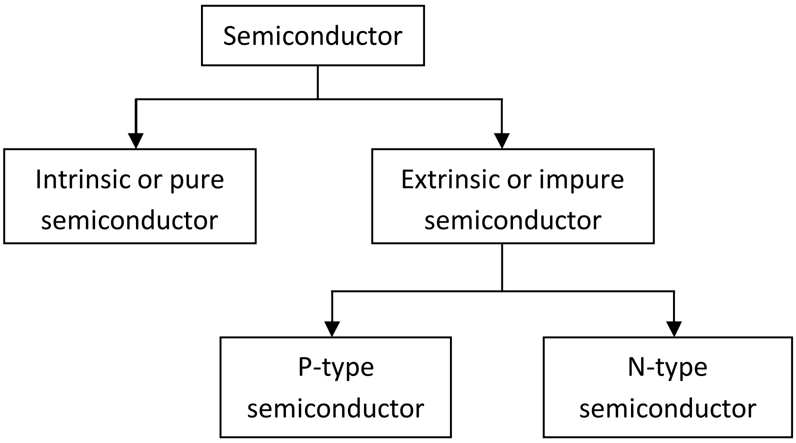
Semiconductor

A substance which has resistivity in between conductors and insulators is known as semiconductor.

Semiconductor are broadly classified into two categories

1) Intrinsic semiconductor
2) Extrinsic semiconductor

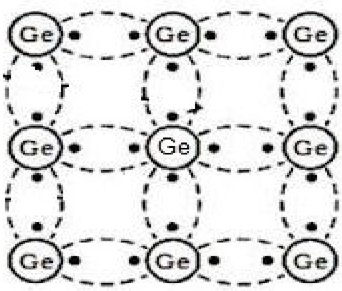


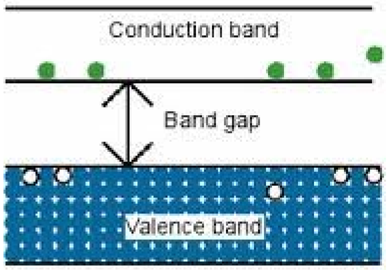
Intrinsic semiconductors

If a semiconductor is sufficiently pure, then it is known as intrinsic semiconductor.

ex:: pure Ge, pure Si

At low temperatures all the valence electrons are bound to the atoms through covalent bonds .but at higher temp, when thermal energy becomes comparable with the bond energy. Some of the covalent bonds will be broken and electron hole pairs will be generated. The electrons can occupy conduction bond and holes will be created in the valence bond. Each broken covalent bond generates one electron and a hole pair. Thus the electron and hole density in an intrinsic semiconductor will be equal and will be depending on the number of broken covalent bonds.





Intrinsic carrier concentration

Let ‘n’ be the number of electrons per unit volume or electron-carrier concentration bond, and ‘p’ be the number of hole per unit volume or hole-carrier concentration in the valence bond.

For an intrinsic semiconductor

$$n = p = n_i$$

Where 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 $p = N_V e^{-(E_F - E_V)/k_B T}$

Where N_C and N_V are known as pseudo-constants depending on temperature.

k_B is the Boltzmann constant

T is the absolute temperature of an intrinsic semiconductor.

$${n_i}^2 = np$$

$$= (N_C N_V) e^{-(E_C - E_V)/k_B T}$$

But $E_C - E_V = E_g$

$${n_i}^2 = (N_C N_V) e^{-E_g/k_B T}$$

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

Form the above relation, 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) n_i Depends on the temperature T.

Fermi level

The Fermi 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_g.

For an intrinsic semiconductor, $n = p$

$$N_C e^{-(E_C - E_F)/k_B T} = N_V e^{-(E_F - E_V)/k_B T}$$

$$\frac{e^{-(E_C-E_F)/k_BT}}{e^{-(E_F-E_V)/k_BT}}=\frac{N_V}{N_C}$$

$$e^{[2E_F-(E_C+E_V)]/k_BT}=\frac{N_V}{N_C}$$

Taking log on both side, we get

$$\frac{[2E_F-(E_C+E_V)]}{k_BT}=\log(\frac{N_V}{N_C})$$

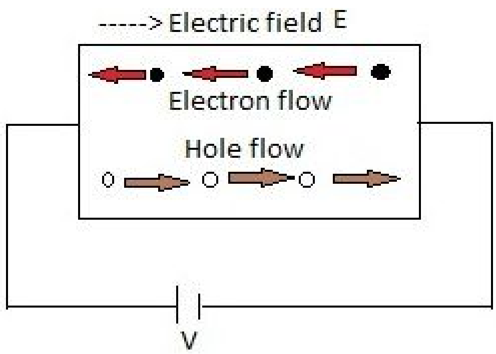
$$E_F=\frac{E_C+E_V}{2}+\frac{1}{2}k_BT\log(\frac{N_V}{N_C})$$

When $N_V=N_C$ then $E_F=\frac{E_C+E_V}{2}$

Thus, the Fermi energy level in an intrinsic semiconductor lies in the middle or centre of the energy gap.

Intrinsic conductivity

Consider an intrinsic semiconductor to which a potential difference V is applied. It establishes an electric field E and the change carriers are forced to drift in the respective directions to constitute an electric current I. The drift velocity acquired by the change carrier is given by



$$v_d=\mu E$$

Where 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 given by

$$J_n=nev_d=ne\mu_nE$$

Similarly, current density due to hole is given by

$$J_p=pe\mu_pE$$

Where p is the hole concentration and $\mu_p$is the mobility of the hole. Total current density

$$J=J_n+J_p$$

$$J=ne\mu_nE+pe\mu_pE$$

$$J=(n\mu_n+p\mu_p)eE \quad \text{------------------- (1)}$$

But total current density $J=\sigma E$ ---------------------- (2)

Where σ is the total conductivity

From (1) and (2), we get

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

For an intrinsic semiconductor, $n = p = n_i$

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

But $n_i = (N_C N_V)^{1/2} e^{-E_g/2k_BT}$

$$\sigma = (\mu_n + \mu_p)e(N_C N_V)^{1/2} e^{-E_g/2k_BT}$$

$$\sigma = Ae^{-E_g/2k_BT} \text{ where } A = (N_C N_V)^{1/2} e(\mu_n + \mu_p)$$

Determination of Energy band gap

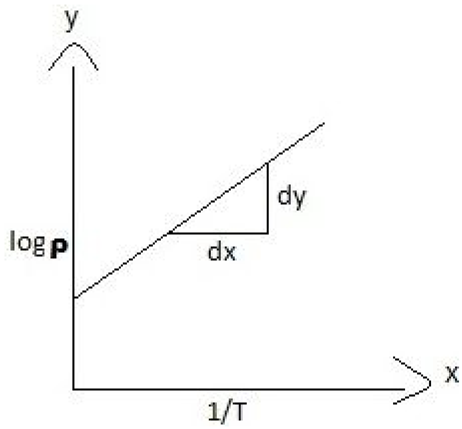
The energy gap between valence and conduction bands is the energy band gap E_g.

From the equation $\sigma = Ae^{-E_g/2k_BT}$, we get

$$\rho = \frac{1}{\sigma} = \frac{1}{A} e^{E_g/2k_BT} = Be^{E_g/2k_BT} \text{ where } B = \frac{1}{A} - constant$$

Taking *log* on both side, we get

$$\log \rho = \log B + E_g/2k_BT$$



log of the resistivity when plotted with *1/T,* produces a straight line. The slope of the line gives the energy band gap of the semiconductor.

From fig., $\frac{E_g}{2k_B} = \frac{dy}{dx}$

$$E_g = 2k_B \frac{dy}{dx}$$

Extrinsic semiconductor

When impurities are added to an intrinsic semiconductor them it becomes an extrinsic semiconductor.

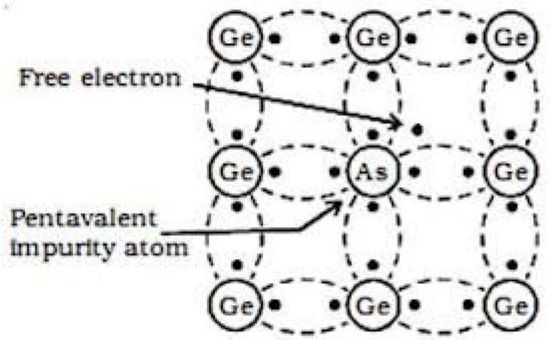
Depending upon the type of impurity added to the intrinsic semiconductors, extrinsic semiconductors are two types.

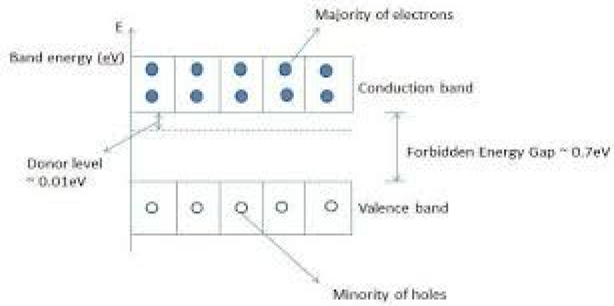
1) n – type extrinsic semiconductor
2) p – type extrinsic semiconductor

n – type extrinsic semiconductor

When a small quantity of pentavalent material is added to an intrinsic semiconductor during the process of crystallization, the resulting crystal is called n – type extrinsic semiconductor.

When penta valent impurity such as p, As, sb, Bi added to pure Ge or Si atoms then form four covalent bonds with neighboring atoms of Ge. The fifth atom electron of impurity atoms from a level is called *donor level*. Here impurity atom is donating the free electron so these atoms are called donor atoms. At room temperature, donor level is so closed to the bottom of the conduction band. If the thermal energy is sufficiently high, in addition to the ionization of donor impurity atoms, breaking of covalent bonds may also occur thereby giving rise to generation of electron – hole pair. Hence, in n – type semiconductors electrons are majority charge carriers and holes are minority charge carriers.

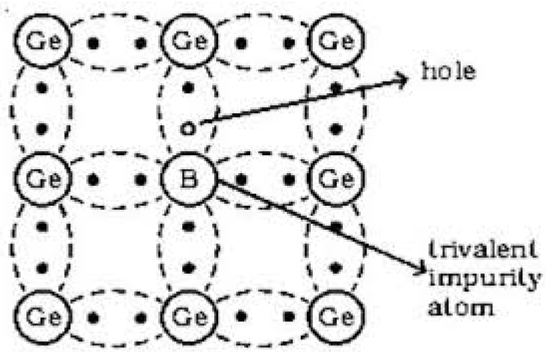


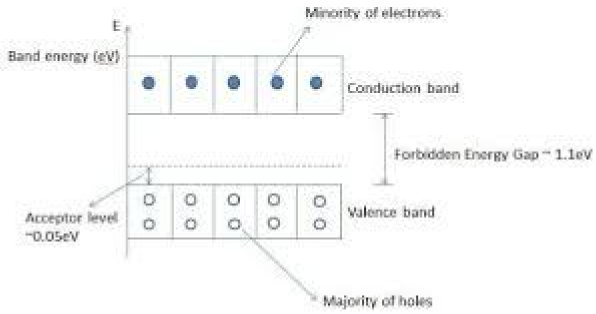


p – type extrinsic semiconductor

When a small quantity of trivalent impurity is added to an intrinsic semiconductor during the process of crystallization, the resulting crystal is called p – type extrinsic semiconductor.

When any tri valent impurity such as B, Al, Ga, In added to pure Ge or Si atoms then form three covalent bonds with neighboring atoms of Ge. Impurity atom needed one more electron to complete its bond. This electron may be supplied by Ge, thereby creating a vacant electron site i.e., hole on the semiconductor atom. Since impurity atom accepts extra electron. So, it is called acceptor impurity and energy level of this impurity atom is called *acceptor level*. Even at low temperatures these acceptors atom get ionized taking electron from valence band and this giving rise to hole in valence band for conduction. In this process no electrons are created. If the temperature is sufficiently high, in addition to the holes, 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 semiconductor.





Fermi level in extrinsic semiconductor

For an n – type semiconductor, the Fermi energy is

$$E_F = E_C - k_B T \log \frac{N_C}{N_D}$$

Where N_D is concentration of donor atoms.

From the above relation, it is clear that Fermi level lies below the conduction band.

For a p – type semiconductor, the Fermi energy level is

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

Where N_A is concentration of acceptor atoms.

From the above relation, it is clear that Fermi level lies above the valence band.

Effects of Temperature on E_F

In an n – type semiconductor, as T increases, more number of electron – hole pairs are formed. At very high temperature T, the concentration of thermally generated electrons in the conduction band will be far greater than the concentration of donor electrons. In such a case, as concentration of electrons and holes become equal, the semiconductor becomes essentially intrinsic and E_F returns to the middle of the forbidden energy gap. Hence, it is concluded that as the temperature of the p – type and n – type semiconductor increases, E_F moves towards the middle of the forbidden energy gap.

Law of Mass Action

The electron and hole concentrations in an intrinsic semiconductor are given by

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

$$\& \quad p = N_V e^{-(E_F - E_V)/k_B T}$$

As $= p = n_i$, we get

$$n_i = (N_C N_V)^{1/2} e^{-E_g/2k_BT}$$

The above relation shows that for any arbitrary value of E_F, the product of n and p is a constant. This conclusion is known as the law of mass action.

The electron and hole concentrations in an extrinsic semiconductor are given by the following expressions. Thus, for an n – type semiconductor,

$$n_n = N_C e^{-(E_C-E_F)/k_BT}$$

$$p_n = N_V e^{-(E_F-E_V)/k_BT}$$

$$\therefore n_n p_n = (N_C N_V) e^{-E_g/k_BT}$$

$$\therefore n_n p_n = {n_i}^2 \text{ ---------------- (1)}$$

The above relation represents law of mass action. For a p – type semiconductor, the above relation becomes

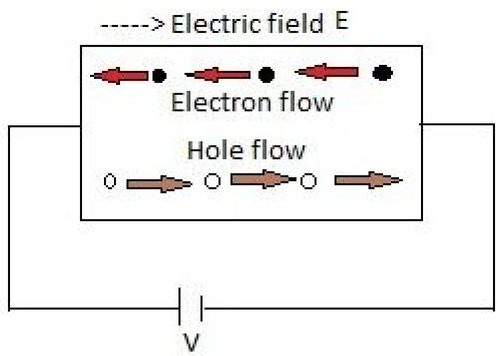
$$p_p n_p = {n_i}^2 \quad \text{------------- (2)}$$

The equations (1) & (2) imply that the product of majority and minority carrier concentrations in an extrinsic semiconductor at a particular temperature is equal to the square of intrinsic carrier concentration at that temperature.

The law suggests that the addition of impurities to an intrinsic semiconductor increase the concentration of one type of carrier, which consequently becomes majority carrier and simultaneously decreases the concentration of the other carrier, which as a result becomes the minority carrier.

Drift

Under the influence of an external electric 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

$$J = nev_d$$

Then conductivity $\sigma = \frac{J}{E} = \frac{nev_d}{E}$

The drift velocity is also given by $v_d = \mu_n E$ where μ_n is the mobility of electrons.

$$\therefore J = ne\mu_n E$$

$$\therefore \sigma = \frac{J}{E} = ne\mu_n$$

In the case of a semiconductor, the drift current density due to electrons is given by $J_n(drift) = ne\mu_n E$ and the drift current density due to hole is $J_p(drift) = pe\mu_p E$.

Then the total drift current density $J(drift) = J_n(drift) + J_p(drift)$

$$J(drift) = ne\mu_n E + pe\mu_p E$$

$$J(drift) = \left(n\mu_n + p\mu_p\right)eE$$

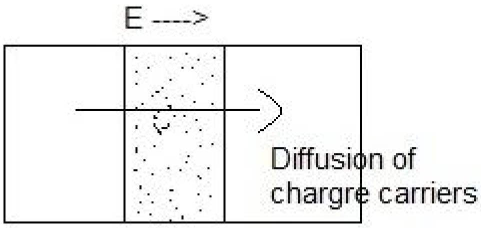
$$\sigma(drift) = \frac{J(drift)}{E} = \left(n\mu_n + p\mu_p\right)e$$

For an intrinsic semiconductor, $n = p = n_i$ then

$$\sigma_i(drift) = n_i e(\mu_n + \mu_p)$$

Diffusion

Due to non – uniform carrier concentration 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 of charge carriers.



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

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

Where D_n is the diffusion coefficient of electrons, the diffusion current density due to electrons is given by $J_n(diffusion)$

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

The diffusion current density due to holes is given by $J_p(diffusion)$

$$= e\left[-D_p \frac{\partial(\Delta p)}{\partial x}\right] = -eD_p \frac{\partial(\Delta p)}{\partial x}$$

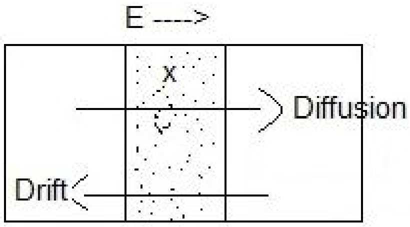
The total current density due to electrons is the sum of the current densities due to drift and diffusion of electrons.

$$J_n = J_n(drift) + J_n(diffusion)$$

$$= ne\mu_n E + eD_n \frac{\partial(\Delta n)}{\partial x}$$

Similarly, $J_p = pe\mu_p E - eD_p \frac{\partial(\Delta p)}{\partial x}$

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 current which creates an internal electric field. This field causes the drifting of charge carriers resulting in a drift current. At equilibrium condition, the drift 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.

i.e., $(\Delta n)e\mu_n E = eD_n \frac{\partial(\Delta n)}{\partial x}$

The force on excess electrons restoring equilibrium in equal to the product of excess charge and electric field i.e., $F = (\Delta \mathrm{n})\mathrm{eE}$. From the above eqn

$$F = e\frac{D_n}{\mu_n}\frac{\partial(\Delta n)}{\partial x} \quad \text{------------- (1)}$$

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

$$F = k_B T\frac{\partial(\Delta n)}{\partial x} \quad \text{------------ (2)}$$

Comparing (1) and (2), we get

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

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

Similarly for holes, we get

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

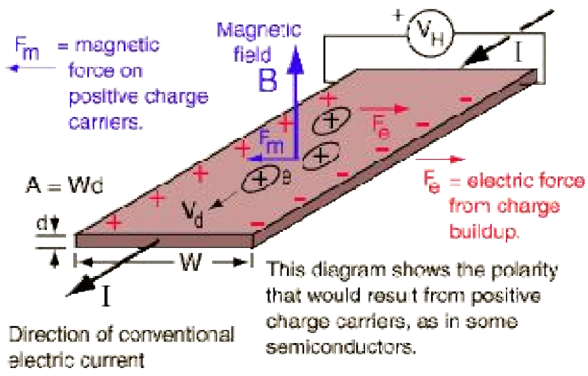
$$\therefore \frac{D_n}{D_p} = \frac{\mu_n}{\mu_p}$$

The above relation is known as Einstein's Relation.

Hall Effect

"When a magnetic field is applied perpendicular to a current carrying conductor, a potential difference is developed between the points on the opposite side of the conductor" is called *Hall Effect*.

Consider a uniform, thick metal strip placed with its length parallel to X – axis. Let a current i is passed in the conductor along the X – axis and magnetic field B is established along Y – axis. Due to the magnetic field, the charge carriers experience a force F perpendicular to XY plane. If the charge carriers are electrons, then they will experience a force in the positive direction of Z. Hence, they will be accumulated on the upper surface of the strip. Due to this fact the upper side will be charged negatively while the lower side will be charged positively. Thus, a transverse potential difference is created. This emf is known as Hall emf. If the charge carriers are positively charged particles (holes or protons) the sign of the emf is reversed.



Due to displacement of charge carriers give rise to a transverse field known as Hall electric field E_H. This field acts inside the conductor to oppose the side way drift of the charge carrier. When the equilibrium is reached, the magnetic deflecting forces on the charge carriers are balanced by the electric forces due to the electric field. Magnetic deflecting force will be $q(v_d x B)$

Hall electric deflecting force1 = qE_H

As the net force on the charge carriers becomes zero

$$q(v_d x B) + qE_H = 0$$

$$E_H = -(v_d x B)$$

In terms of magnitude $E_H = v_d B$ ------------- (1)

We know that drift velocity v_d is related to the current density J is $v_d = \frac{J}{nq}$ --------- (2)

Where n is the number of charge carriers per unit volume. By eqn(2) in eqn(1), we get

$$E_H = \frac{1}{nq} JB \quad \text{----------- (3)}$$

If V_H be the Hall voltage in equilibrium, then

$$E_H = \frac{V_H}{d} \quad \text{------------ (4)}$$

The ratio of Hall electric field E_H to the product of current density J and magnetic induction B is known as Hall coefficients. This is denoted by R_H.

So $R_H = \frac{E_H}{JB}$

From eqn(3) $\frac{E_H}{JB} = \frac{1}{nq}$

$$\therefore \; R_H = \frac{1}{nq}$$

Applications of Hall Effect

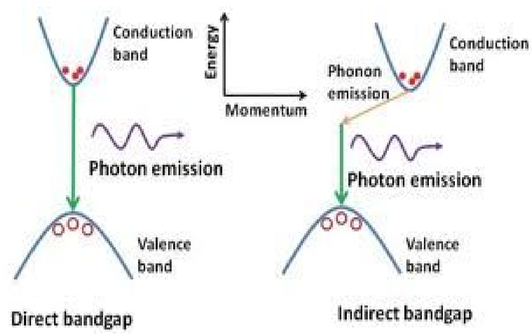
1) It gives the information about the sign of charge carriers in electric conductor. From this most metals have negatively charged electrons.
2) It can be used to measure the drift velocity of the charge carriers. i.e., $v_d = \frac{J}{nq}$
3) Hall measurements give the number of charge carriers per unit volume (n).
   If A is the face area of the plate. Then
   $$i = nqA\, v_d = nqA \frac{E_H}{B}$$
   Let b be the breadth and d be the width of face then face area of the conductor is $A = bd$
   $$i = nqbd \frac{E_H}{B}$$
   $$n = \frac{iB}{qbdE_H}$$

For metals, the Hall coefficient is smaller than that for semiconductors. The carrier concentration n in semiconductor is much smaller.

4) Strong magnetic field can be measured by the application of Hall Effect.
   $$B = \frac{nqbdE_H}{i}$$
   By measuringE_H, the magnetic field strength B can be determined.
5) The mobility of the charge carriers can be measured by the conductivity of the material and Hall coefficient.
   $$\mu = \sigma R_H$$
6) Hall Effect quite helpful in understanding the electrical conduction in metals and semiconductors.

Direct and Indirect band gap semiconductors

We know the relation between energy and wave number for an one dimensional lattice. In real crystals the E – k relationship is much more complicated. In crystals the interatomic distances and internal potential energy distribution vary with direction of the



crystal. Hence the E – K relationship and hence energy band formation depends on the orientation of the electron wave vector to the crystallographic axes. In few crystals like GaAs, the maximum of the valence band occurs at the same value of K as the minimum of the conduction band. This is called *direct band gap semiconductor*. In few semiconductors like Si the maximum of the valence band does not always occur at the same K values the maximum of the conduction band. This we call *indirect band gap semiconductor*.

In direct band gap semiconductors the direction of motion of an electron during a transition across the energy gap, remains unchanged. Hence the efficiency of transition of charge carriers across the band gap is more in direct band gap than in indirect band gap semiconductors.

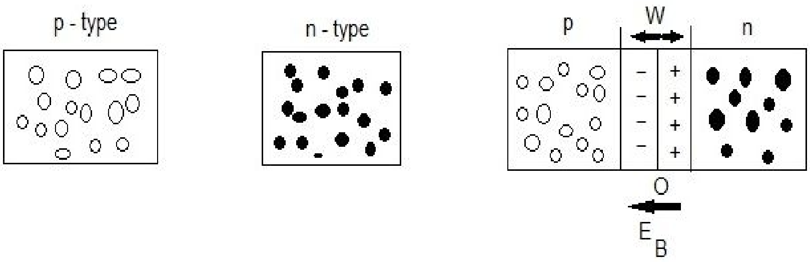
<u>Working principle of p – n junction diode</u>

When p-type and n-type semiconductors are formed by doping trivalent and pentavalent impurity atoms on either end regions of a semiconductor, such a way that the crystal structure remains continuous at the boundary of two doped regions, then p-n junction is formed. Such p-n junctions were widely used for various electronic applications.

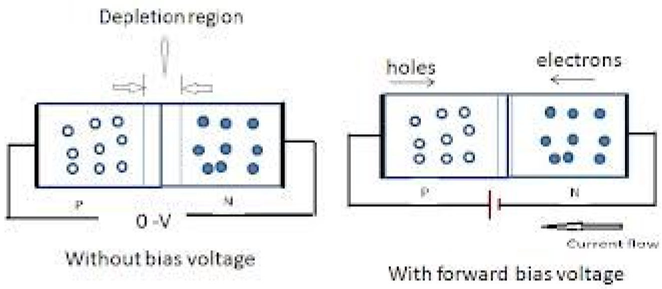
<u>Formation of p-n junction</u>

When a layer of p – type semiconductor material is placed with a layer of n – type semiconductor material in such a way that the atoms of p – type combine with the atoms of n – type across the surface of contact. Such a surface junction where combination has occurred is known as p – n junction. Combined p – type and n – type semiconductors with p – n junction is known as junction diode or pn diode.

Let us consider the formation of a sharp junction when two separate semiconductors of p and n type are brought together. The p – type has holes as majority carriers and electrons as minority carriers while n – type has electrons as majority carriers and holes as minority carriers. When they are joined, in the region of contact the free electrons diffuse from n – type region and combine with holes in p region. This leaves n – region near the boundary positively charged and p – region negatively. As a result, electric field E_B appears in a small region W on either side of the junction O as shown in fig. This region is called depletion region. The thickness of this region is in the order of $6\,x\,10^{-6}\,cm$. Due to the electric field E_B potential difference appears across the depletion region and this potential V_B is called contact potential or barrier potential or junction barrier.

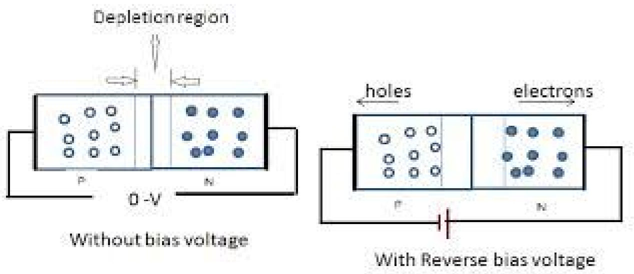


Forward biased p – n junction



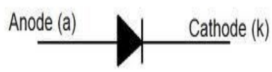
In forward biased p – n junction, p type is connected to positive terminal of battery and n type is connected to negative terminal of battery. This forward biased applied potential difference decreases the potential barrier which in turn reduces the width of the depletion region. As a result more number of charge carriers cross the junction and are accelerated by the forward biased voltage, which in turn causes the flow of current and we get the conductivity through the p – n junction and is as shown in the corresponding band structure.

Reverse biased p-n junction



In reverse biased p-n junction, p type is connected to negative terminal and n type is connected to positive terminal of battery. This reverse biased applied voltage increases the potential barrier with increase in the width of depletion region as shown in the band diagram. As a result, the change carriers are forced to move away from the junction which in turn causes no current flow through the junction and conductivity vanishes.

p – n Junction Diode

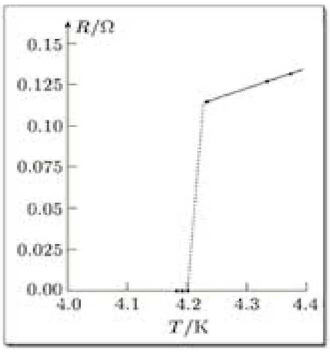


When the pn junction is forward biased conductivity takes place through the junction and in reverse biased no conductivity exists. Thus it can act as a switch; hence it is known as p – n junction diode. This diode is widely used in electron applications and its symbol is as shown in Fig.

SUPERCONDUCTIVITY

Introduction

The phenomenon of attaining zero resistivity or infinite conductivity at low temperature is known as superconductivity. The material becomes a super conductor and it will be in super conducting state.



Superconductivity was first observed by kammerlingh Onnes in the case of mercury. When the temperature of mercury is decreased then the resistance also decreases and it is nearly to zero at 4.2 K.

The temperature at which the material undergoes a transition from normal state to super conducting state is known as critical temperature or transition temperature (T_C).

Properties

1. Superconductivity is a low temperature phenomenon.

2. The transition from normal state to superconducting state occurs below the critical temperature.

3. Different materials will have different critical temperatures.

4. The current once setup in a superconductor persists for a long time due to zero resistivity.

5 superconductors do not allow magnetic field through them and behaves a diamagnetic. This property of expulsion of magnetic field is known as Meissner effect.

6. The magnetic field at which a superconductor loses it's superconductivity and becomes a normal conductor is known as critical magnetic field H_C.

7. The induced current in a superconductor induces a magnetic field in it. If the magnetic field is equal to the critical magnetic field then it converts into a normal conductor. The current in it is known as critical current (I_C). If 'r' is the radius of the super conductor then

$$I_C = 2\pi r H_C$$

The current density at which it occurs is known as critical current density and is given by $J_C = I_C/A$, where A is the area of cross section of the super conductor.

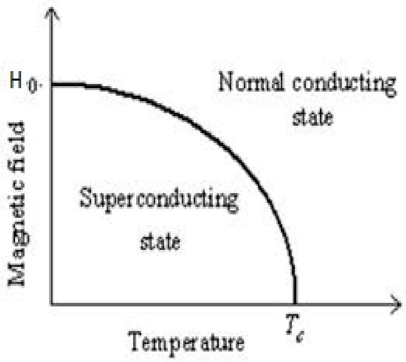
8. Superconductivity occurs in metallic elements in which the number of valence electrons lies between 2 and 8.

9. Materials having high normal resistivity exhibit super conductivity.

10. Superconducting materials are not good conductors at room temperature.

Critical magnetic field (H_C)

When a magnetic field is applied to a superconductor then for a particular value of applied field it loses superconductivity and becomes a normal conductor. The magnetic field for which a superconductor becomes a normal conductor is known as Critical magnetic field (H_C) and is given by



$$H_C = H_0\left[1-\left(\frac{T}{T_C}\right)^2\right]$$

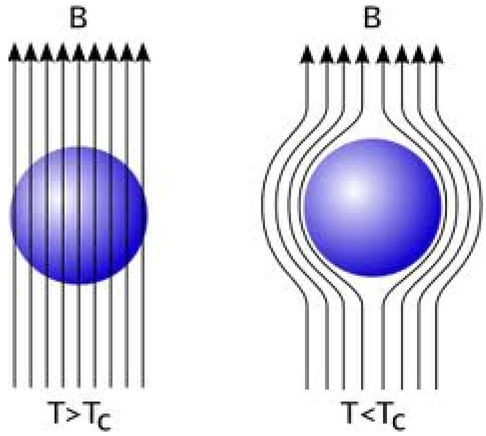
Where H_0 is the field required to destroy the superconducting property at 0 K, T_C is the critical temperature of the superconductor and T is the temperature of the super conductor.

Meissner Effect

When a weak magnetic field is applied to a superconducting specimen at a temperature below transition temperature T_C, the magnetic flux lines are expelled. The specimen acts as an ideal diamagnet. This effect is called Meissner effect. This effect is reversible. Under this condition, the magnetic induction inside the specimen is given by

$$B = \mu_0(H+M)$$

Where H is the external applied magnetic field and M is the magnetization produced inside the specimen.



When the specimen is superconducting according to Meissner effect, inside the bulk superconductor B = 0. Hence

$$0 = \mu_0(H+M)$$

$$M = -H$$

Thus the material is perfectly diamagnetic. Magnetic susceptibility can be expressed as

$$\chi = \frac{M}{H} = -1$$

London penetration depth

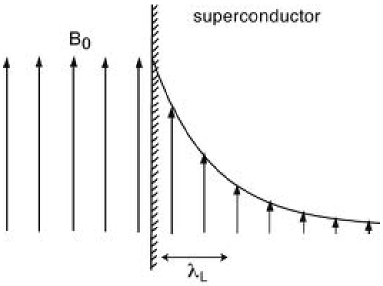
Consider a super conductor for which a magnetic field H_0 is applied to one of its faces. To obey Meissner effect, it will not allow magnetic lines to pass through it, but in practice a small portion of H_0 penetrates to a small distance into the superconductor.

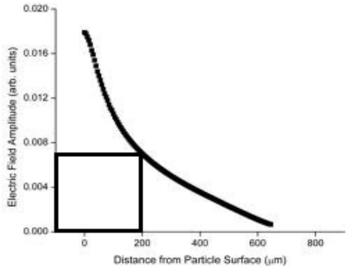
The penetrating field at a distance x from the face is given by

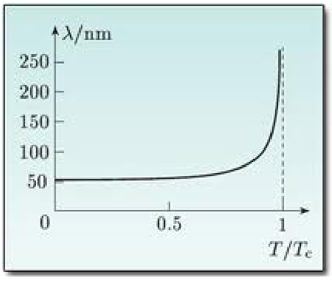
$$H = H_0 e^{-x/\lambda}$$

Where λ is known as penetration depth. When $x = \lambda$, then $H = H_0/e$. The λ is the distance inside the super conductor at which the penetrating magnetic field is equal to 1/e times the applied magnetic field H_0. λ Ranges from 10 to 100 nm. This depth is significant for a thin film superconductor rather than a bulk superconductor. The variation of λ with temperature T is given by

$$\lambda = \frac{\lambda_0}{\left[1-\left(\frac{T}{T_C}\right)^4\right]^{1/2}}$$







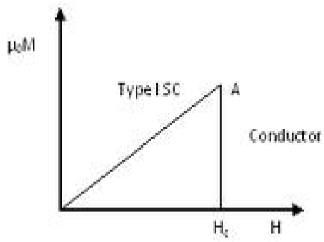
Types of super conductor

In the presence of critical magnetic field, a superconductor convents into a normal conductor. Based on the conversion process, superconductors are classified into two types.

1. Type I super conductor
2. Type II super conductor

Type I super conductor

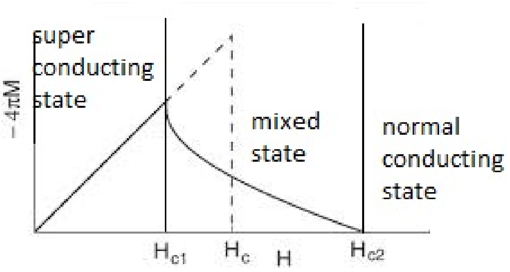
Consider a cylindrical superconductor to which a magnetic field H is applied along the axis of it. It will not allow the magnetic lines and obeys Meissner effect. Inside the super conductor, the magnetization acting opposite to H opposes the field. When the magnetic field is equal to the critical field Hc then immediately – M becomes zero & converts into normal conductor. Here, conversion is fast and is known as Type I superconductor. It is also known as soft super conductor.



Ex : Sn, Hg, Nb, V, etc

Type II superconductor

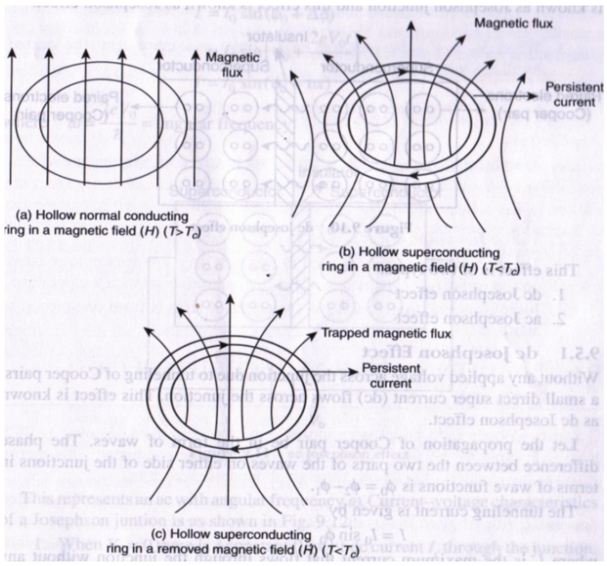
Consider a spherical superconductor in the magnetic field H. As per Meissner effect, it expels the magnetic line and $H = -M$. The curved magnetic lines are concentrated at the two ends marked as θ in such that intensity H is predominant at those ends. Up to lower critical field (H_{C_1}) it behaves as a super conductor. When the magnetic field exceeds H_{C_1}, then the penetration starts at those ends marked as θ This is because the intensity at those ends reaches H_{C_1}value at first. As a aresult $-M$ value decreases and the penetrated portion loses superconductivity and becomes a normal conductor. This conversion is usually completed at $H_{C_2}$where the penetration covers the entire surface. Thus between H_{C_1} and H_{C_2} it has a mixed state of superconducting as well as normal conducting state. After H_{C_2} it is converted into normal conductor. In this case the conversion is slow & is known as Type II superconductor. They are also known as hard superconductor.



Ex : Nb_3, Sn, Nb_3Ge, etc.

Flux Quantization

Consider a hollow normal conducting ring in a magnetic field. It allows the magnetic flux due to the field. So, we observe magnetic flux outside and inner hollow space & also on the ring. When the temperature of the ring is lowered to its critical temperature (Tc) it becomes a superconductor & it obeys Meissner effect. As result, persistent current comes into existence so that $H = -M$ and the superconducting ring will not allow the flux to pass through it.



Here, we observe flux outside and inner hollow space of the ring only. When applied magnetic field is removed, the opposing persistent current tries to adjust itself such that some magnetic flux is trapped inside its hollow space. The trapped flux is given by

$$\emptyset = \frac{nh}{2e} \text{ where n = 1, 2, 3,……}$$

Where e is change of electron

∅ is quantized in terms of h/2e. This h/2e is treated as fundamental trapped flux and is known as fluxon or fluxoid. This phenomenon is known as flux quantization of superconductor.

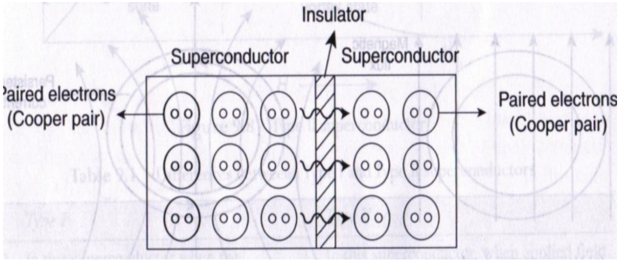
Josephson Effect

Consider two superconductors which are joined together with the help of a thin insulating layer. These superconductors consist of paired electrons known as cooper pairs in the super-conducting state. These cooper pairs will try to penetrate or funnel through the thin insulator and consistitute a small super current. The insulator which forms the junctions between superconductors is known as Josephson junction and this effect is known as Josephson Effect.

This effect is of two types

1. dc Josephson Effect
2. ac Josephson Effect

dc Josephson Effect



Without any applied voltage across the junction due to tunneling of cooper pairs, a small direct super current (dc) flows across the junction. This is dc Josephson Effect.

Let the propagation of cooper pair be in the form of waves. The phase difference between the two parts of the waves on either side of the junctions in terms of wave function is $\emptyset_0 = \emptyset_2 - \emptyset_1$.

The tunneling current is given by

$$I = I_0 \sin \emptyset_0$$

Where I_0 is the maximum current that flows through the junction without any voltage across junction.

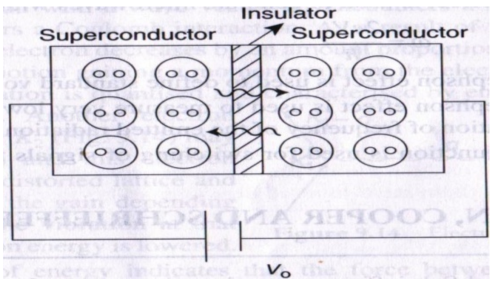
ac Josephson Effect

When a static potential V_0 is applied across the junction then the cooper pairs start oscillating through the insulating layer. As a result, an alternating current flows through the junction. This effect is known as ac Josephson Effect.

Due to V_0, an additional phase difference of $\Delta\emptyset = \frac{Et}{\hbar}$ is introduced for the cooper pairs, where E is the total energy of the cooper pairs at any time ‘t’.

$$E = 2eV_0$$

$$\Delta\emptyset = \frac{2eV_0 t}{\hbar}$$



The tunneling current can be written as

$$I = I_0 \sin(\emptyset_0 + \Delta\emptyset)$$

$$= I_0 \sin\left(\emptyset_0 + \frac{2eV_0 t}{\hbar}\right)$$

$$I = I_0 \sin(\emptyset_0 + \omega t) \text{ where } \omega = \frac{2eV_0}{\hbar} = \text{angular frequency}$$

Current – voltage characteristics of a Josephson junction are:

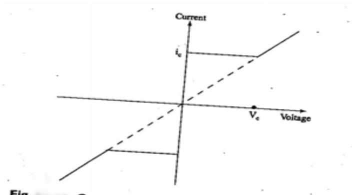


Fig. Current-voltage characteristic of a Josephson effect.

1. When $V_0 = 0$, there is a constant flow of dc current I_C through the junction. This current is called superconducting current and the effect is the dc Josephson effect.
2. So long $V_0 < V_C$, a constant dc current I_C flows.
3. When $V_0 > V_C$, the junction has a finite resistance and the current oscillates with a frequency $\omega = \frac{2eV_0}{\hbar}$. This effect is the ac Josephson effect.

Applications

1. Josephson effect is used to generate microwaves with frequency $= \frac{2eV_0}{\hbar}$.

2. The ac Josephson Effect is used to define standard volt.

3. Josephson Effect is used to switching of signals from one circuit to another.

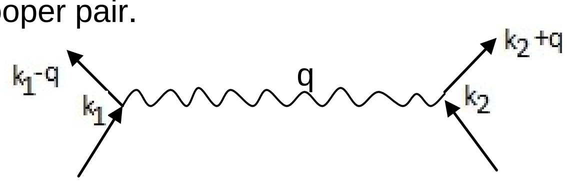
BCS Theory

Bardeen, cooper and Schrieffer proposed a microscopic theory known as BCS theory. It explains the super – conducting state of a superconductor. This theory involves the electron interactions through phonon as mediators.

In normal conductor, the electrons will be moving at random. When they approach vibrating atoms the repulsive force predominate, than the attractive force. As a result, they get scattered and resistance comes into existence. When it is converted into superconductor by decreasing its temperature below the critical temperature, due to decrease in energy the scattering of electrons by lattice vibrations also decreases and to maintain stable state the electrons get paired up and are known as cooper pairs.

This means that electrons travelling in a solid interact with lattice vibration by the virtue of electrostatic forces between them. The oscillator distortion of the lattice in quantized in terms of phonons. This interaction is called electron – phonon interaction, which leads to scattering of electrons and hence, cause a change in the electrical resistivity. The resistivity is sensitive with temperature, particularly in the low temperature region, since the number of phonons increases with temperature.

It is assumed from the BCS theory that the electron – phonon interaction produces an attractive interaction between two electrons. For example, an electron of wave vector k emits a virtual phonon, which is absorbed by an electron k1. Thus, k is scattered as k - q & k^1 + q. The resulting electron – electron interaction depends on the relative magnitude on the electronic energy change and phonon energy. Once the phonon energy exceeds the electronic energy, the interaction becomes attractive interaction. Thus, for attractive interaction, the wave vector & spin are represented as K↑ & K↓. Therefore, the two electrons interacting attractively in the phonon field are called cooper pair.



High T_C superconductors

For most of the superconductors, superconductivity occurs only at low critical temperatures (T_C). For attaining low temperature we should use liquid helium which is costly process. In attaining the superconductivity at high temperature or, to discover high temperature superconductors, scientists made the following progressive steps:

1. Superconductivity was discovered on a thin film of niobium and germanium at 23.2 K.
2. Compound of the form Ba – PbBi – O_3 was found to be superconductor at 38 K.
3. Oxide compound of the form $Y_1Ba_2Cu_3O_7$ (123 superconductors) was found to be superconductor at 92 K.

4. Oxide compound of the form Bi – Sr – Ca – Cu – O was found to be superconductor at 115 K.
5. The form Ti – Ba – Ca – Cu – O was found to be superconductor at 125 K.

In this high temperature superconductors phenomenon, liquid nitrogen (77 K) is used which is safer than liquid helium (4 K) or liquid hydrogen (23 K). It has been understood that oxygen atoms playa a major role in high temperature superconductors. Most of them have layered structure of copper and oxygen atoms.

Properties

1. They are highly anisotropic.
2. They have the presence of CuO_3 layers.
3. They have inherent metallic properties.

Application of superconductors

Electric generators

Super – conducting generators are smaller in size, with less weight, consume very low energy. The low – loss super – conducting coil is rotated in a strong magnetic field. This is the basis of new generation of energy saving power system.

Magnetic levitation

Diamagnetic property of a superconductor is the basis of magnetic levitation. This effect can be used for the high speed transportation.

Low loss transmission lines and transformers

When super – conducting wires are used as electric cables then the transmission losses are minimized. If superconductors are used for winding of transformer, the power losses will be very small.

Generation of high magnetic fields

Superconducting materials are used for producing high magnetic fields with low power consumption.

Fast electrical switching

The application of magnetic field greater than H_C, changes the superconducting state to normal state and removal of the field reverse the process. This principle is used in switching element cryotrons.

Logic and storage functions in computers

The C – V characteristics of Josephson Effect is used for memory elements in computers. Thus, superconductors are sued to perform logic and storage functions in computers.

Superconducting Quantum Interface Devices (SQUIDS)

Two Josephson junctions mounted on a superconducting ring form SQUID. These are used to study tiny magnetic signals from the brain and heart.