Lecture 6 - Carrier generation and recombination *(cont.)*

Carrier drift and diffusion

September 13, 2002

Contents:

1. Dynamics of excess carriers in uniform situations
2. Thermal motion

Reading assignment:

del Alamo, Ch. 3, §§3.5,3.7, Ch. 4, §4.1.

Key questions

- 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?
- Are carriers sitting still in thermal equilibrium?

1. Dynamics of excess carriers in uniform situations

Consider:

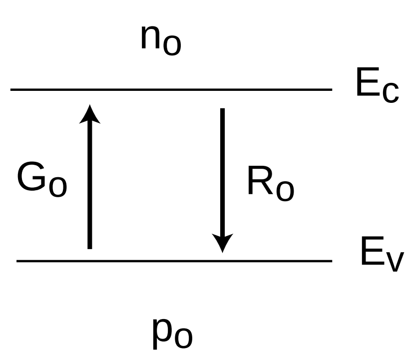
- extrinsic uniformly doped semiconductor
- no surfaces nearby

In thermal equilibrium:

$$n = n_o$$

$$p = p_o$$

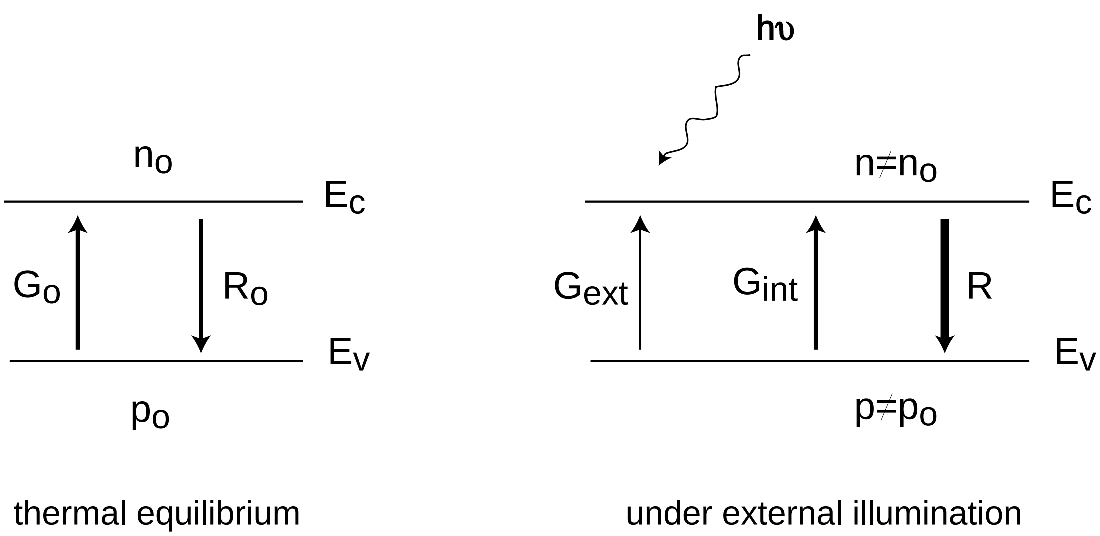
$$G_o - R_o = 0$$



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:

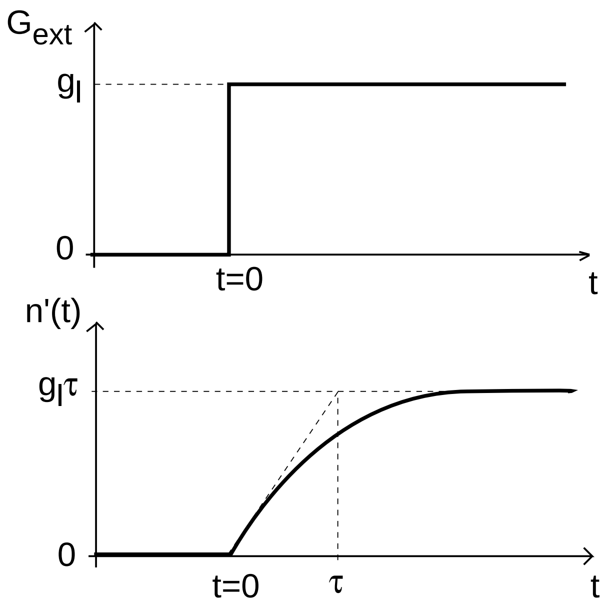
$$\frac{dn}{dt} = \frac{dn'}{dt}$$

Then:

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

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

• Example 1: Turn-on transient



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

Define:

steady-state ≡ initial transient died out (need a few τ's)

In steady state:

$$generation = recombination$$

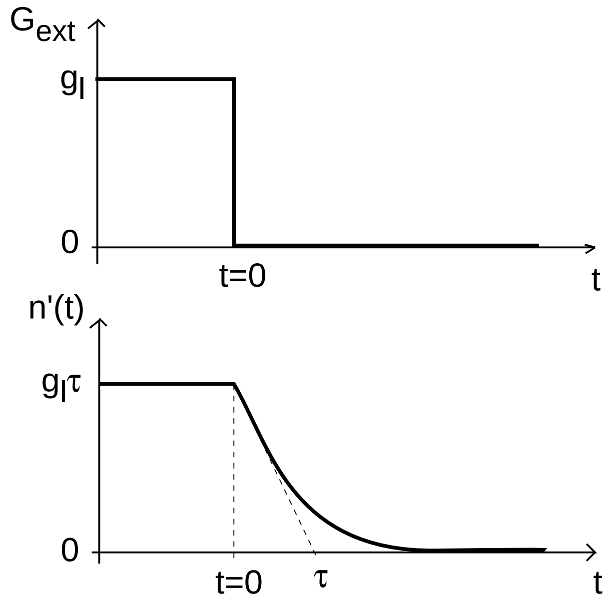
or

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

Then

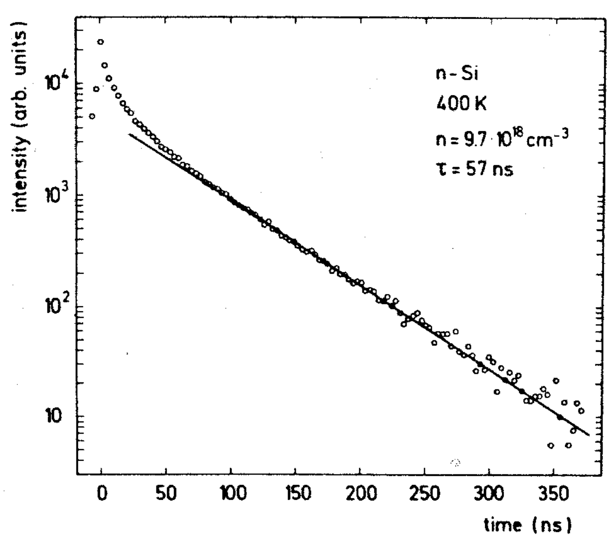
$$n' = g_l \tau$$

• Example 2: Turn-off transient



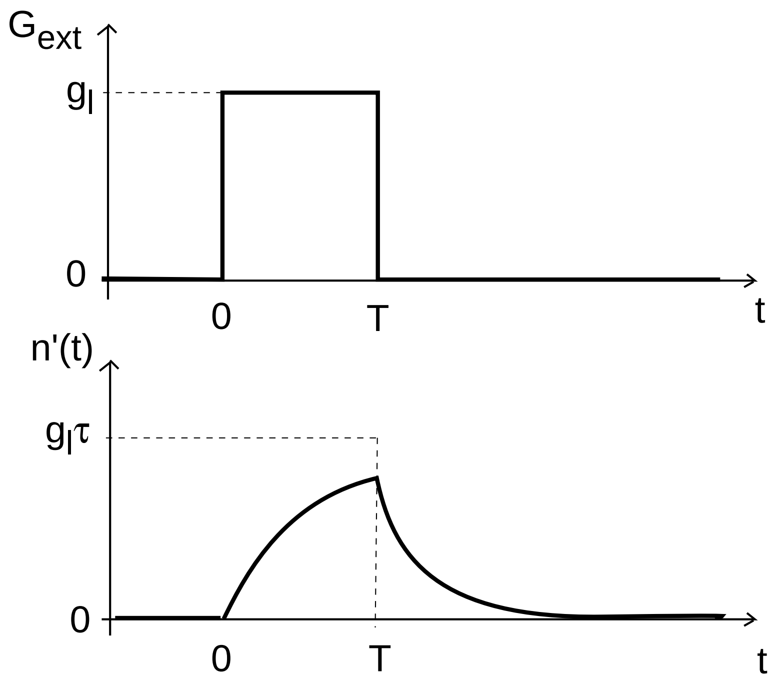
$$n'(t) = g_l \tau e^{-t/\tau} \quad \text{for } t \geq 0$$

Technique to measure τ:



[Dziewior & Silber, 1977]

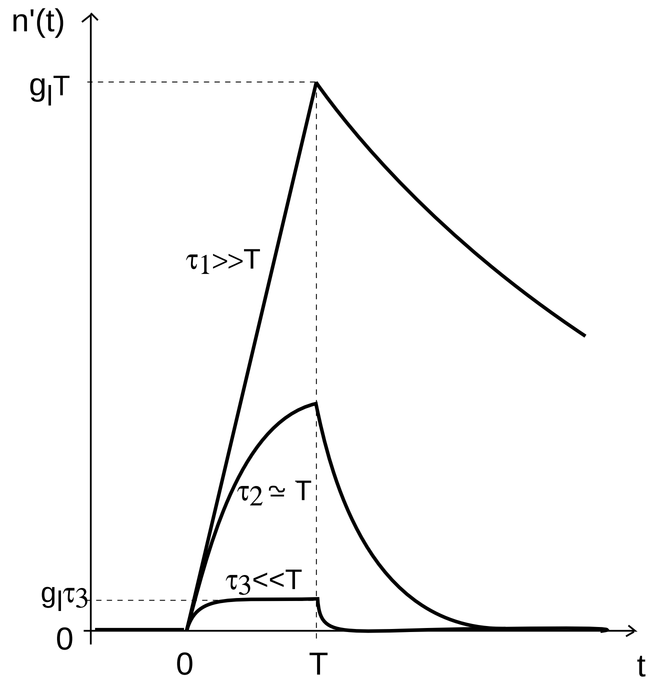
• Example 3: A pulse of light



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

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

Two extreme cases:



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

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

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

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

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

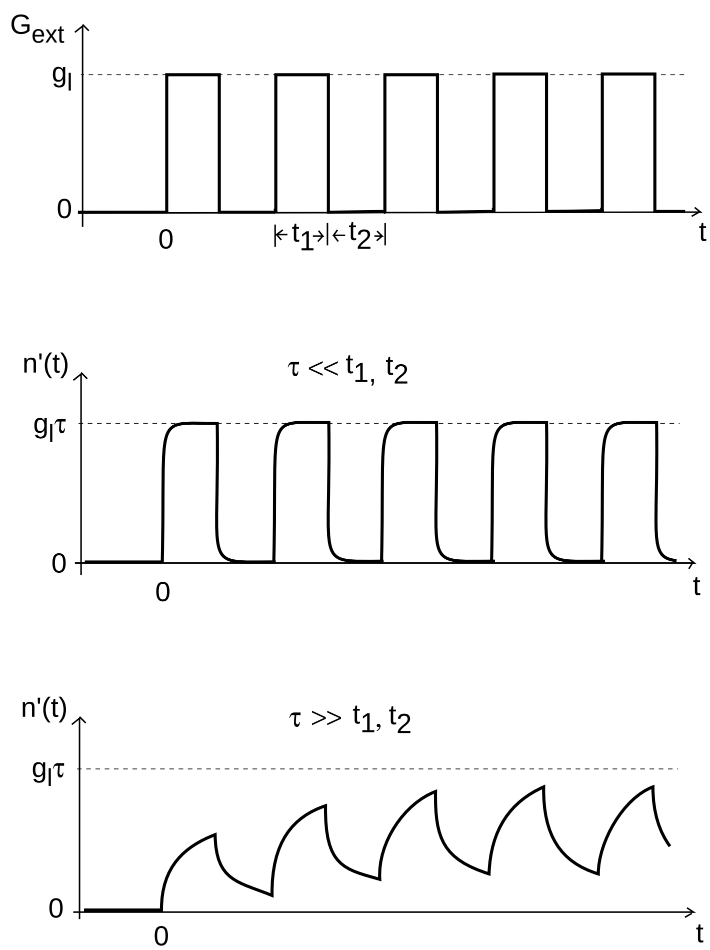
$$\frac{dn'}{dt} = G_{ext} - \frac{n'}{\tau} \;\Rightarrow\; n'(t) \simeq G_{ext}(t)\,\tau$$

• Example 4: A pulse train

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

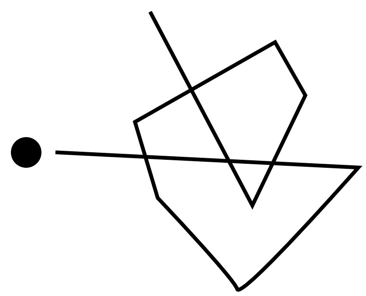
-*steady-state*: initial transient associated with turn-on of excitation has died off

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



2. Thermal motion

At finite T, carriers moving around in a random way suffering frequent collisions with vibrating lattice, ionized impurities, etc.



Define:

- *Thermal velocity*, v_{th}: average magnitude of carrier velocity between collisions $[cm/s]$.
- *Mean free path*, l_c: average distance travelled between collisions $[cm]$.
- *Scattering time*, τ_c: average time between collisions $[s]$.

Then:

$$l_c = v_{th}\tau_c$$

□ Thermal velocity depends on material and temperature:

$$v_{th} = \sqrt{\frac{8}{\pi}\frac{kT}{m_c^*}}$$

Where:

$$m_c^* \equiv \text{conductivity effective mass } [eV \cdot s^2/cm^2]$$

m_c^* accounts for all interactions between the carriers and the perfect periodic potential of the lattice.

For electrons in Si at 300 K ($m_{ce}^* = 0.28 m_o$), $v_{the} \simeq 2 \times 10^7\ cm/s$.

□ Scattering mechanisms:

1. *lattice or phonon scattering*: carriers collide with vibrating lattice atoms (phonon absorption and emission)

   ⇒ some energy exchanged ($\sim$ tens of meV)

2. *ionized impurity scattering*: Coulombic interaction between charged impurities and carriers

   ⇒ no energy exchanged

3. *surface scattering* in inversion layer
4. *neutral impurity scattering* with neutral dopants, interstitials, vacancies, etc
5. *carrier-carrier scattering*

No need for detailed models.

Order of magnitude of $\tau_c < 1\ ps$ (will learn to estimate next time).

Then, order of magnitude of $l_c < 50\ nm$.

Key conclusions

- 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 τ.
- *Steady-state situation*: condition established after initial transient has died off.
- At finite temperatures, carriers move around in a random way suffering many collisions *(thermal motion)*.
- Dominant scattering mechanisms in Si at 300K: phonon scattering, ionized impurity scattering, and surface scattering (in inversion layer).
- Order of magnitude of key parameters for Si at 300K:
  - $v_{th} \sim 2 \times 10^7 \ cm/s$
  - $\tau_c < 1 \ ps$
  - $l_c < 50 \ nm$