Lecture 5 - Carrier generation and recombination *(cont.)*

September 12, 2001

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1. G&R rates outside thermal equilibrium
2. Surface generation and recombination

Reading assignment:

del Alamo, Ch. 3, §§3.4, 3.6

Key questions

- What happens to the balance between generation and generation when carrier concentrations are perturbed from thermal equilibrium values?
- How is this balance upset for each G&R mechanism?
- What are the key dependencies of this imbalance in G&R rates?
- How can surface G&R be characterized?

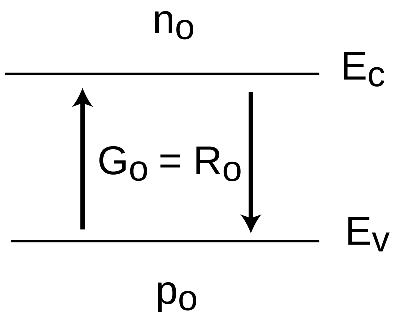
1. G&R rates outside equilibrium

- In thermal equilibrium:

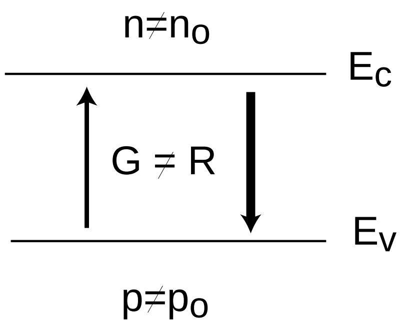
$$\begin{aligned} n &= n_o \\ p &= p_o \\ G_{oi} &= R_{oi} \\ G_o &= R_o \end{aligned}$$

- 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 there are several mechanisms acting simultaneously, define:

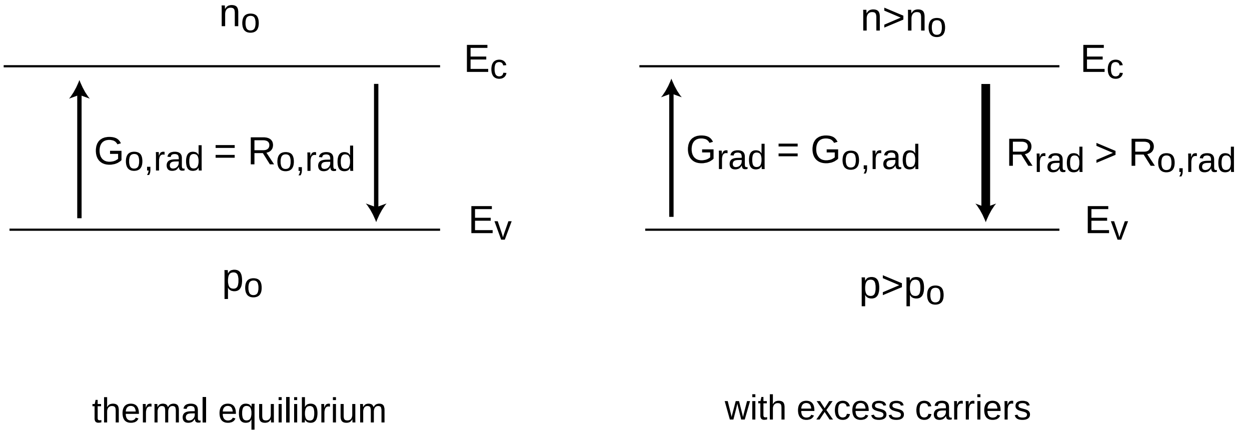
$$U_i = R_i - G_i$$

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*:

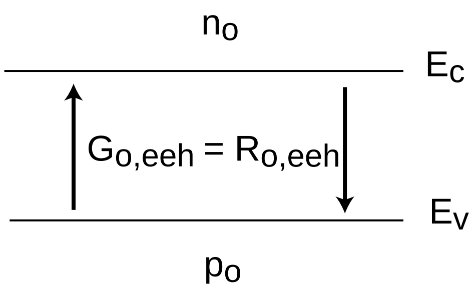
$$U_{rad} = R_{rad} - G_{rad} = r_{rad}(np - n_o p_o)$$

  - if $np > n_o p_o$, $U_{rad} > 0$, net recombination prevails
  - if $np < n_o p_o$, $U_{rad} < 0$, net generation prevails

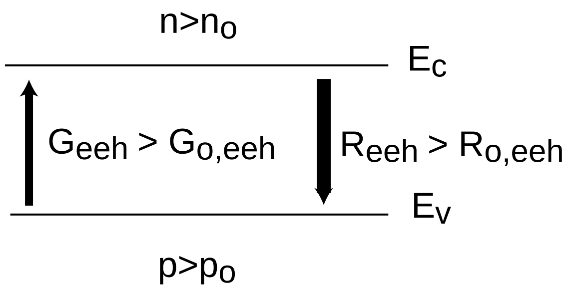
- note: we have assumed that g_{rad} and r_{rad} are unchanged from equilibrium

b) *Auger G&R*

- Involving hot electrons:



thermal equilibrium



with excess carrier

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

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

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

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

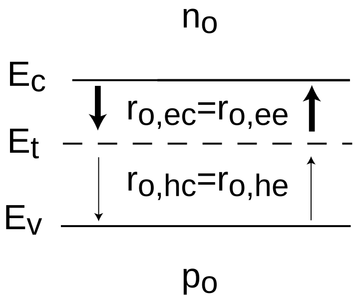
- Involving hot holes, similarly:

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

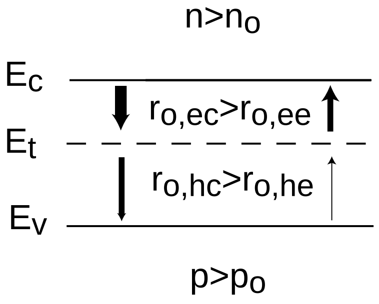
- Total Auger:

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

c) *Trap-assisted thermal G&R*



thermal equilibrium



with excess carriers

Out of equilibrium, if rate constants are not affected:

$$\begin{aligned} r_{ec} &= c_e n(N_t - n_t) \\ r_{ee} &= e_e n_t = c_e n_i n_t \\ r_{hc} &= c_h p n_t \\ r_{he} &= e_h(N_t - n_t) = c_h n_i (N_t - n_t) \end{aligned}$$

Recombination: capture of one electron + one hole ⇒

$$\begin{aligned} \textit{net recombination rate} &= \textit{net electron capture rate} \\ &= \textit{net hole capture rate} \end{aligned}$$

$$U_{tr} = r_{ec} - r_{ee} = r_{hc} - r_{he}$$

From this, derive n_t, and finally get U_{tr}:

$$U_{tr} = \frac{np - n_o p_o}{\tau_{ho}(n + n_i) + \tau_{eo}(p + n_i)}$$

d) *All processes combined*

$$U = U_{rad} + U_{Auger} + U_{tr}$$

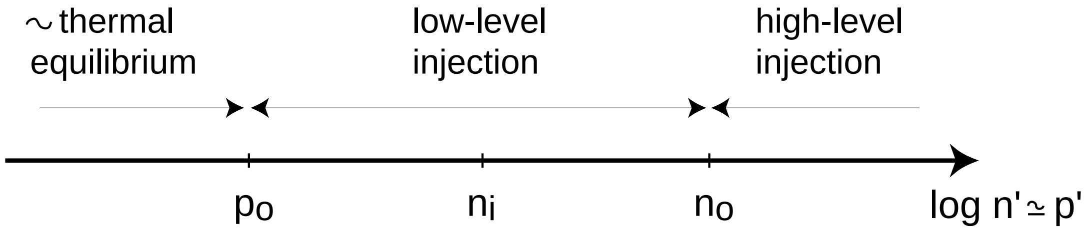
□ Special case: **Low-level Injection**

Define *excess* carrier concentrations:

$$n = n_o + n'$$

$$p = p_o + p'$$

LLI: Equilibrium minority carrier concentration overwhelmed but majority carrier concentration negligibly disturbed



- for n-type:

$$p_o \ll n' \simeq p' \ll n_o$$

- for p-type:

$$n_o \ll n' \simeq p' \ll p_o$$

In LLI:

$$np - n_o p_o = n_o p_o + n_o p' + p_o n' + n'p' - n_o p_o \simeq (n_o + p_o)n'$$

All expressions of U follow the form:

$$U_i \simeq \frac{n'}{\tau_i}$$

τ_i is *carrier lifetime* of process i, a constant characteristic of each G&R process:

$$\tau_{rad} = \frac{1}{r_{rad}(n_o + p_o)}$$

$$\tau_{Auger} \simeq \frac{1}{(r_{eeh} n_o + r_{ehh} p_o)(n_o + p_o)}$$

$$\tau_{tr} \simeq \frac{\tau_{ho} n_o + \tau_{eo} p_o}{n_o + p_o}$$

Under LLI, net recombination rate depends linearly on *excess carrier concentration* through a constant that is characteristic of material and temperature.

If all G&R processes are independent, combined process:

$$U \simeq \frac{n'}{\tau}$$

with

$$\frac{1}{\tau} = \Sigma \frac{1}{\tau_i}$$

The G&R process with the *smallest* lifetime dominates.

Physical meaning of *carrier lifetime*:

- U is rate of net recombination rate in unit volume in response to excess carrier concentration n' (linear in n')
- $\frac{1}{U}$ is mean time between recombination events in unit volume
- $\tau = \frac{n'}{U}$ is mean time between recombination event *per excess carrier*,

  or average time excess carrier will "survive" before recombining

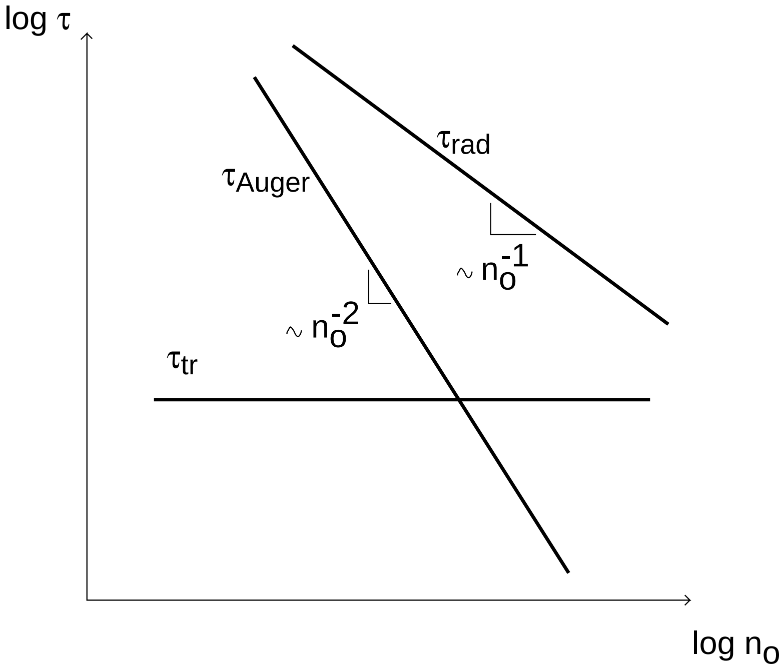
  → constant characteristic of material

For n-type material, $n_o \gg p_o$:

$$\tau_{rad} = \frac{1}{r_{rad} n_o}$$

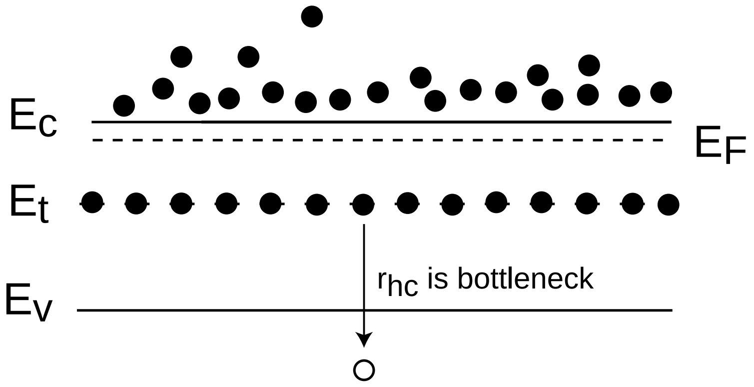
$$\tau_{Auger} = \frac{1}{r_{eeh} n_o^2}$$

$$\tau_{tr} = \tau_{ho} \propto \frac{1}{N_t}$$

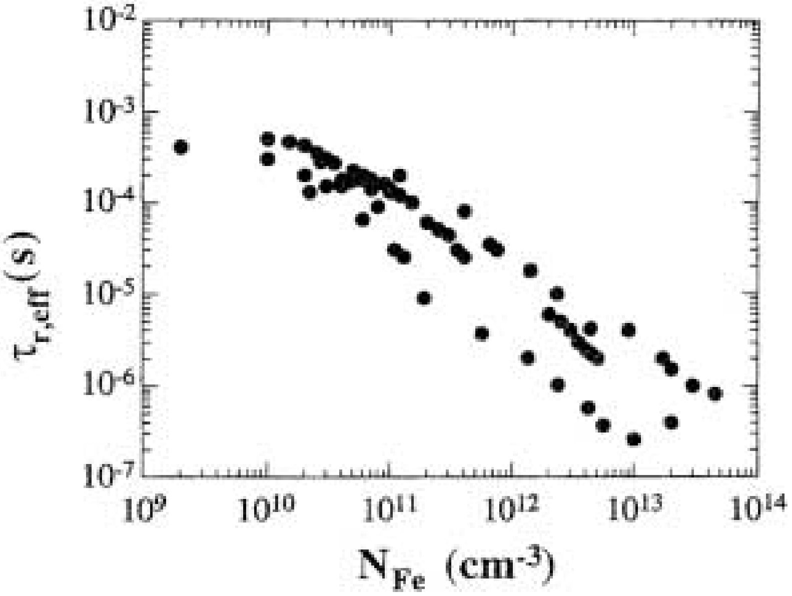


Trap recombination (n-type material):

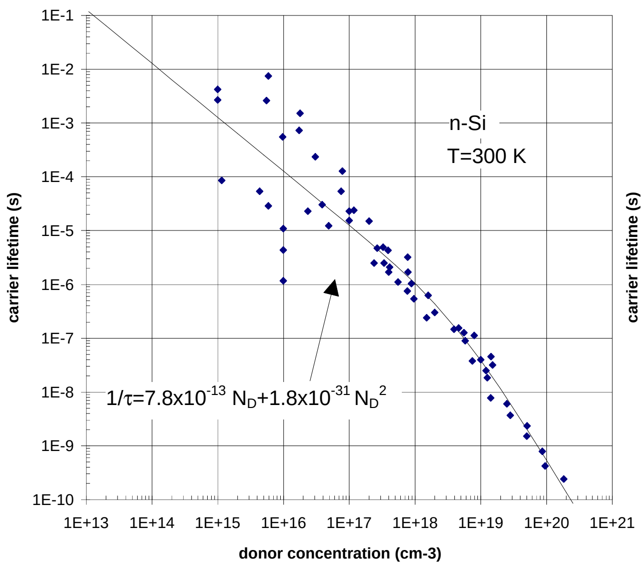
- Lifetime does not depend on n_o [trap occupation probability rather insensitive to n_o]

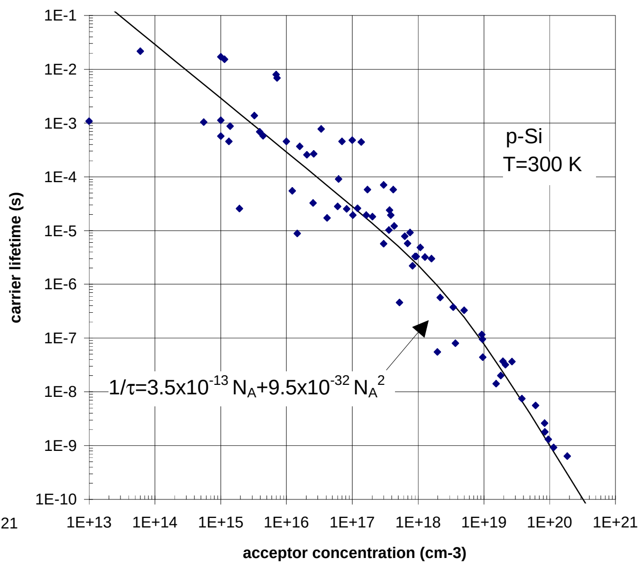


- Lifetime depends on trap concentration as $\tau \propto N_t^{-1}$



□ Measurements of carrier lifetime in Si at 300 K





For low doping levels, $N_{A,D} < 10^{17}\ cm^{-3}$, τ_{tr} dominates:

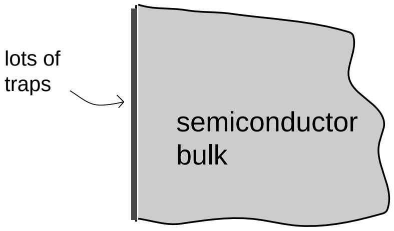
- τ depends on material quality and process → wide data scatter
- N_t correlated with $N_{A,D} \rightarrow \tau \propto N_{A,D}^{-1}$

For high doping levels, $N_{A,D} > 10^{18}\ cm^{-3}$, τ_{Auger} dominates:

- "intrinsic" recombination: → tight data distribution
- $\tau \propto N_{A,D}^{-2}$

2. Surface generation and recombination

Surface: severe disruption of periodic crystal ⇒ lots of traps (G&R centers)



Under LLI:

$$U_s \simeq S n'(s)$$

$$S \equiv \text{surface recombination velocity } (cm/s)$$

note units:

$$U_s(cm^{-2} \cdot s^{-1}) = S(cm \cdot s^{-1})\ n'(cm^{-3})$$

S is perpendicular component of velocity with which excess carriers "dive" into the surface to recombine.

Key conclusions

- *Excess np product* is driving force for net generation/recombination.
- Under *low-level injection*:

$$U \sim \frac{n'}{\tau}$$

  with $\tau \equiv$ *carrier lifetime*.

- Carrier lifetime: mean time that an average excess carrier "survives" before recombining.
- In Si around 300K,
  - $\tau \sim N^{-1}$ for low N (trap-assisted recombination),
  - $\tau \sim N^{-2}$ for high N (Auger recombination).
- Order of magnitude of key parameters for Si at 300K:
  - $\tau \sim 1\ ns\ -\ 1\ ms$, depending on doping

Self study

- Carrier extraction, generation lifetime