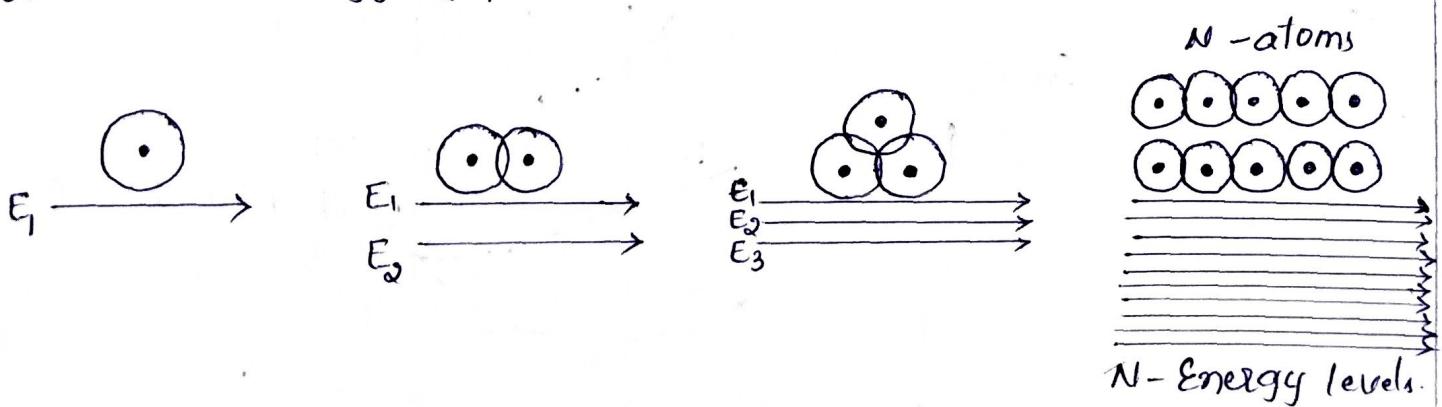


5. Semiconductors

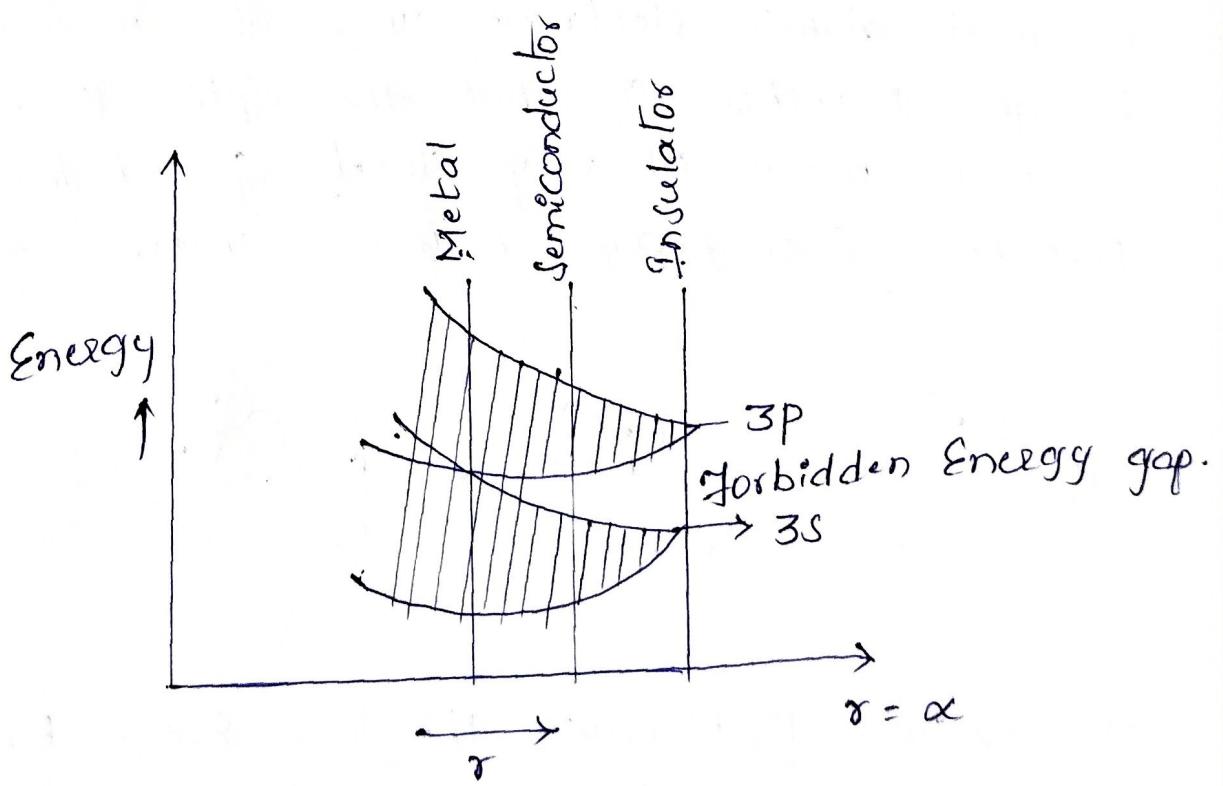
Formation of Energy band :-

In an isolated atom, the electrons are tightly bound and have discrete, sharp energy levels. When two identical atoms are brought closer the outermost orbits of these atoms overlap and interact. When the wave functions of the electrons of the different atoms begin to overlap considerably, the energy levels corresponding to those wave functions split into two. If more atoms are brought together more levels are formed and for a solid of N atoms, each of the energy levels of an atom splits into N levels of energy. The levels are so close together that they form an almost continuous band. The width of this band depends on the degree of overlap of electrons of adjacent atoms and is largest for the outermost atomic electrons. In a solid many atoms are brought together so that the split energy levels form a set of bands of very closely spaced levels with forbidden energy gaps between them.

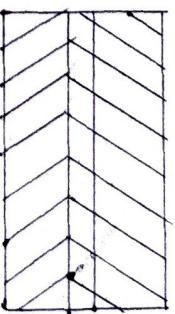
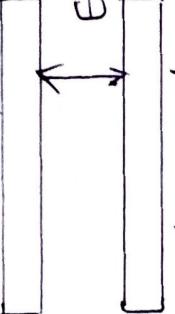
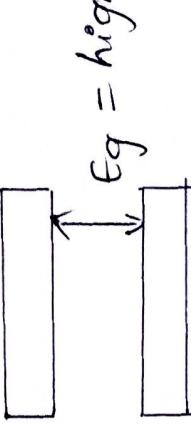


The electrons first occupy the lower energy bands and are of no importance in determining many of the electrical properties of solids. Instead the electrons in the higher energy

bands of solids are important in determining many of the physical properties of solids. Hence we are interested are in those two Energy bands called valence and conduction bands. The band corresponding to the outermost orbit is called conduction band and the next inner band is called valence band. The gap between these two allowed bands is called forbidden energy gap. Since electrons can't have energy values within the forbidden energy gap. Normally we are interested in the valence band occupied by valence electrons since they are responsible for electrical, thermal and optical properties of solids. Above the valence band we have the conduction band which is vacant at 0°K . According to the width of the gap between the bands and band occupied by electrons, all solids can be classified broadly into 3 groups, namely metals, semiconductors and insulators.



Classification of Solids based on Energy gap :-

Conductor	Semiconductor	Insulator
 <p>Conduction band</p> <p>valence band</p> <p>$E_g = 0$</p>	 <p>Conduction band</p> <p>valence band</p> <p>$E_g = 10\text{eV}$</p>	 <p>Conduction band</p> <p>valence band</p> <p>$E_g = \text{high}$</p>

1. For conductor the Energy band structure will be overlapped valence and conduction band.

2. Due to overlapping of bands there is no band gap $E_g = 0$

③ The electrons from the valence band freely enter into the conduction band due to over-lapping of bands.

1. For semiconductors the Energy band structure consists of separated valence and conduction bands with band gap.

2. The band gap E_g is low.

③ In the presence of external electric field, the electrons enter into the conduction band by acquiring sufficient energy to overcome the band gap.

③ Even in the presence of external electric field the electrons does not enter into the conduction band since they are tightly bound to their nucleus of respective atoms.

④ Due to the absence of band gap, free electrons are available in the conduction band at room temperature.

④ Due to low band gap, only few electrons are available in the conduction band at room temperature.

⑤ The electrical conductivity is mainly due to electrons only.

③ The electrical conductivity may be either electrons (or) holes depending upon the type of semiconductor.

⑥ The large free electrons of conductor contributes to high electrical conductivity.

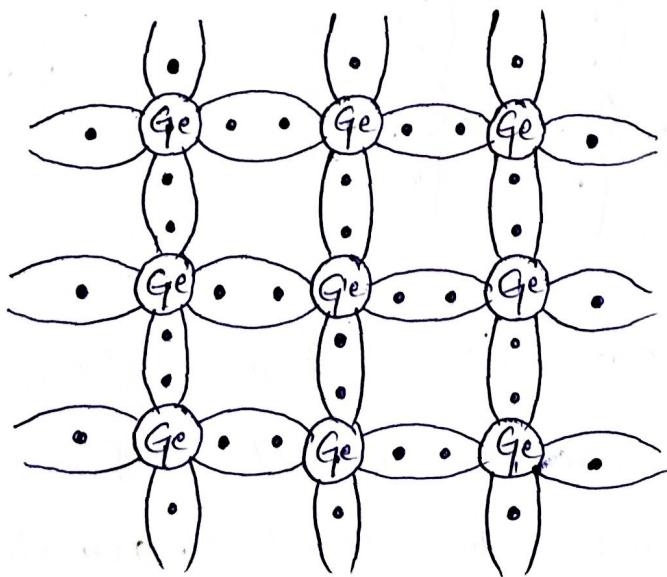
⑤ No charge carriers are available for the electrical conductivity in insulator.

⑥ Electrical Conductors is almost zero for insulators.

Intrinsic Semiconductors:-

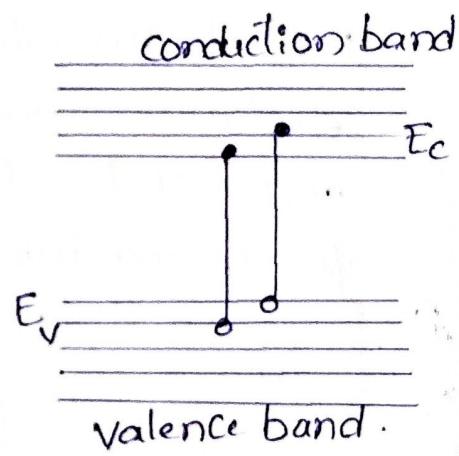
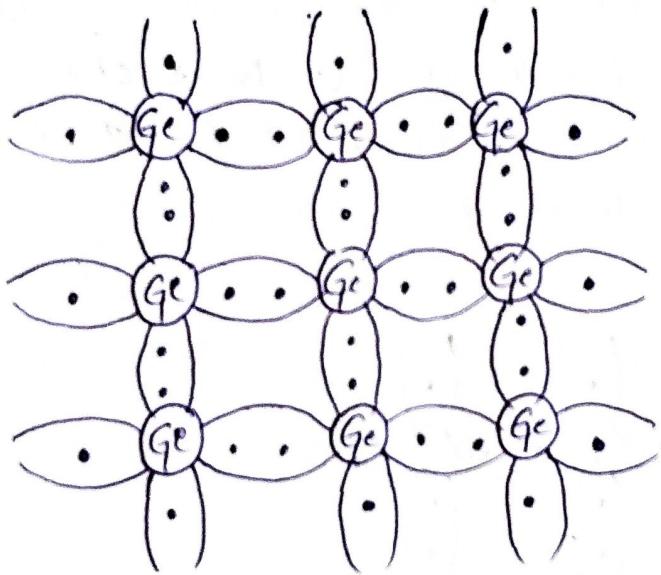
pure semiconductors are called as Intrinsic Semiconductors. Ex:- Ge, Si, these elements are IV group Elements.

Germanium has 3 σ electrons and silicon has 4 electrons in their atomic structures. Since each of them have 4 valence electrons, they have tetravalent atoms. The neighbouring atoms form covalent band by sharing four electrons with each other. Since all the four valence electrons and covalently bound to the four neighbouring atoms the crystal acts as a perfect insulator at 0K. In order to provide conduction electrons, covalent bands are to be broken. The Energy required to break such a covalent band is about 0.72 eV for Germanium and 1.1 eV for Silicon.



At room temperature, the thermal energy is sufficient to break covalent bands. When a covalent bond is broken an electron escapes to the conduction band leaving behind an empty site in the valence band called a hole. It is relatively easy for a valence electron in a neighbouring atom to leave its covalent bond to fill this hole thereby

leaving a hole in its initial position. Thus the hole effectively moves in the direction opposite to that of Electrons. Hence the conduction of electricity is due to the motion of free electrons in one direction and holes in the opposite direction. Therefore in a semiconductor both holes and electrons are charge carriers and the current transport is effectively taking place by holes and electrons. Since these charge carriers are due to breaking of covalent bonds. So the number of holes is equal to the number of free electrons.



Density of Charge Carriers - Intrinsic Semiconductors :-

In an intrinsic semiconductor, each broken bond leads to generation of two carriers, namely an electron and a hole. At any temperature T , the number of electrons generated will be therefore equal to the number of holes generated.

Let ' n ' be the number of electrons per unit volume and ' p ' be the number of holes per unit volume.

For an intrinsic semiconductor

$$n = p = n_i$$

(4)

whereas n_i is known as Intrinsic carrier concentration.
Electron concentration in the conduction band is

$$n = N_c e^{-(E_c - E_f)/k_B T}$$

Hole concentration in the valence band is

$$p = N_v e^{-(E_f - E_v)/k_B T}$$

N_c & N_v are known as pseudo constants.

k_B is Boltzmann Constant & T is the Temperature.

$$n_i^2 = np$$

$$n_i^2 = \left[N_c e^{-(E_c - E_f)/k_B T} \right] \left[N_v e^{-(E_f - E_v)/k_B T} \right]$$

$$n_i^2 = (N_c N_v) e^{-(E_c - E_v)/k_B T}$$

But $E_c - E_v = E_g$

$$n_i^2 = (N_c N_v) e^{-E_g/k_B T}$$

$$n_i = (N_c N_v)^{1/2} e^{-E_g/2k_B T}$$

From above Eq., it is clear that

- (1) The Intrinsic Carrier concentration is independent of the Fermi level position.
- (2) The intrinsic Carrier concentration is a function of the band gap E_g .
- (3) The intrinsic carrier concentration depends on the temperature T .

Electrical conductivity :-

Consider an intrinsic semiconductor to which a potential difference 'V' is applied. It establishes an electric field 'E' and the charge carriers are forced to drift in the respective directions to constitute an electric current 'I'. The drift velocity acquired by the charge carrier is given by $v_d = \mu E$, μ is the mobility of charge carriers.

Let ' n ' be the concentration of electrons in the semiconductor. Then the current density due to an electron is

$$J_n = n e v_d$$

$$J_n = n e \mu_n E, \mu_n$$
 is the

mobility of electron.

Similarly $J_p = p e \mu_p E$, p is hole concentration and μ_p is the mobility of the hole.

$$\text{Total current density } J = J_n + J_p$$

$$J = n e \mu_n E + p e \mu_p E$$

$$J = [n \mu_n + p \mu_p] E$$

But total current density

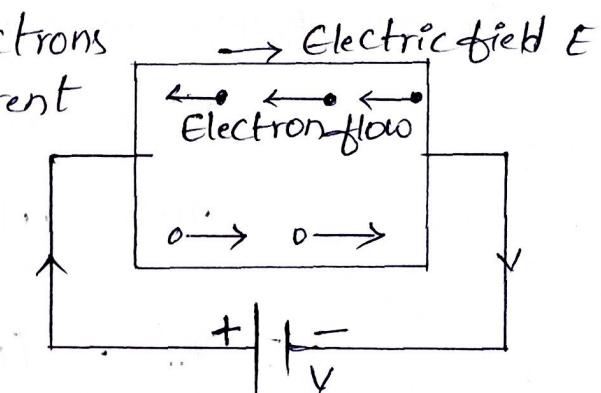
$$J = \sigma E, \sigma$$
 is total conductivity

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

For an intrinsic semiconductor $n = p = n_i$

$$\sigma = n_i e (\mu_n + \mu_p)$$

$$\text{But } n_i = (N_c N_v)^{1/2} e^{-E_g/2k_B T}$$



$$\sigma = (N_c N_v)^{1/2} e(\mu_n + \mu_p) e^{-E_g/k_B T}$$

$$\sigma = A e^{-E_g/2k_B T}$$

where $A = (N_c N_v)^{1/2} e(\mu_n + \mu_p) = \text{constant.}$

Fermi level :-

The Fermi Energy level indicates the probability of occupation of Energy levels in Conduction and valence bands. For an intrinsic semiconductor, hole and electron concentrations are equal, and it indicates that the probability of occupation of Energy levels in conduction and valence bands are equal. Thus, the Fermi level lies in the middle of the energy gap E .

For an intrinsic semiconductors $n = p$

$$N_c \cdot e^{-(E_c - E_F)/k_B T} = N_v e^{-(E_F - E_v)/k_B T}$$

$$\frac{N_v}{N_c} = \frac{e^{-(E_c - E_F)/k_B T}}{e^{-(E_F - E_v)/k_B T}}$$

$$\frac{N_v}{N_c} = e^{[2E_F - (E_c + E_v)]/k_B T}$$

Taking log on both sides; we have :

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

$$E_F = \frac{E_c + E_v}{2} + \frac{1}{2} k_B T \log \left(\frac{N_v}{N_c} \right).$$

When $N_v = N_c$, then $E_F = \frac{E_v + E_c}{2}$

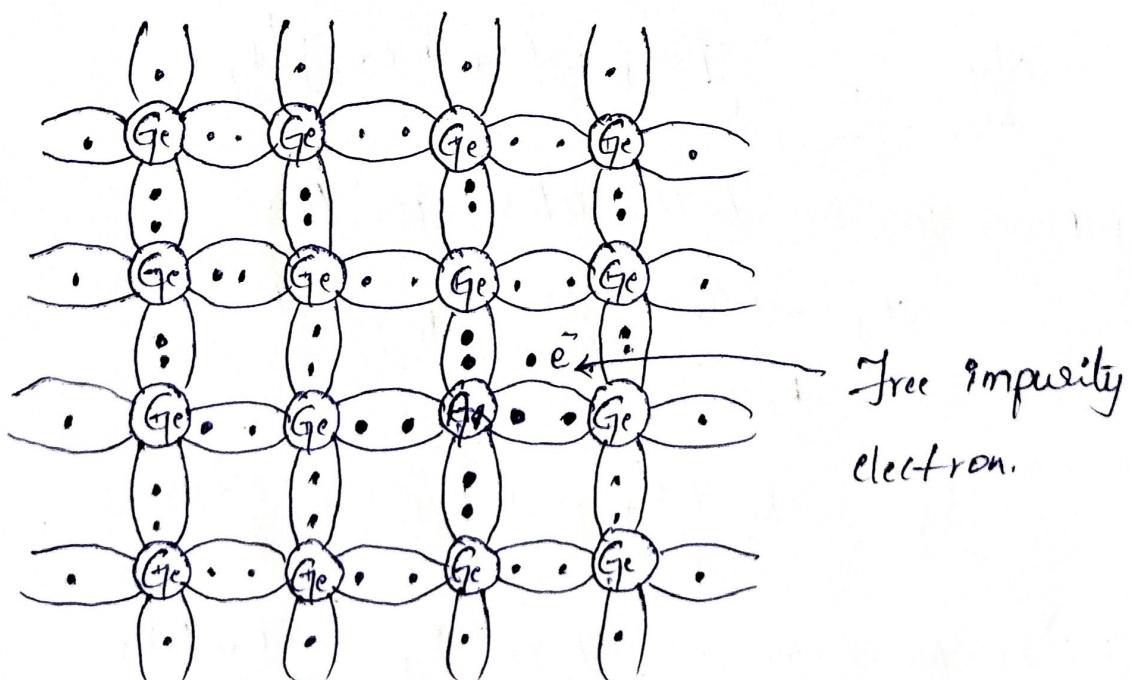
Thus, the fermi Energy level in an intrinsic Semiconductor lies in the middle (or) centre of the Energy gap. In practice, the fermi Energy level is independent of temperature.

Extrinsic Semiconductor:-

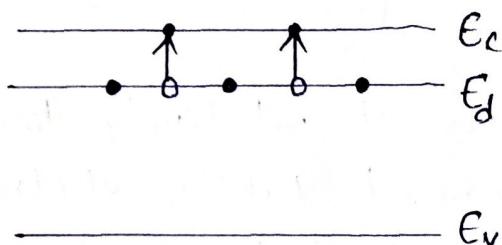
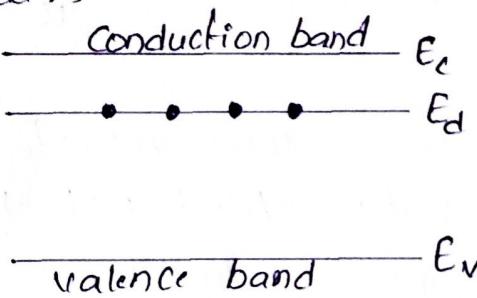
The addition of impurity increases the carrier concentration and hence the conductivity of the conductor also increases. There are 2 types of impurities possible.

(i) N-type Semiconductor:-

pentavalent elements such as phosphorous (P), Arsenic (As) or Antimony (Sb) have five electrons in their outermost orbits. When any one such impurity is added to the Intrinsic Semiconductor in small amount the crystal is grown, four electrons are engaged in covalent bonding with four neighbouring pure semiconductor atoms. The fifth electron is weakly bound to the parent atom. Even for lesser thermal energy this fifth electron is released leaving the parent atom positively ionised.



Since these pentavalent elements donate negative charges they are called N-type impurities and the semiconductors doped with pentavalent impurities are called N-type semiconductors. In the energy level diagram the energy level of the fifth electron is called donor level. The donor level is so close to the bottom of the conduction band, most of the donor level electrons are excited into the conduction band at room temperature become the majority charge carriers. If the thermal energy is sufficiently high, in addition to the ionisation of donor impurity atoms, breaking of covalent bonds may also occur thereby giving rise to generation of electron hole pairs.

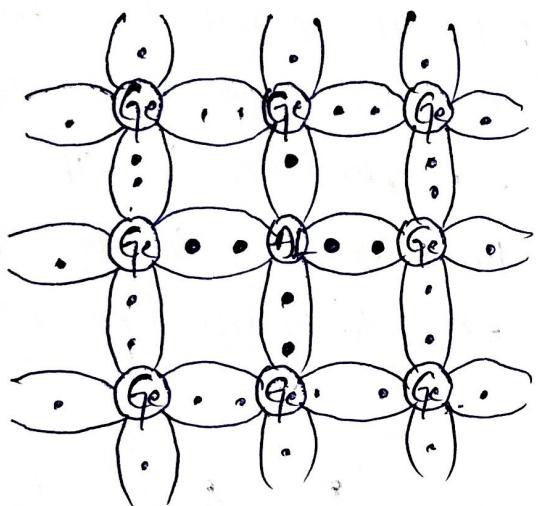


Hence in N-type semiconductors electrons are majority carriers and holes are minority carriers.

(ii) P-type Semiconductors :-

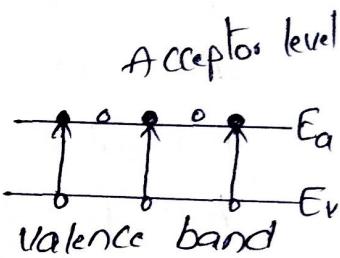
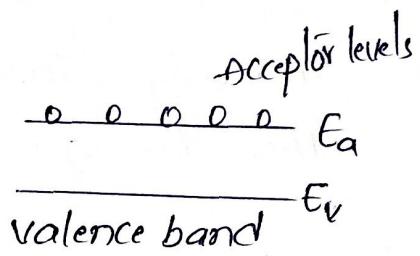
Trivalent elements such as Aluminium (Al), Gallium (Ga) or Indium (In) have three electrons in their outermost orbits. When any one such impurity is added to the intrinsic semiconductor say Germanium in small amount while the crystal is grown. All the three electrons of aluminium are engaged in covalent bonding with three neighbouring Ge atoms. Aluminium needs one more electron to complete its bond. This electron may be supplied by Ge, thereby

creating a vacant electron site or hole on the semiconductor atom. Since aluminium accepts one extra electron, the energy level of this impurity atom is called acceptor level. This acceptor level lies just above the valence band. These type of trivalent impurities are called acceptor impurities and the semiconductor doped with acceptor impurities are called p-type semiconductors.



Conduction Band E_C

Conduction Band E_C



Even at relatively low temperatures, these acceptor atoms get ionized taking electrons from valence band and thus giving rise to holes in valence band for conduction. Due to ionization of acceptor atoms only holes and no electrons are created. If the temperature is sufficiently high, in addition to the above process, electron-hole pairs are generated due to breaking of covalent bonds. Thus holes are more in number than electrons and hence holes are majority carriers and electrons are minority carriers in p-type semiconductors.

Density of charge carrier in n-type & p-type Semiconductors:

A Semiconductor, whether intrinsic or extrinsic is an electrically neutral body in its equilibrium condition. In an n-type Semiconductor, the total number of electrons in the conduction band must be equal to the sum of the

electrons originated from the donor atoms and electrons excited from the valence band. Electrons coming from donor levels leave behind positive donor ions while electrons excited from valence band leave behind holes. These charges have not created any additional charges so that Equality between the δ^- ve charges remains undisturbed. The charge neutrality condition applied to the n-type Semiconductor implies that the total -ve charge of mobile electrons is equal to the total +ve charge created in the crystal.

$$n_n = N_D + P_n, \quad N_D = \text{donor concentration}$$

The charge neutrality for a p-type Semiconductor requires that $P_p = N_A + n_p, \quad N_A = \text{acceptor concentration}$.

In n-type Semiconductor

$$n_n > P_n; \quad n_n = N_D$$

where n_n, P_n are the electron and hole concentration in an n-type Semiconductor.

From the law of mass action $P_n = \frac{n_i^2}{N_D}$ which is $\ll n_n (0) N_D$

For a p-type Semiconductor

$$P_p > n_p.$$

which gives $n_p = \frac{n_i^2}{N_A} \quad P_p = N_A \quad \text{which is } \ll P_p (0) N_A$

which gives n_p

where N_A, P_p and n_p are the concentrations of acceptor impurities, holes and electrons in a p-type Semiconductor.

Applications of Semiconductors :-

- (1) S.C are used in pocket calculators, T.V's and portable radios.
- (2) They are used in research labs of electric instruments to perform tests, measurements and numerous.
- (3) They are used in industrial control systems and automatic telephone exchanges.
- (4) They are used to convert large amounts of power into electricity for electric railroads.
- (5) They are used in military equipments, Data display systems and data processing units.

Drift and diffusion :-

Drift :-

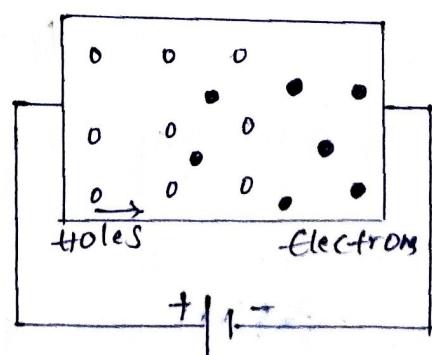
Under the influence of an external field, the charge carriers are forced to move in a particular direction constituting electric current. This phenomena is known as the drift. Let there be n electrons in a semiconductor under the electric field E . They are drifted with a drift velocity v_d . Then the current density

$$J = nev_d, \text{ where } e \text{ is the charge of electron}$$

$$\text{Conductivity } \sigma = \frac{J}{E}$$

$$\sigma = \frac{nev_d}{E}$$

$$\text{mobility } \mu_n = \frac{v_d}{E} \Rightarrow v_d = \mu_n E$$



then $J = n e \mu_n E$.

$$\sigma = \frac{n e \mu_n E}{E}$$

$$\sigma = n e \mu_n$$

$$\text{Resistivity } (\rho) = \frac{1}{\sigma} = \frac{1}{n e \mu_n}$$

In the case of a semiconductor, the drift current density due to electrons is given by.

$$J_n(\text{drift}) = n \mu_n e E \text{ and}$$

drift current due to holes is $J_p(\text{drift}) = p \mu_p e E$

Then the total drift current density

$$\begin{aligned} J_{\text{drift}} &= J_n(\text{drift}) + J_p(\text{drift}) \\ &= n \mu_n e E + p \mu_p e E \\ &= e E (n \mu_n + p \mu_p) \end{aligned}$$

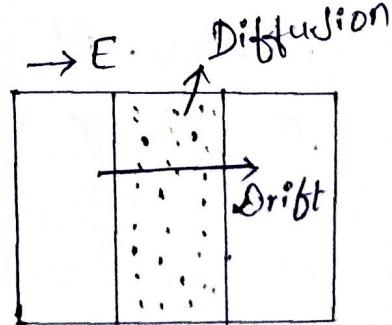
$$\sigma(\text{drift}) = \frac{J_{\text{drift}}}{E} = e [n \mu_n + p \mu_p]$$

For an intrinsic semiconductor, $n = p = n_i$ then $\sigma(\text{drift}) = e n_i [\mu_n + \mu_p]$

Diffusion :-

Due to non-uniform carrier concentrations in a semiconductor the charge carriers moves from a region of higher concentration to a region of lower concentration. This process is known as diffusion.

Let Δn be the excess electron concentration. Then according to Fick's law the rate of diffusion of electrons $\propto - \frac{\partial}{\partial x} (\Delta n)$



$$= D_n \frac{\partial}{\partial x} (\Delta n)$$

where D_n is the diffusion coefficient of electrons.

The diffusion current density due to electrons is given by

J_n (diffusion)

$$J_n = -e \left(-D_n \frac{\partial}{\partial x} (\Delta n) \right)$$

$$= e D_n \frac{\partial}{\partial x} (\Delta n)$$

The diffusion current density due to holes.

$$J_p \text{ (diffusion)} = +e \left(-D_p \frac{\partial}{\partial x} (\Delta p) \right)$$

$$= -e D_p \frac{\partial}{\partial x} (\Delta p)$$

The total current density due to electrons is the sum of the current densities due to drift and diffusion of electrons.

$$J_n = J_n \text{ (drift)} + J_n \text{ (diffusion)}$$

$$= n e \mu_n E + e D_n \frac{\partial}{\partial x} (\Delta n)$$

$$J_p = p e \mu_p E + -e D_p \frac{\partial}{\partial x} (\Delta p)$$

Einstein's relation :-

The relation between mobility μ and diffusion coefficient D of charge carriers in a semiconductor is known as Einstein's relation. At equilibrium with no applied electric field, if the charge distribution is uniform, there is no net current flow. Any disturbance in equilibrium state leads to diffusion of charge carriers resulting in a diffusion current which creates an internal electric field. This field causes the drifting of charge carriers resulting in a drift current.

(9)

At Equilibrium Condition, the drift current and diffusion current balance each other.

Let Δn be the Excess Electron concentration of a semiconductor.

Then at equilibrium the drift and diffusion current densities due to Excess Electrons are equal. $\Delta n e E \mu_n = e D_n \frac{\partial (\Delta n)}{\partial x}$.

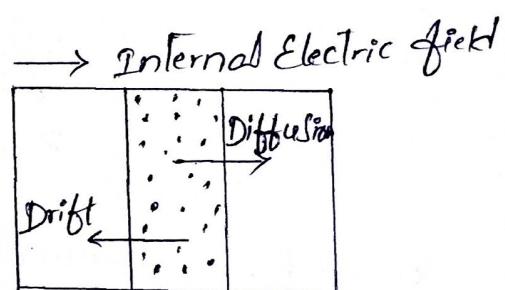
where 'E' is the electric field.

The force on Excess electrons restoring equilibrium is equal to the product of excess charge and electric field

$$F = (\Delta n) e E$$

$$\Delta n e E = e \frac{D_n}{\mu_n} \frac{\partial (\Delta n)}{\partial x}$$

$$F = e \frac{D_n}{\mu_n} \frac{\partial (\Delta n)}{\partial x} \rightarrow \textcircled{1}$$



From kinetic theory of gases, the force on gas molecules is given by

$$F = k_B T \frac{\partial (\Delta n)}{\partial x} \rightarrow \textcircled{2}$$

Compare Eq \textcircled{1} & \textcircled{2}

$$k_B T = \frac{e D_n}{\mu_n}$$

$$D_n = \frac{\mu_n k_B T}{e}, \quad \frac{D_n}{\mu_n} = \frac{k_B T}{e}$$

Similarly for holes, we get

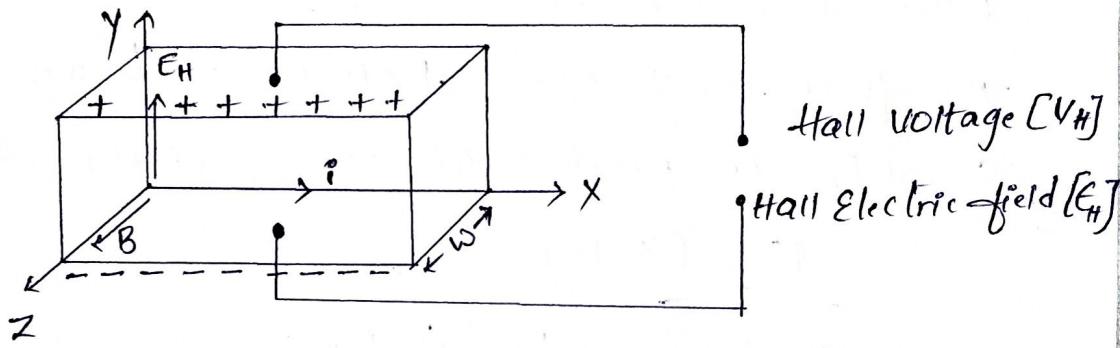
$$\frac{D_p}{\mu_p} = \frac{k_B T}{e}$$

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} \Rightarrow \boxed{\frac{D_n}{D_p} = \frac{\mu_n}{\mu_p}}$$

The above relation is known as Einstein's relation.

Hall Effect :-

when a current carrying semiconductor is subjected to a perpendicular magnetic field, then a potential difference (or) electric field is developed across the semiconductor (or) conductor in a direction perpendicular to both current and the applied magnetic field. This phenomenon is known as Hall Effect. The established potential difference is known as Hall Voltage and the electric field becomes Hall Electric field.



consider a semiconductor slab of thickness ' d ' and width ' w ' in which a current ' i ' is flowing along x -direction. It is subjected to a magnetic field of strength ' B ' along y -direction. The charge carriers inside the semiconductor experiences a force due to the applied magnetic field. As a result, electrons will be accumulated at the bottom surface of the semiconductor due to the magnetic force on them along y -direction. Thus -ve charges builds up at the bottom surface and the corresponding +ve charge on upper surface of the semiconductor. Thus a potential difference and electric field is established across the surfaces. This developed electric field along z -direction exerts a force on the electrons to prevent further accumulation at the bottom surface. At steady state, both the forces balances each other and the electrons can move freely to constitute an electric current.

Let E_H be the Hall Electric field on the semiconductor
the force on the electron due to E_H is eE_H

where ' e ' is the charge of electron.

The force on Electron due to magnetic field ' B ' is Bev
where ' v ' is the electron velocity.

At Steady State

$$eE_H = Bev$$

$$E_H = Bv$$

If V_H is the Hall voltage, then $E_H = \frac{V_H}{d}$

From the above Eq's, we get

$$\frac{V_H}{d} = Bv$$

$$V_H = Bvd$$

If ' n ' is the concentration of electrons in the semiconductor, then Current density.

$$J = nev$$

$$v = \frac{J}{ne}$$

$$V_H = \frac{BJd}{ne}$$

$$\text{But } J = \frac{i}{A}$$

where ' A ' is the area of cross section of a semiconductor

$$J = \frac{i}{dw}$$

$$V_H = \frac{Bd}{ne} \times \frac{i}{dw} = \frac{Bi}{new}$$

The Hall Coefficient R_H is given by

$$R_H = \frac{1}{ne}$$

$$V_H = \frac{B_i R_H}{\omega}$$

$$R_H = \frac{V_H \omega}{B_i}$$

The Conductivity in a semiconductor due to electrons is given by $\sigma = ne\mu$

$$\mu = \frac{\sigma}{ne} = R_H \sigma$$

The above Expression represents Hall voltage, Hall Coefficients and conductivity in terms of Hall Coefficient.

Applications:-

- (1) Knowing R_H and σ the mobility μ of Charge Carriers can be determined.
- (2) By determining the sign of R_H , we can know the type of charge carrier as well as Semiconductor. If the sign is +ve then the charge carriers are electrons and it is a n-type S.C & vice versa.
- (3) Carrier concentration can be determined by knowing R_H .
- (4) We can measure the conductivity of the given specimen knowing μ and R_H .
- (5) We can measure the magnetic field strength B by measuring the relative Quantities.

Variation of Fermi level with temperature in an n-type Semiconductor :-

The donor atoms in the n-type semiconductor at low temperatures are ionized and supply electrons to the conduction band. Electrons in the conduction band are only from the donor levels.

At $T = 0\text{K}$, E_F (Fermi level) lies midway between the donor levels and the bottom of the conduction band.

$$E_F = \frac{E_C + E_D}{2}$$

As the temperature increases the donor levels gradually get depleted and the Fermi level moves downward.

At the temperature of complete depletion of donor levels, the Fermi level coincides with the donor level E_D .

$$\text{at } T = T_d \Rightarrow E_F = E_D$$

As the temperature grows further above T_d , the Fermi level shifts downward, at high temperatures, the n-type semiconductor loses its extrinsic character and behaves as an intrinsic semiconductor. In the intrinsic region, the electron concentration in conduction band increases and Fermi level approaches the intrinsic value.

$$E_F = \frac{E_g}{2}$$

Variation of Fermi level with temperature in a p-type Semiconductor :-

In case of p-type semiconductor, in the low temperature region, holes in the valence band are only due to the transitions of electrons from the valence band to the

acceptor levels.

when $T = 0\text{K}$ fermi level lies midway between the acceptor levels and the top of the valence band

$$E_F = \frac{E_V + E_A}{2}$$

as the temperature increases the acceptor levels gradually get filled and the fermi level moves upward. At the temperature of T_s , the fermi level coincides with the acceptor level E_A .

$$E_F = E_A \text{ at } T = T_s$$

As the temperature grows above T_s the fermi level shifts upwards.

At higher temperatures, the p-type semiconductor loses its extrinsic character and behaves as an intrinsic semiconductor. In the intrinsic region, the hole concentration in the valence band increases and fermi level approaches the intrinsic value

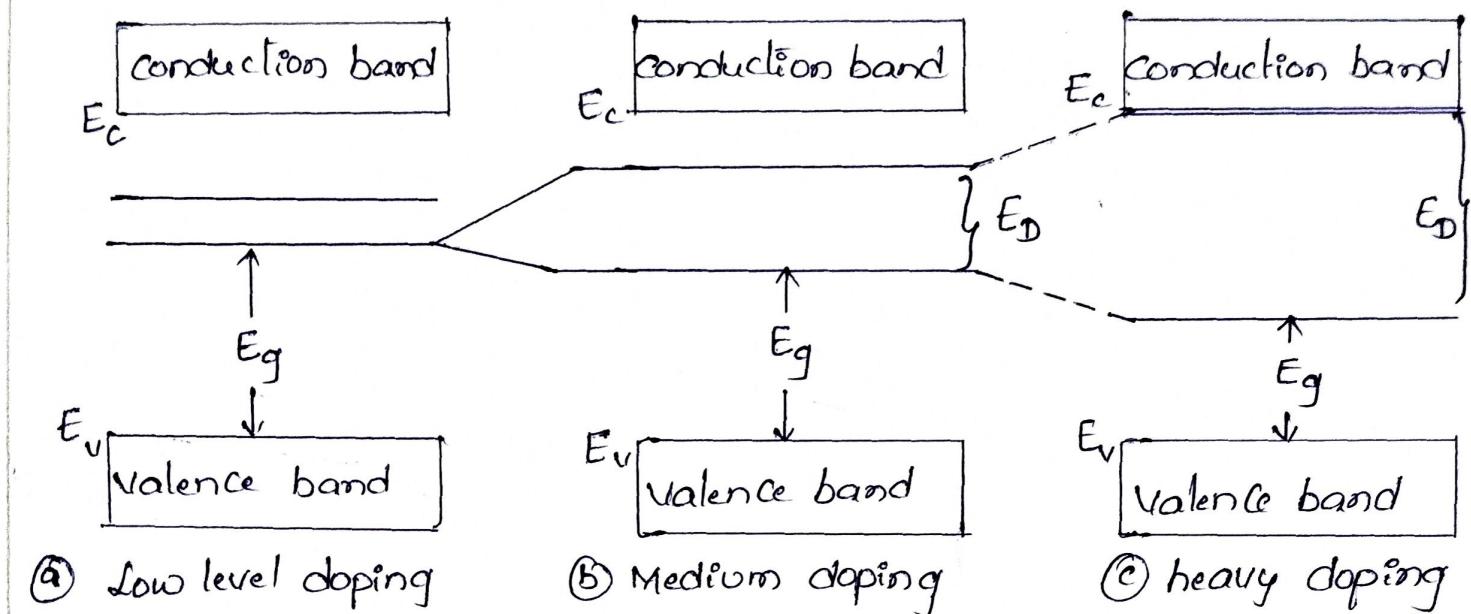
$$E_F = \frac{E_g}{2}$$

Variation of fermi level with impurity concentration :-

② n-type Semiconductor :-

when donor impurity is added to an intrinsic semiconductor, discrete donor levels form below the bottom edge of the conduction band. At low concentrations, the impurity atoms are far apart and they do not interact with each other. On increasing the impurity concentration the separation between impurity atoms reduces and they tend to interact. As a result, the donor levels undergo

Splitting and form an Energy band below the conduction band.



the larger the doping concentration, the broader is the impurity band, and at one stage the impurity band overlaps on the conduction band.

The fermi level shifts closer and closer to the conduction band with increasing impurity concentration and finally moves into the conduction band.

P-type Semiconductor :-

In p-type semiconductor, the acceptor levels broaden and form into a band with increasing impurity concentration. The acceptor band ultimately overlaps on the valence band. The fermi level moves down closer to the valence band and finally at very high impurity concentration it will shift into the valence band.