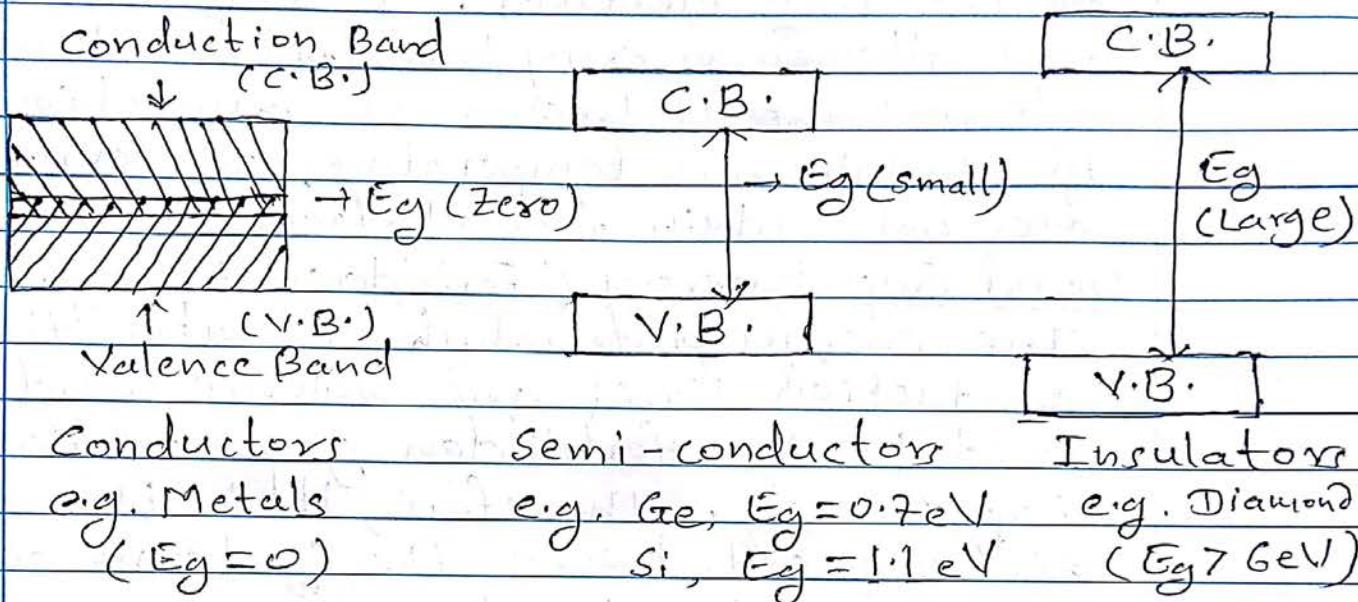


* Classification of Solids on the basis of energy band structure:



Solids are characterized by energy band structures. Therefore, based on these energy band structures mainly the valence band, conduction band and the separation between these two energy bands can be used to classify the solids as conductors, semi-conductors and insulators.

Therefore first we see what is conduction band? what is valence band and what is the Bandgap energy.

Valence Band: It is the higher energy band containing all the valence shell electrons. It formed by grouping the range of the energy levels containing valence shell of atoms of the solids. Therefore the topmost filled band at absolute zero temperature is known as valence band.

Conduction Band: It is the energy band formed by grouping the range of energy levels of the free electrons. Therefore it is the first allowed energy band placed above the valence band is known as conduction band. At absolute zero temperature, conduction band does not contain free electrons.

Band Gap Energy (Forbidden Energy Gap):

The energy gap which separates the conduction band and valence band is said to be forbidden gap or Band Gap Energy. Therefore, it is the energy difference between the bottom energy of conduction band and ^{the} top energy of the valence band.

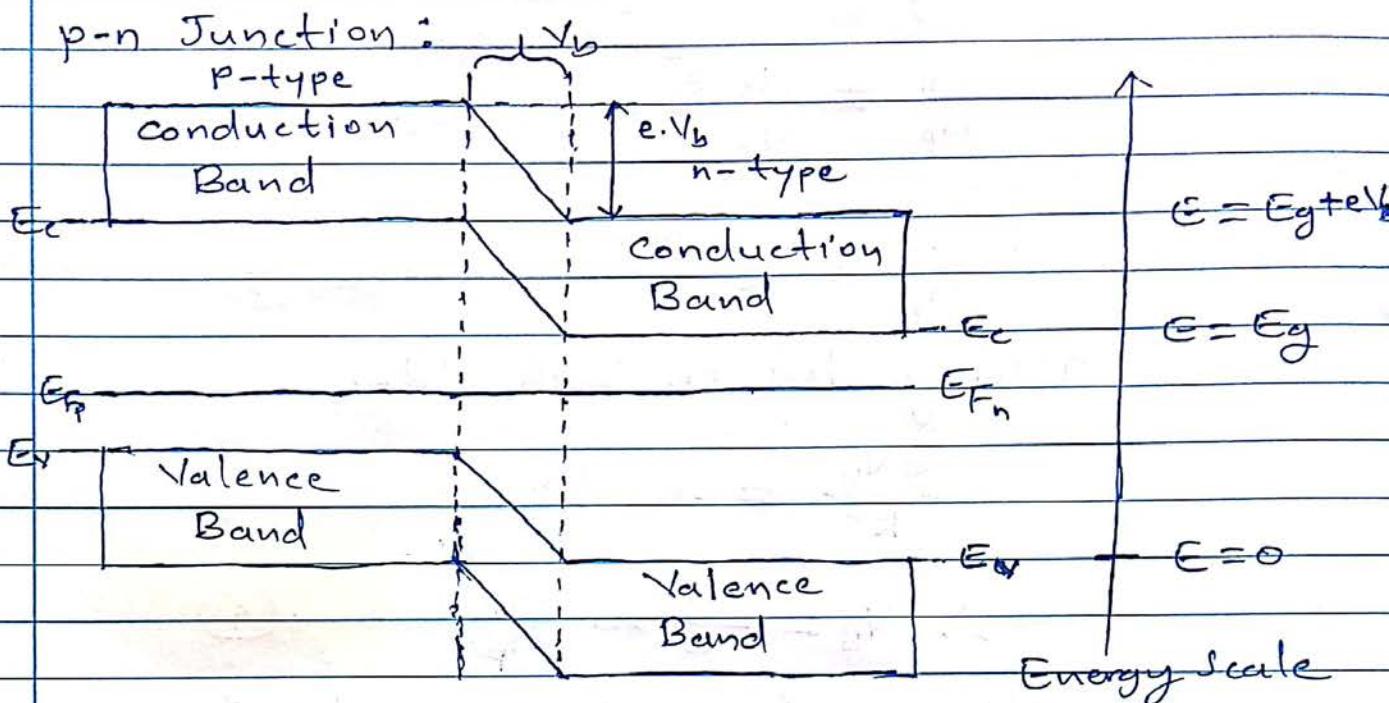
From above fig. it is clearly observed that in case of metals/conductors, the conduction band and valence band are usually overlapped with each other, therefore the bandgap energy for this class of solid is zero. Hence, metals/conductors already contains free electrons to constitute electric current and they can acts as good conductor of electricity. The typical resistivity range for good conductors is from $10^{-2} \Omega\text{-m}$ to $10^{-8} \Omega\text{-m}$.

If the band gap energy for given solid is moderate, then it is said to be semi-conductors. If we take the case of Si, then the band gap energy value, E_g is 1.1 eV and for Ge, E_g is 0.7 eV.

Therefore for this class of solids its conductivity lies between the conductors and insulators. The typical value of resistivity for semiconductors is $10^{-6} \Omega\text{m}$ to $10^{+6} \Omega\text{m}$.

In insulators/bad conductors of electricity, the conduction band and valence band are separated by very large band gap energy. Generally the band gap energy value is greater than 5 to 6 eV. An insulator does not contain any free electrons and there is no possibility to create any free electrons even by connecting them to external source. Therefore insulator does not conduct any electricity. There is nothing like any ideal conductor or ideal insulator. Only if the conductivity value for given solid is very very small then it is said to be insulator. The typical resistivity values range for insulator is $10^{11} \Omega\text{m}$ to $10^{19} \Omega\text{m}$.

* Derivation for Barrier Potential (V_b) of p-n Junction:



Let, $n_n \rightarrow$ be the electron conc. in the conduction band of n-type region.

$n_p \rightarrow$ be the electron conc. in the conduction band of p-type region.

$p_n \rightarrow$ be the hole conc. in the valence band of n-type region

$p_p \rightarrow$ be the hole conc. in the valence band of p-type region.

Then n_n and n_p will be given by following equations for n and p regions of p-n junction.

i.e;

$$n_n = N_c e^{-(E_c - E_f)/KT} = N_c e^{-(E_g - E_f)/KT} \quad (1)$$

As $E_c = E_g$ on energy scale in n-type region,

$$n_p = N_c e^{-(E_c - E_f)/KT} = N_c e^{-[(E_g + eV_b) - E_f]/KT} \quad (2)$$

As $E_c = E_g + eV_b$ on energy scale in p-type region

Dividing eqn ① by ②

$$\frac{n_n}{n_p} = \frac{N_c e^{-(E_g - E_f)/kT}}{N_c e^{-(E_g + eV_b) - E_f/kT}}$$

$$\therefore \frac{n_n}{n_p} = e^{eV_b/kT} \quad \text{--- } ③$$

Taking log on both sides

$$\frac{eV_b}{kT} = \ln \frac{n_n}{n_p}$$

$$\therefore V_b = \frac{kT}{e} \ln \frac{n_n}{n_p} \quad \text{--- } ④$$

According to "Law of mass action" in semi-conductor

$$n_n p_n = n_i^2 \quad \text{for n-type region}$$

$$P_p N_p = n_i^2 \quad \text{for p-type region} \quad \text{--- } ⑤$$

And "n_i" is known as intrinsic carrier concentration

[Law of mass action states that for given semi-conductor the product of majority and minority charge concentration is always constant]

At room temp.

$$n_n = N_D \quad \text{for n-type region} \quad (N_D = \text{conc. of donor})$$

$$P_p = N_A \quad \text{for p-type region} \quad (N_A = \text{conc. of acceptor})$$

$$\therefore V_b = \frac{kT}{e} \ln \left(\frac{n_n}{n_p} \times \frac{P_p}{P_n} \right) = \frac{kT}{e} \ln \left(\frac{N_D \cdot N_A}{n_i^2} \right) \quad \text{--- } ⑥$$

$$V_b = \frac{kT}{e} \ln \frac{N_D \cdot N_A}{n_i^2}$$

* Conductivity of Conductors (Metals)

Let's consider a piece of metal consisting of large number of free electrons (which are also known as conduction electrons). Now consider the two situations as shown in the figure.

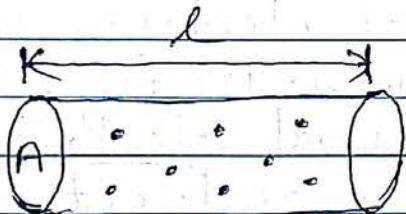


Fig. ① Random thermal motion of free electrons.

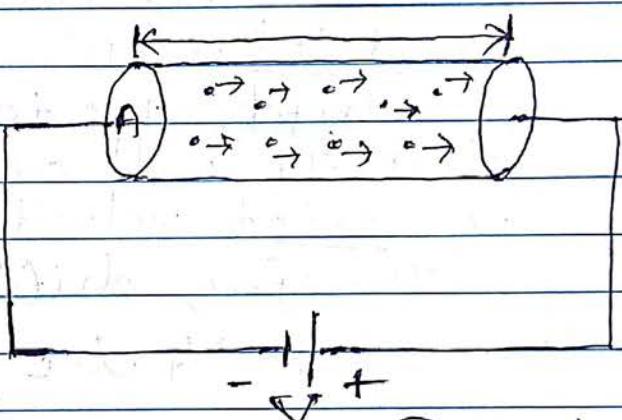


Fig. ② Directed motion of free electrons.

Here,

l is the length of conductor

A is its area of cross-section.

n_e is number density of free electrons

v_d is drift velocity of free electrons

μ_e is mobility of free electrons.

ρ is known as resistivity

σ is known as conductivity

Q is the total charge in conductor

N is the total number of free electrons

I is the current flowing through conductor

V is applied potential

R is resistance offered by conductor to the flow of current.

E is the electric field.

From the case of fig. ①, in the absence of external electric field or applied potential, all the free electrons in the metal are always in a state of random motion. But, when an external field is applied, all these randomly moving electrons will acquire a directed motion. This directed motion of electrons is known as drift, which is shown in fig. ②.

In drift, due to external electric field electrons will acquire a velocity, known as drift velocity.

Therefore, drift velocity v_d is

$$\therefore v_d \propto E$$

$$\therefore v_d = \mu_e E \quad \text{--- } ①$$

where μ_e is known as mobility of electron.

From equation ① :

$$\mu_e = \frac{v_d}{E}$$

Thus, mobility of electron is defined as the drift velocity gain by electron per unit applied external electric field. It is also known as moving ability of electrons inside given conductor.

The dependence of resistance of the conductor can be expressed as

$$R \propto \frac{l}{A} = S \cdot \frac{l}{A} \quad \text{--- } ②$$

And also from Ohm's law

$$V = I R$$

$$\therefore R = \frac{V}{I} \quad \text{--- (3)}$$

Current flowing through conductor can be defined as

$$I = \frac{d\phi}{dt} \quad \text{--- (4)}$$

And ϕ , the total in the conductor can be expressed as

$$\phi = e \cdot N = e \cdot n_e \cdot l \cdot A \quad \text{--- (5)}$$

$$\therefore I = \frac{d\phi}{dt} = e \cdot n_e \cdot A \left(\frac{dl}{dt} \right)$$

$$\therefore I = e \cdot n_e \cdot A \cdot V_d \quad \text{--- (6)}$$

The term $\left(\frac{dl}{dt} \right)$ represents drift velocity of electrons. Let's substitute value of V_d from equation (1).

$$\therefore I = e \cdot n_e \cdot A \cdot u_e E \quad \text{--- (7)}$$

but 'E' can be expressed as

$$E = \frac{V}{l} \quad \text{--- (8)}$$

$$\therefore I = e \cdot n_e \cdot A \cdot u_e \cdot \frac{V}{l} \quad \text{--- (8)}$$

$$\therefore \frac{V}{I} = \frac{l}{e \cdot n_e \cdot A \cdot u_e} \quad \text{--- (9)}$$

The term $\frac{V}{I}$ is a resistance

$$\therefore R = \frac{1}{e \cdot n_e \cdot m_e} \frac{l}{A} \quad (10)$$

And $R = \rho \cdot \frac{l}{A}$ from equation (2)

$$\therefore \rho = \frac{l}{e \cdot n_e \cdot m_e} \quad (11)$$

The reciprocal of resistivity is known as conductivity (σ) .

$$\therefore \sigma = e \cdot n_e \cdot m_e \quad (12)$$

Thus, the conductivity of conductors depends upon number density of electrons n_e and the mobility of electrons m_e .

* Conductivity of semi-conductors
(semi-metals)

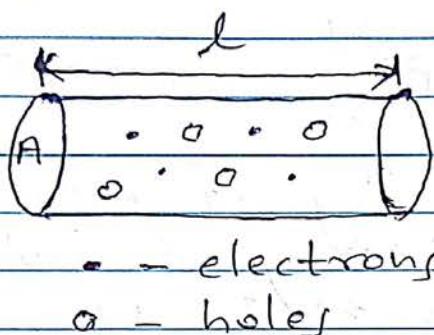


Fig. ① Random

thermal motion
of electrons & holes

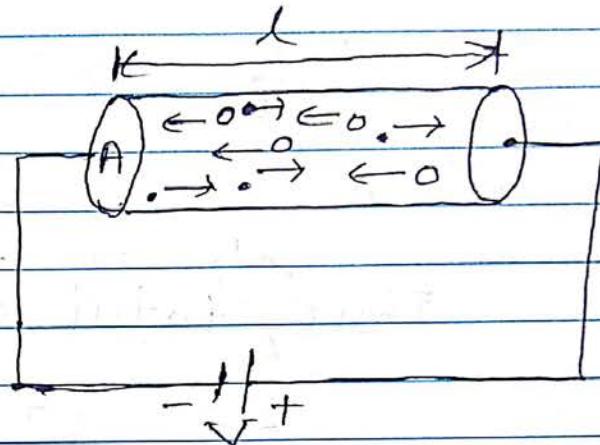


Fig. ② Directed motion
of electrons & holes.

In case of semi-conductors, net electric current will be mainly because free electrons and free holes.

$$\therefore I = I_e + I_p \quad \text{--- (1)}$$

where 'I_e' is current due to electrons and 'I_p' is current due to holes.
As current due to electrons can be expressed as

$$I_e = e \cdot n_e \cdot A \cdot V_{de} \quad \text{--- (2)}$$

$$\text{And } I_p = e \cdot n_p \cdot A \cdot V_{dp} \quad \text{--- (3)}$$

where n_e is electron no. density.
and n_p is hole no. density.

V_{de} is known as drift velocity
of electron

V_{dp} is the drift velocity of holes.

$$\therefore V_{de} = \mu_e E = \mu_e \cdot \frac{V}{l} \quad \text{--- (4)}$$

$$V_{dp} = \mu_p E = \mu_p \cdot \frac{V}{l} \quad \text{--- (5)}$$

where μ_e is mobility of electron
and μ_p is mobility of holes.
Thus, total current, I is

$$I = I_e + I_p$$

$$\therefore I = e \cdot n_e A \cdot V_{de} + e \cdot n_p A \cdot V_{dp}$$

$$\therefore I = e \cdot n_e \cdot A \cdot \mu_e \frac{V}{l} + e \cdot n_p \cdot A \cdot \mu_p \cdot \frac{V}{l}$$

$$\therefore I = (n_e \mu_e + n_p \mu_p) \cdot e \cdot A \frac{V}{l} \quad \text{--- (6)}$$

$$\therefore R = \frac{V}{I} = \frac{1}{(n_e \mu_e + n_p \mu_p) \cdot e \cdot A} \quad \text{--- (7)}$$

$$\text{And } R = \rho \cdot \frac{l}{A} \quad \text{--- (8)}$$

From equation (7) and (8).

$$\rho = \frac{1}{e(n_e \mu_e + n_p \mu_p)} \quad \text{--- (9)}$$

And as conductivity is reciprocal of resistivity.

$$\therefore \sigma = e(n_e \mu_e + n_p \mu_p) \quad \text{--- (10)}$$

Equation ⑩ is the general equation of conductivity of semi-conductor.
 For intrinsic semi-conductor

$$n_e = n_p \approx n;$$

$$\therefore G_i = e \cdot (n_i u_e + n_i u_p)$$

$$\therefore G_i = e \cdot n_i (u_e + u_p) \quad \text{--- } ⑪$$

For extrinsic semiconductors.

In n-type extrinsic semiconductors

$$n_e u_e \gg n_p u_p$$

$$\therefore G_n = e \cdot n_e u_e \quad \text{--- } ⑫$$

In p-type extrinsic semiconductors

$$n_p u_p \gg n_e u_e$$

$$\therefore G_p \approx e \cdot n_p u_p \quad \text{--- } ⑬$$

* Diode Equation:

The equation giving the relationship of current flowing through diode as a function of voltage is known as Diode Equation.

The most general form of diode equation is as follows

$$I = I_0 \left(e^{\frac{qV}{nKT}} - 1 \right)$$

Where, I is the net current flowing through the diode

I_0 is known as reverse saturation current

V is applied voltage across diode

q is absolute value of electron charge.

K is Boltzmann's constant

T is absolute temperature in Kelvin.

And n is known as ideality factor of a diode

usually its value is in between 1 and 2.

And it increases with decrease in current.

In diode equation, if ideality factor $n=1$, then it is known as Ideal Diode Equation.

i.e;

$$I = I_0 \left(e^{\frac{qV}{KT}} - 1 \right)$$

The same equation can also be expressed as in terms of current densities.

i.e;

$$J = J_0 \left(e^{\frac{qV}{KT}} - 1 \right)$$

where, $J = I/A$, A is area of cross-section of the junction.

To understand diode equation, we need to understand the fundamentals of diode currents.

There are two types of currents in p-n junction diode - i) Diffusion current (due to majority charges)
ii) Drift current (due to minority charges)

Here we are expressing currents in terms of current densities.

Let, J_{en} represent current due to electrons in n-type (majority charges)

J_{hn} represents current due to holes in n-type (minority charges)

J_{hp} represents current due to holes in p-type (due to majority charges)

J_{ep} represents current due to electrons in p-type when p-n junction forms, due to concentration gradients of majority charges across the junction diffusion of electrons from n to p region and diffusion of holes from p to n will set up diffusion current. Therefore net diffusion current will be given by

$$J(\text{diffusion}) = J_{hp} + J_{en}$$

The electric field in space charge (depletion) region will cause drifting of minority charges across the junction and sets up drift current. The net drift current will be given by .

$$J(\text{drift}) = J_{hn} + J_{ep}$$

Under thermal equilibrium

$$J(\text{diffusion}) = J(\text{drift})$$

$$J_{hp} + J_{en} = J_{hn} + J_{ep}$$

As there is no net build up of holes or electrons on either side during equilibrium. Therefore diffusion and drift current must cancel each other for electrons and for holes separately.

$$\text{i.e;} \quad J_{hp} - J_{hn} = 0 \Rightarrow J_{hp} = J_{hn}$$

$$J_{en} - J_{ep} = 0 \Rightarrow J_{en} = J_{ep}$$

During forward biasing, the barrier at junction will be reduced by an amount of energy eV_F . and the probability of majority carrier crossing the junction will increase by a factor of $e^{qV_F/kT}$.

Therefore, diffusion current density increases by a factor of $e^{qV_F/kT}$ due to majority charges.

$$\text{i.e;} \quad J_{hp}^* = J_{hp} e^{qV_F/kT} = J_{hn} e^{qV_F/kT}$$

$$J_{en}^* = J_{en} e^{qV_F/kT} = J_{ep} e^{qV_F/kT}$$

where J_{hp}^* and J_{en}^* are the values of current densities during forward biasing.

And the drift current densities will be unchanged. Therefore net hole current density and electron current density.

$$J_h = J_{hp}^* - J_{hn} = J_{hn} (e^{qV_F/kT} - 1)$$

$$J_e = J_{en}^* - J_{ep} = J_{ep} (e^{qV_F/kT} - 1)$$

And total current density J will be

$$J = J_e + J_h = (J_{hn} + J_{ep}) (e^{qV_F/kT} - 1)$$

$$\therefore J = J_0 (e^{qV_F/kT} - 1)$$

In terms of current

$$I = I_0 (e^{qV_F/kT} - 1) = I_0 (e^{qV_F/kT} - 1)$$

As V_F represent forward biasing voltage.

* Fermi Dirac Distribution Function:

Fermions: It is a class of elementary particles which are indistinguishable and are characterized by half integer spin values.

e.g. electrons, holes, protons, neutrons etc

Fermi Dirac Distribution Function is a pure mathematical function of energy 'E' and temperature 'T' that gives probability of distributions of fermions among available energy states at given temperature.

i.e;

$$f(E, T) = \frac{1}{1 + e^{(E - E_f)/kT}}$$

where, 'E' is the energy of given energy state

'T' is temperature in Kelvin.

'k' is Boltzmann Constant.

And 'E_f' is known as Fermi-Energy

Let us consider a system of energy states containing fermions. These fermions are distributed in these energy states according to fermi dirac distribution function.

The energy states are as shown in figure.

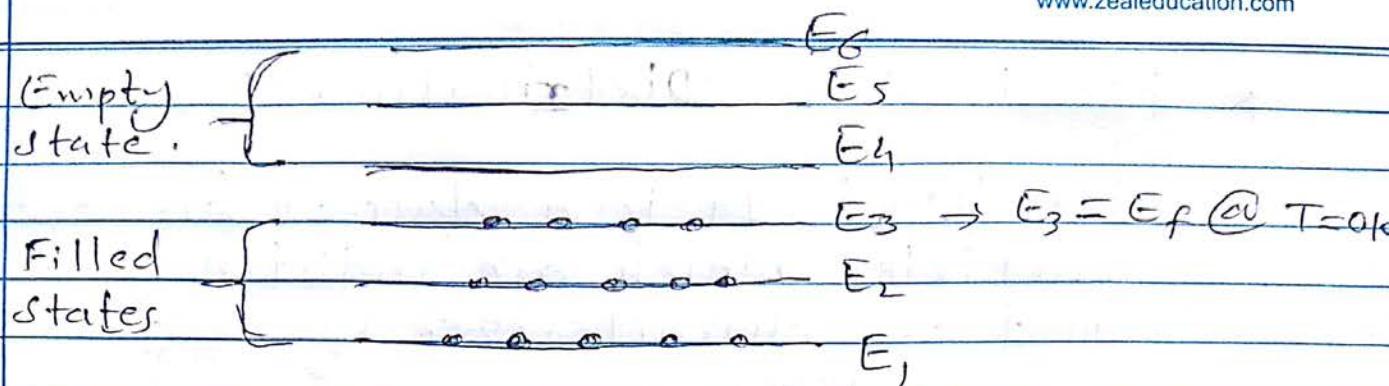


Fig. Distribution of fermions @ T=0K.

Fermi Level: The highest occupied level at T=0K is known as Fermi Level and the corresponding energy of the level is said to be Fermi Energy.

According to Fermi Dirac Distribution Function (also known as Fermi Function), a given energy level can accommodate finite number of fermions as per its energy and temperature.

Let us find out the probability of given energy state for particular values of 'E' and 'T'.

Case 1: If E < E_f and T=0K,

$$\therefore f(E, T) = \frac{1}{1 + e^{(E - E_f)/kT}}$$

$$\therefore f(E, T) = \frac{1}{1 + e^{-\text{No. of states}}} = \frac{1}{1 + e^{-\infty}} = 1$$

$$= \frac{1}{1 + e^{-\infty}} = \frac{1}{1 + \frac{1}{e^{\infty}}} = \frac{1}{1 + \frac{1}{\infty}}$$

$$f(E, T) = \frac{1}{1 + 0} = 1.$$

Therefore, when $E < E_f$ and $T = 0K$, the $f(E, T)$ comes out to be 1, it means all such energy states are certainly filled.

Case 2: $E > E_f$ and $T = 0K$

$$\therefore f(E, T) = \frac{1}{1 + e^{(E-E_f)/kT}}$$

$$= \frac{1}{1 + e^{+ve\ number/0}}$$

$$= \frac{1}{1 + e^{+\infty}} = \frac{1}{\infty} = \frac{1}{\infty} = 0$$

$$\therefore f(E, T) = 0.$$

i.e; when $E > E_f$ and $T = 0K$, then

$f(E, T)$ comes out to be zero; therefore all such energy states are empty.

These states do not contain any Fermions. From above two cases, we can also define Fermi Energy by following way.

At $T = 0K$ the energy level which indicates or acts as a separation between filled states and empty states is known as Fermi Level.

Case 3: If $E = E_f$ and $T \neq 0K$

$$\therefore f(E, T) = \frac{1}{1 + e^{(E-E_f)/kT}}$$

$$\therefore f(E, T) = \frac{1}{1 + e^0} / \text{finite number}$$

$$= \frac{1}{1 + e^0} = \frac{1}{1+1} = \frac{1}{2} = 0.5$$

$$\therefore f(E, T) = 0.5$$

Thus, when $E = E_f$ and $T \neq 0K$ then $f(E, T)$ comes out to be 0.5.

Therefore, we can also define Fermi level as "At finite temperatures the half filled energy level is said to be Fermi Level".

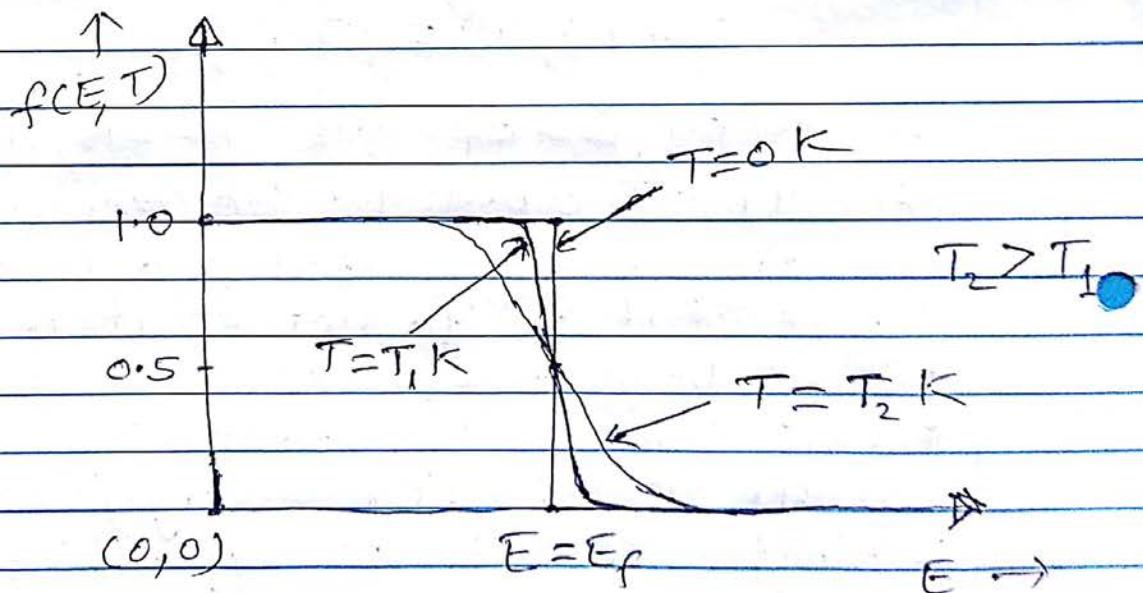


Fig. $f(E, T)$ Vs Energy

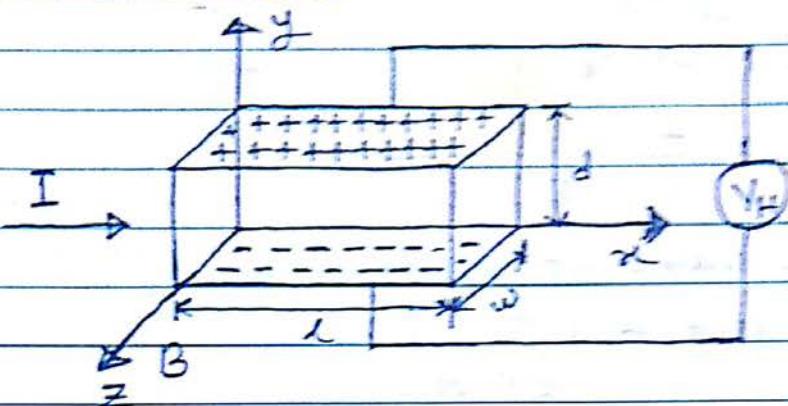
Above fig. of $f(E, T)$ Vs E shows the possible variations of $f(E, T)$ with all possible combinations of E and T .

At finite temperature, again there are two possible cases, case 1: $E < E_f$ and $T \neq 0K$

and cases is $E > E_f$ and $T \neq 0K$. These cases indicates the effect of temperature on the value of probability of fermions to be present in given energy states.

From the plots of $T = T_1 K$ and $T = T_2 K$, it is clear that, the value of $f(E, T)$ changes slightly as compared to its value at $T = 0K$ for only those energy states which are close to Fermi Energy, ' E_f '. This indicates that, the probability of Fermions gets affected only for those energy states which are just situated below and above the fermi level, whereas the probability of fermions for the energy states which are far from fermi level is remains unaffected.

* Hall Effect:



When a current carrying conductor or semiconductor specimen is subjected to transverse magnetic field, an electric field is getting induced in the specimen in a direction which is perpendicular to both the direction of current and applied magnetic field.

The applied magnetic field will bend the path of moving charges. This will result into selective accumulation of charges on top and bottom faces of specimen along 'y' axis. This successive addition of charges on top and bottom faces will lead to develop Hall voltage which will exert opposing forces on further incoming charges i.e; this electric force opposes Lorentz force. Under equilibrium both these forces balances each other and develops constant Hall Voltage ' V_H '.

$$F_B = F_H \quad \text{--- (1)}$$

$$F_B = q V_B B \quad \text{--- (2)} \quad \text{And} \quad F_H = q E_H = q \frac{V_H}{d} \quad \text{--- (3)}$$

Substitute eqⁿ (2) and eqⁿ (3) in eqⁿ (1).

$$\therefore \frac{q V_H}{d} = q V_B B \quad \text{--- (4)}$$

current flowing specimen will be given by

$$I = e \cdot n \cdot V_d \cdot A \quad \textcircled{5}$$

$$\therefore V_d = \frac{I}{e \cdot n \cdot A} \quad \textcircled{6}$$

Substitute value of V_d from eqⁿ $\textcircled{6}$ in eqⁿ

$$\therefore \frac{V_H}{d} = \frac{I}{e \cdot n \cdot A} \cdot B$$

$$\frac{V_H}{d} = \frac{I \cdot B}{e \cdot n \cdot A} = \frac{1}{e \cdot n} \frac{I \cdot B}{w \cdot d}$$

$$\therefore V_H = \frac{1}{e \cdot n} \frac{I \cdot B}{w} \quad \textcircled{7}$$

$$\therefore V_H = R_H \frac{I \cdot B}{w} \quad \textcircled{8}$$

where $R_H = \frac{1}{e \cdot n}$; known as Hall coefficient

Applications : ① Sign of Hall coefficient will decide the type of semiconductors. (If R_H is +Ve, semiconductor is p-type and if -Ve, then n-type)

② Carrier concentration can be determined from R_H ;

$$n = \frac{1}{e \cdot R_H}$$

③ Mobility can be determined from R_H

$$\text{As } G = e \cdot n \cdot \mu \Rightarrow \mu = G / R_H \cdot n = G \cdot R_H$$

④ Hall effect can be used to measure magnetic fields.