on behalf of Sumitomo/CDT believed printed POLEDs would come out on top. Reason being that POLEDs have fewer layers and can easily be printed because they are in solution (see figure 6.9 below); this equates to higher yields, cheaper manufacturing, ability to print on flexible substrates and increase in the possible applications pool - all advantages the manufacturers would covet (CDT Annual Report, 2006 at p7). Moreover, manufacturers dabbling in POLED product development are already well established in other display technologies such as LCD, whose manufacturing infrastructure can be borrowed and adopted to POLED. And further, the stronghold that SMOLED currently holds in small displays can easily be toppled as POLED large substrate sheets can easily be cut into small displays, further reducing the cost of manufacture (CDT Annual Report, 2006 at p10).

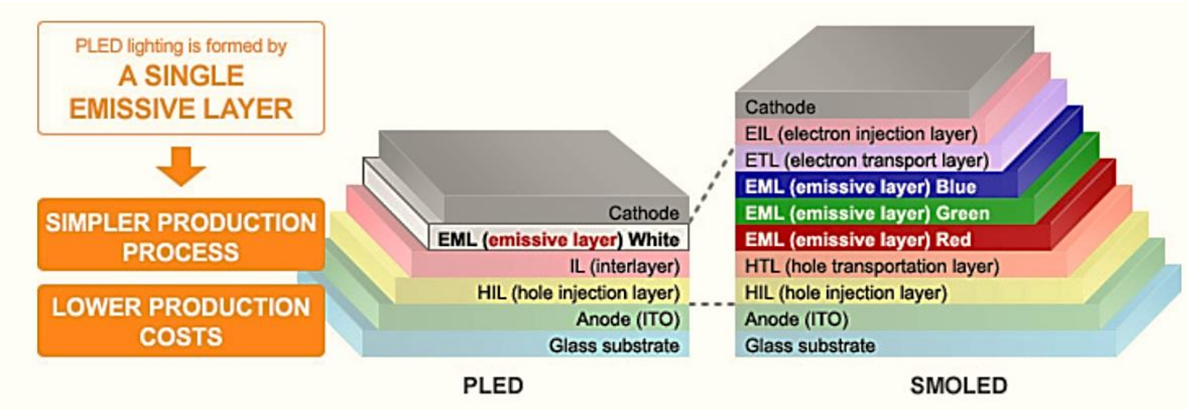



***Figure 6.9: A schematic representation of the structures of POLEDs and SMOLEDs. (Source: Sumitomo)***

It is also clear that there is competition from extant technologies, particularly flat panel displays (FPDs) such as LCDs and plasma display, whose main advantage over POLEDs at the moment is price; otherwise POLED technology is technically far more superior. Table 6.3 outlines the numerous technical advantages OLEDs have over the FPD, as well as other extant and emerging technologies. POLED technology is still relatively new in comparison to the FPDs technologies - the manufacturing infrastructure is still under construction and material lifetime issues as well as other teething problems expected of a new technology are taking a huge chunk of R&D resources. As a result, the prices of the consumer products with large displays are really high and are made in small volumes; those with small-medium displays such as mobile phones, cameras or MP3 players are in line with other products on the market (OLED Association).

| Display Technology | Need for backlight and its power | Power consumption | Thickness | Weight | Sustainability (lifetime) | Readability in daylight | Brightness | Response time | Flexibility of format/ screen size |
|---|---|---|---|---|---|---|---|---|---|
| LCD | Yes | + | + | + | + | + | + | + | + |
| OLED | No | ++ | ++ | ++ | - | ++ | 0 | ++ | ++ |
| E-paper | No | ++ | ++ | ++ | 0 | ++ | - | - | ++ |
| Plasma | No | - | 0 | 0 | ++ | - | 0 | ++ | ++ |
| LED | No | + | 0 | 0 | 0 | 0 | + | - | - |
| CRT | No | - | - | - | 0 | - | 0 | 0 | - |
| SED/FED | No | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

*++ better performance than LCD ; 0 same as LCD; - poorer than LCD; + LCD performance level for comparison*

***Table 6.3: A comparison of the performance of extant and emerging display technologies in comparison to the display market leader, LCD. (Source: Forge and Blackman, 2009 in Table 1-2 at p21)***

In contrast, FPD technologies were discovered in the 1950s so their value chain and manufacturing capability are far more streamlined. The commercial products are popular and affordable, and the global recession has done much in driving the prices even lower (Forge and Blackman, 2009 at p11). IDTechEx notes that fierce competition amongst the top five LCD players (in order: Samsung, LG Display, Innolux, AUO and Sharp) as well emerging giants from China, such as BOE and China Star, is further driving LCD product prices down (Das and Harrop, 2016 at p78). The multi-billion-dollar industry continues to invest heavily in LCD technology so this is setting the bar even higher for OLEDs.

Plasma displays offer better picture quality than LCD but are much more expensive to produce as they require the use of the inert gases, neon and xenon; they are also heavier and consume more power than LCD (Forge and Blackman, 2009 at p18). They have been overtaken in popularity by LCD, especially since most of the major players including Panasonic have been exiting the plasma market since 2014. CRT dominated the display market from around the 1930s until 2007 when LCD took over; today it is mostly present in the professional field as it is considered as the standard reference for displays.

POLED technology is eco-friendly; this particularly makes it a good display contender for large size displays. The lower power consumption - given that

OLEDs do not require a backlight - is a big plus in this increasingly 'green' and portable device generation. POLED also has a much wider range of applications because of its extreme thinness, lightness and ability to be manufactured on flexible substrates. The products have the potential to be adopted very easily and quickly by the consumer, not just in mobile phones and TVs but in the 'out-of-the-box' applications the technology supports: such as wall-sized wallpaper, wall-mountable TVs that can become invisible when not in use, curved displays, mirrored displays, transparent displays on windshields etc. (Forge and Blackman, 2009 at p91-92; Mertens, 2016; Lucas, 2015; Kunic and Sego, 2012).

Moreover, POLEDs have fewer layers and are thus easier than FPDs to manufacture (see figure 6.15). Accordingly, they require fewer materials, fewer manufacturing operations (even in a continuous method at low temperatures) and the solubilisation makes it even cheaper to manufacture via relatively cheap solution-processing methods such as ink jet printing. LCDs on the other hand have to be batch processed in high temperature clean-rooms (Forge and Blackman, 2009 at p10).

Usefully, the OLED value chain can very easily borrow from already established LCD and plasma manufacturing infrastructure, decreasing the technology's maturation time and learning curve (CDT Annual Report, 2006 at p10). The major display players putting FPDs on the market are already major OLED licensees who only have to make adjustments to their current products to incorporate OLED technology. Several have already started volume production of OLED based products - LG being the only one with the capacity to mass produce OLED TVs - and have established reputations and brands on the consumer market (see Table 6.4). As has already been pointed out, industry insiders and analysts assert that POLED prices will drop to even lower than that of FPDs once the manufacturing issues are streamlined.

| AMOLED panel manufacturer | Fab name | Glass size (Generation) | Volume sheets/month | Production Date | Backplane Technology | Location |
|---|---|---|---|---|---|---|
| Samsung | A2 | 5.5 | 140,000 | Online | LTPS | Korea |
| Samsung | A3 | 6 | Up to 50,000 | Online | LTPS | Korea |
| LG Display | E2 | 4.5 | 14,000 | Online | LTPS | Korea |
| LG Display | Paju M2 | 8 | Up to 34,000 | Online | Oxide IGZO | Korea |
| LG Display | Gumi E5 | 6 | 7,500 | 2017 | LTPS | Korea |
| LG Display | Paju P10 | 9 | | 2018 | ? | Korea |
| AUO | | 4.5 | Up to 15,000 | Online | LTPS | Singapore |
| Sony | | 3.5 | 800 | Online | LTPS | Japan |
| JOLED | | 4.5 | ? | ? | ? | Japan |
| BOE Display | Ordos | 5.5 | Up to 54,000 | ? | LTPS | China |
| BOE Display | Chengdu | 6 | 48,000 | 2017 | LTPS | China |
| BOE Display | Hefei | 8.5 | ? | ? | Oxide IGZO | China |
| EverDisplay (EDO) | | 4.5 | 15,000 | Online | LTPS | China |
| Visionox | | 5.5 | 4,000 | Online | LTPS | China |
| Tianma | | 5.5 | 15,000 | ? | LTPS | China |
| Truly | | 4.5 | Up to 30,000 | ? | LTPS | China |

***Table 6.4: Volume production plans for some of the major players in OLED consumer devices. Samsung is manufacturing small-medium size display sheets for smartphones and tablets. LG is manufacturing large-size display sheets for TVs. Generation refers to the size of the glass substrate; the higher the generation, the bigger the display. (Source: IDTechEx)***

Notably, LCD is a moving target. Investments and developments in LCD are concurrent to the same in OLEDs. One of the most promising at the moment is quantum dot LCD (QD-LCD) already touched on in section 6.2.3. It offers technical advantages better than conventional LCDs and almost as good as OLED, albeit still requiring an inorganic LED backlight. It comes at a cheaper price than OLEDs and is thus considered to be a major threat to OLED technology (IDTechEx). Several LCD manufacturers including Sony, Philips and Samsung have been heavily investing in it since 2013; Samsung is already selling QD-LCD TVs (Chansin et al., 2016 at p110-112). The technology has also appeared in some commercial LCD displays like notebooks, tablets (e.g. Amazon's Kindle tablets) and lightbulbs but mostly in biological imaging systems (Bullis, 2013; Bourzac, 2012; IDTechEx). HD LCD (aka 4k resolution) and flexible LCDs which are being made possible by several of the advances already discussed in section 6.2.3 are also increasing the appeal of LCD technology. Pioneering work in the latter is promising roll-to-roll production and a simpler device layout (see Das and Harrop, 2016 at p100-101).

Moreover, the competition between LCD players is cutting their profits significantly so many are seeking to get established in other technologies including OLED. In fact, Samsung categorically stated in 2013 that AMOLED was driving the growth of their company so they started to aggressively invest in AMOLED technology and even predicted that their AMOLED sales would overtake those of LCD (see Figure 6.10). Notably, given the falling profits of LCD, IDTechEx is sceptical about whether there will even be have enough to invest in OLED technology, but for the intervention of governments and research consortia.

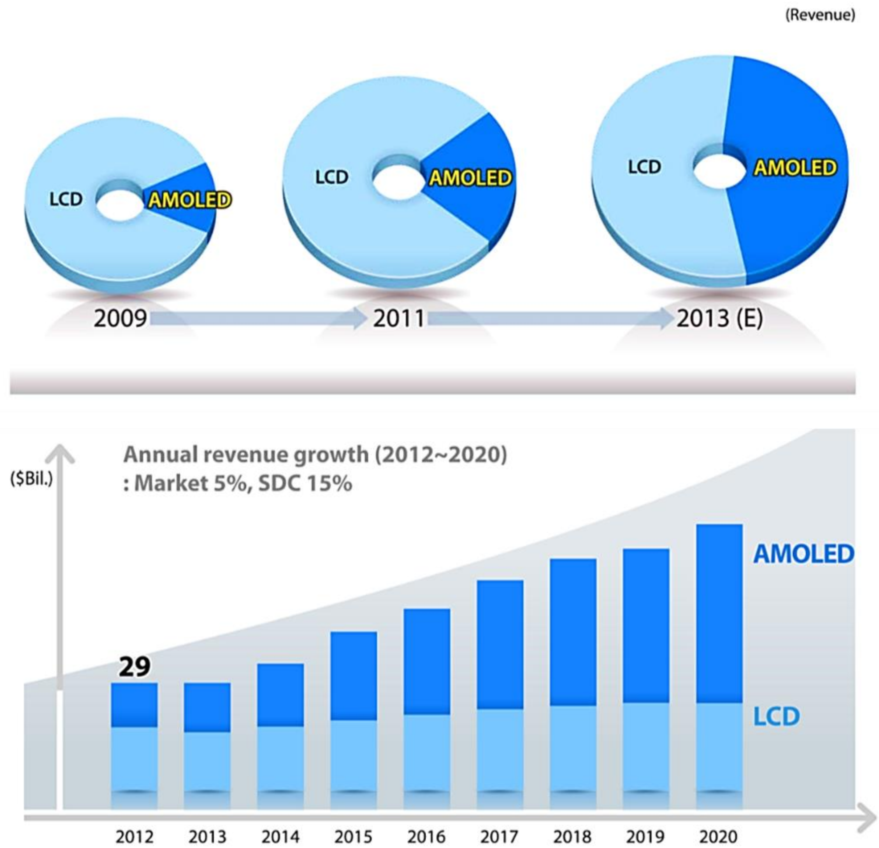



***Figure 6.10: Showing the effect of AMOLED growth on the LCD market share for Samsung and the predicted annual growth for the two technologies from 2012 to 2020 (Source: Kim, 2013)***

A study by the European Commission's Institute for prospective technological studies into the EU's position in emerging technologies recognised that even though LCD dominated the display market, there were two emerging technologies that had the potential to disrupt that equilibrium: OLEDs and electronic paper/E-paper (Forge and Blackman, 2009). For OLEDs, they concurred that this depended on the issues already discussed throughout this chapter and concluded that even though the technology was at the time making an appearance in premium products and small display products, it was more likely to hold a significant market share in larger-sized consumer products around 2015-2020 (Forge and Blackman, 2009 at p12). They also viewed OLED application in lighting as likely to remain only in niche markets such as automotive, emergency and decorative lighting as well as to premium clientele like museums, theatres, or festivals, at least for the short to medium term (also see section 6.4.1 for background and Mertens, 2016 at p78-98). As for use in ICT applications, they concluded that this was limited to providing a backlight for LCDs, in place of currently LED-light LCDs.

The study also submitted that OLED technology would follow three main steps: firstly, limited uptake in niche applications; secondly, consumer and industry education about the technology during which a precursor market is nurtured; and thirdly, volume production of a few applications from 2016 onwards (Forge and Blackman, 2009 at p57). So far, that assertion has panned out. Throughout this chapter, we have discussed several OLED products that have been demonstrated and sold from as far back as 1997, captivating both industry and consumer attention - a more detailed history can be found in Mertens (2016 at p191-196). In 2014, Taiwan's AU Optronics started mass producing small AMOLED displays and is yet to progress to TVs (Chansin et al., 2016 at p48-50). In 2015, both flexible OLEDs and OLED TVs reached mass production and plastic OLED for smartwatches by LG (who also committed in 2015 to invest $8.71 billion in building a large OLED plant) and in 2017, Samsung and China's BOE Display are rumoured to follow suit (Mertens, 2016 at p73-77; Chansin et al., 2016 at p12 & 44). In lighting, the first OLED panels were sold for niche markets by Osram back in 2008 (a lamp at a massive 25,000 euros), and in 2009 by Philips (the Lumiblade). Today several premium lamps, including flexible ones, are sold by LG, Osram, Konica Minolta etc. upwards of $200 (Mertens, 2016 at p78-79). Prospectively, only Konica Minolta has been tipped to reach mass production, albeit not until 2018 (Mertens, 2016 at p79). Notably, all the aforementioned manufacturers use both SMOLED and POLED, with AUO, BOE, Philips, Osram and Konica using CDT/Sumitomo's materials; LG uses Merck's materials and Samsung makes its own.

Several other technologies, established and new, are noteworthy - Tables 6.3 & 6.5 detail some of the most publicised. Some have the ability to offer similar advantages to OLED but with a narrower scope of application, some are only sufficient to take a fraction of the market (in either display or lighting) from OLED technology but most are not mature enough to compete effectively with OLEDs. FEDs (Field Emission Displays) operate similar to CRTs except with multiple nanoscopic electron guns (carbon nanotubes) instead of the conventional single one - they were rumoured to have the potential to revolutionalise the HDTV experience (see Fink et al., 2007 for detail). SEDs (Surface conduction Electron-emitter Displays) are a variation of FED technology. Both technologies offer similar advantages to LCD, with the exception of not requiring a backlight (see Table 6.3). The trail for both however seems to have gone cold since Sony (which was the major player in FEDs) sold the assets to AU Optronics in 2010 when LCD started dominating the display market, and Canon (one of the major IP holders in SED) got embroiled in lengthy patent disputes. The industry now largely considers both technologies dead, mainly because of the production costs (Larsen, 2010). E-paper is more of an application than a technology. It is literally portable, thin, flexible and reusable electronic paper that substitutes printed paper as we know it, and can be powered by several technologies, including OLED (see Forge and Blackman, 2009 for detail).

| TYPE | STATUS | USES/ TRIALS TODAY INCLUDE | COLOURS/ EMIT LIGHT | LIFE | FLEXIBLE | POWER |
|---|---|---|---|---|---|---|
| Cathode ray tube | Established | TV, radar | Excellent/ yes | Good to excellent | No | High |
| Liquid crystal LCD | Established | Cellphone, TV, computer | Excellent/ no | Good to excellent | No | Low |
| Plasma panel | Established | Airport displays | Good/ yes | Good | No | High |
| OLED | Relatively new | Cellphones, cameras, TV | Excellent/ yes | Fair-good | Not yet commercially | Medium becoming low |
| Electrochromic | New | Gift card | Poor/ no | Poor as yet | Yes | Low |
| Thermochromic | Established | Battery testers, smart packaging, games | No | Good | Yes | High |
| Electrophoretic | established | E book, Supermarket adjustable promotions, roll up cellphone display | Poor as yet/no (reflexive) | Excellent | Yes | Low |
| Photonic | New | None | Poor/ no | NA | Yes | Low |
| Electroluminescent | Established | Billboards, posters, signage, backlighting | Poor/ yes | Medium | Yes | High |

***Table 6.5: A comparison of new and established technologies, which are current or potentially future competitors of OLED technology (Source: IDTechEx)***

Inorganic LEDs (ILEDs) are another potential competitor of OLEDs; both offer very similar characteristics except ILEDs have superior lifetimes and efficiencies, and are much cheaper (see Figure 6.11). As such, ILEDs have long been established as an alternative lighting source in some sectors such as outdoor and automotive; they however have several competitors in the general lighting segment (residential, commercial, industrial, decorative etc.) so are currently at premium prices (Das and Harrop, 2016 at p103-108). Efforts are also underway to adapt them to flexible/curved devices.

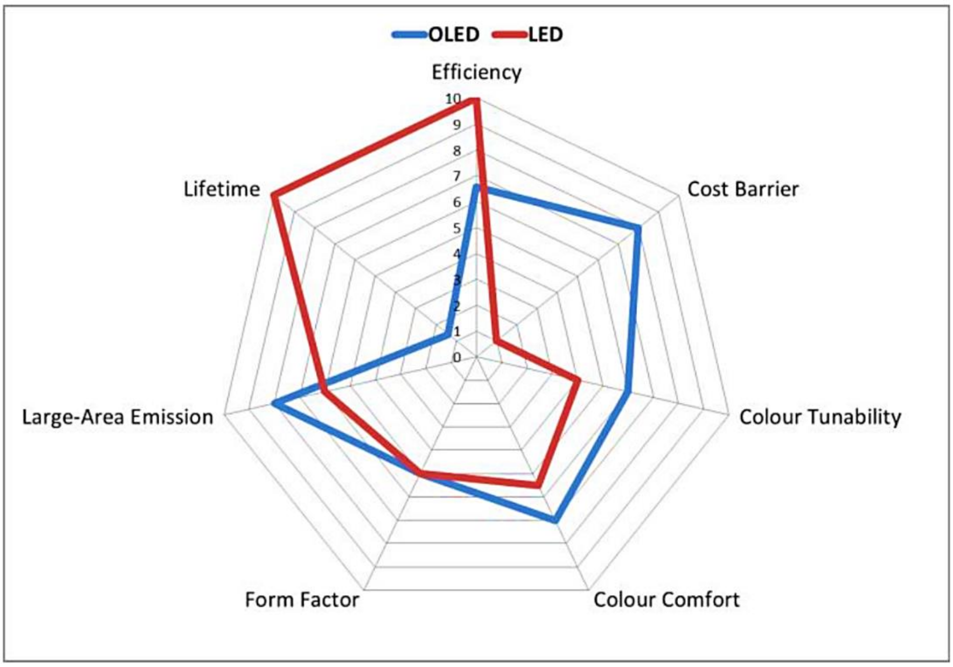



***Figure 6.11: A radar chart comparing the characteristics of OLED to ILED lighting. The attributes are rated on a scale of 1 (minimum) - 10 (maximum) (Source: IDTechEx)***

OLEDs have a broader emission spectrum; the quality of light is closer to natural light so they are envisioned to replace ILEDs once the efficiency and lifetime issues have been dealt with. Besides, ILEDs are better suited for point source applications while OLEDs suit uniform large area lighting panels that support a wider range of applications. At the moment, OLEDs are just about penetrating the lighting market and the commercial products are still on the premium end as the aforementioned issues are driving the cost up. As for displays, ILEDs found their niche as highly reliable backlights for LCDs as this greatly decreased the power consumption and facilitated thinner displays. ILEDs are the reason LCD is dominating the displays market but this is set to change as self-lighting OLED displays eventually replace LCDs (Das and Harrop, 2016 at p104).

The POLED colour lifetimes, power consumption and efficiency have been improved over the years - some characteristics comparable and most, better than LCDs. Inkjet printing (by Seiko Epson) and roll printing (by Toppan Printing) have been demonstrated as a viable manufacturing options and several companies, including Sumitomo have set up a supply chain for the equipment. Exciting prototypes have been demonstrated and consumer curiosity is at its peak. The market is ripe, investment and interest by major display manufacturers continues and the value chain has been established on a global scale. Volume production by some of the industry giants continues to progress, being led by Samsung and LG. The main competing technologies are technically inferior so they can easily be eliminated once POLED manufacturing issues are settled. Moreover, work on several enabling technologies (discussed in section 6.2.3) that are accentuating the efficiency of POLED technology over its competitors is gaining ground. So the question is not if POLED technology will dominate but when it will literally light up the future.

## 6.4 Market

### 6.4.1 Precursor Market

OLED has application in many sectors but for the purposes of this discussion, attention will be drawn to the two main arms of the electronics markets that it is likely to dominate in future: the displays and lighting markets. We will first briefly deal with lighting. Conventional lighting technologies such as incandescent, halogens and fluorescent lamps are being replaced by ILED and OLED technologies, because of the latter's advantages and also largely driven by government initiatives and mandates, namely long life and low energy consumption (MarketsandMarkets, 2015a). Fluorescent lighting being the most popular of the conventional types is being replaced for its basis on poisonous mercury which is an environmental hazard (Runde, 2016). Moreover, OLEDs have several advantages over all extant lighting technologies. They are plastic - lighting panels can thus be made thin, light and easily moulded into a plethora of innovative applications. In contrast, incandescent bulbs and fluorescent tubes use fragile expensive glass, conventional ILEDs lamps are made of brittle silicon or III-V compound semiconductors while compact fluorescent lights are made with glass, ceramic and metal (Keeping, 2013).

OLEDs now have several applications in lighting, complementary to extant lighting technologies (see Figure 6.12). In particular, they emit a lower amount of heat, do not emit any harsh glare or electromagnetic radiation - with the exception of incandescent lamps, OLED lighting is the closest to natural light - so it has become the niche lighting for sensitive objects in museums and phototherapy (Druzik and Michalski, 2011). Their light weight also makes them well suited for weight sensitive applications in cars and aircrafts (Keeping, 2013). Additionally, OLED is the only technology suited for large lighting panels; LEDs and fluorescent bulbs produce point or line lighting (OLED-info, 2015).


***Figure 6.12: A depiction of several applications of OLED lighting (Source: IDTechEx)***

The global OLED lighting market is currently driven by major players such as Philips, Osram, LG Chem, Konica Minolta, Samsung, GE and Panasonic (Young, 2016; Zissis and Bertoldi, 2014). It was predicted, as in figure 6.13, to reach US$82million in 2015 by the marketing and consulting agency, UBI Research (Mertens, 2015). IDTechEx predicts US$150million by 2018 and US$1.9billion by 2025 (Bardsley and Ghaffarzadeh, 2014). Markets and Markets, another premium market research firm, predicts the solid-state lighting (which include LED and OLED) market size to reach $22.2 billion by 2020 (MarketsandMarkets, 2015a).

Not all market researchers predict figures as high as the aforementioned however (Mertens, 2015; Zissis and Bertoldi, 2014; Mukish and Rosina, 2012). Some even doubt it will take off at all. Notwithstanding, OLED technology is expected to rise above other alternatives based on the advantages it offers and the possibility of the currently high prices dropping as capacities expand - the largest available panel on the market at the moment is 320 x320mm by LG Chem, priced at a hefty US$680 per panel (OLED-info, 2015). Moreover, there is the likelihood of producing flexible, transparent and even dual-sided OLED panels and thus more marketable lighting fixtures. Reasonably, OLED technology is poised to secure a sizeable percentage of the future lighting market, at the very least, in combination with ILED technology.

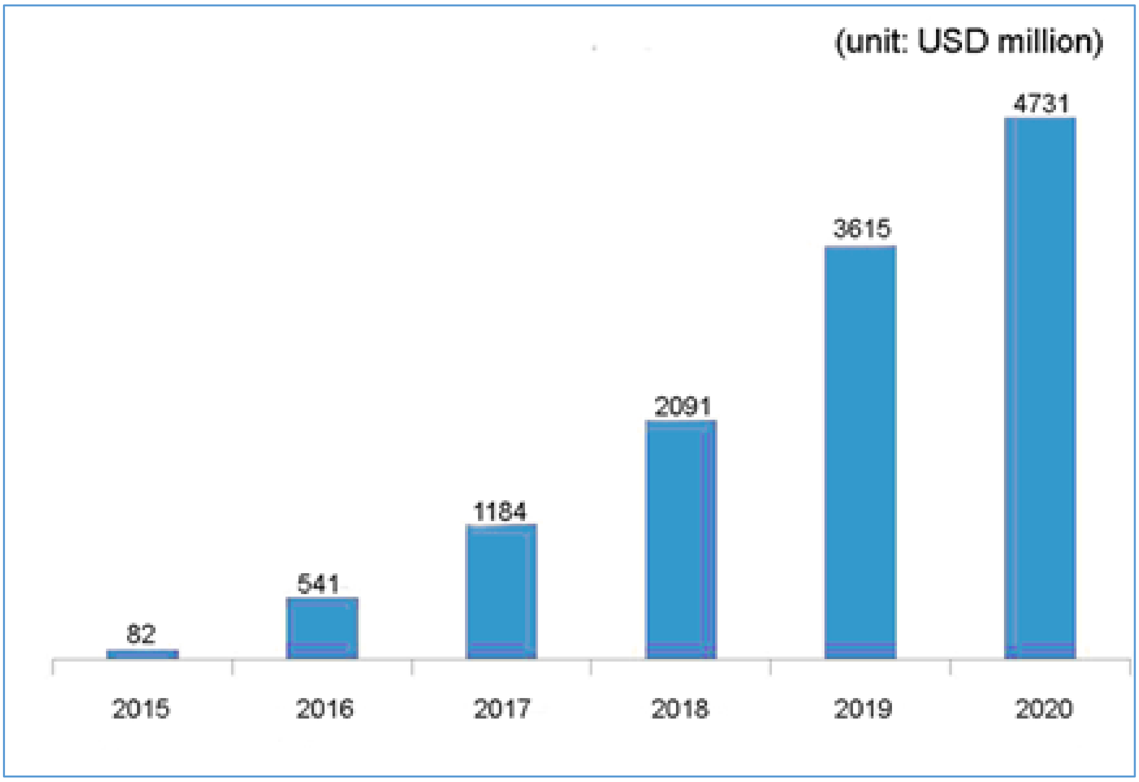



***Figure 6.13: Annual prediction of OLED lighting market for 2015-2020 (Mertens, 2015)***

The modern displays market can be divided into two major groups: (1) mobile displays such as those utilised in mobile phones, e-readers, laptops/notebooks, digital cameras and watches, and (2) desktop displays such as flat panel displays used in televisions. There are several types of display technologies on the market, a detailed look at which can be found in appendix 8. For the purposes of this discussion however, we shall only highlight LCD as marketwise, it is the closest rival to OLED technology, and has dominated the display market for the past three decades (Gelsen, 2003). The premium market research firm, Markets and Markets, reported that LCD displays made up 86.80% of the global display panel market in 2014, which was at the time valued at US$114.16 billion (MarketsandMarkets, 2015b).

In comparison to the other display technologies on the market, LCD technology is currently dominating for its ability to support thinner, lighter and lower power consumption applications that are more popular with the consumer. It exhibits several other advantages over the other technologies (refer to appendix 8), and despite its shortcomings, its economic benefits trump its technical disadvantages. It has over the past few years replaced several display types, such as the popular plasma displays, and even made extinct most other display types. As such, LCD displays are currently mass produced with rapidly falling costs (Salmon, 2012). Paul Semenza, senior vice-president for DisplaySearch reported that the LCD market grew from US$1 billion to 10 billion and to 100 billion from early to late 1990s to 2010 respectively (Semenza, 2012). The market research firm IHS Markit in 2016 placed the large-size LCD panel market alone at US$73 billion, this being a decrease from US$82.6 billion between 2014 and 2015 (IHS Markit).

Despite the huge market success, the technology is set back by its dependence on a backlight unit to create light, which in itself creates a host of challenges. Most LCDs now use ILEDs as a backlight. ILEDs - which are in the form of small chips - make LCD displays extremely slim. Unlike the conventional lamps that were originally used for backlight, ILEDs do not have a filament; this means they do not burn out or get too hot so their lifespan is greater than that of a lamp by thousands of hours. In fact, ILEDs last as long as the transistors discussed in chapter 3. According to Haitz's law, which for ILEDs is similar in concept to Moore's law for semiconductors, the brightness of an ILED doubles roughly every two years due to improved efficiency. This therefore halves the overall cost for the same amount of light. Increased reliability, low cost and lower power consumption, which is a big issue with larger displays, has established a multi-million market for ILED backlit LCDs in the display market. However, they still have a lot of inherent problems; see chapter 3 for details.

OLED display devices are by far the biggest forerunner amongst the available alternatives to LCDs. They are far more superior to LCD and ILED technology. At the moment lower-cost LCD technology competes with premium-priced OLED products: the latter's market is rapidly growing due to its domination of high-end niche applications. As already discussed, improvements to OLED technology will increase production capacities, lower prices and very easily poach the ready-made LCD market (Mertens, 2015; OLED-info, 2015; CDT; Runde, 2016).

Moreover, OLED displays can be used in applications currently served by LCDs. In addition to not requiring a backlight, OLEDs are more-energy efficient, one-thousand times faster, brighter, compact, light weight, have a wider viewing angle and better contrast, and most importantly, have the potential to be manufactured cheaply (Friend, 2010; Kunic and Sego 2012; Seldon et al., 2005, etc.). OLED panels only emit light from the necessary pixels required to form a specific image instead of the entire panel (such as is the case with LCDs) so that their power consumption is 20-80% of that of LCDs (Borchardt, 2004; Runde, 2016). This power consumption further continues to decrease with improvements to OLED materials and fabrication methods. Advantageously, OLEDs have a wider range of applications because they can be deposited on both rigid and flexible substrates; the latter is more difficult to do with LCD without compromising the operation of the device.

The earliest applications of OLED displays were in the smaller devices; mobile telephones, PDAs and MP3 products (Seldon et al., 2005), because SMOLEDs were developed ahead of POLEDs and the former is particularly suited for small displays. As we have seen in chapter 5, with the developments in usable materials, device topographies and deposition methods such as ink-jet printing, especially using POLED, it is now possible to coat larger areas with arrays of POLEDs, making it feasible to devise large area display screens.

SMOLEDs were first discovered at Kodak (see chapter 5), so it is no surprise that they, along with Samsung and Pioneer are leading development in this area. The first SMOLED display reached the market in 1999 - a multi-colour display for a car stereo - introduced by Pioneer (Gelsen, 2003), followed by a digital camera with a **2.2-inch** SMOLED screen by Kodak in 2003 (Seldon et al., 2005). Several products followed in increasing size and by 2010, Mitsubishi Electric had unveiled the world's first prototype **155-inch** large-scale SMOLED display - called Diamond Vision (CEATEC, 2009).

2002 saw the first POLED display on the market - Philips' "James Bond - *Die Another Day"* shaver with a **1.1-inch** multi-colour display to indicate battery charge (Gelsen, 2003). CDT showed **5.5-inch** and **14-inch** displays in 2005 (CDT). In 2007, Sony produced a very thin **11-inch** stylish POLED TV for domestic use that went on sale in Europe in 2009 for £2500, marketed as an organic TV (Kunic, 2012). Samsung showed a **40-inch** POLED TV prototype in 2008 that never made it into production. In 2013, Panasonic showcased a **56-inch** POLED TV panel prototype produced using inkjet printing deposition of Sumitomo/CDTs POLED materials, although it withdrew from the OLED TV display race later that year (Mertens, 2016). Most recently in May 2015, LG unveiled the thinnest TV so far (wallpaper thin), a **55-inch** display that can be peeled off a magnetic wall mount. It is rumoured to be commercially available in 2017 (Rose, 2015). These prototypes are shown in figure 6.14. There are too many prototypes to mention (an exhaustive list can be found in OLED-info, 2016) but for the purposes of this discussion, it is clear that OLED commercialisation has and continues to be full steam ahead.


a) Kodak's 2.2-inch camera with a SMOLED screen (2003)


b) Philip's shaver with a 1.1-inch multi-colour POLED display (2002)


c) Panasonic's 56-inch POLED TV panel prototype (2013)


d) LG's 1.9kg 55-inch wallpaper thin White OLED TV poised on a magnetic wall mount (2015)

***Figure 6.14: OLED displays in commercial products (Photos from: Kodak, Philips, Panasonic, LG)***

Development-wise, SMOLEDs had a 10-year head-start on POLEDs as they were discovered earlier. However, given the difficulties associated with working with SMOLEDs, the bulk of the development in the field over the past decade has majorly centred on POLEDs, so that the latter is only about 2-3 years behind in commercial development (Seldon et al., 2005). By 2002, Kodak - the leading licensor of SMOLEDs - had only sold nine licences in its SMOLED technology with only major display manufacturers (Sanyo), whereas CDT had sold several licences for POLEDs including some to industry giants such as Philips, Seiko Epson, Osram, Dow Chemicals and Covion (University of Oxford, 2002; Seldon et al., 2005). Other giants like Toshiba state that they opted to take licences for POLEDs over SMOLEDs because of the latter's limitations (Seldon et al., 2005).

OLED technology has particularly been well received by the consumer because of its extreme thinness, lightness and lower power consumption. Moreover, given the solution-processability of POLEDs, it shares many common and well-established manufacturing steps with extant technologies such as LCDs; this provides potential for easier and cheaper manufacture of POLED display devices. At the moment, large display applications are expensive because the OLED manufacturing infrastructure is yet to transition - OLED makers are currently using the same factories to make large displays as those they used to fabricate small displays (Runde, 2016). This inevitably increases their plant costs. LCD factories are purpose built for large displays. It is envisioned, as with any technology, that as the infrastructure develops, manufacturing costs will plummet, directly reflecting on the price of the applications on the market. Moreover, this will be supported by the simpler structure of OLEDs as compared to LCDs, as shown in figure 6.15. One could even speculate that in future, the already established LCD manufacturing infrastructure could serve OLED device production as the former comes to the end of its road.

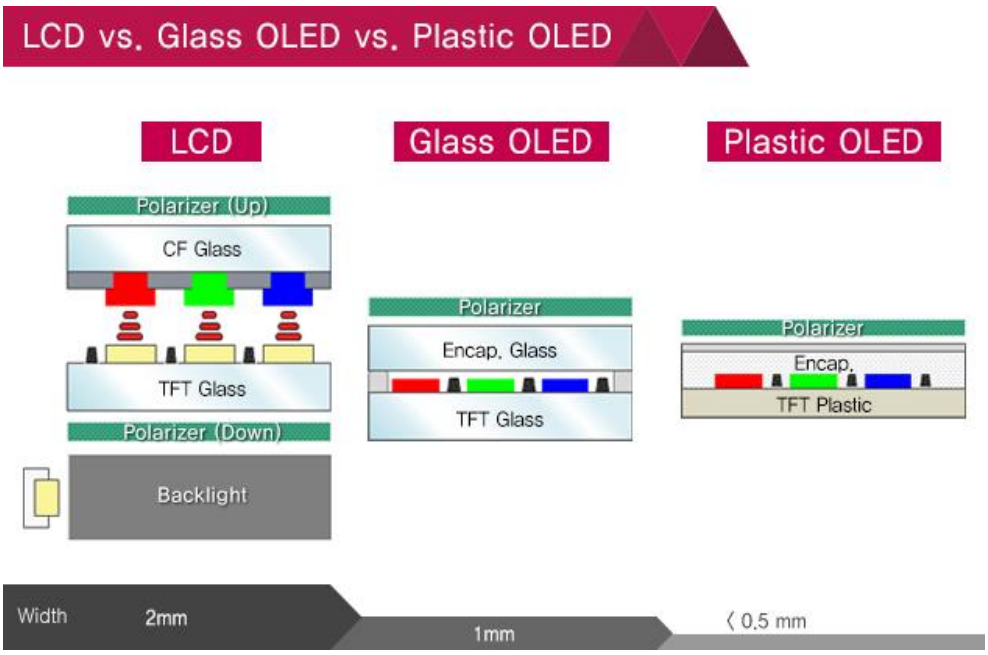



***Figure 6.15: A schematic diagram highlighting the differences in the complexity of the structure of an LCD versus that of an OLED (glass and plastic) (Source: Oledexpert, 2014)***

To make OLEDs even more marketable, there is a possibility of producing them on plastic and flexible substrates rather than on the glass or silicon substrates currently utilised (Chansin, Ghaffarzadeh and Zervos, 2015; Mertens, 2016). As already discussed, plastic substrates are fast becoming feasible, presenting a wider range of applications such as electronic paper (such as a newspaper that could refresh itself to reveal the next day's news), electronic clothing, electronic wallpaper, smart packaging and even foldable mobile phones. Several industry players have showcased prototype applications using plastic substrates. Samsung's "Youm" prototype phone was revealed at the internationally renowned Consumer Electronics Show (CES) in 2013, and said to be available by 2016 (CES, 2013; Jha, 2015; Samsung). In 2013 - 2014, Samsung started selling flexible smartwatches and smartphones including the Galaxy Round smartphone, and LG in 2015 started shipping the G Flex smartphone that is curved from top to bottom (see figure 6.16, Mertens, 2016 at p57-60). Moreover, flexible substrates present the possibility of producing displays on a continuous roll. LG showcased the world's largest flexible/foldable HD screen; an 18 inch display in 2014 (figure 6.16), rumoured to go on the market in 2017 (CES, 2014; Prigg, 2014), and another 18-inch rollable display at the recent 2016 CES (CES, 2016; OLED Association, 2016). Samsung and LG also recently showed impressive flat and curved OLED TVs both at the 2015 and 2016 CES events (CES, 2015; Chansin et al., 2015; OLED Association, 2016).


***Figure 6.16: Figure showing several flexible OLED devices (Source: Samsung, LG)***

Other interesting applications that have been suggested include: electronic supermarket shelf displays programmable to reflect change in price; DVD cases that could provide a preview of the enclosed film to an interested customer; t-shirts with screens and programmable wall-sized displays for airports and malls etc. (Edwards, 2007; EPO, 2006). Edwards (2007) also speculates on the creation of reversible display panels that could provide inexpensive solar panels. CDT and other OLED researchers envision that once this is possible, flexible OLED devices will require fewer processing steps as they will be less complex than current OLED devices, making them cheaper to produce and about one-third less expensive than LCDs (Gelsen, 2003; Borchardt, 2004; Forge and Blackman, 2009; Zissis and Bertoldi, 2014).

Notably, not all researchers are optimistic about the feasibility of flexible displays as the plastic would have to emulate the properties of glass. Several other solutions were discussed in section 6.2.3. Nevertheless, the OLED display market is climbing steadily and is expected to continue to do so. At the moment, it is characterised in eight major segments whose market predictions in the display industry over the next decade are shown in figure 6.17. Segment by segment revenue and shipment forecasts can be found in Chansin et al., 2016 at p132-146. For the immediate future, mobile phone and TV display revenues are projected to reach \$4B and \$3B respectively by 2017 (Colegrove, 2010).

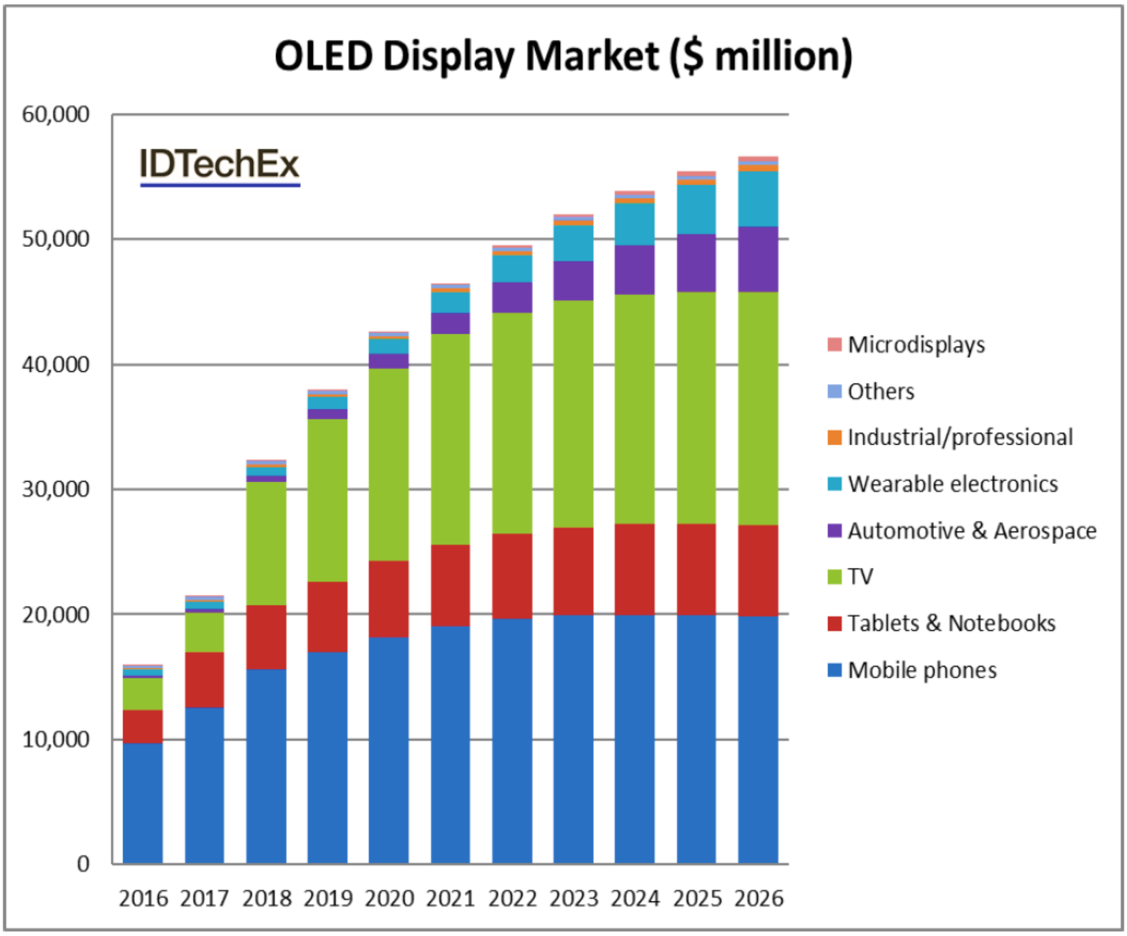



***Figure 6.17: Graph showing the different segments of the OLED display market. (Source: IDTechEx)***

Given the foregoing, it is not surprising that OLEDs (especially POLEDs) are poised to take over the display market. iSuppli/Stanford Resources which provides the leading market intelligence on the global electronic display industry predicted that the global market for OLED displays would increase from \$112 million in 2003 to \$2.3 billion in 2008 (Borchardt, 2004). Another leader in display market research and consulting, DisplaySearch, stated at the OLEDs World Summit in 2010 that the OLED lighting market alone would reach \$1.5 billion by 2015 and \$6.3 billion by 2018, and OLED display revenues would exceed $8 billion in 2017 (Colegrove, 2010). Based on the presumption that the first phone with a flexible display will be available in 2017, IDTechEx analysts predict the latter will rise to $16 billion by 2020 (Chansin et al., 2015).

Further, IDTechEx in analysing current, embryonic and future research into printed, flexible and organic electronics by more than 3000 organisations predicted in 2015 that the total market for those types of electronics will grow from $26 billion in 2016 to $69 billion in 2026, the majority of that being attributable to OLEDs - see figure 6.18 (Das and Harrop, 2016 at p152-154). They predicted a slow beginning that eventually picks up when the technical difficulties are better addressed. The forecasts come with a disclaimer: due to the infancy of many of the technologies, the figures are "*highly speculative*", depend on whether industry players meet their proposed development timelines, and account for the varying speeds of maturity of the different technology sectors. For example, organic displays have already reached the market and are picking up speed whilst OLED lighting still has some ten years to transition from high-end applications to the consumer market. They do however account for unmet deadlines and give, according to them, "*a realistic view of adoption rather than an over optimistic forecast*" (at p31). Other specific assumptions made are detailed on pages 7, 15 and 32.

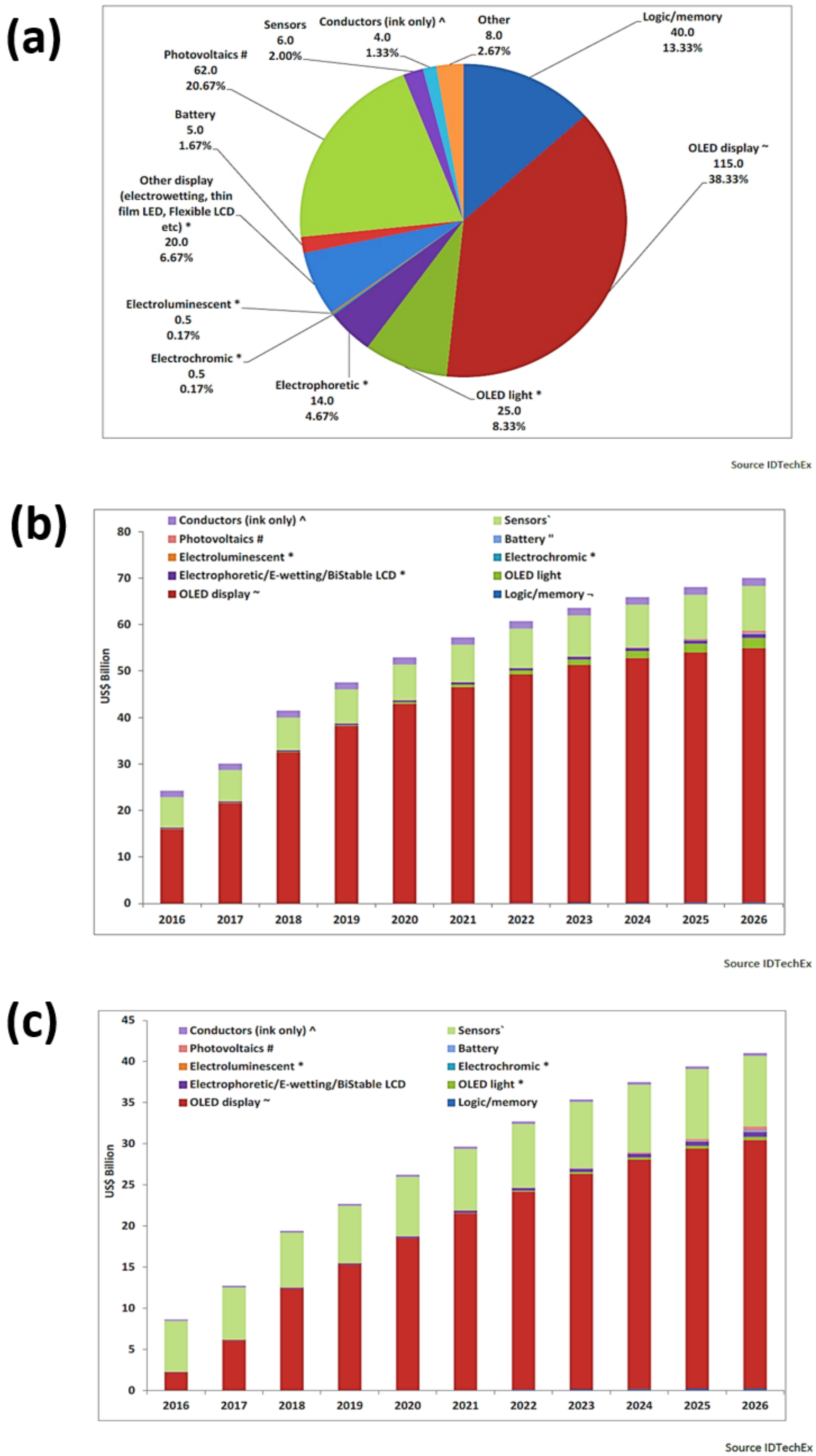



***Figure 6.18: (a) Predicted market for 2026 in US$ billions for different sectors of printed, flexible and organic electronics; (b) Predicted market for 2016 - 2026 in US$ billions for different sectors of printed and potentially printed electronics (organic, inorganic and a combination); and (c) Predicted market for 2016 - 2026 in US$ billions of different sectors of flexible electronics (Source: IDTechEx)***

The available market for OLEDs is improved by the technological thirst for the next best thing of this electronically savvy and information-based generation; the world is becoming more digitised and readily available high-speed internet connectivity is boosting demand for better display technologies. Increasingly, the consumer has an insatiable demand for larger screen sizes in end products such as smartphones, tablets and TVs. Emerging wearable technologies such as smartwatches, smart glasses, Virtual Reality headsets, health & fitness devices etc., in which OLED technology has application, is adding fuel to the fire. The past decade has also seen an increase in consumer preference for more organic and environmentally friendly products; in comparison to other technologies, OLED applications are both low power consumption and are not associated with materials that are harmful to the human body or the environment (Kunic, 2012). In fact, along with two of its collaborators, CDT won the Environmental Award in 2010 for creating energy efficient lighting technology, awarded by the influential magazine, The Engineer, in its annual Technology & Innovation Awards (CDT).

In developing the biological analogy to technology (see chapter 2), Cullis summarises innovation markets to consist of 4 major phases (Cullis, 2004). The "lion" phase is where the first patentee/original innovator solely enjoys the exclusivity of the initial temporary monopoly by virtue of being the first in the field. The length of this phase is determined by whether he quickly establishes a dominant position (through IP rights and the like) and how quickly his competitors respond. With time, other competitors/innovators, like predators design around that idea eventually sharing the market; the "hyena" phase. Next comes the "vulture" phase - when the innovation has passed its peak, the market has decayed and is now characterised by those who pick at leftovers for the occasional profit. The final and rarest is the "phoenix" stage; where a micro innovation in a once decaying technology catapults subsequent innovative efforts, and may even briefly dominate the market. The foregoing points to OLED technology transitioning from the "lion" phase into the "hyena" phase - CDT's fundamental patents expired in 2010, 2011 and 2015, and the remaining portfolio expires between 2017 and 2024. Thanks to CDT's extensive licensing programme and the current demand for OLED technology, more competitors and researchers are getting in on the action.

It can accordingly be concluded that the ripe market is driving OLED research at CDT (POLED) and Kodak (SMOLED); most other academic and industry participants have obtained licences from these pioneers. The technology has developed at an impressive rate over the last decade and in record time, the currently available devices have challenged and are now surpassing the industry's well-established LCD and plasma displays, in both small and large displays. Not unexpectedly, the technology, like many others before it, will continue to require effort and time before a clear niche for it in the market can be established. The key factor is the willingness of current participants to continue investing in ironing out the technology's technical shortcomings and optimising manufacturing processes so as to lower prices of end products.

### 6.4.2 Multi-disciplinary Collaborations: Industry and Academic Players

More often than not, inventions are team efforts. A finished product in such a technology generally involves extensive interactions between material suppliers, manufacturers of components, device physicists and those who manufacture the actual products for consumer consumption. The flagship OLED invention itself was created by a multidisciplinary collaboration; for the first time, a relationship with between Physics (SRF) and Chemistry (Andrew Holmes) at Cambridge University (Friend, 2004-2005), with the chemistry group making incremental modifications to the OLEDs that had been discovered by Physics. Such was the discovery that randomly mixing repeat units in a copolymer chain led to an average of the properties of the units as opposed to an addition which would be obtained if the building blocks were in well-defined positions (see chapter 1, section 1.8 for further explanation). As stated by Andrew Holmes, the application of this principle went on to be the backbone of some of the most important commercial devices (Friend, 2004-2005).

Another very important relationship was between Sir Richard Friend and Jim Feast from the University of Durham. The latter had a reputation for producing "*the world's most interesting polymers in the early 1980s*" (Friend, 2004-2005). Feast devised an easier way to make the polymer polyacetylene; the conventional polymer is crystalline and difficult to solubilise - the downside to this was discussed throughout chapter 5. The Durham route as it came to be known involved making a soluble precursor of the polymer that could be deposited as thin films onto a substrate, and thereafter, heated to form insoluble polyacetylene. At that time, it was brilliant chemistry that enabled the Cambridge group actually to make working transistors.

These collaborations were beneficial for both sides; both obtained the materials they desperately needed to advance their research. The inventors also stated that it was an enjoyable activity that pushed both sides to understand and appreciate each other's work - both educationally and in an *iron sharpeneth iron* kind of way - so that both their boundaries were pushed to higher dimensions of research (Friend, 2004-2005). Their seed efforts undoubtedly led to an increased interest in the technology.

The existence of such partnerships has not changed; as the technology continues to mature to a commercial level, multi-disciplinary collaborations are now on a much grander scale. By the end of 2016, over 200 academic institutions (including Queen Mary University of London) and companies were reported to be involved in the OLED race (OLED-info). Due to the existence of IP rights, most have come to be involved either through licensing agreements and/or through mutual benefit commercial or research collaborations.

CDT now has collaborations with academic researchers and industry heavyweights in all aspects of OLED production. It has accordingly gained a firm position in the OLED value chain that is the journey 'from molecule/polymer to product'. In essence, the chain comprises of: (1) basic R&D IPR licensing; (2) development and synthesis of materials; (3) incorporation of those materials into components and subsequently devices, as well as the associated process and plant development; (4) sale and distribution of the devices; and finally, (5) return and recycling. A simplified illustration of the OLED value chain is adapted from Forge and Blackman (2009), shown in figure 6.19.

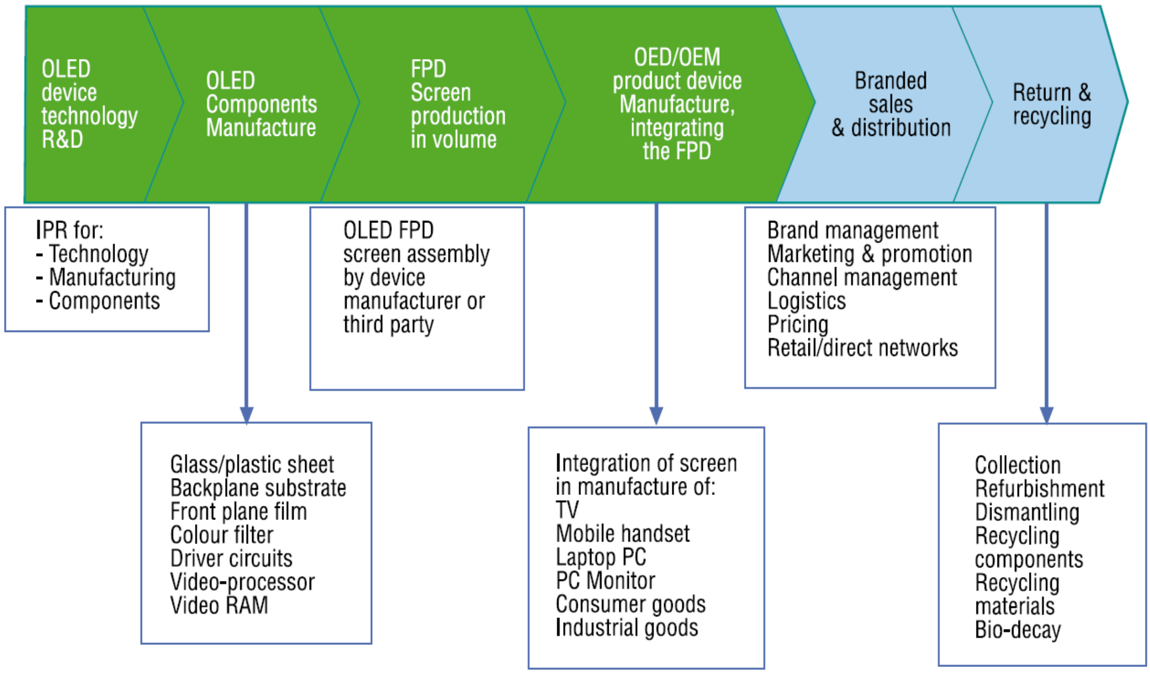



***Figure 6.19: A simplified depiction of the OLED value chain (Source: Forge and Blackman, 2009 at p43)***

These collaborations are necessary for the development of the technology. Oftentimes, material manufacturers are fundamentally chemists and require the expertise of physicists to incorporate these materials into viable components. The latter also require the expertise of engineers with the requisite process, fabrication and manufacturing knowledge to integrate those components into devices for consumer products. Another group is then required to market, distribute and retail the consumer products; given the type of technology, consumer prices and level of detail required by the consumer, it is not usual for this group to intersect with previously mentioned players. None of these stages can thrive independently of the others so there has to be a continuous dialogue amongst all the participants of the chain.

As we have discussed in section 6.2.1 above, materials greatly influence the performance of OLED devices and subsequently their reception by the consumer. Accordingly, their availability, development and synthesis is a major addition of value to the chain (Zissis and Bertoldi, 2014). Forge and Blackman (2009) estimated this at 20% value addition (p44). The same researchers - looking into the disruptive potential of OLED technology for the European display market - conducted interviews of OLED industry participants and rated the marginal value of the different elements of the chain (see Table 3-1, p44). They concluded that players in the earlier stages of the chain, i.e. the owners of the technology and materials IPR - who supply materials (20% value added) and components (40% value added) - had much higher margins than those in the later stages. Devices/products were the main value generators adding an estimated 50-90% value but this was dependent on the state of the materials and components. Thus they asserted that it may be more advantageous to occupy earlier positions in the chain.

The figures were attributed to the latter stages tending to comprise several players among whom competition is fierce, so that a party may be knocked out of the game or deemed expendable (see Table 3.2, p46 of the same paper). In contrast, the former stages comprise only a few and usually indispensable participants who more often than not are the pioneers of the technology. CDT falls in this category; it secured this position by amassing an expansive amount of fundamental IPR in fluorescent POLED materials, methods of their manufacture and their use in electronic devices. They used this IPR as a bargaining chip to set up an extensive licensing program to invite other members of the value chain (see section 6.6.2). This not only gave other players an opportunity to get a seat at the table but gave CDT the top position at the table. Indeed CDT is considered a major player in Europe at the materials and device manufacture stages; its parent company, Sumitomo Chemical is listed as a major a player in Japan in both the early and later stages (see Table 3-2 of Forge and Blackman, 2009 at p46). Its licensees span the value chain.

For an expansive but non-exhaustive list of the players in the OLED community, see Forge and Blackman, 2009; Zissis and Bertoldi, 2014; Reineke, 2015; Das and Harrop, 2016, and for those involved with CDT: Lubik, 2010; Forge et al., 2013 and the discussion in section 6.3.1. Notably, the value chain is global (see figure 6.20). The early stages are mainly dominated by US and European centres such as Kodak and CDT as this is where much of the original research started whilst the intermediate and final stages are dominated by Asian companies, where production and assembly of display devices takes place by players such as Samsung, Philips, LG, Sony, Hitachi, Toshiba etc.


***Figure 6.20: The OLED value chain as of May 2016 (source: IDTechEx)***

And finally, as we have already discussed, the government plays a major role in exposing CDT to several of these partners, specifically through academic-based, national, regional and international research consortia to promote developments in particularly emerging technologies. Notably, CDT is actively involved in the European Photonics Industry Consortium which was founded in 2003 by itself, Aixtron, Osram, Philips and Sagem, to focus on advancing OLED and LED research (EPIC). In addition to other sources of funding, the initiative is heavily funded by the UK and other European countries' governments, and membership covers the entire OLED/LED value chain and currently stands at 180 universities, research organisations and industry partners. This provides a rich resource of learning and collaborative work for CDT. Several other initiatives have been mentioned throughout this chapter.

### 6.4.3 Finances/Economics

CDT was formed in 1992 when it was clear that Cambridge University did not have the funds to license the technology. It initially tried to license the technology to a British electronics company, failing which it attained its first seed funding from Cambridge University's seed fund and from local seed investor Cambridge Research Innovation Limited (CRIL) (Lubik, 2010 at p173). 1996 saw the acquisition of over £3 million of venture seed capital from the aforementioned as well as from prominent individuals in the electronics industry - the Sculley Brothers (of Apple Computers) & Herman Hauser (founder of Acorn Computers) - the Hill Samuel Bank; the Generics Group; and even the rock group Genesis (Lubik, 2010; Forge et al., 2013 at p75). In 1997, it received a further investment of £6.25 million from a group headed by a former UK Secretary of State for Trade and Industry who was CDT's chairman at the time, and later, an unknown sum from Intel (Forge et al., 2013 at p75).

In 1999, CDT was bought and controlled by US private equity firms Kelso & Company and Hillman Capital Corporation, who transferred CDT's parent company to the US. Jointly, they injected a sum of about US$160 million, for a 42% and 22% share in CDT common stock, following the company's initial public offering on the NASDAQ National Market under the symbol 'OLED' at an initial price of $14.00 per share (CDT Inc., 2004; Fyfe and Nicklin, 2004; CDT, 2006). A listing on the NASDAQ exposed the company to a greater pool of funding than was available in the UK and this further placed it visibly amongst major technology companies in the US. It raised a further $216.4 million through selling shares in the company and for a while this was its main source of funding (CDT Annual Report, 2006 at p45). The main investors at the time were Sumitomo Chemical, DuPont and Toppan Printing. CDT was subsequently bought for approximately $285 million in 2007 and is now a wholly owned subsidiary of Sumitomo Chemical, which provides the working capital.

A substantial part of CDT funding is now through its business model; generating revenues through licences, technology development and service provision, and through the sale of their products and equipment. A significant portion of its revenue is provided by the former, concentrated on key licensees (CDT). The revenue is dispensed on R&D, acquiring and maintaining resultant IP, and subsequently licensees, and on the day-to-day running of the business, including costs associated with the facilities, plants, equipment and associated software which it leases or buys in England and abroad. A significant portion, albeit on a one-off basis, is spent on venture capital (CDT). Just like any other business, the money needs to come in at the right time and in the right amounts.

Being highly associated with an academic institution, and in the interest of promoting UK innovations, CDT also received several six-figure UK government and Research Council grants. These included the UK government's innovation agency - the Technology Strategy Board (aka Innovate UK) - and the Engineering and Physical Science Research Council (EPSRC), the main UK agency that funds university-based research. Notably, it was funded by the Department of Trade and Industry in 2002 to develop plastic solar cells based on OLED technology, and in 2007, a sum of £250,000 to develop fluid modelling simulation techniques with ANSYS Europe (Shim, 2002; Lubik, 2010 at p174). They were awarded £1.6 million in 2008 as part of an initiative to provide more environmentally friendly lighting options, for the development of white light POLED. This was part of a UK consortium comprising Sumation, the University of Durham and Thorn Lighting Ltd, a UK based manufacturer and supplier of lighting fittings (Bünnagel et al., 2008). Again in 2008, it was part-funded by Innovate UK with £250,000 to develop POLED based transistors for use in integrated circuits together with Silvaco Data Systems - a leading software developer (CDT). Additional significant funding came from Cambridge University, especially in the early years and when the university was a large CDT shareholder (Maine and Garnsey, 2006 at p384). After CDT was bought by Sumitomo, a Japanese chemical company, it now gets additional funding from the Japanese government (Forge and Blackman, 2009 at p27). CDT's financials from 1992 to 2009 are summarised in figure 6.21 - some years' financial figures were not publicised.

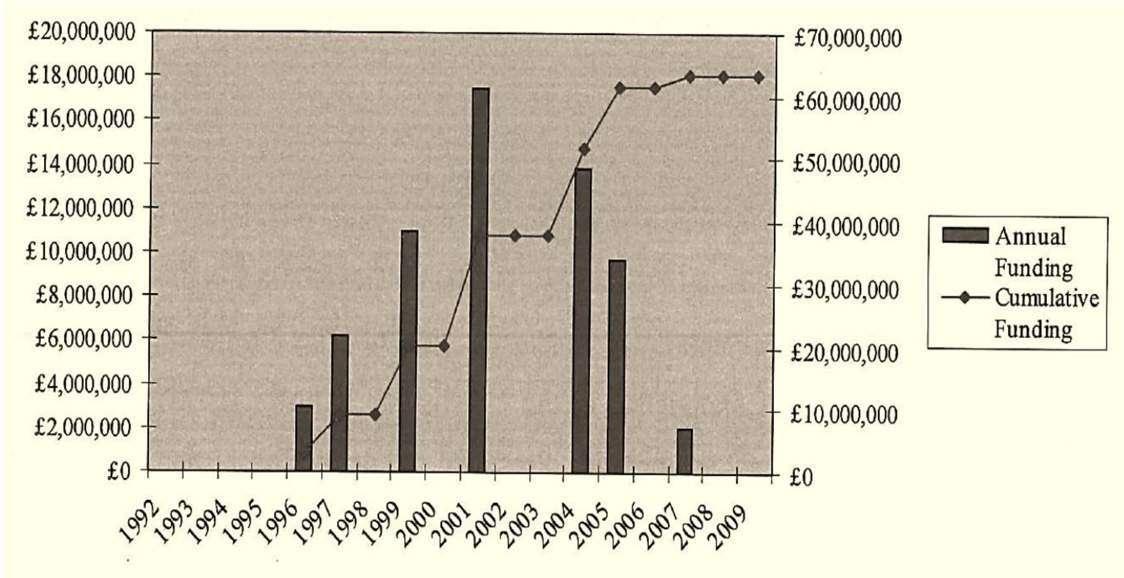



***Figure 6.21: CDT's funding figures from 1992 to 2009 (Source: Lubik, 2010)***

However, in its financial statements of 2004 and 2006 - available because it was at the time listed as an IPO - CDT stated that it had "*generated limited revenues while incurring significant losses*" since its inception in 1992 (CDT Inc., 2004; CDT, 2006). To quote, it made net losses of $5.3 million, $31.7 million and $22.8 million in 2001, 2002, and 2003 respectively (CDT Inc., 2004). Even though it had raised over $250 million in capital, $25 million of which it used to build the R&D centre in Cambridge, this was still not enough to cement the full commercial development of the technology. Development of advanced materials is a longstanding and resource-intensive process during which revenue must flow continuously to support the technology optimisation to market (Forge et al., 2013 at p76; Lubik et al., 2013 at p18). A bigger percentage of this revenue is most likely to come from well-resourced industry players who have to be convinced of a worthwhile return on their investment, especially given that they may have to support the technology development financially over a lengthy period of time (Lubik et al., 2013).

By the end of 2006, it had accumulated a deficit of over $195 million, largely due to its R&D efforts (CDT Annual Report, 2006). It stated that it expected this to be the case until OLED technology had reached a ripe time for commercial exploitation. Further, as advice to its potential stake holders, it categorically stated that that subsequent revenue may never be sufficient to be profitable; that the technology may never be broadly commercially adopted; and that it may have a limited market in the display industry (CDT Inc., 2004). Its reality at the time was explained by Dr Fyfe in an interview in 2006, "*With a business like ours, it's very difficult to see how we are doing quarter to quarter. Revenues are inherently 'lumpy' with a licensing model, especially prior to major commercialisation, and investors need to look at the big picture. Our story is also rather more complex than some other tech stocks…*" (Fyfe, 2006). It also never expected fully to recover its R&D costs from its licensing programme. That was 2006.

CDT's financial statements now are confidential since it was bought by Sumitomo Chemical so the latest figures no longer are available to the public (Burroughes, J. 2015. Email. 10 December). However, according to Endole UK company Insights - credible producers of comprehensive company credit reports - CDT's net worth spiked up from £-36.3 million in 2007 to £19.7 million in 2008. This coincides with the time it was bought by Sumitomo Chemical in 2007. The net worth then remained consistent at the £20 million mark and only started to fall last year (figure 6.22). Figures for late 2015 - 2016 are not yet available from Endole.

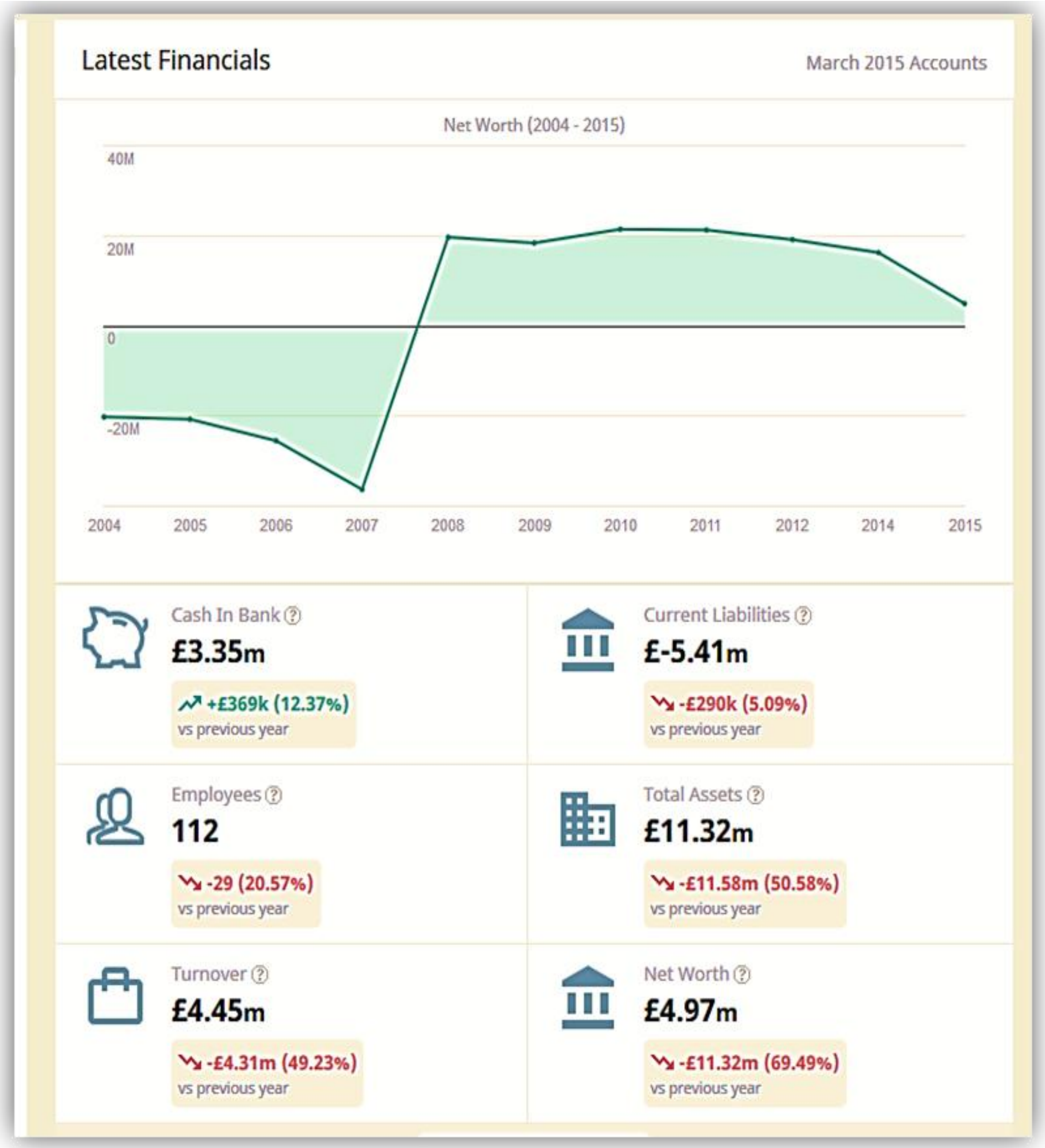



***Figure 6.22: A snapshot of CDT's financial net worth between 2004 and 2015 (Source: Endole, extracted April 2016)***

Further, beside administration, its subsidiary companies CDT Oxford Limited, CDT Holdings Limited and CDT Licensing Limited also pose significant financial implications. For the 2014-2015 tax year, CDT invested £12million into CDT Oxford Limited and it issued shares to CDT Holdings to a tune of £11million (CDT Annual Report, 2015). A detailed look at these companies is outside the scope of this thesis. On a secondary note, CDT and/or its subsidiaries may also be involved in legal proceedings that are not related to technology and this may cost CDT finances in the form of legal costs and remedies, as well as time and effort.

By way of example, CDT, CDT Oxford Limited and Opsys Limited (also a subsidiary of CDT at the time) were sued in 2005 by Sunnyside Development Company LLC (a lessor of commercial properties) for breach of contract and fraud in relation to a property lease agreement between Sunnyside and Opsys, after the US arm of Opsys was forced into involuntary bankruptcy (*Sunnyside Development Corporation, LLC v. Opsys U.S. Corporation et al.* (2010). No. 3:2005cv01447 MHP). Thankfully, all claims against CDT were dismissed as without merit and part of the suit against Opsys US was also unsuccessful - the remaining part of the matter went to trial in 2007. Sunnyside was awarded damages of $4.85 million by a jury but the motion was dismissed for failure on Sunnyside's part to establish that CDT had carried out "substantial activities" that would subject it to the jurisdiction of the Californian court (*Sunnyside Development Corporation, LLC v. Cambridge Display Technology, Inc. et al.* (2008). No. C 08-01780 MHP). Had the outcome been different at first instance, Sunnyside had alleged in excess of $10 million compensatory damages and $25 million punitive damages which it intended to collect from CDT on the premise that it was financially responsible for both its subsidiaries. The author is not aware of any other disputes involving CDT's subsidiaries.

Being a holding company, CDT has also from time to time invested in other companies that would further the development of POLED research. It invested in the UK university spinout, MicroEmissive Displays ($1.1 million in 2004); Add-Vision Inc (£1 million in 2005); the joint venture Sumation ($1.6million in 2005 and $8million in 2006); Next Sierra; and Plastic Logic (another Cambridge University spinout spearheaded by Sir Richard Friend, specialising in OLED enabling technologies) (CDT Annual Report, 2006 at p47). These are the only publicised figures; there may well be further information that is confidential. Moreover, acquired companies come with an inherent administrative burden: in addition to expenses, costs associated with running the businesses, liabilities, and potential disruption to CDT's ongoing business and the difficulties associated with integrating into CDT on both the technology and staff fronts (CDT). Failing a smooth transition, the investment may fail and have adverse effects on CDT's financials. An example was MicroEmissive Displays, which had commenced high volume commercial production of displays incorporating CDT's technology after producing a POLED colour display that held the Guinness World Record for the world's smallest colour TV screen in 2004; unfortunately it went into liquidation shortly after that (EPO, 2006; Lubik, 2010 at p180). On the other hand, it could also prove successful such as was the case with Litrex and Add-Vision.

On the technology side, yes, POLED technology has matured somewhat since 2006 but there are still risks and uncertainties as to whether and when the current drawbacks will be overcome to generate enough revenue to sustain CDT's ongoing activities. OLED technology has already demonstrated theoretical advantages over extant technologies but continuous developments are required to demonstrate its viability satisfactorily to consumer product manufacturers. As explained in the preceding sections, the technology has already been successfully commercialised in small-to-medium sized products; for larger applications - which are undoubtedly more profitable - there is currently a move from "proof of concept" prototypes into volume production, alongside efforts to provide longer material lifetimes required for displays of this size. And with this, there are other factors to consider: timely adoption of the technology by manufacturers; refinement of the processes by which the technology is incorporated into commercial products; development of the manufacturing infrastructure; and sufficient consumer acceptance of POLED products to support a market. As such, manufacturers, are required to invest a significant amount of time, money and effort - in some cases they may have to redesign applications that already use competing technologies to suit incorporation of OLED technology - so they have to be convinced that their investment will pay off. Its licensees, being major industry players, may more likely than not have collaborations with CDT's competitors in extant and alternative emerging technologies and this may further prejudice its ability to secure long-standing funding.

Additionally, the relationship between CDT and its licensees is a complex one. CDT does not manufacture or sell POLED products to end users. It depends on its display manufacturer licensees to incorporate POLED technology into their commercial products while it earns money through royalties. The downside to this business model is that whatever affects the licensees directly affects CDT's income. The licensees may easily be able to control certain aspects of their business, such as: their R&D and how long it takes to put the products on the market; capital; optimising their production costs; offering attractive consumer products at competitive prices; customer care and after-sale service; and meeting consumer demand for the products. Other aspects of their business however are out of their control, namely: the growing capacity of the FPD industry which introduces more competitors and subsequently, additional pressure on competitive pricing and profit; the global economic condition (recovering credit crunch); and the seasonal nature of the type of end products they manufacture (CDT Annual Report, 2006). Accordingly, disruptions in the supply chain, increase in manufacturing costs or any other reason that may affect the licensees' ability to incorporate POLED technology into commercial products, or cause them to terminate, renegotiate or scale back on taking licences to reflect their reality, or at worst case, exit the display market altogether, in turn affects CDT's ability to benefit financially from its technology.

Furthermore, its willingness to continue to license CDT technology, particularly in view of volume production of POLED products, is affected by an assurance of availability of not just the POLED materials but the components and suitable manufacturing equipment. According to CDT, the equipment for several of the process steps is currently readily available; it can be borrowed, at least for small-medium sized displays, from already established technologies such as LCD and plasma with which several of its licensees - LG, Samsung, Toshiba and Philips - already work. Even though the processes and equipment to make large-sized displays has for the past decade been under development, optimisation is still required.

Inkjet printing, which has emerged as the leading deposition method, has as we have already discussed, made sufficient strides to enable some manufacturers to make and successfully sell large-sized displays, albeit at premium prices. LG, the current leader in producing OLED TVs sells 55-65 inch models between $2000-7000, with the 55-inch discounted from the staggering $14,999 price at which it debuted (Archer, 2015). The curved 55-inch it sells was also reduced from $15,000 to $6000 and it planned to start selling a cheaper model at $3,500 in 2016 (Chansin et al., 2016 at p109). Moreover, the inherent versatility of IJP equipment, in that it applies to and provides advantages for many diverse industries - from the electronics and display industry to textile, ceramics, glass, building etc. - make IJP equipment expensive. According to analysts Smithers Pira, the worldwide authority on the print industry, the IJP market was sized at $51.7 billion in 2014 at an annual growth rate of 12.7%, and sales in 2012 of IJP equipment ranged from $350,000 to $1.5 million (Smithers Pira, 2016). IJP equipment, as well as other integral components of POLEDs are also available from a select number of suppliers, further affecting the prices at which they are sold (Smithers Pira, 2016; CDT Annual Report, 2006). This has also contributed to the high manufacturing costs. Other alternative deposition methods that are likely to rival IJP are at the moment only available from a select number of pioneers (see section 6.2.2 and 6.2.3). This is reminiscent of planar transistors and photolithography equipment used for inorganic semiconductors (Cullis, 2007).

Licence agreements are also somewhat fragile: it takes a considerable amount of time and effort to attract and keep licensees - this is not without its associated financial implications. Licences are not easy to negotiate; they are subject to time limits; and once in place, and dependent on the contractual terms, may be terminated without further payment if the licensee no longer sees benefit in the technology (CDT). So the trick lies in retaining the "key" licensees and gaining new ones.

Moreover, CDT's licensees more often than not have commercial agreements with companies that deal in POLED competing technologies, for example, LG - which is CDT's licensee - bought all assets of Kodak's SMOLED business in 2009, before Kodak filed for bankruptcy in 2011 (Mertens, 2016). For economic reasons, it may choose to focus on these technologies, especially if CDT's technology takes longer than expected to mature. One of the biggest challenges perhaps is the reality that in order to incorporate CDT's technology into their extant commercial products, licensees may have to adjust their products - the costs associated with doing this may deter them altogether (CDT, 2006).

As already explained in section 6.6.1, CDT and/or its licensees may be drawn either into patent infringement proceedings if the use of CDT's patented technology infringes another party's patents or other legal proceedings such as licensor/licensee disputes. An example was already given wherein CDT and its licensee DuPont went to court over a dispute as to the timings of payment of royalty fees. In 2002, CDT was also sued by its licensee, Luxell, for a breach of contract with regard to the incorporation of Luxell's 'Black Layer' technology (see section 6.6.2) into CDT's POLED technology (CDT Inc., 2004). According to CDT, the agreement had been made on the basis that Luxell's technology was compatible with its own; CDT had paid Luxell an initial sum of $1 million for use of IP related to the technology, and proceeded to work on blending Luxell's technology into its own, with a view to later sub-licensing the outcome to their commercial partners. When CDT ran into technical difficulties, it proposed to suspend the licence agreement and instead continue via a joint development venture until the technological issues had been resolved. Luxell was less than impressed, terminated the licence and sued CDT seeking damages in excess of $25 million. According to CDT, the dispute was later resolved, both agreed to terminate the licence in favour of a renewed collaboration and CDT had to write-off the initial $1 million investment (CDT Inc., 2004 at p33). Interestingly, Luxell had undertaken a similar project with Pioneer relating to SMOLEDs and similar compatibility issues had arisen; the parties decided to pursue joint research instead.

Additionally, the fast turnover of innovation in the technology industry makes timing a significant issue (see section 6.6). The technology has to ripen during its optimum season so that it does not lose its seat at the table; the longer it takes to iron out the drawbacks, the more the R&D expenditure. The time at which this happens will also subsequently affect the profits that can be realised from its commercialisation. The financial crisis of 2008 would have no doubt had a knock-on effect on how much was invested in OLED development, and technology in general. The global financial outlook is however improving, and governments are increasingly investing in environmentally-friendly technologies. In 2010, CDT was awarded an environmental award - a Technology & Innovation Award - for its Topless project (Thin Organic Polymeric Light Emitting Semiconductor Surfaces) in which it collaborates with Durham University and Thorn Lighting to create energy efficient lighting technology as a replacement for incandescent bulbs (CDT). The £3.3m project was 50% funded by Innovate UK. In 2003, CDT was also awarded the annual European Union Descartes Prize - which recognises '*outstanding scientific and technological achievements resulting from European collaborative research*' - worth a sum of

700,000 Euro to coordinate a pan-European research project surrounding POLED application in display screens with researchers from Belgium, Germany, the Netherlands and Sweden (European Commission: Community Research, 2006 at p20-21). For the interest of the reader, several other Awards can be found on the CDT, Innovate UK, EPSRC and European Commission websites.

Like any other company, CDT's financials are also subject to employee remuneration, company insurance, taxes, interest rates and foreign currency conversion rates. The author is not privy to detailed financial figures as these are confidential but with the publicly available information is able to conclude that for a small company, CDT seems to be doing well financially. It is kept afloat by Sumitomo, government grants, its licensees and sales of the products and proprietary material. According to CDT, it is reasonably expected that Sumitomo will continue to provide working capital, and its financial future will be even brighter as industries continue to invest in and adopt its technology.

Commercially, the technology has not been around long enough to draw definite conclusions as to whether or not it will make it. So far, all we have to go on are analyst predictions, most of which are in favour, and the success of currently available POLED devices. Hopefully, this will be enough to keep the technology on the map. Like any emerging technology, CDT has to battle with unpredictable technical setbacks as well as securing the right amount of interest and revenue to support the background R&D. So it is safe to say that the commercial success of the technology lies in the ability, or absence thereof, of CDT and its licensees to resolve the current technical issues with POLED materials lifetime, efficiency and stability. It follows that the rest of the value chain would respond to the outcome of that initial step in the chain.

## 6.5 Government/Military Interventions

In addition to the involvement of the government in funding CDT's activities and connecting it with other research partners as we have already extensively discussed above, the military has also played an interesting role in POLED development.

CDT was tasked in 2001 by the US army to produce a handheld battlefield display device (Fell, 2001). It was reported to have both day and night-time viewing, with the latter only feasible with infrared glasses won by the operating soldier; this was to reduce the risk of that soldier being seen by the enemy. UDC had also in 2008 developed prototype daytime/night-time OLED displays for the US army (UDC Annual Report, 2013 at p11). It is not surprising that OLED technology has application on the battlefield given its ability to produce compact, light weight, low-power consumption devices that have an extended lifetime: such are desirable characteristics for portable and battery-powered devices such as those required in combat. POLEDs displays also offer nanosecond switching speeds and wide viewing angles, all at a temperature range of minus $40^0$C to plus $70^0$C, making them suitable for military applications (Fyfe and Nicklin, 2004). The military is also not averse to higher cost technologies that offer technical advantages in comparison to extant ones; they are more willing to pay the premium prices because frankly, it is a matter of national security.

It is not possible to ascertain whether the aforementioned devices were produced, or indeed others, as the information would understandably be confidential. It is however easy to see the technology's application in this field, especially with future improvements and the feasibility of flexible substrates (which will favour rugged devices). Indeed, CDT envisioned application of its All-Printed OLEDs (AP-OLEDs) - a special type of POLEDs that has a simpler structure and is air-stable and thus much cheaper to produce - in speciality products such as military wearable displays. Current POLEDs are sensitive to moisture and oxygen, and the devices have to be assembled in a vacuum or under controlled environments. In 2010, over 200 of these military devices were produced and were the first and largest collection of printed flexible OLED products (MacKenzie, 2010; Ma, Hack and Brown, 2010). AP-OLED assets were acquired by Sumitomo Chemical from a US company, Add-Vision Inc., and are now managed by CDT through the Sumation venture. Forge and Blackman also mention two OLED military devices that were near maturity as of 2009, one by eMagin and the other, a flexible device developed by UDC (UDC Annual Report, 2013 at p11). It further speculates on wearable displays that could be used by pilots, drivers and divers, and "smart" windows and shades that could change to camouflage on the battlefield.

Interestingly, the development of inorganic semiconductors (discussed in chapter 3) was in the early stages largely driven and funded by military needs and government involvement, especially given the external stimulus of the Cold War of 1947-1991 at the time of its boom, before later succumbing to the usual economic rules of supply and demand where various East Asian companies under government impetus were seen leading the charge (Cullis, 2004 in chapter 15). In contrast and in absence of an external stimulus, organic semiconductor development has been driven by the latter, involving the same players as in the first technology type because both technologies share manufacturing infrastructure. However, with the ongoing instability in the Middle East and the underlying need that promised OLED applications are likely to meet, there is a high probability that the technology's future development is likely to be boosted by military procurement. Without the prerequisite security clearance, I can only speculate privately.

## 6.6 Timing

Inventions are solutions to problems. As discussed in section 2.3 of chapter 2, the time an invention is introduced on the market is important. Innovators will more likely choose the moment the market is most favourable to them so that they can attain maximum profits (Barzel, 1968; Cullis, 2004) and recover innovation rents. Further, these profits will initially be determined by the temporary response-time monopoly afforded to the innovator (such as in Intel Corporation's case), and later affected by competitors' actions and by the speed or lack thereof of consumer adoption (Cullis, 2004; Mann, 2006; Cullis, 2008). Both will be determined by whether or not the parties view the innovation as a solution to a problem they may directly or indirectly face. These conditions frame a limited window through which the success of an invention may be realised. Accordingly, it is reasonable to assert that the optimum time for an invention to attain the maximum commercial impact is when: (1) the consumer is aware of the problem and welcomes the solution, subsequently providing a ready market; (2) all the necessary resources to actualise the invention are available at the same time; and, (3) the relevant players in the field are savvy enough collaboratively to seize the opportunity and meet consumer need.

From the preceding discussion, I submit that this is the start of the optimal decade for OLED technology. Aside from the uncertainty recently introduced by the UK Brexit vote, the global economic recession of the late 2000s is changing for the better. The market conditions for OLED technology are favourable given its advantages over the current market leader, LCD. Socially, the larger (up to wall size) and clearer displays afforded by the technology appease the appetite of this current technologically-savvy first-adopter generation. So do flexible, bendable and curved applications. Larger displays definitely favour the information age in which we live and that has seen an increase in advertising and public displays. Its lower power consumption, extreme thinness, light weight, fast response time and wide viewing angles, amongst other things, not only render the technology easily adaptable to the consumer market, especially for portable devices such as mobile phones but also to niche markets such as the military and other security services, which given the current state of the world (June 2016), are in great need of "smarter" applications (see section 6.5).

Moreover, the technology offers an environmentally friendly option (in both the display and lighting sectors) which suits the shift towards energy conservation and reduction of our carbon footprint that has progressively developed over the past couple of decades. One such example is the application of OLED technology as electronic paper which would greatly reduce the environmental harm due to the traditional paper industry (Forge and Blackman, 2009) - consumer adoption and sales for such, e.g. in e-books via the Amazon Kindle, are going up. The technology's superior resolution over extant counterparts could also see much needed applications in medical devices. OLED technology now has application in most fields: from the electronics industry to retail and banking to military to automotive to fashion, but to mention a few, and this list continues to grow with cumulative improvements to the technology.

OLED materials have progressively developed to a diversity of available options. The biggest challenge, blue materials lifetime, although not up to par with the other colours has made sufficient leaps in the past decade to allow for commercialisation of OLED devices. The current blue lifetimes are acceptable for some applications such as medical devices that largely focus on resolution and contrast as opposed to colour (Forge and Blackman, 2009), and in military application that mostly rely on infrareds and other advantages of the technology such as wide viewing angles, light weight and operation at a wide range of temperatures (Fyfe and Nicklin 2004). They are however more problematic in applications where image is everything, such as in televisions, PCs and mobile phones. What is currently available is suitable for small - medium display sizes. Prototypes have been shown at larger sizes and a significant number of commercial devices have been sold. Material suppliers are investing in better materials and forecasting volume production.

Several improvements in device fabrication methods have made it easier and cheaper to build OLED devices with better structures and thus improved performances, the most enabling of which has been inkjet printing technology. Moreover, established manufacturing plants that currently serve large size LCD production are tipped to double as OLED plants, especially given that most of the LCD players are also dabbling in OLED technology to recover losses from the now overcrowded LCD market. This is anticipated to ease the move into volume production of large sized consumer products. Complementary technologies are bypassing some of the technology's performance issues, shortening the learning curve and catapulting it to higher levels.

The requisite intellectual property monopolies have built a framework of licensing programs, joint development ventures, technology transfer and process packages through which it has been made easier to disseminate know-how and exchange expertise. In turn, this has nurtured an industry-wide dialogue that has developed into a global OLED value chain, roping in big and small fish alike. Given there are two different types of OLED - POLEDs and SMOLEDs - competition amongst OLED players is not unexpected but all involved seem to have found their place and are thriving to the benefit of the technology. With collaborations have come greater finances, resources, established infrastructure and expertise to move the technology forward. New prototypes demonstrated annually show that there is constant progress in R&D. Volume production has been manifested by some of the major players. Consumer curiosity is well oiled and developing from the LCD precursor market. Industrial policy is also in favour; continued investments from governments pushing for environmentally favourable technologies; research consortia and industry are fuelling the fire. The end result has been an impressive speed of growth and if the technology continues to mature at or faster than the rate at which it has been over the past three decades, based on the predictions by technology analysts, it is only a matter of time before the technology becomes a household name.

Moreover, most of the necessary resources are available now, albeit some requiring fine tuning. This is important since an innovation cannot thrive in isolation; in order for it to blossom and eventually establish itself on the market, all the aforementioned factors must interact within the same time zone, feeding from and back into each other. For example, R&D (an improved material, a better fabrication method or a complementary technology), which is usually a result of multidisciplinary collaborations, requires financial input which may come from the government, the military or generated through licensing programmes built on IP, which itself resulted from previous R&D and was put in place to curb competition in the market place. The interaction of these factors will be discussed in detail in the next chapter but for the purposes of this section, the conclusion is that all the factors must be "activated" within the same time frame for maximum benefit of the invention to be realised. A break in the chain may delay the maturity of the technology and accordingly affect its market, interested players and thus available resources.

## 6.7 Discussion

This analysis has been carried out based on knowledge current in 2016; published knowledge available from the usual literal sources mentioned in chapter 4; correspondence with the inventors, and the author's comprehension of the technological narrative in chapter 5.

The factors affecting the development of POLED technology that we have identified and discussed paint an interesting, albeit not unusual, picture. As we have seen from the materials discussion, cumulative efforts by CDT have more than tripled the lifetime of its blue materials, and together with the industry numerous and better POLED materials are now available. Hybrid systems incorporating the useful advantages of small molecules with the solution-processability of polymers are very promising. Parallel and successful efforts in producing solution-processable SMOLEDs dictate that there should be more communication between SMOLED and POLED players as regards to process know-how so that better materials can be realised on both ends. The reality of course is not as straight forward as they are competitors in the market place. LG's proprietary white OLED approach, if picked up by other researchers, will also go a long way in improving overall device performance. Even if they have come a long way, blue fluorescent POLED materials are not yet up to par, in comparison with red and green materials and this is hindering volume production as well as lower prices for OLEDs. Phosphorescent blue materials (reported by the likes of UDC and DuPont) and the already discussed hybrid systems are making bigger strides so perhaps these are the future of POLEDs.

Materials development has to be concurrent with improvements in device fabrication; each new type of material requires the right processing method to allow it to shine, as one size does not always fit all. Device structures have evolved from those containing single polymer layers to those comprising multiple, patterned or blended layers of polymers. Addition of supporting layers such as those for hole and electron transport, light filtering, doping etc. has led to cleaner/purer light and thus better device performance. Improved deposition methods have also played a key role with printing methods superseding others; printing allows deposition of all the devices layers in a single continuous step reducing susceptibility to biodegradation, and processing time, and allowing for more accurate and cheaper manufacture. Printing methods are set to give an even greater push to commercial viability, in particular, inkjet printing which is heralded as the 'best-in-class' method. Roll-to-roll printing has also introduced interesting possibilities for applications that were previously not thought possible, in addition to further decreasing manufacturing costs. Even though all-printed POLEDs have so far not been commercialised, prototypes have been demonstrated and with increased investment in development of these methods, it looks to only be a matter of time. And finally, device fabrication has so developed to allow for the manufacture of integrated circuits, providing further potential for cheaper manufacturing synonymous to that of inorganic semiconductors discussed in chapter 3.

With all the desirable features of POLED technology, it is not easy to find a substitute so the next best thing is to examine enabling/complementary technologies at every level of the device structure that will enhance and speed up the technology's maturity. Due to the novelty requirement for patentability and the fact that know-how is more valuable when kept secret, several of the emerging technologies will be kept under wraps but even the well-publicised ones discussed here are very promising. For the substrate, flexible and shatterproof glass as well as plastic are making strides. Samsung and LG, the biggest commercial manufacturers of OLED products are already using the latter in products that are soon to be mass produced. The feasibility of roll-to-roll plastic sheets with their intrinsic ultra-thinness will further lower manufacturing costs. These are already being successfully being mass produced in other sectors (solar panels and lighting) in the US. There are also several promising backplane technologies with superior performance to that of the current market leader - silicon. LTPS and oxide-TFT are taking the lead - already being mass produced for both LCDs and OLEDs for both small-medium and large sized displays. The other contenders are expected to reach the market within the next few years. In addition to the aforementioned material developments, frontplane technologies include the conversion of materials into silicon inks - a very interesting concept that borrows process and development know-how from the well-established inorganic semiconductor industry. The inks are well suited for the rapidly proliferating ink jet printing systems. Graphene - currently the highest profile new technology - for producing transparent conductors is very attractive for its flexibility and extreme thinness. Increasing interest about it in the industry is leading to more investments into R&D by governments and research consortia, and as any new technology can demonstrate, will go a long way in speeding up its maturity. It has already been proven for small area displays in under a decade and efforts towards large area displays should not be that far behind. Carbon and silver nanotubes are also very promising. For the barrier, flexible glass again will be a good enabler, as are several thin-film encapsulation techniques, with IJP once again emerging as the frontrunner. Commercial IJP equipment is already being sold to major players and several have previewed printed OLED TVs, including two that are using CDT/Sumitomo's POLED inks. And finally, Q-dot technology matches OLEDs in performance, shares its device structure and accentuates LCD performance, so much so that it has already reached the market in LCD products in just over a decade since its discovery. Even though this could be a major threat to OLED technology, it could also prove very useful. The two technologies share device structure and almost all of the technical issues including the fight for good blues so it can decrease the learning curves by sharing knowledge and jointly troubleshooting, albeit much more so for Q-dot which is a lot less mature.

The response to this new technology, in the form of IP, was also an interesting story. In relation to the potential of POLED technology, the inventors at CDT, whose resources were limited, were reasonably unlikely to make a major contribution to the commercial exploitation of the technology. Even if the inventors had to dip into their pockets, it was a wise decision first to seek a patent for the fundamental discovery of POLEDs, as well as for the subsequent R&D. This paid off; the discovery caught the attention of the electronics industry and several players wanted to participate. As CDT's IP portfolio grew, it was able to enjoy the dominant position afforded to it by its IP ownership. So IP - which is sometimes argued to inhibit market fluidity because of the inherent exclusivity - actually through the licensing programme further established existing market participants as well as enabled new entrants who met the licensee criteria to enter the market through collaborative work. Licensees brought with them expertise, complementary assets and resources that would have otherwise been beyond CDT's reach, in addition to a recognised commercial brand that would provide the vehicle to put POLED technology on the consumer market. As the licensees would have otherwise been its commercial competitors, it was a win-win for all.

The strength of CDT's IP was demonstrated by its ability to gain and retain major industry players as well as academia as licensees, joint development partners, service customers or investors. Concurrent with this, CDT continued to file and acquire more patents from R&D that resulted from these ventures, as well as acquiring companies (along with their IP assets) whose technologies furthered the success of its own. In addition to patents, know-how in the form of manufacturing process and engineering expertise also played a major role in supplementing and complementing CDT's commercial agreements. Thus far, trade marks have not needed a major stage as CDT/Sumitomo have not yet mass produced POLED devices (although this is happening through their commercial partners who use their own brands).

CDT's business model is also seen evolving severally, from being based on R&D and some licensing, to incorporating small scale manufacturing (which enabled it to demonstrate value to its partners in addition to attracting new ones), to integrating service packages and extensively expanding its licensing programme. Expectedly, this would have had a knock on effect on CDT's financial growth and employee stability. This was especially important as emerging technologies can easily be choked by incumbent and already well established and popular technologies, especially if they have inherent developmental issues, and miss their window of opportunity.

CDT is seen flourishing off a licensing business model similar to that set up by Bell Laboratories, Texas Instruments and Fairchild Semiconductors with inorganic semiconductors because of this ownership of fundamental patents, or in the language of this thesis, patents that covered major paradigm shifts. Quality rather than quantity of patents was fundamental to the success of its licensing programme, and to fostering further connections. This has enabled it to become a major organ of the global POLED value chain. But "*with great power comes great responsibility*", so because it holds the most extensive and significant IP as far as POLEDs are concerned, CDT in its dealings has to take care not to abuse this dominant position and risk falling foul of competition law or patent misuse provisions. To adhere with competition law and/or patent misuse provisions, Bell Laboratories was prevented by a Consent Decree from directly manufacturing transistors for sale (so it instituted a licensing programme instead), while Texas Instruments and Fairchild Semiconductors largely benefited from military procurement (Cullis, 2007).

On the competition front, CDT does not face notable resistance from other fluorescent POLED materials because of its extensive IP portfolio in that area but faces some competition from the likes of Merck and DuPont who were established in phosphorescent POLED research before it branched into them. SMOLEDs offer sizeable competition but given their lack of solution processability, that is limited to the small area display market. The biggest challenge to POLED comes in the large area arena, in particular, by extant technologies such as LCD which is the current market leader in the display industry, and is itself a moving target. IDTechEx however states that the LCD industry is now very crowded and profits are not what they used to be so with the advantages POLED offers over LCD, the display industry is shining a light on POLED technology as the clear successor. In an effort to recoup their investments, most of the major players are dabbling in both technologies. As POLED technology is steadily maturing, enabled by complementary technologies, several companies are projecting volume production between 2016 and 2018. POLED technology can also very easily borrow from LCD manufacturing infrastructure, process expertise, industry and academic players, end products and especially customers. Thus in conjunction with the advantages it offers over LCD, and the complementary technologies that are speeding up its maturity, POLED is well-positioned to overthrow LCD in the display market. The current major setbacks are the high manufacturing costs connected to a slightly younger infrastructure and blue materials lifetimes.

The electronics industry is one characterised by fast turnover so OLED technology has to evolve rapidly to maintain the precursor market it has carved out and avoid annihilation. While it is itself seeking to be established, it is threatening to disrupt market structures of extant technologies, particularly LCD. Just like most technologies, there is a clear time lag between discovery and when applications are available on the market. Nevertheless, the technology has made significant strides in the past two decades. Analyst predictions have largely been favourable, forecasting steady growth over the next decade in especially the display and lighting sectors, and in other niche applications. Demonstrated prototypes in the display sector have captivated the industry and consumer alike; feasibility of flexible devices is literally stretching electronic boundaries. Commercial devices have sold like hot cakes, even at the hefty prices they currently command. The future is just as bright in the lighting market, with OLEDs having already curved out a niche in museums and the delicate lighting market. With curved smartphones, ultra-thin portable devices, wearable technologies and other 'out-of-the-box' applications like proposed electronic wallpaper, it is evident that there is a market for the technology. It will further bite a chunk out of LCD's market dominance, the speed and the extent of which will be determined by whether and how quickly the technology's technical shortcomings are resolved to lower manufacturing prices. For this, continued commitment is required not just on the R&D front but also from device manufacturers tasked to keep the consumer's eye on the technology.

This requires continued intercourse between academia, industry and end product manufacturers. Collaborations have played a major role in advancing the development of POLED materials - giving CDT access to R&D and processing expertise, personnel, resources and manufacturing plants that would otherwise be beyond their reach or capability. Government initiatives provided access to other research partners through research consortia. Their choice of corporate partners is also seen to provide distribution channels of sorts that directly influenced their entry onto the consumer market, and determined how well they navigated the OLED ecosystem. Afforded in addition was the ability to pool patents with collaborators through sub-licensing agreements which in turn strengthened its IP portfolio. With this, a global OLED value chain has been firmly established where pioneers like CDT who exist in the earlier stages of the chain are upon whom the rest of the value chain is cemented. This subsequent chain, in addition to governments, the military, research councils, private equity firms and venture capitalists is what medium firms like CDT rely on to continue to fund their R&D and run their businesses.

Further, through its numerous and broad types of collaborations, CDT is seen raising funds from seed funders, its parent university, government grants (as part of consortia involving other OLED researchers and university spinouts), individual investors, venture capitalists, its licensing and joint development partners as well as from its two sales (to the US private equity firms and Sumitomo). It also raised money from the sales of its products & equipment, and technology development & process packages. The finances were used to run all aspects of the business - the good, the bad and the ugly - but most profitably acquiring other companies whose technologies furthered their own. As the technology continues to mature, the above ventures should bring in more revenue for CDT.

Timing is also important. In order for the maturation of the technology not to drag out, all the aforementioned factors have to interact within a similar timeframe. The finances for R&D (generated from collaborations, licenses, the government/military etc.) have to be available at the time technology developments are 'hot' so as to take maximum benefit of them. Similarly, the complementary technologies have to develop alongside the material/fabrication developments for optimal advantage, all the while priming consumer attention with prototypes and marketing gimmicks to lay a foundation for a market for subsequent products. For the foregoing to happen, collaborations between the involved players also have to happen at the same time. Luckily, all the stars have aligned for OLED technology to take off; materials suppliers and consumer product manufacturers are investing and promising volume production, and industrial policy is also in favour of the ecologically favourable technology.

## 6.8 Conclusion

From the foregoing, we can conclude that the success of an invention is a dynamic process. It is more than the conception of an idea in a lab, it involves the timely interaction of several factors, each of which contributes a unique facet to the subsequent diamond. It could be lengthily debated which of the factors plays the most significant role but the reality is that without a seed technological development (with all the materials, device manipulations and enabling inventions that go with it), there would be no need for regulation (in the form of IP and management of competition) and thus no market to be established (in the form of a precursor market, oiled by finances/resources supplied through multidisciplinary collaborations and the government/military). Even though the contribution towards commercialisation of the invention may vary by factor, each is just as indispensable as the other. Timing is the glue that sticks all the factors together; without it, they are merely pieces of an unsolved puzzle. In the proceeding chapter, we shall look at how these factors closely interact by looking through the glass of the Black Box model.

# 7.0 Thesis Reflection

## 7.1 Introduction

Before we delve into the final remarks of this research, we shall first have a recap of the journey so far. Chapter 1 taught us the molecular chemical basis of OLED technology, based on the quantum physical properties of semiconductor materials. Chapter 2 painted a picture of the socioeconomic factors that may affect the technology's development, and chapter 3 surveyed an analogous technology - inorganic semiconductors - to provide at least a starting point to reduce these factors for organic semiconductors. Chapter 4 taught the patent analysis methodology to be followed in obtaining technology data to be analysed, chapter 5 analysing these data to make some observations from the patent trends analysis. Chapter 6 then discussed at length several of the major socioeconomic factors that affected the technology's developmental history. In particular, that discussion focussed on CDT's commercial strategy for the technology, and the resultant effect on and reaction of the OLED industry. This chapter aims to marry the aforementioned factors and paint a bigger commercial picture in context of the future of the technology. It will commence with a general discussion of several observations from the findings, analysing the interaction of the discussed socioeconomic factors within the context of a model for innovation dynamics - the Black Box model. The use of CDT's patent portfolio as a commercial tool will be examined in light of the results of this study as well as other economic studies on CDT, followed by patent citation data analysis that will illustrate the importance of individual patents in CDT's portfolio. The chapter concludes with a general outlook on the future of CDT and OLED technology.

## 7.2 Observations from the Innovation's Journey

Irrespective of how an invention is arrived at, its journey from conception to market does not happen in a vacuum. It is not an isolated event but rather one that interacts with and is influenced by its environment. External stimuli or so-called enabling processes or events are crucial for achieving steady progress in the research and development of the invention so as to reach maturity and reap maximum benefit from the invention while it is still relevant. As already discussed in chapter 2, these stimuli may be: finances, discovery of a suitable material or method for construction of a device, the availability of precursor market for the end product, the role played by the inventor(s), knowledge dissemination, Intellectual Property, the influence of cartels, loss of continuity in extant technologies or external stimuli such as war that encourage government or military funding of new or complementary technologies to enhance defence systems, or urbanisation that may blow investment in a particular direction. The degree to which these factors affect innovation is dependent on the type of technology at issue.

As affecting the development of the technology at discussion here, we looked at and categorised some of these factors as follows: (1) technology development - availability of suitable materials and device fabrication methods, and complementary technologies that further the materials and methods; (2) regulation - which included the influence of and ownership of IP and the commercial strategies or licensing frameworks that may result from such, as well as the role played by competition amongst players in the field; (3) market - where we looked at the presence or otherwise of a market for the end product of the technology, the bringing together of several parties in view of a profit and the finances that result from such collaborations; (4) external interventions such as those from the government or the military; and (5) the vital role played by timing.

From the patent data analysis, I could glean that all the factors of technology developments, regulation and collaborations would play a major role. The rest were an obvious consequence in light of the advantages afforded by the technology, in addition to being at the forefront of the discussions in most of the secondary reading. Other material, mentioned in section 2.4 of chapter 2, confirmed that CDT's patents were vital to the OLED industry, and this was confirmed by the licensing programme it had going with several big name industry players. Timing is the vital ingredient that marries all the factors together; the necessary resources (technological, financial, knowledge etc.) to further the technology have to be available at the time the consumer's arms are open to the invention to create a precursor market, and whilst the players (both industry and academic) are latched onto the new paradigm. The factors chosen for discussion were also influenced by the Black Box - the same or closely related factors had to be examined in order to justly test the model.

Looking onto the personalities of the inventors involved in the work would be a monstrous task for the timeframe of the study. The nature of this information age, and in particular patents, means that it is easier for researchers on different parts of the globe to find out what others are doing. It is then useful for them to collaborate and build onto each other's work as opposed to their having to start from scratch; this leads to a whole team of named inventors on a single patent. Of the 53 patents examined, there was a total of 77 different inventors. It would not be pragmatic to profile each inventor's personality or indeed the 'core' CDT team (because they do not appear on all the patents), to forge their relative contribution to the development of the invention. The question then begs as to why wasn't Sir Richard Friend profiled since the initial patent search was directed by patents he was named as inventor? The answer would be that the nature of collaborations and joint-inventorship do not always allow for precise determination of the slice of the pie contributed by each inventor - there would be too many anomalies in forging an estimate of his exact contribution which would no doubt skew the outcome. It is the role of the patent attorney who drafts the patent application to satisfy the statutory requirement of contribution to the invention. In contrast, during the development of the inorganic semiconductors devices in the 1960s-1970s, the research industry was more parochial and inventions were more easily attributable to either one or a very small team of inventors.

Some other factors that affect the innovation process highlighted in chapter 2, although contributory to a certain extent, were omitted from the analysis because they were not pertinent to this discussion. For example, although knowledge dissemination would play a role, especially between collaborators, it would be redundant given the information age we live in and the side of the world the work is located, so that it is not unique to the development of this technology or technology as a whole. This would perhaps play a significant role if the technology were being developed in a remote part of the world for example. Urbanisation could also play a discussible role given that the increase in population would possibly increase the consumer market, and increase in innovation would perhaps create more competitors for OLED technology. The former is not yet a major issue given the stage of maturity of the technology– only a few consumer products have reached the market and for now a precursor market suffices to gauge consumer interest. The latter assertion is highly speculative.

For the factors highlighted, it would be presumptuous to put a percentage to the extent to which each affected the technology's role but I make the case that it is clear that IP played a major role. Aside from its obvious importance in driving the commercial direction taken by CDT and the attractive force to investors and the various range of collaborators, IP initiated a licensing programme that generated most of the finances that funded and still fund CDT's R&D. The precursor market was further enhanced by these big name licensees that already had established commercial brands, and raised consumer curiosity through the OLED prototypes they have introduced in the marketplace over the years. IP also encouraged collaborations (to avoid infringement) with both academia (to further R&D) and industry (to reduce competition).

In addition to the importance of IP, the other resounding theme throughout the discussion in chapter 6 is the importance of interaction between the different socio-economic factors. Most if not all the factors interact to a certain degree - see figure 7.1. For example, IP results from: (1) the discovery of a novel material, a device fabrication method, or an enabling technology; and (2) pooling of extant IP from licensees or joint development partners. IP may be put in place to curb competition from those seeking to benefit from the discovery, and may, in turn, direct the company business strategy, leading to a licensing programme. In addition to other financial sources, that licensing programme provides funds that may (1) feed back into the acquisition of more IP and/or enforcement of extant IP; (2) be used for R&D to generate more IP; and (3) foster collaborations with parties that bring in much needed resources and expertise. The collaborations enhance R&D, generate more IP, and limit competition as it is usually commercially more expedient for competitors to collaborate rather than compete (particularly where there are IP restrictions). Generated finances fund more R&D in the short term and marketing and commercialisation strategies in the long term to oil the precursor market. This communication is what drives the whole process if there is no perfect timing, or luck as one would have it. I consider that it could be the catalyst to the success of the innovation process.

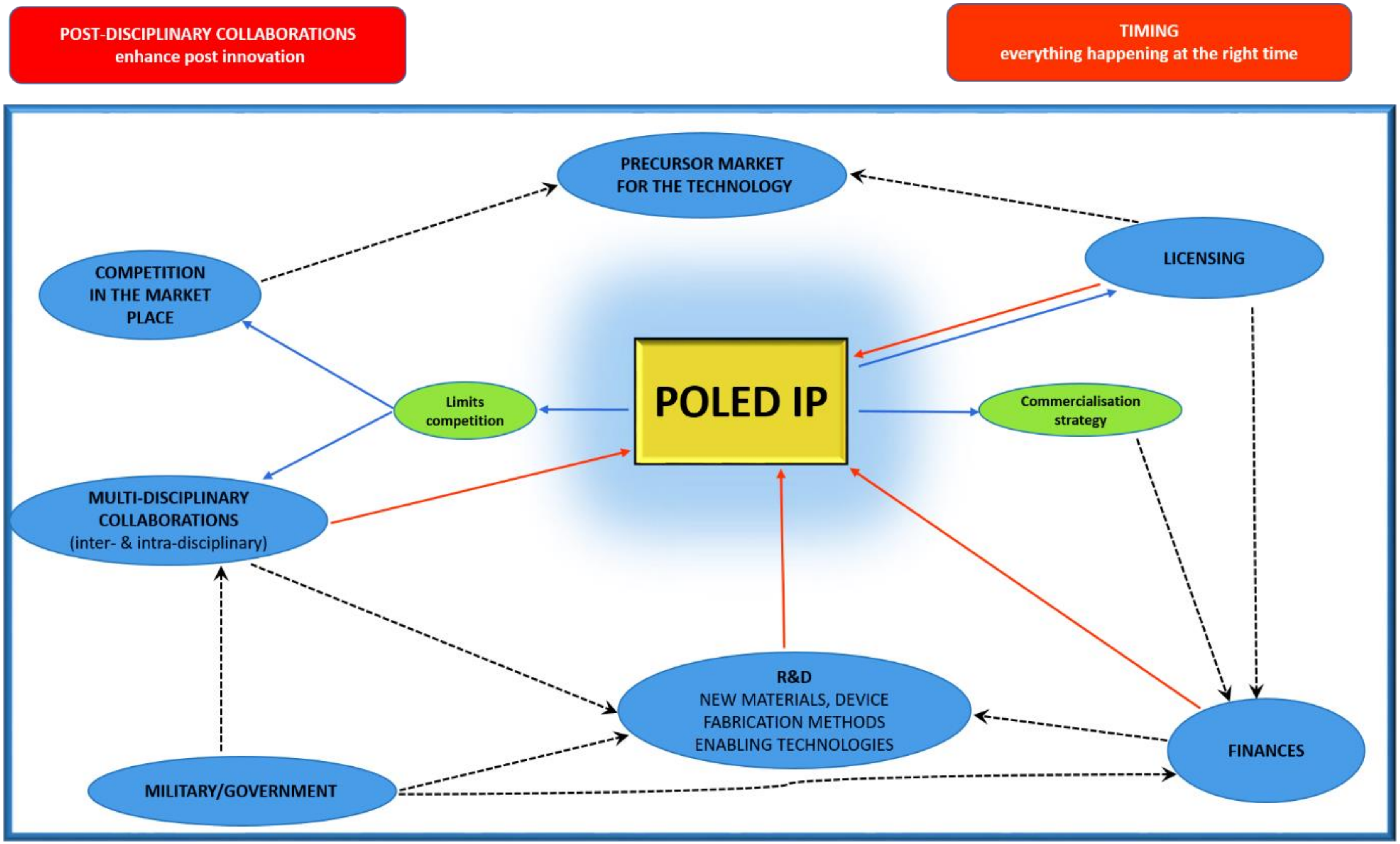



***Figure 7.1: An illustration of the extensive interaction between the socioeconomic factors influencing the POLED innovation's journey. KEY: black dotted arrows - interdisciplinary collaborations, blue arrows - IP feeding into the environment, red arrows - the environment contributing to the generation of IP (Source: Deborah Sewagudde)***

Further, the communication could be looked at in three distinct ways: (1) intra-disciplinary, (2) inter-disciplinary, and (3) post-disciplinary. Intra-disciplinary communication is very important for pooling resources and expertise, and furthering each arm of the puzzle. For example, there has to be a dialogue between materials scientists and chemists in the development of materials just like there has to be a constant dialogue between physicists and device engineers in the development of more effective device structures and fabrication of novel devices.

On the other hand, inter-disciplinary communication brings all the aforementioned groups of people together to effectively construct the final product. Instances for this are vast but an example would be where device fabricators who damage materials/polymer layers by high temperatures or otherwise as they lay down the device structures have either to brainstorm with the material scientists as to making more durable polymers or they have to adjust their polymer deposition methods. The latter may fall into the ambit of enabling technologies such as IJP, to facilitate more accurate laying down of layers at low temperatures, prompting more communication and collaboration with those expert in that technique. These groups of people are oftentimes intertwined within one research group. For maximum profitability, end-product assemblers and device manufacturers would also need to interact directly with those knowledgeable in the consumer market to produce what the consumer wants.

Perhaps sometimes overlooked is the importance of post-disciplinary communication. To use the example of the classified factors (technology development, regulation and market), especially after the technology has matured and the products are already on the market, there has to exist a constant dialogue amongst the three so as to share and benefit from each other's collective memory. Arguably, intra-disciplinary communication can only achieve incremental steps to better the technology before they border on introducing a new paradigm and moving on to something new altogether; such is the nature of innovation. Inter-disciplinary efforts are more or less synchronising with the beat of the consumers' drum and responding to competition in the market place, so not exactly taking leaps to further the technology. What I believe, will create big leaps for the technology is the three groups sharing accumulated knowledge from the technology development process, response of the market and effect of regulation. The lessons learnt here are what is transferable to other technologies, and industries, and is equally what the development of POLEDs learned from that of the transistor. It is the author's opinion that regardless of the brilliance of an emerging technology, such lessons are what will enable it to have a shorter and more thorough maturation process to cease its fifteen minutes of fame on the market before the novelty wears off, or it is replaced by a shinier technology, or before we are all replaced by humanoids, whichever is sooner.

## 7.3 Black Box Model

### 7.3.1 What is the Black Box Model?

At some point in our lives, we have all heard the phrase "*learn from history in order not to repeat the mistakes of the past*". It has been proven many a time that a future than learns from the past is a better future. Accordingly, it is useful to devise a relationship between the past, present and the future so that the first two aspects can be used to predict the last one.

In mathematics for example, entry of certain variables into a predetermined equation or theory will lead to a defined answer. From the answer, the relationship between the variables can be then understood, and even manipulated to influence the outcome. A similar concept occurs in certain fields such as accounting, science and engineering in which so called inputs can be entered into a system or device called a Black Box (because the inner workings of the system/device do not have to be clear) to produce certain outputs. The focus is on the relationships between the inputs and outputs and not necessarily on the how, why, when or where.

This concept was applied by Roger Cullis in developing a model to study innovation dynamics. It was based on the premise that understanding the relationship between the past and present events in the path of a particular innovation would assist in predicting its future course (Cullis, 2007 at p236). This model provides a quantitative method for examining the intricate interdependence of the socioeconomic factors in the innovation lifecycle discussed above.

Cullis, a physicist and patent attorney, from 1994-2004 carried out a multidisciplinary study of the dynamics of innovation. He analysed the influences of the developmental history of four major innovations spanning four key industries and covering a similar period of history (1800-1970s). The case studies were based on: (1) the incandescent filament lamp from the lighting industry; (2) the thermionic valve from the electronics industry; (3) the transistor from the inorganic semiconductor industry; and (4) the silicon chip from the communications industry (Cullis, 2004 chapter 4).

He studied the chronological development of each invention from patent specifications and other secondary sources, analysing the socioeconomic factors that contributed to the commercial success of each invention. He considered factors such as the effect of chance/serendipity; timing; the personality and motivation of the inventor; the effect of the laws of physics; communication; statutory monopolies such as IP; external agencies such as government policy, regulatory controls and economic cycles; the effect of war; the influence of cartels; competition law; finance; market structure and market power (chapters 6-11). His narrative illustrated a high degree of dialogue between the different factors as they crossed paths on the innovations' journey, the interaction being influenced by factors both internal and external to the innovations' ecosystems. This qualitative analysis is similar to the discussion in chapter 6.

The quantitative analysis of the influence of these factors was not as straight forward. Some of the influences of the factors could be quantified (e.g. finances in terms of capital and revenue) but others like the effect of regulation controls or market power could not. However, and in most cases, the end goal of innovation is to solve a problem and to mostly make money while doing it. Therefore, each factor that influences the innovation's path would have an influence on the revenue.

To articulate this, Cullis likened the process of innovation to an accountant's Black Box that views a business in terms of capital flow - incoming finances for the purpose of trade, investments and other company business needs etc. - and revenue - the resultant earnings of a company. He considered the socioeconomic factors as mathematical inputs that would elicit an output. For example, a raw materials input would produce an output of finished goods, or a raw information input would become refined information/know-how at the end of the innovation process (see figure 7.2). By so doing, he divided the process of innovation into its individual components (socioeconomic factors), analysed the behaviour of each, and then how they interacted with each other.

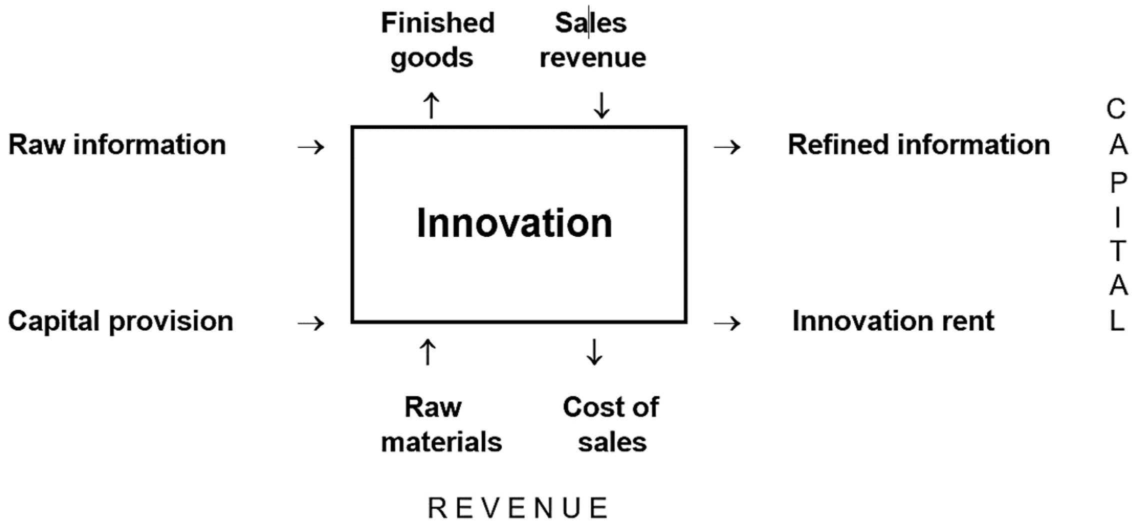



***Figure 7.2: A depiction of the Black Box model for innovation (Source: Cullis, 2007 at p237)***

A further dimension of the model illustrated the interaction of the innovation with its environment to provide for the fact that innovation does not happen in a vacuum (see figure 7.3). Cullis considered the environment as comprising: (1) suppliers of good and services; (2) other innovators; and (3) the markets for which they jointly competed (at p236).

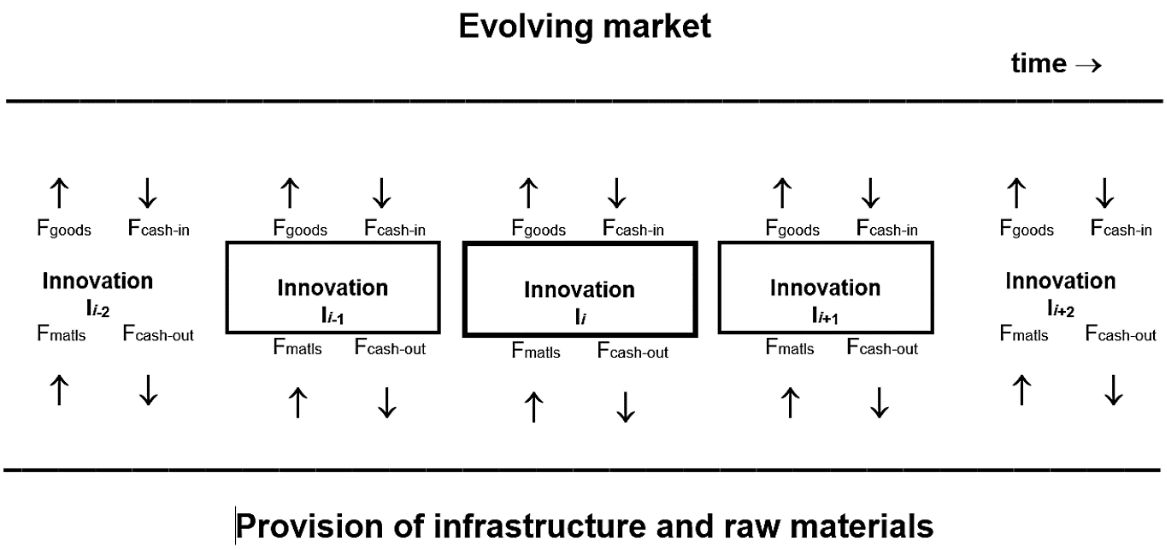



***Figure 7.3: An illustration of an innovation ($I_i$) interacting with the environment. $I_{i+1}$, $I_{1+2}$, $I_{i-1}$ and $I_{i-2}$ indicate successive innovation models for other innovations in proximity to the main innovation, with which they share markets and a supply of raw materials and infrastructure. Matls - materials (Source: Cullis, 2007 at p237)***

He further asserted that the innovations all had complementary demands (markets) and offers to supply (materials, processes etc.) in the external environment, and that these sometimes overlapped where the end products of the innovations could substitute each other (at p238). In essence, that related innovations often shared markets and sources of supply, in addition to some innovation similarities - this is embodied in figure 7.4. We saw this concept manifest in the discussion in chapter 6 for the different display technologies, where for example, LCDs and POLEDs displays shared the same device fabrication processes, manufacturing infrastructure, consumer electronics market and were even promoted and sold by the same manufacturers.

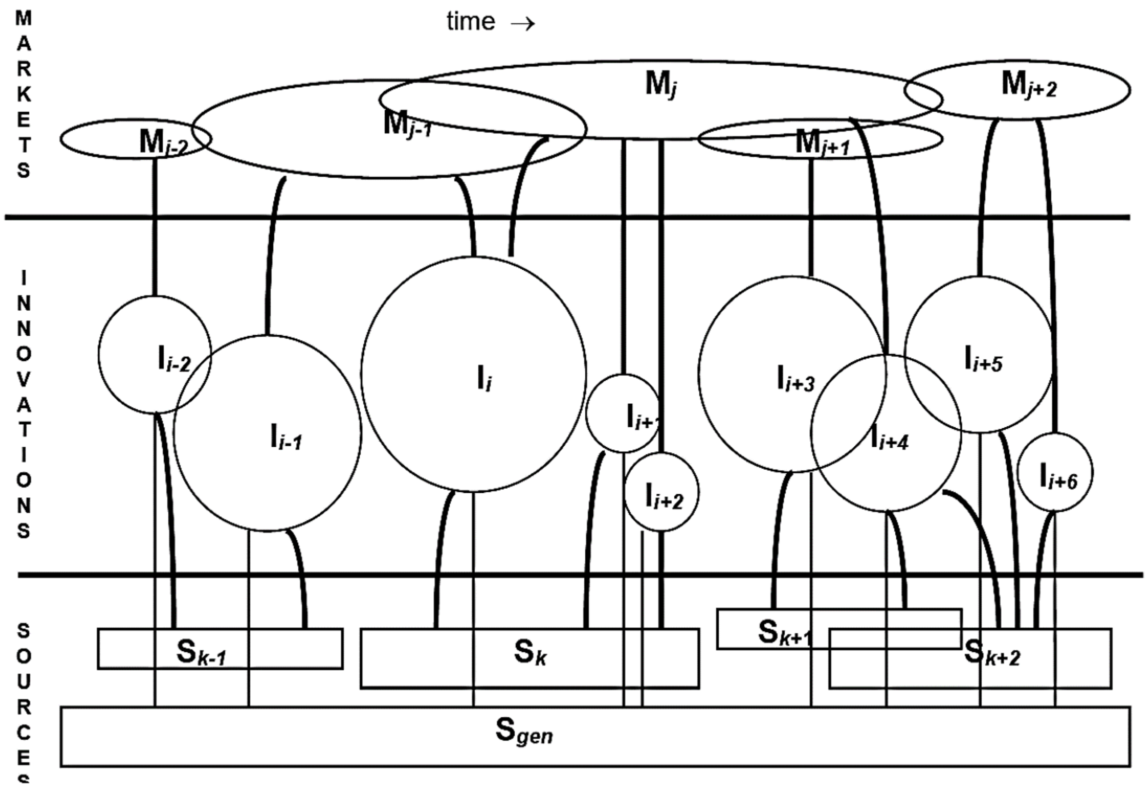



***Figure 7.4: An illustration of interactions between different innovations and their environments. The innovations are this time represented by circles. $S_{gen}$ denotes certain utilities etc. that are common to all innovations. The other denotations are self-explanatory from the titles on the left and following the convention in figure 7.2 above (Source: Cullis, 2007 at p238)***

He then classified the different socioeconomic factors into inputs, outputs, parameters and variables. Inputs were taken to be what was obtained from the environment, for example, raw materials and capital. Outputs were what was given to the environment, e.g. innovation rent and refined information/know-how (refer to figure 7.2). Variables as the name suggests were always changing and could therefore not be measured - they however gave an indication of the immediate condition of the innovation system, and accordingly affected the outputs. They included know-how, working capital, infrastructure, derived inventions, market structure etc. Parameters were considered to be part and parcel of the structure of the innovation system, changing with time and determining the relationship between the inputs and outputs. These included the properties of the materials, the laws of physics that governed them, statutory monopolies, competition law, military and government intervention, collaborative partners etc. He also observed that inputs and parameters were independent of other classes; outputs depended on all the other three while variables were affected by inputs, parameters and each other (at p243). The categories are shown in table 7.1, extracted verbatim from Cullis, 2007.

| **Element** | **Symbol** | **Interactions** |
|---|---|---|
| **Flows** | | |
| Capital provision | $F_{Cin}$ | |
| Innovation rent, dividend | $F_{Cout}$ | $F_{Rin}$ $F_{Rout}$ $V_{MS}$ |
| Knowledge input | $F_{Kin}$ | $F_{Cin}$ $P_{Fac}$ |
| Know-how out | $F_{Kout}$ | $V_{KH}$ $V_{InD}$ $P_{InS}$ |
| Cost of sales | $F_{Rout}$ | $F_{GMin}$ ($V_{MS}$) |
| Sales | $F_{Rin}$ | $F_{GMout}$ $V_{MS}$ $P_{IP}$ $P_{DM}$ $P_{RM}$ $P_{Reg}$ $P_{Fac}$ $P_{Mil}$ $P_{Gov}$ |
| Raw materials | $F_{GMin}$ | $V_{Inf}$ $P_{Phy}$ $P_{InS}$ |
| Finished goods | $F_{GMout}$ | $V_{KH}$ $V_{WC}$ $V_{Inf}$ $V_{WiP}$ $V_{InD}$ $V_{MS}$ $P_{Phy}$ $P_{DM}$ |
| **Variables** | | |
| Know-how | $V_{KH}$ | $F_{Kin}$ $P_{Fac}$ ($P_{Mil}$) |
| Working capital | $V_{WC}$ | $F_{Cin}$ $F_{Cout}$ $F_{Rin}$ $F_{Rout}$ $F_{GMin}$ |
| Infrastructure | $V_{Inf}$ | $V_{InD}$ $F_{Cin}$ $F_{Kin}$ $F_{Kout}$ $F_{Rin}$ $F_{Rout}$ $P_{InS}$ |
| Work-in-progress | $V_{WiP}$ | $F_{Cin}$ $F_{Kin}$ $F_{Rin}$ $F_{Rout}$ $F_{GMin}$ $F_{GMout}$ |
| Derived inventions | $V_{InD}$ | $P_{InS}$ $P_{Phy}$ $P_{Fac}$ $P_{Mil}$ $P_{Gov}$ |
| Market structure | $V_{MS}$ | $V_{InD}$ $P_{IP}$ $P_{DM}$ $P_{RM}$ $P_{CL}$ $P_{Reg}$ $P_{Mil}$ $P_{Gov}$ |
| **Parameters** | | **Time dependency** |
| Seminal inventions | $P_{InS}$ | erendipitous, environment-sensitive, may be dependent on inventors |
| Properties of materials and the laws of physics | $P_{Phy}$ | No |
| Statutory monopolies | $P_{IP}$ | Yes Microeconomic (renewal fees, statutory term), macroeconomic (new laws) |
| *De facto* monopolies | $P_{DM}$ | Yes Microeconomic |
| Response time monopolies | $P_{RM}$ | Yes Microeconomic |
| Competition law | $P_{CL}$ | Microeconomic, macroeconomic (new laws, public attitudes) |
| Physical regulation | $P_{Reg}$ | Microeconomic, macroeconomic (new laws, public attitudes) |
| Facilitators | $P_{Fac}$ | Discrete steps (hiring and departure of facilitators) |
| Military procurement | $P_{Mil}$ | Yes Oligocratic |
| Government intervention | $P_{Gov}$ | Yes May be oligocratic |

***Table 7.1: A table showing the categorisation of the different factors that affect the innovation. Flows indicate the inputs and outputs, denoted by the acronyms F..$_{in}$ and F..$_{out}$. The assumed interactions between the factors are also shown (Source: Cullis, 2007 at p244-245)***

In light of the knowledge of the interactions between the different factors, and using the symbols in table 7.1, mathematical equations could thus be formulated to work out for example innovation rent. Following the introduction of an innovation onto the market, the capital generated would initially be in the form of what is called innovation rent. This is the benefit earned by the innovator in the period between which the innovation is introduced onto and is successfully diffusing into the current market structure, and importantly, before competitors surface to take a chunk out of the innovator's profit. So established mathematical rules could be employed to define dependency equations in the form of X = X (A, B, C, …) where an input X would give an output of X affected by parameters and/or variables A, B and C. For example, an input of capital provision ($F_{Cin}$) for example would produce an output of innovation rent ($F_{Cout}$), affected by sales ($F_{Rin}$) and cost of sales ($F_{Rout}$). The resultant equation would be:

$$F_{Cin} = F_{Cout} - F_{Rin} + F_{Rout}$$

Or as Cullis puts it in equation 12.1 p244, innovation rent, $F_{Cout} = F_{Cin} + F_{Rin} - F_{Rout}$

Moreover, $F_{Cin}$, $F_{Rin}$, and $F_{Rout}$ are themselves influenced by other variables and parameters so the equation develops into:

$$\begin{aligned} F_{Cout} &= F_{Cin} + F_{Rin} - F_{Rout} \\ &= F_{Cin}\,(P_{InS}, P_{Fac}) \\ &\quad + F_{Rin}\,(V_{KH}, V_{WC}, V_{Inf}, V_{WiP}, V_{InD}, V_{MS}, P_{Phy}, P_{DM}, P_{IP}, P_{DM}, P_{RM}, P_{Reg}, P_{Fac}, P_{Mil}, P_{Gov}) \\ &\quad - F_{Rout}\,(V_{Inf}, P_{Phy}, P_{InS}, V_{MS}) \end{aligned}$$

This gives an indication of the extent to which the factors are affected by each other. From this he drew some general conclusions. Firstly, that of course the equation would vary by innovation, depending on which of the tabulated factors played a role in its development. And secondly, that it was possible to make some general statements based on the relationships of the factors in the equation, such as the high dependence of capital provision on seminal inventions and facilitators ($F_{Cin}$ ($P_{InS}$, $P_{Fac}$)), or in the language of this thesis, enabling technologies and collaborative partners.

The model would of course be more helpful if actual values were available. This is problematic given the confidential nature of company commercial data, so for an outside observer, the equations offer a signpost to the factors to expect to have influenced a particular innovation's dynamics. For an insider, however, the equations can be used to calculate actual capital flows and revenue streams, following which certain components could be adjusted to achieve a desired result or to increase awareness towards a particular input. Pragmatically, this means that an innovator by considering the expansive interaction between the diverse factors in the innovation environment can better understand the innovation process, and further be enabled to make minute adjustments to their innovation system to effect the outcome they desire.

### 7.3.2 Caveats of the Model

The details, together with the process of construction of the model and equations proposed can be found in chapter 12, p236-247. In addition to the general caveats that apply to established mathematical rules, several other caveats were acknowledged and factored into the model building.

Firstly, in addition to the evidence from the case studies, Cullis' observations about the interdependence between the factors were supplemented by intuition based on his then 45-year experience as an engineer/physicist and patent attorney, studying and filing patents of his own in the particular technology he analysed.

Secondly, and as with any construction exercise, the process was iterative: gathering relevant data, hypothesising a relationship between the socioeconomic factors, comparing those predicted relationships to the data, making adjustments were necessary, and extrapolating results where appropriate (p240-241). Each stage within the model building was tested to avoid cumulative error (at p242). The accuracy of the model thus depended on the accuracy of the hypotheses, idealisations and assumptions made. In other words, the end was determined by the beginning. If the end (observed data) did not match the beginning (hypothesis, assumptions etc.), Cullis submitted that either: the mathematical equations or hypotheses were erroneous or overly generalised; his intuition about the field was insufficient; or a new norm had been established.

Thirdly, in categorising the socioeconomic factors, he noted that making a distinction between parameters and inputs was not straightforward, so he took inputs to be those that varied greatly and parameters to be those that remained fairly constant (at p243).

Albeit imperfect, this mathematical model still provides a useful tool to articulate the relationship between the different factors that influence innovation; just like borrowing from biology of such concepts as evolution, ecosystem, macroinvention, microinvention etc. in the previous chapters of this thesis shed more light on understanding the POLED innovation process.

### 7.3.3 Justification of the Methodology

The model has so far been reviewed by Dr Rosa Ballardini, a researcher in commercial law from the IP HANKEN-Swedish School of Economics and Business Administration & INNOCENT Graduate School- IPR University Centre. She concluded that it was a "*highly valuable contribution to the deep understanding of the dynamics of innovation, one of the most relevant topics of our global economy*" (Ballardini, 2008). To the author's knowledge, an in-depth analysis or review of the model itself has not yet been done.

Several other mathematical models for innovation dynamics exist, albeit looking through different theoretical lenses. Notably, Utterback & Abernarthy for example looked at the process of innovation within a firm in relationship to its characteristics, namely how innovation influences how the firm chooses to develop its production process technology, and the strategy it subsequently employs to compete and grow (Utterback and Abernarthy, 1975). Using mathematical tools similar to those used to study biological evolution, Ebeling and Scharnhorst took a top-down approach to look at how a new technology or idea is created, evolves and survives through the lens of the random nature of technological change (Ebeling and Scharnhorst, 2000). In other words, using the end result of the proliferation or success of an innovation to explain the what, when, why, how and where it may have started its journey. Kunc, who reviewed several innovation models based on system dynamics - a mathematical modelling technique that explains complex systems, such as innovation, by classifying their components into stocks, flows, and feedback processes, all under the influence of time - concluded that they had not considered the hierarchical nature of the socioeconomic factors that affect innovation (Kunc, 2012). The discussions of this thesis reveal that hierarchy is of course key in innovation dynamics. Besides, most of these models highly focussed on economic issues related to resource acquisition and profit generation, seldom covering intellectual property, if at all, and certainly not in sufficient detail.

The author particularly chose to review the Black Box model of innovation dynamics and not others because its genesis was based on an understanding of the innovation dynamics of a technology analogous to that which is the subject of this study. The influence of several socioeconomic factors on the analogous technology's developmental history mostly and directly mirror that on POLED technology, particularly the effect of new materials and device fabrication processes that form the core of both technologies. Also reflected are the influences of complementary technologies and intellectual property monopolies that lead to licensing programmes which catapulted both technologies forward. The differences are attributed to a change in the external environment - the decades of 1930-1970s vs those of 1990-present - which deem certain factors considered in the analogue less important in POLEDs. Moreover, just as this study takes a bottom-up approach on the role of intellectual property in the innovation dynamics of POLEDs, the Black Box was modelled on a bottom-up approach based on empirical evidence from four case studies, a POLED technology analogue and three other technologies related to POLEDs. As we have discussed above, it was based on the author's experience, initially as an inventor and later as a patent attorney, culminating in interdependent relationships between the different socioeconomic factors. These mathematical relationships were then deconstructed as a set of questions, the answers to which indicated the potential success of the analogous technology. As such, it is expected that the essence of the model considered caveats, assumptions, hypotheses and idealisations relevant to POLED technology, making it more relevant to studying POLED innovation dynamics.

### 7.3.4 Relevance to POLED Research?

As regard to meeting the objective of this research, this model would tell us quantitatively how the different socioeconomic factors influencing POLED development interact. The factors we extracted from the qualitative analysis included: new materials, device fabrication methods, enabling technologies, intellectual property, competition, availability of a precursor market, multidisciplinary collaborations, finances, government/military interventions and timing. We could categorise the factors according to the Black Box convention as indicated in table 7.1 above and accordingly, devise mathematical equations based on which factors interact with which, aided by the chapter 6 narrative. Deconstructing these mathematical relationships would result into a series of questions about the innovation journey; the answers would signpost the potential influencers in the success of POLEDs. This would enable us to draw hypotheses and propose relationships of interdependence between the factors.

Moreover, some of the factors can be quantified while others cannot. Of the former, an estimate figure of patent application fees, prosecution and renewal fees is obtainable from the EPO website for the entire portfolio. However, this would not make up the bulk of the figure required for the IP factor alone - financial figures related to the licensing programme as well as patent attorney fees and other patent administration fees that are not recorded on the EPO website are highly confidential. Minus the publicised data we discussed in section 6.4.3 and 6.5 in chapter 6, we also cannot paint a full picture of CDT's finances or ascertain the full scale of the contribution from the government or the military, again because of the confidential nature of the data. So we remain on the side of one on the outside looking in, using the equations as a signpost to point to the factors that influenced the POLED innovation's journey and being satisfied with determining their interdependence based on the equations. As luck would have it, this is sufficient to meet the objective of this thesis.

### 7.3.5 Development of the Model

Is the model a '*one size fits all*'? Certainly not! As its construction involved a look at the analogous technology - inorganic semiconductors, the author submits that it can easily be superimposed on similar technologies or technologies in closely related industries that are likely to encounter the same factors along their innovation path. However, minute customisation would be required depending on the number and types of different factors (based on the four categories - input, output, parameter, variable) involved. The categorisation will also vary from one technology to another. The devised equations however are general enough to fit any scenario of categories since the empirical research from which they resulted was based on fairly diverse industries. Thus the resultant questions would be a '*one size fits all*', within the limitations of the selected factors.

Further, the interdependence equations are not exhaustive and others fitting different scenarios or zooming in on particular outputs can be devised. Each new system would have to take care to its own caveats, assumptions, idealisations and hypothesis, particularly, the further the technology is away from inorganic semiconductors. For industries that are far from technology, and in particular, where different external agencies apply, the author can only speculate the general idea of the model could be borrowed but the substance would significantly differ.

### 7.3.6 Conclusion

The Black Box model was found to be sufficient for aiding the study of the innovation dynamics for organic semiconductors, usefully providing a starting point for determining the dependency relationships between the socioeconomic factors that influenced the innovation's path. Quantitative data could not be obtained for reasons of confidentiality, but not on account of the model itself.

## 7.4 IP as a Commercial Tool

The analyses in chapter 5 revealed that CDT's patenting behaviour was regular, rigorous, global, building brick by brick upon the fundamental patents. The frequency of patenting showed that the technology has moved from emerging to growth and finally to maturity. The result, a large and expansive POLED IP portfolio that was used to build an equally impressive network of academic and industrial partners with CDT at the nucleus. The journey to creation of that nucleus was however a bumpy one.

Given CDT's relatively small size at the outset, its IP was especially crucial to its success in the electronics industry. Its limited resources and manufacturing capability was neither a match for incumbent and competing technologies nor for its funding and market support by established multinational corporations in the value chain. CDT had stumbled upon something revolutionary but it was not enough to file for a patent and hope for the best - it had to make its voice both heard and loud enough to attract the requisite resources to take the technology forward.

The discussion in chapter 6 (section 6.3.1) showed that at its formation in 1992, CDT had originally intended to be a sort of one-stop shop for all your POLED needs, for everything from polymer materials, to device fabrication techniques, the requisite know-how, personnel and expertise, to fully assembled devices. However, its resource base did not permit this. Its commercially aware management team, comprising senior researchers and renowned commercial guru CEOs, recognised this and adjusted the business model to focus on the development of polymer materials and licensing subsequent IP to incumbent companies to raise the resources it needed. These were sufficient in personnel and expertise but required finances for, aside from the day-to-day demands of a business, advancing the technology from its infancy level, in addition to filing, executing and maintaining the patent portfolio.

That strategy paid off; it licensed to a major player in 1996, Philips Electronics, followed by three more licensees the following year (see chapter 6, section 6.3.1.2 for details). The benefits? Credibility for its revolutionary technology, resources in the form of licensing revenue, permission to cross-license and sub-license its licensees' IP, and an appearance on the commercial stage by way of prototypes of the technology shown to the consumer. This signalled to the industry that it had something worthy of attention.

CDT continued, promoting adoption of the technology by the industry and at the same time, raising funds through government and academic channels, venture seed capital, angel investments, private equity firms, a listing on the Nasdaq before eventually being bought by a large chemical multinational, Sumitomo Chemicals (see section 6.4.3). The asset on which all this hinged - IP covered one of the most revolutionary technologies of our time.

However, for the speed at which CDT wanted to move, the pool of licensees was not sufficient. So it built a manufacturing facility in Cambridge and adjusted its business model to include small-scale manufacturing. It could now, as part of the licence deals, offer: service packages; aid licensees' staff in training and troubleshooting, particularly with regard to bypassing the technical issues encountered by its licensees in incorporating the technology into commercial products; and substantially make and sell products of their research, such as materials and equipment. This went a long way in demonstrating the viability and value of its POLED technology to the industry, and its voice was now becoming too loud to ignore.

Not before long, the licensing pool had grown from 4 in 1997 to 14 by 2004 and to 36 by 2010 (see section 6.3.1.2 of chapter 6). In addition to access to continuous resources, expertise, personnel, manufacturing infrastructure, market entry on well-known brands, credibility etc. CDT's licensees provided, several were joint development partners in POLED technology research (both fluorescent and phosphorescent POLEDs, the latter following acquisition of Opsys' dendrimer technology), as well as in several enabling technologies such as inkjet printing (with Litrex), black layer technology (with Luxell) etc. This is evidenced by the licensees either being named on POLED patents as co-innovators with CDT (see appendix 6) or acquisition by CDT of some of its licensees' IP portfolios, and sometimes in addition the entire company (e.g. Opsys, Next Sierra, Maxderm Inc., Toppan Printing etc.). The obvious advantage of gaining IP covering complementary technologies would be continuity in innovation that would in turn further POLED development.

Interestingly, CDT's licences remained extant since they applied to patents valid at the execution of the licence agreement, in addition to any future patents, and until the expiry of the very last of the patents (CDT Inc., 2004 at p58). This potentially created a lifelong bond between CDT and its partners, or for at least as long as both parties were willing to keep the partnership running. In addition, CDT gave and was in turn given permission to cross-license and sub-license its licensees' proprietary material. In addition to increasing both parties' learning and tying them into a longer relationship, this increased the potential pool of IP available to both for negotiations of future partnerships. These relationships were further enhanced by IP CDT acquired from companies dealing in complementary or enabling technologies that it bought.

Eventually, CDT's business model had developed to include research and development, small-scale-manufacturing, provision of training and service packages, overarched by an extensive and generous licensing programme of which the key point was that it included those that had a "*positive contribution*" to the technology's development (Seldon et al., 2005, p11). In this way, CDT developed many close and mutually fruitful collaborations with its partners, rooted and grounded on its IP. It thus created a new type of POLED-based ecosystem at which it was the heart, interacting extensively with both up and downstream players for the advancement of the technology.

Further, although POLED technology was well suited for a niche market, CDT opted for initial commercialisation in a mass market with the assistance of its big name licensees who consistently and in a timely manner launched prototypes and commercial products utilising its technology, albeit necessitating the investment at hefty sums in the beginning. CDT aided them in adapting the technology to their commercial products through trouble shooting technical assistance at its manufacturing facility, to further solidify their relationship and prove viability of its technology. This proved very fruitful; several of them, discussed in chapter 6, have plans for volume production of POLED based display products (see table 4, chapter 6). This should subsequently result in the lowering of the cost of POLED display applications in the near future, to a number low enough to knock the current market leader, LCD, off its throne.

The aforementioned observations complemented the conclusions of the top-down economic studies on CDT discussed in chapter 2. Lubik (2010) for example, was aimed at understanding how spinout companies created value analysed 67 university spinouts "*identified as actively involved in and most likely to be*" commercialising advanced materials from 14 top-tier UK universities - see Lubik, 2010 at p100 for the list of the spinouts. The classification of 'advanced materials' was based on spinouts whose "*core technology [was] focussed around the development of novel materials, novel and/or improved processes for producing materials, or both*". The average age of the spinouts was 6.3 years.

To capitalise on the common experiences and challenges faced by the spinouts, and further examine the different strategies they individually developed to navigate challenges so as to create value for their materials, 7 spinouts were chosen out of the 67 for in-depth studies. CDT was one of the 7 spinouts - see Lubik, 2010 at p125. These spinouts were chosen based on a range of value creation experiences (no value, low, moderate and high), and on the business ideas, available resources and how well they interacted within their ecosystems.

The study concluded that, of all the spinouts sampled, CDT had created the most value - total revenue/age - for its materials (at p126) as it had raised the most extensive funds from its collaborators (see Lubik, 2010 for figures 57 & 59). It was also found to have amassed the "*most expansive access to complementary assets*" (Lubik, 2010 at p210). All the foregoing was a consequence of the breadth of partnerships and extensive licensing programme it had formed throughout the lifecycle of POLED development in comparison to the other spinouts, and of the business model it had adopted (see Lubik, 2010 at p93). This was discussed at length in chapter 6, and spanned corporate partnerships (e.g. Sumitomo, Seiko Epson etc.), other university spin outs (e.g. Plastic Logic, MicroEmissive Displays etc.), the government (through research consortia), the parent institution (i.e. Cambridge University), and other higher education institutions (e.g. University of Singapore, ETH Zurich, Northwestern University etc.). As such, CDT was also found to have accumulated the largest amount of IP, reflecting its need to manage these relationships (Lubik, 2010 at p189).

The study further went on to observe that the growth and success of the spinouts highly depended on their collaborative partners, their ability to access resources from them, and how well they had tailored their business strategies to create value particularly for themselves and others in their innovation ecosystem. CDT and two other firms were found to have undergone the most extensive evolution of their business models in response to different obstacles they encountered along the path, and as a result were found to be the closest to the consumer in their respective value chains (Lubik, 2010 at p197). CDT was hailed as the most successful spinout, this success being hinged on its ability to partner with "*industry leaders early in development process*" as well as "*creating a new ecosystem of firms working on the new POLED technology and altering the old value chain*" (Lubik, 2010 at p194). In my view, CDT's patent portfolio was the grease behind that machine.

This and other studies of university spin outs, science-based ventures and SMEs that included CDT as part of their case studies all echoed the same conclusion - that maximisation of these diverse relationships, both very early on in the development stages and later, is what led to CDT's success (Lubik, 2008; Lubik et al., 2013; Maine and Garnsey, 2006; Minshall et al., 2007). Namely, to enable it to take advantage of mainstream markets (as opposed to a niche one); to plant itself firmly within the existing ecosystem without requiring downstream players to make major changes; and additionally to create a new ecosystem around itself in which it played a central role (aka the extensive licensing programme). That business model, centred on effective management of collaborative relationships through IP, was found to be more successful than say for example those that targeted a niche market to protect themselves against competitors, or those that primarily focussed on developing their technologies and manufacturing final products.

Lubik et al. (2013) - which focussed on the market strategies of spinouts - additionally concluded that by planting itself in a central position in the emerging POLED ecosystem, CDT had reduced the risk of potentially detrimental partner dependence (at p17). This dependence would, for example, manifest itself in a reliance, for the success of POLED innovation, on the market success of other innovations (particularly the display end products) or on the adoption of the technology by the industry before it has even reached the consumer (at p9). CDT had avoided this by co-patenting and sharing its IP with some of its partners - both parties being equally involved in the development of POLEDs from the ground up as it were. Co-dependence would have also been reduced in part by CDT's demonstration of the value of the technology through, for example, its manufacturing plant at Cambridge from which it was able to provide service packages to assist some of its partners to incorporate the technology in consumer end products.

Maine and Garnsey (2006) also concluded that CDT's option for a mass market, and in particular focusing on a single large industry as opposed to opting for multiple mass industries or a niche market is what contributed to its and POLED technology's proliferation (at p389). CDT had opted for several applications within consumer display electronics - televisions, computers, tablets, cameras, mobile phones, public electronic displays etc. Because CDT lacked the accumulated process know-how sufficiently to lower manufacturing prices that would have been gained through years of research and development, Maine and Garnsey stated that this choice of market entry was crucial to convince the display industry value chain of the viability of its highly uncertain technology. CDT had, in particular, to persuade: (1) players below themselves in the value chain to incorporate POLED materials into their components such as chips to be used directly in end products, and (2) players above themselves in the value chain to manufacture POLED materials at costs lower or comparable to those at which they already manufactured lucrative and incumbent technologies such as LCDs. As we have seen, all these relationships, in addition to the activities that took place at the in-house small-scale manufacturing facility to meet the same objective, were effectively managed and based on CDT's IP portfolio.

## 7.5 Patent Citation Analysis

### 7.5.1 What is Patent Citation?

From the foregoing, we have seen that IP played a major role in the commercial development of POLED technology, as well as the growth of CDT as a company. From the narratives in chapters 5 & 6, we ascertained that the IP at discussion here is patents, in particular, those related to POLED development that name Sir Richard Friend as an inventor, and are indicated in the data analysis and the appendices. The following discussion will be focussed on these patents. At the time of the analysis, CDT had 6 trade marks, no registered designs or copyright, and also owned a multitude of other patents related to complementary technologies that it had acquired throughout the course of its development. This non-patent IP, in addition to any other CDT may own, is not the subject of the discussion.

The next useful thing is then to determine whether all the patents in the analysed pool played a similar role or whether some were more important than others. The PTA in appendix 6 and analysis in chapter 6 also mentioned that some were considered as fundamental patents. These are so named because they covered the pioneering paradigms/technology as opposed to an 'improvement patent' which by definition, merely builds upon, extends or modifies the technology of the fundamental patent. These more important patents are what may be infringed by the making, using or selling of the technology covered by the improvement patent or indeed, related patents. As such they are usually the basis of licensing programmes - through which others obtain permission to make, use, sell or perform any of the other exclusive right of a patentee.

For CDT, these fundamental patents were: **PCT/GB90/00584** (priority application: **GB8909011**) - covering the use of an organic polymer in a light-emitting device; **PCT/GB91/01421** (priority application: **GB9018698**) - covering use of organic copolymers in luminescent devices; and **PCT/GB93/00131** (priority application: **GB9201240**) - that covered the use of conjugated polymers in luminescent devices. CDT itself stated that these particular patents were fundamental to OLED technology (CDT Annual Report, 2006 at p13 & 24). Not surprisingly, CDT stated in its annual reports that its extensive licensing programme was built upon these patents (CDT Annual Report, 2006 at p13 & 24). From a technological point of view and the patent data analysis in chapter 5, it is easy to see how the whole POLED development could possibly stand on these three patents. This indication is qualitative.

Another way to study the importance of individual patents in a given patent portfolio is by using quantitative methods. Several of these methods are detailed in Tekic et al. 2013 and Wu et al. 2015. Tekic et al. (2013) in particular groups patent valuation methods into two main streams: the first is based on an analysis of patent indicators such as patent citations, patent family size, the scope of a patent, patent lifetime, number of claims, grant decisions, grant oppositions etc., while the second surveys opinions of patent value from experts, patent owners and inventors. While the latter is subject to the responder, the former is more likely to provide an objective conclusion to meet the purposes of this study.

Further, against an investment background of identifying the highest quality patents that were most likely to be purchased, brokered or licensed out of a large pool of patents, Oliver, Costa and Richardson (2016) reviewed some of the available quantitative methods, several of which were listed in the first group of Tekic et al. (2013). The authors focussed on the five most effective methods, ranking them in order of significance as: (1) forward citations; (2) the age of the patent; (3) the number of independent claims; (4) the number of words in the patent's claim 1; and (5) the size of the patent family. Out of the pool of millions of patents they evaluated, forward citation analysis was found to be the main predictor of a patent's value, at a ranking of 45% in relation to the other methods. As such, forward citation was considered as the quantitative method of choice; the other four will not be discussed.

Forward citation analysis indicates the number of citations received by a particular patent in subsequent patent applications and granted patents. These citations are made by the Patent Examiner who would have at his disposal all published and unpublished patent data relating to a particular subject matter; Examiners are trained for this more than the average scientist. The authors in Oliver et al. (2016) went on to state that within the pool they analysed, patents that had been sold or brokered had exponentially higher forward citation rates than litigated and issued patents. They accordingly submitted that forward citations were a representation of the usefulness of the invention covered by the cited patent and subsequent industry-wide R&D investment in that particular area. In addition to the aforementioned empirical studies, courts have also agreed with the use of patent citation data to value a patent (*In re Innovatio IP Ventures, LLC Patent Litig.* (2013). WL 5593609 9; *Oracle America, Inc. v. Google, Inc.* (2014). 750 F.3d 1339 and *Good Technology Corporation et al. v. MobileIron, Inc.* (2015). No. 5:12-cv-5826-PSG).

### 7.5.2 Justification of the Methodology

Citation data is said to give an indication of how an industry, in general, views the subject matter of the patent in question (Ellis, Hepburn and Oppenheim, 1978; Trajtenberg, 1990; Albert et al., 1991; Shane, 1993; Harhoff et al., 1999; Hall, Jaffe and Trajtenberg, 2005; Tekic et al., 2013). A good patent application must cite all precedent ideas to the inventive concept enshrined in the application; however, opinion on what is relevant depends on a compromise between the Examiner and the prosecuting patent attorney. In a commercial setting, acknowledgment is required to incorporate the subject thereof in similar or sometimes related consumer products to avoid patent infringement liability. In a similar vein, it is prudent to cite the use of the subject matter correctly in scholarly work to avoid plagiarism or copyright infringement liability. Accordingly, there is a general assumption in the aforementioned literature that forward citation gives an indication of how strong or weak the content of the cited patent is. The hypothesis is that strong patents - those that cover valuable inventions - will severally be cited because they are likely to indicate further research, and subsequently, patenting in that area, while weaker patents - covering less valuable inventions or perhaps alternative and/or optional solutions to problems - would indicate a lesser degree of research and hence attract fewer citations. The relationship between citation data and the importance of a patent is thus a longstanding one.

Not all agree however with correlating the citation rate of a patent to its value. Abrams, Akcigit and Popadak (2013) strongly asserts that patent citation does not directly translate to patent value, in fact, they explored empirical and theoretical evidence that showed that the relationship between the two is non-linear (at p2). Having extensively reviewed other analysts' approaches to the subject, they attributed this longstanding and erroneously industry-wide assumption to the fact that most company patent data are confidential; the portfolios studied, usually belonging to a single company, usually do not have the technological breadth and sample size from which to draw a solid conclusion; and it is not the norm for companies to assign revenues to a specific patent (at p2). Bearing this in mind, the researchers nullified the assumption by analysing a large and diverse patent portfolio that was free of these limitations. They then concluded that the relationship between patent citation and value was in fact more like an inverted-U shape resulting from two types of innovation efforts; the first exhibiting the traditional linear relationship as a result of what they called productive patents, and the second, a negative relationship resulting from defensive patents. In the language of this thesis, productive patents would be those filed behind the preamble of the patent system - to promote innovation - while defensive patents are synonymous to blocking patents filed by competitors - see discussion in section 6.3.1 in chapter 6. Defensive patents by their nature would supress innovation and this would explain the negative relationship with the citation data. To the author's knowledge, Abrams et al., 2013 is the first study of its kind to offer a revision of the traditional assumption.

Other technical objections to the traditional assumption which also fuel the fire include assertions like: (1) Patent Examiners' references are sometimes more encyclopaedic in nature than relevant to the subject matter; (2) patent attorneys purposely cite their clients' patents and applications leading to so-called self-citations that are likely to skew such an analysis (Cullis, R. 2017, personal communication, 10 February); (3) as will citations relating to divisional or continuation applications that are essentially extensions of main patents (Oliver et al., 2016). Further, caution has been advised as not all highly cited patents are used to create commercialised products - consideration of actual or threatened infringement of a product or process has been deemed a better indicator of value by way of actual use of the subject matter of the patent (Tekic et al., 2013).

From the foregoing objections, it clear that evidence of use of the actual patents in the form of patent-specific revenues would be the gold standard, and that looking at the citation data in context of the highlighted sources of error would undoubtedly improve the patent citation analysis. Nevertheless, and considering that that information is either not publicly available or has to be obtained through actual practice, I concluded that a patent citation analysis was sufficient to meet the current research objective - to identify, or at the very least, give an indication of the most valuable patents in CDT's patent portfolio. In any event, a large number of innovation studies based on the original assumption have provided invaluable credit to the relationship between citation data and patent value so perhaps it is a question of revising the old to the new.

### 7.5.3 Methodology

Several patent citation databases are available online. Amongst other factors, their ease of use greatly varies according to whether the citations searched are purely by other patents, or both patents and literature; on the breadth of the aforementioned; on how the results are presented; and on how big the subject data pool is. I sampled several of the highly recommended databases available and settled with using the Patent Integration Database (Patent Integration Database). This provides only patent-to-patent citations and claims to "*contain over 46 million patent gazettes from Japan, America, Europe, China and Taiwan, and specialised client software to access that database... [and to be] one of the world's largest citation patent database covering 120 million citation records*".

The "Advanced Search" in the database was utilised. Each patent in CDT's portfolio was analysed. The search was based on the PCT numbers - entered into the database by their publication number, e.g. **PCT/GB90/00584** was searched as **WO90/13148**. National patent numbers were not used because some of the PCT applications were abandoned by CDT before they went on to the national phase, and several of the applications that went to the national phase sometimes had multiple applications in a single national phase (such as **PCT/GB95/03043, PCT/GB91/01421** and **PCT/GB99/00741** that had multiple US continuation applications relating to a single US national patent application). This would have otherwise created too many variables.

The method itself involved selecting the all databases option in the Advanced Search, setting the first search field to "Main Ref. Cite." (to search for all patent data citing the patent to be searched) and inputting the patent to be searched by its international publication number. Hitting the search button returned a list of citing patent data, which was downloaded and saved into an Excel file, with the added function to sort it by ascending filing date. Appendix 7 contains a tab for each patent, showing the bibliographic data for the citing patents and applications. From this, the number of citations per year, for the range of 1988 - 2016, for each patent was determined (black columns) and the cumulative citation frequency calculated (red columns) - see the Analysis tab. The total number of citations per patent is also indicated.

In light of what we have already discussed about CDT's commercialisation strategy, the results should reveal that the highest citation rates correspond to CDT's fundamental patents. The citation tendencies should be similar for the strongest patents right from the beginning so that those types of patents can be identified outright or even extrapolated without the need for several years of citation data. The practical benefit of this is of course enabling companies to avoid or reduce the risk of infringing these patents even before their fundamental nature surfaces through the maturation process of a technology. They should also give an indication of the quality of the rest of the patent portfolio.

### 7.5.4 OLED Patents' Citation Data

Appendix 7 contains the citation raw data. The analysis encompassed citation analysis of between the years of 1988 and 2016. The data includes all the 53 patents analysed in chapter 5 and 6, with the exception of **PCT/GB99/00060, PCT/SG2010/000454, PCT/GB2011/050038, PCT/GB2011/052503** and **PCT/GB2013/051726** for which citation data were not available. **PCT/GB99/00060** was abandoned before the national phase so there is no citation data available. The remaining patent applications (the last four in the above list) all had zero citations. These were filed from late 2009 onwards and the lack of citations may be attributed to the fact that some of the national phase applications have been rejected and several are still going through the prosecution process.

Firstly, the patents were cited on average 2.2 years after their filing date; 32 out of 53 patents (60%) were cited within 2 years of their filing date (see tab "Year of 1st citation" in Appendix 7). As discussed in section 6.3.1 in chapter 6, this indicates the level of steady interest in the technology and the flurry of R&D activity that typically follows the publication of a paradigm changing technology or solution to an industrywide problem.

Secondly, the citations per patent drastically increase as the years go on, with several plateauing in the final few years of the analysis. Figure 7.5 shows a plot of the patents against the cumulative frequency of citation - a larger version of this can be found in Chart 1 in Appendix 7, with the advantage of zooming into individual data points. This is indicative of the growth of interest in the technology as the new paradigm starts to influence the industry, leading to more players getting involved and subsequently more research as the technology goes through the maturation process. As was discussed in the patent trends analysis in section 5.6 of chapter 5, the annual speed of CDT's patenting - distinguishing the levels of maturity of the technology to emerging, growth and maturation stages - almost directly mirrors the citation numbers. This is also illustrated in figure 7.6, taken from Chart 2 in Appendix 7.

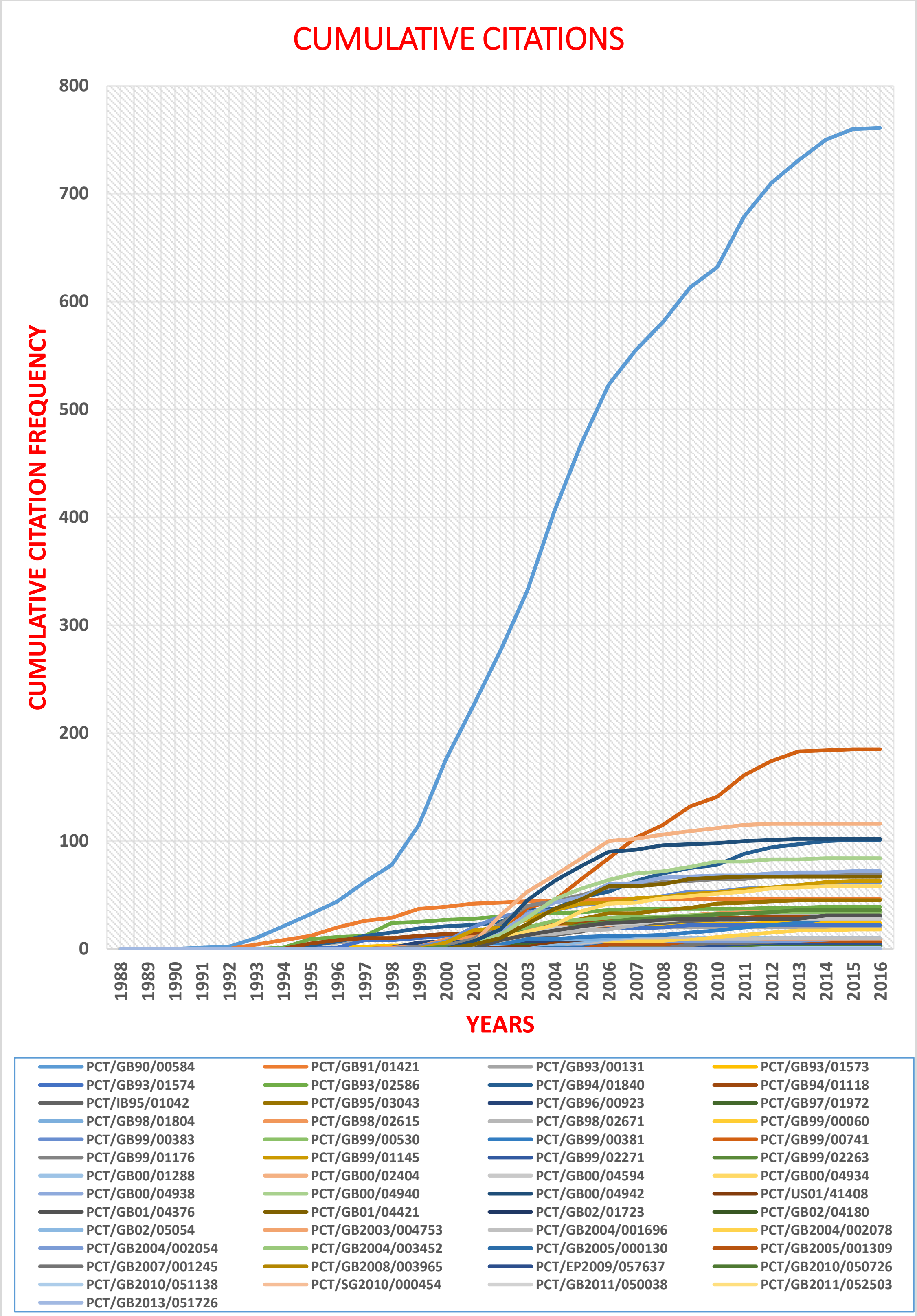



***Figure 7.5: A plot of cumulative citation frequencies per patent over the period of 1988 to 2016 (Source: Chart 1 in Appendix 7)***

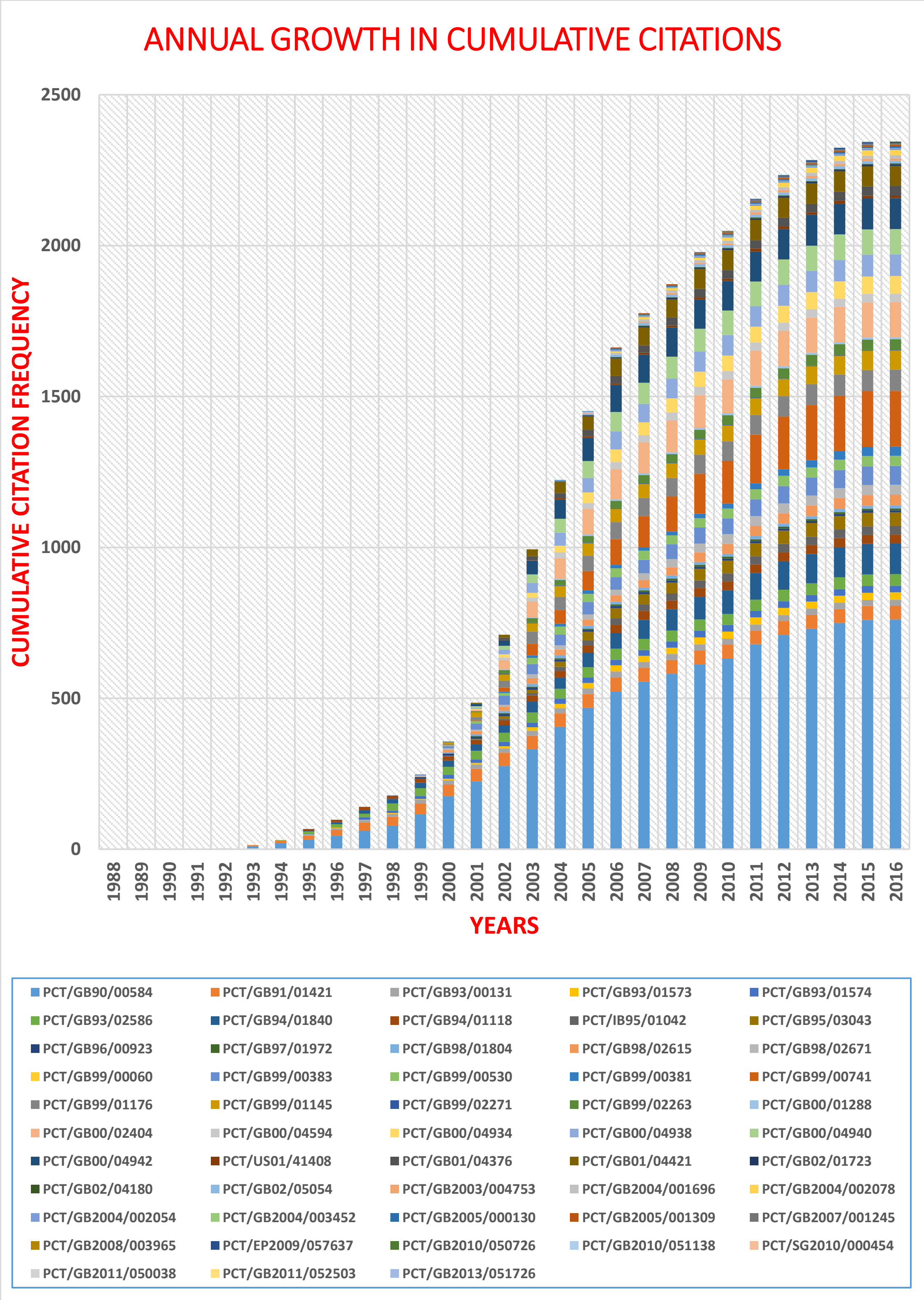
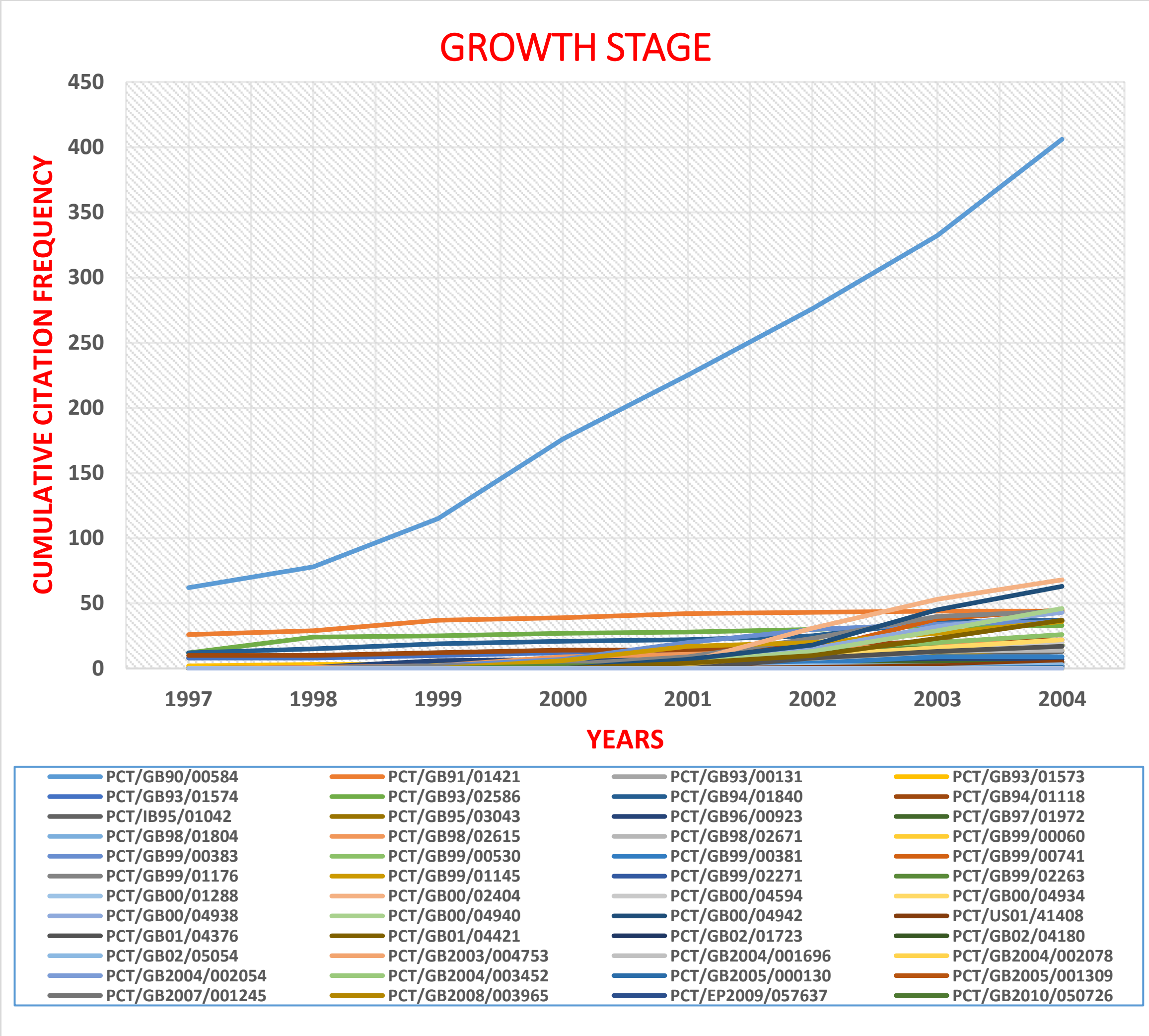



***Figure 7.6: A bar chart illustrating annual increase in cumulative citation frequencies for the period of 1988 to 2016 (Source: Chart 2 in Appendix 7)***

The emergent years were 1989 - 1996, when CDT filed an average of two patents per year. With the exception of the first fundamental patent, **PCT/GB90/00584,** the citations for this period (only relevant for patents 1-11 that had been filed) were zero to very low; this is clearly seen in figure 7.5 and 7.6 above. This is not unusual given that the technology only had a lifetime of about 7 years.

The growth stage was adduced as 1997 - 2004 when CDT on average filed four patents a year; this is matched by a steady increase in citations for nearly every patent (see figure 7.7). An exponential increase in patents filed (from the patent trends analysis) matched by an exponential increase in citations is indicative of growth in the technology. Additionally, more researchers/commercial partners were collaborating with the pioneer, CDT, and getting in on the action. The reader may cast a glance to section 6.3.1 in chapter 6 to see the matching growth of CDT's collaborations from 4 licences to 14 licences for that period.



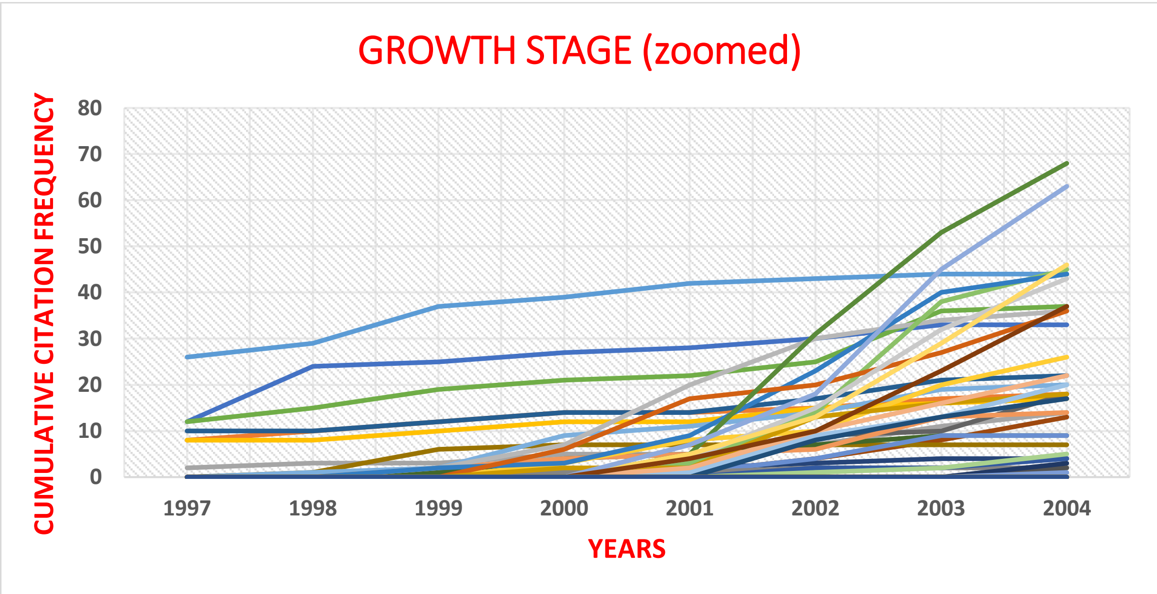
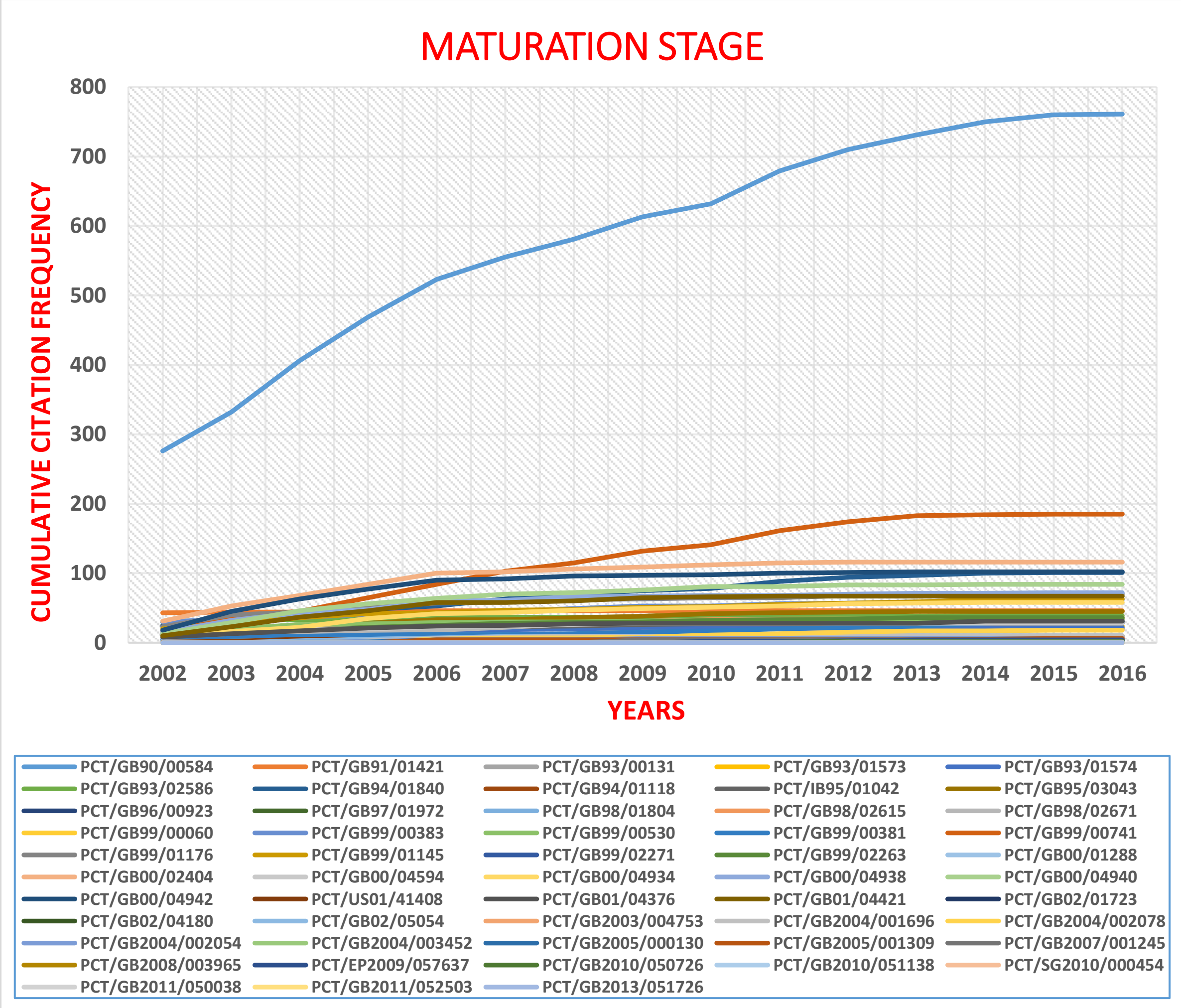




***Figure 7.7: A plot of cumulative citation frequencies for the growth period of between 1997 and 2004, with the second plot showing an enlarged view of the patents minus PCT/GB90/00584 and the 5 zero citation patents (Source: Chart 3 and 4 in Appendix 7)***

With the exception of **PCT/GB90/00584** (one of the fundamental patents) and several others to be discussed shortly, the plateau in citations observed from 2005 - 2016 indicates the attainment of the maturity stage - the citation numbers are fairly constant (see figure 7.8). This can for example be seen in **PCT/GB93/01573, PCT/GB93/01574, PCT/IB95/01042, PCT/GB96/00923, PCT/GB99/00530, PCT/GB99/01176, PCT/GB99/01145** etc.



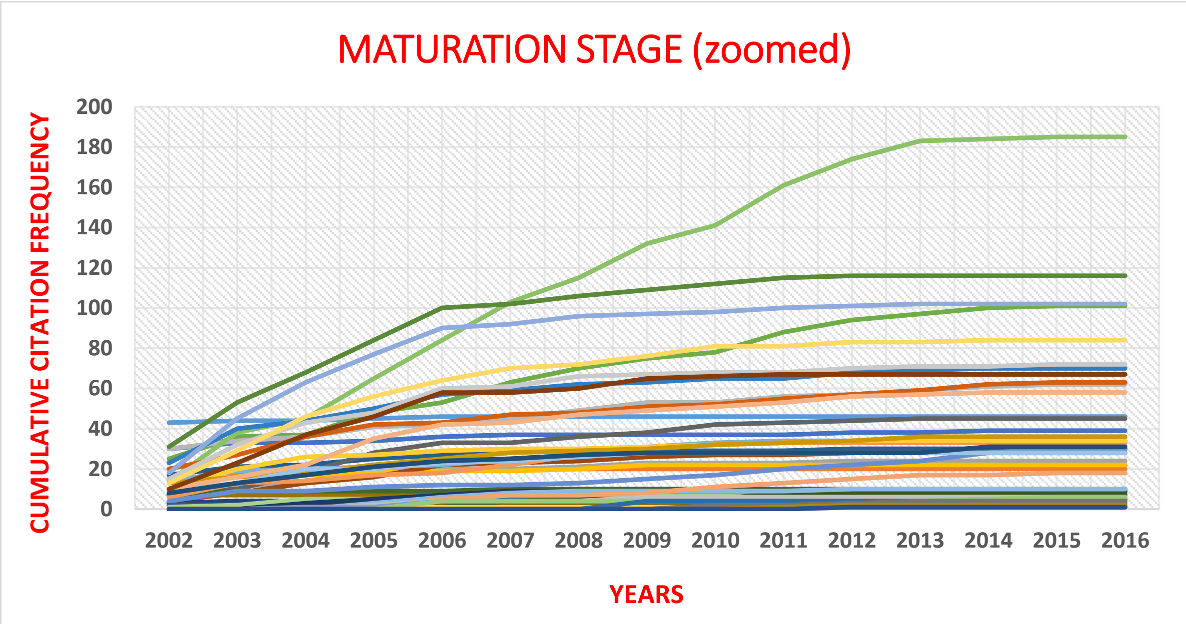




***Figure 7.8: An illustration of the maturation stage, which is between the years of 2005 - 2016, with the second plot showing an enlarged view of the patents minus PCT/GB90/00584 and the 5 zero citation patents (source: Chart 5 and 6 in Appendix 7)***

For the patents whose citations are still increasing during the maturation period (i.e. **PCT/GB94/01840, PCT/GB99/00383, PCT/GB99/00381, PCT/GB99/00741** and **PCT/GB99/01145**), two explanations come to mind. Firstly, it could indicate an adoption of the principles therein by complementary or enabling technologies, to aid the adoption of POLED technology for consumer products as market appearance becomes a real possibility, and secondly, a multidisciplinary cross-over of the concepts contained in those patents into other disciplines as the scope of applications becomes more feasible. **PCT/GB94/01840** for example introduced the idea of forming a single electroluminescent device from multiple complete devices, stacked but yet each independently operable. This would for instance allow for one device to be switched on in one mode while the other was off, or both devices to be on or off at the same time; the result would be an expansion of possible applications, opening up a new avenue of R&D that would lead to more citations. Similarly, **PCT/GB99/00383** introduced the concept of including switch and drive means to an electroluminescent device so as to permit separate control of individual pixels; this would also increase the number of possible applications and encourage further R&D. **PCT/GB99/00381**, which introduced the use of inkjet printing to deposit polymer layers, **PCT/GB99/00741** that taught the manipulation of heterojunctions for light production and **PCT/GB99/01145** that allowed for lower power consumption would all have the same effect of stimulating further R&D. These explanations are also supported by the addition to CDT's portfolio and licensing pool of collaborators and partners involved complementary technologies, such as Seiko Epson, Konica Minolta and Ulvac for ink jet printing technologies just before 2005, a collaboration in 2006 with Toppan Printing in relation to roll-printed displays, acquisition of the chip manufacturer, Next Sierra, in 2007 etc. (see chapter 6).

Further, the highest cited patent, **PCT/GB90/00584** (GB priority: **GB8909011**), had a cumulative citation rate of 9544 in comparison to the lowest cited patent, **PCT/GB2010/051138,** that ranked at 5. This is not surprising - **PCT/GB90/00584** was the application filed when Jeremy Burroughes serendipitously observed the emission of yellow-green light when he was experimenting as a post-doctoral student with the organic copolymer materials at the Cavendish Laboratory. This paradigm shift initiated the whole POLED revolution, and the discovery was later nominated as European

Invention of the Year in 2006 (EPO, 2006). This patent is equivalent to Bell Laboratories' point contact transistor patents **US2524034**, **US2524035** and **US2617865** and bipolar junction transistor patents **US2569347** and **US2623102** (see chapter 3, section 3.3). **PCT/GB2010/051138** probably has that low a citation rate because it was only filed in 2010 and relative to **PCT/GB90/00584,** has only 6 years' worth of citation data. This same explanation can be offered for other patents filed around the same time - **PCT/GB2010/050726, PCT/EP2009/057637, PCT/GB2008/003965** etc.

The fundamental patents **PCT/GB90/00584, PCT/GB91/01421, PCT/GB93/00131** which mark dominant paradigms characterising Schumpeterian A-phases all had fairly high citation rates, at 9544, 899 and 357 respectively. This confirms my hypothesis that the most important patents, the fundamental ones, would have the high citation rates to correspond with their strength. This is indicative of the scope of what they protect - the use of organic polymers, organic copolymers and organic conjugated polymers in a light-emitting devices respectively. Any activity that related to any kind of use of these polymers luminescent devices of any type, whether individually or in combination with another device, would fall into the ambit of those patents. And so, any subsequent patent application in any jurisdiction would prudently have to cite those foundation patents in the preamble to the patent specification to pre-empt objections from a patent examiner. Failure to do so would be pointed out in the patent application search report, triggering another citation.

Moreover, the citation rates of the fundamental patents (as identified by CDT) appear to exhibit an hierarchy based on their subject matter. It is not surprising that **PCT/GB90/00584** (organic polymers) has the highest citation rate being that the class of polymers it protects would encompass both those protected by **PCT/GB91/01421** (organic copolymers) and **PCT/GB93/00131** (organic conjugated polymers). The last two patent applications would therefore have to cite it, and similarly, **PCT/GB93/00131** would have to cite **PCT/GB91/01421**. Subsequent applications citing either of the three would have to follow the same convention. It appears therefore that the narrower the class of polymers claimed, the lower the citation rate. This also confirms my categorisation of **PCT/GB90/00584** as a paradigm shift introducing invention, and

**PCT/GB91/01421** and **PCT/GB93/00131** respectively as a "sailing ship" effect and a solution to a specific problem (see Appendix 4)

The next patents in the list **PCT/GB93/01573** and **PCT/GB93/01574,** that introduced the idea of using multiple light-emissive layers in a single device, had citation rates matching that of the third fundamental patent (**PCT/GB93/00131**). Both were the subject of a new paradigm but yet **PCT/GB93/01574** had a higher citation than **PCT/GB93/01573**; 352 in comparison to 320. A closer look at the subject matter of the patent answers this conundrum; **PCT/GB93/01574** related to a light-emitting device itself while **PCT/GB93/01573** related to the manufacture of such a device. As there would be several methods of manufacturing light-emissive devices, as we have seen throughout the thesis discussion, it is not unusual that the patent related to manufacture has the lower citation. The low citation rate could also be explained by the fact that a device can still be effective without multiple light-emissive layers.

The aforementioned variance in citation rates led to a categorisation of all the data into three main groups: high (1000 - 2000), medium (500 - 1000) and low (30 - 500) (see figure 7.9). The extremely highly cited patent at 9544 is **PCT/GB90/00584** and the reasons for that have already been dealt with. Likewise, the reasons for the patents with no or extremely low citations such as applications still undergoing prosecution and the lower lifetime of those patents in comparison to say **PCT/GB90/00584** since they were filed much later have also already been discussed.

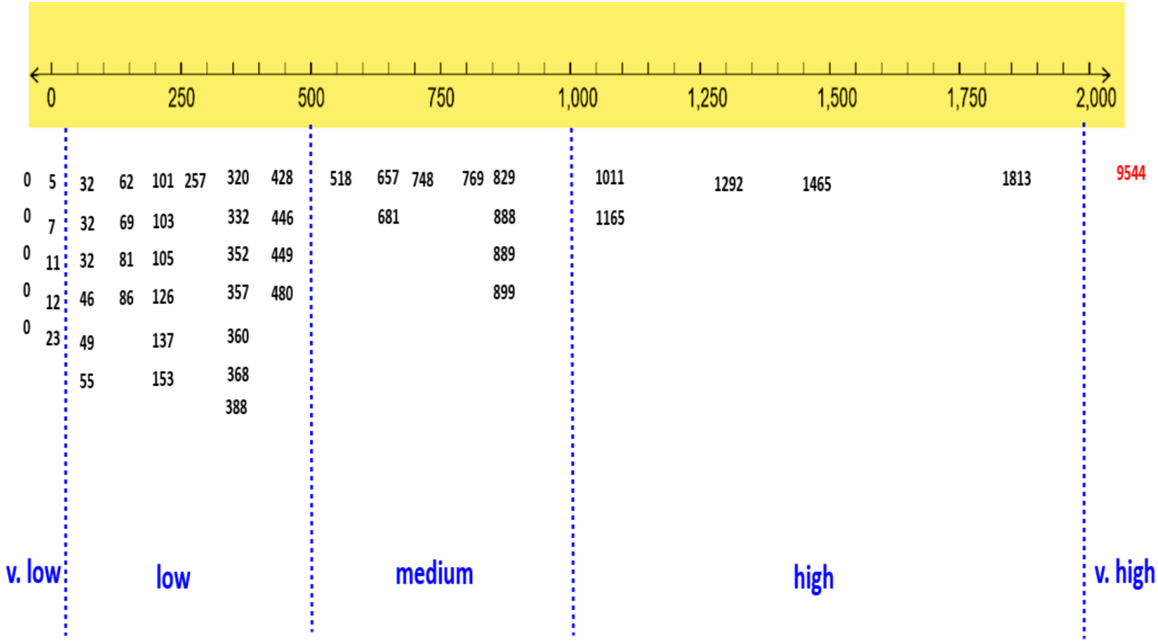



***Figure 7.9: A classification of the citation data into categories of occurrence (Source: Deborah Sewagudde)***

All the high citation rates, i.e. 1165, 1813, 1465, 1011 and 1292, related to the paradigm shift introducing patents **PCT/GB94/01840**, **PCT/GB99/00741**, **PCT/GB00/02404**, **PCT/GB00/04940** and **PCT/GB00/04942** respectively, as categorised in Appendix 4 and chapter 6. **PCT/GB94/01840** for example covered the first organic device comprising stacked and complete devices that were each independently operable. **PCT/GB99/00741** concerned specific manipulation of heterojunctions for light production. **PCT/GB00/02404** introduced a novel processing technique to align polymer chains to the axis of the plane of the polymer film so that for the first time it was possible to produce linearly polarised light. **PCT/GB00/04940** taught a method of forming conductive interconnects extending through the sequence of layers in a multi-layered device, allowing for better communication and conductivity between layers. **PCT/GB00/04942** introduced a method of forming a solution-processed device with multiple electrically separated regions. All these were deviations from the normal science the introduction of which rightly sparked off further R&D that resulted in several citations.

Surprisingly, the remaining paradigm shift patents all had low citation rates: **PCT/GB93/01573**, **PCT/GB93/01574, PCT/GB97/01972, PCT/GB99/00530** and **PCT/GB00/04594** at 320, 352, 81, 449 and 360 respectively. Reasons pertaining to the first two have already been discussed above. **PCT/GB97/01972** is particularly surprising; the patent related to the use for the first time of organic semiconductors in transistors. This was expected to be a game changer. However, transistors based on inorganic semiconductors exhibited much superior performance to those based on organic semiconductors because of the inherent lifetime issues of the latter; this perhaps explains why the industry did not jump onto this bandwagon. **PCT/GB99/00530** introduced a method for depositing layers in a TFT using ink jet printing; the low citation could be explained by the fact that the same result could be achieved using an alternative deposition method. **PCT/GB00/04594** related to a novel copolymer that covered the entire visible spectrum to provide good colour tuning; alternative polymers and/copolymers could also achieve the same result.

Patents filed in between paradigm shifts and covering improvements to the dominant paradigms all had medium to low citation rates (see figure 7.9). Patents with medium citation rates such as **PCT/GB91/01421** (at 899), **PCT/GB99/00383** (at 769), **PCT/GB99/01145** (at 748), **PCT/GB93/02586** (at 681) and **PCT/GB95/03043** (at 518) covered major issues that were likely to have been faced by everyone in the industry. Respectively, these related to a method for the semiconductive polymer layer to produce different regions of different optical characteristics so as to allow for the emission of different wavelengths and thus colour from the same light-emissive layer; mechanisms to effectively control pixel switching; means to lower power consumption of a device; addition of chemical dyes to organic polymers to produce blue light; and a method for making polymer resistant to solvent dissolution when multiple layers of the device are being laid down. These problems were shared across the industry so it is not surprising that these citations rates mirror the background R&D in the search for solutions.

The lowest cited patents such as **PCT/GB96/00923** (at 126), **PCT/IB95/01042** (at 332), **PCT/GB94/01118** (at 480), **PCT/GB99/02271** (at 32) and **PCT/GB99/02263** (at 428) covered alternative, and hence optional, ways of achieving a particular result. Respectively, this covered a method involving laminating two devices to form a single light-emitting device, achieving even charge distribution throughout a polymer blend, the use of electron-withdrawing groups to improve device efficiency, a method for preparing nanoparticles to be added to the polymers, and a device utilising polymers with such nanoparticles. All these problems would have had multiple solutions so R&D efforts would have matched this diversity; this would in turn lead to a low citation of a singular solution. These characterise typical Schumpeterian B-phases were continuous improvements are made to different arms of the dominant paradigm once it has settled and been adopted by the industry.

An exception to the classification was **PCT/GB99/01176** (priority date: 16/04/1998) that had a citation rate of 889 yet it covered the first POLED integrated circuit. This was a major paradigm change and the value was expected to be higher, in fact, almost as high as the main fundamental patent (**PCT/GB90/00584**). A possible explanation for this is the age of the patent at the 2016 cut-off date of the analysis relative to that of the fundamental patent - that is, 18 years in comparison to 26 years old. This 8-year gap would be significant considering, for example, that **PCT/GB90/00584** had an average of 55 cumulative citations per year during the growth stage at the 8-year span of 2000 - 2007 or of 25 cumulative citations during the maturation stage between the years of 2008 and 2015. This same explanation can be offered for **PCT/GB00/04938** (priority date: 21/12/1999) with a citation rate of 888 covering the first POLED integrated circuit that was at least part built using ink-jet printing.

### 7.5.5 Discussion

In the famous words of George Orwell in *Animal Farm*, the citation data illustrates that all patents are equal but some are more equal than others. The data are consistent with my hypotheses and expectations thus far. They have revealed the hierarchical nature of CDT's patent portfolio. The main fundamental patent has the highest citation rate, followed by those that introduced major paradigms, those that covered solutions to common industrywide problems, and finally, those that covered improvements within the dominant paradigms that could be attained through alternative means. Accordingly, the importance of the patents in CDT's portfolio follows that same hierarchy. The data also confirms CDT's assertion that **PCT/GB90/00584** was fundamental to OLED technology, but questions the perhaps overstated fundamental nature of **PCT/GB91/01421** and **PCT/GB93/00131** given their lower than expected citation rates. In so doing, it instead reveals a hierarchical relationship among those patents.

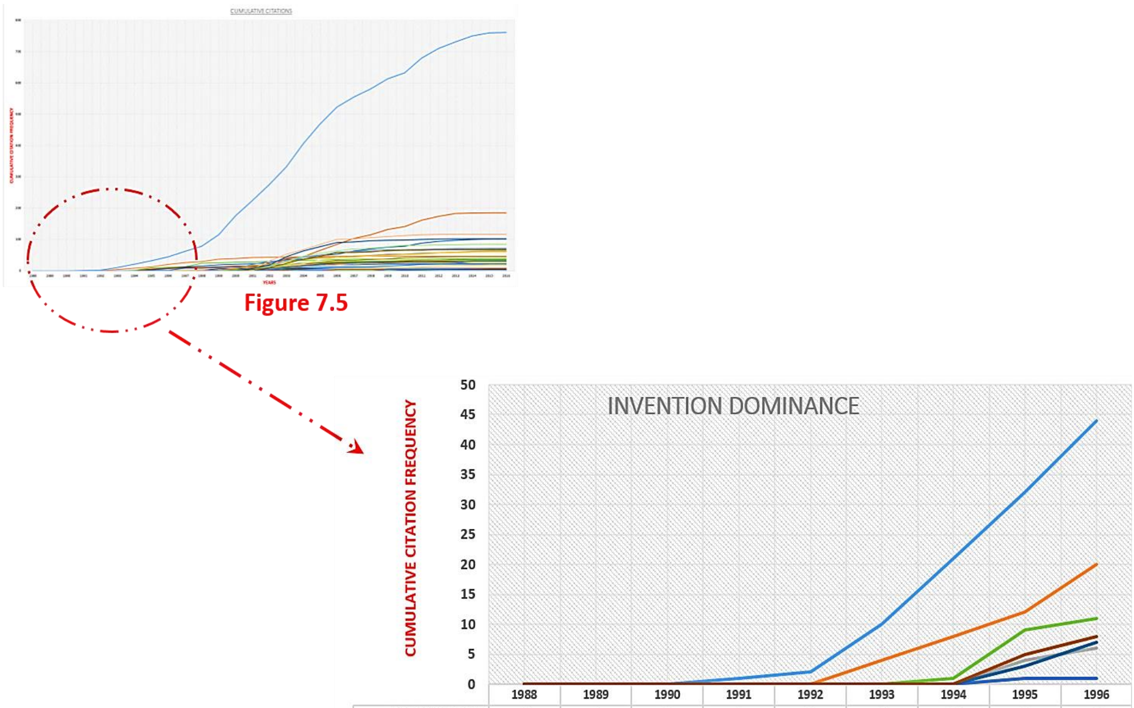
The increase in citation rates as the years progress is also consistent with the maturation stages of the technology. The emerging stage showed a very low increase in citations as the rate of annual patents filed was equally low. Perhaps the industry needed to be made more aware of the new technology, its adoption pushed and R&D encouraged. The growth stage, which is symbolised by a high increase in annual patents filed, is also matched by a high increase in citations as interest in the technology picked up, more participants emerged, more R&D was carried out, and in turn more publications. Then came the maturity stage; annual patents were still being filed, albeit it at a lower speed than in the growth stage, so citations also increased (again, at a lower rate than in the growth stage) until they levelled off into a plateau. This symbolises I believe the current state of the technology where several of the technical setbacks have been ironed out, producing enough progress to enable volume commercialisation in certain applications, as we discussed in chapter 6. Incremental and regular improvements are still being attained in the remaining impediments, such as the blue colour lifetimes. Required perhaps is an enabling external factor that will drive the technology to the next level; this would most likely start a new paradigm or scientific revolution.

Since I am not privy to the details of CDT's commercial dealings, particularly those related to the licences or joint development partnerships, I submit that CDT built its licensing programme around the fundamental patents, embellishing it with those that covered both the major and lesser paradigms. Offering the patents as a package would make commercial sense as several of the workable concepts, as we discussed in chapter 5, build upon each other like pieces of a big puzzle. Several of the commercial partners with whom they were involved had a vision to put consumer products utilising POLED technology on the market, either in display or lighting applications or as complete fabrication methods or processes. The journey to those end products would involve the interaction of several concepts that fell within the ambit of several patents. This would also explain why CDT's licensing programme was very selective and highly coveted by the display industry, and why it turned out to be the most extensive POLED patent portfolio (Seldon et al., 2005; CDT Inc., 2004; CDT

Annual Report, 2006). It would also explain why Maine and Garnsey submitted that CDT's fundamental patents were "*virtually impossible*" to patent around, causing players with blocking patents - patents whose scope of protection intersected with that of CDT's patents - to collaborate rather than compete with CDT (2006 at p390). Rather than quantity of patents, the quality of this tight leash I believe is what was key to the success of CDT's licensing programme, to fostering further connections and firmly grounding them at the centre of the POLED value chain. This echoes the development of the licensing programme for the transistor established by Bell Laboratories, Texas Instruments and Fairchild Semiconductors for inorganic semiconductors, discussed in chapter 3.

Further, the data reveal a linear relationship between citation frequency and time. The slope of the curve, *prima facie*, indicates the importance of the patent from the level of activity by third parties in that area, identifies who the players are, and further points to the success of the patent publication. On a secondary level, it reveals the dominance of a particular invention; this is evident from the slope of **PCT/GB90/00584** in figures 7.5, 7.7 and 7.8 above.

On a practical note, a company can use citation data analysis to determine, or at least predict, the importance of individual patents in its patent portfolio based on such slopes. In the short term, the citation frequency is a good indicator as it is a direct mirror of how the industry views the invention in question. In the long term, looking at the slope of the citation frequency curve (with extrapolation if necessary) will enable the company to allocate correctly resources and R&D to a dominant invention even before the resultant products hit the market. Advantageously, this can even happen in the early years of innovation without the need for several years of citation data. Take for example, a zoom into the 1995 marker on figure 7.5 reveals that the slope for **PCT/GB90/00584** at 32 cumulative citations had already surpassed that of all the other patents (see figure 7.10).




| | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 |
|---|---|---|---|---|---|---|---|---|---|
| PCT/GB90/00584 | 0 | 0 | 0 | 1 | 2 | 10 | 21 | 32 | 44 |
| PCT/GB91/01421 | 0 | 0 | 0 | 0 | 0 | 4 | 8 | 12 | 20 |
| PCT/GB93/00131 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 6 |
| PCT/GB93/01573 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| PCT/GB93/01574 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| PCT/GB93/02586 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 9 | 11 |
| PCT/GB94/01840 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 7 |
| PCT/GB94/01118 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 8 |

***Figure 7.10: Using the slope of the frequency citation curve to determine early dominance of an invention (Source: Chart 7 in Appendix 7)***

Moreover, the main fundamental patent (**PCT/GB90/00584**) and two of the highly cited patents (**PCT/GB99/00741** and **PCT/GB00/02404**) show the seedlings of an "inverted U" shaped relationship that Abrams et al. (2013) argued exists to reflect the reality of both productive and defensive patents. It would be interesting to see if this theory was confirmed or otherwise, with at least a further ten years' worth of citation data, say 2016 to 2026.

The citation data are also in line with the Schumpeterian phase dichotomy; high citation rates for patents indicating the emergence and establishment of dominant paradigms as the standard (A-phases), and lower citation rates for the patents covering improvements to the dominant paradigms and alternative solutions (B-phases). It is evident that there are distinct A- and B- phases for the device types discussed in chapter 5, i.e. for OLEDs, TFTs and FETs. For organic solar cells, the citation data revealed an A-phase that was not followed up into the B-phase.

We could conclude that the citation data covering the integrated circuit could be extrapolated to follow the same pattern - high citation rates matching the filing of the initial patents that covered this new paradigm (A-phase), followed by a fall in citations to symbolise improvements to the paradigm (B-phase). The citation analysis shows that the former is well on its way there; the picture for the latter is so far not clear as the author believes the technology is currently just about revealing the seedlings of this stage. According to Kuhn, the foregoing would mark several complete revolutions through which technological innovation progresses (see chapter 2, section 2.2).

### 7.5.6 Conclusion

From the citation data we have established that knowing that some patents, and thus inventions, are more important than others is crucial not just for the patentee but on an industrywide scale. For the patentee, it is a useful feature that may direct further research, determine the business model and facilitate one's establishment in a particular product's/technology's value chain by determining the choice of partners with whom to navigate the journey to market. For the industry, it is a useful indicator of its view of a particular invention, a signpost to R&D investment and a guiding light to avoid possible patent infringement liability.

## 7.6 Future of CDT and POLED Technology

It is clear that even before it has reached full maturity, POLED technology is a revolutionary and potentially disruptive technology to the electronics industry, particularly to displays in the short term. Its nature allows for very thin displays on both small and large areas, opening up a host of unimaginable applications. On the one hand, it can be used to make very small displays - the world's smallest colour TV screen to be precise (EPO, 2006; Rose, 2015; Bourzac, 2016; Das and Harrop, 2016 at p172 & 186) - and on the other hand, extremely large displays such as billboards and electronic wall paper (Forge and Blackman, 2009 at p91-92; Mertens, 2016; Lucas, 2015; Kunic and Sego, 2012), all the while, at a much lower power consumption than established display technologies. By far, no single technology has that capability. The solution processability of the materials puts it at advantage over its closest rival, SMOLED technology, and renders manufacturing possible with methods such as ink jet printing, which again puts it at advantage over the current display market leader, LCD technology.

Moreover, complementary technologies are advancing POLED technology towards not only better displays with lifetimes that pose a serious risk to replacing the current industry standard, LCD, but have also made unbreakable and flexible displays a reality. Soon, foldable, rollable and wearable displays, flexible smart phones, electronic newspapers and smart packaging will be daily bread. Transparent or dual-sided displays are also underway. As such, the market possibilities are endless: displays, lighting, fashion, automotive, medical, military, and other niche applications to mention a few. Proposed roll-to-roll printing, which will see these applications printed off in a roll, will further lower manufacturing costs as companies would get more bang for their buck.

In addition to opening doors to brand new and almost futuristic applications, POLED technology can be used to improve existing products - this so called substitution effect (Forges and Blackman, 2009 at p61-62). The nature of the technology industry is that older technologies are eventually replaced by newer shinier ones the cost of which is better favoured by the manufacturer, and the technical effects of which are coveted by the consumer. POLED technology has already proved its lifetime superiority (in terms of hours in service) over LCDs in small display applications such as in Samsung mobile phones. Work in large displays lifetimes, and more specifically, blue colour lifetimes, is rapidly improving (see chapter 6). Device fabrication and process techniques are concurrently being optimised. The current LCD manufacturing infrastructure that is owned by LCD players, who are now heavily involved in OLED research, is likely to lower OLED device manufacturing costs, and consequently, the price of consumer products. The possibility of POLED matching silicon is on the horizon, so that silicon chips can eventually be replaced by POLED chips (Cheung and Brach, 2014 at p325-327). It appears likely that POLED will supplant LCD and even some silicon applications.

The innovation has come a long way. What started out as a dim light emitting polymer has, with years of improvements, evolved into a composition of complex polymers coupled to equally complex device structures, capable of easily surpassing previous industry standards. CDT in pioneering and subsequently spearheading the POLED race has evidently carved out a central and significant part in the POLED ecosystem, primarily using its IP as the building block for its ever evolving business strategy. IP has been the leverage used to build an impressively extensive licensing programme that has pulled in partners from all levels of the ecosystem and given CDT credibility, access to scientific resources and complementary technologies that have furthered its R&D. It has gained a direct entry route into the market, off the backs of already established industry giants who are attracting consumer attention by periodically exhibiting prototypes. Its maximisation of its other funding and collaborative avenues has enabled it to remain visible, further taking up opportunities to expand into other applications, markets and even geographical arenas.

However, CDT continues to battle with some challenges that are affecting the technology's commercialisation. At the R&D level, it has to overcome blue materials lifetime issues repeatedly, and in a consistently progressive manner to demonstrate value to its commercial partners and to potential customers of end products incorporating its technology. Device fabrication methods to suit those developments also have to be concurrent. This has to a great extent been enabled by complementary technologies but developments are still needed on all those counts to lower manufacturing prices significantly and to provide consumer friendly prices for the end products. Market entry does not seem to be a problem as the technology can easily be incorporated into pre-existing consumer products, several without disruptive alterations, so this is favourable for end product manufacturers. Progress is steady on the R&D front, the only possible setback being competition from SMOLED technology which is itself a moving target as advances are also progressive. The advantages POLED technology offer over SMOLED make manufacturing easier, quicker, and cheaper, and right into the quiver of display industry. The other contending emerging technologies are still too young to pose a significant competitive threat, so POLED technology is in a good position.

And so, with the right collaborations in place, the consumer has received the innovation with open arms. The current setbacks have been ironed out enough to proceed to volume production so prices will fall significantly in the very near future. The only obstacle then that remains is the price of the established LCD market, which in comparison, is priced like a pint of milk. If the R&D advances continue at the current pace, that giant looks set to be toppled sooner than we realise.

But could it possibly be that the publicised hyperbole surrounding the technology has peaked? Maybe end product manufacturers are too optimistic, feeding into the consumer's curiosity and the promise of an insatiable market with endless profits? Maybe the technologists are too hopeful? Maybe we will ask these same questions in 10 years' time? Or maybe, just maybe, it is all justified, and you are reading this off of your 100-inch wallpaper thin flexible computer screen you mounted to your living room wall, and are just about to peel it off and reattach it to your bedroom wall because you fancy a nap after checking a few emails? Or maybe you are reading it off your mobile smartphone that you are about to fold up and place into your jacket pocket because you need to hail a taxi and make your 7pm dinner reservation? Or maybe, just maybe, the super-thin surface of the eyeglasses you are wearing is receiving a digital signal from your computer or television and giving you a cinema-like reading experience?

*"Hope lies in dreams, in imagination, and in the courage of those who dare to make dreams into reality"* **Jonas Salk**

*"Hope is patience with the lamp lit"* **Tertullian**

*"Let your hopes, not your hurts, shape your future"* **Robert H. Schuller**

## 7.7 Conclusion

Pioneering a technology in an industry that has a propensity to file patents, CDT's success was greatly aided by its tailored business model - benefiting from the licensing programme built around its strong IP portfolio to pull in required resources and expertise but also some in-house value creation based on small-scale manufacture of products and custom service packages. The latter is what demonstrated value to the industry and kept feeding the former. Its ability to maximise the different tiers of its relationships has enabled it not only to stay at the centre of R&D but also eased the way for POLED technology to build and retain market share.

# 8.0 Thesis Conclusion

## 8.1 Research Journey and Chapter Summary

This journey began with a teaching of the technology basics in **chapter 1** - the foundation in chemistry and physics of the underlying working principles of heterojunctions in organic copolymer semiconductors. A brief history of the development of chemical elements was given from the work of medieval alchemist, culminating into what we now know as the periodic table. Atomic theory based on Bohr's model for the atom was introduced, putting a microscope to the behaviour of charge carriers - electrons and holes - within an atom, and their interaction with other charge carriers in their proximity. We then looked at permitted electron spins and energy levels, leading us to the theory of valence and conduction bands (HUMO and LUMO levels). Using carbon allotropes as a case study, we journeyed on to explore how the aforementioned theories could be used to explain the behaviours of common carbon allotropes such as graphite, diamond and fullerenes, and how the bonding therewith could be utilised to form complex carbon structures called polymers. A closer look revealed the benefits of juxtaposing the energy levels - HUMO and LUMO levels - to create different types of heterojunctions between differing polymer materials, including permitting the movement of charge carriers from one material to another. This introduced the concept of luminescence - production of light due to this movement - and more specifically, electroluminescence - that response induced by the flow of electricity. And we were off, looking at how a team of researchers at CDT, after serendipitously discovering that a particular type of carbon polymers - organic semiconductors - produced light in response to electricity applied the aforementioned concepts to develop complex light-emitting polymer materials that would later be used in commercial devices. Such devices include polymer light-emitting diodes (POLEDs).

In **chapter 2**, we switched gears to looking at the process of conception of scientific invention. We discussed that scientific breakthroughs usually came in abrupt revolutions called paradigm shifts - a way of thinking that completely changed the norm. We extended this analogy to describe multifactorial incremental changes in technology, in particular, where those changes significantly shifted the technology's trajectory and led to the emergence of a completely different technology. The paradigm changes we said happened either randomly, blindly or systematically, all the while in the normal 'revolution' of science that saw constant day-to-day puzzle solving of encountered scientific problems. The new paradigm would then create an anomaly, uncharted territory if you like, whose technical glitches opened up a new can of worms that led to a crisis. The resolution of such a crisis would usually lead to another paradigm, more often enabled by an outside agent. These agents we mentioned could include: a burst of finances; a breakthrough in research and development that would yield a suitable material or device fabrication method; a precursor market for the new paradigm; pressure resulting from competition on the market; multidisciplinary collaborations with an objective of solving a shared problem; restrictions resulting from regulatory policies; an event like war or urbanisation that would drive focus or interest in a particular direction etc. We established a discontinuous nature to innovation, boiling down to two phases as stated by the economist Joseph Schumpeter; the first being characterised by a dominant paradigm (the A-phase), followed by the second, in which the industry jumped onto that paradigm to make minute adjustments that resulted into incremental changes to the development of the dominant paradigm (the B-phase). This discontinuity was found in literature to be reminiscent of biological evolution. The workings of this concept, in addition to that of biological ecosystems, were adopted to technology to aid the understanding of the minute interactions of the aforementioned enabling factors. The conclusion was that innovation, just like biological evolution, is not an isolated event. It is influenced by its environment and often an external factor(s) may play a major role in either catapulting it forward or stagnating its development.

Having chosen organic semiconductors - particularly POLEDs - as the case study to aid the understanding of the innovation process, **chapter 3** examined the historical development of an analogous technology - inorganic semiconductors, particularly transistors. The map was provided by a previous innovation dynamics study that examined the factors that affected the growth and proliferation of the analogue in the 1930s-1960s, during the global electronic boom that gave us transistors, silicon chips and computers. The study on transistors revealed that of the environmental factors examined, intellectual property especially played a major role in developmental history of the technology. The teaching of the technology itself was based on key patents, providing microscopic details into the materials and device fabrication advances, the role of the inventors involved, the advantage of knowledge sharing, and subsequently the licensing programme that arose from those patent monopolies. In combination with the innovation dynamics review, this technology review provided the blueprint for the factors to look out for in examining POLED development.

So a patent analysis methodology was developed in **chapter 4**. Firstly, to put a microscope to the POLED technological developments by analysing the key patents that protected the invention - this provided a history of the materials and device fabrication developments, as well as the emergence of complementary technologies that would later further POLED technology. Secondly, and having identified the other environmental factors that affected the innovation path, an analysis with a mathematical Black Box model for innovation dynamics illustrated the extent of interaction and interdependence between those factors. Thirdly, a patent trends analysis highlighted the patenting behaviour of CDT, to aid us to later draw parallels with its business strategy, and the contribution thereof to the commercial development of the technology. And finally, a patent citation analysis revealed the significance of individual patents and the extent to which they influenced the technology's commercial direction.

In addition to teaching the technology, **Chapter 5** walked us through the minute developments in POLED materials, device fabrication methods and their relative co-development with complementary and enabling technologies. The patent trends analysis revealed CDT's patenting strategy in relation to the jurisdiction in which protection was sought, the nature of its employee turnover, and how the frequency of patent filings exhibited the rate of maturation of the technology.

**Chapter 6** discussed in great detail the individual influence on the POLED innovation journey of each of the major environmental factors considered to be pivotal to the technology's development. The narrative pointed out CDT's value in relation to its patent portfolio; the scientific value of the technology; and the progression in knowledge as the technology matured. The licensing programme CDT established as result of its IP attested to what the potential investors and collaborators saw in both the technology and CDT, evidence of which were several giant academic, industry and commercial collaborators. Several of these were named as coassignees on some of CDT's patents. It further discussed the numerous benefits of these multidisciplinary collaborations including the enhancement of CDT's resource base, access to an established manufacturing infrastructure, access to a mass market in the displays consumer electronics market and the ability to navigate competition from both incumbent technologies and the other type of OLED technology, SMOLED. The roles played by the government/military intervention was also examined. All the foregoing was looked at through the lens of time, examining how timely decisions had aided CDT to make the most of the technology's fifteen minutes of fame for the mutual benefit of the industry and the consumer.

**Chapter 7** started off with a justification of the chosen environmental factors for discussion before showcasing their interdependence through the Black Box model for innovation dynamics, reducing these factors to mathematical elements connected by equations. This illustrated that even though each factor individually exerted due influence on the innovation's developmental path, its effect was further influenced and determined by other environmental factors, and accordingly proved that innovation indeed did not happen in a vacuum. IP, particularly patents, was adduced to be the main influencer and the key component onto which most, if not all, of the other factors were hinged. A closer look at the relative importance of each patent in their portfolio was provided by the patent citation data. The range in citation rates revealed that not all patents were of equal value. A sizeable fraction of the patent portfolio was cited most frequently; these were the fundamental patents and on which the most value for the company was created. Several other patents that covered solutions to shared industrywide technical problems had medium citation rates while those patents that covered improvements, alternative methods and alternative means of achieving a particular solution had low citation rates. It thus offered for licensing a patent portfolio package balanced by these three types of patents, which was in addition, "*living*" or relating to all current and subsequent patents for the duration of the agreement. This position was enhanced by IP relating to complementary and enabling technologies that CDT acquired through acquisition of companies working with those technologies, in addition to IP owned by its licensees that it had permission to sub- and cross-licence. This strategy enabled it to pool patents with major academic institutions, industry and commercial partners for the furtherance of the technology's development, for its positioning in the existent POLED ecosystem, and further, establishing a new ecosystem around itself. Accordingly, the patent portfolio was established as the key to CDT's commercial success, specifically the ownership of fundamental POLED patents as the tool that aided its indispensable and central insertion into the POLED value chain, transposing the POLED discovery from a scientific wow moment to a tangible revenue generating asset.

## 8.2 Limitations and Caveats

It must first be stressed that the data available to the author was sufficient to meet the objective of this study - to show that intellectual property has played a major role in the commercial development of POLEDs. The author however wishes to highlight some limitations and caveats of the study. Several were mentioned throughout the thesis as and when it was relevant. These will not be repeated here. The following are what she believes had a significant effect on the depth and breadth of the work as a whole:

Firstly, the patent databases are not 100% accurate. Although they take utmost care to provide sufficient information that can be used to accurately achieve the objective of this study, and indeed any other IP related study, they disclaim 100% guarantee that the data are either up to date or correct. However, the patents in the pool were valid at the time of the search. Search account was not taken for, although rare, those patents that may have been withdrawn or abandoned by the applicant after the search. They do not claim to have listed every patent filed by a particular company or inventor, especially as the different jurisdictions that submit this information to them vary in record keeping efficiencies. Additionally, at the time of the search and even towards the tail end of the study, there was no ascertaining how many applications related to the subject matter searched were pending publication. For the obvious reason, inventions that had been kept back by the company as confidential were not included in the pool.

Secondly, because of the sensitivity of its nature, commercial data such as licensee details, terms of licences, specific IP that was licensed, CDT's joint development partners or the details of the companies they acquired etc. was not publicly available. The POLED IP they own could be easily searched on online databases but there was no ascertaining which would have been licensed and/or assigned to or by CDT. Even though many patent registers provide for registration of patent licences, a recordal of such a licence is not mandatory in most jurisdictions so these transactions are often kept a secret for strategic and commercial reasons. Including this IP in the PTA or the patent citation exercise would have painted a better picture of CDT's IP activities. As such, most conclusions to that end were based on secondary sources as well as expected commercial norms. Further, after CDT ceased trading as an IPO and was subsequently bought by Sumitomo Chemical, a bigger pool of information was pulled back as confidential and most available on their website or through their employees would understandably be subject to a certain degree of bias. The bulk of the financial data that was obtained was to a larger extent a reflection of ingoing as opposed to outgoing finances so a real sense of CDT's revenue flow could not be gauged, especially for the purposes of the Black Box analysis.

And thirdly, the nature of the citations in the official search does not take into account the drafting strategy of the patent attorney. It is not unusual for a patent attorney to cite, in the patent specification, irrelevant prior art patents so as to create a prejudice that would allow him to obtain a stronger patent (Cullis, R. 2017, personal communication, 10 February). This would for example result from a creation of precedence for several independent claims to allow for freedom to amend the subject matter in multiple inconceivable directions so as to permit the patent to cover anticipated developments in the technology. These citations would somewhat skew the citation data analysis. I submit however that should they exist in the analysed pool, the differences would probably be insignificant given the sample size.

## 8.3 Suggestions for Further Work

The analysis carried out was sufficient, within the prescribed time frame, to meet the objective of the thesis. Several improvements to enhance the outcome can be suggested however.

It would be useful going forward to conduct a patent citation exercise for the inorganic semiconductor patents analysed similar to that carried out for POLEDs. This would cement the qualitative literature conclusion of the most important patents onto which Bell Laboratories, Texas Instruments and

Fairchild Semiconductors built their licensing programmes upon by quantitatively showing us the opinion of those patents by the wider industry based on their appearance in citations. As was the case with CDT, the author was not privy to or reasonably expected to obtain confidential commercial information as to which exact patents were the basis of the licences, neither was this information obtainable from patent licence recordal systems on the patent registers. All the key companies were based in the United States and these records would have spanned the 1930s-1970s - the difficulty is obtaining such old and confidential records need not be spelt out. After identifying patents relating to the Schumpeter A- and B-phases, a further extension of the patent citation exercise would be to work out a citation rate average for each phase. This would perhaps give an indication of the relative importance of each phase in the innovation's journey, as viewed by the relevant industry.

For the POLED patent analysis, it would be useful to construct invention phylogenetic trees to show how subsequent inventions arose out of the 'foundational' paradigms. This would not only cement the analysis and allocation of categories to individual patents in appendix 4 based on the author's understanding of the inventions, but would also add meat to the parallel drawn between the development of biology and technology in chapter 2. This again is a time- intensive exercise.

Extending the analysed patent pool to cover inventions related to POLEDs, filed by CDT and not exclusively naming Sir Richard Friend as inventor might reveal patents that would be useful in grounding our conclusions for the PTA and the patent citation, as well as filling any technological knowledge gaps that may exist in the patent data analysis. Such would also be the usefulness of extending this pool of data to POLED patents owned by other companies but within the same timeframe. As the previous suggestion, this would most likely increase the patent pool by more than an hundredfold - again, a time-intensive exercise.

As the technology is very near the commercialisation stage, it would be useful to look at patents filed since the beginning of this project (October 2012 - until now) to ascertain quantitatively whether the conclusions I have come to, especially in regard to the submission that the technology is currently at the maturation stage will be confirmed.

It would also be useful to conduct the patent citation analysis with several other databases of varying functionalities to draw an average of the conclusions.

## 8.4 Lessons Learned

The author has made some general observations from this bottom-up study of CDT's journey, in addition to others' top-down view, that could especially benefit similar small-medium firms at the early stage of commercialising a radical technology, and even those in an unrelated industry.

Firstly, multidisciplinary collaboration is an absolute must, and that it has to take place on all levels available to one. In addition to the obvious benefits of credibility and a shorter learning curve through learning by others' mistakes, joint R&D with other academic or research institutions will usually cover the technology side of things - many a time academics/researchers are working on different solutions to the same problem, and often in different fields. Opening up dialogue usually helps all involved to arrive at their destinations sooner than hoped or at least readjust expectations and move in a more pragmatic direction. Partnerships with larger industry firms brings in complementary resources, expertise and infrastructure that would normally have taken years to establish or taken an extensive chunk out of one's resources. Commercial partners, in addition to their wealth of R&D resources, will also bring in established and time tested market strategies, consumer familiar brands, a loyal customer following and commercial platforms that would otherwise be unavailable to lab-based ventures. Moreover, pooling together IP increases the exclusive wealth of knowledge to which one is privy, in-licensing within the industry grants access to technologies without the requisite requirement to develop them by oneself, and out-licensing IP to commercial partners, especially in technology, cuts costs by providing access to large manufacturing capabilities and granting clear entry to market (Brant and Lohse, 2013). Post disciplinary collaborations are also very important, having the benefit of learning from accumulated knowledge, not just in your industry but also between those that will play/played a major role in getting your product to the market as well as keeping it there. The benefit of this to subsequent improvement products/technologies is obvious. As the mothers' adage states: *everyone wins when we work together*.

Secondly, it is good to be optimistic but have a realistic target and not be overzealous; radical technologies are particularly unpredictable and will often throw unexpected curveballs. A failure to adjust to this will lead to depletion or misallocation of funds. This is especially risky in the beginning exploratory stages when the path ahead is sufficiently unclear or when finances are flowing into the work and excitement gets the better of one.

Thirdly, seek funding from all available avenues, and choose partners not just for what they can do for you but how you can develop together for the advancement of the technology. Tapping from more than one outlet offers security in addition to much needed resources and exposure to potential partners. However, beware not to become too reliant on one partner and risk being left out in the cold if they pull funding, get impatient with technological progress, change direction for their company or cause you to lose control of the direction/original focus of your own (Lubik, 2010 at p200-210). Available resources should also be allocated not just to R&D but equally to seeking new collaborative partners, and to perhaps finding other opportunities in which to invest, especially in complementary technologies that will further your own technology.

Fourthly, fiercely protecting and enforcing IP is crucial to effectively managing these new relationships, not just in setting boundaries as to what can or cannot be done, but also as a way of making oneself central to the ecosystem. That IP will also provide a useful bargaining chip to pull in more collaborations and as a tool to barter as licences for access to others' technologies or developments. Caution however has to be exercised as these licensee relationships could go wrong and lead to horrendously expensive litigation.

Fifthly, the choice of business partners, especially in the early stages of development, should consider their position in the ecosystem and for the access they are likely to provide you with regard to market entry or maintenance of one's market position. As such, they will also aid you with where to position yourself in the value chain, especially if your technology is not lucky enough to be disruptive or revolutionary. This may make the difference between your extinction and survival (Lubik, 2010 at p207-208).

Sixthly, the point of market entry is very crucial to one's success. Choosing a niche market may be advantageous for exclusivity but it does not always guarantee success. Sticking one's hand in multiple markets will provide multiple streams of income as well as certainty for your technology. Caution must be exercised however in not overstretching oneself. Further, having identified the market of entry, it is important to focus on the right customer base and on choosing collaborators that will help with marketing and commercialisation in that specific sector. Thereafter, it is prudent to keep an eye on the evolving market, adjusting accordingly to what the consumer needs or is projected to need. That way, the coals under one's potential market will be kept burning, in addition to delivering what is relevant when the time is right.

And finally, CDT's constantly evolving business strategy has taught that it is important to always be ready to make adjustments. Business needs, market demands and the business environment will change with time. Letting evolution be one's classroom will produce the type of adaptation required to remain relevant in the face of change.

## 8.5 Conclusion

This study set out to take a wide look at the innovation dynamics of POLED technology from the cradle to the shelf, by drawing on some of the factors that majorly influenced its growth and maturation. The main objective was to illustrate the role of intellectual property law, in particular patents, in its commercial development. It achieved this through a chronological developmental history of the technology through patent specifications, walking through the polymer material developments, device fabrication methods and complementary techniques; a patent trends analysis that revealed information about the companies patenting strategy, around which it established its business model; a patent citation analysis that revealed the relative importance of each patent in light of the business model; and embellished by secondary analysis, the Black Box model for innovation dynamics that quantitatively illustrated the interaction between the factors that affected the innovation. It found that CDT's business model, which was largely built around an extensive licensing programme enabled by the existence of hierarchical patents, facilitated it to centrally establish itself in the POLED ecosystem. This pulled in collaborative academic and industry partners and commercial licensees with the requisite resources to jointly develop the technology to a mature enough stage to commercialise it.

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## 9.3 Inorganic semiconductor patents, in order of appearance in chapter 3

| | |
|---|---|
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## 9.7 Company websites

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| **CDT** | Cambridge Display Technology. Available at: https://www.cdtltd.co.uk/ |
| **Companies House** | Companies House. Available at: https://www.gov.uk/government/organisations/companies-house |
| **Endole** | Endole UK Company Insights. Available at: https://www.endole.co.uk/company/02672530/cambridge-display-technology-limited?page=people |
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| **Espacenet** | Espacenet. Available at: https://worldwide.espacenet.com/ |
| **HowStuffWorks** | HowStuffWorks. Available at: http://electronics.howstuffworks.com/diode1.htm |
| **IHS Markit** | IHS Markit. Available at: https://www.ihs.com/index.html |
| **LG** | LG. Available at: http://www.lg.com/uk |
| **OSRAM** | OSRAM. Available at: http://ww.osram.co.uk/osram_uk/index.jsp |
| **Patent Integration Database** | Patent Integration Database. Available at: https://patent-i.com/ |
| **Philips** | Philips. Available at: http://www.lighting.philips.co.uk/home |
| **Royal Society of Chemistry** | Royal Society of Chemistry. Available at: http://www.rsc.org/about-us/ |
| **Samsung** | Samsung. Available at: http://www.samsung.com/uk/ |
| **SID** | Society for Information Display (SID). Available at: http://www.sid.org/ |
| **Sumitomo** | Sumitomo. Available at: http://www.sumitomo-chem.co.jp/english/pled/ |
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| **UDC** | Universal Display Corporation. Available at: http://www.udcoled.com/ |
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| **University of Manchester** | University of Manchester. Available at: http://www.graphene.manchester.ac.uk/explore/what-can-graphene-do/ |

## 10.0 Appendices

### 10.1 Appendix 1 - Organic semiconductor patents naming Sir Richard Friend as inventor (BOUND ON CD)

### 10.2 Appendix 2 - Inorganic semiconductor patents (BOUND ON CD)

### 10.3 Appendix 3 - Key stages in the development of inorganic semiconductors (BOUND ON CD)

### 10.4 Appendix 4 - Key stages in the development of organic semiconductors (BOUND ON CD)

### 10.5 Appendix 5 - Bibliographic information for organic semiconductor patents (BOUND ON CD)

### 10.6 Appendix 6 - Patent Trends Analysis (BOUND ON CD)

### 10.7 Appendix 7 - Patent Citation Analysis (BOUND ON CD)

### 10.8 Appendix 8 - Richard Salmon's Lecture: An overview of display technologies (BOUND ON CD)

### 10.9 Appendix 9 - VEGA Video 2004-2005 Transcript (with illustrations) (BOUND ON CD)

### 10.10 John Russell's Presidential Address 2011 (BOUND ON CD)