EE2003 Semiconductor Fundamentals

Semiconductor in Non-Equilibrium

Non-Equilibrium

- When the concentration of electrons (n) and holes (p) in a semiconductor **deviate** from the thermal equilibrium values (n_0 and p_0, respectively), the semiconductor is said to be in non-equilibrium.
- Such deviations occur when an external excitation is applied to the semiconductor.
- Ways by which an external excitation may be applied:
  - Applying an external voltage
  - Exposing the semiconductor to light
  - Changing the temperature (less common)
- When a semiconductor deviates from thermal equilibrium, the law of mass action ($n_0 p_0 = n_i^2$) **no longer** holds true, i.e. $np \neq n_i^2$.

Non-Equilibrium

- **Case 1 - Excess carriers: $np > n_i^2$**
  - Also referred to as carrier injection. The corresponding changes in the carrier concentrations, defined as $\Delta n = n - n_0$ and $\Delta p = p - p_0$, are greater than zero.
  - The recombination rate increases. i.e. R $(=\alpha_r np)$ > G_{th} $(=\alpha_r n_0 p_0)$ and the semiconductor tries to restore thermal equilibrium by eliminating the excess carriers.
- **Case 2 - Deficit of carriers: $np < n_i^2$**
  - Also referred to as carrier extraction. Δn and Δp are less than zero (i.e. negative).
  - The recombination rate decrease, i.e. $R < G_{th}$ and the semiconductor tries to restore thermal equilibrium by generating more carriers.

Non-Equilibrium

- **Degree of deviation:**
  - ***Low-level injection/extraction***: The change in the minority carrier concentration is **much smaller** compared to the majority carrier concentration at thermal equilibrium.
    - For example, in a p-type semiconductor, if $|\Delta n| << p_0$, then low-level injection/extraction is said to prevail.
    - Where to draw the line? Rule-of-thumb would be for the change in the minority carrier concentration **not to exceed 10%** of the majority carrier concentration at thermal equilibrium.
  - ***High-level injection***: The change in minority carrier concentration is **comparable to or greater than** the majority carrier concentration at thermal equilibrium (usually not of interest as secondary effects dominate the characteristics of the semiconductor device).

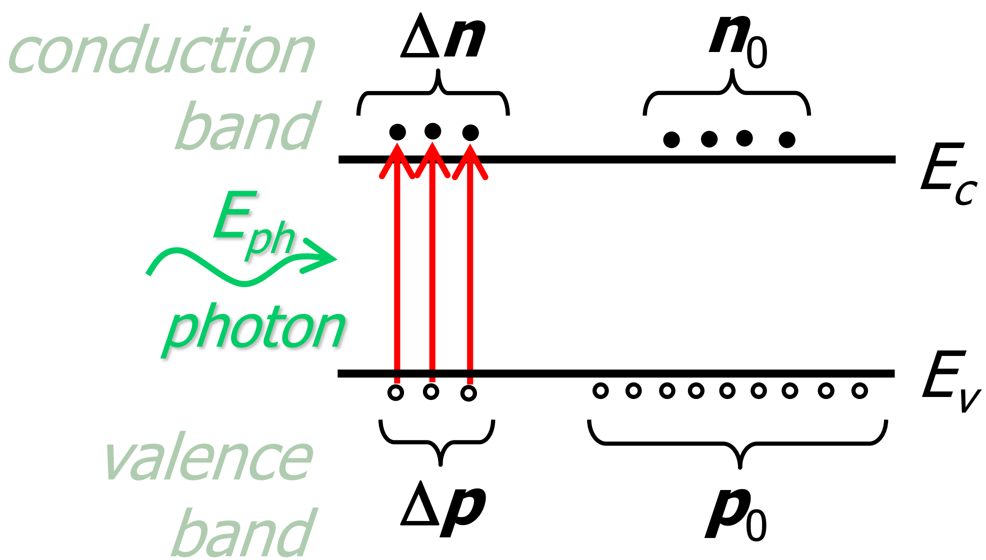
Minority Carrier Lifetime

- Whenever there is a departure from thermal equilibrium, a "restoring force" would act to revert the semiconductor to thermal equilibrium.
- Under **low-level injection[1] condition**, the length of time it takes the semiconductor to revert to thermal equilibrium is determined by the **excess[2] minority carrier concentration** and **lifetime**.
  - The average time that excess minority carriers exist in the system before they recombine with the majority carriers is termed **recombination lifetime**.
  - The average time it takes for a minority carrier to be created is termed **generation lifetime**.

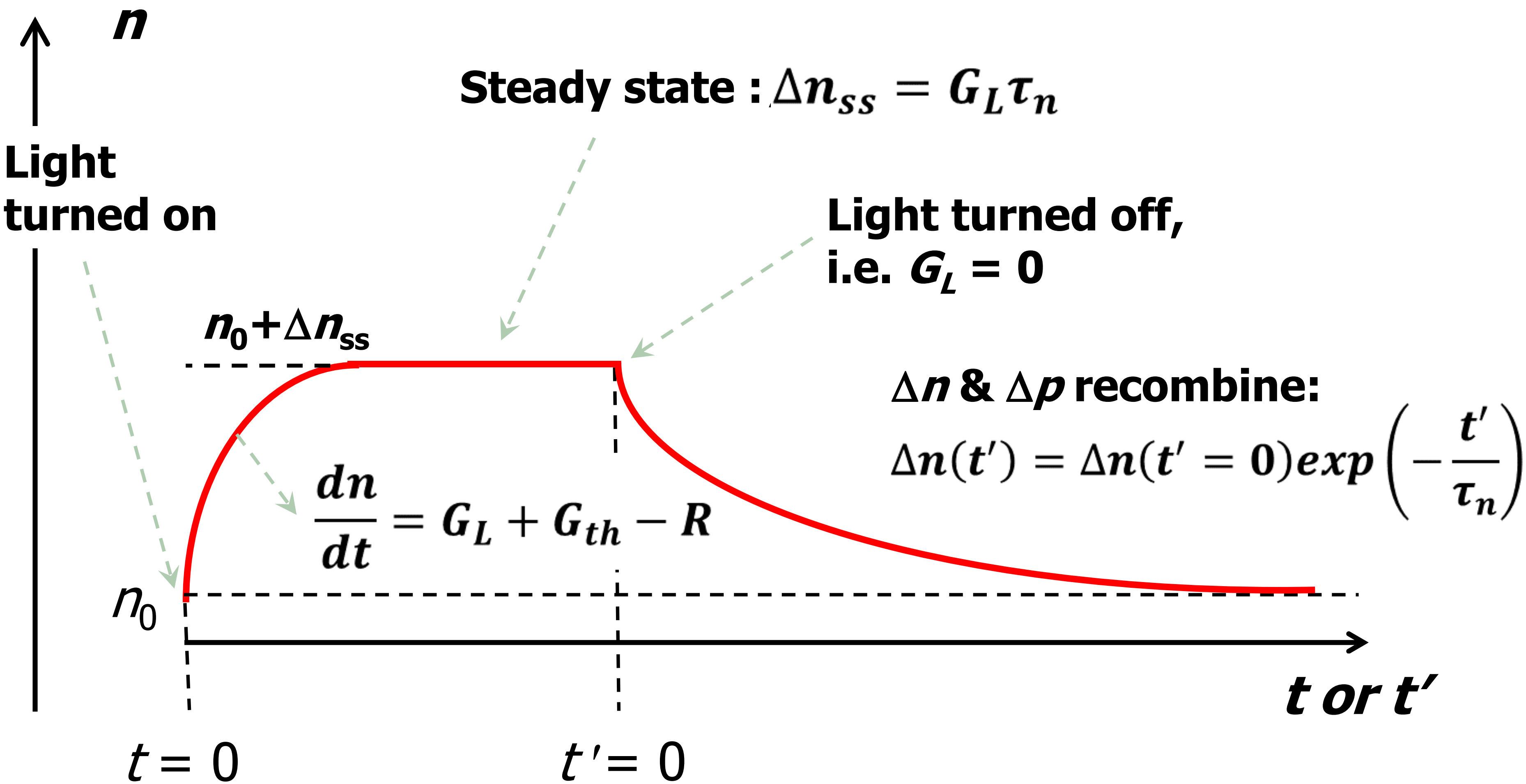
[1] The term "carrier injection" is inclusive of the case of carrier extraction.
[2] A negative excess refers to a deficit of minority carriers.

Example: Optical Illumination

- Consider a p-type semiconductor (minority carrier is electron) exposed to light of a constant intensity at a given temperature. The light generates electron-hole pairs at a rate G_L ($\text{cm}^{-3}\text{s}^{-1}$).
- With photon energy $E_{ph} > E_g$, additional electrons (Δn) are generated in the conduction band, in addition to those arising from thermal generation (n_0).



p-type semiconductor where: $p_0 >> n_0$ & low injection: $\Delta n << p_0$



Example: Optical Illumination

- The new electron and hole concentration are, respectively, $n = n_0 + \Delta n$, $p = p_0 + \Delta p$. Obviously, the product np ($= n_0p_0 + n_0\Delta p + p_0\Delta n + \Delta n\Delta p$) $> n_0p_0$.
- The recombination rate R ($=\alpha_r np$) $>$ G_{th} ($=\alpha_r n_0 p_0=\alpha_r n_i^{\,2}$) and the semiconductor tries to restore thermal equilibrium by getting rid of the excess carriers.
- The rate of change of the electron concentration may be expressed as the difference between the total generation rate ($G_L + G_{th}$) and the recombination rate R:

$$\frac{dn}{dt} = G_L + G_{th} - R$$

Low-Level Injection (Example)

- Consider a piece of p-type semiconductor (Si), of uniform doping 1×10^{16} cm^{-3}. If the electron concentration changes to 1×10^{14} cm^{-3}, is low-level injection condition valid? Given $n_i = 1.5 \times 10^{10}$ cm^{-3}.
  - The majority carrier concentration at thermal equilibrium, $p_0 \approx 1\times10^{16}$ cm^{-3}. Note: $n_0 = n_i^2/p_0 = 2.25 \times 10^4$ cm^{-3}.
  - Since $\Delta n (= n - n_0 = 1\times10^{14}$ cm^{-3}) is much less than 10% of p_0, low-level injection condition is valid in this case.
  - Under low level-injection, the minority carrier concentration can change by many orders of magnitude whereas the majority carrier concentration remains almost unchanged.
  - Note that if $\Delta n > 1\times10^{15}$ cm^{-3} ($> 0.1p_0$), then low-level injection would no longer be valid.

Example: Optical Illumination

$$\frac{dn}{dt} = G_L + G_{th} - R$$

- With a constant light intensity and temperature, G_L + G_{th} is fixed and time invariant.
- In the initial stage, Δn (and Δp) are small and *R* is only marginally larger than G_{th}; (G_L + G_{th}) >> *R* and thus *n* or Δn increases with time.
- With Δn (and Δp) and hence *R* increasing but (G_L + G_{th}) fixed, the increase of *n* or Δn will eventually slow down.

Recall: $\boldsymbol{R = \alpha_r np = \alpha_r(n_0 + \Delta n)(p_0 + \Delta p)}$

$$\boldsymbol{= G_{th} + \alpha_r(n_0\Delta p + p_0\Delta n + \Delta n\Delta p)}$$

Example: Optical Illumination

- After some time, R will eventually become equal to (G_L + G_{th}). This **balance** will be maintained thereafter as any minute difference will be offset by either excess carrier generation or recombination.
- This special condition is called **steady state**. Under steady state, $dn/dt = 0$, i.e. n as well as p stop increasing and become a constant.
- Under steady state,

$$\begin{aligned} \boldsymbol{G_L} &= -\boldsymbol{G_{th}} + \boldsymbol{R} = -\boldsymbol{\alpha_r}\left(\boldsymbol{n_i^2} - \boldsymbol{np}\right) \\ &= \boldsymbol{\alpha_r}(\boldsymbol{n_0}\Delta\boldsymbol{p} + \boldsymbol{p_0}\Delta\boldsymbol{n} + \Delta\boldsymbol{n}\Delta\boldsymbol{p}) \end{aligned}$$

- The term on the right hand side, i.e. $\boldsymbol{-G_{th} + R}$ may be interpreted as the **net recombination rate**.

Example: Optical Illumination

- For a p-type semiconductor, $p_0 >> n_0$. Assuming band-to-band transitions dominate, i.e. $\Delta n = \Delta p$, and since $\Delta n << p_0$ under low-level injection, the above eqn. simplifies to

steady state

cm^{3}s^{-1}

cm^{-3}

$$G_L = \alpha_r p_0 \Delta n_{ss} = \frac{\Delta n_{ss}}{\tau_n}; \quad \tau_n = \frac{1}{\alpha_r p_0}$$

where τ_n is the minority carrier (electron) lifetime.

- Note: **Under low-level injection, the net recombination rate is determined by the excess minority carrier concentration Δn and lifetime τ_n.**

Example: Optical Illumination

- Now consider the case when the light is turned off (i.e. $G_L = 0$) at an instant $t' = 0$, after steady state is reached.

$$\frac{dn}{dt'} = G_L - (-G_{th} + R) = -\frac{\Delta n}{\tau_n}$$

- This means that the electron concentration will start to decrease with time due to recombination of the excess carriers. Again, the recombination is determined by the excess minority carrier concentration Δn and lifetime τ_n.

Example: Optical Illumination

- Noting that $dn/dt = d(n_0+\Delta n)/dt = d(\Delta n)/dt$, a solution to the above first-order differential equation is given as

$$\Delta n(t') = \Delta n(t' = 0)exp\left(-\frac{t'}{\tau_n}\right)$$

where $\Delta n(t' = 0)$ is excess electron concentration at the instant when the light is turned off. This is equal to the steady state Δn or Δn_{ss}.

- **The excess electron concentration decays exponentially with time, characterized by a time constant τ_n. That is why τ_n is called the minority carrier lifetime.**

Example: Optical Illumination

- Similarly, for an n-type semiconductor with $n_0 >> p_0$ and under low-level injection (i.e. $\Delta p << n_0$), we have

  for steady state: $G_L = \alpha_r n_0 \Delta p_{ss} = \frac{\Delta p_{ss}}{\tau_p}; \quad \tau_p = \frac{1}{\alpha_r n_0}$

  after turning off the light:

$$\Delta p(t') = \Delta p(t' = 0) exp\left(-\frac{t'}{\tau_p}\right)$$

  where τ_p is the minority carrier (hole) lifetime.

A Numerical Example

Consider a **p-type** semiconductor sample at 300 K doped to a concentration $N_a = 1\times10^{15}$ cm^{-3}. The intrinsic carrier concentration is 1.5×10^{10} cm^{-3}. Assume that 1×10^{14} electron-hole pairs per cm^{-3} have been created and existed in the sample for $t < 0$. The minority carrier lifetime is 10 ns. With the external excitation removed for $t \geq 0$, calculate the **excess carrier concentration** for t = 10 ns, 20 ns, 30 ns & ∞.

Plot the carrier concentrations versus time showing the decay of the excess carrier concentration.

Comment on the percentage change of the minority & majority carrier concentration.

A Numerical Example

Assume complete ionization at 300 K and since $N_a >> n_i$, $p_0 = N_a = 1\times10^{15}\ \text{cm}^{-3}$.

The initial excess minority carrier concentration $\Delta n = 1\times10^{14}\ \text{cm}^{-3} = 0.1p_0$; low-level injection is valid.

After switching off the light at $t = 0$, the excess minority carrier concentration decays exponentially according to

$$\Delta n(t) = \Delta n(t = 0)exp\left(-\frac{t}{\tau_n}\right)$$

with $\Delta n(t = 0) = 10^{14}\ \text{cm}^{-3}$ and $\tau_n = 10$ ns.

A Numerical Example

Assuming band-to-band recombination, $\Delta n(t) = \Delta p(t)$.

At $t = 10$ ns,

$$\Delta n(t = 10\text{ ns}) = 10^{14} \times \exp\left(-\frac{10\text{ ns}}{10\text{ ns}}\right) = 3.7 \times 10^{13}\ \text{cm}^{-3}$$

At $t = 20$ ns,

$$\Delta n(t = 20\text{ ns}) = 10^{14} \times \exp\left(-\frac{20\text{ ns}}{10\text{ ns}}\right) = 1.35 \times 10^{13}\ \text{cm}^{-3}$$

At $t = 30$ ns,

$$\Delta n(t = 30\text{ ns}) = 10^{14} \times \exp\left(-\frac{30\text{ ns}}{10\text{ ns}}\right) = 5.0 \times 10^{12}\ \text{cm}^{-3}$$

At $t = \infty$,

$$\Delta n(t = \infty) = 10^{14} \times \exp\left(-\frac{\infty}{10\text{ ns}}\right) = 0$$

i.e. the semiconductor has completely revert to thermal equilibrium.

A Numerical Example

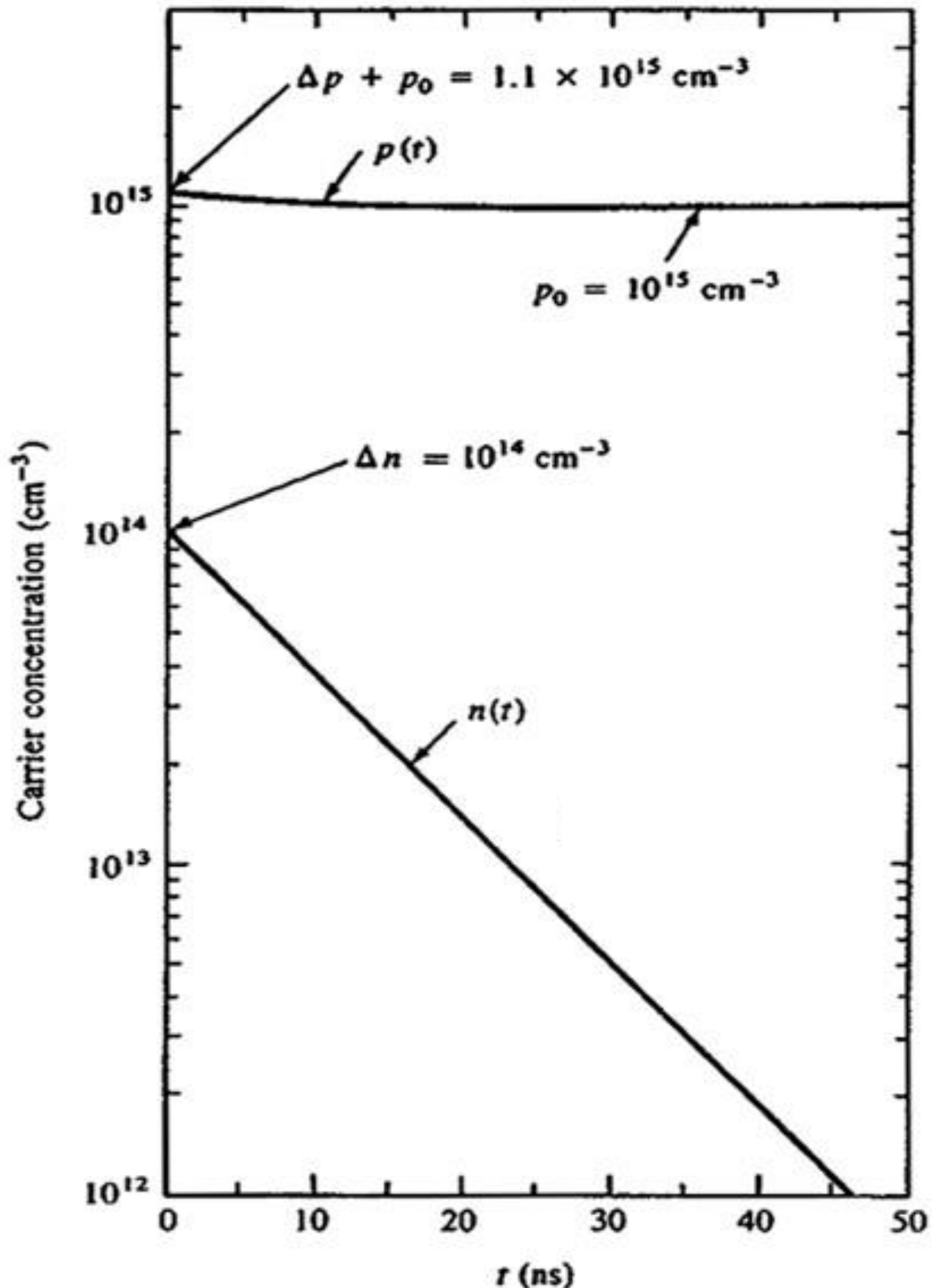
On a log-linear plot, the decay of Δn varies linearly with time.

$$\Delta n(t) = \Delta n(t=0)exp\left(-\frac{t}{\tau_n}\right)$$

$$log_{10}\Delta n = log_{10}\Delta n(0) - \frac{t}{2.3\tau_n}$$

Minority carrier lifetime τ_n can be determined from the slope of the log-linear plot.

Note that $p \approx p_0$ (due to low-level injection) whereas n is changed significantly (n_0 ~10^5 cm^{-3}).



Summary

- Important concepts discussed in this section include:
  - Non-equilibrium
  - Low-level injection
  - Minority carrier lifetime