Silicon-based organic light-emitting diode operating at a wavelength of 1.5 μm

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1.5-μm light-emitting diodes which operate at room temperature have been fabricated on silicon substrates. The devices use an erbium-containing organic light-emitting diode (OLED) structure which utilizes p^{++} silicon as the hole injection contact. The OLEDs use N, N′-diphenyl-N,N′-bis(3-methyl)-1,1′-biphenyl-4,4′-diamine as the hole transporting layer and erbium tris(8-hydroxyquinoline) as the electron conducting and emitting layer. © *2000 American Institute of Physics.* [S0003-6951(00)00841-X]

Silicon has consistently been the material of choice for the microelectronics industry, due to a mature and relatively straight-forward processing technology. However, it is a very poor emitter of light due to its indirect band gap. As a consequence modern optoelectronics, which is responsible for the bulk of land-based telecommunications, is dependent on III–V materials which cannot be easily integrated with silicon technology. This has been the driving force behind a number of attempts to produce a means of obtaining light emission from silicon and, hence, develop integrated optoelectronic devices. Various approaches have been explored for obtaining light emission from silicon, particularly at the key telecommunications wavelength of 1.5 μm. For example, silicon has been doped with erbium, which has an intra-atomic transition ($^{4}I_{13/2} - ^{4}I_{15/2}$) at ~1.5 μm, to produce electroluminescence.[1] More recently Fe^{+} ion implantation has been used to fabricate β-iron disilicide which has been shown to be an optically active direct band gap material.[2] However, neither of these approaches have yet to demonstrate useful electroluminescence at room temperature and both require dedicated ion implanters to introduce the heavy ions to a useful depth.

The development of organic light-emitting diodes (OLEDs), based on sublimed small molecules, has proceeded rapidly since the initial work by Tang and VanSlyke.[3] Current devices now have efficiencies of >10% and extrapolated lifetimes of 10^{7} h.[4] The use of rare earth containing organic compounds in such devices has been attracting increasing interest, particularly for visible emitters, due to the potential to increase efficiency and improve the color purity compared with some of the more traditional organic systems.[5,6] The use of organolanthanides to obtain infrared sources is also attracting more interest and devices containing erbium for 1.5 μm emission,[7] neodymium for 0.9, 1, and 1.3 μm emission[8,9] and ytterbium for 0.98 μm emission[10] have now been demonstrated. All of these devices have so far relied on the use of indium tin oxide coated glass substrates as used for the visible light-emitting devices. In this work we demonstrate that it is possible to deposit an erbium-based OLED directly on to a silicon substrate to produce a room temperature 1.5 μm emitting device. Due to the relatively simple vacuum sublimation process needed to produce these devices we believe that this technology should be suitable for producing silicon based integrated optoelectronic devices.

The OLEDs were deposited by vacuum sublimation on to 0.01–0.02 Ω cm, *p*-type Czochralski 100 boron-doped silicon substrates. Prior to the organic deposition these substrates were patterned with a 50 nm layer of plasma enhanced chemical vapor deposition silicon nitride to provide isolation regions to prevent the top contact from shorting to the underlying silicon. The silicon was cleaned using a standard organic solvent process (dichloromethane, acetone, methanol) although no attempt was made to remove any native oxide that may have been present. To provide an electrical contact to the silicon substrate a 20 nm layer of aluminum was evaporated. No sintering process was used on this electrode to try to reduce the contact resistance. The OLEDs were fabricated using a 40 nm layer of N,N′-diphenyl-N,N′-bis(3-methyl)-1, 1′-biphenyl-4,4′-diamine as the hole transport layer, which was deposited directly on to the silicon substrate at a rate of 1–2 Å/s. Following this a 50 nm layer of erbium tris(8-hydroxyquinoline) (ErQ) was deposited at a rate of 2–3 Å/s, which acted as both the electron transporting layer and the emitting layer and finally a 200 nm layer of aluminum was deposited as a top contact. The base pressure in the evaporation chamber was $\sim 10^{-7}$ Torr and during evaporations the pressure was below $\sim 10^{-6}$ Torr.

Luminescence from the diode was recorded at room temperature and collected through the backsurface of the silicon. This backsurface was the as received chemically etched surface and no extra roughening to improve the external efficiency was performed. All measurements were performed with the devices operating in air. The luminescence was dispersed in a 1 m scanning spectrometer fitted with a 1 μm blazed grating and detected using a liquid nitrogen cooled germanium *p*-type intrinsic *n*-type diode.

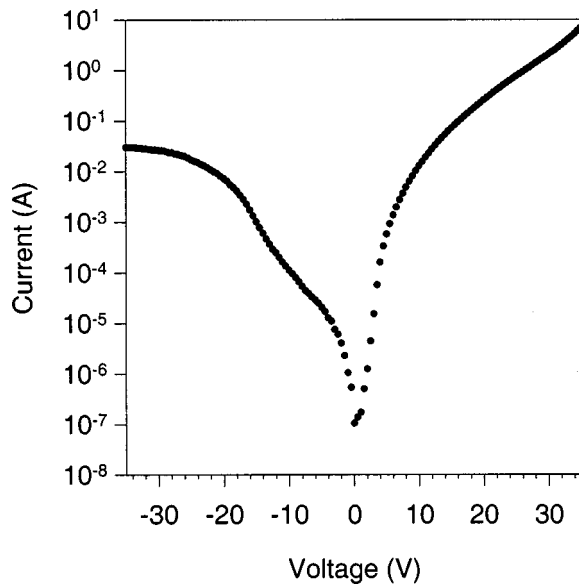Current–voltage ($I-V$) measurements were made using a Keithley 236 source measure unit to check for diode integ-

FIG. 1. A typical $I-V$ characteristic for the OLED. Note that the ordinate is the absolute current in the device.

rity. Figure 1 shows the $I-V$ characteristic of a typical device. It can be seen that in reverse bias the diode starts to exhibit some leakage current at around -10 V although this appears to be saturating at about 0.03 mA. In forward bias we find that for drive voltages greater than 6 V and $I-V$ characteristic is described by $I \propto V^{m+1}$ with m varying from ~ 4 in the region where electroluminescence starts to be observed >17 V to ~ 7 in the high current region where the electroluminescence spectra were measured. This is consistent with the trapped charge limited conduction model proposed by Burrows *et al.*[11] The high voltages needed to achieve this high current domain may well be a result of inefficient carrier injection. In particular we have only used aluminum as the cathode electrode in our devices which is known not to be a particularly good electron injector in AlQ-based devices.[12] Similarly for the anode we have made no attempt to optimize the silicon/organic interfaces. It is possible that removal of any native oxides prior to deposition, changing the doping concentration in the silicon or using different hole transport layers may allow us to improve hole injection.

Figure 2 shows the luminescence intensity as a function of the current density in the device. The devices start to exhibit luminescence at current densities of ~ 3 mA/cm^2 which corresponds to a drive voltage of 17 V. The luminescence intensity shows an apparently sublinear increase with current density up to the maximum current density of 250 mA/cm^2 that we used. This sublinear behavior is reproducible, and whilst we do not know the origin of it at the moment, we do not believe that it is indicative of saturation of the available erbium ions in the device.

The erbium $^4I_{13/2}-^4I_{15/2}$ transition, which is responsible for the 1.5 μm emission, has a relatively long spontaneous lifetime. Because of this it might be expected that diodes based on erbium for the emission process would not suitable for use as conventional LEDs due to low optical power generation, as has been suggested for erbium implanted silicon devices.[13] We have made some preliminary measurements of this lifetime in ErQ using a frequency resolved spectroscopy
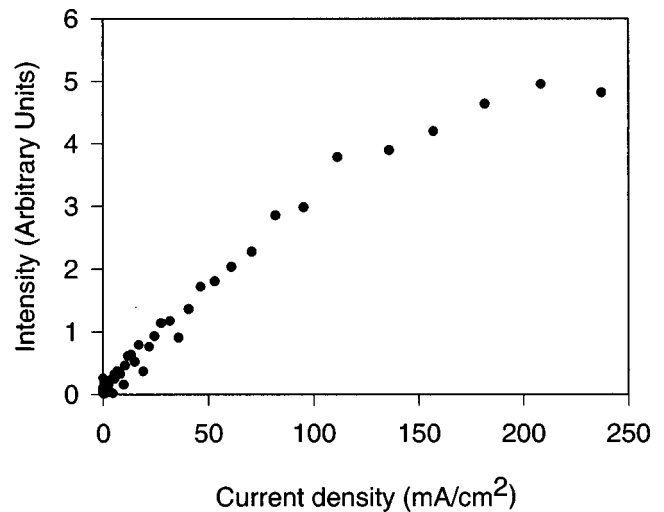

FIG. 2. The electroluminescence intensity, measured at 1532 nm, as a function of the current density in the device. The active area for these diodes was 4 mm^2.

technique and have determined the lifetime of the erbium $^4I_{13/2}-^4I_{15/2}$ transition to be of the order of 200 μs. Given this lifetime and estimating $\sim 10^{14}$ erbium atoms present in our diodes (which have an active area of 4 mm^2) this indicates a theoretical maximum optical power generation within the device of ~ 100 mW. Naturally the available external power available will be lower than this but this shows that these devices have potential as useful sources. For laser applications where it is the stimulated emission which is important then even this limitation ceases to apply.

Figure 3 shows the electroluminescence spectra for the silicon-based ErQ diode operating at a drive voltage of 33 V. This spectra was recorded using the electroluminescence emitted through the backsurface of the silicon. Due to the very high refractive index of the silicon ($n=3.5$) there is a very low critical angle for total internal reflection and, hence, we would not expect the device to have a high external efficiency. However, we estimate that the internal efficiency of this device at the 33 V drive voltage is of the order of 0.01%. This high drive voltage and poor efficiency is partly due to
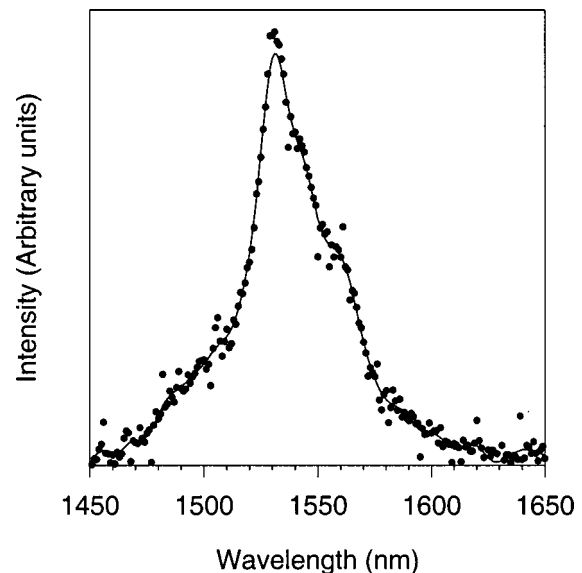

FIG. 3. A typical room temperature electroluminescence spectra for one of these devices, recorded using a drive voltage of 33 V.

the use of aluminum as the cathode and due to our not optimizing the silicon/organic interface. Such optimization will very likely reduce the drive voltage and improve the device efficiency. However, even without these improvements we are currently only utilizing a small amount of the available erbium ions in the device and by increasing this there is the potential to significantly improve device performance. It should be noted that recent work by Mathine *et al.*[14] has demonstrated that it is possible to integrate an array of conventional visible emitting OLEDs directly on to a complementary metal–oxide–semiconductor circuit. These devices were operated with a compliance voltage of ~10 V although they state that they have improved their process so that they can achieve turn on voltages on silicon based devices of 2.5 V. This is very encouraging for the possibility of integrating our devices in to a silicon-based optoelectronic device.

In conclusion we have demonstrated that it is possible to obtain room temperature electroluminescence at 1.5 μm from an erbium containing OLED grown on to a silicon substrate and using that substrate as the anode.

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