Q.1

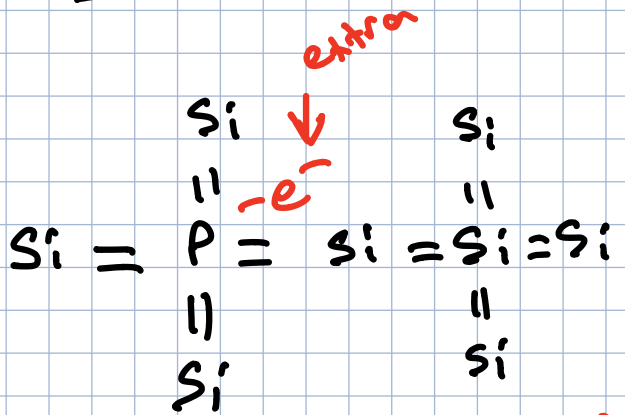
a.)

Donor: Donates an e^- for current conduction. If we are talking about Silicon which is from IV A in periodic table, Donors come from V A. When they replace one of the Si atoms, they will have one extra free e^- that can be used for current conduction.

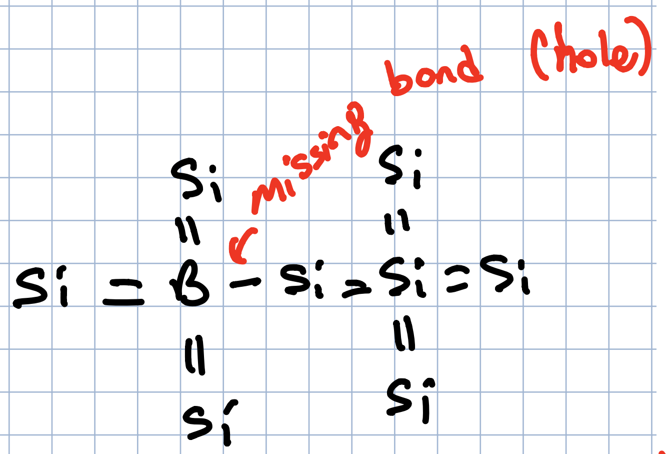
examples: Phosphorus (P), Arsenic (As)

Acceptor: Donates a hole, or equivalently accepts an e^- for current conduction, creates a space for neighbor e^- to jump into. Acceptors come from III-A. When replaced with a Si atom, there will be one missing e^- which can be used by e^- to jump into and contribute to current conduction.

examples: Boron (B)

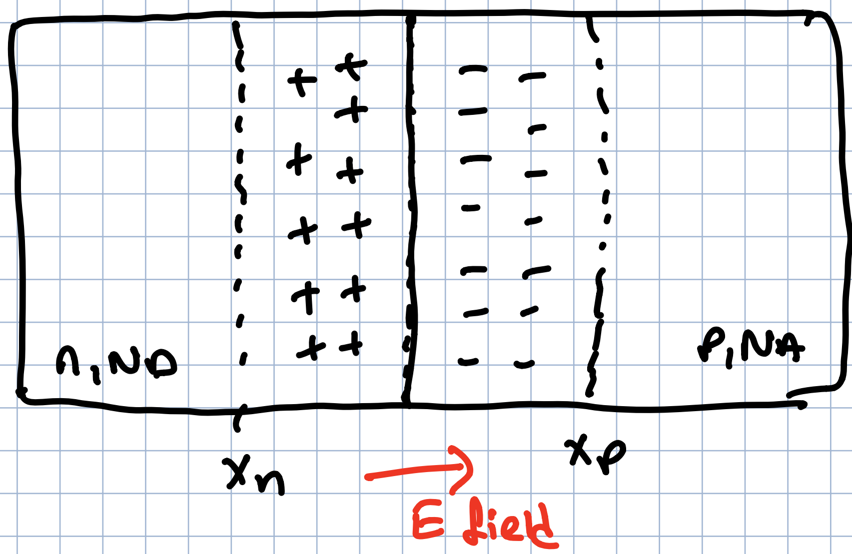


Donor atom (P)



Acceptor Atom (B)

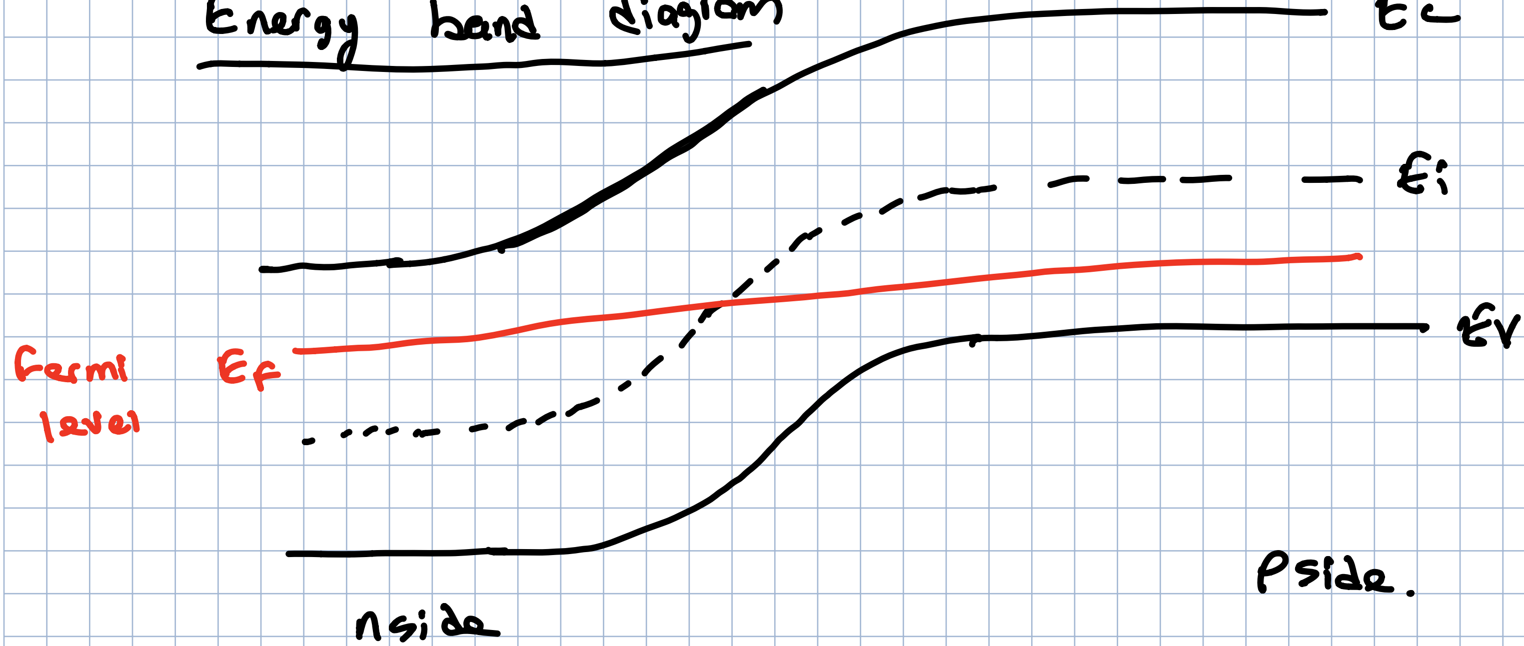
b)



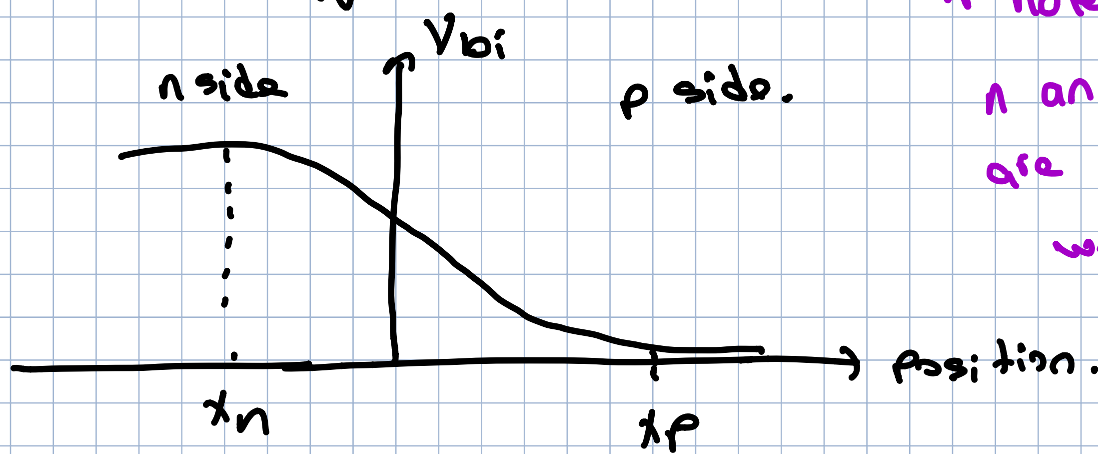
n-side has a lot of e^- from donor atoms, and p-side has a lot of holes from acceptor atoms. Once n and p-sides touch each other the diffusion process starts. e^- diffuse into the p side and holes diffuse into the p side. One e^-s leave donors on n-side a (+) charged region is created. Similarly a (−) charged region is created on the p side. There are no mobile regions in this "depletion region".

The (+) and (−) charged regions created by diffusion creates an E field that opposes the diffusion of e^- from the n-side to p-side and " " holes from the p-side to n-side. The E field creates the drift current that balances the diffusion current. The charge flow stops when these drift and diffusion processes are equal to each other.

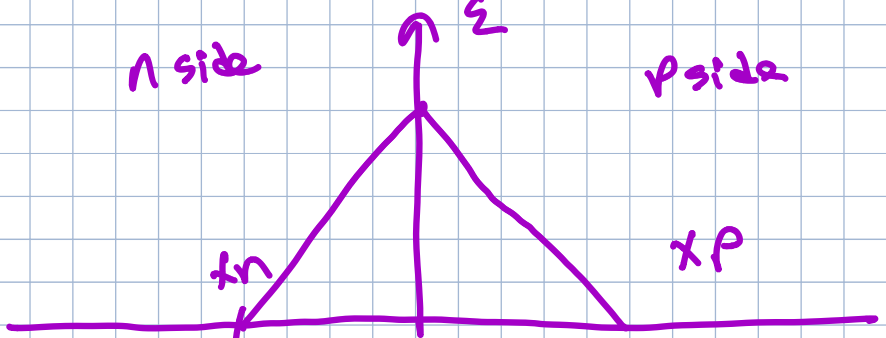
Energy band diagram



Energy = $-q \cdot V$

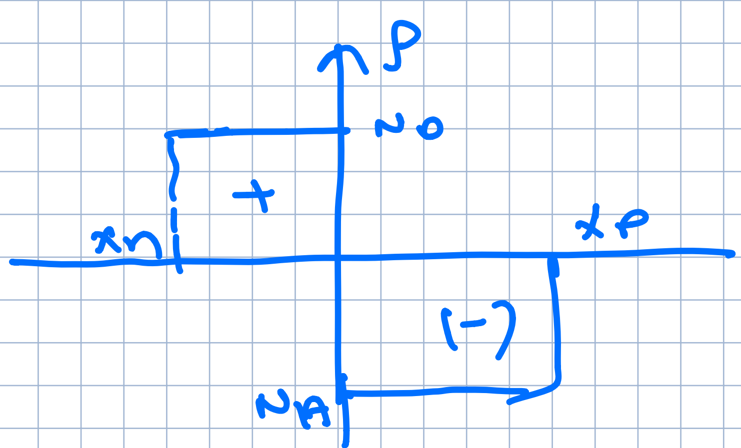


* Note that n and p sides are swapped here w.r.t. class.



ℰ: Electric fied

$$\mathcal{E} = \frac{-dV}{dx}$$

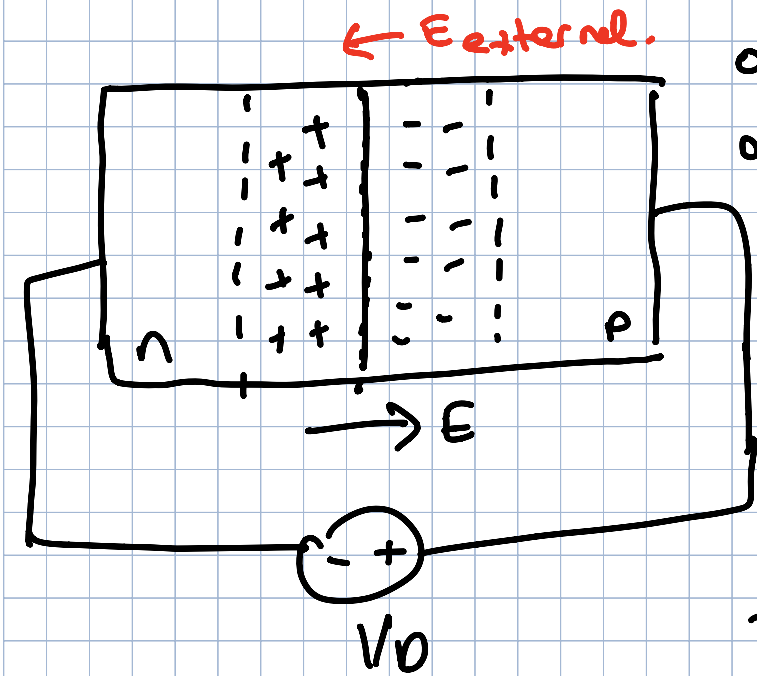


ρ: Charge density.

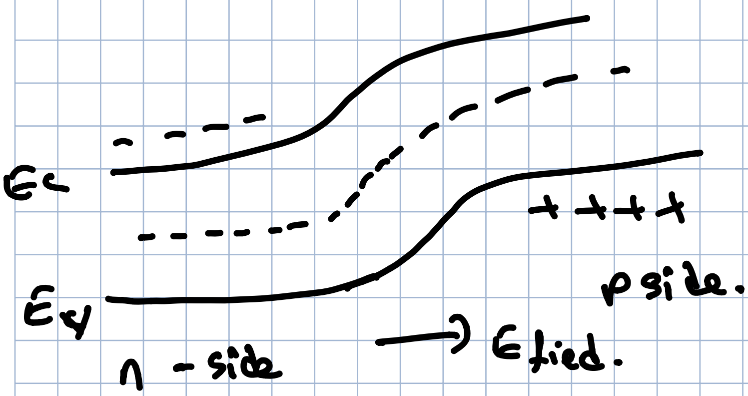
$$\rho : \frac{d\mathcal{E}}{dx}$$

c) forward bias ($V_D > V_{on}$)

* $E_{external}$ formed by V_D opposes the internal E field and hence reduces the energy barrier between the sides.

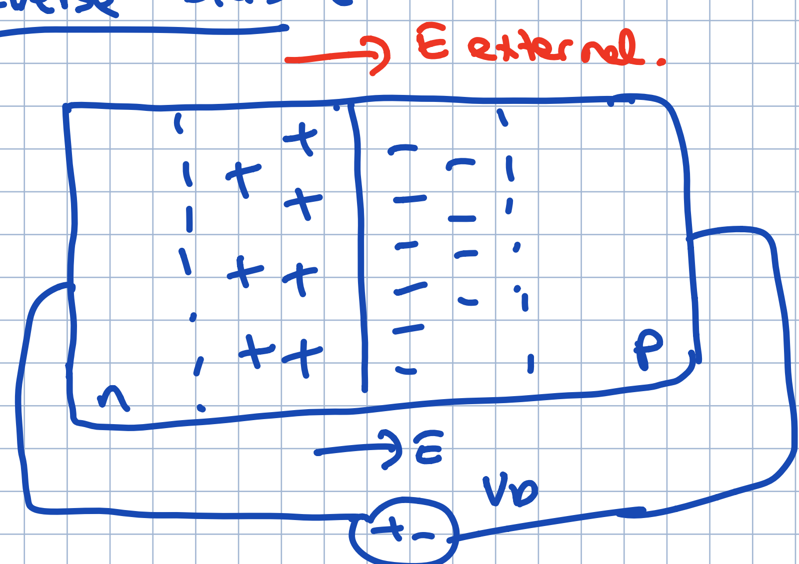


The possibility of finding an e^- on n side and a hole on p side (majority carriers) that has the energy to pass the energy barrier is exponential. Reducing this energy height with forward

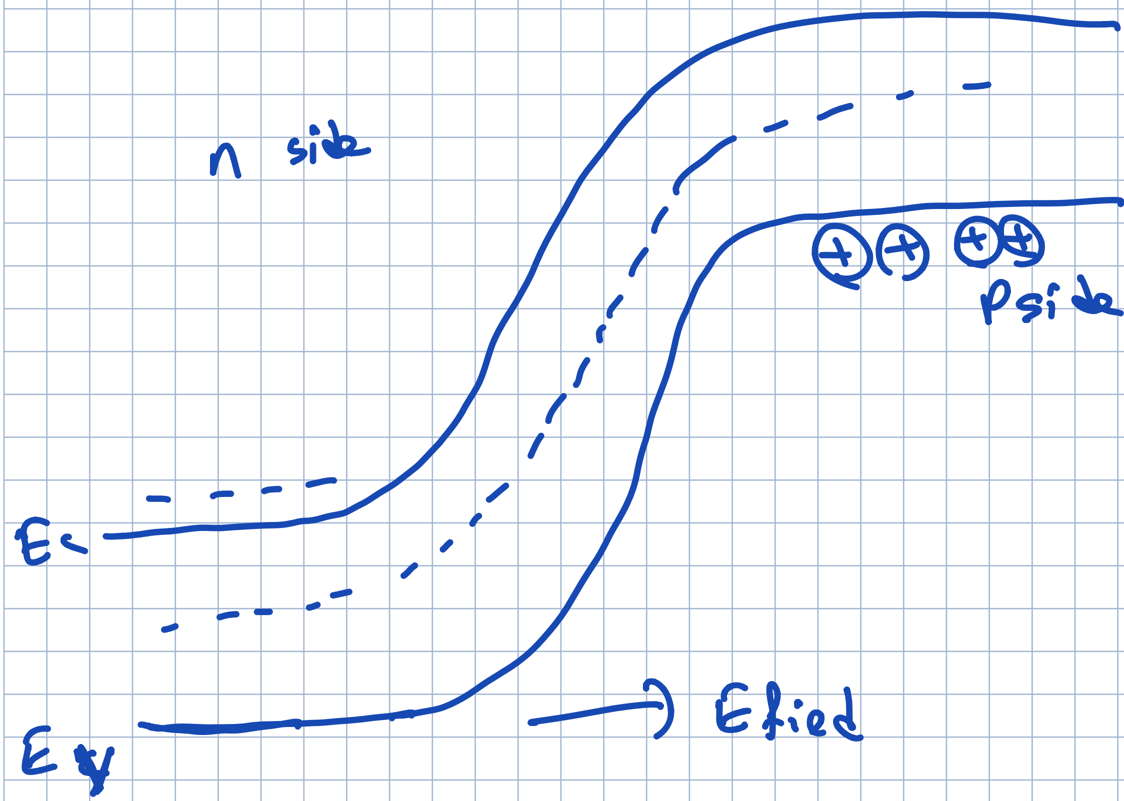


bias with V_D leads to an exponential I-V relationship.

reverse bias ($V_D < V_{on}$)



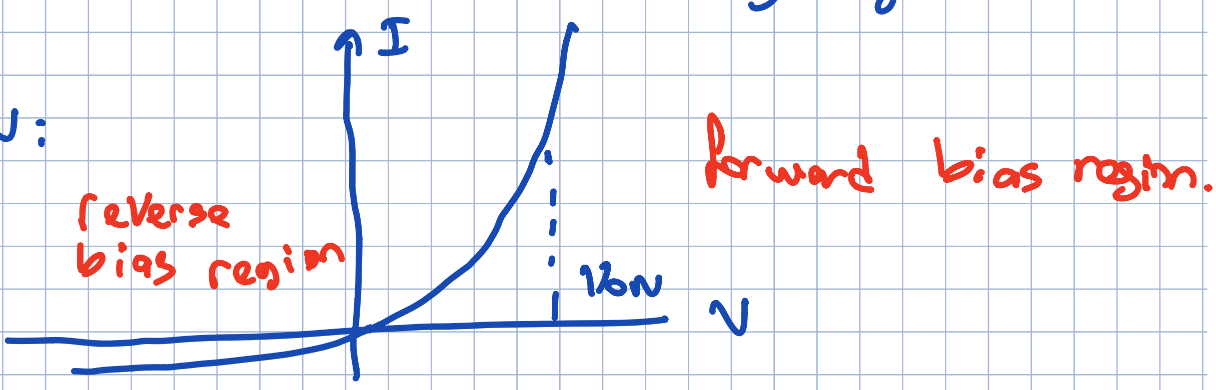
Applying a (+) voltage to the n side increases the potential barrier between the n and p sides.



The possibility of finding an e^- on n side and a hole on p-side that can pass the energy barrier is extremely low. (exponential relationship)

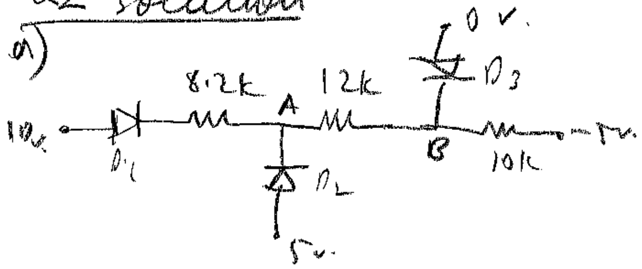
Instead minority carriers on n side, holes
and " " " p side, e^-
will form the reverse bias current. These carriers flow with the applied E field. Since the minority carriers form the reverse bias current, it is small and independent of reverse bias. (ignoring break down)

diode I-V:

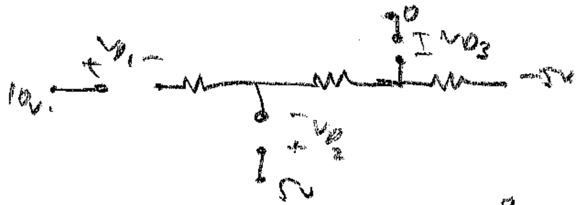


Q2 solution

a)



Assume all diodes are OFF

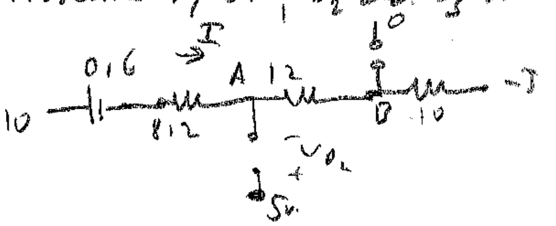


$V_{D_1} = 10 - (-5) = 15 \overset{?}{<} 0.6$ X

$V_{D_2} = 5 < 0.6$ X

$V_{D_3} = 0 - (-5) = 5v. < 0.6$ X

Assume D_1 ON, D_2 and D_3 OFF



$I = \dfrac{10 - 0.6 - (-5)}{8.2 + 12 + 10} = \dfrac{14.4}{30.2} = 0.477 mA$

$V_A = 10 - 0.6 - 8.2 \times 0.477 = 5.49 v.$

$V_{D_2} = 5 - 5.49 = -0.49 < 0.6$ ✓

$V_B = -5 + 10 \times 0.477 = -0.23 v$

$V_{D_3} = 0 - (-0.23) = 0.23 \overset{?}{<} 0.6$ ✓

$\therefore$ $V_A = 5.49 v$

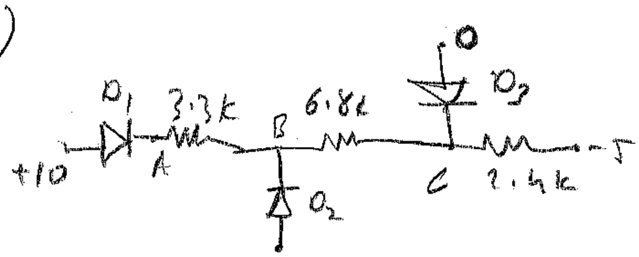
$V_B = -0.23 v$

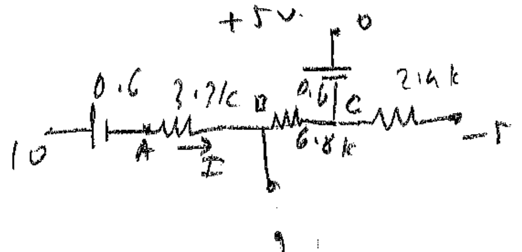
$i_{D_1} = 0.477 mA$

$i_{D_2} = i_{D_3} = 0$

D_1 ON, D_2 OFF, D_3 OFF

b)





Assume D_1 ON, D_2 OFF, D_3 ON

$I = \dfrac{10 - 0.6 - (-0.6)}{3.3 + 6.8} = 0.99 mA > 0$ ✓

$V_A = 10 - 0.6 = 9.4 v$

$V_B = 9.4 - 3.3 \times 0.99 = 6.1 v.$

$V_C = -0.6 v.$

$I_{D_1} = 0.99 mA$ $I_{D_2} = 0$

$-I_{D_3} = 0.99 - \dfrac{-0.6 - (-5)}{2.4}$

$= 0.99 - \dfrac{4.4}{2.4} = -0.843 mA$

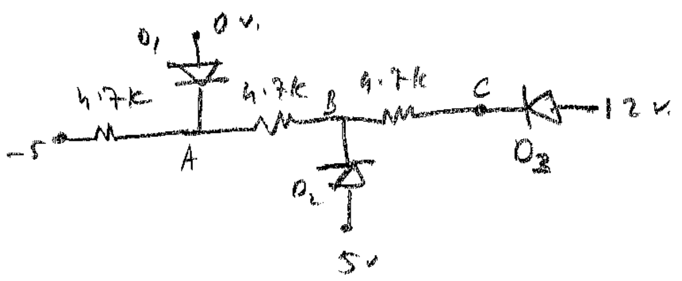
$I_{D_3} = 0.843 mA >$ ✓

$V_{D_2} = 5 - V_B = 5 - 6.1$ 1.1

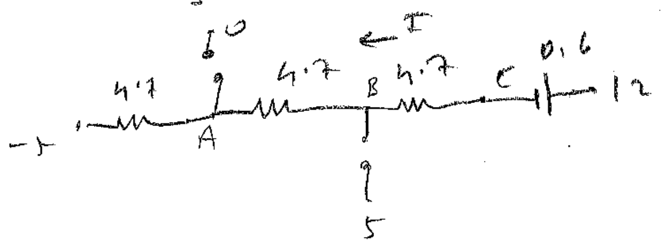
$= -1.1 < 0.6$ ✓

1+2v

c)



Assume D_3 is ON and the others are OFF



$$I = \frac{12 - 0.6 - (-5)}{3 \times 4.7} = 1.163 \text{ mA} > 0 \checkmark$$

$V_C = 12 - 0.6 = 11.4$ V

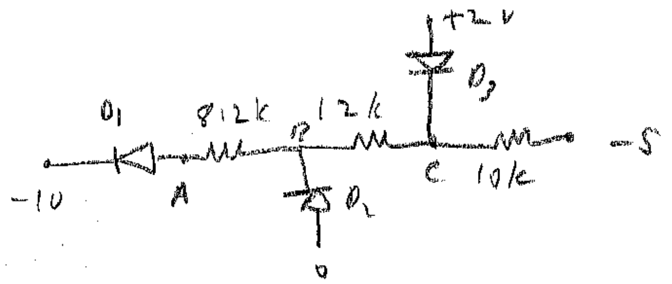
$V_B = 11.4 - 4.7 \times 1.163 = 5.933$ V

$V_A = 5.933 - 4.7 \times 1.163 = 0.467$ V

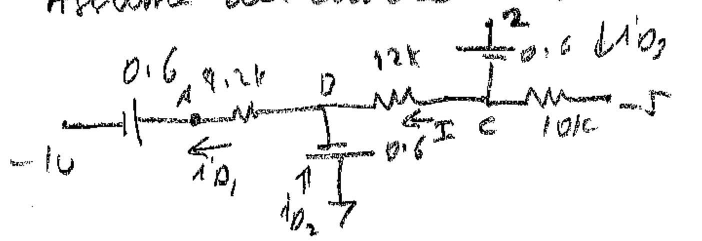
$V_{D_2} = 5 - 11.4 < 0.6 \checkmark$

$V_{D_1} = 0 - V_A = -0.467 < 0.6 \checkmark$

d)



Assume all diode are ON



$V_A = -10 + 0.6 = -9.4$ V

$V_B = -0.6$ V

$V_C = -0.6 + 2 = 1.4$ V

$$i_{D_1} = \frac{V_B - V_A}{8.2} = \frac{-0.6 - (-9.4)}{8.2} = \frac{8.8}{8.2} = 1.073 \text{ mA} > 0 \checkmark$$

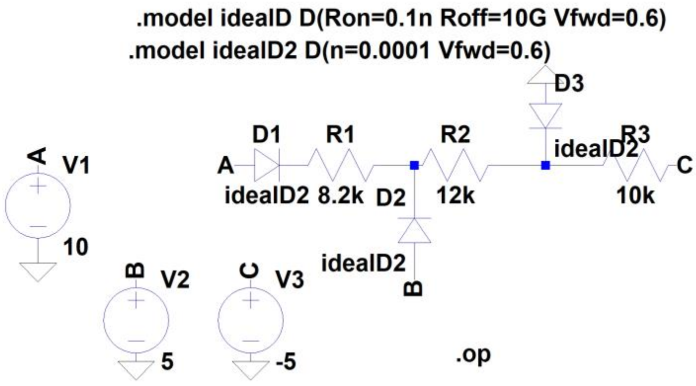
$$I = \frac{V_C - V_B}{12} = \frac{1.4 - (-0.6)}{12} = \frac{2}{12} = 0.1667 \text{ mA}$$

$$i_{D_2} = i_{D_1} - I = 1.073 - 0.1667 = 0.9063 \text{ mA} > 0 \checkmark$$

$$i_{D_3} = I + \frac{V_C - (-5)}{10} = 0.1667 + \frac{6.4}{10} = 0.8067 \text{ mA} > 0 \checkmark$$

The same circuits are then solved using LTSpoice and very close results are obtained:

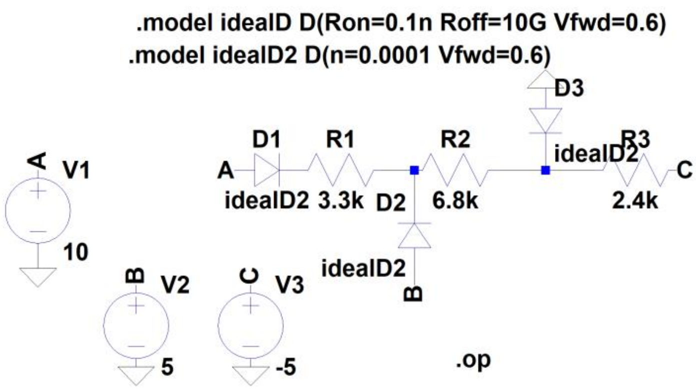
a)




```
       --- Operating Point ---

V(a):           10             voltage
V(p001):        9.4            voltage
V(n002):        -0.231788      voltage
V(n001):        5.49007        voltage
V(c):           -5             voltage
V(b):           5              voltage
I(D2):          -9.80132e-013  device_current
I(D3):          4.63576e-013   device_current
I(D1):          0.000476821    device_current
I(R3):          0.000476821    device_current
I(R2):          0.000476821    device_current
I(R1):          0.000476821    device_current
I(V3):          0.000476821    device_current
I(V2):          9.80132e-013   device_current
I(V1):        -0.000476821      device_current
```

b)

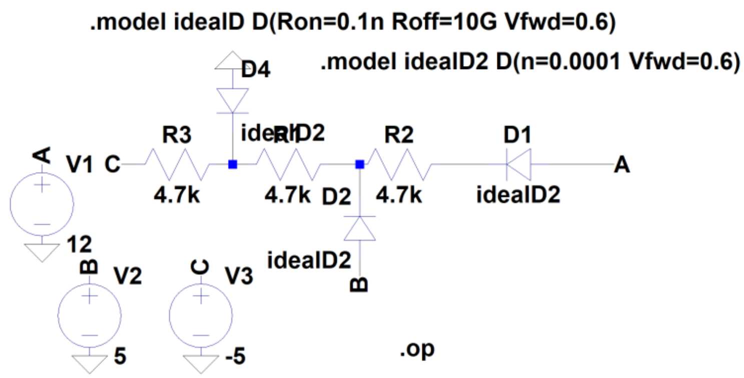



```
       --- Operating Point ---

V(a):           10             voltage
V(p001):        9.4            voltage
V(n002):        -0.600001      voltage
V(n001):        6.13267        voltage
V(c):           -5             voltage
```

```
V(b):           5              voltage
I(D2):          -2.26534e-012  device_current
I(D3):          0.000843234    device_current
I(D1):          0.000990099    device_current
I(R3):          0.00183333     device_current
I(R2):          0.000990099    device_current
I(R1):          0.000990099    device_current
I(V3):          0.00183333     device_current
I(V2):          2.26534e-012   device_current
I(V1):        -0.000990099      device_current
```

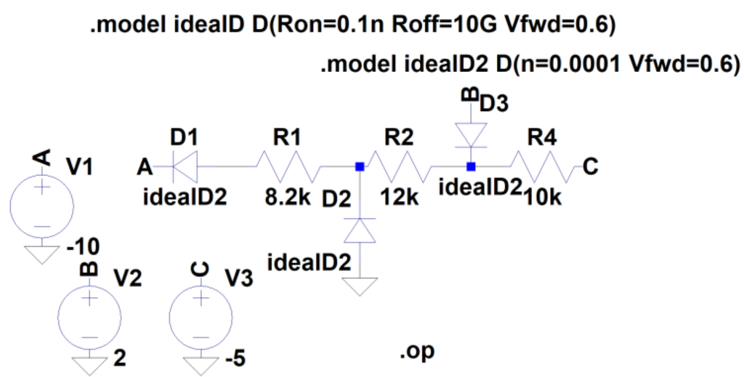
c)




```
    --- Operating Point ---

V(n001):        0.466666       voltage
V(n002):        5.93333        voltage
V(n003):        11.4           voltage
V(a):           12             voltage
V(b):           5              voltage
V(c):           -5             voltage
I(D4):          -9.33333e-013  device_current
I(D1):          0.00116312     device_current
I(D2):          -1.86667e-012  device_current
I(R3):          -0.00116312    device_current
I(R2):          -0.00116312    device_current
I(R1):          -0.00116312    device_current
I(V3):          0.00116312     device_current
I(V2):          1.86667e-012   device_current
I(V1):          -0.00116312    device_current
```

d)

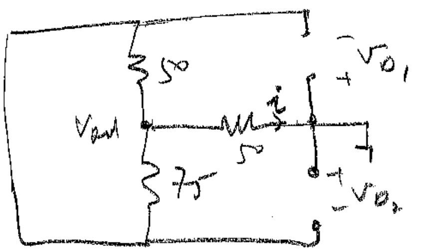



```
    --- Operating Point ---
```

V(n001):	-9.4	voltage
V(n002):	-0.600001	voltage
V(n003):	1.4	voltage
V(a):	-10	voltage
V(b):	2	voltage
V(c):	-5	voltage
I(D1):	0.00107317	device_current
I(D3):	0.000806667	device_current
I(D2):	0.000906504	device_current
I(R4):	0.00064	device_current
I(R2):	-0.000166667	device_current
I(R1):	-0.00107317	device_current
I(V3):	0.00064	device_current
I(V2):	-0.000806667	device_current
I(V1):	0.00107317	device_current

Q3 solution.

When $V_s = 0$ both diodes are OFF. Let's check this.

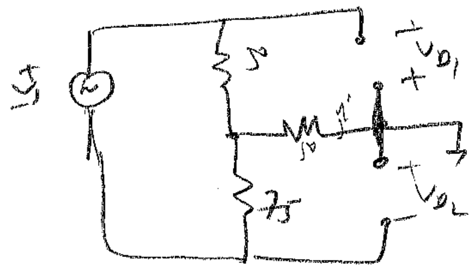


$i = 0 \Rightarrow V_{out} = 0$

Also $V_{D_1} = 0 \overset{?}{<} 0.7$ ✓

$V_{D_2} = 0 \overset{?}{<} 0.7$ ✓

For small V_s



$i = 0$

$$V_{D_2} = \frac{75}{75+50} \times V_s = \frac{3}{5} V_s$$

$$V_{D_1} = -\frac{50}{50+75} V_s = -\frac{2}{5} V_s$$

As V_s increases in the +ve direction D_1 is OFF and D_2 is OFF if $V_{D_2} < 0.7$.

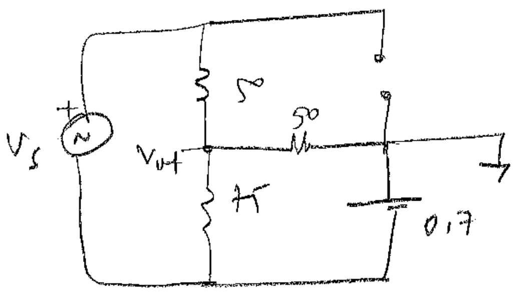
$$\Rightarrow \frac{3}{5} V_s < 0.7 \quad V_s < 0.7 \times \frac{5}{3} = \frac{3.5}{3} = 1.1667V.$$

This happens when. $8 \sin wt = 1.1667$

$$\sin wt = \frac{1.1667}{8} \quad wt = 0.1464 \text{ rad}$$

$$t = \frac{0.1464}{2\pi \times 10000} = 2.33 \mu\text{sec}.$$

After this time D_2 is ON



$$V_{out} = \frac{50//75}{50//75+50} V_s - 0.7 \times \frac{50}{50+50//75}$$

$$= \frac{30}{30+50} V_s - 0.7 \times \frac{50}{50+30}$$

$$= \frac{3}{8} V_s - 0.7 \times \frac{5}{8}$$

$$= \frac{3}{8} \times 8 \sin wt - \frac{3.5}{8}$$

$$= 3 \sin wt - 0.4375$$

$V_{out\,peak} = 2.5625 v.$

During the negative half cycle as V_s decreases
D_2 is OFF but D_1 is OFF as long as $V_{O_1} = -\frac{2}{5} V_s < 0.7$

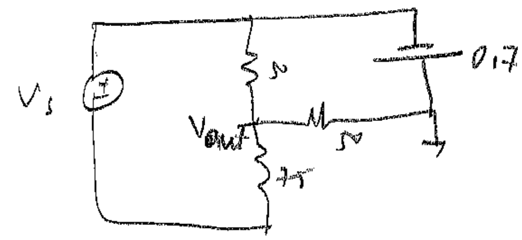
$$V_s > \frac{5 \times 0.7}{2} = \frac{3.5}{2} = 1.75$$

This happens when $8 \sin \omega t = 1.75$

$$\omega t = \sin^{-1}\left(\frac{1.75}{8}\right) = 0.2205$$

$\Rightarrow t = 3.51\,\mu sec$ (We have assumed that $t=0$ at the beginning of the $-$ve cycle)

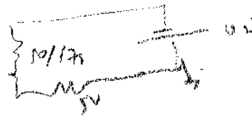
For more negative values D_1 is ON



$$V_{out} = -\frac{50//150}{50//150+75} V_s - 0.7 \frac{50}{50+50//175}$$

$$= -\frac{25}{100} V_s - 0.7 \times \frac{50}{80} \qquad \frac{3.5}{8}$$

$$= -\frac{1}{4} V_s - 0.4375$$

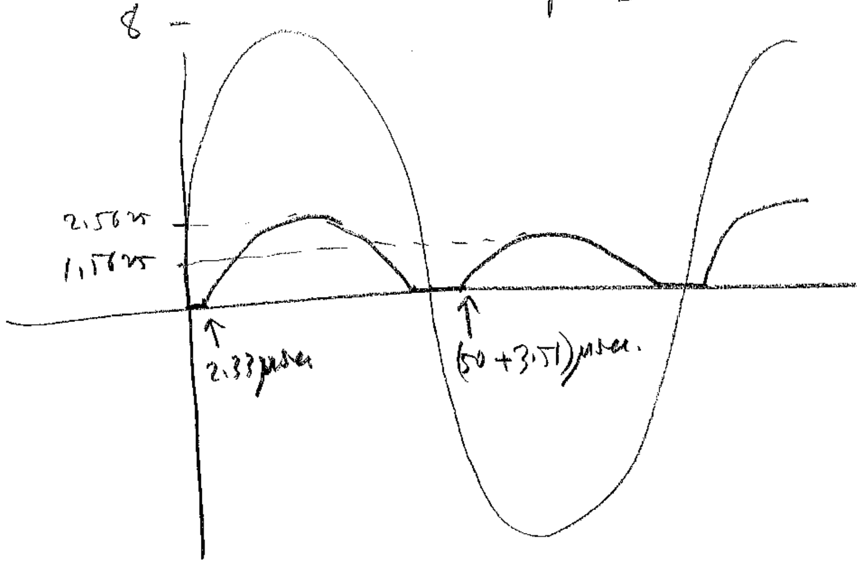


If we start time at the beginning of $-$ve cycle

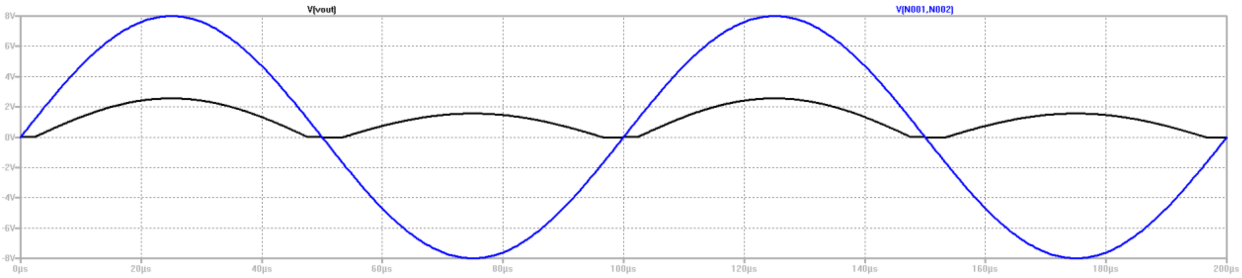
$$V_{out}(t) = -\frac{1}{4}(-8 \sin \omega t) - 0.475$$

$$= 2 \sin \omega t - 0.4375$$

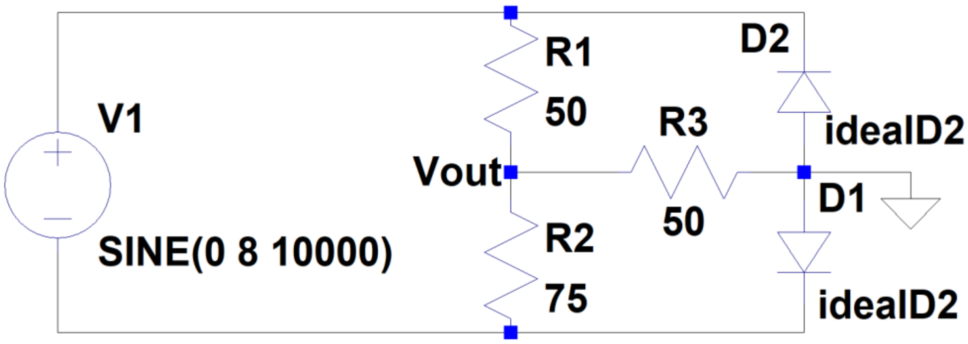
$$V_{out\,peak} = 1.5625$$



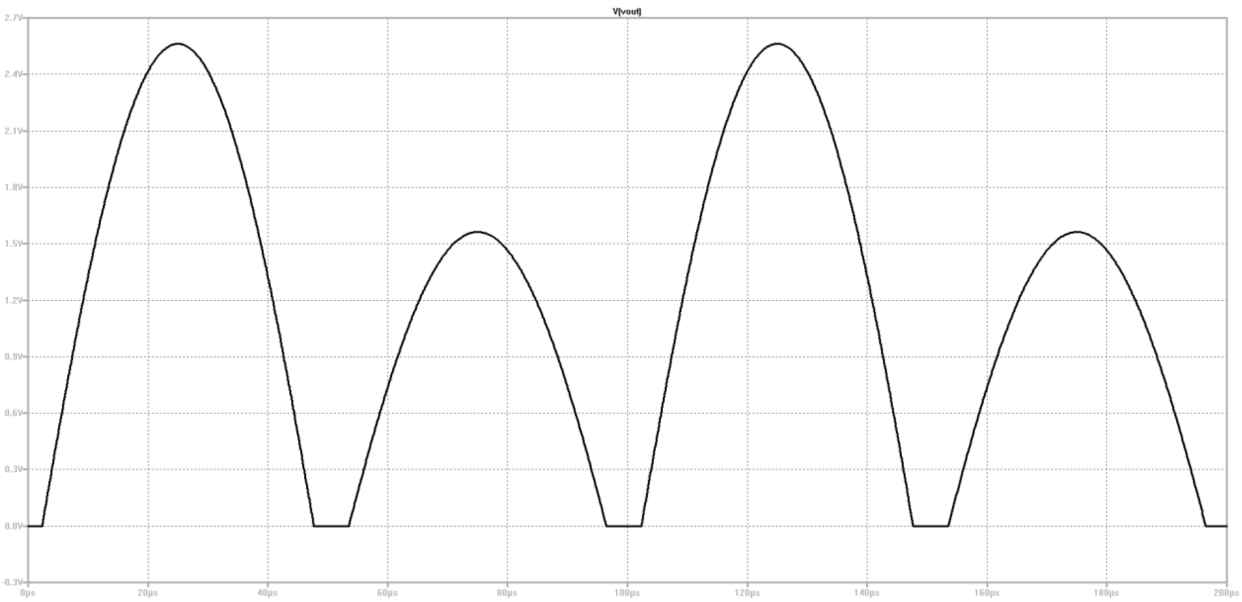
Although not required, we have also solved the problem Q3 using LTSpice and the results are the same



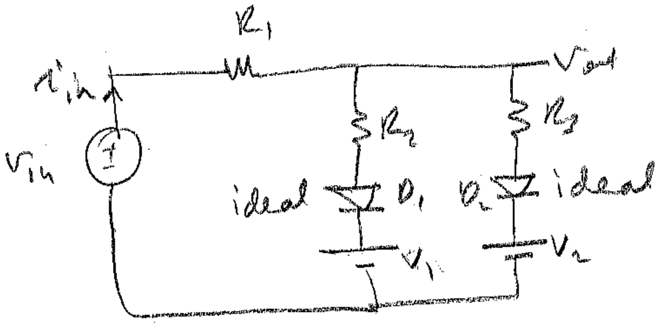
.model idealD D(Ron=0.1n Roff=10G Vfwd=0.6)
.model idealD2 D(n=0.0001 Vfwd=0.7)



.tran 0 0.2m 0 0.00001m



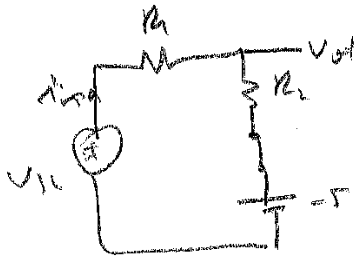
Q4 solution



Let us take $V_1 = -5$ and V_2 larger. Then

for $v_{in} < -5$, $i_{in} = 0$

For $v_{in} > -5$, D_1 is ON



$i_{in} = \frac{v_{in} - (-5)}{R_1+R_2} = \frac{v_{in}}{R_1+R_2} + \frac{5}{R_1+R_2}$

slope $\frac{1}{R_1+R_2} = \frac{3.75}{13.75-(-5)} = \frac{3.75}{18.75} = \frac{1}{5}$

$\Rightarrow \boxed{R_1 + R_2 = 5k}$ $\quad i_{in} = \frac{v_{in}}{5} + 1$

$V_{out} = i_{in} \times R_2 - 5$

When V_{out} reaches V_2 then D_2 also turns on and this is the 2nd break point. At ~~this point $i_{in} = 3.75$ mA~~

and $V_{out} = 3.75 \times R_2 - 5 = V_2$

After this point R_3 comes in and changes the slope.

So let us design until this point.

Since $R_1 + R_2 = 5$ let us take $\boxed{R_1 = 1k \text{ and } R_2 = 4k}$.

Then $3.75 \times 4 - 5 = V_2 = 15 - 5 = 10$ v. $\boxed{V_2 = 10V}$

After the breakpoint slope becomes

$\frac{1}{R_1 + R_2 // R_3} = \frac{6 - 3.75}{19 - 13.75} = \frac{2.25}{5.25} = \frac{9}{21}$

$\frac{1}{1 + 4 // R_3} = \frac{9}{21} = \frac{1}{1 + \frac{4R_3}{4+R_3}} = \frac{4 + R_3}{4 + R_3 + 4R_3} = \frac{4 + R_3}{4 + 5R_3} = \frac{9}{21}$

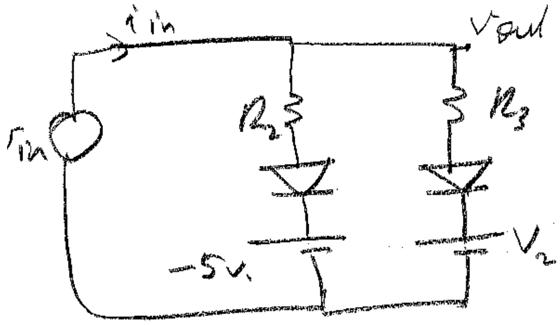
$36 + 45R_3 = 84 + 21R_3$

$24R_3 = 48 \quad \boxed{R_3 = 2K}$

Q4 solution continued

Alternative solution.

As you may have noticed $R_1 + R_2 = 5$ and we have many choices. Let us take $R_1 = 0$ and $R_2 = 5$



When V_{out} reaches V_2 then R_3 branch comes in and the slope becomes $\frac{1}{R_2 // R_3}$

Therefore we take $V_2 = 13.75$

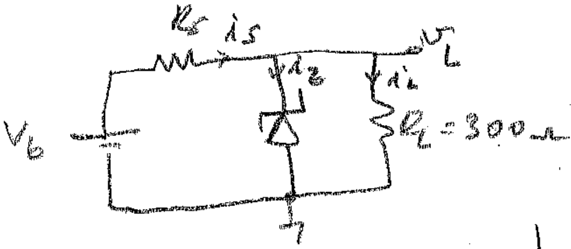
and $\frac{1}{R_2 // R_3} = \frac{9}{21}$ $\quad \frac{R_2 + R_3}{R_2 R_3} = \frac{9}{21}$ $\quad \frac{5 + R_3}{5 R_3} = \frac{9}{21}$

$105 + 21 R_3 = 45 R_3$

$105 = 24 R_3$

$R_3 = \frac{105}{24} = 4.375\ k\Omega$

Q5 solution



a) $r_z = 0$

$$i_{z_{min}} = \frac{10.8-9}{R_s} - \frac{9}{0.3} > 10\,mA$$

$$\frac{1.8}{R_s} > 10+30 \qquad R_s < \frac{1.8}{40} = 0.045\,k\Omega.$$

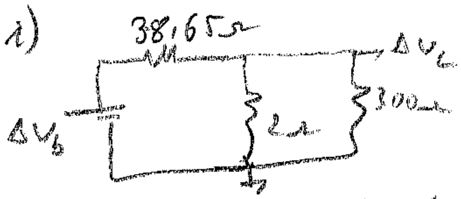
$$i_{z_{max}} = \frac{13.2-9}{R_s} - \frac{9}{0.3} = \frac{4.2}{R_s} - 30 < 100$$

$$\frac{4.2}{R_s} < 100+30 \qquad R_s > \frac{4.2}{130} = 0.0323\,k\Omega$$

$$32.3\,\Omega < R_s < 45\,\Omega.$$

b) $R_s = \frac{32.2+45}{2} = 38.65\,\Omega$

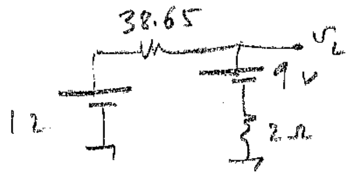
i)



$$2 // 300 = \frac{600}{302} = 1.987\,\Omega.$$

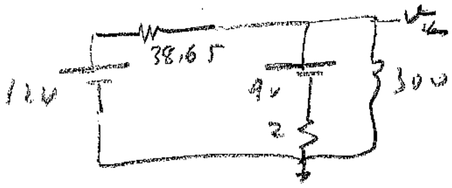
$$S.R. = \frac{\Delta V_L}{\Delta V_b}\times 100 = \frac{1.987}{1.987+38.65}\times 100 = 4.89\,\%$$

ii) No load condition:



$$V_L = \frac{2}{2+38.65}\times 12 + 9\times\frac{38.65}{38.65+2} = 0.59 + 8.557 = 9.147\ V.$$

Full load condition



$$= 12\times\frac{2//300}{2//300+38.65} + 9\times\frac{38.65//300}{38.65//300+2}$$

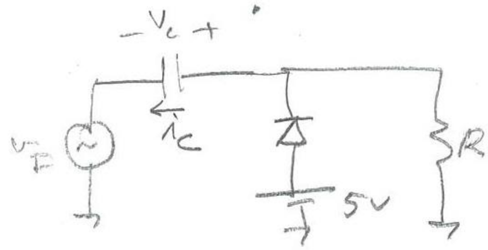
$$= 12\times\frac{1.987}{1.987+38.65} + 9\times\frac{34.24}{34.24+2}$$

$$= 0.5868 + 8.5033 = 9.09\ V.$$

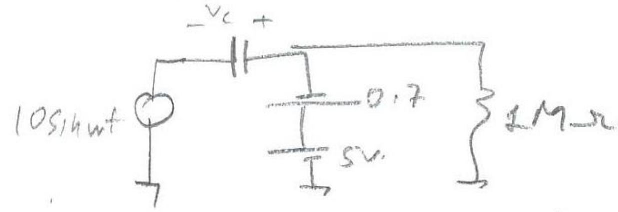
$$L.R. = \frac{9.147-9.09}{9.09}\times 100$$

$$= 0.63\,\%$$

Q6 solution



a) During the charging of the capacitor



At time $t=0$ capacitor charges to $5-0.7-0 = 4.3$ V immediately with ∞ current. During to numerical approximations LTSpice finds it to be 4.2 KA.

→ Later on capacitor charges again when V_I becomes less than zero and the formula for capacitor voltage becomes

$V_C(t) = -0.7+5-(-10\sin\omega t)$ (by taking $v_I=0$ as the time $t=0$)

At the peak V_C becomes $15-0.7 = 14.3$ V.

During this time $i_C = C\frac{d}{dt}V_C = C\times 10\omega\cos\omega t$

and $i_{C\,peak} = C\times 10\omega = 10^{-6}\times 10\times 100\pi$
$= 3.14\times 10^{-3} = 3.14$ mA

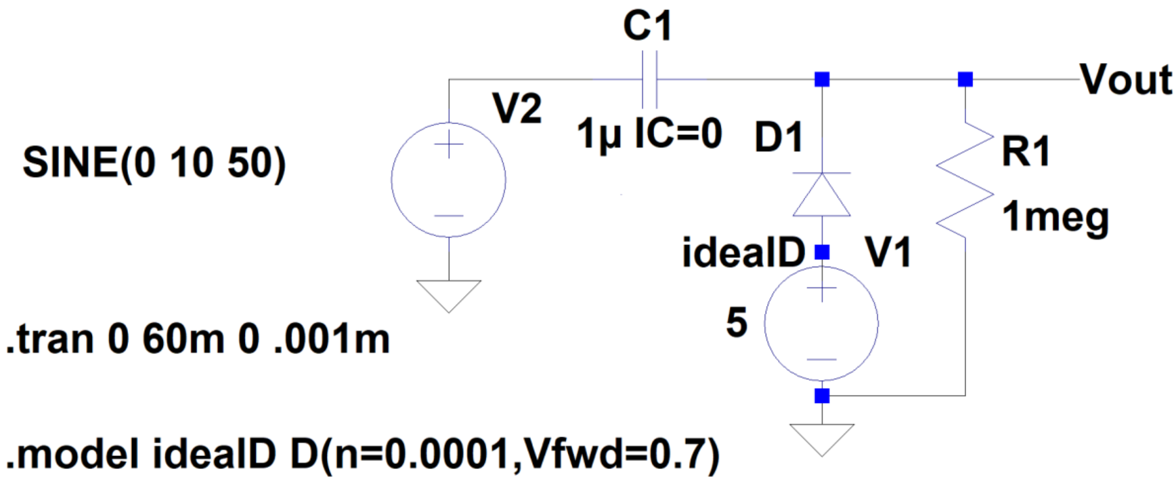
LTSpice notes

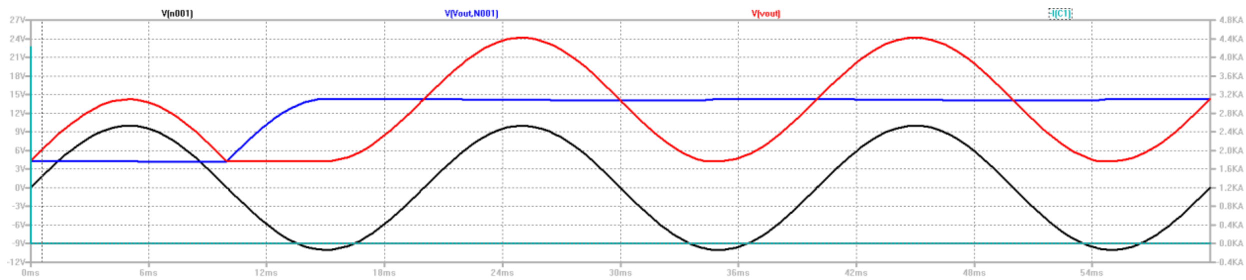
(Please pay attention on the polarities for V_c and i_c we have shown on the circuit above)

Note: In specifying the value of the capacitor we write 1μF IC=0 to also specify that the initial value of the capacitor voltage is 0 volts.

Q6 LTSpice results are given below:

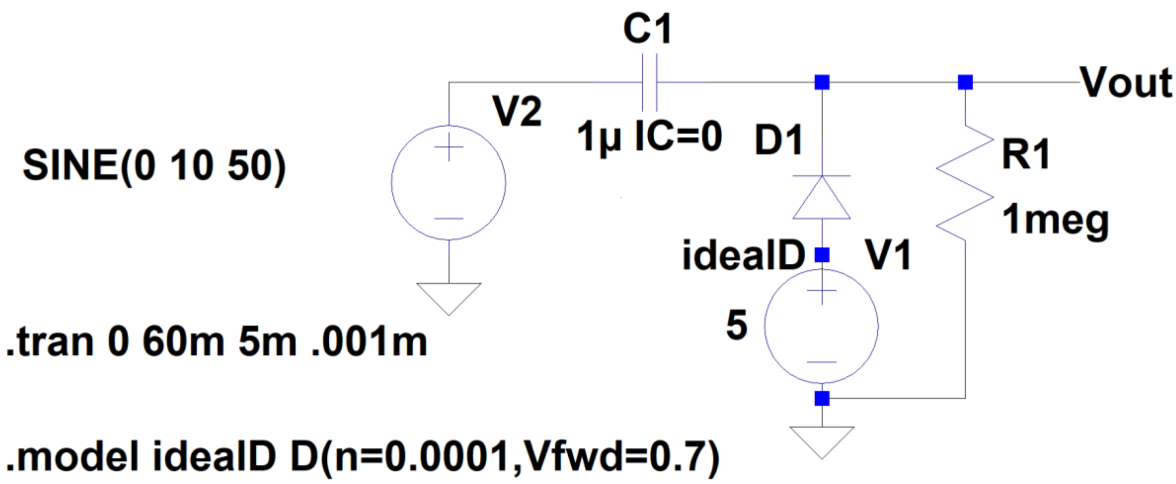
a)

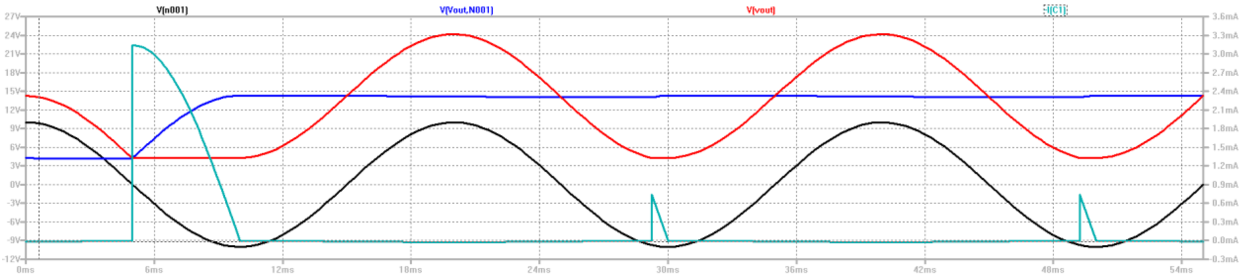




In the figure drawn above the capacitor current is very very large at time t=0.

To see the current at later times we must decrease the scale . To achive this we plot the graph starting from t=5msec which is shown below.





Now the peak current during the second time charging is about 3.14 mA as expected. Later due to discharge throug the rsistor the cap must recharged at every cycle and the peak current is 737 microA.

b)

When the capacitor is made 100Mohms the peak current at later cycles becomes 74 microA as shown below because ripple on the capacitor is less. Other results are very close.