2.14

(a) Referring to Fig. 2.20, one concludes:

(i) n_i(Si) = n_i(Ge, 300K) at $T \cong 430$K.

(ii) n_i(GaAs) = n_i(Ge, 300K) at $T \cong 600$K.

(b) With the differences in the effective masses neglected,

$$\frac{n_{iA}}{n_{iB}} = \frac{e^{-E_{GA}/2kT}}{e^{-E_{GB}/2kT}} = e^{(E_{GB}-E_{GA})/2kT} = e^{1/0.0518} = \mathbf{2.42 \times 10^8}$$

2.16

(a) As $T \to 0$, $\boldsymbol{n \to 0}$ and $\boldsymbol{p \to 0}$. (See the discussion in Subsection 2.5.7.)

(b) Since $N >> n_i$, one would have

$$n = N_D \text{ and } p = n_i^2/N_D \quad \text{...if a donor}$$

$$p = N_A \text{ and } n = n_i^2/N_A \quad \text{...if an acceptor}$$

We are told $n = N$ and $p = n_i^2/N$. Clearly the impurity is a **donor** .

(c) Here we are given the minority carrier concentration, $n = 10^5/\text{cm}^3$. As long as the Si is nondegenerate, one can always write

$$np = n_i^2$$

Thus

$$p = n_i^2/n = \frac{(10^{10})^2}{10^5} = \mathbf{10^{15}/cm^3}$$

Note: From previous problems we recognize that the above carrier concentrations do indeed correspond to a nondegenerate semiconductor.

(d) Given $E_F - E_i = 0.259\text{eV}$ and $T = 300\text{K}$,

$$n = n_i e^{(E_F - E_i)/kT} = (10^{10})\, e^{0.259/0.0259} = \mathbf{2.20 \times 10^{14}/cm^3}$$

$$p = n_i e^{(E_i - E_F)/kT} = (10^{10})\, e^{-0.259/0.0259} = \mathbf{4.54 \times 10^{5}/cm^3}$$

(e) Employing the np product relationship,

$$np = n^2/2 = n_i^2$$

$$n = \sqrt{2} n_i = \mathbf{1.414 \times 10^{13}/cm^3}$$

Next employing the charge neutrality relationship,

$$p - n + N_D - N_A = n/2 - n + N_D = 0$$

$$N_D = n/2 = n_i/\sqrt{2} = \mathbf{0.707 \times 10^{13}/cm^3}$$

2.17

(a) At room temperature in Si, $n_i = 10^{10}/\text{cm}^3$. Thus here $N_D >> N_A$, $N_D >> n_i$ and

$$n = N_D = 10^{15}/\text{cm}^3$$
$$p = n_i^2/N_D = 10^5/\text{cm}^3$$

(b) Since $N_A >> N_D$ and $N_A >> n_i$,

$$p = N_A = 10^{16}/\text{cm}^3$$
$$n = n_i^2/N_A = 10^4/\text{cm}^3$$

(c) Here we must retain both N_A and N_D, but $N_D - N_A >> n_i$.

$$n = N_D - N_A = 10^{15}/\text{cm}^3$$
$$p = n_i^2/(N_D - N_A) = 10^5/\text{cm}^3$$

(d) We deduce from Fig. 2.20 that, at 450K, $n_i(\text{Si}) \simeq 5 \times 10^{13}/\text{cm}^3$. Clearly, n_i is comparable to N_D and we must use Eq.(2.29a).

$$n = \frac{N_D}{2} + \left[\left(\frac{N_D}{2}\right)^2 + n_i^2\right]^{1/2} = 1.21 \times 10^{14}/\text{cm}^3$$

$$p = \frac{n_i^2}{n} = \frac{(5 \times 10^{13})^2}{1.21 \times 10^{14}} = 2.07 \times 10^{13}/\text{cm}^3$$

(e) We conclude from Fig. 2.20 that, at 650K, $n_i \simeq 10^{16}/\text{cm}^3$. Here $n_i >> N_D$. Thus

$$n = n_i \simeq 10^{16}/\text{cm}^3$$
$$p = n_i \simeq 10^{16}/\text{cm}^3$$

(d) Using the results of Problems 2.13 and 2.20, we know

$$N_C = 4.26 \times 10^{17}/\text{cm}^3$$

$$N_V = 9.41 \times 10^{18}/\text{cm}^3 \qquad \text{...GaAs at 300K}$$

and

$$N_{\text{DImax}} = N_C\, e^{-3} = (4.26 \times 10^{17})\, e^{-3} = 2.12 \times 10^{16}/\text{cm}^3$$

$$N_{\text{AImax}} = N_V\, e^{-3} = (9.41 \times 10^{18})\, e^{-3} = 4.68 \times 10^{17}/\text{cm}^3$$

Please note that *n-type GaAs becomes degenerate at relatively low donor dopings*. This fact is very important in the modeling of certain GaAs devices; constructive use is made of this fact in other GaAs devices.

HW3 Solutions

Problem 1

2.18

(i) As established in the text [Eq.(2.36)],

$$E_i = \frac{E_c + E_v}{2} + \frac{3}{4} kT \ln(m_p^*/m_n^*)$$

Taking m_p^*/m_n^* to be temperature independent and employing the values listed in Table 2.1, one concludes

part	T(K)	kT (eV)	E_i displacement from midgap (eV)
(a-c)	300	0.0259	−0.0073
(d)	450	0.0388	−0.0109
(e)	650	0.0560	−0.0158

Alternatively, the m_p^*/m_0 and m_n^*/m_0 versus T fit-relationships cited in Exercise 2.4 may be used to compute the m_p^*/m_n^* ratio. One finds

part	T(K)	m_p^*/m_n^*	kT (eV)	E_i displacement from midgap (eV)
(a-c)	300	0.680	0.0259	−0.0075
(d)	450	0.703	0.0388	−0.0103
(e)	650	0.719	0.0560	−0.0139

(ii) $E_F - E_i$ is computed using the appropriate version of Eq.(2.37) or (2.38).

(a) $E_F - E_i = kT \ln(N_D/n_i) = 0.0259 \ln(10^{15}/10^{10}) = 0.298$ eV

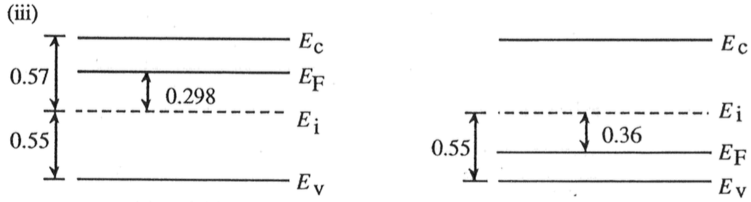
(b) $E_i - E_F = kT \ln(N_A/n_i) = 0.0259 \ln(10^{16}/ 10^{10}) = 0.358$ eV

(c) $E_F - E_i = kT \ln[(N_D-N_A)/n_i] = 0.0259 \ln(10^{15}/10^{10}) = 0.298$ eV

(d) $E_F - E_i = kT \ln(n/n_i) = 0.0388 \ln(1.21 \times 10^{14}/5 \times 10^{13}) = 0.034$ eV

(e) $E_F - E_i = kT \ln(n/n_i) \cong 0$ ...($n \cong n_i$)

(iii)



(a) and (c)

(b)

Problem 2

5.4

(a)

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) = (0.0259)\ln\left[\frac{(2\times10^{15})(10^{15})}{(10^{20})}\right] = \mathbf{0.614\ \ V}$$

(b)

$$x_p = \left[\frac{2K_S\varepsilon_0}{q}\frac{N_D}{N_A(N_A+N_D)}V_{bi}\right]^{1/2} = \mathbf{3.655\times10^{-5}\ cm}$$

$$x_n = \left[\frac{2K_S\varepsilon_0}{q}\frac{N_A}{N_D(N_A+N_D)}V_{bi}\right]^{1/2} = \mathbf{7.31\times10^{-5}\ cm}$$

$$W = x_n + x_p = \mathbf{1.10\times10^{-4}\ cm}$$

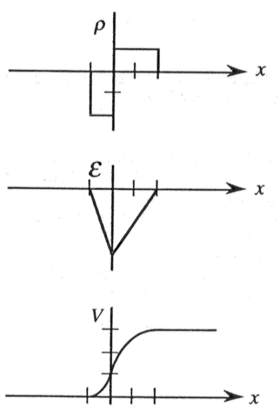
(c)

$$\mathcal{E}(0) = -\frac{qN_D}{K_S\varepsilon_0}x_n = -\frac{(1.6\times10^{-19})(10^{15})(7.31\times10^{-5})}{(11.8)(8.85\times10^{-14})} = \mathbf{-1.12\times10^{4}\ \ V/cm}$$

(d)

$$V(0) = \frac{qN_A}{2K_S\varepsilon_0}x_p^2 = \frac{(1.6\times10^{-19})(2\times10^{15})(3.655\times10^{-5})^2}{(2)(11.8)(8.85\times10^{-14})} = \mathbf{0.205\ \ V}$$

(e)



Problem 3

5.5

(a)

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) = (0.0259)\ln\left[\frac{(10^{17})(10^{15})}{(10^{20})}\right] = \mathbf{0.716\ V}$$

(b)

$$x_p = \left[\frac{2K_S\varepsilon_0}{q}\frac{N_D}{N_A(N_A+N_D)}V_{bi}\right]^{1/2} = \mathbf{9.62\times10^{-7}\ cm}$$

$$x_n = \left[\frac{2K_S\varepsilon_0}{q}\frac{N_A}{N_D(N_A+N_D)}V_{bi}\right]^{1/2} = \mathbf{9.62\times10^{-5}\ cm}$$

$$W = x_n + x_p = \mathbf{9.72\times10^{-5}\ cm}$$

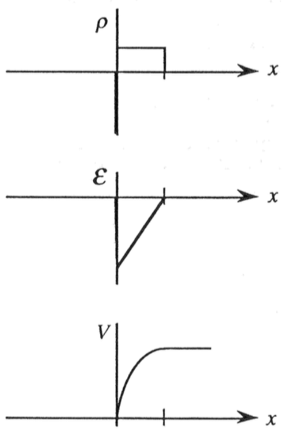
(c)

$$\mathcal{E}(0) = -\frac{qN_D}{K_S\varepsilon_0}x_n = -\frac{(1.6\times10^{-19})(10^{15})(9.62\times10^{-5})}{(11.8)(8.85\times10^{-14})} = \mathbf{-1.47\times10^{4}\ V/cm}$$

(d)

$$V(0) = \frac{qN_A}{2K_S\varepsilon_0}x_p^2 = \frac{(1.6\times10^{-19})(10^{17})(9.62\times10^{-7})^2}{(2)(11.8)(8.85\times10^{-14})} = \mathbf{7.09\times10^{-3}\ V}$$

(e)



In Problem 5.4 the widths of the *n*- and *p*-sides of the depletion region and the corresponding variation of the electrostatic variables are comparable reflecting the fact that $N_A \sim N_D$. Here with $N_A >> N_D$, we find the depletion width and potential drop lie almost exclusively on the lowly doped *n*-side of the junction.