Chapter 5

5.1

(a)

$$\rho = \frac{1}{e\mu_n N_d} = \frac{1}{(1.6\times10^{-19})(1300)(10^{15})}$$
$$= 4.808\ \Omega\text{-cm}$$

(b) $\sigma = \frac{1}{\rho} = \frac{1}{4.8077} = 0.208\ (\Omega\text{-cm})^{-1}$

5.2

$$\sigma = e\mu_p N_a$$

or $N_a = \frac{\sigma}{e\mu_p} = \frac{1.80}{(1.6\times10^{-19})(380)}$

$$= 2.96\times10^{16}\ \text{cm}^{-3}$$

5.3

(a) $\sigma = e\mu_n N_d$

$$10 = (1.6\times10^{-19})\mu_n N_d$$

From Figure 5.3, for $N_d = 6\times10^{16}$ cm $^{-3}$ we find $\mu_n \cong 1050$ cm ^{2} /V-s which gives

$$\sigma = (1.6\times10^{-19})(1050)(6\times10^{16})$$
$$= 10.08\ (\Omega\text{-cm})^{-1}$$

(b) $\rho = \frac{1}{e\mu_p N_a}$

$$0.20 = \frac{1}{(1.6\times10^{-19})\mu_p N_a}$$

From Figure 5.3, for $N_a = 10^{17}$ cm $^{-3}$ we find $\mu_p \cong 320$ cm ^{2} /V-s which gives

$$\rho = \frac{1}{(1.6\times10^{-19})(320)(10^{17})} = 0.195$$

Ω -cm

5.4

(a) $\rho = \frac{1}{e\mu_p N_a}$

$$0.35 = \frac{1}{(1.6\times10^{-19})\mu_p N_a}$$

From Figure 5.3, for $N_a = 8\times10^{16}$ cm $^{-3}$ we find $\mu_p \cong 220$ cm ^{2} /V-s which gives

$$\rho = \frac{1}{(1.6\times10^{-19})(220)(8\times10^{16})}$$
$$= 0.355\ \Omega\text{-cm}$$

(b) $\sigma = e\mu_n N_d$

$$120 = (1.6\times10^{-19})\mu_n N_d$$

From Figure 5.3, for $N_d = 2\times10^{17}$ cm $^{-3}$, then $\mu_n \cong 3800$ cm ^{2} /V-s which gives

$$\sigma = (1.6\times10^{-19})(3800)(2\times10^{17})$$
$$= 121.6\ (\Omega\text{-cm})^{-1}$$

5.5

$$R = \frac{\rho L}{A} = \frac{L}{\sigma A} = \frac{L}{(e\mu_n N_d)A}$$

or $\mu_n = \frac{L}{(eN_d)RA}$

$$= \frac{2.5}{(1.6\times10^{-19})(2\times10^{15})(70)(0.1)}$$
$$= 1116\ \text{cm}^2\text{/V-s}$$

5.6

(a) $n_o = N_d = 10^{16}$ cm $^{-3}$

and

$$p_o = \frac{n_i^2}{n_o} = \frac{(1.8\times10^6)^2}{10^{16}} = 3.24\times10^{-4}$$

cm $^{-3}$

(b)

$$J = e\mu_n n_o \mathrm{E}$$

For GaAs doped at $N_d = 10^{16}$ cm $^{-3}$,

$\mu_n \cong 7500$ cm ^{2} /V-s

Then

$$J = (1.6\times10^{-19})(7500)(10^{16})(10)$$

or

$J = 120$ A/cm ^{2}

(b) (i) $p_o = N_a = 10^{16}$ cm $^{-3}$

$$n_o = \frac{n_i^2}{p_o} = 3.24\times10^{-4} \text{ cm}^{-3}$$

(ii) For GaAs doped at $N_a = 10^{16}$ cm $^{-3}$,

$\mu_p \cong 310$ cm ^{2} /V-s

$$J = e\mu_p p_o \text{E}$$

$$= (1.6\times10^{-19})(310)(10^{16})(10)$$

or

$J = 4.96$ A/cm ^{2}

5.7

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

or

$R = 100\,\Omega$

(b)

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

or

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

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

or

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

Then

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

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

or

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

Then

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

So

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

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

5.8

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

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

$\mu_p \cong 400$ cm ^{2} /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 $I = 29.0$ 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 $I = 9.67$ mA

(c) $J = ep_o \upsilon_d$

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

Then

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

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

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

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

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

5.9

(a) For $N_d = 2\times10^{15}$ cm $^{-3}$, then

$\mu_n \cong 8000$ cm ^{2} /V-s

$$R = \frac{V}{I} = \frac{5}{25\times10^{-3}} = 200\,\Omega$$

$$R = \frac{L}{(e\mu_n N_d)A}$$

or $L = (e\mu_n N_d)RA$

$= (1.6\times10^{-19})(8000)(2\times10^{15})(200)(5\times1($

$= 0.0256$ cm

(b) $J = \dfrac{I}{A} = en_o\upsilon_d$

or $\upsilon_d = \dfrac{I}{A(en_o)}$

$$= \frac{25\times10^{-3}}{(5\times10^{-5})(1.6\times10^{-19})(2\times10^{15})}$$

$= 1.56\times10^{6}$ cm/s

(c) $I = (en_o\upsilon_d)A$

$= (1.6\times10^{-19})(2\times10^{15})(5\times10^{6})(5\times10^{-5})$

$= 0.080$ A

or $I = 80$ mA

5.10

(a) $\mathrm{E} = \dfrac{V}{L} = \dfrac{3}{1} = 3$ V/cm

$\upsilon_d = \mu_n \mathrm{E} \Rightarrow \mu_n = \dfrac{\upsilon_d}{\mathrm{E}} = \dfrac{10^4}{3}$

or

$\mu_n = 3333$ cm^2/V-s

(b)

$\upsilon_d = \mu_n \mathrm{E} = (800)(3)$

or

$\upsilon_d = 2.4\times10^{3}$ cm/s

5.11

(a) Silicon: For $\mathrm{E} = 1$ kV/cm,

$\upsilon_d = 1.2\times10^{6}$ cm/s

Then

$t_t = \dfrac{d}{\upsilon_d} = \dfrac{10^{-4}}{1.2\times10^{6}} = 8.33\times10^{-11}$ s

For GaAs: $\upsilon_d = 7.5\times10^{6}$ cm/s

Then

$t_t = \dfrac{d}{\upsilon_d} = \dfrac{10^{-4}}{7.5\times10^{6}} = 1.33\times10^{-11}$ s

(b) Silicon: For $\mathrm{E} = 50$ kV/cm,

$\upsilon_d = 9.5\times10^{6}$ cm/s

Then

$t_t = \dfrac{10^{-4}}{9.5\times10^{6}} = 1.05\times10^{-11}$ s

For GaAs: $\upsilon_d = 7\times10^{6}$ cm/s

Then

$t_t = \dfrac{10^{-4}}{7\times10^{6}} = 1.43\times10^{-11}$ s

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5.12

$$\rho = \frac{1}{e\mu_n n_o + e\mu_p p_o} = \frac{1}{e(\mu_n + \mu_p)n_i}$$

(a) $N_a = N_d = 10^{14}$ cm^{-3}

$\Rightarrow \mu_n \cong 1350$ cm^2/V-s

$\mu_p \cong 480$ cm^2/V-s

$$\rho = \frac{1}{(1.6\times10^{-19})(1350+480)(1.5\times10^{10})}$$

$= 2.28\times10^{5}\ \Omega$-cm

(b) $N_a = N_d = 10^{16}$ cm^{-3}

$\Rightarrow \mu_n \cong 1250$ cm^2/V-s

$\mu_p \cong 410$ cm^2/V-s

$$\rho = \frac{1}{(1.6\times10^{-19})(1250+410)(1.5\times10^{10})}$$

$= 2.51\times10^{5}\ \Omega$-cm

(c) $N_a = N_d = 10^{18}$ cm^{-3}

$\Rightarrow \mu_n \cong 290$ cm^2/V-s

$\mu_p \cong 130$ cm^2/V-s

$$\rho = \frac{1}{(1.6\times10^{-19})(290+130)(1.5\times10^{10})}$$

$= 9.92\times10^{5}\ \Omega$-cm

5.13

(a) GaAs:

$\sigma \cong e\mu_p p_o \Rightarrow 5 = \left(1.6\times10^{-19}\right)\mu_p p_o$

From Figure 5.3, and using trial and error, we find

$p_o \cong 1.3\times10^{17}$ cm $^{-3}$ and

$\mu_p \cong 240$ cm ^{2}/V-s

Then

$$n_o = \frac{n_i^2}{p_o} = \frac{\left(1.8\times10^6\right)^2}{1.3\times10^{17}} = 2.49\times10^{-5}$$

cm $^{-3}$

(b) Silicon:

$$\sigma = \frac{1}{\rho} \cong e\mu_n n_o$$

or

$$n_o = \frac{1}{\rho e\mu_n} = \frac{1}{(8)\left(1.6\times10^{-19}\right)(1350)}$$

which gives

$n_o = 5.79\times10^{14}$ cm $^{-3}$

and

$$p_o = \frac{n_i^2}{n_o} = \frac{\left(1.5\times10^{10}\right)^2}{5.79\times10^{14}} = 3.89\times10^5$$

cm $^{-3}$

Note: For the doping concentrations obtained in part (b), the assumed mobility values are valid.

5.14

$\sigma_i = en_i\left(\mu_n + \mu_p\right)$

Then

$10^{-6} = \left(1.6\times10^{-19}\right)(1000+600)n_i$

or

n_i (300 K) $= 3.91\times10^9$ cm $^{-3}$

Now

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

or

$$E_g = kT\ln\left(\frac{N_c N_\upsilon}{n_i^2}\right)$$

$$= (0.0259)\ln\left[\frac{\left(10^{19}\right)^2}{\left(3.91\times10^9\right)^2}\right]$$

which gives

$E_g = 1.122$ eV

Now

n_i^2 (500K)

$$= \left(10^{19}\right)^2 \exp\left[\frac{-1.122}{(0.0259)(500/300)}\right]$$

$$= 5.15\times10^{26}$$

or

n_i (500 K) $= 2.27\times10^{13}$ cm $^{-3}$

Then

$$\sigma_i = \left(1.6\times10^{-19}\right)\left(2.27\times10^{13}\right)(1000+600)$$

which gives

σ_i (500 K) $= 5.81\times10^{-3}$ (Ω-cm) $^{-1}$

5.15

(a) (i) Silicon: $\sigma_i = en_i\left(\mu_n + \mu_p\right)$

$$\sigma_i = \left(1.6\times10^{-19}\right)\left(1.5\times10^{10}\right)(1350+480)$$

or

$\sigma_i = 4.39\times10^{-6}$ (Ω-cm) $^{-1}$

(ii) Ge:

$$\sigma_i = \left(1.6\times10^{-19}\right)\left(2.4\times10^{13}\right)(3900+1900)$$

or

$\sigma_i = 2.23\times10^{-2}$ (Ω-cm) $^{-1}$

(iii) GaAs:

$$\sigma_i = \left(1.6\times10^{-19}\right)\left(1.8\times10^6\right)(8500+400)$$

or

$\sigma_i = 2.56\times10^{-9}$ (Ω-cm) $^{-1}$

(b) $R = \dfrac{L}{\sigma A}$

(i) Si:

$$R = \frac{200\times10^{-4}}{\left(4.39\times10^{-6}\right)\left(85\times10^{-8}\right)} = 5.36\times10^9\ \Omega$$

(ii) Ge:

$$R = \frac{200\times10^{-4}}{(2.23\times10^{-2})(85\times10^{-8})} = 1.06\times10^{6}\ \Omega$$

(iii) GaAs:

$$R = \frac{200\times10^{-4}}{(2.56\times10^{-9})(85\times10^{-8})} = 9.19\times10^{12}\ \Omega$$

5.16

(a) $\sigma = e\mu_n N_d$

$$0.25 = (1.6\times10^{-19})\mu_n N_d$$

From Figure 5.3, for $N_d = 1.2\times10^{15}$ cm $^{-3}$, then $\mu_n \cong 1300$ cm ^{2} /V-s

So

$$\sigma = (1.6\times10^{-19})(1300)(1.2\times10^{15})$$
$$= 0.2496\ (\Omega\text{-cm})^{-1}$$

(b) Using Figure 5.2,

(i) For $T = 250$ K ($-23°$ C),

$$\Rightarrow \mu_n \cong 1800 \text{ cm}^2\text{/V-s}$$

$$\sigma = (1.6\times10^{-19})(1800)(1.2\times10^{15})$$
$$= 0.346\ (\Omega\text{-cm})^{-1}$$

(ii) For $T = 400$ K ($127°$ C),

$$\Rightarrow \mu_n \cong 670 \text{ cm}^2\text{/V-s}$$

$$\sigma = (1.6\times10^{-19})(670)(1.2\times10^{15})$$
$$= 0.129\ (\Omega\text{-cm})^{-1}$$

5.17

$$\sigma_{avg} = \frac{1}{t}\int_0^t \sigma(x)dx$$

$$= \frac{1}{t}\int_0^t \sigma_o \exp\left(\frac{-x}{d}\right)dx$$

$$= \frac{\sigma_o}{t}(-d)\exp\left(\frac{-x}{d}\right)\Bigg|_0^t$$

$$= \frac{-\sigma_o d}{t}\left[\exp\left(\frac{-t}{d}\right)-1\right]$$

$$= \frac{(20)(0.3)}{(1.5)}\left[1-\exp\left(\frac{-1.5}{0.3}\right)\right]$$

$$= 3.97\ (\Omega\text{-cm})^{-1}$$

5.18

(a) $\text{E} = \dfrac{V}{L} = \dfrac{2}{150\times10^{-4}} = 133.3$ V/cm

(b) $\sigma(x) = e\mu_n N_d(x)$

$$\sigma_{avg} = e\mu_n \cdot \frac{1}{T}\int_0^T (2\times10^{16})\left(1-\frac{x}{1.111T}\right)dx$$

$$= \frac{e\mu_n(2\times10^{16})}{T}\left[x-\frac{x^2}{2(1.111T)}\right]\Bigg|_0^T$$

$$= \frac{e\mu_n(2\times10^{16})}{T}\left[T-\frac{T^2}{2(1.111T)}\right]$$

$$= e\mu_n(2\times10^{16})(0.55)$$

$$= (1.6\times10^{-19})(750)(2\times10^{16})(0.55)$$

$$\sigma_{avg} = 1.32\ (\Omega\text{-cm})^{-1}$$

(c)

$$I = \frac{\sigma_{avg}A}{L}\cdot V = \frac{(1.32)(7.5\times10^{-4})(10^{-4})}{150\times10^{-4}}\cdot 2$$

$$= 1.32\times10^{-5}\text{ A}$$

or $I = 13.2\ \mu$ A

(d) Top surface;

$$\sigma = (1.6\times10^{-19})(750)(2\times10^{16})$$
$$= 2.4\ (\Omega\text{-cm})^{-1}$$
$$J = \sigma\text{E} = (2.4)(133.3) = 320 \text{ A/cm}^2$$

Bottom surface:

$$\sigma = (1.6\times10^{-19})(750)(2\times10^{15})$$
$$= 0.24\ (\Omega\text{-cm})^{-1}$$
$$J = \sigma\text{E} = (0.24)(133.3 = 32) \text{ A/cm}^2$$

5.19

Plot

5.20

(a) $\text{E} = 10$ V/cm

so

$$\upsilon_d = \mu_n \text{E} = (1350)(10) = 1.35\times10^4$$
cm/s

or

$$\upsilon_d = 1.35\times10^2 \text{ m/s}$$

Then

$$T = \frac{1}{2} m_n^* \upsilon_d^2$$

$$= \frac{1}{2}(1.08)(9.11\times10^{-31})(1.35\times10^2)^2$$

or

$$T = 8.97\times10^{-27} \text{ J} \Rightarrow 5.60\times10^{-8} \text{ eV}$$

(b) $\text{E} = 1$ kV/cm

$$\upsilon_d = (1350)(1000) = 1.35\times10^6 \text{ cm/s}$$

or

$$\upsilon_d = 1.35\times10^4 \text{ m/s}$$

Then

$$T = \frac{1}{2}(1.08)(9.11\times10^{-31})(1.35\times10^4)^2$$

or

$$T = 8.97\times10^{-23} \text{ J} \Rightarrow 5.60\times10^{-4} \text{ eV}$$

5.21

(a) $n_i^2 = N_c N_\upsilon \exp\left(\frac{-E_g}{kT}\right)$

$$= (2\times10^{19})(1\times10^{19})\exp\left(\frac{-1.10}{0.0259}\right)$$

$$= 7.18\times10^{19}$$

or

$$n_i = 8.47\times10^9 \text{ cm}^{-3}$$

For $N_d = 10^{14}$ cm^{-3} $>> n_i \Rightarrow n_o = 10^{14}$ cm^{-3}

Then

$$J = \sigma\text{E} = e\mu_n n_o \text{E}$$

$$= (1.6\times10^{-19})(1000)(10^{14})(100)$$

or

$$J = 1.60 \text{ A/cm}^2$$

(b) A 5% increase is due to a 5% increase in electron concentration, so

$$n_o = 1.05\times10^{14} = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_i^2}$$

which becomes

$$(1.05\times10^{14} - 5\times10^{13})^2 = (5\times10^{13})^2 + n_i^2$$

and yields

$$n_i^2 = 5.25\times10^{26}$$

$$= (2\times10^{19})(1\times10^{19})\left(\frac{T}{300}\right)^3 \exp\left(\frac{-E_g}{kT}\right)$$

or

$$2.625\times10^{-12} = \left(\frac{T}{300}\right)^3 \exp\left[\frac{-1.10}{(0.0259)(T/300)}\right]$$

By trial and error, we find

$$T = 456 \text{ K}$$

5.22

(a) $\sigma = e\mu_n n_o + e\mu_p p_o$ and $n_o = \frac{n_i^2}{p_o}$

Then

$$\sigma = \frac{e\mu_n n_i^2}{p_o} + e\mu_p p_o$$

To find the minimum conductivity, set

$$\frac{d\sigma}{dp_o} = 0 = \frac{(-1)e\mu_n n_i^2}{p_o^2} + e\mu_p$$

which yields

$$p_o = n_i\left(\frac{\mu_n}{\mu_p}\right)^{1/2} \quad \text{(Answer to part (b))}$$

Substituting into the conductivity expression

$$\sigma = \sigma_{\min} = \frac{e\mu_n n_i^2}{\left[n_i(\mu_n/\mu_p)^{1/2}\right]} + e\mu_p\left[n_i(\mu_n/\mu_p)^{1/2}\right]$$

which simplifies to

$$\sigma_{\min} = 2en_i\sqrt{\mu_n\mu_p}$$

The intrinsic conductivity is defined as

$$\sigma_i = en_i(\mu_n + \mu_p) \Rightarrow en_i = \frac{\sigma_i}{\mu_n + \mu_p}$$

The minimum conductivity can then be written as

$$\sigma_{\min} = \frac{2\sigma_i\sqrt{\mu_n\mu_p}}{\mu_n + \mu_p}$$

5.23

(a) n-type: $n_o = N_d = 5\times10^{16}$ cm $^{-3}$

$$p_o = \frac{n_i^2}{n_o} = \frac{\left(1.5\times10^{10}\right)^2}{5\times10^{16}}$$

$= 4.5\times10^3$ cm $^{-3}$

p-type: $p_o = N_a = 2\times10^{16}$ cm $^{-3}$

$$n_o = \frac{\left(1.5\times10^{10}\right)^2}{2\times10^{16}} = 1.125\times10^4 \text{ cm}^{-3}$$

compensated: $n_o = N_d - N_a$

$= 5\times10^{16} - 2\times10^{16}$

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

$$p_o = \frac{\left(1.5\times10^{10}\right)^2}{3\times10^{16}} = 7.5\times10^3$$

cm $^{-3}$

(b) From Figure 5.3,

n-type: $\mu_n \cong 1100$ cm ^{2} /V-s

p-type: $\mu_p \cong 400$ cm ^{2} /V-s

compensated: $\mu_n \cong 1000$ cm ^{2} /V-s

(c) n-type: $\sigma = e\mu_n n_o$

$= \left(1.6\times10^{-19}\right)(1100)\left(5\times10^{16}\right)$

$= 8.8$ (Ω -cm) $^{-1}$

p-type: $\sigma = e\mu_p p_o$

$= \left(1.6\times10^{-19}\right)(400)\left(2\times10^{16}\right)$

$= 1.28$ (Ω -cm) $^{-1}$

compensated: $\sigma = e\mu_n n_o$

$= \left(1.6\times10^{-19}\right)(1000)\left(3\times10^{16}\right)$

$= 4.8$ (Ω -cm) $^{-1}$

(d) $J = \sigma \mathrm{E} \Rightarrow \mathrm{E} = \dfrac{J}{\sigma}$

n-type: $\mathrm{E} = \dfrac{120}{8.8} = 13.6$ V/cm

p-type: $\mathrm{E} = \dfrac{120}{1.28} = 93.75$ V/cm

compensated: $\mathrm{E} = \dfrac{120}{4.8} = 25$ V/cm

5.24

$$\frac{1}{\mu} = \frac{1}{\mu_1} + \frac{1}{\mu_2} + \frac{1}{\mu_3}$$

$$= \frac{1}{2000} + \frac{1}{1500} + \frac{1}{500}$$

$= 0.00050 + 0.000667 + 0.0020$

or

$$\frac{1}{\mu} = 0.003167$$

Then

$\mu = 316$ cm ^{2} /V-s

5.25

$$\mu_n = (1300)\left(\frac{T}{300}\right)^{-3/2} = (1300)\left(\frac{300}{T}\right)^{+3/2}$$

(a) At $T = 200$ K,

$$\mu_n = (1300)\left(\frac{300}{200}\right)^{3/2} = 2388 \text{ cm}^2\text{/V-s}$$

(b) At $T = 400$ K, $\mu_n = 844$ cm ^{2} /V-s

5.26

$$\frac{1}{\mu} = \frac{1}{\mu_1} + \frac{1}{\mu_2} = \frac{1}{250} + \frac{1}{500} = 0.006$$

Then

$\mu = 167$ cm ^{2} /V-s

5.27

Plot

5.28

Plot

5.29

$$J_n = eD_n \frac{dn}{dx} = eD_n \left(\frac{5\times10^{14} - n(0)}{0.01 - 0} \right)$$

$$0.19 = (1.6\times10^{-19})(25)\left(\frac{5\times10^{14} - n(0)}{0.010} \right)$$

Then

$$\frac{(0.19)(0.010)}{(1.6\times10^{-19})(25)} = 5\times10^{14} - n(0)$$

which yields

$$n(0) = 0.25\times10^{14} \text{ cm}^{-3}$$

5.30

$$J_n = eD_n \frac{dn}{dx} = eD_n \frac{\Delta n}{\Delta x}$$

$$J_n = (1.6\times10^{-19})(27)\left[\frac{2\times10^{16} - 5\times10^{15}}{0 - 0.012} \right]$$

$$J_n = -5.4 \text{ A/cm}^2$$

5.31

(a) $J_n = eD_n \frac{dn}{dx} = eD_n \frac{\Delta n}{\Delta x}$

$$-2 = (1.6\times10^{-19})(30)\left[\frac{10^{15} - n(x_1)}{0 - 20\times10^{-4}} \right]$$

$$4\times10^{-3} = 4.8\times10^{-3} - 4.8\times10^{-18}\, n(x_1)$$

which yields

$$n(x_1) = 1.67\times10^{14} \text{ cm}^{-3}$$

(b)

$$-2 = (1.6\times10^{-19})(230)\left[\frac{10^{15} - n(x_1)}{0 - 20\times10^{-4}} \right]$$

$$4\times10^{-3} = 3.68\times10^{-2} - 3.68\times10^{-17}\, n(x_1)$$

$$n(x_1) = 8.91\times10^{14} \text{ cm}^{-3}$$

5.32

$$J_p = -eD_p \frac{dp}{dx} = -eD_p \frac{d}{dx}\left[10^{16}\left(1 + \frac{x}{L}\right)^2 \right]$$

$$= -eD_p \cdot \frac{10^{16}}{L} \cdot 2\left(1 + \frac{x}{L}\right)$$

(a) For $x = 0$,

$$J_p = \frac{-(1.6\times10^{-19})(10)(10^{16})(2)}{12\times10^{-4}}$$

$$= -26.7 \text{ A/cm}^2$$

(b) For $x = -6\ \mu$m,

$$J_p = \frac{-(1.6\times10^{-19})(10)(10^{16})(2)\left(1 - \frac{6}{12}\right)}{12\times10^{-4}}$$

$$= -13.3 \text{ A/cm}^2$$

(c) For $x = -12\ \mu$m,

$$J_p = 0$$

5.33

For electrons:

$$J_n = eD_n \frac{dn}{dx} = eD_n \frac{d}{dx}\left[10^{15} e^{-x/L_n}\right]$$

$$= \frac{-eD_n(10^{15})e^{-x/L_n}}{L_n}$$

At $x = 0$,

$$J_n = \frac{-(1.6\times10^{-19})(25)(10^{15})}{2\times10^{-3}} = -2$$

A/cm²

For holes:

$$J_p = -eD_p \frac{dp}{dx} = -eD_p \frac{d}{dx}\left[5\times10^{15} e^{+x/L_p}\right]$$

$$= \frac{-eD_p(5\times10^{15})e^{+x/L_p}}{L_p}$$

For $x = 0$,

$$J_p = \frac{-(1.6\times10^{-19})(10)(5\times10^{15})}{5\times10^{-4}}$$

$$= -16 \text{ A/cm}^2$$

$$J_{Total} = J_n(x=0) + J_p(x=0)$$

$$= -2 + (-16) = -18 \text{ A/cm}^2$$

5.34

$$J_p = -eD_p \frac{dp}{dx} = -eD_p \frac{d}{dx}\left[5\times10^{15} e^{-x/L_p}\right]$$

$$= \frac{eD_p\left(5\times10^{15}\right)e^{-x/L_p}}{L_p}$$

(a) (i)

$$J_p = \frac{\left(1.6\times10^{-19}\right)(10)\left(5\times10^{15}\right)}{50\times10^{-4}}$$
$$= 1.6 \text{ A/cm}^2$$

(ii)

$$J_p = \frac{\left(1.6\times10^{-19}\right)(48)\left(5\times10^{15}\right)}{22.5\times10^{-4}}$$
$$= 17.07 \text{ A/cm}^2$$

(b) (i)

$$J_p = \frac{\left(1.6\times10^{-19}\right)(10)\left(5\times10^{15}\right)e^{-1}}{50\times10^{-4}}$$
$$= 0.589 \text{ A/cm}^2$$

(ii)

$$J_p = \frac{\left(1.6\times10^{-19}\right)(48)\left(5\times10^{15}\right)e^{-1}}{22.5\times10^{-4}}$$
$$= 6.28 \text{ A/cm}^2$$

5.35

$$J_n = e\mu_n n\mathrm{E} + eD_n \frac{dn}{dx}$$

or

$$-40 = \left(1.6\times10^{-19}\right)(960)\left[10^{16}\exp\left(\frac{-x}{18}\right)\right]\mathrm{E} + \left(1.6\times10^{-19}\right)(25)\left(10^{16}\right)$$

$$\times\left(\frac{-1}{18\times10^{-4}}\right)\exp\left(\frac{-x}{18}\right)$$

Then

$$-40 = (1.536)\left[\exp\left(\frac{-x}{18}\right)\right]\mathrm{E} - 22.22\exp\left(\frac{-x}{18}\right)$$

We find

$$\mathrm{E} = \frac{(22.22)\exp\left(\frac{-x}{18}\right) - 40}{(1.536)\exp\left(\frac{-x}{18}\right)}$$

or

$$\mathrm{E} = 14.5 - (26.0)\exp\left(\frac{+x}{18}\right)$$

5.36

(a)

$$J_n = eD_n \frac{dn}{dx} = eD_n \frac{d}{dx}\left[2\times10^{15} e^{-x/L}\right]$$
$$= \frac{-eD_n\left(2\times10^{15}\right)e^{-x/L}}{L}$$

$$= \frac{-\left(1.6\times10^{-19}\right)(27)\left(2\times10^{15}\right)e^{-x/L}}{15\times10^{-4}}$$
$$= -5.76e^{-x/L}$$

(b)

$$J_p = J_{Total} - J_n = -10 - \left(-5.76e^{-x/L}\right)$$
$$= \left[5.76e^{-x/L} - 10\right] \text{ A/cm}^2$$

(c) We have $J_p = \sigma\mathrm{E} = \left(e\mu_p p_o\right)\mathrm{E}$

$$5.76e^{-x/L} - 10 = \left(1.6\times10^{-19}\right)(420)\left(10^{16}\right)\mathrm{E}$$

So $\mathrm{E} = \left[8.57e^{-x/L} - 14.88\right]$ V/cm

5.37

(a) $J = e\mu_n n(x)\mathrm{E} + eD_n \dfrac{dn(x)}{dx}$

We have $\mu_n = 8000 \text{ cm}^2$/V-s, so that

$$D_n = (0.0259)(8000) = 207 \text{ cm}^2\text{/s}$$

Then

$$100 = \left(1.6\times10^{-19}\right)(8000)(12)n(x) + \left(1.6\times10^{-19}\right)(207)\frac{dn(x)}{dx}$$

which yields

$$100 = \left(1.536\times10^{-14}\right)n(x) + \left(3.312\times10^{-17}\right)\frac{dn(x)}{dx}$$

Solution is of the form

$$n(x) = A + B\exp\left(\frac{-x}{d}\right)$$

so that

$$\frac{dn(x)}{dx} = \frac{-B}{d}\exp\left(\frac{-x}{d}\right)$$

Substituting into the differential equation, we have

$$100 = \left(1.536\times10^{-14}\right)\left[A + B\exp\left(\frac{-x}{d}\right)\right]$$

$$-\frac{\left(3.312\times10^{-17}\right)}{d}B\exp\left(\frac{-x}{d}\right)$$

This equation is valid for all *x*, so

$$100 = \left(1.536\times10^{-14}\right)A$$

or

$$A = 6.51\times10^{15}$$

Also

$$1.536\times10^{-14}B\exp\left(\frac{-x}{d}\right)$$

$$-\frac{\left(3.312\times10^{-17}\right)}{d}B\exp\left(\frac{-x}{d}\right) = 0$$

which yields

$$d = 2.156\times10^{-3} \text{ cm}$$

At $x = 0$, $e\mu_n n(0)\mathrm{E} = 50$

so that

$$50 = \left(1.6\times10^{-19}\right)(8000)(12)(A + B)$$

which yields

$$B = -3.255\times10^{15}$$

Then

$$n(x) = 6.51\times10^{15} - 3.255\times10^{15}\exp\left(\frac{-x}{d}\right)$$

cm $^{-3}$

(b)

At $x = 0$,

$$n(0) = 6.51\times10^{15} - 3.255\times10^{15}$$

Or

$$n(0) = 3.26\times10^{15} \text{ cm}^{-3}$$

At $x = 50\,\mu$m,

$$n(50) = 6.51\times10^{15} - 3.255\times10^{15}\exp\left(\frac{-50}{21.56}\right)$$

or

$$n(50) = 6.19\times10^{15} \text{ cm}^{-3}$$

(c)

At $x = 50\,\mu$m,

$$J_{drf} = e\mu_n n(50)\mathrm{E}$$

$$= \left(1.6\times10^{-19}\right)(8000)\left(6.19\times10^{15}\right)(12)$$

or

$$J_{drf}(x = 50) = 95.08 \text{ A/cm}^2$$

Then

$$J_{diff}(x = 50) = 100 - 95.08$$

or

$$J_{diff}(x = 50) = 4.92 \text{ A/cm}^2$$

5.38

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

(a) $E_F - E_{Fi} = ax + b$, $b = 0.4$

$$0.15 = a\left(10^{-3}\right) + 0.4$$

which yields

$$a = -2.5\times10^2$$

Then

$$E_F - E_{Fi} = 0.4 - 2.5\times10^2 x$$

so

$$n = n_i\exp\left(\frac{0.4 - 2.5\times10^2 x}{kT}\right)$$

(b) $J_n = eD_n\dfrac{dn}{dx}$

$$= eD_n n_i\left(\frac{-2.5\times10^2}{kT}\right)\exp\left(\frac{0.4 - 2.5\times10^2 x}{kT}\right)$$

Assume $T = 300$ K, so $kT = 0.0259$ eV

and

$$n_i = 1.5\times10^{10} \text{ cm}^{-3}$$

Then

$$J_n = \frac{-\left(1.6\times10^{-19}\right)(25)\left(1.5\times10^{10}\right)\left(2.5\times10^2\right)}{(0.0259)}$$

$$\times\exp\left(\frac{0.4 - 2.5\times10^2 x}{0.0259}\right)$$

or

$$J_n = -5.79\times10^{-4}\ \exp\left(\frac{0.4-2.5\times10^2 x}{0.0259}\right)$$

(i) At $x=0$, $J_n = -2.95\times10^3$ A/cm ^{2}

(ii) At $x = 5\,\mu$m, $J_n = -23.7$ A/cm ^{2}

5.39

(a) $J_n = e\mu_n n\mathrm{E} + eD_n \dfrac{dn}{dx}$

$$-80 = \left(1.6\times10^{-19}\right)(1000)\left(10^{16}\right)\left(1-\frac{x}{L}\right)\mathrm{E}$$

$$+\left(1.6\times10^{-19}\right)(25.9)\left(\frac{-10^{16}}{L}\right)$$

where $L = 10\times10^{-4} = 10^{-3}$ cm

We find

$$-80 = (1.6)\mathrm{E} - (1.6)\left(\frac{x}{10^{-3}}\right)\mathrm{E} - 41.44$$

or

$$80 = (1.6)\left(\frac{x}{L}-1\right)\mathrm{E} + 41.44$$

Solving for the electric field, we find

$$\mathrm{E} = \frac{24.1}{\left(\dfrac{x}{L}-1\right)} \text{ V/cm}$$

(b) For $J_n = -20$ A/cm ^{2}

$$20 = (1.6)\left(\frac{x}{L}-1\right)\mathrm{E} + 41.44$$

Then

$$\mathrm{E} = \frac{13.3}{\left(1-\dfrac{x}{L}\right)} \text{ V/cm}$$

5.40

(a) $\mathrm{E}_X = -\left(\dfrac{kT}{e}\right)\cdot\dfrac{1}{N_d(x)}\cdot\dfrac{dN_d(x)}{dx}$

$$= \frac{-(0.0259)}{N_{do}e^{-x/L}}\cdot\frac{d}{dx}\left[N_{do}e^{-x/L}\right]$$

$$= \frac{-(0.0259)}{N_{do}e^{-x/L}}\cdot\left(\frac{-1}{L}\right)N_{do}e^{-x/L}$$

$$= \frac{0.0259}{L} = \frac{0.0259}{10\times10^{-4}}$$

or $\mathrm{E}_X = 25.9$ V/cm

(b) $\phi = -\int_0^L \mathrm{E}_X\,dx = -(25.9)(L-0)$

$$= -(25.9)\left(10\times10^{-4}\right) = -0.0259 \text{ V}$$

or $\phi = -25.9$ mV

5.41

From Example 5.6

$$\mathrm{E}_x = \frac{(0.0259)\left(10^{19}\right)}{\left(10^{16}-10^{19}x\right)} = \frac{(0.0259)\left(10^3\right)}{\left(1-10^3 x\right)}$$

$$V = -\int_0^{10^{-4}} \mathrm{E}_x\,dx$$

$$= -(0.0259)\left(10^3\right)\int_0^{10^{-4}} \frac{dx}{\left(1-10^3 x\right)}$$

$$= -(0.0259)\left(10^3\right)\left(\frac{-1}{10^3}\right)\ln\left[1-10^3 x\right]\Big|_0^{10^{-4}}$$

$$= (0.0259)\left[\ln(1-0.1) - \ln(1)\right]$$

or

$V = -2.73$ mV

5.42

$$\mathrm{E}_x = -\left(\frac{kT}{e}\right)\cdot\frac{1}{N_d(x)}\cdot\frac{dN_d(x)}{dx}$$

For $N_d(x) = N_{do}e^{-x/L}$

So $\mathrm{E}_X = \dfrac{0.0259}{L} = 500$ V/cm

Which yields $L = 5.18\times10^{-5}$ cm

5.43

(a) We have

$$J_{diff} = eD_n \frac{dn}{dx} = eD_n \frac{dN_d(x)}{dx}$$

$$= \frac{eD_n}{(-L)} \cdot N_{do} \exp\left(\frac{-x}{L}\right)$$

We have

$$D_n = \mu_n\left(\frac{kT}{e}\right) = (6000)(0.0259)$$

or

$D_n = 155.4$ cm^2/s

Then

$$J_{diff} = \frac{-(1.6\times10^{-19})(155.4)(5\times10^{16})}{(0.1\times10^{-4})} \exp\left(\frac{-x}{L}\right)$$

or

$$J_{diff} = -1.243\times10^5 \exp\left(\frac{-x}{L}\right) \text{ A/cm}^2$$

(b)

$0 = J_{drf} + J_{diff}$

Now

$J_{drf} = e\mu_n n \mathrm{E}$

$$= (1.6\times10^{-19})(6000)(5\times10^{16})\left[\exp\left(\frac{-x}{L}\right)\right]\mathrm{E}$$

or

$$J_{drf} = (48)\left[\exp\left(\frac{-x}{L}\right)\right]\mathrm{E}$$

We have

$J_{drf} = -J_{diff}$

so

$$(48)\left[\exp\left(\frac{-x}{L}\right)\right]\mathrm{E} = 1.243\times10^5 \exp\left(\frac{-x}{L}\right)$$

which yields

$\mathrm{E} = 2.59\times10^3$ V/cm

5.44

Plot

5.45

(a) (i) $D_n = (0.0259)(1150) = 29.8$ cm^2/s

(ii) $D_n = (0.0259)(6200) = 160.6$ cm^2/s

(b) (i) $\mu_p = \dfrac{8}{0.0259} = 308.9$ cm^2/V-s

(ii) $\mu_p = \dfrac{35}{0.0259} = 1351$ cm^2/V-s

5.46

$L = 10^{-1}$ cm, $W = 10^{-2}$ cm, $d = 10^{-3}$ cm

(a)

$$V_H = \frac{-I_X B_Z}{ned} = \frac{-(1.2\times10^{-3})(5\times10^{-2})}{(2\times10^{22})(1.6\times10^{-19})(10^{-5})}$$

$= -1.875\times10^{-3}$ V

or $V_H = -1.875$ mV

(b)

$$\mathrm{E}_H = \frac{V_H}{W} = \frac{-1.875\times10^{-3}}{10^{-2}} = -0.1875 \text{ V/cm}$$

5.47

(a) $V_H = \dfrac{-I_x B_z}{ned}$

$$= \frac{-(250\times10^{-6})(5\times10^{-2})}{(5\times10^{21})(1.6\times10^{-19})(5\times10^{-5})}$$

or

$V_H = -0.3125$ mV

(b)

$$\mathrm{E}_H = \frac{V_H}{W} = \frac{-0.3125\times10^{-3}}{2\times10^{-2}}$$

or

$\mathrm{E}_H = -1.56\times10^{-2}$ V/cm

(c)

$$\mu_n = \frac{I_x L}{enV_x Wd}$$

$$= \frac{(250\times10^{-6})(10^{-3})}{(1.6\times10^{-19})(5\times10^{21})(0.1)(2\times10^{-4})(5\times10^{-5})}$$

---

or
$\mu_n = 0.3125$ m^2/V-s $= 3125$ cm^2/V-s

5.48

(a) $V_H < 0 \Rightarrow$ n-type

(b)
$$n = \frac{-I_X B_Z}{edV_H} = \frac{-\left(0.50\times10^{-3}\right)(0.10)}{\left(1.6\times10^{-19}\right)\left(10^{-5}\right)\left(-5.2\times1\right.}$$
$= 6.01\times10^{21}$ m^{-3}
or $n = 6.01\times10^{15}$ cm^{-3}

(c) $\mu_n = \dfrac{I_X L}{enV_X Wd}$

$$= \frac{\left(0.5\times10^{-3}\right)\left(10^{-3}\right)}{\left(1.6\times10^{-19}\right)\left(6.01\times10^{21}\right)(15)\left(10^{-4}\right)\left(10^{-}\right.}$$
$= 0.03466$ m^2/V-s
or $\mu_n = 346.6$ cm^2/V-s

5.49

(a)
$V_H = \mathrm{E}_H W = -\left(16.5\times10^{-3}\right)\left(5\times10^{-2}\right)$
or
$V_H = -0.825$ mV

(b) V_H = negative $\Rightarrow$ n-type

(c) $n = \dfrac{-I_x B_z}{edV_H}$

$$= \frac{-\left(0.5\times10^{-3}\right)\left(6.5\times10^{-2}\right)}{\left(1.6\times10^{-19}\right)\left(5\times10^{-5}\right)\left(-0.825\times10^{-3}\right)}$$
or
$n = 4.924\times10^{21}$ m^{-3}
$= 4.924\times10^{15}$ cm^{-3}

(d)
$$\mu_n = \frac{I_x L}{enV_x Wd}$$
$$= \frac{\left(0.5\times10^{-3}\right)\left(0.5\times10^{-2}\right)}{\left(1.6\times10^{-19}\right)\left(4.924\times10^{21}\right)(1.25)\left(5\times10^{-4}\right.}$$
or

$\mu_n = 0.1015$ m^2/V-s $= 1015$ cm^2/V-s

5.50

(a) V_H = negative $\Rightarrow$ n-type

(b) $n = \dfrac{-I_x B_z}{edV_H}$

$$= \frac{-\left(2.5\times10^{-3}\right)\left(2.5\times10^{-2}\right)}{\left(1.6\times10^{-19}\right)\left(0.01\times10^{-2}\right)\left(-4.5\times10^{-3}\right)}$$
or
$n = 8.68\times10^{20}$ m^{-3} $= 8.68\times10^{14}$ cm^{-3}

(c) $\mu_n = \dfrac{I_x L}{enV_x Wd}$

$$= \left[\frac{\left(2.5\times10^{-3}\right)\left(0.5\times10^{-2}\right)}{\left(1.6\times10^{-19}\right)\left(8.68\times10^{20}\right)(2.2)}\right]$$
$$\times\left[\frac{1}{\left(0.05\times10^{-2}\right)\left(0.01\times10^{-2}\right)}\right]$$
or
$\mu_n = 0.8182$ m^2/V-s $= 8182$ cm^2/V-s

(d) $\sigma = \dfrac{1}{\rho} = e\mu_n n$

$= \left(1.6\times10^{-19}\right)(8182)\left(8.68\times10^{14}\right)$
or
$\rho = 0.88$ (Ω-cm)
