Chapter 1:

Semiconductor Diode

Based on the electrical conductivity, all the materials in nature are classified as insulators, semiconductors and conductors.

Materials

- Insulators
- Semiconductors
- Conductors

Insulators

An insulator is a material that are characterized by poor electrical conductivity. For eg: Glass, quartz, rubber, porcelain, bakellite, mica etc. The resistivity level of an insulator is of the order of 10^{10} to $10^{12}\ \Omega$-m.

The energy band structure of an insulator is as shown below:

Band structure of a material defines the band of energy level that an electron can occupy. Valance band is the range of electron energy where the electron remain binded to the atom & do not contribute to the electric current.

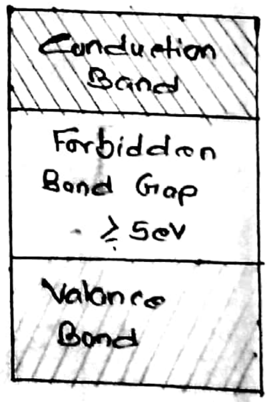


Fig: Energy Band structure of Insulator

Conduction band is the range of electron energies higher than valance band where e's are free to accelerate under the influence of external voltage source resulting flow of charge.

The energy band between the valance band & conduction band is called Forbidden band gap or Forbidden Energy Gap. It is the energy required by an e⁻ to move from Valance band to Conduction band.

$$1eV = 1.6 \times 10^{-19} J$$

There is a large Forbidden band gap $\geq 5eV$. Because of this large gap, there are very few e's in the Conduction Band & hence conductivity of insulator is poor. Even an increase in temperature or applied electric field is insufficient to transfer e's from VB to CB.

Conductors:

Conductor or conducting materials are good conductors of electricity and characterized by a large conductivity & small resistivity. For eg, Copper, Aluminium, Silver etc. The resistivity of conductors is in the range of $10^{-8}\ \Omega m$.

In a conductor, there is no forbidden energy gap between valance band & conduction band i.e. they overlap each other. Electrons randomly move through the solid. So electrons in the conductors are called free e's. Therefore at a room temperature when electric field is applied, an electric current flows through a conductor. The resistance of conductor increases with increase in temp.

Semi conductor

A semiconductor is a material that has its conductivity somewhere between the insulator & conductor. The resistivity of semiconductor material lies in the range of 10^{-5} to $10^{5}\ \Omega$-m

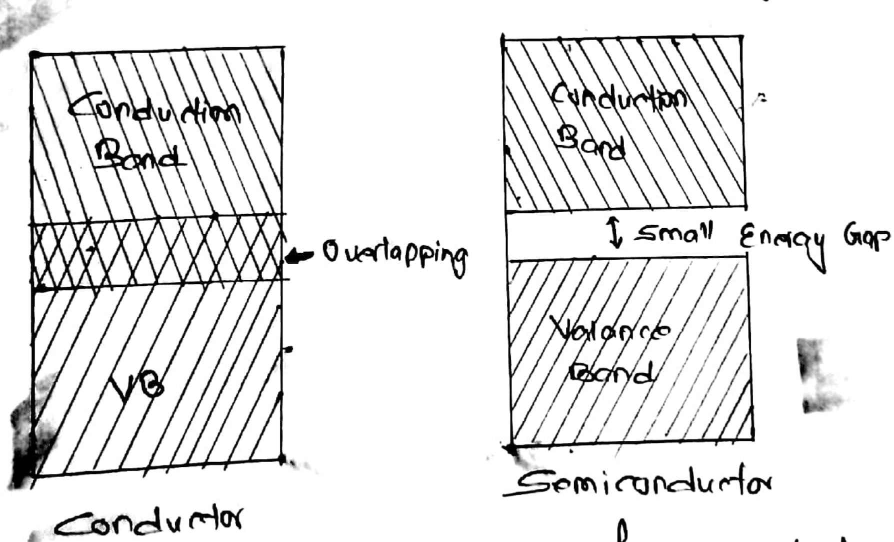


Fig: Energy Band diagrams for conductor and Semi conductors.

For eg, Silicon, Germanium etc. The Energy Gap for Si, Ge & GaAs is 1.21 eV, 0.785 eV & 1.42 eV respectively at absolute zero (i.e. zero kelvin or -273.16^{0}c). And at this temperature, the valance band e do not have sufficient energy to move from valance band to conduction band.

Thus semiconductor acts as Insulator at absolute zero. However at normal room temperature (25°c), some e⁻s can easily jump to conduction band due to low energy gap between valance band and conduction band. Thus semiconductors are capable of conducting small current even at normal room temperature. The resistance of semiconductor decreases with an increase in temperature.

Types of Semiconductor

The resistance of semiconductor decreases with an increase of temperature. i.e. tempr coefficient of resistance of semiconductor is negative. They behave like an insulator at very low temperature but act as conductor at high temperatures.

The mostly used semiconductors are Germanium (Ge) & Silicon (Si). Selenium (Se) & Tellurium (Te) are also a semiconductor.

Properties of Semiconductor (S/C)

1. The resistivity of s/c depends on illumination and decreases in bighter surroundings.
2. The resistivity of s/c depends on the magnitude of electric field.
3. S/C are non-linear elements.
4. The conductivity of s/c changes considerably when small amount of impurities added to it. So that its conductivity can be controlled.

There are 2 types of s/c

i) Intrinsic (pure) s/c
ii) Extrinsic (impure) s/c.

- Semiconductor
  - Intrinsic
  - Extrinsic
    - P-type
    - N-type

Intrinsic Semiconductor

An intrinsic s/c is the purest form of s/c. The impurity content is less than one part in 100 million parts of the intrinsic s/c. There are many s/c materials such as Germanium, Silicon, Selenium, Tellurium, Gallium Arsenide etc & among these Ge & Si are widely used in a s/c devices.

Production of holes & free electrons

Let us consider a structure of Silicon atom. Silicon atomic no. is 14 & has 4 valance electrons. These 4 e's are shared by 4 neighboring atoms in the crystal structure by means of covalent bond.

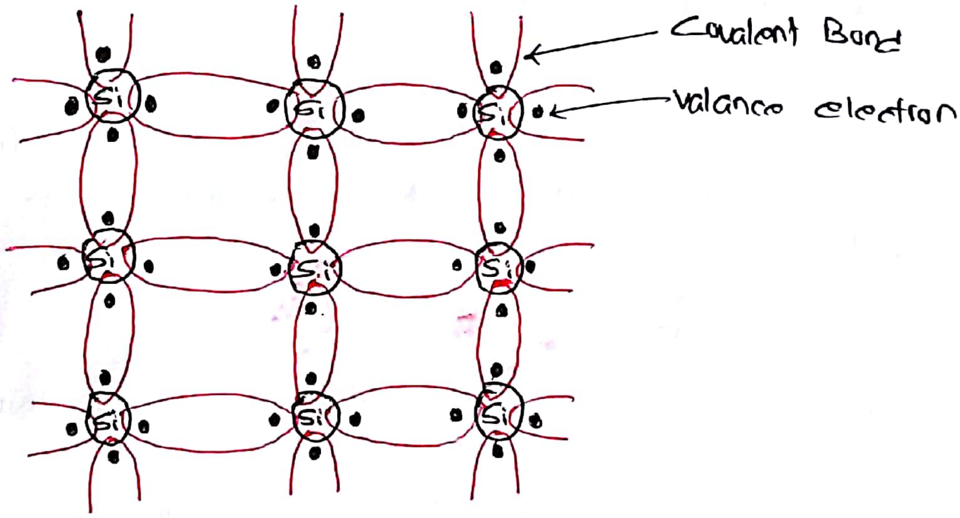


Fig: Crystal structure of Si at absolute zero (-273°c)

Above fig shows the crystal structure of Si at absolute zero temperature. Thus pure s/c acts as poor conductor (due to lack of free e's) at a low temperature or at absolute zero temperature.

At room temp, some of the covalent bonds break up. As a result, e's are released and move to the conduction band, are called free e's. The vacancy created in broken bond is called a Hole. Since hole is created after a removal of e⁻ from the covalent bond, it is considered as a positive charge.

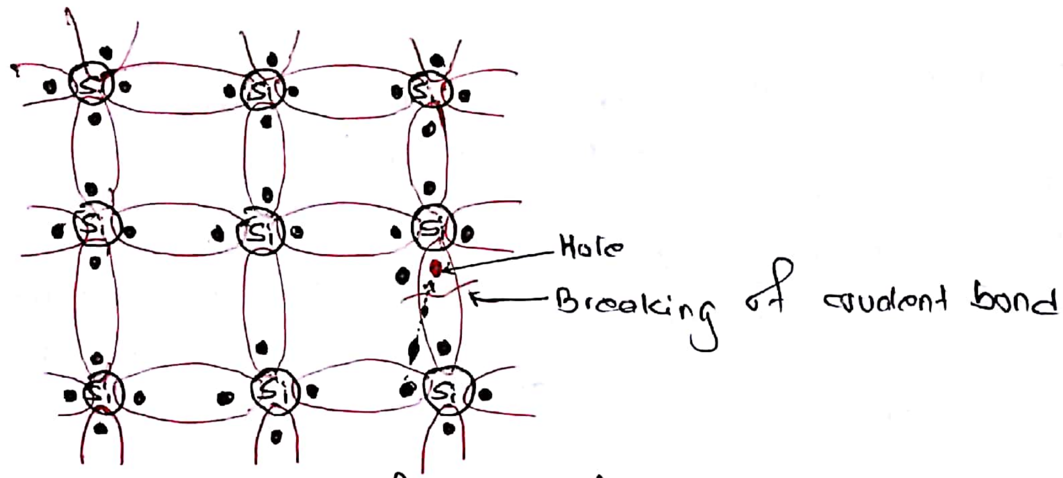


Fig: production of hole & free e⁻

Electrons & holes are created in pairs. When a free electron approaches the hole, it gets attracted and falls into the hole. This process of merging of free e⁻ & a hole is called recombination. During this process, both the free e's & hole disapper. However, an energy is released and causes another covalent bond to break-down & generate a new electron hole pair.

Conduction in Intrinsic Semiconductors

When an e's are released during the breakdown of covalent bonds, they move randomly through a crystal lattice. When an external electric field is applied to the pure intrinsic s/c, the free e's in the conduction band move towards the +ve terminal while holes move towards the -ve terminal of power supply (battery). As a result, an electric current flow. This current is very small.

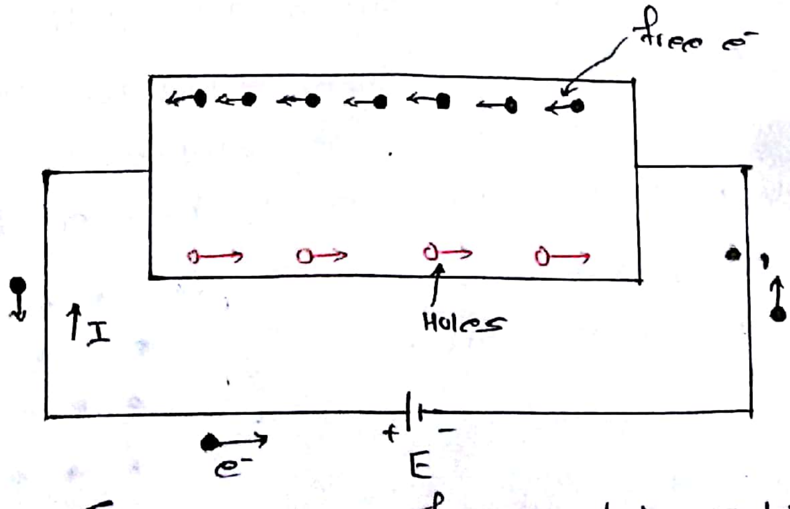


Fig: Conduction of current in Intrinsic s/c

Conduction in Semiconductor

S/C consists of 2 type of charge carriers: positive charge carriers called holes & negative charge carriers called electrons.

The movement of these charge carriers give rise to the flow of current in S/C. Thus we can say that S/C posses two types of current.

i) Electron current

ii) Hole current

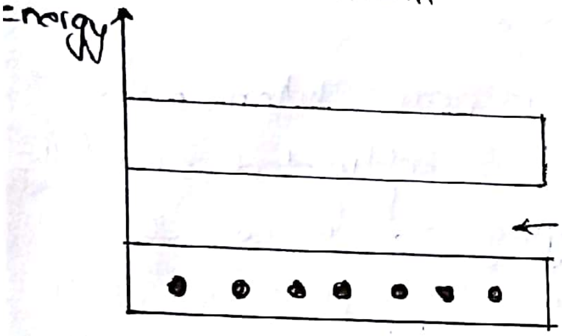


Fig: When no energy is applied.

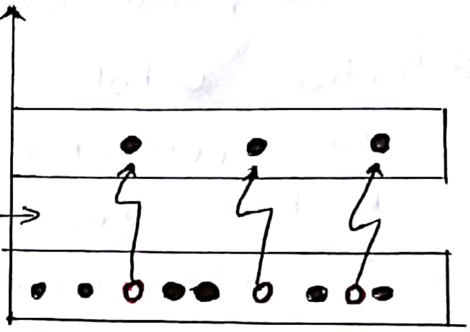


Fig: When energy is applied

i) Electron Current

When an energy is applied to a S/C, the valance e^- at valance band can gain sufficient energy and jumped to the conduction band and become free e^-s. The movement of these free e^-s gives rise to a electron current (I_e).

ii) Hole Current

When a valance e^- gain sufficient energy & jumped to conduction band, they leave a hole at the valance band. Further valance electrons can move through this hole. Thus relative motion of valance e^-s at valance band through holes give rise to hole current (I_h)

Thus, total current in a S/C is the sum of e^- current & hole current.

i.e. $I = I_e + I_h$

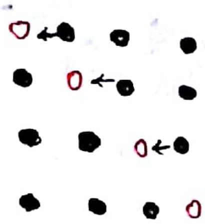


Fig: movement of hole

Extrinsic Semiconductor

An intrinsic s/c has very limited applications/significance as it conduct very small amount of current at room temperature. However, the electrical conductivity of intrinsic s/c can be increased significantly by adding small amount of impurity to it during a crystallization process. This process of adding an impurity to a pure s/c is called Doping and the resultant s/c formed is called extrinsic s/c. The amount of impurity added is 1 part in 10^6 atoms.

- There are 2 types of Extrinsic s/c
  1) N-type s/c
  2) P-type s/c

1) P-type Semiconductor

When a small amount of trivalent impurity such as aluminium, Gallium, Indium, Boron is added to a pure s/c, then P-type s/c is formed.

The crystal structure of P-type s/c is as shown below:

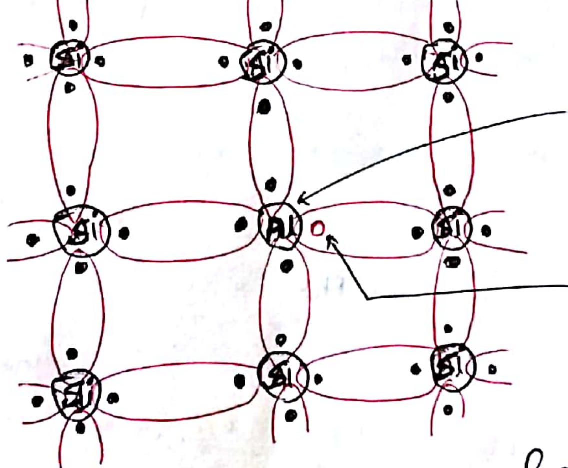


Fig: Crystal structure of P-type s/c

The 3 valance e⁻s of the trivalent impurity forms 3 covalent bonds with the neighboring atoms and a vacancy exists in the fourth bond giving rise to the holes, which can accept an electron. So, trivalent impurities are also called acceptor impurities or acceptor agents.

In P-type s/c, holes are majority carriers & e⁻s are minority carrers.

The energy band diagram of P-type s/c is

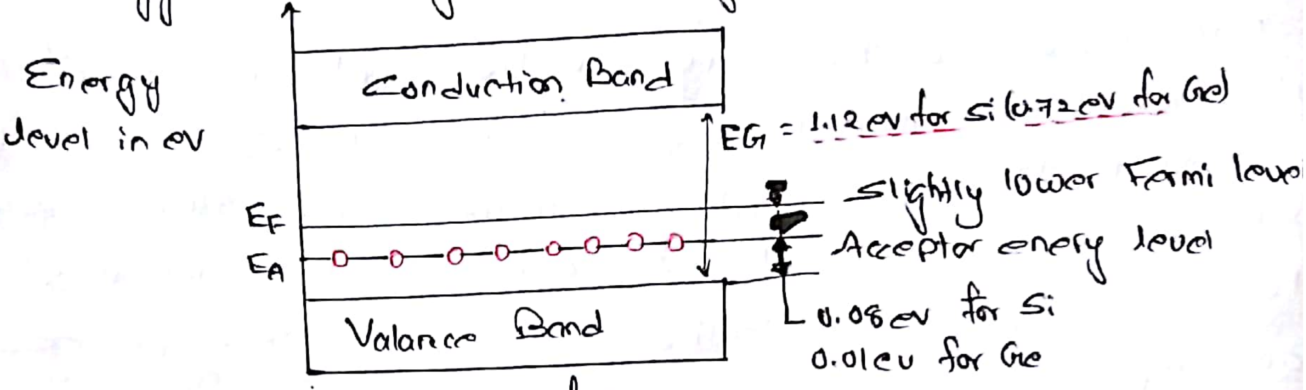


Fig: Energy band diagram of P-type s/c

A very small amount of energy (0.08 eV in case of Silicon & 0.01 eV in case of Germanium) is required for an e^- to leave the valance band and occupy the acceptor energy level, holes are created in the valance band by these electrons.

The holes so created constitute the larger number of carriers in the s/c materials.

2) **N-Type Semiconductor**

When a small amount of pentavalent impurity is added, such as Arsenic, Antimony, Bismuth, Phosphorous, to a pure s/c during crystalization process, the resulting crystal is called N-type s/c.

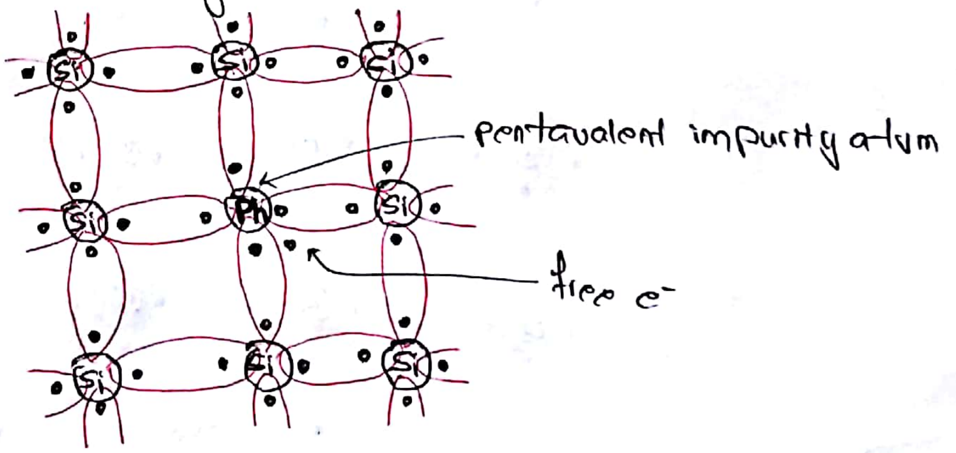


Fig: Crystal structure of N-type s/c

For each impurity added, one free e^- is generated, which then moves to conduction band. As the pentavalent impurity donates electron to crystal lattice, it is also called Donor impurity or donor agent. In N-type s/c, e^-s are majority charge carriers.

* Fermi Level is the highest energy state occupied by e^- in a material at absolute zero tempr.

The energy band diagram for N-type s/c is,

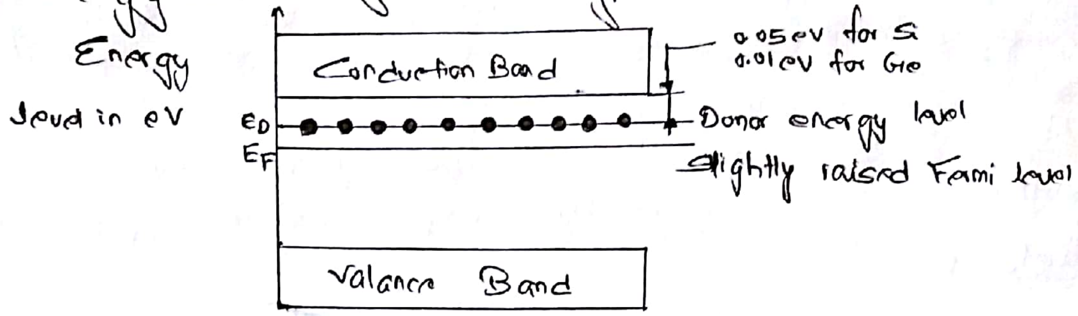


Fig: Energy band diagram for N-type s/c

Here, the energy required to detach the fifth e^- from the atom is only 0.05eV for silicon & 0.01 eV for Germanium. This energy is so small that at room temperature practically all such e^-s become free.

Conductivity of Semiconductor

In a pure s/c, the no. of holes is equal to the no. of electrons. Thermal agiation continue to produce new electron-hole pairs and e^--hole pairs disappear because of recombination. With each electron hole pair created, two charge carrying particles are formed. One is -ve which is free e^- with mobility μ_e (μ_n). The other is +ve, i.e. hole with mobility μ_h (μ_p).

[The e^- & hole move in opposite direction in an electric field E, but since they are of opposite sign, the current due to each is in the same direction.] Hence total current density J within the intrinsic s/c is given by,

$$J = J_e + J_h \qquad J = J_n + J_p$$

$$= qn\mu_e E + qp\mu_h E$$

$$J = (n\mu_e + p\mu_h)\, qE = \sigma E$$

* J = electric current per unit area of cross section = I/A

$= \frac{Ne}{AT} = \frac{NeL}{ATL}$ $\left(\because \frac{dq}{dt} = \frac{Ne}{T}\right)$

$= \frac{N}{AL} \cdot \frac{L}{T} \cdot e = nve$ $(\because n = \frac{N}{AL}$, L ← length

$= ne\mu E = nq\mu E$ $\quad v = \frac{L}{T}$ = drift velocity

$(\because v = \mu E)$

where, n = no. of e^-s per unit volume.

p = no. of holes " " "

q = charge of e^- or holes in Coulombs

E = applied electric field strength, V/m

Hence, σ i.e. conductivity of s/c σ is given by.

The resistivity of s/c is reciprocal of conductivity,

$$\rho = 1/\sigma$$

It is evident from the above eqn that, current densi[ty] within a s/c is directly proportional to applied ele[ctric] field E.

For pure s/c, $n = p = n_i$

where n_i = intrinsic concentration.

The value of n_i is given by,

$$n_i^2 = A T^3 \exp(-E_{G0}/kT)$$

where, A = constant & is independent of tem[p]
$= 2.33 \times 10^{43}$

k = Boltzmann constant in eV per K

E_{G0} = Energy gap in eV at absolute zero tempr. EG

T = tempr

Thus,

$$J = (n\mu_e + p\mu_h) qE$$

$$= (n_i\mu_e + n_i\mu_h) qE$$

$$= n_i(\mu_e + \mu_h) qE$$

Hence conductivity in intrinsic s/c is,

$$\sigma_i = n_i(\mu_e + \mu_h) q$$

Intrinsic conductivity increases at the rate of 5% per °C for Ge & 7% per °C for Si

Conductivity in Extrinsic s/c

The conductivity of intrinsic s/c is given by

$$\sigma_i = n_i(\mu_e + \mu_h) q = (n\mu_e + p\mu_h) q$$

For N-type, $n >> p$

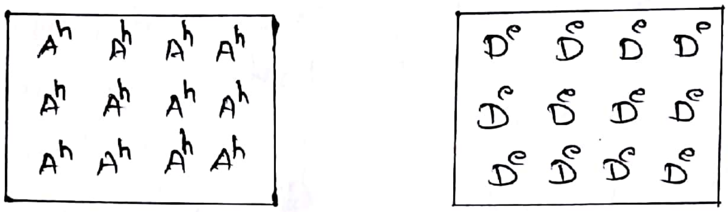
$$\therefore \sigma = n\mu_e q$$

For P-type, $p >> n$

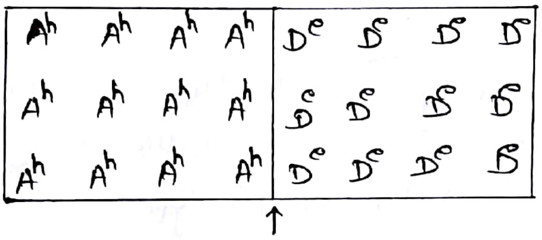
$$\therefore \sigma = p\mu_h q$$

Theory of PN Junction

When a block of P-type semiconductor is joined with a block of N-type s/c, then a junction is formed in between them, which is called PN junction.



P-type s/c　　　　N-type s/c



PN Junction

Fig: Formation of PN junction

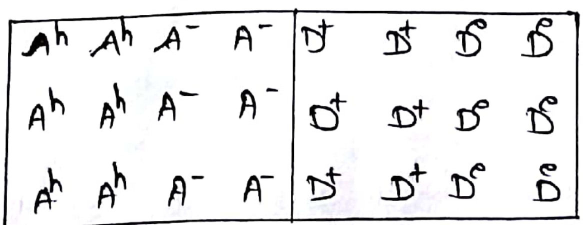
Here, A = Acceptor atom (Trivalent)

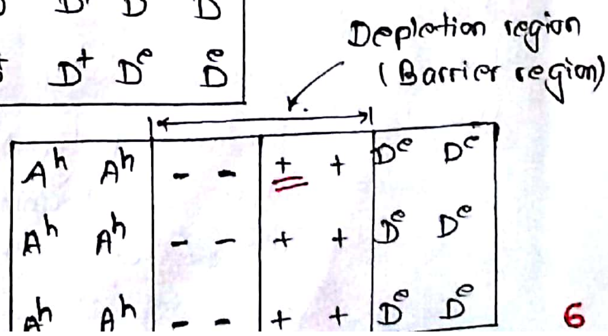
D = Donor atom (Pentavalent)

e = electron

h = hole.

During the formation of PN junctions, the e's from N-type s/c move towards the P-type s/c & combine with the holes. The donor atoms of N-type losses e^- so it becomes +ve charged ion (D^+) where as the Acceptor atom of P-type accepts e's, so it becomes -ve charged ion (A^-).





These +ve & -ve charged ions form a layer on both sides of PN junction which is called depletion region or barrier region. This depletion region prevents the further movements of e⁻s from N-type to P-type s/c.

The -ve & +ve charge ions of depletion region (also called space charge) offers certain potential difference or voltage, which is called barrier potential or depletion potential or junction potential.

The value of barrier potential for Silicon is 0.7V and is 0.3V for Germanium.

PN Junction Diode

When a block of P-type & N-type s/c are joined, a PN junction is formed. If a metallic wires are connected, to each side of P-type & N-type s/c, the resulting structure is called PN junction diode.

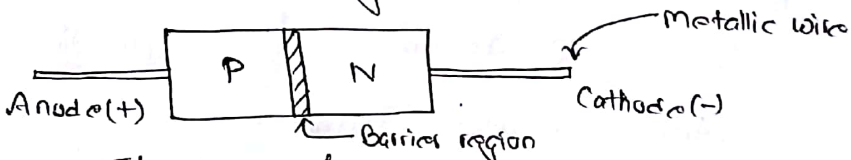


Fig: Structure of PN Junction Diode

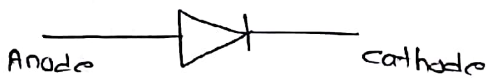


Fig: Circuit symbol of PN junction diode.

Diode Biasing (Operation of PN Junction Diode)

The methods of connecting a voltage source to a diode is called diode biasing.

A PN junction diode can be biased in two ways:

1) Forward Biasing
2) Reverse Biasing

1) Forward Biasing

When a +ve terminal of a source is connected to positive terminal of a diode (P-type) & -ve terminal of a source is connected to a -ve terminal of a diode (N-type s/c), then the diode is said to be forward biased.

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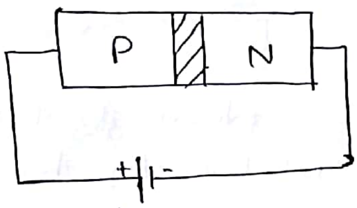


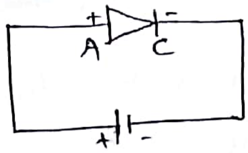


Fig: Forward Biasing

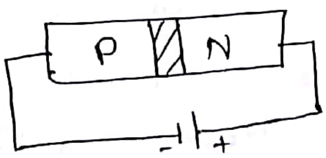
In forward biasing, the +ve terminal of source repels the holes whereas -ve terminal of source repels the electrons due to which there is flow of electron & hole across the junction. Thus, diode conduct current in forward biasing.

In forward bias, diode conducts current only if the supply voltage is greater than the barrier potential of a diode (0.07V for Si & 0.3V for Ge).

The depletion region becomes narrower when a diode is forward biased.

2) Reverse Biasing

When a +ve terminal of a source is connected to -ve terminal of a diode(N-type sid) & -ve terminal of a source is connected to +ve terminal of a diode (p-type sid), then the diode is said to be Reverse Biased.



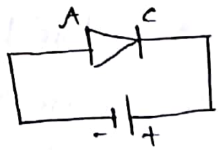


Fig: Reverse biasing of PN Junction diode

In reverse biasing, the +ve terminal of a source attracts the e⁻s from N-type s/c whereas the -ve terminal of a source attracts the holes from P-type s/c, away from the junction. Due to the movement of e⁻s & holes the depletion region widens & diode doesn't conduct current.

When a diode is reverse biased, the minority charge carriers gives rise to small current, which is negligible.

When reverse bias voltage is greater than a breakdown voltage, the diode break-down & acts as a short circuit so it conducts high current.

Voltage Current (VI) Characteristics of PN Junction Diode

If 'V' is the voltage (applied) across a diode & 'I' be the current flowing through it, then the relationship between V & I is given by,

$$I = I_S \left(e^{\frac{V}{\eta V_T}} - 1 \right) \quad \text{——— (1)}$$

where, I_S = reverse saturation current

V_T = thermal voltage = 0.026V at room temp.

η = constant $(1 \leq \eta \leq 2)$

When eqn (1) is plotted in a graph, then VI characteristics of diode is obtained as shown below:

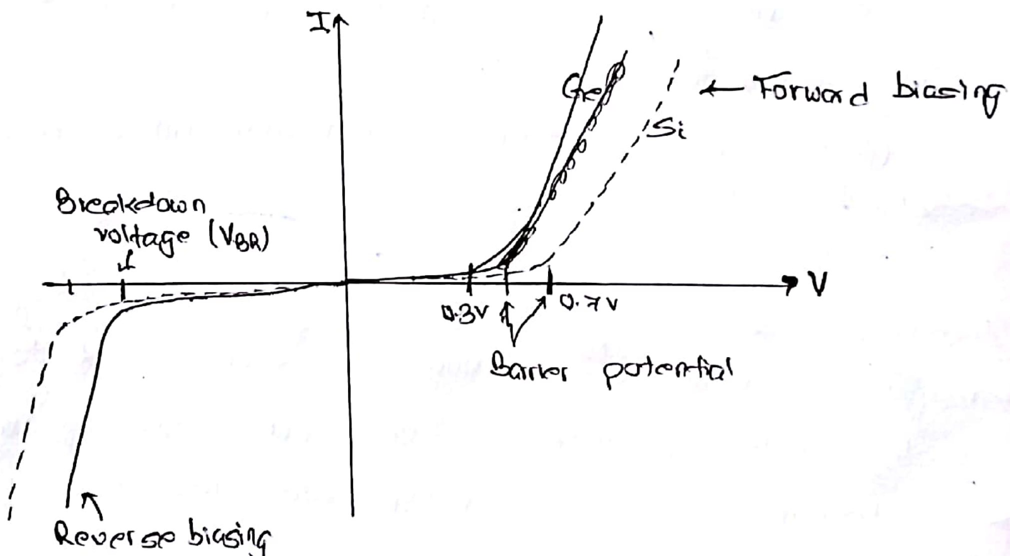


Fig: VI characteristics of a diode

When a diode is forward biased, small amount of current flows through it untill the supply voltage is greater than barrier potential.

When the supply voltage exceeds the barrier potential, then the current rises sharply as shown in above figure.

Also, when the diode is reverse biased, negligible amount of current flows through it, but if the supply voltage exceeds the breakdown voltage (V_{BR}), the diode is broken down (destroyed) & it acts as short circuit due to which the current increases sharply as shown in above fig.

Effect of temperature in VI characteristics

The VI characteristics of PN junction diode is given by,

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

In above eqn (1), reverse saturation current I_S & thermal voltage V_T are temperature dependent factors.
When tempr increases V_T also increases which cause I to decrease. Similarly on increase in tempr I_S also increases (i.e. I_S doubles for every 10°c rise in tempr), due to which I increases. Since the effect of increase of I_S is greater than the effect of increase of V_T, the current through diode increases with the increase in temperature.
The effect of tempr in VI characteristics of diode can be shown as below:

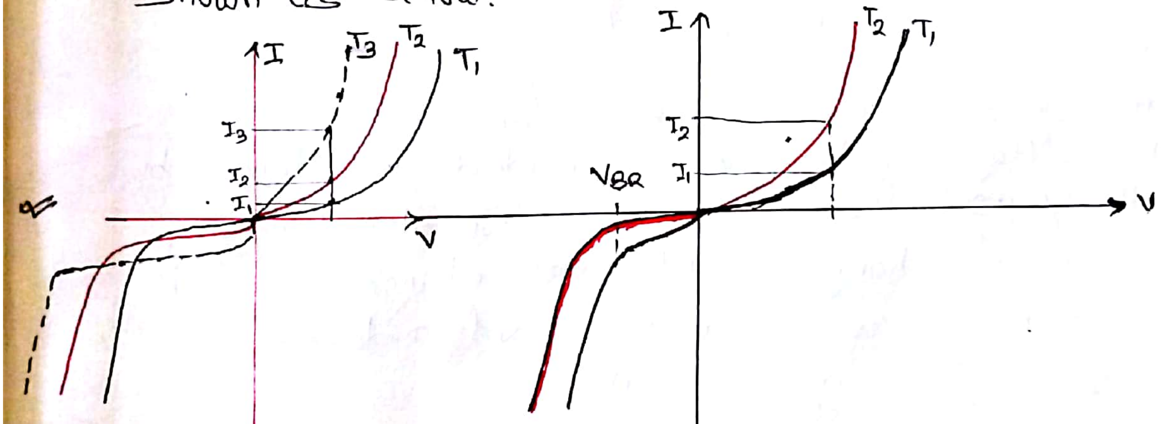


Fig: Effect of tempr on VI characteristics of diode

The VI characteristics of diode shift towards left as tempr increased. From figure (graph), it is observed that as $T_3 > T_2 > T_1$ thus $I_3 > I_2 > I_1$. i.e. as ~~current~~ temperature is increased, current increases sharply.

The reverse saturation current of diode is 5nA at 25°c. Find reverse saturation current at 125°c.

Soln: Given, $I_{S1} = 5nA$ at $T_1 = 25°c$

$I_{S2} = ?$ at $T_2 = 125°c$

As we know that reverse saturation current I_S doubles for every 10°c rise in tempr.

i.e. $I_{S2} = 2^n I_{S1}$

where, $n = \frac{T_2 - T_1}{10} = \frac{125-25}{10} = 10$

Now, $I_{S2} = 2^{10} \times I_{S1}$

$\therefore I_{S2} = 2^{10} \times 5\,nA = 5120\,nA = (1024 \times 5\,nA)$

Diode Resistance

Diode shows two types of resistive effects:

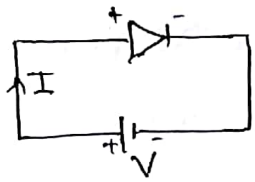
i) Static resistance (DC Resistance)

ii) Dynamic resistance (AC Resistance)

i) Static Resistance (DC Resistance)

If 'V' be the dc voltage applied to a diode and 'I' be the current flowing through it, then the ratio of V and I is called static resistance of a diode.

i.e. $R_{DC} = \frac{V}{I}$

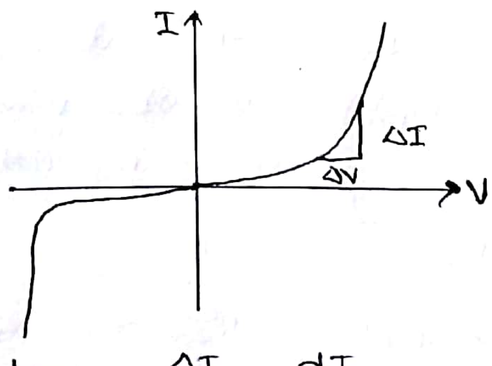


ii) Dynamic Resistance (AC Resistance)

When the voltage applied across a diode is changed by ΔV, then the current flowing through it will also change by ΔI. The ratio of change in voltage to change in current is called dynamic or AC resistance of a diode.

$$r_{AC} = \frac{\Delta V}{\Delta I} = \frac{dV}{dI} \quad \text{—— (1)}$$

The VI-characteristics of diode is,



Here, slope $= \frac{\Delta I}{\Delta V} = \frac{dI}{dV}$

$$\Rightarrow \frac{dV}{dI} = \frac{1}{\text{slope}}$$

Thus, $r_{AC} = \frac{dV}{dI} = \frac{1}{\text{slope}}$ —— (2)

The AC resistance of diode can also be defined as the reciprocal of slope of its VI characteristics.

We know that, $I = I_S \left(e^{\frac{V}{\eta V_T}} - 1\right) = I_S e^{\frac{V}{\eta V_T}}$ —— (3)

on Differentiating w.r.to V,

$$\frac{dI}{dV} = I_S * \frac{1}{\eta V_T} * e^{\frac{V}{\eta V_T}}$$

$$\boxed{\frac{d\, e^{3x}}{dx} = 3 \cdot e^{3x}}$$

$$\frac{dI}{dV} = \frac{I_S}{\eta V_T} e^{\frac{V}{\eta V_T}} = \frac{I_S e^{V/\eta V_T}}{\eta V_T} = \frac{I}{\eta V_T}$$

$$\text{or, } \frac{dV}{dI} = \frac{\eta V_T}{I}$$

$$\therefore \; r_{AC} = \frac{dV}{dI} = \frac{\eta V_T}{I}$$

Diode Capacitance/ Junction Capacitance

(capacitive effects:)

~~Diode shows 2 types of capacitive effects:)~~

The depletion region across the junction behaves as an insulating material or dielectric constant of the capacitor and the P & N sides act as parallel plates.

Thus, the junction exhibits the property of capacitance & is called junction capacitance or diode capacitance.

Diode shows 2 types of capacitive effects'.

1) Transition capacitance (Space charge capacitance)

2) Diffusion capacitance

1) Transition Capacitance (C_T)

When a diode is reverse biased, the depletion region increases. The depletion region consists of a layer of positive & negative charged ions. These ions behave as +ve & -ve plate of a parallel plate capacitor due to which capacitive effect is produced in a diode, known as transition capacitance.

Thus transition capacitance is the capacitive effect shown by diode when it is reverse biased.

The transition capacitance of a diode is given by,

$$C_T = \frac{\epsilon A}{W} \quad \text{——} (1)$$

where, ϵ = permittivity

A = Area of cross section (of a junction)

W = width of depletion region.

Also, Depletion width (W) is expressed by,

$$W^2 = \frac{2\epsilon V_B}{e}\left[\frac{1}{N_A}+\frac{1}{N_D}\right] \quad \text{——— (2)}$$

where, N_A = No. of Acceptor atoms

N_D = No. of Donor atoms

ϵ = Permittivity

e = charge of e^-

V_B = [junction voltage = $V_0 - V_R$] = applied reverse voltage.

(V_0 = contact potential and V_R is negative voltage applied to diode)

From eqn (1) & (2)

$$C_T = \frac{\epsilon A}{\sqrt{\frac{2\epsilon V_B}{e}\left[\frac{1}{N_A}+\frac{1}{N_B}\right]}} = \frac{\epsilon A}{\sqrt{\frac{2\epsilon V_B (N_A+N_D)}{e N_A N_D}}}$$

or, $$C_T = \epsilon A * \sqrt{\frac{e N_A N_D}{2\epsilon V_B (N_A+N_D)}}$$

$$\Rightarrow C_T \propto \frac{1}{\sqrt{V_B}} \quad \text{——— (3)}$$

Thus, transition capacitance is inversely proportional to the square root of applied reverse voltage, V_B.

2) Diffusion Capacitance (C_D)

When a diode is forward biased, there is a movement of electron & holes through the PN junction. This movement of charged carrier give rise to a capacitive effect in a diode, which is called diffusion capacitance.

In forward biased diode, there is effect of transition capacitance, but the effect is suppressed by the capacitive effect due to movement of charge carriers. [Thus forward biased diode posses diffusion capacitance only.]

The Diffusion capacitance of diode is due to the movement of charge carriers across the junction.

i.e. $C_D = \frac{dQ}{dV}$ —(1)

Also, $Q = I\tau = I\tau$, $\tau = \tau$, mean life time of carrier, constant

So, from eqn (1),

$$C_D = \frac{d(I\tau)}{dV} = \tau \frac{dI}{dV} \quad \text{—(2)}$$

The characteristic eqn of Diode is,

$$I = I_S \left(e^{\frac{V}{\eta V_T}} - 1\right) = I_S e^{\frac{V}{\eta V_T}} \quad \text{(neglecting } 1 I_S\text{)}$$

On differentiating w.r.t o V,

$$\frac{dI}{dV} = \frac{I_S e^{\frac{V}{\eta V_T}}}{\eta V_T} = \frac{I}{\eta V_T}$$

Then from eqn (2),

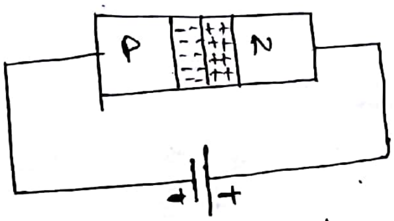
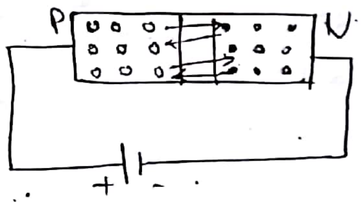
$$C_D = \tau * \frac{I}{\eta V_T} = \frac{\tau I}{\eta V_T}$$

∴ Diffusion capacitance, $C_D = \frac{I}{\eta V_T}\tau$

where, τ = mean life time of carrier
I = forward current
η = constant = $1 \leq \eta \leq 2$
V_T = thermal voltage.

Since, τ, η and V_T are constant. Thus Diffusion capacitance is directly proportional to forward current I.

Differences between Transition & Diffusion Capacitance

Transition Capacitance	Diffusion Capacitance
1. The capacitive effect shown by diode when it is reverse biased is called transition capacitance.	1. The capacitive effect shown by diode when it is forward biased is called diffusion capacitance.
2. When diode is reverse biased, the depletion region widens. The depletion region consists of +ve & -ve charge ions, behaves as parallel plate capacitor, Due to which capacitive effect arises in diode & is a transition capacitance.	2. When a diode is forward biased, the +ve & -ve charge carriers move through the PN junction. This movement of charge carrier gives an capacitive effect, known as diffusion capacitance.
 Fig: Reverse biased diode	 Fig: Forward biased diode.
3. The transition capacitance of diode can be expressed as; $C_T = \frac{\epsilon A}{W}$ where, ϵ = permitivity, A = Area of crossection of depletion region, W = width of depletion region.	3. The diffusion capacitance of a diode is expressed as; $C_D = \frac{I}{\eta V_T} \tau$ where τ = mean lifetime of carriers, I = forward current of diode, η = constant $(1 \le \eta \le 2)$, V_T = Thermal voltage.
4. The transition capacitance is inversely proportional to the reverse voltage.	4. Diffusion capacitance is directly proportional to the forward current of diode.

Diode Switching Time (Reverse Recovery Time of Diode)

When a diode is forward biased it conducts current (switch ON) & when it is reverse biased it doesn't conduct current (S/W OFF)

When a forward biased diode is suddenly reverse biased, the diode doesn't change its state from conduction (switch ON) to non-conduction (S/W OFF). The diode takes certain time to change its ~~state~~ from conduction (forward biased) to non-conduction (reverse biased), which is called reverse recovery time (diode switching time) of a diode.

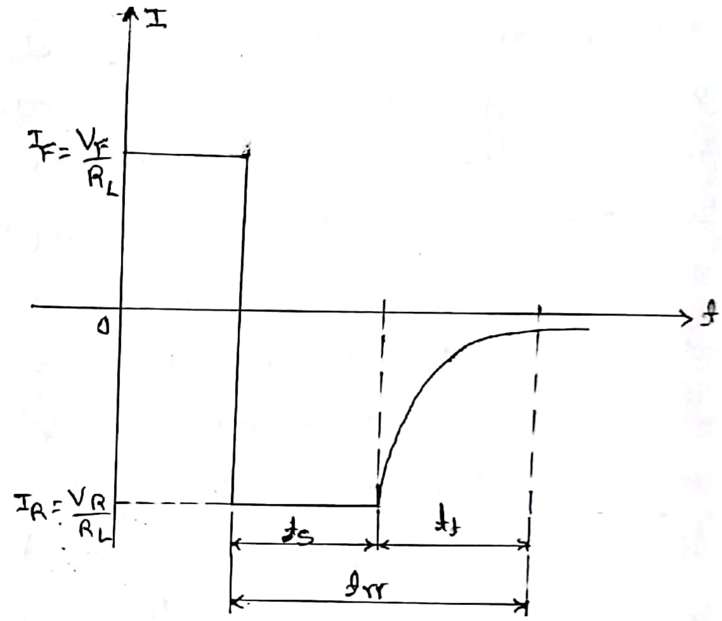


Fig: Reverse recovery time of diode

When the forward biased diode is reverse biased, the current simply reverse & stay measurable for certain period of time, called storage time (t_s).

After the storage phase has passed, the current gradually decreases & becomes zero to take diode into non-conduction state (reverse bias). This period of time is called transition time (t_t)

The reverse recovery time (t_{rr}) is the sum of storage time (t_s) & transition time (t_t).

i.e. $t_{rr} = t_s + t_t$

- ## Junction Breakdown / Diode Breakdown

In reverse biasing, a very small current flows due to minority charge carriers, which is known as leakage saturation current (I_s).

If reverse voltage is further increased, a current rises sharply at a certain reverse-bias voltage. This mechanism of producing a large reverse current is called breakdown.

There are two types of breakdown mechanisms:

1) Zener breakdown
2) Avalanche breakdown

1) Avalanche Breakdown

When a diode is reverse biased, the free e⁻s present on it can gain (high) sufficient energy from supply voltage. These highly energetic e⁻s move with greater speed & can break-down (rupture) a covalent bond to generate free e⁻. (i.e. a e⁻ can rupture a covalent bond & generate two free e⁻s). These newly generated free e⁻s also gain energy & further generate free e⁻s. by rupturing covalent bonds. The process continues & in a short period of time, large no. of free e⁻s are generated in a diode. The flows of these e⁻s give rise to large current. This phenomenon is called avalanche breakdown.

- The avalanche breakdown occurs in a diode with higher breakdown voltage.

2) Zener Breakdown

When a diode is reverse biased, the supplied reverse voltage can generate an electric field. Due to which covalent bonds are ruptured & free e⁻s are generated. If the diode has lower breakdown voltage, then the supply voltage can rupture (break-down) large no. of covalent ~~st~~ bonds & generate large no. of free e⁻s, due to which large no. of current flows through a diode. This phenomenon is called zener breakdown.

Zener breakdown occurs in zener diode with smaller breakdown voltage (zener voltage, V_z).

→ The main differences between zener breakdown and avalanche breakdown are as follows:

Zener Breakdown	Avalanche Breakdown
1.

Zener Diode

Zener diode is a special purpose diode designed to be used as a voltage regulator. They are highly doped diode, thus have very small barrier region (less than 1μm).
It can conduct current in reverse biasing. If it is forward biased it shows the property of forward biased PN Junction diode. It has sharp breakdown voltage, known as zener voltage (V_z).

Fig: circuit symbol of zener diode.

The VI characteristics of zener diode is;

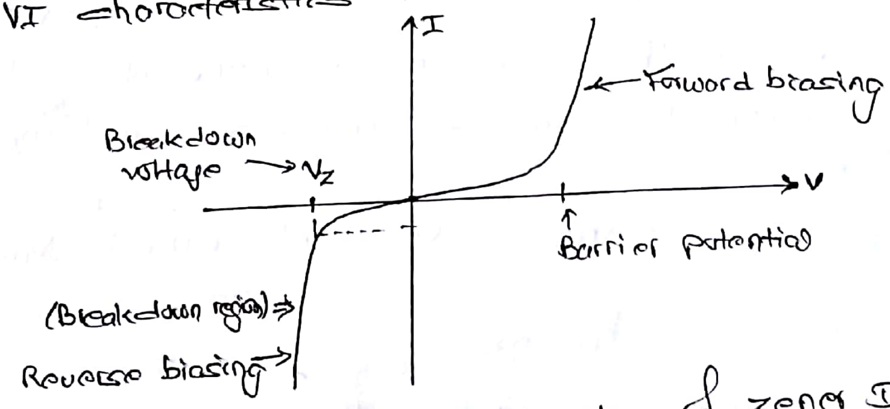


Fig: VI characteristics of zener Diode

Zener Diode as a Voltage Regulator

To use Zener diode as a voltage regulator, following condition must be satisfied,

1) Zener diode must be operated in reverse-bias & connected in parallel with load.
2) Input voltage must be greater than zener voltage ($V_{in} > V_z$)
 i.e. it must be operated in a breakdown region).

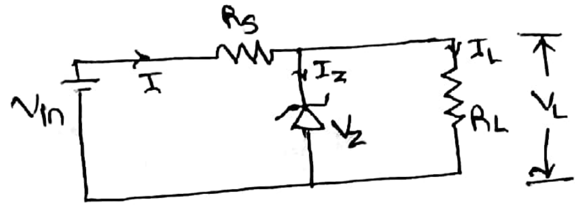


Fig: Zener diode as a voltage regulator

Here, V_{in} = i/p voltage
R_S = source resistance
R_L = Load resistance
I = source current
I_L = Load current
I_Z = zener current
V_Z = Zener voltage
V_L = Load voltage

When zener diode regulate voltage across load, the load voltage will be equal to zener voltage.

i.e. $V_L = V_Z$.

From above figure, $I = I_Z + I_L$

and, $V_L = I_L \cdot R_L$

Case-I: When Vin changes

Let Vin is increased. As Vin increases, the current I also increases. If I increased, both I_L & I_Z must be increased, but the zener diode conducts the increased current (i.e. only I_Z increases) and maintain I_L constant.

Thus, $V_L = I_L R_L$ becomes constant even if Vin increa[ses]

Case-II: When R_L changes

Suppose R_L increases. When R_L increases, the zener diode conducts more (i.e. I_Z increases) & minimizes the value of I_L. So that even increase of R_L, as I_L decreases, $V_L = I_L \cdot R_L$ remains constant.

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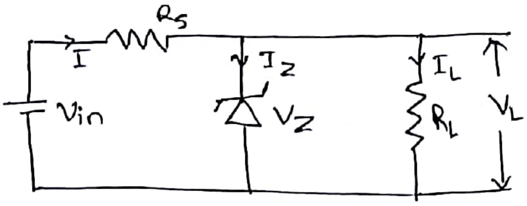
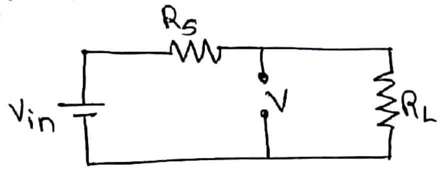
Zener Diode Numerical: Different cases

1) Case I: V_{in} = constant & R_L = constant



Here, we have to find whether the zener diode is 'ON' or 'OFF'. For that, remove zener diode from circuit & find open ckt voltage 'V'.



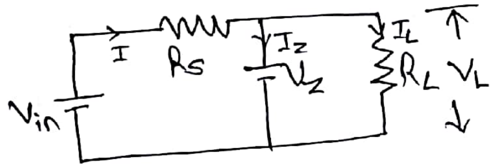
Here, $V = \frac{R_L}{R_L + R_S} * V_{in}$

a) If $V < V_Z$, zener diode is OFF

b) If $V > V_Z$, zener diod is ON

a) If zener diode is ON

Replace zener diode by voltage source with value V_Z.



Here, $V_L = V_Z$

$$I = \frac{V_{in} - V_Z}{R_S}$$

$$I_L = \frac{V_L}{R_L}$$

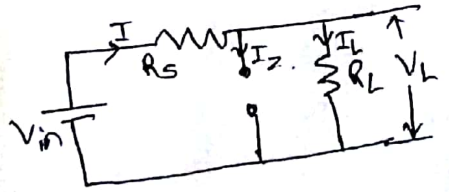
$$I_Z = I - I_L$$

$$V_R = I \cdot R_S$$

$$P_Z = V_Z \cdot I_Z$$

b) If zener diode is OFF

Replace zener diode by open circuit



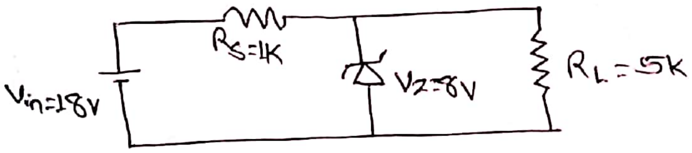
Here, $I_Z = 0$

$$V_L = \frac{R_L}{R_L + R_S} * V_{in}$$

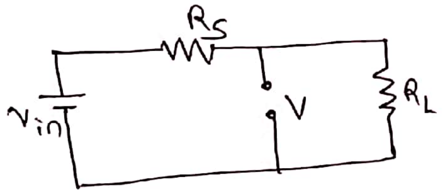
$$I = I_L = \frac{V_{in}}{R_L + R_S} \quad \text{or} \quad I_L = \frac{V_L}{R_L}$$

$V_R = I \cdot R_S$ & $P_Z = V_Z \cdot I_Z = 0$

For the circuit shown below; find
i) Load ~~current~~ voltage (V_L)
ii) Zener current (I_Z), (iii) Power across zener diode.

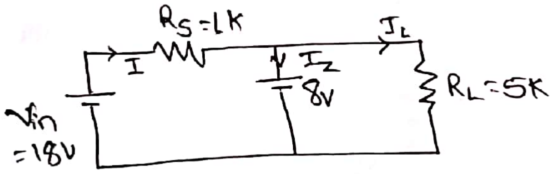


Soln: Removing zener diode & have to find open ckt voltage



Here, $V = \dfrac{R_L}{R_L+R_S} * V_{in} = \dfrac{5}{5+1} \times 18 = 6V = 15V$

Since $V > V_Z$. So Zener diode is ON.
Now, replacing zener diode by its (breakdown) voltage source with value V_Z.



From above circuit,
i) Load voltage (V_L) = $V_Z = 8V$

ii) Current flowing through zener diode (I_Z) = ?

we known that, $I_Z = I - I_L$

where, $I = \dfrac{18-8}{R_S} = \dfrac{18-8}{1} = 10mA$

$I_L = \dfrac{V_L}{R_L} = \dfrac{8}{5} = 1.6\,mA$

$\therefore I_Z = I - I_L = 10 - 1.6 = 8.4\,mA$

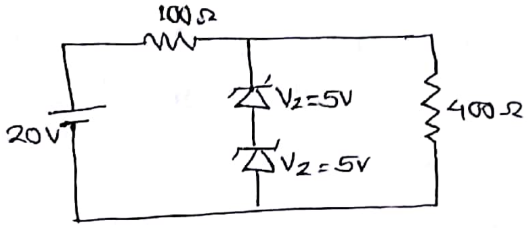
iii) Power across zener diode,

$P_Z = I_Z \cdot V_Z$

$= 8.4\,mA * 8V$

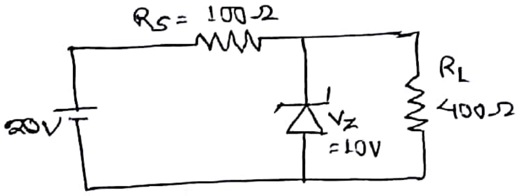
$= 67.2\,mW$

For the circuit shown below, find
i) Load voltage (V_L).
ii) Current through zener Diode (I_Z).
iii) Voltage across series resistance.
iv) Power dissipated across zener diode.

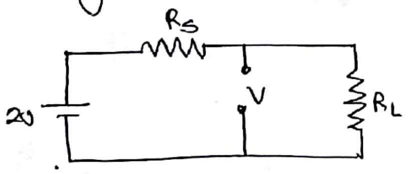


Soln:

The equivalent circuit is,



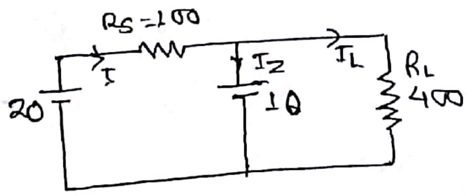
Calculating open circuit voltage



$$V = \frac{R_L}{R_S + R_L} \times 20 = \frac{400}{400 + 100} \times 20 = 16V$$

Here, $V > V_Z$. So Zener diode is ON.

Now,



Now,

i) Load voltage, $V_L = V_Z = 5 + 5 = 10V$

ii) $I_Z = I - I_L = \frac{20-10}{100} - \frac{10}{40} = \frac{V_{in} - V_Z}{R_S} - \frac{V_L}{R_L}$

$= 0.1 - 0.025$

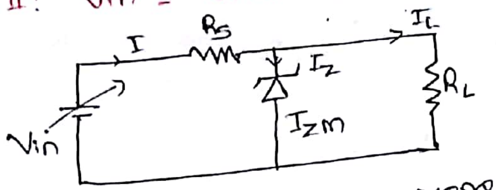
$= 0.075\,A.$

iii) Voltage across series resistance, $V_R = IR_S = 0.1 \times 100 = 10V$

iv) Power dissipated in zener diode,

$P_Z = I_Z V_Z = 0.075 * 10 = 0.75$ Watt

CASE II: V_{in} = Variable, R_L = constant



I_{ZM} = maximum zener current.

Here, we have to find range of V_{in} [i.e. $V_{in(min)}$ and $V_{in(max)}$] required for safe turn 'ON' of zener diode.

Zener must be ON. Thus,

$$V_L = V_Z$$

For minimum value of V_{in} [$V_{in(min)}$]

— The open ckt voltage is given by,

$$V = \frac{R_L}{R_S+R_L} * V_{in}$$

For minimum condition:, $V = V_Z$

So, $$V_Z = \frac{R_L}{R_S+R_L} * V_{in}$$

or, $V_Z(R_S+R_L) = R_L \cdot V_{in}$

$$\Rightarrow V_{in(min)} = \frac{V_Z(R_S+R_L)}{R_L}$$

Also, $$I_{min} = \frac{V_{in(min)} - V_Z}{R_S}$$

For maximum value of V_{in} [$V_{in(max)}$]

We know that, $I = \frac{V_{in} - V_Z}{R_S}$

or, $IR_S = V_{in} - V_Z$

$$\Rightarrow V_{in} = I \cdot R_S + V_Z \quad \text{—— (1)}$$

Here, $V_{in} \to V_{in(max)}$, when $I \to I_{max}$

$V_{in(max)} = I_{max} R_S - V_Z$

Again,

$$I = I_L + I_Z$$

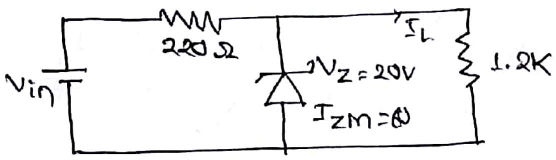
Here, $I \to I_{max}$ when $I_Z \to I_{ZM}$ $\Rightarrow I_{max} = I_L + I_{ZM}$

where, $I_L = V_L/R_L$

Now, from eqn(1),

$$\therefore V_{in(max)} = (I_L + I_{ZM})R_S + V_Z$$

Determine the range of values of Vin that maintain zener diode in ON-state. Also find the max^m power that can be dissipated in diode.



Soln:

$V_{in(max)} = (I_L + I_{zm}) R_S + V_Z$

Here, $V_Z = V_L = I_L R_L$

$\Rightarrow I_L = \frac{V_Z}{R_L} = \frac{20}{1.2 \times 10^3} = 16.67 \, mA$

$\therefore V_{in(max)} = (16.67 + 60) mA * 220 \Omega + 20$

$= 16.867 + 20$

$= 36.867 V$

Also, $V_{in(min)} = \frac{R_S + R_L}{R_L} * V_Z = \frac{(1.2 \times 10^3 + 220)}{1.2 \times 10^3} \times 20$

$\therefore V_{in(min)} = 23.67 V.$

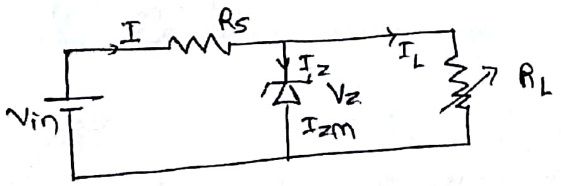
Thus, the range of values of Vin that maintain zener diode in ON-state = 23.67V to 36.867V

Again,

maximum power dissipated in zener diode is,

$P_{max} = I_{zm} * V_Z = 60 \times 20 = 1200 \, mW = 1.2 \, Watt$

CASE III: Vin = constant, R_L = variable



Here, I_{zm} = Maximum zener current

Here, we have to find range of R_L [$R_{L(min)}$ & $R_{L(max)}$] required for safe turn ON of zener diode.

Since, Zener diode must be ON,

$V_L = V_Z$.

For minimum value of R_L [$R_{L,min}$]

— The open ckt voltage is given by,

$$V = \frac{R_L}{R_L + R_S} * V_{in}$$

For minimum condition, $V = V_Z$

i.e. $V_Z * (R_L + R_S) = R_L * V_{in}$

or, $$R_{L,min} = \frac{V_Z \cdot R_S}{V_{in} - V_Z}$$

& $$I_{L,max} = \frac{V_L}{R_{L,min}}$$

For maximum value of R_L [$R_{L,max}$]

As we know, $R_L = \dfrac{V_L}{I_L}$

$$R_{L,max} = \frac{V_L}{I_{L,min}} \quad \text{———} \quad (1)$$

Again,

$I = I_L + I_Z$

$\Rightarrow I_L = I - I_Z$

Here, $I_L \rightarrow I_{L,min}$, when $I_Z \rightarrow I_{Zm}$

$\therefore I_{L,min} = I - I_{Zm}$ ——— (2)

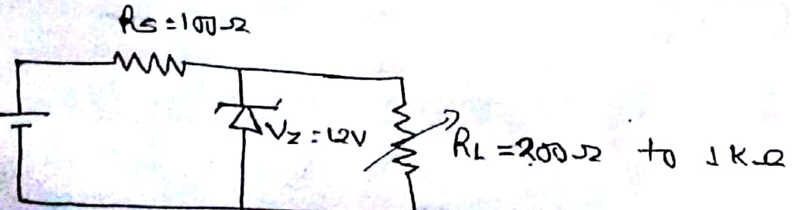
From eqn (1), (2)

$$\therefore R_{L(max)} = \frac{V_L}{I - I_{Zm}}$$

where, $I = \dfrac{V_{in} - V_Z}{R_S}$

A zener regulator has 12V zener voltage with variable load resistance. Calculate,

i) Maximum & minm load current.
ii) Maxm & minm power dissipation across load.
iii) voltage drop across series resistance.
iv) minimum value of load resistance to ensure that zener diode is ON.



Soln: Given, $V_{in} = 20V$

$R_S = 100\Omega$

$V_Z = 12V$

$R_{L(min)} = 200\Omega$

$R_{L(max)} = 1K = 1000\Omega$

i) Maximum load current, $I_{L(max)} = \dfrac{V_L}{R_{L,min}} = \dfrac{V_Z}{R_{L(min)}}$

$= \dfrac{12}{200} = 60mA$

& $I_{L(min)} = \dfrac{V_L}{R_{L(max)}} = \dfrac{12}{1000} = 12\,mA$

ii) $P_{Z(min)} = V_Z . I_{Z(min)}$

$P_{Z(max)} = V_Z . I_{Z(max)}$

Here, $I = \dfrac{V_{in} - V_Z}{R_S} = \dfrac{20-12}{100} = 80mA$

$\therefore$ $I_{Z(min)} = I - I_{L(max)} = 80 - 60 = 20mA$

& $I_{Z(max)} = I - I_{L(min)} = 80 - 12 = 68mA$

$\therefore$ $P_{Z(min)} = 12 * 20 = 240mW$

$P_{Z(max)} = 12 * 68 = 816\,mW$

iii) Voltage drop across series resistance,

$V_R = I R_S = 80mA * 100\Omega = 8V$

(or, $V_R = V_{in} - V_Z = 20-12 = 8V$)

iv) $R_{L(min)} = \dfrac{V_Z . R_S}{V_{in} - V_Z} = \dfrac{12 * 0.1K}{20-12} = 0.15K\Omega$

For the given circuit, load current varies from 12 to 100 mA. Find the value of series resistance R_S to maintain 7.2V across the load. Minimum zener diode current is 10mA.

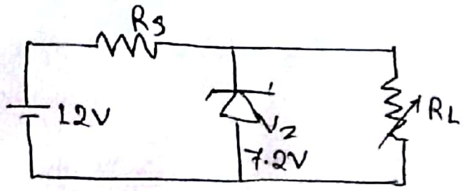
Soln: Given, $V_{in} = 12V$

$V_Z = 7.2V$

$I_{L(min)} = 12\,mA$

$I_{L(max)} = 100mA$

$I_{Z(min)} = 10mA$

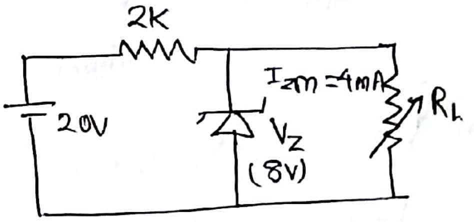


Here, $I = I_{Z(min)} + I_{L(max)} = 10 + 100 = 110 mA$

$\therefore$ Series resistance, $R_S = \dfrac{V_{in} - V_Z}{I} = \dfrac{(12 - 7.2)V}{110 \times 10^{-3} A}$

$= 43.63 \Omega$.

For the circuit given, find the max^m & min^m value of load resistor R_L required for safe turn 'ON' of zener diode. Also find the maximum & minimum power that can be dissipated across load.



Soln: Given, $V_{in} = 20V$

$R_S = 2K$

$V_Z = 8V$

$I_{zm} = 4mA$

Now, $R_{L(min)} = \dfrac{V_Z R_S}{V_{in} - V_Z} = \dfrac{8V * 2 \times 10^3 \Omega}{20 - 8} = 1.333 K\Omega$

and, $R_{L(max)} = \dfrac{V_L}{I - I_{zm}} = \dfrac{V_Z}{I - I_{zm}}$

where, $I = \dfrac{(20 - 8)V}{2 \times 10^3 \Omega} = 6 mA$

$\therefore R_{L(max)} = \dfrac{8V}{(6 - 4) \times 10^{-3} A} = 4 K\Omega$

Also, $I_{L(min)} = \dfrac{V_L}{R_{L(max)}} = \dfrac{8V}{4 \times 10^3 \Omega} = 2mA$

$I_{L(max)} = \dfrac{V}{R_{L(min)}} = \dfrac{8V}{1.333K} = 6 mA$

Thus, Power dissipated on load is,

$P_{L(min)} = V_L \cdot I_{L(min)} = 8V * 2 \times 10^{-3} A = 16mW$

& $P_{L(max)} = V_L \cdot I_{L(max)} = 8V * 6 \times 10^{-3} A = 48mW$.

Schottky Diode

It is a metal semiconductor diode designed to be used for fast switching applications.
It consist of metal & s/c region. The metals used are high conductive metals like silver, gold, platinum etc. whereas s/c used are normally N-type s/c (because majority carrier is e^- & for conduction of maximum current).
It is a unipola diode (i.e. only e^-s conduct current). It is also called hot carrier diode, because the e^- must gain high energy to cross metal-s/c junction to conduct current.
— The metal-s/c junction is called schottky junction.

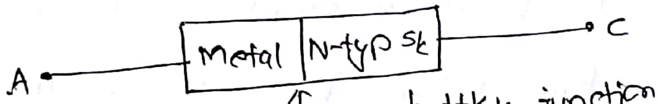
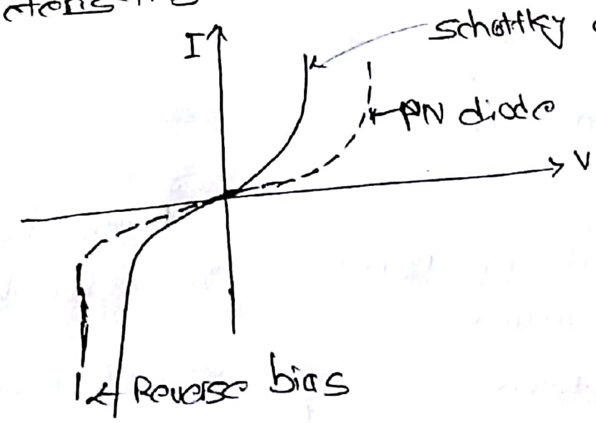


fig: Structure of schottky diode.

fig: Circuit symbol of schottky diode.

— The metal region of schottky diode is called +ve terminal or anode, whereas the s/c region is called -ve terminal or cathode.
The VI characteristics of PN & schottky diode is,



Varactor Diode

The varactor diode is a variable capacitor diode. It is a reverse-biased PN junction diode whose transition capacitance varies with the applied reverse-bias voltage.

The varactor is also called varicap, voltcap, epicap, voltage variable capacitor, or tunning capacitor.

A reverse-biased PN junction diode possesses transition capacitance C_T which is given by

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

where, ϵ = permittivity
A = Area of cross-section
W = width of depletion region

When the reverse-bias voltage 'V' is varied, the width of depletion region 'W' varies due to which C_T also varies. Thus, C_T can be controlled by varying reverse-voltage. This property of reverse-biased PN junction diode is called varactor.

fig: Symbol of varactor

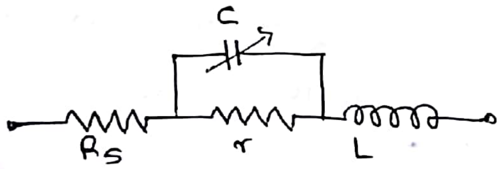


fig: Equivalent circuit

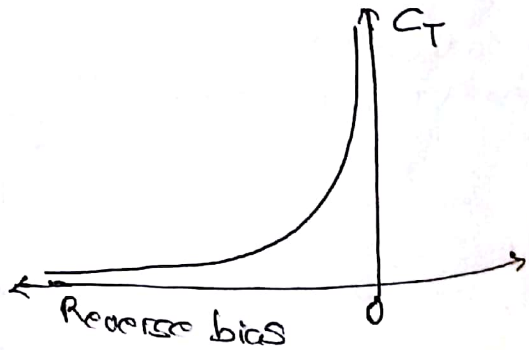


fig: Characteristic Curve

Varactor diodes are used in:
- Tunning circuits
- FM modulators
- Adjustable bandpass filters
- Automatic frequency control devices.

EL only

Tunnel Diode

A tunnel diode is a high conductivity two-terminal PN junction doped heavily about 1000 times greater than conventional junction diode. Because of heavy doping depletion width is reduced to an extremely small value of the order of 10^{-5} mm.

When a small +ve voltage is applied across tunnel diode, it can conduct significant amount of current due to a phenomenon called tunnelling phenomena.

Tunnel diode posses resistance i.e. current decreases when voltage is increased.

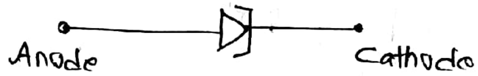


fig: Symbol of Tunnel diode.

VI Characteristics of Tunnel Diode

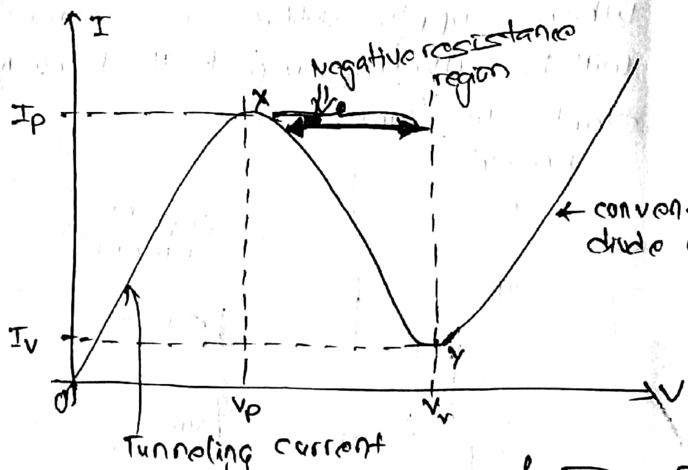


fig: VI characteristics of Tunnel Diode.

When a small +ve voltage is applied across a tunnel diode, it starts to conduct current. When the voltage is gradually increased the current also increases. When the voltage across tunnel diode $V = V_p$ (peak voltage), maximum current flow through it, called peak current I_p.

When the voltage across diode is increased beyond V_p (i.e. $V > V_p$), the current start to decrease. The current becomes minimum called Valley current, I_v, when the voltage across diode is equal to valley voltage ($V = V_v$).

When the voltage is increased beyond V_v ($V > V_v$), the tunnel diode gains the property of normal PN junction diode & the current increases gradually like in PN junction diode.

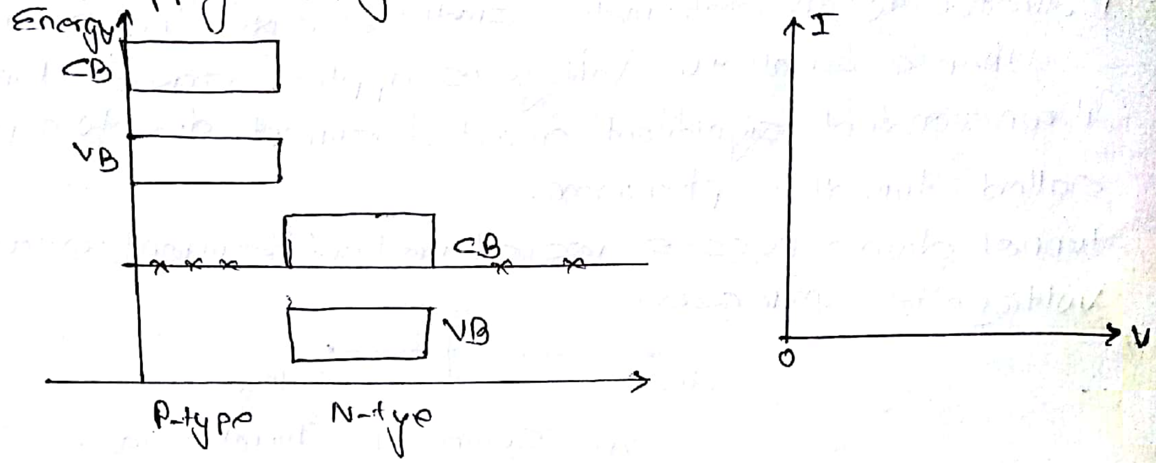
Between peak point X & valley point Y, in VI characteristic the current decreases when voltage is increased. Thus a Tunnel diode posses negative resistance in this region.

Tunneling Phenomenon of Tunnel Diode

The tunneling phenomenon of tunnel diode can be explained by following steps:

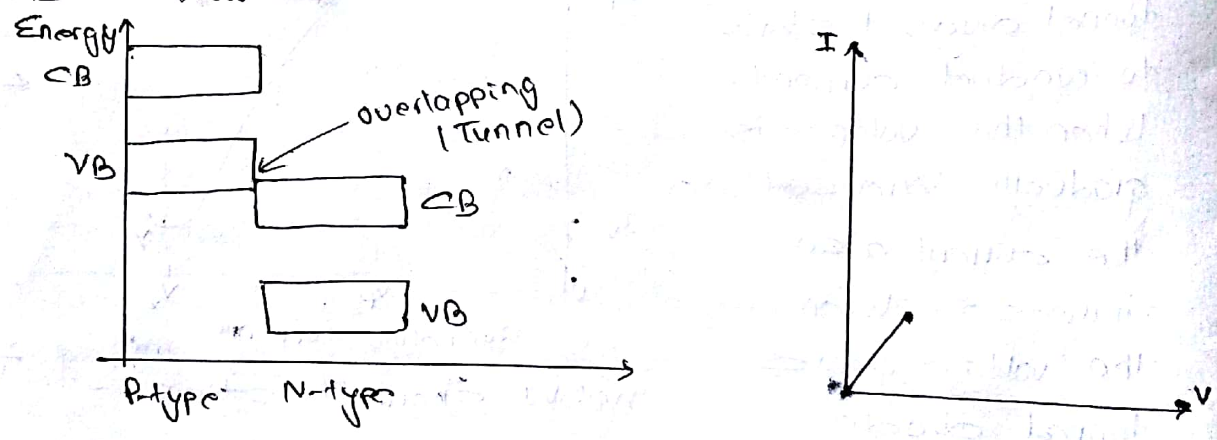
Step I: When V=0

When supply voltage is zero, there is flow of current.



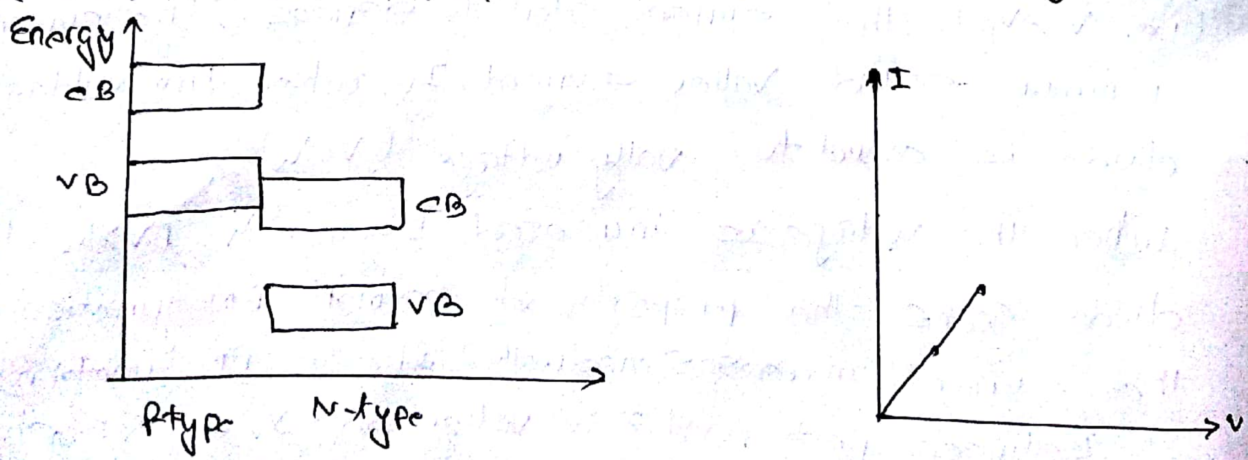
Step II: When V= +ve

When supply voltage is increased i.e. V= +ve, there will be overlapping both P- & N-type and current starts to flow.



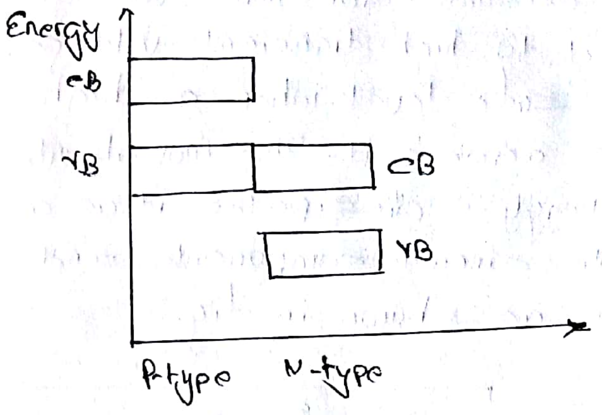
Step III: When V is increased

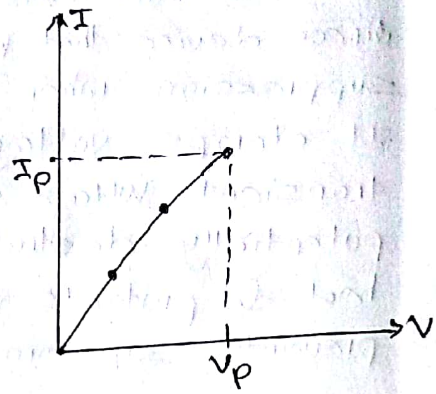
When V is further increases then overlapping increases & current also increases.



Step IV: When V=Vp

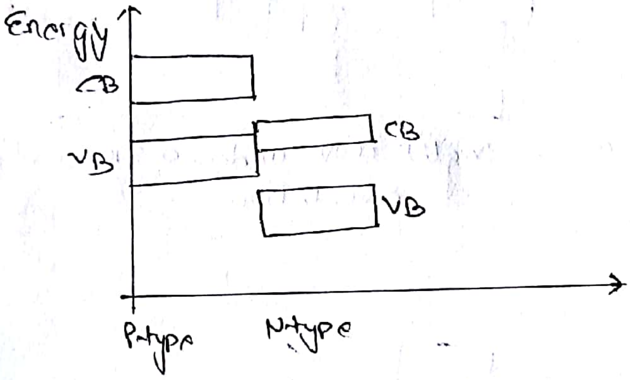
When V=Vp, at this condition current is maximum & overlapping also maximum.

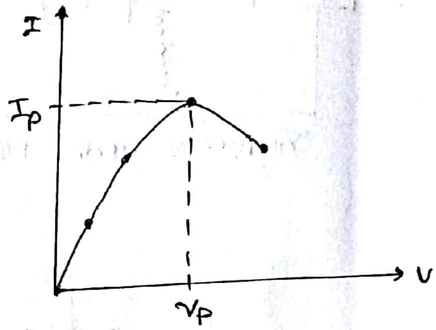




Step V: When V>Vp

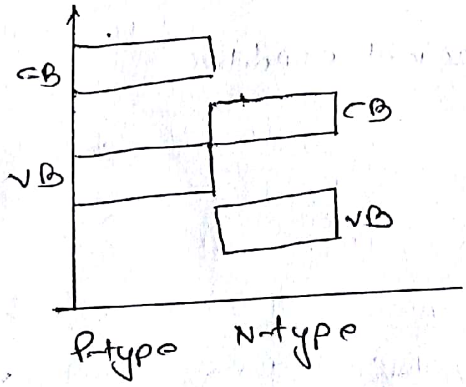
When V>Vp, current starts to decreases

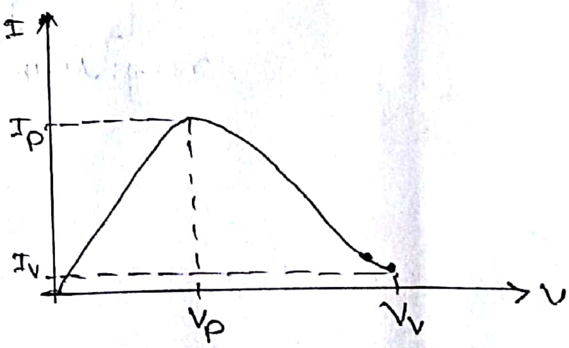




Step VI: When V=Vv

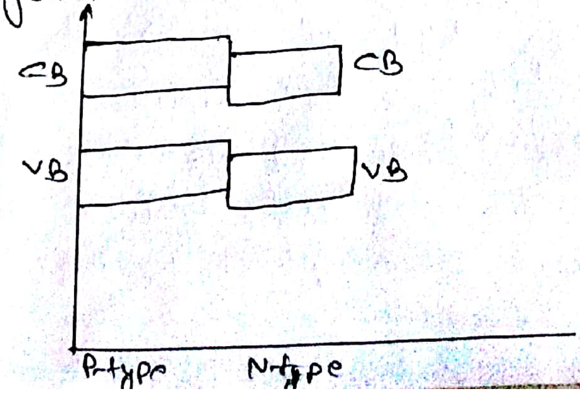
At this condition, current becomes minimum.

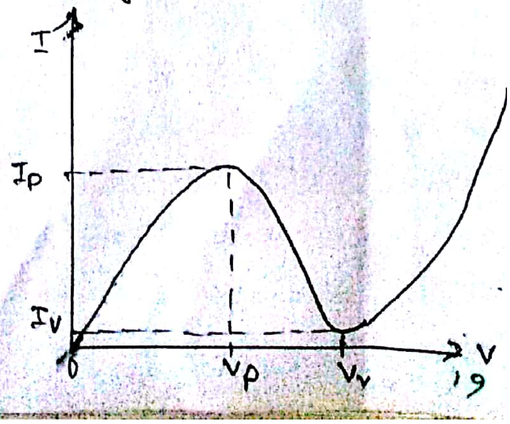




Step VII: When V>Vv

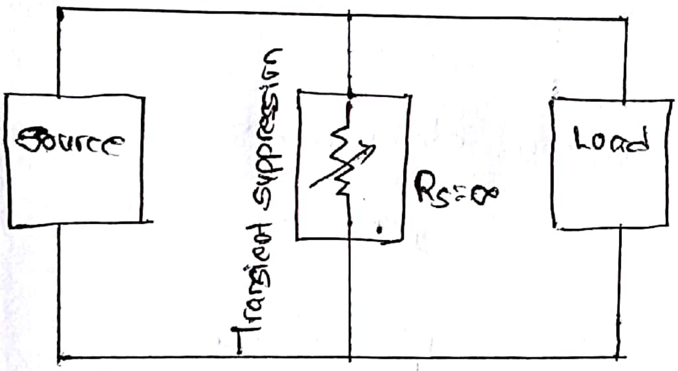
When further increasing voltage, it gain the property of PN junction diode & current increases gradually.



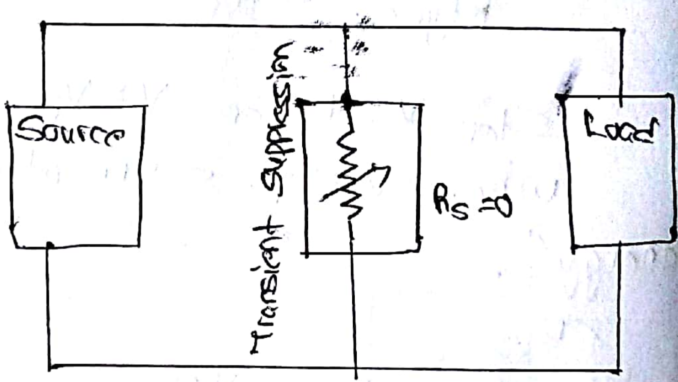


Metal Oxide Varistor

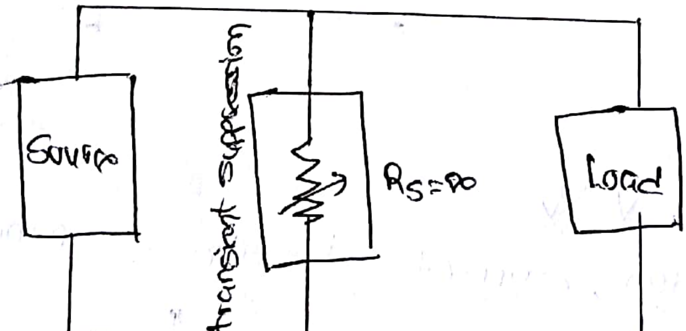
The metal oxide varistor, mov, is a voltage dependent, non-linear device that provides excellent transient voltage suppression when exposed to high transient voltage. It clamps voltage to a safe level when a high transient voltage appears across it. The mov absorbs potentially destructive energy & dissipates it as a heat & protects vulnerable circuit components and prevents system damage as shown in fig.



Fig(1): mov under normal condition



Fig(2): Mov under a transient condition



Fig(3): At the end of transient condition