Lecture #6

OUTLINE

– Generation and recombination
– Excess carrier concentrations
– Minority carrier lifetime

Reading: Chapter 3.3

Clarification: Quasi-Neutrality

- If the dopant concentration profile varies gradually with position, then the majority-carrier concentration distribution does not differ much from the dopant concentration distribution.

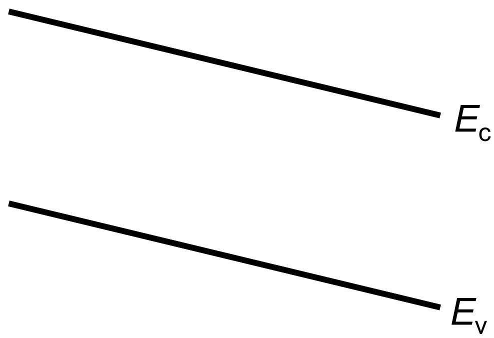
$$N_D(x) + p(x) = N_A(x) + n(x)$$

– n-type material: $n(x) \cong N_D(x) - N_A(x)$

– p-type material: $p(x) \cong N_A(x) - N_D(x)$

$$\rightarrow \mathcal{E} = \frac{kT}{q}\left(\frac{1}{n}\right)\frac{dn}{dx} = \frac{kT}{q}\left(\frac{1}{N_D}\right)\frac{dN_D}{dx}$$ in n-type material

Carrier Drift (Band Diagram Visualization)



Generation and Recombination

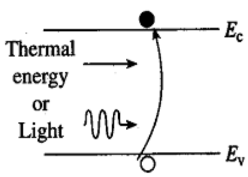
- Generation:

- Recombination:

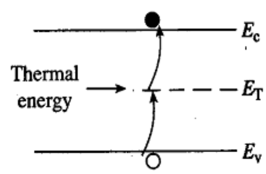
- Recombination and Generation processes act to change the carrier concentrations, and thereby indirectly affect current flow

Generation Processes

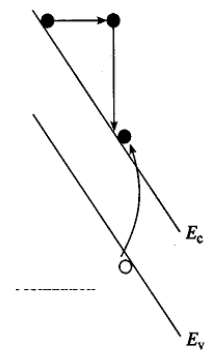
Band-to-Band



R-G Center

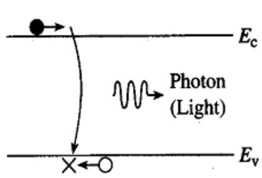


Impact Ionization

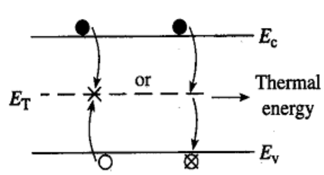


Recombination Processes

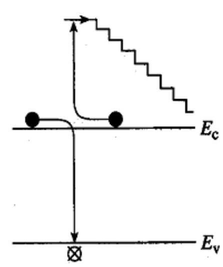
Direct



R-G Center

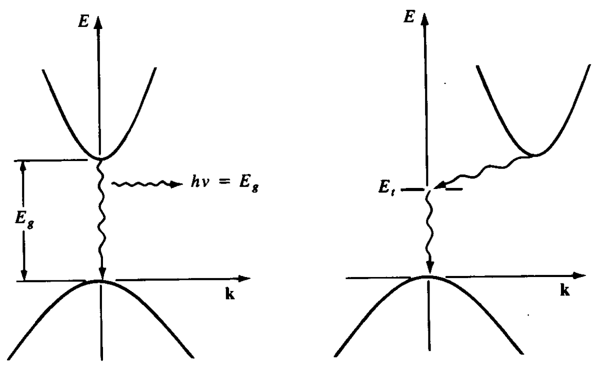


Auger



Direct *vs.* Indirect Band Gap Materials

E-k Diagrams



(a) Direct

(b) Indirect

Excess Carrier Concentrations

equilibrium values

$$\Delta n \equiv n - n_0$$

$$\Delta p \equiv p - p_0$$

Charge neutrality condition:

$$\Delta n = \Delta p$$

"Low-Level Injection"

- Often the disturbance from equilibrium is small, such that the majority-carrier concentration is not affected significantly:
  - For an n-type material:

$$|\Delta n| = |\Delta p| << n_0 \quad \text{so} \quad n \cong n_0$$

  - For a p-type material:

$$|\Delta n| = |\Delta p| << p_0 \quad \text{so} \quad p \cong p_0$$

- However, the minority carrier concentration can be significantly affected

Indirect Recombination Rate

- Consider hole recombination in n-Si through a number of traps, N_T:

$$\left.\frac{\partial p}{\partial t}\right|_R = -c_p N_T p$$

- Since total generation = recombination at equilibrium:

$$\left.\frac{\partial p}{\partial t}\right|_G = -\left.\frac{\partial p}{\partial t}\right|_R = c_p N_T p_0$$

- If we introduce excess carriers (*e.g.* using light) and watch the decay in Δp:

$$\left.\frac{\partial p}{\partial t}\right|_{R-G} = -c_p N_T (p - p_0) \equiv -\frac{\Delta p}{\tau_p}$$

$$\tau_p = \frac{1}{c_p N_T}$$

Recombination Lifetime

The ***minority carrier lifetime*** τ is the average time an excess minority carrier "survives" in a sea of majority carriers

τ ranges from 1 ns to 1 ms in Si and depends on the density of metallic impurities (contaminants) such as Au and Pt, and the density of crystalline defects. These ***deep traps*** capture electrons or holes to facilitate recombination and are called ***recombination-generation centers.***

Example: Photoconductor

Consider a sample of Si doped with 10^{15} cm^{-3} boron, with recombination lifetime 10 μs. It is exposed to light such that electron-hole pairs are generated throughout the sample at the rate of 10^{20}/s·cm^3.

Find:

(a) n_0 and p_0

(b) Δn and Δp

(c) p, n, and the np product

Solution:

(a) What is p_0?

$p_0 = N_a = 10^{15}\ \text{cm}^{-3}$

(b) What is n_0?

$n_0 = n_i^2/p_0 = 10^5\ \text{cm}^{-3}$

(c) What is Δp?

In steady-state, the rate of generation is equal to the rate of recombination.

$$10^{20}/\text{s-cm}^3 = \Delta p/\tau$$

$$\therefore \Delta p = 10^{20}/\text{s-cm}^3 \cdot 10^{-5}\text{s} = 10^{15}\ \text{cm}^{-3}$$

(d) What is Δn?

$\Delta n = \Delta p = 10^{15}\ \text{cm}^{-3}$

(e) What is p?

$p = p_0 + \Delta p = 10^{15}\text{cm}^{-3} + 10^{15}\text{cm}^{-3} = 2\times10^{15}\text{cm}^{-3}$

(f) What is n?

$n = n_0 + \Delta n = 10^5\text{cm}^{-3} + 10^{15}\text{cm}^{-3} \sim 10^{15}\text{cm}^{-3}$ *since* $n_0 << \Delta n$

(g) What is np?

$np \sim 2\times10^{15}\text{cm}^{-3} \cdot 10^{15}\text{cm}^{-3} = 2\times10^{30}\text{cm}^{-6} >> n_i^2 = 10^{20}\text{cm}^{-6}$.

Note: The np product can be very different from n_i^2.