Chapter 1
Exercise Problems

EX1.1

$$n_i = BT^{3/2}\exp\left(\frac{-E_g}{2kT}\right)$$

GaAs: $n_i = \left(2.1\times10^{14}\right)\left(300\right)^{3/2}\exp\left(\frac{-1.4}{2\left(86\times10^{-6}\right)\left(300\right)}\right)$ or $\underline{n_i = 1.8\times10^{6}\ cm^{-3}}$

Ge: $n_i = \left(1.66\times10^{13}\right)\left(300\right)^{3/2}\exp\left(\frac{-0.66}{2\left(86\times10^{-6}\right)\left(300\right)}\right)$ or $\underline{n_i = 2.40\times10^{13}\ cm^{-3}}$

EX1.2

(a) majority carrier: holes, $p_o = 10^{17}\ cm^{-3}$ minority carrier: electrons,

$$n_o = \frac{n_i^2}{p_o} = \frac{\left(1.5\times10^{10}\right)^2}{10^{17}} = 2.25\times10^{3}\ cm^{-3}$$

(b) majority carrier: electrons, $n_o = 5\times10^{15}\ cm^{-3}$ minority carrier: holes,

$$p_o = \frac{n_i^2}{n_o} = \frac{\left(1.5\times10^{10}\right)^2}{5\times10^{15}} = 4.5\times10^{4}\ cm^{-3}$$

EX1.3

For n-type, drift current density $J \cong e\mu_n n\mathrm{E}$ or $200 = \left(1.6\times10^{-19}\right)\left(7000\right)\left(10^{16}\right)\mathrm{E}$ which yields $\mathrm{E} = 17.9\ V/cm$

EX1.4

Diffusion current density due to holes:

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

$$= -eD_p\left(10^{16}\right)\left(\frac{-1}{L_p}\right)\exp\left(\frac{-x}{L_p}\right)$$

(a) At $x = 0$

$$J_p = \frac{\left(1.6\times10^{-19}\right)\left(10\right)\left(10^{16}\right)}{10^{-3}} = 16\ A/cm^2$$

(b) At $x = 10^{-3}\ cm$

$$J_p = 16\exp\left(\frac{-10^{-3}}{10^{-3}}\right) = 5.89\ A/cm^2$$

EX1.5

$$V_{bi} = V_T\ln\left[\frac{N_aN_d}{n_i^2}\right] = \left(0.026\right)\ln\left[\frac{\left(10^{16}\right)\left(10^{17}\right)}{\left(1.8\times10^{6}\right)^2}\right] \text{ or } V_{bi} = 1.23\ V$$

EX1.6

$$C_j = C_{jo}\left(1+\frac{V_R}{V_{bi}}\right)^{-1/2}$$

and

$$V_{bi} = V_T \ln\left[\frac{N_a N_d}{n_i^2}\right]$$

$$= (0.026)\ln\left[\frac{(10^{17})(10^{16})}{(1.5\times10^{10})^2}\right] = 0.757\ V$$

Then $0.8 = C_{jo}\left(1+\frac{5}{0.757}\right)^{-1/2} = C_{jo}(7.61)^{-1/2}$

or

$C_{jo} = 2.21\ pF$

EX1.7

$$i_D = I_S\left[\exp\left(\frac{v_D}{V_T}\right)-1\right]$$

so $10^{-3} = (10^{-13})\left[\exp\left(\frac{v_D}{0.026}\right)-1\right]$

Solving for the diode voltage, we find $v_D = (0.026)\ln\left[\frac{10^{-3}}{10^{-13}}+1\right]$

or

$v_D \cong (0.026)\ln(10^{10})$

which yields

$v_D = 0.599\ V$

EX1.8

$V_{PS} = I_D R + V_D$ and $I_D \cong I_S \exp\left(\frac{V_D}{V_T}\right)$

so $4 = I_D(4\times10^3) + V_D \Rightarrow I_D = \frac{(4-V_D)}{4\times10^3}$

and

$I_D = (10^{-12})\exp\left(\frac{V_D}{0.026}\right)$

By trial and error, we find $I_D \cong 0.864\ mA$ and $V_D \cong 0.535\ V$

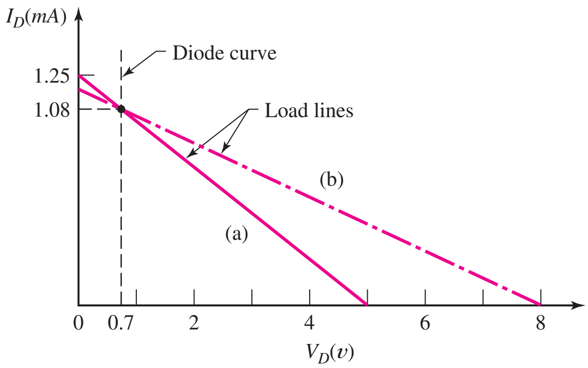
EX1.9

(a) $I_D = \frac{V_{PS}-V_\gamma}{R} = \frac{5-0.7}{4} \Rightarrow I_D = 1.08\ mA$

(b) $I_D = \frac{V_{PS}-V_\gamma}{R} \Rightarrow R = \frac{V_{PS}-V_\gamma}{I_D}$

Then $R = \frac{8-0.7}{1.075} = 6.79\ k\Omega$

(c)



EX1.10
PSpice analysis

EX1.11

Quiescent diode current $I_{DQ} = \dfrac{V_{PS} - V_\gamma}{R} = \dfrac{10 - 0.7}{20} = 0.465\ mA$

Time-varying diode current:

We find that $r_d = \dfrac{V_T}{I_{DQ}} = \dfrac{0.026}{0.465} = 0.0559\ k\Omega$

Then $i_d = \dfrac{v_I}{r_d + R} = \dfrac{0.2\sin\omega t}{0.0559 + 20} \cdot \dfrac{(V)}{(k\Omega)}$ or $i_d = 9.97\sin\omega t\,(\mu A)$

EX1.12

For the pn junction diode, $V_D \cong V_T \ln\left(\dfrac{I_D}{I_S}\right) = (0.026)\ln\left(\dfrac{1.2\times 10^{-3}}{4\times 10^{-15}}\right)$ or $V_D = 0.6871\ V$

The Schottky diode voltage will be smaller, so $V_D = 0.6871 - 0.265 = 0.4221\ V$

Now $I_D \cong I_S \exp\left(\dfrac{V_D}{V_T}\right)$

or

$$I_S = \frac{1.2\times 10^{-3}}{\exp\left(\dfrac{0.4221}{0.026}\right)} \Rightarrow I_S = 1.07\times 10^{-10}\ A$$

EX1.13

$P = I \cdot V_Z \Rightarrow 10 = I(5.6) \Rightarrow I = 1.79\ mA$

Also $I = \dfrac{10 - 5.6}{R} = 1.79 \Rightarrow R = 2.46\ k\Omega$

Test Your Understanding Exercises

TYU1.1
(a) $T = 400K$

Si: $n_i = BT^{3/2}\exp\left(\dfrac{-E_g}{2kT}\right)$

$$n_i = \left(5.23\times 10^{15}\right)(400)^{3/2}\exp\left[\frac{-1.1}{2\left(86\times 10^{-6}\right)(400)}\right]$$

or

$n_i = 4.76\times 10^{12}\ cm^{-3}$

Ge: $n_i = \left(1.66 \times 10^{15}\right)\left(400\right)^{3/2} \exp\left[\dfrac{-0.66}{2\left(86 \times 10^{-6}\right)\left(400\right)}\right]$

or

$n_i = 9.06 \times 10^{14}\ cm^{-3}$

GaAs:

$n_i = \left(2.1 \times 10^{14}\right)\left(400\right)^{3/2} \exp\left[\dfrac{-1.4}{2\left(86 \times 10^{-6}\right)\left(400\right)}\right]$

or

$n_i = 2.44 \times 10^{9}\ cm^{-3}$

(b) $T = 250\ K$

Si: $n_i = \left(5.23 \times 10^{15}\right)\left(250\right)^{3/2} \exp\left[\dfrac{-1.1}{2\left(86 \times 10^{-6}\right)\left(250\right)}\right]$

or

$n_i = 1.61 \times 10^{8}\ cm^{-3}$

Ge: $n_i = \left(1.66 \times 10^{15}\right)\left(250\right)^{3/2} \exp\left[\dfrac{-0.66}{2\left(86 \times 10^{-6}\right)\left(250\right)}\right]$

or

$n_i = 1.42 \times 10^{12}\ cm^{-3}$

GaAs: $n_i = \left(2.10 \times 10^{14}\right)\left(250\right)^{3/2} \exp\left[\dfrac{-1.4}{2\left(86 \times 10^{-6}\right)\left(250\right)}\right]$

or

$n_i = 6.02 \times 10^{3}\ cm^{-3}$

TYU1.2

(a) $n = 5 \times 10^{16}\ cm^{-3},\ p <<< n,\ \text{so}\ \sigma \cong e\mu_n n = \left(1.6 \times 10^{-19}\right)\left(1350\right)\left(5 \times 10^{16}\right)$

or

$\sigma = 10.8\left(\Omega - cm\right)^{-1}$

(b) $p = 5 \times 10^{16}\ cm^{-3},\ n <<< p,\ \text{so}\ \sigma \cong e\mu_p p = \left(1.6 \times 10^{-19}\right)\left(480\right)\left(5 \times 10^{16}\right)$

or

$\sigma = 3.84\left(\Omega - cm\right)^{-1}$

TYU1.3

$J = \sigma E = \left(10\right)\left(15\right)$ or $J = 150\ A/cm^2$

TYU1.4

(a) $J_n = eD_n \dfrac{dn}{dx} = eD_n \dfrac{\Delta n}{\Delta x}$ so $J_n = \left(1.6 \times 10^{-19}\right)\left(35\right)\left(\dfrac{10^{15} - 10^{16}}{0 - 2.5 \times 10^{-4}}\right)$

or

$J_n = 202\ A/cm^2$

(b) $J_p = -eD_p \dfrac{dp}{dx} = -eD_p \dfrac{\Delta p}{\Delta x}$ so $J_p = -\left(1.6 \times 10^{-19}\right)\left(12.5\right)\left(\dfrac{10^{14} - 5 \times 10^{15}}{0 - 4 \times 10^{-4}}\right)$

or

$J_p = -24.5\ A/cm^2$

TYU1.5

(a) $n_o = N_d = 8\times10^{15}\ cm^{-3}$

$$p_o = \frac{n_i^2}{n_o} = \frac{\left(1.5\times10^{10}\right)^2}{8\times10^{15}} = 2.81\times10^4\ cm^{-3}$$

(b) $n = n_o + \delta n = 8\times10^{15} + 0.1\times10^{15}$
or
$n = 8.1\times10^{15}\ cm^{-3}$
$p = p_o + \delta p = 2.81\times10^4 + 10^{14}$
or
$p \cong 10^{14}\ cm^{-3}$

TYU1.6

(a) $V_{bi} = V_T \ln\left[\frac{N_a N_d}{n_i^2}\right]$ so $V_{bi} = (0.026)\ln\left[\frac{\left(10^{15}\right)\left(10^{17}\right)}{\left(1.5\times10^{10}\right)^2}\right] = 0.697\ V$

(b) $V_{bi} = (0.026)\ln\left[\frac{\left(10^{17}\right)\left(10^{17}\right)}{\left(1.5\times10^{10}\right)^2}\right] = 0.817\ V$

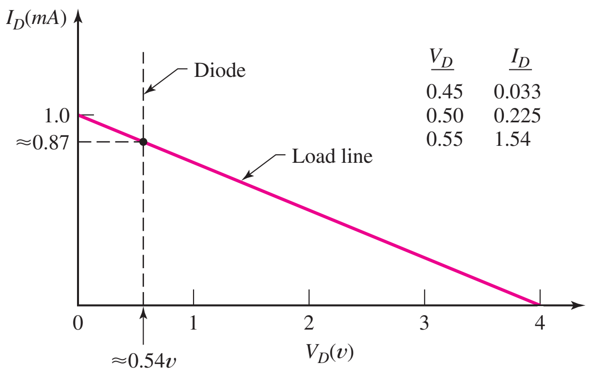
TYU1.7

(a) $I_D = I_S\left[\exp\left(\frac{V_D}{V_T}\right) - 1\right]$

$I_D \cong 10^{-14}\exp\left(\frac{0.5}{0.026}\right)$
Then, for
$V_D = 0.5\ V,\ I_D = 2.25\ \mu A$
$V_D = 0.6\ V,\ I_D = 0.105\ mA$
$V_D = 0.7\ V,\ I_D = 4.93\ mA$
(b) $I_D \cong -I_S = -10^{-14}\ A$
for both cases.

TYU1.8
$\Delta T = 100C$ so $\Delta V_D \cong 2\times100 = 200\ mV$
Then $V_D = 0.650 - 0.20 = 0.450\ V$

TYU1.9



TYU1.10
$P = I_D V_D \Rightarrow 1.05 = I_D(0.7)$ so $I_D = 1.5\ mA$

Now $R = \frac{V_{PS} - V_\gamma}{I_D} = \frac{10 - 0.7}{1.5} \Rightarrow R = 6.2\ k\Omega$

TYU1.11

$$g_d = \frac{I_D}{V_T} = \frac{0.8}{0.026} = 30.8\ mS$$

TYU1.12

$$r_d = \frac{V_T}{I_D} \Rightarrow 50 = \frac{0.026}{I_D} \Rightarrow I_D = \frac{0.026}{50}$$

or

$$I_D = 0.52\ mA$$

TYU1.13

For the pn junction diode,

$$I_D = \frac{4 - 0.7}{4} = 0.825\ mA$$

For the Schottky diode, $I_D = \frac{4 - 0.3}{4} = 0.925\ mA$

TYU1.14

$V_z = V_{zo} + I_z r_z \Rightarrow V_{zo} = V_z - I_z r_z$ so $V_{zo} = 5.20 - \left(10^{-3}\right)\left(20\right) = 5.18\ V$

Then $V_z = 5.18 + \left(10 \times 10^{-3}\right)\left(20\right) \Rightarrow V_z = 5.38\ V$

Chapter 1
Problem Solutions

1.1

$n_i = BT^{3/2} e^{-E_g/2kT}$

(a) Silicon

(i) $n_i = \left(5.23\times10^{15}\right)\left(250\right)^{3/2} \exp\left[\dfrac{-1.1}{2\left(86\times10^{-6}\right)\left(250\right)}\right]$

$= 2.067\times10^{19} \exp\left[-25.58\right]$

$\underline{n_i = 1.61\times10^{8}\ \text{cm}^{-3}}$

(ii) $n_i = \left(5.23\times10^{15}\right)\left(350\right)^{3/2} \exp\left[\dfrac{-1.1}{2\left(86\times10^{-6}\right)\left(350\right)}\right]$

$= 3.425\times10^{19} \exp\left[-18.27\right]$

$\underline{n_i = 3.97\times10^{11}\ \text{cm}^{-3}}$

(b) GaAs

(i) $n_i = \left(2.10\times10^{14}\right)\left(250\right)^{3/2} \exp\left[\dfrac{-1.4}{2\left(86\times10^{-6}\right)\left(250\right)}\right]$

$= \left(8.301\times10^{17}\right)\exp\left[-32.56\right]$

$\underline{n_i = 6.02\times10^{3}\ \text{cm}^{-3}}$

(ii) $n_i = \left(2.10\times10^{14}\right)\left(350\right)^{3/2} \exp\left[\dfrac{-1.4}{2\left(86\times10^{-6}\right)\left(350\right)}\right]$

$= \left(1.375\times10^{18}\right)\exp\left[-23.26\right]$

$\underline{n_i = 1.09\times10^{8}\ \text{cm}^{-3}}$

1.2

a. $n_i = BT^{3/2} \exp\left(\dfrac{-Eg}{2kT}\right)$

$10^{12} = 5.23\times10^{15} T^{3/2} \exp\left(\dfrac{-1.1}{2(86\times10^{-6})(T)}\right)$

$1.91\times10^{-4} = T^{3/2} \exp\left(-\dfrac{6.40\times10^{3}}{T}\right)$

By trial and error, $T \approx 368$ K

b. $n_i = 10^{9}\ \text{cm}^{-3}$

$10^{9} = 5.23\times10^{15} T^{3/2} \exp\left(\dfrac{-1.1}{2\left(86\times10^{-6}\right)\left(T\right)}\right)$

$1.91\times10^{-7} = T^{3/2} \exp\left(-\dfrac{6.40\times10^{3}}{T}\right)$

By trial and error, $T \approx 268°$ K

1.3

Silicon

(a) $$n_i = \left(5.23\times10^{15}\right)\left(100\right)^{3/2}\exp\left[\frac{-1.1}{2\left(86\times10^{-6}\right)\left(100\right)}\right]$$

$$= \left(5.23\times10^{18}\right)\exp\left[-63.95\right]$$

$$\underline{n_i = 8.79\times10^{-10}\ \text{cm}^{-3}}$$

(b) $$n_i = \left(5.23\times10^{15}\right)\left(300\right)^{3/2}\exp\left[\frac{-1.1}{2\left(86\times10^{-6}\right)\left(300\right)}\right]$$

$$= \left(2.718\times10^{19}\right)\exp\left[-21.32\right]$$

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

(c) $$n_i = \left(5.23\times10^{15}\right)\left(500\right)^{3/2}\exp\left[\frac{-1.1}{2\left(86\times10^{-6}\right)\left(500\right)}\right]$$

$$= \left(5.847\times10^{19}\right)\exp\left[-12.79\right]$$

$$\underline{n_i = 1.63\times10^{14}\ \text{cm}^{-3}}$$

Germanium.

(a) $$n_i = \left(1.66\times10^{15}\right)\left(100\right)^{3/2}\exp\left[\frac{-0.66}{2\left(86\times10^{-6}\right)\left(100\right)}\right] = \left(1.66\times10^{18}\right)\exp\left[-38.37\right]$$

$$\underline{n_i = 35.9\ \text{cm}^{-3}}$$

(b) $$n_i = \left(1.66\times10^{15}\right)\left(300\right)^{3/2}\exp\left[\frac{-0.66}{2\left(86\times10^{-6}\right)\left(300\right)}\right] = \left(8.626\times10^{18}\right)\exp\left[-12.79\right]$$

$$\underline{n_i = 2.40\times10^{13}\ \text{cm}^{-3}}$$

(c) $$n_i = \left(1.66\times10^{15}\right)\left(500\right)^{3/2}\exp\left[\frac{-0.66}{2\left(86\times10^{-6}\right)\left(500\right)}\right] = \left(1.856\times10^{19}\right)\exp\left[-7.674\right]$$

$$\underline{n_i = 8.62\times10^{15}\ \text{cm}^{-3}}$$

1.4

a. $N_d = 5\times10^{15}\ \text{cm}^{-3} \Rightarrow \underline{\text{n}-\text{type}}$

$\underline{n_0 = N_d = 5\times10^{15}\ \text{cm}^{-3}}$

$$p_0 = \frac{n_i^2}{n_0} = \frac{\left(1.5\times10^{10}\right)^2}{5\times10^{15}} \Rightarrow \underline{p_0 = 4.5\times10^{4}\ \text{cm}^{-3}}$$

b. $N_d = 5\times10^{15}\ \text{cm}^{-3} \Rightarrow \underline{n-\text{type}}$

$\underline{n_o = N_d = 5\times10^{15}\ \text{cm}^{-3}}$

$$n_i = \left(2.10\times10^{14}\right)\left(300\right)^{3/2}\exp\left(\frac{-1.4}{2(86\times10^{-6})(300)}\right)$$

$$= \left(2.10\times10^{14}\right)\left(300\right)^{3/2}\left(1.65\times10^{-12}\right)$$

$$= 1.80\times10^{6}\ \text{cm}^{-3}$$

$$p_0 = \frac{n_i^2}{n_0} = \frac{\left(1.8\times10^{6}\right)^2}{5\times10^{15}} \Rightarrow \underline{p_0 = 6.48\times10^{-4}\ \text{cm}^{-3}}$$

1.5

(a) n-type

(b) $n_o = N_d = 5\times10^{16}\ \text{cm}^{-3}$

$$p_o = \frac{n_i^2}{n_o} = \frac{\left(1.5\times10^{10}\right)^2}{5\times10^{16}} = 4.5\times10^3\ \text{cm}^{-3}$$

(c) $n_o = N_d = 5\times10^{16}\ \text{cm}^{-3}$

From Problem 1.1(a)(ii) $n_i = 3.97\times10^{11}\ \text{cm}^{-3}$

$$p_o = \frac{\left(3.97\times10^{11}\right)^2}{5\times10^{16}} = 3.15\times10^6\ \text{cm}^{-3}$$

1.6

a. $N_a = 10^{16}\ \text{cm}^{-3} \Rightarrow \underline{p-\text{type}}$

$\underline{p_0 = N_a = 10^{16}\ \text{cm}^{-3}}$

$$n_0 = \frac{n_i^2}{p_0} = \frac{\left(1.5\times10^{10}\right)^2}{10^{16}} \Rightarrow \underline{n_0 = 2.25\times10^4\ \text{cm}^{-3}}$$

b. Germanium

$N_a = 10^{16}\ \text{cm}^{-3} \Rightarrow \underline{p-\text{type}}$

$\underline{p_0 = N_a = 10^{16}\ \text{cm}^{-3}}$

$$n_i = \left(1.66\times10^{15}\right)\left(300\right)^{3/2}\exp\left(\frac{-0.66}{2\left(86\times10^{-6}\right)\left(300\right)}\right)$$

$$= \left(1.66\times10^{15}\right)\left(300\right)^{3/2}\left(2.79\times10^{-6}\right)$$

$$= 2.4\times10^{13}\ \text{cm}^{-3}$$

$$n_0 = \frac{n_i^2}{p_0} = \frac{\left(2.4\times10^{13}\right)^2}{10^{16}} \Rightarrow \underline{n_0 = 5.76\times10^{10}\ \text{cm}^{-3}}$$

1.7

(a) p-type

(b) $p_o = N_a = 2\times10^{17}\ \text{cm}^{-3}$

$$n_o = \frac{n_i^2}{p_o} = \frac{\left(1.5\times10^{10}\right)^2}{2\times10^{17}} = 1.125\times10^3\ \text{cm}^{-3}$$

(c) $p_o = 2\times10^{17}\ \text{cm}^{-3}$

From Problem 1.1(a)(i) $n_i = 1.61\times10^8\ \text{cm}^{-3}$

$$n_o = \frac{\left(1.61\times10^8\right)^2}{2\times10^{17}} = 0.130\ \text{cm}^{-3}$$

1.8

(a) $n_o = 5\times10^{15}\ cm^{-3}$

$$p_o = \frac{n_i^2}{n_o} = \frac{\left(1.5\times10^{10}\right)^2}{5\times10^{15}} \Rightarrow p_o = 4.5\times10^4\ cm^{-3}$$

(b) $n_o \gg p_o \Rightarrow$ n-type

(c) $n_o \cong N_d = 5\times10^{15}\ cm^{-3}$

1.9

a. <u>Add Donors</u>

$\underline{N_d = 7\times10^{15}\ \text{cm}^{-3}}$

b. Want $p_o = 10^6 \text{ cm}^{-3} = n_i^2 / N_d$

So $n_i^2 = (10^6)(7\times10^{15}) = 7\times10^{21}$

$$= B^2T^3 \exp\left(\frac{-Eg}{kT}\right)$$

$$7\times10^{21} = (5.23\times10^{15})^2 T^3 \exp\left(\frac{-1.1}{(86\times10^{-6})(T)}\right)$$

By trial and error, $T \approx 324°$ K

1.10

$I = J\cdot A = \sigma EA$

$I = (2.2)(15)(10^{-4}) \Rightarrow I = 3.3\ mA$

1.11

$$J = \sigma E \Rightarrow \sigma = \frac{J}{E} = \frac{85}{12}$$

$\underline{\sigma = 7.08\ (\text{ohm}-\text{cm})^{-1}}$

1.12

$$g \approx \frac{1}{e\mu_p N_a} \Rightarrow N_a = \frac{1}{e\mu_p g} = \frac{1}{(1.6\times10^{-19})(480)(0.80)}$$

$N_a = 1.63\times10^{16}\ \text{cm}^{-3}$

1.13

$\sigma = e\mu_n N_d$

$$N_d = \frac{\sigma}{e\mu_n} = \frac{(0.5)}{(1.6\times10^{-19})(1350)}$$

$N_d = 2.31\times10^{15}\ \text{cm}^{-3}$

1.14

(a) For n-type, $\sigma \cong e\mu_n N_d = (1.6\times10^{-19})(8500)N_d$

For $10^{15} \le N_d \le 10^{19}\ cm^{-3} \Rightarrow 1.36 \le \sigma \le 1.36\times10^4\ (\Omega - cm)^{-1}$

(b) $J = \sigma E = \sigma(0.1) \Rightarrow 0.136 \le J \le 1.36\times10^3\ A/cm^2$

1.15

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

$$= (1.6\times10^{-19})(180)\left[\frac{10^{15}-10^2}{0.5\times10^{-4}}\right]$$

$\underline{J_n = 576\ \text{A/cm}^2}$

1.16

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

$$= -eD_p \left(10^{15}\right)\left(\frac{-1}{L_p}\right)\exp\left(\frac{-x}{L_p}\right)$$

$$J_p = \frac{\left(1.6\times 10^{-19}\right)(15)\left(10^{15}\right)}{10\times 10^{-4}}\exp\left(\frac{-x}{L_p}\right)$$

$$J_p = 2.4\, e^{-x/L_p}$$

(a) $x = 0 \qquad J_p = 2.4 \text{ A/cm}^2$

(b) $x = 10\ \mu\text{m} \qquad J_p = 2.4\, e^{-1} = 0.883 \text{ A/cm}^2$

(c) $x = 30\ \mu\text{m} \qquad J_p = 2.4\, e^{-3} = 0.119 \text{ A/cm}^2$

1.17

a. $N_a = 10^{17} \text{ cm}^{-3} \Rightarrow \underline{p_o = 10^{17} \text{ cm}^{-3}}$

$$n_o = \frac{n_i^2}{p_o} = \frac{\left(1.8\times 10^{6}\right)^2}{10^{17}} \Rightarrow \underline{n_o = 3.24\times 10^{-5} \text{ cm}^{-3}}$$

b. $n = n_o + \delta n = 3.24\times 10^{-5} + 10^{15} \Rightarrow \underline{n = 10^{15} \text{ cm}^{-3}}$

$p = p_o + \delta p = 10^{17} + 10^{15} \Rightarrow \underline{p = 1.01\times 10^{17} \text{ cm}^{-3}}$

1.18

(a) $$V_{bi} = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$= (0.026)\ln\left[\frac{\left(10^{16}\right)\left(10^{16}\right)}{\left(1.5\times 10^{10}\right)^2}\right] = 0.697 \text{ V}$$

(b) $$V_{bi} = (0.026)\ln\left[\frac{\left(10^{18}\right)\left(10^{16}\right)}{\left(1.5\times 10^{10}\right)^2}\right] = 0.817 \text{ V}$$

(c) $$V_{bi} = (0.026)\ln\left[\frac{\left(10^{18}\right)\left(10^{18}\right)}{\left(1.5\times 10^{10}\right)^2}\right] = 0.937 \text{ V}$$

1.19

$$V_{bi} = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

a. $$V_{bi} = (0.026)\ln\left[\frac{\left(10^{16}\right)\left(10^{16}\right)}{(1.8\times 10^{6})^2}\right] \Rightarrow V_{bi} = 1.17 \text{ V}$$

b. $$V_{bi} = (0.026)\ln\left[\frac{\left(10^{18}\right)\left(10^{16}\right)}{(1.8\times 10^{6})^2}\right] \Rightarrow V_{bi} = 1.29 \text{ V}$$

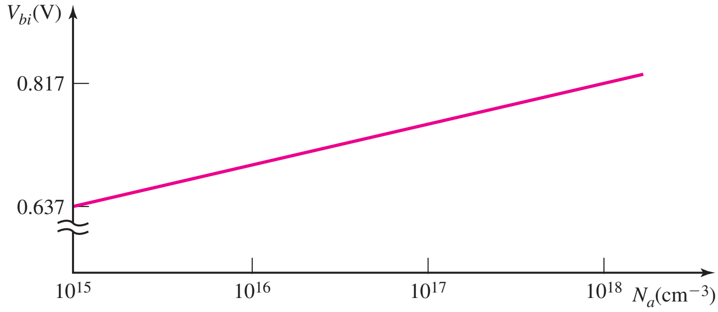
c. $$V_{bi} = (0.026)\ln\left[\frac{\left(10^{18}\right)\left(10^{18}\right)}{(1.8\times 10^{6})^2}\right] \Rightarrow V_{bi} = 1.41 \text{ V}$$

1.20

$$V_{bi} = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right) = (0.026)\ln\left[\frac{N_a\left(10^{16}\right)}{(1.5\times 10^{10})^2}\right]$$

For $N_a = 10^{15}\ cm^{-3}$, $V_{bi} = 0.637\ V$

For $N_a = 10^{18}\ cm^{-3}$, $V_{bi} = 0.817\ V$



1.21

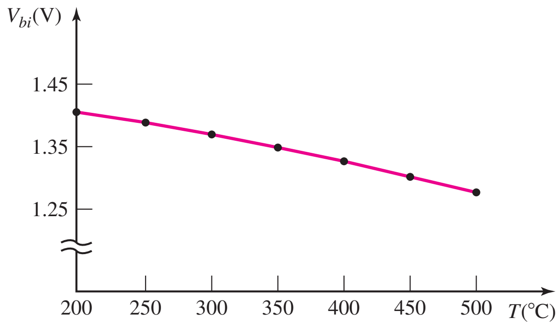
$$kT = (0.026)\left(\frac{T}{300}\right)$$

T	kT	$(T)^{3/2}$
200	0.01733	2828.4
250	0.02167	3952.8
300	0.026	5196.2
350	0.03033	6547.9
400	0.03467	8000.0
450	0.0390	9545.9
500	0.04333	11,180.3

$$n_i = \left(2.1\times10^{14}\right)\left(T^{3/2}\right)\exp\left(\frac{-1.4}{2\left(86\times10^{-6}\right)(T)}\right)$$

$$V_{bi} = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

T	n_i	V_{bi}
200	1.256	1.405
250	6.02×10^3	1.389
300	1.80×10^6	1.370
350	1.09×10^8	1.349
400	2.44×10^9	1.327
450	2.80×10^{10}	1.302
500	2.00×10^{11}	1.277



1.22

$$C_j = C_{jo}\left(1+\frac{V_R}{V_{bi}}\right)^{-1/2}$$

$$V_{bi} = (0.026)\ln\left[\frac{(1.5\times10^{16})(4\times10^{15})}{(1.5\times10^{10})^2}\right] = 0.684 \text{ V}$$

(a) $C_j = (0.4)\left(1+\dfrac{1}{0.684}\right)^{-1/2} = 0.255 \text{ pF}$

(b) $C_j = (0.4)\left(1+\dfrac{3}{0.684}\right)^{-1/2} = 0.172 \text{ pF}$

(c) $C_j = (0.4)\left(1+\dfrac{5}{0.684}\right)^{-1/2} = 0.139 \text{ pF}$

1.23

(a) $C_j = C_{jo}\left(1+\dfrac{V_R}{V_{bi}}\right)^{-1/2}$

For $V_R = 5\ V$, $C_j = (0.02)\left(1+\dfrac{5}{0.8}\right)^{-1/2} = 0.00743\ pF$

For $V_R = 1.5\ V$, $C_j = (0.02)\left(1+\dfrac{1.5}{0.8}\right)^{-1/2} = 0.0118\ pF$

$C_j(avg) = \dfrac{0.00743+0.0118}{2} = 0.00962\ pF$

$v_C(t) = v_C(final) + (v_C(initial) - v_C(final))e^{-t/\tau}$

where

$\tau = RC = RC_j(avg) = (47\times10^3)(0.00962\times10^{-12})$

or

$\tau = 4.52\times10^{-10}\ s$

Then $v_C(t) = 1.5 = 0 + (5-0)e^{-t_1/\tau}$

$\dfrac{5}{1.5} = e^{+t_1/\tau} \Rightarrow t_1 = \tau\ln\left(\dfrac{5}{1.5}\right)$

$\underline{t_1 = 5.44\times10^{-10}\ s}$

(b) For $V_R = 0\ V$, $C_j = C_{jo} = 0.02\ pF$

For $V_R = 3.5\ V$, $C_j = (0.02)\left(1+\dfrac{3.5}{0.8}\right)^{-1/2} = 0.00863\ pF$

$C_j(avg) = \dfrac{0.02+0.00863}{2} = 0.0143\ pF$

$\tau = RC_j(avg) = 6.72\times10^{-10}\ s$

$v_C(t) = v_C(final) + (v_C(initial) - v_C(final))e^{-t/\tau}$

$3.5 = 5 + (0-5)e^{-t_2/\tau} = 5(1-e^{-t_2/\tau})$

so that $\underline{t_2 = 8.09\times10^{-10}\ s}$

1.24

$$V_{bi} = (0.026)\ln\left[\frac{(10^{18})(10^{15})}{(1.5\times10^{10})^2}\right] = 0.757 \text{ V}$$

a. $V_R = 1 \text{ V}$

$C_j = (0.25)\left(1+\dfrac{1}{0.757}\right)^{-1/2} = 0.164 \text{ pF}$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{\left(2.2\times10^{-3}\right)\left(0.164\times10^{-12}\right)}}$$

$\underline{f_0 = 8.38 \text{ MHz}}$

b. $V_R = 10$ V

$$C_j = (0.25)\left(1+\frac{10}{0.757}\right)^{-1/2} = 0.0663 \text{ pF}$$

$$f_0 = \frac{1}{2\pi\sqrt{\left(2.2\times10^{-3}\right)\left(0.0663\times10^{-12}\right)}}$$

$\underline{f_0 = 13.2 \text{ MHz}}$

1.25

a. $$I = I_S\left[\exp\left(\frac{V_D}{V_T}\right)-1\right] - 0.90 = \exp\left(\frac{V_D}{V_T}\right)-1$$

$$\exp\left(\frac{V_D}{V_T}\right) = 1-0.90 = 0.10$$

$V_D = V_T \ln\left(0.10\right) \Rightarrow \underline{V_D = -0.0599 \text{ V}}$

b.

$$\left|\frac{I_F}{I_R}\right| = \frac{I_S}{I_S}\cdot\frac{\left[\exp\left(\frac{V_F}{V_T}\right)-1\right]}{\left[\exp\left(\frac{V_R}{V_T}\right)-1\right]} = \left|\frac{\exp\left(\frac{0.2}{0.026}\right)-1}{\exp\left(\frac{-0.2}{0.026}\right)-1}\right|$$

$$= \left|\frac{2190}{-1}\right|$$

$$\underline{\frac{I_F}{I_R} = 2190}$$

1.26

a.

$I \cong (10^{-11})\exp\left(\frac{0.5}{0.026}\right) \Rightarrow \underline{I = 2.25 \text{ mA}}$

$I = (10^{-11})\exp\left(\frac{0.6}{0.026}\right) \Rightarrow \underline{I = 0.105 \text{ A}}$

$I = (10^{-11})\exp\left(\frac{0.7}{0.026}\right) \Rightarrow \underline{I = 4.93 \text{ A}}$

b.

$I \cong (10^{-13})\exp\left(\frac{0.5}{0.026}\right) \Rightarrow \underline{I = 22.5\ \mu\text{A}}$

$I = (10^{-13})\exp\left(\frac{0.6}{0.026}\right) \Rightarrow \underline{I = 1.05 \text{ mA}}$

$I = (10^{-13})\exp\left(\frac{0.7}{0.026}\right) \Rightarrow \underline{I = 49.3 \text{ mA}}$

1.27

(a) $I = I_S\left(e^{V_D/V_T}-1\right)$

$150\times10^{-6} = 10^{-11}\left(e^{V_D/V_T}-1\right) \cong 10^{-11}e^{V_D/V_T}$

Then $V_D = V_T \ln\left(\frac{150\times10^{-6}}{10^{-11}}\right) = (0.026)\ln\left(\frac{150\times10^{-6}}{10^{-11}}\right)$

Or $\underline{V_D = 0.430\ V}$

(b)

$V_D = V_T \ln\left(\frac{150\times10^{-6}}{10^{-13}}\right)$

Or $\underline{V_D = 0.549\ V}$

1.28

(a) $10^{-3} = I_S \exp\left(\frac{0.7}{0.026}\right)$

$I_S = 2.03\times10^{-15}$ A

(b)

V_D	$I_D(A)(n=1)$	$I_D(A)(n=2)$
0.1	9.50×10^{-14}	1.39×10^{-14}
0.2	4.45×10^{-12}	9.50×10^{-14}
0.3	2.08×10^{-10}	6.50×10^{-13}
0.4	9.75×10^{-9}	4.45×10^{-12}
0.5	4.56×10^{-7}	3.04×10^{-11}
0.6	2.14×10^{-5}	2.08×10^{-10}
0.7	10^{-3}	1.42×10^{-9}

1.29

(a)

$I_S = 10^{-12}\,A$

V_D(v)	I_D(A)	$\log_{10} I_D$
0.10	4.68×10^{-11}	−10.3
0.20	2.19×10^{-9}	−8.66
0.30	1.03×10^{-7}	−6.99
0.40	4.80×10^{-6}	−5.32
0.50	2.25×10^{-4}	−3.65
0.60	1.05×10^{-2}	−1.98
0.70	4.93×10^{-1}	−0.307

(b)

$I_S = 10^{-14}\,A$

V_D(v)	I_D(A)	$\log_{10} I_D$
0.10	4.68×10^{-13}	−12.3
0.20	2.19×10^{-11}	−10.66
0.30	1.03×10^{-9}	−8.99
0.40	4.80×10^{-8}	−7.32
0.50	2.25×10^{-6}	−5.65
0.60	1.05×10^{-4}	−3.98
0.70	4.93×10^{-3}	−2.31

1.30

a.

$$\frac{I_{D2}}{I_{D1}} = 10 = \exp\left(\frac{V_{D2}-V_{D1}}{V_T}\right)$$

$\Delta V_D = V_T \ln(10) \Rightarrow \underline{\Delta V_D = 59.9\text{ mV} \approx 60\text{ mV}}$

b. $\Delta V_D = V_T \ln(100) \Rightarrow \underline{\Delta V_D = 119.7 \text{ mV} \approx 120 \text{ mV}}$

1.31

(a) (i) $V_D = V_t \ln\left(\frac{I_D}{I_S}\right) = (0.026)\ln\left(\frac{150\times10^{-6}}{10^{-15}}\right)$

$V_D = 0.669$ V

(ii) $V_D = (0.026)\ln\left(\frac{25\times10^{-6}}{10^{-15}}\right)$

$V_D = 0.622$ V

(b) (i) $I_D = (10^{-15})\exp\left(\frac{0.2}{0.026}\right) = 2.19\times10^{-12}$ A

(ii) $I_D = 0$

(iii) $I_D = -10^{-15}$ A

(iv) $I_D = -10^{-15}$ A

1.32

$V_D = V_t \ln\left(\frac{I_D}{I_S}\right) = (0.026)\ln\left(\frac{2\times10^{-3}}{5\times10^{-14}}\right) = 0.6347$ V

$V_D = (0.026)\ln\left(\frac{2\times10^{-3}}{5\times10^{-12}}\right) = 0.5150$ V

$\underline{0.5150 \le V_D \le 0.6347 \text{ V}}$

1.33

(a) $I_D = I_S \exp\left(\frac{V_D}{V_t}\right)$

$12\times10^{-3} = I_S \exp\left(\frac{1.10}{0.026}\right) \Rightarrow \underline{I_S = 5.07\times10^{-21} \text{ A}}$

(b) $I_D = (5.07\times10^{-21}) \exp\left(\frac{1.0}{0.026}\right)$

$\underline{I_D = 2.56\times10^{-4} \text{A} = 0.256 \text{ mA}}$

1.34

(a) $I_D = 10^{-23}\exp\left(\frac{1.0}{0.026}\right) = 5.05\times10^{-7}$ A

(b) $I_D = 10^{-23}\exp\left(\frac{1.1}{0.026}\right) = 2.37\times10^{-5}$ A

(c) $I_D = 10^{-23}\exp\left(\frac{1.2}{0.026}\right) = 1.11\times10^{-3}$ A

1.35

I_S doubles for every 5C increase in temperature.

$I_S = 10^{-12}\ A$ at T = 300K

For $I_S = 0.5\times10^{-12}\ A \quad \Rightarrow$ <u>T = 295 K</u>

For $I_S = 50\times10^{-12}\ A,\quad (2)^n = 50 \Rightarrow n = 5.64$

Where n equals number of 5C increases.

Then $\Delta T = (5.64)(5) = 28.2\ K$

So $\underline{295 \le T \le 328.2\ K}$

1.36

$$\frac{I_S(T)}{I_S(-55)} = 2^{\Delta T/5}, \quad \Delta T = 155° \text{ C}$$

$$\frac{I_S(100)}{I_S(-55)} = 2^{155/5} = 2.147\times10^9$$

V_T @100°C ⇒ 373°K ⇒ $V_T = 0.03220$

V_T @− 55°C ⇒ 216°K ⇒ $V_T = 0.01865$

$$\frac{I_D(100)}{I_D(-55)} = (2.147\times10^9)\times\frac{\exp\left(\frac{0.6}{0.0322}\right)}{\exp\left(\frac{0.6}{0.01865}\right)}$$

$$= \frac{\left(2.147\times10^9\right)\left(1.237\times10^8\right)}{\left(9.374\times10^{13}\right)}$$

$$\underline{\frac{I_D(100)}{I_D(-55)} = 2.83\times10^3}$$

1.37

$3.5 = I_D\,(10^5) + V_D$

(a) $I_D = 5\times10^{-9}\exp\left(\frac{V_D}{0.026}\right) \Rightarrow V_D = 0.026\ \ln\left(\frac{I_D}{5\times10^{-9}}\right)$

Trial and error.

V_D	I_D	V_D
0.50	3×10^{-5}	0.226
0.40	3.1×10^{-5}	0.227
0.250	3.25×10^{-5}	0.228
0.229	3.271×10^{-5}	0.2284
0.2285	3.2715×10^{-5}	0.2284

So $V_D \cong 0.2285$ V

$I_D \cong 3.272\times10^{-5}$ A

(b) $\underline{I_D = I_S = 5\times10^{-9}\,\text{A}}$

$V_R = \left(5\times10^{-9}\right)\left(10^5\right) = 5\times10^{-4}$ V

$\underline{V_D = 3.4995 \text{ V}}$

1.38

$10 = I_D\left(2\times10^4\right) + V_D$ and $V_D = (0.026)\ln\left(\frac{I_D}{10^{-12}}\right)$

Trial and error.

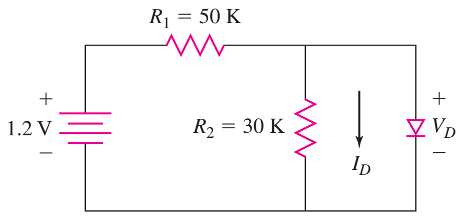
V_D(v)	I_D(A)	V_D(v)
0.50	4.75×10^{-4}	0.5194
0.517	4.7415×10^{-4}	0.5194
0.5194	4.740×10^{-4}	0.5194

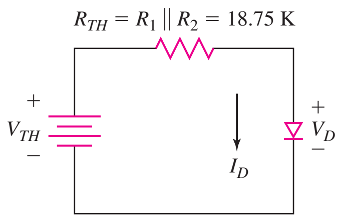
$\underline{V_D = 0.5194 \text{ V}}$

$\underline{I_D = 0.4740 \text{ mA}}$

1.39

$I_s = 5\times10^{-13}$ A





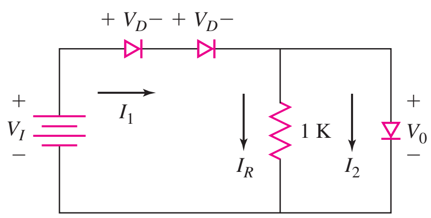
$$V_{TH} = \left(\frac{R_2}{R_1+R_2}\right)(1.2) = \left(\frac{30}{80}\right)(1.2) = 0.45 \text{ V}$$

$$0.45 = I_D R_{TH} + V_D, \quad V_D = V_T \ln\left(\frac{I_D}{I_S}\right)$$

By trial and error:

$\underline{I_D = 2.56\ \mu\text{A}}, \quad \underline{V_D = 0.402 \text{ V}}$

1.40



$I_S = 2\times10^{-13}\ A$

$V_0 = 0.60$ V

$$I_2 = I_S \exp\left(\frac{V_0}{V_T}\right) = \left(2\times10^{-13}\right)\exp\left(\frac{0.60}{0.026}\right)$$

$$= 2.105 \text{ mA}$$

$$I_R = \frac{0.6}{1\text{ K}} = 0.60 \text{ mA}$$

$$I_1 = I_2 + I_R = 2.705 \text{ mA}$$

$$V_D = V_T \ln\left(\frac{I_1}{I_S}\right) = (0.026)\ln\left(\frac{2.705\times10^{-3}}{2\times10^{-13}}\right)$$

$$= 0.6065$$

$$V_I = 2V_D + V_0 \Rightarrow \underline{V_I = 1.81 \text{ V}}$$

1.41

(a) Assume diode is conducting.

Then, $V_D = V_\gamma = 0.7\ V$

So that $I_{R2} = \dfrac{0.7}{30} \Rightarrow 23.3\ \mu A$

$I_{R1} = \frac{1.2-0.7}{10} \Rightarrow 50\ \mu A$

Then $I_D = I_{R1} - I_{R2} = 50 - 23.3$

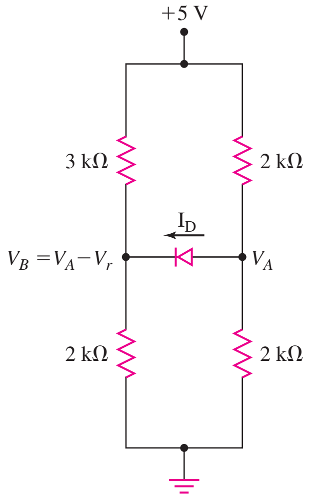
Or $\underline{I_D = 26.7\ \mu A}$

(b) Let $R_1 = 50\ k\Omega$ Diode is cutoff.

$V_D = \frac{30}{30+50} \cdot (1.2) = 0.45\ V$

Since $V_D < V_\gamma$, $I_D = 0$

1.42



$A\&V_A$:

(1) $\frac{5-V_A}{2} = I_D + \frac{V_A}{2}$

$A\&V_A - V_r$

(2) $\frac{5-(V_A-V_r)}{2} + I_D = \frac{(V_A-V_r)}{2}$

So $\frac{5-(V_A-V_r)}{3} + \left[\frac{5-V_A}{2} - \frac{V_A}{2}\right] = \frac{V_A-V_r}{2}$

Multiply by 6:

$10 - 2(V_A - V_r) + 15 - 6V_A = 3(V_A - V_r)$

$25 + 2V_r + 3V_r = 11V_A$

(a) $V_r = 0.6$ V

$11V_A = 25 + 5(0.6) = 28 \Rightarrow V_A = 2.545$ V

From (1) $I_D = \frac{5-V_A}{2} - \frac{V_A}{2} = 2.5 - V_A \Rightarrow I_D$ Neg. $\Rightarrow \underline{I_D = 0}$

Both (a), (b) $\underline{I_D = 0}$

$V_A = 2.5,\ V_B = \frac{2}{5} \cdot 5 = 2\text{ V} \Rightarrow \underline{V_D = 0.50\text{ V}}$

1.43

Minimum diode current for V_{PS} (min)

$I_D(\text{min}) = 2\ mA,\quad V_D = 0.7\ V$

$I_2 = \frac{0.7}{R_2},\quad I_1 = \frac{5-0.7}{R_1} = \frac{4.3}{R_1}$

We have $I_1 = I_2 + I_D$

so (1) $\quad \dfrac{4.3}{R_1} = \dfrac{0.7}{R_2} + 2$

Maximum diode current for V_{PS}(max)

$P = I_D V_D \quad 10 = I_D(0.7) \Rightarrow I_D = 14.3\ mA$

$I_1 = I_2 + I_D$

or

(2) $\quad \dfrac{9.3}{R_1} = \dfrac{0.7}{R_2} + 14.3$

Using Eq. (1), $\dfrac{9.3}{R_1} = \dfrac{4.3}{R_1} - 2 + 14.3 \Rightarrow \quad \underline{R_1 = 0.41\ k\Omega}$

Then $\underline{R_2 = 82.5\Omega} \quad 82.5\Omega$

1.44

(a) $\quad V_o = 0.7$ V

$I = \dfrac{5-0.7}{20} \Rightarrow I = 0.215$ mA

(b) $\quad I = \dfrac{10-0.7}{20+20} \Rightarrow I = 0.2325$ mA

$V_o = I(20\text{ K}) - 5 \Rightarrow V_o = -0.35$ V

(c) $\quad I = \dfrac{10-0.7}{5+20} \Rightarrow I = 0.372$ mA

$V_o = 0.7 + I(20) - 8 \Rightarrow V_o = +0.14$ V

(d) $\quad I = 0$

$V_o = I(20) - 5 \Rightarrow \underline{V_o = -5\ \text{V}}$

1.45

(a) $\quad 5 = I\left(2\times10^9\right) + V_D \qquad V_D = (0.026)\ln\left(\dfrac{I}{2\times10^{-12}}\right)$

V_D →	I_D →	V_D	$V_o = V_D = 0.482$ V
0.6	2.2×10^{-4}	0.481	
0.482	2.259×10^{-4}	0.482	$\underline{I = 0.226\ mA}$

(b) $\quad 10 = I\left(4\times10^4\right) + V_D \qquad V_D = (0.026)\ln\left(\dfrac{I}{2\times10^{-12}}\right)$

V_o →	I →	V_D	$V_D = 0.483\ V$
0.5	2.375×10^{-4}	0.4834	$I = 0.238\ mA$
0.484	2.379×10^{-4}	0.4834	$V_o = -0.24\ V$

(c) $\quad 10 = I\left(2.5\times10^4\right) + V_D \qquad V_D = (0.026)\ln\left(\dfrac{I}{2\times10^{-12}}\right)$

V_o →	I →	V_D	$V_D = 0.496\ V$
0.480	3.808×10^{-4}	0.496	$I = 0.380\ mA$
0.496	3.802×10^{-4}	0.496	$V_o = -0.10\ V$

(d) $\quad I = -I_S \Rightarrow \quad \underline{I = 2\times10^{-12}\text{ A}}$

$\underline{V_o \cong -5\text{ V}}$

1.46

(a) $\quad$ Diode forward biased $V_D = 0.7$ V

$5 = (0.4)(4.7) + 0.7 + V \Rightarrow \underline{V = 2.42 \text{ V}}$

(b) $\quad P = I \cdot V_D = (0.4)(0.7) \Rightarrow \underline{P = 0.28 \text{ m}\omega}$

1.47

(a) $\quad I_{R2} = I_{D1} = \dfrac{0.65}{1} = \underline{0.65 \text{ mA} = I_{D1}}$

$$I_{D2} = 2(0.65) = 1.30 \text{ mA}$$

$$I_{D2} = \frac{V_I - 2V_r - V_0}{R_1} = \frac{5 - 3(0.65)}{R_1} = 1.30 \Rightarrow \underline{R_1 = 2.35 \text{ K}}$$

(b) $\quad I_{R2} = \dfrac{0.65}{1} = 0.65 \text{ mA}$

$$I_{D2} = \frac{8 - 3(0.65)}{2} \Rightarrow \underline{I_{D2} = 3.025 \text{ mA}}$$

$$I_{D1} = I_{D2} - I_{R2} = 3.025 - 0.65$$

$$\underline{I_{D1} = 2.375 \text{ mA}}$$

1.48

a. $\quad \tau_d = \dfrac{V_T}{I_{DQ}} = \dfrac{(0.026)}{1} = 0.026 \text{ k}\Omega = 26\Omega$

$$i_d = 0.05 I_{DQ} = 50\ \mu\text{A} \quad \text{peak-to-peak}$$

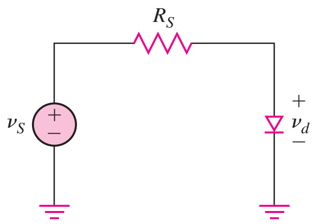
$$v_d = i_d \tau_d = (26)(50)\ \ \mu\text{A} \Rightarrow \underline{v_d = 1.30 \text{ mV} \ \ \text{peak-to-peak}}$$

b. $\quad$ For $I_{DQ} = 0.1 \text{ mA} \Rightarrow \tau_d = \dfrac{(0.026)}{0.1} = 260\Omega$

$i_d = 0.05 I_{DQ} = 5\ \mu\text{A}$ peak-to-peak

$v_d = i_d \tau_d = (260)(5)\ \ \mu\text{V} \Rightarrow \underline{v_d = 1.30 \text{ mV} \ \ \text{peak-to-peak}}$

1.49



a. $\quad$ diode resistance $r_d = V_T / I$

$$v_d = \left(\frac{r_d}{r_d + R_S}\right) v_S = \left(\frac{V_T/I}{\dfrac{V_T}{I} + R_S}\right) v_S$$

$$v_d = \left(\frac{V_T}{V_T + IR_S}\right) v_s = v_o$$

b. $\quad R_S = 260\Omega$

$$I = 1 \text{ mA}, \ \frac{v_0}{v_S} = \left(\frac{V_T}{V_T + IR_S}\right) = \frac{0.026}{0.026 + (1)(0.26)} \Rightarrow \underline{\frac{v_0}{v_S} = 0.0909}$$

$$I = 0.1 \text{ mA}, \ \frac{v_0}{v_s} = \frac{0.026}{0.026 + (0.1)(0.26)} \Rightarrow \underline{\frac{v_0}{v_S} = 0.50}$$

$$I = 0.01 \text{ mA}. \ \frac{v_0}{v_S} = \frac{0.026}{0.026 + (0.01)(0.26)} \Rightarrow \underline{\frac{v_0}{v_S} = 0.909}$$

1.50

$$I \cong I_S \exp\left(\frac{V_a}{V_T}\right), \quad V_a = V_T \ln\left(\frac{I}{I_S}\right)$$

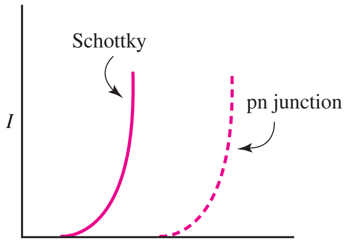
pn junction, $V_a = (0.026) \ln\left(\frac{100 \times 10^{-6}}{10^{-14}}\right)$

$\underline{V_a = 0.599 \text{ V}}$

Schottky diode, $V_a = (0.026) \ln\left(\frac{100 \times 10^{-6}}{10^{-9}}\right)$

$\underline{V_a = 0.299 \text{ V}}$

1.51



Schottky: $I \cong I_S \exp\left(\frac{V_a}{V_T}\right)$

$$V_a = V_T \ln\left(\frac{I}{I_S}\right) = (0.026) \ln\left(\frac{0.5 \times 10^{-3}}{5 \times 10^{-7}}\right)$$
$$= 0.1796 \ V$$

Then

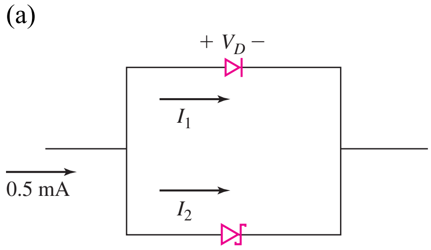
V_a of pn junction $= 0.1796 + 0.30$
$= 0.4796$

$$I_S = \frac{I}{\exp\left(\frac{V_a}{V_T}\right)} = \frac{0.5 \times 10^{-3}}{\exp\left(\frac{0.4796}{0.026}\right)}$$

$\underline{I_S = 4.87 \times 10^{-12} \text{ A}}$

1.52

(a)



$I_1 + I_2 = 0.5 \times 10^{-3}$

$$5\times10^{-8}\ \exp\left(\frac{V_D}{V_T}\right)+10^{-12}\ \exp\left(\frac{V_D}{V_T}\right)=0.5\times10^{-3}$$

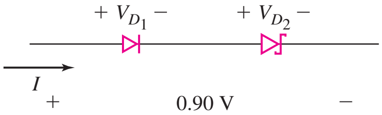
$$5.0001\times10^{-8}\ \exp\left(\frac{V_D}{V_T}\right)=0.5\times10^{-3}$$

$$V_D=(0.026)\ \ln\left(\frac{0.5\times10^{-3}}{5.0001\times10^{-8}}\right)\Rightarrow \underline{V_D=0.2395}$$

Schottky diode, $\underline{I_2=0.49999\text{ mA}}$

pn junction, $\underline{I_1=0.00001\text{ mA}}$

(b)



$$I=10^{-12}\ \exp\left(\frac{V_{D1}}{V_T}\right)=5\times10^{-8}\ \exp\left(\frac{V_{D2}}{V_T}\right)$$

$$V_{D1}+V_{D2}=0.9$$

$$10^{-12}\ \exp\left(\frac{V_{D1}}{V_T}\right)=5\times10^{-8}\ \exp\left(\frac{0.9-V_{D1}}{V_T}\right)$$

$$=5\times10^{-8}\ \exp\left(\frac{0.9}{V_T}\right)\exp\left(\frac{-V_{D1}}{V_T}\right)$$

$$\exp\left(\frac{2V_{D1}}{V_T}\right)=\left(\frac{5\times10^{-8}}{10^{-12}}\right)\ \exp\left(\frac{0.9}{0.026}\right)$$

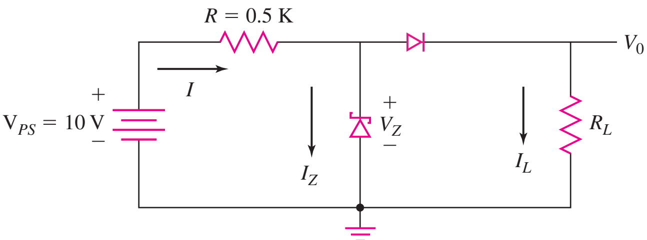
$$2V_{D1}=V_T\ \ln\left(\frac{5\times10^{-8}}{10^{-12}}\right)+0.9=1.1813$$

$\underline{V_{D1}=0.5907}$ pn junction

$\underline{V_{D2}=0.3093}$ Schottky diode

$$I=10^{-12}\ \exp\left(\frac{0.5907}{0.026}\right)\Rightarrow \underline{I=7.35\text{ mA}}$$

1.53



$V_Z=V_{Z0}=5.6\text{ V at }I_Z=0.1\text{ mA}$

$r_Z=10\Omega$

$I_Zr_Z=(0.1)(10)=1\text{ mV}$

$V_{Z0}=5.599$

a. $R_L\to\infty\Rightarrow$

$$I_Z=\frac{10-5.599}{R+r_Z}=\frac{4.401}{0.50+0.01}=8.63\text{ mA}$$

$$V_Z=V_{Z0}+I_Zr_Z=5.599+(0.00863)(10)$$

$\underline{V_Z=V_0=5.685\text{ V}}$

b. $V_{PS} = 11 \text{ V} \Rightarrow I_Z = \dfrac{11 - 5.599}{0.51} = 10.59 \text{ mA}$

$V_Z = V_0 = 5.599 + (0.01059)(10) = 5.7049 \text{ V}$

$V_{PS} = 9 \text{ V} \Rightarrow I_Z = \dfrac{9 - 5.599}{0.51} = 6.669 \text{ mA}$

$V_Z = V_0 = 5.599 + (0.006669)(10) = 5.66569 \text{ V}$

$\Delta V_0 = 5.7049 - 5.66569 \Rightarrow \underline{\Delta V_0 = 0.0392 \text{ V}}$

c. $I = I_Z + I_L$

$I_L = \dfrac{V_0}{R_L}, \quad I = \dfrac{V_{PS} - V_0}{R}, \quad I_Z = \dfrac{V_0 - V_{Z0}}{r_Z}$

$\dfrac{10 - V_0}{0.50} = \dfrac{V_0 - 5.599}{0.010} + \dfrac{V_0}{2}$

$\dfrac{10}{0.50} + \dfrac{5.599}{0.010} = V_0 \left[\dfrac{1}{0.50} + \dfrac{1}{0.010} + \dfrac{1}{2} \right]$

$20.0 + 559.9 = V_0\,(102.5)$

$\underline{V_0 = 5.658 \text{ V}}$

1.54

a. $I_Z = \dfrac{9 - 6.8}{0.2} \Rightarrow \underline{I_Z = 11 \text{ mA}}$

$P_Z = (11)(6.8) \Rightarrow \underline{P_Z = 74.8 \text{ mW}}$

b. $I_Z = \dfrac{12 - 6.8}{0.2} \Rightarrow \underline{I_Z = 26 \text{ mA}}$

$\% = \dfrac{26 - 11}{11} \times 100 \Rightarrow \underline{136\%}$

$P_Z = (26)(6.8) = 176.8 \text{ mW}$

$\% = \dfrac{176.8 - 74.8}{74.8} \times 100 \Rightarrow \underline{136\%}$

1.55

$I_Z r_Z = (0.1)(20) = 2 \text{ mV}$

$V_{Z0} = 6.8 - 0.002 = 6.798 \text{ V}$

a. $R_L = \infty$

$I_Z = \dfrac{10 - 6.798}{0.5 + 0.02} \Rightarrow I_Z = 6.158 \text{ mA}$

$V_0 = V_Z = V_{Z0} + I_Z r_Z = 6.798 + (0.006158)(20)$

$\underline{V_0 = 6.921 \text{ V}}$

b. $I = I_Z + I_L$

$\dfrac{10 - V_0}{0.50} = \dfrac{V_0 - 6.798}{0.020} + \dfrac{V_0}{1}$

$\dfrac{10}{0.30} + \dfrac{6.798}{0.020} = V_0 \left[\dfrac{1}{0.50} + \dfrac{1}{0.020} + \dfrac{1}{1} \right]$

$359.9 = V_0\,(53)$

$V_0 = 6.791 \text{ V}$

$\Delta V_0 = 6.791 - 6.921$

$\underline{\Delta V_0 = -0.13 \text{ V}}$

1.56