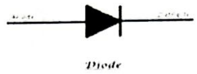
## Semiconductor Physics (18PYB103J)

## UNIT-II

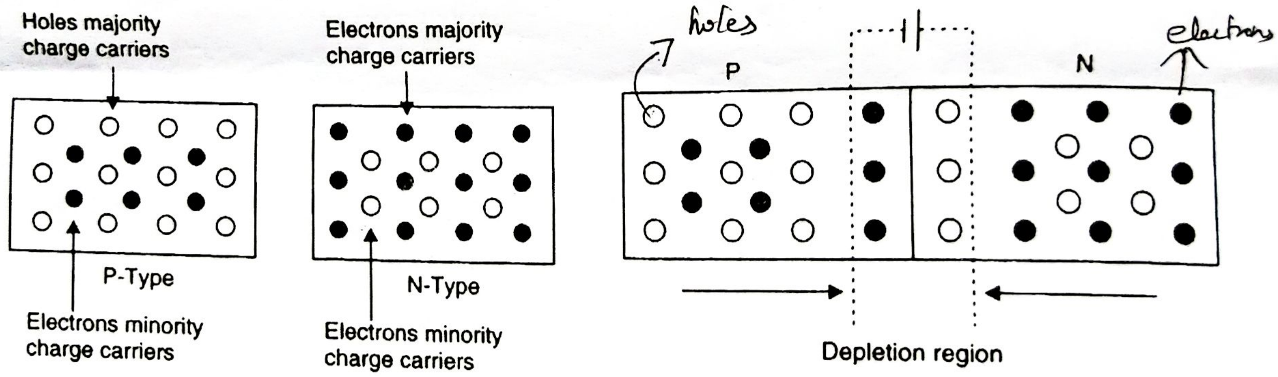
### PN junction diode

- A p-n junction Diode is formed by doping one side of a piece of silicon with a p-type dopant (bor~~a~~on) and the other side with a n-type dopant (phosphorus). The *Ge* can be used instead of Silicon.
- It is one of the simplest semiconductor devices as it allows current to flow in only one direction. The symbol of the p-n junction diode is given here.



### PN Junction at Equilibrium

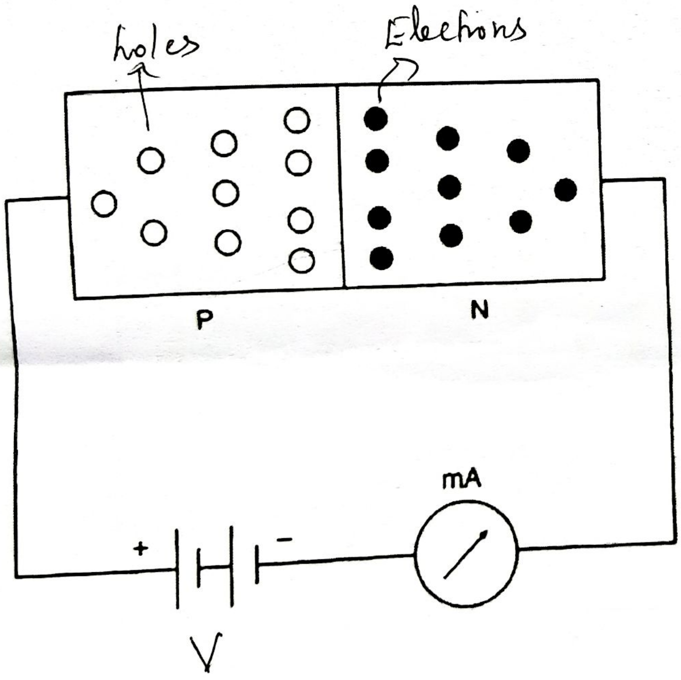
- When two semiconducting materias, p-type and n-type are brought into contact, the majority carrier of each type would diffuse across the junction.
- The diffusion would stop after an electric field is built up sufficiently high to oppose diffusion.
- As the majority carrier such as hole diffuses across the junction, it combines with electron in the n-type side, which creates a net positive charge.

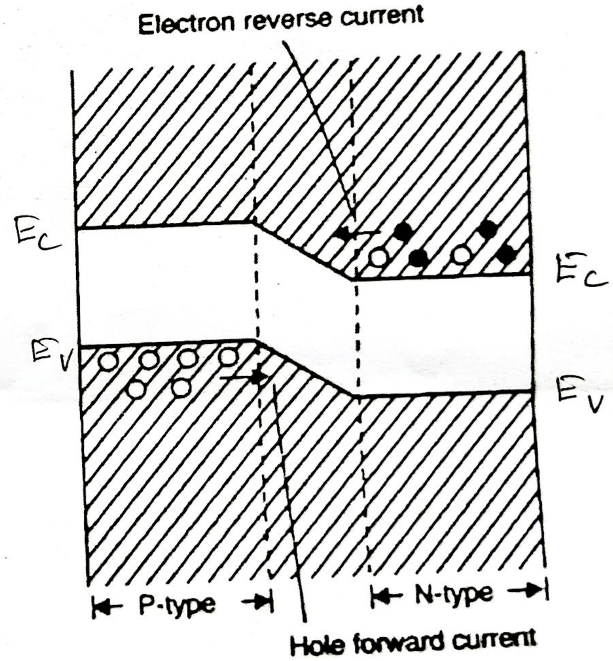



- Likewise, the majority carrier electron from n-type material diffuses across the junction recombines with hole in p-type side creates net negative charge.
- The net charge at each side creates an electric field in the direction, which would oppose further diffusion. This region is called as diffusion region.
- The electric field created would drift the minority carrier in the opposite direction across the junction.
- Thus when equilibrium attained, the drift carriers and diffused carriers should be balanced.

## Forward Bias

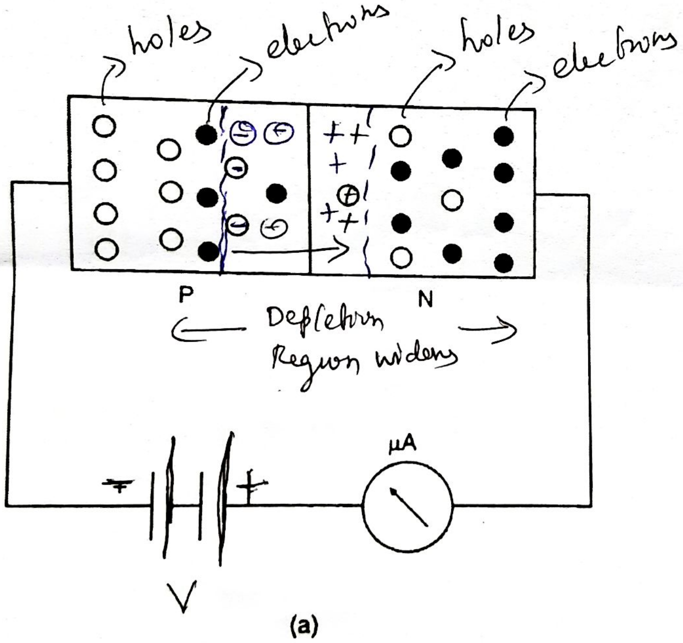
- In the forward bias condition, the negative terminal of the battery is connected to the n-type material and the positive terminal of the battery is connected to the p-type material.
- When the forward bias voltage is increased, the depletion region decreases.
- Now, the electrons from the n-region cross the junction and enter into the p-region. Similarly, the holes from the p-region cross the junction and enter into the n-region.
- Due to the attractive force that is generated in the p-region the electrons are attracted and move towards the positive terminal.
- Simultaneously, the holes are attracted towards the negative terminal of the battery. By the movement of electrons and holes current flows. So, the p-n junction diode conducts electric current in forward bias condition.



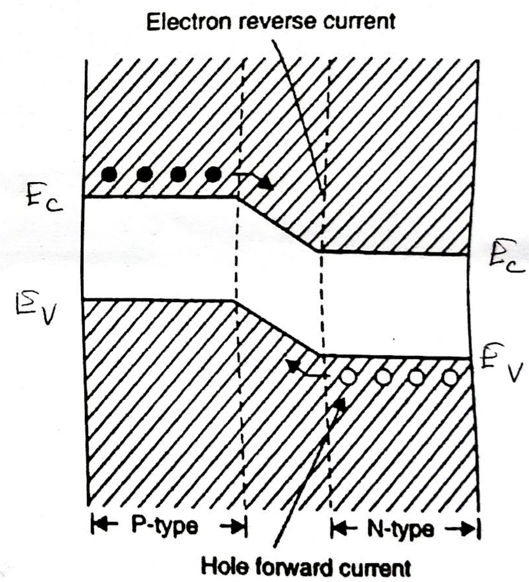



## Reverse Bias

- In the reverse bias condition, the negative terminal of the battery is connected to the p-type material and the positive terminal of the battery is connected to the n-type material.
- When the reverse bias voltage is increased, the depletion region widens. So, no majority carriers cross the junction.
- But, the minority charge carriers are crossing the junction i.e. the minority electrons from p-region move into n-region. Simultaneously, minority holes from n-region move into p-region.
- The movement of minority carriers can cause very low current is in the order of micro ampere range. This current is called as reverse saturation current.
- So, the p-n junction diode does not conduct electric current in forward bias condition.



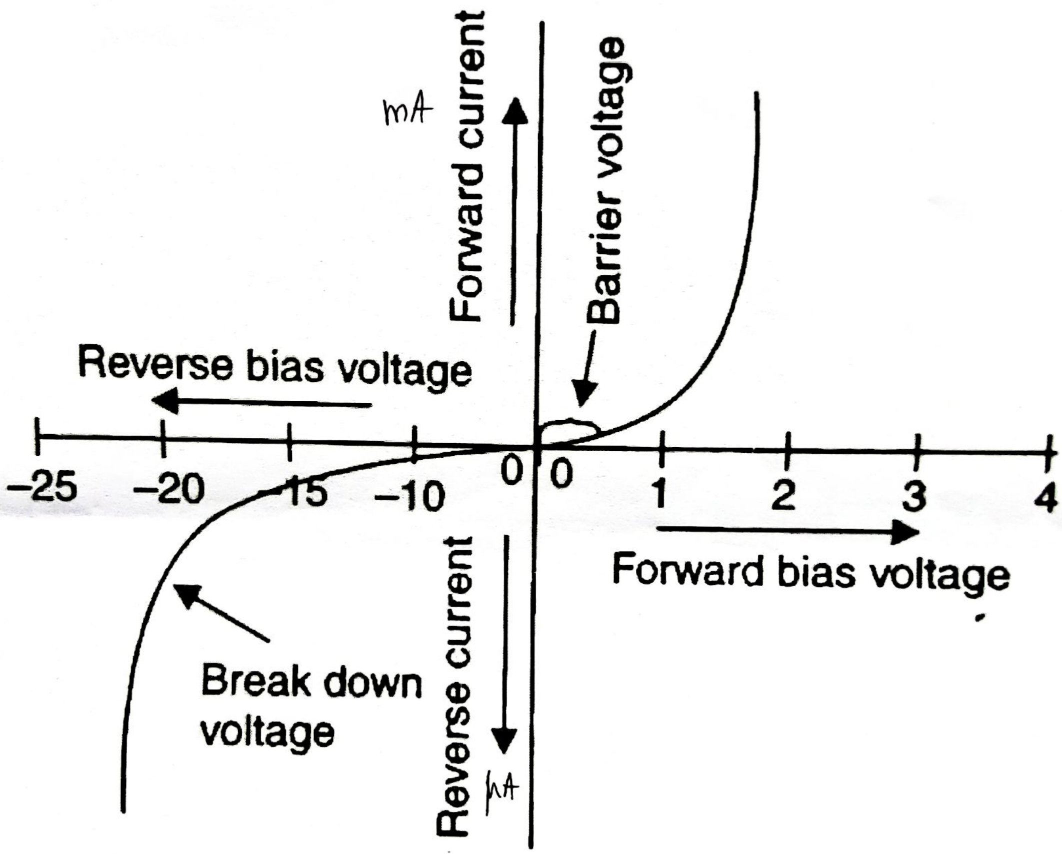

(a)




(b)

## V-I Characteristics

- When the p-n junction diode is forward biased, the electrons get enough energy to overcome depletion layer and cross the junction and the same thing happens with the holes as well.
- The amount of energy required by the electrons and holes for crossing the junction is equal to the barrier potential 0.3 V for Ge and 0.7 V for Si. This is also known as Voltage drop.
- The voltage drop across the diode occurs due to internal resistance.
- The V-I characteristics of p-n junction diode is shown in the graph given below.




- When the p-n junction diode is reverse bias, the movement of minority carriers causes less current flow.
- When the reverse voltage is increased beyond the limit, then the reverse current increases drastically.
- This particular voltage that causes the drastic change in reverse current is called reverse breakdown voltage.

## Variation of Fermi level ($E_F$) on carrier-concentration and temperature in an intrinsic semiconductor:

At temperature 0K, the semiconductor behaves like an insulator. When the temperature of the semiconductor slightly increased some covalent bonds are broken and electron - hole pairs are created. For an intrinsic semiconductor, the charge carriers are electrons in conduction band and holes in valence band in equilibrium the electron concentration and hole concentration are equal.

$$Density\ of\ electrons\ in\ conduction\ band\quad n_e = \int_{E_c}^{\infty} \frac{\pi}{2}\left[\frac{8m_e^*}{h^2}\right]^{\frac{3}{2}} E^{\frac{1}{2}} F(E)\,dE$$

$$n_e = 2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{\frac{3}{2}} \exp\left(\frac{E_F - E_C}{kT}\right) \qquad (1)$$

$$Density\ of\ holes\ in\ valance\ band\quad n_h = \int_{-\infty}^{E_V} \frac{\pi}{2}\left[\frac{8m_h^*}{h^2}\right]^{\frac{3}{2}} E^{\frac{1}{2}}[1 - F(E)]\,dE$$

$$n_h = 2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{kT}\right) \qquad (2)$$

For intrinsic semiconductors, the density of electrons and the density of holes are equal.

$$n_e = n_h$$

$$2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{\frac{3}{2}} \exp\left(\frac{E_F - E_C}{kT}\right) = 2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{kT}\right)$$

$$(m_e^*)^{\frac{3}{2}} e^{\left(\frac{E_F}{kT} - \frac{E_C}{kT}\right)} = (m_h^*)^{\frac{3}{2}} e^{\left(\frac{E_V}{kT} - \frac{E_F}{kT}\right)}$$

$$e^{\left(\frac{E_F}{kT} + \frac{E_F}{kT}\right)} = \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} e^{\left(\frac{E_V}{kT} + \frac{E_C}{kT}\right)}$$

$$e^{\left(\frac{2E_F}{kT}\right)} = \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} e^{\left(\frac{E_V}{kT} + \frac{E_C}{kT}\right)}$$

Taking log on both sides, then we have,

$$Ln\left[e^{\frac{2E_F}{kT}}\right] = Ln\left[\left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} e^{\left(\frac{E_V}{kT}+\frac{E_C}{kT}\right)}\right]$$

$$\frac{2E_F}{kT} = Ln\left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} + Ln\left[e^{\left(\frac{E_V}{kT}+\frac{E_C}{kT}\right)}\right]$$

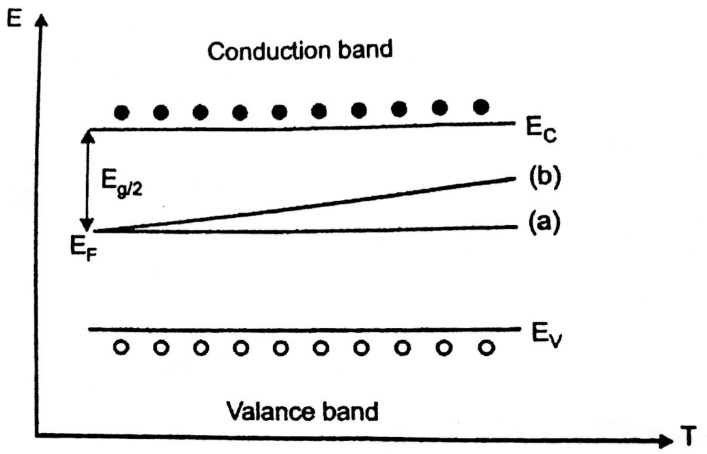
$$E_F = \frac{kT}{2} Ln\left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} + \frac{kT}{2}\left[\frac{E_V + E_C}{kT}\right]$$

$$E_F = \frac{3kT}{4} Ln\left(\frac{m_h^*}{m_e^*}\right) + \left[\frac{E_V + E_C}{2}\right] \qquad (3)$$

If we assume $m_h^* = m_e^*$, then $Ln\left(\frac{m_h^*}{m_h^*}\right) = Ln 1 = 0$

Equation (3) becomes $$E_F = \frac{E_V + E_C}{2} \qquad (4)$$

- From Eq (4), it is noted that the Fermi level $E_F$ is located halfway between the valence and conduction band at lower temperatures.
- If the temperature of the intrinsic semiconductor is slightly increased, then $m_h^* > m_e^*$ and so form just lies above the middle as shown in the figure.




***(a) At T = 0 K the Fermi level is in the middle of the forbidden band***

***(b) AT higher temperatures, the Fermi level shifts upwards.***

## Variation of Fermi level ($E_F$) on Temperature and Carrier Concentration in N-type semiconductor:

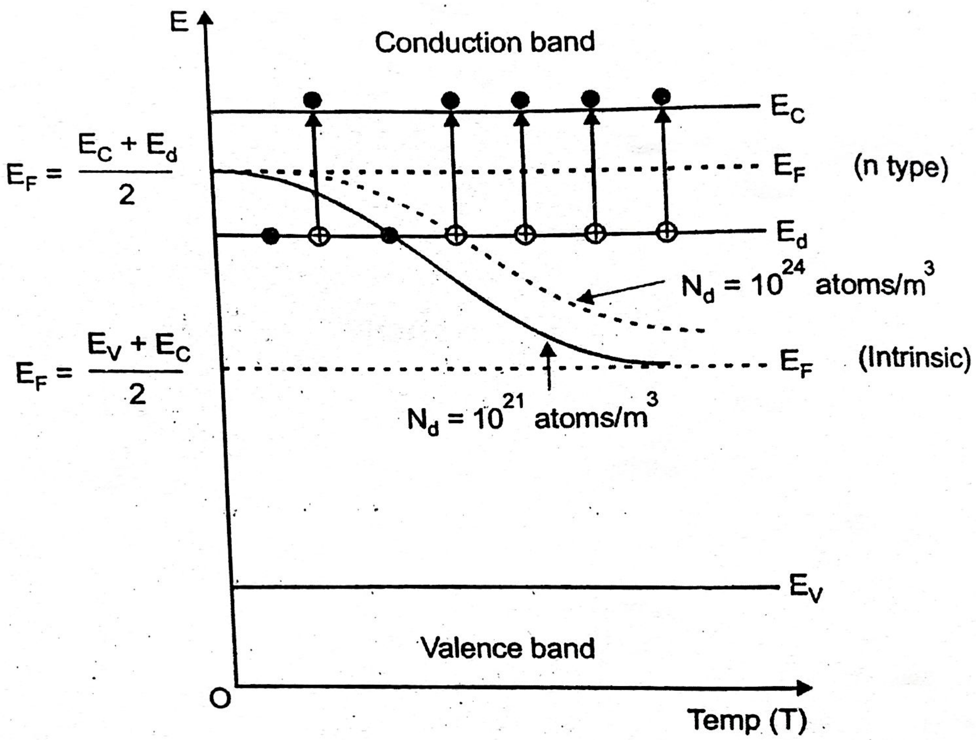
The Fermi level for N-type semiconductor is given by

$$E_F = \frac{E_c + E_d}{2} + \frac{kT}{2} \ln \left[ \frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}} \right] \rightarrow (1)$$

When Temperature $T = 0K$, eqn (1) becomes

$$E_F = \frac{E_c + E_d}{2} \rightarrow (2)$$

- At $T = 0K$, The Fermi level lies exactly half way between $E_c$ and $E_d$.
- When temperature is increased, the donor atoms are ionised and the contribution of electrons from $E_d$ to $E_c$ increases.
- This results the Fermi level $E_F$ shifts down as shown in figure.
- Further increase in temperature results in generation of electron-hole pair due to the breaking of covalent bonds and the material behave like in intrinsic manner.




- When the impurity concentration increases, the extrinsic behaviour is maintained even at high temperature. That is, the Fermi level shifts upwards for $N_d = 10^{24}$ atoms/$m^3$.

## Variation of Fermi level ($E_F$) on temperature and carrier concentration in P-type semiconductor:

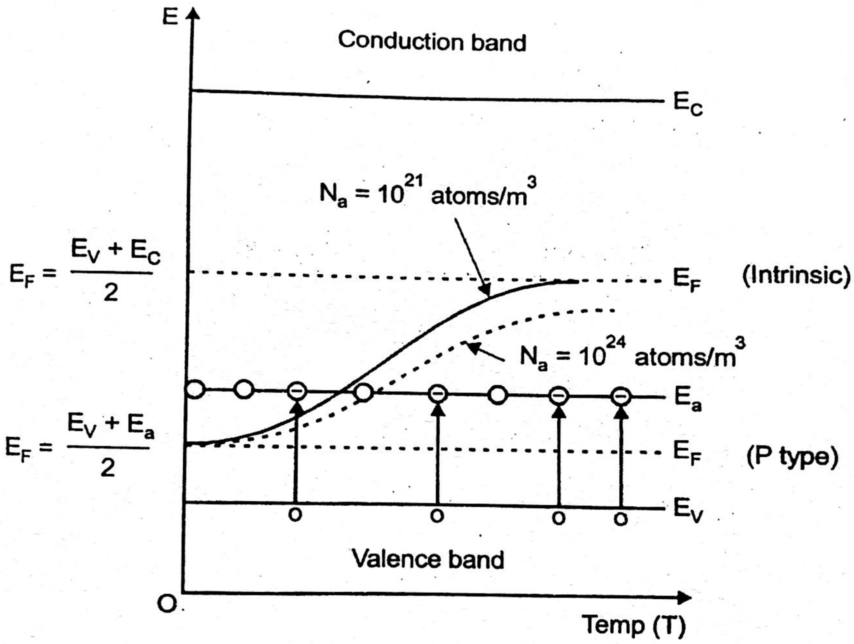
The Fermi level for P-type semiconductor is given by

$$E_F = \frac{E_v + E_a}{2} - \frac{kT}{2} \ln \left[ \frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}}} \right] \rightarrow (1)$$

When Temperature $T = 0k$, eqn (1) becomes

$$E_F = \frac{E_v + E_a}{2} \rightarrow (2)$$

- At $T = 0k$, the Fermi level lies exactly half way between $E_V$ and $E_a$.
- When temperature is increased, the acceptor atoms are ionised and the contribution of electrons from $E_V$ to $E_a$ increases.
- This results the Fermi level $E_F$ moves up as shown in figure.
- Further increase in temperature, results in generation of electron-hole pair due to the breaking of covalent bonds and the material behave like intrinsic manner.




- When the Impurity concentration increases, the extrinsic behaviour is maintained even at high temperature. So, the Fermi level shifts downwards for $N_a = 10^{24}$ atoms/$m^3$.

## Drift and diffusion transport:

The net current flow in a semiconductor is due to

1. Drift current
2. Diffusion current.

### Drift current:

In general, the movement of a charge carrier will be like a wave model rather than a particle model in a defect free crystal. i.e. the electron moves freely in a defect free crystal.

In the absence of electric field, the random motion of charge carriers will not contribut current.

In the presence of electric field $\vec{E}$, then the electrons are drifted towards the positive terminal and the holes are drifted to the negative terminal. This net movement of charge carriers are called as drift transport.

The drift velocity of electrons $V_d = \mu_e E \rightarrow (1)$

The current density due to electron drift is $\Big\}$ $J_e = n e V_d \rightarrow (2)$

Using (1) in (2) $\quad J_e = n e \mu_e E \rightarrow (3)$

For holes $\quad J_p = p e \mu_p E \rightarrow (4)$

Total drift current density $J = J_e + J_p \rightarrow (5)$

Using eqn (1) and (2) in (3)

$$\boxed{J = n e \mu_e E + p e \mu_p E}$$

## Diffusion current:

In addition to the drift current, the diffusion current is set up in the semiconductor due to the diffusion of charge carriers. The excess charge carriers are introduced within a semiconductor, either by causing carrier generation by heating or incident radiation or by injecting carriers into material. This results a non uniform distribution of charge within the material.

The excess charges in the region of higher density will move to region of lower density tending to produce uniform distribution. This current is called as diffusion current.

The diffusion current density for electrons $\Big\}$ $J_n = e D_n \frac{dn}{dx}$ → (1)

where $D_n$ → diffusion coefficient for electrons.

The diffusion current density for holes $\Big\}$ $J_p = -e D_p \frac{dp}{dx}$ → (2)

Total current in semiconductor = drift current + diffusion current

For electrons, N-type

$$J_n = ne\mu_n E + e D_n \frac{dn}{dx}$$

For P-type

$$J_p = pe\mu_p E - e D_p \frac{dp}{dx}.$$

# Carrier generation and Recombination

## Carrier generation

Carrier generation is a process where electron-hole pairs are created by exciting an electron from the valence band of the semiconductor to the conduction band, thereby creating a hole in the valence band.

The product of the electron and for densities is constant at equilibrium.

$$n_0 p_0 = n_i^2$$

When there is a surplus of carriers i.e. $np > n_i^2$, the rate of recombination becomes greater than the rate of generation driving the system back towards equilibrium.

## Carrier Recombination

Recombination is the reverse process where electrons and holes from the conduction respectively valence band recombine and are annihilated.

When there is a deficit of carriers i.e. $np < n_i^2$ the rate of generation becomes greater than the rate of recombination driving the system back towards equilibrium.

As an electron moves from one energy band to another, the energy and momentum that it has loss or gain must go to or come from the other particles (Photons, electrons and vibrating lattice atoms) involved in the process.

There are two types of recombination namely,

1. Direct recombination
2. Indirect recombination

## Direct recombination

- The direct transition of an electron from the conduction band to the valence band is unlikely, however, since the free electron and a hole will only be combined if momentum is conserved in the system.
- That is if the electron and hole initially have nearly equal and opposite momenta.
- The probability for this in Germanium and silicon is low and another recombination mechanism must be invoked.

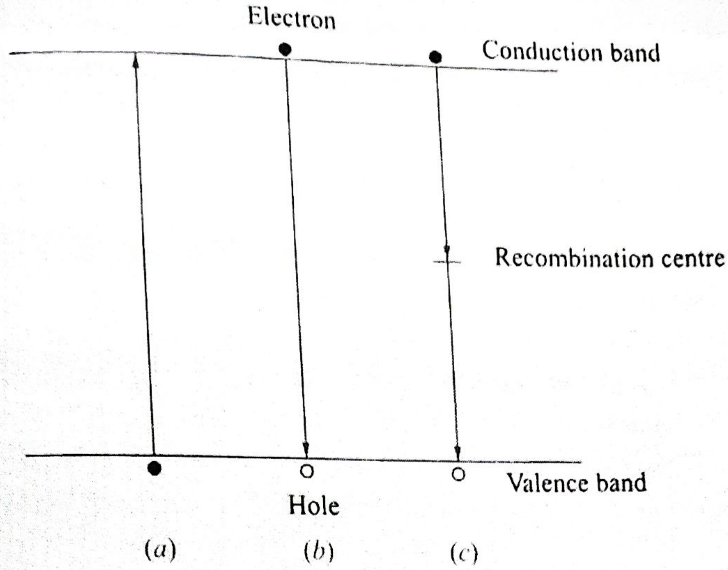



Fig. 10.30 (a) Generation of an electron-hole pair (b) Direct recombination of an electron and a hole (c) Recombination through a recombination centre

## Indirect recombination

- The majority of recombination events are found to take place at the site of an impurity atom or a lattice defect in the crystal.
- Such a location acts as a trap or recombination centre.
- This can satisfy the momentum requirements in the electron hole position. The electron move from conduction band into the trap level and remains there for short time before passing down in the valence band.
- The electron is in trap is not free to move and does not contribute to the conductivity.

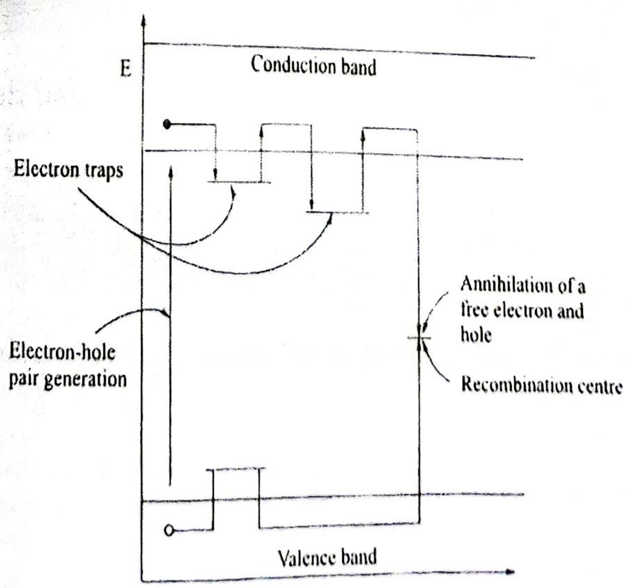



Fig. 10.31 Band model representation of generation and recombination in a semiconductor

- Non-uniformity occurs at an interface between two crystals results termination of regular array of atoms.
- These disturbances in the electric field create levels which have a high probability of capturing an electron, hole or both types of carriers.
- Such levels corresponding to energies near conduction band are called electron traps as they have high probability of capturing free electrons, wild those having energies near valence band levels are called whole traps having a high probability of capturing a hole.
- During recombination process the electrons and holes can be trapped at these levels. The average time that an electron or hole remains free after generation is known as lifetime ($\tau$).

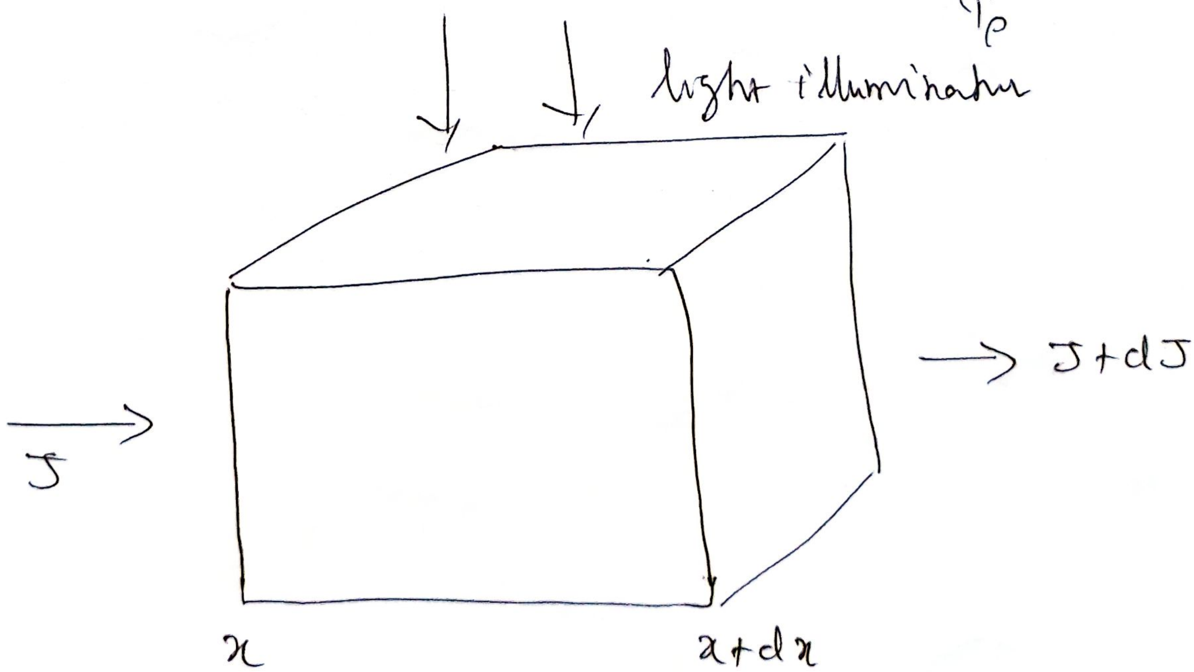
# Continuity equation:

Since the action of semiconductor devices like the diodes and the transistor depend on the generation and transport of excess minority carriers, it is necessary to have an equation governing their motion in a semiconducting crystal. This equation is known as continuity equation.

Let $P$ be the concentration of charge carriers at the instant time 't'. The electrons and holes are generated by thermal processes. So the generation of generation and recombination of electrons and holes must be considered.

The carrier generation rate $g = \frac{P_0}{\tau_p}$ → (1)

The carrier recombination rate $r = \frac{P}{\tau_p}$ → (2)



The rate of carrier concentration $\frac{dP}{dt} = \frac{P_0 - P}{\tau_P} \rightarrow (3)$

The sum of drift and diffusion current $\Big\}$ $J = eE\mu_P P - eD_P \frac{dP}{dx} \rightarrow (4)$

Differentiate eqn. (4) w.r.t 'x'

$$\frac{dJ}{dx} = eE\mu_P \frac{dP}{dx} - eD_P \frac{d^2P}{dx^2} \rightarrow (5)$$

The change in current density in the element 'dx' $\Big\}$ $dJ = -e\left(\frac{dP}{dt}\right)dx \rightarrow (6)$

From eqn (6) $\frac{dP}{dt} = -\frac{1}{e}\frac{dJ}{dx} \rightarrow (7)$

Sub. eqn (5) in eqn (7)

$$\frac{dP}{dt} = -\frac{1}{e}\left[eE\mu_P \frac{dP}{dx} - eD_P \frac{d^2P}{dx^2}\right]$$

$$\frac{dP}{dt} = -E\mu_P \frac{dP}{dx} + D_P \frac{d^2P}{dx^2} \rightarrow (8)$$

~~The~~ complete continuity equation by combining eqns (3) and (8)

$$\frac{dP}{dt} = \frac{P_0 - P}{\tau_P} - E\mu_P \frac{dP}{dx} + D_P \frac{d^2P}{dx^2}$$

For electrons,

$$\boxed{\frac{dn}{dt} = \frac{n_0 - n}{\tau_n} + E\mu_n \frac{dP}{dx} + D_n \frac{d^2n}{dx^2}}$$

## Photo Current in PN junction diode

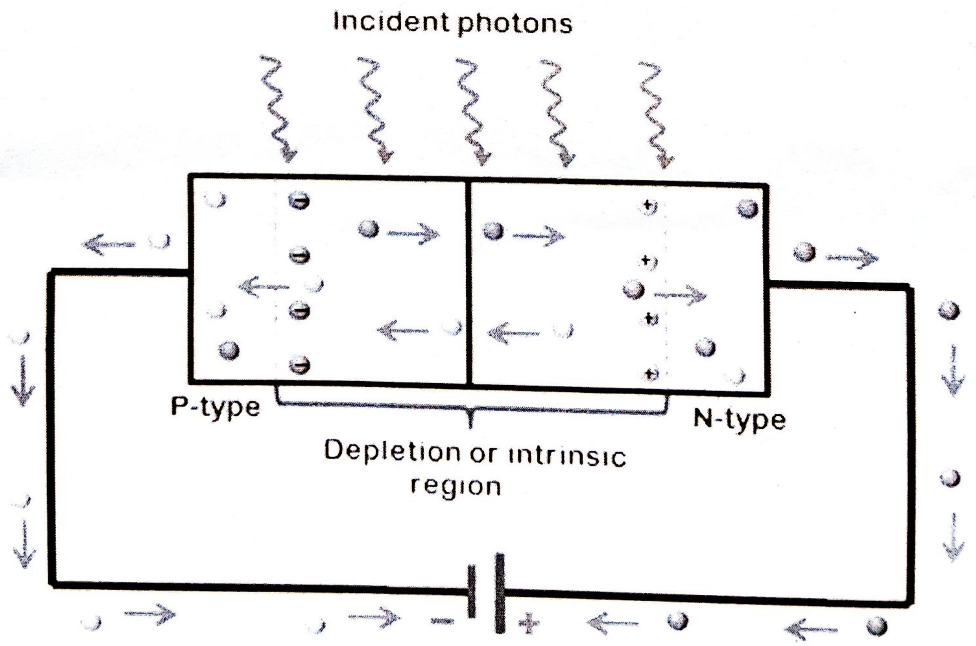
A photodiode is a p-n junction diode that consumes light energy to produce electric current. Sometimes it is also called as photo-detector, a light detector, and photo-sensor. These diodes are particularly designed to work in reverse bias condition.

The required materials to make a photodiode and the range of electromagnetic spectrum wavelength range include the following:

- For silicon material, the electromagnetic spectrum wavelength range will be (190-1100) nm.
- For Germanium material, the electromagnetic spectrum wavelength range will be (400-1700) nm.
- The Si-based photodiodes produce lower noise than Ge-based photodiodes.

## Working of Photodiode

- Let us consider a p-n junction diode in which excess charge carriers are generated uniformly at the rate $G_L$ and the depletion layer of width $W$ is formed near the junction.




- When a photon of energy greater than the depletion width strikes the diode, it makes the electron to move towards n region and holes move towards p region.

- The photo current through the diode arising due to the absorption of light is given by,

$$I_L = \int_0^W AeG_L\, dx$$

$$I_L = AeG_L w$$

Where $A \rightarrow$ Area of the diode, $e \rightarrow$ Charge, $w \rightarrow$ width of depletion layer,

$G_L \rightarrow$ Carrier generation rate.

- In addition to the carriers generated in the depletion region, the electron – hole pairs are generated in the neutral n and p regions.
- So, the photo current produced in the diode is due to all the carriers in depletion region, p and n region.

# Light Emitting Diode [LED]

The Light Emitting Diode (LED) is a semiconductor p-n junction diode which converts electrical energy into light energy under forward bias. It emits light in both visible and Infra Red (IR) region...

There are two types of LED

(1) Surface emitting LED

(2) Dome shaped LED.

LED Symbol

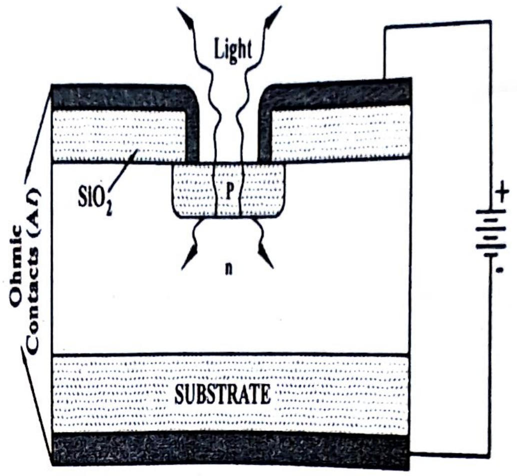
Let us discuss about Surface emitting LED.

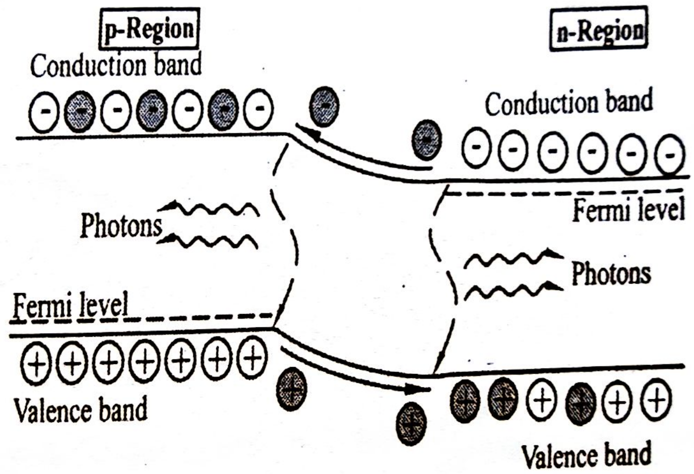
## Principle:

When the ~~dio~~ LED is forward biased, the majority charge carriers moves from 'p' region to 'n' region and vice versa. The recombination of excess minority electrons in 'p' region with majority holes in valance band produce light.

## Construction:

* The p-n junction is formed by doping Si with GaAs.
* To increase the rate of recombination, the thickness of 'n' type is made larger than that of 'p' type as shown in figure.
* Ohmic Contacts are made with the help of metal Al in the top and bottem for the proper biasing.
* A small gap is left uncovered in the top for the emission of light.
* The entire p-n junction is surrounded by plastic material to avoid losses due to reflection.




## Working:

* When the diode is forward biased, the majority carriers from 'n' and 'p' regions cross the junction and become minority in the other region.
* The electrons in 'n'-region cross the junction get ~~in to~~ ~~and move~~ into 'p'-region and become minority carriers in 'p' region
* Similarly, holes in p-region move to n-region and become minority carrier in 'n' region.
* This phenomenon is called minority carrier injection.
* When the voltage increased further, the excess minority carriers diffuse away from junction and directly recombine with holes in p region.
* This electron-hole recombination occur more and more and thereby light photons are emitted through the top layer of the 'p' material which is left uncovered.

* The number of recombination is proportional to the carrier injection rate and the total current flowing through LED.

Total current $I = I_0 \left[ \exp\left(\frac{eV}{\beta kT}\right) - 1 \right]$

where $I_0 \rightarrow$ Saturation current, $V \rightarrow$ forward bias voltage

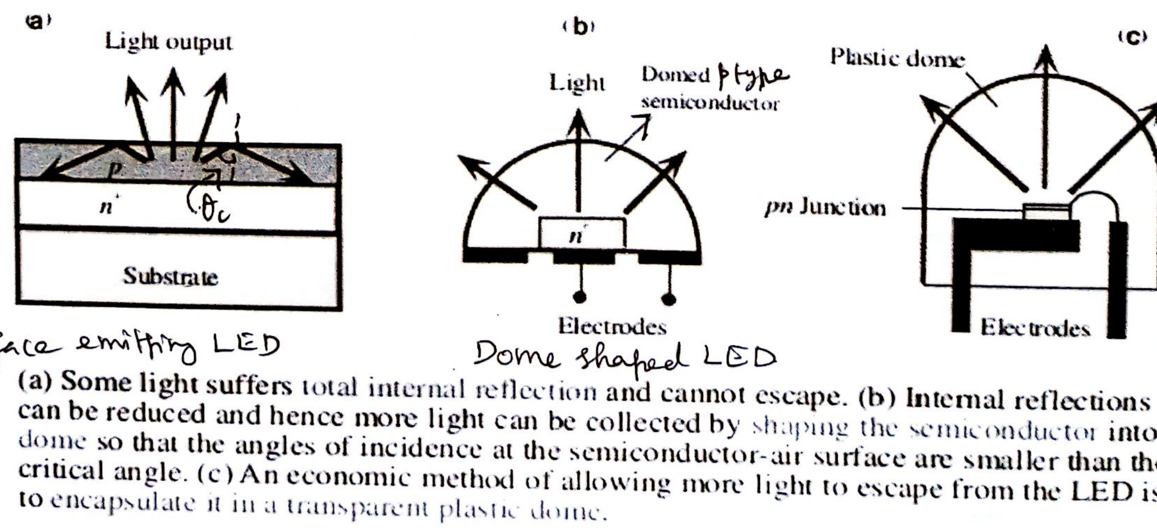
$\beta \rightarrow$ Varies from 1 to 2 ; $k \rightarrow$ Boltzmann Const

* The energy of photon $h\nu = E_g$ $\boxed{\because \nu = \frac{c}{\lambda}}$

$E_g = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E_g}$

## Dome Shaped LED:

The loss of light due to internal reflection can be minimised by making 'p' type material in the shape of a hemispherical dome as shown in figure.




Surface emitting LED          Dome shaped LED

(a) Some light suffers total internal reflection and cannot escape. (b) Internal reflections can be reduced and hence more light can be collected by shaping the semiconductor into a dome so that the angles of incidence at the semiconductor-air surface are smaller than the critical angle. (c) An economic method of allowing more light to escape from the LED is to encapsulate it in a transparent plastic dome.

The rays of light incident on the interface at an angle greater than the critical angle $\theta_c$ will suffer total internal reflection. So most of the light rays reflected back within the device. This will reduce the effeciency of LED.

To minimise the loss, the p-type material of the LED is made in the form of dome structure. Another method to increase efficiency is to cover the p-n junction by a plastic medium of higher refractive index in the shape of hemispherical dome.

# Organic Light Emitting Diode (OLED)

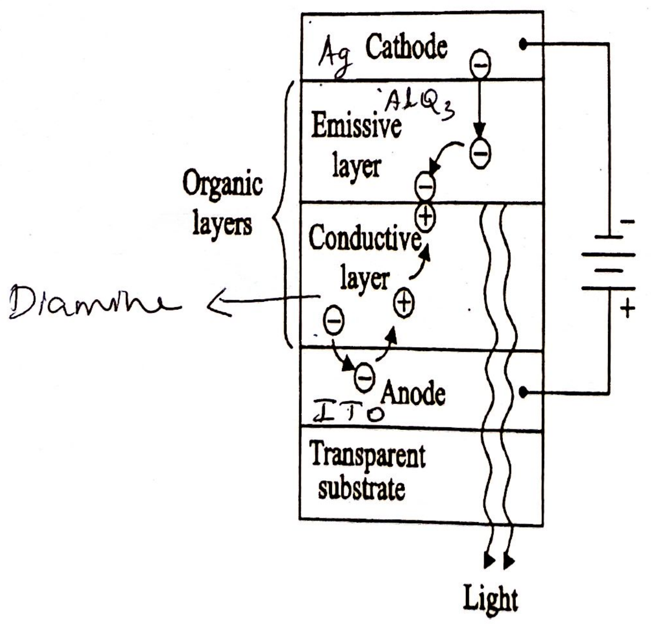
## Principle:

*An electron moves from the cathode to emissive layer and the hole moves from the anode to conductive layer and the recombine to produce photons.*

Organic Light Emitting Diode (OLED) is commonly known, as a new class of materials where the emissive layer is an organic compound sandwiched between two electrodes. The structure of an OLED device is shown in figure.

## Construction:

- A simple OLED is made up of many layers. On the top and bottom there are layers of protective glass or plastic.
- The cathode is usually a reflective material, like a metal film (Ag, Mg etc) having thickness of 200nm, and is deposited on the substrate.
- The anode is a transparent material like Indium Tin oxide (ITO), so that the light emitted can be extracted out of the device.
- In between the anode and cathode are two layers made from organic molecules called the emissive layer and the conductive layer.
- The emissive layer is made from organic material $AlQ_3$ Tris (8-hydroxy quinolinato) aluminum and conductive layer is made from aromatic diamine.
- To light up the OLED, The anode and cathode are connected to the source to provide potential difference.



## Working:

- The working principle of OLED is similar to that of solid state LED.
- For organic molecules, instead of valence and conduction bands, there are discrete electron energy states called HOMO (highest occupied molecular orbital) and LUMO (lowest unoccupied molecular orbital) and recombination occurs across these levels.
- The color of the radiation depends on the energy gap between these two levels.
- Due to the applied voltage, the cathode emits electrons to the emissive layer.
- The anode withdraws an electron from the conductive layer and creates a hole in that layer. The aromatic Nitrogen in diamine structure (emissive) layer has a lone electron pair which is easily ionized to accept holes
- Now, the emissive layer becomes rich in electron and the conductive layer becomes rich in holes.
- Due to the recombination of electron and hole produces light is emitted through the transparent substrate as shown in figure.

## Advantages of OLEDs

- They can be used to form flexible displays by depositing on suitable substrates.
- The devices are light weight, have wider viewing angles, and a faster response time.

## Disadvantages of OLEDs

- They are costly, and have a short lifespan due to degradation of the organic layer.
- The color balance, especially in the blue region, is not good.
- They are susceptible to water damage and consume more power than solid state LEDs.

## Metal-semiconductor junctions

- Formation of electronic devices requires putting together two or more dissimilar materials (semiconductors, metals, insulators).
- The interface between these materials becomes crucial because it affects the electrical properties (transport) of the devices. This interface is called as junction.
- An ideal junction is one in which no defects is formed at the interface.
- Forming ideal junctions is challenging and most real materials have defects at the interface which can affect the electronic properties.
- When a metal and semiconductor are brought into contact, there are two types of junctions formed depending on the work function of the semiconductor and its relation with the metal.

1. Schottky junction (Rectifying) - $\phi_m > \phi_s$
2. Ohmic junction (Non-Rectifying) - $\phi_m < \phi_s$

Where $\phi_m$ and $\phi_s$ are the work function of the metal and semiconductor respectively.

## Schottky junctions:

- Consider a metal and n-type semiconductor. Before contact, the Fermi level of the semiconductor is higher than that of the metal.
- When the metal and semiconductor are in contact, the electrons are moving from n-type semiconductor to the empty energy states above Fermi Energy level of metal due to the low charge density.
- This leaves a positive charge on the semiconductor side and due to the excess electrons, a negative charge on the metal side.
- So, a positive contact potential $V_0$ is formed on the semiconductor side and the Fermi levels of both metal and semiconductor line up at equilibrium as shown in figure.

  *This leads to the formation of the Schottky junction between the metal and semiconductor.*

  *The difference of the work function* $eV_0 = \phi_m - \phi_s$

- The work function of the metal is a constant while the semiconductor work function depends on the dopant concentration.

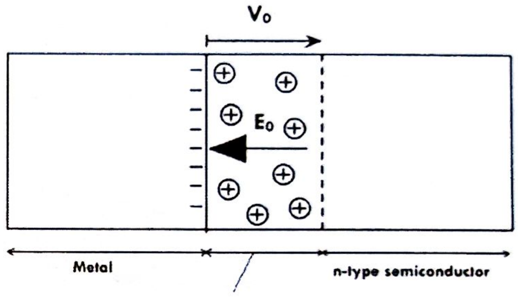
- The contact potential $V_0$ thus formed prevents further motion of the electrons to the metal. There is also a barrier for electrons to move from metal to semiconductor.

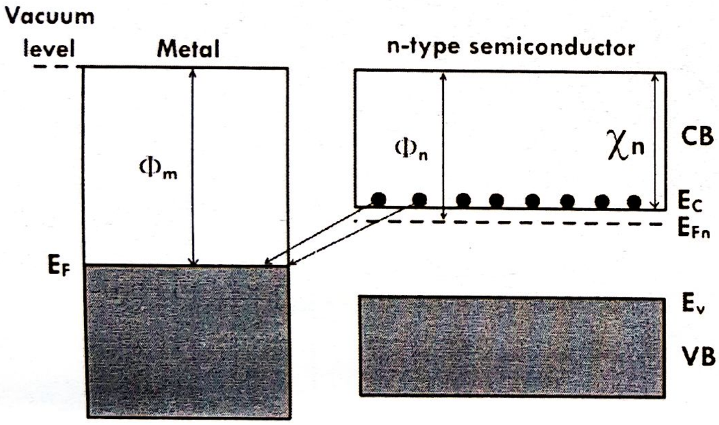
  This is called the Schottky barrier $\phi_B$ and denoted by

$$\phi_B = \phi_m - \chi_n.$$

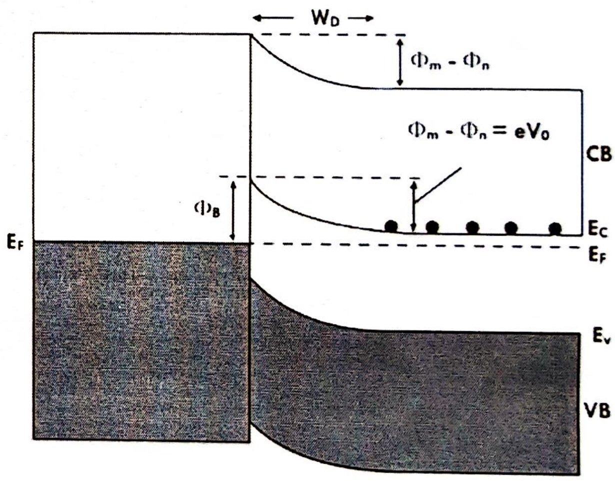
  Where $\chi_n$ is the electron affinity for n-type semiconductor.

- At equilibrium, the motion of electrons from the semiconductor to metal is balanced by the contact potential $V_0$ so that there is no net current.




Before contact




After contact

The Schottky junction can be biased by application of an external potential. There are two types of bias viz.

- **Forward bias** - metal is connected to positive terminal and n-type semiconductor connected to negative terminal.
- **Reverse bias** - metal is connected to negative terminal and n-type semiconductor connected to positive terminal.

## Forward bias

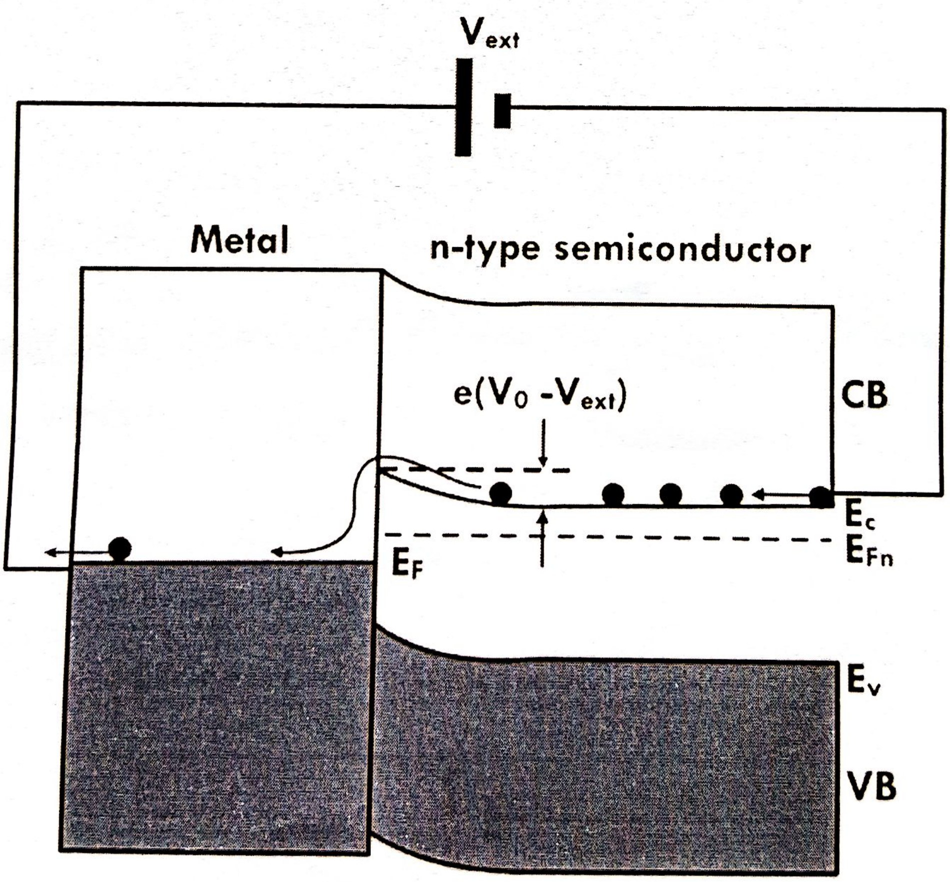
- When Schottky junction is forward biased, the external potential is applied to opposes the contact potential $V_0$.
- Under forward bias, the Fermi levels no longer line up, but they are shifted with respect to one another and the magnitude of the shift depends on the applied voltage.
- Hence, the electrons injected from the semiconductor to metal.
- This leads to a current in the circuit which increases with increasing external potential.

Now, the current in a Schottky diode under forward bias is given by

$$J = J_0\left[exp\left(\frac{eV}{kT}\right) - 1\right]$$

Where $J$ is the current density for an applied potential of $V$.

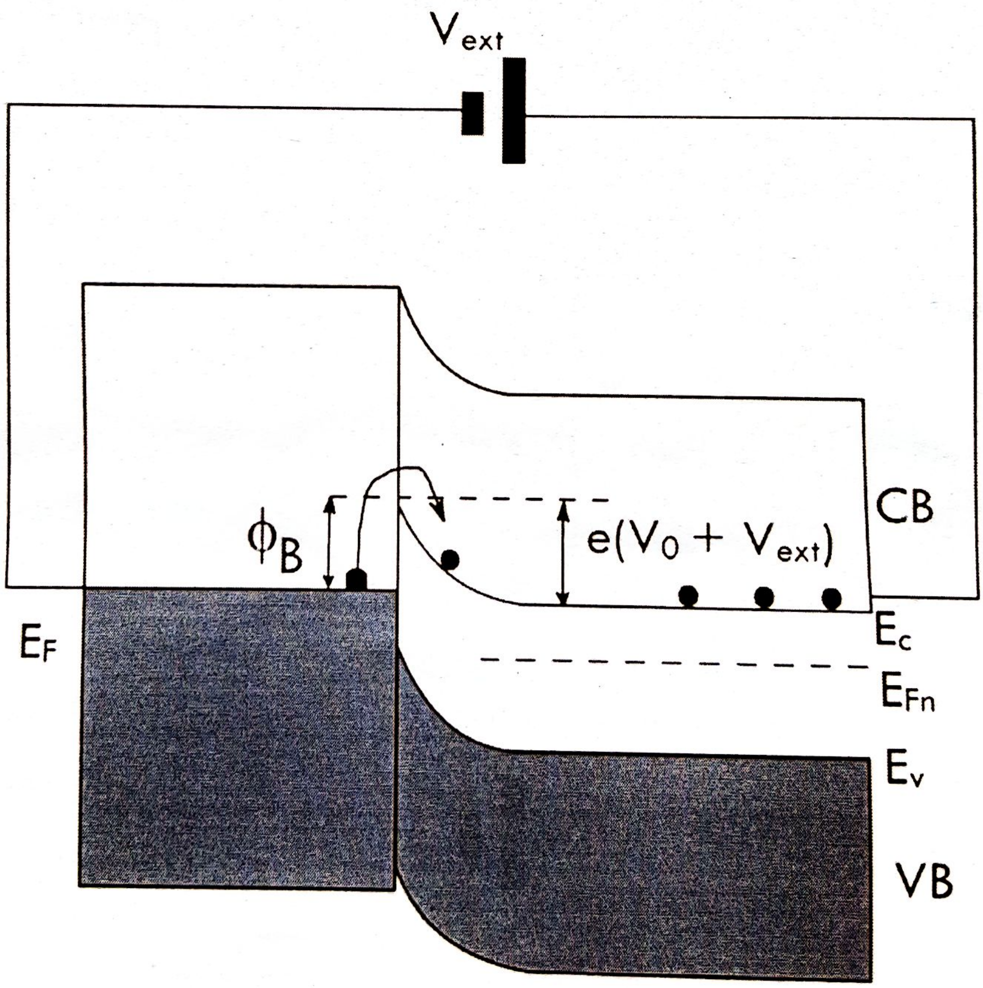
$J_0$ is constant and depends on the Schottky barrier $\phi_B$. $J_0 = AT^2 exp\left(\frac{-\varphi_B}{kT}\right)$




Forward bias of Schottky junction

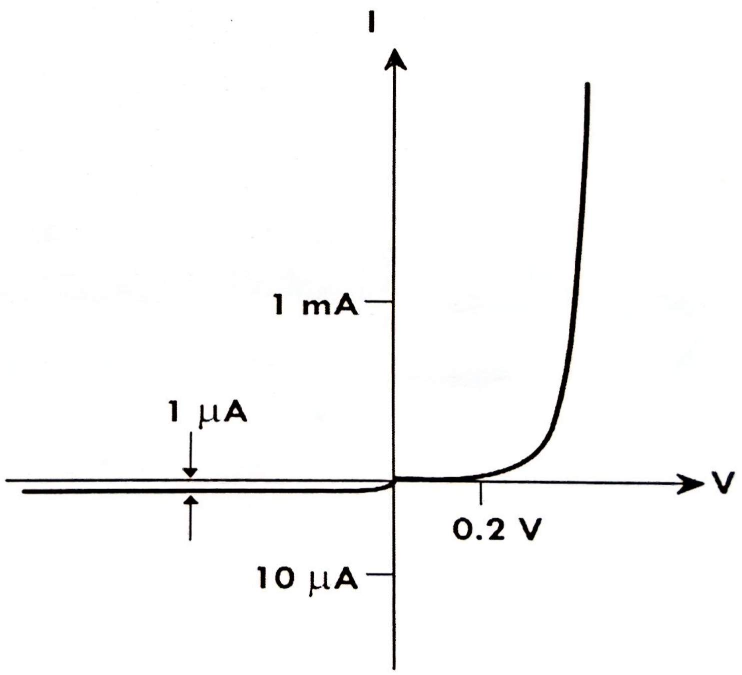
## Reverse bias

- In the case of a reverse bias, once again the Fermi levels no longer line up but the barrier for electron motion from the n-type semiconductor to metal becomes higher.
- The electron flow is now from the metal to the semiconductor and the barrier for this is given by the Schottky barrier.
- So there is a constant current in reverse bias, whose magnitude is equal to $J_0$.
- In Schottky junction, the current in the forward bias is orders of magnitude higher than the current in reverse bias.
- So, the Schottky junction acts as a rectifier i.e. it conducts in forward bias but not in reverse bias.



## The *I* -*V* characteristics of Schottky junction:

- The forward voltage drop of the Schottky barrier ranges from 0.2 volts to 0.5 volts and is very low compared to a p- n junction diode.
- The curve increases exponentially as the forward voltage increases.
- When a reverse bias voltage is applied, the depletion width increases. As a result, the electric current stops flowing.
- However, a small leakage current flows due to the thermally excited electrons in the metal.
- If the reverse bias voltage is increased, a sudden rise in electric current takes place.
- The V-I characteristics of a Schottky barrier diode are very steeper compared to the V-I characteristics of normal PN junction diode due to the high concentration of current carriers.




$I - V$ characteristics of a Schottky junction :

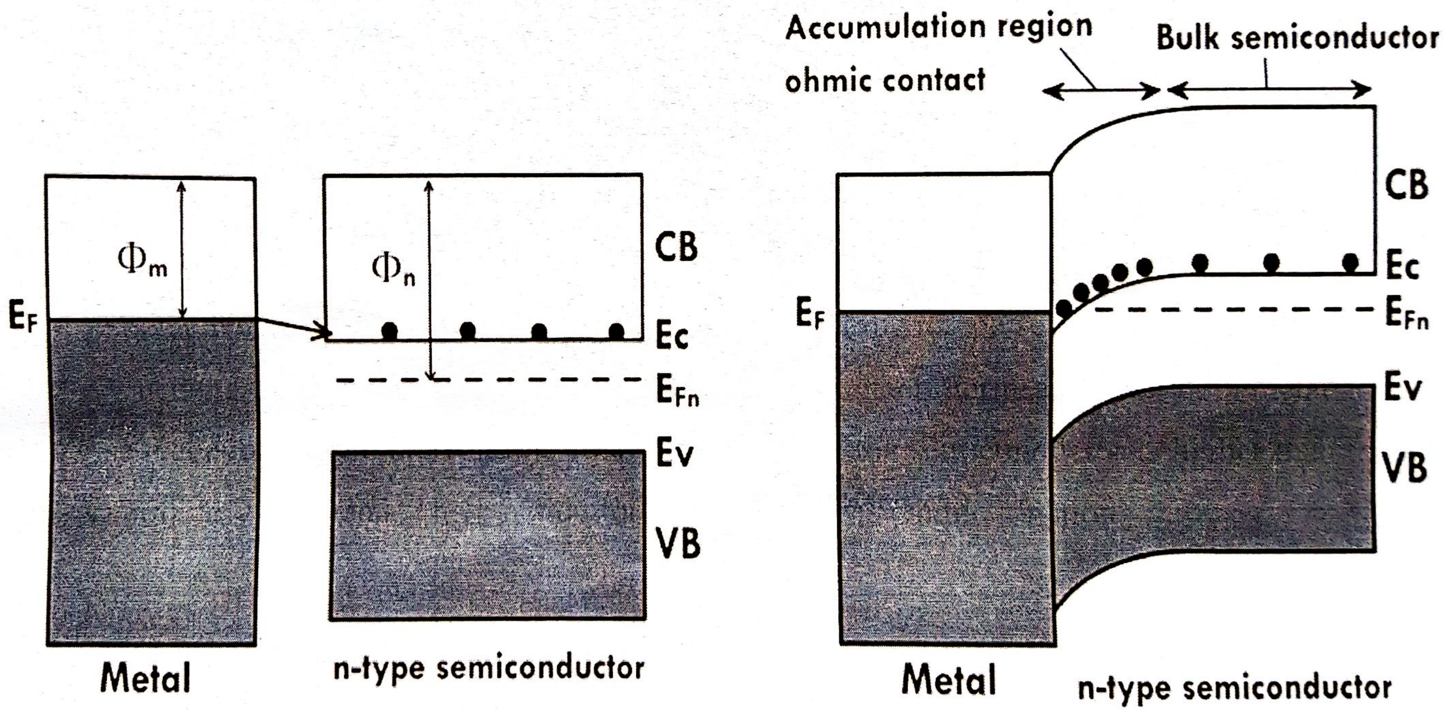
## Ohmic contact/ junction

- The Ohmic contact is a low resistance junction (non-rectifying) provides current conduction from metal to semiconductor and vice versa.
- Ideally the current through the Ohmic contact is a linear function with the applied voltage with an immediate response.

- There are two types of the Ohmic contact:
  1. Ideal non-rectifying barrier.
  2. Tunneling barrier.

## Ideal non-rectifying barrier

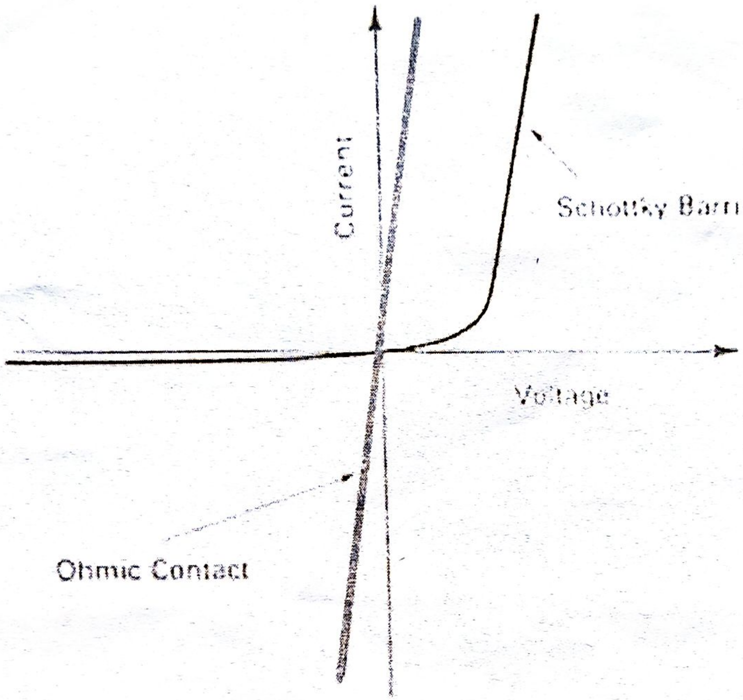
- Consider an ideal metal – n type semiconductor contact.
- Before contact, the Fermi energy level for metal is higher than that of the semiconductor.
- So, the work function of the metal is less than that of the n type semiconductor.
- When the metal and semiconductor contact are in contact, Fermi levels of both metal and semiconductor line up. But, the conduction band of the semiconductor is higher than the Fermi level of metal. The junction formed is called the Ohmic junction.




(a) Before contact (b) After contact

- When the positive potential is given to metal and negative potential given to n-type semiconductor, then the electrons are flowing from n-type semiconductor into metal.
- When the positive potential is given to n-type semiconductor and negative potential give to metal, then the electrons are flowing from metal into n-type semiconductor.
- Thus, an Ohmic junction behaves as a resistor and conducting in both forward and reverse bias.

- For Ohmic junction, depending on the direction of current flow (forward or reverse bias), heat can be generated or absorbed. This is observed in Peltier effect.
- The comparision of *I* - *V* characteristics of Ohmic contact with Scottky junction is shown in figure.



## Tunneling barrier

- The space-charge width in a metal-semiconductor contact is inversely proportional to the square root of semiconductor doping.

$$The\ width\ of\ depletion\ region\ W \propto \frac{1}{\sqrt{Doping\ Concentration}}$$

- Thus, as doping concentration increases, the probability of tunneling through the barrier increases. So, in a heavily doped semiconductor, the depletion width is in the order of $A^0$.