Carrier Recombination

Professor Mark Lundstrom
Electrical and Computer Engineering
Purdue University, West Lafayette, IN USA
lundstro@purdue.edu

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carrier recombination-generation

N-type, equilibrium

\[ \Delta p(t = 0) \]

\[ n_0 = 10^{17} \text{ cm}^{-3} \quad p_0 = n_i^2 / n_0 = 10^3 \text{ cm}^{-3} \]

expect:

\[ \Delta p(t) = \Delta p(t = 0)e^{-qt} \quad \Delta p \text{ may be either positive or negative.} \]

\[ \Delta p(t = 0) \gg p_0 \]

\[ \Delta n(t = 0) = \Delta p(t = 0) \ll n_0 \]

(low-level injection)
how can excess carriers recombine?

1) Band-to-band recombination

\[ \frac{\partial n}{\partial t} |_{b\rightarrow b} = -B(n_p - n_i^2) \]

(Note that this is zero in equilibrium – as it should be.)

excess carriers

\[ n = n_0 + \Delta n \]
\[ p = p_0 + \Delta p \]
\[ \Delta n \approx \Delta p \]
example: \[ \Delta n = 10^8 \text{ cm}^{-3} \ll n_0 \]
\[ \Delta p = \Delta n = 10^8 \text{ cm}^{-3} \gg p_0 \]

“low level injection”
The term “low level injection” means that the excess carrier concentration is orders of magnitude smaller than the equilibrium majority carrier concentration but orders of magnitude larger than the equilibrium minority carrier concentration.
excess carrier concentration vs. time

\[ \frac{\partial \Delta n}{\partial t} \bigg|_{bb} = -\frac{\Delta n}{\tau_{bb}} \]

\[ \Delta n(t) = C e^{-t/\tau_{bb}} \]

\[ \Delta n(0) = C \]

\[ \Delta n(t) = \Delta n(0) e^{-t/\tau_{bb}} \]

\[ \tau_{bb} = \text{“minority carrier lifetime”} \]

\[ \tau_{bb} = \frac{1}{BN_A} \]

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how can excess carriers recombine?

2) Auger recombination

\[ \frac{\partial n}{\partial t} \bigg|_{\text{Auger}} = C_e n (np - n_i^2) + C_p p (np - n_i^2) \]

(Note that this is zero in equilibrium – as it should be.)
low level injection in a p-type semi

\[ \frac{\partial n}{\partial t}_{\text{Lager}} = -C_p p (np-n_i^2) \]

\[ n = n_0 + \Delta n = \Delta n \]

\[ p = p_0 + \Delta p = N_A \]

\[ \Delta n \approx \Delta n \]

\[ p = n \Delta n N_A \]

\[ np = \Delta n N_A \gg n_i^2 \]

energy given to a second electron

3) **SRH recombination** (defect assisted recombination)

\[ \frac{\partial n}{\partial t}_{\text{SRH}} = \frac{\partial p}{\partial t}_{\text{SRH}} = \frac{-np - n_i^2}{\tau_p (n + n_i) + \tau_a (p + p_i)} \]

energy released as thermal energy

“donor like” or “acceptor like”
SRH recombination

\[ \frac{\partial n}{\partial t}_{\text{SRH}} = \frac{\partial p}{\partial t}_{\text{SRH}} = -\left( np - n_i^2 \right) \tau_p (n + n_i) + \tau_n (p + p_i) \]

(steady-state)

\[ n_i = n_i e^{(E_i-E_T)/k_B T} \quad p_i = n_i e^{(E_T-E_i)/k_B T} \]

\[ \tau_n = \frac{1}{c_n N_T} \quad \tau_p = \frac{1}{c_p N_T} \]

SRH recombination (low injection)

\[ \frac{\partial n}{\partial t}_{\text{SRH}} = \frac{\partial p}{\partial t}_{\text{SRH}} = -\left( np - n_i^2 \right) \tau_p (n + n_i) + \tau_n (p + p_i) \]

p-type

\[ \Delta n >> n_0 \]
\[ \Delta p << p_0 \]
\[ \frac{\partial \Delta n}{\partial t}_{\text{SRH}} = -\frac{\Delta n}{\tau_n} \]
\[ \tau_n = \frac{1}{c_n N_T} \]

n-type

\[ \Delta p >> p_0 \]
\[ \Delta n << n_0 \]
\[ \frac{\partial \Delta p}{\partial t}_{\text{SRH}} = -\frac{\Delta p}{\tau_p} \]
\[ \tau_p = \frac{1}{c_p N_T} \]
SRH recombination (high injection)

\[
\frac{\partial n}{\partial t}_{\text{SRH}} = \frac{\partial p}{\partial t}_{\text{SRH}} = \frac{-(np - n_i^2)}{\tau_p (n + n_i) + \tau_n (p + p_i)}
\]

\[
\Delta n > n_0, \quad \Delta p > p_0, \quad \Delta n = \Delta p
\]

\[
\frac{\partial \Delta n}{\partial t}_{\text{SRH}} = -\frac{\Delta n}{\tau_n + \tau_p}
\]

\[
\tau_n = \frac{1}{c_n N_T}, \quad \tau_p = \frac{1}{c_p N_T}
\]

SRH recombination (depletion)

\[
\frac{\partial n}{\partial t}_{\text{SRH}} = \frac{\partial p}{\partial t}_{\text{SRH}} = \frac{-(np - n_i^2)}{\tau_p (n + n_i) + \tau_n (p + p_i)}
\]

\[
np < n_i^2, n < n_i, p < p_i
\]

\[
\frac{\partial n}{\partial t}_{\text{SRH}} = \frac{\partial p}{\partial t}_{\text{SRH}} = \frac{n_i}{\tau_p + \tau_n}
\]

\[
\tau_n = \frac{1}{c_n N_T}, \quad \tau_p = \frac{1}{c_p N_T}
\]
low level injection (summary)

\[
\frac{\partial \Delta n}{\partial t}_{\text{tot}} = - \frac{\Delta n}{\tau_{\text{eff}}} - \frac{\Delta n}{\tau_{\text{Auger}}} - \frac{\Delta n}{\tau_{\text{SRH}}} = \frac{\Delta n}{\tau_{\text{eff}}} = \frac{1}{\tau_{\text{b-b}}} + \frac{1}{\tau_{\text{Auger}}} + \frac{1}{\tau_{\text{SRH}}}
\]

\[
\Delta n(t) = \Delta n(0) e^{-t/\tau_{\text{eff}}}
\]

\[
\begin{align*}
\frac{\partial \Delta n}{\partial t} &\bigg|_{b-b} = \frac{\Delta n}{\tau_{b-b}} \quad \tau_{b-b} = \frac{1}{BN_A} \\
\frac{\partial \Delta n}{\partial t} &\bigg|_{\text{Auger}} = - \frac{\Delta n}{\tau_{\text{Auger}}} \quad \tau_{\text{Auger}} = \frac{1}{C_p N_A^2} \\
\frac{\partial \Delta n}{\partial t} &\bigg|_{\text{SRH}} = \frac{\Delta n}{\tau_n} \quad \tau_n = \frac{1}{c_p N_T}
\end{align*}
\]
recombination-generation

\[ R = X \left( np - n_i^2 \right) \]

- \( X = B \) \text{ band-to-band radiative} \[ (np > n_i^2) \]
- \( X = C_n n + C_p p \) \text{ Auger} \[ (np < n_i^2) \]
- \( X = \frac{1}{\tau_p (n+n_i) + \tau_n (p+p_i)} \) \text{ SRH} \text{ net generation}

summary

1) Band-to-band radiative recombination
   - dominates in direct gap semiconductors
   - makes lasers and LEDs possible

2) Auger recombination
   - dominates when the carrier densities are very high
   - (heavily doped semiconductors or lasers)

3) SRH recombination
   - dominates in high quality, indirect gap semiconductors
   - and in low quality direct gap semiconductors
other types of generation

1) Impact ionization
   "Inverse of Auger recombination"

2) Optical generation
   "Inverse of band-to-band recombination"

photoelectric effect

\[ E = hf > \Phi_M \]

Einstein, in 1905, when he wrote the Annus Mirabilis papers

http://en.wikipedia.org/wiki/Photoelectric_effect
how many photons can be absorbed?

Example: Silicon $E_G = 1.1$ eV. Only photons with a wavelength smaller than 1.13 $\mu$m will be absorbed.

![Solar spectrum (AM1.5G)](image)

wasted energy

Energy is lost for photons with energy greater than the bandgap.

$hf > E_G$

Electron is excited above the conduction band.

However, extra energy is lost due to thermalization as electron relaxes back to the band edge.
absorption coefficient

Incident flux: \( \Phi_0 \)

Flux at position, \( x \) : \( \Phi(x) = \Phi_0 e^{-\alpha(\lambda)x} \)

optical absorption coefficient:
\( \alpha(\lambda) > 0 \) for \( E > E_G (\lambda < h\nu / E_G) \)

Generation rate at position, \( x \) :
\[
G(x) = -\frac{d\Phi(x)}{dx} = \Phi_0 \alpha(\lambda) e^{-\alpha(\lambda)x}
\]

\( \alpha(\lambda) \)

direct vs. indirect

Direct gap: strong absorption (high alpha)  Indirect gap: weaker absorption lower alpha
The direct bandgap of CIGS allows it to absorb light much faster than Silicon. A layer of silicon must be $10^4$ microns thick to absorb ~100% of the light, while CIGS need only be about 2 microns thick.