Hw3 Solution

1.

(a) $E_{Fi} - E_{midgap} = \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*}\right)$

$= \frac{3}{4}(0.0259)\ln\left(\frac{0.70}{1.21}\right)$

$\Rightarrow -10.63$ meV

(b) $E_{Fi} - E_{midgap} = \frac{3}{4}(0.0259)\ln\left(\frac{0.75}{0.080}\right)$

$\Rightarrow +43.47$ meV

2.

(a) $E_F - E_\upsilon = kT\ln\left(\frac{N_\upsilon}{p_o}\right)$

$= (0.0259)\ln\left(\frac{1.04\times10^{19}}{5\times10^{15}}\right)$

$= 0.1979$ eV

(b) $E_c - E_F = E_g - (E_F - E_\upsilon)$

$= 1.12 - 0.19788 = 0.92212$ eV

(c) $n_o = (2.8\times10^{19})\exp\left[\frac{-0.92212}{0.0259}\right]$

$= 9.66\times10^3\ \text{cm}^{-3}$

(d) Holes

(e) $E_{Fi} - E_F = kT\ln\left(\frac{p_o}{n_i}\right)$

$= (0.0259)\ln\left(\frac{5\times10^{15}}{1.5\times10^{10}}\right)$

$= 0.3294$ eV

3.

(a) Ge: $n_i = 2.4\times10^{13}\ \text{cm}^{-3}$

(i) $n_o = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_i^2}$

$= \frac{2\times10^{15}}{2} + \sqrt{\left(\frac{2\times10^{15}}{2}\right)^2 + (2.4\times10^{13})^2}$

or

$n_o \cong N_d = 2\times10^{15}\ \text{cm}^{-3}$

$p_o = \frac{n_i^2}{n_o} = \frac{(2.4\times10^{13})^2}{2\times10^{15}}$

$= 2.88\times10^{11}\ \text{cm}^{-3}$

(ii) $p_o \cong N_a - N_d = 10^{16} - 7\times10^{15}$

$= 3\times10^{15}\ \text{cm}^{-3}$

$n_o = \frac{n_i^2}{p_o} = \frac{(2.4\times10^{13})^2}{3\times10^{15}}$

$= 1.92\times10^{11}\ \text{cm}^{-3}$

(b) GaAs: $n_i = 1.8\times10^6\ \text{cm}^{-3}$

(i) $n_o \cong N_d = 2\times10^{15}$ cm

$p_o = \frac{(1.8\times10^6)^2}{2\times10^{15}} = 1.62\times10^{-3}\ \text{cm}^{-3}$

(ii) $p_o \cong N_a - N_d = 3\times10^{15}\ \text{cm}^{-3}$

$n_o = \frac{(1.8\times10^6)^2}{3\times10^{15}} = 1.08\times10^{-3}\ \text{cm}^{-3}$

(c) The result implies that there is only one minority carrier in a volume of $10^3\ \text{cm}^3$.

4.

(a) $N_a > N_d \Rightarrow$ p-type

Majority carriers are holes

$p_o = N_a - N_d = 3\times10^{16} - 1.5\times10^{16}$

$= 1.5\times10^{16}\ \text{cm}^{-3}$

Minority carriers are electrons

$n_o = \frac{n_i^2}{p_o} = \frac{(1.5\times10^{10})^2}{1.5\times10^{16}} = 1.5\times10^4\ \text{cm}^{-3}$

(b) Boron atoms must be added

$p_o = N_a' + N_a - N_d$

$5\times10^{16} = N_a' + 3\times10^{16} - 1.5\times10^{16}$

So $N_a' = 3.5\times10^{16}\ \text{cm}^{-3}$

$n_o = \frac{(1.5\times10^{10})^2}{5\times10^{16}} = 4.5\times10^3\ \text{cm}^{-3}$

5.

(a) $n_o = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_i^2}$

$n_o = 1.05N_d = 1.05\times10^{15}\ \text{cm}^{-3}$

$(1.05\times10^{15} - 0.5\times10^{15})^2$

$= (0.5\times10^{15})^2 + n_i^2$

so $n_i^2 = 5.25\times10^{28}$

Now

$$n_i^2 = (2.8\times10^{19})(1.04\times10^{19})\left(\frac{T}{300}\right)^3 \times \exp\left[\frac{-1.12}{(0.0259)(T/300)}\right]$$

$$5.25\times10^{28} = (2.912\times10^{38})\left(\frac{T}{300}\right)^3 \times \exp\left[\frac{-12972.973}{T}\right]$$

By trial and error, $T = 536.5$ K

(b) At $T = 300$ K,

$$E_c - E_F = kT\ln\left(\frac{N_c}{n_o}\right)$$

$$E_c - E_F = (0.0259)\ln\left(\frac{2.8\times10^{19}}{10^{15}}\right)$$

$$= 0.2652 \text{ eV}$$

At $T = 536.5$ K,

$$kT = (0.0259)\left(\frac{536.5}{300}\right) = 0.046318 \text{ eV}$$

$$N_c = (2.8\times10^{19})\left(\frac{536.5}{300}\right)^{3/2}$$

$$= 6.696\times10^{19} \text{ cm}^{-3}$$

$$E_c - E_F = kT\ln\left(\frac{N_c}{n_o}\right)$$

$$E_c - E_F = (0.046318)\ln\left(\frac{6.696\times10^{19}}{1.05\times10^{15}}\right)$$

$$= 0.5124 \text{ eV}$$

then $\Delta(E_c - E_F) = 0.2472$ eV

(c) Closer to the intrinsic energy level.

6.

(a) $$E_{Fi} - E_{midgap} = \frac{3}{4}kT\ln\left(\frac{m_p^*}{m_n^*}\right)$$

$$= \frac{3}{4}(0.0259)\ln(10)$$

or

$$E_{Fi} - E_{midgap} = +0.0447 \text{ eV}$$

(b) Impurity atoms to be added so

$$E_{midgap} - E_F = 0.45 \text{ eV}$$

(i) p-type, so add acceptor atoms

(ii) $E_{Fi} - E_F = 0.0447 + 0.45 = 0.4947$ eV

Then

$$p_o = n_i\exp\left(\frac{E_{Fi} - E_F}{kT}\right)$$

$$= (10^5)\exp\left(\frac{0.4947}{0.0259}\right)$$

or

$$p_o = N_a = 1.97\times10^{13} \text{ cm}^{-3}$$

7.

(a) Replace Ga atoms $\Rightarrow$ Silicon acts as a donor

$$N_d = (0.05)(7\times10^{15}) = 3.5\times10^{14} \text{ cm}^{-3}$$

Replace As atoms $\Rightarrow$ Silicon acts as an acceptor

$$N_a = (0.95)(7\times10^{15}) = 6.65\times10^{15} \text{ cm}^{-3}$$

(b) $N_a > N_d \Rightarrow$ p-type

(c) $p_o = N_a - N_d = 6.65\times10^{15} - 3.5\times10^{14}$

$$= 6.3\times10^{15} \text{ cm}^{-3}$$

$$n_o = \frac{n_i^2}{p_o} = \frac{(1.8\times10^6)^2}{6.3\times10^{15}} = 5.14\times10^{-4} \text{ cm}^{-3}$$

(a) $$E_{Fi} - E_F = kT\ln\left(\frac{p_o}{n_i}\right)$$

$$= (0.0259)\ln\left(\frac{6.3\times10^{15}}{1.8\times10^6}\right) = 0.5692 \text{ eV}$$

8.

(a) $V = IR \Rightarrow 10 = (0.1)R$

or

$$R = 100\,\Omega$$

(b)

$$R = \frac{L}{\sigma A} \Rightarrow \sigma = \frac{L}{RA}$$

or

$$\sigma = \frac{10^{-3}}{(100)(10^{-3})} = 0.01\ (\Omega\text{-cm})^{-1}$$

(c) $\sigma \cong e\mu_n N_d$

or

$$0.01 = (1.6\times10^{-19})(1350)N_d$$

Then

$$N_d = 4.63\times10^{13} \text{ cm}^{-3}$$

(d) $\sigma \cong e\mu_p p_o$

or

$$0.01 = (1.6\times10^{-19})(480)p_o$$

Then

$$p_o = 1.30\times10^{14}\ \text{cm}^{-3} = N_a - N_d$$

So

$$N_a = 1.30\times10^{14} + 10^{15} = 1.13\times10^{15}\ \text{cm}^{-3}$$

Note: For the doping concentrations obtained, the assumed mobility values are valid.

9.

(a) $R = \dfrac{L}{\sigma A} = \dfrac{L}{(e\mu_p N_a)A}$

For $N_a = 2\times10^{16}\ \text{cm}^{-3}$, then

$$\mu_p \cong 400\ \text{cm}^2/\text{V-s}$$

$$R = \frac{(0.075)}{(1.6\times10^{-19})(400)(2\times10^{16})(8.5\times10^{-4})}$$

$$= 68.93\,\Omega$$

$$I = \frac{V}{R} = \frac{2}{68.93} = 0.0290\ \text{A}$$

or $I = 29.0\ \text{mA}$

(b) $R \propto L \Rightarrow R = (68.93)(3) = 206.79\,\Omega$

$$I = \frac{V}{R} = \frac{2}{206.79} = 0.00967\ \text{A}$$

or $I = 9.67\ \text{mA}$

(c) $J = ep_o\upsilon_d$

For (a), $J = \dfrac{29.0\times10^{-3}}{8.5\times10^{-4}} = 34.12\ \text{A/cm}^2$

Then $\upsilon_d = \dfrac{J}{ep_o} = \dfrac{34.12}{(1.6\times10^{-19})(2\times10^{16})}$

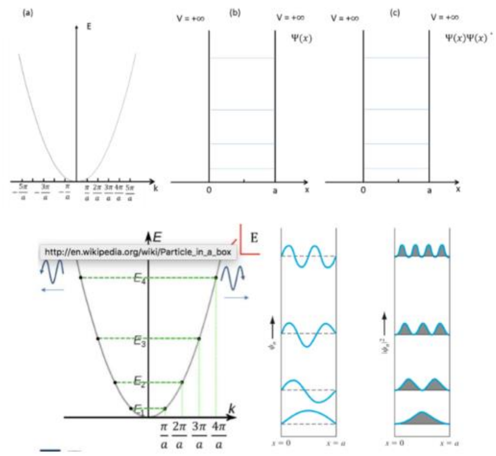
$$= 1.066\times10^{4}\ \text{cm/s}$$

For (b), $J = \dfrac{9.67\times10^{-3}}{8.5\times10^{-4}} = 11.38\ \text{A/cm}^2$

$$\upsilon_d = \frac{11.38}{(1.6\times10^{-19})(2\times10^{16})}$$

$$= 3.55\times10^{3}\ \text{cm/s}$$

10.



11.

Metal: upper band partially filled; lower band completely filled

Semiconductor: conduction/upper band empty; valence/lower band completely filled

At absolute zero temperature, metals already have moveable electrons in the upper band, where electrons are fixed in their own energy orbits. However, there is no extra energy can be absorbed by the electrons in the lower band to jump across the bandgap, into the upper one. Hence, semiconductors are not conducting.