SOLUTION (Tutorial-1)

1) Ans)
(a) $K = 8.617 \times 10^{-5}\ eV/K$

$$n_i(T=300K) = 1.66\times10^{15}(300K)^{3/2} \exp\left[-\frac{0.66\,eV}{2(8.617\times10^{-15}\,eV/K)(300K)}\right]$$

$$= \boxed{2.465\times10^{13}\ cm^{-3}}$$

$$n_i(T=600K) = 1.66\times10^{15}(600K)^{3/2} \exp\left[-\frac{0.66\,eV}{2(8.617\times10^{-15}\,eV/K)(600K)}\right]$$

$$= \boxed{4.124\times10^{16}\ cm^{-3}}$$

Compared to the values obtained in example 2.1, we can see that the intrinsic carrier concentration in Ge at $T=300K$ is $\frac{2.465\times10^{13}}{1.08\times10^{10}} = 2282$ times higher than the intrinsic carrier concentration in Si at $T=300K$, similarly, at $T=600K$, the intrinsic carrier concentration in Ge is $\frac{4.124\times10^{16}}{1.54\times10^{15}} = 26.8$ times higher than that in Si.

(b). Since phosphorus is a group V element, it is a donor, meaning $N_D = 5\times10^{16}\ cm^{-3}$. For an n-type material, we have,

$$n = N_D = \boxed{5\times10^{16}\ cm^{-3}}$$

$$p(T=300K) = \frac{[n_i(T=300K)]^2}{n} = \boxed{1.215\times10^{10}\ cm^{-3}}$$

$$p(T=600K) = \frac{[n_i(T=600K)]^2}{n} = \boxed{3.401\times10^{16}\ cm^{-3}}$$

2) Ans →

(a). Mobility of e^-s in Si = 1350 $cm^2/V\text{-}s$

Mobility of holes in Si = 480 $cm^2/V\text{-}s$

Velocity of e^- = $\mu_n E$ = $(1350\ cm^2/V\text{-}s) \times (0.1\ V/\mu m)$

$= \boxed{1.35 \times 10^4\ m/s}$

velocity of holes = $\mu_p E$ = $(480\ cm^2/V\text{-}s) \times (0.1\ V/\mu m)$

$= \boxed{4.8 \times 10^3\ m/s}$

b). Given $E = 0.1\ V/\mu m$, Hole current is negligible,

$\mu_n = 1350\ cm^2/V\text{-}s$, $\mu_p = 480\ cm^2/V\text{-}s$.

$J_{tot} = 1\ mA/\mu m^2 = q[\mu_n n E + \mu_p P E] \simeq q\mu_n n E$.

$$\therefore n = \frac{J_{tot}}{q\mu_n E} = \frac{1\ mA/\mu m^2}{(1.6 \times 10^{-19} C)(1350\ cm^2/V\text{-}s)(0.1\ V/\mu m)}$$

$= \boxed{4.6 \times 10^{17}\ cm^{-3}}$

3) Ans)

(a). from problem 1, we can calculate n_i for Ge.

$n_i(T=300k) = 2.465 \times 10^{13}\ cm^{-3}$

$I_{tot} = q(n\mu_n + p\mu_p)AE$

$n = 10^{17}\ cm^{-3}$

$p = \frac{n_i^2}{n} = 6.076 \times 10^{9}\ cm^{-3}$

$\mu_n = 3900\ cm^2/V\text{-}s$, $\mu_p = 1900\ cm^2/V\text{-}s$.

$E = V/d = \frac{1V}{0.1\mu m} = \boxed{10^5\ V/cm}$

$A = 0.05\mu m \times 0.05\mu m = \boxed{2.5 \times 10^{-11}\ cm^2}$

since $n\mu_n >> p\mu_p$, we can write

$I_{tot} \approx qn\mu_n AE = 1.6 \times 10^{-19} \times 10^{17} \times 3900 \times 2.5 \times 10^{-11} \times 10$

$= \boxed{156\ \mu A}$

(b). All of the parameters are the same except n_i, which means we must re-calculate p.

$n_i(T=400K) = 9.230 \times 10^{14}\ cm^{-3}$

$p = \frac{n_i^2}{n} = 8.520 \times 10^{12}\ cm^{-3}$

since $n\mu_n >> p\mu_p$ still holds (note that n is 5 order of magnitude larger than p), the hole concentration once again drop out of the equation and we have

$I_{tot} \approx qn\mu_n AE$

$= \boxed{156\ \mu A}$

4) Ans→

(a). $n_n = N_D = \boxed{5 \times 10^{17}\ cm^{-3}}$

$p_n = \dfrac{n_i^2}{n_n} = \boxed{233\ cm^{-3}}$

$p_p = N_A = \boxed{4 \times 10^{16}\ cm^{-3}}$

$n_p = \dfrac{n_i^2}{p_p} = \boxed{2916\ cm^{-3}}$

(b). We can express the formula for V_0 in its full form, showing its temperature dependence:

$$V_0(T) = \frac{kT}{q} \ln\left[\frac{N_A N_D}{(5.2 \times 10^{15})^2 T^3 e^{-(E_g/kT)}}\right]$$

$V_0(T=250k) = \boxed{906\ mV}$, $V_0(T=300k) = \boxed{849\ mV}$,

$V_0(T=350k) = \boxed{789\ mV}$

Looking at the expression for $V_0(T)$, we can expand it as follows:

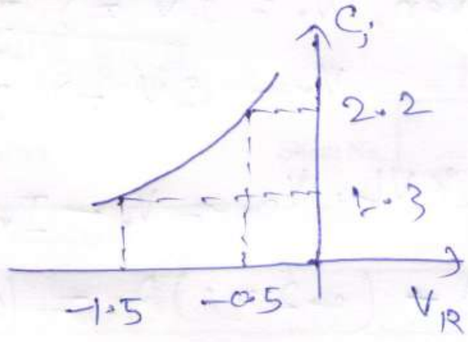
$$V_0(T) = \frac{kT}{q}\left[\ln(N_A) + \ln(N_D) - 2\ln(5.2 \times 10^{15}) - 3\ln(T) + \frac{E_g}{kT}\right]$$

Let's take the derivative of this expression to get a better idea of how V_0 varies with temperature.

$$\frac{dV_0(T)}{dT} \doteq \frac{k}{q}\left[\ln(N_A) + \ln(N_D) - 2\ln(5.2 \times 10^{15}) - 3\ln(T) - 3\right]$$

From this expression, we can see that if $\ln(N_A) + \ln(N_D) <$ $2\ln(5.2 \times 10^{15}) + 3\ln(T) + 3$, or equivalently, if $\ln(N_A N_D) <$ $\ln[(5.2 \times 10^{15})^2 T^3] - 3$, then V_0 will decrease with temperature, which we observe in this case. In order for this not to be true (i.e, in order for V_0 to increase with temperature), we must have either very high doping concentration or very low temp

5) Ans)



$$\frac{C_{j0}}{\sqrt{1+\frac{0.5}{V_0}}} = 2.2 \quad \text{—} (1)$$

$$\frac{C_{j0}}{\sqrt{1+\frac{1.5}{V_0}}} = 1.3 \quad \text{—} (2)$$

(1) divided by (2)

$$\frac{1+\frac{1.5}{V_0}}{1+\frac{0.5}{V_0}} = \left(\frac{2.2}{1.3}\right)^2 \Rightarrow \boxed{V_0 = 0.0365\,V}$$

substitute V_0 into (1):

$$C_{j0} = 2.2 \times \sqrt{1+\frac{0.5}{V_0}} \simeq 8.43\ fF/\mu m^2.$$

$$\Rightarrow \frac{N_A N_D}{N_A+N_D} = (C_{j0})^2 V_0 \cdot \frac{2}{\varepsilon_{Si}\, q} = (8.43\ fF/\mu m^2)^2 \times (0.0365V) \times \frac{2}{\varepsilon_{Si}\, q}$$

$$\simeq 3.13 \times 10^{17}\ cm^{-3}$$

Fix a value for $N_A > \frac{N_A N_D}{N_A+N_D} \triangleq y$

$$N_A = 2\times10^{18}\ cm^{-3} \Rightarrow N_D = \frac{y N_A}{N_A - y}$$

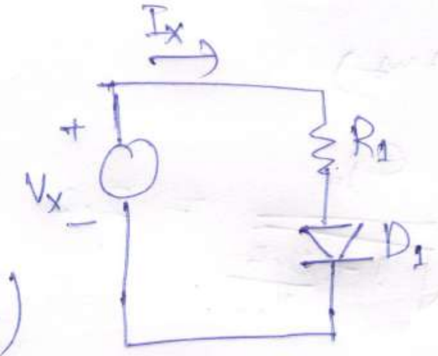
$$= \frac{(3.13\times10^{17}\ cm^{-3})(2\times10^{18}\ cm^{-3})}{(2\times10^{18} - 3.13\times10^{17})\ cm^{-3}}$$

$$\approx \boxed{3.71\times10^{17}\ cm^{-3}}$$

6) Ans →

Given, $V_x = 1\,V \Rightarrow I_x = 0.2\,mA$

$V_x = 2V \Rightarrow I_x = 0.5\,mA$



By KVL, $V_{D1} = V_x - I_x R_1 = V_T \ln\left(\frac{I_x}{I_s}\right)$

$\Rightarrow 1 - (0.2\,mA)R_1 = (0.026\,V)\ln\left(\frac{0.2\,mA}{I_s}\right)$ — (1)

$2 - (0.5\,mA)R_1 = (0.026\,V)\ln\left(\frac{0.5\,mA}{I_s}\right)$ — (2)

subtract (1) from (2) :

$1 - (0.3\,mA)R_1 = (0.026\,V)\ln\left(\frac{0.5}{0.2}\right)$

$\Rightarrow R_1 = \frac{1 - (0.026)V}{0.3\,mA} = \boxed{3.25\,k\Omega}$

substitute R_1 into (1):

$I_s = I_x \exp\left[-\frac{V_x - I_x R_1}{V_T}\right]$

$= (0.2\,mA)\exp\left[-\frac{1-(0.2\,mA)(3.25\,k)}{0.026}\right] \simeq \boxed{2.94\times10^{-10}\,A}$.

$\therefore \boxed{R_1 \simeq 3.25\,k\Omega}$

$\boxed{I_s \simeq 2.94\times10^{-10}\,A}$

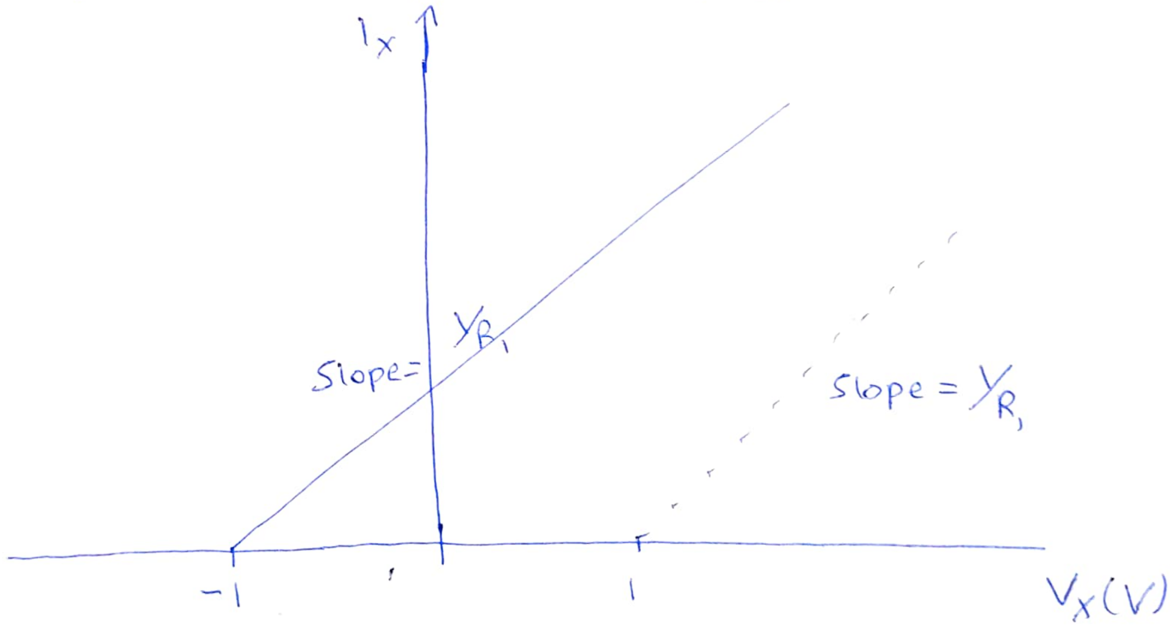
Soln 7

When $V_B < 0$ the diode will be on even when $V_X = 0$

When $V_B > 0$ the diode will be in ON state when $V_X > V_B$

$$\therefore \quad I_X = \begin{cases} 0 & V_X < V_B \\ \dfrac{V_X - V_B}{R_1} & V_X > V_B \end{cases}$$

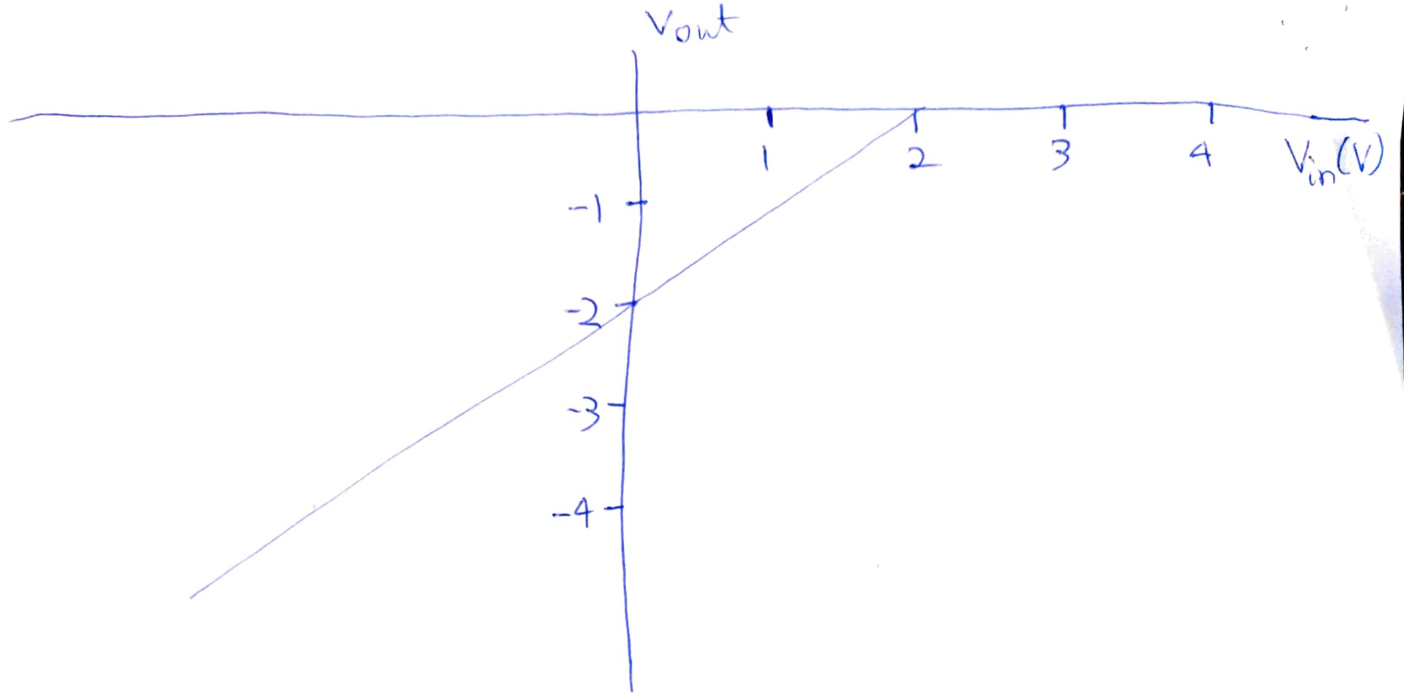
We will get two different curves



Soln 8

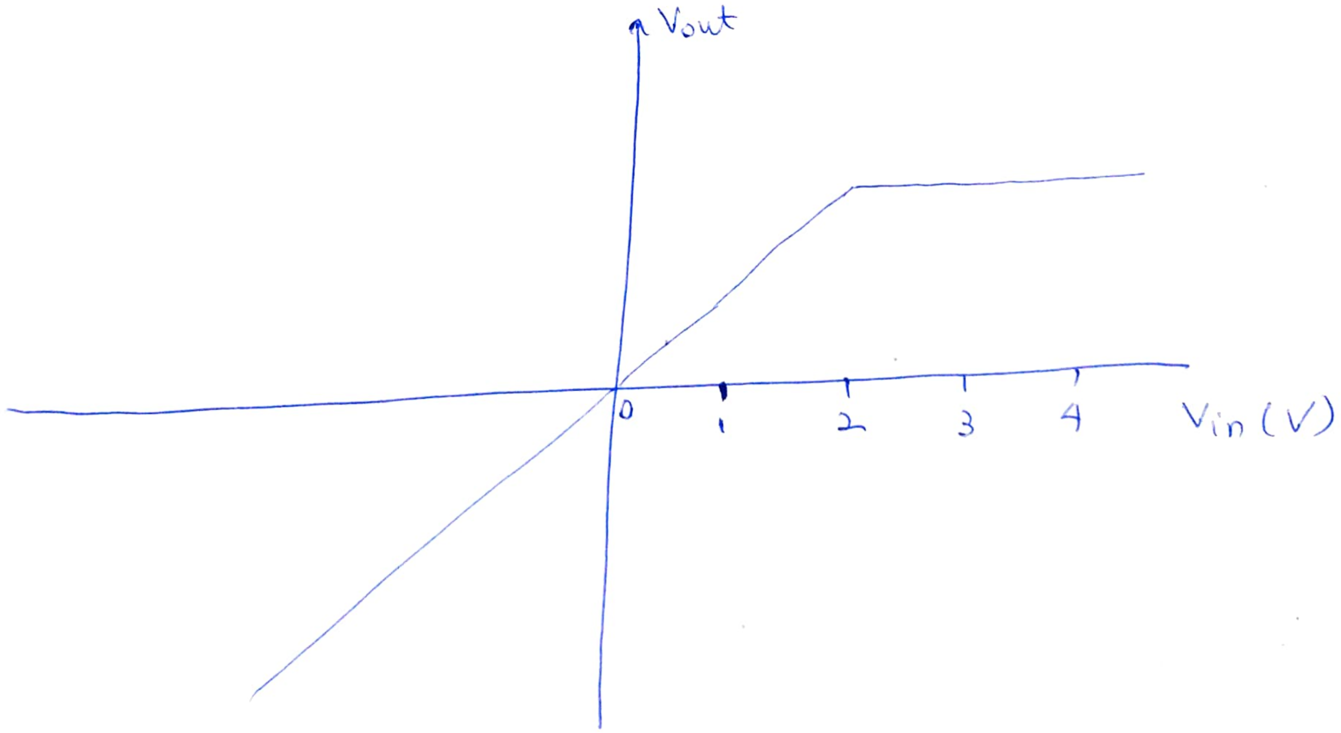
(a) V_{out} will be zero when diode is reversed biased

$$\therefore \quad V_{out} = \begin{cases} V_{in} - V_B & V_{in} < V_B \\ 0 & V_{in} > V_B \end{cases}$$



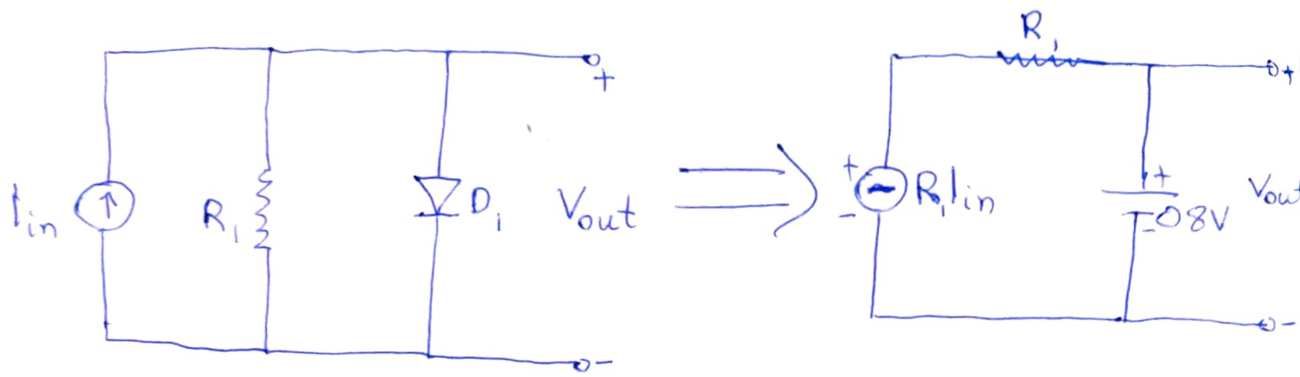
(b) When diode is in OFF states $V_{out} = V_B$ otherwise $V_{out} = V_{in}$ $\therefore$

$$V_{out} = \begin{cases} V_{in} & V_{in} < V_B \\ V_B & V_{in} > V_B \end{cases}$$



Soln 9

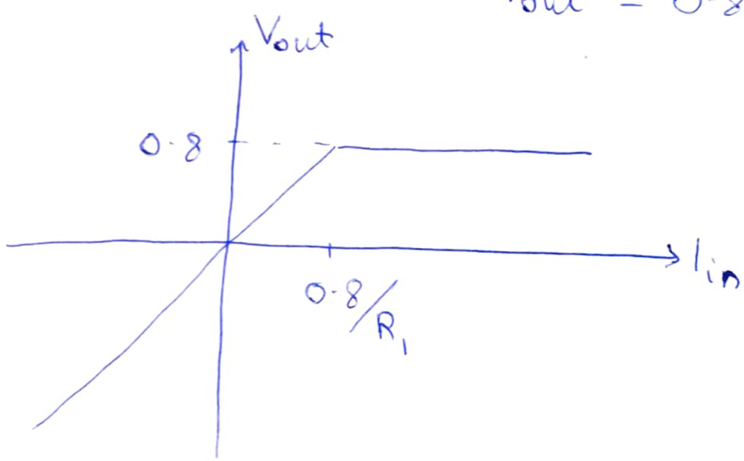
(a)



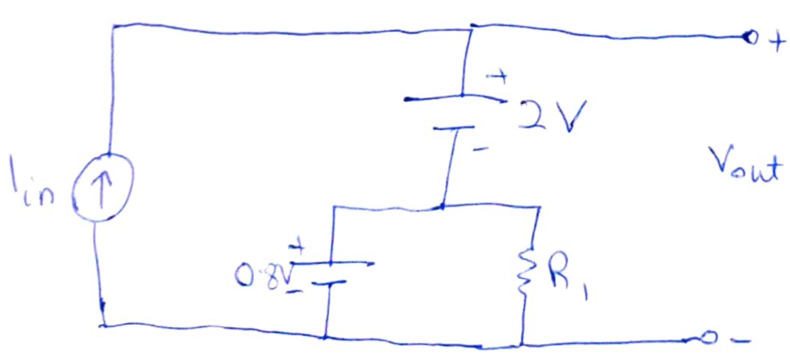
Converting current source to voltage source and applying constant voltage of diode of 0.8V

When diode is OFF $V_{out} = R_1 I_{in}$

When diode is ON $V_{out} = 0.8V$

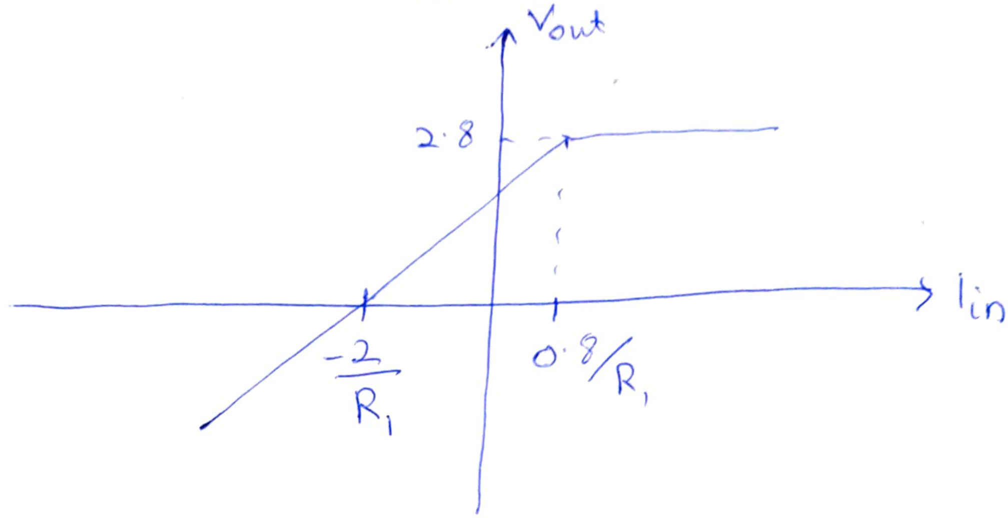


(b) Considering $V_B = 2V$ and constant voltage of diode of 0.8V



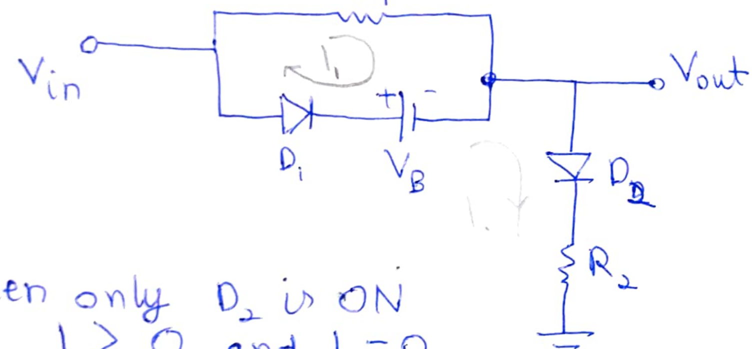
When diode is OFF $\quad V_{out} = 2 + I_{in} R_1$

When diode is ON $\quad V_{out} = 2 + 0.8 = 2.8$



Soln 10

(a)



Von is constant voltage of diode

When only D_2 is ON

$I > 0$ and $I_1 = 0$

$V_{in} = I(R_1 + R_2) + V_{on}$ — (1)

$$I = \frac{V_{in} - V_{on}}{R_1 + R_2} \Rightarrow \frac{V_{in} - V_{on}}{R_1 + R_2} > 0$$

$$V_{in} > V_{on}$$

For diode D_1 to be in ON state

$$V_{in} - V_{out} > V_B + V_{on}$$

$V_{out} = I R_2 + V_{on}$ — (2)

$$V_{in} = I_1 R_1 + V_{on} + I R_2$$

$$I = \frac{V_{in} - V_{on}}{R_1 + R_2} \rightarrow \text{from } ①$$

$$V_{in} - V_{out} > V_B + V_{on}$$

$$V_{in} - (I R_2 - V_{on}) > V_B - V_{on} \rightarrow \text{by substituting eq } ②$$

$$V_{in} - \left(\left(\frac{V_{in} - V_{on}}{R_1 + R_2} \right) \cdot R_2 + V_{on} \right) > V_{on} + V_B \rightarrow \text{substituting value of } I$$

Solving the above in equation we will get

$$V_{in} > \frac{2 V_{on} R_1 + V_B (R_1 + R_2) + V_{on} R_2}{R_1}$$

$$\left[V_{in} > V_{on} + \frac{R_1 + R_2}{R_1} (V_{on} + V_B) \right]$$

condition for both diodes to be in ON state

When ~~both~~ only D_2 is in ON state

$$V_{in} = I R_1 + V_{on} + I R_2$$

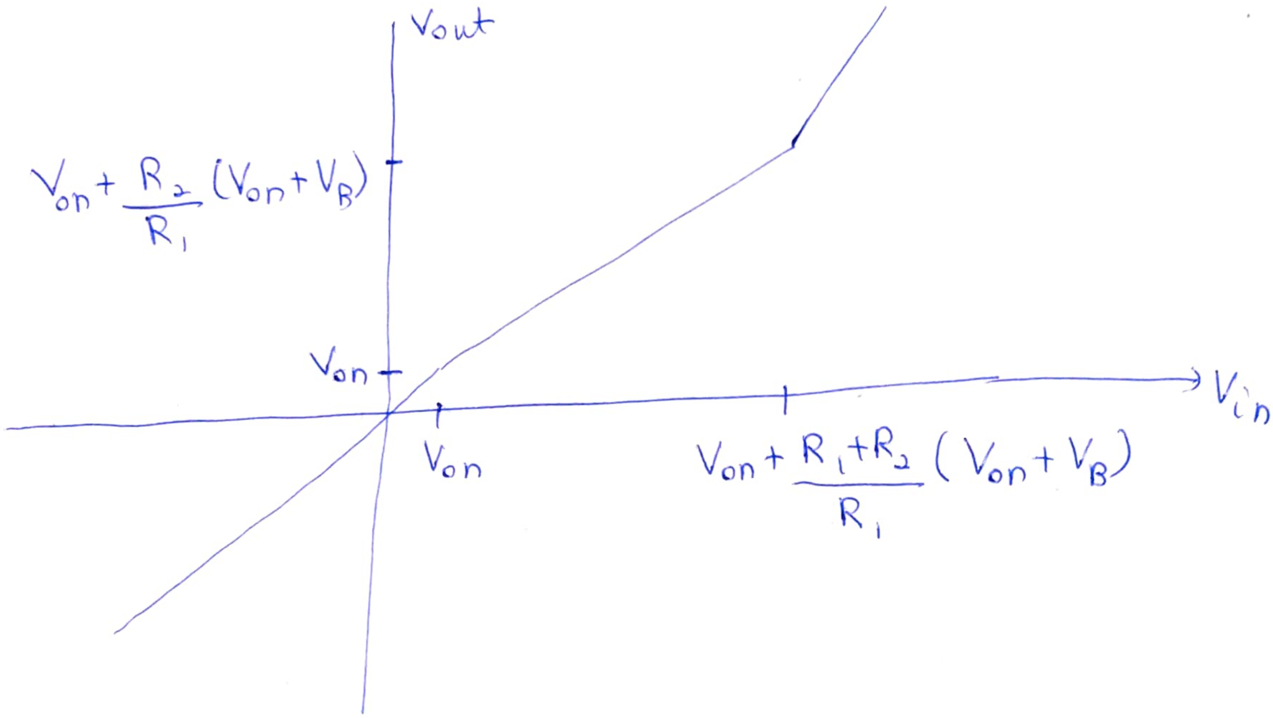
$$I = \frac{V_{in} - V_{on}}{R_1 + R_2}$$

$$\boxed{V_{out} = V_{on} + \frac{(V_{in} - V_{on}) R_2}{R_1 + R_2}}$$

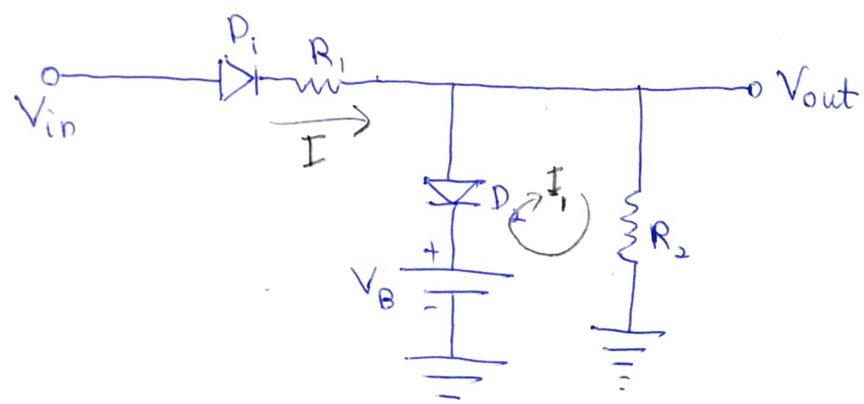
When both diodes are in ON state

$$V_{in} = V_{on} + V_B + V_{out}$$

$$\boxed{V_{out} = V_{in} - V_{on} - V_B}$$



(b)



When both diode in OFF state

$V_{out} = 0$

$\underline{\underline{D_1 \text{ ON} \quad D_2 \text{ OFF}}}$ $\rightarrow$ condition $I > 0$

$$V_{in} = V_{on} + IR_1 + IR_2$$

$$I = \frac{V_{in} - V_{on}}{R_1 + R_2} \Rightarrow \frac{V_{in} - V_{on}}{R_1 + R_2} > 0$$

$\boxed{V_{in} > V_{on}} \Rightarrow$ condition only for D_1 in ON state

$\underline{\underline{D_1 \text{ ON} \quad D_2 \text{ ON}}}$

$$V_{in} = V_{on} + IR_1 + V_{on} + V_B$$

$$\cancel{V_{in} = V_{on} + IR_1 + I_1 R_2}$$

$$I = \frac{V_{in} - 2V_{on} - V_B}{R_1}$$

For D_2 in ON state $\quad V_{out} > V_B + V_{on}$

$$V_{out} = I R_2$$

$$\therefore \quad \frac{R_2}{R_1}(V_{in} - 2V_{on} - V_B) > V_B + V_{on}$$

$$R_2(V_{in} - 2V_{on} - V_B) > R_1(V_B + V_{on})$$

$$R_2 V_{in} > R_1(V_B + V_{on}) + (2V_{on} + V_B)R_2$$

$$\boxed{V_{in} > V_{on} + \frac{R_1 + R_2}{R_2}(V_B + V_{on})}$$

$\Downarrow$

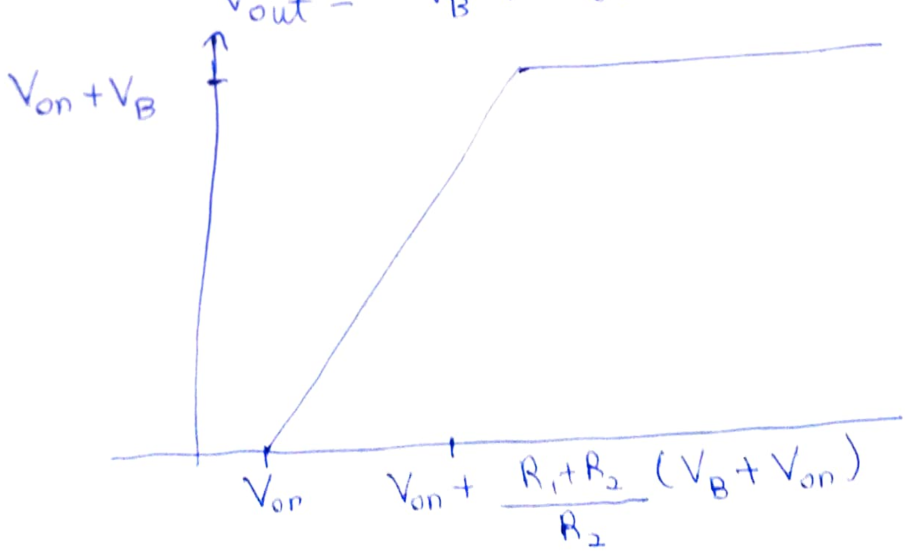
condition for D_1 ON and D_2 ON

For D_1 in ON state and D_2 OFF

$$\boxed{V_{out} = \frac{R_2(V_{in} - V_{on})}{R_1 + R_2}}$$

For D_1 ON and D_2 ON

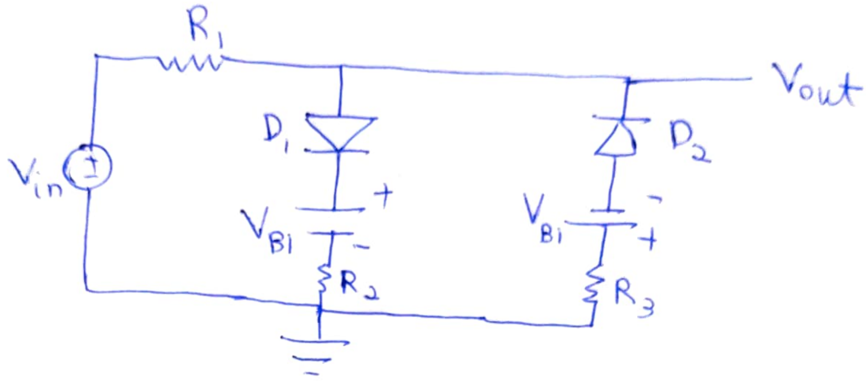
$$V_{out} = V_B + V_{on}$$



Q4

Soln 11

The required circuit is



$$V_{B1} = V_{B2} = 2 - 0.8 = 1.2\,V$$

For $V_{in} > 2\,V$ $\frac{V_{out}}{V_{in}}$, has a value of 0.5

$\therefore$ $R_2 = R_1$

Similarly $R_3 = R_1$

$\therefore$ $R_1 = R_2 = R_3 = 1\,K\Omega$