Chapter 1

Exercise Solutions

E1.1

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

GaAs :

$$n_i = (2.1 \times 10^{14})(300)^{3/2} \exp\left(\frac{-1.4}{2(86 \times 10^{-6})(300)}\right)$$

$\underline{n_i = 1.8 \times 10^6 \text{ cm}^{-3}}$

Ge :

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

$\underline{n_i = 2.40 \times 10^{13} \text{ cm}^{-3}}$

E1.2

Si :

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

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

GaAs :

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

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

Ge :

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

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

E1.3

a. majority carrier: $\underline{p_0 = 10^{17} \text{ cm}^{-3}}$
minority carrier:

$$\underline{n_0 = \frac{n_i^2}{N_a} = \frac{(1.5 \times 10^{10})^2}{10^{17}} = 2.25 \times 10^3 \text{ cm}^{-3}}$$

b. $n_0 = N_d - N_a = 5 \times 10^{15}$

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

minority carrier:

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

E1.4

(a) $n_o = 5x10^{16}\ cm^{-3}$, $p_o << n_o$

$\sigma \cong e\mu_n n_o = (1.6x10^{-19})(1350)(5x10^{16}) \Rightarrow$

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

(b) $p_o = 5x10^{16}\ cm^{-3}$, $n_o << p_o$

$\sigma \cong e\mu_p p_o = (1.6x10^{-19})(480)(5x10^{16}) \Rightarrow$

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

E1.5

a. $n_0 = N_d = 8 \times 10^{15} \text{ cm}^{-3}$

$$p_0 = \frac{n_i^2}{n_0} = \frac{(1.5 \times 10^{10})^2}{8 \times 10^{15}} \Rightarrow$$

$\underline{p_0 = 2.81 \times 10^4 \text{ cm}^{-3}}$

b. $n = n_0 + \delta n = 8 \times 10^{15} + 0.1 \times 10^{15} \Rightarrow$

$\underline{n = 8.1 \times 10^{15} \text{ cm}^{-3}}$

$p = p_0 + \delta p \Rightarrow$

$\underline{p \approx 10^{14} \text{ cm}^{-3}}$

E1.6

$J = \sigma E = (10)(15) \Rightarrow$

$\underline{J = 150 \text{A/cm}^2}$

E1.7

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

$$V_{bi} = (0.026) \ln\left[\frac{(10^{15})(10^{17})}{(1.5 \times 10^{10})^2}\right]$$

$\underline{V_{bi} = 0.697 \text{ V}}$

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

$\underline{V_{bi} = 0.817 \text{ V}}$

E1.8

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

$\underline{V_{bi} = 1.23 \text{ V}}$

E1.9

$$C_j = C_{j0}\left(1+\frac{V_R}{V_{bi}}\right)^{-1/2}$$

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

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

$$0.8 = C_{j0}\left(1+\frac{5}{0.757}\right)^{-1/2} = C_{j0}(7.61)^{-1/2}$$

$$= C_{j0}(0.362)$$

$\underline{C_{j0} = 2.21 \text{ pF}}$

E1.10

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

For $V_D = 0.5$: $I \cong 10^{-14}\exp\left(\frac{0.5}{0.026}\right)$

For $V_D = 0.6$: $I = 10^{-14}\exp\left(\frac{0.6}{0.026}\right)$

For $V_D = 0.7$: $I = 10^{-14}\exp\left(\frac{0.7}{0.026}\right)$

So we have

V_D	I
0.5	2.25 μA
0.6	0.105 mA
0.7	4.93 mA

b. 10^{-14} A both cases

E1.11

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

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

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

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

E1.12

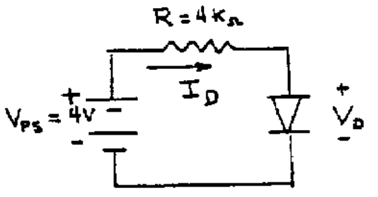
$\Delta T = 100°\text{C}$

$\Delta V_D \approx 2 \times 100 = 200 \text{ mV}$

$\Rightarrow V_D = 0.650 - 0.2$

$\Rightarrow \underline{V_D = 0.450 \text{ V}}$

E1.13



$I_S = 10^{-12}$ A

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

So

$4 = I_D(4) + V_D \Rightarrow I_D = (4 - V_D)/4$ mA

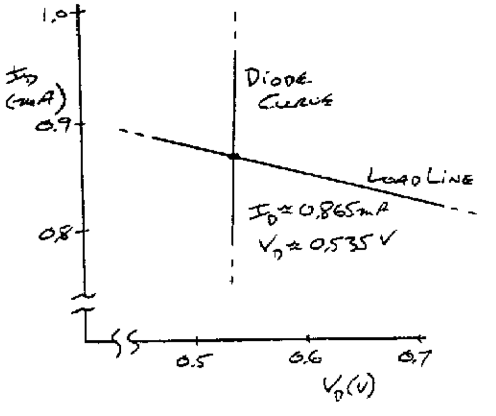
and

$I_D \cong I_S \exp\left(\frac{V_D}{V_T}\right) \Rightarrow I_D = 10^{-9}\exp\left(\frac{V_D}{0.026}\right)$ mA

By trial and error:

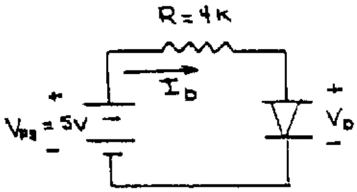
$I_D = 0.864$ mA and $V_D = 0.535$ V

E1.14



E1.15

a.

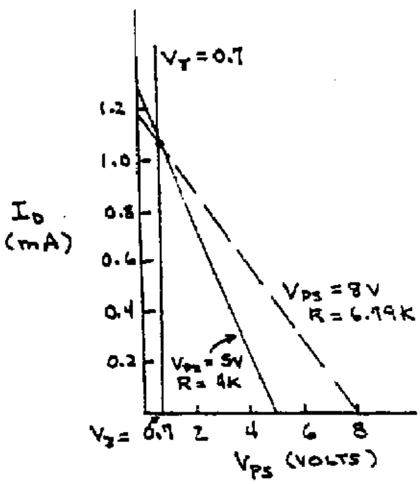


$$I_D = \frac{V_{PS} - V_\gamma}{R} = \frac{5 - 0.7}{4} \Rightarrow \underline{I_D = 1.08 \text{ mA}}$$

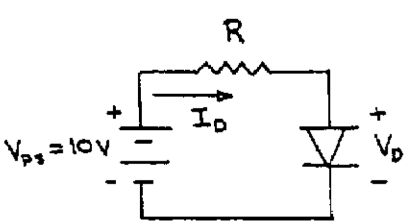
b. $$I_D = \frac{V_{PS} - V_\gamma}{R} \Rightarrow R = \frac{V_{PS} - V_\gamma}{I_D}$$

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

c.



E1.16



Power dissipation in diode $= I_D V_D$

$1.05 \text{ mW} = I_D(0.7) \Rightarrow \underline{I_D = 1.5 \text{ mA}}$

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

E1.17

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

E1.18

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

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

E1.19

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

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

pn junction: $V_D = (0.026)\ln\left(\frac{10^{-3}}{10^{-12}}\right)$

$\underline{V_D = 0.539 \text{ V}}$

Schottky Diode: $V_D = (0.026)\ln\left(\frac{10^{-3}}{10^{-8}}\right)$

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

E1.20

For the *pn* junction diode

$$V_D = V_T \ln\left(\frac{I_D}{I_S}\right) = (0.026)\ln\left(\frac{1.2 \times 10^{-3}}{4 \times 10^{-15}}\right)$$

$V_D = 0.6871 \text{ V}$

Schottky diode voltage will be smaller

$\Rightarrow V_D = 0.5871 - 0.265 = 0.4221 \text{ V}$

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

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

E1.21

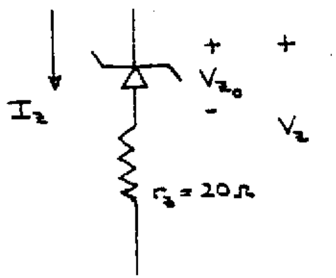
$$\text{Power} = I \cdot V_Z$$

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

$$I = \frac{10 - 5.6}{R} = 1.79$$

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

E1.22



$$V_Z = V_{Z0} + I_Z r_Z$$

So $V_{Z0} = V_Z - I_Z r_Z$

$$V_{Z0} = 5.20 - (10^{-3})(20) = 5.20 - 0.02 = 5.18$$

Then

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

Chapter 1

Problem Solutions

1.1

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

(i) Silicon, T=275K

$n_i = (5.23x10^{15})(275)^{3/2}e^{-1.1/2(86x10^{-6})(275)}$

$\underline{n_i = 1.90x10^9\ cm^{-3}}$

(ii) T=325K

$n_i = (5.23x10^{15})(325)^{3/2}e^{-1.1/2(86x10^{-6})(325)}$

$\underline{n_i = 8.71x10^{10}\ cm^{-3}}$

(b) GaAs

(i) T=275K

$n_i = (2.1x10^{14})(275)^{3/2}e^{-1.4/2(86x10^{-6})(275)}$

$\underline{n_i = 1.34x10^5\ cm^{-3}}$

(ii) T=325K

$n_i = (2.10x10^{14})(325)^{3/2}e^{-1.4/2(86x10^{-6})(325)}$

$\underline{n_i = 1.63x10^7\ cm^{-3}}$

1.2

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

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

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

By trial and error, $T \approx 367°$ K

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

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

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

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

1.3

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

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

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

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

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

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

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

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

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

1.4

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

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

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

b. Germanium

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

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

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

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

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

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

1.5

(a) $n_o = 5x10^{15}\ cm^{-3}$

$p_o = \frac{n_i^2}{n_o} = \frac{(1.5x10^{10})^2}{5x10^{15}} \Rightarrow p_o = 4.5x10^4\ cm^{-3}$

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

(c) $n_o \cong N_d = 5x10^{15}\ cm^{-3}$

1.6

a. <u>Add Donors</u>

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

b. Want $p_0 = 10^6$ cm^{-3} $= n_i^2/N_d$

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

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

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

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

1.7

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

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

1.8

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

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

1.9

(a) For n-type,

$$\sigma \cong e\mu_n N_d = (1.6x10^{-19})(8500)N_d$$

For $10^{15} \le N_d \le 10^{19}\ cm^{-3} \Rightarrow$

$$1.36 \le \sigma \le 1.36x10^4\ (\Omega - cm)^{-1}$$

(b) $J = \sigma E = \sigma(0.1) \Rightarrow$

$$0.136 \le J \le 1.36x10^3\ A/cm^2$$

1.10

a. $N_a = 10^{17}\ \text{cm}^{-3} \Rightarrow \underline{p_0 = 10^{17}\ \text{cm}^{-3}}$

$$n_0 = \frac{n_i^2}{p_0} = \frac{(1.8 \times 10^6)^2}{10^{17}} \Rightarrow \underline{n_0 = 3.24 \times 10^{-5}\ \text{cm}^{-3}}$$

b. $n = n_0 + \delta n = 3.24 \times 10^{-5} + 10^{15} \Rightarrow \underline{n = 10^{15}\ \text{cm}^{-3}}$

$p = p_0 + \delta p = 10^{17} + 10^{15} \Rightarrow \underline{p = 1.01 \times 10^{17}\ \text{cm}^{-3}}$

1.11

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

a. $V_{bi} = (0.026)\ln\left[\frac{(10^{15})(10^{15})}{(1.5 \times 10^{10})^2}\right] \Rightarrow V_{bi} = 0.578\ \text{V}$

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

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

1.12

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

a. $V_{bi} = (0.026)\ln\left[\frac{(10^{15})(10^{15})}{(1.8 \times 10^6)^2}\right] \Rightarrow V_{bi} = 1.05\ \text{V}$

b. $V_{bi} = (0.026)\ln\left[\frac{(10^{15})(10^{18})}{(1.8 \times 10^6)^2}\right] \Rightarrow V_{bi} = 1.23\ \text{V}$

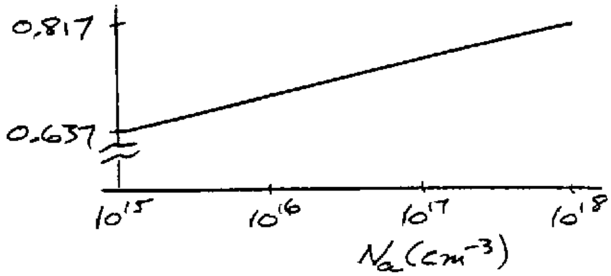
c. $V_{bi} = (0.026)\ln\left[\frac{(10^{18})(10^{18})}{(1.8 \times 10^6)^2}\right] \Rightarrow V_{bi} = 1.41\ \text{V}$

1.13

$$V_{bi} = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right) = (0.026)\ln\left[\frac{N_a(10^{16})}{(1.5x10^{10})^2}\right]$$

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

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



1.14

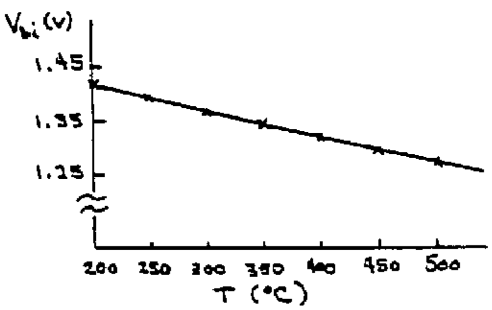
$$kT = (0.026)\left(\frac{T}{300}\right)$$

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

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

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

T	n_i	V_{bi}
200	1.256	1.405
250	6.02×10^3	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



1.15

$$C_j = C_{j0}\left(1 + \frac{V_R}{V_{bi}}\right)^{-1/2}$$

$$V_{bi} = (0.026)\ln\left[\frac{(2 \times 10^{16})(2 \times 10^{15})}{(1.5 \times 10^{10})^2}\right] = 0.673 \text{ V}$$

a. $V_R = 1$ V

$$C_j = (1)\left(1 + \frac{1}{0.673}\right)^{-1/2} \Rightarrow \underline{C_j = 0.634 \text{ pF}}$$

b. $V_R = 5$ V

$$C_j = (1)\left(1 + \frac{5}{0.673}\right)^{-1/2} \Rightarrow \underline{C_j = 0.344 \text{ pF}}$$

1.16

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

For $V_R = 5V$,

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

For $V_R = 1.5V$,

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

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

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

where

$$\tau = RC = RC_j(avg) = (47x10^3)(0.00962x10^{-12})$$

or

$$\tau = 4.52x10^{-10}\ s$$

Then

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

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

$$\underline{t_1 = 5.44x10^{-10}\ s}$$

(b) For $V_R = 0V$,

$$C_j = C_{jo} = 0.02\ pF$$

For $V_R = 3.5V$,

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

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

$$\tau = RC_j(avg) = 6.72x10^{-10}\ s$$

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

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

so that $\underline{t_2 = 8.09x10^{-10}\ s}$

1.17

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

a. $V_R = 1$ 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. $V_R = 10$ V

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

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

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

1.18

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.

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

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

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

1.19

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.

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

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

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

1.20

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

$$150x10^{-6} = 10^{-11}\left(e^{V_D/V_T} - 1\right) \cong 10^{-11}e^{V_D/V_T}$$

Then

$$V_D = V_T \ln\left(\frac{150x10^{-6}}{10^{-11}}\right) = (0.026)\ln\left(\frac{150x10^{-6}}{10^{-11}}\right)$$

Or

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

(b)

$$V_D = V_T \ln\left(\frac{150x10^{-6}}{10^{-13}}\right)$$

Or

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

1.21

a. $I_D \cong I_S \exp\left(\frac{V_D}{nV_T}\right)$

$10^{-3} = I_S \exp\left(\frac{0.7}{2(0.026)}\right) \Rightarrow \underline{I_S = 1.42 \times 10^{-9} \text{ A}}$

b. $I_D = (1.42 \times 10^{-9})\exp\left(\frac{0.8}{2(0.026)}\right)$

$\underline{I_D = 6.82 \text{ mA}}$

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

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

$I_D = (2.03 \times 10^{-15})\exp\left(\frac{0.8}{0.026}\right)$

$\underline{I_D = 46.8 \text{ mA}}$

1.22

I_S doubles for every 5C increase in temperature.

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

For $I_S = 0.5x10^{-12}\ A \Rightarrow$ $\underline{\text{T = 295K}}$

For $I_S = 50x10^{-12}\ A$, $(2)^n = 50 \Rightarrow n = 5.64$

Where n equals number of 5C increases.

Then

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

So

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

1.23

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

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

V_T@$100°$C $\Rightarrow 373°$K $\Rightarrow V_T = 0.03220$

V_T@$-55°$C $\Rightarrow 216°$K $\Rightarrow V_T = 0.01865$

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

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

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

1.24

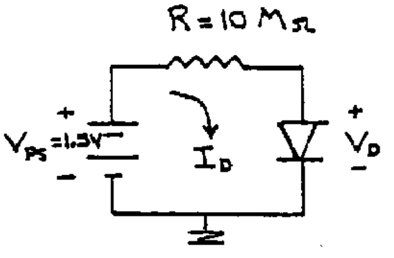
a. $\frac{I_{D2}}{I_{D1}} = 10 = \exp\left(\frac{V_{D2} - V_{D1}}{V_T}\right)$

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

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

1.25

a.



$1.5 = I_D(10 \times 10^6) + V_D$ and

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

$$1.5 = (10 \times 10^6)(30 \times 10^{-9})\left[\exp\left(\frac{V_D}{V_T}\right) - 1\right] + V_D$$

$$= 0.3\left[\exp\left(\frac{V_D}{V_T}\right) - 1\right] + V_D$$

By trial and error, $\underline{V_D = 0.046 \text{ V}}$

Then $I_D = \frac{1.5 - 0.046}{10} \Rightarrow \underline{I_D = 0.145\ \mu\text{A}}$

b. Reverse-Bias

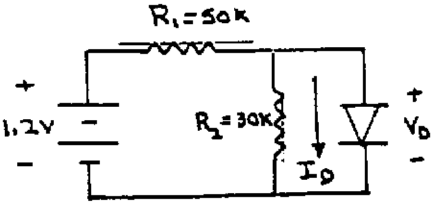
$\underline{I = I_S = 30 \text{ nA}}$

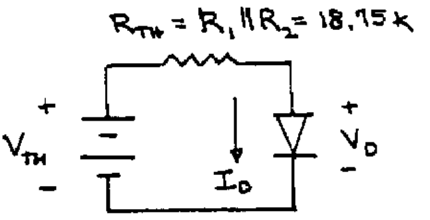
$V_R = (30 \times 10^{-9})(10 \times 10^6) = 0.30$ V

$V_D = -1.5 + 0.3 \Rightarrow \underline{V_D = -1.2 \text{ V}}$

1.26

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





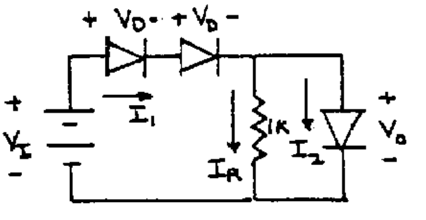
$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)(1.2) = \left(\frac{30}{80}\right)(1.2) = 0.45 \text{ V}$$

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

By trial and error:

$\underline{I_D = 2.6\ \mu\text{A}}$, $\underline{V_D = 0.402 \text{ V}}$

1.27



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

$V_0 = 0.60$ V

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

$$= 2.105 \text{ mA}$$

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

$I_1 = I_2 + I_R = 2.705$ mA

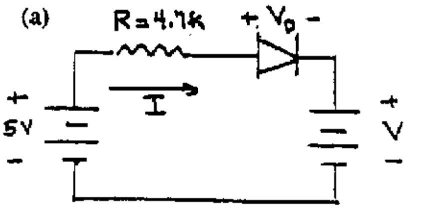
$$V_D = V_T \ln\left(\frac{I_1}{I_S}\right) = (0.026) \ln\left(\frac{2.705 \times 10^{-3}}{2 \times 10^{-13}}\right)$$

$$= 0.6065$$

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

1.28

(a)



$I_S = 5 \times 10^{-12}$ A

$I = 0.50$ mA

$V_D = (0.026)\ln\left(\dfrac{0.5 \times 10^{-3}}{5 \times 10^{-12}}\right)$

$\underline{V_D = 0.479 \text{ V}}$

$5 = IR + V_D + V$

$\quad = (0.5 \times 10^{-3})(4.7 \times 10^{3}) + 0.479 + V$

$\underline{V = 2.17 \text{ V}}$

(b) $P = I_D V_D = (0.5)(0.479)$

or

$\underline{P = 0.24\ mW}$

1.29

(a) Assume diode is conducting.

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

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

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

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.

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

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

1.30

(a) Diode is conducting

$5 = I_D(10) + V_\gamma - 5$

or

$I_D = \dfrac{10 - 0.6}{10} \Rightarrow \underline{I_D = 0.94\ mA}$

$V_O = V_\gamma - 5 = 0.6 - 5 \Rightarrow \underline{V_O = -4.4\ V}$

(b) Diode is conducting

$5 = V_\gamma + I_D(10) - 5$

or

$I_D = \dfrac{10 - 0.6}{10} \Rightarrow \underline{I_D = 0.94\ mA}$

$V_O = I_D R - 5 = (0.94)(10) - 5 \Rightarrow \underline{V_O = 4.4\ V}$

(c) Diode is reverse biased

$\underline{I_D = 0}$ $\underline{V_D = -10\ V}$

1.31

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

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

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

We have

$I_1 = I_2 + I_D$

so

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

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

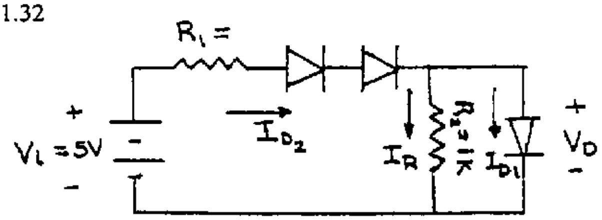
Using Eq. (1),

$\dfrac{9.3}{R_1} = \dfrac{4.3}{R_1} - 2 + 14.3 \Rightarrow \underline{R_1 = 0.41\ k\Omega}$

Then

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

1.32

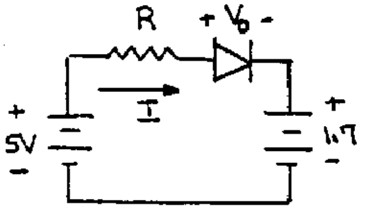


$I_{D1} = \frac{1}{2} I_{D2} \Rightarrow I_{D1} = I_R = \dfrac{0.65}{1} = 0.65$ mA

$I_{D2} = 1.3 \text{ mA} = \dfrac{5 - 3(0.65)}{R_1}$

$\underline{R_1 = 2.35\ \text{k}\Omega}$, $\underline{I_{D1} = 0.65 \text{ mA}}$, $\underline{I_{D2} = 1.30 \text{ mA}}$

1.33



$V_\gamma = 0.65$ V

Power $= I \cdot V_\gamma = 0.2$ mW $= I(0.65)$

$$\Rightarrow I = 0.308 \text{ mA}$$

$$I = \frac{5 - 0.65 - 1.7}{R} = 0.308$$

$$\Rightarrow R = \frac{2.65}{0.308} \Rightarrow \underline{R = 8.60 \text{ k}\Omega}$$

1.34

For forward bias

$$I_D = \frac{1.5 - 0.7}{10\ M\Omega} = 0.08\ \mu A$$

For reverse bias

$$I_D = 0, \quad V_D = -1.5\,V$$

1.35

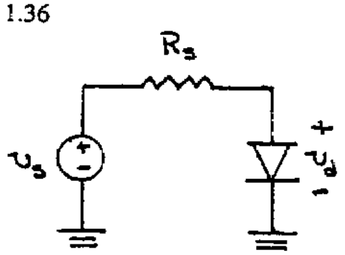
a. $r_d = \dfrac{V_T}{I_{DQ}} = \dfrac{(0.026)}{1} = 0.026\ \text{k}\Omega = 26\Omega$

$i_d = 0.05 I_{DQ} = 50\ \mu$A peak-to-peak
$v_d = i_d r_d = (26)(50)\ \mu$A
$\Rightarrow$ $\underline{v_d = 1.30 \text{ mV peak-to-peak}}$

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

$i_d = 0.05 I_{DQ} = 5\ \mu$A peak-to-peak
$v_d = i_d r_d = (260)(5)\ \mu$V
$\Rightarrow$ $\underline{v_d = 1.30 \text{ mV peak-to-peak}}$

1.36



ac equivalent circuit

a. diode resistance $r_d = V_T / I$

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

$$v_d = \left(\frac{V_T}{V_T + I R_S}\right) v_S = v_0$$

b. $R_S = 260\Omega$

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

$$\Rightarrow \underline{\frac{v_0}{v_S} = 0.0909}$$

$$I = 0.1 \text{ mA}, \quad \frac{v_0}{v_S} = \frac{0.026}{0.026 + (0.1)(0.26)}$$

$$\Rightarrow \underline{\frac{v_0}{v_S} = 0.50}$$

$$I = 0.01 \text{ mA}, \quad \frac{v_0}{v_S} = \frac{0.026}{0.026 + (0.01)(0.26)}$$

$$\Rightarrow \underline{\frac{v_0}{v_S} = 0.909}$$

1.37

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

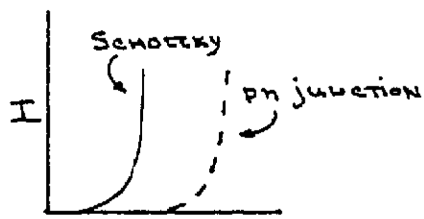
pn junction, $V_a = (0.026) \ln\left(\dfrac{100 \times 10^{-6}}{10^{-14}}\right)$

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

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

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

1.38



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

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

$$= 0.1796 \text{ V}$$

Then

V_a of pn junction $= 0.1796 + 0.30$

$$= 0.4796$$

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

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

1.39

pn junction $I_D = 0.5\,mA$

$$I_D \cong I_S e^{V_D/V_T} \Rightarrow V_D = V_T \ln\left(\frac{I_D}{I_S}\right)$$

Then

$$V_D = (0.026)\ln\left(\frac{0.5x10^{-3}}{10^{-12}}\right) = 0.521\,V$$

Schottky diode

$$V_D = (0.026)\ln\left(\frac{0.5x10^{-3}}{10^{-8}}\right) = 0.281\,V$$

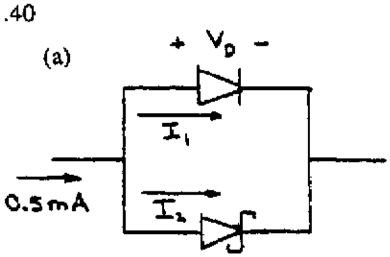
Then

$$R = \frac{V_D(pn) - V_D(S)}{0.5} = \frac{0.521 - 0.281}{0.5} \Rightarrow$$

$$\underline{R = 480\,\Omega}$$

1.40

(a)



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

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

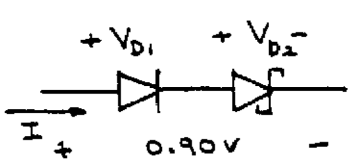
$$5.001 \times 10^{-8} \exp\left(\frac{V_D}{V_T}\right) = 0.5 \times 10^{-3}$$

$$V_D = (0.026)\ln\left(\frac{0.5 \times 10^{-3}}{5.001 \times 10^{-8}}\right) \Rightarrow \underline{V_D = 0.2395}$$

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

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

(b)



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

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

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

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

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

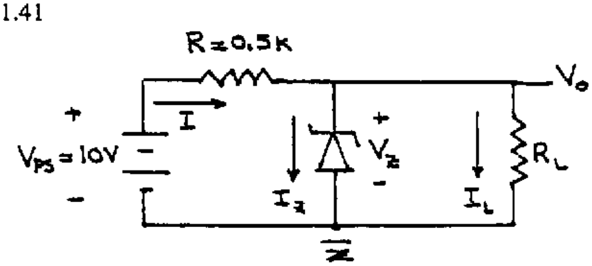
$$2V_{D1} = V_T \ln\left(\frac{5 \times 10^{-8}}{10^{-12}}\right) + 0.9 = 1.1813$$

$\underline{V_{D1} = 0.591}$ pn junction

$\underline{V_{D2} = 0.309}$ Schottky diode

$$I = 10^{-12} \exp\left(\frac{0.5907}{0.026}\right) \Rightarrow \underline{I = 7.36\text{ mA}}$$

1.41



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

$r_Z = 10\Omega$

$I_Z r_Z = (0.1)(10) = 1$ mV

$V_{Z0} = 5.599$

a. $R_L \to \infty \Rightarrow$

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

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

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

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

$$V_Z = V_0 = 5.599 + (0.01059)(10) = 5.705\text{ V}$$

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

$$V_Z = V_0 = 5.599 + (0.006669)(10) = 5.666\text{ V}$$

$$\Delta V_0 = 5.705 - 5.666 \Rightarrow \underline{\Delta V_0 = 0.039\text{ V}}$$

c. $I = I_Z + I_L$

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

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

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

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

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

1.42

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

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

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

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

1.43

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

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

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. $I = I_Z + I_L$

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

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

$$359.9 = V_0(53)$$

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

$$\Delta V_0 = 6.791 - 6.921$$

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