

VE320

Intro to Semiconductor Devices

HOMEWORK 3

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1. (a) The density of states in the conduction band is

$$g_c(E) = \frac{4\pi(2m_n^*)^{3/2}}{h^3} \sqrt{E - E_c}.$$

Since $E = E_c + kT$,

$$g_c(E) = \frac{4\pi(2m_n^*)^{3/2}}{h^3} \sqrt{kT}.$$

The density of states in the valence band is

$$g_v(E) = \frac{4\pi(2m_p^*)^{3/2}}{h^3} \sqrt{E_v - E}.$$

Since $E = E_v - kT$,

$$g_v(E) = \frac{4\pi(2m_p^*)^{3/2}}{h^3} \sqrt{kT}.$$

The ratio of the density of states in the conduction band at $E = E_c + kT$ to the density of states in the valence band at $E = E_v - kT$ is

$$\frac{g_c(E)}{g_v(E)} = \frac{\frac{4\pi(2m_n^*)^{3/2}}{h^3} \sqrt{kT}}{\frac{4\pi(2m_p^*)^{3/2}}{h^3} \sqrt{kT}} = \left(\frac{m_n^*}{m_p^*} \right)^{3/2}.$$

According to textbook page 83 Table 4.1, we have $m_n^*/m_0 = 1.08$ and $m_p^*/m_0 = 0.56$ for Si. Thus, the ratio of the density of states in the conduction band at $E = E_c + kT$ to the density of states in the valence band at $E = E_v - kT$ is

$$\frac{g_c(E)}{g_v(E)} = \left(\frac{1.08}{0.56} \right)^{3/2} = 2.678.$$

(b) For GaAs, $m_n^*/m_0 = 0.067$ and $m_p^*/m_0 = 0.48$. Thus, the ratio of the density of states in the conduction band at $E = E_c + kT$ to the density of states in the valence band at $E = E_v - kT$ is

$$\frac{g_c(E)}{g_v(E)} = \left(\frac{0.067}{0.48} \right)^{3/2} = 0.0521.$$

2. (a) The probability of a state being occupied by an electron in the conduction band is

$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}.$$

We have $E_c - E_F = 0.30$ eV and $T = 300$ K. Thus, The probability of a state being occupied by an electron in the conduction band is

$$f_F(E) = \frac{1}{1 + \exp\left(\frac{0.30 \times 1.602176565 \times 10^{-19} + x}{1.3806488 \times 10^{-23} \times 300}\right)}$$

over the range $E_c \leq E \leq E_c + 2 \times 1.3806488 \times 10^{-23} \times 300$ where $x = E - E_c$ over the range $0 \leq x \leq 0.05170399431$ eV.

The graph of $f_F(E)$ is shown in Figure 1.

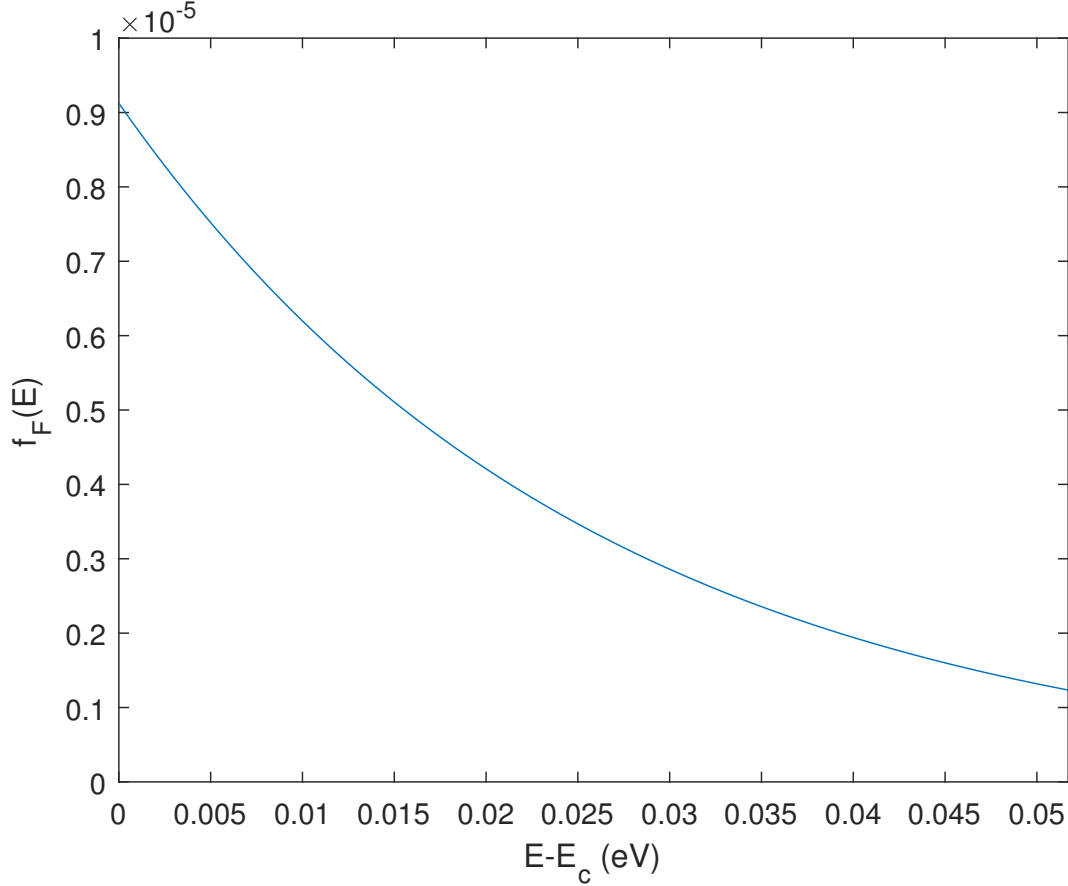


Figure 1: 3-2(a).

(b) The probability of a state being empty by an electron in the valence band is

$$1 - f_F(E) = 1 - \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}.$$

We have $E_F - E_v = 0.25$ eV and $T = 300$ K. Thus, The probability of a state being empty by an electron in the valence band is

$$f_F(E) = 1 - \frac{1}{1 + \exp\left(\frac{-0.25 \times 1.602176565 \times 10^{-19} + x}{1.3806488 \times 10^{-23} \times 300}\right)}$$

over the range $E_v - 2 \times 1.3806488 \times 10^{-23} \times 300 \leq E \leq E_v$ where $x = E - E_v$ over the range $-0.05170399431 \leq x \leq 0$ eV.

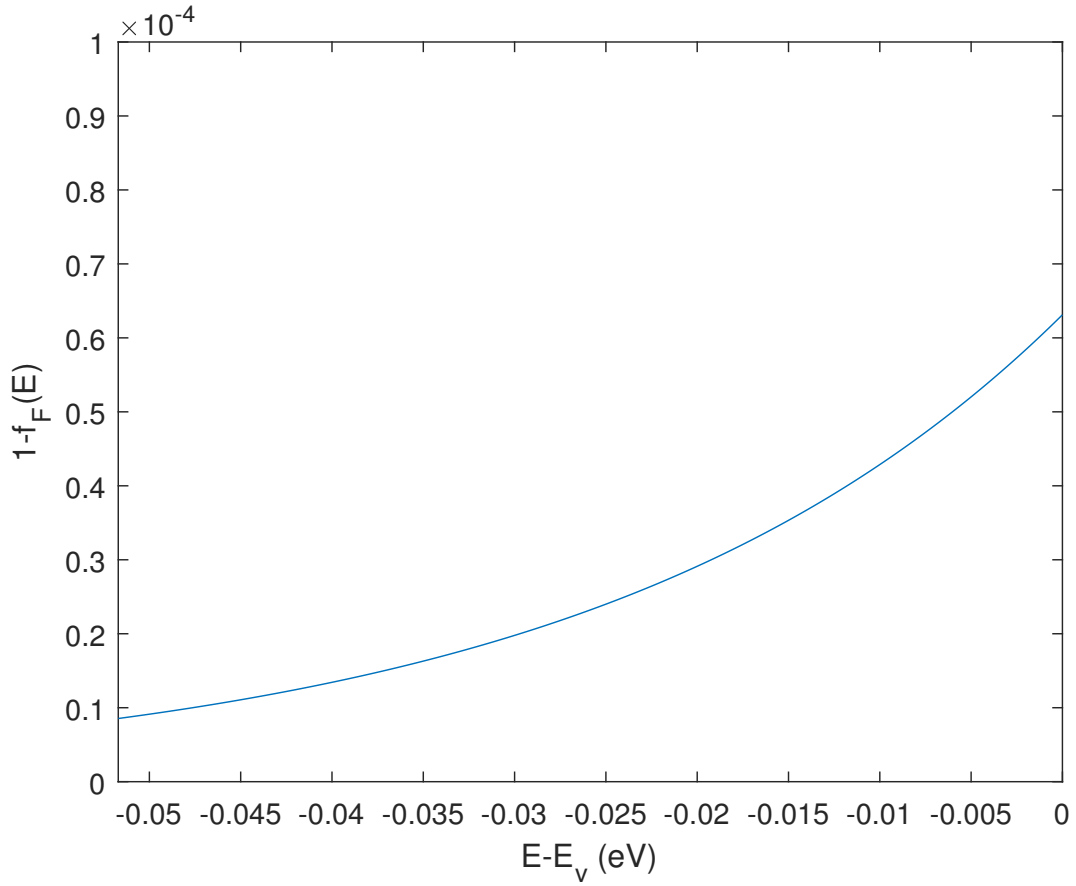


Figure 2: 3-2(b).

3. (a) Since the probability is

$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E-E_F}{kT}\right)},$$

we have the temperature is

$$T = \frac{E - E_F}{k \ln\left(\frac{1}{f_F} - 1\right)}.$$

Substituting 10^{-8} for f_F and 0.60 eV for $E - E_F$, the temperature at which there is a 10^{-8} probability that an energy state 0.60 eV above the Fermi energy level is occupied by an electron is

$$T = \frac{0.6 \times 1.602176565 \times 10^{-19}}{1.3806488 \times 10^{-23} \times \ln\left(\frac{1}{10^{-8}} - 1\right)} = 378.0 \text{ K}.$$

(b) Similarly, substituting 10^{-6} for f_F and 0.60 eV for $E - E_F$, the temperature at which there is a 10^{-6} probability that an energy state 0.60 eV above the Fermi energy level is occupied by an electron is

$$T = \frac{0.6 \times 1.602176565 \times 10^{-19}}{1.3806488 \times 10^{-23} \times \ln\left(\frac{1}{10^{-6}} - 1\right)} = 504.0 \text{ K}.$$

4. (a) The position of the intrinsic Fermi level with respect to the center of the bandgap is:

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

Therefore, the position of the intrinsic Fermi level with respect to the center of the bandgap at $T = 300$ K is

$$E_{Fi} - E_{\text{midgap}} = \frac{3}{4} \times 1.3806488 \times 10^{-23} \times 300 \ln \left(\frac{0.70m_0}{1.21m_0} \right) = -1.70 \times 10^{-21} \text{ V} = -0.0106 \text{ eV}.$$

(b) Similarly, the position of the intrinsic Fermi level with respect to the center of the bandgap at $T = 300$ K is

$$E_{Fi} - E_{\text{midgap}} = \frac{3}{4} \times 1.3806488 \times 10^{-23} \times 300 \ln \left(\frac{0.75m_0}{0.080m_0} \right) = 6.95 \times 10^{-21} \text{ V} = -0.0434 \text{ eV}.$$

5. (a) The concentration of holes

$$p_0 = N_v \exp \left[\frac{-(E_F - E_v)}{kT} \right].$$

Thus, the expression for $E_F - E_v$ is

$$E_F - E_v = -kT \ln \left(\frac{p_0}{N_v} \right).$$

Substituting 300 K for T , $5 \times 10^{15} \text{ cm}^{-3}$ for p_0 , and $1.04 \times 10^{19} \text{ cm}^{-3}$, we have

$$E_F - E_v = -1.3806488 \times 10^{-23} \times 300 \ln \left(\frac{5 \times 10^{15}}{1.04 \times 10^{19}} \right) = 3.16 \times 10^{-20} \text{ V} = 0.198 \text{ eV}.$$

(b) Since the width of a forbidden energy band E_g of silicon is 1.12 eV, we have

$$E_c - E_F = E_g - (E_F - E_v) = 1.12 - 0.198 = 0.922 \text{ eV}.$$

(c) The concentration of electrons is

$$n_0 = N_c \exp \left[\frac{-(E_c - E_F)}{kT} \right] = N_c \exp \left[- \left(\frac{E_g}{kT} + \ln \left(\frac{p_0}{N_v} \right) \right) \right].$$

Substituting $2.8 \times 10^{19} \text{ cm}^{-3}$ for N_c and 300 K for T ,

$$n_0 = 2.8 \times 10^{19} \exp \left[- \left(\frac{1.12 \times 1.602176565 \times 10^{-19}}{1.3806488 \times 10^{-23} \times 300} + \ln \left(\frac{5 \times 10^{15}}{1.04 \times 10^{19}} \right) \right) \right] = 8.91 \times 10^3 \text{ cm}^{-3}.$$

(d) According to (c), $n_0 < p_0$, so hole is the majority carrier.

(e) The concentration of holes is

$$p_0 = n_i \exp \left[\frac{-(E_F - E_{Fi})}{kT} \right] = n_i \exp \left[\frac{E_{Fi} - E_F}{kT} \right],$$

thus,

$$E_{Fi} - E_F = kT \ln \left(\frac{p_0}{n_i} \right).$$

According to Chapter 4 Section 4.1.3 of the textbook, there is discrepancy between the commonly accepted value of n_i and the value of n_i calculated from Equation (4.23) for $E_g = 1.12$ eV, though we take the intrinsic carrier concentration n_i of silicon as $1.5 \times 10^{10} \text{ cm}^{-3}$. Therefore,

$$E_{Fi} - E_F = 1.3806488 \times 10^{-23} \times 300 \times \ln \left(\frac{5 \times 10^{15}}{1.5 \times 10^{10}} \right) = 5.27 \times 10^{-20} \text{ V} = 0.329 \text{ eV}.$$

6. (a) (i) The thermal equilibrium electron concentration is

$$n_0 = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2} \right)^2 + n_i^2}.$$

Substituting $2 \times 10^{15} \text{ cm}^{-3}$ for N_d , 0 for N_a , and $2.4 \times 10^{13} \text{ cm}^{-3}$ for n_i , the thermal equilibrium electron concentration is

$$n_0 = \frac{2 \times 10^{15}}{2} + \sqrt{\left(\frac{2 \times 10^{15}}{2}\right)^2 + (2.4 \times 10^{13})^2} = 2.00 \times 10^{15} \text{ cm}^{-3}.$$

The thermal equilibrium hole concentration is

$$p_0 = \frac{n_i^2}{n_0}.$$

Substituting $2.4 \times 10^{13} \text{ cm}^{-3}$ for n_i , the thermal equilibrium hole concentration is

$$p_0 = \frac{(2.4 \times 10^{13})^2}{\frac{2 \times 10^{15}}{2} + \sqrt{\left(\frac{2 \times 10^{15}}{2}\right)^2 + (2.4 \times 10^{13})^2}} = 2.88 \times 10^{11} \text{ cm}^{-3}.$$

(ii) The thermal equilibrium hole concentration is

$$p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}.$$

Substituting 10^{16} cm^{-3} for N_a , $7 \times 10^{15} \text{ cm}^{-3}$ for N_d , and $2.4 \times 10^{13} \text{ cm}^{-3}$ for n_i , the thermal equilibrium hole concentration is

$$p_0 = \frac{10^{16} - 7 \times 10^{15}}{2} + \sqrt{\left(\frac{10^{16} - 7 \times 10^{15}}{2}\right)^2 + (2.4 \times 10^{13})^2} = 3.00 \times 10^{15} \text{ cm}^{-3}.$$

The thermal equilibrium electron concentration is

$$n_0 = \frac{n_i^2}{p_0}.$$

Substituting $2.4 \times 10^{13} \text{ cm}^{-3}$ for n_i , the thermal equilibrium electron concentration is

$$n_0 = \frac{(2.4 \times 10^{13})^2}{\frac{10^{16} - 7 \times 10^{15}}{2} + \sqrt{\left(\frac{10^{16} - 7 \times 10^{15}}{2}\right)^2 + (2.4 \times 10^{13})^2}} = 1.92 \times 10^{11} \text{ cm}^{-3}.$$

(b) (i) Similarly, substituting $2 \times 10^{15} \text{ cm}^{-3}$ for N_d , 0 for N_a , and $1.8 \times 10^6 \text{ cm}^{-3}$ for n_i , the thermal equilibrium electron concentration is

$$n_0 = \frac{2 \times 10^{15}}{2} + \sqrt{\left(\frac{2 \times 10^{15}}{2}\right)^2 + (1.8 \times 10^6)^2} = 2.00 \times 10^{15} \text{ cm}^{-3}.$$

The thermal equilibrium hole concentration is

$$p_0 = \frac{(1.8 \times 10^6)^2}{\frac{2 \times 10^{15}}{2} + \sqrt{\left(\frac{2 \times 10^{15}}{2}\right)^2 + (1.8 \times 10^6)^2}} = 1.62 \times 10^{-3} \text{ cm}^{-3}.$$

(ii) Similarly, substituting 10^{16} cm^{-3} for N_a , $7 \times 10^{15} \text{ cm}^{-3}$ for N_d , and $1.8 \times 10^6 \text{ cm}^{-3}$ for n_i , the thermal equilibrium hole concentration is

$$\begin{aligned} p_0 &= \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2} \\ &= \frac{10^{16} - 7 \times 10^{15}}{2} + \sqrt{\left(\frac{10^{16} - 7 \times 10^{15}}{2}\right)^2 + (1.8 \times 10^6)^2} \\ &= 3.00 \times 10^{15} \text{ cm}^{-3}. \end{aligned}$$

The thermal equilibrium electron concentration is

$$n_0 = \frac{n_i^2}{p_0} = \frac{(2.4 \times 10^{13})^2}{\frac{10^{16} - 7 \times 10^{15}}{2} + \sqrt{\left(\frac{10^{16} - 7 \times 10^{15}}{2}\right)^2 + (1.8 \times 10^6)^2}} = 1.08 \times 10^{-3} \text{ cm}^{-3}.$$

(c) The minority carrier concentration, i.e., the concentration of electrons in the conduction band decreases below the intrinsic carrier concentration as we add acceptor impurity atoms. At the same time, the majority carrier hole concentration increases above the intrinsic carrier concentration as we add acceptor atoms. As we add acceptor impurity atoms and the corresponding acceptor holes, there is a redistribution of holes among available energy states. A few of the acceptor holes will rise into the empty states in the conduction band and in doing so will annihilate some of the intrinsic electrons. The minority carrier electron concentration will therefore decrease.

7. (a) Since boron atoms are acceptor and arsenic atoms are donor, the concentration of boron atoms is $N_a = 3 \times 10^{16} \text{ cm}^{-3}$ that is higher than the concentration of arsenic atoms $N_d = 1.5 \times 10^{16} \text{ cm}^{-3}$, the material is p type.

The thermal equilibrium concentrations of majority carriers is

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

The thermal equilibrium concentrations of minority carriers is

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

(b) To make holes to be the majority carrier and the thermal equilibrium concentration to be $p_0 = 5 \times 10^{16} \text{ cm}^{-3}$, boron atoms must be added.

We have

$$n_0 + N_a = p_0 + N_d.$$

Since $n_0 \ll p_0$, we can ignore n_0 . N_a here is the sum of the original and the added concentration of acceptor atoms. Denote the concentration of the acceptor atoms to be added as N'_a , then we have

$$N'_a = p_0 + N_d - N_a.$$

Substituting $1.5 \times 10^{16} \text{ cm}^{-3}$ for N_d , $3 \times 10^{16} \text{ cm}^{-3}$ for N_a , and $5 \times 10^{16} \text{ cm}^{-3}$ for p_0 , the concentration of impurity atoms must be added is

$$N'_a = 5 \times 10^{16} + 1.5 \times 10^{16} - 3 \times 10^{16} = 3.5 \times 10^{16} \text{ cm}^{-3}.$$

The new value of n_0 is

$$n_0 = \frac{n_i^2}{p_0} = \frac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3 \text{ cm}^{-3}.$$

8. (a) Since the silicon device is only doped with donor impurity atoms, we have the concentration of electrons is

$$n_0 = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_i^2}.$$

Since the intrinsic carriers must contribute no more than 5 percent to the total electron concentration, when the temperature is at the maximum,

$$n_i = 0.05n_0.$$

Therefore, the concentration of electrons is

$$n_0 = \frac{10^{15}}{2} + \sqrt{\left(\frac{10^{15}}{2}\right)^2 + (0.05n_0)^2}.$$

Solving the equation above, we have the majority carrier electron is

$$n_0 = 1.00 \times 10^{15} \text{ cm}^{-3},$$

thus, the concentration of the intrinsic carrier is

$$n_i = 5.01 \times 10^{13} \text{ cm}^{-3}.$$

We have

$$n_i^2 = N_c N_v \exp\left(\frac{-E_g}{kT}\right),$$

so

$$T = \frac{-E_g}{k \ln\left(\frac{n_i^2}{N_c N_v}\right)}.$$

Substituting $5.01 \times 10^{13} \text{ cm}^{-3}$ for n_i , $2.8 \times 10^{19} \text{ cm}^{-3}$ for N_c , $1.04 \times 10^{19} \text{ cm}^{-3}$ for N_v , and 1.12 eV for E_g , the maximum temperature that the device may operate is

$$T = \frac{-1.12 \times 1.602176565 \times 10^{-19}}{1.3806488 \times 10^{-23} \times \ln\left(\frac{n_i^2}{2.8 \times 10^{19} \times 1.04 \times 10^{19}}\right)} = 510 \text{ K}.$$

(b) We have

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

Therefore,

$$\Delta(E_c - E_F) = k\Delta T \ln\left(\frac{N_c}{N_d}\right).$$

Substituting $2.8 \times 10^{19} \text{ cm}^{-3}$ for N_c and 10^{15} cm^{-3} for N_d , the change in $E_c - E_F$ from the $T = 300 \text{ K}$ value to the maximum temperature value determined in part (a) is

$$\Delta(E_c - E_F) = 1.3806488 \times 10^{-23} \times (510 - 300) \times \ln\left(\frac{2.8 \times 10^{19}}{10^{15}}\right) = 2.97 \times 10^{-20} \text{ J} = 0.185 \text{ eV}.$$

(c) As the temperature increases, the intrinsic carrier concentration increases. Therefore, the Fermi level is closer to the intrinsic value at the higher temperature.

9. (a) The position of the intrinsic Fermi energy level with respect to the center of the bandgap is

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

Substituting 10 for $\frac{m_p^*}{m_n^*}$, 300 K for T , the position of the intrinsic Fermi energy level with respect to the center of the bandgap is

$$E_{Fi} - E_{\text{midgap}} = \frac{3}{4} \times 1.3806488 \times 10^{-23} \times 300 \times \ln 10 = 7.15 \times 10^{-21} \text{ V} = 0.0446 \text{ eV}.$$

(b) (i) Since the Fermi energy level is lower, acceptor atoms are added.

(ii) The concentration of impurity atoms added is

$$p_0 = n_i \exp\left(\frac{E_{Fi} - E_F}{kT}\right).$$

According to (a),

$$E_{Fi} - E_F = 0.45 + 0.0446 = 0.4946 \text{ eV}.$$

Substituting $1 \times 10^5 \text{ cm}^{-3}$ for n_i , 0.4946 eV for $E_{Fi} - E_F$, and 300 K for T , the concentration of impurity atoms added is

$$p_0 = 10^5 \exp\left(\frac{0.4946 \times 1.602176565 \times 10^{-19}}{1.3806488 \times 10^{-23} \times 300}\right) = 2.04 \times 10^{13} \text{ cm}^{-3}.$$

10. (a) The donor concentrations is

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

The accept concentration is

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

(b) Since $N_a > N_d$, the material is p type.

(c) The hole concentration is

$$p_0 = N_a - N_d.$$

Substituting $6.65 \times 10^{15} \text{ cm}^{-3}$ for N_a and $3.5 \times 10^{14} \text{ cm}^{-3}$ for N_d , the hole concentration is

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

The electron concentration is

$$n_0 = \frac{n_i^2}{p_0}.$$

Substituting $6.3 \times 10^{15} \text{ cm}^{-3}$ for p_0 and $1.8 \times 10^6 \text{ cm}^{-3}$ for n_i , the electron concentration is

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

(d) We have

$$E_{Fi} - E_F = kT \ln \left(\frac{p_0}{n_i} \right).$$

Substituting $6.3 \times 10^{15} \text{ cm}^{-3}$ for p_0 , $1.8 \times 10^6 \text{ cm}^{-3}$ for n_i , and 300 K for T , the position of the Fermi level with respect to E_{Fi} is

$$E_{Fi} - E_F = 1.3806488 \times 10^{-23} \times 300 \times \ln \left(\frac{6.3 \times 10^{15}}{1.8 \times 10^6} \right) = 9.10 \times 10^{-20} \text{ V} = 0.568 \text{ eV}.$$

11. (a) We have

$$n_i^2 = N_c N_v \exp \left(\frac{-E_g}{kT} \right), \quad (1)$$

thus

$$n_i = \sqrt{N_c N_v \exp \left(\frac{-E_g}{kT} \right)}.$$

At $T = 300 \text{ K}$, substituting $2.0 \times 10^{19} \text{ cm}^{-3}$ for N_c , $1 \times 10^{19} \text{ cm}^{-3}$ for N_v , 1.10 eV for E_g , and 300 K for T , the intrinsic carrier concentration is

$$n_i = \sqrt{2.0 \times 10^{19} \times 10^{19} \exp \left(\frac{-1.10 \times 1.602176565 \times 10^{-19}}{1.3806488 \times 10^{-23} \times 300} \right)} = 8.15 \times 10^9 \text{ cm}^{-3}.$$

The donor concentration $N_d = 10^{14} \text{ cm}^{-3}$ which is much larger than n_i , so the electron concentration is

$$n = N_d = 10^{14} \text{ cm}^{-3}.$$

The electric-current density is

$$J = e\mu_n nE.$$

Substituting $1000 \text{ cm}^2/\text{V}\cdot\text{s}$ for μ_n , 10^{14} cm^{-3} for n , and 100 V/cm for E , the electric-current density is

$$J = 1.602176565 \times 10^{-19} \times 1000 \times 10^{14} \times 100 = 1.60 \text{ A/cm}^2.$$

(b) To make this current increase by 5 percent, the intrinsic carrier concentration n' would increase to $1.05n = 1.05 \times 10^{14} \text{ cm}^{-3}$. To derive the intrinsic carrier concentration n_i , we have

$$n_0 = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2} \right)^2 + n_i^2},$$

thus,

$$n_i = \sqrt{n_0^2 - n_0 N_d}.$$

Substituting $1.05 \times 10^{14} \text{ cm}^{-3}$ for n_0 and 10^{14} cm^{-3} for N_d , we have

$$n_i = \sqrt{(1.05 \times 10^{14})^2 - 1.05 \times 10^{14} \times 10^{14}} = 2.29 \times 10^{13} \text{ cm}^{-3}.$$

Using Eq. (1), substituting 1.10 eV for E_g , $2 \times 10^{19}(T/300)^{3/2} \text{ cm}^{-3}$ for N_c , and $1 \times 10^{19}(T/300)^{3/2} \text{ cm}^{-3}$ for N_v , we have

$$(1.05 \times 10^{14})^2 - 1.05 \times 10^{14} \times 10^{14} = 2 \times 10^{38} \left(\frac{T}{300} \right)^3 \exp \left(\frac{-1.10 \times 1.602176565 \times 10^{-19}}{1.3806488 \times 10^{-23} \times T} \right).$$

Solving the equation, the temperature at which this current will increase by 5 percent is

$$T = 457 \text{ K}.$$

12. The intrinsic carrier concentration

$$n_i = p_i = \sqrt{N_c N_v \exp \left(\frac{-E_g}{kT} \right)} = \sqrt{2.912 \exp \left(\frac{-1.12e}{kT} \right) \times 10^{19} \left(\frac{T}{300} \right)^{3/2}}.$$

The intrinsic conductivity is

$$\begin{aligned} \sigma &= e(\mu_n n + \mu_p p) \\ &= e \sqrt{2.912 \exp \left(\frac{-1.12e}{kT} \right) \times 10^{19} \left(\frac{T}{300} \right)^{3/2}} \times 1830 \left(\frac{T}{300} \right)^{-3/2} \\ &= 1.83e \times 10^{22} \sqrt{2.912 \exp \left(\frac{-1.12e}{kT} \right)} \end{aligned}$$

The graph of the intrinsic conductivity as a function of T over the range $200 \leq T \leq 600 \text{ K}$ is shown in Figure 3.

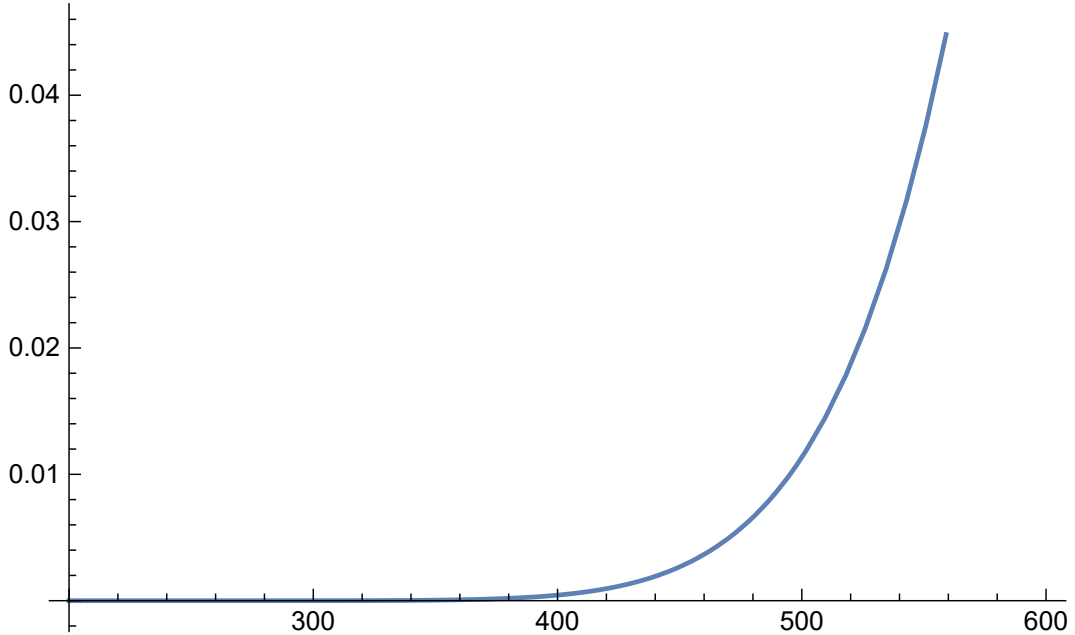


Figure 3: 3-12.

13. (a) The electron field is

$$E_x = -\left(\frac{kT}{e}\right) \frac{1}{N_d(x)} \frac{dN_d(x)}{dx}.$$

Since $N_d(x) = N_{d0}e^{-x/L} = 10^{16}e^{-x/L}$ and its derivative is $-\frac{10^{16}}{L}e^{-x/L}$, the electron field as a function of x for $0 \leq x \leq L$ is

$$\begin{aligned} E_x &= -\left(\frac{1.3806488 \times 10^{-23} \times 300}{1.602176565 \times 10^{-19}}\right) \frac{1}{10^{16}e^{-x/L}} \frac{-10^{16}}{L} e^{-x/L} \\ &= \frac{1.3806488 \times 10^{-23} \times 300}{1.602176565 \times 10^{-19} \times 10^{-5}} \\ &= 2.59 \times 10^3 \text{ V/m.} \end{aligned}$$

(b) Since the electron field is a constant, the potential difference is

$$V = E_x L.$$

Therefore, the potential difference between $x = 0$ and $x = L$ is

$$V = \frac{1.3806488 \times 10^{-23} \times 300}{1.602176565 \times 10^{-19}} = 2.59 \times 10^{-2} \text{ V.}$$

14. (a) (i) Using the Einstein relation

$$\frac{D_n}{\mu_n} = \frac{kT}{e},$$

we have the diffusion coefficient is

$$D_n = \frac{kT\mu_n}{e}.$$

Substituting 300 K for T and $1150 \text{ cm}^2/\text{V} \cdot \text{s}$ for μ_n , the diffusion coefficient is

$$D_n = \frac{1.3806488 \times 10^{-23} \times 300 \times 1150}{1.602176565 \times 10^{-19}} = 29.7 \text{ cm}^2/\text{s}.$$

(ii) Similarly, substituting 300 K for T and $6200 \text{ cm}^2/\text{V} \cdot \text{s}$ for μ_n , the diffusion coefficient is

$$D_n = \frac{1.3806488 \times 10^{-23} \times 300 \times 1150}{1.602176565 \times 10^{-19}} = 160 \text{ cm}^2/\text{s}.$$

(b) (i) Using the Einstein relation

$$\frac{D_p}{\mu_p} = \frac{kT}{e},$$

we have the hole mobility is

$$\mu_p = \frac{eD_p}{kT}.$$

Substituting 300 K for T and $8 \text{ cm}^2/\text{s}$ for D_p , the hole mobility is

$$\mu_p = \frac{1.602176565 \times 10^{-19} \times 8}{1.3806488 \times 10^{-23} \times 300} = 309 \text{ cm}^2/\text{V} \cdot \text{s}.$$

(ii) Similarly, substituting 300 K for T and $8 \text{ cm}^2/\text{s}$ for D_p , the hole mobility is

$$\mu_p = \frac{1.602176565 \times 10^{-19} \times 35}{1.3806488 \times 10^{-23} \times 300} = 1.35 \times 10^3 \text{ cm}^2/\text{V} \cdot \text{s}.$$

15. The electron difference current density is

$$J_{nx|\text{dif}} = eD_n \frac{dn}{dx}.$$

Since the steady-state electron distribution in silicon can be approximated by a linear function of x , we can calculate the derivative by

$$\frac{dn}{dx} = \frac{n(0.012) - n(0)}{0.012 - 0} = -1.25 \times 10^{18} \text{ cm}^{-4}.$$

Substituting $27 \text{ cm}^2/\text{s}$ for D_n , the electron difference current density is

$$J_{nx|\text{dif}} = 1.602176565 \times 10^{-19} \times 27 \times (-1.25 \times 10^{18}) = -5.41 \text{ A/cm}^2.$$

Appendices

A. MATLAB Code for 3-2

```
clear, clc
E=linspace(0,0.05170399431,1000);
x=linspace(0,2,1000);
% f=exp(-0.3*1.602176565*10^(-19)/(1.3806488*10^(-23)*300)-x);
f=1./(1+exp(0.3*1.602176565*10^(-19)/(1.3806488*10^(-23)*300)+x));
plot(E,f);
xlabel('E-E_c (eV)');
ylabel('f_F(E)');
axis([0 0.05170399431 0 1e-5]);
text(0.33,5e-6,'$f_F(E)=\frac{1}{1+\exp\{\big(\frac{E-E_F}{kT}\big)\}}$', 'Interpreter','latex');
saveas(gcf,'3-2(a)','eps'); % Alternatively use function
% 'exportgraphics'
T=table(E,f);
writetable(T,'3-2(a).csv');
E=linspace(-0.05170399431,0,1000);
x=linspace(-2,0,1000);
f=1-1./(1+exp(-0.25*1.602176565*10^(-19)/(1.3806488*10^(-23)*300)+x));
plot(E,f);
xlabel('E-E_v (eV)');
ylabel('1-f_F(E)');
axis([-0.05170399431 0 0 1e-4]);
text(0.2,3.3e-5,'$f_F(E)=1-\frac{1}{1+\exp\{\big(\frac{E-E_F}{kT}\big)\}}$', '','Interpreter','latex');
saveas(gcf,'3-2(b)','eps');
T=table(E,f);
writetable(T,'3-2(b).csv');
```

B. Mathematica Code for 3-12

```
(* Content-type: application/vnd.wolfram.mathematica *)
```



```

FractionBox[
  RowBox[{
    RowBox[{"-", "1.12"}], "*", "1.602176565", "*",
    SuperscriptBox["10",
      RowBox[{"-", "19"}]]]],
  RowBox[{"1.3806488", "*",
    SuperscriptBox["10",
      RowBox[{"-", "23"}]]], "*", "T"}]], ""]}}]]], ",",
  RowBox[{"{",
    RowBox[{"T", ",", "200", ",", "600"}], ""]}], "Input",
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  3.811079158599968*^9, 3.8110792401741157`*^9}, {3.81107927092765*^9,
  3.8110792716030073`*^9}},
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↪ ad3"],

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CellLabel->"In[6] :=", ExpressionUUID->"76de5bb8-5ec1-4ca3-bc08-295822719"
↪ b78"],

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↪ cd4"]
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↪ (2020\5e746\67089\
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(* Internal cache information *)
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```

```
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↪ "Output",ExpressionUUID->"e72d7bc2-2127-43bd-ba86-f21d5b3fec4"]
}, Open  ]]
}
]
*)
```