Supplemental Material

1 Calculation of defect density using the SRH model

Defect density N_t can be calculated from the decay constant, $\tau = 11.1\ \mu s$, obtained in Fig. 1(e) in the article, assuming that the defect type is interstitial iron (Fe_i), a deep-level defect center commonly found in Si wafers. Because the surface effect is negligible in this case, $\tau \simeq \tau_{bulk}$. In addition, since the injection level is moderate, the SRH process is the predominant recombination mechanism *i.e.* $\tau_{bulk} \simeq \tau_{SRH}$. Hence the SRH model enables us to calculate N_t based on the recombination parameters of Fe_i in Si in RT: $\Delta E = 0.38$ eV, $\sigma_n = 5 \times 10^{-14}$ cm^2, and $\sigma_p = 7 \times 10^{-17}$ cm^2, where ΔE is energy level of the Fe_i defect center measured from the valence band maximum, and σ_n and σ_p are its capture cross section for electrons and holes respectively (D. Macdonald and L. J. Geerligs, Applied Physics Letters 85, 4061 (2004)). The actual equations for the SRH model can be found in, for example, Chapter 3 in S. Rein, Lifetime Spectroscopy: A Method of Defect Characterization in Silicon for Photovoltaic Applications (Springer Science & Business Media, 2006). The straightforward calculation gives $N_t = 7 \times 10^{13}$ cm^{-3} for this wafer.

2 Lifetime measurement in low temperature

The same procedure as Fig. 1 in the main article can be applied for lifetime measurement in low temperature. However higher fields are necessary to decouple the Mu hyperfine interaction and slow down the intrinsic (light-OFF) relaxation, because a small light-OFF relaxation rate λ' defines the minimum light-ON relaxation rate λ (see the article). Therefore LF 0.15 T is applied on the sample in 77 K, which gives $\lambda' = 0.0118(3)\ \mu s^{-1}$. Fig. A(a) and (b) show the obtained λ *vs.* Δn curve and the carrier decay curve respectively. The obtained carrier lifetime, $\tau = 1.8(1)\ \mu s$, is significantly shorter than τ in room temperature.

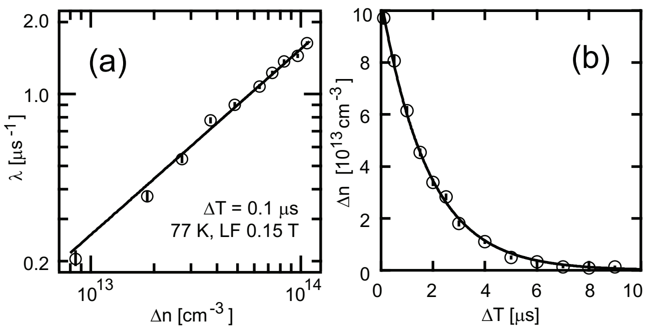

Figure A: Carrier lifetime measurement in 77 K, LF 0.15 T. (a) λ *vs.* Δn curve. The solid line denotes the curve fit, and gives $(\alpha,\ \beta\ \left[\mu s^{-1}\right],\ \Delta n_0\ \left[cm^{-3}\right]) = (0.78(7),\ 1.63(6),\ 1.1 \times 10^{14})$. (b) Carrier decay curve. The fit gives $\Delta n(0) = 1.04(3) \times 10^{14} cm^{-3}$ and $\tau = 1.8(1)\ \mu s$.

3 Lifetime measurement using Mu_T^0 precession signal

Fig. B(a) shows a precession of Mu_T^0, which is readily observable under a weak TF, where the Mu_{BC}^0 precession is normally too fast to observe in pulsed muon facilities. The light OFF spectrum shows an oscillation with a finite relaxation rate λ'. With the photoinduced relaxation λ, the fit function is given by $A(t) = A_B + A_0\ e^{-(\lambda'+\lambda)t} cos(2\pi f t + \phi)$, where A_B denotes the baseline, and A_0, f, and ϕ are the amplitude, frequency, and phase of the damped oscillation respectively. The same procedure as Fig. 1 in the article can be applied to measure the λ *vs.* Δn curve (Fig. B(b)) and the carrier decay curve (Fig. B(c)).

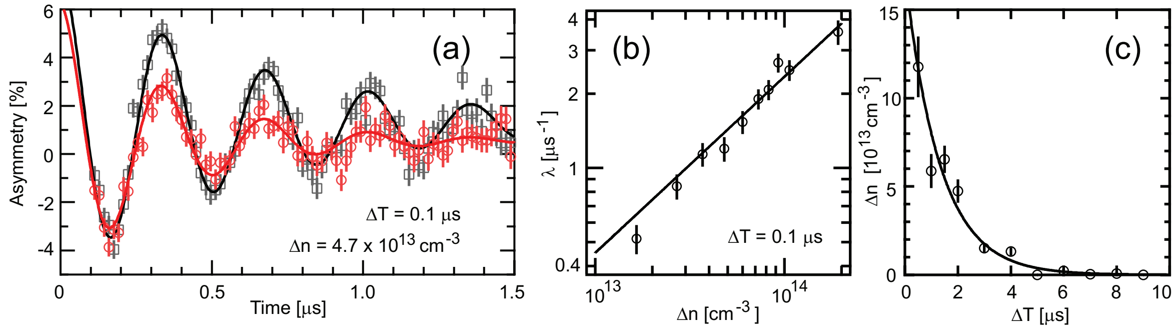

Figure B: Carrier lifetime measurement in 77 K and TF 0.2 mT. (a) Representative μSR time spectra for light OFF (black open squares) and ON (red open circles). $1{\times}10^7$ events are averaged for each spectrum. Fitting (see the text) is performed on the light OFF spectrum and gives $A_B = 1.27(2)$ %, $A_0 = 6.08(8)$ %, $f = 2.939(5)\ MHz$, $\phi = 0.5(8)\ ^\circ$, and $\lambda' = 1.50(3)\ \mu s^{-1}$. The light ON spectrum is then fitted with A_B, A_0, and λ as fit parameters ($A_B = 0.55(5)$ %, $A_0 = 5.8(4)$ %, and $\lambda = 1.2(1)\ \mu s^{-1}$), and fixing the others. The finite baseline in the light OFF spectrum is mainly attributed to the remaining component of Mu^0_{BC} in the $\mathrm{m}_F = +1$ state, which is parallel to the initial muon spin direction. (b) λ *vs.* Δn curve. The data is fitted to $\lambda = \beta\,(\Delta n/\Delta n_0)^\alpha$ with $\alpha = 0.7(1)$, $\beta = 3.7(4)\ \mu s^{-1}$, and $\Delta n_0 = 1.9 \times 10^{14}\ cm^{-3}$. (c) Excess carrier decay curve fitted to the single exponential with $\Delta n(0) = 1.7(2) \times 10^{14}\ cm^{-3}$ and $\tau = 1.3(3)\ \mu s$.

4 Fitting μSR time spectra using the four-state model

As shown in Fig. C we fit a series of μSR spectra with different Δn using the four-state model. The transition rate Λ's in Fig. 3(a) in the article are calculated using the equations shown in Table A. Constants in the fit are listed in Table B, where the prefactors and activation energies are adapted from the previous measurements in dark Si (I. Fan et al., Phys. Rev. B 77, 35203 (2008)). The net electron/hole density can be calculated from a donor concentration n_d estimated from the resistivity, intrinsic carrier concentration n_i, and the excess carrier concentration Δn. The thermal velocities can be readily calculated from $v = \sqrt{3k_BT/m^*}$, where m^* is the effective mass for electron/hole. The simultaneous fit is then performed on all of the time spectra in Fig. C, using Mantid's fit routine based on the Levenberg-Marquardt algorithm, to give σ's and a scaling factor. The fit function subroutine calculates the transition rates for each Δn and uses QUANTUM to simulate the time evolution of the Mu system. Fitted parameters are shown in Table C and some calculated transition rates are shown in Table D.

Table A: Equations for the Mu transitions *

Mu^0_{BC} relaxation	$\Lambda^0_{BC} = nv_n\sigma^0_{BC}$ $\Lambda^{0/+}_{BC} = \alpha^{0/+}_{BC}\exp[-E^{0/+}_{BC}/k_BT] + pv_p\sigma^{0/+}_{BC}$ $\Lambda^{0/-}_{BC/T} = nv_n\sigma^{0/-}_{BC/T}\exp[-E^{0/-}_{BC/T}/k_BT]$
Mu^+_{BC} relaxation	$\Lambda^{+/0}_{BC} = nv_n\sigma^{+/0}_{BC}$ $\Lambda^{+/0}_{BC/T} = nv_n\sigma^{+/0}_{BC/T}\exp[-E^{+/0}_{BC/T}/k_BT]$
Mu^0_{T} relaxation	$\Lambda^0_{T} = nv_n\sigma^0_{T}$ $\Lambda^{0/0}_{T/BC} = \alpha^{0/0}_{T/BC}\exp[-E^{0/0}_{T/BC}/k_BT]$ $\Lambda^{0/+}_{T/BC} = pv_p\sigma^{0/+}_{T/BC}\exp[-E^{0/+}_{T/BC}/k_BT]$ $\Lambda^{0/-}_{T} = nv_n\sigma^{0/-}_{T}$
Mu^-_{T} relaxation	$\Lambda^{-/0}_{T} = \alpha^{-/0}_{T}\exp[-E^{-/0}_{T}/k_BT] + pv_p\sigma^{-/0}_{T}$

* These equations calculate the transition rate Λ's defined in Fig. 3(a) in the article, where one can find the meaning of sub/superscript for Λ's. The same convention applies to α, E, and σ. Here, k_B: Boltzmann constant, n, p: net electron/hole density [cm^{-3}], $v_{n,p}$: electron/hole thermal velocity [cm/s], α: prefactor frequency [MHz], E: activation energy [eV], σ: scattering/capture cross section [cm^2].

Table B: Constants for the fitting *

T [K]	n_d [cm^{-3}]	n_i [cm^{-3}]	n [cm^{-3}]	p [cm^{-3}]	v_n [cm/s]	v_p [cm/s]
291	5.0×10^{10}	4.5×10^{9}	$n_d + n_i + \Delta n$	$n_i + \Delta n$	2.3×10^{7}	1.9×10^{7}

$\alpha^{0/+}_{BC}$ [MHz]	$E^{0/+}_{BC}$ [eV]	$E^{0/-}_{BC/T}$ [eV]	$E^{+/0}_{BC/T}$ [eV]	$\alpha^{0/0}_{T/BC}$ [MHz]	$E^{0/0}_{T/BC}$ [eV]	$E^{0/+}_{T/BC}$ [eV]	$\alpha^{-/0}_{T}$ [MHz]	$E^{-/0}_{T}$ [eV]
3.1×10^{7}	0.21	0.34	0.38	2.5×10^{7}	0.38	0.15	1.0×10^{7}	0.56

* These parameters are used to calculate Λ's in Table A, and fixed in the fitting procedure. The net electron/hole concentration, n and p, are calculated for each time spectra in Fig. C using the corresponding Δn.

Table C: Fitted scattering/capture cross sections (in cm^2) and scaling factor *

σ^0_{BC}	$\sigma^{0/+}_{BC}$	$\sigma^{0/-}_{BC/T}$	$\sigma^{+/0}_{BC}$	$\sigma^{+/0}_{BC/T}$
$1(2)\times10^{-8}$	$3(1)\times10^{-11}$	$1.9(8)\times10^{-9}$	$3(1)\times10^{-12}$	$5.0(2)\times10^{-9}$

σ^0_{T}	$\sigma^{0/+}_{T/BC}$	$\sigma^{0/-}_{T}$	$\sigma^{-/0}_{T}$	Scale
$3(4)\times10^{-16}$	$8(9)\times10^{-13}$	$7(8)\times10^{-16}$	$1.0(1)\times10^{-16}$	18.78(6)

* Cross section σ's are also necessary for calculating Λ's in Table A. Together with the scaling factor, they are the global parameters for fitting the time spectra in Fig. C.

Table D: Calculated transition rate Λ's (in MHz) *

Δn [cm^{-3}]	Λ^0_{BC}	$\Lambda^{0/+}_{BC}$	$\Lambda^{0/-}_{BC/T}$	$\Lambda^{+/0}_{BC}$	$\Lambda^{+/0}_{BC/T}$	Λ^0_{T}	$\Lambda^{0/0}_{T/BC}$	$\Lambda^{0/+}_{T/BC}$	$\Lambda^{0/-}_{T}$	$\Lambda^{-/0}_{T}$
1.04×10^{14}	3.4×10^{7}	7.0×10^{4}	5.8	7.4×10^{3}	3.1	0.77	6.6	4.0	1.7	0.21
1.56×10^{13}	5.2×10^{6}	1.7×10^{4}	0.88	1.1×10^{3}	0.46	0.12	6.6	0.60	0.26	3.3×10^{-2}
1.43×10^{12}	4.9×10^{5}	8.0×10^{3}	8.3×10^{-2}	1.1×10^{2}	4.4×10^{-2}	1.1×10^{-2}	6.6	5.5×10^{-2}	2.4×10^{-2}	4.8×10^{-3}

* Using the parameters in Table C for the best fit, here is a list of the transition rates for the three representative Δn's in Fig. 3(b) in the article.

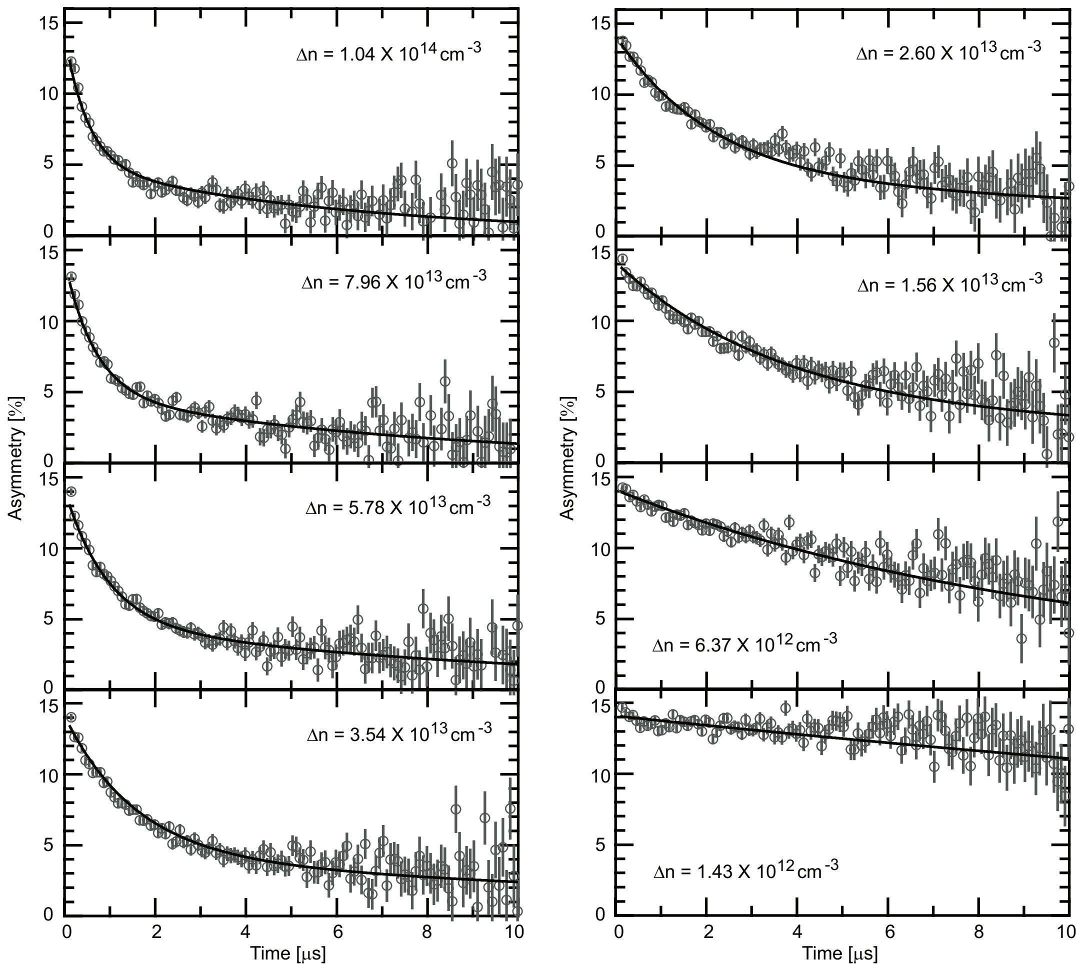

Figure C: Light ON ($\Delta T = 0.1$ μs) μSR time spectra in 291 K under LF 10 mT for various Δn. The plots show reduced data points for easy viewing. The solid lines denote the fit.