Module-2

→ Intrinsic & Extrinsic Semiconductors
→ Dependence of fermi level on Carrier Concentration & temp.
→ Carrier generation & recombination
→ Carrier transport: diffusion & drift
→ p-n Junction
→ Metal-Semiconductor Junction (Ohmic- & Schottky)
→ Semiconductor materials of interest for optoelectronic devices

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Module :- 2

Semiconductor

Intrinsic Semiconductors

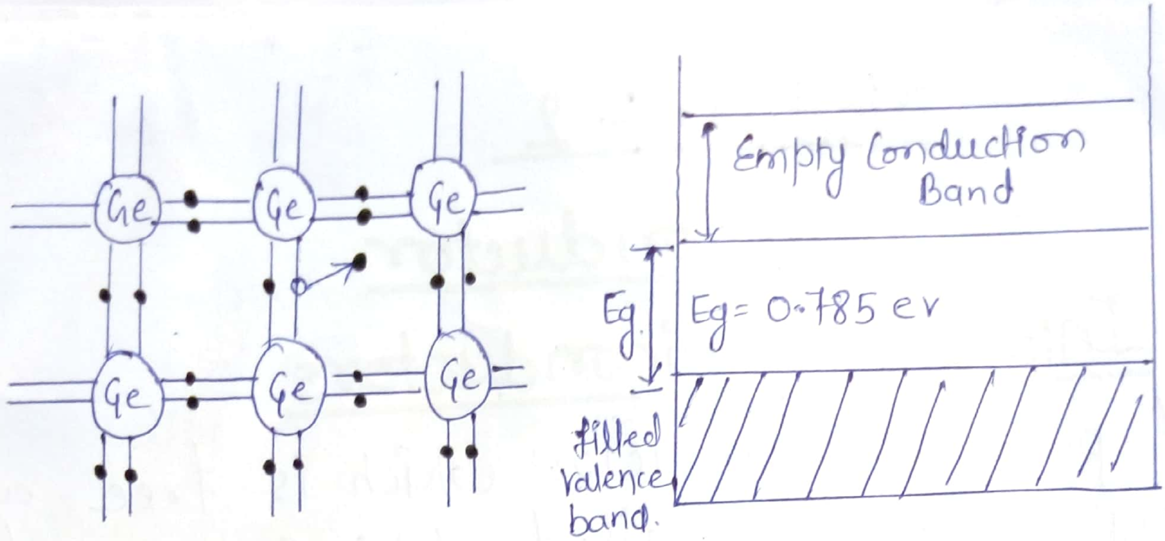
A pure semiconductor which is free of every impurity is called Intrinsic semiconductor. Electrical conductivity of pure semiconductor is totally due to number of electrons excited from valence band to conduction Band.

Example :- Silicon & Germanium

Silicon (atomic no:- 14) $1s^2 2s^2 2p^6 3s^2 3p^2$

Germanium (atomic no-32) $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^2$

Both the atoms have four valence electrons. Crystal structure of germanium is shown below. The four valence electrons of germanium atom forms four covalent bond by sharing the electrons from neighbouring four germanium atom. Each covalent bond shares two electrons one from each atom. Hence Outermost Orbit of each Ge atom is Complete with eight electrons.



→ Even at room temp. thermal vibrations of the atom provide Energy to $e^{\ominus}$ so that these $e^{\ominus}$ jump from valence band to Conduction band leaving hole in valence band

→ In Intrinsic SemiConductor.

$$\boxed{n_e = n_h = n_i}$$

where n_e = density $e^{\ominus}$ in Conduction band

n_h = density of holes in valence band

n_i = intrinsic Carrier density

→ Here Concentration of holes & $e^{\ominus}$'s are equal but 2/3 of Current is due to $e^{\ominus}$ & 1/3 by holes because $e^{\ominus}$'s are much mobile than holes

→ Resistivity decreases (↓) & Conductivity (↑) increases with Rise in temperature.

★ Conductivity of Semiconductor depends upon

→ Concentration of Mobile charge Carriers (holes & $e^{\ominus}$)

→ Mobility of charge Carriers

When electric field is applied, Current density due to motion of $e^{\ominus}$ & holes are.

$$\boxed{J_n = e n v_n} \quad A/m^2$$

$$\boxed{J_p = e n v_p} \quad A/m^2$$

where n = density of free $e^{\ominus}$
p = density of holes
v_n = drift velocity of $e^{\ominus}$
v_p = drift velocity of holes

→ Conductivity due to $e^{\ominus}$ is

$$\sigma_n = \frac{J_n}{E} = \frac{e n v_n}{E} = e n \mu_n$$

→ Conducity due to holes

$$\sigma_p = \frac{J_p}{E} = \frac{e p v_p}{E} = e p \mu_p$$

where μ_n & μ_p are mobility of $e^{\ominus}$ & holes

→ Now, Total Conductivity $\sigma = \sigma_n + \sigma_p$

$$\sigma = e n \mu_n + e p \mu_p$$

$$\boxed{\sigma = e(n\mu_n + p\mu_p)}$$

In case of intrinsic semiconductors

$$n = p = n_i$$

So, conductivity of intrinsic semiconductor is

$$\boxed{\sigma_i = e n_i (\mu_n + \mu_p)}$$

Extrinsic Semiconductor

AT room temperature intrinsic semi-conductor has little current conduction capability. In order to use the semiconductor in electronic devices, its conduction properties should be increased by adding some impurities in the process of crystallization. The added impurities are very small of the order of one atom per million atom of pure semiconductor.

Doping ⇒ The process by which controlled impurities are added to pure semiconductors.

Type of Extrinsic Semiconductor

- N type Semiconductor
- P type Semiconductor

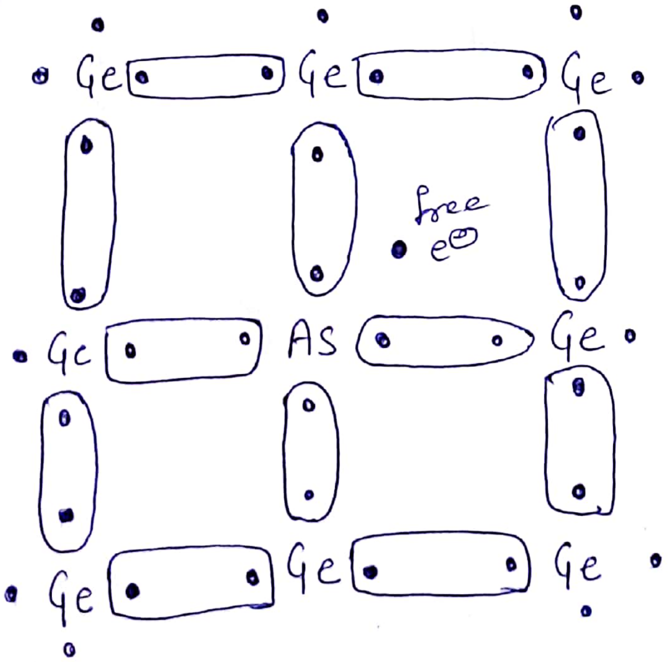
N type Semiconductor

→ when a small amount of Pentavalent impurities are added to pure Semiconductor

Example :- Arsenic (Z=33)
Antimony (Z=51)

→ act as donor impurities

→ when Pentavalent arsenic is added to pure germanium its four valence $e^{\ominus}$ form Covalent bond with four Germanium atom + fifth $e^{\ominus}$ remains free



→ Majority Carriers are $e^{\ominus}$

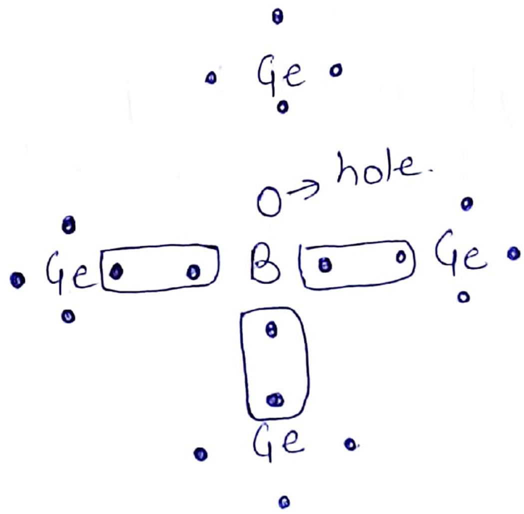
P type Semiconductor

when small amount of trivalent impurities are added to pure SemiConductor.

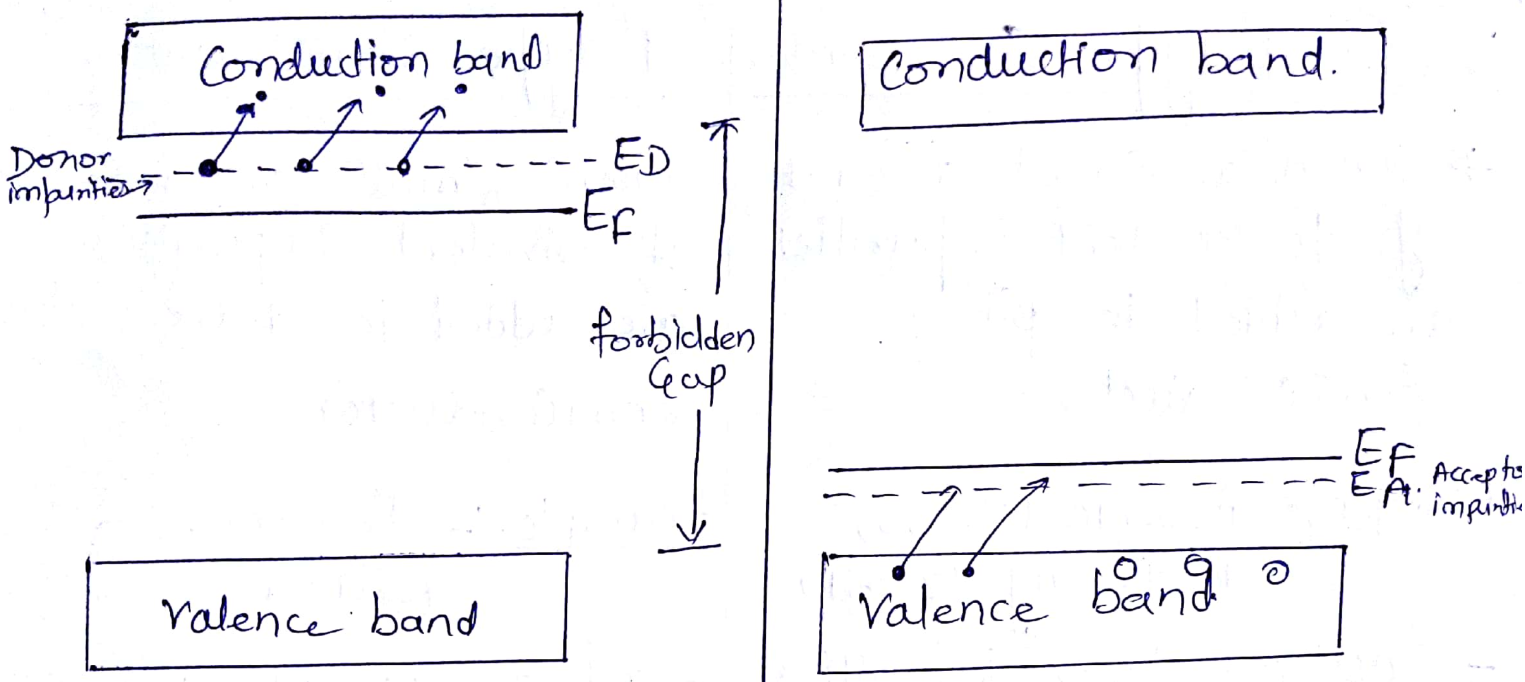
Example :- Boron, Gallium.

→ act as acceptor impurities

→ Three covalent bonds are there. whereas. fourth bond is Incomplete that is missing of $e^{\ominus}$ known as hole



→ Majority Carriers are holes



→ Conductivity of N type is double that of P type as e⊖ are much more mobile than holes.

→ N type & P type semiconductors are electrically neutral.

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Number of Electrons in Conduction Band

Let us consider electrons in conduction Band behaves as free particles with effective mass m_e^* & number of conduction electrons (dn) whose energies is lies b/w E & E+dE is

$$dn = N(E)\, f(E)\, dE \quad \text{——— (1)}$$

where N(E) is density of states of conduction Band is given by

$$N(E) = \frac{4\pi}{h^3}(2m_e^*)^{3/2}(E-E_c)^{1/2} \quad \text{——— (2)}$$

where $E > E_c$

E_c = energy at the bottom of conduction band

and f(E) = fermi Dirac distribution function

$$f(E) = \frac{1}{1+e^{(E-E_f)/k_BT}} \quad \text{——— (3)}$$

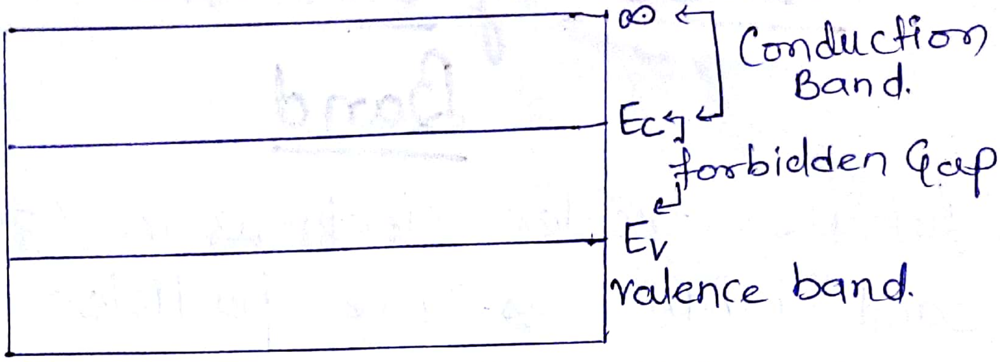
where k_B = Boltzmann Const

T = Temp.

Now, electrons in conduction band having energy b/w E_c to ∞.

So, concentration of electrons in conduction band is given by.

$$n = \int_{E_c}^{\infty} N(E)\, f(E)\, dE \quad \text{——— (4)}$$



Now put the value of N(E) & f(E) using Eq^n (2) & (3) in (4)

$$n = \int_{E_c}^{\infty} \frac{4\pi}{h^3} (2 m_e^*)^{3/2} \frac{(E-E_c)^{1/2}}{1 + e^{(E-E_F)/K_B T}} \, dE$$

as $E - E_F >> K_B T$; So neglected 1 in denominator

$$n = \frac{4\pi}{h^3} (2 m_e^*)^{3/2} \int_{E_c}^{\infty} (E-E_c)^{1/2} \, e^{-(E-E_F)/K_B T} \, dE$$

$$n = \frac{4\pi}{h^3} (2 m_e^*)^{3/2} \int_{E_c}^{\infty} (E-E_c)^{1/2} \, e^{(E_F - E)/K_B T} \, dE$$

Now, dividing numerator & Denominator by $(K_B T)^{1/2}$ & adding & Subtracting E_c

$$n = \frac{4\pi}{h^3} (2 m_e^*)^{3/2} (K_B T)^{1/2} \int_{E_c}^{\infty} \left(\frac{E-E_c}{K_B T} \right)^{1/2} e^{(E_F - E_c + E_c - E)/K_B T} \, dE$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2}(K_BT)^{1/2} e^{(E_F-E_c)/K_BT} \int_{E_c}^{\infty} \left(\frac{E-E_c}{K_BT}\right)^{1/2} e^{(E_c-E)/K_BT} \, dE \quad \text{———— (5)}$$

Let $\frac{E-E_c}{K_BT} = x$ or $\frac{dE}{K_BT} = dx$.

So; $dE = (K_BT)\,dx$

Now these values in above Eq^n (5) we get

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2}(K_BT)^{1/2} e^{(E_F-E_c)/K_BT} \int_0^{\infty} x^{1/2} e^{-x} (K_BT)\, dx.$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2}(K_BT)^{3/2} e^{(E_F-E_c)/K_BT} \int_0^{\infty} x^{1/2} e^{-x}\, dx$$

$$n = \frac{\cancel{4}^{2}\pi}{h^3}(2m_e^*)^{3/2}(K_BT)^{3/2} e^{(E_F-E_c)/K_BT} \left(\frac{\sqrt{\pi}}{\cancel{2}}\right)$$

(becoz $\int_0^{\infty} x^{1/2} e^{-x} dx = \frac{\sqrt{\pi}}{2}$

$$\boxed{n = 2\left[\frac{2\pi m_e^* K_BT}{h^2}\right]^{3/2} e^{(E_F-E_c)/K_BT}}$$

$\Rightarrow$ This is Concentration (density) of electrons in Conduction Band in Intrinsic SemiConductor

or

$$\boxed{n = N_c\, e^{-(E_c-E_F)/K_BT}}$$

where $N_c = 2\left[\frac{2\pi m_e^* K_BT}{h^2}\right]^{3/2}$

Number of Holes in Valence Band

- Hole means vacancy of electron

$f(E) \Rightarrow$ Means Occupational probability for electrons

So, for Holes Probability function becomes

$$1 - f(E) = 1 - \frac{1}{1 + e^{(E-E_F)/k_BT}}$$

$$= 1 - [1 + e^{(E-E_F)/k_BT}]^{-1}$$

$$= 1 - [1 - e^{(E-E_F)/k_BT}] \quad \{\text{using Binomial expansion}\}$$

$$= e^{(E-E_F)/k_BT} \quad \text{——— (1)}$$

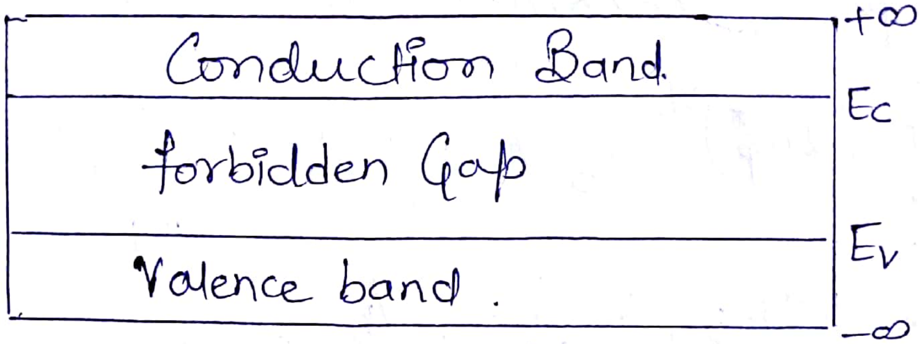
for top of valence band (maximum energy) density of states is

$$N(E) = \frac{4\pi}{h^3}(2m_p^*)^{3/2}(E_v - E)^{1/2} \quad \text{——— (2)}$$

where. $m_p^* \Rightarrow$ is effective. mass of hole near top of valence band

Now, number of Holes is

$$p = \int_{-\infty}^{E_v} N(E)[1 - f(E)]\,dE \quad \text{——— (3)}$$



Now, put the value of $N(E)$ & $[1-f(E)]$ from Eq^n (1) & (2) in Eq^n (3)

$$P = \int_{-\infty}^{E_v} \frac{4\pi}{h^3} (2m_p^*)^{3/2} (E_v - E)^{1/2} \, e^{(E-E_F)/K_BT} \, dE$$

$$P = \frac{4\pi}{h^3} (2m_p^*)^{3/2} \int_{-\infty}^{E_v} (E_v - E)^{1/2} \, e^{(E-E_F)/K_BT} \, dE$$

$$P = \frac{4\pi}{h^3} (2m_p^*)^{3/2} (K_BT)^{1/2} \int_{-\infty}^{E_v} \left(\frac{E_v - E}{K_BT}\right)^{1/2} e^{(E-E_F+E_v-E_v)/K_BT} \, dE.$$

($\because$ dividing numerator & denominator by $(K_BT)^{1/2}$ & add & subtracting E_v.)

$$P = \frac{4\pi}{h^3} (2m_p^*)^{3/2} (K_BT)^{1/2} e^{(E_v-E_F)/K_BT} \int_{-\infty}^{E_v} \left(\frac{E_v - E}{K_BT}\right)^{1/2} e^{(E-E_v)/K_BT} \, dE. \quad (4)$$

Let us put $\frac{E_v - E}{K_BT} = x$.

$$\frac{-dE}{K_BT} = dx$$

So; $dE = -(K_BT)\, dx$.

So Eq^n (4) become

$$P = \frac{4\pi}{h^3}(2m_p^*)^{3/2}(K_BT)^{1/2} e^{(E_v-E_F)/K_BT}\int_{-\infty}^{0} x^{1/2}\, e^{-x}(-K_BT)\,dx.$$

$$P = \frac{4\pi}{h^3}(2m_p^*)^{3/2}(K_BT)^{1/2} e^{(E_v-E_F)/K_BT}\int_{0}^{-\infty} x^{1/2}\, e^{-x}(K_BT)\,dx.$$

$$P = \frac{4\pi}{h^3}(2m_p^*)^{3/2}(K_BT)^{1/2} e^{(E_v-E_F)/K_BT}\; K_BT\int_{0}^{-\infty} x^{1/2}\, e^{-x}\,dx.$$

as $\int_{0}^{-\infty} x^{1/2}\, e^{-x}\,dx = \frac{\sqrt{\pi}}{2}$

So above Eq^n becomes

$$P = \frac{\cancel{4}^{2}\pi}{h^3}(2m_p^*)^{3/2}(K_BT)^{1/2} e^{(E_v-E_F)/K_BT}(K_BT)\frac{\sqrt{\pi}}{\cancel{2}}$$

$$\boxed{P = 2\left[\frac{2\pi m_p^* K_BT}{h^2}\right]^{3/2} e^{(E_v-E_F)/K_BT}}$$

$\Rightarrow$ This Eq^n is Concentration of Holes in Valence band.

or

$$\boxed{P = N_v\, e^{(E_v-E_F)/K_BT}}$$

where $N_v = 2\left[\frac{2\pi m_p^* K_BT}{h^2}\right]^{3/2}$

Fermi level in intrinsic Semiconductor

In intrinsic Semiconductor

No. of free electrons = No. of Holes

$$n = p$$

so

$$N_c\, e^{-(E_c-E_F)/k_BT} = N_v\, e^{-(E_F-E_v)/k_BT}$$

Taking log both sides & rearraging terms

$$-\frac{(E_c-E_F)}{k_BT} = \log\left(\frac{N_v}{N_c}\right) - \frac{(E_F-E_v)}{k_BT}$$

Now, multiply both sides by. k_BT

$$-(E_c-E_F) = k_BT \log\left(\frac{N_v}{N_c}\right) - (E_F-E_v)$$

$$2E_F = k_BT \log\left(\frac{N_v}{N_c}\right) + (E_c+E_v)$$

$$E_F = \frac{E_c+E_v}{2.} + \frac{1}{2}\log k_BT \log\left(\frac{N_v}{N_c}\right) \quad \text{---} (1)$$

as $N_v = 2\left[\frac{2\pi m_p^* k_BT}{h^2}\right]^{3/2}$

& $N_c = 2\left[\frac{2\pi m_e^* k_BT}{h^2}\right]^{3/2}$

Now, put the value of N_v & N_c in Eq^n (1) we get

$$E_F = \frac{(E_c + E_v)}{2} + \frac{3}{2\times2} K_B T \log\left(\frac{m_p^*}{m_e^*}\right)$$

as intrinsic semiconductors

$$m_p^* = m_e^*$$

So above Eq^n becomes

$$\boxed{E_F = \frac{E_c + E_v}{2}}$$

Thus, fermi level in intrinsic semiconductors lies exactly half way between top of valence band & bottom of conduction band. i.e. Centre of forbidden energy gap.

Fermi level in Extrinsic Semiconductor

In Extrinsic Semiconductors, the number of $e^{\ominus}$ in conduction band & number of holes in valence band are not equal. Hence, the probability of occupation of energy level in conduction band & valence band are not equal. Therefore, the fermi level for extrinsic Semiconductor lies close to Conduction or Valence band

fermi level in N type Semiconductor

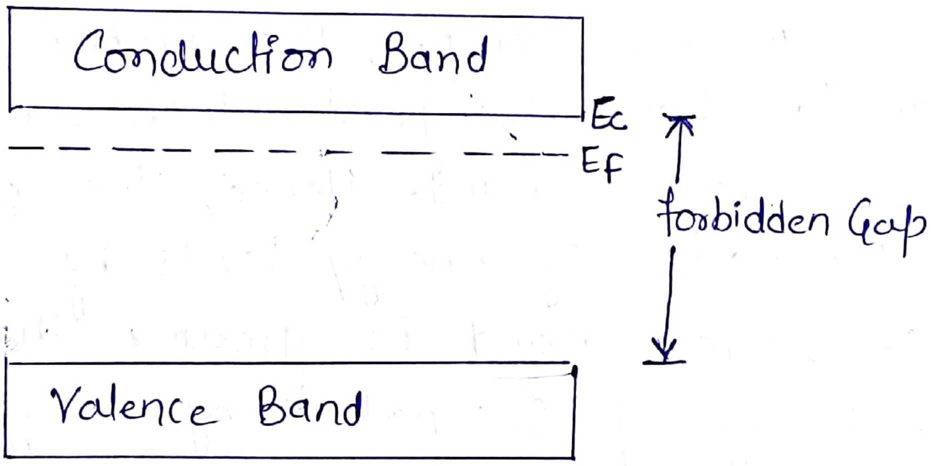
In N type Semiconductor pentavalent impurities are added. Each pentavalent impurity donates free $e^{\ominus}$. The addition of pentavalent impurity Creates large number of free $e^{\ominus}$ in Conduction band.

At room temp., the number of $e^{\ominus}$ in Conduction band is greater than number of Holes in Valence band. Hence, the probability of Occupation of energy levels by electrons in Conduction band is greater than the probability of Occupation of energy levels by Holes in Valence band. This probability of Occupation of energy levels is represented in terms of fermi level. Therfore, the fermi level in n type Semiconductor lies close to the Conduction band.

fermi level for N type Semiconductor is

$$\boxed{E_F = E_c - K_B T \log \frac{N_c}{N_D}}$$

Where E_F = fermi level
E_C = Conduction Band
k_B = Boltzmann Constant
T = absolute Temp.
N_C = density of states in Conduction band
N_D = Concentration of donor atoms.



fermi level in p type Semiconductor

In p type Semiconductor trivalent impurity is added. Each trivalent impurity creates a hole in valence band & ready to accept an electron. The addition of trivalent impurity creates large number of holes in valence band.

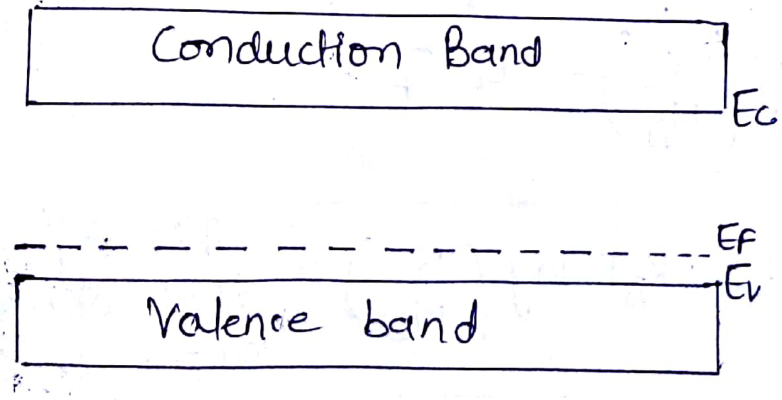
AT room temp. number of holes in

Valence band is greater than the number of electrons in conduction band. Hence, the probability of occupation of energy levels by holes in valence band is greater than probability of occupation of energy levels by electrons in conduction band. This probability of occupation of energy level is represented by fermi level. Therefore, the fermi level in p type semiconductor lies close to valence band & is given as

$$\boxed{E_F = E_V + k_B T \log \frac{N_V}{N_A}}$$

where N_V = density of states in valence band

N_A = concentration of acceptor atoms.



Effect of Temperature on fermi level

(1) N Type Semiconductors

for n type Semiconductor number of electrons is more than number of holes That is mostly because there are additional electron being supplied by donor atoms (pentavalent atom)

So let us consider

$$n \simeq N_D$$

where N_D = Concentration of Donor atoms

as we know Carrier Concentration in N type Semiconductor is

$$n = N_C \, e^{-(E_C - E_F)/k_B T}$$

So

$$N_D = N_C \, e^{-(E_C - E_F)/k_B T}$$

where $N_C = 2\left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{3/2}$

$$\frac{N_C}{N_D} = e^{(E_C - E_F)/k_B T}$$

$$\log\left(\frac{N_C}{N_D}\right) = \frac{E_C - E_F}{k_B T}$$

(Taking log both sides)

$$k_B T \log\left(\frac{N_C}{N_D}\right) = E_C - E_F$$

$$\boxed{E_F = E_C - k_B T \log\left(\frac{N_C}{N_D}\right)}$$

$\Rightarrow$ This Eq

This Eq^n shows that rise in temperature, fermi level drops. because at higher temperature. Semiconductor will produce more electron hole pair. Due to this production of extra. $e^{\ominus}$ hole pair fermi level moves down toward the valence band.

(2) P type Semiconductor

In p type semiconductor concentration of holes can be approximately equal to

$$p \simeq N_A$$

where N_A = Concentration of acceptor atom (trivalen atom)

We know, for carrier concentration in p type semiconductor.

$$p = N_v \, e^{-(E_F - E_v)/k_BT} \quad \text{———} (1)$$

where $N_v = 2\left[\frac{2\pi m_p^* k_BT}{h^2}\right]^{3/2}$ called density of states in valence band

So Eq^n (1) becomes

$$N_A = N_v \, e^{-(E_F - E_v)/k_BT}$$

$$\frac{N_v}{N_A} = e^{(E_F - E_v)/k_BT}$$

$$\log\left(\frac{N_v}{N_A}\right) = \frac{(E_F - E_v)}{k_BT}$$

$$K_B T \log\left(\frac{N_v}{N_A}\right) = E_F - E_V$$

$$\boxed{E_F = E_V + K_B T \log\left(\frac{N_v}{N_A}\right)}$$

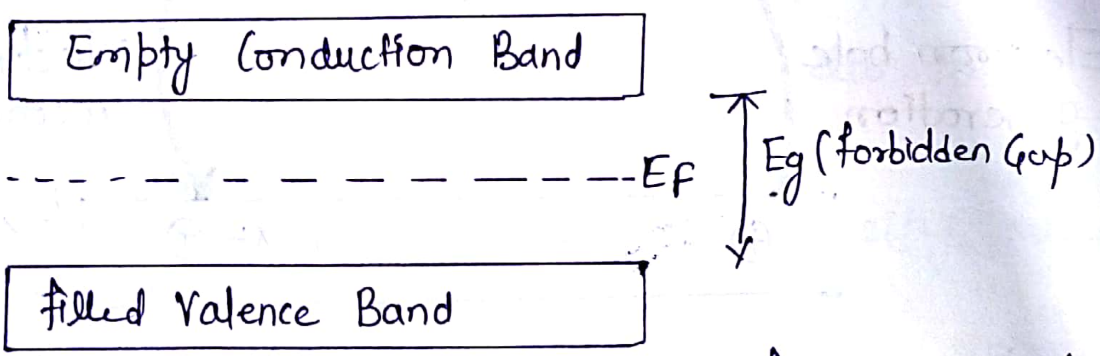
⇒ This Eqⁿ shows that with rise in temp fermi level rise toward Conduction band.

Because more temperature means more Energy of electron tends to more towards the Conduction band, which push the fermi level up.

Carrier Generation & Recombination

Carrier Generation & recombination may be defined as "Generation is process where electrons & holes are created & recombination is the process where electrons & holes are annihilated.

In semiconductors, at absolute zero all the energy levels below fermi level are completely filled, while all the energy levels above fermi level are completely empty.

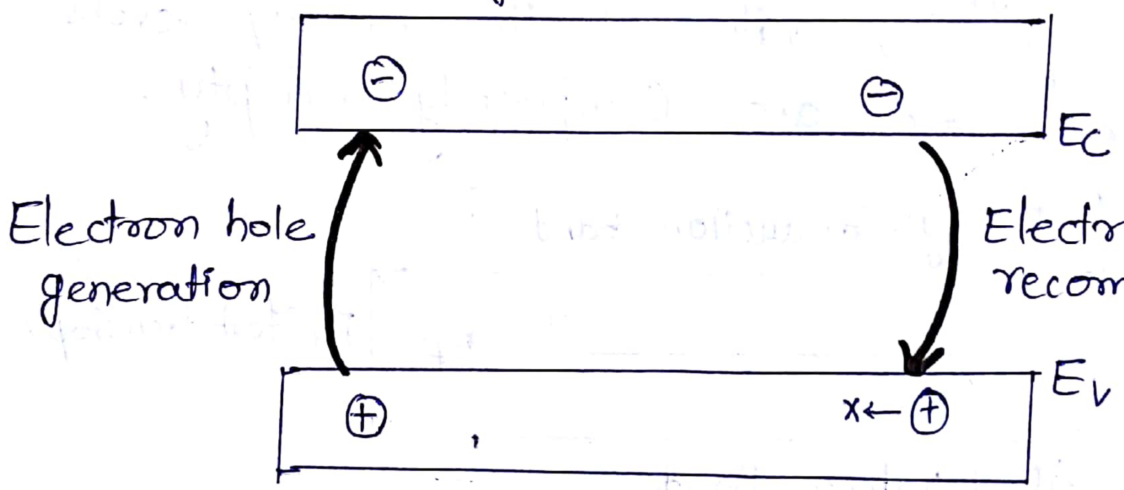


In intrinsic semiconductors, fermi level lies in the middle of valence band & conduction band.

If an electron in valence band acquire energy greater than forbidden gap (Eg) Energy then, electron will reach into conduction band & leave a hole in valence band. Now, this electron will freely moves in the conduction band. Thus, in carrier

Generation process two mobile charge. Carriers (electrons & holes) are generated.

At the same time, electrons moving in Conduction band may come in close proximity to holes & fall in the empty states in valence band. This recombination process annihilates both electrons & holes as shown in fig.



Net charge Carrier Concentration are independent of time in thermal equilibrium So the rate of electron hole pair generated & rate of which electron & holes recombine must be equal.

Recombination & Generation are always happening in Semi Conductors & their rates are constant at equilibrium.

So, product of product of electron & hole densities is constant i.e.

$$\boxed{np = n_i^2} \text{ at Equilibrium}$$

Carrier Generation & recombination process in fundamental to operation of many opto electronic semi conductor devices such as photodiodes, LED & laser diodes.

Carrier Transport :- Drift & Diffusion

There are two basic transport mechanism

drift :- Movement of charge Carriers due to electric field.

diffusion :- flow of charges due to density gradient

Drift Current :- When electric field applied to the semiconductor, it produces a force on electrons & holes so that they experience a net acceleration & net movement. This net movement of charge carriers due to electric field is called drift. The net drift of charge give rise to drift current.

So, drift Current density due to motion of electrons in Conduction band is

where n = no. of free e^-
μ_e = mobility of e^-
E = Electric field applied

$$\boxed{J_e = n e \mu_e E}$$

Drift Current due to motion of holes in Valence band

$$\boxed{J_h = p e \mu_h E}$$

So, total Current density $J = J_e + J_h$

$$J = n e \mu_e E + p e \mu_h E$$

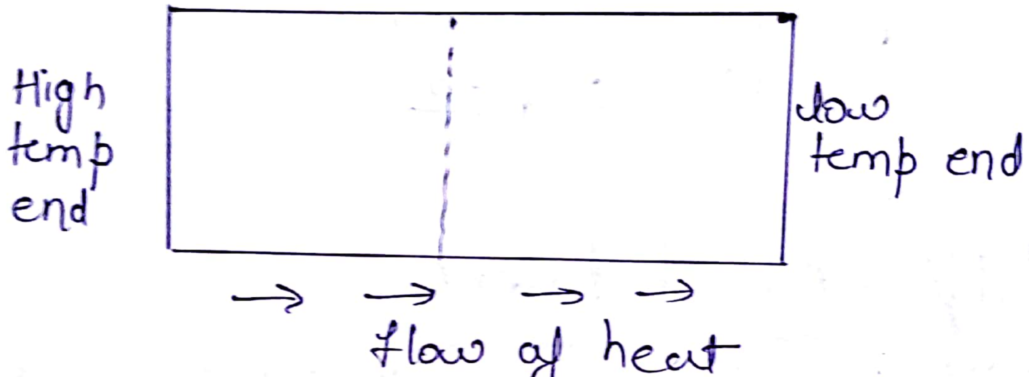
$$\boxed{J = eE(n\mu_e + p\mu_h)}$$

Note:- Drift Current flows only when external electric field is applied across the SemiConductor.

Diffusion Current

In Case of Semiconductors, Current Can also be flow without the application of external electric field.

Let us Consider the material having two different temperatures across its two ends. Due to temperature gradient heat flows from higher temperature region to lower temperature region until the temperature is uniform throughout the material.



Similarly an electric current flow in semiconductor even in the absence of applied Electric field provided a concentration gradient that exist in the material.

A concentration gradient exist if the number of electrons or holes is greater in one region of semiconductor as compare to rest of region

In semiconductors charge carriers have tendency to move from the region of higher concentration to lower concentration. Thus the movement of charge carriers takes place resulting in current called diffusion current.

Diffusion Current density due to flow of electrons

$$\boxed{J_e\,(diff) = e\,D_e\,\frac{dn}{dx}}$$

Diffusion Current density due to flow of holes

$$\boxed{J_h\,(diff) = e\,D_h\,\frac{dp}{dx}}$$

Difference between

Diffusion Current	Drift Current
→ Diffusion Current may Occur even electric field not applied to Semiconductor	Drift Current required the presence of electric field.
→ Magnitude of diffusion Current depends of the slope of Carrier Concentration	Drift Current depends on the Concentration of Semiconductor material
→ Diffusion Current flow in the direction of slope of Carrier concentration & Does not obey ohm's law	Drift Current flows in the direction of electric field & depends on ohm's law

P-N Junction

P-N Junction is formed by diffusing P type material to one half side & N type material to other half side. The plane dividing the two zones is known as junction.

P-type & N type semiconductor pieces before joining. is shown in fig.

In figure, P type semiconductor has negative acceptor ion (shown by encircled minus sign) & positive charge holes. Similarly in N-type semiconductor has positive donor ions (shown by positive sign) & negative charged free electrons.

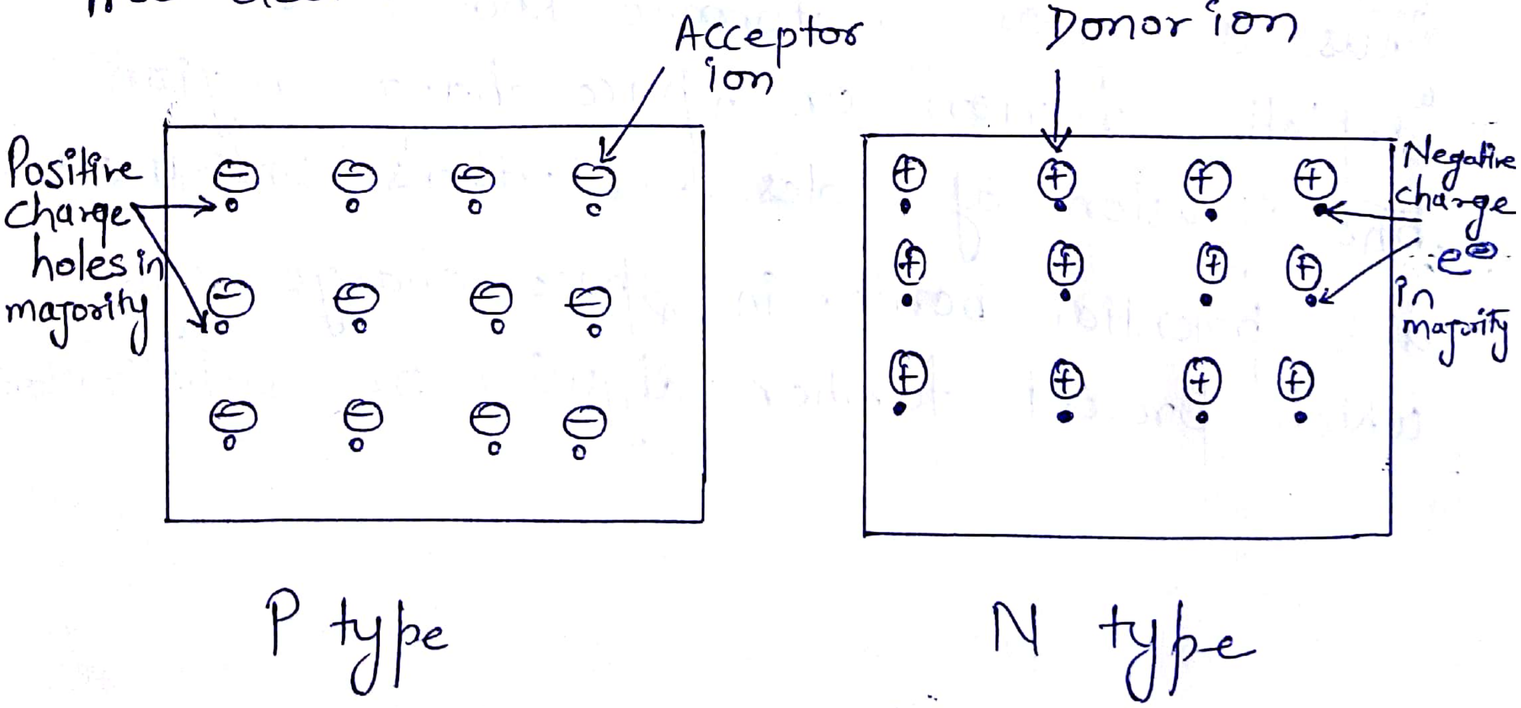
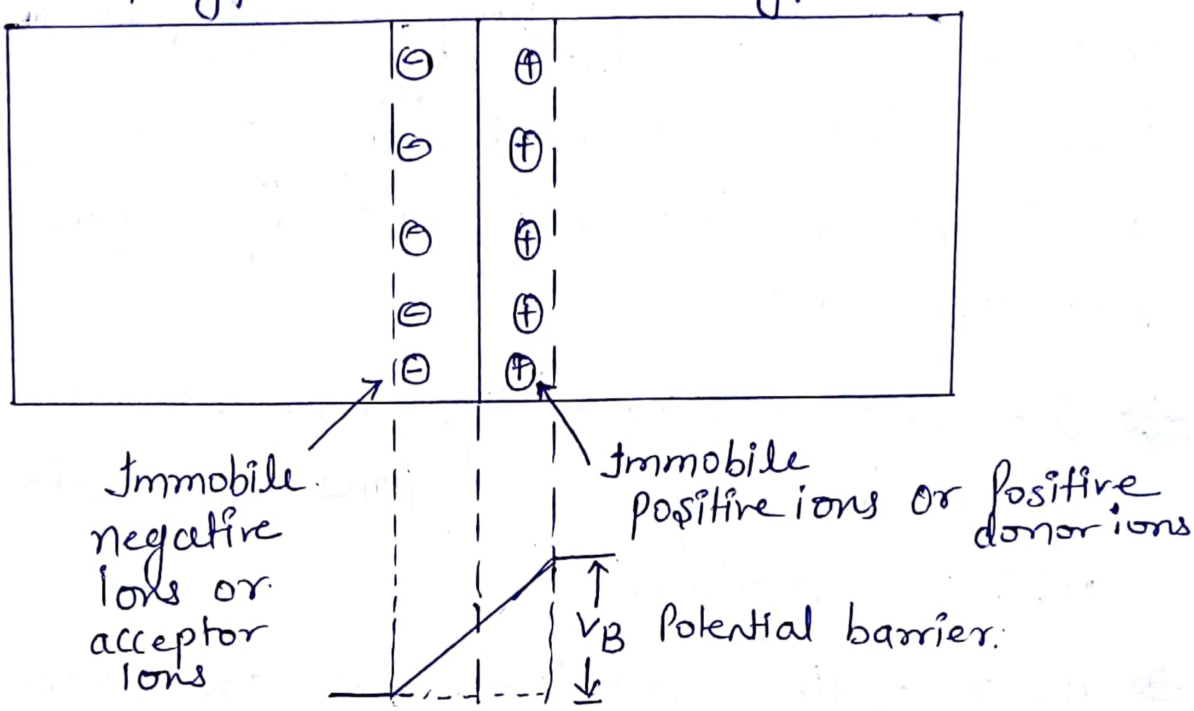


fig. P-type & N-type Semiconductor before joining.

Formation of depletion Layer

Now, Consider that two pieces are joined together as shown in fig. below. As P type material has high Concentration of holes & N type material has high Concentration of electrons. hence there is tendency of holes to diffuse over N-side & electrons to p-side.. This process is called diffusion. So due to diffusion some of holes from p-side cross over to N-Side & become neutral. Similarly, some of electrons from N-side cross over to p-side where they Combine with holes & become neutral.

Thus, a region is formed known as "depletion region" or space charge region. The diffusion of holes & electrons Continues till potential barrier in space charge region which prevent further diffusion or neutralization



Some important points

⇒ When P-N junction is formed, the holes from P region diffuse to N-region where they disappear due to recombination with electrons

⇒ The electrons from N region diffuse to P region where they disappear due to recombination with holes

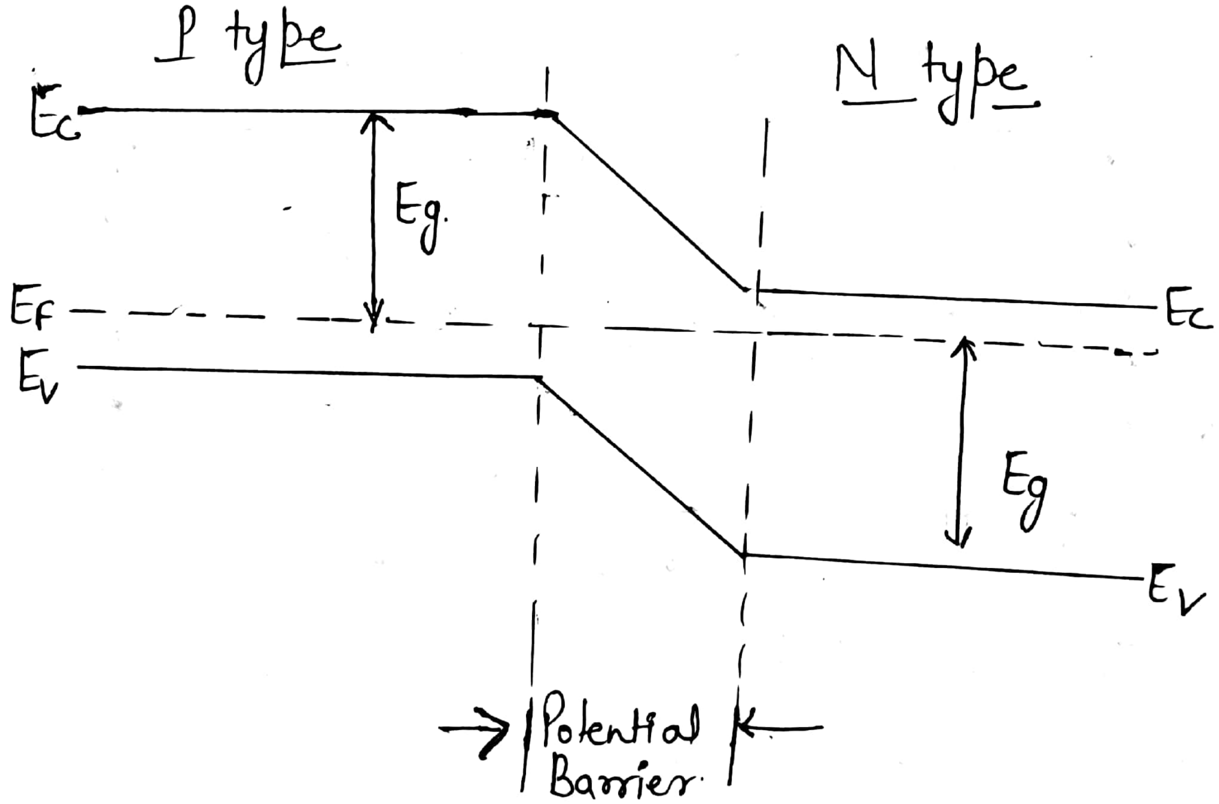
⇒ In this procedure, negative immobile acceptor ions in P-region & positive immobile donor ions in N-region are left near junction

⇒ Now, no further diffusion of holes & electrons takes place across the junction because holes trying to diffuse in N region are repelled by immobile positive ions & the electrons trying to diffuse in P-region are repelled by immobile negative ions

⇒ The region containing immobile negative & immobile positive ions is called depletion region.

⇒ As negative ions (immobile) are created on P-side of junction so P-type acquire negative potential. similarly positive ions are created on N-side so N side acquire positive potential. Hence the voltage "V_B" is developed across the junction under equilibrium condition. This voltage is known as junction voltage or internal voltage or potential barrier voltage "V_B" which is about 0.3 V for Ge & 0.7 V for Si at room temp. 300 K

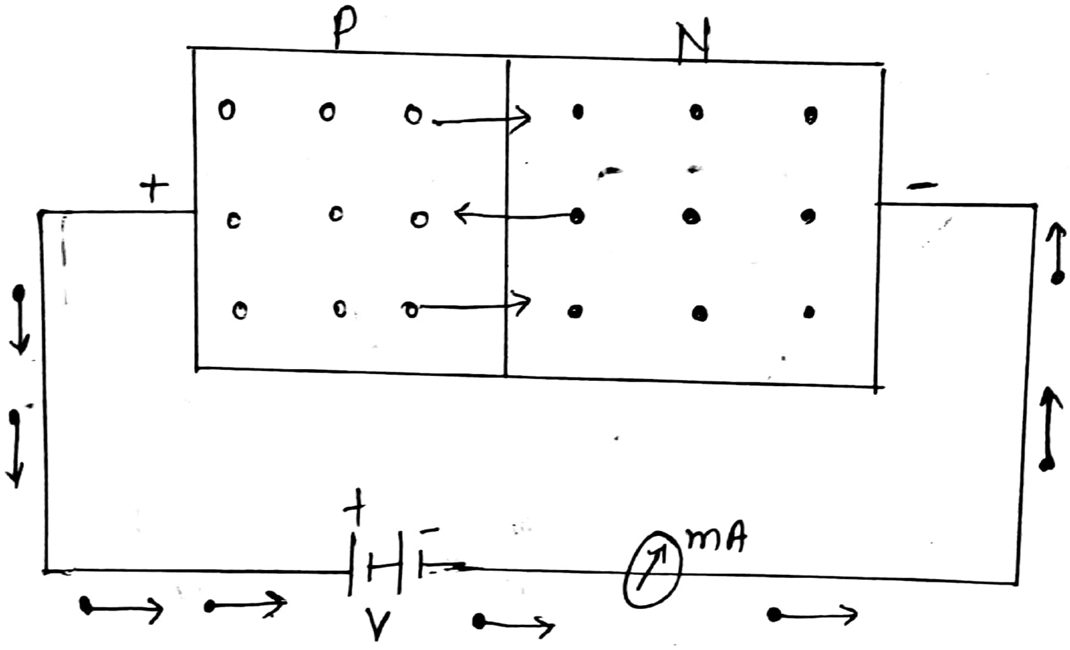
⇒ we know fermi level lies near the valence band in P type & near the conduction band in N type semiconductors under thermal equilibrium, the average energy of P & N regions are become equal so fermi level (E_F) of P & N regions will be at same level as shown in fig. below. The equlization of fermi level in P & N type is analogous to equalization of level of water in two containers on being joined together.



P-N Junction Diode

1. Forward Bias

When an external voltage is applied to PN Junction in such a direction that it cancel the potential barrier & permits the current flow is called forward bias.



In forward bias

(1) holes from P type semiconductor is repelled by positive terminal of battery towards the junction & simultaneously, the electron of N type semiconductor are repelled by negative terminal toward junction.

2. Here battery voltage should be high to impart sufficient energy to these carriers to overcome the potential barrier & enable to cross through it.

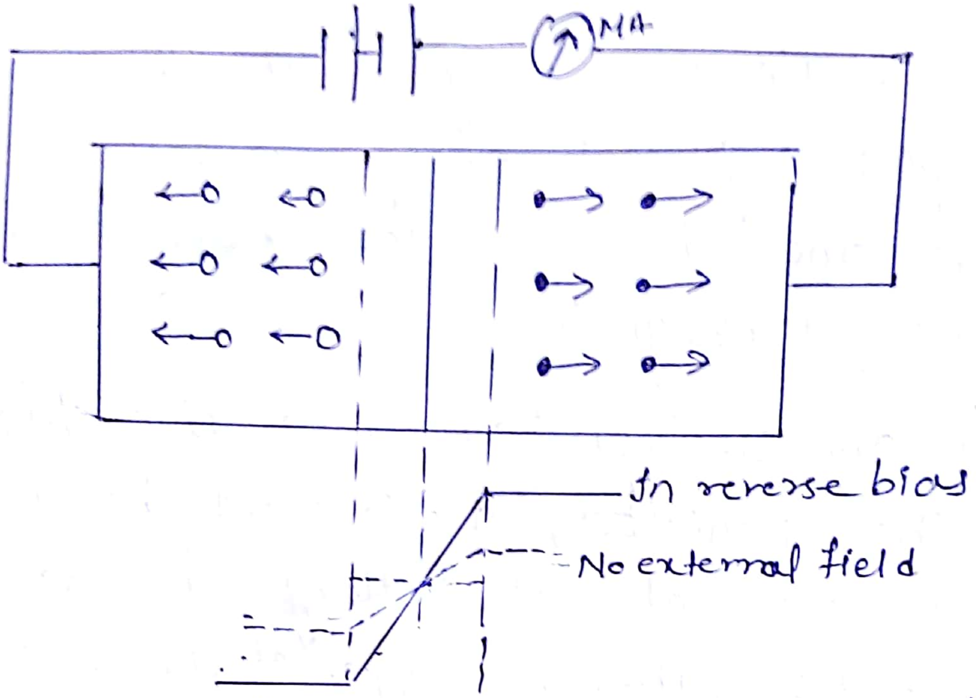
3. when an electron hole recombine takes place near the Junction, a covalent bond near positive terminal of battery breaks down. This causes liberation of electron which enters positive terminal of battery.

4. This action creates a new hole which moves towards the Junction.

5. for each electron in N-region that combines with a hole from P region, an electron enters the crystal from negative terminal of the battery. The constant movement of electrons toward positive terminal & the holes towards the negative terminal produces a high forward current.

2. Reverse Bias

when external voltage is applied to PN Junction in such a direction that it increases the potential barrier then it is called reverse bias.



1. In reverse bias, reverse voltage establishes an electric field in the same direction of potential barrier. Therefore, the resultant field at junction is strengthened & barrier height is increased.
2. This increased potential barrier prevents the flow of charge carriers across the junction. Thus high resistance established.
3. In reverse bias electrons in N type & holes in p type semiconductor are attracted away from junction. Since there is no recombination of electron hole pair, so no current flow in circuit.

following points are important

(1) Junction potential barrier is strengthened.

(2) It offers high resistance

(3) There will be little current (in μA) flows through the junction due to minority Carriers.

Conclusions:- PN Junction diode is one way device which offers low resistance when forward bias & behaves like an insulator when reverse bias Thus, it can be used as rectifier i.e. for Converting a.c in d.c

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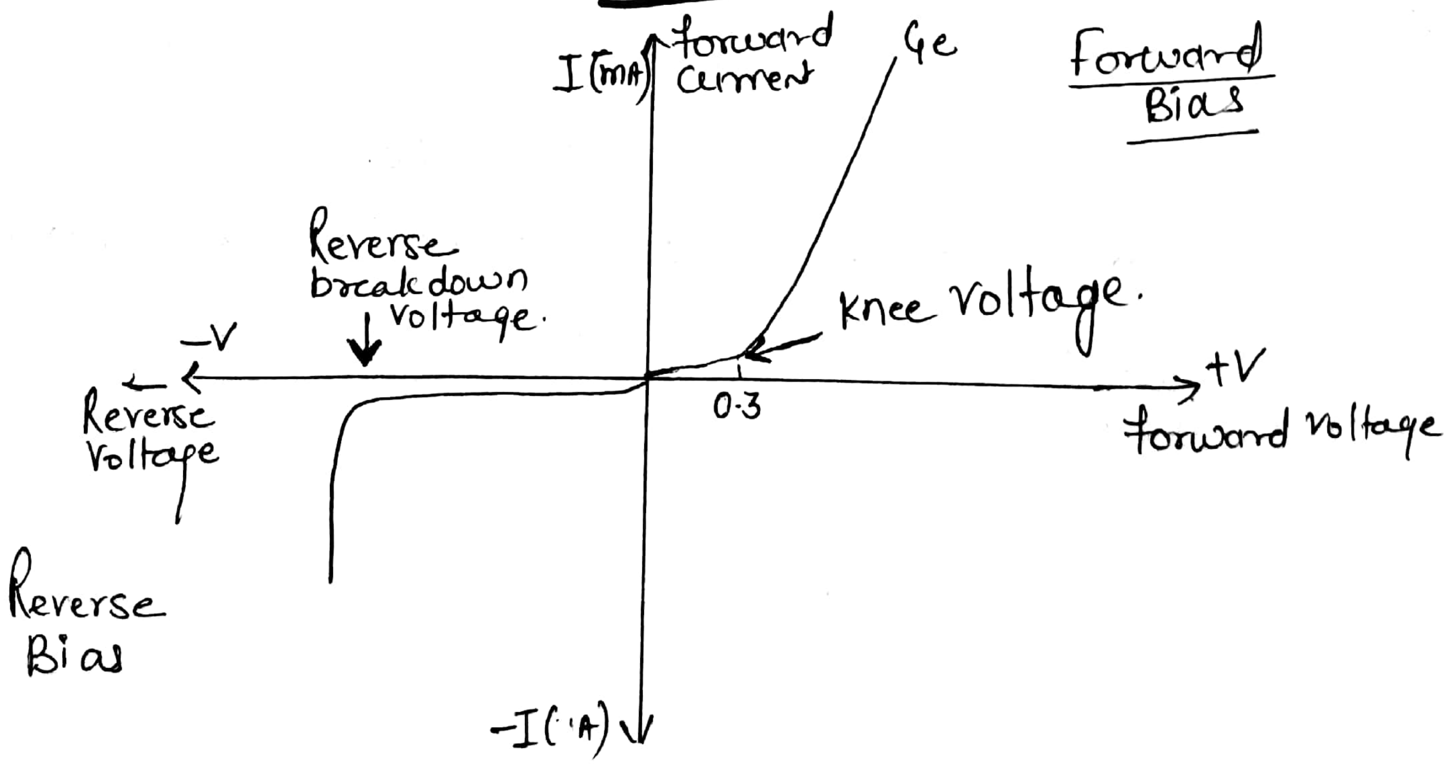
V-I Characteristics of PN Junction



→(1) In forward bias at forward Voltage (0-3V for Ge & 0-7 V for Si) the potential barrier across p-n junction is eliminated & Current starts flow. This voltage is called "threshold voltage" or "knee voltage"

→(2) As applied voltage further increases, the forward Current rises Exponentially. as shown in Graph.

→(3) In reverse bias, as the reverse voltage is increased from zero, the reverse Current quickly rises to its maximum or saturation value. The slightly increase is due to impurities on the surface of semiconductor. so Current produced is called surface leakage Current

→(4) If reverse Voltage is further increases kinetic Energy of minority Carriers becomes so high that they knock out the electron from atom. At this stage "junction breakdown" Occur & there is sudden rise of reverse Current.

Reverse Bias characteristics
Zener and Avalanche Breakdown

⇒ Avalanche Breakdown

The charge carriers of P N junction diode sometime absorb the heat from the enviornment at normal room temperature. When reverse bias applied across the junction, the kinetic energy of electrons increases & they start moving with high velocity. While moving they collide with other atoms & creates number of free electrons which causes reverse saturation current. Because of this saturation current, the avalanche breakdown occur in diode

⇒ Zener Breakdown

Zener breakdown takes place in heavily doped diodes. when high electric field is applied across the diode, then electron start moving across the junction. This develop small reverse bias current. but when movement of electron is increases beyond the rated capacity of diode, then current rapidly increases. This is known as zener breakdown

Difference between

Avalanche Breakdown	Zener Breakdown
→ Avalanche breakdown occur because of collision of electrons	→ Zener breakdown occur because of high electric field
→ It will destroy the the junction	→ It will not destroy the junction
→ Pair of electrons & holes are produced	→ Electrons are produced
→ It occurs with low doping	→ It occurs with high doping
→ Breakdown voltage is directly proportional to temperature	→ Breakdown voltage is inversly proportional to temperature
→ Temperature cofficient of avalanche breakdown is positive	→ Temperature cofficient of zener breakdown is negative
* positive temp cofficient means temperature of material increases with reverse voltage	* negative temp cofficient means temperature decreases with reverse voltage.

Diode Equation

In PN Junction forward bias, beyond Knee voltage forward Current rises exponentially according to following Equation

$$I = I_0 \left[\exp\left(\frac{V}{\eta V_T}\right) - 1 \right] \quad \text{———} (1)$$

where I = diode Current

I_0 = diode reverse saturation Current at room temp

V = applied forward voltage.

η = constant [1 for Ge, 2 for Si]

$V_T = \frac{KT}{q} = \frac{T}{11,600}$ volt Equivalent to temp

K = Boltzmann Const $= 1.3806 \times 10^{-23}$ J/K

q = electronic charge $= 1.6 \times 10^{-19}$ C

T = Temp (K)

In forward bias

$$\exp\left[\frac{V}{\eta V_T} \gg 1\right]$$

So Eq^n (1) becomes

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

Reverse Bias:- In Reverse bias, a constant reverse current saturation current I_0 flow due to minority carriers.

Here V is negative so Eqn (1) can be modified as

$$I = I_0\left[\exp\left(-\frac{V}{\eta V_T}\right) - 1\right]$$

In reverse region

$$\exp\left[\frac{-V}{\eta V_T}\right] << 1$$

so

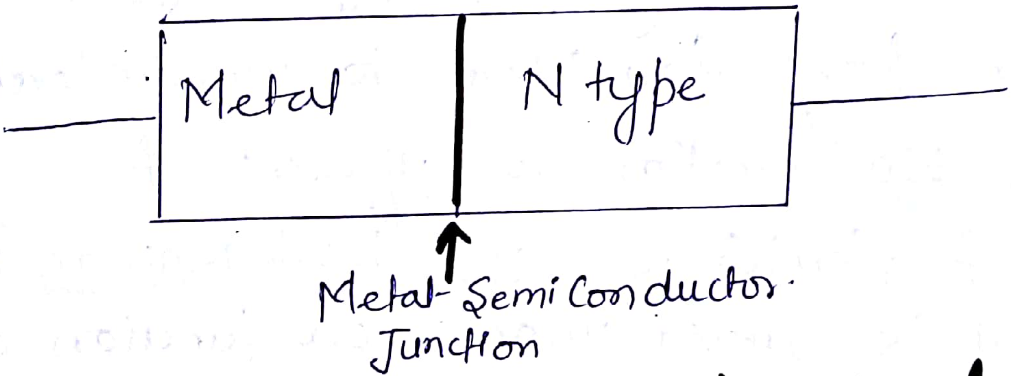
$$\boxed{I = -I_0}$$

Metal Semiconductor Junction or Schottky Diodes

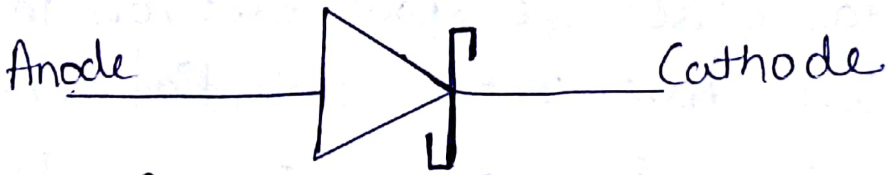
Schottky diode is a metal semiconductor junction diode that has less forward voltage drop than PN junction & can be used in high speed switching applications.

When p type & N type Semi Conductors are Joined than p-N Junction is formed while in Schottky diode metals such as aluminium or platinum replace the p type semiconductor.

When aluminium or platinum metal is Joined with N type semiconductor, a Junction is formed between metal & N type semiconductor. This Junction is known as metal semi conductor Junction & depletion layer known as Schottky barrier.



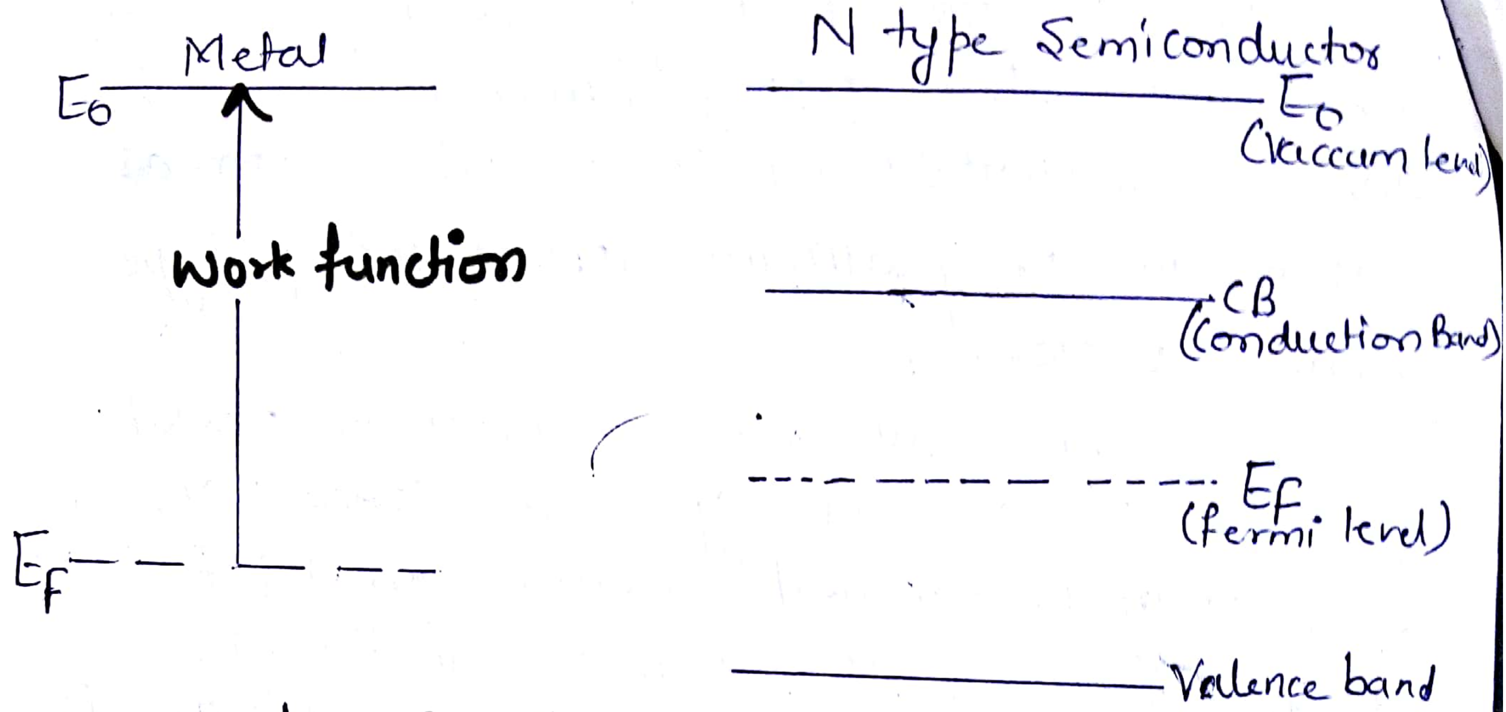
Symbol of Schottky diode



Energy Band diagram

Energy band diagram of Schottky diode.

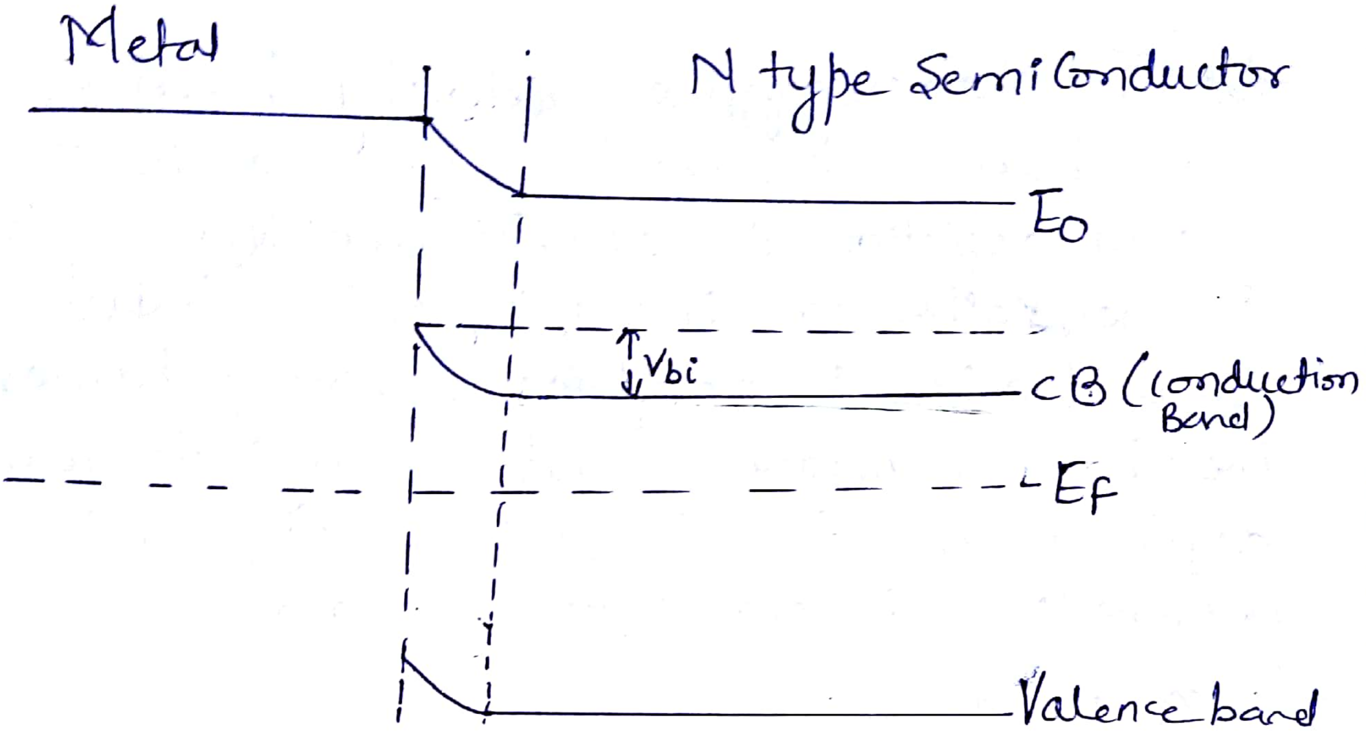
is shown below



Vaccum level is the energy level of electrons that are outside the material & workfunction is defined as energy required to more electron from fermi level to vaccum level (E_0)

The workfunction is different for metal & Semiconductor. Work function of a metal is greater than work function of semiconductor. In Energy level diagram fermi level at N type semiconductor lies above the metal side. We know electron in higher energy level have more potential energy than electrons in lower Energy level.

So the electrons in N type Semiconductor have more potential energy than electrons in metals.



where V_{bi} = Built in voltage barrier.

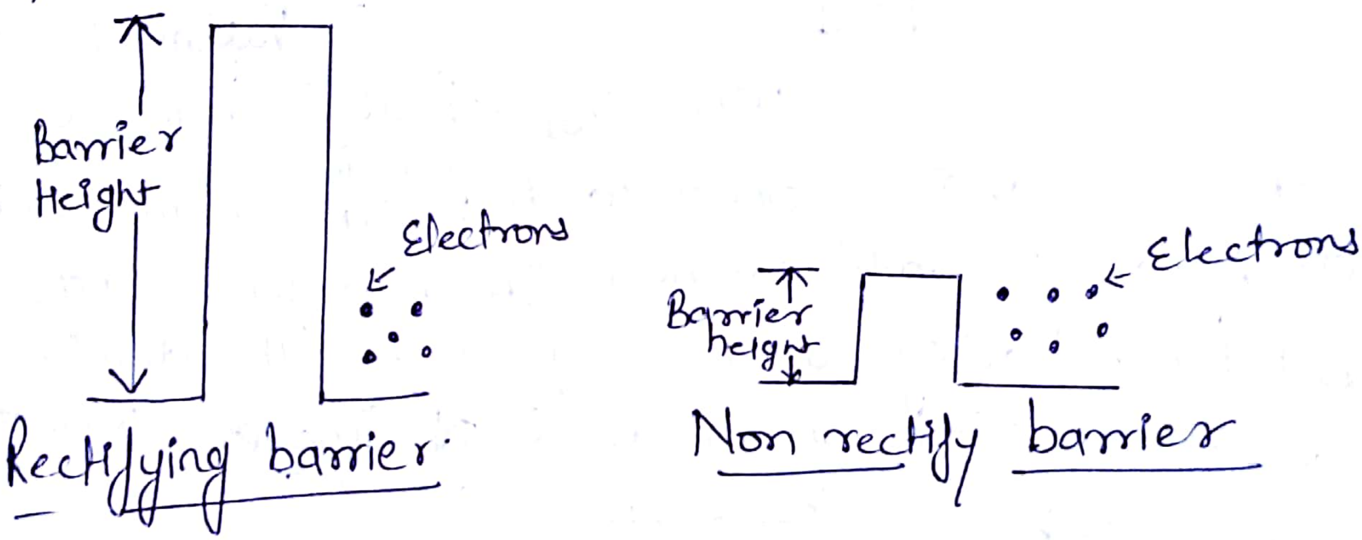
When metal is joined with N type Semiconductor then Schottky diode formed. The built in Voltage (V_{bi}) for Schottky diode is given by the difference b/w workfunction of metal & N type Semiconductor

Some Important Concepts

→ When Metal is in Contact with lighly doped Semiconductor then rectifying Schottky diode (Non ohmic Contact) formed while if metal is in contact with heavily doped Semiconductor then Non rectifying Schottky diode formed. (ohmic Contact)

→ Non rectifying metal Semiconductor (ohmic Contact) offer very low resistance than Rectifying metal Semiconductor junction (Non-Ohmic Contact)

→ In Non rectifying Schottky barrier, the barrier height is not enough to form depletion region. So depletion region is negligible or absent in ohmic Contact diode while, in rectifying Schottky barrier, the barrier height is high enough to form depletion region. So depletion region is present in non ohmic junction diode



Advantages:-

→ Schottky diode can switch on & off much faster than PN Junction diode

→ Schottky diode produce less unwanted noise than PN Junction diode

→ Schottky diode has a less voltage drop (approx 0.2 to 0.3 volts) than PN Junction (0.6 to 0.7 volts)

Because of these advantages it is (Schottky diodes) used for high speed switching power circuits

→ High Efficiency
→ Schottky diodes operates at high frequencies

Disadvantages

→ Schottky diode produce large reverse saturation current than p-N junction diode.

Semiconductor materials for optoelectronic devices

Si & Ge are the commonly used semiconductors. They are belongs to group IV of periodic table & used either in pure (intrinsic) or doped (extrinsic) form. The intrinsic & extrinsic semiconductor are known as "elemental semiconductors".

A compound semiconductor is a semiconductor composed of elements from two or more different groups of periodic table for eg:- one element from column III & one from column V, so called compound III-V semiconductor such as GaAs, InP & GaN.

The elemental semiconductors Si and Ge are indirect band gap semiconductors & therefore not suitable for producing light.

So they are basically used for making rectifying diodes while Compound Semiconductors are direct band gap Semiconductors & have high optoelectronic Conversion capacity. due to which they are widely used in fabrication of optoelectronic devices such as Semiconductor Lasers, LED, photodiodes, solar cells etc.