Unit- 2

Solid State Physics

Free Electron Model:

Free electron model is provided to understand the structure and properties of solids through electron structure .This theory is applicable to all solids i.e. both metals and nonmetals

Development of Free electron model :

1. Classical Free electron Model or Lorentz and Drude Free electron model:

To explain the properties of metals Lorentz and Drude produced the free e^- model in 1900. It is a simple model for the behavior of valence electrons in a crystal structure of metallic solid. According to this model the metal containing the free electron obeys the law of classical Mechanics.

The main postulate of this model is as follows-

1. The metals consist of positive ion cores with the valance electrons moving randomly among these cores.
2. The outer most electrons of constituent atoms of a metal are most weakly bound with the atoms. This e^- are called free electrons or the conduction electrons.
3. There is large no. of free e^- inside a metal and they behave like the molecules of gas enclosed in a vassal, hence it is also called the free e^- gas. These free e^- 's are responsible for the thermal and electrical conduction inside the metal.
4. According to Maxwell and Boltzmann statistics, mean energy per electron in the absence of field at an absolute temp. T is $\frac{3}{2}KT$ where K is Boltzmann constant.
5. The free e^- s move through the lattice structure of the metal in random directions with average speed of the order of 10^6 m/s and suffer repeated collisions with the lattice vibrations', defects and impurities .The e^- motion between two collisions is linear and uniform. Because of the randomness of motion there is no net current flowing through the metal.
6. When an e^- field is impressed across the metal, the equilibrium condition is disturbed.
   The electric field accelerates the electron's is a specific direction. The electron acquire velocity due to the force exerted by the electric field and move in a direction opposite to that of electric field. The directional motion of electrons due to action of electric field is called drift. The drift velocity gained by an electron due to acceleration is lost completely whenever a collision occurs. After that the e^- gets accelerated once again and loses its velocity at the next collision. The process goes on repeating and the e- moves on an average with a mean drift velocity v_d.
7. The average distance travelled by an electron between two successive collisions in the presence of applied electric field is known as mean free path λ. The time taken by an electron between two successive collisions is known as mean collision time of the electron. The drift motion of electron causes current flow in a conductor. The current is called drift current or conduction current.

Some Important Terms and there expression :

Drift Velocity (V_d): The average velocity acquired by the electron due to the force exerted by the electric field .

Relaxation Time (τ_r) : Relaxation time is the time gap between two successive electron collisions in a conductor. Or Time taken by the free electron to reach its equilibrium position after collision in the presence of electric field.

Collision Time (τ) : It is defined as the average time taken by the electron between two successive collisions.

Mean Free path (λ) : The distance travelled by the electron between two successive collision is called as free path and their mean is called mean free path. $\boldsymbol{\lambda = \bar{c}\ \tau}$

Where $\bar{c}$ = Root mean square velocity = $\sqrt{\frac{3KT}{m}}$. K= Boltzman Constant and T= Absolute Tempeature

Success of Classical Free electron Theory :

1. It verifies Ohm's Law
2. It explains electrical and Thermal conductivity of metals.
3. It derives relation between electrical and thermal conductivity i.e. Widemann –Franz law.

Limitation of classical free e- theory: -

The classical free e- theory in used to calculate the transport properties of the gas, including electrical and thermal conductivity, which agree with the general features of observations. But when this theory is used to calculate such quantities as electronic specific heat, mean free path and diamagnetic and paramagnetic susceptibility, the result have no resemblance to observe values.

The draw backs of this theory are.

1. Electrical Conductivity of semiconductors and Insulators could not be explained .
2. Widddmnn- Frennnz law isnot applicable at lower temperature.
3. Specific heat Cv (metallic crystal is 50% higher than Cv (insulator) But experimentally it is found that the difference is not so much.
4. According to free e- model, each free e- due to its spin motion has some magnetic moment due to which the magnetic susceptibility of paramagnetic substances is inversely propositional to the absolute temperature $\chi \propto 1/T$. But experimentally it is found that the magnetic susceptibility is independent of temperature. Experimental value of magnetic susceptibility χ is very less than the theoretical value.
5. The classical theory of free electrons could also not able to explain Ferromagnetism.

Summerfield's free e- model : -

Drawbacks of classical free e- theory are explained by Summerfield. According to Summerfield each free e- inside metal in the attractive field due to positive ions and a repulsive electric field due to positive ions and a repulsive electric field due to remaining all electrons. The force of repulsing due to mutual interactions of e- can be assumed to be negligible and attractive field due to positive ion can be considered to be uniform everywhere inside the crystal. Since the crystal structure of the solid is periodic Summerfield assumed that this potential inside the metal is constant.

Fermi – Dirac distribution function

$$F(E) = \frac{1}{e^{(E-Ef)/KT)}+1}$$

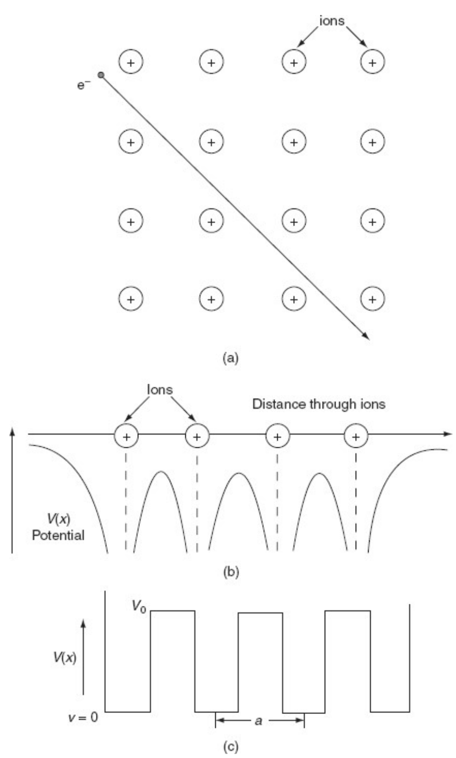
At T = Ok for E<EF $F(E) = \frac{1}{e^{-\infty}+1} = \frac{1}{0+1} = 1$

E > EF $F(E) = \frac{1}{e^{\infty}+1} = \frac{1}{\infty} = 0$

At T > OK E = EF $F(E) = \frac{1}{e^{0}+1} = \frac{1}{1+1} = \frac{1}{2}$

The Kronig Penny Model: -

Kronig penny model explains the behavior of an e- in a crystal. To study the behavior, a periodic arrangement of potential wells and potential barrier is assumed. One dimensional representation of periodic lattice is shown in Fig( ).



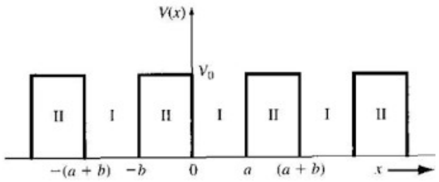


Fig (2)

Fig(2) Shows The potential distribution shows potential well of length 'a' (region I) are separated by potential barriers of height V_0 is assumed to be larger than the energy E of the electron.

The Schrödinger equation for region I and II are –

Region I $\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}E\psi = 0 \quad [0 < x < a]$

Or $\frac{d^2\psi}{dx^2} + \alpha^2\psi = 0 \quad \ldots\ldots\ldots\ldots.(1) \qquad where\ \alpha^2 = \frac{2mE}{\hbar^2}$

Region II $\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}(E - v_0)\psi = 0 \quad [-b < x < 0]$

Or $\frac{d^2\psi}{dx^2} - \gamma^2\psi = 0 \quad \ldots\ldots\ldots\ldots(2) \qquad where\ \gamma^2 = \frac{2m}{\hbar^2}(v_0 - E)$

According to Bloch the solution of this type of equation i.e.[equation (1)&(2) has the following form

$$\psi(x) = u(x).e^{ikx} \quad \ldots\ldots\ldots.(3)$$

Where u(x) is a periodic function which passes the periodicity of the lattice in x-direction. Therefore u(x) is no longer a constant but changes periodically with increasing x.

Differentiating equation (3) twice with respect to x.

$$\frac{d^2\psi}{dx^2} = \left(\frac{d^2u}{dx^2} + \frac{du}{dx}2ik - k^2u\right)e^{ikx} \quad \ldots\ldots.(4)$$

Putting the equation (4) in equation (1)&(2)

Region I $\frac{d^2u}{dx^2} + 2ik\frac{du}{dx} - (k^2 - \alpha^2)u = 0 \quad \ldots\ldots\ldots.(5)$

II $\frac{d^2u}{dx^2} + 2ik\frac{du}{dx} - (k^2 + \gamma^2)u = 0 \quad \ldots\ldots\ldots.(6)$

Equation (5)&(6) have the form of an equation of a damped vibration. The solution of equation (5) & (6) are

Region I $u = e^{-ikx}\left(Ae^{i\alpha x} + Be^{-i\alpha x}\right) \quad \ldots\ldots..(7)$

II $u = e^{-ikx}\left(ce^{-\gamma x} + De^{\gamma k}\right) \quad \ldots\ldots\ldots(8)$

Where A,B and C,D are constants in the region I & II respectively. There values can be obtained by applying following boundary conditions

$$|\psi_1(x)|_{x=0} = |\varphi_2(x)|_{x=0} \dots\dots\dots\dots..(9)$$

$$[\frac{d\psi_1(x)}{dx}]_{x=0} = [\frac{d\psi_2(x)}{dx}]_{x=0} \dots\dots\dots\dots\dots(10)$$

$$\therefore \ A + B = C + D \quad \dots\dots\dots\dots.(11\,a)$$

$$Ae^{(i\alpha-ik)x} + Be^{(-i\alpha-ik)X} = Ce^{(-\gamma-ik)x} + De^{(\gamma-ik)} \quad \dots\dots\dots\dots\dots\dots(11\,b)$$

Further ψ and therefore u is continuous at the distance (a+b). This means that equation I and x=0 must be equal to equation II at x= a+b or simply equation (1) at x=a = equation II at x=-b

This yields

$$Ae^{(i\alpha-ik)a} + Be^{(-i\alpha-i\ \ )b} = Ce^{(\gamma+ik)b} + De^{(ik-\gamma)b} \quad \dots\dots\dots\dots\dots(12)$$

On simplifying this equation (11) &(12)

$$cosk\ (a + B) = \left(\frac{\gamma^2-\alpha^2}{2\alpha\gamma}\right)\sin\alpha a \sin h\gamma b + \cos\alpha a \cos h\gamma b \quad \dots\dots\dots\dots.(13)$$

In order to simplify equation (13) further kronig and penny assumed that the potential energy is zero at lattice and equals V_0 between them. They further assumed that as the height of the potential barrier V tends to infinity and the width of the barrier b approaches zero in such a way that V_0b remains finite

Under this assumption $\sin h\,\gamma b \rightarrow \gamma b$ as $b \rightarrow 0$

$\text{Cos h}\,\gamma b \rightarrow 1$

Hence equation (13) cecomes

$$cosk\ a = \frac{\gamma^2-\alpha^2}{2\gamma\alpha}\gamma b \sin\alpha a + \cos\alpha a \dots\dots\dots\dots\dots\dots..(14)$$

Where $\gamma^2 - \alpha^2 = \frac{2m}{\hbar^2}(v_0 - E) - \frac{2mE}{\hbar^2}$

$$= \frac{2m}{\hbar^2}(v_0 - E)$$

If v_0>>E

Then $\gamma^2 - \alpha^2 = \frac{2m}{\hbar^2}v_0$

Substituting this in equation (14) we obtain

$$\cos ka = \frac{2mv_0}{\hbar^2.2\gamma\alpha}\gamma b \sin\alpha a + cos\alpha a$$

$$\cos ka = \frac{m}{\hbar^2.\alpha}v_0 b \sin\alpha a + cos\alpha a \quad \dots\dots\dots\dots\dots\dots(15)$$

Let $\frac{mav_{0b}}{\hbar^2} = P\ then$

$$coska = P\frac{\sin\alpha a}{\alpha a} + \cos\alpha a \;\ldots\ldots\ldots\ldots\ldots\ldots.(16)$$

This is desired relation which provides the allowed solutions to the schrodinger equation (1) and (2)

Equation (16)is schematically represented in figure(2). The quality on its R.H.S. is plotted as a function of αa .

The cosine term on the L.H.S. of the equation can only have values between -1 and +1 as indicated by horizontal lines in the figure. A consequence of this limitation is that only certain values of α (and hence E) are allowed. Further from the L.H.S. it is clear that for a specific value of energy $E\left[as\ \alpha^2 = \frac{2mE}{\hbar^2}\right]$

Cos ka can have only one value. Moreover since cos ka is an even periodic function. It well have the same value whether ka is positive, negative or it is increased by integral multiple of 2π.

The following important conclusion can be drawn.

(1) The energy spectrum consist of an infinite number of allowed energy bands separated by intervals in which there are no energy levels. This are known as forbidde bands.
(2) The boundaries of allowed ranges of αa corresponds to the values of $\cos ka = \pm 1 \quad or\ \ ka = n\pi$

$$or\ k = \frac{n\pi}{a}$$

(3) When αa increases the first term on the L.H.S. decreases so the width of the allowed energy band increases and forbidden region become narrower.
(4) The width of the allowed band decreases with the increasing value of P i.e. with increasing the binding energy of e^-.

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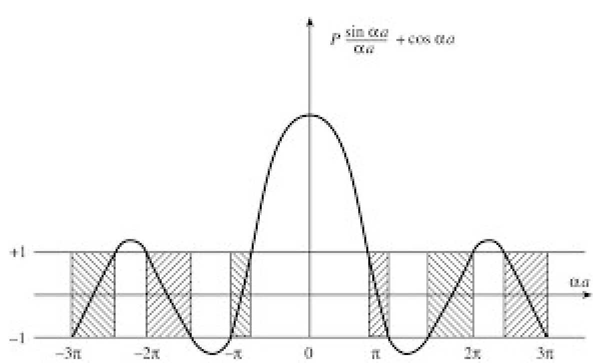

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(8) The width of the allowed band decreases with the increasing value of P i.e. with increasing the binding energy of e^-.

Now in order to get the energy in the lattice we take case

Case- I $\boldsymbol{P = \infty}$

According to eq. 16 $$\boldsymbol{P\frac{\sin \alpha a}{\alpha a} + \cos \alpha a = cos ka}$$

We can write this equations as

$$\boldsymbol{\frac{\sin \alpha a}{\alpha a} + \frac{\cos \alpha a}{P} = \frac{cos\ ka}{P}}$$

Since $P = \infty\ \ then$ $\quad \frac{\cos \alpha a}{P} = 0$ and $\frac{cos\ ka}{P} = 0$

Then $\boldsymbol{\frac{\sin \alpha a}{\alpha a} = 0}$

$$\alpha a = n\pi$$

$$\alpha = \frac{n\pi}{a} \qquad \alpha^2 = \frac{n^2\pi^2}{a^2}$$

$$\frac{2mE}{\hbar^2} = \frac{n^2\pi^2}{a^2}$$

$$\boldsymbol{E = \frac{n^2\pi^2\hbar^2}{2ma^2}} \qquad \text{....(17)}$$

This equation reveals that energy is independent of 'K' and energy level in this case are discrete and electron are completely bound.

Case – II

P= 0 then According to eq. 16 $\boldsymbol{P\frac{\sin\alpha a}{\alpha a} + \cos\alpha a = coska}$

$\cos\alpha a = coska$

$\alpha a = ka$

$\alpha = k$

i.e. $\alpha^2 = k^2$

$\boldsymbol{k^2} = \frac{2mE}{\hbar^2}$

$\boldsymbol{E = \frac{\hbar^2 k^2}{2m}}$ **…….(18)**

Equation (18) Reveals that the energy corresponding to completely free particle. No Energy level in this case exists therefore all energies are allowed to electrons.

* Effective Mass of Electron

Experimentally we take the mass of an electron in a solid ,same as that the mass of a free electron. Experimentally it is found that for some solids the mass is lrger while the others it is slightly smaller than the free electron mass. This experimentally determined electron mass is known as effective mass m*. The reason of the deviation of effective mass m* from the free electron mass m_0 is that the electron in the crystal are not completely free, but instead interact with the periodic potential of the lattice.

The movement of an electron in lattice will, in general ,be different from that of an electron in free space . In addition to an external applied force , there are internal forces in the crystal due to positively charged ions or protons and negatively charged electrons, which will influence the motion of electrons in the lattice.

We can write

$F_{(total)} = F_{(ext)} + F_{(int)} = ma$

Where

$F_{(total)}$ = Total force $F_{(ext)}$ = externally applied force $F_{(int)}$ = internal forces , m= rest mass of the particle , a= acceleration

Respectively, acting on a particle in a crystal.

Since it is difficult to take into account all the internal forces, we write the equation

$F_{(ext)} = m^*a$

Where the acceleration a is now directly related to external force . The parameter m* , called the effective mass, takes into account the particle mass and also takes into account the effect of internal forces.

As energy and momentum are related by the expression.

$$E = \frac{1}{2}\frac{P^2}{m}$$

$$E = \frac{1}{2}\frac{\hbar^2 k^{\,2}}{m}$$

Thus the energy is parabolic , with wave vector k. The electron mass is inversely related to the curvature (second derivative) of the E-k relationship.

$$\frac{\boldsymbol{d^2E}}{\boldsymbol{dk^2}} = \frac{\hbar^2}{m^*}$$

$$m^* = \hbar^2\left(\frac{\boldsymbol{d^2E}}{\boldsymbol{dk^2}}\right)^{-1}$$

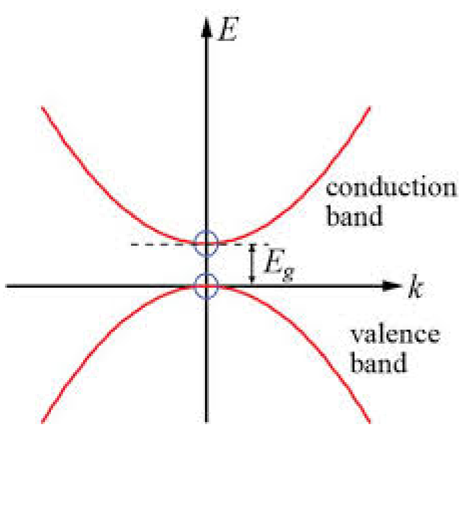


Fig: A schematic Energy- Momentum diagram for a semiconductor

Semiconductors: -

Semiconductors are those materials whose electrical conductivity lies between the conductors and insulators according to the energy band theory, the width of the forbidden energy gap in between the conduction band and the valence band in semiconductors is very small (~ 1eV) as shown in Fig-1

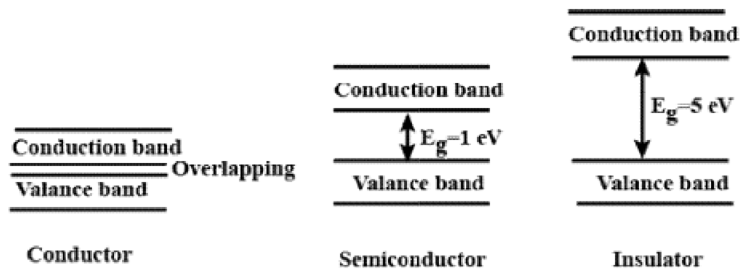


Fig.1- Energy band diagram of conductor, insulator & semi conductor

At absolute zero temperature (T = 0k) the valence band of semiconductor is completely filled and conduction band remain completely empty. Hence at T=0K semiconductors behave as a perfect insulator. However as the temperature increases some of the valence electrons acquire energy and jump in to the conduction band and semiconductor show some conductivity. It is thus obvious that the conductivity of semiconductor increases with increase in temp. The electrical conductivity of semiconductor is in the range of 10^{-3} to 10^{-6} per Ω per cm.

Types of semiconductors: -

1) Elemental or intrinsic semiconductors.
2) Extrinsic semiconductors
3) Compound semiconductors

Intrinsic Semiconductors: -

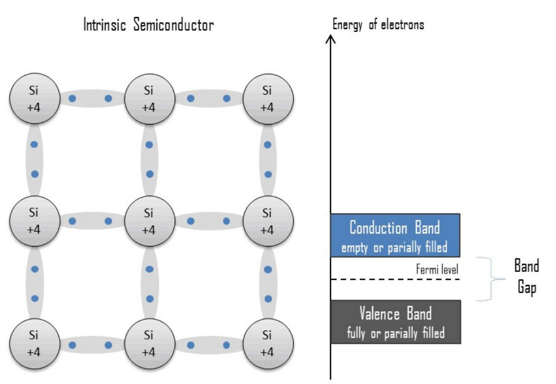


Fig. 2 : Intrinsic semiconductors at 0K

Intrinsic semiconductors are pure semiconductors whose electrical conductivity arises from thermal excitation and determined by their inherent conductive properties pure **silicon and germanium** are intrinsic semiconducting materials. An atom of Si has 14 e^- outside the nucleas with electron distribution 2,8,4 in different shells and an atom of Ge has 32 e^- with e^- distribution 2,8,4 in different shells. Thus these atoms have four e^- in their outermost orbit those e^- are called valence electrons. Each of the four e^- of an atom shared with one of its four nearest atoms.

Due to this sharing covalent bonds are formed, which are shown in dashed line. At temp. near absolute zero, all valence electron are tightly bounded and so no free e^- are available to conduct electricity. Therefore these semiconductors behave as insulator at 0K

Conduction in Intrinsic Semiconductor: -

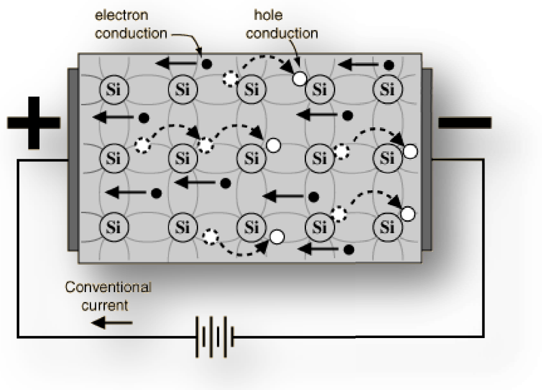


Fig-3: Conduction in Intrinsic semiconduictor

In an intrinsic semiconductor at room temperature (i.e. 300 ~k) the thermal energy is sufficient to produce a large no. of electron hole pairs (Fig-3). When an electric field is applied the current flows through the semiconductor due to the movement of free e^- in an one direction and holes in the opposite direction .Thus in an intrinsic semiconductor current density J is equal to the sum of conduction due to both e^- and hole.

$$J = nev_{dn} + pev_{dp}$$

Where n and p are no. of e^- and holes per unit volume respectively, e is electronic charge and vdn and vdp are drift velocities of e^- and holes respectively.

Dividing both the side by electric field E.

$$\frac{J}{E} = \frac{nev_{dn}}{E} + \frac{pev_{dp}}{E}$$

$$\sigma = ne\mu_n + pe\mu_p$$

Where μ_n and μ_p are electron and hole motilities .

For pure (intrinsic semiconductor) $n = p = n_i$

$$\boldsymbol{\sigma = n_i e(\mu_n + \mu_p)}$$

Extrinsic Semiconductor: -

Intrinsic semiconductors are not useful for device manufacture because of low conductivity. When a small amount of impurity is mixed in a pure or intrinsic semiconductor, the conductivity of semiconductor increases. Such an impure semiconductor is called the extrinsic semiconductors to depending upon the nature of impurity added in intrinsic semiconductors the extrinsic semiconductors are of two types.

1) N- type semiconductor
2) P- type semiconductors

The process of adding small amounts of impurities to the semiconductor material is known as doping and the impurity element that replaces a regular lattice atom is known as dopaert.

N type semiconductor:-

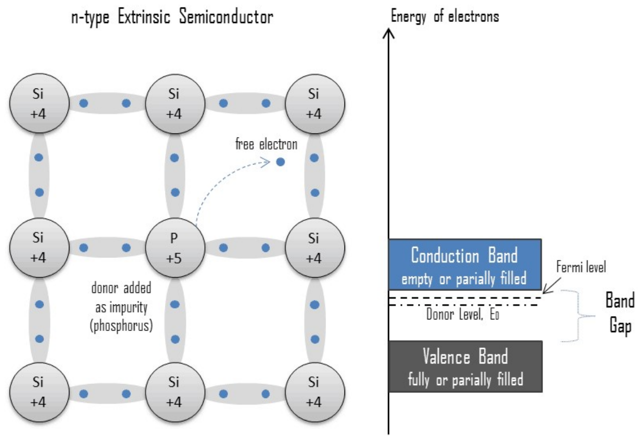


Fig. 4 : atomic arrangement and energy band diagram of N-type semiconductor

An N-type semiconctor is produced when a pure semiconductor is doped with a pentavalent impurity such as antimony, phosphorus, or arsenic). Pentavalent atom has five valence electrons, out of them four valence electrons form regular e^- pair bonds with their neighboring Ge or Si atoms. The fifth electron however is loosely bound to host, at room temperature this extra electron becomes disassociated from its atom and move through the crystal as a conduction electron when a voltage is applied to the crystal. This type of extra electron are called " donors" . And the crystal becomes n-type semiconductor because the conduction in this is predominated by negative charge carriers i.e. electrons.

The impurity atoms introduce discrete energy levels for the e^- just below the conduction band. These are called 'donor impurity levels', which are only 0.01eV in case of Si.

P- type semiconductors: -

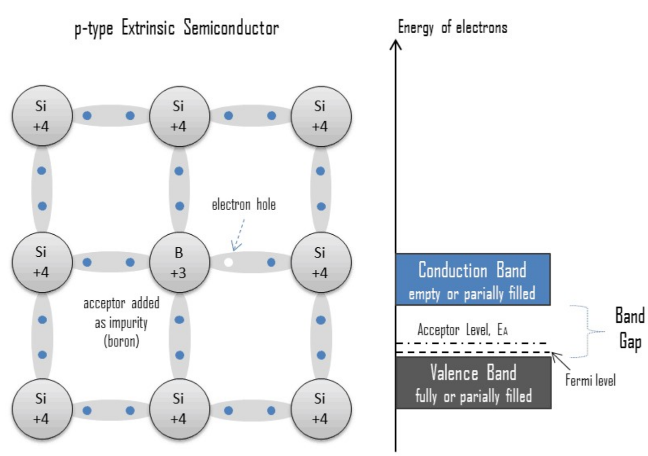


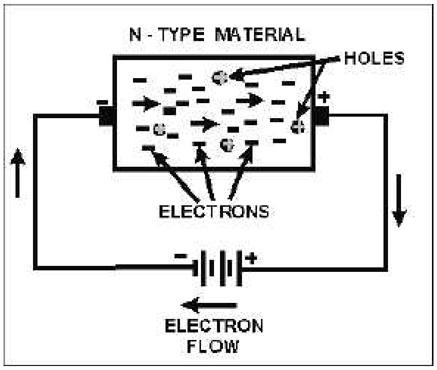
Fig. 5 : atomic arrangement and energy band diagram of P-type semiconductor

P–type semiconductor is produced when a pure semiconductor is doped with a trivalent impurity such as Boron, aluminum , Indium or gallium. In this case only three valence electrons are available to from covalent bonds with the neighboring Ge or Si atoms. This results in to an empty space or position 'hole'. When a voltage is applied to the crystal then an electron bound to a neighboring Ge or Si atom occupies the hole position, thereby creating a new hole. The conduction mechanism in this semiconductor with accepter impurities is predominated by positive carriers which are introduced in to valance band. This type of semiconductors is called P – type semiconductors.

The trivalent impurity atoms introduced vacant discrete energy levels just above the top of the valance band. These are called 'accepter impurity levels' which are only 0.01ev above the valence band in case of Ge and 0.05ev in case of Si.

Thus in a p – type semiconductors the holes are the 'majority carriers' and the few electrons thermally excited from the valence band to the conduction band are minority carriers.

Conductivity in N – type and P – type semiconductor: -



We know that conductivity in Intrinsic semiconductor

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

For N type n >> p there fore $\sigma = n.e.\,\mu_n$

For P type p >> n therefore $\sigma = pe\mu_p$

Fermi levels: -

Electrons in solids obey Fermi – dirac statistic.This staticstics results that the distribution of electrons over a range of allowed energy levels

$$F(E) = \frac{1}{\exp\,[\,(E-E_{F})/KT]+1}$$

Where EF is known as Fermi level. The Fermi – Dirac distribution function F(E) gives the probability that an available energy state of E will be occupied by an e- at absolute temperature T.

At T = 0K: -

At absolute zero, electrons occupy energy levels in pairs starting from the bottom of the band up to an upper level designated as E_f. Therefore Fermi level can be defined as the upper most filled energy levels in a conductor at ok. Correspondingly, Fermi energy is defined as maximum energy that a free e- can have is a conductor at ok. The energy band and the Fermi function at 0k are shown in Fig.

T > 0K : -

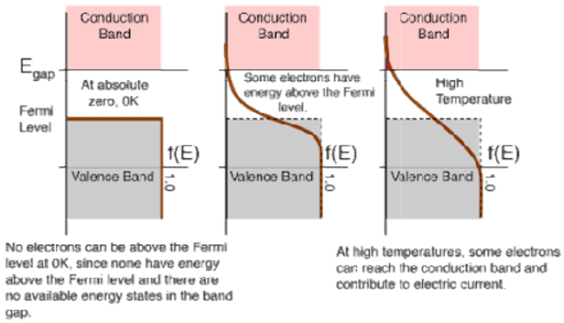
On heating the conductor, electron are exited to higher energy levels. In general Ef >> KT therefore, for most of the electrons lying deep in the conduction band the thermal energy is not sufficient to cause a transition to an upper unoccupied level. At normal temperature only those electrons occupying the energy levels near the Fermi level can be exited . These levels make up a narrow band of width KT directly adjacent to the Fermi level . Therefore upon heating the solid, electrons having energy little below EF jump in to levels with energy somewhat above EF and new energy distribution of electron is obtained .

Thus as a result of thermal excitation, the probability of finding electrons in the level immediately below E_F will decrease and above E_F increases. As shown in fig.

Thus at T > 0K if we consider an energy E equal to the Fermi level Ef the occupation probability is

$$F(E) = \frac{1}{e^{0}/_{KT+1}} = \frac{1}{1+1} = \frac{1}{2}$$

Thus an energy state at the Fermi level has a probability $^1/_2$ of being occupied by an e- .



Fermi level in intrinsic semiconductor:

In an intrinsic semiconductor, the free electron and hole concentrations are equal.

i.e. n=p

$$N_c\ e^{\frac{-(E_c - E_f)}{KT}} = N_V\ e^{\frac{-(E_f - E_v)}{KT}}$$

Taking log on both sides and rearranging the terms.

$$\frac{-(E_c - E_f)}{KT} = \ln\frac{N_V}{N_c} - \frac{-(E_f - E_v)}{KT}$$

$$-(E_c - E_f) = \mathrm{KT}\ln\frac{N_V}{N_c} - E_f + E_v$$

$$2E_f = \mathrm{KT}\ln\frac{N_V}{N_c} + (E_c + E_v)$$

But $N_c = 2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2}$ and $N_v = 2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2}$

Therefore $\frac{N_v}{N_c} = \left[\frac{m_h^*}{m_e^*}\right]^{3/2}$

$$\ln\frac{N_v}{N_c} = \frac{3}{2}\ln\frac{m_h^*}{m_e^*}$$

$$E_f = \frac{3}{4}KT\ln\left(\frac{m_h^*}{m_e^*}\right) + \frac{(E_c + E_v)}{2}$$

If $m_h^* = m_e^*$ then $\ln\left(\frac{m_h^*}{m_e^*}\right) = 0$

i.e. $E_f = \frac{(E_c + E_v)}{2}$

We can write $E_f = \frac{(E_c + E_v + E_v - E_v)}{2} = \frac{(E_c - E_v)}{2} + E_v$

As $(E_c - E_v) = E_g$

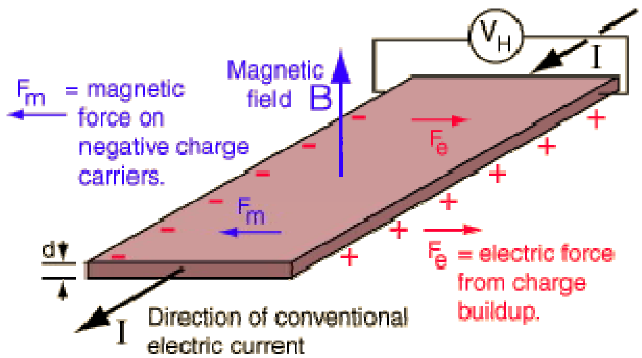
$$E_f = \frac{E_g}{2} + E_v$$

If we denote the top of the valence band at zero level

$E_f = \frac{E_g}{2}$ Thus the Fermi level in an intrinsic semiconductor lies at the centre of the energy gap.

Hall Effect:

When a metal or a semiconductor carrying a current I is placed in a transverse magnetic field B, a potential difference is produced in the direction normal to both the current and magnetic field directions. These phenomenon is called Hall Effect.



Let us consider an N-type semiconductor in which the conduction is predominated by electrons. Suppose an electric current I flows in the positive x-direction and a magnetic field B is applied normal to this electric field in z-direction. A force called the Lorentz force is exerted on each electron which causes the electron paths to bend. As a result of this thelectrons accumulate onone side of the slab and are deficient on other side. Thus an electric field is created in the y-direction which is called the Hall field.

In equilibrium condition

$F_E{=}F_L$

$-eE_H = -eB_z V_x$ where V_x is the velocity of e^- and 'e' the electronic charge

Therefore $E_H = B_z V_x$ …………..(1)

As current density $J_x = -nV_x e$

$J_x = \frac{-neE_H}{B_z} = \frac{-neV_H}{B_z d}$ ………….. (2) $\left[where \quad V_x = \frac{E_H}{B_z} \; and \; E_H = \frac{V_H}{d}\right]$

$V_H = -\frac{J_x B_z d}{ne} = -\frac{IB_z d}{neA}$ $[where \; A = Area \; of \; cross \; section]$

If t is the thickness of the semiconductor specimen. A= td and above equation reduces to

$V_H = -\frac{B_z I}{net}$ ……………(3)

Hall field per unit current density, per unit magnetic induction is called Hall coefficient 'R_H'

Thus $R_H = \frac{E_H}{J_x B_z} = \frac{V_H/d}{J_x B_z}$

From eq. (2) $\frac{V_H}{d} = -\frac{J_x B_z}{ne}$

Therefore $R_H = -\frac{J_x B_z}{ne\ _x B_z}$

Or Hall Coefficient $R_H = -\frac{1}{ne}$

Hall voltage in terms of Hall coefficient can be written as .

Hall voltage $V_H = R_H \frac{B_Z\ I}{t}$

The sign of the Hall coefficient R_H indicates whether electrons or holes predominate in the conduction process.

Hall Mobility:

Mobility is defined as the drift velocity acquired in unit electric field.

We know that current density $J = nev_d$ (1)

And $J = \sigma E$ (2)

By (1) and (2) $nev_d = \sigma E$

$$\frac{v_d}{E} = \frac{\sigma}{ne}$$

Therefore $Hall\ mobility\ \mu_e = \sigma R_H$

Importance of Hall Effect:

The importance of hall Effect in the field of semiconductors is that it helps to determine:

(i) the type of semiconductor

(ii) the sign of majority charge carriers

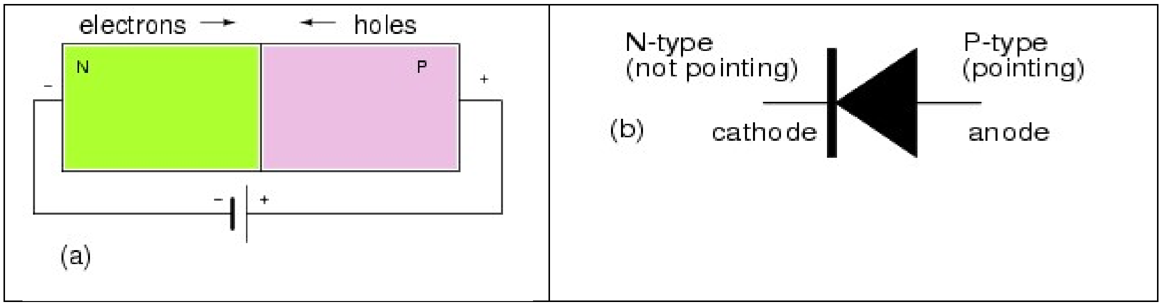
(iii) the majority charge carrier concentration

(iv) the mobility of majority charge carriers, and

(v) the mean drift velocity of majority charge carriers.

P-N Junction diode: -

A P-N junction diode consists of a P-N junction formed either by germanium or silicon crystal. The diode has two terminals namely anode and cathode. The anode refers to the P-type region and cathode refers to the N- type region. Circuit symbol of P-N junction diode is shown in Fig (1).



Forward characteristics: -

Fig (b) shows the circuit arrangement for obtaining the forward characteristics of a P-N junction diode. In this circuit the diode is connected to a dc voltage source (VAA) through a potentiometer (p) and a resistance R. The potentiometer help in varying the voltage applied across the diode. The resistance (R) limits the current through the circuit. The positive terminal of the voltage source is connected to the anode of a diode and negative terminal is connected to cathode. Hence the device is forward biased.

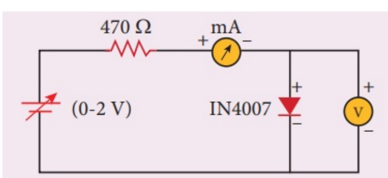


Figure (b) PN junction diode in forward bias

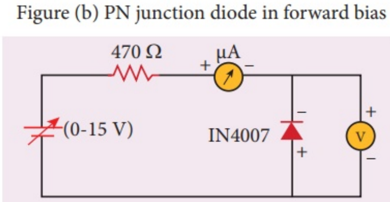


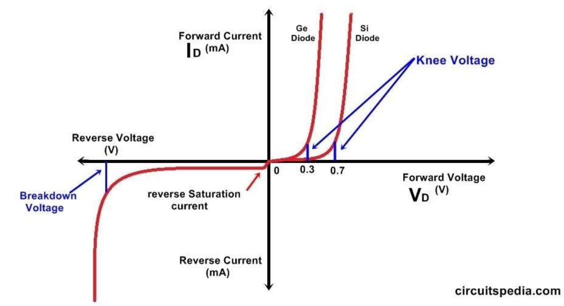
Figure (c) PN junction diode in reverse bias

If we gradually increase the voltage across the diode, we found that there is no current till the barrier potential is reached. It is because of the fact, that the external applied voltage is being opposed by the junction voltage, however as the voltage is increased above junction voltage or barrier potential i.e 0.7 v for Si and 0.3V for Germanium , the diode current increases rapidly. , The voltage at which the diode starts conducting is called a knee- voltage or cut-in voltage.

2). Reverse characteristics: - Fig (c) shows the circuit diagram for obtaining reverse characteristic is same as forward except two changes that diode terminals are reversed and mA is replaced with μA .

When the applied voltage is gradually increased below the breakdown voltage, the diode current is small and remains constant. This value is called reverse saturation current. When the reverse voltage is increased to a sufficiently large value, the diode reverses current increases rapidly. The applied reverse voltage at which the breakdown occurs is known as breakdown voltage.

V-I Characteristic of a P-N junction diode: -



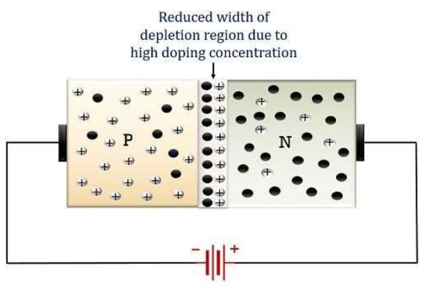
P-N Junction Diode V-I Characteristics

Volt – ampere (or V-I) characteristics of a device gives the information that how a device respond when it is connected in an electrical circuit.

It is a graph between the voltage applied across the terminals of a device and currents that flows through it Fig(2) shows the volt – ampere characteristic curve of a P-N junction diode. It is seen that the characteristic is not linear hence a P-N junction is non linear device.

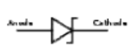
Zener diode:

The Zener diode is a silicon PN junction device which is optimized to operate in the break down region. The break down voltage of a zener diode is set by carefully controlling the doping level during manufacture.



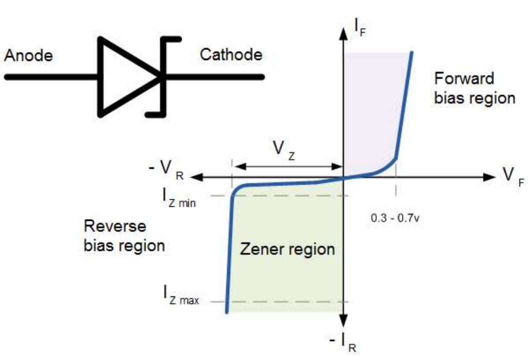
Zener breakdown mechanism

Zener effect: The zener breakdown occurs when the electric field across the junction, produced due to reverse voltage, is sufficiently high. This electric field exerts a force on the electron in the outer most shell. This force is so high that the electrons are pulled away from their parent nuclei and become free carriers. This ionization, which occurs due to the electrostatic force of attraction, is known as Zener effect. It causes an increase in the number of free carriers and hence increases in the reverse current.



Characterization of Zener diode:-

The V-I characteristics of a Zener diode are shown in Fig (). The following points are worth noting:



1. Its characteristics are similar to an ordinary P-N junction diode with the exception that it has a sharp break down voltage known as Zener voltage Vz.

2. There is a minimum value of Zener current called break over current designated as I_{zk} or $I_{z(min)}$ which must be maintained in order to keep the diode in breakdown or regulation region when the current is reduced below the knee of the curve, the voltage changes drastically and the regulation is lost.

3. There is a maximum value of Zener current designated as Izm or Iz(max) above which the diode may be damaged the value of this current is given by the maximum power dissipation of the Zener diode.

Rating or specification of zener diode:-

The zener diodes are genrally specified by following factors

(1) Zener voltage (2) Tolerance (3) Power dissipation (4) Maximum current

(5) Zener resistance

There ratings are given by manufacturer. This rating helps to use the diode for particular application.

Zener Voltage (Vz) : -

The voltage at which a zener diode breaks in the reverse bias condition is known as zener voltage. The value of break down voltage depends upon doping more the doping lesser the break down voltage . commercially available zener diodes are having zener voltage rating from 3v to 200v.

Tolerence: -

The range of voltages about the break down voltage in which a zener diode conducts in reverse direction is called tolerance.

Power rating (P_{zm}) : -

The maximum power which Zener diode can dissipate without damage is known as its power rating (P_{zm}) commercially available Zener diodes have power ratings from 1/4 w to more than 50w. Power rating is a product of maximum current I_{zm} which a zener diode can handle and the rated and operated voltage of zener diode.

$$P_{zm} = I_{zm}V_z$$

Maximum current rating (Izm): -

The maximum value of current which a zener diode can handle at its rated voltage with out damage is known as its maximum current rating (Rzm).

Zener resistance (R_{zt}) : -

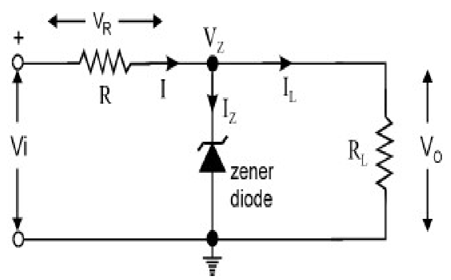
The oppositions offered to the current flowing through the zener diode in the operating region is known as zener resistinace (R_z) or zener impedance(Zz).

Application of Zener diode: -

Zener diodes have number of commercial and industrial application. Important application are as follows.

(1)As a Voltage regulator

As voltage regulation is the ability of a circuit to maintain a constant our put voltage even when either input voltage or load current varies. This circuit makes use of the fact that under reverse bias breakdown, the voltage across the zener diode remains constant even if larger current is drawn. Since the load resistance R_L is parallel to the zener diode, the voltage across the load resistance does not vary even though current through the load changes. Hence the voltage across the load resistanc does not vary even though the load changes. Hence the voltage across the load is regulated against the variation in the load current fig ( ) shows the circuit arrange ment.

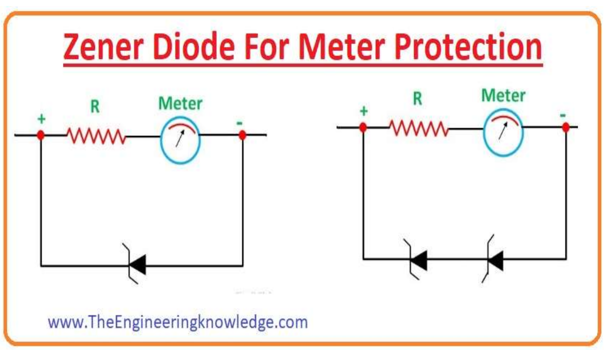


The zener diode of zener voltage Vz is reverse connected across the load R_L across which constant voltage (V_0 = Vz) is desired. A resistor R is connected in series with the circuit which absorbs the out put voltage fluctuation so as to maintain constant voltage V_0 across the load.

Let a variable voltage Vin be applied across the load RL. When the value of Vin is less than zener voltage Vz of the zener diode, no current flows through it and the same voltage appears across the load. When the input voltage Vin is more than Vz, this will cause the zener diode to conduct a large current Iz.

Consequently, more current flows through series resistor R which increases the voltage drop across it. Thus the input voltage excess of Vz (i.e Vin –Vz) is absorbed by the series resistor. Hence a constant voltage V_0(=Vz) is maintained across the load R_L.

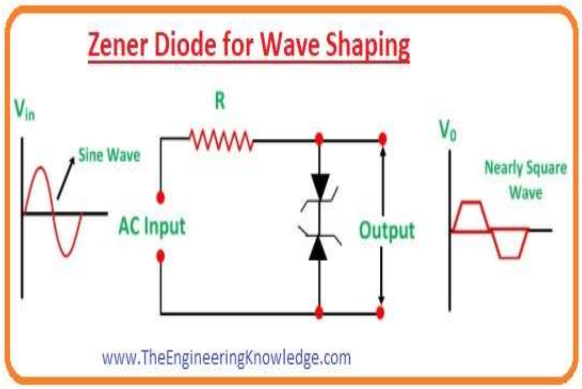
(2) For meter protection: -



Zener diodes are generally employed in multimeters to protect the meter movement against damage from accidental overloads. For this purpose the zener diode is connected in parallel with the meter. In case of an accidental overload most of the current will pass through the diode. Two zener diodes are employed as shown in figure .to provide protection regardless of the polarity of the applied voltage.

3. For wave shaping : -

Zener diodes are also used to convert sin wave into almost square wave. For this purpose circuit is arranged as shown in fig ( ) . During positive as well as negative half cycle, when the voltage across the diodes is below zener value they offer a high resistance path and input voltage appears across the output terminals.



However as the input voltage increases beyond zener value, the zener diode offers a low resistances path and conduct large current. This results heave voltage drop across series resistor R and hence the peaks of the input wave are clipped off when appear at the output as shown in figure . Thus an input sin wave is clipped off at the peaks and almost a square wave appear at the output.

Photo detectors: -

Photo detectors are semi conductor devices that can convert optical signals in to electrical signals.

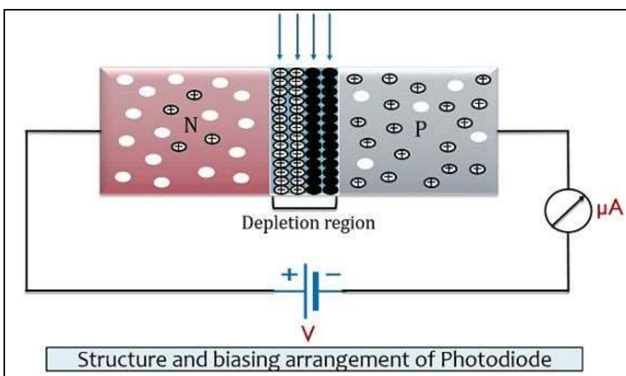
Photo detectors are of three types –

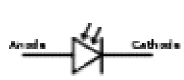
(i) Photo emissive type (photo tubes and photo multiplier tube)

(ii) Photo diodes

(iii) Photo conductors

Photo diodes: -

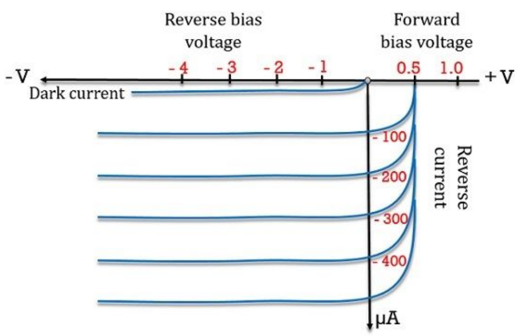




A photo diode is a two terminal P-N junction device, which operates in a reverse bias. It has a small transparent window, which allows light to strike the P-N junction . fig(a) and fit(b) shows the structure and basic symbol of a photo diode. The biasing arrangement of a photo diode is as shown in fig (c).

Working: - When a reverse bias is applied across the junction, the depletion layer widens as mobile carriers are swept to their respective majority sides . The motion of minority carriers forms the reverse leakage current of the diode. Thus even no light radiation is present a small leakage current exists. This leakage current is called the dark current. The amount of dark current depends on the reverse bias voltage, the series resistance and ambient temp.

When the diode is illuminated by light, photons are absorbed mainly in the depletion region and also in the neutral regions. A photon of energy incident in or near the depletion layer of the diode will excite an electron from the balance band in to the conduction band. This process generates a hole in the balance band. Thus an e^- - hole pair is generated by the optical photon . These are known as photo carriers. The electron –hole pairs generated in the depletion layer separate and drift in opposite direction under the action of the electric field. Such a transport process induces an electric current in the external circuit in excess of the already existing dark current. An increase in the amount of light energy produces an increase in the reverse current. Fig( ) shows the characteristic of PN photodiode.

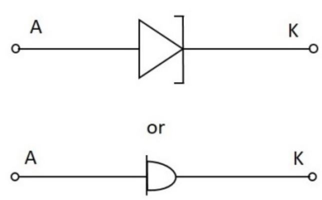


Characteristics curve of Photodiode

Advantages of Photodiode

It shows a quick response when exposed to light.
Photodiode offers high operational speed.
It provides a linear response.
It is a low-cost device.

Tunnel Diode:



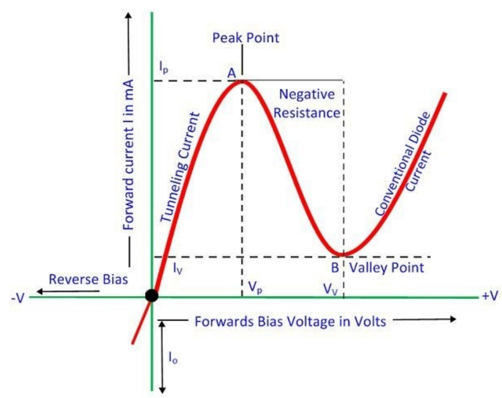
Symbol of Tunnel diode

The tunnel diode is a heavily doped PN-junction diode.It is also known as Esaki Diode. The concentration of impurity in the normal PN-junction diode is about 1 part in 10^8. And in the tunnel diode, the concentration of the impurity is about 1 part in 10^3.

Because of the heavy doping, the diode conducts current both in the forward as well as in the reverse direction.IN tunnel Diode current induces because of the tunnelling. The tunnelling is the phenomenon of conduction in the semiconductor material in which the charge carrier punches the barrier instead of climbing through it.It is a fast switching device; thereby it is used in high-frequency oscillators, computers and amplifiers.Symbol of the tunnel diode is shown in figure above.

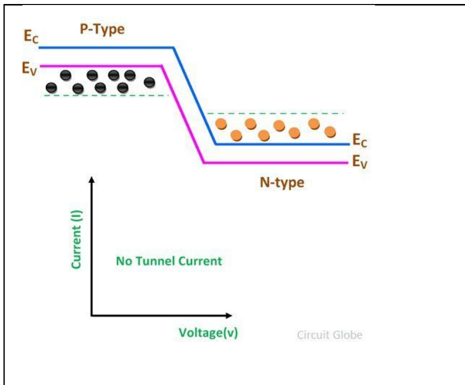
Volt-Amp Characteristic

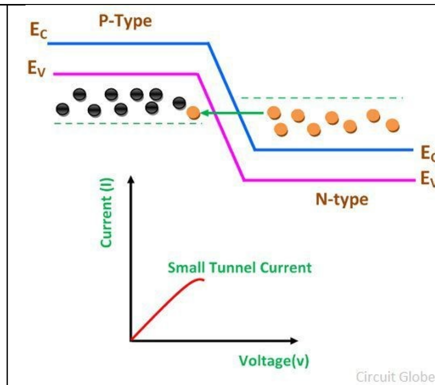
In forward biasing, the immediate conduction occurs in the diode because of their heavy doping. The current in a diode reached their maximum value I_P when the V_p voltage applied across it. When further the voltage increases, the current across the terminal decreases. And it decreases until it reaches their minimum value. This minimum value of current is called the valley current I_v.

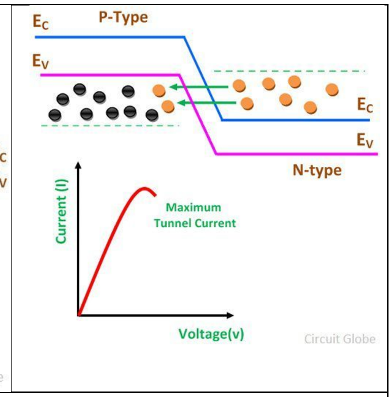


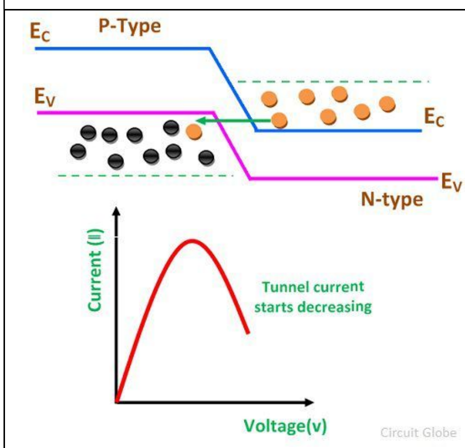
The graph above shows that from point A to point B the value of current decreases with the increase of voltage. So, from A to B, the graph shows the negative resistance region of the tunnel diode. This region shows the most important property of the diode. Here in this region, the tunnel diode produces the power instead of absorbing it.

Energy Band Diagram of different positions in V-I Curve









Advantages of Tunnel Diode

The tunnel diode has low cost. It produces low noise, and their fabrication is also very simple. The diode gives a fast response, and it is moderate in operation. The tunnel diode works on low power.

Disadvantages of Tunnel Diode

The disadvantage of the tunnel diode is that output voltage of the diode swings. It is a two terminal device, but their input and output circuits are not isolated from each other

Applications of Tunnel Diode

The tunnel diode can be used as an amplifier and as an oscillator for detecting small high-frequency or as a switch. It is a high-frequency component because it gives the very fast responses to the inputs.The tunnel diode is not widely used because it is a low current device.

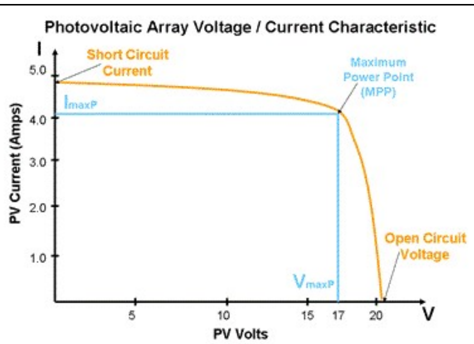
Solar Cells :

A **solar cell** (also known as a photovoltaic cell or PV cell) is defined as an electrical device that converts light energy into electrical energy through the photovoltaic effect. It is basically a p-n junction diode. Solar cells are a form of photoelectric cell, defined as a device whose electrical characteristics – such as current, voltage, or resistance – vary when exposed to light.

Individual solar cells can be combined to form solar panels. The common single junction silicon solar cell can produce a maximum open-circuit voltage of approximately 0.5 to 0.6 volts. By itself this isn't much. When combined into a large solar panel, considerable amounts of renewable energy can be generated.

Working Principle of Solar Cell

When light reaches the p-n junction, the light photons can easily enter in the junction, through very thin p-type layer. The light energy, in the form of photons, supplies sufficient energy to the junction to create a number of electron-hole pairs. The incident light breaks the thermal equilibrium condition of the junction. The free electrons in the depletion region can quickly come to the n-type side of the junction.
Similarly, the holes in the depletion can quickly come to the p-type side of the junction. Once, the newly created free electrons come to the n-type side, cannot further cross the junction because of barrier potential of the junction.
Similarly, the newly created holes once come to the p-type side cannot further cross the junction became of same barrier potential of the junction. As the concentration of electrons becomes higher in one side, i.e. n-type side of the junction and concentration of holes becomes more in another side, i.e. the p-type side of the junction, the p-n junction will behave like a small battery cell. A voltage is set up which is known as photo voltage. If we connect a small load across the junction, there will be a tiny current flowing through it.



V-I Characteristics of a Photovoltaic Cell

Advantages of Solar Cell

1. No pollution associated with it.
2. It must last for a long time.
3. No maintenance cost.

Criteria for Materials to be Used in Solar Cell

1. Must have band gap from 1ev to 1.8ev.
2. It must have high optical absorption.
3. It must have high electrical conductivity.
4. The raw material must be available in abundance and the cost of the material must be low.

Disadvantages of Solar Cell

1. It has high cost of installation.
2. It has low efficiency.
3. During cloudy day, the energy cannot be produced and also at night we will not get solar energy.

Superconductor :-

Introduction :-

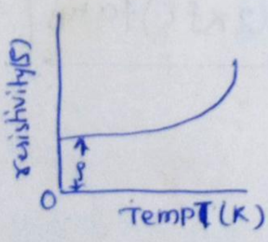
The phenomenon of Superconductivity was discovered by kammerlingh onnes in 1911, when he was measuring the resistivity of mercury at low temp. He observed that the electrical resistivity of pure mercury drops to zero at temp about 4.2K. This sudden drop in resistivity was not according to expectation. He gave this phenomenon name Superconductivity. i.e.

When ~~a material~~ the electrical resistance of a Substance drops suddenly to zero, when it is cooled below a certain temperature, the phenomenon is known as superconductivity.

The substance showing this property is called as Super conductors.

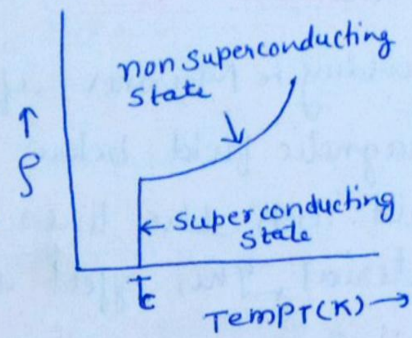
Temperature dependence of Resistivity.

Metals are good conductors of electricity as they have plenty of free electrons. However, they offer resistance to the flow of current. Even at OK, the metal offers some resistance, known as residual resistance. The temp. dependence of resistivity of metal is shown in fig (1).



Fig

In case of Super conductors the resistance decreases with decrease in temp as in case of normal metal in non superconducting state. But at a particular temp. T_c, the resistivity abruptly drops to zero. T_c is called the critical temp. critical temp. is diff for diff. materials.



Critical temperature T_c :-

Critical temp. T_c is the characteristic of a super Conductor. It is the temp. at which a normal material turns in to a superconductor. It is different for different materials.

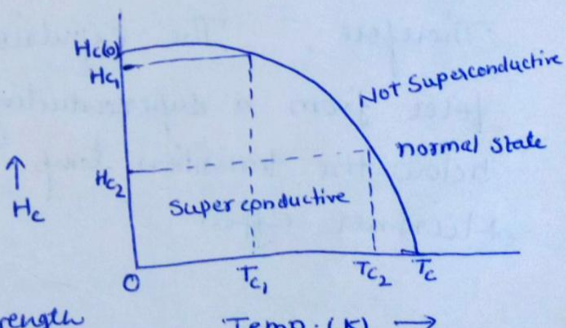
Effect of external field

In 1913, Kammerlingh onnes observed that superconductivity is destroyed if a sufficient strong magnetic field is applied.

The minimum value of applied magnetic field when the superconductor losses its superconductivity is called the critical magnetic field. $H_c(0)$.

If the applied magnetic field exceeds the critical value $H_c(0)$, the superconducting state is destroyed. The Variation of critical magnetic field with temp. is shown in fig.

$$H_c(T) = H_c(0)\left[1 - \frac{T^2}{T_c^2}\right]$$



where $H_c(T)$ = maximum critical field strength at temp. T.

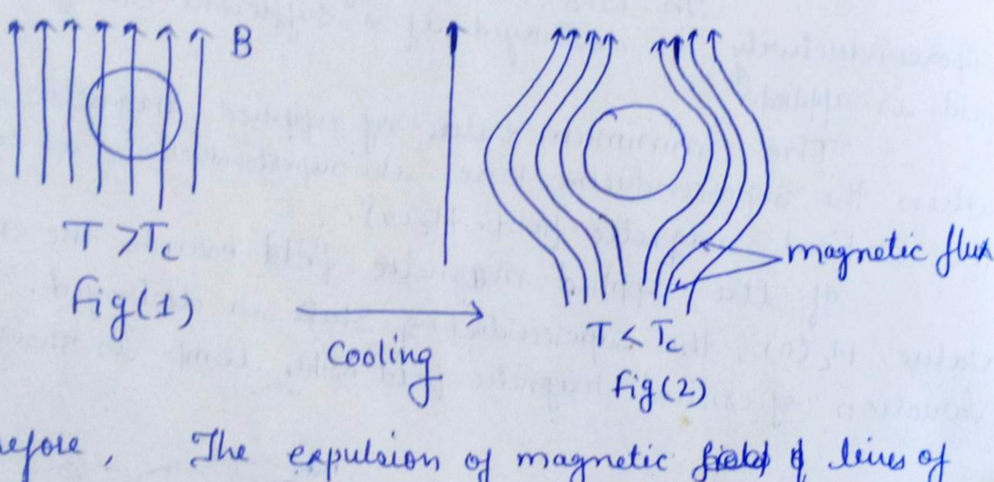
$H_c(0)$ = max. critical field strength occuring at absolute zero

T_c - critical temp.

Meissner Effect :

According to Meissner if a superconductor is cooled in magnetic field, below critical temp. corresponding to a field, then the lines of induction are expelled from material. This effect is called Meissner effect.

Fig (1) shows a superconductor in normal state and the magnetic lines of force pass through it. But when the specimen is cooled below its transition temp. [fig (2)], the magnetic lines of force are expelled out of the specimen.



Fig(1)

Fig(2)

Therefore, The expulsion of magnetic field & lines of force from a superconducting material when it is cooled below the transition temp. in a magnetic field is called Meissner effect.

Type-I & Type-II Superconductor :-

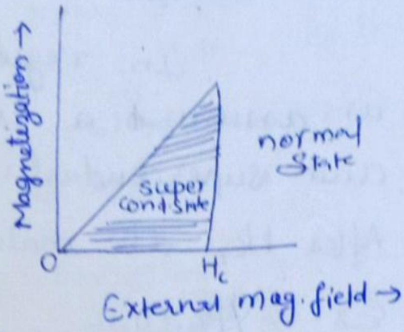
On the basis of magnetic behaviour, the superconductor are classified in to following two categories -

(1) Type-I superconductor or Soft superconductor

(2) Type-II superconductor or Hard Superconductor

Type-I Superconductor :-

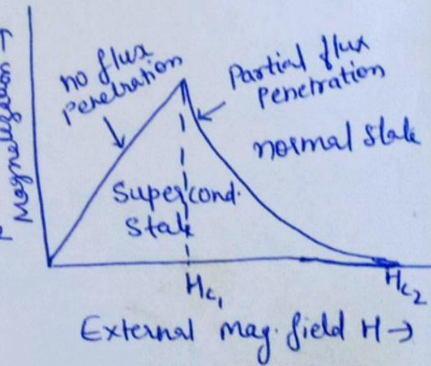
Superconductors in which the transition from superconducting state to normal state in presence of magnetic field occurs sharply at the critical value H_c.



In presence of external magnetic field $H < H_c$, type-I superconductor in superconducting state is a perfect dimagnet. When H exceeds H_c, the superconductor enters the normal state, i.e. it losses its dimagnetic property completely. Ex- Aluminium, lead, indium. H_c is very low in case of I superconductors.

Type-II Superconductor -

Superconductors in which the transition from super conducting state to normal state in presence of magnetic field take place gradually as magnetic field increased from H_{c_1} to H_{c_2}.



The magnetization curve of type II superconductor is shown in fig -
The type-II superconductor is characterized by two critical magnetic fields H_{c_1} and H_{c_2}.
The description of the curve is as follows -

(1) For the field strength below H_{c_1}, the superconductor exp... the magnetic field from its body completely and behav... as a perfact dimagnet. H_{c_1} is called the lower cri... field. The curve is represented by AB.

(2) As the magnetic field increases from H_{c_1}, the magn... field lines begin to penetrate the material. The penetr... increases until H_{c_2} is reached. H_{c_2} is called upper Critical field. At H_{c_2}, the magnetization vanishes compl... i.e. external field has completely penetrated in to super Conductor and destroyed the superconductivity.

In region from H_{c_1} ~~as~~ to H_{c_2} the Specimen is assumed a complicated mixed Structure of norm... and superconducting state known as Vortex State. After H_{c_2} the material turns in to normal state.

Ex- $YBa_2Cu_3O_{7-\delta}$, lead - Aluminium alloy.