Module 2

Problem #1

The mobility of free electrons and holes in pure germanium are 3800 and 1800 cm^2 /V-s respectively. The corresponding values for pure silicon are 1300 and 500 cm^2/V-s, respectively. Determine the values of intrinsic conductivity for both germanium and silicon. Assume ni = $2.5 \times 10^{13}\ cm^{-3}$ for germanium and ni = $1.5 \times 10^{10}\ cm^{-3}$ for silicon at room temperature.

Solution (i) The intrinsic conductivity for germanium,

$$\begin{aligned}\sigma_i &= qn_i(\mu_n + \mu_p)\\ &= (1.602 \times 10^{-19})\,(2.5 \times 10^{13})\,(3800 + 1800)\\ &= 0.0224\ \text{S/cm}\end{aligned}$$

(ii) The intrinsic conductivity for silicon,

$$\begin{aligned}\sigma_i &= qn_i\,(\mu_n + \mu_p)\\ &= (1.602 \times 10^{-19})\,(1.5 \times 10^{10})\,(1300 + 500)\\ &= 4.32 \times 10^{-6}\ \text{S/cm}\end{aligned}$$

Problem #2

In an N-type semiconductor, the Fermi level is 0.3 eV below the conduction level at a room temperature of 300 K. If the temperature is increased to 360 K, determine the new position of the Fermi level.

Solution The Fermi level in an *N*-type material is given by

$$E_F = E_C - kT \ln \frac{N_C}{N_D}$$

Therefore,

$$(E_C - E_F) = kT \ln \frac{N_C}{N_D}$$

At $T = 300$ K,

$$0.3 = 300\, k \ln \frac{N_C}{N_D} \tag{1}$$

Similarly,

$$E_C - E_{F1} = 360\, k \ln \frac{N_C}{N_D} \tag{2}$$

Equation (2) divided by Eq. (1) gives

$$\frac{E_C - E_{F1}}{0.3} = \frac{360}{300}$$

Therefore,

$$E_C - E_{F1} = \frac{360}{300} \times 0.3 = 0.36 \text{ eV}$$

Hence, the new position of the Fermi level lies 0.36 eV below the conduction level.

Problem #3

In a P-type semiconductor, the Fermi level lies 0.4 eV above the valence band. Determine the new position of Fermi level if the concentration of acceptor atoms is multiplied by a factor of (a) 0.5 and (b) 4. Assume kT = 0.025 eV.

Solution In a P-type material, the concentration of acceptor atoms is given by

$$N_A = N_V e^{-(E_F - E_V)/kT}$$

Let initially $N_A = N_{AO}$, $E_F = E_{FO}$ and $E_{FO} - E_V = 0.4$ eV

Therefore, $$N_{AO} = N_V e^{-0.4/0.025} = N_V e^{-16}$$

(a) When $N_A = 0.5,\ N_{AO}$ and $E_F = E_{F1}$, then

$$0.5N_{AO} = N_V e^{-(E_{F1} - E_V)/0.025} = N_V e^{-40\,(E_{F1} - E_V)}$$

Therefore, $$0.5 \times N_V e^{-16} = N_V e^{-40(E_{F1} - E_V)}$$

Therefore, $$0.5 = e^{-40\,(E_{F1} + E_V) + 16}$$

Taking natural logarithm on both sides, we get

$$\ln(0.5) = -40(E_{F1} - E_V) + 16$$

Therefore, $$E_{F1} - E_V = 0.417 \text{ eV}$$

(b) When $N_A = 4N_{AO}$ and $E_F = E_{F2}$, then

$$\ln 4 = -40(E_{F2} - E_V) + 16$$

Therefore, $$E_{F2} - E_V = 0.365 \text{ eV}$$

Problem #4 (Law of Mass Action)

Consider a silicon PN junction at T = 300 K so that $n_i = 1.5 \times 10^{10}$ cm^{-3}. The N-type doping is 1×10^{10} cm^{-3} and a forward bias of 0.6 V is applied to the PN junction. Calculate the minority hole concentration at the edge of the space charge region.

Solution Given $T = 300\text{K}$, $n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$, $n \times 1 \times 10^{10}\ \text{cm}^{-3}$ and $V_F = 0.6$ V.

Mass Action law

$$n \cdot p = n_i^2$$

Therefore, the concentration of holes, $p = \dfrac{n_i^2}{n}$

$$= \frac{(1.5 \times 10^{10})^2}{1 \times 10^{10}} = 2.25 \times 10^{10}\ \text{cm}^{-3}$$

Problem #5 (Law of Mass Action)

Find the concentration (densities) of holes and electrons in N-type silicon at 300 K, if the conductivity is 300 S/cm. Also find these values for P-type silicon. Given that for Silicon at 300 K, $n_i = 1.5 \times 10^{10}/cm^3$, $\mu_n = 1300\ cm^2/V\text{-}s$ and $\mu_P = 500\ cm^2/V\text{-}s$.

Solution (a) Concentration in *N*-type silicon

The conductivity of an *N*-type silicon is $\sigma = qn\mu_n$

Concentration of electrons, $$n = \frac{\sigma}{q\mu_n}$$

$$= \frac{300}{(1.602 \times 10^{-19})(1300)} = 1.442 \times 10^{18}\ \text{cm}^{-3}$$

Hence concentration of holes, $$p = \frac{n_i^2}{n} = \frac{(1.5 \times 10^{10})^2}{1.442 \times 10^{18}} = 1.56 \times 10^2\ \text{cm}^{-3}$$

(b) Concentration in P-type silicon

The conductivity of a P-type silicon is $\sigma = qp\mu_p$

Hence, concentration of holes $\quad p = \dfrac{\sigma}{q\mu_p}$

$$= \frac{300}{(1.602 \times 10^{-19})\,(500)} = 3.75 \times 10^{18}\ \text{cm}^{-3}$$

and concentration of electrons, $\quad n = \dfrac{n_i^2}{p} = \dfrac{(1.5 \times 10^{10})^2}{3.75 \times 10^{18}} = 0.6 \times 10^2\ \text{cm}^{-3}$

Problem #6

A sample of silicon at a given temperature T in intrinsic condition has a resistivity of 25×10^4 Ω-cm. The sample is now doped to the extent of 4×10^{10} donor atoms/cm³ and 10^{10} acceptor atoms/cm³. Find the total conduction current density if an electric field of 4 V/cm is applied across the sample. Given that μ_n= 1250 cm²/V-s, μ_P = 475 cm²/V-s at the given temperature.

Solution $$\sigma_i = qn_i(\mu_n + \mu_p) = \frac{1}{25 \times 10^4}$$

Therefore, $$n_i = \frac{\sigma_i}{q(\mu_n + \mu_p)} = \frac{1}{(25 \times 10^4)\,(1.602 \times 10^{-19})\,(1250 + 475)}$$

$$= 1.45 \times 10^{10}\ \text{cm}^{-3}$$

Net donor density $$N_D\,(= n) = (4 \times 10^{10} - 10^{10}) = 3 \times 10^{10}\ \text{cm}^{-3}$$

Hence, $$p = \frac{n_i^2}{N_D} = \frac{(1.45 \times 10^{10})^2}{3 \times 10^{10}} = 0.7 \times 10^{10}\ \text{cm}^{-3}$$

Hence,
$$\sigma = q(n\mu_n + p\mu_p)$$
$$= (1.602 \times 10^{-19})\,(3 \times 10^{10} \times 1250 + 0.7 \times 10^{10} \times 475)$$
$$= 6.532 \times 10^{-6}\ \text{S/cm}$$

Therefore, total conduction current density,
$$J = \sigma E = 6.532 \times 10^{-6} \times 4 = 26.128 \times 10^{-6}\ \text{A/cm}^2$$