

**Chapter 1**  
**Exercise Problems**

**EX1.1**

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

$$\text{GaAs: } n_i = (2.1 \times 10^{14})(300)^{3/2} \exp\left(\frac{-1.4}{2(86 \times 10^{-6})(300)}\right) \text{ or } \underline{n_i = 1.8 \times 10^6 \text{ cm}^{-3}}$$

$$\text{Ge: } n_i = (1.66 \times 10^{13})(300)^{3/2} \exp\left(\frac{-0.66}{2(86 \times 10^{-6})(300)}\right) \text{ or } \underline{n_i = 2.40 \times 10^{13} \text{ cm}^{-3}}$$

**EX1.2**

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

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

(b) majority carrier: electrons,  $n_o = 5 \times 10^{15} \text{ cm}^{-3}$  minority carrier: holes,

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

**EX1.3**

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

**EX1.4**

Diffusion current density due to holes:

$$\begin{aligned} J_p &= -eD_p \frac{dp}{dx} \\ &= -eD_p (10^{16}) \left(\frac{-1}{L_p}\right) \exp\left(\frac{-x}{L_p}\right) \end{aligned}$$

(a) At  $x = 0$

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

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

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

**EX1.5**

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

**EX1.6**

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

and

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

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

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

or

$$C_{jo} = 2.21 \text{ pF}$$

### EX1.7

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

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

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

or

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

which yields

$$v_D = 0.599 \text{ V}$$

### EX1.8

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

$$\text{so } 4 = I_D (4 \times 10^3) + V_D \Rightarrow I_D = \frac{(4 - V_D)}{4 \times 10^3}$$

and

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

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

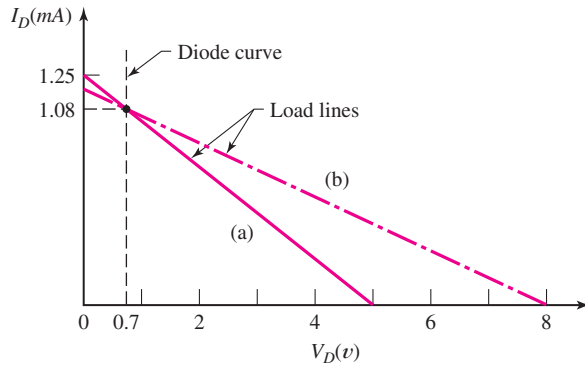
### EX1.9

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

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

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

(c)



### EX1.10

PSpice analysis

### EX1.11

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

Time-varying diode current:

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

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

### EX1.12

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

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

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

or

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

### EX1.13

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

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

### Test Your Understanding Exercises

#### TYU1.1

(a)  $T = 400 \text{ K}$

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

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

or

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

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

or

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

GaAs:

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

or

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

(b)  $T = 250 \text{ K}$

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

or

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

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

or

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

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

or

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

### TYU1.2

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

or

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

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

or

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

### TYU1.3

$$J = \sigma E = (10)(15) \quad \text{or} \quad J = 150 \text{ A/cm}^2$$

### TYU1.4

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

or

$$J_n = 202 \text{ A/cm}^2$$

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

or

$$J_p = -24.5 \text{ A/cm}^2$$

### TYU1.5

(a)  $n_o = N_d = 8 \times 10^{15} \text{ cm}^{-3}$   

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

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

**TYU1.6**

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

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

**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

$V_D = 0.5 \text{ V}, I_D = 2.25 \mu\text{A}$

$V_D = 0.6 \text{ V}, I_D = 0.105 \text{ mA}$

$V_D = 0.7 \text{ V}, I_D = 4.93 \text{ mA}$

(b)  $I_D \cong -I_S = -10^{-14} \text{ A}$

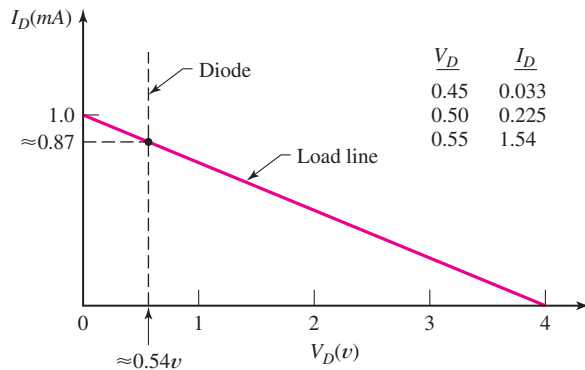
for both cases.

**TYU1.8**

$\Delta T = 100\text{C}$  so  $\Delta V_D \cong 2 \times 100 = 200 \text{ mV}$

Then  $V_D = 0.650 - 0.20 = 0.450 \text{ V}$

**TYU1.9**



**TYU1.10**

$P = I_D V_D \Rightarrow 1.05 = I_D (0.7)$  so  $I_D = 1.5 \text{ mA}$

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

**TYU1.11**

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

**TYU1.12**

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

or

$$I_D = 0.52 \text{ mA}$$

**TYU1.13**

For the pn junction diode,

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

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

**TYU1.14**

$$V_z = V_{z0} + I_z r_z \Rightarrow V_{z0} = V_z - I_z r_z \text{ so } V_{z0} = 5.20 - (10^{-3})(20) = 5.18 \text{ V}$$

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

**Chapter 1**  
**Problem Solutions**

1.1

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

(a) Silicon

$$\begin{aligned} \text{(i)} \quad n_i &= (5.23 \times 10^{15})(250)^{3/2} \exp\left[\frac{-1.1}{2(86 \times 10^{-6})(250)}\right] \\ &= 2.067 \times 10^{19} \exp[-25.58] \\ \underline{n_i} &= \underline{1.61 \times 10^8 \text{ cm}^{-3}} \end{aligned}$$

$$\begin{aligned} \text{(ii)} \quad n_i &= (5.23 \times 10^{15})(350)^{3/2} \exp\left[\frac{-1.1}{2(86 \times 10^{-6})(350)}\right] \\ &= 3.425 \times 10^{19} \exp[-18.27] \\ \underline{n_i} &= \underline{3.97 \times 10^{11} \text{ cm}^{-3}} \end{aligned}$$

(b) GaAs

$$\begin{aligned} \text{(i)} \quad n_i &= (2.10 \times 10^{14})(250)^{3/2} \exp\left[\frac{-1.4}{2(86 \times 10^{-6})(250)}\right] \\ &= (8.301 \times 10^{17}) \exp[-32.56] \\ \underline{n_i} &= \underline{6.02 \times 10^3 \text{ cm}^{-3}} \end{aligned}$$

$$\begin{aligned} \text{(ii)} \quad n_i &= (2.10 \times 10^{14})(350)^{3/2} \exp\left[\frac{-1.4}{2(86 \times 10^{-6})(350)}\right] \\ &= (1.375 \times 10^{18}) \exp[-23.26] \\ \underline{n_i} &= \underline{1.09 \times 10^8 \text{ cm}^{-3}} \end{aligned}$$

1.2

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

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

$$1.91 \times 10^{-4} = T^{3/2} \exp\left(-\frac{6.40 \times 10^3}{T}\right)$$

By trial and error,  $T \approx 368 \text{ K}$

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

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

$$1.91 \times 10^{-7} = T^{3/2} \exp\left(-\frac{6.40 \times 10^3}{T}\right)$$

By trial and error,  $T \approx 268^\circ \text{ K}$

1.3

Silicon

$$\begin{aligned}
 \text{(a)} \quad n_i &= (5.23 \times 10^{15})(100)^{3/2} \exp\left[\frac{-1.1}{2(86 \times 10^{-6})(100)}\right] \\
 &= (5.23 \times 10^{18}) \exp[-63.95] \\
 \underline{n_i} &= \underline{8.79 \times 10^{-10} \text{ cm}^{-3}}
 \end{aligned}$$

$$\begin{aligned}
 \text{(b)} \quad n_i &= (5.23 \times 10^{15})(300)^{3/2} \exp\left[\frac{-1.1}{2(86 \times 10^{-6})(300)}\right] \\
 &= (2.718 \times 10^{19}) \exp[-21.32] \\
 \underline{n_i} &= \underline{1.5 \times 10^{10} \text{ cm}^{-3}}
 \end{aligned}$$

$$\begin{aligned}
 \text{(c)} \quad n_i &= (5.23 \times 10^{15})(500)^{3/2} \exp\left[\frac{-1.1}{2(86 \times 10^{-6})(500)}\right] \\
 &= (5.847 \times 10^{19}) \exp[-12.79] \\
 \underline{n_i} &= \underline{1.63 \times 10^{14} \text{ cm}^{-3}}
 \end{aligned}$$

Germanium.

$$\begin{aligned}
 \text{(a)} \quad n_i &= (1.66 \times 10^{15})(100)^{3/2} \exp\left[\frac{-0.66}{2(86 \times 10^{-6})(100)}\right] = (1.66 \times 10^{18}) \exp[-38.37] \\
 \underline{n_i} &= \underline{35.9 \text{ cm}^{-3}}
 \end{aligned}$$

$$\begin{aligned}
 \text{(b)} \quad n_i &= (1.66 \times 10^{15})(300)^{3/2} \exp\left[\frac{-0.66}{2(86 \times 10^{-6})(300)}\right] = (8.626 \times 10^{18}) \exp[-12.79] \\
 \underline{n_i} &= \underline{2.40 \times 10^{13} \text{ cm}^{-3}}
 \end{aligned}$$

$$\begin{aligned}
 \text{(c)} \quad n_i &= (1.66 \times 10^{15})(500)^{3/2} \exp\left[\frac{-0.66}{2(86 \times 10^{-6})(500)}\right] = (1.856 \times 10^{19}) \exp[-7.674] \\
 \underline{n_i} &= \underline{8.62 \times 10^{15} \text{ cm}^{-3}}
 \end{aligned}$$

1.4

a.  $N_d = 5 \times 10^{15} \text{ cm}^{-3} \Rightarrow$  n-type

$$\underline{n_0 = N_d = 5 \times 10^{15} \text{ cm}^{-3}}$$

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

b.  $N_d = 5 \times 10^{15} \text{ cm}^{-3} \Rightarrow$  n-type

$$\underline{n_0 = N_d = 5 \times 10^{15} \text{ cm}^{-3}}$$

$$\begin{aligned}
 n_i &= (2.10 \times 10^{14})(300)^{3/2} \exp\left(\frac{-1.4}{2(86 \times 10^{-6})(300)}\right) \\
 &= (2.10 \times 10^{14})(300)^{3/2} (1.65 \times 10^{-12}) \\
 &= 1.80 \times 10^6 \text{ cm}^{-3}
 \end{aligned}$$

$$p_0 = \frac{n_i^2}{n_0} = \frac{(1.8 \times 10^6)^2}{5 \times 10^{15}} \Rightarrow \underline{p_0 = 6.48 \times 10^{-4} \text{ cm}^{-3}}$$

1.5



(a)  $n$ -type

(b)  $n_o = N_d = 5 \times 10^{16} \text{ cm}^{-3}$

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

(c)  $n_o = N_d = 5 \times 10^{16} \text{ cm}^{-3}$

From Problem 1.1(a)(ii)  $n_i = 3.97 \times 10^{11} \text{ cm}^{-3}$

$$p_o = \frac{(3.97 \times 10^{11})^2}{5 \times 10^{16}} = 3.15 \times 10^6 \text{ cm}^{-3}$$

1.6

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

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

$$n_o = \frac{n_i^2}{p_o} = \frac{(1.5 \times 10^{10})^2}{10^{16}} \Rightarrow n_o = 2.25 \times 10^4 \text{ cm}^{-3}$$

b. Germanium

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

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

$$n_i = (1.66 \times 10^{15})(300)^{3/2} \exp\left(\frac{-0.66}{2(86 \times 10^{-6})(300)}\right)$$

$$= (1.66 \times 10^{15})(300)^{3/2} (2.79 \times 10^{-6})$$

$$= 2.4 \times 10^{13} \text{ cm}^{-3}$$

$$n_o = \frac{n_i^2}{p_o} = \frac{(2.4 \times 10^{13})^2}{10^{16}} \Rightarrow n_o = 5.76 \times 10^{10} \text{ cm}^{-3}$$

1.7

(a)  $p$ -type

(b)  $p_o = N_a = 2 \times 10^{17} \text{ cm}^{-3}$

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

(c)  $p_o = 2 \times 10^{17} \text{ cm}^{-3}$

From Problem 1.1(a)(i)  $n_i = 1.61 \times 10^8 \text{ cm}^{-3}$

$$n_o = \frac{(1.61 \times 10^8)^2}{2 \times 10^{17}} = 0.130 \text{ cm}^{-3}$$

1.8

(a)  $n_o = 5 \times 10^{15} \text{ cm}^{-3}$

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

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

(c)  $n_o \cong N_d = 5 \times 10^{15} \text{ cm}^{-3}$

1.9

a. Add Donors

$$N_d = 7 \times 10^{15} \text{ cm}^{-3}$$

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

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

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

$$7 \times 10^{21} = (5.23 \times 10^{15})^2 T^3 \exp\left(\frac{-1.1}{(86 \times 10^{-6})(T)}\right)$$

By trial and error,  $T \approx 324^\circ \text{ K}$

1.10

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

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

1.11

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

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

1.12

$$g \approx \frac{1}{e\mu_p N_a} \Rightarrow N_a = \frac{1}{e\mu_p g} = \frac{1}{(1.6 \times 10^{-19})(480)(0.80)}$$

$$N_a = 1.63 \times 10^{16} \text{ cm}^{-3}$$

1.13

$$\sigma = e\mu_n N_d$$

$$N_d = \frac{\sigma}{e\mu_n} = \frac{(0.5)}{(1.6 \times 10^{-19})(1350)}$$

$$N_d = 2.31 \times 10^{15} \text{ cm}^{-3}$$

1.14

$$\text{(a) For n-type, } \sigma \cong e\mu_n N_d = (1.6 \times 10^{-19})(8500) N_d$$

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

$$\text{(b) } J = \sigma E = \sigma(0.1) \Rightarrow 0.136 \leq J \leq 1.36 \times 10^3 \text{ A/cm}^2$$

1.15

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

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

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

1.16

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

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

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

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

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

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

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

1.17

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

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

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

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

1.18

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

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

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

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

1.19

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

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

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

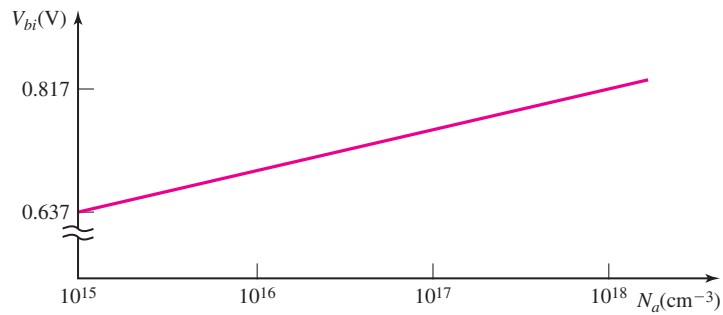
$$c. \quad V_{bi} = (0.026) \ln\left[ \frac{(10^{18})(10^{18})}{(1.8 \times 10^6)^2} \right] \Rightarrow V_{bi} = 1.41 \text{ V}$$

1.20

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

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

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



1.21

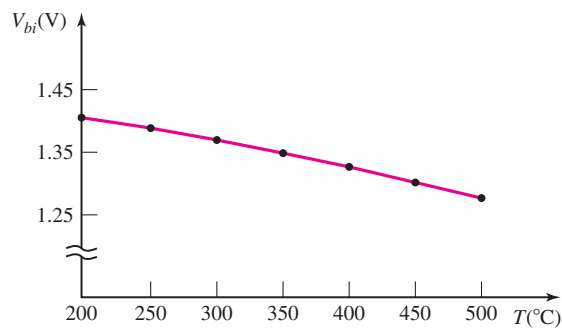
$$kT = (0.026) \left( \frac{T}{300} \right)$$

$T$	$kT$	$(T)^{3/2}$
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

$$n_i = (2.1 \times 10^{14}) (T^{3/2}) \exp \left( \frac{-1.4}{2(86 \times 10^{-6})(T)} \right)$$

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

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



1.22

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

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

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

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

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

1.23

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

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

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

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

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

where

$$\tau = RC = RC_j(\text{avg}) = (47 \times 10^3)(0.00962 \times 10^{-12})$$

or

$$\tau = 4.52 \times 10^{-10} \text{ s}$$

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

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

$$t_1 = 5.44 \times 10^{-10} \text{ s}$$

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

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

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

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

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

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

$$\text{so that } t_2 = 8.09 \times 10^{-10} \text{ s}$$

1.24

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

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

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

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(2.2 \times 10^{-3})(0.164 \times 10^{-12})}}$$

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

b.  $V_R = 10 \text{ V}$

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

$$f_0 = \frac{1}{2\pi\sqrt{(2.2 \times 10^{-3})(0.0663 \times 10^{-12})}}$$

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

1.25

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

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

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

b.

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

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

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

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)  $I = I_S (e^{V_D/V_T} - 1)$

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

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

Or  $V_D = 0.430 V$

(b)

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

Or  $V_D = 0.549 V$

1.28

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

$I_S = 2.03 \times 10^{-15} A$

(b)

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

1.29

(a)

$I_S = 10^{-12} A$

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

(b)

$I_S = 10^{-14} A$

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

1.30

a.

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

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

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

1.31

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

$V_D = 0.669 \text{ V}$

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

$V_D = 0.622 \text{ V}$

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

(ii)  $I_D = 0$

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

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

1.32

$V_D = V_T \ln\left(\frac{I_D}{I_S}\right) = (0.026) \ln\left(\frac{2 \times 10^{-3}}{5 \times 10^{-14}}\right) = 0.6347 \text{ V}$

$V_D = (0.026) \ln\left(\frac{2 \times 10^{-3}}{5 \times 10^{-12}}\right) = 0.5150 \text{ V}$

$0.5150 \leq V_D \leq 0.6347 \text{ V}$

1.33

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

$12 \times 10^{-3} = I_S \exp\left(\frac{1.10}{0.026}\right) \Rightarrow I_S = 5.07 \times 10^{-21} \text{ A}$

(b)  $I_D = (5.07 \times 10^{-21}) \exp\left(\frac{1.0}{0.026}\right)$

$I_D = 2.56 \times 10^{-4} \text{ A} = 0.256 \text{ mA}$

1.34

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

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

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

1.35

$I_S$  doubles for every 5C increase in temperature.

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

For  $I_S = 0.5 \times 10^{-12} \text{ A} \Rightarrow T = 295 \text{ K}$

For  $I_S = 50 \times 10^{-12} \text{ A}$ ,  $(2)^n = 50 \Rightarrow n = 5.64$

Where n equals number of 5C increases.

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

So  $295 \leq T \leq 328.2 \text{ K}$



1.36

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

$$\frac{I_s(100)}{I_s(-55)} = 2^{155/5} = 2.147 \times 10^9$$

$$V_T @ 100^\circ \text{C} \Rightarrow 373^\circ \text{K} \Rightarrow V_T = 0.03220$$

$$V_T @ -55^\circ \text{C} \Rightarrow 216^\circ \text{K} \Rightarrow V_T = 0.01865$$

$$\frac{I_D(100)}{I_D(-55)} = (2.147 \times 10^9) \times \frac{\exp\left(\frac{0.6}{0.0322}\right)}{\exp\left(\frac{0.6}{0.01865}\right)}$$

$$= \frac{(2.147 \times 10^9)(1.237 \times 10^8)}{(9.374 \times 10^{13})}$$

$$\frac{I_D(100)}{I_D(-55)} = 2.83 \times 10^3$$

1.37

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

$$(a) \quad I_D = 5 \times 10^{-9} \exp\left(\frac{V_D}{0.026}\right) \Rightarrow V_D = 0.026 \ln\left(\frac{I_D}{5 \times 10^{-9}}\right)$$

Trial and error.

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

So  $V_D \cong 0.2285 \text{ V}$

$$I_D \cong 3.272 \times 10^{-5} \text{ A}$$

$$(b) \quad \underline{I_D = I_s = 5 \times 10^{-9} \text{ A}}$$

$$V_R = (5 \times 10^{-9})(10^5) = 5 \times 10^{-4} \text{ V}$$

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

1.38

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

Trial and error.

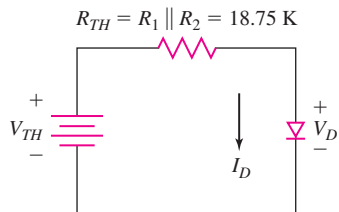
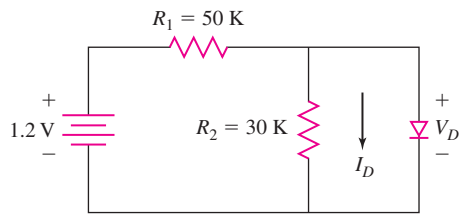
$V_D(\text{V})$	$I_D(\text{A})$	$V_D(\text{V})$
0.50	$4.75 \times 10^{-4}$	0.5194
0.517	$4.7415 \times 10^{-4}$	0.5194
0.5194	$4.740 \times 10^{-4}$	0.5194

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

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

1.39

$$I_s = 5 \times 10^{-13} \text{ A}$$



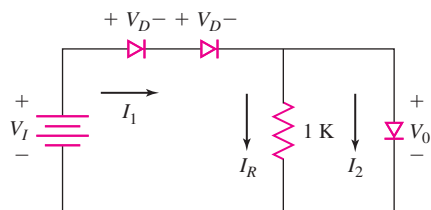
$$V_{TH} = \left( \frac{R_2}{R_1 + R_2} \right) (1.2) = \left( \frac{30}{80} \right) (1.2) = 0.45 \text{ V}$$

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

By trial and error:

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

1.40



$$I_s = 2 \times 10^{-13} \text{ A}$$

$$V_0 = 0.60 \text{ V}$$

$$I_2 = I_s \exp \left( \frac{V_0}{V_T} \right) = (2 \times 10^{-13}) \exp \left( \frac{0.60}{0.026} \right) = 2.105 \text{ mA}$$

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

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

$$V_D = V_T \ln \left( \frac{I_1}{I_s} \right) = (0.026) \ln \left( \frac{2.705 \times 10^{-3}}{2 \times 10^{-13}} \right) = 0.6065$$

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

1.41

(a) Assume diode is conducting.

$$\text{Then, } V_D = V_y = 0.7 \text{ V}$$

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

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

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

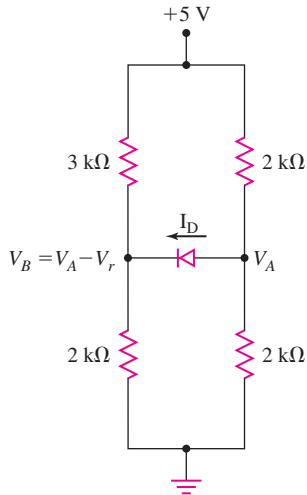
$$\text{Or } I_D = 26.7 \mu A$$

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

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

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

1.42



A &  $V_A$ :

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

A &  $V_A - V_r$

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

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

Multiply by 6:

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

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

$$(a) \quad V_r = 0.6 \text{ V}$$

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

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

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

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

1.43

Minimum diode current for  $V_{PS}$  (min)

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

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

We have  $I_1 = I_2 + I_D$

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

Maximum diode current for  $V_{PS}(\text{max})$

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

$I_1 = I_2 + I_D$

or

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

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

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

1.44

(a)  $V_o = 0.7 \text{ V}$

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

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

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

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

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

(d)  $I = 0$

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

1.45

(a)  $5 = I(2 \times 10^9) + V_D \quad V_D = (0.026) \ln\left(\frac{I}{2 \times 10^{-12}}\right)$

$V_D$	$\rightarrow$	$I_D$	$\rightarrow$	$V_D$	$V_o = V_D = 0.482 \text{ V}$
0.6		$2.2 \times 10^{-4}$		0.481	
0.482		$2.259 \times 10^{-4}$		0.482	$I = 0.226 \text{ mA}$

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

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

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

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

(d)  $I = -I_s \Rightarrow \underline{I = 2 \times 10^{-12} \text{ A}}$   
 $\underline{V_o \cong -5 \text{ V}}$

1.46

(a) Diode forward biased  $V_D = 0.7 \text{ V}$

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

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

1.47

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

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

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

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

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

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

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

1.48

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

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

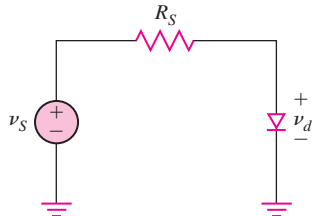
$$v_d = i_d \tau_d = (26)(50) \mu\text{A} \Rightarrow v_d = 1.30 \text{ mV peak-to-peak}$$

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

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

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

1.49



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

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

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

$$b. \quad R_S = 260\Omega$$

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

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

$$I = 0.01 \text{ mA}, \frac{v_0}{v_s} = \frac{0.026}{0.026 + (0.01)(0.26)} \Rightarrow \frac{v_0}{v_s} = 0.909$$

1.50

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

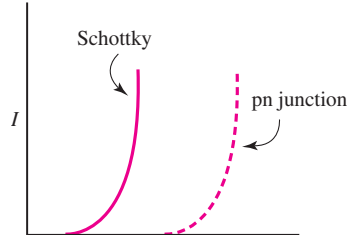
$$\text{pn junction, } V_a = (0.026) \ln\left(\frac{100 \times 10^{-6}}{10^{-14}}\right)$$

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

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

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

1.51



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

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

Then

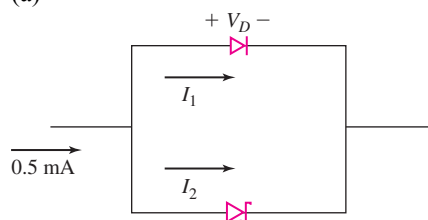
$$V_a \text{ of pn junction} = 0.1796 + 0.30 = 0.4796$$

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

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

1.52

(a)



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

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

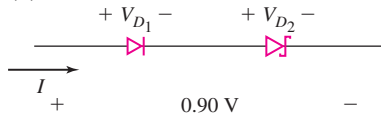
$$5.0001 \times 10^{-8} \exp\left(\frac{V_D}{V_T}\right) = 0.5 \times 10^{-3}$$

$$V_D = (0.026) \ln\left(\frac{0.5 \times 10^{-3}}{5.0001 \times 10^{-8}}\right) \Rightarrow \underline{V_D = 0.2395}$$

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

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

(b)



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

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

$$\begin{aligned} 10^{-12} \exp\left(\frac{V_{D1}}{V_T}\right) &= 5 \times 10^{-8} \exp\left(\frac{0.9 - V_{D1}}{V_T}\right) \\ &= 5 \times 10^{-8} \exp\left(\frac{0.9}{V_T}\right) \exp\left(\frac{-V_{D1}}{V_T}\right) \end{aligned}$$

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

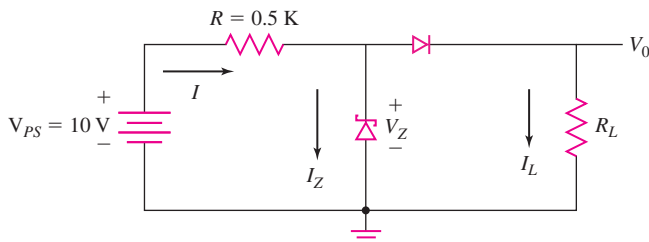
$$2V_{D1} = V_T \ln\left(\frac{5 \times 10^{-8}}{10^{-12}}\right) + 0.9 = 1.1813$$

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

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

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

1.53



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

$$r_z = 10 \Omega$$

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

$$V_{Z0} = 5.599$$

a.  $R_L \rightarrow \infty \Rightarrow$

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

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

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

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

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

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

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

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

$$\text{c. } I = I_Z + I_L$$

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

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

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

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

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

1.54

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

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

$$I_Z = \frac{12 - 6.8}{0.2} \Rightarrow \underline{I_Z = 26 \text{ mA}}$$

b.

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

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

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

1.55

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

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

a.  $R_L = \infty$

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

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

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

b.  $I = I_Z + I_L$

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

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

$$359.9 = V_0 (53)$$

$$V_0 = 6.791 \text{ V}$$

$$\Delta V_0 = 6.791 - 6.921$$

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

1.56



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