Lecture 4 - Carrier generation and recombination

September 9, 2002

Contents:

1. G&R mechanisms
2. Thermal equilibrium: principle of detailed balance
3. G&R rates in thermal equilibrium

Reading assignment:

del Alamo, Ch 3. §§3.1-3.3

Seminar:

Sept. 10 - K. Soumyanath (Intel), *Challenges and Opportunities for Mixed-Signal Systems in Sub-100 nm CMOS Technologies*. Rm. 34-101, 4PM.

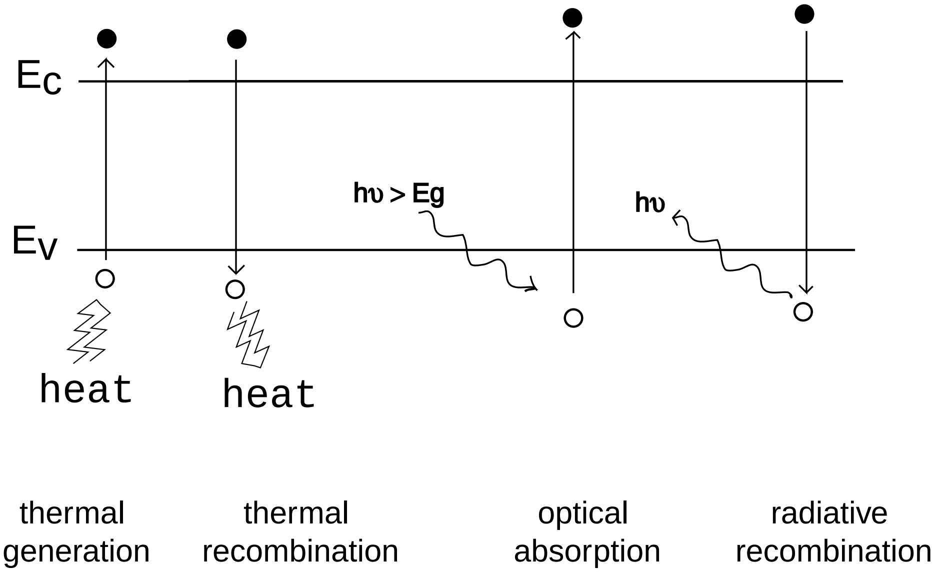
Key questions

- What are the physical mechanisms that might 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?

1. Generation and recombination mechanisms

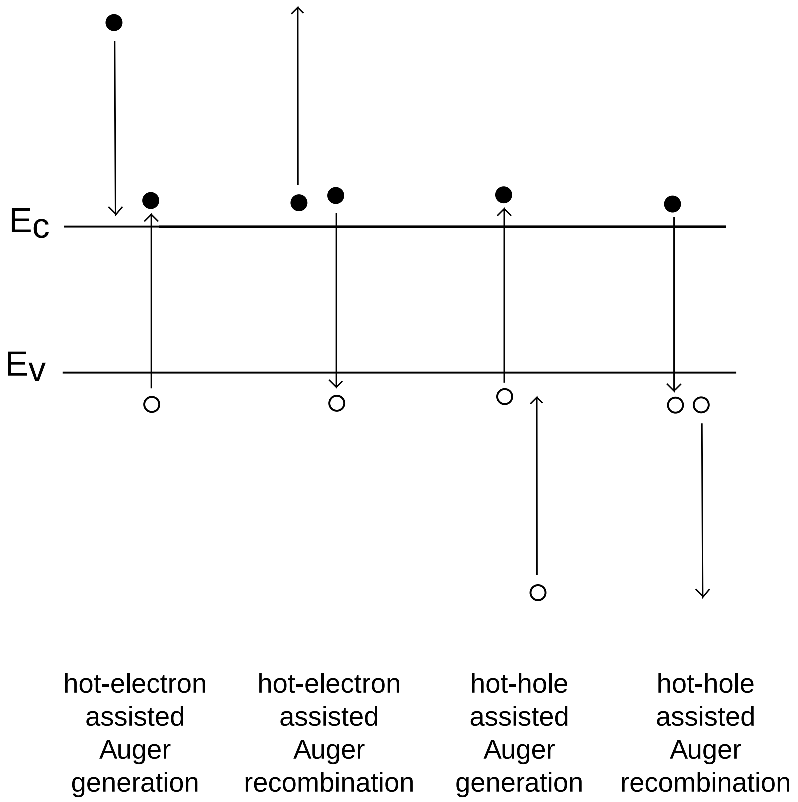
a) *Band-to-band G&R*, by means of:

- 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

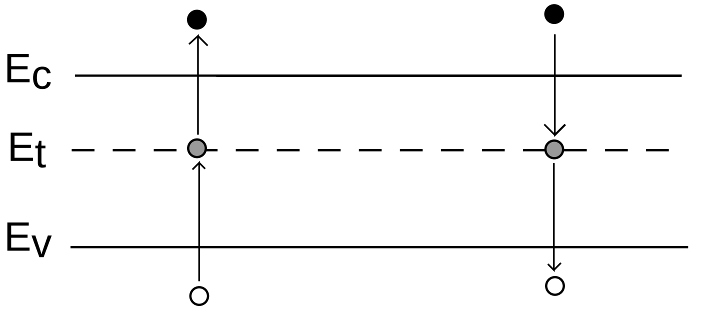
b) *Auger generation and recombination*, involving a third carrier



- 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 thermal generation

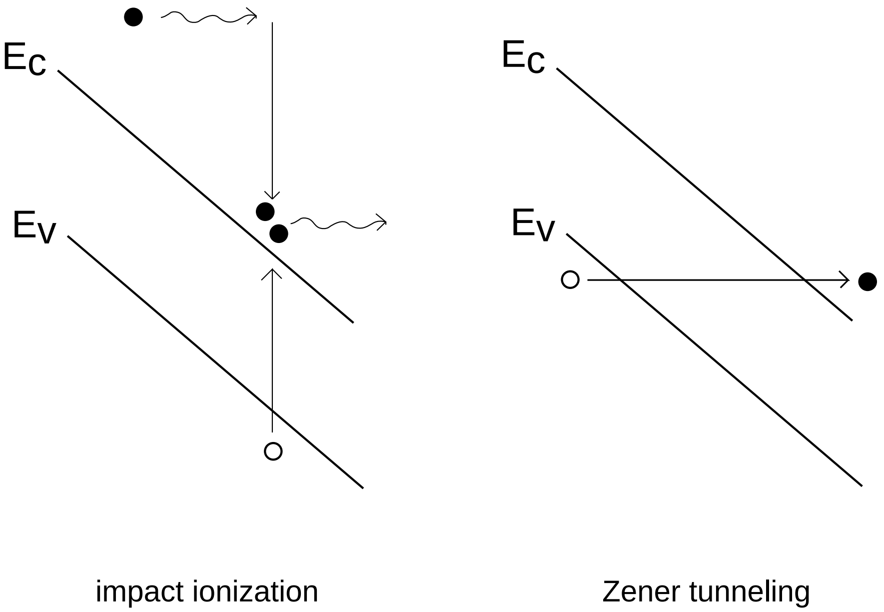
trap-assisted thermal recombination

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



- *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:

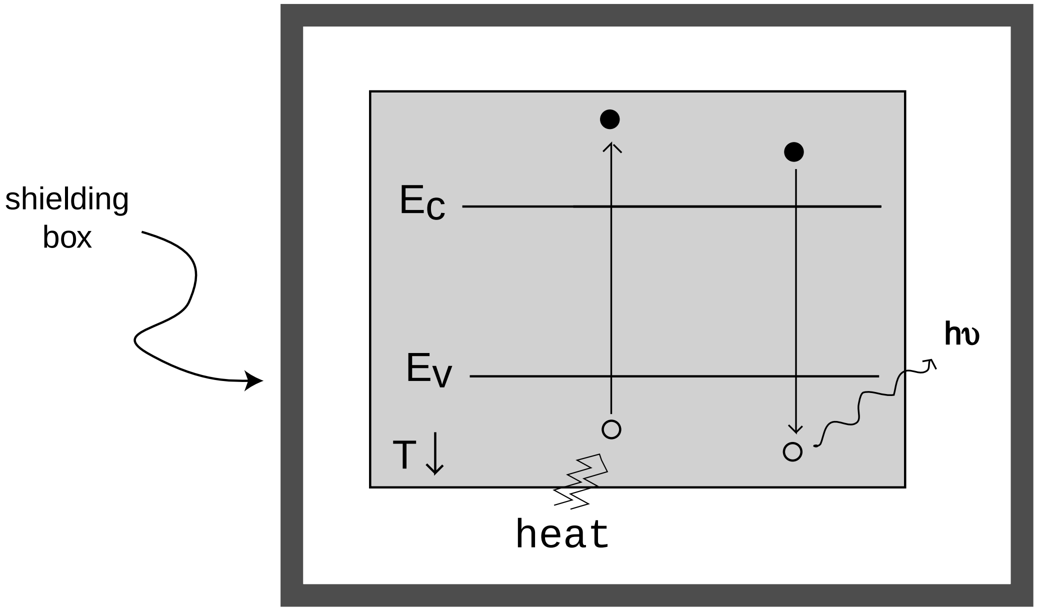
$$R_{oi} = G_{oi} \qquad \text{for all } i$$

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

Without detailed balance, TE not possible.

Consider sample in TE ($G_o = R_o$), but

- G_o takes place through phonon absorption,
- R_o takes place through photon emission



The sample spontaneously cools down!

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:

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

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:

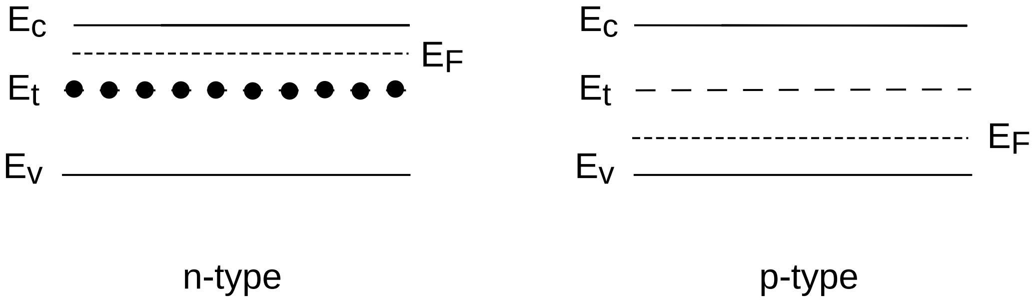
$$n_{to} = N_t f(E_i) = N_t \frac{n_i}{n_i + p_o}$$

Concentration of empty traps:

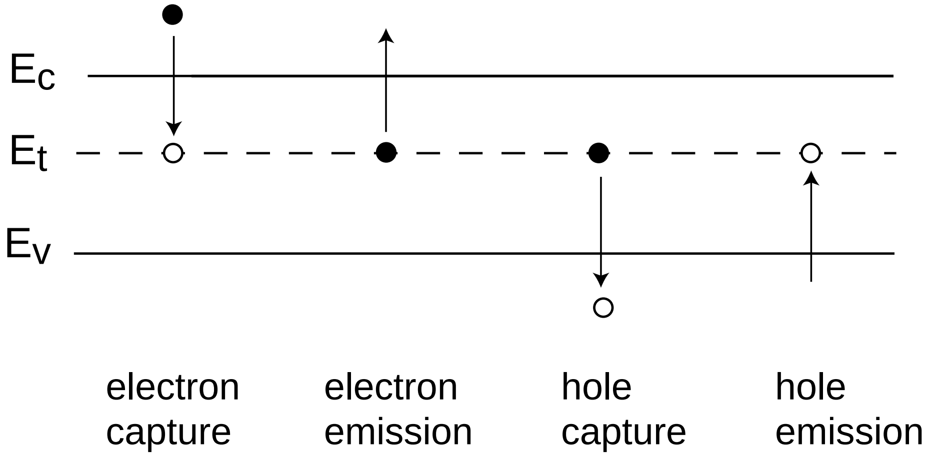
$$N_t - n_{to} = N_t - N_t \frac{n_i}{n_i + p_o} = N_t \frac{p_o}{n_i + p_o}$$

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.

To get expressions for rates at which trap communicates with CB and VB, rewrite rate equations:

$$r_{o,ec} = r_{o,ee} = c_e n_i n_{to} = c_e N_t \frac{n_i^2}{n_i + p_o}$$

$$r_{o,hc} = r_{o,he} = c_h n_i (N_t - n_{to}) = c_h N_t \frac{n_i p_o}{n_i + p_o}$$

Now 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. Then:

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

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

Rates depend on trap and doping level.

Simplify for n-type semiconductor:

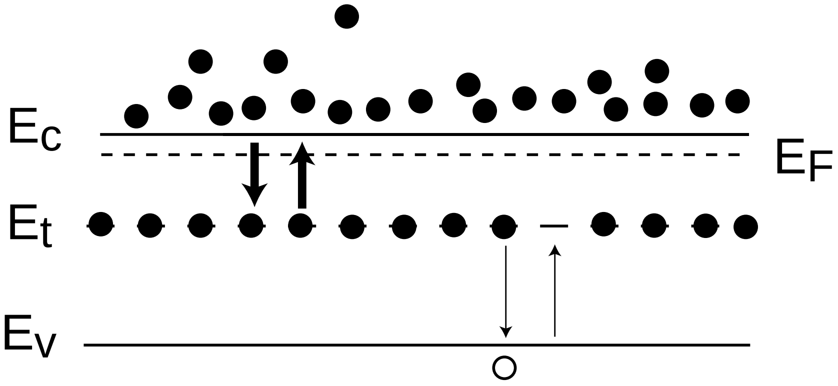
$$r_{o,ec} = r_{o,ee} \simeq \frac{n_i}{\tau_{eo}}$$

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

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.

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.