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

February 14, 2007

## Contents:

1. G&R rates outside thermal equilibrium *(cont.)*
2. Dynamics of excess carriers in uniform situations
3. Surface generation and recombination

## Reading assignment:

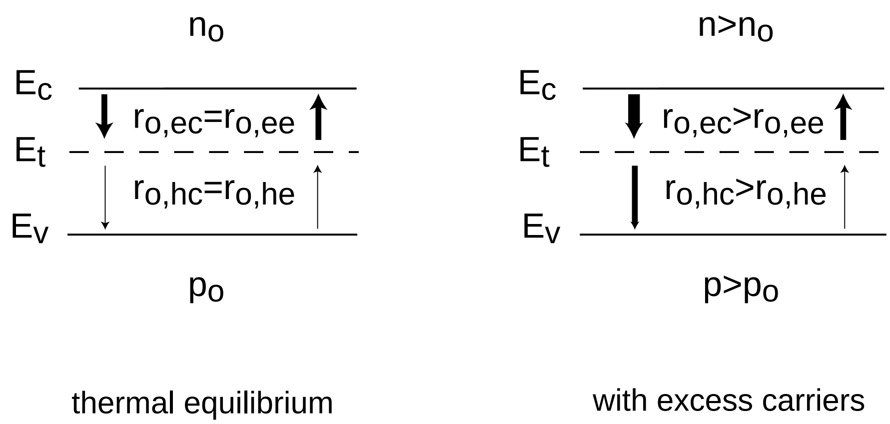
del Alamo, Ch. 3, §§3.4-3.7

## Key questions

- Outside thermal equilibrium, how is the balance between generation and recombination upset for each G&R mechanism? *(cont.)*
- What governs the carriers dynamics in semiconductors outside equilibrium?
- In particular, if one shines light onto a semiconductor, how do the carrier concentrations evolve in time?
- What happens when the light is turned off?
- How about if the light excitation is turned on and off very quickly?
- How can surface G&R be characterized?

# 1. G&R rates outside equilibrium *(cont.)*

c) *Trap-assisted thermal G&R*




Out of equilibrium, if rate constants are not affected:

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

Recombination: capture of one electron + one hole ⇒

$$\textit{net recombination rate} = \textit{net electron capture rate} = \textit{net hole capture rate}$$

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

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*

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

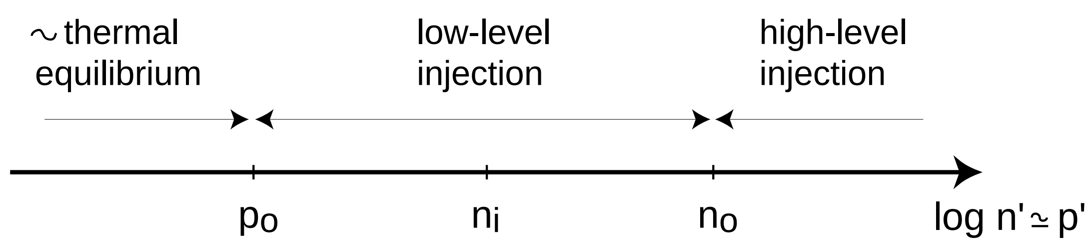
□ Special case: **Low-level Injection**

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:

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

$\tau_i$ 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 net recombination rate in unit volume in response to excess carrier concentration $n'$ (linear in $n'$) $[cm^{-3} \cdot s^{-1}]$
- $\frac{U}{n'}$ is net recombination rate in unit volume per unit excess carrier $[s^{-1}]$
- $\tau = \frac{n'}{U}$ is mean time between recombination event *per excess carrier* $[s]$

  or average time excess carrier will "survive" before recombining

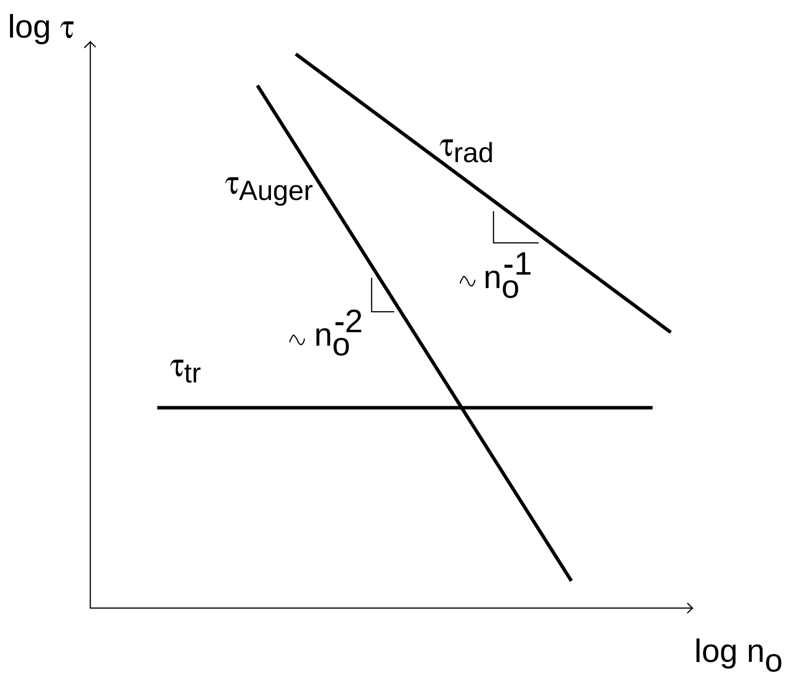
  → constant characteristic of material

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

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

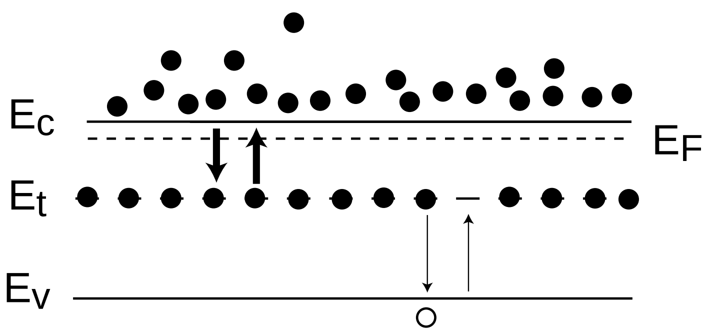
$$\tau_{Auger} = \frac{1}{r_{eeh} n_o^2}$$

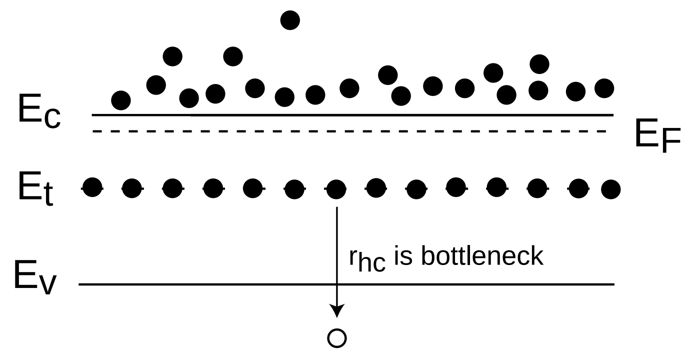
$$\tau_{tr} = \tau_{ho} \propto \frac{1}{N_t}$$



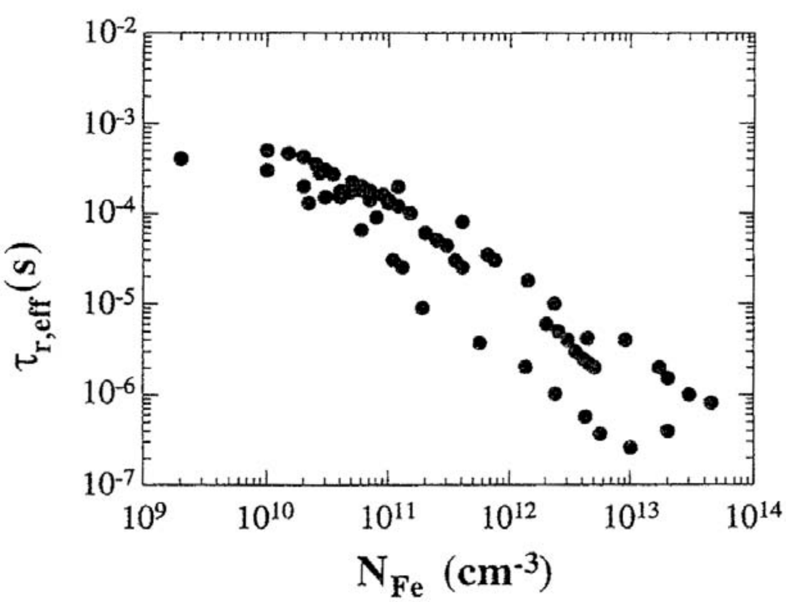
Trap recombination (n-type material):

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



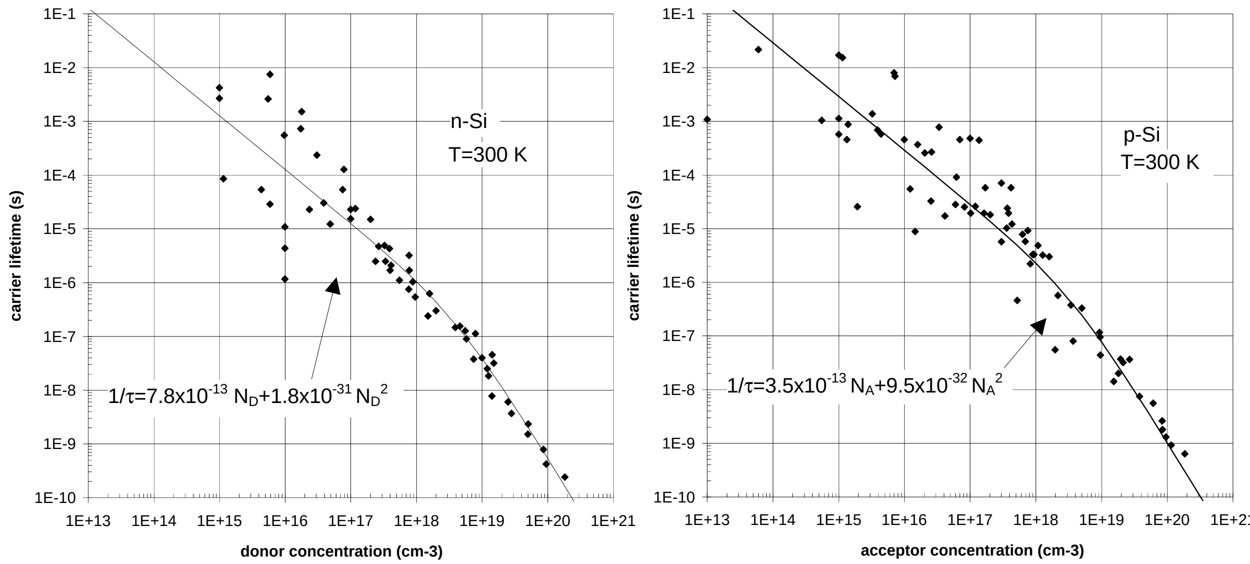




• Lifetime depends on trap concentration as $\tau \propto N_t^{-1}$




Schroder, D. K. "Carrier Lifetimes in Silicon." *IEEE Transactions on Electron Devices* 44, no. 1 (1997): 160-170.

# □ Measurements of carrier lifetime in Si at 300 K




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

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

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

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

Common range of lifetimes: $\tau = 1\ ns \sim 100\ \mu s$

## 2. Dynamics of excess carriers in uniform situations

Consider:

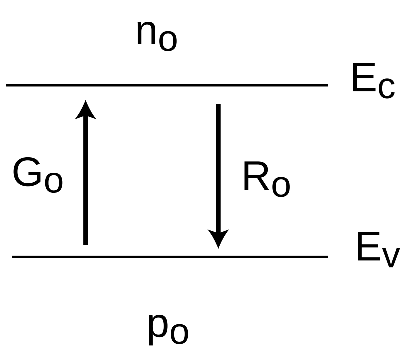
- extrinsic uniformly doped semiconductor
- no surfaces nearby

In thermal equilibrium:

$$n = n_o$$

$$p = p_o$$

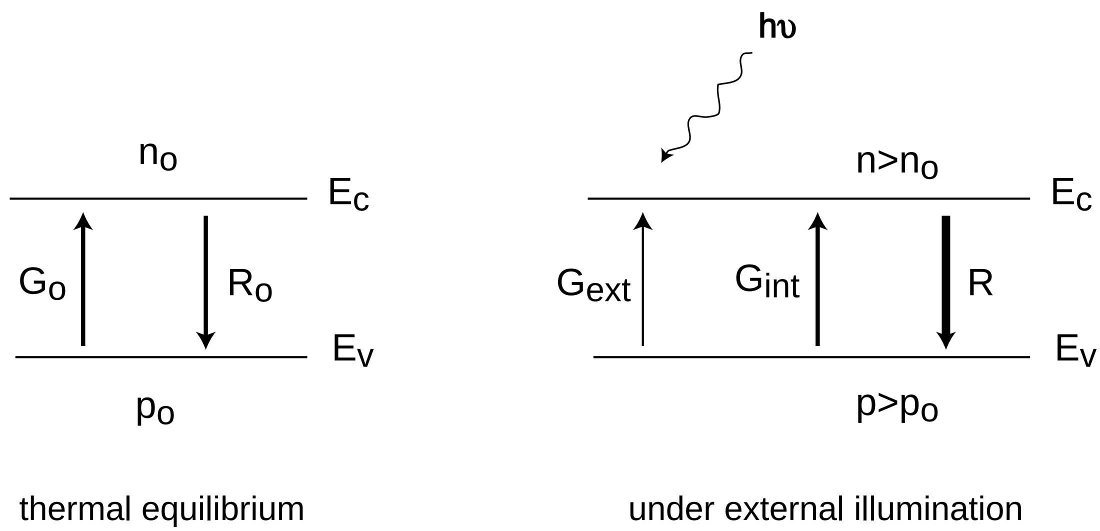
$$G_o - R_o = 0$$




thermal equilibrium

Now add:

- uniform excitation throughout body, $G_{ext}$




If there is imbalance between total generation and recombination, carrier concentrations change in time:

$$\frac{dn}{dt} = \frac{dp}{dt} = G - R$$

- if $G > R \;\Rightarrow\; n,\; p \uparrow$
- if $G < R \;\Rightarrow\; n,\; p \downarrow$

Distinguish between *internal* and *external* generation:

$$G = G_{ext} + G_{int}$$

Then:

$$G - R = G_{ext} + G_{int} - R = G_{ext} - U$$

and:

$$\frac{dn}{dt} = \frac{dp}{dt} = G_{ext} - U$$

- if $G_{ext} > U \;\Rightarrow\; n,\ p \uparrow$
- if $G_{ext} < U \;\Rightarrow\; n,\ p \downarrow$

Under LLI:

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

Also:

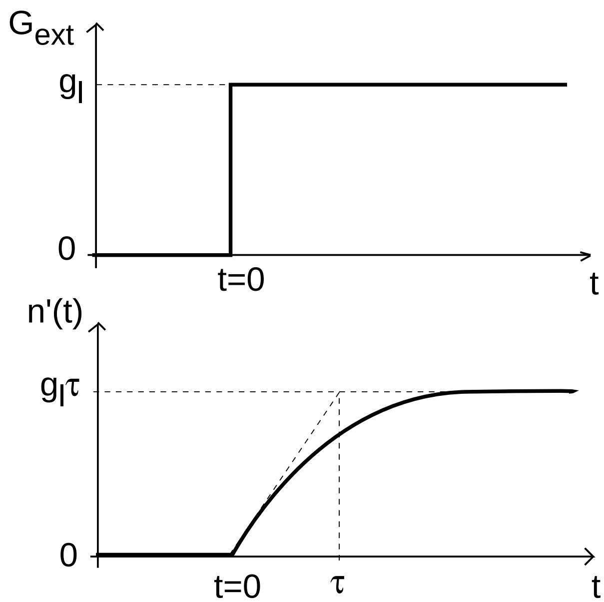
$$\frac{dn}{dt} = \frac{dn'}{dt}$$

Then:

$$\frac{dn'}{dt} = G_{ext} - \frac{n'}{\tau}$$

Homogeneous solution ($G_{ext} = 0$) is: $e^{-t/\tau}$

## • Example 1: Turn-on transient




$$n'(t) = g_l \tau (1 - e^{-t/\tau}) \qquad \text{for } t \geq 0$$

Define:

*steady-state* $\equiv$ initial transient died out (need a few $\tau$'s)

In steady state:

$$generation = recombination$$

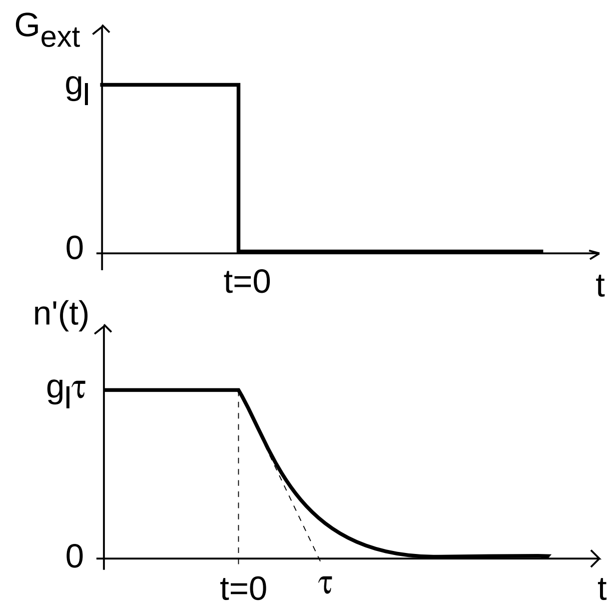
or

$$g_l = \frac{n'}{\tau}$$

Then

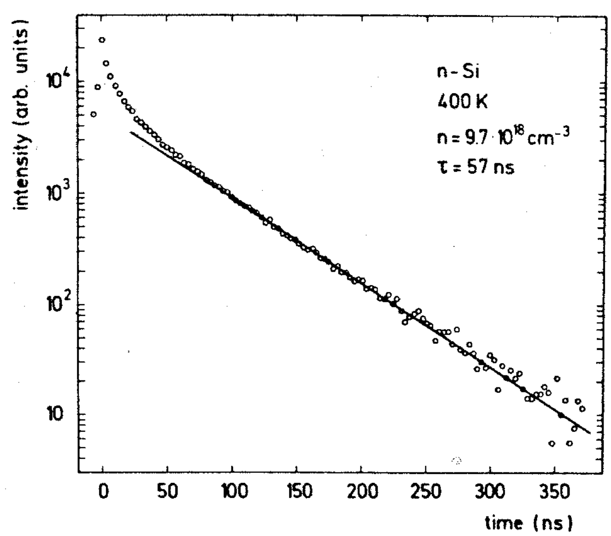
$$n' = g_l \tau$$

## • Example 2: Turn-off transient




$$n'(t) = g_l \tau e^{-t/\tau} \qquad \text{for } t \geq 0$$

Technique to measure $\tau$:

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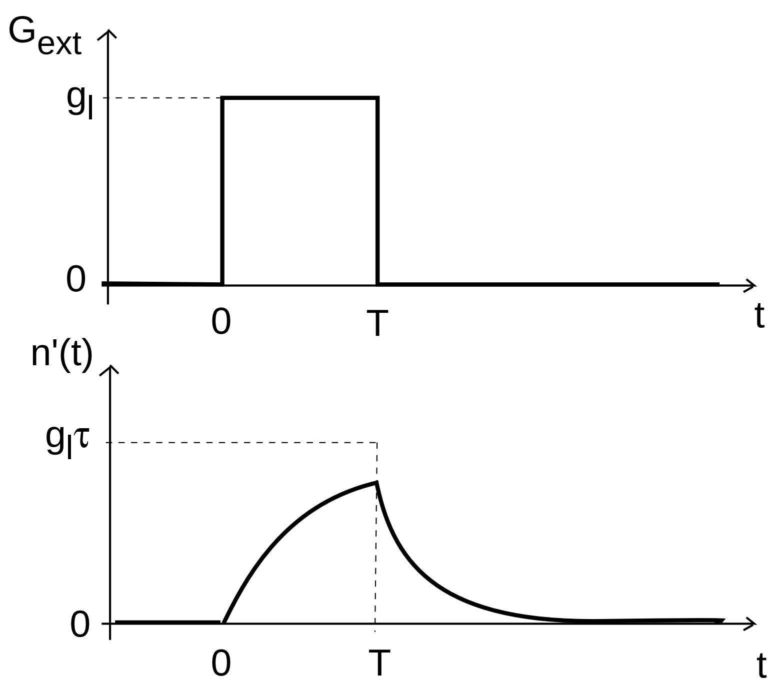
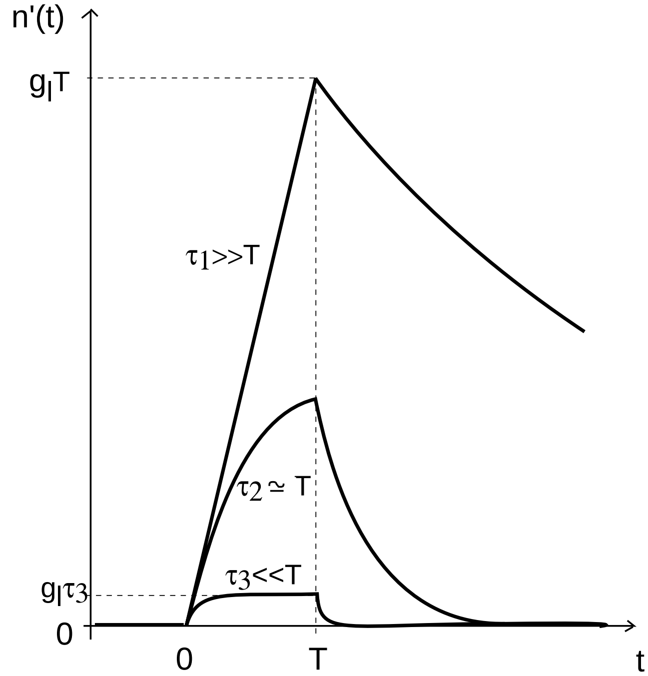
## • Example 3: A pulse of light




$$n'(t) = g_l\tau(1 - e^{-t/\tau}) \qquad \text{for } 0 \le t \le T$$

$$n'(t) = g_l\tau(1 - e^{-T/\tau})e^{-(t-T)/\tau} \qquad \text{for } T \le t$$

Two extreme cases:




- If $\tau_1 \gg T$, pulse too short for final value of $n'$ to be reached:

$$n'(t) \simeq g_l t \qquad \text{for } 0 \leq t \leq T$$

- If $\tau_3 \ll T$, final value of $n'$ achieved quickly:

$$n'(t) \simeq g_l \tau_3 \qquad \text{for } 0 \leq t \leq T$$

shape of $n'(t)$ similar to shape of light pulse: **quasi-static situation** $\equiv$ no memory effect

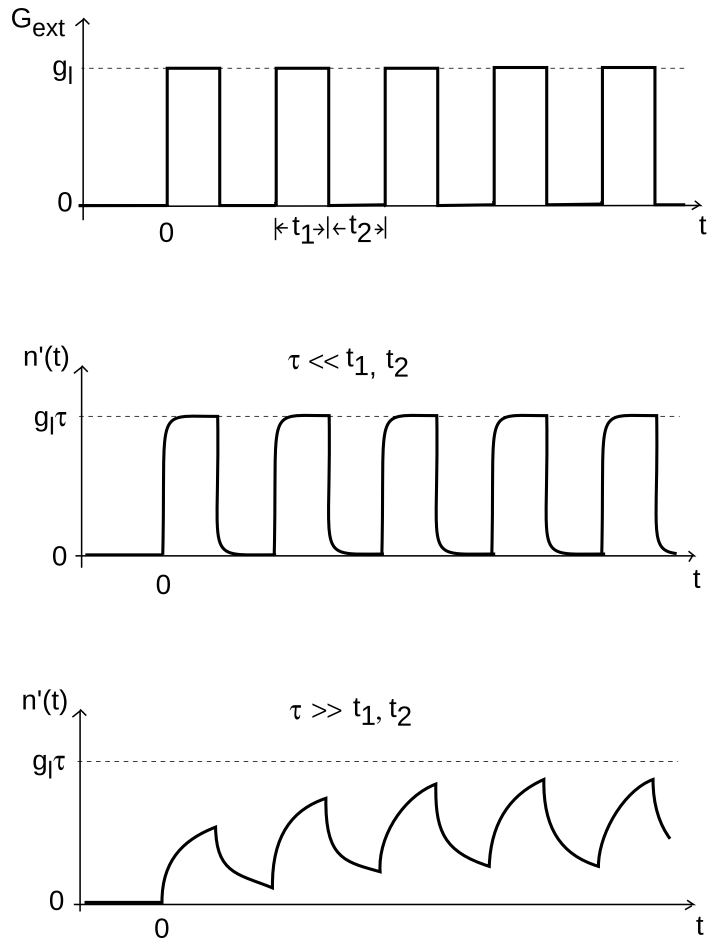
$$\frac{dn'}{dt} = G_{ext} - \frac{n'}{\tau} \;\Rightarrow\; n'(t) \simeq G_{ext}(t)\,\tau$$

# • Example 4: A pulse train

Important point: difference between quasi-static and steady-state

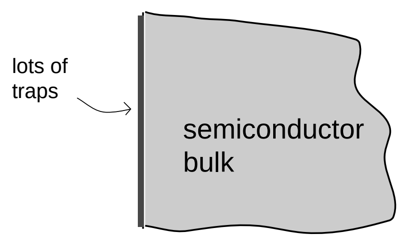
-*steady-state*: initial transient associated with turn-on of excitation has died off

-*quasi-static*: time derivatives irrelevant in time scale of interest



## 3. Surface generation and recombination

Surface: severe disruption of periodic crystal $\Rightarrow$ lots of traps (G&R centers)




Under LLI:

$$U_s \simeq Sn'(s)$$

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

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.
- Dynamics of carrier concentrations in quasi-neutral low-level injected situations governed by *carrier lifetime*.
- *Quasi-static situation*: perturbations with time scale much longer than $\tau$.
- *Steady-state situation*: condition established after initial transient has died off.
- 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