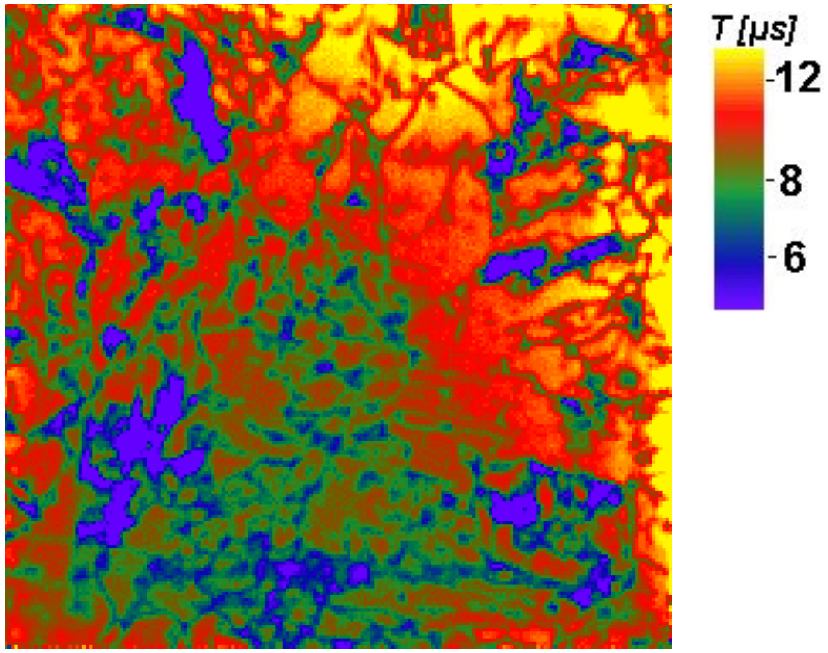
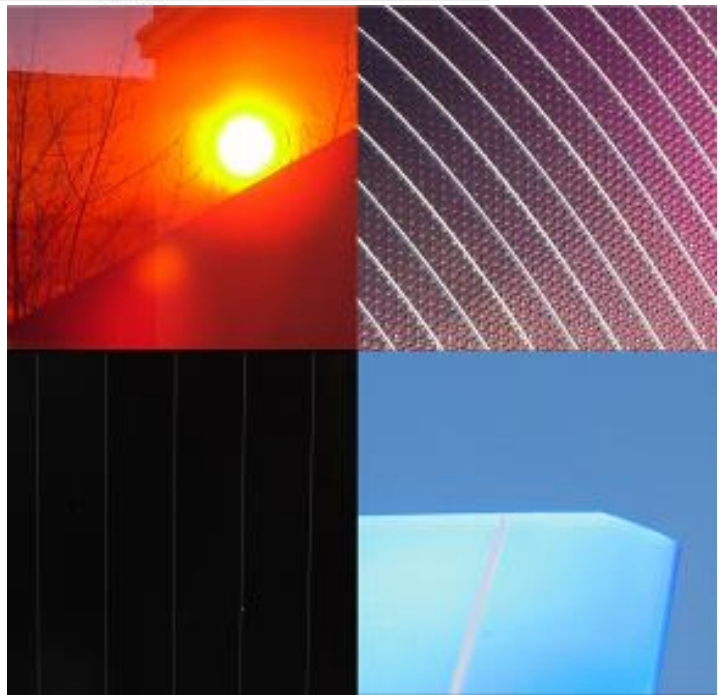


Generation/ recombination



Lecture Outline

1. Generation/Recombination
   - Lifetime
   - Carrier density in steady state
   - Quasi Fermi-levels

2. Recombination processes
   - Radiative photon emission
   - Auger excitation
   - Capture into defect states
   - Surface states

Generation/recombination in equilibrium

F.-J. Haug

Recall from semiconductor physics:
in dark & equilibrium thermal carriers are created (subscript “0” denotes equilibrium)

$$n = n_0$$
$$p = p_0$$

$$n_0 p_0 = n_i^2$$

Without extraction, generated charges do not accumulate to infinity

=> in addition to *thermal generation* there must be *recombination*

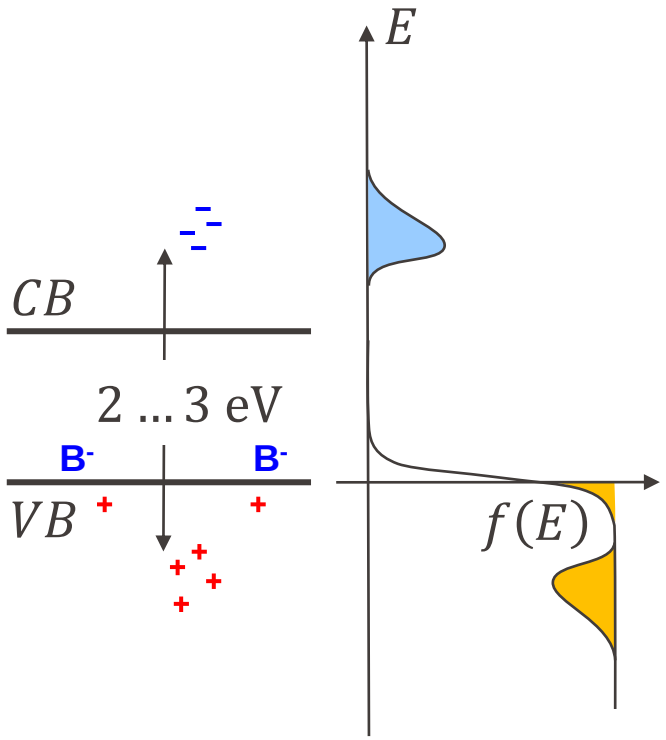
Units of G and R: [$cm^{-3}s^{-1}$]

$$G_{th} = R_{th} \qquad (6.1)$$

Optical generation and thermalisation

F.-J. Haug

Illumination excites states deep in the bands
The distribution function $f(E)$ is given by convolution of the illumination spectrum and the DOS occupation, but the carriers are **not in equilibrium** (for sunlight: 6000 K => “hot carriers”)



Hot carriers interact with phonons on a time scale of the relaxation time τ_r (fs…ps)

Eventually they arrive at the band edges where they can stay for the duration of the bulk lifetime τ_{bulk} (µs … ms)

The process is called **thermalization**, resulting in a **steady state** between supply of thermalizing carriers and recombination across the bandgap

Excess carrier density

Under light or with carrier injection:
steady state with excess carrier density

$$n = n_0 + \Delta n$$
$$p = p_0 + \Delta p$$

$$np > n_i^2 \qquad (6.2)$$

Definition τ_{bulk}: average time between generation and recombination of an e-h pair (normally much longer than relaxation time τ_r)

$$\tau_n \equiv \frac{\Delta n}{R} \qquad \tau_p \equiv \frac{\Delta p}{R} \qquad (6.3)$$

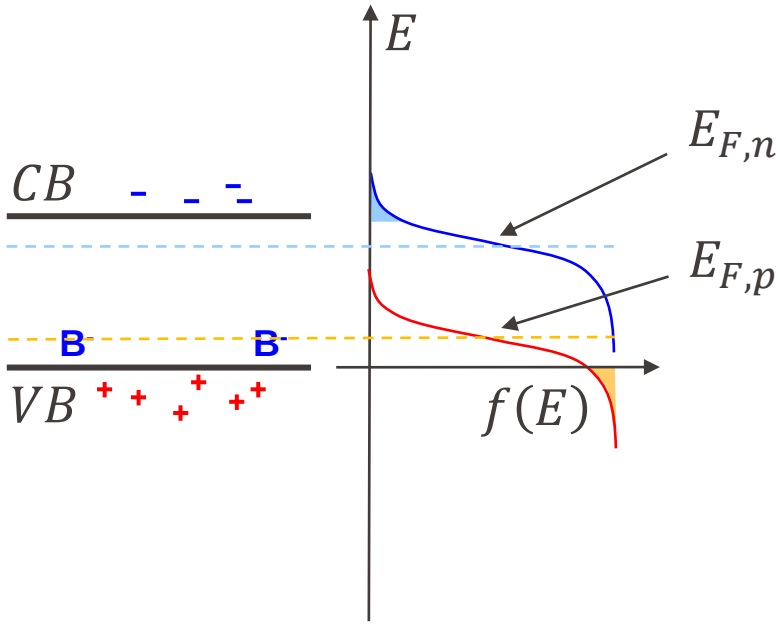
R: Recombination rate

Quasi Fermi-levels

F.-J. Haug

Since $\tau_{bulk} \gg \tau_r$

- Treat the steady-state concentrations n and p as **independent** carrier populations
- Define two quasi Fermi-levels: $E_{F,p}$ (for VB) and $E_{F,n}$ (for CB)
- For QFLs not too close to the their band edges and $T = 300\ \mathrm{K}$: apply the usual Boltzmann approximation



Note: $E_{F,p}$ and $E_{F,n}$ are sometimes called “imref” (backwards reading of “Fermi”)

QFL splitting

When no carriers are extracted

(semiconductor w/o contacts or solar cell at Voc):

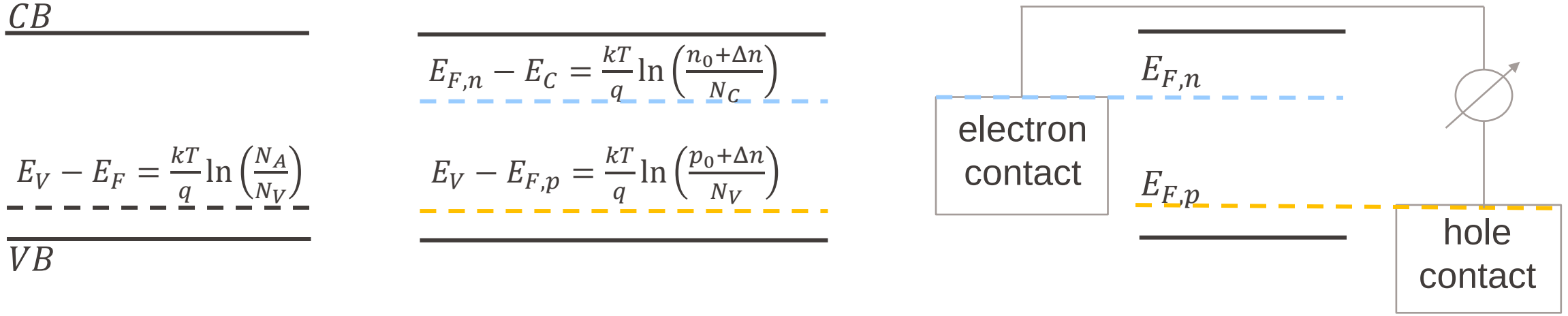
Recombination rate R = Optical generation rate G

$$\Delta n = G\tau \quad (6.4)$$

Dark:
p-type semiconductor
in thermal equilibrium
=> unique Fermi level

Illuminated:
Define independent
quasi Fermi levels (QFLs)

With idealized contacts:
QFL splitting equal to
achievable voltage



Lifetime measurement

F.-J. Haug

- apply known generation rate G (use calibrated lamp, know your optics)
- measure Δn (e.g. through reflectivity of charge carrier plasma)
- determine τ
  - transient by exponential decay of Δn (e.g. flash lamp or pulsed laser)
  - (quasi)-steady state, apply eq. (6.4)
- assess recombination process (in the bulk and at the surfaces)

In particular for $G = 1\ \text{sun}$, we define the **implied open circuit voltage** (iV_{oc}):

$$iV_{oc} \equiv \left(E_{F,n} - E_{F,p}\right)/q$$

$$= E_C/q + kT \ln\left(\frac{n_0+\Delta n}{N_C}\right) - E_V/q + kT \ln\left(\frac{p_0+\Delta n}{N_V}\right) = kT \ln\left(\frac{(n_0+\Delta n)(p_0+\Delta n)}{n_i^2}\right)$$

(using $E_C - E_V = E_g$ and $N_V N_C = n_i^2 \exp\left(E_g/kT\right)$

Lifetime measurement in Si - The Sinton tool

F.-J. Haug

Flashlamp
- quasi-steady state
- transient mode

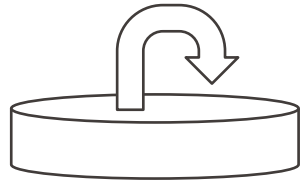
Optical generation G
=> free carrier plasma

Ref. Diode

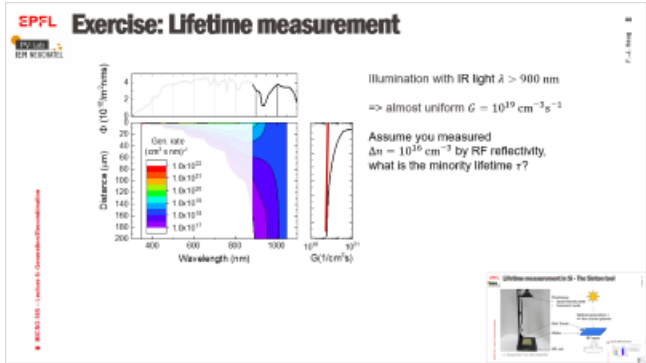
Wafer

RF wave

RF coil



c.f. manual of WCT 120, Sinton Instruments



Recombination processes in semiconductors

F.-J. Haug

- **Radiative recombination** by emission of a photon
- Recombination by excitation of an **Auger-Meitner** process
- Recombination through defect states (**Shockley-Read-Hall**)
- Recombination through states at the **surface**

Radiative recombination

F.-J. Haug

Recombination of an electron and a hole (band to band)

- inverse process to absorption, always present (reciprocity)
- in direct SCs: very effective (needed for LEDs and solid state lasers)
- in indirect SCs: needs phonon assistance (inverse of indirect absorption)

$$R_e = R_{ec} \cdot np \quad (6.5)$$ ← Intuitively proportional to n and p

R_e: recombination rate (index "e" for "emission")

R_{ec}: recombination coefficient (material parameter, related to absorption coefficient α)

Si: $R_{ec} = 4.7 \times 10^{-15}\ \mathrm{cm^3 s^{-1}}$

GaAs: $R_{ec} = 7 \times 10^{-10}\ \mathrm{cm^3 s^{-1}}$

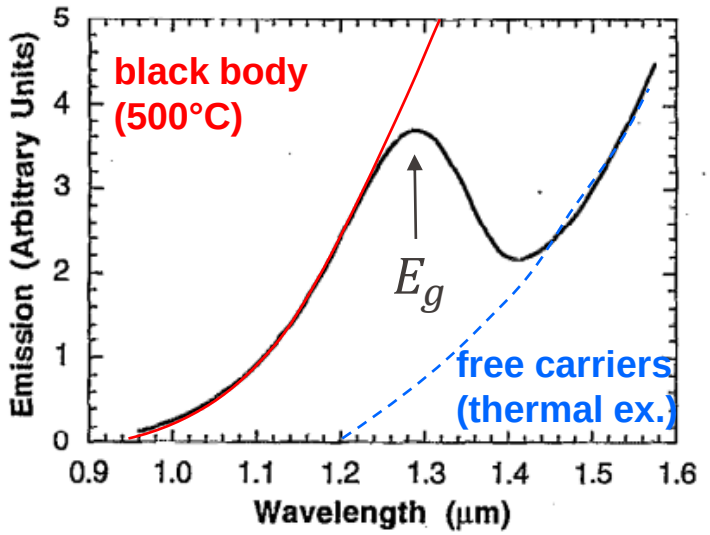
on $\alpha(T)$ and $R_{ec}(T)$ in Si:
Trupke, JAP (2003)
Nguyen, APL (2014)

F.-J. Haug

Radiative recombination

In thermal equilibrium (dark):

$$R_e = R_{e,th} = R_{ec} \cdot \underbrace{n_0 p_0}_{n_i^2} = G_{th}$$



At T > 0 K, there is thermal radiation

- **Radiative recombination of thermally generated carriers (ca. 1200 nm from carriers at the band-edges)**
  => inverse of fundamental absorption

- **Emission of free carrier plasma in IR**
  => inverse of free carrier absorption

In steady state with illumination: net radiative recombination rate

$$R_{rad} = R_e - G_{th} = R_{ec}\left(pn - n_i^2\right)$$

Timans, JAP (1993)

Radiative recombination (Example I)

F.-J. Haug

Assume n-type solar cell material

- $n_0 \approx N_D = 10^{16}\ \mathrm{cm}^{-3}$ (majority carriers)
- $p_0 = n_i^2/n_0 \approx 10^4\ \mathrm{cm}^{-3}$ (minority carriers)

Low injection, e.g. overcast sky: $\Delta n = \Delta p \approx 10^{14}\ \mathrm{cm}^{-3}$

Thus: $\Delta n < n_0$

$\Delta p \gg p_0$

=> $n \approx n_0$ and $p \approx \Delta p$

$$R_{rad} = R_{ec} n_0 \Delta p \overset{\text{def}}{=} \frac{\Delta p}{\tau_p} \qquad \Rightarrow \qquad \tau_p = \frac{1}{R_{ec} n_0}$$

constant,
not dependent on Δn

Radiative recombination (Example II)

F.-J. Haug

Assume n-type material: $N_D \approx 10^{16}\ \mathrm{cm}^{-3}$

High injection, e.g. concentrated light:

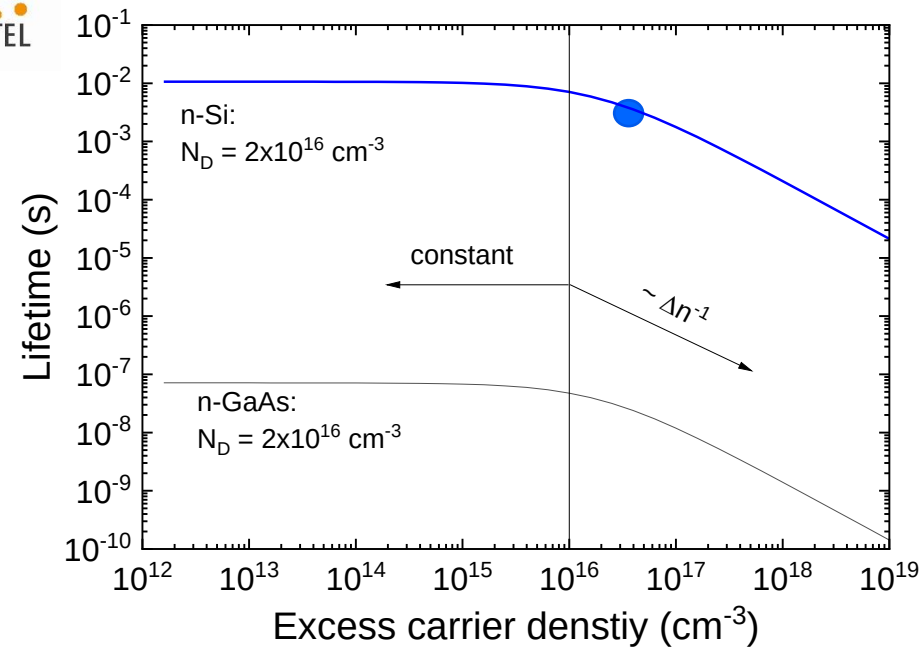
=> $\Delta n > n_0$ and $\Delta p \gg p_0$

=> $n \approx \Delta n$ and $p \approx \Delta \mathrm{p}$

$$R_{rad} = R_{ec}\Delta n \Delta p \overset{\text{def}}{=} \frac{\Delta p}{\tau_p} \quad \Rightarrow \quad \tau_p = \frac{1}{R_{ec}\Delta n}$$

proportional $\sim(\Delta n)^{-1}$

Lifetime vs. excess carrier density



Assume n-type material with $N_D = 10^{16}\ \mathrm{cm}^{-3}$:

Si: $\tau_{p,rad}$ up to $20\ \mathrm{ms}$ (very long)

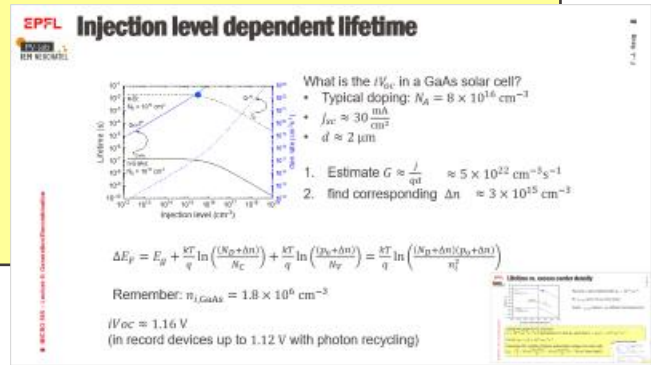
GaAs: $\tau_{p,rad}$ below $1\ \mu\mathrm{s}$ (efficient luminescence)

Using this graph for Si, one sun:
$G \approx 10^{19}\ \mathrm{cm}^{-3}\mathrm{s}^{-1}$ (c.f. last lecture) => find Δn such that $G = \Delta n/\tau = 10^{19}\ \mathrm{cm}^{-3}\mathrm{s}^{-1}$

For Si: $\Delta n \approx 2.5 \times 10^{16}\ \mathrm{cm}^{-3}\mathrm{s}^{-1}$

Calculate QFL splitting (highest extractable voltage of a solar cell)

$$iV_{oc} = \frac{E_g}{q} - kT\ln\left(\frac{(N_D+\Delta n)}{N_C}\right) - kT\ln\left(\frac{(p_0+\Delta n)}{N_V}\right) = 770\ \mathrm{mV}\ \text{(very high!)}$$



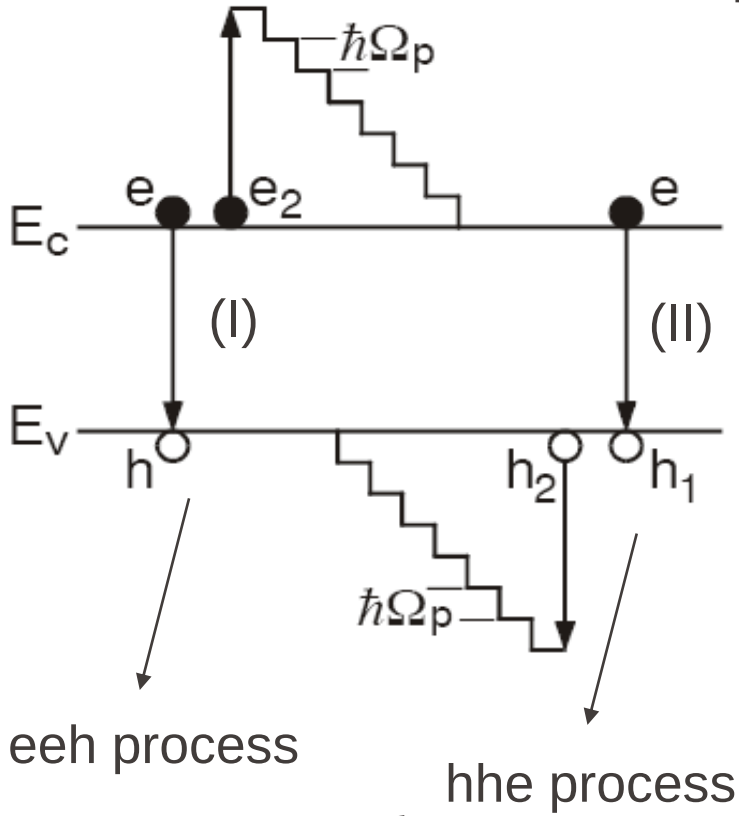
Auger-Meitner recombination

F.-J. Haug

Energy of recombination transferred to another charge carrier instead of a photon:

- electron into high CB state (I)
- hole into low VB state (II)

=> hot carriers, followed by thermalization to the band edge



Auger recombination rate: $R_{Aug} = C_n n^2 p + C_p n p^2$ (6.6)

Auger recombination (Example)

F.-J. Haug

Assume n-type material: $N_D \approx 10^{16}\ \mathrm{cm}^{-3}$

- low injection ($\Delta n < n_0$, thus $n \approx n_0$ and $p = p_0 + \Delta n \approx \Delta n$)

$$\tau_{p,Aug} = \frac{\Delta n}{R_{Aug}} = \frac{\Delta n}{C_n n_0^2 \Delta n + C_p n_0 \Delta n^2} \approx \frac{1}{C_n n_0^2}$$

constant,
not dependent on Δn

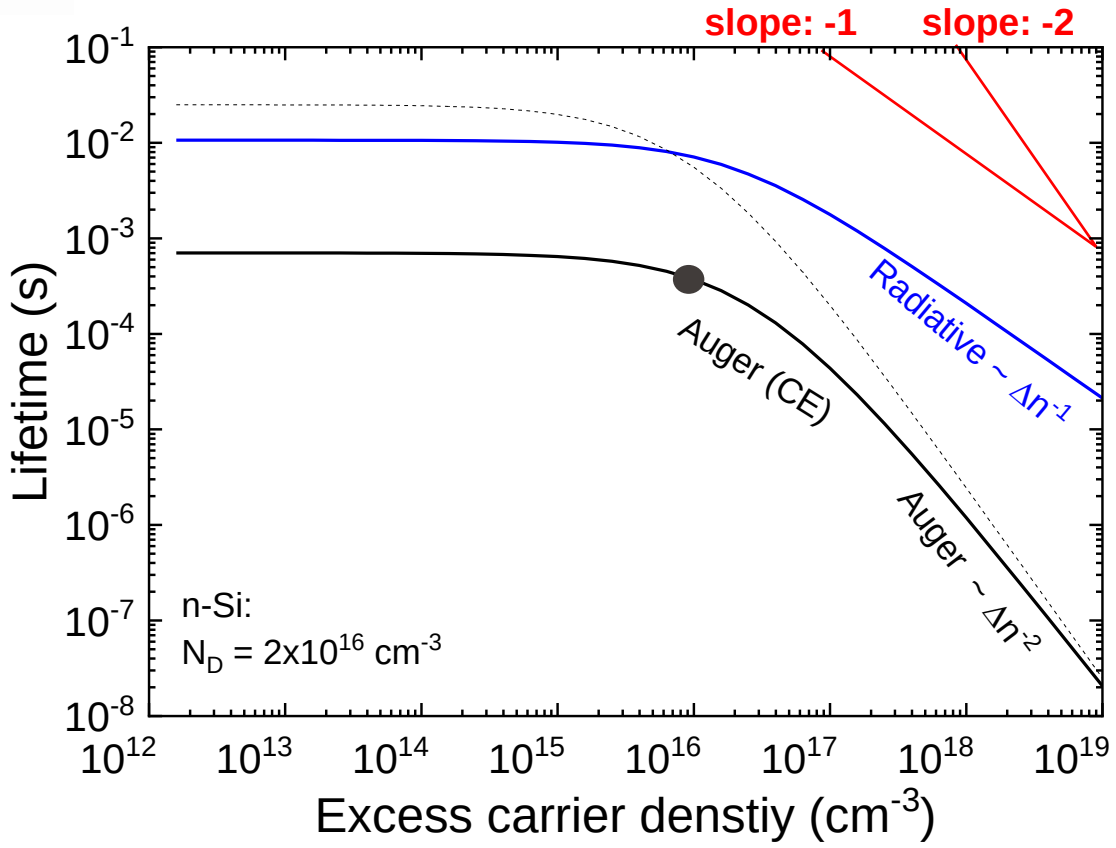
- high injection ($n \approx \Delta n$ and $p \approx \Delta n$)

$$\tau_{p,Aug} = \frac{\Delta p}{R_{Aug}} = \frac{\Delta p}{(C_n + C_p)\Delta n^3} = \frac{1}{(C_n + C_p)\Delta n^2}$$

proportional $\sim(\Delta n)^{-2}$

Radiative and Auger recombination in Si

F.-J. Haug



For high doping and Δn ($> 5 \times 10^{-18}$ cm^{-3}):
$C_n = 1 \times 10^{-31}$ cm^{6}s^{-1} and $C_p = 3 \times 10^{-31}$ cm^{6}s^{-1}
For low and intermediate Δn:
additional effect of Coulomb enhancement (CE)

Radiative recombination little relevant for Si solar cells, they are limited by Auger processes

Auger processes are always relevant for high carrier densities, regardless whether *doping* or *injection* (=> doped contact layers)

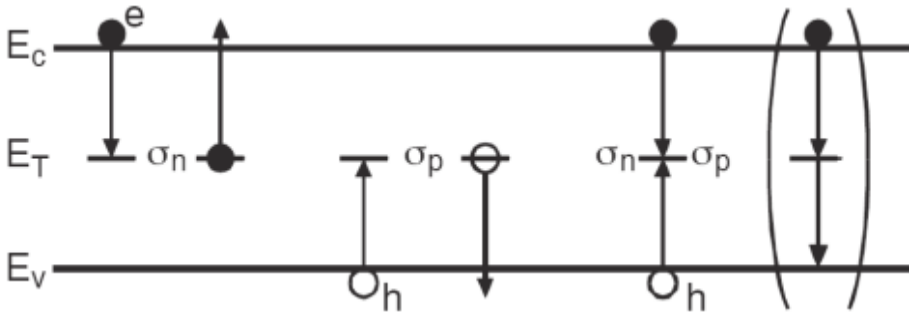
In PERC cells, Auger recombination is critical:

- in the emitter (high N_D) and in the local BSF (high N_A)
- in thin and well passivated Si solar cells ($V_{oc} > 700$ mV means $\Delta n > 10^{16}$ cm^{-3})

Shockley-Read-Hall recombination

Recombination via trapping levels close to midgap

Often the most important recombination process in solar cells !



$\sigma_n \gg \sigma_p$: electron trap

$\sigma_n \approx \sigma_p$: recombination centre

$\sigma_n \ll \sigma_p$: hole trap

σ_n and σ_p: *capture cross-sections* ($\approx 10^{-14} \ldots 10^{-17}\ \mathrm{cm}^2$)

Shockley, Read, Phys Rev. (1952)
Hall, Phys Rev. (1952)

Shockley-Read-Hall recombination

F.-J. Haug

For defect states with density N_t at an energy E_t:*

Net recombination rate U_{SRH} $[\mathrm{cm^{-3}s^{-1}}]$:

$$R_{SRH} = \frac{v_{th} N_t \left(np - n_i^2\right)}{\frac{1}{\sigma_p}(n + n_1) + \frac{1}{\sigma_n}(p + p_1)} \qquad (6.7)$$

Here, we defined:

$$n_1 = N_C e^{-(E_C - E_t)/kT} = n_i e^{(E_t - E_F^i)/kT}$$

$$p_1 = N_V e^{-(E_t - E_V)/kT} = n_i e^{(E_F^i - E_t)/kT}$$

Large σ and high N_t lead to strong recombination
(note: thermal velocity, $v_{th} \approx 10^7$ cm s^{-1})

* index “t” historically for trap state

SRH recombination (example I)

F.-J. Haug

Assume n-type material: $N_D \approx 10^{16}\ \mathrm{cm}^{-3}$

- low injection: $\Delta n < n_0$, thus $n \approx n_0$
- $\sigma_n = \sigma_p \equiv \sigma$
- trap at mid-gap ($E_t = E_i$) => $n_1 = p_1 = n_i$

$$R_{SRH} = \frac{v_{th} N_t n_0 \Delta n}{\frac{1}{\sigma}(n_0 + n_i) + \frac{1}{\sigma}(\Delta n + n_i)} \approx \frac{v_{th} N_t n_0 \Delta n}{\frac{n_0}{\sigma}}$$

$$\tau_{p,SRH} = \frac{\Delta n}{R_{SRH}} = \frac{1}{\sigma v_{th} N_t}$$

constant, not dependent on Δn

SRH recombination (example I ctd.)

F.-J. Haug

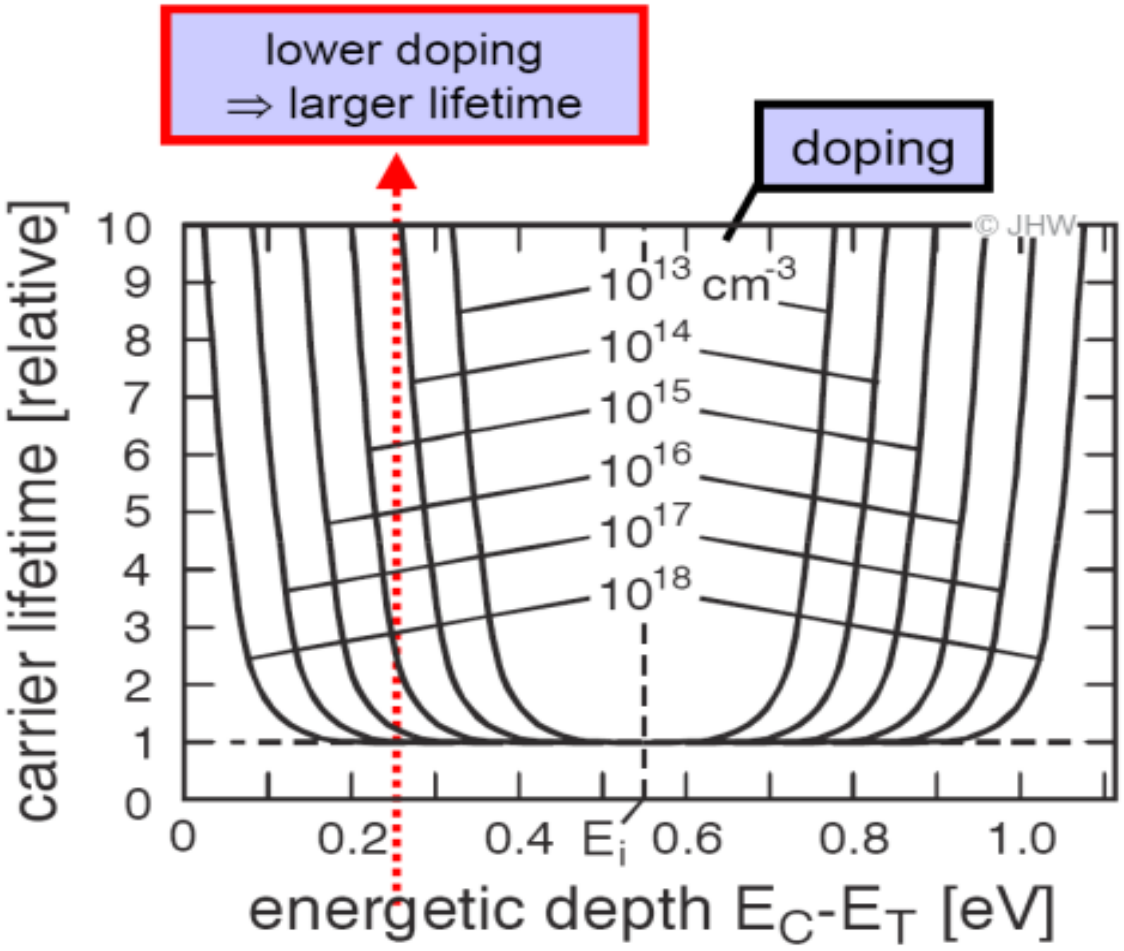
Same assumptions but $E_t \neq E_i$:

$$\tau_{SRH} = \frac{\Delta p}{R_{SRH}} = \frac{1 + \frac{2n_i}{N_D}\cosh\left(\frac{E_t - E_i}{kT}\right)}{\sigma v_{th} N_t}$$

$E_t = E_i$ yields worst τ_{SRH},
"window" of poor τ_{SRH} widens with doping N_D

In other words:

High doping can "activate" a defect far from mid-gap



SRH recombination (example II)

F.-J. Haug

Assume n-type material: $N_D \approx 10^{16}\ \mathrm{cm}^{-3}$

- high injection: $\Delta n = \Delta p > n_0, p_0$ and $\Delta n = \Delta p > n_1, p_1$

$$R_{SRH} \approx \frac{\Delta n}{\frac{1}{\sigma_p v_{th} N_t} + \frac{1}{\sigma_n v_{th} N_t}} = \frac{\Delta n}{\tau_{p,0} + \tau_{n,0}}$$

Here: $\tau_{n,0} \equiv \frac{1}{\sigma_n v_{th} N_t}$ and $\tau_{p,0} \equiv \frac{1}{\sigma_p v_{th} N_t}$

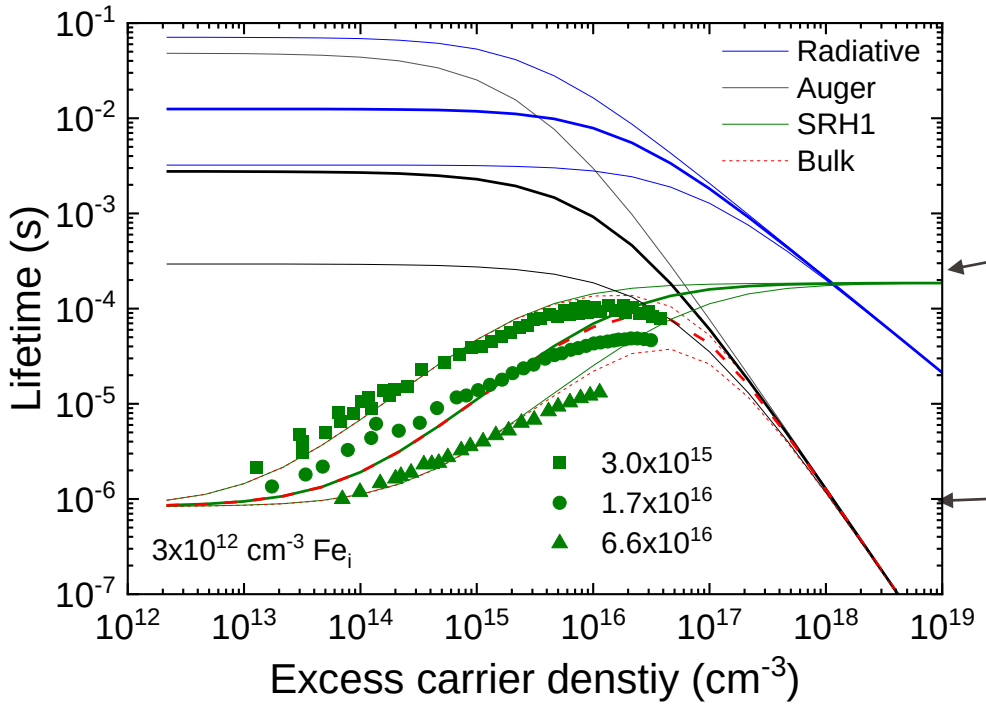
$$\tau_{p,n} = \frac{\Delta n}{U_{SRH}} = \tau_{p,0} + \tau_{n,0}$$

also constant,
but different value

Example: FeB complex

Common impurity in p-type cast Si:
Fe_i close to midgap at $E_t = E_C - 0.38$ eV (measured with DLTS)

Here: p-type FZ material, intentionally contaminated with 3×10^{12} cm^{-3} iron, light soaked to obtain Fe_i



$\tau_{n,0} + \tau_{p,0} = 1.5 \times 10^{-4}$ s

$\tau_{n,0} = 1 \times 10^{-6}$ s

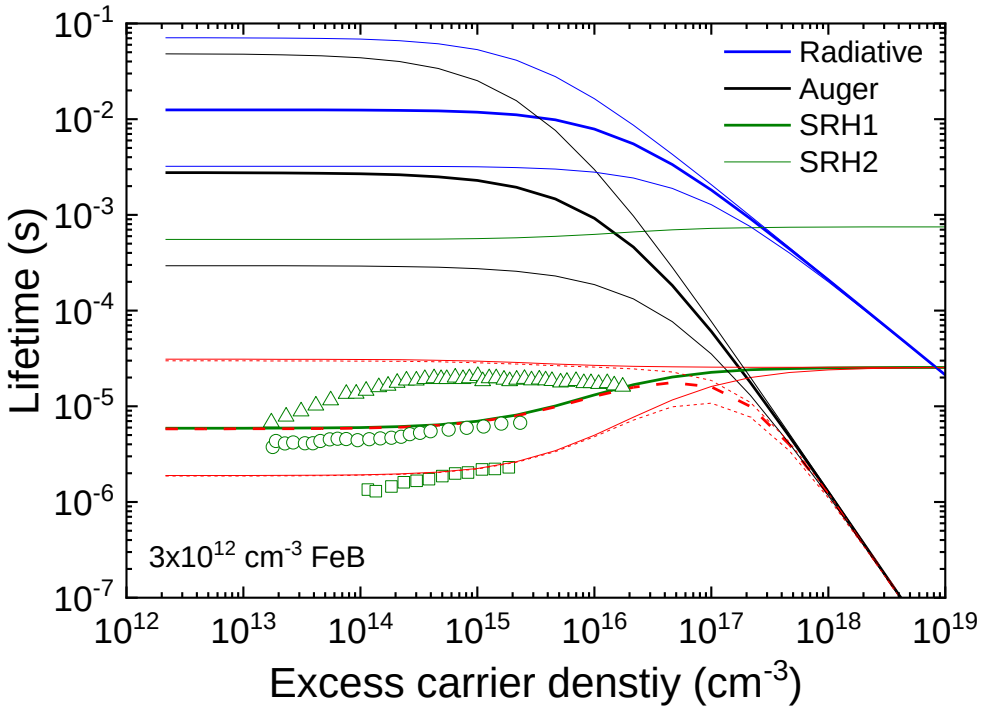
for defects close to midgap:
=> $\tau_{n,0}$ and $\tau_{p,0}$ can be read directly from the graph
(better: use bound fit to samples with varied doping and Fe content)

MacDonald, JAP (2001)

Example: FeB complex

Relaxation in dark: $Fe_i + B \rightarrow FeB$

FeB defect at $E_t = E_C - 0.23$ eV
(shallow defect, $\tau_{n,0}$ and $\tau_{p,0}$ require fitting)

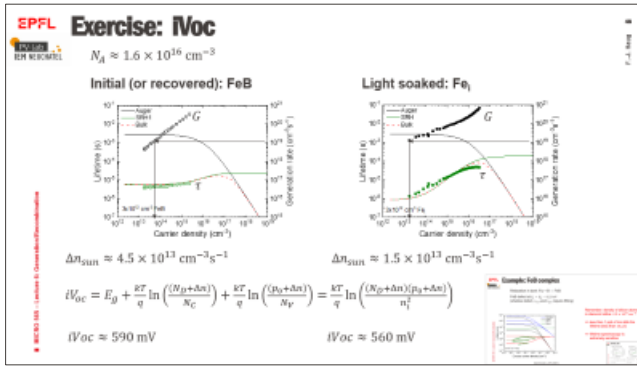


MacDonald, JAP (2001)

Remember: density of silicon atoms in diamond lattice: 2.5×10^{22} cm^{-3}

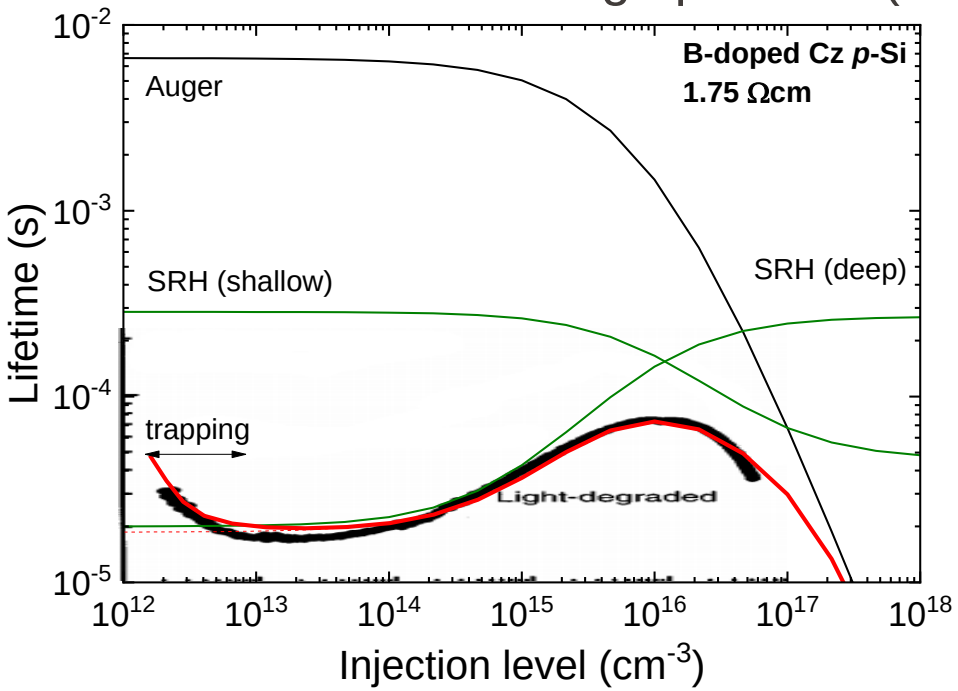
=> less than 1 ppb of iron kills the lifetime (less than 10 µs!)

=> lifetime spectroscopy is extremely sensitive



Example: BO complex

Common impurity in p-type Cz-Si (incorporated during ingot pulling), defect formed during operation (here: 1 sun, 40 h)



Shallow state:
- does not change
- (other samples: can be absent)

Deep state
- created by light or by carrier injection under bias
  => creation by recombination
- N_t reduced by anneal
- $N_t \sim c_O^2$ (complex of B and two O)

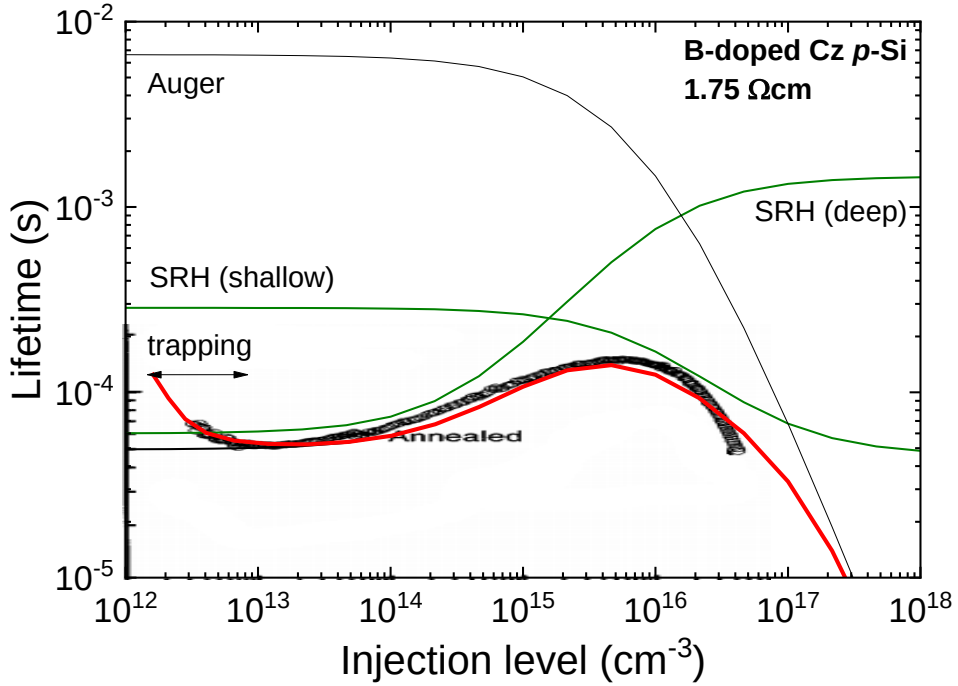
Extraction of SRH contribution: => two defects
- very shallow $E_t = E_V + 0.15$ eV (identified by down-turn)
- deep at $E_t = E_C - 0.4$ eV

Enhanced lifetime at low Δn: artefact by trapping/release from shallow states

Schmidt, JAP (1999)
Schmidt, Phys. Rev. (2004)
Schmidt, JAP (2006)
Herguth, Prog. in PV (2008)
Herguth, AIP Conf. Proc. (2018)

Example: BO complex

Reversible recovery of initial state by annealing



Mitigation:

- pull ingot into Ar ambient
- reduce turbulence in the melt (O can still come from crucible)
- use Ga doping (or n-type material)
- deactivate defect (combine injection, high T, hydrogen)

Schmidt, JAP (1999)
Schmidt, Phys. Rev. (2004)
Schmidt, JAP (2006)
Herguth, Prog. in PV (2008)
Herguth, AIP Conf. Proc. (2018)

Recombination processes

F.-J. Haug

The total recombination rate is the sum of multiple processes

=> Inverse lifetimes are additive

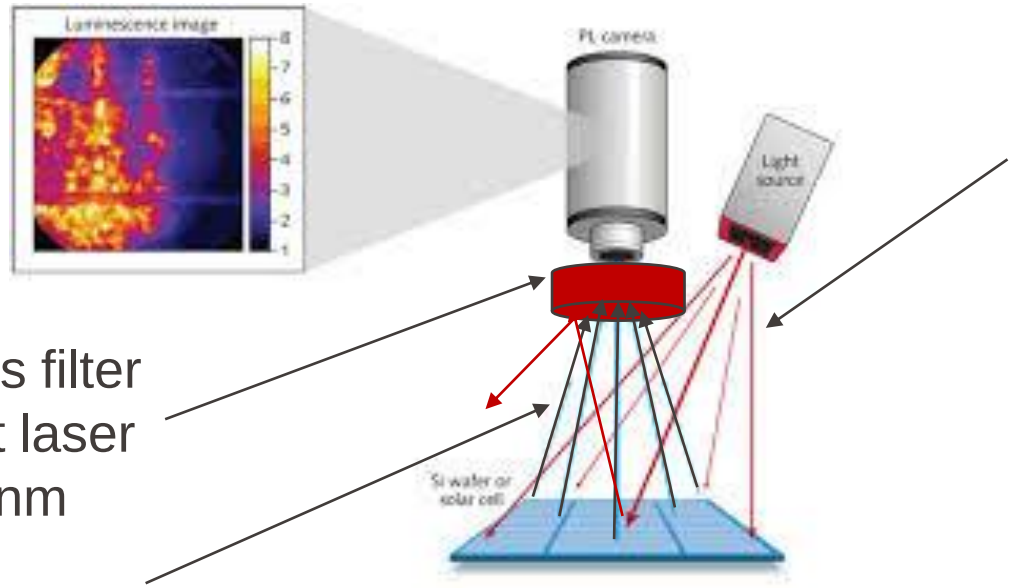
$$\frac{1}{\tau_{bulk}} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{SRH}} \quad (6.8)$$

Radiative Auger SRH

Photoluminescence imaging

F.-J. Haug

- Radiative emission only visible when other recombination mechanisms are weak
- Bright areas in PL image <=> “good material”



IR light source
for uniform $G(x)$
e.g 808 nm

Low pass filter
to reflect laser
e.g 850 nm

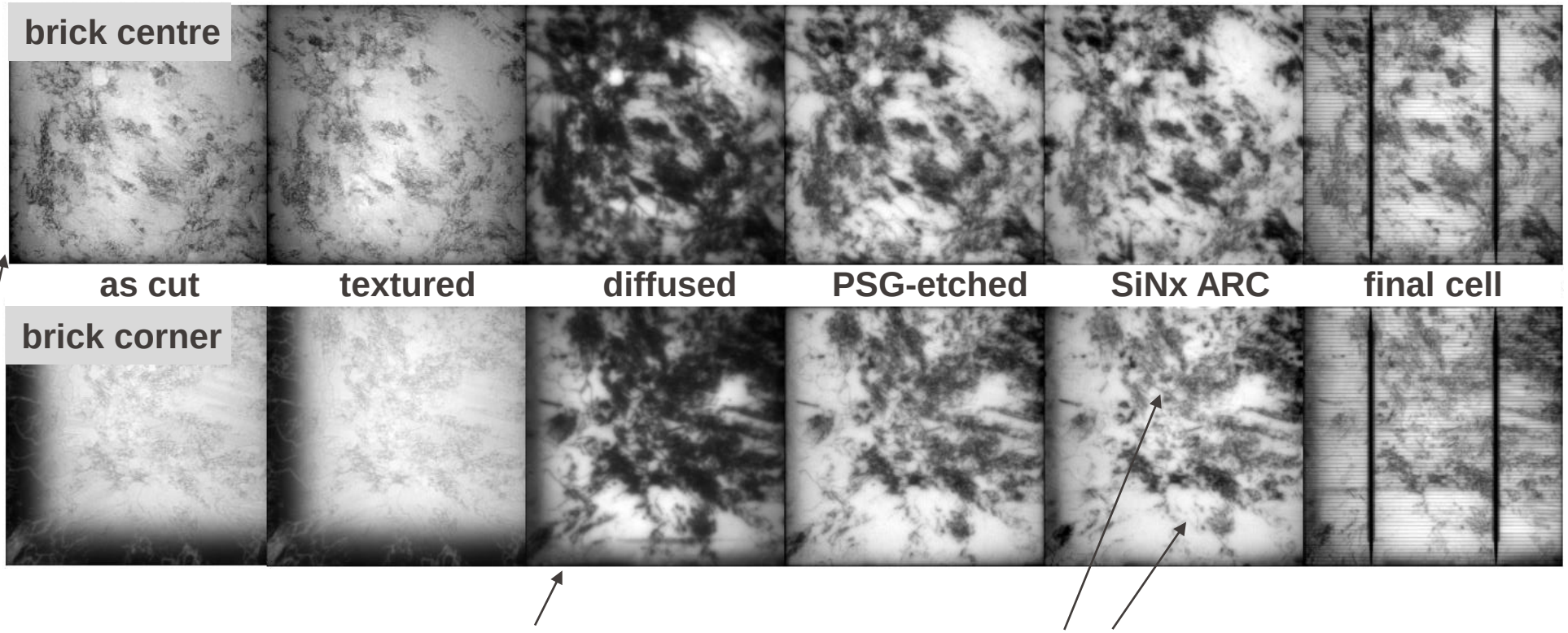
Si emission at ≈ 1100 nm

bT imaging Inc. (spin-off of UNSW)

PL imaging (qualitative)

F.-J. Haug

Qualitative evaluation: dark areas indicate low lifetimes



Corner: impurities from crucible walls

$POCl_3$ diffusion: gettering of impurities

SiN_x firing: release H to passivate grain boundaries

Johnston, IEEE PVSC (2011)

F.-J. Haug

PL imaging (quantitative)

Quantitative evaluation needs careful calibration:

PL-intensity ~ rate of spontaneous emission:

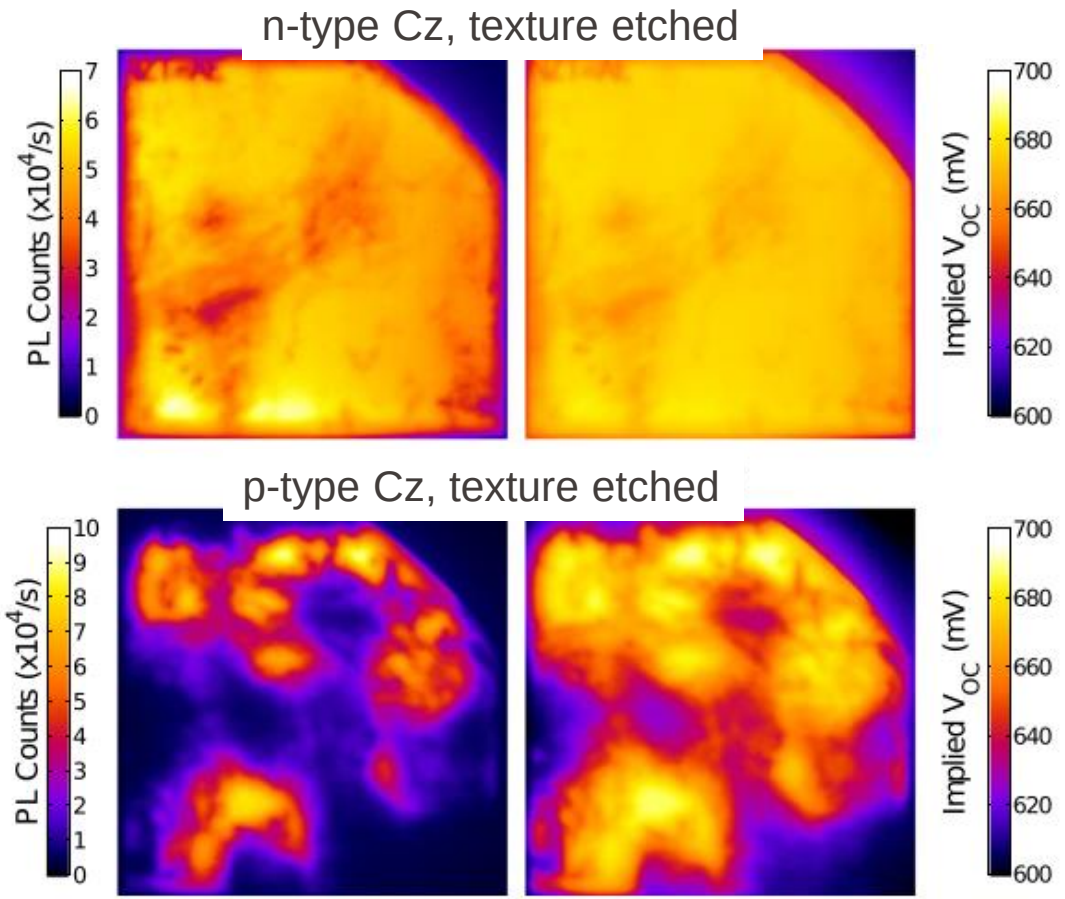
$$r_{em} = \alpha(\hbar\omega) \times \frac{(n\hbar\omega)^2}{\pi^2\hbar^3c^2} \times \frac{1}{\exp\{(\hbar\omega - \Delta E_F)/kT\} - 1}$$

← abs. coeff.

← Density of statesof black body $\sim(\hbar\omega)^2$

$\Delta E_F \sim \ln(\Delta n)$

$iV_{oc} \sim \ln(\Delta n)$



Würfel, J. Phys. C (1982)

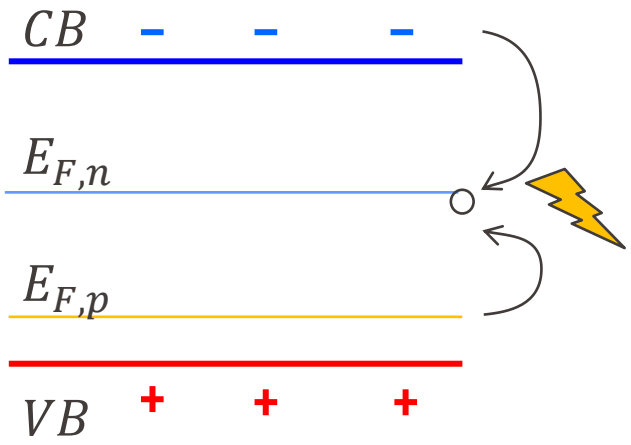
Hallam, JAP (2014)

Surface recombination

F.-J. Haug

Wafer surface <=> abrupt ending of crystal lattice usually creates states within gap

Ideal p-SC with G



Define surface recombination rate: $R_S = S\Delta n_S$

S: surface recombination velocity (SRV)

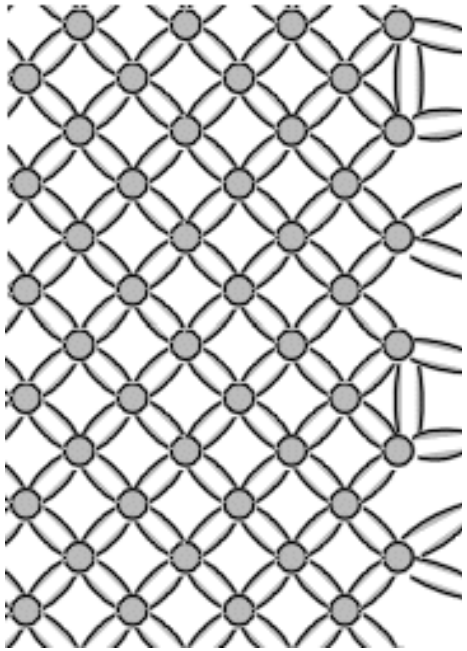


image: PV-education

Surface recombination rate

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Treat analogously to SRH recombination in bulk:

$$R_{S,SRH} = \frac{v_{th} D_{it} \left(n_s p_s - n_i^2\right)}{\frac{1}{\sigma_p}\left(n_s + n_1\right) + \frac{1}{\sigma_n}\left(p_s + p_1\right)} \qquad (6.9)$$

D_{it}: Surface state density $[\mathrm{cm}^{-2}]$

as before:

$$n_1 = N_C e^{-(E_C - E_t)/kT} = n_i e^{\left(E_t - E_F^i\right)/kT}$$
$$p_1 = N_V e^{-(E_t - E_V)/kT} = n_i e^{\left(E_F^i - E_t\right)/kT}$$

Surface recombination: example

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Assume n-Si , low Δn, midgap surface state and $n_s = n$ and $p_s = p$ (flat bands)

$$R_{S,SRH}(n_S, p_s) \approx \frac{n_s \Delta n \sigma_p}{n_s} v_{th} D_{it} = \Delta n \sigma_p v_{th} D_{it}$$

Similar to definition of lifetime:

$$S_p = \frac{R_{S,SRH}(n,p)}{\Delta n} = \sigma_p v_{th} D_{it}$$

S: surface recombination velocity (recombination parameter, no real velocity)

Typical values
S_n ~ 0.1…50 cm/s (SiO_x, SiN, a-Si)
S_p ~ 10^4-10^5 cm/s at the emitter front side of solar cells (with n_s ~10^{20} cm^{-3})

Example: continuous D_{it} of Si/SiO_2 interface

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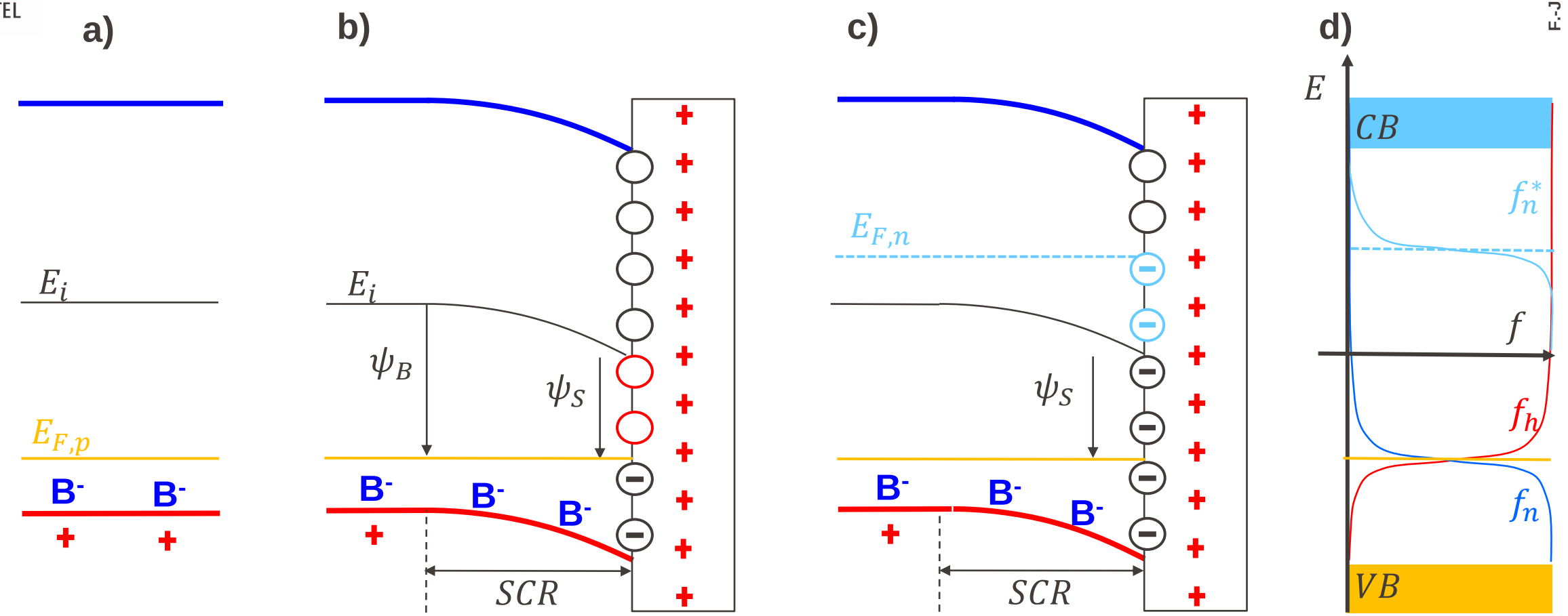


equilibrium p-type semiconductor

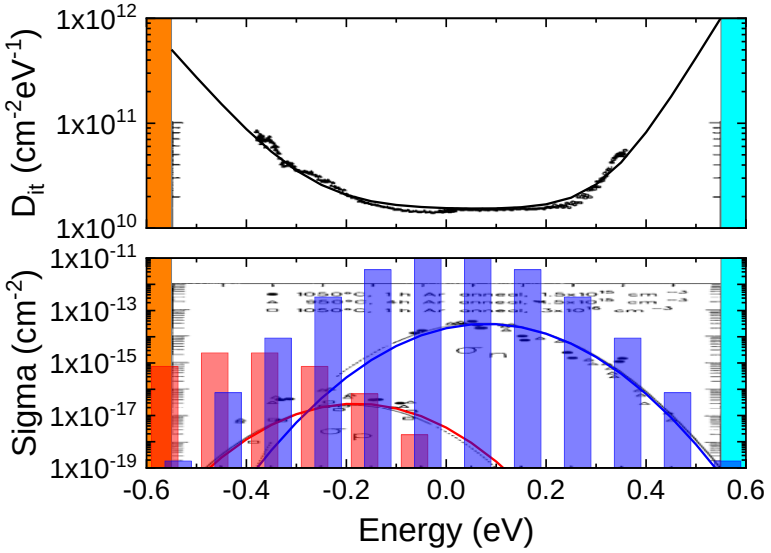
- drop e^- from D_{it} above E_F
- fixed charge of SiO_2 repels h^+ (interesting for n-Si)

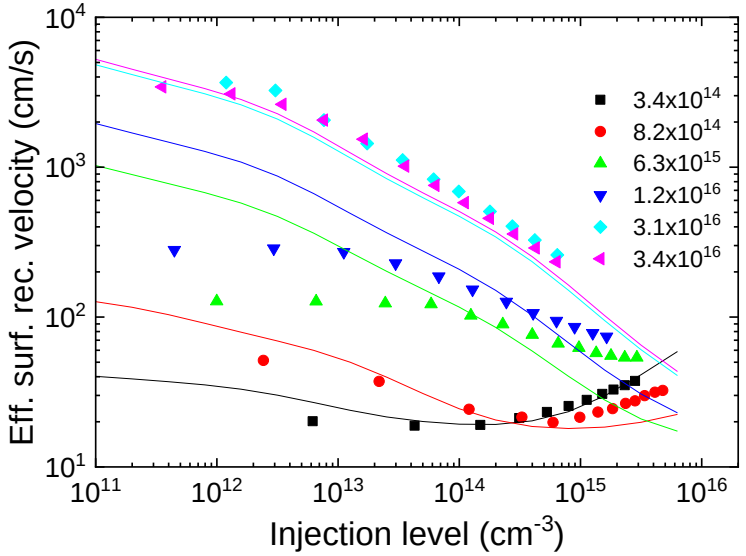
QFL splitting (light) => charge D_{it} with e^-

QFL distribution fns. at interface

Extended SRH formalism

Use Q_f, $D_{it}(E)$ (band tails with flat centre), $\sigma_n(E)$, $\sigma_p(E)$ (Gaussian)
Determine E_F at interface through charge neutrality
Calculate $U_{S,SRH}$ by integration of E over E_g





Model provides:

- midgap $D_{it} \approx 1.5 \times 10^{10}\ \mathrm{cm}^{-2}\mathrm{eV}^{-1}$
- oxide fixed charge $Q_f \approx 2.5 \times 10^{11}\ \mathrm{cm}^{-2}$

Glunz, JAP (1999)
Aberle, JAP (1992)
Knobloch, EU-PVSEC (1988)

Effective surface recombination

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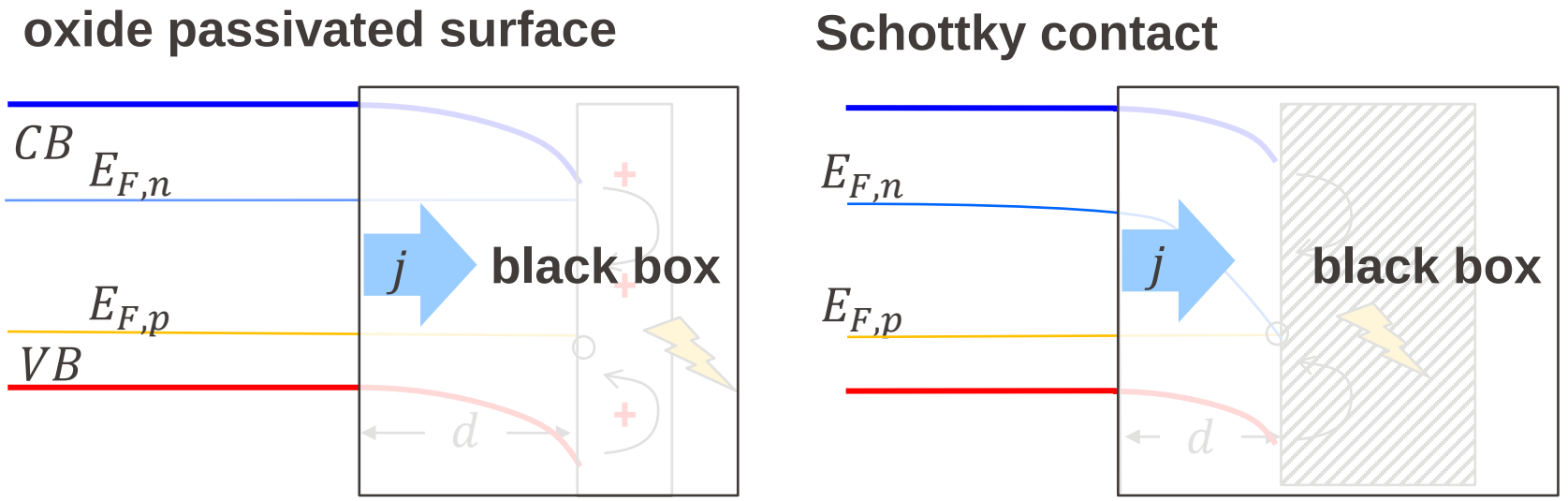

Define U_s at edge of space charge region (last known place before band bending starts)

$$R_S = S_{eff}\Delta n(x = d)$$

S_{eff}: effective surface recombination velocity

$$qS_{eff}\Delta n(x = d) = qU_S(n,p) = j_{surf}$$

j_{surf}: surface recombination current

Effective lifetime

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For the lifetime, recombination in bulk and at the surface are equivalent => combine all terms

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{bulk}} + \frac{1}{\tau_{surf}} =$$

$$= \left(\frac{1}{\tau_{rad}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{SRH}}\right) + \frac{1}{\tau_{surf}}$$

Two limiting cases:

- **Badly passivated surfaces**

$$\tau_{surf} = \frac{1}{D}\left(\frac{W}{\pi}\right)^2$$

- **Well passivated surfaces**

$$\tau_{surf} = \frac{W}{S_{front}+S_{rear}}$$

Sproul, JAP (1994)

Key takeway

- radiative recombination: fundamental process
- Auger recombination: relevant for Si, esp. contact regions
- SRH recombination: critical for some impurities (keep Fe in c-Si < 1ppb)
- surface recombination:
  - chemical passivation: saturate bonds e.g. H or SiO_2 on Si
  - field effect passivation: fixed charge (positive in SiO_2 and SiNx, negative in AlOx)

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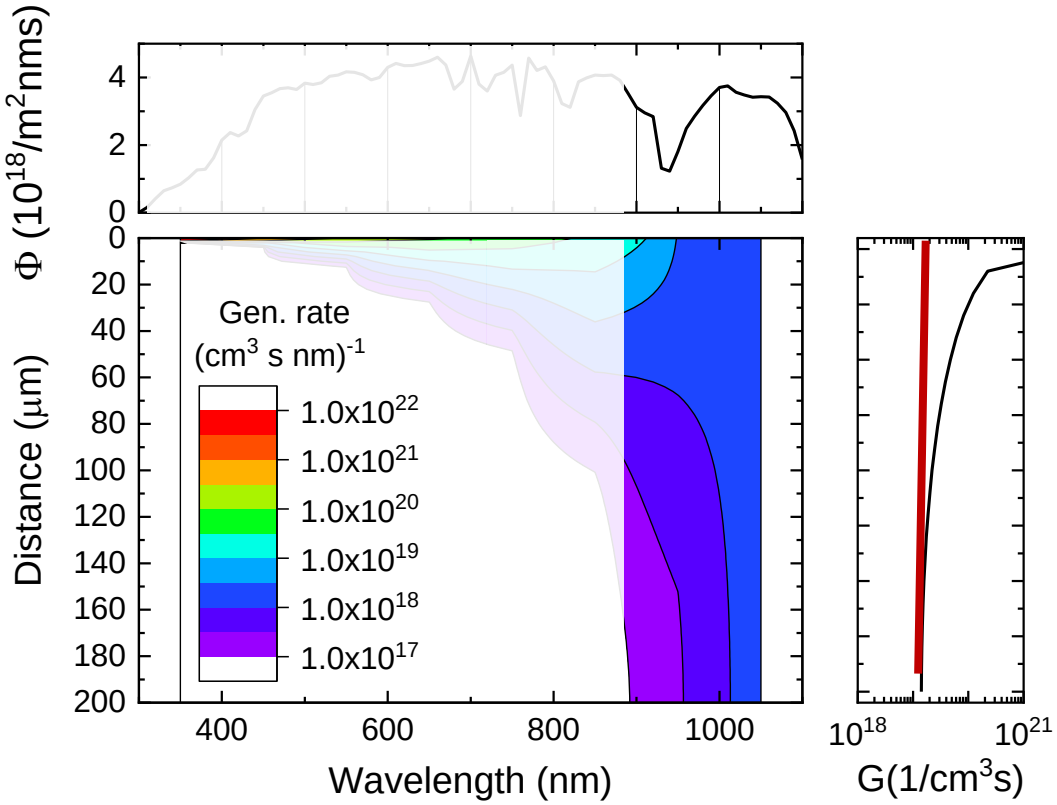
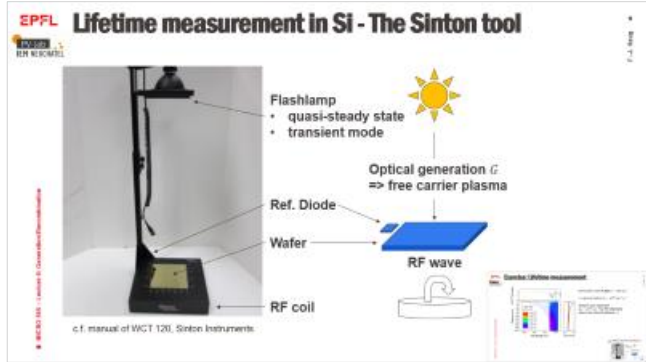
Exercise: Lifetime measurement



Illumination with IR light $\lambda > 900$ nm

=> almost uniform $G = 10^{19}\ \mathrm{cm^{-3}s^{-1}}$

Assume you measured
$\Delta n = 10^{16}\ \mathrm{cm^{-3}}$ by RF reflectivity,
what is the minority lifetime τ?



Injection level dependent lifetime

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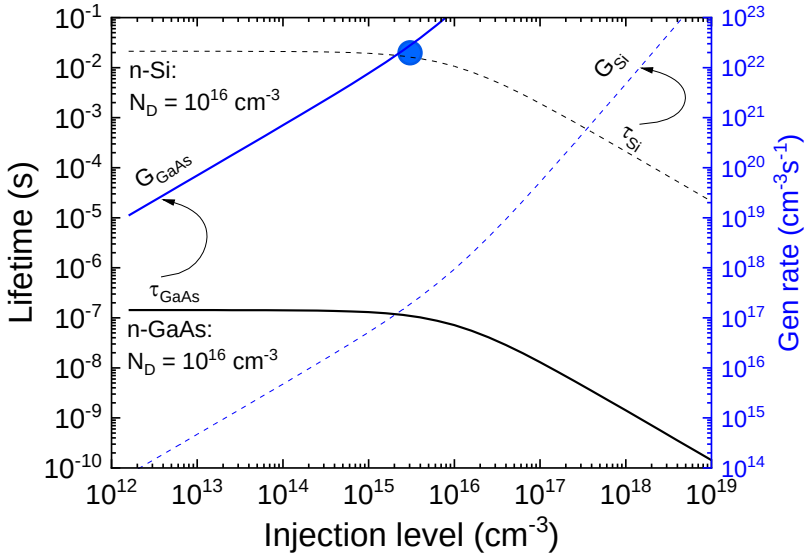


What is the iV_{oc} in a GaAs solar cell?

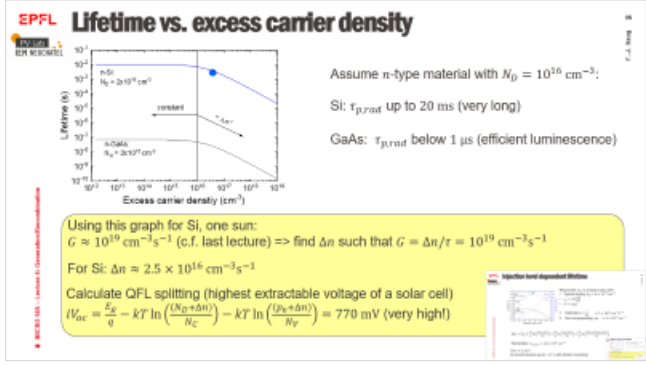
- Typical doping: $N_A = 8 \times 10^{16}\ \mathrm{cm}^{-3}$
- $j_{sc} \approx 30\ \frac{\mathrm{mA}}{\mathrm{cm}^2}$
- $d \approx 2\ \mu\mathrm{m}$

1. Estimate $G \approx \frac{j}{qd}$ $\approx 5 \times 10^{22}\ \mathrm{cm}^{-3}\mathrm{s}^{-1}$
2. find corresponding Δn $\approx 3 \times 10^{15}\ \mathrm{cm}^{-3}$

$$\Delta E_F = E_g + \frac{kT}{q}\ln\left(\frac{(N_D+\Delta n)}{N_C}\right) + \frac{kT}{q}\ln\left(\frac{(p_0+\Delta n)}{N_V}\right) = \frac{kT}{q}\ln\left(\frac{(N_D+\Delta n)(p_0+\Delta n)}{n_i^2}\right)$$

Remember: $n_{i,\mathrm{GaAs}} = 1.8 \times 10^6\ \mathrm{cm}^{-3}$

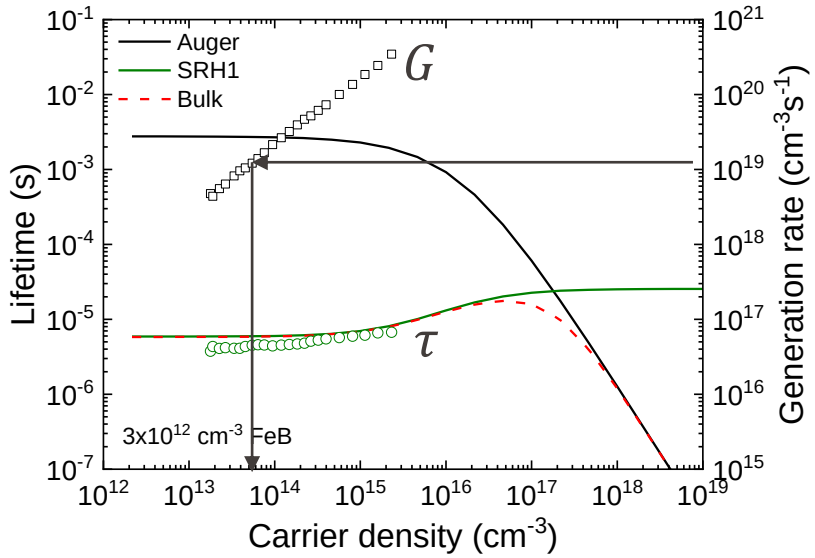
$iVoc \approx 1.16\ \mathrm{V}$
(in record devices up to 1.12 V with photon recycling)



Exercise: iVoc

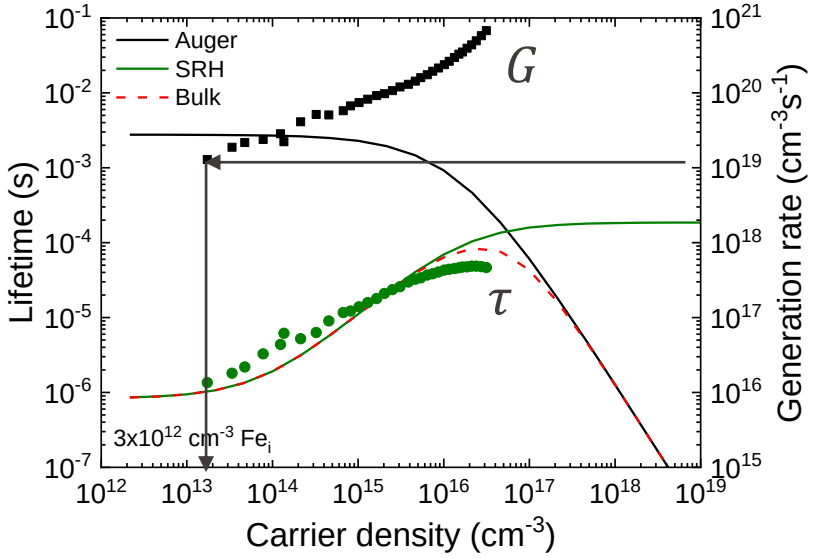
$$N_A \approx 1.6 \times 10^{16}\ \mathrm{cm}^{-3}$$

Initial (or recovered): FeB



$$\Delta n_{sun} \approx 4.5 \times 10^{13}\ \mathrm{cm}^{-3}\mathrm{s}^{-1}$$

Light soaked: Fe_i

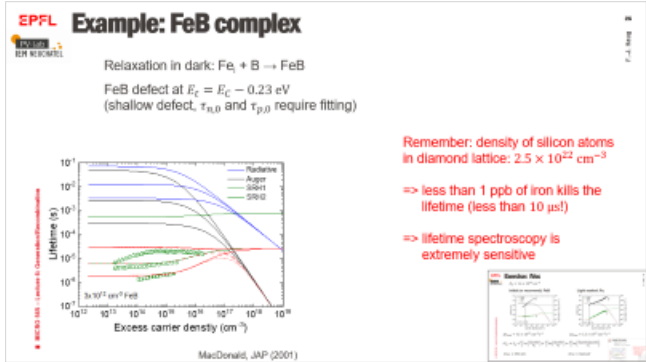


$$\Delta n_{sun} \approx 1.5 \times 10^{13}\ \mathrm{cm}^{-3}\mathrm{s}^{-1}$$

$$iV_{oc} = E_g + \frac{kT}{q}\ln\left(\frac{(N_D+\Delta n)}{N_C}\right) + \frac{kT}{q}\ln\left(\frac{(p_0+\Delta n)}{N_V}\right) = \frac{kT}{q}\ln\left(\frac{(N_D+\Delta n)(p_0+\Delta n)}{n_i^2}\right)$$

$$iVoc \approx 590\ \mathrm{mV}$$

$$iVoc \approx 560\ \mathrm{mV}$$



Reserve slides

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