Recitation #5

ENEE 313: Introduction to Device Physics

Fall, 2018

1 Week Notes Summary

Two main mechanism of current flow in semiconductors: drift current (objective of the chapter 3) and diffusion current (objective of the chapter 4, will talk about this later)

1. Drift current: $J = q(nv_n + pv_p) = q(n\mu_n + p\mu_p)E$, where J is the current density, q is the charge, n is the concentration of electrons, p is the concentration of holes, v_n and μ_n are the velocity of electrons, v_p and μ_p are the velocity of holes, and E is the electric field.

2. Electrons in solids obey Fermi-Dirac statistics. The distribution is

$$f(E) = \frac{1}{1 + exp(E - E_F)/kT}$$

   where E_F is the Fermi level and kT at room temperature is $0.026V$.

3. The concentration of electrons in the conduction band is

$$n_0 = N_C exp(-(E_C - E_F)/kT) = n_i exp((E_F - E_i)/kT)$$

   where N_C is the effective density of states in the conduction band, E_i is the intrinsic level, and n_i is the intrinsic electron concentration.

4. The concentration of holes in the valence band is

$$p_0 = N_v exp(-(E_F - E_V)/kT) = n_i exp((E_i - E_F)/kT)$$

   where N_V is the effective density of states in the valence band.

5. Law of mass action

$$n_i^2 = n_0 p_0$$

6. Worthy noting, $E_C - E_i = E_g/2$ is true if N_C and N_V are equal. So, E_i can displace from the middle of the band.

7. Compensation occurs when N_d and N_a are approximately equal but the magnitude of the difference between them is less than n_i

8. Useful intrinsic concentration of semiconductors

   (a) Silicon: $n_i = 1.5 \times 10^{10} 1/cm^3$
   (b) Gallium Arsenide: $n_i = 1.8 \times 10^{6} 1/cm^3$
   (c) Germanium: $n_i = 2.4 \times 10^{13} 1/cm^3$

Exercise 1. Carrier concentrations with doping
Consider a silicon crystal at 300 K, with the Fermi level $0.18eV$ above the valence band. What type is the material? What are the electron and hole concentrations?

Solution. Known $n_i = 1.45 \times 10^{10} 1/cm^3$ and $E_g = 1.1eV$ of silicon at room temperature, we know $E_i = E_g/2 = 0.55eV$. Since E_F is below E_i, it's p type semiconductor.

To calculate the concentration of holes and electrons, the hole concentration is as

$$\begin{aligned} p_0 &= n_i exp(E_i - E_F/kT) \\ &= 1.45 \times 10^{10} \times exp(0.37eV/0.026eV) \\ &= 3.3 \times 10^{16} 1/cm^3 \end{aligned}$$

Furthermore, by the law of mass action, we have

$$\begin{aligned} n_i^2 &= n_0 p_0 \\ n_0 &= n_i^2/p_0 = 6.5 \times 10^3 1/cm^3 \end{aligned}$$

□

Exercise 2. Carrier concentrations with doping
Consider a silicon crystal at room temperature, doped with both donor and acceptor atoms so that $N_d = 2 \times 10^{15} 1/cm^3$ and $N_a = 1 \times 10^{15} 1/cm^3$. What type of material would this yield? Find the location of the Fermi level.

Solution. Given $N_d > N_a$, this will be n type material.

$$n_0 \approx N_d - N_a = 1 \times 10^{15} 1/cm^3$$

Since $n_0 = n_i exp((E_i - E_F)/kT)$ and $E_i = 0.55eV$, we have

$$\begin{aligned} E_F - E_i &= kT \times ln(\frac{n_0}{n_i}) \\ &= 0.29eV \end{aligned}$$

Therefore, E_F is $0.29eV$ above E_i □

Exercise 3. Current in semiconductor
Consider a Germanium sample at room temperature in which $N_d = 5 \times 10^{13} 1/cm^3$ and $N_a = 0$, what is the concentration of electrons and holes?

Solution. The intrinsic concentration of Germanium is $n_i = 2,4 \times 10^{13} 1/cm^3$. Since the donor density is not much greater than the intrinsic density, we cannot assume the concentration of electrons is approximately equal to the density of the donor. By the law of mass action and the charge neutrality condition, we have

$$\begin{aligned} n_i^2 &= n_0 p_0 \\ n_0 + N_a^- &= p_0 + N_d^+ \end{aligned}$$

Thus, assume fully ionized, we have

$$\begin{aligned} n_0 &= \frac{1}{2}(N_d - N_a) + \sqrt{(N_d - N_a)^2 + 4n_i^2} \\ &= 9.5 \times 10^{13} 1/cm^3 \\ p_0 &= 6 \times 10^{12} 1/cm^3 \end{aligned}$$

□