Homework 2

Thursday, September 23, 2021 7:25 PM

"I pledge my honor I have abided by the Stevens Honor system."

- Alex [signature]

4.1 Calculate the intrinsic carrier concentration, n_i, at $T = 200$, 400, and 600 K for (*a*) silicon, (*b*) germanium, and (*c*) gallium arsenide.

$$n_i^2 = N_c N_v \exp\left[\frac{-(E_c - E_{F_i})}{kT}\right]$$

a.)

$T = 200K$

$$n_i^2 = (2.8\times10^{19})(1.04\times10^{19})\left(\frac{200}{300}\right)^{3/2}\left(\frac{200}{300}\right)^{3/2}\exp\left(\frac{-1.12}{0.0259\left(\frac{200}{300}\right)}\right)$$

$$n_i^2 = 5.83\times10^{9}$$

$$\boxed{n_i = 7.6\times10^{4}/cm^3}$$

$T = 400K$

$$n_i^2 = (2.8\times10^{19})(1.04\times10^{19})\left(\frac{400}{300}\right)^{3/2}\left(\frac{400}{300}\right)^{3/2}\exp\left(\frac{-1.12}{0.0259\left(\frac{400}{300}\right)}\right)$$

$$n_i^2 = 5.67\times10^{24}$$

$$\boxed{n_i = 2.38\times10^{12}/cm^3}$$

$T = 600K$

$$n_i^2 = (2.8\times10^{19})(1.04\times10^{19})\left(\frac{600}{300}\right)^{3/2}\left(\frac{600}{300}\right)^{3/2}\exp\left(\frac{-1.12}{0.0259\left(\frac{600}{300}\right)}\right)$$

$$n_i^2 = 9.49\times10^{29}$$

$$\boxed{n_i = 9.74\times10^{14}/cm^3}$$

b.)

$T = 200K$

$$n_i^2 = (6\times10^{18})(1.04\times10^{19})\left(\frac{200}{300}\right)^{3/2}\left(\frac{200}{300}\right)^{3/2}\exp\left(\frac{-0.66}{0.0259\left(\frac{200}{300}\right)}\right)$$

$$n_i^2 = 4.64\times10^{20}$$

$$\boxed{n_i = 2.16\times10^{10}/cm^3}$$

$T = 400K$

$$n_i^2 = (6\times10^{18})(1.04\times10^{19})\left(\frac{400}{300}\right)^{3/2}\left(\frac{400}{300}\right)^{3/2}\exp\left(\frac{-0.66}{0.0259\left(\frac{400}{300}\right)}\right)$$

$$n_i^2 = 7.41\times10^{29}$$

$$\boxed{n_i = 8.6\times10^{14}/cm^3}$$

$T = 600K$

$$n_i^2 = (6\times10^{18})(1.04\times10^{19})\left(\frac{600}{300}\right)^{3/2}\left(\frac{600}{300}\right)^{3/2}\exp\left(\frac{-0.66}{0.0259\left(\frac{600}{300}\right)}\right)$$

$n_i^2 = 1.46 \times 10^{33}$

$\boxed{n_i = 3.82 \times 10^{16} / cm^3}$

c.)

$T = 200K$

$n_i^2 = (4.7 \times 10^{17})(1.04 \times 10^{19}) \left(\frac{200}{300}\right)^{3/2} \left(\frac{200}{300}\right)^{3/2} \exp\left(\frac{-1.42}{0.0259\left(\frac{200}{300}\right)}\right)$

$n_i^2 = 1.87$

$\boxed{n_i = 1.37 / cm^3}$

$T = 400K$

$n_i^2 = (4.7 \times 10^{17})(1.04 \times 10^{19}) \left(\frac{400}{300}\right)^{3/2} \left(\frac{400}{300}\right)^{3/2} \exp\left(\frac{-1.42}{0.0259\left(\frac{400}{300}\right)}\right)$

$n_i^2 = 1.08 \times 10^{19}$

$\boxed{n_i = 3.29 \times 10^{9} / cm^3}$

$T = 600K$

$n_i^2 = (4.7 \times 10^{17})(1.04 \times 10^{19}) \left(\frac{600}{300}\right)^{3/2} \left(\frac{600}{300}\right)^{3/2} \exp\left(\frac{-1.42}{0.0259\left(\frac{600}{300}\right)}\right)$

$n_i^2 = 3.27 \times 10^{25}$

$\boxed{n_i = 5.72 \times 10^{12} / cm^3}$

4.12 (*a*) The carrier effective masses in a semiconductor are $m_n^* = 1.21\, m_0$ and $m_p^* = 0.70\, m_0$. Determine the position of the intrinsic Fermi level with respect to the center of the bandgap at $T = 300$ K. (*b*) Repeat part (*a*) if $m_n^* = 0.080\, m_0$ and $m_p^* = 0.75\, m_0$.

a.)

$E_{Fi} - \frac{E_g}{2} = \frac{3}{4} kT \left[\ln\left(\frac{m_p^*}{m_n^*}\right)\right]$

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

$= -0.0106\ eV$

$= \boxed{-10.6\ meV}$

b.)

$E_F = \frac{3}{4} kT \left[\ln\left(\frac{m_p^*}{m_n^*}\right)\right]$

$= \frac{3}{4}(0.0259)\left[\ln\left(\frac{0.75}{0.08}\right)\right]$

$= 0.043\ eV$

$$= \boxed{43 \text{ meV}}$$

4.17 Silicon at $T = 300$ K is doped with arsenic atoms such that the concentration of electrons is $n_0 = 7 \times 10^{15}$ cm^{-3}. (*a*) Find $E_c - E_F$. (*b*) Determine $E_F - E_v$. (*c*) Calculate p_0. (*d*) Which carrier is the minority carrier? (*e*) Find $E_F - E_{Fi}$.

a.) $E_c - E_f = kT\left[\ln\left(\frac{N_c}{n_0}\right)\right]$

$$= (0.0259)\left[\ln\left(\frac{2.8\times 10^{19}}{7\times 10^{15}}\right)\right]$$

$$= \boxed{0.215 \text{ eV}}$$

b.) $E_f - E = E_g - [E_c - E_f]$

$$= 1.12 - 0.2148$$

$$= \boxed{0.905 \text{eV}}$$

c.) $n_0 p_0 = N_c N_v \exp\left(\frac{-E_g}{kT}\right)$

$$p_0 = \frac{N_c N_v \exp\left(\frac{-E_g}{kT}\right)}{n_0}$$

$$p_0 = \frac{(2.8\times 10^{19})(1.04\times 10^{19})\exp\left(\frac{-1.12}{0.0259}\right)}{7\times 10^{15}}$$

$$\boxed{p_0 = 6.9 \times 10^3 /\text{cm}^3}$$

d.)

$n_0 > p_0$ @ Thermal Equilibrium

There is a higher concentration of electrons than holes, making holes the minority carrier.

e.) $n_0 = n_i \exp\left[\frac{E_f - E_{f_i}}{kT}\right]$

$$E_f - E_{f_i} = kT\left[\ln\left(\frac{n_0}{n_i}\right)\right]$$

$$= 0.0259\left[\ln\left(\frac{7\times 10^{15}}{1.5\times 10^{10}}\right)\right]$$

$$= \boxed{0.338 \text{ eV}}$$

4.20 (*a*) If $E_c - E_F = 0.28$ eV in gallium arsenide at $T = 375$ K, calculate the values of n_0 and p_0. (*b*) Assuming the value of n_0 in part (*a*) remains constant, determine $E_c - E_F$ and p_0 at $T = 300$ K.

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

$$N_c = 2\left[\frac{2\pi m_n^* kT}{h^2}\right]^{3/2} \quad \text{where } N_c \propto T^{3/2}$$

For N_c @ 375 K:

$$\frac{N_{c_1}}{N_{c_2}} = \left(\frac{T_1}{T_2}\right)^{3/2}$$

$$N_{c_1} = N_{c2}\left(\frac{T_1}{T_2}\right)^{3/2}$$

$$= 4.7\times10^{17}\left(\frac{375}{300}\right)^{3/2} = 6.57\times10^{17}/cm^3$$

a.)

$$n_o = 6.57\times10^{17}\exp\left(\frac{-0.28}{0.029\left(\frac{375}{300}\right)}\right) = \boxed{11.52\times10^{13}/cm^3}$$

$$N_{v_1} = N_{v2}\left(\frac{T_1}{T_2}\right) = 7\times10^{18}\left(\frac{375}{300}\right)^{3/2}$$

$$N_{v_1} = 9.78\times10^{18}/cm^3$$

$$p_o = 9.78\times10^{18}\exp\left[\frac{-(1.42-0.28)}{0.032375}\right]$$

$$\boxed{p_o = 4.9\times10^3/cm^3}$$

b.)

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

$$E_c - E_F = kT\left[\ln\left(\frac{N_c}{n_o}\right)\right] = 0.0259\left[\ln\left(\frac{4.7\times10^{17}}{11.52\times10^{13}}\right)\right]$$

$$\boxed{E_c - E_F = 0.22\text{ eV}}$$

$$E_F - V_v = E_g - (E_c - E_F) = 1.42 - 0.22 = 1.2$$

$$p_o = 7 \times 10^{18} \exp\left[\frac{-1.2}{0.0259}\right]$$

$$\boxed{p_o = 0.044/cm^3}$$

4.24 Silicon at $T = 300$ K is doped with boron atoms such that the concentration of holes is $p_0 = 5 \times 10^{15}$ cm^{-3}. (*a*) Find $E_F - E_v$. (*b*) Determine $E_c - E_F$. (*c*) Determine n_0. (*d*) Which carrier is the majority carrier? (*e*) Determine $E_{Fi} - E_F$.

$N_c = 2.8 \times 10^{19}/cm^3$ $\quad N_v = 1.04 \times 10^{19}/cm^3$ $\quad E_g = 1.12\,eV$

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

$$5 \times 10^{15} = 1.04 \times 10^{19} \exp\left[\frac{-(E_f - E_v)}{0.0259}\right]$$

$$\boxed{E_F - E_v = 0.198\,eV}$$

b.)
$$(E_c - E_F) = E_g - (E_f - E_v)$$

$$E_c - E_f = 1.12 - 0.198$$

$$\boxed{E_c - E_f = 0.922\,eV}$$

c.)
$$n_o = N_c \exp\left[\frac{-(E_c - E_f)}{kT}\right] = 2.8 \times 10^{19} \exp\left[\frac{-0.922}{0.0259}\right]$$

$$\boxed{n_o = 9.66 \times 10^3/cm^3}$$

d.) $p_o > n_o$ Positive charge carrier (holes) are in the majority. Thus, it is p-type.

e.)
$$E_{Fi} - E_F = kT\left[\ln\left(p_o/n_i\right)\right]$$

$$E_{Fi} - E_F = (0.0259)\left[\ln\left(\frac{5 \times 10^{15}}{1.5 \times 10^{10}}\right)\right]$$

$$\boxed{E_{F_i} - E_F = 0.3293\ eV}$$

4.39 A silicon semiconductor material at $T = 300$ K is doped with arsenic atoms to a concentration of 2×10^{15} cm^{-3} and with boron atoms to a concentration of 1.2×10^{15} cm^{-3}. (*a*) Is the material n type or p type? (*b*) Determine n_0 and p_0. (*c*) Additional boron atoms are to be added such that the hole concentration is 4×10^{15} cm^{-3}. What concentration of boron atoms must be added and what is the new value of n_0?

a.) $2\times10^{15}/cm^3$ donors $>$ $1.2\times10^{15}/cm^3$ acceptors

$$\boxed{\therefore \text{ The material is n-type}}$$

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

$$n_o = \frac{((2\times10^{15}) - (1.2\times10^{15}))}{2} + \sqrt{\left(\frac{((2\times10^{15}) - (1.2\times10^{15}))}{2}\right)^2 + (1.5\times10^{10})^2}$$

$$\boxed{n_o = 8\times10^{14}/cm^3}$$

$$n_i^2 = n_o p_o$$

$$p_o = \frac{n_i^2}{n_o} = \frac{(1.5\times10^{10})^2}{8\times10^{14}}$$

$$\boxed{p_o = 2.81\times10^{5}/cm}$$

c.) $$p_o \cong (N_{af} + N_a) - N_d$$

$$4\times10^{15} \cong (N_{af} + 1.2\times10^{15})$$

$$\boxed{N_{af} = 4.8\times10^{15}/cm^3}$$ ← Number of Boron atoms to be added

$$n_i^2 = n_o p_o$$

$$n_o = \frac{n_i^2}{p_o} = \frac{(1.5\times10^{10})^2}{4\times10^{15}}$$

$$\boxed{n_o = 5.62 \times 10^4 / cm^3}$$

4.54 Silicon at $T = 300$ K contains acceptor atoms at a concentration of $N_a = 5 \times 10^{15}$ cm^{-3}. Donor atoms are added forming an n-type compensated semiconductor such that the Fermi level is 0.215 eV below the conduction-band edge. What concentration of donor atoms are added?

$$n_o = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right] = (2.8 \times 10^{19}) \exp\left[\frac{-0.215}{0.0259}\right]$$

$$n_o = 6.95 \times 10^{15} / cm^3$$

$$n_o = N_d - N_a$$

$$6.95 \times 10^{15} = N_d - 5 \times 10^{15}$$

$$\boxed{N_d = 1.2 \times 10^{16} / cm^3}$$