Chapter 5

Problem Solutions

5.1

(a) $\underline{n_O = 10^{16}\ cm^{-3}}$

and

$$p_O = \frac{n_i^2}{n_O} = \frac{\left(1.8x10^6\right)^2}{10^{16}} \Rightarrow$$

$$\underline{p_O = 3.24x10^{-4}\ cm^{-3}}$$

(b)

$J = e\mu_n n_O \text{E}$

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

$\mu_n \approx 7500\ cm^2 / V-s$

Then

$J = \left(1.6x10^{-19}\right)(7500)\left(10^{16}\right)(10)$

or

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

(b) (i) $\underline{p_O = 10^{16}\ cm^{-3}}$, $\underline{n_O = 3.24x10^{-4}\ cm^{-3}}$

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

$\mu_p \approx 310\ cm^2 / V-s$

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

$= \left(1.6x10^{-19}\right)(310)\left(10^{16}\right)(10) \Rightarrow$

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

5.2

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

$$\underline{R = 100\ \Omega}$$

(b)

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

$$\sigma = \frac{10^{-3}}{(100)\left(10^{-3}\right)} \Rightarrow$$

$$\underline{\sigma = 0.01\ (\Omega - cm)^{-1}}$$

(c)

$\sigma \approx e\mu_n N_d$

or

$0.01 = \left(1.6x10^{-19}\right)(1350)N_d$

or

$$\underline{N_d = 4.63x10^{13}\ cm^{-3}}$$

(d)

$\sigma \approx e\mu_p p_O \Rightarrow$

$0.01 = \left(1.6x10^{-19}\right)(480)p_O$

or

$p_O = 1.30x10^{14}\ cm^{-3} = N_a - N_d = N_a - 10^{15}$

or

$$\underline{N_a = 1.13x10^{15}\ cm^{-3}}$$

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

5.3

(a) $R = \dfrac{\rho L}{A} = \dfrac{L}{\sigma A}$ and $\sigma \approx e\mu_n N_d$

For $N_d = 5x10^{16}\ cm^{-3}$, $\mu_n \approx 1100\ cm^2 / V-s$

Then

$$R = \frac{0.1}{\left(1.6x10^{-19}\right)(1100)\left(5x10^{16}\right)(100)\left(10^{-4}\right)^2}$$

or

$$\underline{R = 1.136x10^4\ \Omega}$$

Then

$$I = \frac{V}{R} = \frac{5}{1.136x10^4} \Rightarrow \underline{I = 0.44\ mA}$$

(b)

In this case

$$\underline{R = 1.136x10^3\ \Omega}$$

Then

$$I = \frac{V}{R} = \frac{5}{1.136x10^3} \Rightarrow \underline{I = 4.4\ mA}$$

(c)

$$\text{E} = \frac{V}{L}$$

For (a), $\text{E} = \dfrac{5}{0.10} = 50\ V / cm$

And

$v_d = \mu_n \text{E} = (1100)(50)$ or $\underline{v_d = 5.5x10^4\ cm / s}$

For (b), $\text{E} = \dfrac{V}{L} = \dfrac{5}{0.01} = 500\ V / cm$

And

$v_d = (1100)(500) \Rightarrow \underline{v_d = 5.5x10^5\ cm / s}$

5.4
(a) GaAs:

$$R = \frac{\rho L}{A} = \frac{V}{I} = \frac{10}{20} = 0.5\ k\Omega = \frac{L}{\sigma A}$$

Now

$$\sigma \approx e\mu_p N_a$$

For $N_a = 10^{17}\ cm^{-3}$, $\mu_p \approx 210\ cm^2/V-s$
Then

$$\sigma = \left(1.6x10^{-19}\right)(210)\left(10^{17}\right) = 3.36\ (\Omega - cm)^{-1}$$

So

$$L = R\sigma A = (500)(3.36)\left(85x10^{-8}\right)$$

or

$$\underline{L = 14.3\ \mu m}$$

(b) Silicon
For $N_a = 10^{17}\ cm^{-3}$, $\mu_p \approx 310\ cm^2/V-s$
Then

$$\sigma = \left(1.6x10^{-19}\right)(310)\left(10^{17}\right) = 4.96\ (\Omega - cm)^{-1}$$

So

$$L = R\sigma A = (500)(4.96)\left(85x10^{-8}\right)$$

or

$$\underline{L = 21.1\ \mu m}$$

5.5
(a) $\mathrm{E} = \frac{V}{L} = \frac{3}{1} = 3\ V/cm$

$$v_d = \mu_n \mathrm{E} \Rightarrow \mu_n = \frac{v_d}{\mathrm{E}} = \frac{10^4}{3}$$

or

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

(b)

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

or

$$\underline{v_d = 2.4x10^3\ cm/s}$$

5.6
(a) Silicon: For $\mathrm{E} = 1\ kV/cm$,

$$v_d = 1.2x10^6\ cm/s$$

Then

$$t_t = \frac{d}{v_d} = \frac{10^{-4}}{1.2x10^6} \Rightarrow \underline{t_t = 8.33x10^{-11}\ s}$$

For GaAs, $v_d = 7.5x10^6\ cm/s$
Then

$$t_t = \frac{d}{v_d} = \frac{10^{-4}}{7.5x10^6} \Rightarrow \underline{t_t = 1.33x10^{-11}\ s}$$

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

$$v_d = 9.5x10^6\ cm/s$$

Then

$$t_t = \frac{d}{v_d} = \frac{10^{-4}}{9.5x10^6} \Rightarrow \underline{t_t = 1.05x10^{-11}\ s}$$

GaAs, $v_d = 7x10^6\ cm/s$
Then

$$t_t = \frac{d}{v_d} = \frac{10^{-4}}{7x10^6} \Rightarrow \underline{t_t = 1.43x10^{-11}\ s}$$

5.7
For an intrinsic semiconductor,

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

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

$$\mu_n = 1350\ cm^2/V-s,\ \mu_p = 480\ cm^2/V-s$$

Then

$$\sigma_i = \left(1.6x10^{-19}\right)\left(1.5x10^{10}\right)(1350 + 480)$$

or

$$\underline{\sigma_i = 4.39x10^{-6}\ (\Omega - cm)^{-1}}$$

(b)
For $N_d = N_a = 10^{18}\ cm^{-3}$,

$$\mu_n \approx 300\ cm^2/V-s,\ \mu_p \approx 130\ cm^2/V-s$$

Then

$$\sigma_i = \left(1.6x10^{-19}\right)\left(1.5x10^{10}\right)(300 + 130)$$

or

$$\underline{\sigma_i = 1.03x10^{-6}\ (\Omega - cm)^{-1}}$$

5.8
(a) GaAs

$$\sigma \approx e\mu_p p_O \Rightarrow 5 = \left(1.6x10^{-19}\right)\mu_p p_O$$

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

$$\underline{p_O \approx 1.3x10^{17}\ cm^{-3},\ \mu_p \approx 240\ cm^2/V-s}$$

Then

$$n_O = \frac{n_i^2}{p_O} = \frac{(1.8x10^6)^2}{1.3x10^{17}} \quad \text{or} \quad \underline{n_O = 2.49x10^{-5}\ cm^{-3}}$$

(b) Silicon:

$$\sigma = \frac{1}{\rho} \approx e\mu_n n_O$$

or

$$n_O = \frac{1}{\rho e\mu_n} = \frac{1}{(8)(1.6x10^{-19})(1350)}$$

or

$$\underline{n_O = 5.79x10^{14}\ cm^{-3}}$$

and

$$p_O = \frac{n_i^2}{n_O} = \frac{(1.5x10^{10})^2}{5.79x10^{14}} \Rightarrow \underline{p_O = 3.89x10^5\ cm^{-3}}$$

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

5.9

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

Then

$$10^{-6} = (1.6x10^{-19})(1000 + 600)n_i$$

or

$$\underline{n_i(300K) = 3.91x10^9\ cm^{-3}}$$

Now

$$n_i^2 = N_C N_V \exp\left(\frac{-E_g}{kT}\right)$$

or

$$E_g = kT \ln\left(\frac{N_C N_V}{n_i^2}\right) = (0.0259)\ln\left[\frac{(10^{19})^2}{(3.91x10^9)^2}\right]$$

or

$$\underline{E_g = 1.122\ eV}$$

Now

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

$$= 5.15x10^{26}$$

or

$$\underline{n_i(500K) = 2.27x10^{13}\ cm^{-3}}$$

Then

$$\sigma_i = (1.6x10^{-19})(2.27x10^{13})(1000 + 600)$$

so

$$\underline{\sigma_i(500K) = 5.81x10^{-3}\ (\Omega - cm)^{-1}}$$

5.10

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

$$\sigma_i = (1.6x10^{-19})(1.5x10^{10})(1350 + 480)$$

or

$$\underline{\sigma_i = 4.39x10^{-6}\ (\Omega - cm)^{-1}}$$

(ii) Ge:

$$\sigma_i = (1.6x10^{-19})(2.4x10^{13})(3900 + 1900)$$

or

$$\underline{\sigma_i = 2.23x10^{-2}\ (\Omega - cm)^{-1}}$$

(iii) GaAs:

$$\sigma_i = (1.6x10^{-19})(1.8x10^6)(8500 + 400)$$

or

$$\underline{\sigma_i = 2.56x10^{-9}\ (\Omega - cm)^{-1}}$$

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

(i) $R = \dfrac{200x10^{-4}}{(4.39x10^{-6})(85x10^{-8})} \Rightarrow$

$$\underline{R = 5.36x10^9\ \Omega}$$

(ii) $R = \dfrac{200x10^{-4}}{(2.23x10^{-2})(85x10^{-8})} \Rightarrow$

$$\underline{R = 1.06x10^6\ \Omega}$$

(iii) $R = \dfrac{200x10^{-4}}{(2.56x10^{-9})(85x10^{-8})} \Rightarrow$

$$\underline{R = 9.19x10^{12}\ \Omega}$$

5.11

(a) $\rho = 5 = \dfrac{1}{e\mu_n N_d}$

Assume $\mu_n = 1350\ cm^2/V-s$

Then

$$N_d = \frac{1}{(1.6x10^{-19})(1350)(5)} \Rightarrow$$

$$\underline{N_d = 9.26x10^{14}\ cm^{-3}}$$

(b)

$T = 200K \rightarrow T = -75C$

$T = 400K \rightarrow T = 125C$

From Figure 5.2,

$T = -75C$, $N_d = 10^{15}\ cm^{-3} \Rightarrow$

$\mu_n \approx 2500\ cm^2/V-s$

$T = 125C$, $N_d = 10^{15}\ cm^{-3} \Rightarrow$

$\mu_n \approx 700\ cm^2/V-s$

Assuming $n_O = N_d = 9.26x10^{14}\ cm^{-3}$ over the temperature range,

For $T = 200K$,

$$\rho = \frac{1}{(1.6x10^{-19})(2500)(9.26x10^{14})} \Rightarrow$$

$$\underline{\rho = 2.7\ \Omega - cm}$$

For $T = 400K$,

$$\rho = \frac{1}{(1.6x10^{-19})(700)(9.26x10^{14})} \Rightarrow$$

$$\underline{\rho = 9.64\ \Omega - cm}$$

5.12

Computer plot

5.13

(a) $E = 10\ V/cm \Rightarrow |v_d| = \mu_n E$

$v_d = (1350)(10) \Rightarrow \quad v_d = 1.35x10^4\ cm/s$

so

$$T = \frac{1}{2}m_n^* v_d^2 = \frac{1}{2}(1.08)(9.11x10^{-31})(1.35x10^2)^2$$

or

$$\underline{T = 8.97x10^{-27}\ J \Rightarrow 5.6x10^{-8}\ eV}$$

(b)

$E = 1\ kV/cm$,

$v_d = (1350)(1000) = 1.35x10^6\ cm/s$

Then

$$T = \frac{1}{2}(1.08)(9.11x10^{-31})(1.35x10^4)^2$$

or

$$\underline{T = 8.97x10^{-23}\ J \Rightarrow 5.6x10^{-4}\ eV}$$

5.14

(a) $$n_i^2 = N_C N_V \exp\left(\frac{-E_g}{kT}\right)$$

$$= (2x10^{19})(1x10^{19})\exp\left(\frac{-1.10}{0.0259}\right)$$

$$= 7.18x10^{19} \Rightarrow n_i = 8.47x10^9\ cm^{-3}$$

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

Then

$$J = \sigma E = e\mu_n n_O E$$

$$= (1.6x10^{-19})(1000)(10^{14})(100)$$

or

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

(b)

A 5% increase is due to a 5% increase in electron concentration. So

$$n_O = 1.05x10^{14} = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_i^2}$$

We can write

$$(1.05x10^{14} - 5x10^{13})^2 = (5x10^{13})^2 + n_i^2$$

so

$$n_i^2 = 5.25x10^{26}$$

$$= (2x10^{19})(1x10^{19})\left(\frac{T}{300}\right)^3 \exp\left(\frac{-E_g}{kT}\right)$$

which yields

$$2.625x10^{-12} = \left(\frac{T}{300}\right)^3 \exp\left(\frac{-1.10}{kT}\right)$$

By trial and error, we find

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

5.15

(a) $\sigma = e\mu_n n_O + e\mu_p p_O$ and $n_O = \dfrac{n_i^2}{p_O}$

Then

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

To find the minimum conductivity,

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

which yields

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

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

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

5.16

$$\sigma = e\mu n_i = \frac{1}{\rho}$$

Now

$$\frac{1/\rho_1}{1/\rho_2} = \frac{1/50}{1/5} = \frac{5}{50} = 0.10 = \frac{\exp\left(\frac{-E_g}{2kT_1}\right)}{\exp\left(\frac{-E_g}{2kT_2}\right)}$$

or

$$0.10 = \exp\left[-E_g\left(\frac{1}{2kT_1} - \frac{1}{2kT_2}\right)\right]$$

$$kT_1 = 0.0259$$

$$kT_2 = (0.0259)\left(\frac{330}{300}\right) = 0.02849$$

$$\frac{1}{2kT_1} = 19.305 \quad , \quad \frac{1}{2kT_2} = 17.550$$

Then

$$E_g(19.305 - 17.550) = \ln(10)$$

or

$$E_g = 1.312\ eV$$

5.17

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

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

$$= 0.00050 + 0.000667 + 0.0020$$

or

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

5.18

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

(a)

At $T = 200K$, $\mu_n = (1300)(1.837) \Rightarrow$

$$\mu_n = 2388\ cm^2/V-s$$

(b)

At $T = 400K$, $\mu_n = (1300)(0.65) \Rightarrow$

$$\mu_n = 844\ cm^2/V-s$$

5.19

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

Then

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

5.20

Computer plot

5.21

Computer plot

5.22

$$J_n = eD_n\frac{dn}{dx} = eD_n\left(\frac{5x10^{14} - n(0)}{0.01 - 0}\right)$$

$$0.19 = (1.6x10^{-19})(25)\left(\frac{5x10^{14} - n(0)}{0.010}\right)$$

Then

$$\frac{(0.19)(0.010)}{(1.6x10^{-19})(25)} = 5x10^{14} - n(0)$$

which yields

$$n(0) = 0.25x10^{14}\ cm^{-3}$$

5.23

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

$$= (1.6x10^{-19})(25)\left(\frac{10^{16} - 10^{15}}{0 - 0.10}\right)$$

or

$$|J| = 0.36\ A/cm^2$$

For $A = 0.05\ cm^2$

$$I = AJ = (0.05)(0.36) \Rightarrow \quad I = 18\ mA$$

5.24

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

so

$$-400 = (1.6x10^{-19}) D_n \left(\frac{10^{17} - 6x10^{16}}{0 - 4x10^{-4}} \right)$$

or

$$-400 = D_n(-16)$$

Then

$$\underline{D_n = 25\ cm^2 / s}$$

5.25

$$J = -eD_p \frac{dp}{dx}$$

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

$$= \frac{(1.6x10^{-19})(10)(10^{16})}{10x10^{-4}}$$

or

$\underline{J = 16\ A/cm^2}$ = constant at all three points

5.26

$$J_p(x=0) = -eD_p \frac{dp}{dx}\Big|_{x=0}$$

$$= -eD_p \frac{10^{15}}{(-L_p)} = \frac{(1.6x10^{-19})(10)(10^{15})}{5x10^{-4}}$$

or

$$J_p(x=0) = 3.2\ A/cm^2$$

Now

$$J_n(x=0) = eD_n \frac{dn}{dx}\Big|_{x=0}$$

$$= eD_n\left(\frac{5x10^{14}}{L_n}\right) = \frac{(1.6x10^{-19})(25)(5x10^{14})}{10^{-3}}$$

or

$$J_n(x=0) = 2\ A/cm^2$$

Then

$$J = J_p(x=0) + J_n(x=0) = 3.2 + 2$$

or

$$\underline{J = 5.2\ A/cm^2}$$

5.27

$$J_p = -eD_p \frac{dp}{dx} = -eD_p \frac{d}{dp}\left[10^{15}\exp\left(\frac{-x}{22.5}\right)\right]$$

Distance x is in μm, so $22.5 \to 22.5x10^{-4}\ cm$.

Then

$$J_p = -eD_p(10^{15})\left(\frac{-1}{22.5x10^{-4}}\right)\exp\left(\frac{-x}{22.5}\right)$$

$$= \frac{+(1.6x10^{-19})(48)(10^{15})}{22.5x10^{-4}}\exp\left(\frac{-x}{22.5}\right)$$

or

$$\underline{J_p = 3.41\exp\left(\frac{-x}{22.5}\right)\quad A/cm^2}$$

5.28

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

or

$$-40 = (1.6x10^{-19})(960)\left[10^{16}\exp\left(\frac{-x}{18}\right)\right]\mathrm{E}$$

$$+(1.6x10^{-19})(25)(10^{16})\left(\frac{-1}{18x10^{-4}}\right)\exp\left(\frac{-x}{18}\right)$$

Then

$$-40 = 1.536\left[\exp\left(\frac{-x}{18}\right)\right]\mathrm{E} - 22.2\exp\left(\frac{-x}{18}\right)$$

Then

$$\mathrm{E} = \frac{22.2\exp\left(\frac{-x}{18}\right) - 40}{1.536\exp\left(\frac{-x}{18}\right)} \Rightarrow$$

$$\underline{\mathrm{E} = 14.5 - 26\exp\left(\frac{+x}{18}\right)}$$

5.29

$$J_T = J_{n,drf} + J_{p,dif}$$

(a) $J_{p,dif} = -eD_p \dfrac{dp}{dx}$ and

$$p(x) = 10^{15}\exp\left(\frac{-x}{L}\right) \quad \text{where} \quad L = 12\ \mu m$$

so

$$J_{p,dif} = -eD_p(10^{15})\left(\frac{-1}{L}\right)\exp\left(\frac{-x}{L}\right)$$

or

$$J_{p,dif} = \frac{(1.6x10^{-19})(12)(10^{15})}{12x10^{-4}}\exp\left(\frac{-x}{12}\right)$$

or

$$J_{p,dif} = +1.6\exp\left(\frac{-x}{L}\right) \quad A/cm^2$$

(b)

$$J_{n,drf} = J_T - J_{p,dif}$$

or

$$J_{n,drf} = 4.8 - 1.6\exp\left(\frac{-x}{L}\right)$$

(c)

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

Then

$$(1.6x10^{-19})(1000)(10^{16})\mathrm{E} = 4.8 - 1.6\exp\left(\frac{-x}{L}\right)$$

which yields

$$\mathrm{E} = \left[3 - 1\times\exp\left(\frac{-x}{L}\right)\right] \quad V/cm$$

5.30

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

Now $\mu_n = 8000\ cm^2/V-s$ so that

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

Then

$$100 = (1.6x10^{-19})(8000)(12)n(x) + (1.6x10^{-19})(207)\frac{dn(x)}{dx}$$

which yields

$$100 = 1.54x10^{-14}n(x) + 3.31x10^{-17}\frac{dn(x)}{dx}$$

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

$$100 = (1.54x10^{-14})\left[A + B\exp\left(\frac{-x}{d}\right)\right] - \frac{(3.31x10^{-17})}{d}B\exp\left(\frac{-x}{d}\right)$$

This equation is valid for all x, so

$$100 = 1.54x10^{-14}A$$

or

$$A = 6.5x10^{15}$$

Also

$$1.54x10^{-14}B\exp\left(\frac{-x}{d}\right) - \frac{(3.31x10^{-17})}{d}B\exp\left(\frac{-x}{d}\right) = 0$$

which yields

$$d = 2.15x10^{-3}\ cm$$

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

so that

$$50 = (1.6x10^{-19})(8000)(12)(A+B)$$

which yields $B = -3.24x10^{15}$

Then

$$n(x) = 6.5x10^{15} - 3.24x10^{15}\exp\left(\frac{-x}{d}\right) \quad cm^{-3}$$

(b)

At $x = 0,\ n(0) = 6.5x10^{15} - 3.24x10^{15}$

Or

$$n(0) = 3.26x10^{15}\ cm^{-3}$$

At $x = 50\ \mu m$,

$$n(50) = 6.5x10^{15} - 3.24x10^{15}\exp\left(\frac{-50}{21.5}\right)$$

or

$$n(50) = 6.18x10^{15}\ cm^{-3}$$

(c)

At $x = 50\ \mu m$, $J_{drt} = e\mu_n n(50)\mathrm{E}$

$$= (1.6x10^{-19})(8000)(6.18x10^{15})(12)$$

or

$$J_{drf}(x = 50) = 94.9\ A/cm^2$$

Then

$$J_{dif}(x = 50) = 100 - 94.9 \Rightarrow$$

$$J_{dif}(x = 50) = 5.1\ A/cm^2$$

5.31

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

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

$0.15 = a\left(10^{-3}\right) + 0.4$ so that $a = -2.5x10^2$

Then

$$E_F - E_{Fi} = 0.4 - 2.5x10^2 x$$

So

$$\underline{n = n_i \exp\left(\frac{0.4 - 2.5x10^2 x}{kT}\right)}$$

(b)

$$J_n = eD_n \frac{dn}{dx}$$

$$= eD_n n_i \left(\frac{-2.5x10^2}{kT}\right)\exp\left(\frac{0.4 - 2.5x10^2 x}{kT}\right)$$

Assume $T = 300K$, $kT = 0.0259\ eV$, and

$n_i = 1.5x10^{10}\ cm^{-3}$

Then

$$J_n = \frac{-\left(1.6x10^{-19}\right)(25)\left(1.5x10^{10}\right)\left(2.5x10^2\right)}{(0.0259)} \times \exp\left(\frac{0.4 - 2.5x10^2 x}{0.0259}\right)$$

or

$$J_n = -5.79x10^{-4} \exp\left(\frac{0.4 - 2.5x10^2 x}{0.0259}\right)$$

(i) At $x = 0$, $\underline{J_n = -2.95x10^3\ A/cm^2}$

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

5.32

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

$$-80 = \left(1.6x10^{-19}\right)(1000)\left(10^{16}\right)\left(1 - \frac{x}{L}\right)\mathrm{E} + \left(1.6x10^{-19}\right)(25.9)\left(\frac{-10^{16}}{L}\right)$$

where $L = 10x10^{-4} = 10^{-3}\ cm$

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

$$\underline{\mathrm{E} = \frac{38.56}{\left(\frac{x}{L} - 1\right)}}$$

(b)

For $J_n = -20\ A/cm^2$

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

Then

$$\underline{\mathrm{E} = \frac{21.44}{\left(1 - \frac{x}{L}\right)}}$$

5.33

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

Let $n = N_d = N_{do} \exp(-\alpha x)$, $J = 0$

Then

$$0 = \mu_n N_{do}\left[\exp(-\alpha x)\right]\mathrm{E} + D_n N_{do}(-\alpha)\exp(-\alpha x)$$

or

$$0 = \mathrm{E} + \frac{D_n}{\mu_n}(-\alpha)$$

Since $\dfrac{D_n}{\mu_n} = \dfrac{kT}{e}$

So

$$\underline{\mathrm{E} = \alpha\left(\frac{kT}{e}\right)}$$

(b)

$$V = -\int_0^{1/\alpha} \mathrm{E}dx = -\alpha\left(\frac{kT}{e}\right)\int_0^{1/\alpha} dx$$

$$= -\left[\alpha\left(\frac{kT}{e}\right)\right]\cdot\left(\frac{1}{\alpha}\right) \text{ so that } \underline{V = -\left(\frac{kT}{e}\right)}$$

5.34

From Example 5.5

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

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

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

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

or

$$\underline{V = -2.73\ mV}$$

5.35

From Equation [5.40]

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

Now

$$1000 = -(0.0259)\left(\frac{1}{N_d(x)}\right)\cdot\frac{dN_d(x)}{dx}$$

or

$$\frac{dN_d(x)}{dx} + 3.86x10^4 N_d(x) = 0$$

Solution is of the form

$$N_d(x) = A\exp(-\alpha x)$$

and

$$\frac{dN_d(x)}{dx} = -A\alpha\exp(-\alpha x)$$

Substituting into the differential equation

$$-A\alpha\exp(-\alpha x) + 3.86x10^4 A\exp(-\alpha x) = 0$$

which yields

$$\underline{\alpha = 3.86x10^4\ cm^{-1}}$$

At $x = 0$, the actual value of $N_d(0)$ is arbitrary.

5.36

(a) $J_n = J_{drf} + J_{dif} = 0$

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

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

We have

$$D_n = \mu_n\left(\frac{kT}{e}\right) = (6000)(0.0259) = 155.4\ cm^2/s$$

Then

$$J_{dif} = \frac{-(1.6x10^{-19})(155.4)(5x10^{16})}{(0.1x10^{-4})}\exp\left(\frac{-x}{L}\right)$$

or

$$\underline{J_{dif} = -1.24x10^5\exp\left(\frac{-x}{L}\right)\quad A/cm^2}$$

(b)

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

Now

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

$$= (1.6x10^{-19})(6000)(5x10^{16})\left[\exp\left(\frac{-x}{L}\right)\right]\mathrm{E}$$

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

We have

$$J_{drf} = -J_{dif}$$

so

$$48\mathrm{E}\exp\left(\frac{-x}{L}\right) = 1.24x10^5\exp\left(\frac{-x}{L}\right)$$

which yields

$$\underline{\mathrm{E} = 2.58x10^3\ V/cm}$$

5.37

Computer Plot

5.38

(a) $D = \mu\left(\frac{kT}{e}\right) = (925)(0.0259)$

so

$$\underline{D = 23.96\ cm^2/s}$$

(b)

For $D = 28.3\ cm^2/s$

$$\mu = \frac{28.3}{0.0259} \Rightarrow \underline{\mu = 1093\ cm^2/V-s}$$

5.39

We have $L = 10^{-1}\ cm = 10^{-3}\ m$,

$W = 10^{-2}\ cm = 10^{-4}\ m$, $d = 10^{-3}\ cm = 10^{-5}\ m$

(a)

We have

$p = 10^{16}\ cm^{-3} = 10^{22}\ m^{-3}$, $I_x = 1\ mA = 10^{-3}\ A$

Then

$$V_H = \frac{I_x B_z}{epd} = \frac{(10^{-3})(3.5x10^{-2})}{(1.6x10^{-19})(10^{22})(10^{-5})}$$

or

$$\underline{V_H = 2.19\ mV}$$

(b)

$$E_H = \frac{V_H}{W} = \frac{2.19x10^{-3}}{10^{-2}}$$

or

$$\underline{E_H = 0.219\ V/cm}$$

5.40

(a) $V_H = \frac{-I_x B_z}{ned} = \frac{-(250x10^{-6})(5x10^{-2})}{(5x10^{21})(1.6x10^{-19})(5x10^{-5})}$

or

$$\underline{V_H = -0.3125\ mV}$$

(b)

$$E_H = \frac{V_H}{W} = \frac{-0.3125x10^{-3}}{2x10^{-2}} \Rightarrow$$

$$\underline{E_H = -1.56x10^{-2}\ V/cm}$$

(c)

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

$$= \frac{(250x10^{-6})(10^{-3})}{(1.6x10^{-19})(5x10^{21})(0.1)(2x10^{-4})(5x10^{-5})}$$

or

$$\underline{\mu_n = 0.3125\ m^2/V-s = 3125\ cm^2/V-s}$$

5.41

(a) V_H = positive $\Rightarrow$ p-type

(b)

$$V_H = \frac{I_x B_z}{epd} \Rightarrow p = \frac{I_x B_z}{eV_H d}$$

$$= \frac{(0.75x10^{-3})(10^{-1})}{(1.6x10^{-19})(5.8x10^{-3})(10^{-5})}$$

or

$$\underline{p = 8.08x10^{21}\ m^{-3} = 8.08x10^{15}\ cm^{-3}}$$

(c)

$$\mu_p = \frac{I_x L}{epV_x Wd}$$

$$= \frac{(0.75x10^{-3})(10^{-3})}{(1.6x10^{-19})(8.08x10^{21})(15)(10^{-4})(10^{-5})}$$

or

$$\underline{\mu_p = 3.87x10^{-2}\ m^2/V-s = 387\ cm^2/V-s}$$

5.42

(a) $V_H = E_H W = -(16.5x10^{-3})(5x10^{-2})$

or

$$\underline{V_H = -0.825\ mV}$$

(b)

V_H = negative $\Rightarrow$ n-type

(c)

$$n = \frac{-I_x B_z}{edV_H}$$

$$= \frac{-(0.5x10^{-3})(6.5x10^{-2})}{(1.6x10^{-19})(5x10^{-5})(-0.825x10^{-3})}$$

or

$$\underline{n = 4.92x10^{21}\ m^{-3} = 4.92x10^{15}\ cm^{-3}}$$

(d)

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

$$= \frac{(0.5x10^{-3})(0.5x10^{-2})}{(1.6x10^{-19})(4.92x10^{21})(1.25)(5x10^{-4})(5x10^{-5})}$$

or

$$\underline{\mu_n = 0.102\ m^2/V-s = 1020\ cm^2/V-s}$$

5.43

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

(b) $n = \frac{-I_x B_z}{edV_H} \Rightarrow \underline{n = 8.68x10^{14}\ cm^{-3}}$

(c) $\mu_n = \frac{I_x L}{enV_x Wd} \Rightarrow \underline{\mu_n = 8182\ cm^2/V-s}$

(d) $\sigma = \frac{1}{\rho} = e\mu_n n = (1.6x10^{-19})(8182)(8.68x10^{14})$

or $\underline{\rho = 0.88\ (\Omega-cm)}$