Recitation #4

ENEE 313: Introduction to Device Physics

Fall, 2018

1 Week Notes Summary

The main objectives of the chapter 3 is to use the concepts of quantum mechanics to describe current flow in semiconductors. The concepts include such as the differences between metals, semiconductors, and insulators; material band structures that give rise to electrons and holes in semiconductors, and other quantum related parameters like effective mass; to learn how to calculate carrier concentrations; to learn how to compute drift current, which are the two main mechanisms of current flow in semiconductors.

1. Band structure: The relationship between energy and the electron wave-vector. It determines some properties of electrons in material such as,
   (a) instantaneous velocity
   (b) effective mass
   (c) intrinsic number of electrons and holes
   (d) mobility of the electrons and holes
   (e) conductivity
2. Electron and Hole
   (a) Negatively charged electrons in the conduction band.
   (b) Positively charged holes in the valence band.
   (c) Electrons and holes have different instantaneous velocities and effective masses, which are determined by the slope and curvature of the conduction and valence bands.
   (d) Semiconductors have current due to electrons in the conduction band and holes in the valence band. And the total current is the vector sum of both.
3. Doping
   (a) intrinsic semiconductor is an undoped semiconductor, where holes in the valence band are vacancies created by electrons that have been thermally excited to the conduction band.

(b) n-type semiconductors are created by doping an intrinsic semiconductor with donor impurities i.e. group-V elements in periodic table.

(c) p-type semiconductors are created by doping an intrinsic semiconductor with acceptor impurities i.e. group-III elements in periodic table.

(d) Fermi level: The energy level where Fermi Statistics says that the probability of a state being occupied is 1/2.

(e) Donor level: extra electrons energy level in n-type semiconductors

(f) Acceptor level: extra holes evergy level in p-type semiconductors

4. mobility: The proportionality factor that relates the electric field to the average velocity of electrons due to drift in the electric field. $\mu_n = \frac{q\bar{t}}{m_n^*}$.

5. conductivity: The proportionality factor that relates the electric field to the current density. $\sigma = q(n\mu_n + p\mu_p)$, where n is mobile electron concentrations and p is mobile hole concentrations

Exercise 1. Carrier concentrations with doping
An unknown semiconductor has $E_g = 1.1eV$ and $N_C = N_V$. It's doped with $10^{15}cm^{-3}$ donors, where the donor level is $0.2eV$ below E_C. Given that E_F is $0.25eV$ below E_C, calculate n_i and the concentration of electrons and holes in the semiconductor at 300K.

Solution. Given the terms, we know

$$\begin{aligned} E_F - E_i &= (E_C - E_i) - (E_C - E_F) \\ &= (E_g/2 - 0.25eV) \\ &= 0.3eV \end{aligned}$$

Since the semiconductor only doped with donors, it is an excellent approximation to say that the electron concentration is equal to the donor concentration $n \approx n_d = 10^{15}cm^{-3}$. By the equation

$$n_0 = n_i exp(\frac{E_F - E_i}{kT})$$

where $kT = 0.026V$ at $300K$. We have

$$\begin{aligned} n_i &= n exp(\frac{E_i - E_F}{kT}) \\ &= 9.3 \times 10^9 cm^{-3} \end{aligned}$$

since $n_i^2 = np$, we have the concentration of holes is $p = \frac{n_i^2}{n} = 8.7 \times 10^4 cm^{-3}$ □

Exercise 2. Carrier concentrations with doping
In a silicon bar uniformly doped with 10^{16} phosphorus atoms per cm^3 and 5×10^{14} boron atoms per cm^3. Calculate the mobile electron and hole concentrations for this bar. (Note that phosphorus is a donor and boron is an acceptor for silicon.)

Solution. Given $N_D = 10^{16}cm^{-3}$ and $N_A = 5 \times 10^{14}cm^{-3}$ and we know n_i of silicon is $1.5 \times 10^{10}cm^{-3}$, we know the relationship between the intrinsic concentration and the mobile hole and electron concentration as well as the space charge neutrality. Thus, solve the equations

$$n_i^2 = n_0 p_0$$
$$n_0 + N_A = p_0 + N_D$$

$n_0 = 9.5 \times 10^{15}$ per cm^3 and $p_0 = 1.1 \times 10^4$ per cm^3. □

Exercise 3. Current in semiconductor
A 2 cm long piece of Si with cross-sectional area of $0.01cm^2$ is doped with donors at $10^{15}cm^{-3}$, and has a resistance of 90 ohms. What is the current through the piece if we apply a voltage of 10^6V across it?

Solution. The electric field $E = \frac{10^6V}{2cm} = 5 \times 10^5 \frac{V}{cm}$. So the velocity is saturated at $10^7 \frac{cm}{s}$. Therefore,

$$\begin{aligned} I = qAnv_s &= 1.6 \times 10^{-19}C \times 0.01cm^2 \times 10^{15}cm^{-3} \times 10^7 \frac{cm}{s} \\ &= 1.6 \frac{C}{s} \end{aligned}$$

□