Lecture 4 - Carrier generation and recombination

February 12, 2007

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Reading assignment:

del Alamo, Ch 3. §§3.1-3.4

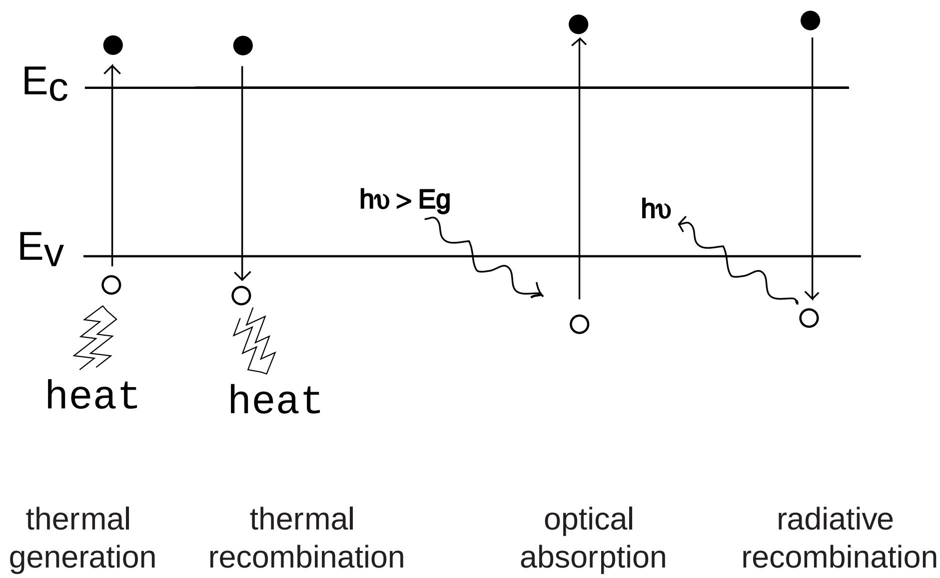
Key questions

- What are the physical mechanisms that result in the generation and recombination of electrons and holes?
- Which one of these are most relevant for Si at around temperature?
- What are the key dependencies of the most important mechanisms?
- If there are several simultaneous but independent mechanisms for generation and recombination, how exactly does one define thermal equilibrium?
- What happens to the balance between generation and recombination when carrier concentrations are perturbed from thermal equilibrium values?

1. Generation and recombination mechanisms

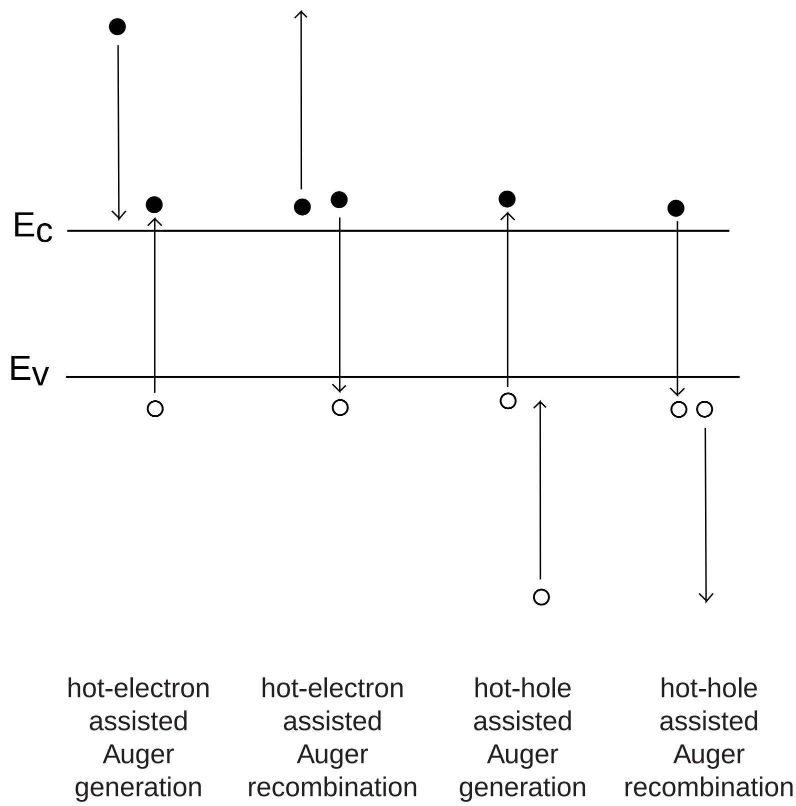
a) *Band-to-band G&R*, by means of:

- phonons (thermal G&R)
- photons (optical G&R)



- thermal G&R: very unlikely in Si, need too many phonons simultaneously (about 20)
- optical G&R: unlikely in Si, "indirect" bandgap material, need a phonon to conserve momentum

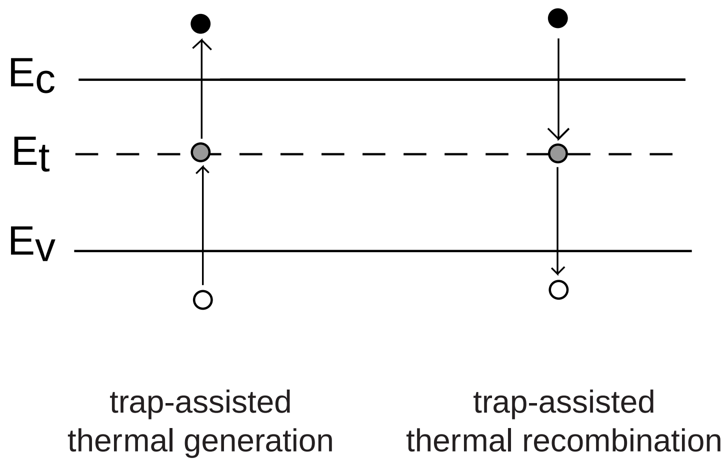
b) *Auger generation and recombination*, involving a third carrier



- Auger generation: energy provided by "hot" carrier
- Auger recombination: energy given to third carrier; needs lots of carriers; important only in heavily-doped semiconductors

c) *Trap-assisted generation and recombination*, relying on electronic states in middle of gap ("deep levels" or "traps") that arise from:

- crystalline defects
- impurities

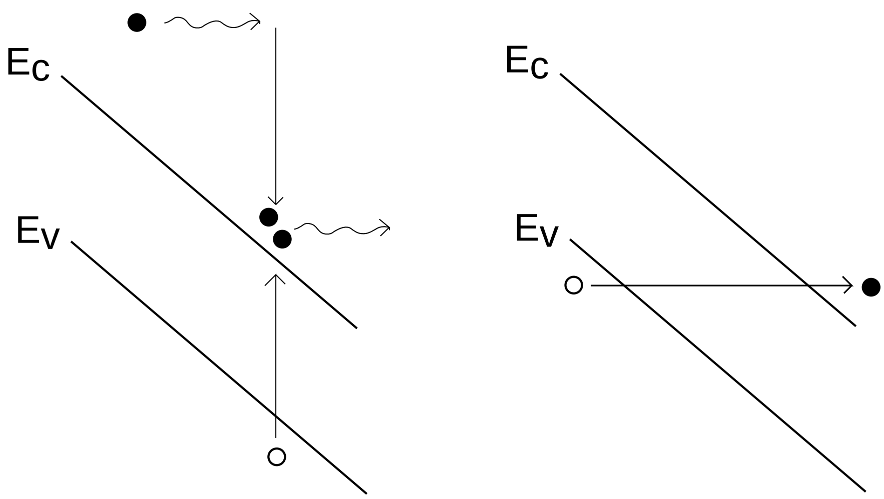


Trap-assisted G/R is:

- dominant in Si
- engineerable: can introduce deep levels to Si to enhance it

d) *Other generation mechanisms*

- *Impact ionization*: Auger generation event triggered by electric-field-heated carrier
- *Zener tunneling* or *field ionization*: direct tunneling of electron from VB to CB in presence of strong electric field



impact ionization Zener tunneling

- *Energetic particles*, such as α-particles (bad for DRAMs)
- *Energetic electrons* incident from outside: electron microscope characterization techniques

2. Thermal equilibrium: principle of detailed balance

Define:

$G_i \equiv$ generation rate by process i $[cm^{-3} \cdot s^{-1}]$
$R_i \equiv$ recombination rate by process i $[cm^{-3} \cdot s^{-1}]$
$G \equiv$ total generation rate $[cm^{-3} \cdot s^{-1}]$
$R \equiv$ total recombination rate $[cm^{-3} \cdot s^{-1}]$

In thermal equilibrium:

$$R_o = \Sigma R_{oi} = G_o = \Sigma G_{oi}$$

Actually, *detailed balance* is also required:

$$R_{oi} = G_{oi} \qquad \text{for all } i$$

In the presence of several paths for G & R, each has to balance out in detail [Principle of Detailed Balance].

[see example in notes illustrating impossibility of TE whithout detailed balance]

3. G&R rates in thermal equilibrium

a) *Band-to-band G&R*

• Will not consider thermal G&R as it is negligible.

• Optical G&R

At finite T, semiconductor is immersed in "bath" of blackbody radiation ⇒ optical generation.

Only a small number of bonds are broken at any one time ⇒ G depends only on T:

$$G_{o,rad} = g_{rad}(T)$$

A recombination process demands one electron and one hole ⇒ R depends of $n_o p_o$:

$$R_{o,rad} = r_{rad}(T)\ n_o p_o$$

In TE, detailed balance implies:

$$g_{rad} = r_{rad} n_o p_o = r_{rad} n_i^2$$

b) *Auger G&R*

• Involving hot electrons:

The more electrons there are, the more likely it is to have hot ones capable of Auger generation:

$$G_{o,eeh} = g_{eeh}(T)n_o$$

A recombination event demands *two* electrons and *one* hole:

$$R_{o,eeh} = r_{eeh}n_o^2p_o$$

In TE, detailed balance implies:

$$g_{eeh} = r_{eeh}n_op_o$$

• Involving hot holes: similar but substitute n_o for p_o and eeh by ehh above.

c) *Trap-assisted thermal G&R*: Shockley-Read-Hall model

Consider a trap at $E_t = E_i$ in concentration N_t.

Trap occupation probability:

$$f(E_t) = f(E_i) = \frac{1}{1 + \exp\frac{E_i - E_F}{kT}} = \frac{n_i}{n_i + p_o}$$

Concentration of traps occupied by an electron:

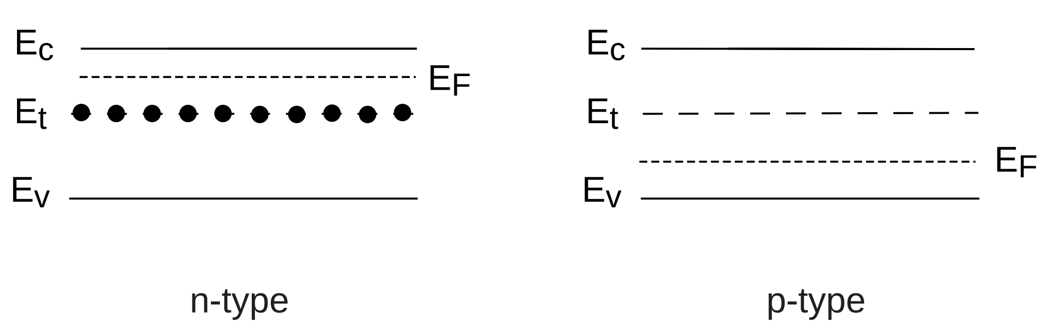
$$n_{to} = N_t f(E_i) = N_t \frac{n_i}{n_i + p_o}$$

Concentration of empty traps:

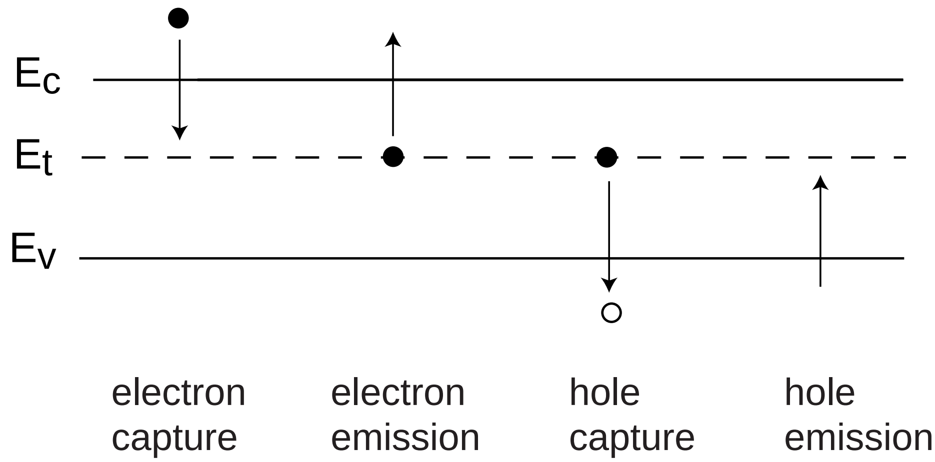
$$N_t - n_{to} = N_t - N_t \frac{n_i}{n_i + p_o} = N_t \frac{p_o}{n_i + p_o}$$

Trap occupation depends on doping:

- n-type: $p_o \ll n_i \rightarrow n_{to} \simeq N_t$, most traps are full
- p-type: $p_o \gg n_i \rightarrow n_{to} \ll N_t$, most traps are empty



Four basic processes:



Rates of four subprocesses in TE:

- electron capture:

$$r_{o,ec} = c_e n_o (N_t - n_{to})$$

- electron emission:

$$r_{o,ee} = e_e n_{to}$$

- hole capture:

$$r_{o,hc} = c_h p_o n_{to}$$

- hole emission:

$$r_{o,he} = e_h (N_t - n_{to})$$

In thermal equilibrium, detailed balance demands:

$$r_{o,ec} = r_{o,ee}$$

$$r_{o,hc} = r_{o,he}$$

Then, relationships that tie up capture and emission coefficients:

$$e_e = c_e n_o \frac{N_t - n_{to}}{n_{to}} = c_e n_i$$

$$e_h = c_h p_o \frac{n_{to}}{N_t - n_{to}} = c_h n_i$$

Capture coefficients can be calculated from first principles, but most commonly they are measured.

Also define:

$$\tau_{eo} = \frac{1}{N_t c_e}$$

$$\tau_{ho} = \frac{1}{N_t c_h}$$

τ_{eo} and τ_{ho} are characteristic of the nature of the trap and its concentration. They have units of s.

All together, rates of communication of trap with CB and VB:

$$r_{o,ec} = r_{o,ee} = \frac{1}{\tau_{eo}} \frac{n_i^2}{n_i + p_o}$$

$$r_{o,hc} = r_{o,he} = \frac{1}{\tau_{ho}} \frac{n_i p_o}{n_i + p_o}$$

Rates depend on trap nature and doping level.

Simplify for n-type semiconductor:

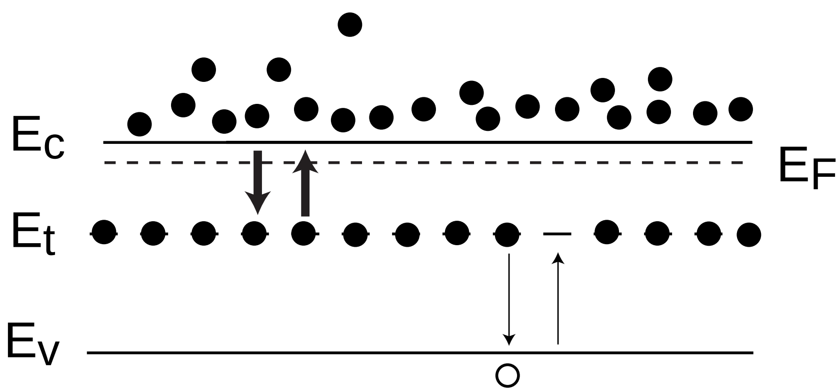
$$r_{o,ec} = r_{o,ee} \simeq \frac{n_i}{\tau_{eo}}$$

$$r_{o,hc} = r_{o,he} = \frac{p_o}{\tau_{ho}}$$

If τ_{eo} not very different from τ_{ho},

$$r_{o,ec} = r_{o,ee} \gg r_{o,hc} = r_{o,he}$$

The rate at which trap communicates with CB much higher than VB.



- lots of electrons in CB and trap ⇒ $r_{o,ec} = r_{o,ee}$ high
- few holes in VB and trap ⇒ $r_{o,hc} = r_{o,he}$ small

Reverse situation for p-type semiconductor.

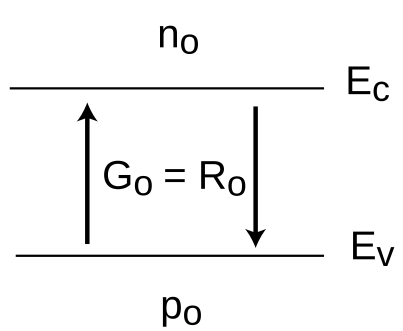
4. G&R rates outside equilibrium

• In thermal equilibrium:

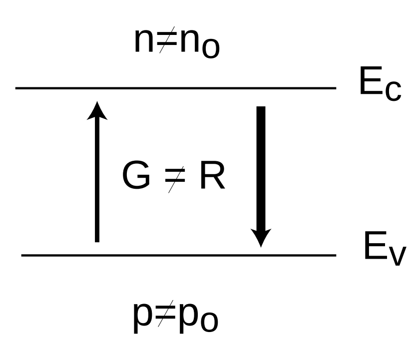
$$
\begin{aligned}
n &= n_o \\
p &= p_o \\
G_{oi} &= R_{oi} \\
G_o &= R_o
\end{aligned}
$$

• Outside thermal equilibrium (with carrier concentrations disturbed from thermal equilibrium values):

$$
\begin{aligned}
n &\neq n_o \\
p &\neq p_o \\
G_i &\neq R_i \\
G &\neq R
\end{aligned}
$$



thermal equilibrium



outside thermal equilibrium

If $G \neq R$, carrier concentrations change in time.

Useful to define *net recombination rate*, U:

$$U = R - G$$

Reflects imbalance between internal G&R mechanisms:

- if $R > G \rightarrow U > 0$, net recombination prevails
- if $R < G \rightarrow U < 0$, net generation prevails
- if $R = G \rightarrow U = 0$, thermal equilibrium

If there are several mechanisms acting simultaneously, define:

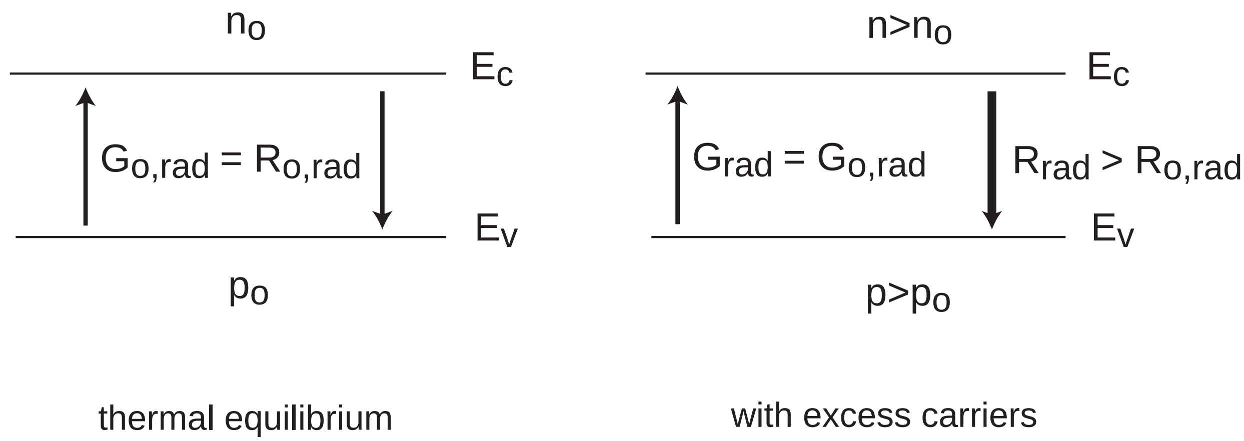
$$U_i = R_i - G_i$$

and

$$U = \Sigma U_i$$

What happens to the G&R rates of the various mechanisms outside thermal equilibrium?

a) *Band-to-band optical G&R*



- optical generation rate unchanged since number of available bonds unchanged:

$$G_{rad} = g_{rad} = r_{rad} n_o p_o$$

- optical recombination rate affected if electron and hole concentrations have changed:

$$R_{rad} = r_{rad} np$$

- define *net recombination rate*:

$$U_{rad} = R_{rad} - G_{rad} = r_{rad}(np - n_o p_o)$$

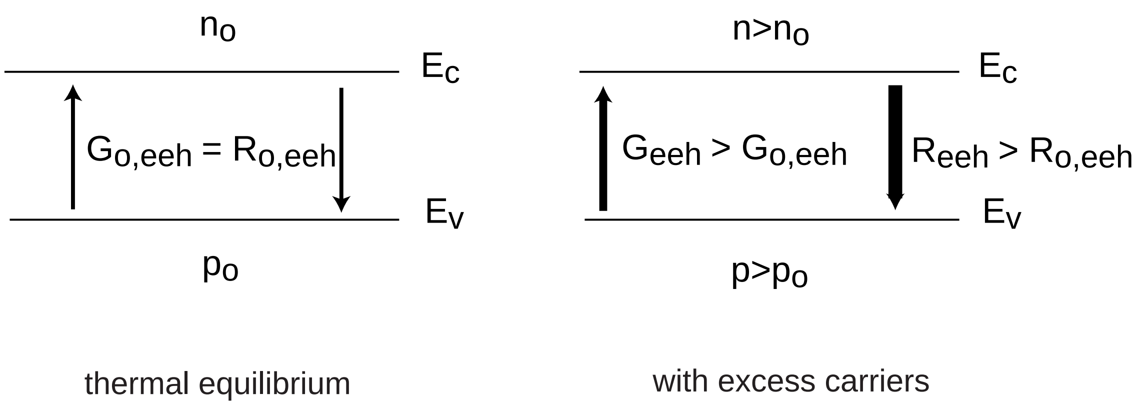
  – if $np > n_o p_o$, $U_{rad} > 0$, net recombination prevails

  – if $np < n_o p_o$, $U_{rad} < 0$, net generation prevails

- note: we have assumed that g_{rad} and r_{rad} are unchanged from equilibrium

b) *Auger G&R*

- Involving hot electrons:



$$G_{eeh} = g_{eeh} n$$

$$R_{eeh} = r_{eeh} n^2 p$$

If relationship between g_{eeh} and r_{eeh} unchanged from TE:

$$U_{eeh} = R_{eeh} - G_{eeh} = r_{eeh} n(np - n_o p_o)$$

- Involving hot holes, similarly:

$$U_{ehh} = r_{ehh} p(np - n_o p_o)$$

- Total Auger:

$$U_{Auger} = (r_{eeh} n + r_{ehh} p)(np - n_o p_o)$$

Key conclusions

- Dominant generation/recombination mechanisms in Si: *trap-assisted* and *Auger*.
- In TE, G and R processes must be balanced *in detail*.
- Auger R rate in TE is proportional to the *square* of the majority carrier concentration and is *linear* on the minority carrier concentration.
- Trap-assisted G/R rates in TE depend on the nature of the trap, its concentration, the doping type and the doping level.
- In n-type semiconductor, midgap trap communicates preferentially with conduction band. In p-type semiconductor, midgap trap communicates preferentially with valence band.