SEMICONDUCTORS

Semiconductors: -

1. Semiconductors have much higher resistivity than metals.

2. Semiconductors have a temperature coefficient of resistivity (α) that is both negative and high. That is the resistivity of semi - Conductors decreases rapidly with temperature, while that of metals increases.

3. Semiconductor have a considerable lower number density of charge carriers (Charge per unit volume) than metals.

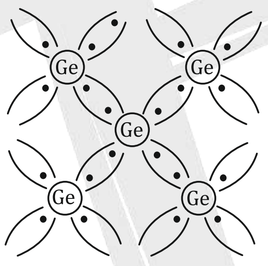
Classification of Semiconductors: -

1. Intrinsic Semiconductors: -

A semiconductor free from impurities, i.e. a pure semiconductor is called an intrinsic semiconductor. It has thermally generated current carriers.

Germanium and silicon are the most widely used semiconductors. The four valance electrons in Ge as well as in Si form covalent bonds with the electrons of the neighbouring atoms in the crystal lattice. As a result of this pure Gi or(Si) is a good insulator.

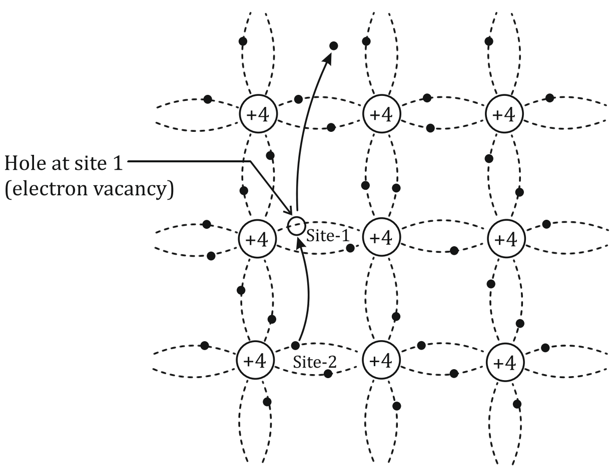
"on increasing the temp of semiconductor its conductivity increases but in metal conductivity decreases with temp."



[Thermal generated electron]

As the temperature increases, the thermal energy of the valance electrons increases an electron may break away from the covalent bond and becomes free to conduct electricity.

This electron leaves behind a vacancy in the covalent bond (at site 1). This vacancy of an electron with an effective positive electronic charge is called hole.



It behaves as an apparent free particle with charge +e.

The process of setting free an electron from a covalent bond and the simultaneous creation of a hole required a kind of ionisation energy E_g.

The number of electrons (n_e) set free at absolute temperature T is given by

$n_e = ce^{-E_g/2kT}$

K = Boltzmann constant or a given E_g clearly n_e increases as the temp increases.

- As each free electrons create one hole, so in an intrinsic semiconductor the number density of free electrons (n_e) is equal to the number density of holes (n_n) and each is equal to the intrinsic charge carrier concentration (n_i).

  ($n_e = n_n = n_i$).
- Holes acts as a positive charge carrier and give rise to a hole current I_n. The thermally generated free electrons give rise to an independent electron current I_e

  Total current is $I = I_e + I_n$

DOPING: -

The process of deliberate addition of a desirable impurity to a pure semiconductor so as to increase its conductivity is called doping.

The impurity atoms added are called dopants and the semiconductor doped with the impurity atoms are called extrinsic or doped semiconductors.

Two types of dopants: -

(i) Pentavalent dopants: - They have 5 valence electrons.

For ex: - arsenic (As), antimony (Sb), and phosphorous (P).

(ii) Trivalent dopants: - They have 3 valence electrons.

For ex - Indium (In), boron (B), and aluminium (Al).

On doping Si or Ge with pentavalent and trivalent impurity atoms, we get two entirely different types of semiconductors, called n-type and p-type semiconductors.

Extrinsic semiconductors: -

A semiconductor doped with some suitable impurity atoms so as to increase its number of charge carriers is called an extrinsic semiconductor.

Two types: - 1. n-type semiconductors

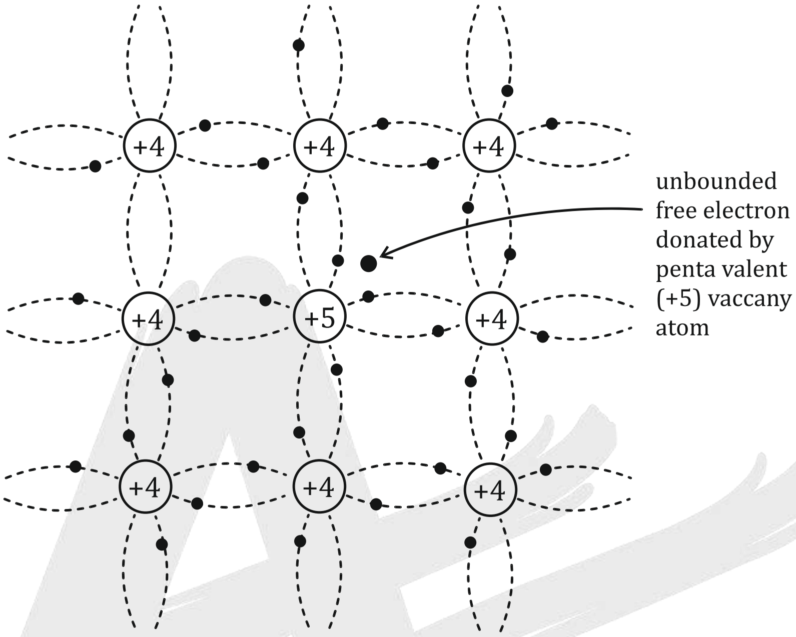
2. P-type semiconductors.

1. n-type semiconductor: -

The semiconductor is obtained by doping the tetravalent Semiconductor (Si) or (Ge) with pentavalent impurities such as As, P or Sb of group V of the periodic table. When a pentavalent impurity atoms substitutes the tetravalent Si atoms, it uses four of its five valence electrons in forming four covalent bonds with neighbour Si atoms while the fifth electron is loosely bound to the impurity atom.

A very small amount of ionization energy (0.01eV) is required

n-type



In n-type semiconductor electrons are the majority charge carries and holes are the minority charge carriers. $n_e \gg n_n$.

P-type semiconductor: -

Such a semiconductor is obtained by doping the tetravalent semiconductor Si or Ge with trivalent impurities such as In, B, Al or Ga.

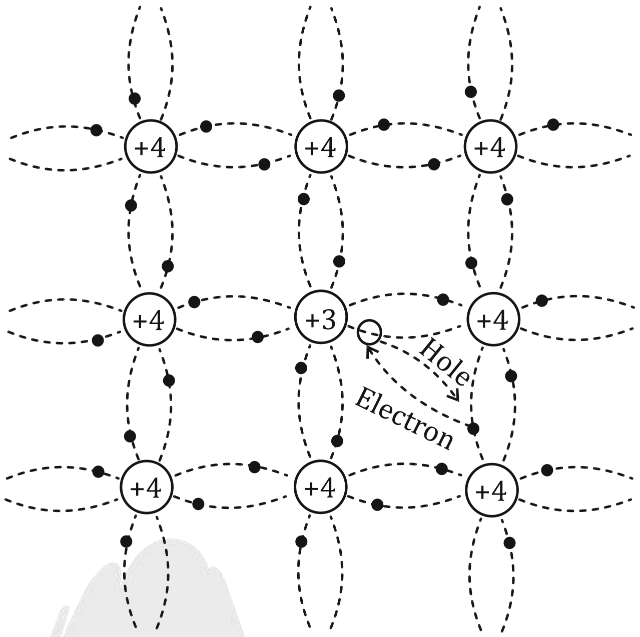
The impurity atom uses its three valence electrons in forming covalent bonds with three neighbouring Si atoms and one covalent bond with a neighboring Si atom is left incomplete due to the deficiency of one atom.

An electron from the neighboring Si-Si covalent bond can slide into this vacant bond, creating a vacancy or hole in that bond.

The hole is now available for conduction.

The trivalent impurity atom is called an acceptor.

Current in these semiconductors is carried by holes which have effective positive charge. For such semiconductors [$n_n \gg n_e$ or $p >> n$]



For Semiconductor

$n_e n_n = n_i^2$

where, n_i = intrinsic charge carrier concentration

n_n = concentration of holes.

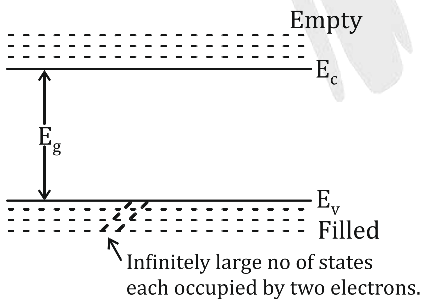
n_e = concentration of electrons:

ENEGRY BANDS IN SOLIDS

A solid in general, has two distinct bands of energies (called valence band and conduction band) which the electrons in a material may lie.

The lowest conduction band energy is E_c and the highest valance band energy is E_v and the energy gap between them is

$E_g = E_c - E_v$



Both valence and conduction bands have an infinitely large number of closely spaced energy levels. All energy levels in the valance band are filled while the energy levels in the conduction band may be fully empty or partially filled.

DISTINCTION BETWEEN METALS, INSULATORS AND SEMICONDUCTORS ON THE BASIS OF BAND THEORY :-

Metals: -

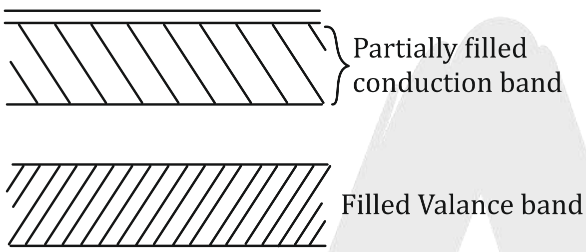
Here the last occupied band, called conduction band is partially filled with electrons

Two type of band structure are found in metals: -

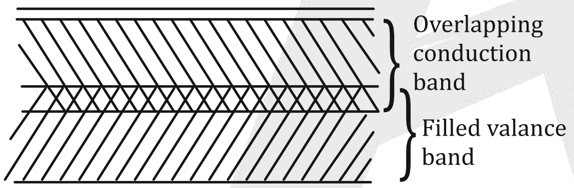
(i) Either there is energy gap between the completely filled valance band and the partially filled conduction band.

Ex. - Alkali metals.; Noble Metals, (Li, Na, K etc.) (Cu, Ag, Au)

Third ground Metals like (Al, Ga, In and Tl).



(ii) Or the Conduction and valance band partially overlap. Ex: - Be, Mg, Zn.



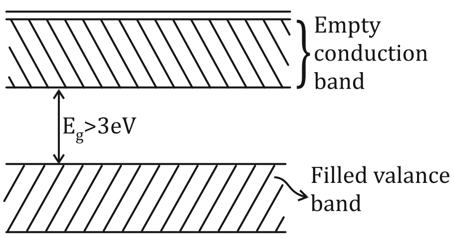
→ The highest energy level in the conduction band filled up with electrons at absolute zero is called Fermi level and energy corresponding to the Fermi level is called Fermi Energy.

→ Many electrons after gaining a slightly amount of energy from any source get excited to the empty energy levels lying immediately above the Fermi level and become free to conduct electricity. This makes available a large no. of conduction electrons.

So, Metals have low resistivity and high conductivity.

Insulators :-

In insulators, the valance band is completely filled while the conduction band is empty.

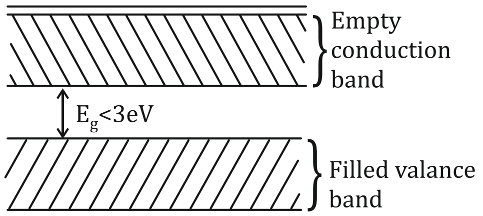


There is a large energy gap [$E_g > 3eV$] between the valence and conduction bands.

Due to lack of free electrons in conduction band the insulators are poor conductors of electricity.

Semiconductors: -

At 0, K the conduction band is empty and the valance band is filled. So, the material is like insulator at low temperature. However, the energy gap between conduction band and valance band is small ($E_g < 3ev$).



$E_g = 1.17ev$ for Si

$E_g = 0.74ev$ for Ge.

At room temp. some valance electrons acquire enough thermal energy and jump to the conduction band where they are free to conduct electricity.

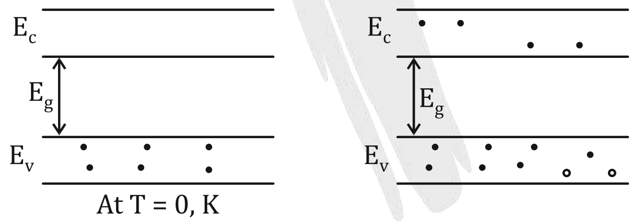
Thus the semiconductor acquire a small conductivity at room temperature.

ENERGY BANDS OF INTRINSIC AND EXTRINSIC SEMICONDUCTORS

Intrinsic conductors

At $T = 0, k$ the valance band of a semiconductor is completely filled with electrons while the conduction band is empty.

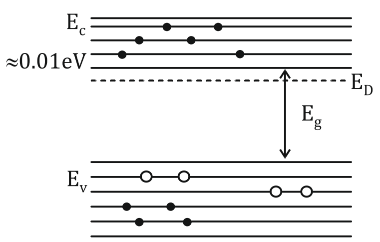
Hence an intrinsic semiconductor be have like an insulator at $T = 0. K$. At higher temp ($T > 0$ K) some electrons of the valance band gain sufficient thermal energy and jump to conduction band creating an equal no. of holes in the valance band.



EXTRINSIC

n-Type semiconductors

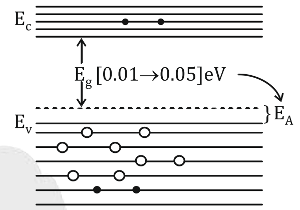
In n-type semiconductors the extra (fifth) electron is very weakly attracted by the donor impurity. A very small energy ($\approx 0.01ev$) is required to free this electron from the donor impurity.



The conduction band has more electrons (than holes in valence band) as they have been contributed both as thermal excitation and donor impurities.

P-Type semiconductors: -

In p-type semiconductors, each acceptor impurity creates a hole Which can be easily filled by an electron of Si-Si covalent bond. i.e. a very small energy ($\approx 0.01 - 0.05$ev) is required by an electron of the valance band to move into this hole. Hence the acceptor energy level E_A lies slightly above the top of the valance band.



At room temp. many of the valance band gets excited to these energy levels leaving behind equal no. of holes in the valance band. These holes can conduct current valance band.

n-type semiconductors

1. These are extrinsic semiconductors obtained by doping impurity atoms of group V to Ge or Si crystal.

2. The impurity atoms added provide free electrons and are called donors

3. The donor impurity level lies just below the conduction band.

4. The electrons are majority charge carriers while holes are minority charge carriers.

5. The free electron density is much greater than hole density i.e. $n_e \gg n_h$

P-type Semiconductors.

1. These are extrinsic semiconductors obtained by doping impurity atoms of group III to Ge or Si crystal.

2. The impurity atoms added create vacancies of electrons (or holes) and are called acceptors.

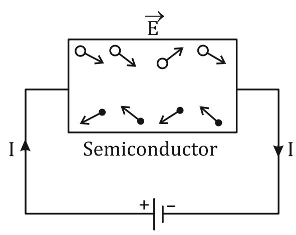
3. The acceptor impurity level just lies above the valance band.

4. The holes are majority charge carriers while electrons are minority charge carriers.

5. The hole density is much greater than free electron density i.e. $n_h \gg n_e$.

ELECTRICAL CONDUCTIVITY OF A SEMICONDUCTOR

Consider a block of semiconductor of length l, area of cross-section A, and having free electron density n_e and hole density n_h.



suppose a potential difference V is applied across its ends. The electric field setup inside it will be $\left[E = \frac{V}{l}\right]$

Electrons begin to drift with velocity v_e in the opposite direction of E while holes drift in the direction of E with velocity v_h.

Total current = Electron current + Hole current

$I = I_e + I_n$ $\quad$ [μ_e = Electron mobility]

$I_e = n_e eAV_e, I_n = n_n\ eAV_h$ $\quad$ [μ_n = Hole Mobility]

$I = eA(n_e v_e + n_h v_h)$

If R is the resistance of the semiconductor block and P its resistivity $R = P\frac{l}{A}$.

If the applied field E is low the Semiconductor obey ohm's law.

$$I = \frac{V}{R} = \frac{El}{Pl/A} = \frac{EA}{P} \Rightarrow I = \frac{EA}{P} = eA(n_e v_e + n_h v_h)$$

$$\frac{E}{P} = e(n_e v_e + n_h v_h), \mu_e = \frac{v_e}{E}, \mu_h = \frac{v_h}{E}$$

$$\frac{E}{P} = e(n_e \mu_e E + n_h \mu_h E) \Rightarrow \frac{1}{p} = e(n_e \mu_e + n_h \mu_h).$$

$$\sigma = \frac{1}{P} \Rightarrow \sigma = e(n_e \mu_e + n_h \mu_h)$$

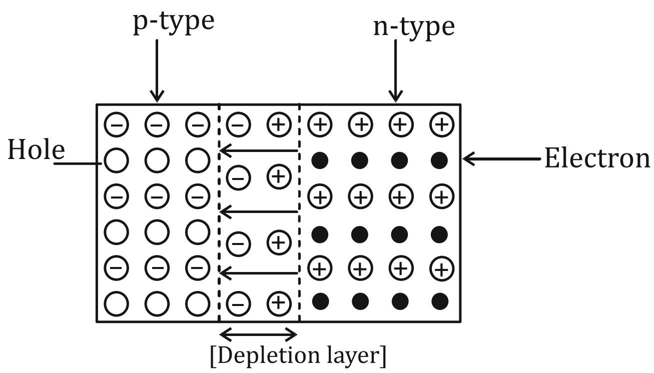
P-N JUNCTION

It is a single crystal of Ge or Si doped in such a manner that one half portion of it acts as p-type semiconductor and other half as n-type semiconductor.

A p-n junction cannot be made just by placing a p-type semiconductor in close contact with n-type semiconductor. It is a single piece of semiconductor crystal having an excess of acceptor impurities into one side and of donor impurities in to the other.

DEPLETION REGION AND POTENTIAL BARRIER

The small region in the vicinity of the junction which is depleted of free charge carriers and has only immobile ions is called depletion region.



Due to concentration gradient at the junction holes begin to diffuse from p-side to n-side

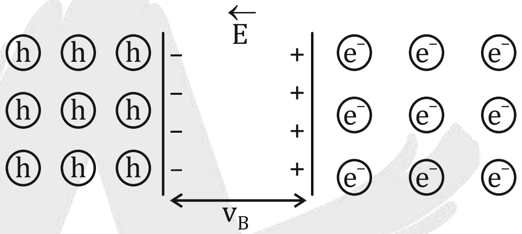
(P → n) and electrons begin to diffuse from n side to p side (n → p).

As holes diffuse from p → n side they leave behind –ve acceptor ions which set up a layer of negative charge or negative space charge region on the p side of the junction, Similarly as the electron diffuse from n – p Side they leave behind +ve donor ions which set up a layer of positive charge or positive space charge on the n-side of the region.

POTENTIAL BARRIER

The distribution of Charge near the junction i.e. The accumulation of negative Charges in the p-region and positive charges in the n-region sets up a potential difference across the junction. This acts as a barrier and called potential barrier.

Which opposes the further diffusion of electrons and holes.



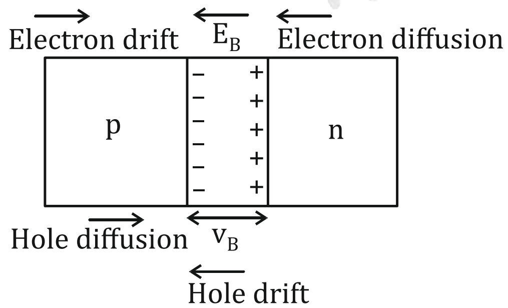
Diffusion Current

Only those electrons and holes which have energy at least eV_B are able to cross the barrier and some diffusion takes place. This diffusion of majority charge carriers across the junction give rise to an electric current from p → n side and is called diffusion current.

Drift current

The electric field E_B immediately pushes the electrons towards the n-side and hole towards the p-side. This current setup by the barrier field from n → p side is called drift current

- The drift current and diffusion current are in opposite directions. In equilibrium state, the diffusion current is equal to the drift current and there is no net flow of charge across the junction.



- The barrier potential V_B depends

  on (i) The nature of the semi conductor

  (ii) Temperature

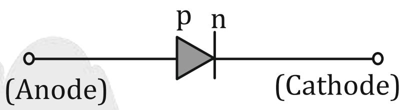
  (iii) Doping concentration.

The value of brier potential is 0.7 V for Si and 0.3 V for Ge semiconductors.

- If the concentrations are small then the diffusion electrons and holes will cover large distances before they suffer a collision with another hole or electron to recombined. Hence the width of the depletion layer will be large and the barrier field will be weak on the other hand, if the doping concentration are large, the depletion layer width will be small and the barriers field will be strong.

Circuit symbol for a p – n junction

A p – n junction has two electron connections one on the P-side and another on the n-side. Hence it is also know as junction diode.

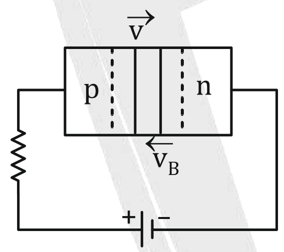


The direction of arrow is from p-region to n-region. The arrow indicates the direction in which the conventional current can flow easily.

Working of a p – n junction

1. Forward biasing

If the positive terminal of the battery is connected to the P - side and the negative terminal to the n-side, then the p – n junction is said to be forward biased.



Here applied voltage opposes the barrier voltage V_B. As a result of this.

(i) The effective barrier potential decreases to $(V_B - V)$ and hence the energy barrier across the junction decreases.

(ii) The majority charge carriers i.e. holes from p-side and electron from n-side begin to flow towards the junction

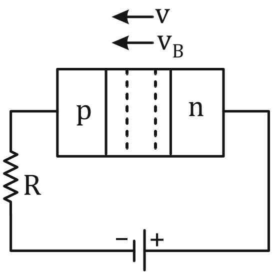
(iii) The diffusion of electrons and holes into the depletion layer decreases it width

(iv) The effective resistance across the p – n junction decreases.

- When V exceeds V_B the majority charge caries starts flowing easily across the junction and setup a large current (mA), called forward current the Ckt. The current increases with the increase in applied voltage.

2. Reverse biasing

If the positive terminal of a battery is connected to the n-side and the negative terminal to the p-side then the p − n junction is said to be reverse biased.



As a result of this

(i) The barrier potential increases to $(V_B + V)$ and hence the energy barrier across the junction increases.

(ii) The majority charge carriers moves away from the junction, increasing the width of the depletion layer.

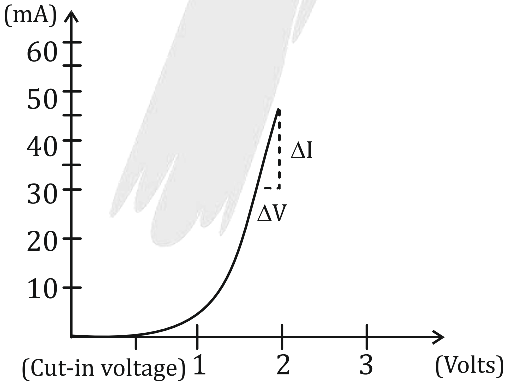
(iii) The resistance of the p − n junction become very large

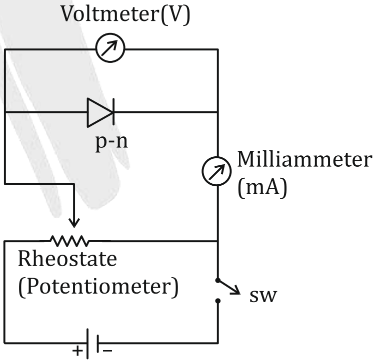
(iv) No current flows across the junction due to majority charge carriers.

V-I CHARACTERISTICS OF A. P-N JUNCTION DIODE

1. Forward bias characteristic

Ckt for studing V-I. Characteristic of a forward biased diode.





- A graph showing the variation of current flowing through a p − n Junction with the voltage applied across it.

Important features: -

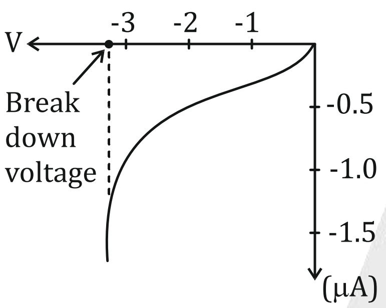
(i) The V-I graph is not a straight line i.e. junction diode doesn't obey ohm's law.

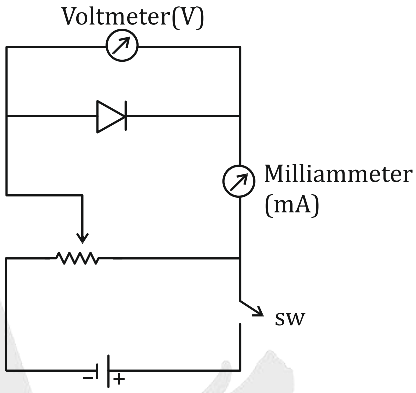
(ii) Initially, the current increases very slowly almost negligibly, till the voltage across the diode crosse a certain value called the threshold-voltage or cut-in-voltage. The value of the cut-in voltage is about 0.2V for a Ge diode and 0.7V for a Si diode.

Before this characteristic voltage, the depletion layer plays a dominant role in controlling the motion of charge carriers.

(iii) After the cut-in voltage, the diode current increases rapidly even for a very small increase in the diode be as voltage. Here the majority charge carriers feel negligible resistance at the junction i.e. the resistance across the junction is quite low.

2. Reverse bias Characteristic





Important features: -

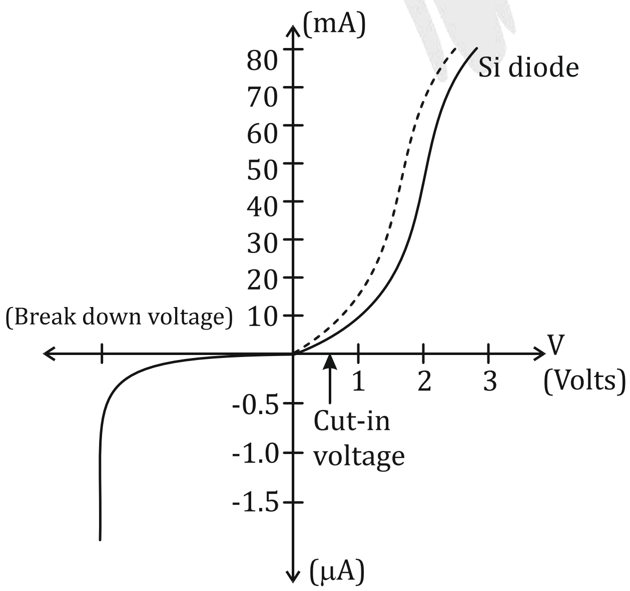
(i) When the diode is reverse biased, the reverse bias voltage produces a very small current. This small current is called reverse saturation current.

It is due to the drift of minority charge carriers (a few holes in the n-region and few electrons in p-region) across the junction.

(ii) When the reverse voltage across the p-n junction reaches a sufficiently high voltage, the reverse current suddenly increases to a large value.

The voltage at which breakdown of the junction diode occurs is called Zener breakdown voltage or peak -inverse voltage of the diode.

<u>V-I of P-n junction</u>



DYNAMIC RESISTANCE OF A JUNCTION DIODE

The current - voltage graph of junction diode is nonlinear i.e. ohm's Law is not obeyed. The resistance of the junction diode varies with the applied voltage.

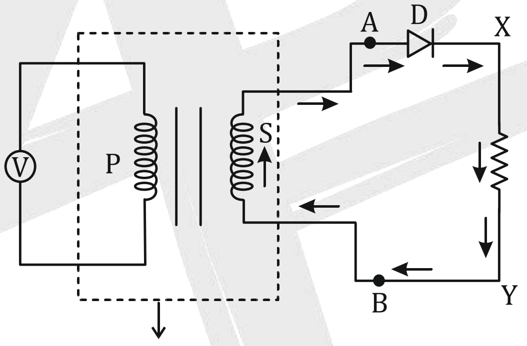
Dynamic resistance is the ratio of the small change in applied voltage ΔV to the corresponding change in current ΔI

$$r_d = \frac{\Delta V}{\Delta I}$$

Above the threshold voltage, the diode characteristic is linear. In the linear region, r_d is almost Independent of V and ohm's Law is obeyed.

Junction diode as a half -wave rectifier

A half wave rectifier consists of a transformer, a junction diode D and a load resistance R_L. The primary coil of the transferer is connected to the a.c mains and the secondary coil is connected in series with the junction diode D and load resistance R_L.



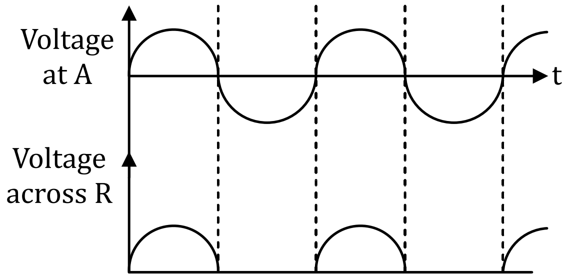
working: -

When a.c is supplied to the primary, the secondary of the transformer supplies desired alternating voltage across A and B. During the positive half cycle of A. C, then end A is +ve and the end B is -ve.

The diode D is forward biased and a current I flows through R_L. As the input voltage increases or decrease, the current I also increases or decreases and so does output 'voltage (IR_L) across. the load R_L.

During the negative half cycle, the end A becomes negative and B positive. The diode is reverse biased and no current flow no voltage appears across R_L. In the next positive half cycle again we get output voltage.

Since, the voltage across the load appears only during the +ve half cycle of the input a.c, this process is called half wave-rectified.



Junction Diode as a full wave Rectifier: -

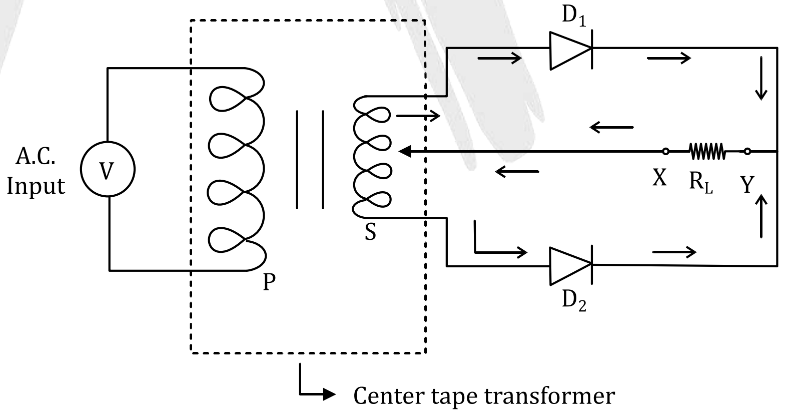
A fill wave rectifier consists of a transformer, two junction diodes D_1 and D_2 and load resistance R_L. The input a · c signal is fed to the primary coil P of the transformer. The two ends A and B of the secondary s are connected to the p − ends of diodes D_1 and D_2. The secondary is tapped at its central point T which is connected to the n-ends of the two diodes through the load resistance R_L.

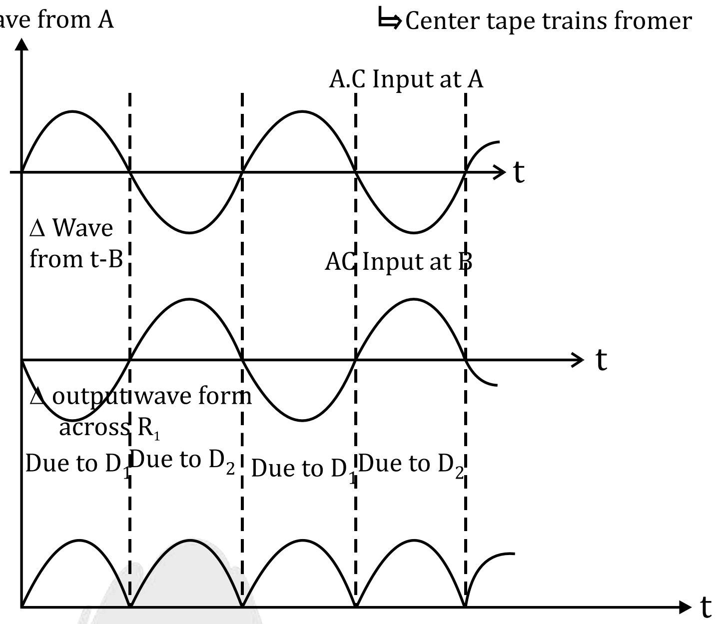
Working: -

Suppose during the positive half cycle of a.c input, the end A is positive and the end B is negative w.r.t the center tap T. Then the diode D_1 gets forward biased and conducts current also the path AD_1 XYTA as indicated by the solid arrows. The diode is reverse biased and does not conduct.

During the negative half cycle, the end A becomes negative and end B becomes positive w.r.t the center tap T. The diode D_1 get reverse biased and does not conduct.

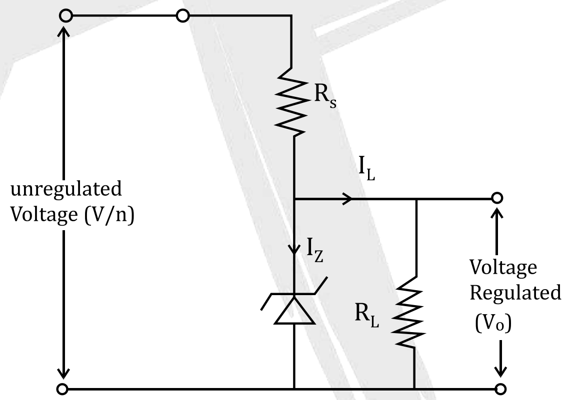
The diode D_2 conducts current along the path BD_2XYTB, as indicated by broken arrows. As during both half cycles of input a.c the current through load R_L flows in the same direction (X → Y), so we get a pulsating d. C.





Zener Diode as a Voltage Regulator: -

When a Zener diode is operated in the reverse breakdown region, the voltage across it remains practically constant (equal to the break down voltage V_z) for a large Change in the reverse current. The use of zener diode as a d.c Voltage regulator is based on this fact.



working: -

Zener diode is connected in reverse bias to a source of fluctuating d.c [the output from a rectifier] through a dropping resistor R_S. Thus the voltage gets divided between R and Zener diode. The output is obtained across the load resistor R_L, connected in parallel with the Zener diode.

If the input voltage increases, the current through R_s and Zener diode also increases. This increase the voltage drop across R_s without any change in the voltage across the Zener diode. This is because in the breakdown region, Zener voltage remain constant even though the current through the Zener diode changes.

Similarly, if the input voltage decreases, the voltage across R_s decrease without any change in the voltage across the Zener diode. Thus any increase/ decrease of the input voltage results in increases or decrease of the input voltage drop across R_s without any change in voltage across Zener diode. Hence the Zener diode acts as a voltage regulator.