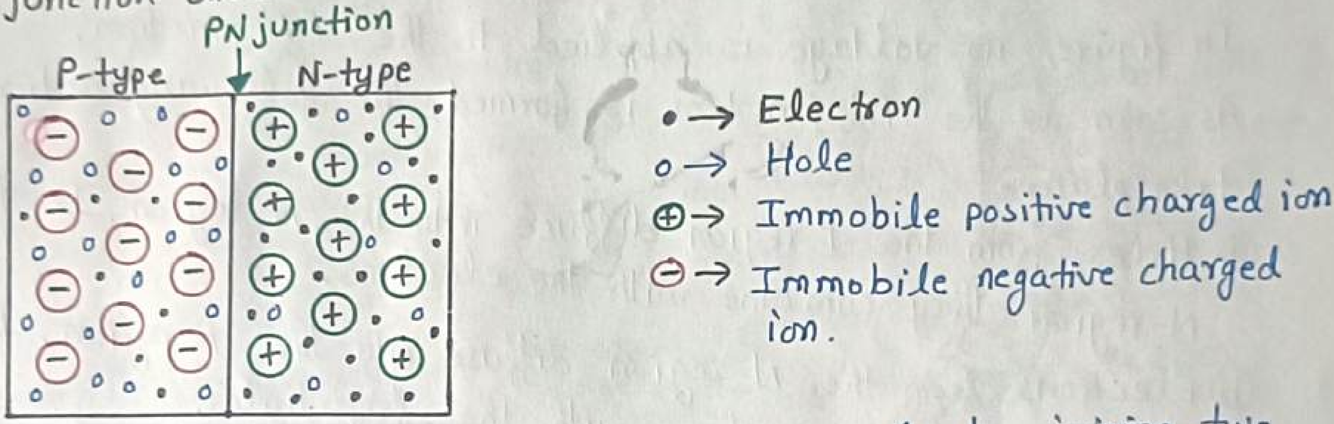
Chapter Two:- Semiconductor Diode

If a piece of P-type semiconductor is joined with a piece of N-type semiconductor in such a manner that the crystal structure remains continuous at the boundary, then a new structure called P-N junction is formed. Such a PN-junction makes a versatile device which is called a semiconductor diode, P-N junction diode or simply diode.

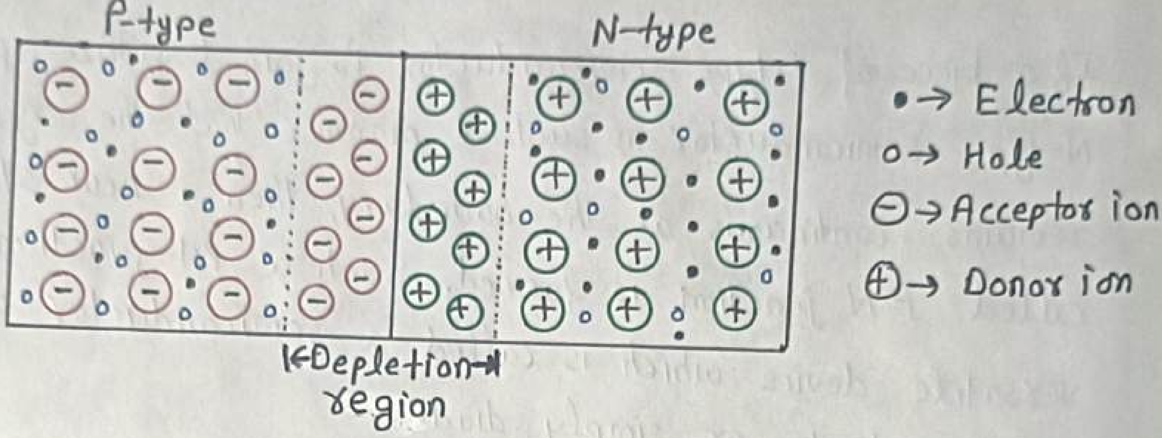


Note:- The P-N junction cannot be made simply by joining two pieces. Special fabrication techniques are required to form a P-N junction. A semiconductor P-N junction is formed when a wafer of the semiconductor material such as silicon is doped so that one region is N-type and the other region is P-type.

Depletion Layer: Depletion Region formation

PN-junction with depletion region formed at the junction is shown in figure. The P-region contains holes as majority carriers, electrons as minority carriers and negative charged immobile ions called acceptor ions.

The N-region contains electrons as majority carriers, holes as minority carriers and positive charged immobile ions called donor ions.



In figure, no voltage is applied to the P-N junction. As soon as the PN-junction is formed, the following actions take place:-

(a) Holes from the P-region diffuse into the N-region. In the N-region, they combine with the electrons.

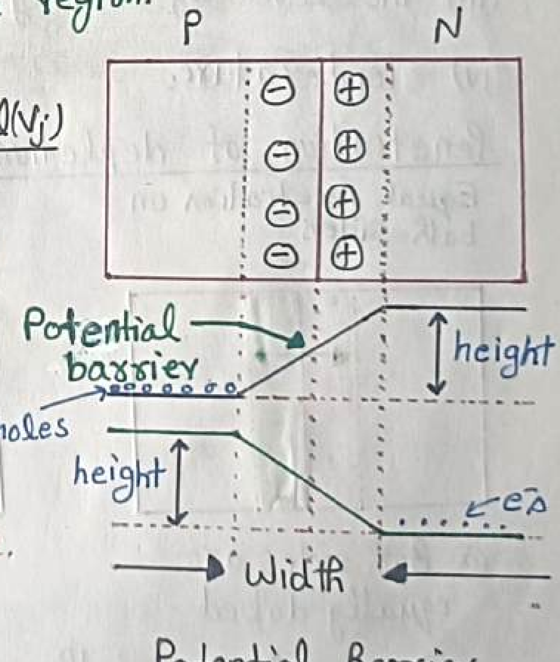
(b) Electrons from the N-region diffuse into the P-region. In the P-region, they combine with the free holes.

(c) As holes are majority carriers in P-type and electrons are majority carriers in the N-type, therefore there is a difference of concentrations in the two regions. A concentration gradient is produced due to the difference in concentration.

(d) The process of diffusion continues only for a short period of time. After a few recombination of holes and electrons, a restraining force is set up automatically in the neighbourhood of the junction. This restraining force is called barrier. As a result of this force, further diffusion of holes and electrons from one region to other is checked [or stopped].

(e) Due to the diffusion of electrons and holes across the junction, the negative acceptor ions in the P-region and positive donor ions in the N-region are left uncovered in the neighbourhood of the junction. Now, when further holes try to diffuse into N-region, they are repelled by the uncovered positive charge of the donor ions. Similarly, further electrons trying to diffuse into the P-region are repelled by the uncovered negative charge of the acceptor ions. As a result, further diffusion of electrons and holes across the junction is stopped.

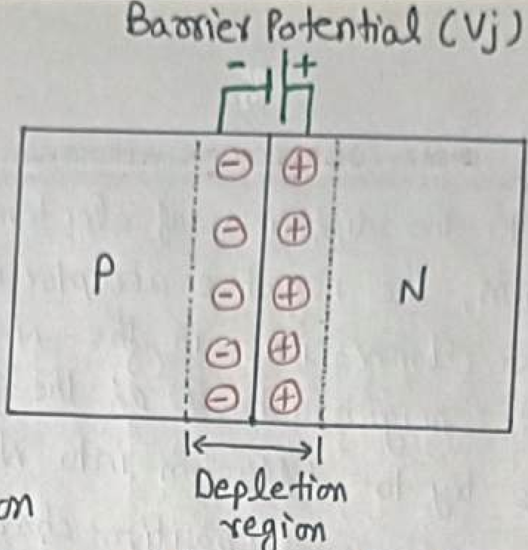
(f) The region having the uncovered acceptor and donor ions is called **depletion region**. The reason for this is that there is a depletion of mobile charge carriers in this region. This region contains immobile or fixed ions which are electrically charged. Therefore, this depletion region is also called as **space-charge region**.



Potential Barrier

Barrier Potential or Junction Potential (V_j)

Due to the presence of immobile positive and negative ions on opposite sides of the junction, an electric field is created across the junction. This electric field is known as **barrier potential or junction potential or cut-in voltage**. It has fixed polarities as show



in the figure. The negative terminal of the barrier potential is on the P-side and positive terminal is on the N-side. This is called as the barrier potential or junction potential because it acts as a barrier to oppose the flow of electrons and holes across the junction. Barrier potential is measured in volts.

S.N	Material	Barrier Potential
1	Si	0.7 V
2	Ge	0.3V.

Factors on which potential barrier depends

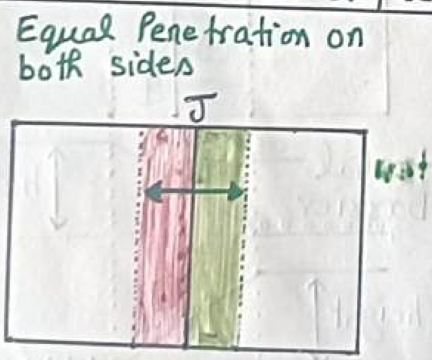
(i) Semiconductor material used [Si or Ge].

(ii) The intrinsic concentration of Si or Ge before doping.

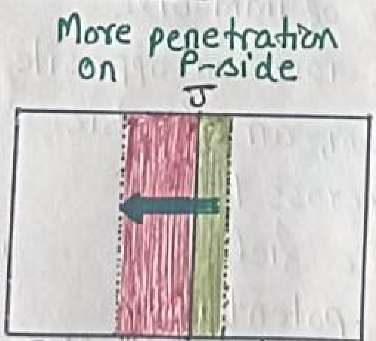
(iii) The level of doping on P and N-sides.

(iv) Temperature

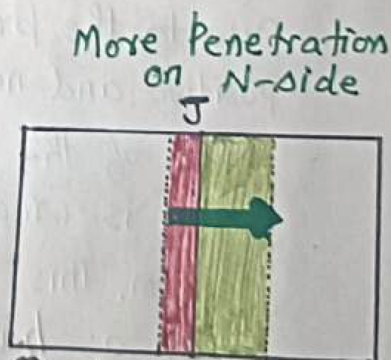
Penetration of depletion region



ⓐ Both sides are equally doped



ⓑ P-side is lightly doped



ⓒ N-side is lightly doped.

The penetration of the depletion region into P or N-side depends on the doping levels.

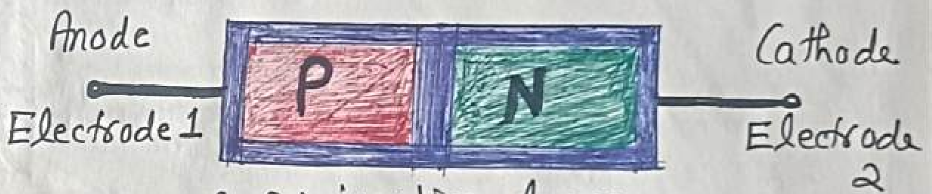
ⓐ If both sides are equally doped then the depletion region penetrates equally on both sides.

ⓑ If P-region is lightly doped as compared to the N-region then the penetration of depletion region is more on the P-side.

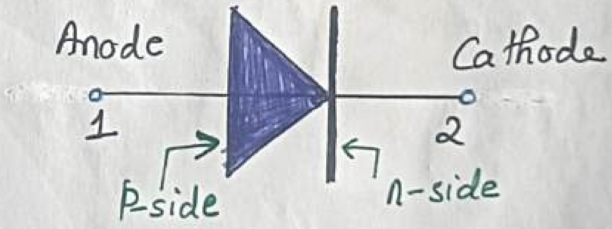
ⓒ Similarly, if N-side is lightly doped as compared to P-side then the depletion region extends more into the N-side.

PN- Junction Diode

The PN-junction itself forms the most basic semiconductor device called semiconductor diode. The meaning of the term diode is that "device having two electrodes [di-ode].



A PN-junction forms a Semiconductor Diode



Circuit Symbol of a diode

The arrowhead in the symbol points in the direction of conventional current through the device.

Biasing of a P-N Junction Diode

When the P-N junction is formed, the depletion region gets created and the movement of electrons and holes stops. Thus, the current flowing through an unbiased P-N junction is zero. To make the current to flow, biasing of the PN-junction diode is done.

Biasing is the process of applying external DC voltage to the semiconductor diode.

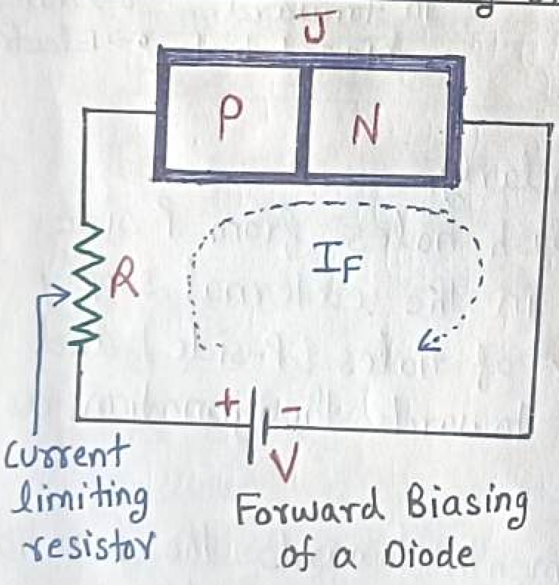
To make the current to flow, it is necessary to bias the diode.

Biasing can be of two types:-

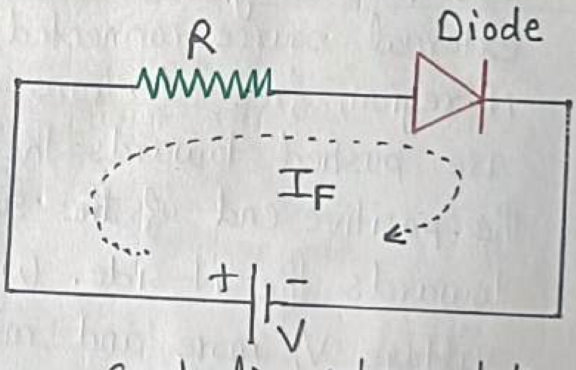
(I) Forward bias

(II) Reverse bias

(I) Forward Biasing of a P-N Junction Diode



Forward Biasing of a Diode

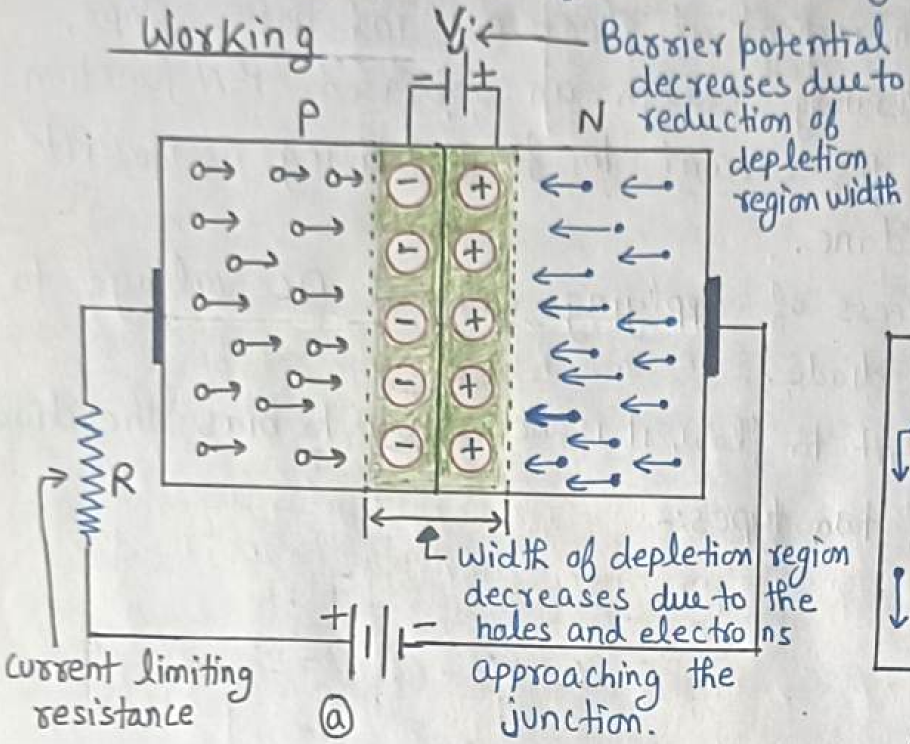


Symbolic representation.

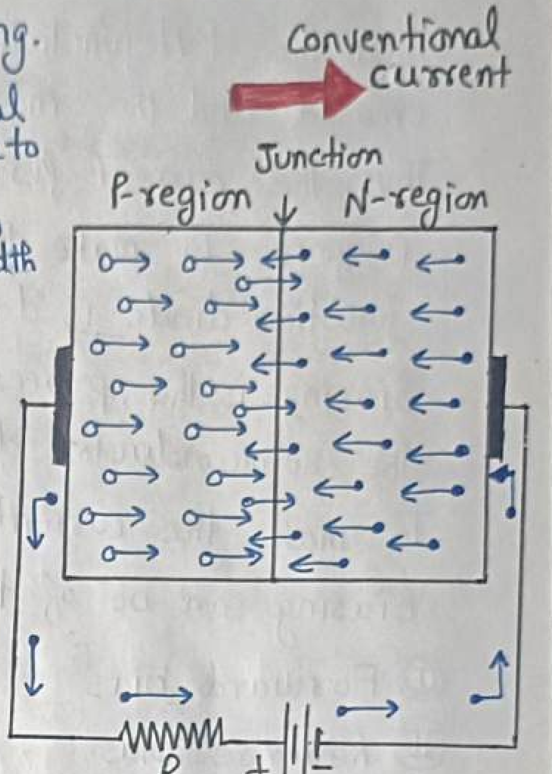
If the P-region is connected to the positive terminal of the external DC source and N-region is connected to the negative terminal of the DC source then the biasing is said to be forward biasing.

Generally, a resistance is connected in series with the diode to limit the current flowing through it. The current I_F is a conventional current that flows in the circuit due to the forward biasing.

Working



ⓐ



ⓑ current flow in forward biased diode

o→ Holes
•→ Electrons

Due to the negative terminal of external source connected to the N-region, free electrons from N-side are pushed towards the P-side. Similarly, the positive end of the supply will push holes from P-side towards the N-side. With increase in the external supply voltage V, more and more number of holes [P-side] and electrons [N-side] start travelling towards the junction as shown in figure ⓐ.

Due to the electrons and holes movements towards the junction, width of the depletion region will reduce. As a result, potential barrier will also reduce. Eventually, at a particular value of V, the depletion region will collapse. Hence, large number of electrons and holes [i.e, majority carriers] will cross the junction and constitute a current called

Forward current.

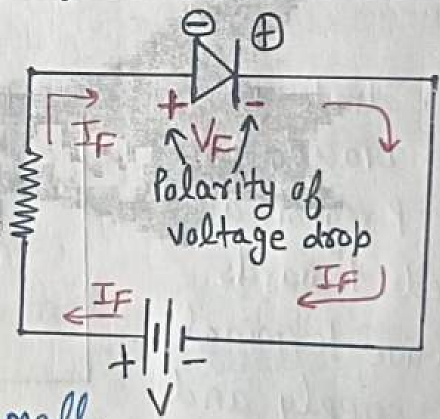
Effect of forward bias on the width of depletion region

With increase in the forward bias, the width of the depletion region decreases and so does the barrier potential.

Current flow in forward biased diode

When free electrons enter into the P-region from the N-side, they become valence electrons. So, these electrons will jump from one atom to the other to fill up the holes present there. Thus, movement of electrons on P-side will be due to the movement of holes.
These electrons will move towards the positive end of the source and the holes will move towards the junction. Hence, movement of majority carriers will cause forward current.

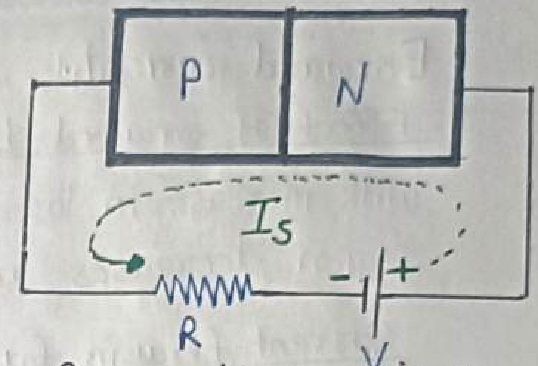
Forward resistance of diode and Voltage drop across the forward biased diode (V_F)



The forward current of a diode (I_F) is the current due to the movement of majority carriers. Hence, I_F is measured in mA.
Due to large current, the forward resistance of the diode is very small.
Typically, of the order of few ohms [10 to 100Ω].
The forward voltage drop is denoted by V_F and it is equal to 0.7V for Silicon and 0.3V for Germanium diode.

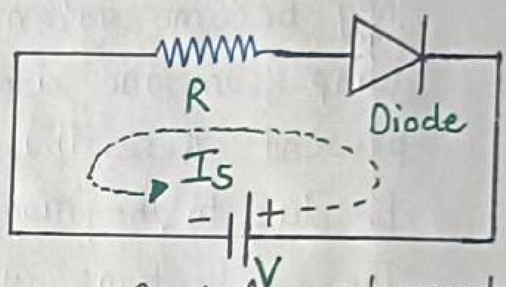
(II) Reverse Biasing of a Diode

If the P-region of a diode is connected to the negative terminal of the external DC supply and N-region is connected to the positive terminal of the DC supply, then a diode is said to be reverse biased.



Reverse biasing in a semiconductor diode

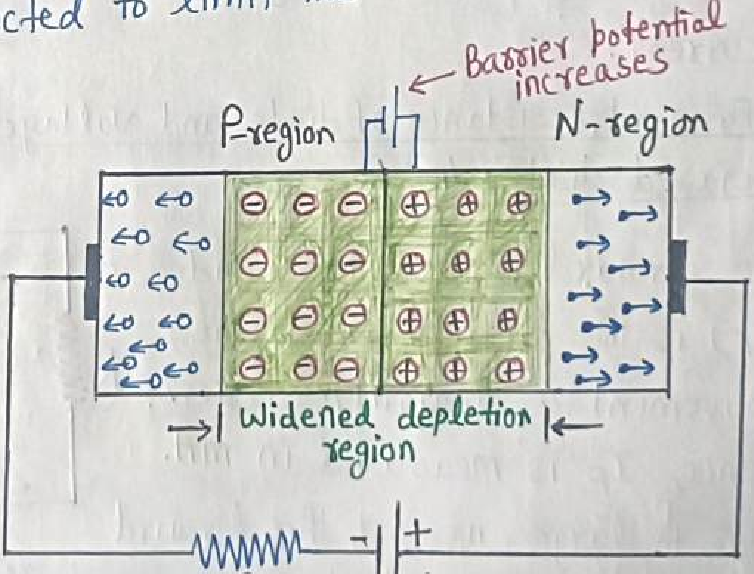
The reverse current is denoted by I_S and it flows from the cathode to anode of the diode. Clearly, reverse current I_S flows exactly opposite to the direction of forward current I_F.



Symbolic representation

Resistance R is connected to limit the reverse current.

Working

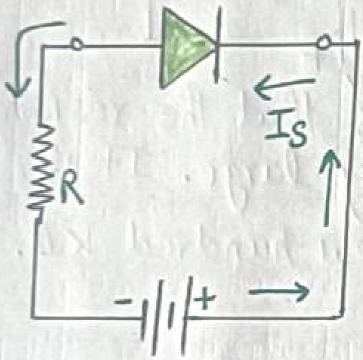


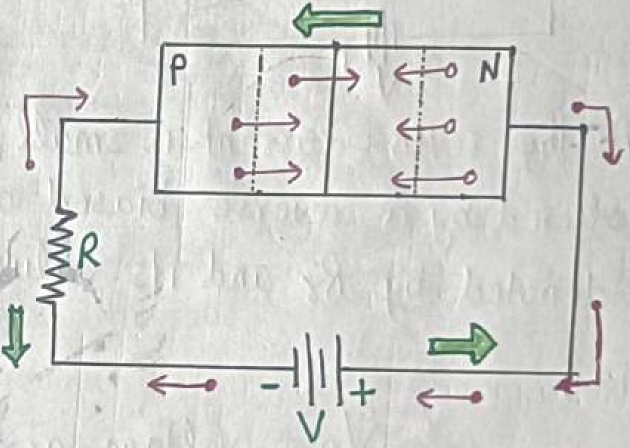
When a diode is reverse biased, holes in the P-region are attracted towards the negative terminal of the supply and electrons on the N-side are attracted towards the positive terminal of the supply.

(a) Widening of depletion region:- Due to the movement of electrons and holes away from the junction, width of the depletion region increases. This happens due to the creation of more number of positive and negative immobile ions.

ⓑ Increase in barrier potential:- Due to more number of immobile charged ions present on opposite sides of the junction, the barrier potential or junction potential will increase.

ⓒ Current flow in the Reverse Biased Diode [Reverse Saturation Current]





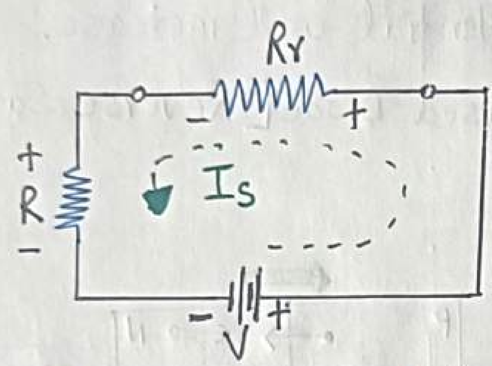
As we know that P-region consists of a small number of electrons and the N-region contains a small number of holes. They are minority carriers which are generated thermally. The minority electrons in the P-region are attracted by the positive end of the dc supply. Hence, these electrons will cross the junction and constitute the reverse current I_S of the diode. The reverse current is also called as Reverse saturation current.

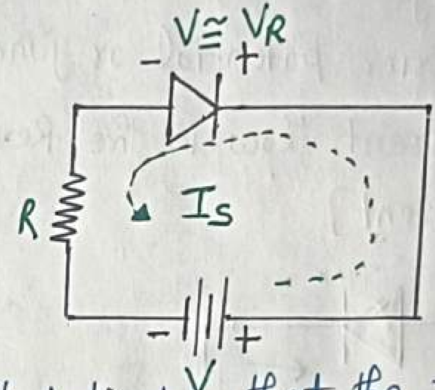
As this current is due to the minority carriers, it is small in amplitude [typically, a few µA → Ge Diode & a few nA → Si Diode]

The reverse saturation current depends on the temperature. It doubles its value for every 10°C rise in temperature.

Note:- Reverse current flows due to minority carriers which exists due to thermal agitation or heat.

(d) Resistance of a Reverse Biased Diode and voltage across reverse biased diode:-





As the reverse current is small, it indicates that the resistance offered by a reverse biased diode is very large. It is denoted by R_r and its value is a few hundred $K\Omega$.

Now,

$$V_R = \text{Voltage across the reverse biased diode}$$

$$= \frac{V \times R_r}{R + R_r} \quad \text{[using voltage divider rule]}$$

But, $R_r >> R$, so,

$$V_R \simeq \frac{V \times R_r}{R_r}$$

$$\Rightarrow \boxed{V_R \cong V}$$

Thus, the reverse voltage is approximately equal to the applied voltage

Barrier Potential and Temperature:-

The junction temperature is the temperature inside a diode i.e. at the PN-junction. The ambient temperature is different and it is the temperature of the air outside the diode. When the diode is conducting, the junction temperature is higher than the ambient temperature due to the heat created by the

Now, the barrier potential depends on the junction temperature. The barrier potential of a silicon diode decreases by 2mV for each degree celsius rise. i.e.,

$$\frac{\Delta V}{\Delta T} = -2mV/^{\circ}C$$

or, $$\Delta V = [-2mV/^{\circ}C]\Delta T$$

Q:- Assuming a barrier potential of 0.7V at an ambient temperature of 25°C, what will be the barrier potential of a silicon diode when the junction temperature is 100°C and at 0°C?

Sol:- When the junction temperature is 100°C, the change in barrier potential will be

$$\Delta V = [-2mV/^{\circ}C]\Delta T$$

or, $\Delta V = [-2mV/^{\circ}C][100-25]$

or, $\Delta V = -2\times10^{-3}\times75 = -150mV.$

It means that the barrier potential decreases by 150mV from its room temperature value. Hence,

$$V_B\Big|_{100^{\circ}C} = 0.7V - 150mV = 0.55V$$

Similarly, $\Delta V = -2\ mV/^{\circ}C\,[\Delta T] = -2\ mV[0-25^{\circ}]$

$= 50mV.$

So, the barrier potential increases by 50mV from its room temperature value. i.e.,

$$V_B\Big|_{0°C} = 0.7 + 0.05 = 0.75V.$$

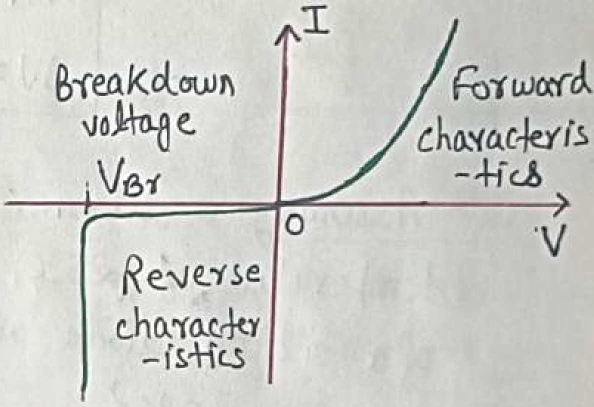
V-I characteristics of a PN-junction diode or Practical Diode

The V-I characteristics of a diode is simply a curve or graph between the voltage applied across its terminals and current that flows through the diode due to this applied voltage.

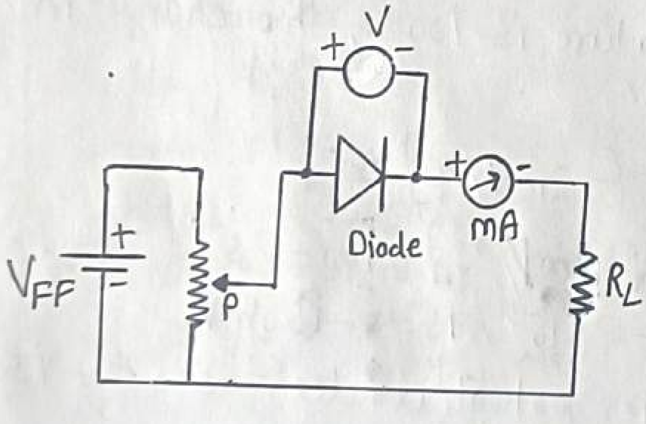
The entire V-I characteristics can be divided into two parts :-

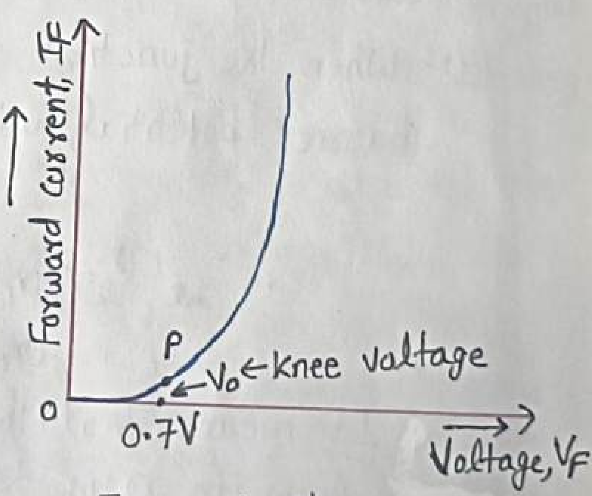
(I) Forward characteristics

(II) Reverse characteristics.



(I) Forward Characteristics



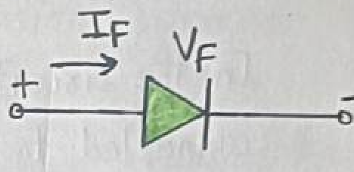


Forward characteris -tics of Si Diode

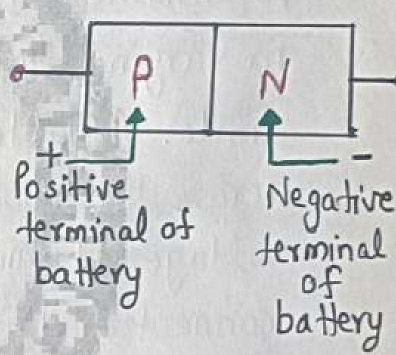
The circuit arrangement shown is used in the laboratory to obtain forward characteristics of a diode. The diode in the circuit is in forward bias state because the battery V_{FF} is pushing the current in the of the arrowhead.

In the circuit, the battery V_{FF} is connected to the diode through potentiometer P. The potentiometer helps in varying the voltage across the diode. The load resistance R_L is used in the circuit to limit the current through the diode. A voltmeter is connected across the diode to measure the voltage. Also, a milliammeter is connected to measure the current in the circuit.

To plot the characteristics, the voltage across the diode is increased gradually and the corresponding increase in the current is noted.



Clearly, from the forward characteristics, we can observe the fact that upto point P, the diode current is very small. This is so because the applied voltage has to overcome the barrier potential and the diode conducts poorly. Once the applied voltage is slightly greater than the barrier potential, the diode current increases rapidly and diode conducts heavily. This voltage at which the current starts increasing is called the knee voltage (V_0). Its value is 0.7V for Si Diode and 0.3V for Ge Diode. The applied voltage across the diode should not increase beyond a specified safe value otherwise the diode will burn out due to heat.



(II) Reverse Characteristics

The circuit arrangement shown is used in the laboratory to obtain reverse characteristics of a diode. The diode in the circuit is in reverse bias state because the battery VRR is pushing the current in the direction opposite to the