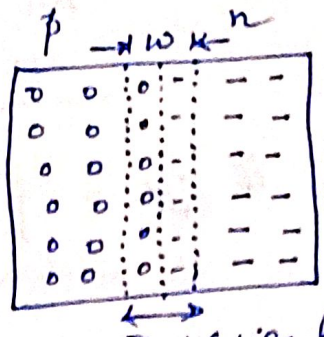
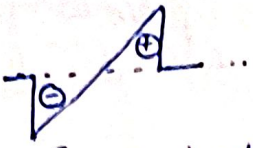
1. P-N Junction diode :-

Open circuit pn junction :



Alloy type junction



Grown junction type

Depletion Region / Space Charge Region.

Mobile charge carriers → holes & electrons

Immobile charge carriers → donor ions & acceptor ions.

P-n junction formation techniques →

a) Alloy type junction
↓
$W \propto \sqrt{V_j}$
↓
step graded junction
↓
sudden change or abrupt change

b) Grown junction type
↓
$W \propto \sqrt[3]{V_j}$
↓
linearly graded junction
↓
diffused type

V_0 or V_j or V_γ → Barrier potential / Built in voltage / Cut in voltage / Contact potential / Depletion voltage / Space charge voltage / Transition voltage.

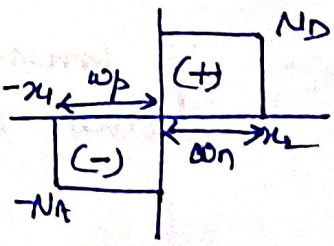
→ Electric field will be more concentrated in the junction area.

Barrier potential, $V_0 = \frac{KT}{q} \ln\left[\frac{N_A \cdot N_D}{n_i^2}\right]$ eV.

→ Formulas based on open circuit pn junction :

Net charge densities = 0

Positive charge densities = Negative charge densities



$$q N_D w_n = q N_A w_p$$

$$\boxed{\frac{N_D}{N_A} = \frac{w_p}{w_n}} \longrightarrow \text{Neutrality concept}$$

Also $E_0 = \left| q \frac{N_D w}{\epsilon} \right| = \left| q \frac{N_A w}{\epsilon} \right|$

E_0 : Energy of $\bar{e}$

& $V_0 = \left| \frac{q N_D w^2}{2\epsilon} \right| = \left| \frac{q N_A w^2}{2\epsilon} \right|$

so $\boxed{w \propto \sqrt{V_0}}$

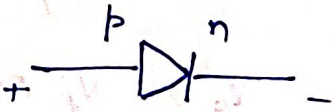
→ When the material is lightly doped, the penetration of depletion region will be more.

→ When the material is heavily doped, the penetration of depletion region will be less.

→ Width of depletion region, $w = \left[\frac{2\epsilon_0 \epsilon_r V_j}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) \right]^{1/2}$

$$w_n = \left[\frac{2\epsilon_0 \epsilon_r V_j}{q} \cdot \frac{1}{N_D} \right]^{1/2}$$

$$w_p = \left[\frac{2\epsilon_0 \epsilon_r V_j}{q} \cdot \frac{1}{N_A} \right]^{1/2}$$



Symbol of diode

Bias in pn junction diode :- There are two type of bias

a) Forward bias b) Reverse bias.

a) Forward bias → p terminal is connected to +ve terminal of battery & n terminal is connected to -ve terminal of battery.

→ If forward bias voltage, V_f > Barrier potential, V_0 then current conduction is possible.

→ Current is possible due to majority carriers & current is zero due to minority carriers.

→ Depletion region becomes narrower.

→ Resistance offered by diode is low.

b) Reverse bias → p terminal is connected to -ve terminal & n terminal is connected to +ve terminal of battery.

→ Current is possible due to minority carriers & zero due to majority carriers.

→ Depletion region becomes wider.

→ Resistance offered by diode is very high in MΩ.

<u>Diode current equation</u> :-

$$I = I_0 \left(e^{(V/\eta V_T)} - 1\right)$$

where I = Total current through diode

I_0 = Reverse saturation current

V = Applied voltage [+ve for FB, -ve for RB]

V_T = Thermal voltage

$= \frac{T}{11600}$ (At 300K, $V_T = 26\,mV$)

η = Idealised factor

= 1 (Ge)

= 2 (Si)

Diode current equation is also called as V-I characteristic equation.

V-I characteristics of p-n diode :-

$$I = I_0 \, e^{\left[\left(V/\eta V_T\right) - 1\right]}$$

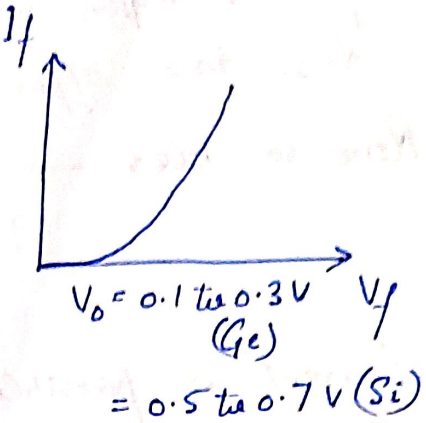
Case 1: Forward Bias

$V \rightarrow +ve$

$$I = I_0 \, e^{\left[V/\eta V_T - 1\right]}$$

$$e^{V/\eta V_T} >> 1$$

$$\therefore \; I = I_0 \, e^{V/\eta V_T}$$



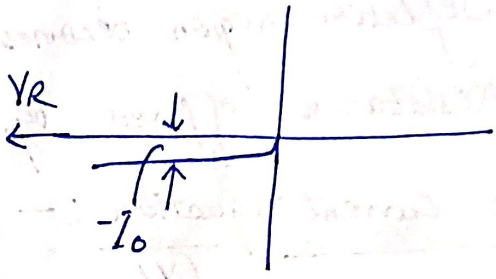
Case 2:- Reverse Bias

$V \rightarrow -ve$

$$I = I_0 \, e^{\left[-V/\eta V_T - 1\right]}$$

$$e^{-V/\eta V_T} << 1$$

$$I = -I_0$$



→ For every 10°C rise in temperature, I_0 will double.

Applied Voltage vs Temperature :

$$\cancel{\frac{dV}{dt}} \quad \frac{dV}{dT} = -2.5 \, mV/°C$$

$$I = I_0 \left[e^{\frac{V}{\eta V_T}} - 1\right]$$

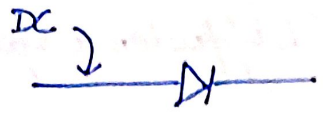
In case of Forward Bias

$$I = I_0 \, e^{V/\eta V_T}$$

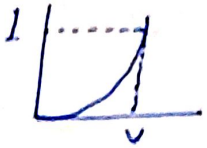
$$V = \eta V_T \ln\left[\frac{I}{I_0}\right]$$

Diode Resistance :

a) Static Resistance

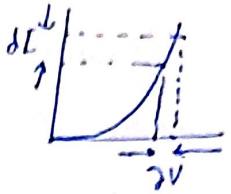


$R = \frac{V}{I}$



b) Dynamic Resistance

$r = \frac{\partial V}{\partial I}$



a) Static Resistance : $R = \frac{V}{I}$

in case of forward bias $R = \frac{V}{I} = \frac{0.7V}{100mA} = 7\Omega$

in case of reverse bias $R = \frac{10V}{1\mu A} = 10M\Omega$

b) Dynamic Resistance : $r = \frac{\Delta V}{\Delta I}$

$$g = \frac{\Delta I}{\Delta V} = \frac{\partial I_0 \cdot \left(e^{\frac{V}{\eta V_T}} - 1\right)}{\partial V}$$

$$= \frac{I_0 \cdot e^{\frac{V}{\eta V_T}}}{\eta V_T}$$

$$\boxed{g = \frac{I + I_0}{\eta V_T}}$$

In case of forward bias $g = \frac{I}{\eta V_T}$

Typically $\eta = 1$, $I = 100mA$, $V_T = 26mV$

$g > 1$

$r \rightarrow$ less

In case of reverse bias

$g = \frac{2I_0}{\eta V_T} < 1$

$r \rightarrow$ high.

Junction Capacitance : a) Transition Capacitance (R.B.)
b) Diffusion Capacitance (F.B.)

→ Transition means depletion region which exists only in reverse bias.

→ Diffusion is the process which occurs in forward bias because of negligible depletion region.

a) Transition Capacitance (C_T) : The rate of change of immobile charge in the depletion region with the applied reverse bias voltage is a capacitive effect called as Transition capacitance.

$$C_T = \frac{\epsilon A}{W}$$

where A = Area of depletion region
W = Width of depletion region.

In case of open circuit

$W \propto \sqrt{V_j}$ → Alloy type

$W \propto \sqrt[3]{V_j}$ → Grown junction

Hence $C_T \propto \frac{1}{\sqrt{V_j}}$ & $C_T \propto \frac{1}{\sqrt[3]{V_j}}$

b) Diffusion Capacitance (C_D) :- The rate of change of injected minority carrier charge with the applied forward bias voltage is a capacitive effect called as diffusion capacitance.

$$C_D = \frac{dQ}{dV}$$

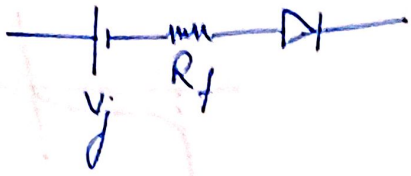
& $Q = I \times t$

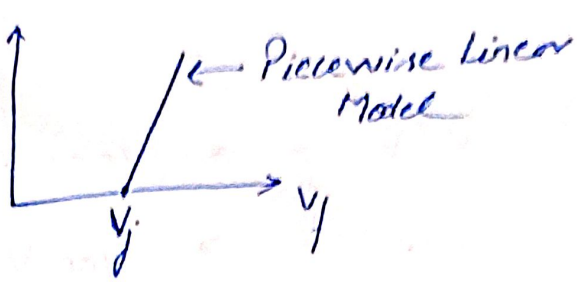
$$\therefore C_D = \frac{I \times t}{V}$$

Diode Equivalent Models:

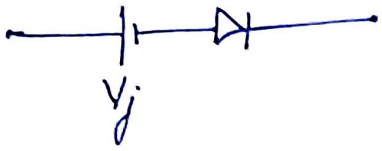
$V_f \geq V_j + I_f R_f$

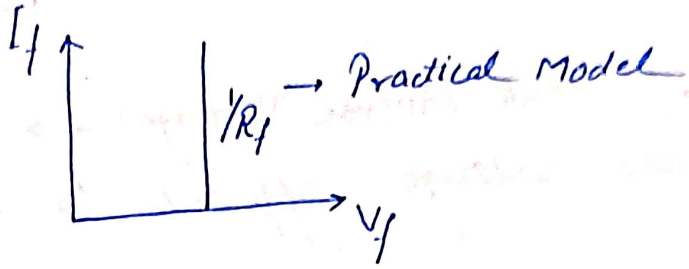
Case 1: R_f = Constant





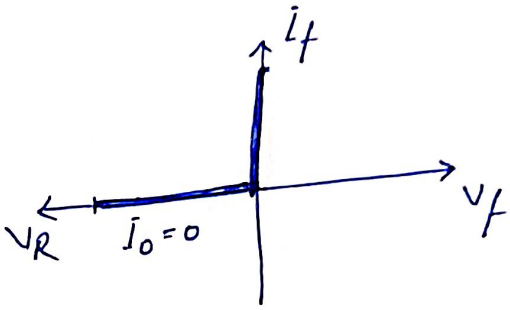
Case 2: $R_f = 0$





Case 3: Ideal model

$V_j = 0 \quad R_f = 0$



Diode switching times:

a) Reverse recovery time, t_{rr} → Time taken for a diode to change from forward biased mode to reverse biased mode. Practically, it will be in the order of μs.

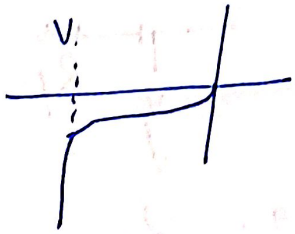
b) Forward recovery time, t_{fr} → Time taken for a diode to change from reverse biased mode to forward biased mode. It is of order of pico seconds.

→ In high frequency applications, forward recovery time is neglected in the analysis but reverse recovery time becomes a serious problem.

Q: Why Si is preferred over Ge in most of the applications.

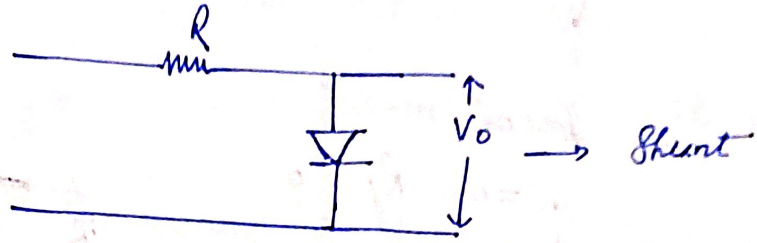
Ans: a) Temperature → 200°C (Si)
→ 100°C (Ge)

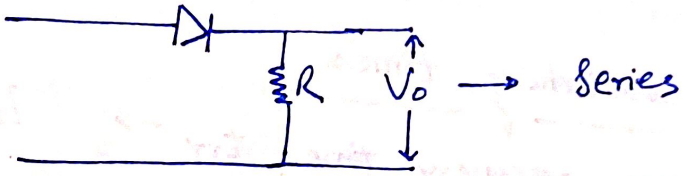
b) PIV → 1000 V (Si)
→ 400 V (Ge)



PIV (Peak Inverse Voltage) → It is the maximum reverse bias voltage applied to a diode.

Clippers :-

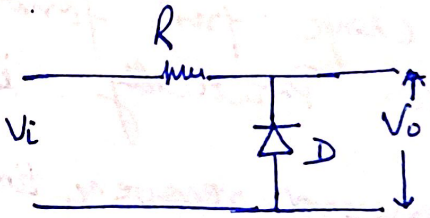




Shunt clippers :

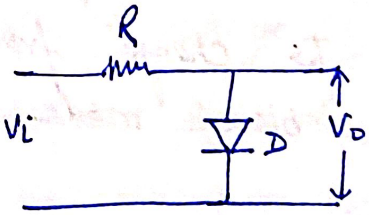
a) $V_i < 0$, $D \rightarrow ON \Rightarrow V_o = 0$

$V_i > 0$, $D \rightarrow OFF \Rightarrow V_o = V_i$



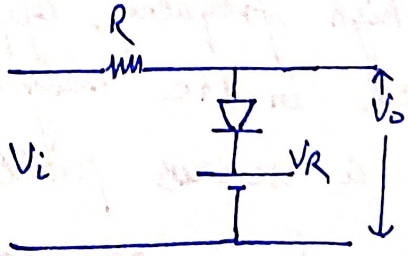
b) $V_i < 0$, $D \rightarrow ON \Rightarrow V_o = V_i$

$V_i > 0$, $D \rightarrow OFF \Rightarrow V_o = 0$



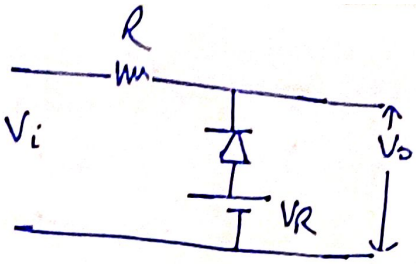
c) $V_i < V_R$, $D \rightarrow OFF$, $V_o = V_i$

$V_i > V_R$, $D \rightarrow ON$, $V_o = +V_R$



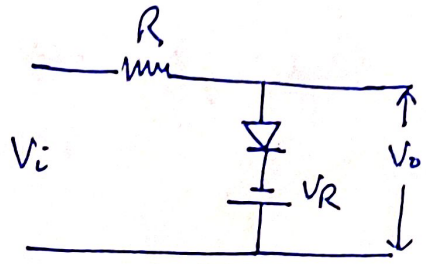
d) $V_i < V_R$, $D \rightarrow ON$ $V_o = V_R$

$V_i > V_R$, $D \rightarrow OFF$ $V_o = V_i$



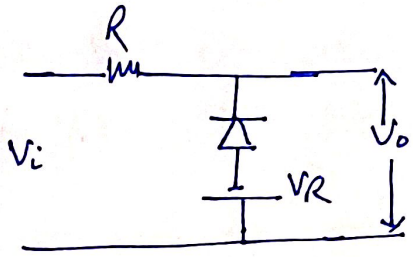
e) $V_i < -V_R$, $D \rightarrow OFF$ $V_o = V_i$

$V_i > -V_R$, $D \rightarrow ON$ $V_o = -V_R$



f) $V_i < -V_R$ $D \rightarrow ON$ $V_o = -V_R$

$V_i > -V_R$ $D \rightarrow OFF$ $V_o = V_i$



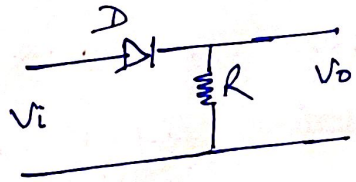
Conclusion: i) When diode is in downword direction, the signal is transmitted below reference voltage

ii) When diode is in upward direction, signal is transmitted above reference voltage.

Series clippers :-

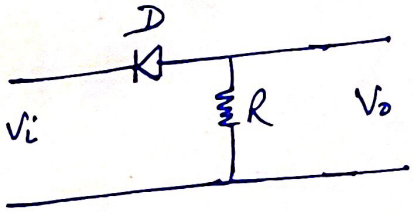
a) $V_i < 0$, $D \rightarrow OFF$ $V_o = 0$

$V_i > 0$, $D \rightarrow ON$ $V_o = V_i$



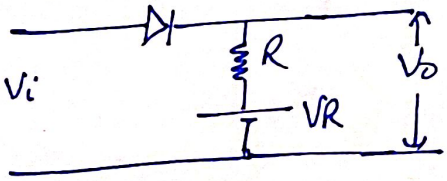
b) $V_i < 0$, $D \rightarrow ON$ $V_o = V_i$

$V_i > 0$, $D \rightarrow OFF$ $V_o = 0$

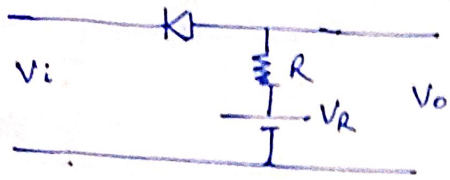


c) $V_i < V_R$ $D \rightarrow OFF$ $V_o = 0$

$V_i > V_R$, $D \rightarrow ON$ $V_o = V_i$



d)

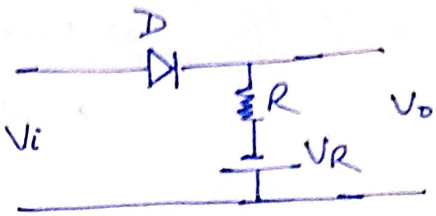


$V_i > V_R$, D → OFF $V_o = V_R$

$V_i < V_R$, D → ON $V_o = V_i$

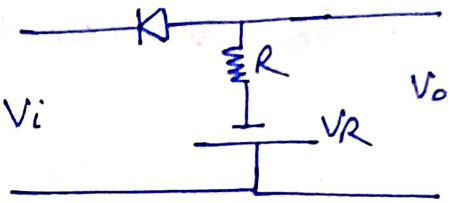
e) $V_i > -V_R$, D → ON, $V_o = V_i$

$V_i < -V_R$ D → OFF $V_o = -V_R$



f) $V_i > -V_R$ D → OFF $V_o = -V_R$

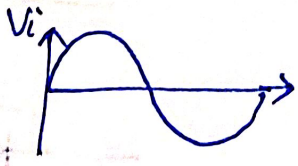
$V_i < -V_R$ D → ON $V_o = V_i$



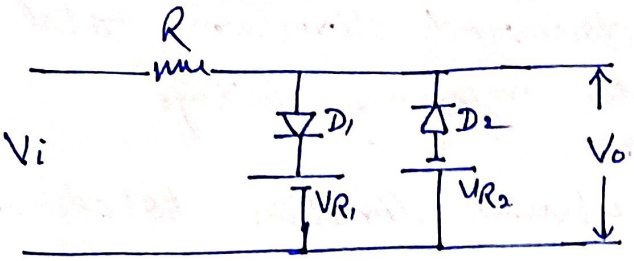
Conclusion: i) When diode is in forward direction to the I/P signal, signal is transmitted above the reference voltage.

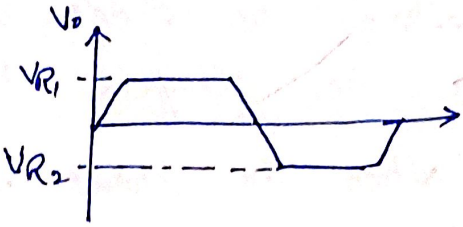
ii) When diode is in reverse direction to the I/P signal, signal is transmitted below the reference voltage.

d: Draw the output waveforms of all the shunt & series clipper circuits considering input as sine wave. ⇒

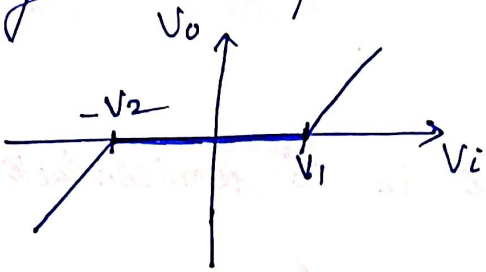


Clipping at two independent levels:





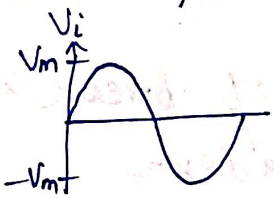
Q: Design a clipping circuit for the transfer curve shown below:

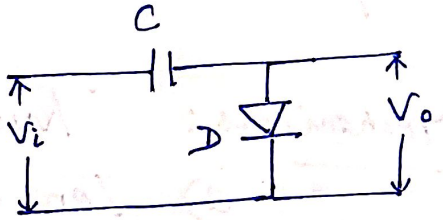


Clamper Circuits

a) Negative clamper:

Input →



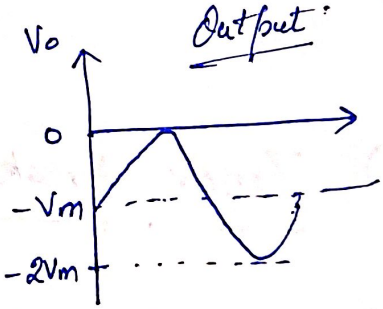


for $V_i = V_m \Rightarrow V_o = 0$

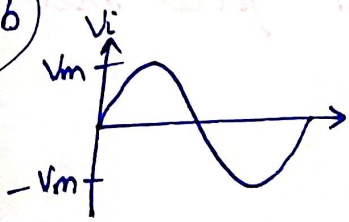
for $V_i = 0 \Rightarrow V_o = -V_m$

for $V_i = -V_m \Rightarrow V_o = -2V_m$

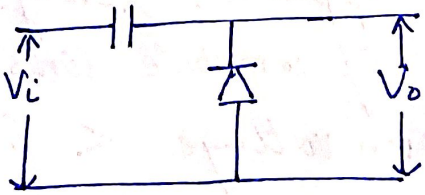
Output:

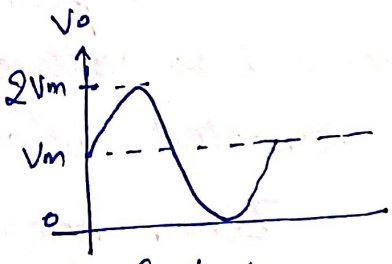


b)



Input





Output.

for $V_i = V_m \Rightarrow V_o = 2V_m$

for $V_i = 0 \Rightarrow V_o = V_m$

for $V_i = -V_m \Rightarrow V_o = 0$

Conclusion:

1) When the diode is in downward direction, total signal will be clamped below the reference voltage.

2) When the diode is in upward direction, total signal will be clamped above the reference voltage.

Special diodes:

If 1 impurity is present in 10^8 semiconductor atoms ⇒ Ordinary diode.

If 1 impurity is present in 10^6 semiconductor atoms ⇒ Zener diode

If 1 impurity is present in 10^3 semiconductor atoms ⇒ Tunnel diode.

Breakdown Mechanisms:

Two types of breakdown
a) Zener breakdown
b) Avalanche breakdown.

a) **Zener breakdown** → It occurs in a ~~a~~ heavily doped pn diode. Due to heavy doping, pn junction depletion region becomes narrower. When small reverse bias voltage is applied, strong electric field will be generated because of immobile ions.

Zener breakdown voltage < 6V.

b) **Avalanche breakdown** → It occurs in a lightly doped pn diode. This type of breakdown occurs because of the velocity of minority charge carriers colliding with stable atoms in the depletion region.

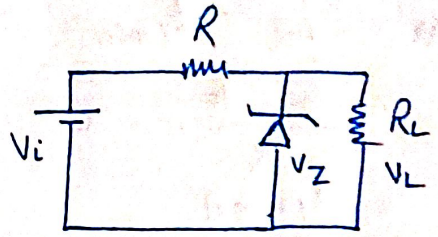
Avalanche breakdown voltage > 6V.

Temperature coefficient of Breakdown voltage :

a) Zener Breakdown → If temperature increases, breakdown voltage decreases (i.e. Negative temperature coefficient).

b) Avalanche Breakdown → If temperature increases, breakdown voltage increases (i.e. Positive temperature coefficient).

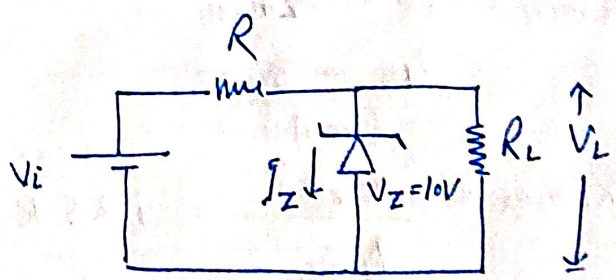
Zener diode as a Voltage Regulator :



1) V_i & R_L are fixed
2) V_i is fixed & R_L is variable
3) V_i is variable & R_L is fixed
4) V_i & R_L are variable.

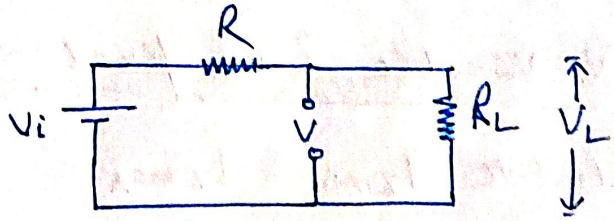
1) V_i & R_L are fixed :

Calculate V_L, I_Z & P_Z ?



Sol:

$$V = V_L = \frac{V_i \times R_L}{R + R_L}$$

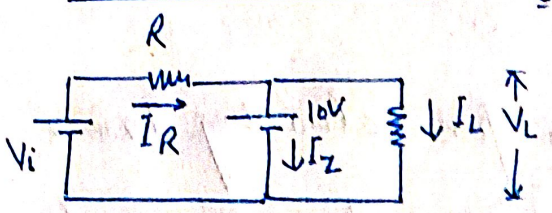


a) If $V > V_Z$

(i) $V_Z = V_L = 10V$

(ii) $I_Z = I_R - I_L$

$$= \frac{V_i - V_Z}{R} - \frac{V_Z}{R_L}$$



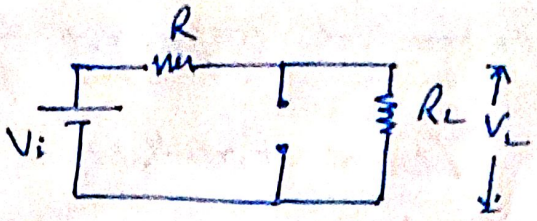
(iii) $P_Z = V_Z \cdot I_Z$

b) If $V < V_Z$

(i) $V_L = V$

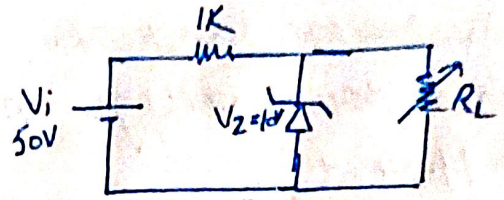
(ii) $I_Z = 0$

(iii) $P_Z = 0$



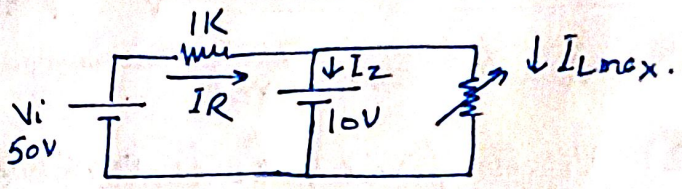
2) <u>Vi fixed & RL variable :</u>

Calculate R_{Lmin}, R_{Lmax}, I_{Lmin}, I_{Lmax}.



$I_{Zmin} = 0$

$I_{Zmax} = 32\,mA$.



$$I_{Lmax} = I_R - I_{Zmin}$$

$$= \frac{50-10}{1K} - 0$$

$$= 40\,mA$$

$$R_{Lmin} = \frac{V_Z}{I_{Lmax}} = \frac{10}{40\,mA} = 250\,\Omega$$

$$I_{Lmin} = I_R - I_{Zmax}$$

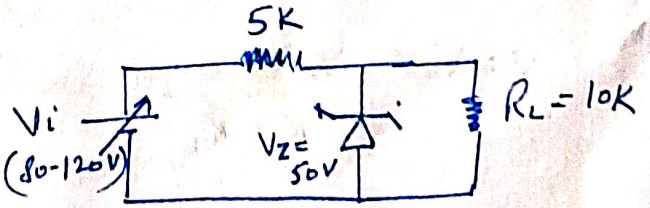
$$= 40 - 32m$$

$$= 8\,mA$$

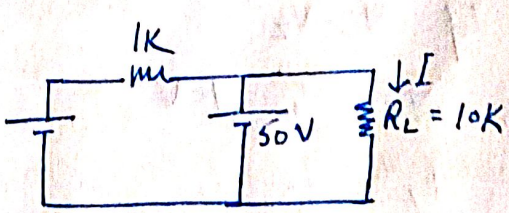
$$R_{Lmax} = \frac{V_Z}{I_{Lmin}} = 1.25\,K.$$

3) <u>Vi variable & RL fixed :-</u>

Calculate I_{Zmin} & I_{Zmax}.



~~I_{Zmax}~~, for calculating I_{Zmax}



$$I_{Rmax} = \frac{120-50}{5K} = \frac{70}{5} = 14\,mA$$

$$I = \frac{50}{10K} = 5\,mA$$

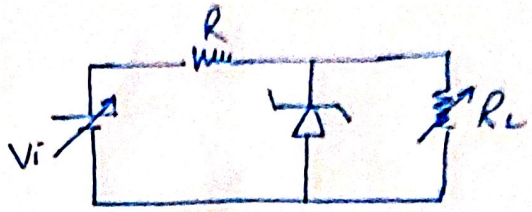
$$I_{Zmax} = 14 - 5 = \underline{9\,mA}$$

for calculating I_{Zmin}.

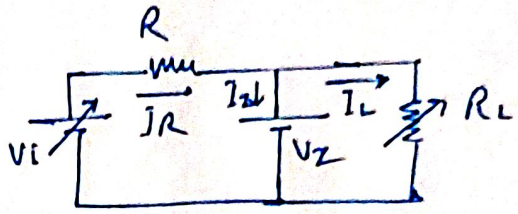
$$I_{Rmin} = \frac{80-50}{5K} = \frac{30}{5} = 6mA.$$

$$I_{Zmin} = 6-5 = 1mA$$

4. V_i & R_L are variable :



Calculate the dynamic range of series resistance R.



$$R_{min} = \frac{V_{imax} - V_Z}{I_{R(max)}}$$

$$R_{max} = \frac{V_{imin} - V_Z}{I_{R(min)}}$$

→ For variable problems in zener diode, we can have equation.

$$\frac{V_i - V_Z}{R} \geq I_Z + I_L$$

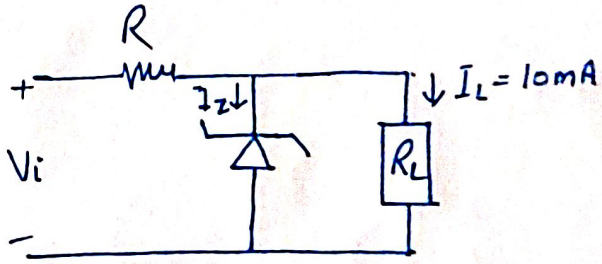
Q: Given,

$V_i = 30$ to $50V$

$I_L = 10mA$

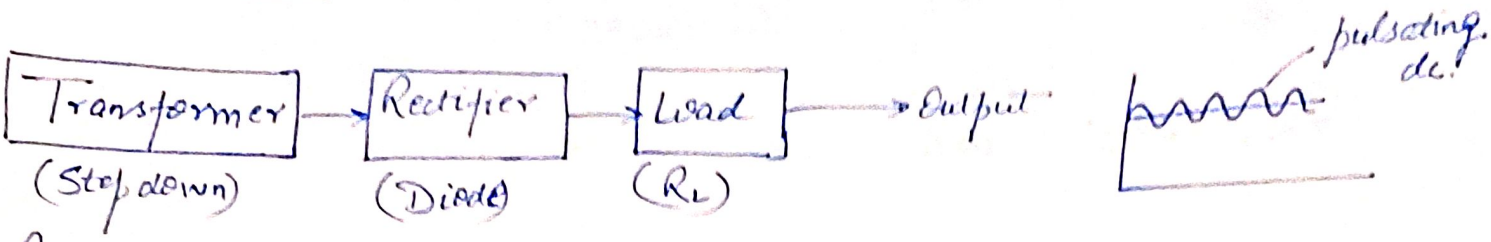
$V_Z = 10V$

$I_{Zmin} = 1mA$.



Calculate the value of dynamic range of series resistance R.

Rectifiers :

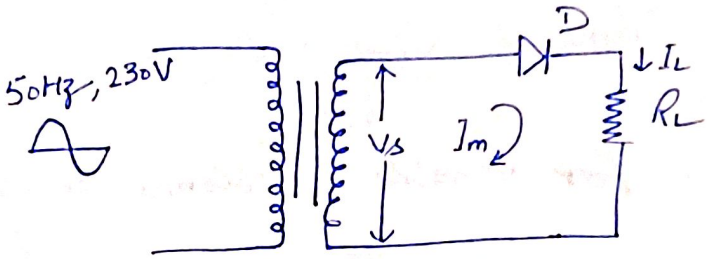


Rectifier is a circuit which converts AC to pulsating D.C.

Practical rectifier designs :

a) Half Wave rectifier
b) Full wave rectifier
c) Bridge rectifier.

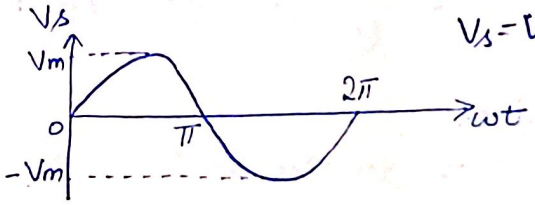
a) Half Wave Rectifier :



Rectifier parameters :

(i) Average current I_{dc}

$$I_{dc} = \frac{I_m}{\pi}$$

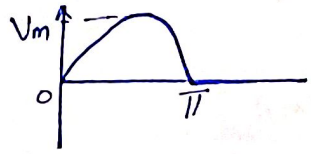


$V_s = V_m \sin\omega t$

(ii) DC output voltage V_{dc}

$$V_{dc} = I_{dc} \times R_L$$

$$V_{dc} = \frac{V_m}{\pi}$$



$V_o = V_m \sin\omega t$ for $0 < \omega t < \pi$

$= 0$ for $\pi < \omega t < 2\pi$

iii) RMS values :

$$I_{rms} = \frac{I_m}{2}$$

iv) Ripple factor

$$= \frac{\text{RMS of alternating component}}{\text{Average value}} = \frac{I_{rms}}{I_{dc}}$$

Ripple factor = 1.21

It shows that 121% of ac component is present in dc value.

v) Voltage Regulation :

$$\text{Percentage Voltage Regulation} = \frac{V_{dcNL} - V_{dcFL}}{V_{dcFL}} \times 100\%$$

where V_{dcNL} = DC voltage at No load

V_{dcFL} = DC voltage at Full load.

vi) Efficiency, $\eta = \frac{\text{DC power delivered to the load}}{\text{AC I/P power}}$

$\eta = 40.6\%$

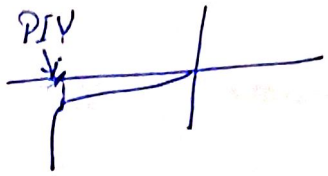
vii) Transformer Utilisation Factor :

$$TUF = \frac{\text{DC power delivered to load}}{\text{AC power}}$$

$TUF = 28\%$.

viii) Peak Inverse Voltage (PIV) : Maximum value a voltage can reach in reverse bias after which the current increases abruptly.

$PIV = V_m$

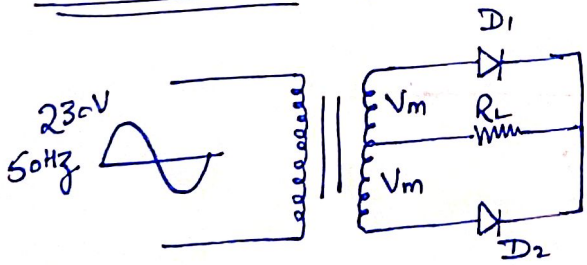


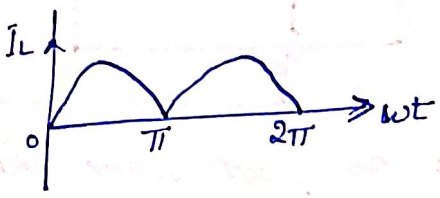
ix) Form factor :

$$= \frac{\cancel{RMS}}{\cancel{AC}} \quad \frac{\text{RMS value}}{\text{Average value}} = \pi/2.$$

x) Peak factor $= \frac{\text{Peak value}}{\text{RMS value}} = 2.$

Full wave Rectifier :





Rectifier parameters :

i) Average current I_{dc} : $I_{dc} = \frac{2I_m}{\pi}$

ii) DC output voltage : $V_{DC} = \frac{2V_m}{\pi}$

iii) RMS forms : $I_{rms} = \frac{I_m}{\sqrt{2}}$, $V_{rms} = \frac{V_m}{\sqrt{2}}$

iv) Ripple factor : R.F. = 48%.

v) Voltage Regulation : $\frac{V_{dcNL} - V_{dcFL}}{V_{dcFL}} \times 100\%$

vi) Efficiency / Rectification : $\eta = \frac{P_{dc}}{P_{ac}} = \frac{I_{dc}^2}{I_{rms}^2} = 81.2\%$

vii) Transformer Utilisation Factor :

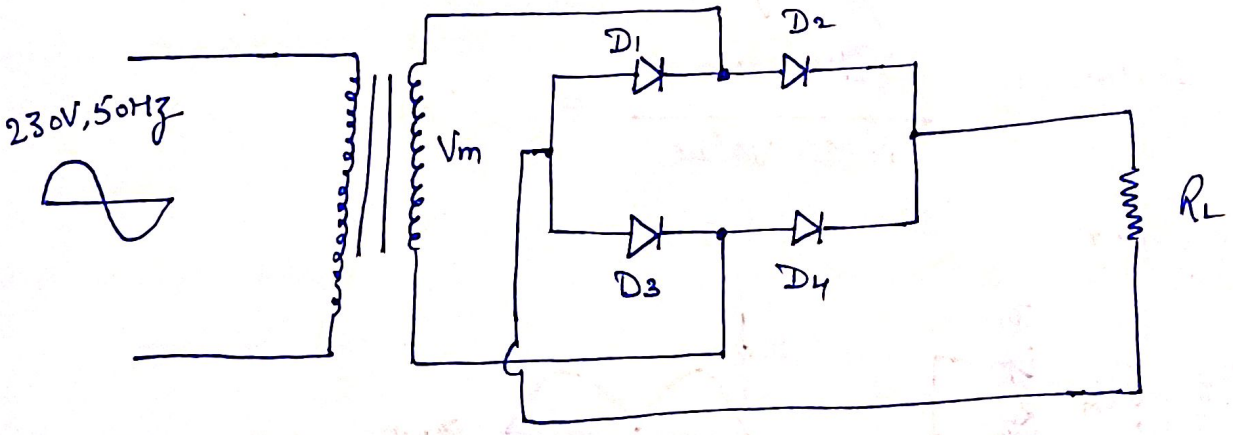
$TUF = 69.3\%$

viii) PIV $\longrightarrow$ $2V_m$

ix) Form factor : $F.F. = \frac{\text{RMS value}}{\text{Average value}} = \frac{\pi}{2\sqrt{2}}$

x) Peak factor : $P.F. = \frac{\text{Peak value}}{\text{RMS value}} = \sqrt{2}$

Bridge Rectifier :



Common parameters as Full Wave Rectifier:

$I_{dc} = \frac{2I_m}{\pi}$, $V_{dc} = \frac{2V_m}{\pi}$,

$I_{rms} = \frac{I_m}{\sqrt{2}}$, $V_{rms} = \frac{V_m}{\sqrt{2}}$

Ripple factor = 48%.

$\eta = 81.2\%$

Other Parameters:

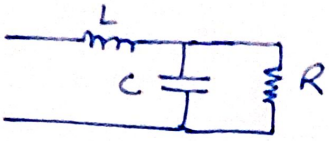
Transformer Utilisation Factor = 81.2 %.

Peak Inverse Voltage, PIV = V_m.

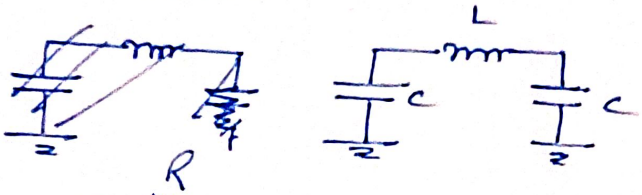
Filters: a) Capacitive filter

b) Inductive filter

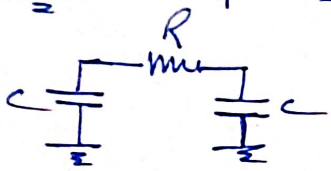
c) L section filter



d) π section filter



e) RC filter



a) Capacitive filters are used for heavier load applications. As the capacitor value increases, ripple factor decreases.

b) Inductive filter designs are used for lighter load applications. If the inductor value is more, ripple factor will be less.

c) L section filters are used for varying load applications.

d) The ripple factor of π section is better compared to L section filters.

e) The main drawback of π section filter is that it cannot be used for heavier load applications because of inductor.

In practical applications, inductor is more costlier, to reduce the cost, we replace inductor with resistor in RC filter.