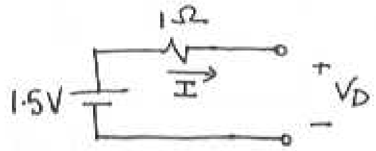
CHAPTER 3 - PROBLEMS

3.1



The diode can be reverse-biased and thus no current would flow, or forward-biased where current would flow.

(a) Reverse biased $I = 0A$ $V_D = 1.5V$

(b) Forward biased $I = 1.5A$ $V_D = 0V$

3.2

(a) Diode is conducting and thus has a 0V drop across it. Consequently

$V = \underline{\underline{-3V}}$

$$I = \frac{3-(-3)}{10k\Omega} = \underline{\underline{0.6\,mA}}$$

(b) Diode is cut off.

$V = \underline{\underline{3V}}$ $\quad I = \underline{\underline{0A}}$

(c) Diode is conducting

$V = \underline{\underline{3V}}$

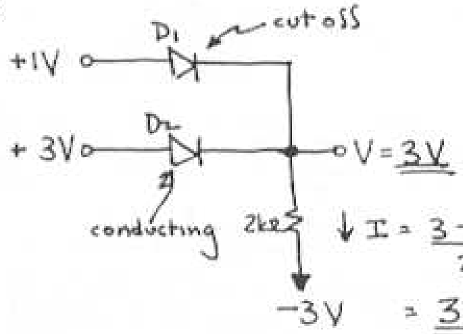
$$I = \frac{3-(-3)}{10k\Omega} = \underline{\underline{0.6\,mA}}$$

(d) Diode is cut off.

$V = \underline{\underline{-3V}}$ $\quad I = \underline{\underline{0A}}$

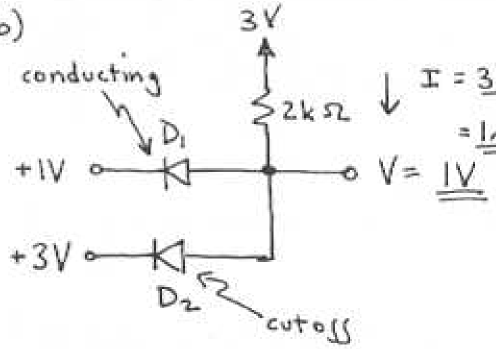
3.3

(a)



$$\downarrow I = \frac{3-(-3)}{2k\Omega} = \underline{\underline{3mA}}$$

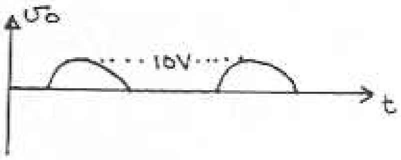
(b)



$$\downarrow I = \frac{3-(-1)}{2} = \underline{\underline{1mA}}$$

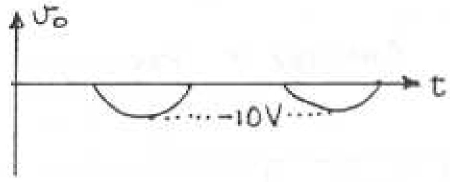
3.4

(a)



$V_{P+} = \underline{\underline{10V}}$ $\quad V_{P-} = \underline{\underline{0V}}$

$f = 1kHz.$

(b) 

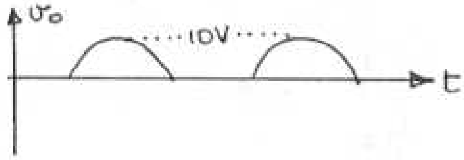
$V_{p+} = \underline{\underline{0V}}$ $V_{p-} = \underline{\underline{-10V}}$

$f = 1kHz$

(c) 

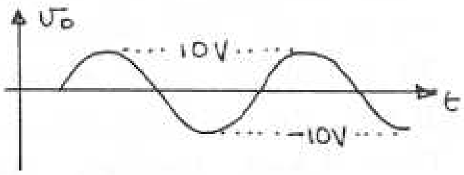
$v_o = \underline{\underline{0V}}$

Neither D_1 nor D_2 conducts so there is no output.

(d) 

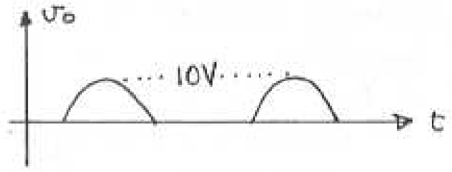
$V_{p+} = \underline{\underline{10V}}$ $V_{p-} = \underline{\underline{0V}}$ $f = 1kHz$

Both D_1 and D_2 conduct when $v_I > 0$

(e) 

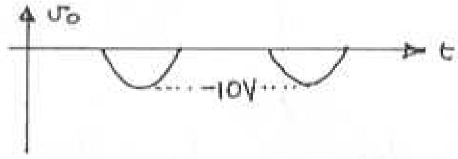
$V_{p+} = \underline{\underline{10V}}$ $V_{p-} = \underline{\underline{-10V}}$ $f = 1kHz$

D_1 conducts when $v_I > 0$ and D_2 conducts when $v_I < 0$. Thus the output follows the input.

(f) 

$V_{p+} = \underline{\underline{10V}}$ $V_{p-} = \underline{\underline{0V}}$ $f = 1kHz$

- D_1 is cutoff when $v_I < 0$

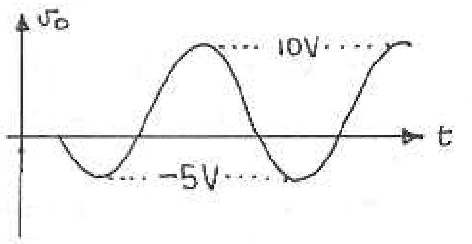
(g) 

$V_{p+} = \underline{\underline{0V}}$ $V_{p-} = \underline{\underline{-10V}}$ $f = 1kHz$

D_1 shorts to ground when $v_I > 0$ and is cut off when $v_I < 0$ whereby the output follows v_I.

(h) 

$v_o = \underline{\underline{0V}}$ ~ The output is always shorted to ground as D_1 conducts when $v_I > 0$ and D_2 conducts when $v_I < 0$.

(i) 

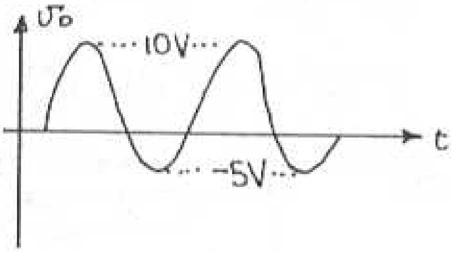
$V_{p+} = \underline{\underline{10V}}$ $V_{p-} = \underline{\underline{-5V}}$ $f = 1kHz$

- When $v_I > 0$, D_1 is cutoff and v_o follows v_I.

- When $v_I < 0$, D_1 is conducting and the circuit becomes a voltage divider where the negative peak is

$$\frac{1k\Omega}{1k\Omega + 1k\Omega} \cdot -10V = -5V$$

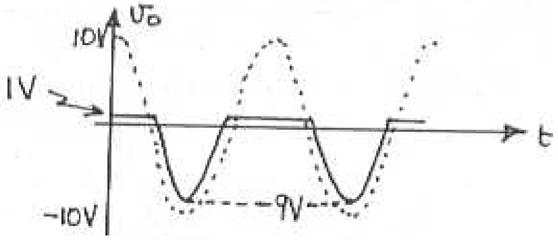
(j)



$V_{p+} = \underline{\underline{10V}}$ $V_{p-} = \underline{\underline{-5V}}$ $f = 1kHz$

- When $v_I > 0$, the output follows the input as D_1 is conducting.
- When $v_I < 0$, D_1 is cut off and the circuit becomes a voltage divider.

(k)



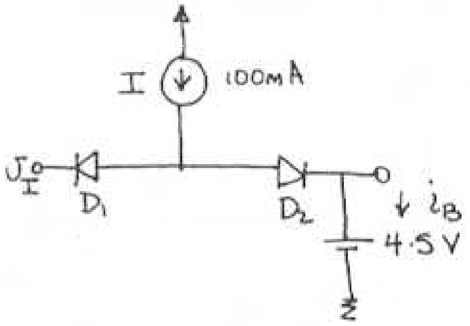
$V_{p+} = \underline{\underline{1V}}$ $V_{p-} = \underline{\underline{-9V}}$ $f = 1kHz$

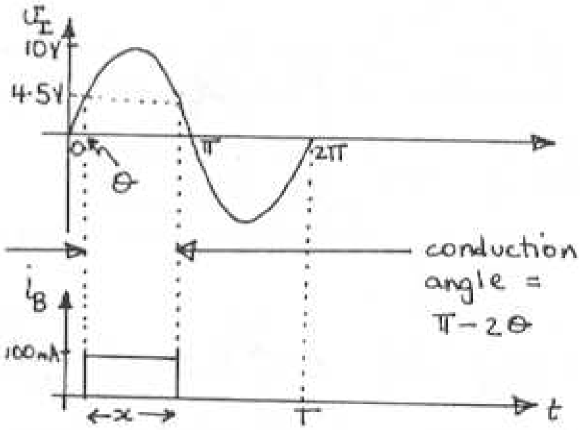
- When $v_I > 0$, D_1 is cutoff and D_2 is conducting. The output becomes 1V.
- When $v_I < 0$, D_1 is conducting and D_2 is cutoff. The output becomes :-

$$v_o = v_I + 1V.$$

CHAPTER 3 PROBLEMS

$\boxed{3.5}$





- When $v_I < 4.5V$ D_1 conducts and D_2 is cutoff so $i_B = 0A$. For $v_I > 4.5V$ D_2 conducts and D_1 is cutoff thus disconnecting the input v_I. All of the current then flows through the battery.

$$10 \sin\theta = 4.5V$$
$$\theta = \sin^{-1}(4.5/10)$$
$$\text{conduction angle} = \pi - 2\theta$$

Fraction of cycle that $i_B = \underline{\underline{100mA}}$ is given by :-

$$x = \frac{\pi - 2\theta}{2\pi} = 0.35$$

$$i_{Bavg} = \frac{1}{T}\int_T i_B \, dt$$

$$= \frac{1}{T}\left[100 \cdot 0.35T\right]$$

$$= \underline{\underline{35\,mA}}$$

If v_I is reduced by 10% the peak value of i_B remains the same

$$i_{B\,peak} = \underline{100mA}$$

but the fraction of the cycle for conduction changes

$$x = \frac{\pi - 2\theta}{2\pi} = \frac{\pi - 2\sin^{-1}(4.5/9)}{2\pi}$$

$$= \frac{1}{3}$$

Thus:

$$i_{Bavg} = \frac{1}{T}\left[100 \cdot \frac{T}{3}\right]$$

$$= \underline{\underline{33.3\,mA}}$$

3.6

A	B	x	y
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	1

$x = \underline{\underline{A\,B}}$ $\quad y = \underline{\underline{A + B}}$

CHAPTER 3 PROBLEMS

- x and y are the same for A = B
- x and y are opposite if $A \neq B$

3.7

$$\frac{5-0}{R} \leq 0.1\,mA$$

$$R \geq 5/0.1 = \underline{\underline{50k\Omega}}$$

3.8

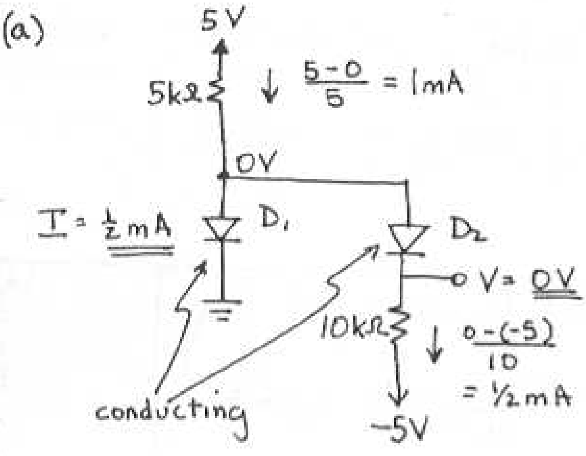
The maximum input current occurs when one input is low and the other two are high.

$$\frac{5-0}{R} \leq 0.1\,mA$$

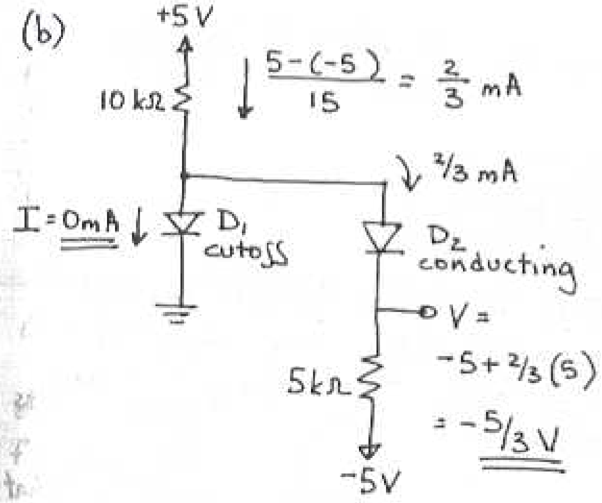
$$R \geq \underline{\underline{50k\Omega}}$$

3.9

(a)

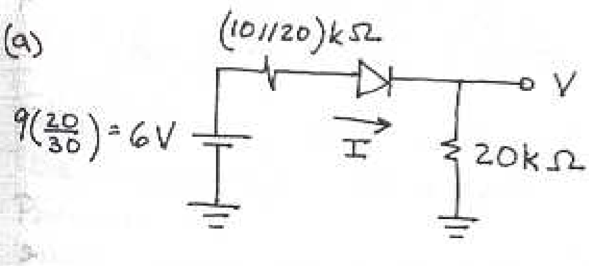


(b)



3.10

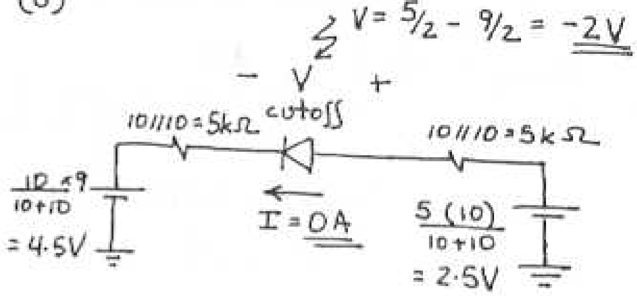
(a)



$$I = \frac{6}{(10\parallel 20)+20} = \underline{\underline{0.225\,mA}}$$

$$V = \frac{20}{(10\parallel 20)+20} \times 6 = \underline{\underline{4.5V}}$$

(b)



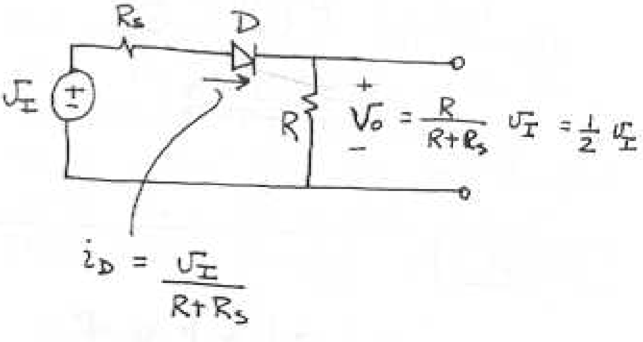
3.11

$$R \geq \frac{120\sqrt{2}}{50} \geq \underline{\underline{3.4\,k\Omega}}$$

The largest reverse voltage appearing across the diode is equal to the peak input voltage

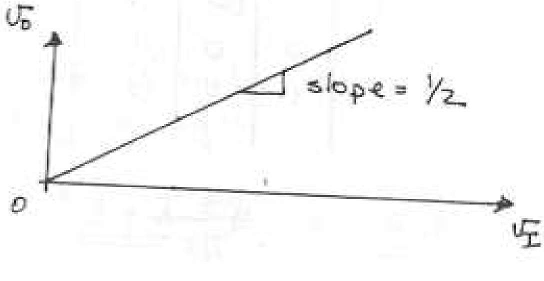
$$120\sqrt{2} = \underline{\underline{169.7V}}$$

3.12

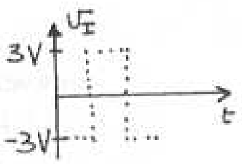


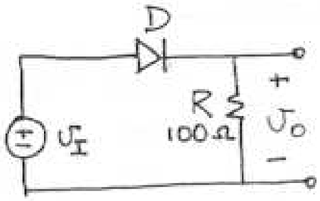
$$i_D = \frac{v_I}{R+R_s}$$

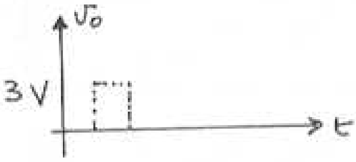
D starts to conduct when $v_I > 0$



3.13







$v_{O,\,peak} = 3V$

$$v_{O,avg} = \frac{1}{T}\int v_O \, dt$$

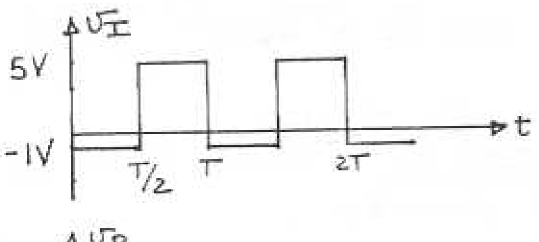
$$= \frac{1}{T}\left[3\,\frac{T}{2}\right] = \underline{\underline{3/2\ V}}$$

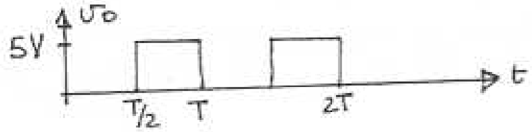
$i_{D,\,peak} = 3/100 = \underline{\underline{30\,mA}}$

$i_{D,\,avg} = \dfrac{3/2}{100} = \underline{\underline{15\ mA}}$

The maximum reverse diode voltage is $\underline{\underline{3\ V}}$

3.14





$v_{O,peak} = \underline{\underline{5V}}$

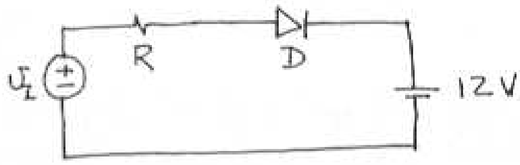
$v_{O,avg} = \underline{\underline{2.5V}}$

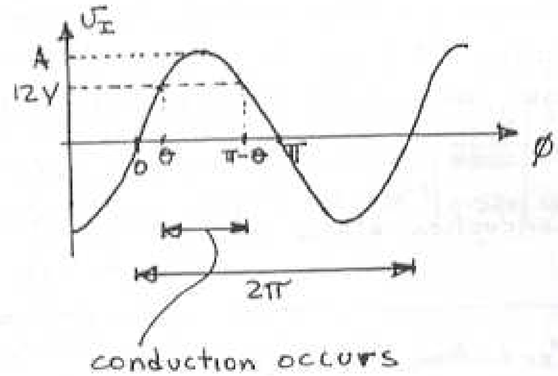
$i_{D,\,peak} = \dfrac{v_{O,\,peak}}{100} = \underline{\underline{50mA}}$

$i_{D,\,avg} = i_{D,\,peak}/2 = \underline{\underline{25mA}}$

maximum reverse voltage = $\underline{\underline{1V}}$

3.15





$v_I = A \sin\theta = 12$ ~ conduction across D occurs

For a conduction angle $(\pi - 2\theta)$ that is 20% of a cycle

$$\frac{\pi - 2\theta}{2\pi} = \frac{1}{5}$$

$$\theta = 0.3\pi$$

$$A = 12/\sin\theta = 14.83V$$

∴ Peak-to-peak sine wave voltage

$$= 2A = \underline{\underline{29.67V}}$$

Given the average diode current to be

$$\frac{1}{2\pi}\int_0^{2\pi} \frac{A\sin\phi - 12}{R}\, d\phi = 100mA$$

$$\frac{1}{2\pi}\left[\frac{-14.83\cos\phi - 12\phi}{R}\right]_{\phi=0.3\pi}^{\phi=0.7\pi} = 0.1$$

$R = \underline{\underline{3.75\,\Omega}}$

Peak diode current $= \dfrac{A-12}{R} = \underline{\underline{0.75A}}$

Peak reverse voltage $= A+12 = \underline{\underline{26.83V}}$

For resistors specified to only one significant digit and peak-to-peak voltage to the nearest volt then choose $A = 15$ so the peak-to-peak sine wave voltage $= \underline{30V}$ and $R = \underline{\underline{3\,\Omega}}$

Conduction starts at $v_I = A\sin\theta = 12$

$15\sin\theta = 12$

$\theta = 0.93\,\text{rad}$

Conduction stops at $\pi - \theta$

$\therefore$ fraction of cycle that current flows is $\dfrac{\pi - 2\theta}{2\pi} \times 100 = 20.5$

$\simeq \underline{\underline{20\%}}$

Average diode current =

$$\frac{1}{2\pi}\left[\frac{-15\cos\phi - 12\phi}{3}\right]_{\phi=0.93}^{2.21} = \underline{\underline{136mA}}$$

Peak diode current

$= \dfrac{15-12}{3} = \underline{\underline{1A}}$

Peak reverse voltage =

$A + 12 = \underline{\underline{27V}}$

3.16

V	RED	GREEN	
3V	ON	OFF	- D_1 conducts
0	OFF	OFF	- No current flows
-3V	OFF	ON	- D_2 conducts

3.17

$V_T = kT/q$ where $k = 1.38\times10^{-23}\,J/K$

$T = 273 + x°C$

$q = 1.60\times10^{-19}\,C$

x [°C]	V_T [mV]
-40	20
0	23.5
40	27
150	36.5

for $V_T = 25mV$

$T = \underline{\underline{16.8°C}}$

3.18

$i = I_S e^{v/2\times0.025}$

$\therefore 1000 I_S = I_S e^{v/0.05}$

$v = \underline{\underline{0.345V}}$

at $v = 0.7V$

$i = I_S e^{0.7/0.05} = \underline{\underline{1.2\times10^{6}\,I_S}}$

3.19

$$i_1 = I_S e^{0.7/V_T} = 10^{-3}$$

$$i_2 = I_S e^{0.5/V_T}$$

$$\frac{i_2}{i_1} = \frac{i_2}{10^{-3}} = e^{\frac{0.5-0.7}{0.025}}$$

$$i_2 = \underline{\underline{0.335\ \mu A}}$$

3.20

$$i = I_S e^{v/nV_T} = I_S e^{0.7/0.025} = 5(10^{-3})$$

$$I_S = 5(10^{-3})\, e^{-0.7/0.025} = \underline{\underline{3.46\times10^{-15}\ A}}$$

v	i
0.71 V	7.46 mA
0.8 V	273.21 mA
0.69 V	3.35 mA
0.6 V	91.65 μA

Let $i_1 = I_S e^{v_1/0.025}$

$$i_2 = 10 i_1 = I_S e^{v_2/0.025}$$

$$\frac{i_2}{i_1} = 10 = e^{\frac{v_2 - v_1}{0.025}}$$

$$\therefore \Delta v = v_2 - v_1 = \underline{\underline{57.56\ mV}}$$

3.21

To calculate I_S use

$$I_S = I e^{-V/nV_T} = I e^{-V/n\times0.025}$$

To calculate the voltage at 1% of the measured current use

$i_2 = 0.01\, i_1$ so,

$$\frac{i_2}{i_1} = 0.01 = e^{\frac{V_2 - V_1}{nV_T}}$$

$$V_2 = V_1 + nV_T \ln 0.01$$

$$= V + n(0.025)\ln(0.01)$$

V [V]	I	I_S $n=1$ [A]	I_S $n=2$ [A]	V $n=1$ [V]	V $n=2$ [V
0.7	1 A	6.91×10^{-13}	8.32×10^{-7}	0.585	0.470
0.650	1 mA	5.11×10^{-15}	2.26×10^{-9}	0.535	0.420
0.650	10 μA	5.11×10^{-17}	2.26×10^{-11}	0.535	0.420
0.7	10 mA	6.91×10^{-15}	8.32×10^{-9}	0.584	0.470

3.22

Let $I_1 = I_S e^{V_1/nV_T}$ and

$$I_2 = I_S e^{V_2/nV_T} = I_1/10$$

Calculate n by :-

$$\frac{I_2}{I_1} = e^{\frac{V_2 - V_1}{nV_T}}$$

$$n = \frac{1}{V_T}\left[\frac{V_2 - V_1}{\ln I_2/I_1}\right] = \frac{1}{0.025}\left[\frac{V_2 - V_1}{\ln 0.1}\right]$$

Calculate I_S by :-

$$I_S = I_1 e^{-V_1/nV_T}$$

Calculate the diode voltage at $10I$ by :- $V_3 = nV_T \ln \frac{10 I_1}{I_S}$

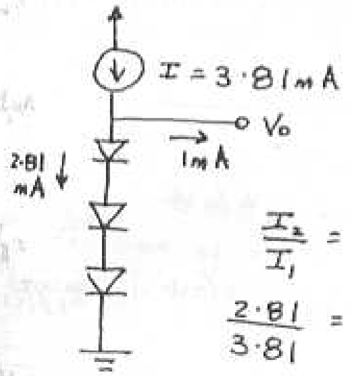
I	V_1 [V]	V_2 [V]	n	I_s [A]	V_3 [V]
10mA	0.7	0.6	1.737	10^{-9}	0.8
1mA	0.7	0.6	1.737	10^{-10}	0.8
10A	0.8	0.7	1.737	10^{-7}	0.9
1 mA	0.7	0.58	2.085	1.47×10^{-9}	0.82
10μA	0.7	0.64	1.042	2.15×10^{-17}	0.7

3.23

$\therefore$ The voltage across each diode is $V_o/3$

$$I = I_s e^{\frac{V_o/3}{nV_T}} = 10^{-14} e^{\frac{2/3}{0.025}}$$

$$= 3.81\text{mA}$$

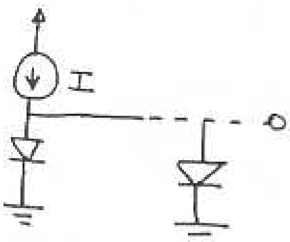


$$\frac{I_2}{I_1} = e^{\frac{(V_2-V_1)/3}{0.025}}$$

$$\frac{2.81}{3.81} = e^{\frac{(V_2-2)/3}{0.025}}$$

$$\Delta V = V_2 - 2 = -22.8\text{mV}$$

3.24



With one diode the current through it is

$$I = I_s e^{V_1/nV_T}$$

With two diodes in parallel, the current splits between each diode so that the diodes each has half the current

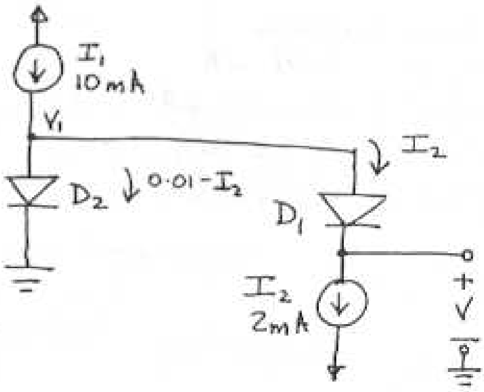
$$\frac{I}{2} = I_s e^{V_2/nV_T}$$

$$\therefore \frac{I/2}{I} = e^{\frac{V_2-V_1}{nV_T}}$$

The change in voltage is

$$\Delta V = V_2 - V_1 = nV_T \ln\left(\tfrac{1}{2}\right) = -17.3\text{mV}$$

3.25



The current through D_1 is

$$10 I_s e^{\frac{V_1-V}{nV_T}} = I_2 \quad (A)$$

The current through D_2 is

$$I_s e^{\frac{V_1}{nV_T}} = 0.01 - I_2$$

$$I_s = (0.01 - I_2)\, e^{\frac{-V_1}{nV_T}} \quad (B)$$

(B) → (A)

$$10(0.01 - I_2)\, e^{\frac{-V}{nV_T}} = I_2$$

$$V = -V_T \ln\left(\frac{I_2}{10(0.01 - I_2)}\right)$$

$$= 0.025 \ln\left(\frac{2}{10(8)}\right) = \underline{\underline{92.2\,mV}}$$

For $V = 50\,mV$

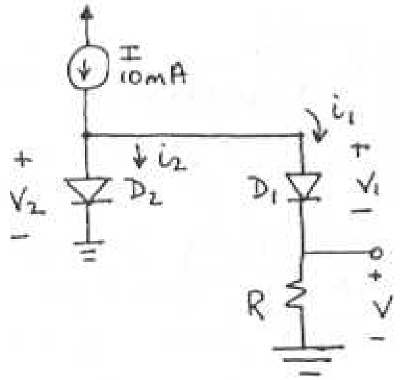
$$-V_T \ln\left(\frac{I_2}{10(10 - I_2)}\right) = 50 \times 10^{-3}$$

$$I_2 = 10(10 - I_2)\,e^{-2}$$

$$I_2(1 + 10e^{-2}) = 100\,e^{-2}$$

$$I_2 = \underline{\underline{5.75\,mA}}$$

3.26



Given for each diode

$$i = I_s e^{V/nV_T} \Rightarrow 10 \times 10^{-3} = I_s e^{0.7/n \times 0.025} \quad (1)$$

$$100 \times 10^{-3} = I_s e^{0.8/n \times 0.025} \quad (2)$$

(2)/(1) $\quad 10 = e^{0.1/n(0.025)}$

$$n = 1.737$$

$$V = V_2 - V_1 = nV_T \ln(i_2/i_1) = 80\,mV$$

$$1.737(25 \times 10^{-3}) \ln\left(\frac{0.01 - i_1}{i_1}\right) = 80$$

$$i_1 = 1.4\,mA$$

$$R = 80/i_1 = 80/1.4 = \underline{\underline{57.1\,\Omega}}$$

3.27

AT A CONSTANT TEMPERATURE, THE DIODE VOLTAGE DROP CHANGES WITH CURRENT ACCORDING TO

$$\Delta V = V_T \ln\left(\frac{I_2}{I_1}\right)$$

WHERE

$$V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23}(273 + \text{Temp. } ^\circ C)}{1.6 \times 10^{-19}}$$

THUS:

TEMP (°C)	0	50	75	100	-50
V_T (mV)	23.5	27.9	30	32.2	19.2

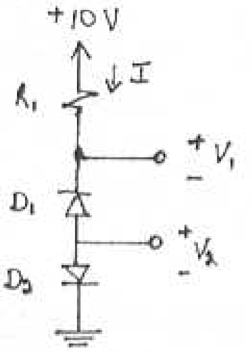
AT A CONSTANT CURRENT, THE DIODE VOLTAGE DROP CHANGES WITH TEMPERATURE ACCORDING TO

$$\Delta V = -2\,(mV) \times \text{Temperature change } (^\circ C)$$

THUS:

(a) 620 mV AT 10 µA AND 0°C
728 mV AT 1 mA AND 0°C
678 mV AT 1 mA AND 25°C

3.28



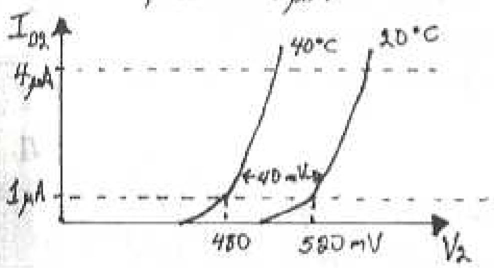
At 20°C:

$V_{R1} = V_2 = 520$ mV

$R_1 = 520$ kΩ

$I = \frac{520 \text{ mV}}{520 \text{ k}\Omega} = 1\ \mu A$

At 40°C, $I = 4\mu A$



$V_2 = 480 + 2.3 \times 1 \times 25 \log 4$
$= 514.6$ mV

$V_{R1} = 4\mu A \times 520$ kΩ $= \underline{\underline{2.08V}}$

At 0°C, $I = \frac{1}{4}\ \mu A$

$V_2 = 560 - 2.3 \times 1 \times 25 \log 4$
$= \underline{\underline{525.4 \text{ mV}}}$

$V_{R1} = \frac{1}{4} \times 520 = \underline{\underline{0.13\ V}}$

3.29

The voltage drop = 700 − 580 = 120mV
Since the diode voltage decreases by approximately 2mV for every 1°C increase in temperature, the junction temperature must have increased by

$\frac{120}{2} = \underline{60\ °C}$

Power being dissipated =

$580 \times 10^{-3} \times 15 = \underline{8.7W}$

Thermal Resistance = temperature rise/watt

$= 60/8.7 = \underline{6.9\ °C/W}$

3.30

$i = I_S e^{v/nV_T}$

$10 = I_S e^{0.8/2(0.025)}$

$I_S = 1.12 \times 10^{-6}$ A

For current varying between $i_1 = 0.5$ mA to $i_2 = 1.5$ mA, the voltage varies from

$v_1 = 2(0.025) \ln\left(\frac{0.5\times10^{-3}}{1.12\times10^{-6}}\right) = \underline{\underline{0.305\ V}}$

to:

$v_2 = 2(0.025) \ln\left(\frac{1.5\times10^{-3}}{1.12\times10^{-6}}\right) = \underline{\underline{0.360\ V}}$

$\therefore$ the voltage decreases by approximately 2mV for every 1°C increase in temperature, the voltage may vary by ∓50mV for the ±25°C temperature variation.

3.31

$$i = I_S e^{v/nV_T}$$

$$\frac{I_{S2}}{I_{S1}} = \frac{1}{0.1 \times 10^{-3}} = 10^4$$

For identical currents

$$I_{S1} e^{v_1/nV_T} = I_{S2} e^{v_2/nV_T}$$

$$e^{\frac{v_1 - v_2}{nV_T}} = 10^4$$

$$v_1 - v_2 = nV_T \ln 10^4$$

$$= 25 \times 10^{-3} \ln 10^4$$

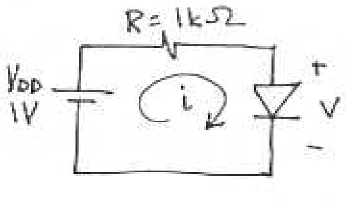
$$= \underline{\underline{+0.23V}}$$

I.E. THE VOLTAGE DIFFERENCE BETWEEN THE TWO DIODES IS +0.23 V INDEPENDENT OF THE CURRENT. HOWEVER, SINCE THE TWO CURRENTS CAN VARY BY A FACTOR OF 3 (0.5 mA TO 1.5 mA) THE DIFFERENCE VOLTAGE WILL BE:

$0.23\,V \pm nV_T \ln 3 = 0.23\,V \pm 2.75\,mV$

SINCE TEMPERATURE CHANGE AFFECTS BOTH DIODES SIMILARLY THE DIFFERENCE VOLTAGE REMAINS CONSTANT.

3.32

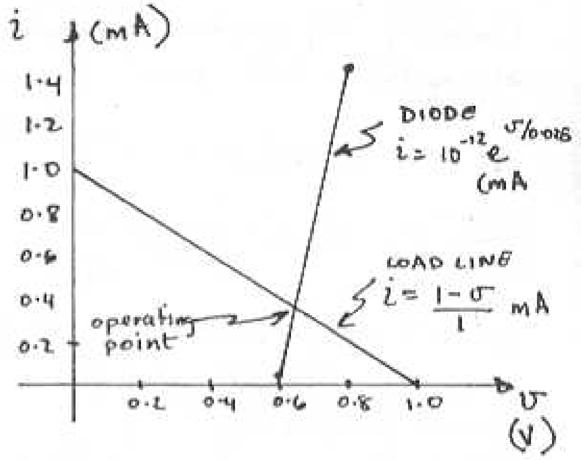


$i = 10^{-15} e^{v/V_T}$ where $n = 1$

$v = 0.7V \quad i = 1.45\,mA$

$v = 0.6V \quad i = 0.026\,mA$

A sketch of the graphical construction to determine the operating point is shown below.



From the above sketch we see that the operating point must lie between $v = 0.6$ and $0.7\,V$ and $i \approx 0.3$ to $0.4\,mA$. To find the point more accurately an enlarged graph is plotted.

For $i = 0.3\,mA = 10^{-12} e^{v/0.025}$

$\Rightarrow v = 660.7\,mV$

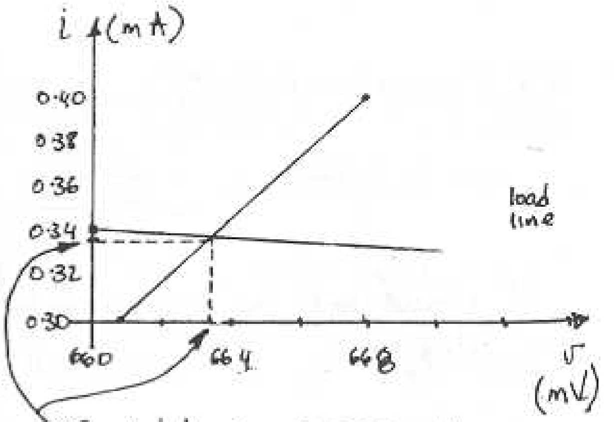
For $i = 0.4\,mA = 10^{-12} e^{v/0.025}$

$\Rightarrow v = 667.9\,mV$

For the load line:

$v = 660\,mV \Rightarrow i = 0.34\,mA$

$v = 670\,mV \Rightarrow i = 0.33\,mA$



Graphical Point $\quad i = 0.337\,mA$

$v = 663.4\,mV$

CONT.

Comparing the graphical results to the exponential model gives:

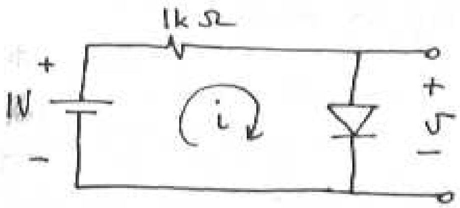
At $i = 0.337\,mA = 10^{-12} e^{v/0.025}$

$\Rightarrow v = 663.6\,mV$

which is only $(663.6 - 663.4) = \underline{\underline{0.2\,mV}}$ greater than the value found graphically!

3.33

Iterative Analysis:



$I_S = 10^{-12}\,mA$
$n = 1$

\#1 $v = 0.7\,V$ $\quad i = \frac{1-0.7}{1} = 0.3\,mA$

\#2 $v = 0.25\ln\left(\frac{0.3}{10^{-12}}\right) = 0.6607\,V$

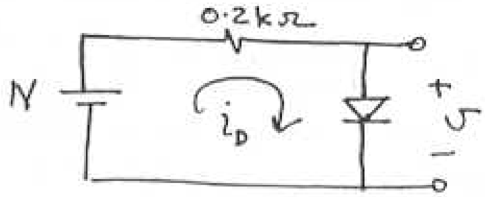
$i = \frac{1-0.6607}{1} = 0.3393\,mA$

\#3 $v = 0.25\ln\left(\frac{0.3393}{10^{-12}}\right) = \underline{\underline{0.6638\,V}}$

$i = \frac{1-0.6638}{1} = \underline{\underline{0.3362}}$

$\therefore$ i did not change by much stop here.

3.34



(a) $i_D = \frac{1-0.7}{0.2} = \underline{\underline{1.5\,mA}}$

(b) Iterative Analysis given $v_D = 0.7\,V$ at $i_D = 1\,mA$

\#1 $v = 0.7\,V$ $\quad i_D = \frac{1-0.7}{0.2} = 1.5\,mA$

\#2 $\because i = I_S e^{v/nV_T}$ $\quad n = 2$

$\frac{i_2}{i_1} = e^{\frac{v_2 - v_1}{0.05}}$

thus $v_2 = v_1 + 0.05\ln i_2/i_1$

$\therefore$ for $i = 1.5\,mA$

$v = 0.7 + 0.05\ln\frac{1.5}{1} = 0.720\,V$ $\quad$ & $i_D = \frac{1-0.720}{0.2} = 1.4\,mA$

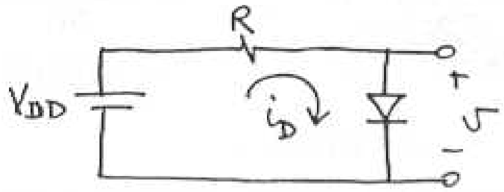
\#3

$v = 0.720 + 0.05\ln\left(\frac{1.4}{1.5}\right) = 0.716\,V$ $\quad$ & $i_D = \frac{1-0.716}{0.2} = 1.42\,mA$

\#4

$v = 0.716 + 0.05\ln\left(\frac{1.42}{1.4}\right) = \underline{\underline{0.716\,V}}$ $\quad$ & $i_D = \underline{\underline{1.42\,mA}}$

3.35



Derivation of iterative equation

$i_D = I_S e^{v/v_T}$

$\frac{i_{D2}}{i_{D1}} = e^{\frac{v_2 - v_1}{n v_T}}$

$v_2 = v_1 + n v_T \ln\left(\frac{i_{D2}}{i_{D1}}\right)$

$= v_1 + \Delta V \log\left(\frac{i_{D2}}{i_{D1}}\right)$

(a) $V = 0.7\,V$ $\quad i_D = \frac{10-0.7}{9.3} = 1\,mA$

(b) $v = 0.7V$ $\quad i_D = \frac{3-0.7}{2.3} = 1mA$

~ for both these cases the diode is rated at 1mA for 0.7V so stop.

(c) $V_{DD} = 2V$ $\quad R = 2k\Omega$

#1 $v = 0.7\,V$ $\quad i_D = \frac{2-0.7}{2} = 0.65mA$

#2 $v = 0.7 + 0.1\log\left(\frac{0.650}{10}\right) = 0.581V$

$i_D = \frac{2-0.581}{2} = 0.709\,mA$

#3 $v = 0.581 + 0.1\log\left(\frac{0.709}{0.650}\right)$

$= \underline{0.584V}$

$i_D = \frac{2-0.584}{2} = \underline{0.708mA}$

(d) $V_{DD} = 2V$ $\quad R = 2k\Omega$

#1 $V = 0.7V$ $\quad i_D = \frac{2-0.7}{2}$

$= 0.650\,mA$

#2.

$V = 0.7 + 0.1\log\left(\frac{0.650}{1}\right)$ $\quad i_D = \frac{2-0.681}{2}$

$= 0.681\,V$ $\quad = 0.659\,mA$

#3

$v = 0.681 + 0.1\log\left(\frac{0.659}{0.650}\right)$ $\quad i_D = \frac{2-0.682}{2}$

$= \underline{0.682V}$ $\quad = \underline{0.659mA}$

(e) $V_{DD} = 1V$ $\quad R = 0.3k\Omega$

#1 $v = 0.7V$ $\quad i_D = \frac{1-0.7}{0.3} = 1mA$

#2

$v = 0.7 + 0.1\log\frac{1}{10}$ $\quad i_D = \frac{1-0.6}{0.3} = 1.333mA$

$= 0.6V$

#3

$v = 0.6 + 0.1\log\frac{1.333}{1}$ $\quad i_D = \frac{1-0.612}{0.3} = 1.293\,mA$

$= 0.612V$

#4

$v = 0.612 + 0.1\log\frac{1.293}{1.333}$ $\quad i_D = \frac{1-0.611}{0.3} = 1.297mA$

$= 0.611V$

#5

$v = 0.611 + 0.1\log\frac{1.297}{1.293}$ $\quad i_D = \underline{1.297mA}$

$= \underline{0.611\,V}$

(f) $V_{DD} = 1V$ $\quad R = 0.3k\Omega$

#1 $v = 0.7\,V$ $\quad i_D = \frac{1-0.7}{0.3} = 1mA$

CONT.

#2

$v = 0.7 + 0.06 \log \frac{1}{10}$ $\quad i_D = \frac{1-0.640}{0.3}$

$= 0.640\,V$ $\quad = 1.2\,mA$

#3

$v = \quad + 0.06 \log \frac{1.2}{1}$ $\quad i_D = \frac{1-0.645}{0.3}$

$= 0.645V$ $\quad = 1.183\,mA$

#4

$v = \quad + 0.06 \log \frac{1.183}{1.2}$

$= \underline{\underline{0.645V}}$ $\quad i_D = \underline{\underline{1.183mA}}$

(g) $V_{DD} = 1V \quad R = 0.3k\Omega$

#1 $v = 0.7$ $\quad i_D = \frac{1-0.7}{0.3} = 1mA$

#2

$v = 0.7 + 0.12 \log \frac{1}{10}$ $\quad i_D = \frac{1-0.580}{0.3}$

$= 0.580V$ $\quad = 1.381\,mA$

#3

$v = 0.580 + 0.12 \log \frac{1.381}{1}$ $\quad i_D = \frac{1-0.697}{0.3}$

$= 0.697V$ $\quad = 1.343\,mA$

#4

$v = 0.697 + 0.12 \log \frac{1.343}{1.381}$ $\quad i_D = \frac{1-0.596}{0.3}$

$= 0.596\,V$ $\quad = 1.347mA$

#5

$v = 0.596 + 0.12 \log \frac{1.347}{1.343}$

$= \underline{\underline{0.596V}}$ $\quad i_D = \underline{\underline{1.347\,mA}}$

(h) $V_{DD} = 0.5V \quad R = 30k\Omega$

#1 let $v = 0.4V$ $\quad i_D = \frac{0.5-0.4}{30}$

$= 3.333\,\mu A$

#2

$v = 0.7 + 0.1 \log \frac{3.333 \times 10^{-3}}{10}$ $\quad i_D = \frac{0.5-0.352}{30}$

$= 0.352V$ $\quad = 4.933\,\mu A$

#3

$v = 0.352 + 0.1 \log \frac{4.933}{3.333}$ $\quad i_D = \frac{0.5-0.369}{30}$

$= 0.369V$ $\quad = 4.367\,\mu A$

#4

$v = 0.369 + 01 \log \frac{4.367}{4.933}$ $\quad i_D = \frac{0.5-0.364}{30}$

$= 0.364V$ $\quad = 4.533\,\mu A$

#5

$v = 0.364 + 0.1 \log \left(\frac{4.533}{4.367}\right)$ $\quad i_D = \frac{0.5-0.366}{30}$

$= 0.366V$ $\quad = 4.467\,\mu A$

#6

$v = 0.366 + 0.1 \log \frac{4.467}{4.533}$ $\quad i_D = \frac{0.5-0.365}{30}$

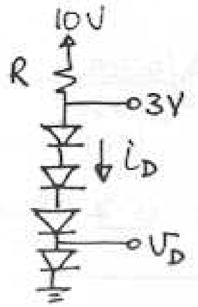
$= 0.365V$ $\quad = 4.5\,\mu A$

#7

$v = 0.365 + 0.1 \log \frac{4.5}{4.467}$

$= \underline{\underline{0.365\,V}}$ $\quad i_D = \underline{\underline{4.5\,\mu A}}$

$\boxed{3.36}$



$V_D = \frac{3}{4} = 0.75V$

$i_D = I_s e^{V_D/nV_T}$

$\frac{i_{D2}}{i_{D1}} = e^{\frac{V_{D2}-V_{D1}}{nV_T}}$

CONT.

$$\therefore\ i_D = i_{D2} = i_{D1}\, e^{\frac{V_{D2}-V_{D1}}{nV_T}}$$

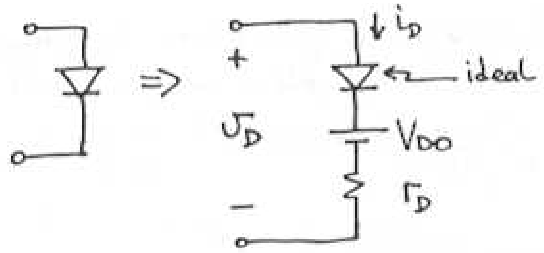
$$= 1 \times e^{\frac{0.75-0.7}{1\times 0.025}}$$

$$= 7.389\ \text{mA}$$

$$\therefore\ R = \frac{10-3}{I_D} = \frac{10-3}{7.389} = \underline{\underline{0.947\,k\Omega}}$$

3.37

Piecewise linear model:



Given $n=2$, $V_D=0.7V$ $i_D=1mA$

The current throug the diode is given by:

$$i_D = \frac{v_D - V_{DO}}{r_D}$$

~ need to find the parameters V_{DO} and r_D

Using the exponential model to find the diode voltage at 10mA

$$\frac{i_{D2}}{i_{D1}} = e^{\frac{V_{D2}-V_{D1}}{nV_T}}$$

$$V_{D2} = nV_T \ln\left(\frac{i_{D2}}{i_{D1}}\right) = 0.05 \ln\left(\frac{10}{1}\right)$$

$$= 0.815V$$

Finding V_{DO} & r_D using the given facts:

$$i_D = \frac{0.7 - V_{DO}}{r_D} = 1mA \quad ①$$

$$i_D = \frac{0.815 - V_{DO}}{r_D} = 10\,mA \quad ②$$

$$②/① \Rightarrow \frac{0.815 - V_{DO}}{0.7 - V_{DO}} = 10$$

$$V_{DO} = \underline{0.687V}$$

$$r_D = \frac{0.7 - V_{DO}}{1} = \underline{\underline{12.8\,\Omega}}$$

Using the piecewise linear model

$$i_D = \frac{v_D - 0.687}{12.8} \Rightarrow v_D = 0.687 + 12.8\, i_D$$

Using the exponential model

$$\frac{i_{D2}}{i_{D1}} = e^{\frac{v_D - 0.7}{0.05}} \Rightarrow v_D = 0.7 + 0.05 \ln\left(\frac{i_{D2}}{1}\right)$$

i_D (mA)	PIECEWISE LINEAR v_D (V)	EXPONENTIAL V_D (V)	Error (mV)
0.5	0.693	0.655	28
5	0.751	0.780	−29.5
14	0.866	0.832	34

3.38

Looking at the copy of FIG 3.12 below, we see at

$i_D = 1mA \rightarrow v_D = 0.7V$

$i_D = 10mA \rightarrow v_D = 0.8V$

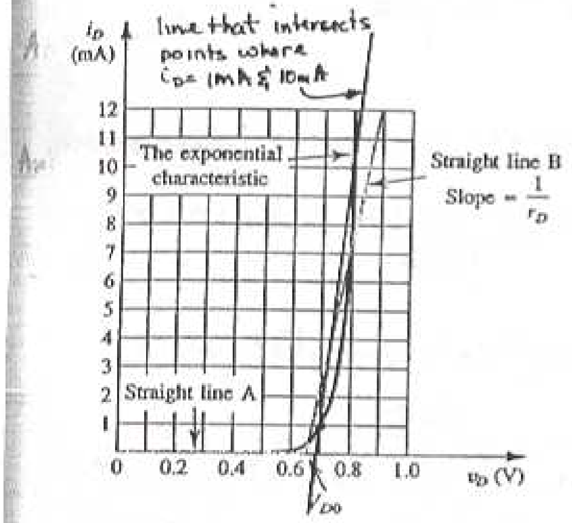
$$\therefore\ \text{slope} = \frac{1}{r_D} = \frac{10-1}{0.8-0.7} = 90\,\frac{mA}{V}$$

$$\therefore\ r_D = \frac{1}{90\times 10^{-3}} = \underline{\underline{11.1\,\Omega}}$$

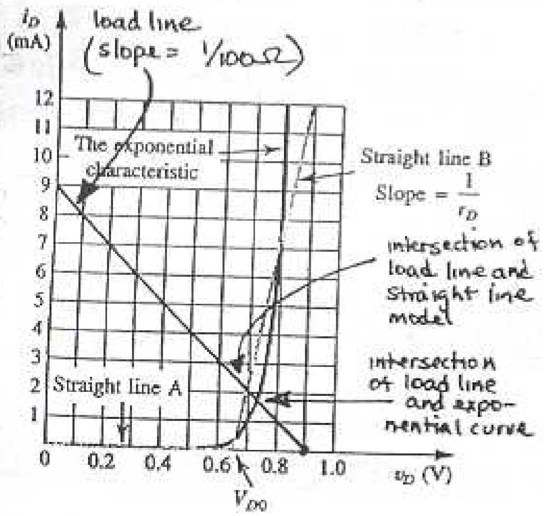
To find V_{DO}:

$$i_D = \frac{v_D - V_{DO}}{r_D}$$

$$10^{-3} = \frac{0.7 - V_{DO}}{11.1} \Rightarrow V_{DO} = \underline{0.689V}$$



3.39



(a) The load line intersects the exponential model at:

$v_D = \underline{0.73V}$ $\quad i_D = \underline{1.7mA}$

(b) The load line intersects the straight-line model at

$v_D = \underline{0.7V}$ $\quad i_D = \underline{2mA}$

3.40

Calculating the parameters r_D & V_{DO} for the battery plus resistor model

$$i_D = I_S e^{v_D/nV_T} \qquad n=1$$

For $i_D = 0.1\, I_D$

$$v_{D2} = 0.7 + 0.025 \ln(0.1) = \underline{0.642V}$$

For $i_D = 10 I_D$

$$v_{D3} = 0.7 + 0.025 \ln(10) = \underline{0.758V}$$

Note that since the specifications for all of the diodes are given for 0.7V, the end voltages are the same as the voltage change for relative currents are independent to I_D & I_S.

$\therefore$ $v_{D2} = V_{DO} + i_{D2} r_D$ ①

$v_{D3} = V_{DO} + i_{D3} r_D$ ②

② → ①

$$v_{D3} - v_{D2} = (i_{D3} - i_{D2}) r_D$$

CONT.

$$0.758 - 0.642 = (10\,I_D - 0.1 I_D)\, r_D$$

$$0.166 = 9.9\, I_D\, r_D$$

$$r_D = \frac{0.0117}{I_D} \qquad (3)$$

for (a) $I_D = 1\text{mA}$ $\quad r_D = \frac{0.0117}{1} = \underline{\underline{11.7\Omega}}$

(b) $I_D = 1\text{A}$ $\quad r_D = \frac{0.0117}{1} = \underline{\underline{0.0117\Omega}}$

(c) $I_D = 10\mu\text{A}$ $\quad r_D = \frac{0.0117}{10\mu\text{A}} = \underline{1.17k\Omega}$

(3) → (1)

$$0.642 = V_{D0} + 0.1 I_D \times \frac{0.0117}{I_D}$$

$$= V_{D0} + 0.00117$$

$V_{D0} = \underline{0.641V}$ ← same for all diodes

3.41

Since for a current of 10 mA, the diode voltage is $\underline{0.8V}$, this would be a suitable choice for the constant-voltage-drop model.

3.42

Constant Voltage drop Model:

Using $v_D = 0.7V \Rightarrow i_{D1} = \frac{V-0.7}{R}$

Using $v_D = 0.6V \Rightarrow i_{D2} = \frac{V-0.6}{R}$

For the difference in currents to vary by only 1% ⇒

$$i_{D2} = 1.01\, i_{D1}$$
$$V - 0.6 = 1.01\,(V - 0.7)$$
$$V = \underline{\underline{10V}}$$

For $V = 2V$ & $R = 1k\Omega$

At $V_D = 0.7V$ $\quad i_{D1} = \frac{2-0.7}{1} = 1.3\text{mA}$

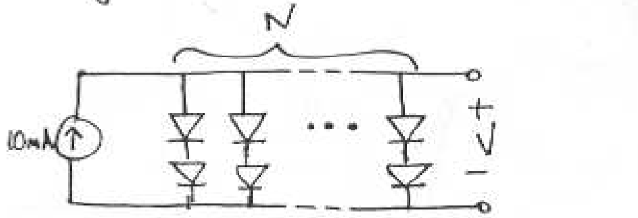
$V_D = 0.6V$ $\quad i_{D2} = \frac{2-0.6}{1} = 1.4\text{mA}$

$$\frac{i_{D2}}{i_{D1}} = \frac{1.4}{1.3} = 1.08$$

Thus the percentage difference is $\underline{8\%}$

3.43

Since $2V_D = 1.4V$ is close to the required 1.25V, use N parallel pairs of diodes to split the current evenly.



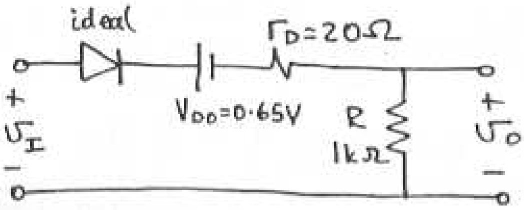
$$\therefore V = 2\left[0.7 + 0.1 \log \frac{10/N}{20}\right] = 1.25V$$

$N = 2.8$ ⇒ Use $\underline{\underline{3 \text{ sets of diodes}}}$

$$V = 2\left(0.7 + 0.1\log\frac{10/3}{20}\right) = \underline{\underline{1.244V}}$$

3.44

Piecewise linear model in a half-wave rectifier.

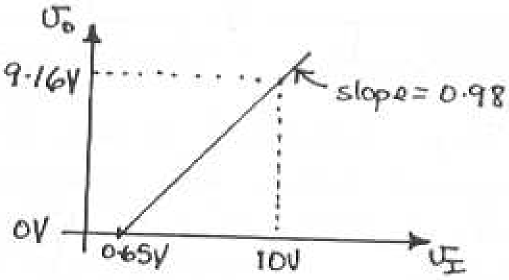


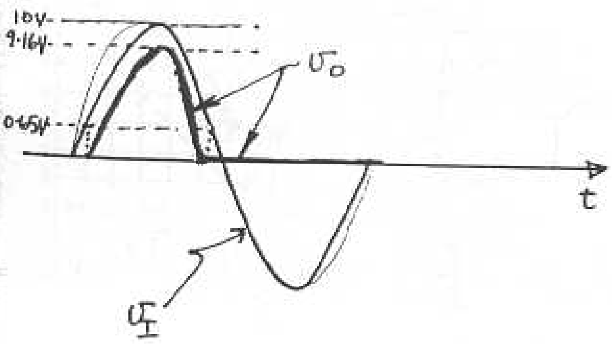
$$v_O = \frac{v_I - V_{D0}}{r_D + R} R \quad , \quad \text{for } v_I \gg V_{D0}$$

Thus, $v_O = 0.98(v_I - 0.65)$ for $v_I \geq 0.65$

$v_O = 0$ for $v_I < 0.65V$

Sketch of transfer characteristic :-

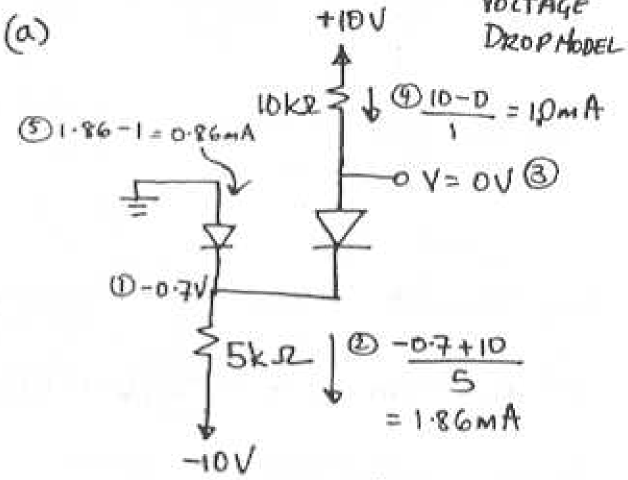




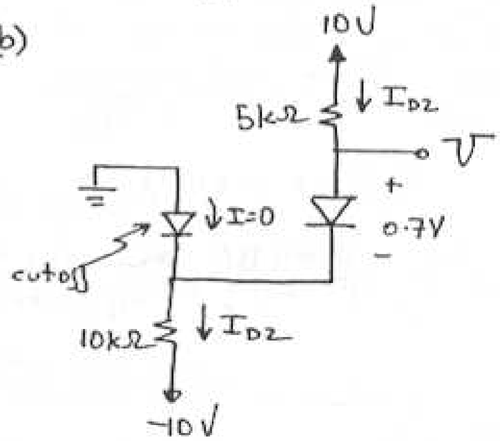
3.45

Refer to example 3-2 ~ CONSTANT VOLTAGE DROP MODEL

(a)



(b)

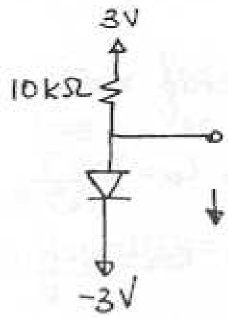


$$I_{D2} = \frac{10-(-10)-0.7}{15} = 1.29mA$$

$$V = -10 + 1.29(10) + 0.7 = \underline{3.6V}$$

3.46

(a)



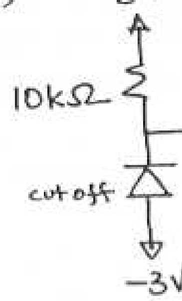
$V = -3 + 0.7 = \underline{-2.3V}$

$$\downarrow I = \frac{3+2.3}{10}$$

$$= \underline{0.53mA}$$

CONT.

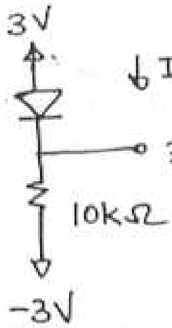
(b)



$V = 3 - I(10) = \underline{\underline{3V}}$

$\downarrow I = \underline{\underline{0A}}$

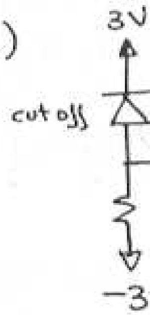
(c)



$\downarrow I = \frac{2.3+3}{10} = \underline{\underline{0.53mA}}$

$3 - 0.7 = \underline{\underline{2.3V}}$

(d)

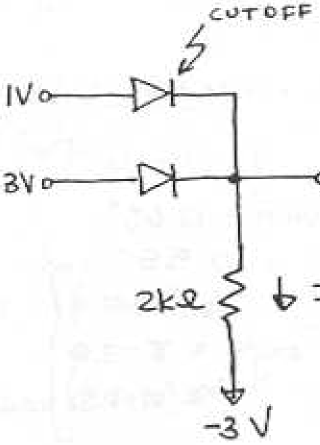


$\downarrow I = \underline{\underline{0A}}$

$V = \underline{\underline{-3V}}$

3.47

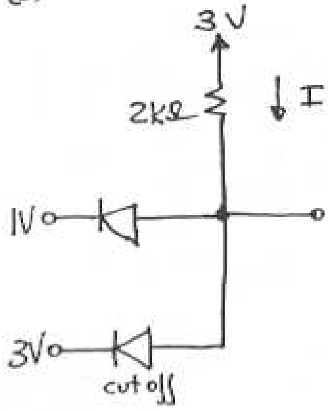
(a)



$V = 3 - 0.7 = \underline{\underline{2.3V}}$

$\downarrow I = \frac{2.3-(-3)}{2} = \underline{\underline{2.65mA}}$

(b)

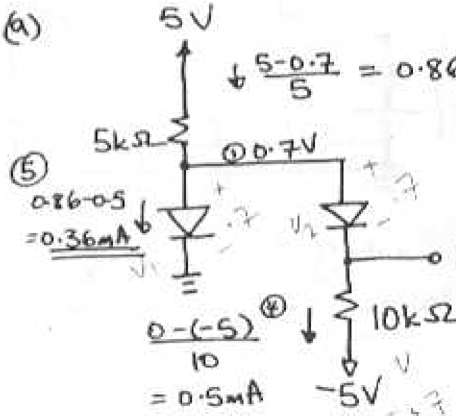


$\downarrow I = \frac{3-1.7}{2} = \underline{\underline{0.65mA}}$

$V = 1 + 0.7 = \underline{\underline{1.7V}}$

3.48

(a)



$\downarrow \frac{5-0.7}{5} = 0.86mA$ ②

⑤ $0.86 - 0.5 = \underline{0.36mA} \downarrow$

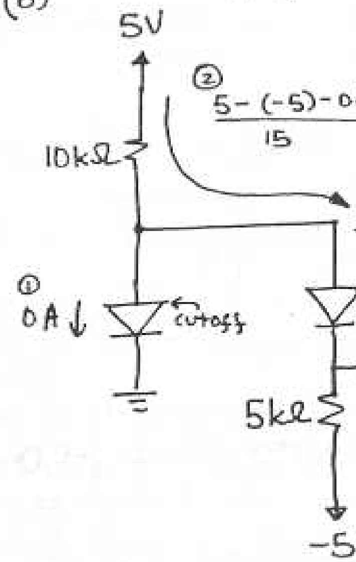
$V = \underline{\underline{0V}}$ ③

$\frac{0-(-5)}{10}$ ④ $\downarrow$ $= 0.5mA$

$V_1 = 0.7,\ V_2 = .7$

$V_1 = V_2 + V \Rightarrow V = 0V$

(b)

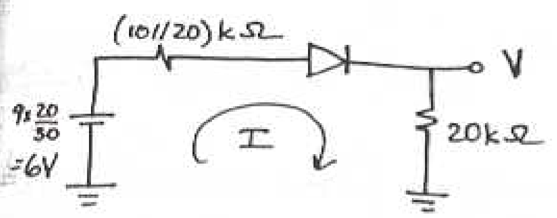


② $\frac{5-(-5)-0.7}{15} = 0.620mA$

$-1.9 + 0.7 = -1.2V$ ④

$V = -5 + 0.62(5) = \underline{\underline{-1.9V}}$ ③

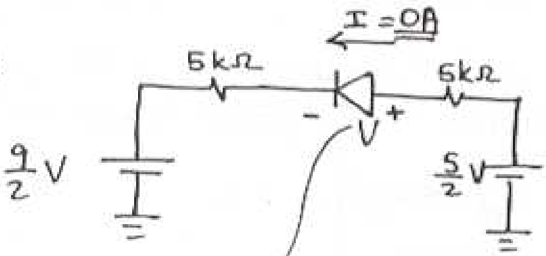
3.49



$$I = \frac{6-0.7}{(10 \parallel 20)+20} = \underline{\underline{0.199\,mA}}$$

$$V = 20I = \underline{\underline{3.98V}}$$

(b)

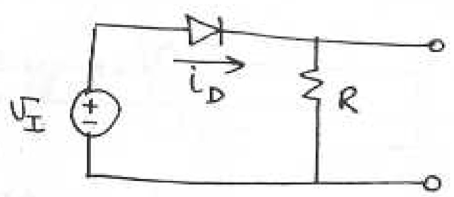


cutoff $\therefore$ $\frac{5}{2} < \frac{9}{2}$

$\therefore$ $I = \underline{\underline{0A}}$

$$V = 5/2 - 9/2 = \underline{\underline{-2V}}$$

3.50



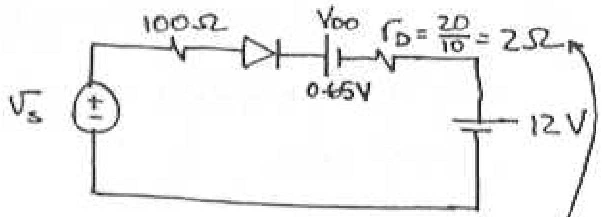
$$i_{D,peak} = \frac{v_{I,peak} - 0.7}{R} \leq 50$$

$$R \geq \frac{120\sqrt{2} - 0.7}{50} = \underline{\underline{3.38k\Omega}}$$

Reverse voltage $= 120\sqrt{2} = 169.7V$.
The design is essentially the same since the supply voltage $>> 0.7V$

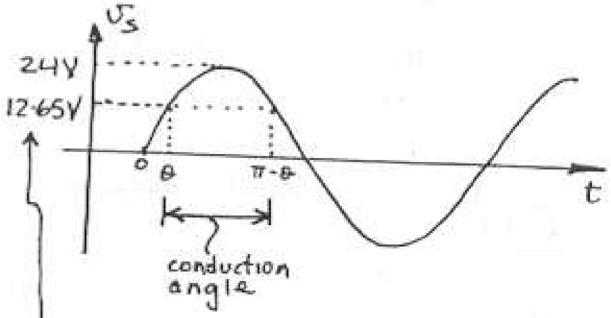
3.51

Battery plus resistance model



since the diode has 10x the area r_D is 1/10 as big.

$$i_D = I_S e^{v/nV_T} = \frac{V_S - V_{DO} - 12}{100+2}$$



Conduction starts when $v_S > 12 + V_{DO}$

$v_S > 12.65V$

$\therefore$ $24 \sin\theta = 12.65°$

$\theta = 0.555$ rad

Conduction angle $= \pi - 2\theta$

$= 2.031$ rad.

Fraction of cycle for conduction $= \frac{2.031}{2\pi} = \underline{\underline{0.323}}$

CONT.

$$i_{D,peak} = \frac{24 - 12.65}{100+2} = \underline{\underline{0.111\ A}}$$

Maximum reverse voltage occurs across the diode when v_s is at its negative peak and is equal to:

$$24 + 12 = \underline{36V}$$

3.52

Using the exponential model

$$i_D = I_s\, e^{\Delta V/nV_T}$$

FOR A +10mV CHANGE

$$\frac{i_{D2}}{i_{D1}} = e^{\Delta V/nV_T} = e^{0.01/n(0.025)}$$

$$= \begin{cases} 1.492 & \sim n=1 \\ 1.221 & \sim n=2 \end{cases}$$

$$\%\ \text{CHANGE} = \frac{i_{D2} - i_{D1}}{i_{D1}} \times 100$$

$$= \begin{cases} (1.492 - 1)\times 100 = \underline{\underline{+49.2\%}} & n=1 \\ (1.221-1)\times 100 = \underline{\underline{22.1\%}} & n=2 \end{cases}$$

FOR A −10mV CHANGE

$$\frac{i_{D2}}{i_{D1}} = 10^{-0.01/n(0.025)} = \begin{cases} 0.670 & n=1 \\ 0.819 & n=2 \end{cases}$$

$$\%\text{CHANGE} = \begin{cases} (0.670-1)\,100 = \underline{-33\%} & n=1 \\ (0.819-1)\,100 = -\underline{18\%} & n=2 \end{cases}$$

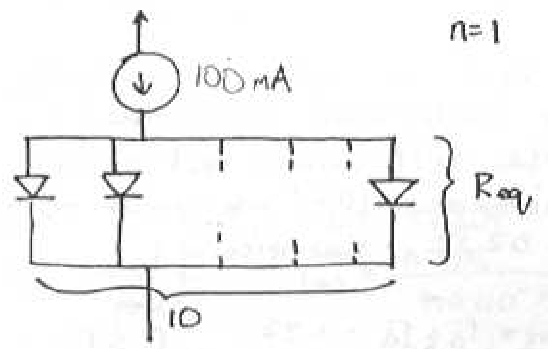
For a current change limited to ±10%

$$\frac{i_{D2}}{i_{D1}} = e^{\Delta V/n\times 0.025} = 0.9 \text{ to } 1.1$$

$$\Delta V = \begin{cases} \underline{\underline{-2.634\text{mV to } 2.383\text{mV}}} & n=1 \\ \underline{\underline{-5.268\text{mV to } 4.766\text{mV}}} & n=2 \end{cases}$$

3.53

n=1



Each diode has the current

$$i_D = \frac{0.1}{10} = 0.01\text{A}$$

Each diode has a small-signal resistance

$$r_d = \frac{nV_T}{I_D} = \frac{0.025}{0.01} = \underline{\underline{2.5\Omega}}$$

$$R_{eq} = r_d/10 = \underline{\underline{0.25\ \Omega}}$$

For one diode conducting 0.1 A

$$r_d = nV_T/0.1 = \frac{0.025}{0.1} = \underline{\underline{0.25\Omega}}$$

This is the same as R_{eq}. We can think of the parallel connection as equivalent to a single diode having 10 times the junction area of each diode. This large diode is fed with 10x the current (or 0.1A) and this exhibits the same small-signal resistance as 10 parallel smaller diodes.

Now consider the series resistance of 0.2Ω to connect a diode. For the parallel combination above:

$$R_{eq} = \frac{1}{10}(0.2 + 2.5) = 0.27\Omega$$

To have an equivalent resistance, the single diode conducting all of the 0.1A would need a series resistance 10x as small or 0.02Ω. Specifically:

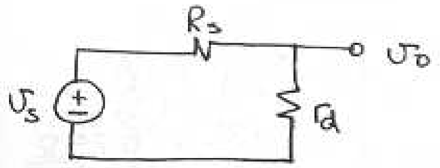
$$r_{out} = r_s + r_d = 0.27$$

$$= r_s + \frac{nV_T}{I_D} = 0.27$$

$$= r_s + 0.25 = 0.27$$

$$r_s = 0.27 - 0.25 = \underline{\underline{0.02\Omega}}$$

3.54



SMALL SIGNAL EQUIVALENT CIRCUIT

To find the small-signal response, v_o, open the dc current source I, and short the capacitors C_1 and C_2. Also replace the diode with its small signal resistance:

$$r_d = \frac{nV_T}{I} \qquad n=2$$

Now:

$$v_o = v_s \frac{r_d}{r_d + R_s}$$

$$= v_s \frac{nV_T/I}{\frac{nV_T}{I} + R_s} = v_s \underline{\underline{\frac{nV_T}{nV_T + IR_s}}}$$

Q.E.D.

$$v_o = 10\text{mV} \frac{0.05}{0.05 + 10^3 I}$$

$$= \begin{cases} 0.476\text{ mV} & \sim I = 1\text{mA} \\ 3.333\text{ mV} & \sim I = 0.1\text{mA} \\ 9.804\text{ mV} & \sim I = 1\mu\text{A} \end{cases}$$

For $v_o = \frac{1}{2} v_s = v_s \times \frac{0.05}{0.05 + 10^3 I}$

$$I = \underline{\underline{50\mu A}}$$

3.55

$R_s = 10k\Omega$, $n=1$, a 1mA diode

$$v_o/v_I = \frac{0.025}{0.025 + R_s I}$$

$$= \frac{0.025}{0.025 + 10^4 I} \quad (1)$$

For the current change limited to $\pm 10\%$ of I & using the exponential model we get

$$\frac{i_{D2}}{i_{D1}} = e^{\Delta V/nV_T} = 0.9 \text{ to } 1.1$$

CONT.

$$\Delta v = \underline{\underline{-2.63\,\text{mV to } 2.38\,\text{mV}}}$$

This is the amount the output will vary for a 10% change in diode current. Divide this by the specific gains given in the problem to find the limit on the input signal.

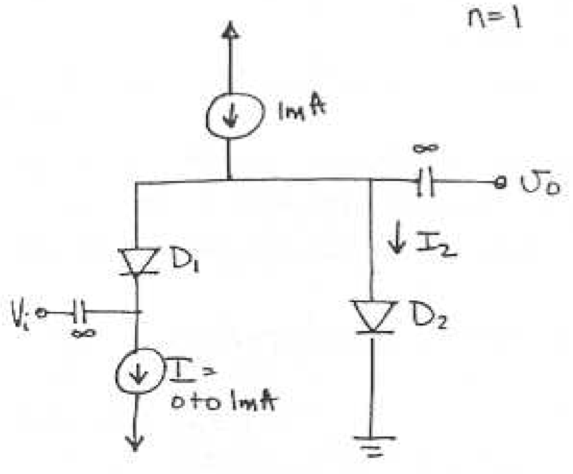
$$\Delta v_S = \frac{\Delta v_O}{v_O/v_I}$$

$$= \frac{-2.63\,\text{mV}}{\Delta v_O/v_I} \text{ to } \frac{2.38\,\text{mV}}{v_O/v_I} \quad ②$$

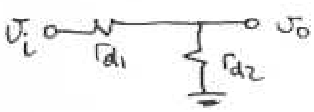
v_O/v_I	I (use ①) (mA)	v_S (using ②) (mV)
0.5	0.0025	5.26 to 4.76
0.1	0.0225	26.3 to 23.8
0.01	0.25	263 to 238
0.001	2.5	2630 to 2380

3.56

$n = 1$



small signal model when D_1 & D_2 are conducting



(a) $I = 0\,\mu A$

D_1 - cutoff $\Rightarrow \dfrac{v_O}{v_I} = \underline{\underline{0\,V/V}}$

$I_2 = 1\,\text{mA}$

(b) $I = 1\,\mu A \qquad I_2 = 999\,\mu A$

$r_{d1} = \dfrac{nV_T}{I} = \dfrac{0.025}{I} = 25\,\Omega \qquad r_{d2} = \dfrac{0.025}{999\times10^{-6}} = 25.025\,\Omega$

$$\frac{v_O}{v_I} = \frac{r_{d2}}{r_{d1}+r_{d2}} = \underline{\underline{0.001\,\frac{V}{V}}}$$

(c) $I = 10\,\mu A \qquad I_2 = 990\,\mu A$

$r_{d1} = \dfrac{0.025}{10\times10^{-6}} = 2.5\,k\Omega \qquad r_{d2} = \dfrac{0.025}{990\times10^{-6}} = 25.25\,\Omega$

$v_O/v_I = \underline{\underline{0.01\,V/V}}$

(d) $I = 100\,\mu A \qquad I_2 = 900\,\mu A$

$r_{d1} = \dfrac{0.025}{100\times10^{-6}} = 250\,\Omega \qquad r_{d2} = \dfrac{0.025}{990\times10^{-6}} = 27.78\,\Omega$

$$\frac{v_O}{v_I} = \underline{\underline{0.1\,V/V}}$$

(e) $I = 500\,\mu A \qquad I_2 = 500\,\mu A$

$r_{d1} = r_{d2} = \dfrac{0.025}{500\times10^{-6}} = 50\,\Omega$

$$\frac{v_O}{v_I} = \underline{\underline{\frac{1}{2}\,V/V}}$$

(f) $I = 600\,\mu A \qquad I_2 = 400\,\mu A$

$r_{d1} = \dfrac{0.025}{600\times10^{-6}} = 41.67\,\Omega \qquad r_{d2} = \dfrac{0.025}{400\times10^{-6}} = 62.5\,\Omega$

56 CONT.

EN THE BIAS CURRENT IN EACH
DE IS $\geq 10 \mu A$, THE DIODE RESISTANCE
L BE $\leq 2.5 k\Omega$. TO LIMIT THE
RENT SIGNAL TO A MAXIMUM OF 10%
BIAS, THE CURRENT SIGNAL MUST BE
μA. THUS, THE SIGNAL VOLTAGE ACROSS
"STARVED" DIODE WILL BE
mV WHICH IS APPROXIMATELY THE
UE TO WHICH THE INPUT SIGNAL
NG SHOULD BE LIMITED.

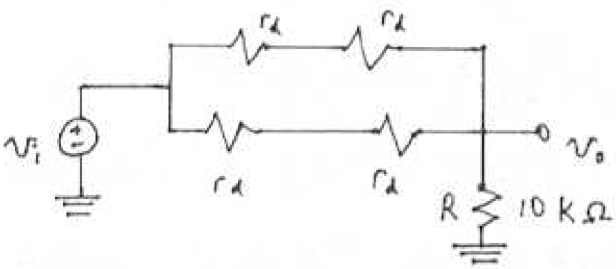
3.57

(a) $$\frac{v_o}{v_i} = \frac{R}{R + (2r_d \,//\, 2r_d)}$$

$$= \frac{R}{R + r_d}$$

WHERE $r_d = \dfrac{V_T}{I/2} = \dfrac{2V_T}{I}$

$$= \frac{0.05\,V}{I}$$



I (mA)	v_o/v_i (V/V)
0	0
10^{-3}	0.167
0.01	0.667
0.1	0.952
1.0	0.995
10	0.9995

(b) IF THE SIGNAL CURRENT IS TO BE LIMITED TO $\pm 10 I$, THE CHANGE IN DIODE VOLTAGE Δv_D CAN BE FOUND FROM

$$\frac{i_D}{I} = e^{\Delta v_D / nV_T} = 0.9 \text{ TO } 1.1$$

THUS, FOR $n = 1$

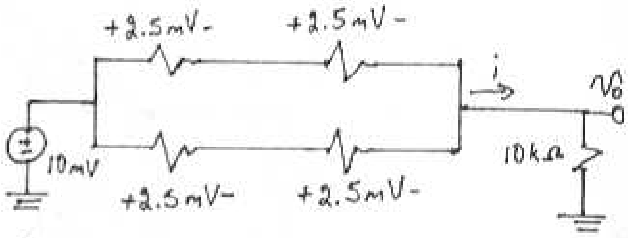
$\Delta v_D = -2.63\,mV$ TO $+2.38\,mV$

OR APPROXIMATELY $\pm 2.5\,mV$

CONT.

3.57 CONT.

(b CONT.) FOR THE DIODE CURRENT TO REMAIN WITHIN ±10% OF THEIR dc BIAS CURRENTS, THE SIGNAL VOLTAGE ACROSS EACH DIODE MUST BE LIMITED TO 2.5 mV. NOW, IF $v_{i\,PEAK} = 10\,mV$ WE CAN OBTAIN THE FOLLOWING SITUATION



WE SEE THAT $v_o = 5\,mV$ AND

$$i = \frac{5\,mV}{10\,k\Omega} = 0.5\,\mu A.$$

THUS, EACH DIODE IS CARRYING A CURRENT SIGNAL OF 0.25 mA. FOR THIS TO BE AT MOST 10% OF THE dc CURRENT, THE dc CURRENT IN EACH DIODE MUST BE AT LEAST 2.5 µA. IT FOLLOWS THAT THE MINIMUM VALUE OF I MUST BE $\underline{\underline{5\,\mu A.}}$

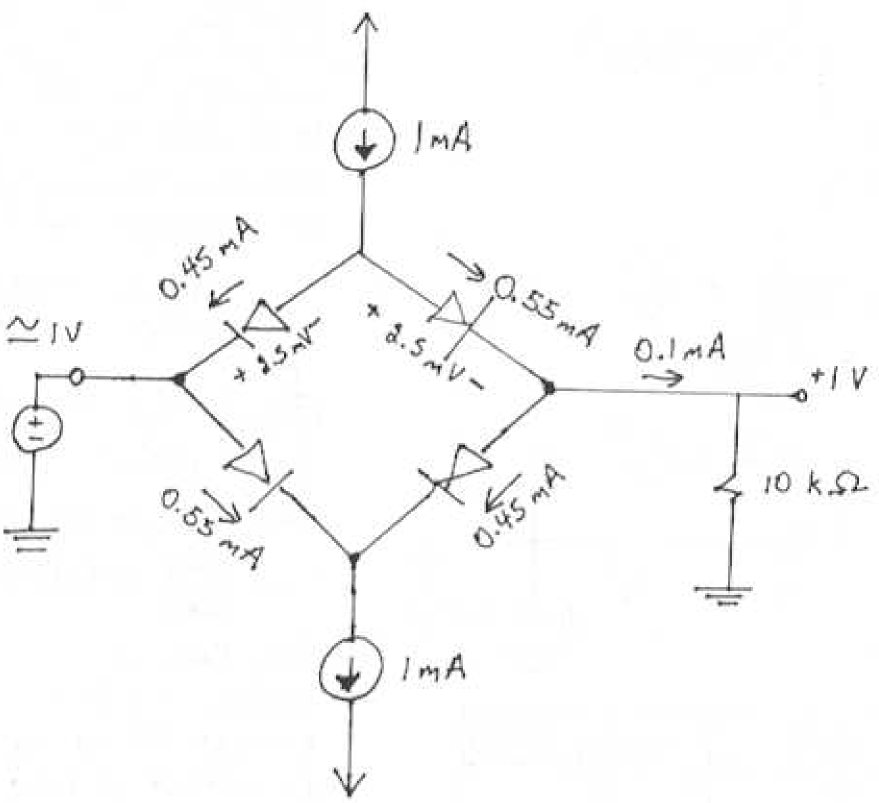
(c) FOR $I = 1\,mA$, $I_D = 0.5\,mA$, AND FOR MAXIMUM SIGNAL OF 10%, $I_D = 0.05\,mA$. THUS $i_D = 2 i_d = 0.1\,mA$ AND THE CORRESPONDING MAXIMUM v_o IS $0.1\,mA \times 10\,k\Omega = 1\,V$.

THE CORRESPONDING PEAK INPUT CAN BE FOUND BY DIVIDING v_o BY THE TRANSMISSION FACTOR OF 0.995, THUS

$$v_{i\,MAX} = \frac{1\,V}{0.995\,V} = \underline{\underline{1.005\,V}}$$

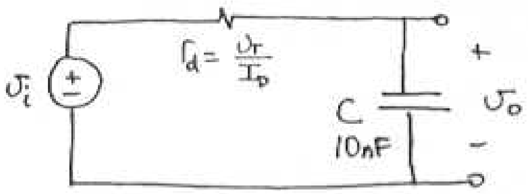
$\boxed{3.57 \text{ CONT.}}$

SEE FIGURE.
EACH DIODE HAS $r_d = 50\,\Omega$



3.58

Opening the current source we get the following small-signal circuit: $(n=1)$



$$\frac{v_o}{v_i} = \frac{1/sC}{1/sC + r_d} = \frac{1}{1 + sCr_d}$$

$$\text{Phase Shift} = -\tan^{-1}\left(\frac{\omega C r_d}{1}\right)$$

$$= -\tan^{-1}\left(2\pi\, 10^5 \times 10\times10^{-9} \times 0.025/I\right)$$

For a phase shift of $-45°$ we have

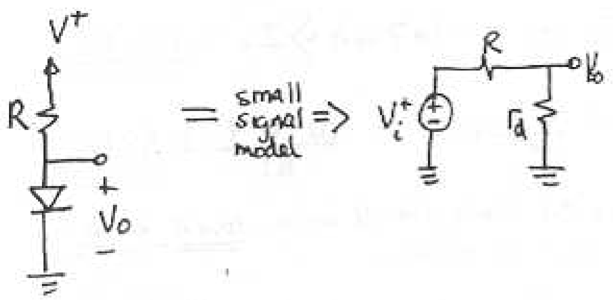
$$2\pi 10^5 \times 10(10^{-9}) \times \frac{0.025}{I} = 1$$

$$I = \underline{\underline{157\,\mu A}}$$

Range of phase shift for $I = 15.7\,\mu A$ to $1570\,\mu A$ is:

$$\underline{\underline{-84.3° \text{ to } -5.71°}}$$

3.59



CONT.

(a) $\frac{\Delta V_o}{\Delta V^+} = \frac{r_d}{r_d + R} = \frac{nV_T/I}{nV_T/I + R}$

$= \frac{nV_T}{nV_T + IR}$ where at no load $I = \frac{V^+ - 0.7}{R}$

$= \frac{nV_T}{nV_T + V^+ - 0.7}$ Q.E.D.

(b) For m diodes in series use

$I = \frac{V^+ - m \times 0.7}{R}$

Thus:

$\frac{\Delta V_o}{\Delta V^+} = \frac{m r_d}{m r_d + R} = \frac{m(nV_T)}{m(nV_T) + IR}$

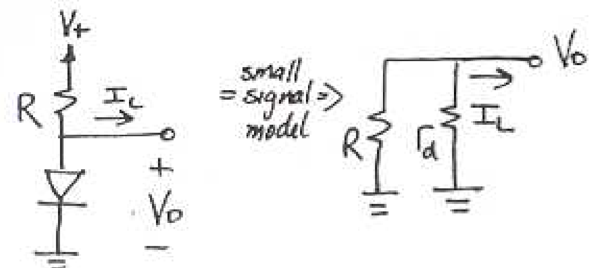
$= \frac{m(nV_T)}{m(nV_T) + V^+ - 0.7m}$

(c) Line Regulation for $V^+ = 10V$, $n = 2$

i) $m = 1$ $\frac{\Delta V_o}{\Delta V^+} = 5.35 mV/V$

ii) $m = 3$ $\frac{\Delta V_o}{\Delta V^+} = 18.63 \; mV/V$

3.60



$\Delta V_o = -I_L (R \| r_d)$

$\frac{\Delta V_o}{I_L} = -(R \| r_d)$ Q.E.D.

(b) Given at DC $I_D = \frac{V^+ - 0.7}{R}$

Also $r_d = \frac{nV_T}{I_D}$

We have:

$\frac{\Delta V_o}{I_L} = -\frac{1}{\frac{1}{R} + \frac{1}{r_d}}$

$= -\frac{1}{\frac{I_D}{V^+ - 0.7} + \frac{I_D}{nV_T}}$

$= -\frac{nV_T}{I_D} \frac{1}{1 + \frac{nV_T}{V^+ - 0.7}}$

$= \frac{-nV_T}{I_D} \frac{V^+ - 0.7}{V^+ - 0.7 + nV_T}$ Q.E.D.

for $\frac{\Delta V_o}{I_L} \leq 5 \frac{mV}{mA}$

$\frac{-2 \times 0.025}{I_D} \times \frac{10 - 0.7}{10 - 0.7 + 0.05} \leq \frac{5 \times 10^{-3}}{10^{-3}}$

$I_D \geq 9.947 mA \Rightarrow I_D = 10 mA$

$R = \frac{V^+ - 0.7}{I_D} = \frac{10 - 0.7}{10} = 930 \Omega$

Thus the diode should be a 10mA diode.

(c) For m diodes

$I_D = \frac{V^+ - 0.7m}{R}$ & $r_d = \frac{m(nV_T)}{I_D}$

CONT.

$$\frac{\Delta V_o}{I_L} = \frac{-1}{\frac{1}{R} + \frac{1}{r_d}}$$

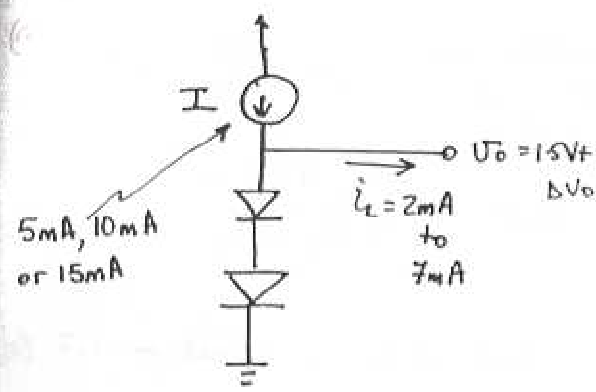
$$= \frac{-1}{\frac{I_D}{V^+ - 0.7m} + \frac{I_D}{mnV_T}}$$

$$= -\frac{mnV_T}{I_D} \frac{1}{\frac{mnV_T}{V^+ - 0.7m} + 1}$$

$$= \frac{-mnV_T}{I_D} \frac{V^+ - 0.7m}{V^+ - 0.7m + mnV_T}$$

3.61

3.62



For a load current of 2 to 7mA, I must be greater than 7 mA. Thus the 5 mA source would not do.

We are left to choose between the 10 and 15 mA sources. The 15mA source provides lower load regulation because the diodes will have more current flowing through them at all times. This is shown below:

Load Regulation if $I = 10mA$

use $\frac{i_{D2}}{i_{D1}} = e^{\Delta V / 2 \times nV_T}$ — 2 diodes

$\therefore e^{\Delta V / 0.05 \times 2} = 3/10$ to $8/10$

$\Delta V_o = -120mV$ to $-22.3mV$

$\therefore$ The peak to peak ripple is $-120 - (-22.3) \approx -100mV$

Load Regulation $= \frac{\Delta V_o}{I_L} = \frac{-100}{5}$

$= -20 \frac{mV}{mA}$

Load Regulation for $I = 15mA$.
Here the current through the diodes change from 8 to 13 mA corresponding to

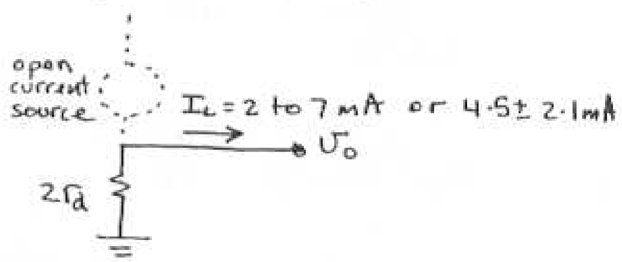
$\Delta V_o = 0.1 \ln(8/13)$

$= -49mV$

Load Regulation $= \frac{-49}{5} \approx -10 \frac{mV}{mA}$.

The obvious disadvantage of using the 15mA supply is the requirement of higher current and higher power dissipation.

Alternate solution of Line Regulation using the small signal model



Load Regulation $= \frac{\Delta V_o}{I_L} = -2r_d = \frac{-2nV_T}{I_D}$

Where the bias current $I_D = 10 - 4.5$ for the 10mA source.

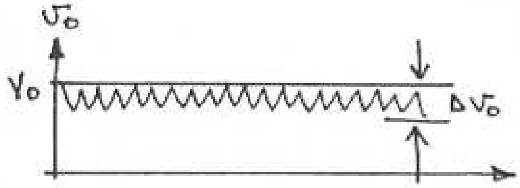
$\Rightarrow \frac{\Delta V_o}{I_L} = \frac{-2 \times 2 \times 0.025}{10 - 4.5} = -18.2 \frac{mV}{mA}$

For 15 mA source $I_D = 15 - 4.5$

$\frac{\Delta V_o}{\Delta I_L} = \frac{-0.1}{15 - 4.5} = -9.5 \frac{mV}{mA}$

CONT.

Sketch of output :-



3.63

3.64

(a) $V_Z = V_{Z0} + r_z I_{ZT}$

$10 = 9.6 + r_z \times 50 \times 10^{-3}$

$r_z = \underline{\underline{8\,\Omega}}$

Power rating:

$V_Z = V_{Z0} + r_z \times 2I_{ZT}$

$= 9.6 + 8 \times 100 \times 10^{-3}$

$= 10.4\,V$

$P = 10.4 \times 100 \times 10^{-3} = \underline{\underline{1.04\,W}}$

(b) $V_Z = V_{Z0} + r_z I_{ZT}$

$9.1 = V_{Z0} + 30 \times 10 \times 10^{-3}$

$V_{Z0} = \underline{\underline{8.8\,V}}$

$V_Z = 8.8 + 30 \times 20 \times 10^{-3} = 9.4\,V$

$P = 9.4 \times 20 \times 10^{-3} = \underline{\underline{188\,mW}}$

(c) $6.8 = 6.6 + 2 \times I_{ZT}$

$I_{ZT} = \underline{\underline{100\,mA}}$

$V_Z = 6.6 + 2 \times 200 \times 10^{-3} = 7\,V$

$P = 7 \times 200 \times 10^{-3} = \underline{\underline{1.4\,W}}$

(d) $18 = 17.2 + r_z \times 5 \times 10^{-3}$

$r_z = \underline{\underline{160\,\Omega}}$

$V_Z = 17.2 + 160 \times 10 \times 10^{-3} = 18.8\,V$

$P = 18.8 \times 10 \times 10^{-3} = \underline{\underline{188\,mW}}$

(e) $7.5 = V_{Z0} + 1.5 \times 200 \times 10^{-3}$

$V_{Z0} = \underline{\underline{7.2\,V}}$

$V_Z = 7.2 + 1.5 \times 400 \times 10^{-3} = 7.8\,V$

$P = 7.8 \times 400 \times 10^{-3} = \underline{\underline{3.12\,W}}$

3.65

(a) Three 6.8V zeners provide $3 \times 6.8 = 20.4\,V$ with $3 \times 10 = 30\,\Omega$ resistance. Neglecting R, we have

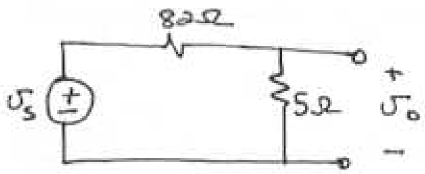
Load Regulation $= \underline{\underline{-30\,mV/mA}}$.

(b) For 5.1 V zeners we use 4 diodes to provide 20.4 V with $4 \times 30 = 120\,\Omega$ resistance.

Load regulation $= \underline{\underline{-120\,mV/mA}}$

3.66

Small signal model for line regulation:



$$\frac{\Delta v_o}{\Delta v_s} = \frac{5}{5+82}$$

$$\Delta v_o = \frac{5}{87} \times \Delta v_s$$

$$= \frac{5}{87} \times 1.3$$

$$= \underline{\underline{74.7\,mV}}$$

3.67

$V_Z = V_{ZO} + r_Z I_{ZT}$

$9.1 = V_{ZO} + 5 \times 28 \times 10^{-3}$

$V_{ZO} = 8.96V$

$V_Z = V_{ZO} + 5I_Z = 8.96 \times 5I_Z$

FOR $I_Z = 10mA$ $V_Z = \underline{\underline{9.01V}}$

FOR $I_Z = 100mA$ $V_Z = \underline{\underline{9.46V}}$

3.68

$r_z = 30\,\Omega$

$I_{ZK} = 0.5\,mA$

$V_Z = 7.5\ V$

$I_Z = 12\ mA$

$7.5 = V_{Z0} + 12 \times 30 \times 10^{-3}$

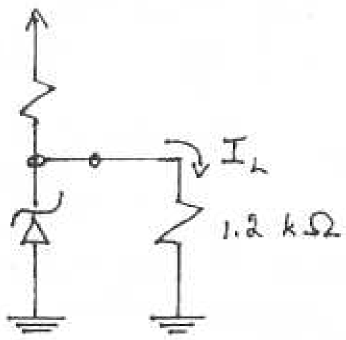
$\Rightarrow V_{Z0} = 7.14\ V$

$I_L = \dfrac{7.5}{1.2} = 6.25\ mA$

SELECT $I = 10\ mA$
SO THAT $I_Z = 3.7\,mA$

WHICH IS $> I_{ZK}$

$R = \dfrac{10 - 7.5}{10} = \underline{\underline{250\ \Omega}}$



FOR $\Delta V^+ = \pm 1V$

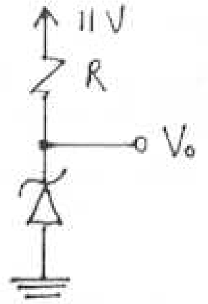
$\Delta V_o = \pm 1 \times \dfrac{1.2 // 0.03}{0.250 + (1.2 // 0.03)}$

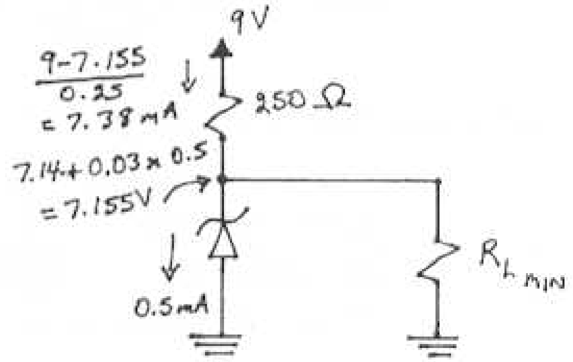
$= \pm\ 0.1\ V$

THUS $V_o = +7.4\ V$ TO $+7.6\ V$
WITH $V^+ = 11\ V$ AND $I_L = 0$

$V_o = V_{Z0} + \dfrac{11 - V_o}{0.25} \times 0.03$

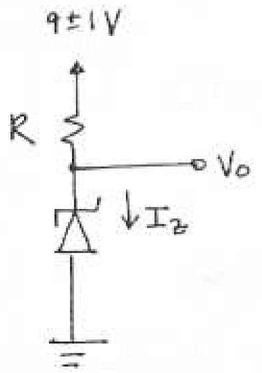
$\Rightarrow V_o = \underline{\underline{7.55\ V}}$





$R_{L_{MIN}} = \dfrac{7.155}{7.38 - 0.5}$
$= \underline{\underline{1.04\ k\Omega}}$

3.69



Given Parameters

$V_Z = 6.8V, r_Z = 5\Omega,$

$I_Z = 20mA$

By knee

$I_{ZK} = 0.25mA$

$r_Z = 750\Omega$

First Design - 9V supply can easily supply current.

Let $I_Z = 20mA$ ~ well above knee

$$\therefore R = \frac{9 - 0.68}{20} = \underline{\underline{110\Omega}}$$

$$\text{Line Regulation} = \frac{\Delta V_O}{\Delta V_S} = \frac{r_Z}{r_Z + R}$$

$$= \frac{5}{5 + 110}$$

$$= \underline{\underline{43.5 \ \frac{mV}{V}}}$$

Second Design ~ limited current from 9V supply

$I_Z = 0.25mA$

$V_Z = V_{ZK} \simeq V_{Z0}$ - calculate V_{Z0} from

$V_Z = V_{Z0} + r_Z I_{ZT}$

$6.8 = V_{Z0} + 5 \times 0.02$

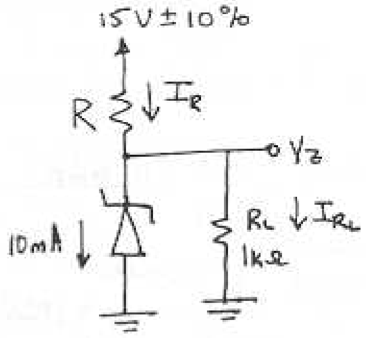
$V_{Z0} = 6.7V$

$$\therefore R = \frac{9 - 6.7}{0.25} = \underline{\underline{9.2k\Omega}}$$

$$\text{Line Regulation} = \frac{\Delta V_O}{\Delta V_S} = \frac{750}{750 + 9200}$$

$$= \underline{\underline{75.4 \ \frac{mV}{V}}}$$

3.70



$V_Z = V_{Z0} + r_Z I_Z$

$9.1 = V_{Z0} + 30(0.009)$

$V_{Z0} = \underline{\underline{8.83V}}$

CONT.

$V_Z = 8.83 + 30(0.01) = 9.13\,V$

$I_{R_L} = 9.13/1k\Omega = 9.13\,mA$

$I_R = 10 + 9.13 = \underline{\underline{19.13\,mA}}$

$\therefore R = \dfrac{15 - 9.13}{19.13} = 306.8\,\Omega$

$\cong \underline{\underline{300\,\Omega}}$

$V_Z = 8.83 + 30\left(\dfrac{15 - V_Z}{300} - \dfrac{V_Z}{1000}\right)$

$= 10.33 - V_Z/10 - 3/100\,V_Z$

$V_Z = 9.14\,V$

$V_Z = 8.83 + 30\left(\dfrac{15 \pm 1.5 - V_Z}{300} - \dfrac{V_Z}{1000}\right)$

$= \dfrac{1}{1.13}\left[8.83 + 1.5 \pm 0.15\right] = 9.14 \pm 0.13\,V$

$\therefore$ $\underline{\pm 0.13\,V}$ variation in output voltage

Halfing the load current $\equiv R_L$ doubling

$V_Z = 8.83 + 30\left(\dfrac{15 - V_Z}{300} - \dfrac{V_Z}{2000}\right)$

$= \dfrac{10.33}{1.115} = 9.26\,V$

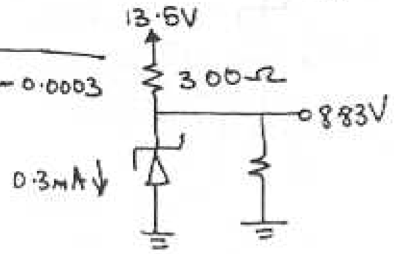
$\therefore 9.26 - 9.14 = 0.12\,V$ increase in output voltage.

At the edge of the breakdown region

$V_Z \cong V_{Z0} = 8.83\,V \quad I_{ZK} = 0.3\,mA$

$R_L = \dfrac{8.83}{\dfrac{13.5 - 8.83}{300} - 0.0003}$

$= \underline{\underline{578\,\Omega}}$



lowest output voltage $= 8.83\,V$

Line Regulation $= \dfrac{r_z}{R + r_z} = \dfrac{30}{300 + 30}$

$= 90\,\dfrac{mV}{V}$

Load Regulation $= -(r_z \parallel R) = \underline{\underline{-29.1\,\dfrac{mV}{mA}}}$

3.71

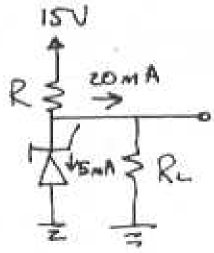
(a) $V_{ZT} = V_{Z0} + r_z I_{ZT}$

$10 = V_{Z0} + 7(0.025)$

$\Rightarrow V_{Z0} = \underline{\underline{9.825\,V}}$

(b) The minimum zener current of 5mA occurs when $I_L = 20\,mA$ and V_S is at its minimum of $20(1 - 0.25) = 15\,V$. See the circuit below:

$R \leq \dfrac{15 - (V_{Z0} + r_Z I_Z)}{20 + 5}$



$\leq \dfrac{15 - (9.825 + 7(0.005))}{25}$

$\leq 205.6\,\Omega$.

$\therefore$ Use $R = \underline{\underline{205\,\Omega}}$

(c) Line Regulation $= \dfrac{7}{205 + 7} = \underline{\underline{33\,\dfrac{mV}{V}}}$

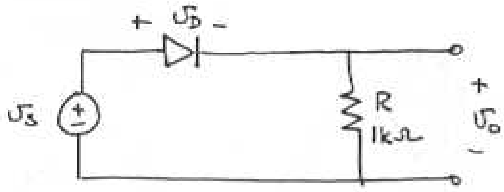
$\pm 25\,\%$ change in $V_S \equiv \pm 5\,V$

V_O changes by $\pm 5 \times 33 = \underline{\underline{\pm 165\,mV}}$

corresponding to $\dfrac{\pm 165}{10} \times 100 = \underline{\underline{\pm 1.65\,\%}}$

CONT.

3.75



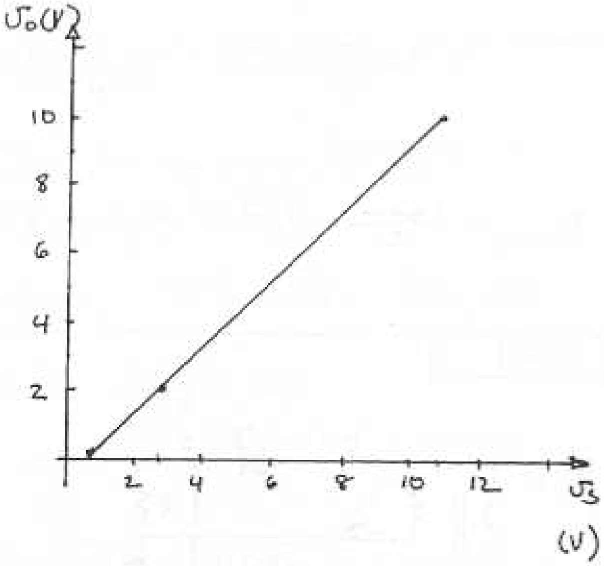
$$i_D = I_S e^{v_D/nV_T}$$

$$\frac{i_D}{1mA} = e^{\frac{v_D - 0.7}{nV_T}}$$

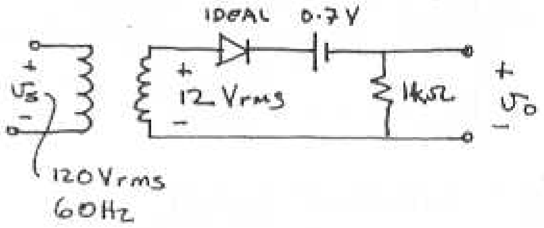
$$v_D - 0.7 = nV_T \ln(i_D/10^{-3}) = 0.1\log\left(\frac{i_D}{10^{-3}}\right)$$

$$v_D = 0.7 + 0.1\log\left(\frac{v_O}{R}\right) \quad R \text{ in } k\Omega$$
$$= 0.7 + 0.1\log\left(\frac{v_O}{1}\right)$$

v_O (V)	v_D (V)	$v_S = v_D + v_O$ (V)
0.10	0.6	0.7
0.5	0.67	1.17
1	0.7	1.7
2	0.73	2.73
5	0.77	5.77
10	0.8	10.8



3.76



$$\hat{V}_o = 12\sqrt{2} - 0.7 = \underline{\underline{16.27V}}$$

Conduction begins at

$$v_S = 12\sqrt{2}\sin\theta = 0.7$$
$$\theta = \sin^{-1}\left(\frac{0.7}{12\sqrt{2}}\right)$$
$$= 0.0412 \text{ rad}$$

Conduction ends at $\pi - \theta$

$\therefore$ Conduction angle $= \pi - 2\theta = \underline{\underline{3.06 rad}}$

The diode conducts for

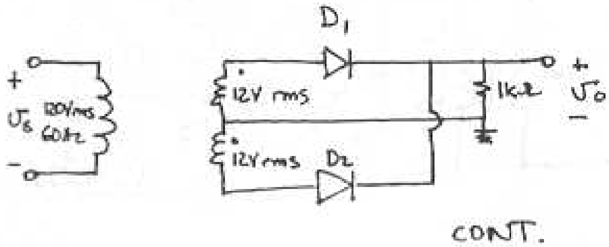
$$\frac{3.06}{2\pi} \times 100 = \underline{\underline{48.7\%}} \text{ of the cycle}$$

$$V_{o,avg} = \frac{1}{2\pi}\int_{\theta}^{\pi-\theta} 12\sqrt{2}\sin\phi - 0.7 \, d\phi$$

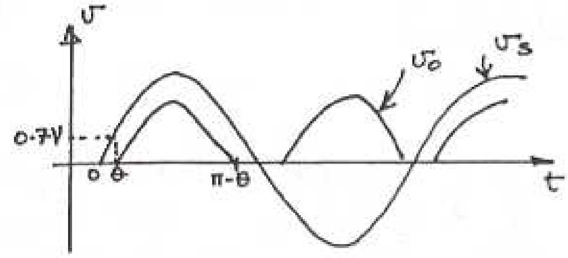
$$= \underline{\underline{5.06V}}$$

$$i_{D,avg} = \frac{v_{O,avg}}{R} = \underline{\underline{5.06mA}}$$

3.77



CONT.



$\hat{v}_0 = 12\sqrt{2} - V_{DO} = \underline{\underline{16.27V}}$

Conduction starts at $\theta = \sin^{-1}\frac{0.7}{12\sqrt{2}}$
$= 0.0412$ rad

and ends at $\pi-\theta$. Conduction angle $= \pi - 2\theta = 3.06$ rad in each half cycle. Thus the fraction of a cycle for which one of the two diodes conduct $= \frac{2(3.06)}{2\pi} \times 100$

$= \underline{\underline{97.4\%}}$

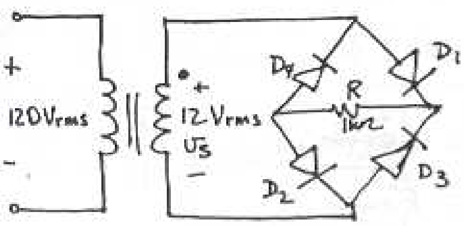
Note that during 97.4% of the cycle there will be conduction. However each of the two diodes conducts for only half the time, i.e. for 48.7% of the cycle.

$$v_{0,avg} = \frac{1}{\pi}\int_{\theta}^{\pi-\theta} 12\sqrt{2}\sin\phi - 0.7 \; d\phi$$

$= \underline{\underline{10.12V}}$

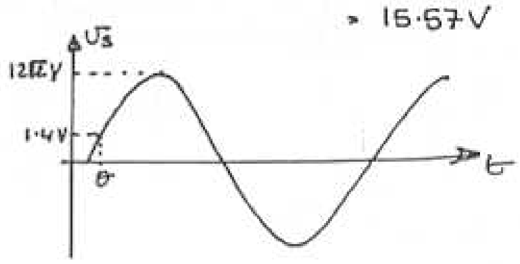
$i_{D,avg} = \frac{10.12}{1k\Omega} = \underline{\underline{10.12mA}}$

3.78



$V_D = 0.7V$

Peak voltage across $R = 12\sqrt{2} - 2V_D$
$= 12\sqrt{2} - 1.4$
$= 15.57V$



$\theta = \sin^{-1}\frac{1.4}{12\sqrt{2}} = 0.0826$ rad

Fraction of cycle that D_1 & D_2 conduct is $\frac{\pi - 2\theta}{2\pi} \times 100 = \underline{\underline{47.4\%}}$

Note D_3 & D_4 conduct in the other half cycle so that there is $2(47.4) =$ 94.8% conduction interval.

$$v_{0,avg} = \frac{2}{2\pi}\int_{\theta}^{\pi-\theta} 12\sqrt{2}\sin\phi - 2V_D \; d\phi$$

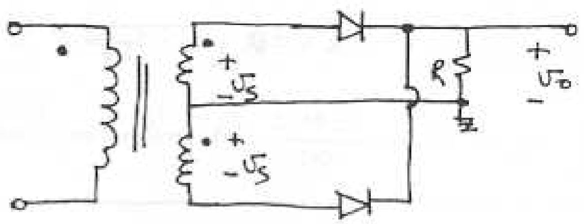
$$= \frac{1}{\pi}\Big[-12\sqrt{2}\cos\phi - 1.4\,\phi\Big]_{\theta}^{\pi-\theta}$$

$$= \frac{2(12\sqrt{2}\cos\theta)}{\pi} - \frac{1.4(\pi-2\theta)}{\pi}$$

$= \underline{\underline{9.44V}}$

$i_{R,avg} = \frac{v_{0,avg}}{R} = \frac{9.44}{1} = 9.44$ mA

3.79



CONT.

For $V_{DO} \ll V_s$,

$V_{O,avg} \cong \frac{2}{\pi} V_s - V_{DO}$

(a) For $v_{O,avg} = 10V$

$10 = \frac{2}{\pi} V_s - 0.7$

$\Rightarrow V_s = 16.81V$

Line peak $= 120\sqrt{2}$

Thus,

turns ratio to each half of the secondary $= \frac{120\sqrt{2}}{16.81} = \underline{\underline{10.1:1}}$

OR $\underline{5.05:1}$ centre tapped

(b) For $v_{O,avg} = 100V$

$V_s = \frac{\pi}{2}(100.7) = \underline{158.2V}$

Turns Ratio $= \frac{120\sqrt{2}}{158.2} = \underline{\underline{1.07:1}}$ to each half

OR $\underline{\underline{0.535:1}}$ centre tapped

3.80

Refer to Fig 3.27.

For $2V_{DO} \ll V_s$,

$v_{O,avg} = \frac{2}{\pi} V_s - 2V_{DO} = \frac{2}{\pi} V_s - 1.4$

(a) For $v_{O,avg} = 10V$

$V_s = \frac{\pi}{2} \times 11.4 = 17.91V$

Turns Ratio $= \frac{120\sqrt{2}}{17.91} = \underline{\underline{9.477 \text{ to } 1}}$

(b) For $v_{O,avg} = 100V$

$V_s = \frac{\pi}{2} \times 101.4 = 159.3V$

Turns Ratio $= \frac{120\sqrt{2}}{159.3} = \underline{\underline{1.065 \text{ to } 1}}$

3.81

$120\sqrt{2} \pm 10\% \;:\; 24\sqrt{2} \pm 10\%$

$\Rightarrow$ turns Ratio $= 5:1$

$V_s = \frac{24\sqrt{2}}{2} \pm 10\%$

$PIV = 2V_s|_{max} V_{DO}$

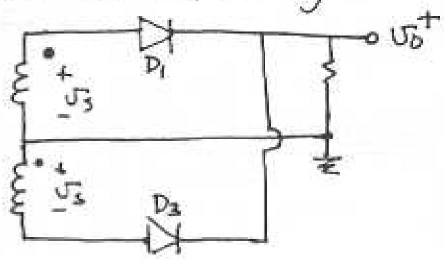
$= 2 \times \frac{24\sqrt{2}}{2} \times 1.1 - 0.7$

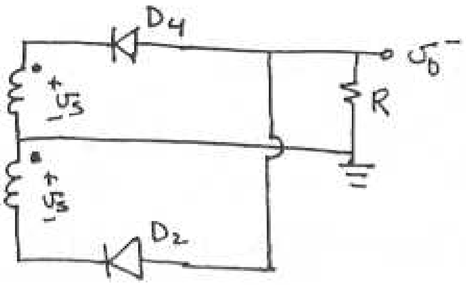
$= \underline{\underline{36.6V}}$

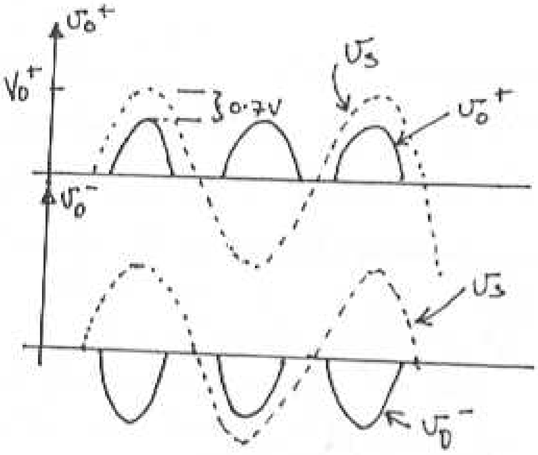
Using a factor of 1.5 for safety we select a diode having a PIV rating of $\underline{\underline{55V}}$

3.82

The circuit is a full wave rectifier with centre tapped secondary winding. The circuit can be analyzed by looking at v_O^+ and v_O^- separately.







$$v_{O,avg} = \frac{1}{2\pi}\int V_S \sin\phi - 0.7 \, d\phi = 15$$

$$= \frac{2V_S}{\pi} - 0.7 = 15 \qquad \text{assumed } V_S >> 0.7V$$

$$V_S = \frac{15+0.7}{2}\pi = 24.66V$$

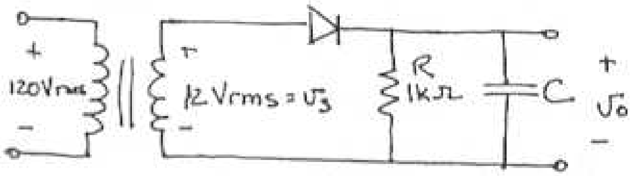
Thus voltage across secondary winding $= 2V_S = \underline{\underline{49.32V}}$

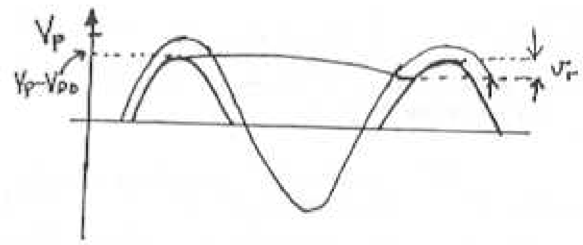
Looking at D4

$$PIV = V_S - V_O^-$$
$$= V_S + (V_S - 0.7)$$
$$= 2V_S - 0.7$$
$$= \underline{\underline{48.6V}}$$

If choosing a diode, allow a safety margin of $1.5 PIV = \underline{\underline{73V}}$

3.83





(i) $V_r \cong (V_P - V_{DO})\frac{T}{CR}$ Eq. (3.28)

$$0.1(V_P - V_{DO}) = (V_P - V_{DO})\frac{T}{CR}$$

$$C = \frac{1}{0.1 \times 60 \times 10^3} = \underline{\underline{166.7\mu F}}$$

(ii) For $v_r = 0.01(V_P - V_{DO}) = (V_P - V_{DO})\frac{T}{CR}$

$$C = \underline{\underline{1667\ \mu F}}$$

(a)

(i) $v_{O,avg} = V_P - V_{DO} - \frac{1}{2}V_r$
$= 12\sqrt{2} - 0.7 - \frac{1}{2}(12\sqrt{2} - 0.7)0.1$
$= (12\sqrt{2} - 0.7)(1 - \frac{0.1}{2})$
$= \underline{\underline{15.5V}}$

ii) $v_{O,avg} = (12\sqrt{2} - 0.7)(1 - \frac{0.01}{2})$
$= \underline{\underline{16.19V}}$

CONT.

(b)

i) Using eq (3.30) we have the conduction angle =

$$\omega \Delta t \cong \sqrt{2V_r/(V_p - V_{DD})}$$

$$= \sqrt{\frac{2 \times 0.1 (V_p - 0.7)}{(V_p - 0.7)}}$$

$$= \sqrt{0.2}$$

$$= 0.447 \text{ rad}$$

∴ Fraction of cycle for conduction $= \frac{0.447}{2\pi} \times 100$

$$= \underline{\underline{7.1\%}}$$

ii) $\omega \Delta t \simeq \sqrt{2 \times 0.01 \frac{(V_p - 0.7)}{V_p - 0.7}} = 0.141 \text{ rad}$

Fraction of cycle $= \frac{0.141}{2\pi} \times 100 = \underline{\underline{2.25\%}}$

(c)(i) Use Eq (3.31)

$$i_{D,avg} = I_L \left(1 + \pi \sqrt{\frac{2(V_p - V_{DD})}{V_r}}\right)$$

$$= \frac{V_{o,avg}}{R} \left(1 + \pi \sqrt{\frac{2(V_p - V_{DD})}{0.1(V_p - V_{DD})}}\right)$$

$$= \frac{15.5}{10^3} \left(1 + \pi \sqrt{\frac{2}{0.1}}\right)$$

$$= \underline{\underline{233 \text{ mA}}}$$

ii) $i_{D,avg} = \frac{16.19}{10^3} \left(1 + \pi \sqrt{200}\right)$

$$= \underline{\underline{735 \text{ mA}}}$$

NB Text uses $I_L \cong V_p/R = \frac{V_p - V_{DD}}{R}$ but here we used $i_{L,avg} = \frac{V_p - V_{DD} - \frac{1}{2}V_r}{R}$ which is more accurate.

(d) i) $i_{D,peak} = I_L \left(1 + 2\pi \sqrt{\frac{2(V_p - V_{DD})}{V_r}}\right)$

$$= \frac{15.42}{10^3} \left(1 + 2\pi \sqrt{2/0.1}\right)$$

$$= \underline{\underline{449 \text{ mA}}}$$

ii) $i_{D,peak} = \frac{16.19}{10^3} \left(1 + 2\pi \sqrt{\frac{2}{0.01}}\right)$

$$= \underline{\underline{1455 \text{ mA}}}$$

3.84

i) $V_r = 0.1(V_p - V_{DD}) = \frac{(V_p - V_{DD})}{2fCR}$

the factor of 2 accounts for discharge occuring only half of the period $T/2 = \frac{1}{2f}$

$$C = \frac{1}{(2fR)0.1} = \frac{1}{2(60)\,10^3 \times 0.1} = \underline{\underline{83.3 \mu F}}$$

ii) $C = \frac{1}{2(60)10^3 0.01} = \underline{\underline{833 \mu F}}$

(a) i) $V_o = V_p - V_{DD} - \frac{1}{2}V_r$

$$= (V_p - V_{DD})\left(1 - \frac{0.1}{2}\right)$$

$$= (16.27)\left(1 - \frac{0.1}{2}\right)$$

$$= \underline{\underline{15.5 V}}$$

ii) $V_o = (16.27)\left(1 - \frac{0.01}{2}\right) = \underline{\underline{16.19 V}}$

(b)

(i) Fraction of cycle $= \frac{2\omega \Delta t}{2\pi} \times 100$

$$= \frac{\sqrt{2V_r/(V_p - V_{DD})}}{\pi} \times 100$$

$$= \frac{1}{\pi}\sqrt{2(0.1)} \times 100 = \underline{\underline{14.2\%}}$$

CONT.

ii) Fraction of Cycle $= \frac{2\sqrt{2(0.01)}}{2\pi} \times 100$

$= \underline{\underline{4.5\%}}$

(c) Use eq (3.34)

i) $i_{D,avg} = I_L \left(1 + \pi\sqrt{\frac{V_P - V_{DO}}{2V_r}}\right)$

$= \frac{15.5}{1}\left(1 + \pi\sqrt{\frac{1}{2(0.1)}}\right) = \underline{\underline{124.4\,mA}}$

ii) $i_{D,avg} = \frac{16.19}{1}\left(1 + \pi \frac{1}{\sqrt{2(0.01)}}\right) = \underline{\underline{376\,mA}}$

(d) Use eq (3.35)

(i) $\hat{i}_D = I_L\left(1 + 2\pi \frac{1}{\sqrt{2(0.1)}}\right) = \underline{\underline{233\,mA}}$

ii) $\hat{i}_D = I_L\left(1 + 2\pi \frac{1}{\sqrt{0.02}}\right) = \underline{\underline{735\,mA}}$

3.85

i) $V_r = 0.1(V_P - V_{DO} \times 2) = \frac{V_P - 2V_{DO}}{2fCR}$

discharge occurs only over $\frac{1}{2}T = \frac{1}{2f}$

$C = \frac{(V_P - 2V_{DO})}{(V_P - 2V_{DO})} \cdot \frac{1}{2(0.1)fR} = \underline{\underline{83.3\,\mu F}}$

ii) $C = \frac{1}{2(0.01)fR} = \underline{\underline{833\,\mu F}}$

(b) i) Fraction of cycle $= \frac{2\omega\Delta t}{2\pi} \times 100$

$= \frac{\sqrt{2(0.1)}}{\pi} \times 100 = \underline{\underline{14.2\%}}$

ii) Fraction of cycle $= \frac{\sqrt{2(0.01)}}{\pi} \times 100 = \underline{\underline{4.5\%}}$

(c) i)

$i_{D,avg} = \frac{14.79}{1}\left(1 + \pi\sqrt{\frac{1}{0.2}}\right) = \underline{\underline{119\,mA}}$

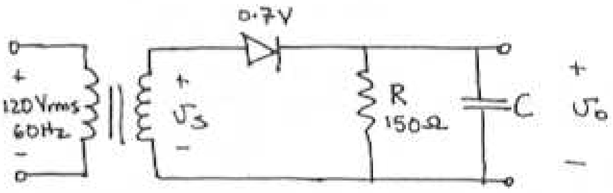
ii) $i_{D,avg} = \frac{15.49}{1}\left(1 + \pi/\sqrt{0.02}\right) = \underline{\underline{356\,mA}}$

(d)

(i) $\hat{i}_D = \frac{14.79}{1}\left(1 + 2\pi\sqrt{\frac{1}{0.2}}\right) = \underline{\underline{223\,mA}}$

(ii) $\hat{i}_D = \frac{15.49}{1}\left(1 + 2\pi\sqrt{\frac{1}{0.02}}\right) = \underline{\underline{704\,mA}}$

3.86



$v_{O,peak} = V_P - V_{DO} = 16$

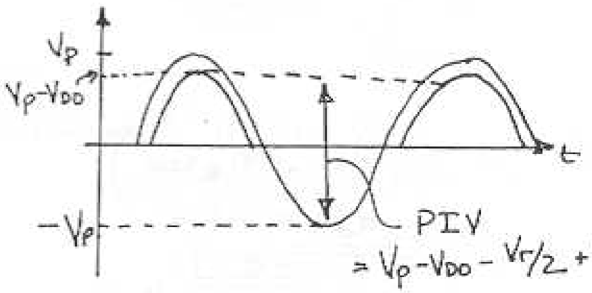
$V_P = 16.7\text{ V}$

$V_{rms} = \frac{16.7}{\sqrt{2}} = 11.8$

(b) $V_r = (V_P - V_{DO})\frac{I}{CR}$ Eq (3.28)

$2 = \frac{16}{60 \times C \times 150}$

$C = 889\,\mu F$



$= V_P - V_{DO} - V_r/2 + V_P$

$= V_{O,avg} + V_P$

$= 15 + 16.7$

$= 31.7\text{ V}$

For a 50% safety margin PIV $= 1.5 \times 31.7$

$= \underline{\underline{47.6\text{ V}}}$

CONT.

(d)

$$i_{D,avg} = I_L\left(1+\pi\sqrt{\frac{2(V_p - V_{DO})}{V_r}}\right)$$

using $I_L = \frac{v_{O,avg}}{R} = \frac{15}{R}$ we have

$$i_{D,avg} = \frac{15}{150}\left(1+\pi\sqrt{\frac{2(16)}{2}}\right)$$

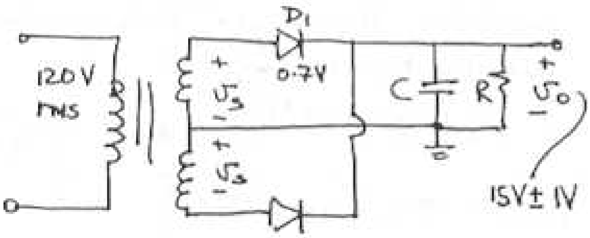
$$= \underline{\underline{1.36A}}$$

(e) $$i_{D,peak} = I_L\left(1+2\pi\sqrt{\frac{2(V_p - V_{DO})}{V_r}}\right)$$

$$= \frac{15}{150}\left(1+2\pi\sqrt{\frac{2(16)}{2}}\right)$$

$$= \underline{\underline{2.61\ A}}$$

3.87



(a) $\hat{v}_O = 16V$

$\therefore \hat{v}_S = 16 + V_{DO} = 16.7V$

RMS Voltage across secondary

$$= \frac{2\times 16.7}{\sqrt{2}}$$

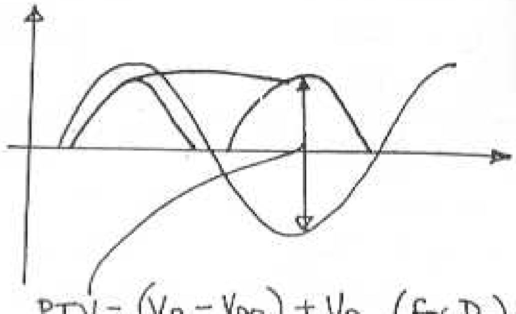
$$= \underline{23.6V}$$

(b) Using Eq. (3.28)

$$V_r = \frac{V_p}{2fCR} = \frac{16}{2\times 60\times C\times 150} = 2$$

$C = \underline{444.4\ \mu F}$

(c)



$$PIV = (V_p - V_{DO}) + V_p \quad (\text{for } D_1)$$

$$= 2(16.7) - 0.7$$

$$= \underline{32.7V}$$

$\therefore$ Using a 50% margin

$$PIV = 1.5(32.7) = \underline{49V}$$

(d) Using Eq (3.34)

$$i_{D,avg} = I_L\left(1+\pi\sqrt{V_p/2V_r}\right)$$

$$= \frac{15}{150}\left(1+\pi\sqrt{\frac{16}{2\times 2}}\right)$$

$$= \underline{\underline{0.73\ A}}$$

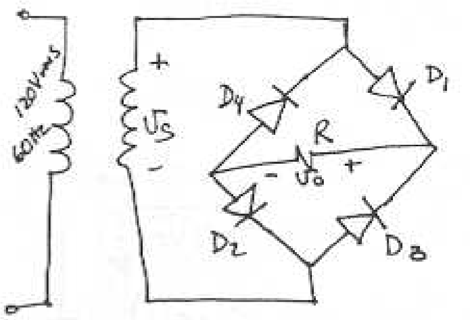
(e) Using Eq. (3.35)

$$i_{D,max} = I_L\left(1+2\pi\sqrt{V_p/2V_r}\right)$$

$$= \frac{15}{150}\left(1+2\pi\sqrt{\frac{16}{2\times 2}}\right)$$

$$= \underline{\underline{1.36A}}$$

3.88



$v_O = 15 \pm 1V$, $R = 150\Omega$

CONT.

$\hat{v}_o = 16V$

$\hat{v}_s = 16 + 2V_{DO} = 17.4V$

RMS Secondary Voltage $= \frac{17.4}{\sqrt{2}} = \underline{\underline{12.3V}}$

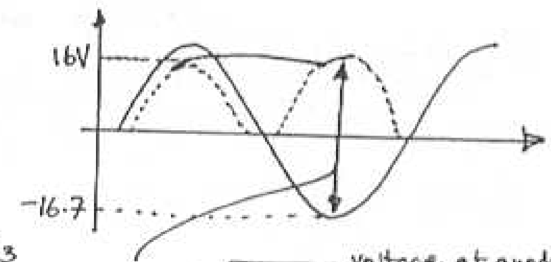
(b) $v_r = \dfrac{V_P}{2fCR}$

$2 = \dfrac{16}{2 \times 60 \times C \times 150}$

$C = \underline{\underline{444.4\,\mu F}}$

note: we got the same value for C as the full wave rectifier as discharge is over the same amt of time T/2 and the peak is the same – 16V.

c)



for D_3

$PIV = 16 - (-V_{DO})$ — voltage at anode of $D_3 = 0 - V_{DO} = -V_{DO}$

$= 16 + 0.7$

$= 16.7V$

Allowing a 50% margin $= 16.7 \times 1.5$

$= \underline{25V}$

(d) Using 3.34

$i_{D,avg} = I_L\left(1 + \pi\sqrt{V_P/2V_r}\right)$

$= \frac{15}{150}\left(1 + \pi\sqrt{16/2\times2}\right)$

$= \underline{\underline{0.73A}}$

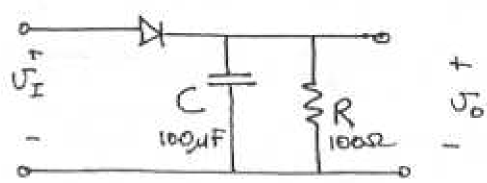
(e) Using (3.35)

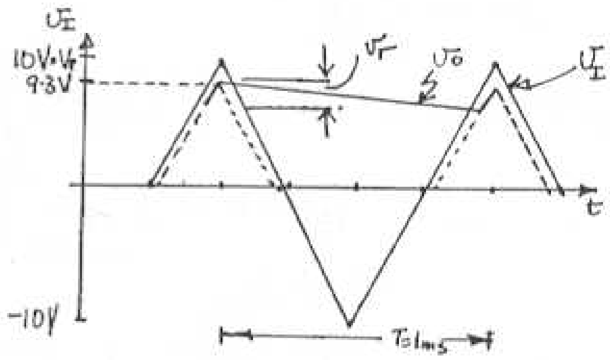
$i_{D,max} = I_L\left(1 + 2\pi\sqrt{V_P/2V_r}\right)$

$= \frac{15}{150}\left(1 + 2\pi\sqrt{16/2\times2}\right)$

$= \underline{\underline{1.36A}}$

3.89





During the diode's off interval, the capacitor discharges through the resistor R according to:

$v_O = 9.3\,e^{-t/RC} \cong 9.3(1 - T/CR)$

$\therefore V_r = 9.3 - 9.3(1 - T/CR)$

$= 9.3T/CR$

$= \dfrac{9.3}{fCR}$ NB this is Eq (3.38)

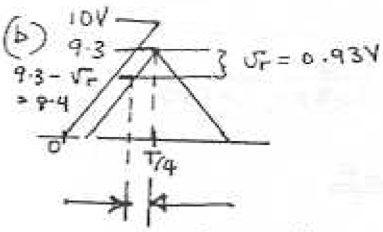
$= 0.93V$

$v_{O,avg} = V_O - V_{DO} - \frac{1}{2}V_r$

$= 9.3 - \frac{1}{2}0.93$

$= \underline{8.84V}$

(b)



$\Delta t \Rightarrow \dfrac{10}{T/4} = \dfrac{0.93}{\Delta t}$

$\Delta t = 0.02325T$

$= \underline{\underline{0.02325\ ms}}$

CONT.

(c) $\therefore$ Charge gained during conduction = Charge lost during discharge

$$i_{C,avg}\,\Delta t = C\,V_r$$

$$i_{C,avg} = \frac{C V_r}{\Delta t} = \frac{100\times10^{-6}\times 0.93}{0.02325\times10^{-3}}$$

$$= 4.0\text{ A}$$

$$i_{D,avg} \cong i_{C,avg} + \underbrace{i_{L,avg}}_{V_{O,avg}/R}$$

$$\cong 4.0 + \frac{8.84}{100} = \underline{4.09\text{A}}$$

(d) $$i_{C,max} = C\left.\frac{\delta V_O}{\partial t}\right|_{\text{at onset of conduction}}$$

$$= C\frac{\delta V_r}{\partial t}$$

$$= 100\times10^{-6}\times 40\times10^{3}$$

$$= \underline{4\text{A}}$$

$$i_{D,max} = i_{C,max} + i_{L,max}$$

$$= 4 + V_{O,max}/100$$

$$= 4 + 9.3/100$$

$$= 4.09\text{ A}.$$

Note that in this case $i_{D,avg} = i_{D,max}$ owing to the linear input (i_C is constant and i_L is approximately constant).

3.90

Refer to Fig P3.82 and let capacitor C be connected across each of the load resistors R. The two supplies, V_O^+ and V_O^- are identical. Each is a full-wave rectifier similar to that based on the centre-tapped-transformer circuit. For each supply, the dc output is 15 V and the ripple is 1V peak-to-peak. Thus $V_O = 15 \pm \frac{1}{2}$V. It follows that the peak value of V_S must be $15.5 + 0.7 = 16.2$V.

$\therefore$ Voltage across secondary $= 2(16.2) = 32.4$ V

RMS across secondary $= \frac{32.4}{\sqrt{2}} = \underline{22.9\text{ V}_{rms}}$

Turns Ratio $= \frac{120}{22.9} = 5.24:1$

Use Eq. (3.35) to find

$$i_{D,max} = I_L\left(1 + 2\pi\sqrt{V_P/2V_r}\right)$$

$$= 0.2\left(1 + 2\pi\sqrt{15.5/2}\right)$$

$$= \underline{3.70\text{A}}$$

$$V_r = \frac{V_P}{2fCR} = 1 \qquad \text{Eq (3.28)}$$

DISCHARGE OCCURS OVER $T/2 = \frac{1}{2f}$

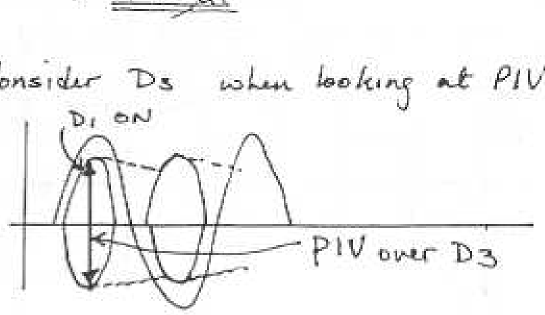
$$\Rightarrow C = \frac{15.5}{2\times60\times75}$$

where $200\text{mA} = \frac{15}{R}$

$R = \frac{15}{0.2} = 75\Omega$

$$= \underline{1722\,\mu\text{F}}$$

Consider D3 when looking at PIV



CONT.

$$PIV = \hat{v}_o + \hat{v}_s$$
$$= 15.5 + 16.2 = 31.7V.$$

Allowing for 50% safety margin

$$PIV = 1.5 \times 31.7 = \underline{47.6V}$$

Use Eq (3.34) to find

$$i_{D,avg} = I_L\left(1 + \pi\sqrt{V_P/2V_r}\right)$$
$$= 0.2\left(1 + \pi.\sqrt{15.5/2}\right)$$
$$= \underline{1.95A}$$

3.91

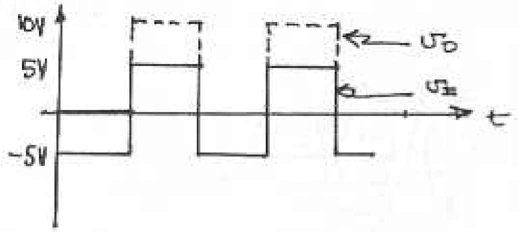
$$v_O = v_I(1 + R/R)$$
$= 2v_I$ when the diode is conducting.

(a) $v_I = \underline{+1V}$ $v_O = \underline{2V}$ $v_A = \underline{1.7V}$ $v_- = v_I = \underline{1V}$

b) $v_I = \underline{2V}$ $v_O = \underline{4V}$ $v_A = \underline{4.7V}$ $v_- = \underline{2V}$

c) $v_I = -1V$ $v_A = \underline{-12V}$ ~ diode is cut off
$v_O = \underline{0V}$
$v_- = \underline{0V}$

d) $v_I = -2V$ $v_A = -\underline{12V}$ $v_O = \underline{0V}$ $v_- = \underline{0V}$

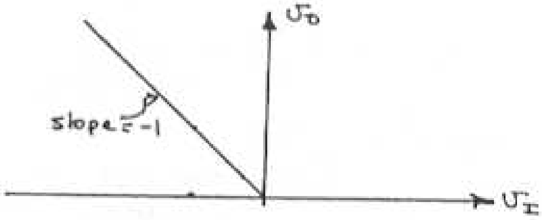


$v_{O,avg} = \underline{5V}$

3.92

$v_I > 0$ D_1 conducts D_2 cutoff

$v_I < 0$ D_1 cut off
D_2 conducts ~ $\frac{v_O}{v_I} = -1$



a) $v_I = 1V$ $v_O = \underline{0V}$
$v_A = \underline{-0.7V}$ - keeps D_2 off so no current flows through R
$\Rightarrow v_- = \underline{0V}$ - virtual gnd as fdbk is closed through D_1

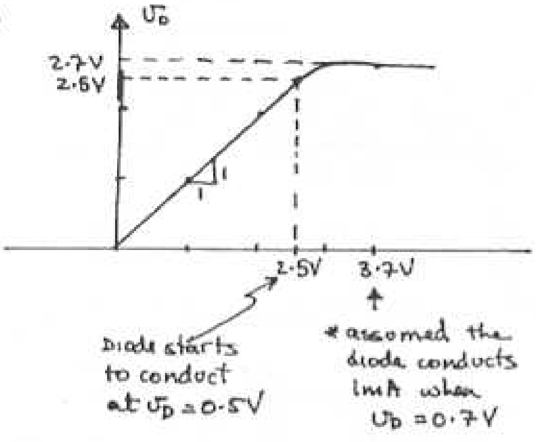
(b) $v_I = 2V$
$v_O = \underline{0V}$
$v_A = -\underline{0.7V}$
$v_- = \underline{0V}$

(c) $v_I = -1V$
$v_O = \underline{1V}$
$v_A = \underline{1.7V}$
$v_- = 0V$ ~ virtual gnd as negative feedback is closed through R.

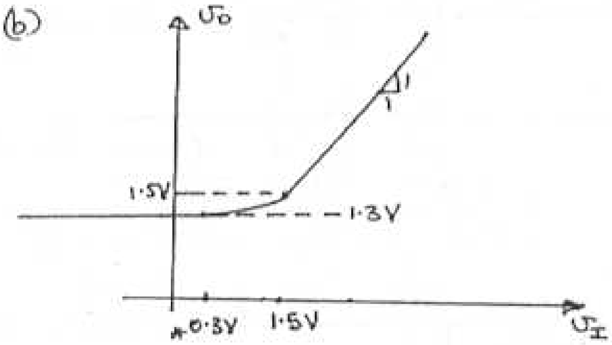
(d) $v_I = -2V \Rightarrow v_O = \underline{2V}$
$v_A = \underline{2.7V}$
$v_- = \underline{0V}$

3.93

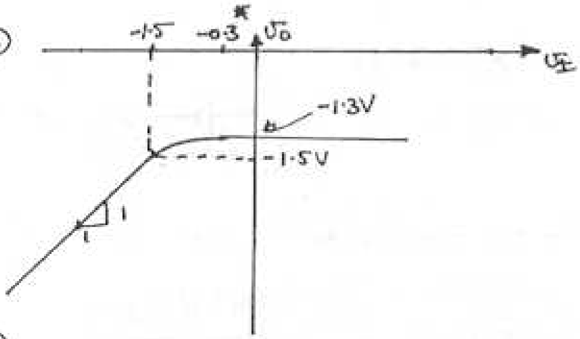
(a)



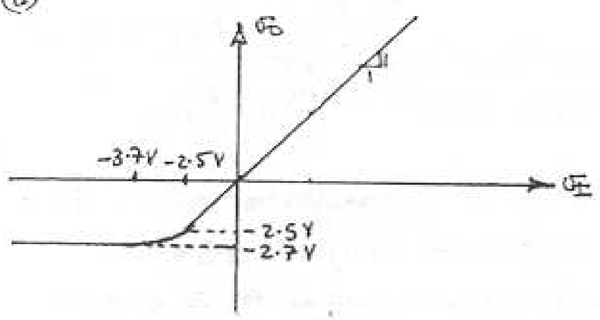
(b)



(c)



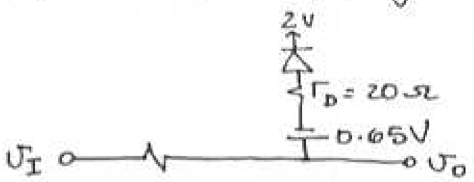
(d)

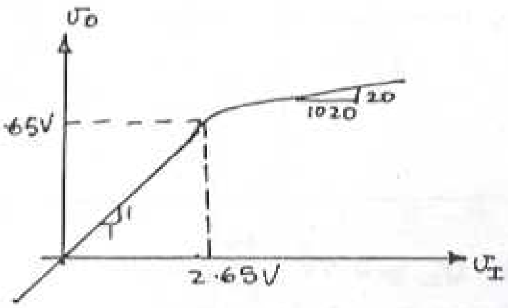


3.94

(a) $v_I < 2.65V$ ~ the diode is off and the circuit reduces to:

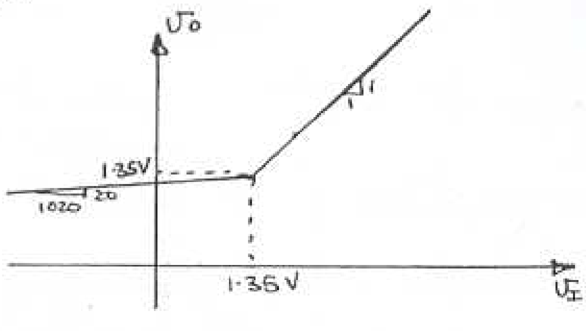
With the diode conducting we have:



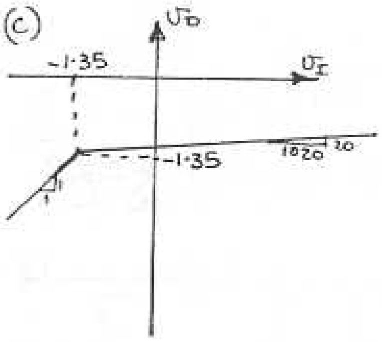


Similarily for (b), (c,) (d)

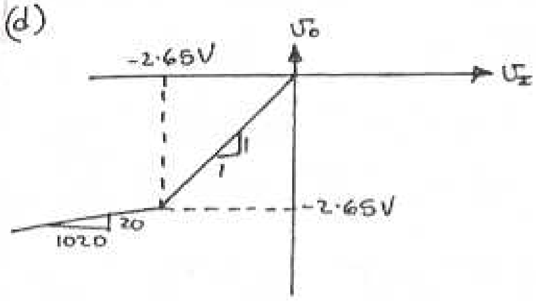
(b)



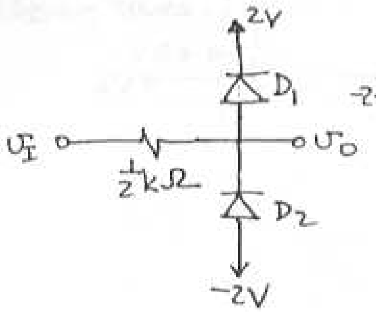
(c)



(d)

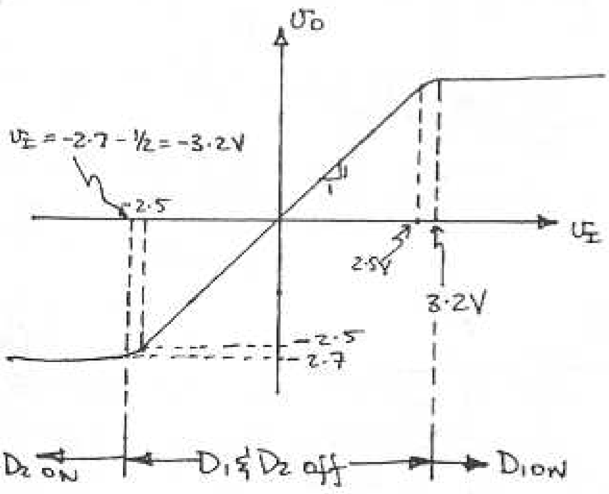


3.95

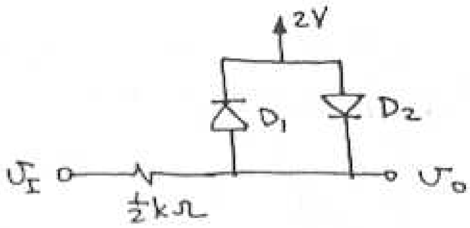


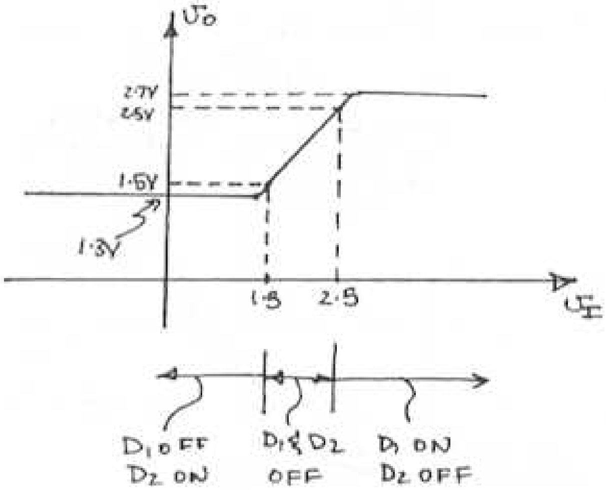
$-2.5 \leq v_I \leq 2.5$
~ both D_1 & D_2 off
$-v_o = v_I$

For $v_I \geq 2.5V$ ~ D_1 on
$v_{D1} = 0.7$ at $i_{D1} \geq 1mA$
$v_O = 2.7V$ at $v_I = 2.7 + \frac{1}{2} \times 1$
$= \underline{\underline{3.2V}}$



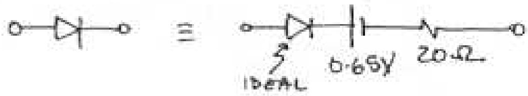
3.96





3.97

For each diode



For the zener diode

$8.2 = V_{Z0} + 10 \times 10^{-3} \times 20$

$V_{Z0} = 8.0V$

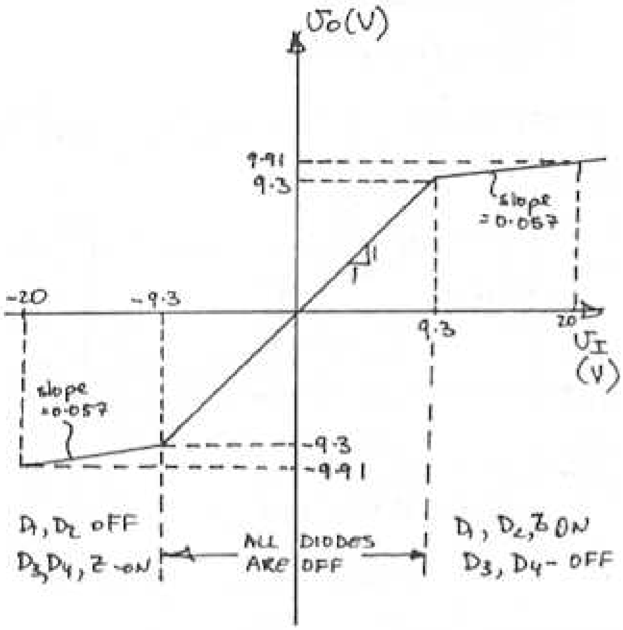
The limiter thresholds are

$\pm(2 \times 0.65 + 8.0) = \pm 9.3V$

For $v_I > 9.3$ (as well as for $v_I < -9.3$)

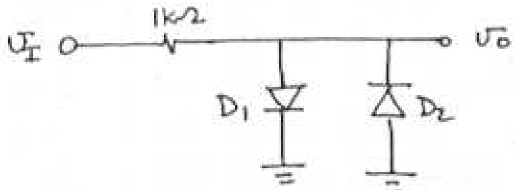
$$\frac{\partial v_O}{\partial v_I} = \frac{r_{D1} + r_z + r_{D2}}{1k\Omega + r_{D1} + r_z + r_{D2}} = \frac{3(20)}{1k\Omega + 3(20)} = 0.057 \frac{V}{V}$$

CONT.



v_O (V)	v_I (V)	
0.5	0.510	D_1 ON
0.6	0.7	
0.7	1.7	
0.8	10.7	
0	0	
-0.5	-0.51	D_2 ON
-0.6	-0.7	
-0.7	-1.7	
-0.8	-10.7	

3.98



For D_1

Given $\frac{i_D}{1mA} = e^{\frac{v_O - 0.7}{nV_T}}$

$$(v_O - 0.7) = nV_T \ln(i_D/1mA)$$

$$= 0.1 \log\left(\frac{i_D}{10^{-3}}\right) \leftarrow \text{can find } v_O \text{ from } i_D$$

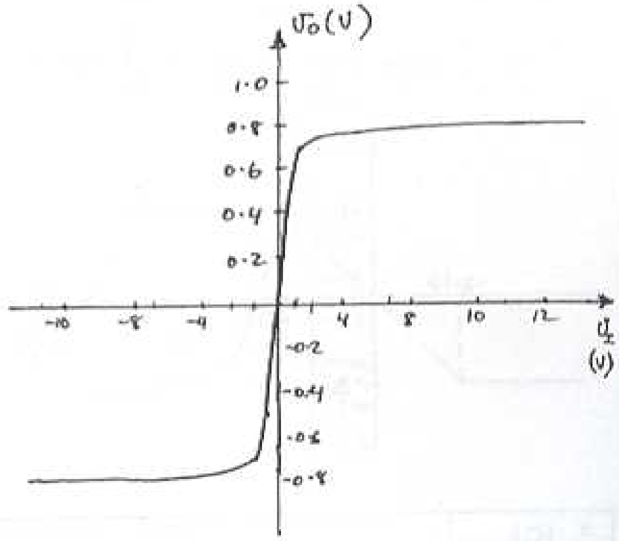
$$\therefore i_D = 10^{-3} \times 10^{\frac{v_O - 0.7}{0.1}}$$

$$= 10^{-3} \times 10^{10(v_O - 0.7)}$$

& $v_I = v_O + i_D \times 10^3$

$$= v_O + 10^{10(v_O - 0.7)}$$

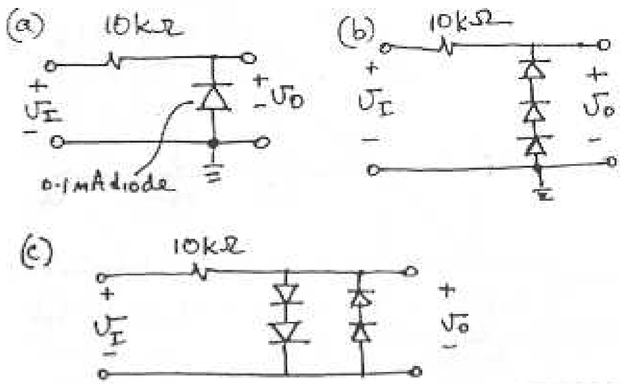
for D_2: $v_I = v_O - 10^{-10(v_O - 0.7)}$



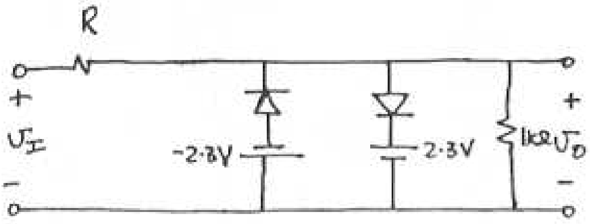
The limiter is fairly hard with a gain $K \cong 1$

$L_+ \cong \underline{\underline{0.8V}}$, $L_- \cong \underline{\underline{-0.8V}}$

3.99



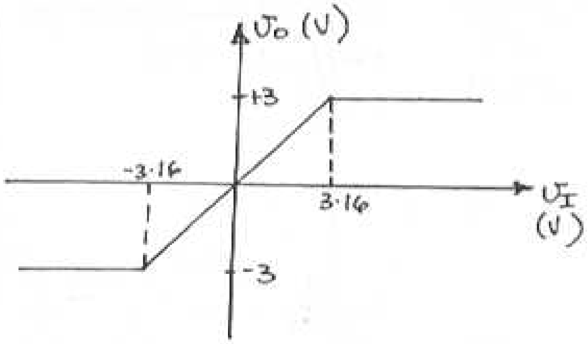
3.100



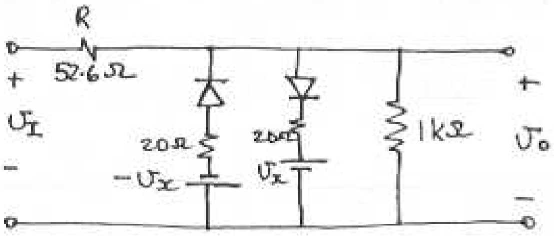
In the limiting region

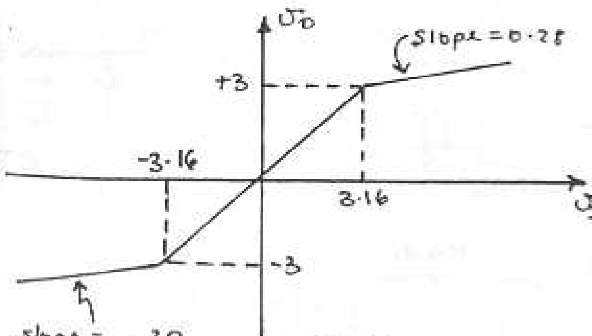
$$\frac{v_O}{v_I} = \frac{1000}{1000+R} \geq 0.95$$

$R \leq \underline{52.6\ \Omega}$



3.101

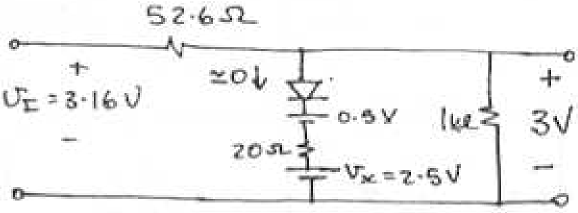




$$\text{slope} = \frac{20}{20+52.6} = 0.28$$

$$\frac{0.2}{10\times10^{-3}} = 20\,\Omega$$

At the verge of limiting in the positive direction we have :-



For $v_I = 10V$

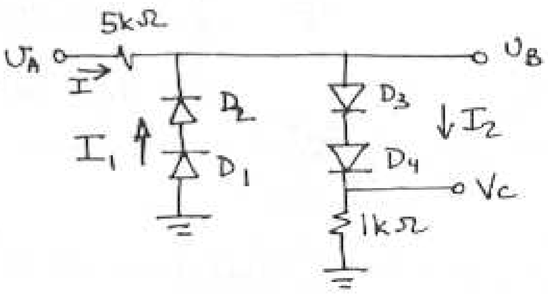
$v_O \cong 3 + 0.28(10 - 3.16)$

$= \underline{4.9V}$

For $v_I = -10V$

$v_O = \underline{-4.9V}$

3.102



$v_D = 0.7 + 0.1\log\left(i_D/0.1\right)$

(a) For $v_A > 0$ $\quad D_1, D_2$ off $\Rightarrow I_1 = 0$

$I = I_2 = v_C/1k\Omega \quad v_A = V_B + I_2 5$

(b) For $v_I < 0$ $\quad D_3, D_4$ off $\Rightarrow v_C = 0$

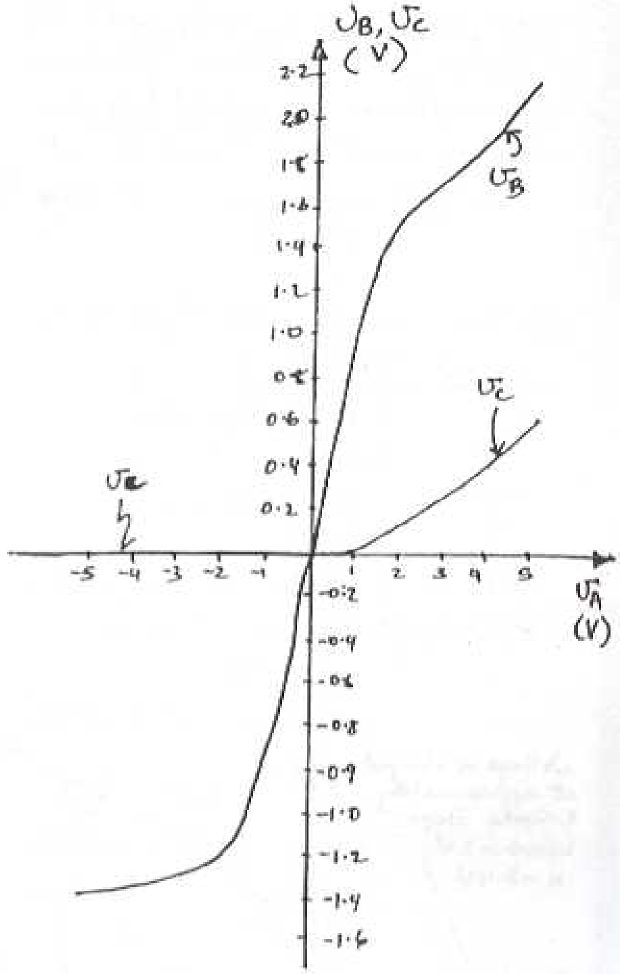
$I = -I_1 \quad v_B = -(v_{D1} + v_{D2})$

$v_A = -(V_B + 5I_1)$

CONT.

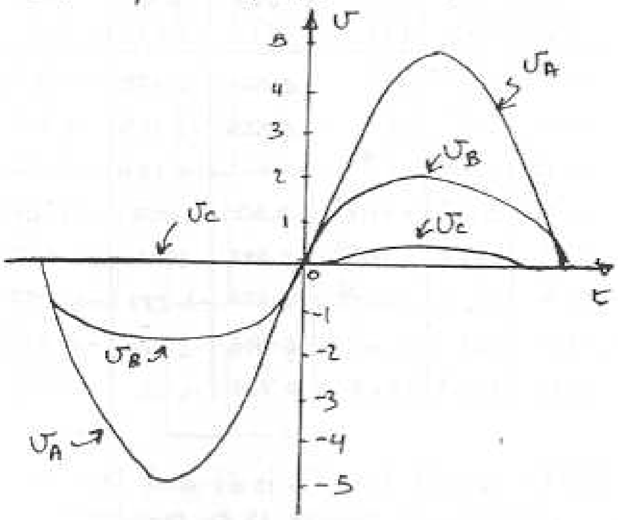
(a) List of points for $V_A > 0$

V_C (V)	I_2 (mA)	V_{D3}, V_{D4} (V)	$V_B = V_C + V_{D3} + V_{D4}$ (V)	V_A (V)
0.0001	0.0001	0.4	0.8	0.8
0.001	0.001	0.5	1.00	1.01
0.01	0.1	0.6	1.21	1.26
0.1	0.1	0.7	1.50	1.90
0.2	0.2	0.73	1.66	2.66
0.3	0.3	0.75	1.80	3.30
0.4	0.4	0.76	1.92	3.92
0.5	0.5	0.77	2.04	4.54
0.6	0.6	0.78	2.16	5.16

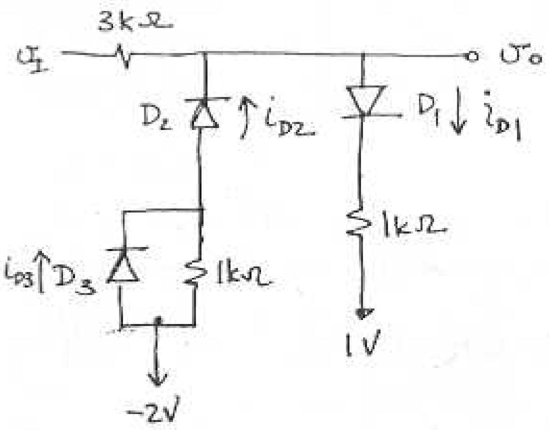


(b) List of Points for $V_A < 0$

I_1 (mA)	V_{D1}, V_{D2} (V)	V_B (V)	V_A (V)
0.0001	0.4	-0.80	-0.80
0.001	0.5	-1.00	-1.01
0.01	0.6	-1.20	-1.25
0.10	0.7	-1.40	-1.90
0.20	0.73	-1.46	-2.46
0.30	0.75	-1.50	-3.00
0.40	0.76	-1.52	-3.52
0.50	0.77	-1.54	-4.04
0.60	0.78	-1.56	-4.56
0.70	0.785	-1.57	-5.07



3.103



At currents $i_{D1} > 1\,mA$, $v_{D1} \simeq 0.7V$

Let $v_{D1} = 0.71V$ $\quad v_I > 5.7V$

CONT.

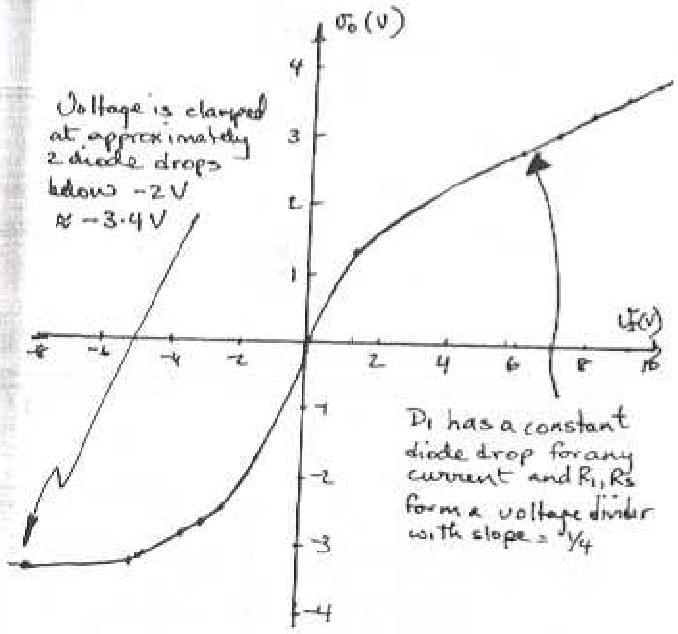
$$v_O = 1.71 + i_{D1} \times 1k\Omega$$

$$= 1.71 + \left(\frac{v_I - 1.71}{4}\right) \times 1$$

$$= \frac{v_I}{4} + 1.2825 \qquad \text{HB slope} = 1/4$$

$\therefore$ for $v_I > 5V$ slope $v_O/v_I \approx 1/4$

$v_I (V)$	$v_O (V)$
5.8	2.7325
6.0	2.7825
7.0	3.0325
8.0	3.2825
9.0	3.5325
10.0	3.7825



where points for $-8 \le v_I \le 6$ V are calculated as shown below:

$i_D = 1mA$ at $v_D = 0.7V \qquad n = 1$

$$i_D = I_S e^{0.7/0.025} = 10^{-3}$$

$$I_S = 6.914 \times 10^{-16} A.$$

$\therefore$ For Diodes use $\underline{i_D = 6.914 \times 10^{-16} e^{v_D/0.025}}$

D_1 conducting $\quad i_{D2} = 0$

i_{D1} (A)	v_{D1} (V)	v_O (V)	$v_I = (4k)i_{D1} + v_{D1} + 1$ (V)
10^{-10}	0.297	1.297	1.297 ← even at small i_{D1}
10^{-6}	0.527	1.528	1.5313 ↙ $v_O > 1V$, $v_O \approx v_I$ since $i_{D1} \approx 0$
10^{-5}	0.584	1.595	1.625
10^{-4}	0.64	1.742	2.042
10^{-3}	0.70	2.7	5.7
0.2×10^{-2}	0.74	6.74	12.74
10^{-2}	0.758	11.75	41.75

For the D_2, D_3 arm conducting use the following equations:
Note $v_I < -2.5V$

Starting with a value for V_A ① we have

$$V_{D3} = V_A + 2$$

$$i_{D3} = I_S e^{v_{D3}/0.025} \qquad ②$$

$$i_{D2} = i_{D3} + \frac{V_A + 2}{1} \qquad ③$$

$$v_{D2} = 0.025 \ln\left(\frac{i_{D2}}{6.914 \times 10^{-16}}\right) \qquad ④$$

$$v_O = v_A - v_{D2} \qquad ⑤$$

$$v_I = v_O - i_{D2} \times 3k\Omega \qquad ⑥$$

① v_A (V)	② i_{D3} (A)	③ i_{D2} (A)	④ v_{D2} (V)	⑤ v_O (V)	⑥ v_I (V)
-2.001	7×10^{-16}	10^{-6}	0.527	-2.528	-2.531 Ⓐ
-2.01	10^{-15}	10^{-5}	0.585	-2.595	-2.625
-2.10	3.8×10^{-14}	10^{-4}	0.642	-2.724	-3.024
-2.20	2×10^{-12}	0.2×10^{-3}	0.659	-2.859	-3.459
-2.5	33μA	0.5×10^{-3}	0.682	-3.128	-4.628 Ⓑ
-2.6	18μA	0.6×10^{-3}	0.687	-3.287	-5.087
-2.7	1mA	1.7×10^{-3}	0.713	-3.413	-8.516 Ⓒ
-2.71	1.5mA	2.2mA	0.720	-3.43	-10

Ⓐ for small i_{D2}, D_3 is off and D_2 is on
$\therefore i_2$ flows through $1k\Omega$ resistor

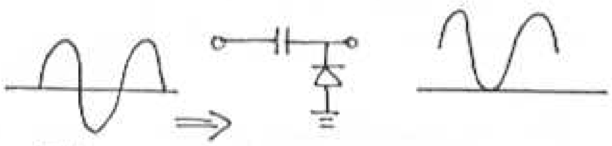
CONT.

Ⓑ 0.5 V drop across D_3 causes D_3 to start to conduct

Ⓒ $V_A = -2.7V$

The 0.7 voltage across D_3 clamps the voltage across R_3 so that D_3 control the current i_{D2}

3.104



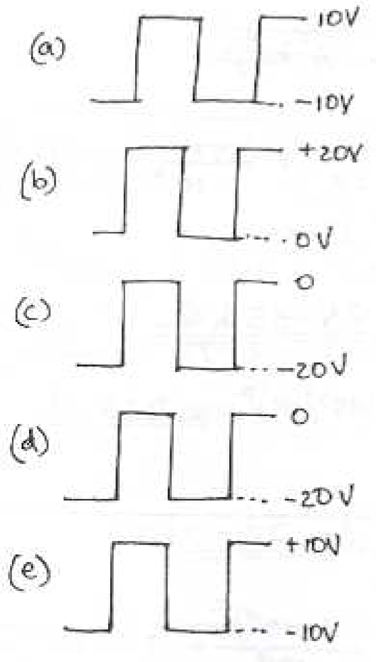
10 V rms

$10\sqrt{2}$ V, peak

Average (dc) value of output $= 10\sqrt{2}$

$= \underline{\underline{14.14V}}$

3.105

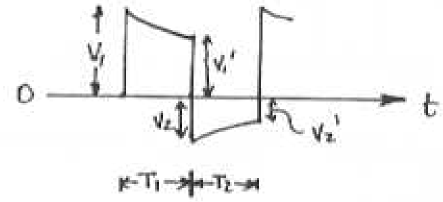


(f) Here there are two different time constants involved. To calculate the output levels we shall exagerate the discharge and charge waveforms.

During T_1 $v_O = V_1 e^{-t/RC}$

At $t = T_1 = T$ $v_O = V_1'$

$= V_1 e^{-T/RC}$



where for $T \ll CR$

$V_1' \cong V_1(1 - T/CR) = V_1(1-\alpha)$ where $\alpha \ll 1$

During the period T_2

$|v_O| = |V_2| e^{-t/CR/2}$

at the end of T_2 $t = T$, $v_O = V_2'$

where

$V_2' = |V_2| e^{-T/CR/2}$

$\cong |V_2|\left(1 - \frac{T}{CR/2}\right) = |V_2|(1 - 2\alpha)$

Now $V_1' + |V_2| = 20 \Rightarrow V_1 + |V_2| - \alpha V_1 = 20$ ①

and $|V_2'| + V_1 = 20 \Rightarrow V_1 + |V_2| - 2\alpha|V_2| = 20$ ②

from ① & ② we find that

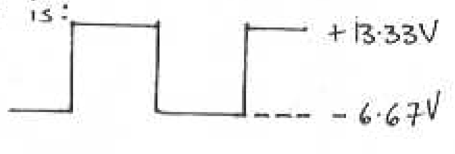
$V_1 = 2V_2$

Then using ① and neglecting αV_1 yields

$3|V_2| = 20 \Rightarrow |V_2| = \underline{\underline{6.67V}}$

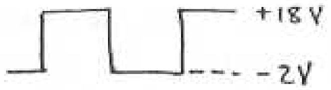
$V_1 = \underline{\underline{13.33V}}$

The result is:

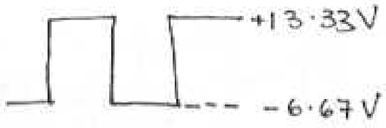


CONT.

(g)



(h) Using a method similar to that employed for case (f) above we obtain.



3.106

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

$B = 5.4 \times 10^{31}$

$E_G = 1.12\,eV$ for silicon

$k = 8.62 \times 10^{-5}\ \frac{eV}{K}$

Fraction of ionized atoms $= n_i / 5 \times 10^{22}$; $T = 273 + x°C$

T (K)	n_i $\left(\frac{\text{carriers}}{cm^3}\right)$	Fraction of ionized atoms.
203	2.68×10^5	5.37×10^{-18}
273	1.53×10^9	3.07×10^{-14}
293	8.65×10^9	1.73×10^{-13}
373	1.44×10^{12}	2.89×10^{-11}
398	4.75×10^{12}	9.51×10^{-11}

3.107

(a) intrinsic silicon

$$\rho = \frac{1}{q(p\mu_p + n\mu_n)}$$

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

$$= 2.28 \times 10^5\ \Omega \cdot cm$$

$$R = \rho L/A = 2.28 \times 10^5 \underbrace{\frac{10 \times 10^{-4}}{3.4 \times 10^{-4}}}_{10^4/3} = \underline{\underline{7.6 \times 10^8\ \Omega}}$$

(b)

$$\rho = \frac{1}{q(p_{no}\mu_p + n_{no}\mu_n)}$$

$$= \frac{1}{(1.6 \times 10^{-19})\left(\frac{(1.5 \times 10^{10})^2}{10^{16}} \times \underbrace{\frac{1200}{2.5}}_{\mu_p} + 10^{16} \times 1200\right)}$$

$$= 0.521\ \Omega \cdot cm$$

$$R = \rho \times 10^4/3 = \underline{\underline{1.74\,k\Omega}}$$

(c) n doped $N_D = n_{no} = 10^{18}$

$n_{po} = n_i^2 / n_{no}$

$$\rho = \frac{1}{1.6 \times 10^{-19}\left(\frac{(1.5 \times 10^{10})^2}{10^{18}} \times \frac{1200}{2.5} + 10^{18} \times 1200\right)}$$

$$= 5.21 \times 10^{-3}\ \Omega \cdot cm$$

$$R = \rho\,\frac{10^4}{3} = \underline{\underline{17.4\ \Omega}}$$

(d) P doped $N_A = P_{PO} = 10^{10}/cm^3$

$$\rho = \frac{1}{q(P_{PO}\mu_p + n_{po}\mu_n)}$$

$$= \frac{1}{1.6 \times 10^{-19}\left(10^{10} \times \frac{1200}{2.5} + \frac{(1.5 \times 10^{10})^2}{10^{10}} \times 1200\right)}$$

$$= 2.05 \times 10^{4}\ \Omega \cdot cm$$

$$R = \rho\,\frac{10^4}{3} = \underline{\underline{68.35\,k\Omega}}$$

(e) $R = 2.8 \times 10^4/3 = \underline{\underline{0.933\ \Omega}}$

3.108

$$p_{no} = \frac{n_i^2}{N_D} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4 /cm^3$$

CONT.

$$\frac{dP}{dx} = \frac{1000P_{no} - P_{no}}{W}$$

$$\cong \frac{2.25\times10^{-1}}{5\times10^{-4}}$$

$$J_P = -qD_P\frac{dP}{dx}$$

$$= -1.6\times10^{-19}\times12\times\frac{-2.25\times10^{-1}}{5\times10^{-4}}$$

$$= \underline{\underline{8.64\times10^{-8}\ A/cm^2}}$$

3.109

$$U_{drift,p} = \mu_P E$$

$$= 480\frac{cm^2}{V\cdot s}\times\frac{1}{10^{-3}}\frac{V}{cm}$$

$$= \underline{\underline{4.8\times10^{5}\ cm/s}}$$

$$U_{drift,n} = \mu_n E$$

$$= 1350\frac{cm^2}{V\cdot s}\times\frac{1}{10^{-3}}\frac{V}{cm}$$

$$= \underline{\underline{1.35\times10^{6}\ cm/s}}$$

3.110

$$J_{drift} = q(n\mu_n + P\mu_P)E \quad A/cm^2$$

$$I_{drift} = q(n\mu_n + P\mu_P)E\cdot A$$

$$= 1.6\times10^{-19}(10^{5}\cdot1350 + 10^{15}\cdot480)\times$$

$$\frac{1}{10^{-3}}\times(5\times4\times10^{-8})$$

$$= \underline{\underline{15.36\ \mu A}}$$

3.111

$$E = \frac{1V}{10\times10^{-4}} = \frac{1}{10^{-3}}\frac{V}{cm}$$

$n_{no} = N_D$ $\quad P_{no} = \frac{n_i^2}{N_D}$ $\quad$ assume $P_{no} \ll n_{no}$

$$\therefore J_{drift} = q(\mu_n n + \mu_P P)E = \frac{10^{-3}}{10^{-8}}\frac{A}{cm^2}$$

$$\cong 1.6\times10^{-19}(1350N_D)\frac{1}{10^{-3}} = 10^{5}$$

$$N_D = 4.6\times10^{17}\ /cm^3$$

3.112

$P_{po} = N_A = 10^{16}\ /cm^3$ at all temperatures

At $25^\circ C \cong 300K$

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

$$= 5.4\times10^{31}(300)^3 e^{-1.12/8.62\times10^{-5}(300)}$$

$$= 2.26\times10^{20}$$

$$n_{po} = \frac{n_i^2}{N_A} = \underline{\underline{2.26\times10^{4}\ /cm^3}}$$

At $125^\circ C \cong 400K$

$$n_i^2 = 5.4\times10^{31}(400)^3 e^{1.12/8.62\times10^{-5}(400)}$$

$$= 2.7\times10^{25}$$

$$n_{po} = \frac{n_i^2}{N_A} = \underline{\underline{2.7\times10^{9}\ /cm^3}}$$

3.113

DOPING CONCENTRATION	μ_n $cm^2/V\cdot s$	μ_p $cm^2/V\cdot s$	D_n cm^2/s	D_p cm^2/s
INTRINSIC	1350	480	34	12
10^{16}	1100	400	28	10
10^{17}	700	260	18	6
10^{18}	360	150	9	4

where $D_n = V_T \mu_n = \underline{\underline{0.025\, \mu_n}}$

$D_p = V_T \mu_p = \underline{\underline{0.025\, \mu_p}}$

3.114

$$V_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.025 \ln\left(\frac{10^{16}\, 10^{16}}{10^{20}}\right)$$

$= 1.27\,V$

$$W_{dep} = x_n + x_p = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_0}$$

$$= \sqrt{\frac{2(11.7)\ 8.85\times10^{-14}}{1.6\times10^{-19}}\left(\frac{1}{10^{16}} + \frac{1}{10^{16}}\right)1.27}$$

$= 57\times10^{-6}$ cm

$= \underline{\underline{0.57\,\mu m}}$

$\frac{x_n}{x_p} = \frac{N_A}{N_D} \Rightarrow x_n = x_p = \underline{\underline{0.28\,\mu m}}$

$$q_J = q_N = q_P = q\frac{N_A N_D}{N_A + N_D} A\, W_{dep}$$

$= \underline{\underline{45.6\times10^{-15}\ C}}$

$$C_j = \frac{\epsilon_s A}{W_{dep}} = \frac{11.7(8.85\times10^{-14})\times100\times10^{-8}}{0.57\times10^{-4}}$$

$= \underline{\underline{18.2\,fF}}$

3.115

$$V_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.025 \ln\left(\frac{10^{16}\, 10^{15}}{10^{20}}\right)$$

$= 0.633\,V$

$$W_{dep} = x_n + x_p = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 + V_R)}$$

$$W_{dep} = \sqrt{\frac{2(11.7)(8.85\times10^{-14})}{1.6\times10^{-19}}\left(\frac{1}{10^{16}} + \frac{1}{10^{15}}\right)(0.633+5)}$$

$= 2.83\times10^{-4}$ cm $= \underline{\underline{2.83\,\mu m}}$

$x_n = \frac{N_A}{N_D} x_p = 10\, x_p$

$\therefore\ x_p = \frac{2.83}{11} = \underline{\underline{0.26\,\mu m}}$

$x_n = \underline{\underline{2.57\,\mu m}}$

$$q_J = q_N = q_P = q\frac{N_A N_D}{N_A + N_D} A\, W_{dep}$$

$$= 1.6\times10^{-19}\left(\frac{10^{16}\, 10^{15}}{10^{16} + 10^{15}}\right)400\times10^{-8}\times2.83\times10^{-4}$$

$= \underline{\underline{1.65\times10^{-13}\ C}}$

$$C_j = \frac{\epsilon_s A}{W_{dep}} = \frac{11.7(8.84\times10^{-14})\,400\times10^{-8}}{2.83\times10^{-4}}$$

$= 14.6\times10^{-15} = \underline{\underline{14.6\,fF}}$

3.116

$q_J = q N_x A = 1.6\times10^{-19}\times10^{16}\times0.1\times10^{-4}\times100\times10^{-8}$

$= \underline{\underline{16\,fC}}$

3.117

$$q_J = q\frac{N_A N_D}{N_A + N_D} A\, W_{dep}$$

$$= q\frac{N_A N_D}{N_A + N_D} A \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 + V_R)}$$

CONT.

$$\frac{dq_J}{dV_R} = q\frac{\cancel{N_A N_D}}{\cancel{N_A+N_D}} A \times \frac{1}{q\sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_0+V_R)}} \times \frac{2\epsilon_s}{q}\cancel{\left(\frac{1}{N_A}+\frac{1}{N_D}\right)}$$

$$= \frac{\epsilon_s A}{W_{dep}}$$

3.118

$$C_j = \frac{C_{j0}}{(1+V_R/V_0)^m}$$

$V_R = 1V$ $\quad C_j = \dfrac{0.6\,pF}{(1+1/0.75)^{1/3}} = \underline{\underline{0.45pF}}$

$V_R = 10V$ $\quad C_j = \dfrac{0.6\,pF}{(1+10/0.75)^{1/3}} = \underline{\underline{0.25pF}}$

3.119

$V_Z = 10$

$I_D = \frac{1}{2}\left(\frac{0.25}{10}\right) = \underline{12.5\,mA}$

Since breakdown occurs only half the time, the average breakdown current can be twice the continuous value i.e. it can be 25 mA if the dissipation is limited to half the rated value or 50 mA if the dissipation is allowed to rise to the rated value.

3.120

$$I_p = Aqn_i^2\left(\frac{D_p}{L_p N_D}\right)\left(e^{V/V_T}-1\right)$$

$$I_n = Aqn_i^2\left(\frac{D_n}{L_n N_A}\right)\left(e^{V/V_T}-1\right)$$

$$\therefore \frac{I_p}{I_n} = \frac{D_p L_n N_A}{D_n L_p N_D} = \frac{10\times10\times10^{18}}{20\times5\times10^{16}} = \underline{\underline{100}}$$

$I = I_p + I_n = 100I_n + I_n = 1mA$

$I_n = 1/101 = \underline{9.9\,\mu A}$

$I_p = 100(9.9) = \underline{990\,\mu A}$

3.121

$$I_p = Aqn_i^2\frac{D_p}{L_p N_D}\left(e^{V/V_T}-1\right)$$

$$I_n = Aqn_i^2\frac{D_n}{L_n N_A}\left(e^{V/V_T}-1\right)$$

For p^+-n $\quad N_A >> N_D$

$$\therefore I \simeq I_p = Aqn_i^2\frac{D_p}{L_p N_D}\left(e^{V/V_T}-1\right)$$

$$I_S \simeq Aqn_i^2\frac{D_p}{L_p N_D} = Aqn_i^2\left(\frac{D_p}{\sqrt{D_p\tau_p}\,N_D}\right)$$

$$= 10^4(10^{-8})1.6\times10^{-19}\frac{(1.5\times10^{10})^2\;\;10}{\sqrt{10\times0.1\times10^{-6}}\times5\times10^{16}}$$

$$= \underline{\underline{0.72\times10^{-15}\,A}}$$

CONT.

$$I = I_s\left(e^{V/V_T} - 1\right) = 0.2\times10^{-3}$$

$$0.72\times10^{-15}\left(e^{V/0.025} - 1\right) = 0.2\times10^{-3}$$

$$V = \underline{0.684\,V}$$

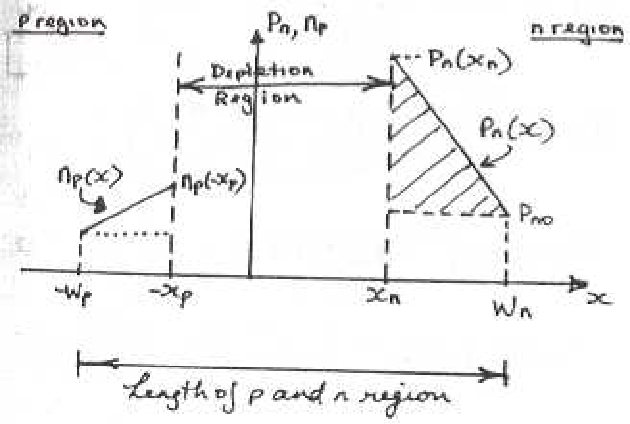
Excess minority charge

$$= Q_p + Q_n$$
$$= \tau_p I_p + \tau_n I_n \simeq \tau_p I_p$$
$$= (0.1\times10^{-6})(0.2\times10^{-3}) = \underline{\underline{2\times10^{-11}\,C}}$$

$$C_d = \frac{\tau_T I}{V_T} \simeq \frac{\tau_p I}{V_T}$$

$$= \frac{0.1\times10^{-6}\times0.2\times10^{-3}}{0.025} = \underline{\underline{800\,pF}}$$

3.122



(a) First consider I_p:

$$p_n(x_n) = p_{no}\,e^{V/V_T},$$
$$I_p = A J_p, \quad \text{and}$$
$$p_{no} = \frac{n_i^2}{N_D}$$

Thus, $I_p = Aqn_i^2 \dfrac{D_p}{(W_n - x_n)N_D}\left(e^{V/V_T} - 1\right)$

& $I_n = Aqn_i^2 \dfrac{D_n}{(W_p - x_p)N_A}\left(e^{V/V_T} - 1\right)$

Thus: $I = I_p + I_n$

$$= Aqn_i^2\left[\frac{D_p}{(W_n - x_n)N_D} + \frac{D_N}{(W_p - x_p)N_A}\right]\times\left(e^{V/V_T} - 1\right)$$

Q.E.D

The excess charge, Q_p, can be found by multiplying the area of the shaded triangle of the $P_n(x)$ distribution graph by Aq.

$$Q_p = Aq\times\frac{1}{2}\left[P_n(x_n) - P_{no}\right]\left[W_n - x_n\right]$$

$$= \frac{1}{2}Aq\,P_{no}\left(e^{V/V_T} - 1\right)(W_n - x_n)$$

$$= \frac{1}{2}Aq\,\frac{n_i^2}{N_D}(W_n - x_n)\left(e^{V/V_T} - 1\right)$$

$$= \frac{1}{2}\frac{(W_n - x_n)^2}{D_p}I_p$$

$$\simeq \frac{1}{2}\frac{W_n^2}{D_p}I_p \qquad \text{for } W_n \gg x_n$$

Q.E.D.//

(c) $C_d = \dfrac{dQ}{dV} = \tau_T\dfrac{dI}{dV}$ But $I = I_s\left(e^{V/V_T} - 1\right)$

$$\frac{dI}{dV} = \frac{I_s e^{V/V_T}}{V_T} \simeq I/V_T$$

$$\therefore C_d \simeq \frac{\tau_T I}{V_T}$$

(d) $C_d = \dfrac{1}{2}\dfrac{W_n^2}{10}\times\dfrac{10^{-3}}{0.025} = 8\times10^{-12}$

$$W_n = \underline{\underline{63.2\,\mu M}}$$

Chapter 4 - Problems

4.1

The capacitance per unit area is: $C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$

$\epsilon_{ox} = 3.45 \times 10^{-11}$ F/m

$t_{ox} = 5nm \Rightarrow C_{ox} = \frac{3.45 \times 10^{-11}}{5 \times 10^{-9}} = 6.9\ fF/\mu m^2$

$t_{ox} = 40nm \Rightarrow C_{ox} = 0.86\ fF/\mu m^2$

For 1pF capacitance, we require an area A:

$A = \frac{10^{-12}}{6.9 \times 10^{-15}} = 145\ \mu m^2$ for $t_{ox} = 5nm$

$A = \frac{10^{-12}}{0.86 \times 10^{-15}} = 1163\ \mu m^2$ for $t_{ox} = 20nm$

For a square plate capacitor of 10pF:

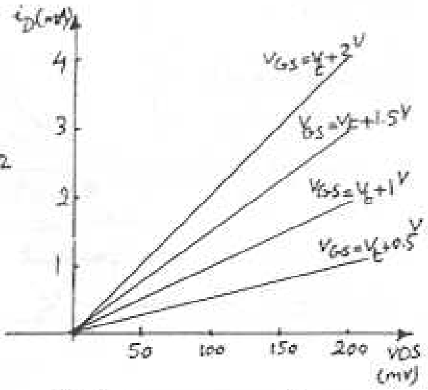
$A = 10 \times 145 = 1450\ \mu m^2$ or $38 \times 38\ \mu m^2$ square for $t_{ox} = 5$ nm

$A = 10 \times 1163 = 11630\ \mu m^2$ or $108 \times 108\ \mu m^2$ square for $t_{ox} = 20$ nm

4.2

Drain current is directly proportional to the width of the chanel. Therefore if width is 10 times greater, then i_D would be 10 times greater as well.

K = Constant of proportionality = $\frac{1}{0.5 \times 0.2} = 10\ mA/V^2$



$r_{DS} = \frac{i_D}{V_{DS}} = \frac{1}{0.2} = 5^{K\Omega}$ for $V_{ov} = 0.5^V$

$r_{DS} = 10^{K\Omega}$ for $V_{ov} = 1^V$

$r_{DS} = 15^{K\Omega}$ for $V_{ov} = 1.5^V$

$r_{DS} = 20K\Omega$ for $V_{ov} = 2^V$

$5^{K\Omega} \leq r_{DS} \leq 20K\Omega$ for $0.5^V \leq V_{ov} \leq 2^V$

4.3

eq. 4.6a : $i_D = \frac{1}{2} K_n' \frac{W}{L} (V_{GS} - V_t)^2 \quad K_n' = \mu_n C_{ox}$

for equal drain currents:

$\mu_n C_{ox} \frac{W_n}{L} = \mu_p C_{ox} \frac{W_p}{L} \Rightarrow \frac{W_p}{W_n} = \frac{\mu_n}{\mu_p} = \frac{1}{0.4} = \boxed{2.5}$

4.4

for small V_{DS}: $i_D \simeq K_n' \frac{W}{L} (V_{GS} - V_t) V_{DS}$

$r_{DS} = \frac{V_{DS}}{i_D} = \frac{1}{K_n' \frac{W}{L}(V_{GS} - V_t)} = \frac{1}{50 \times 10^{-6} \times 20 \times (5 - 0.8)}$

$r_{DS} = 238\Omega \qquad V_{DS} = r_{DS} \times i_D = 238mV$

For the same performance of a p-channel device: $\frac{W_p}{W_n} = \frac{\mu_n}{\mu_p} = 2.5 \Rightarrow \frac{W_p}{L} = \frac{W_n}{L} \times 2.5 = 20 \times 2.5$

$\Rightarrow \frac{W_p}{L} = 50$

4.5

Eq. 4.5a: $i_D = K_n' \frac{W}{L} \left[(V_{GS} - V_t) V_{DS} - \frac{1}{2} V_{DS}^2 \right]$ triode region

for small V_{DS}:

$i_D \simeq K_n' \frac{W}{L} (V_{GS} - V_t) V_{DS}$

$r_{DS} = \frac{V_{DS}}{i_D} = \frac{1}{K_n' \frac{W}{L} (V_{GS} - V_t)}$

for $r_{DS} = 1K\Omega$:

$K_n' = 100\ \mu A/V^2$: $1000 = \frac{1}{100 \times 10^{-6} \frac{W}{1} \times (5 - 0.8)}$

$\Rightarrow W = 2.4\mu m$

4.6

a) $C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.45 \times 10^{-11}}{15 \times 10^{-9}} = 2.3\ fF/\mu m^2$

$K_n' = \mu_n C_{ox} = 550 \times 10^{-4} \times 2.3 \times 10^{-3} = 126.5\ \mu A/V^2$

b) $i_D = \frac{1}{2} K_n' \frac{W}{L} (V_{GS} - V_t)^2 \Rightarrow 100 = \frac{1}{2} \times 126.5 \times \frac{16}{0.8} (V_{GS} - 0.7)^2$

$V_{GS} - 0.7 = 0.28 \Rightarrow V_{OV} = 0.28V$

$V_{GS} = 0.98V$

$V_{DS min} = V_{GS} - V_t = 0.28V$

c) For small V_{DS}: (triode region) $i_D \simeq K_n' \frac{W}{L} V_{OV} \cdot V_{DS}$

Cont.