VE320 Homework3

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Ex 3.1

(a)

$$n_i = 2.4 \times 10^{13}\,\mathrm{cm}^{-3}$$

(i)

$$\frac{N_d - N_a}{2} = \frac{2 \times 10^{15}\,\mathrm{cm}^{-3}}{2} = 10^{15}\,\mathrm{cm}^{-3}$$

$$\begin{aligned}
n_0 &= \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2} \\
&= 10^{15}\,\mathrm{cm}^{-3} + \sqrt{(10^{15}\,\mathrm{cm}^{-3})^2 + (2.4 \times 10^{13}\,\mathrm{cm}^{-3})^2} \\
&= 2.000 \times 10^{15}\,\mathrm{cm}^{-3}
\end{aligned}$$

$$p_0 = \frac{n_i^2}{n_0} = \frac{(2.4 \times 10^{13}\,\mathrm{cm}^{-3})^2}{2.000 \times 10^{15}\,\mathrm{cm}^{-3}} = 2.88 \times 10^{11}\,\mathrm{cm}^{-3}$$

(ii)

$$\frac{N_a - N_d}{2} = \frac{10^{16}\,\mathrm{cm}^{-3} - 7 \times 10^{15}\,\mathrm{cm}^{-3}}{2} = 1.5 \times 10^{15}\,\mathrm{cm}^{-3}$$

$$\begin{aligned}
p_0 &= \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2} \\
&= 1.5 \times 10^{15}\,\mathrm{cm}^{-3} + \sqrt{(1.5 \times 10^{15}\,\mathrm{cm}^{-3})^2 + (2.4 \times 10^{13}\,\mathrm{cm}^{-3})^2} \\
&= 3.000 \times 10^{15}\,\mathrm{cm}^{-3}
\end{aligned}$$

$$n_0 = \frac{n_i^2}{p_0} = \frac{(2.4 \times 10^{13}\,\mathrm{cm}^{-3})^2}{3.000 \times 10^{15}\,\mathrm{cm}^{-3}} = 1.92 \times 10^{11}\,\mathrm{cm}^{-3}$$

(b)

$$n_i = 1.8 \times 10^6\,\mathrm{cm}^{-3}$$

(i)

$$\frac{N_d - N_a}{2} = \frac{2 \times 10^{15}\,\mathrm{cm}^{-3}}{2} = 10^{15}\,\mathrm{cm}^{-3}$$

$$\begin{aligned}
n_0 &= \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2} \\
&= 10^{15}\,\mathrm{cm}^{-3} + \sqrt{(10^{15}\,\mathrm{cm}^{-3})^2 + (1.8 \times 10^{6}\,\mathrm{cm}^{-3})^2} \\
&= 2.000 \times 10^{15}\,\mathrm{cm}^{-3} \\
p_0 &= \frac{n_i^2}{n_0} = \frac{(1.8 \times 10^{6}\,\mathrm{cm}^{-3})^2}{2.000 \times 10^{15}\,\mathrm{cm}^{-3}} = 1.62 \times 10^{-3}\,\mathrm{cm}^{-3}
\end{aligned}$$

(ii)

$$\frac{N_a - N_d}{2} = \frac{10^{16}\,\mathrm{cm}^{-3} - 7 \times 10^{15}\,\mathrm{cm}^{-3}}{2} = 1.5 \times 10^{15}\,\mathrm{cm}^{-3}$$

$$\begin{aligned}
p_0 &= \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2} \\
&= 1.5 \times 10^{15}\,\mathrm{cm}^{-3} + \sqrt{(1.5 \times 10^{15}\,\mathrm{cm}^{-3})^2 + (1.8 \times 10^{6}\,\mathrm{cm}^{-3})^2} \\
&= 3.000 \times 10^{15}\,\mathrm{cm}^{-3} \\
n_0 &= \frac{n_i^2}{p_0} = \frac{(1.8 \times 10^{6}\,\mathrm{cm}^{-3})^2}{3.000 \times 10^{15}\,\mathrm{cm}^{-3}} = 1.08 \times 10^{-3}\,\mathrm{cm}^{-3}
\end{aligned}$$

(c)

It means that there is about only one minor minority carrier every $10^3\,\mathrm{cm}^3$.

Ex 3.2

(a)

$$N_a = 3 \times 10^{16}\,\mathrm{cm}^{-3}, N_d = 1.5 \times 10^{16}\,\mathrm{cm}^{-3}$$
$$n_i = 1.5 \times 10^{10}\,\mathrm{cm}^{-3}$$

Since $N_a > N_d$, it is p-type. And $n_i \ll N_a - N_d$, so the majority carriers are holes, the concentration is

$$p_0 = N_a - N_d = 3 \times 10^{16}\,\mathrm{cm}^{-3} - 1.5 \times 10^{16}\,\mathrm{cm}^{-3} = 1.5 \times 10^{16}\,\mathrm{cm}^{-3}$$

The minority carriers are electrons, the concentration is

$$n_0 = \frac{n_i^2}{p_0} = \frac{(1.5 \times 10^{10}\,\mathrm{cm}^{-3})^2}{1.5 \times 10^{16}\,\mathrm{cm}^{-3}} = 1.5 \times 10^{4}\,\mathrm{cm}^{-3}$$

(b)

$$\begin{aligned}
p_0 &= N_a + \Delta N_a - N_d \\
\Delta N_a' &= p_0 - (N_a - N_d) = 5 \times 10^{16}\,\mathrm{cm}^{-3} - 1.5 \times 10^{16}\,\mathrm{cm}^{-3} = 3.5 \times 10^{16}\,\mathrm{cm}^{-3} \\
n_0 &= \frac{n_i^2}{p_0} = \frac{(1.5 \times 10^{10}\,\mathrm{cm}^{-3})^2}{5 \times 10^{16}\,\mathrm{cm}^{-3}} = 4.5 \times 10^{3}\,\mathrm{cm}^{-3}
\end{aligned}$$

Ex 3.3

(a)

$$n_0 = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_i^2} = \frac{N_d}{0.95} = 1.05 \times 10^{15}\,\text{cm}^{-3}$$

$$n_i^2 = \left(\frac{N_d}{0.95} - \frac{N_d}{2}\right)^2 - \left(\frac{N_d}{2}\right)^2 = \left(\frac{10^{15}\,\text{cm}^{-3}}{0.95} - \frac{10^{15}\,\text{cm}^{-3}}{2}\right)^2 - \left(\frac{10^{15}\,\text{cm}^{-3}}{2}\right)^2 = 5.25 \times 10^{28}\,\text{cm}^{-6}$$

$$n_i^2 = N_c N_v \left(\frac{T}{T_0}\right)^3 \exp\left[\frac{-E_g}{kT}\right]$$

$$5.25 \times 10^{28}\,\text{cm}^{-6} = 2.8 \times 10^{19}\,\text{cm}^{-3} \cdot 1.04 \times 10^{19}\,\text{cm}^{-3} \left(\frac{T}{300\,\text{K}}\right)^3 \exp\left[\frac{-1.12\,\text{eV}}{8.62 \times 10^{-5}\,\text{eV/K} \cdot T}\right]$$

$$T = 537.25\,\text{K}$$

(b)

For $T = 300K$,

$$E_c - E_F = kT \ln\left[\frac{N_c}{n_0}\right] = 0.0259\,\text{eV} \ln\left[\frac{2.8 \times 10^{19}\,\text{cm}^{-3}}{1.05 \times 10^{15}\,\text{cm}^{-3}}\right] = 2.64 \times 10^{-1}\,\text{eV}$$

For $T = 537.25\,\text{K}$,

$$kT = 8.62 \times 10^{-5}\,\text{eV/K} \cdot 537.25\,\text{K} = 4.63 \times 10^{-2}\,\text{eV}$$

$$N_c' = N_c \left(\frac{T}{T_0}\right)^{3/2} = 2.8 \times 10^{19}\,\text{cm}^{-3} \cdot \left(\frac{537.25\,\text{K}}{300\,\text{K}}\right)^{3/2} = 6.71 \times 10^{19}\,\text{cm}^{-3}$$

$$E_c - E_F = kT \ln\left[\frac{N_c}{n_0}\right] = 4.63 \times 10^{-2}\,\text{eV} \ln\left[\frac{6.71 \times 10^{19}\,\text{cm}^{-3}}{1.05 \times 10^{15}\,\text{cm}^{-3}}\right] = 5.12 \times 10^{-1}\,\text{eV}$$

So

$$\Delta(E_c - E_F) = 5.12 \times 10^{-1}\,\text{eV} - 2.64 \times 10^{-1}\,\text{eV} = 2.48 \times 10^{-1}\,\text{eV}$$

(c)

It is closer to the intrinsic value at high temperature.

Ex 3.4

(a)

$$E_{Fi} - E_{midgap} = \frac{3}{4} kT \ln\left[\frac{m_p^*}{m_n^*}\right] = \frac{3}{4} \cdot 0.0259\,\text{eV} \cdot \ln 10 = 4.47 \times 10^{-2}\,\text{eV}$$

(b)

(i)

Since impurity atoms are added so that $E_{Fi} < E_{midgap}$, it is p-type, acceptors should be added.

(ii)

$$E_{Fi} - E_F = 0.45\,\text{eV} + 4.47 \times 10^{-2}\,\text{eV} = 0.494\,\text{eV}$$

$$p_0 = n_i \exp\left[\frac{E_{Fi} - E_F}{kT}\right] = 10^5\,\text{cm}^{-3} \cdot \exp\left[\frac{0.494\,\text{eV}}{0.0259\,\text{eV}}\right] = 1.92 \times 10^{13}\,\text{cm}^{-3}$$

Ex 3.5

(a)

When replacing gallium, silcon is the donor,

$$N_d = 0.05 \cdot 7 \times 10^{15}\,\text{cm}^{-3} = 3.5 \times 10^{14}\,\text{cm}^{-3}$$

When replacing arsenic, silcon is the accepetor,

$$N_a = 0.95 \cdot 7 \times 10^{15}\,\text{cm}^{-3} = 6.65 \times 10^{15}\,\text{cm}^{-3}$$

(b)

Since $N_a > N_d$, it is p-type.

(c)

$$n_i = 1.8 \times 10^6\,\text{cm}^{-3}$$

Since $n_i \ll N_a - N_d$, so the majority carriers are holes, the concentration is

$$p_0 = N_a - N_d = 6.65 \times 10^{15}\,\text{cm}^{-3} - 3.5 \times 10^{14}\,\text{cm}^{-3} = 6.3 \times 10^{15}\,\text{cm}^{-3}$$

The minority carriers are electrons, the concentration is

$$n_0 = \frac{n_i^2}{p_0} = \frac{(1.8 \times 10^6\,\text{cm}^{-3})^2}{6.3 \times 10^{15}\,\text{cm}^{-3}} = 5.14 \times 10^{-4}\,\text{cm}^{-3}$$

(d)

$$E_{Fi} - E_F = kT \ln\left[\frac{p_0}{n_i}\right] = 0.0259\,\text{eV} \ln\left[\frac{6.3 \times 10^{15}\,\text{cm}^{-3}}{1.8 \times 10^6\,\text{cm}^{-3}}\right] = 5.69 \times 10^{-1}\,\text{eV}$$

Ex 3.6