

### Q:Expression for electrical conductivity and hence electrical resistivity from CFET.

Electrical conductivity,  $\sigma = \frac{ne^2\tau}{m}$  where  $n$ = concentration of electrons,  $e$ = charge on electron,  $\tau$  = mean collision time,  $m$ = mass of the electron.

Also, Electrical resistivity,  $\rho = \frac{1}{\sigma}$

$$\therefore \rho = \frac{m}{ne^2\tau}$$

### Q:Explain the failures of classical free electron theory(CFET).

Failures of CFET are:-

#### 1. Dependence of electrical conductivity ( $\sigma$ ) on $T$ :

According to CFET kinetic energy  $\frac{1}{2}mv^2 = \frac{3}{2}kT$

$$\therefore v \propto \sqrt{T} \dots (1)$$

But mean collision time  $\tau \propto \frac{1}{v}$

$$\therefore \tau \propto \frac{1}{\sqrt{T}} \dots (2) \quad \therefore v \propto \sqrt{T}$$

Also from  $\sigma = \frac{ne^2\tau}{m}$ , we get  $\sigma \propto \tau \dots (3)$

From eqns 2 & 3 we get  $\sigma \propto \frac{1}{\sqrt{T}}$ , but experimentally it has been observed that  $\sigma \propto \frac{1}{T}$ , thus CFET fail to explain the dependence of  $\sigma$  on  $T$ .

#### 2. Dependence of ' $\sigma$ ' on electron concentration ' $n$ ' :

Metal	Valency/Atomicity	Conductivity ' $\sigma$ ' .. $\times 10^7$ $\Omega/m$	Concentration ' $n$ ' ... $\times 10^{28}/m^3$
Ag	1 (Monoatomic)	6.30	5.85
Zn	2 (Diatomic)	1.09	13.10
Al	3 (Triatomic)	3.65	18.06

From  $\sigma = \frac{ne^2\tau}{m}$ , we get  $\sigma \propto n$ , according to CFET  $\sigma$  of tri-atomic metals must be more than that of di-atomic and mono-atomic metals but from experimental results as shown in the tabular column, it has been found that  $\sigma$  of mono-atomic metals of low  $n$  are more than that of di and tri-atomic metals of large  $n$ . Thus CFET fail to explain dependence of  $\sigma$  on concentration  $n$ .

## Q:State/Mention the assumptions of (Sommerfeld's)quantum free electron theory(QFET)

The assumptions of QFET are:

- 1.The energy of free electrons are quantized.
2. Free electrons obey Pauli's exclusion principle.
3. The distribution of free electrons in energy levels is governed by Fermi-Dirac statistics.
3. Free electrons move in uniform potential field due to ionic cores in a metal .
5. The electrostatic electron-ion attractions and electron-electron repulsions are negligible.
6. Electrons are considered as wave like particles.

## Q:Explain the success of QFET.

QFET explained the following experimental facts which were not explained by CFET.

### 1.Dependance of electrical resistivity ' $\sigma$ ' on ' $T$ '(temperature):

We know that(WKT)  $\sigma = \frac{ne^2\tau}{m^*}$  and  $\tau = \frac{\lambda}{v_F}$  where  $v_F$ =Fermi velocity,  $\lambda$ =Mean free path

$$\therefore \sigma = \frac{ne^2}{m^*} \frac{\lambda}{v_F} \therefore \sigma \propto \lambda \dots\dots(1)$$

Also it has been shown that mean free path,  $\lambda \propto \frac{1}{T}$ ...(2) where , $T$ =temperature.

$\therefore$  from eqns 1&2,we get  $\sigma \propto \frac{1}{T}$  which is the experimentally determined relation.

### 2.Dependance of ' $\sigma$ ' on ' $n$ ':

WKT conductivity  $\sigma = \frac{ne^2}{m^*} \frac{\lambda}{v_F}$  , thus  $\sigma$  depends both on  $n$  and  $\frac{\lambda}{v_F}$  .With the decreases of atomicity,  $n$  decreases and  $\frac{\lambda}{v_F}$  increases so that  $n \cdot \frac{\lambda}{v_F}$  increases ,so that  $\sigma$  is more for monoatomic metals than that of di&tri-atomic metals.This explains the conductivity of mono-atomic metals is more than that of di & tri-atomic metals.

**Q: Expression for electrical conductivity and hence resistivity based on QFET.**

Electrical conductivity,  $\sigma = \frac{ne^2\tau}{m^*}$ , where  $n$  = concentration of electrons,  $e$  = charge on electron,  $\tau$  = mean collision time,  $m^*$  is called effective electron mass

**Q: Explain the terms: Mobility, Fermi velocity, Fermi temperature, Fermi Level & Fermi energy.**

- a) **Mobility ( $\mu$ )** of electrons is defined as the drift velocity ( $v_d$ ) acquired by the electrons per unit electric field ( $E$ ). ie:  $\mu = \frac{v_d}{E} \Rightarrow \mu = \frac{\sigma}{ne} \Rightarrow \mu = \frac{e\tau}{m}$
- b) **Fermi velocity ( $v_F$ )** of an electron is defined as it's velocity when it's energy is equal to the Fermi energy. ie:  $\frac{1}{2}mv_F^2 = E_F \Rightarrow v_F = \left(\sqrt{\frac{2E_F}{m}}\right)$
- c) **Fermi temperature ( $T_F$ )** is defined as the ratio of Fermi energy at 0K to Boltzmann constant. ie:  $T_F = \frac{E_F}{k}$  where  $k$  = Boltzmann constant.
- d) **Fermi level** is defined as the highest filled energy level in a metal at 0K.
- e) **Fermi energy ( $E_F$ )** is defined as the energy of the highest occupied Fermi level in a metal at 0K.

**Q: What is Fermi-Dirac statistics ? Explain.**

Fermi-Dirac statistics is the statistical rule applied to the distribution of identical, indistinguishable particles of spin  $\frac{1}{2}$  called fermions like electrons, which obey Pauli's exclusion principle. The probability of occupation of a state by an electron is given by Fermi factor/Fermi-Dirac distribution function given

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

where  $E_F$  = Fermi energy,  $E$  = energy of State,

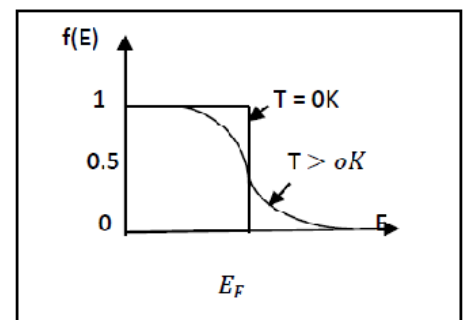
$k$  = Boltzmann constant and  $T$  = temperature.

Case 1. At  $T=0K$  &  $E < E_F$ ,  $f(E) = 1$

Case 2. At  $T=0K$  &  $E > E_F$ ,  $f(E) = 0$  and

Case 3. At  $T > 0K$  &  $E = E_F$ ,  $f(E) = 0.5$

Variation of  $f(E)$  with  $E$  is as shown in the graph.



**Q:What is meant by Fermi factor ? Explain the variation of Fermi factor with temperature & energy.**

**Fermi factor** is the probability of occupation of a given energy state by an electron in a metal at thermal equilibrium. It is given by the relation

$$f(E) = \frac{1}{1+e^{(E-E_F)/kT}}, \text{ where } E_F \text{ Fermi energy,}$$

E = energy of State, k = Boltzmann constant and T = temperature

The variation of f(E) with temperature and energy is discussed below:

**When T = 0K**

**Case-1:** If  $E < E_F \Rightarrow (E - E_F)$  is -ve, then  $e^{(E-E_F)/kT} = e^{-\infty} = 0$

$$\therefore f(E) = \frac{1}{1+e^{(E-E_F)/kT}} = \frac{1}{1+0} = 1,$$

Thus the probability of occupation up to Fermi level is 100%.

**Case-2:** If  $E > E_F \Rightarrow (E - E_F)$  is +ve, then  $e^{(E-E_F)/kT} = e^{\infty} = \infty$

$$\therefore f(E) = \frac{1}{1+e^{(E-E_F)/kT}} = \frac{1}{1+\infty} = \frac{1}{\infty} = 0,$$

Thus the probability of occupation above Fermi level is 0%.

**Case-3:** If  $E = E_F \Rightarrow (E - E_F) = 0$ , then  $e^{(E-E_F)/kT} = e^0 = 1$  indeterminate

**When T > 0K**

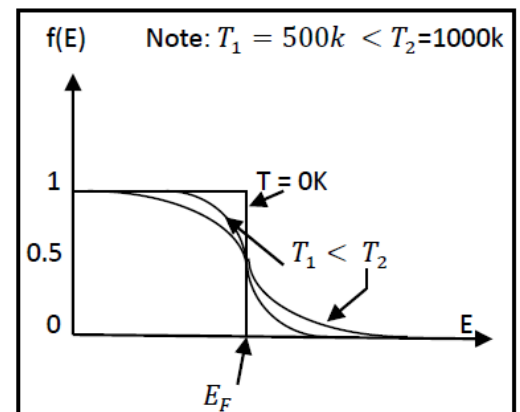
$$\therefore f(E) = \frac{1}{1+e^{(E-E_F)/kT}}$$

If  $E = E_F \Rightarrow (E - E_F) = 0$  then  $e^{(E-E_F)/kT} = e^0 = 1$

$$\therefore f(E) = \frac{1}{1+e^{(E-E_F)/kT}} = \frac{1}{1+1} = \frac{1}{2}$$

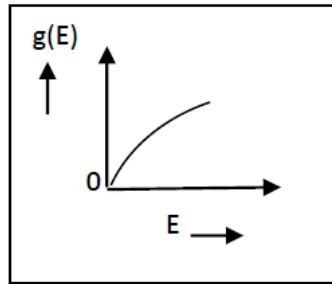
Thus the probability of occupation of Fermi level is 50% above 0K.

The variation of f(E) with temperature(T) and energy(E) is shown in the graph .



**Q:What is meant by Density of states ? Explain.**

**Density of states**  $[g(E)]$  is defined as the number of electronic states present in a unit energy range, given by  $g(E) dE = \frac{8\sqrt{2}\pi m^{3/2}}{h^3} E^{1/2} dE$ . It is a continuous function and the product  $g(E)dE=dN$  gives the number of states per unit volume in an energy range  $(dE)$  between  $E$  and  $E+dE$ . The number of electrons per unit volume,  $n = \int g(E)f(E)dE$  and the variation of  $g(E)$  with  $E$  is shown in the graph.

**Q:What is meant by effective mass? Explain.**

When an electric field is applied to a metal, electrons in the K-shell are not at all accelerated as they are tightly bound to the nucleus. These electrons possess infinite mass called effective mass denoted by  $m^*$ .

Effective mass is equal to the true mass if the electron is in vacuum.

**Q:Derivation of an expression for Fermi-energy at 0K**

WKT, density of states  $g(E) = \frac{8\sqrt{2}\pi m^{3/2}}{h^3} E^{1/2} \dots (1)$

Fermi factor,  $f(E) = \frac{1}{1 + e^{\frac{E - E_F}{kT}}} \dots (2)$

Then the number of electrons /unit volume in the material in energy range  $dE$  at  $E$  is given by

$n = \int_0^{E_{max}} g(E)dE \times f(E) \dots (3) \quad \because g(E)dE \times f(E) = N(E)dE, \text{no. of electrons in the range } dE \text{ at } E$

But at  $T = 0K$ ,  $f(E) = 1$  and  $E_{max} = E_{F0}$ , Fermi energy.....(4)

$\therefore$  from eqns 1,2,3 &4, we get

$$\begin{aligned} n &= \int_0^{E_{F0}} \frac{8\sqrt{2}\pi m^{3/2}}{h^3} E^{1/2} dE \\ &= \frac{8\sqrt{2}\pi m^{3/2}}{h^3} \int_0^{E_{F0}} E^{1/2} dE \\ &= \frac{8\sqrt{2}\pi m^{3/2}}{h^3} \left[ \frac{2}{3} E^{3/2} \right]_0^{E_{F0}} \end{aligned}$$

$$= \frac{8\sqrt{2}\pi m^{3/2}}{h^3} \frac{2}{3} (E_{F_0})^{3/2}$$

$$(E_{F_0})^{3/2} = \frac{h^3}{(8m)^{3/2}} \left(\frac{3n}{\pi}\right)$$

$$E_{F_0} = \frac{h^2}{8m} \left(\frac{3}{\pi}\right)^{2/3} n^{2/3} \quad \text{or} \quad E_{F_0} = 5.85 \times 10^{-38} n^{2/3}$$

## SEMICONDUCTORS

**Q: Derive an expression for electrical conductivity of a semi-conductor.**

In a semiconductor the net current is due to both electrons and holes .

The current due to electrons is  $I_e = n_e e a v_e$ , where  $n_e$  = number density,  $a$  = area,  $v_e$  = drift velocity &  $e$  = charge

Also current due to holes is  $I_h = n_h e a v_h$

But the total current  $I = I_e + I_h$   
 $= e a (n_e v_e + n_h v_h)$

$$\frac{I}{a} = e (n_e v_e + n_h v_h)$$

WKT, current density  $J = \frac{I}{a}$

$$\therefore J = e (n_e v_e + n_h v_h)$$

but from Ohm's law  $J = \sigma E$

$$\text{ie: } \sigma E = e (n_e v_e + n_h v_h)$$

$$\sigma = e \left( n_e \frac{v_e}{E} + n_h \frac{v_h}{E} \right)$$

$$\sigma = e(n_e \mu_e + n_h \mu_h)$$

where  $\mu_e$  &  $\mu_h$  mobilities of electrons and holes respectively.

For an intrinsic semiconductor

$n_e = n_h = n_i$  called the density of intrinsic charge carriers.

Then,  $\sigma = e n_i (\mu_e + \mu_h)$

For n-type semiconductor  $n_e \gg n_h \Rightarrow \sigma = e n_e \mu_e$

For p-type semiconductor,  $n_e \ll n_h \Rightarrow \sigma = e n_h \mu_h$



**Q: Derive an expression for electron charge carrier density (concentration) in an intrinsic semiconductor.**

We know that the number of energy levels between the energy interval  $E$  and  $E+dE$  is given by

$$g(E)dE = \left( \frac{8\sqrt{2}\pi(m_e^*)^{3/2}}{h^3} \right) E^{1/2}dE, \text{ where } m_e^* = \text{effective mass of electron.}$$

Also, the probability of occupation of an energy level is given by

$$\text{Fermi factor } f(E) = \frac{1}{1 + e^{\left(\frac{E-E_F}{kT}\right)}}$$

where  $E_F = \text{Fermi energy}$  &  $k = \text{Boltzmann constant}$

Then, the concentration of electron charge carriers is given by

$$n_e = \int_{E_g}^{\infty} f(E) g(E) dE$$

$$= \int_{E_g}^{\infty} \frac{1}{e^{\left(\frac{E-E_F}{kT}\right)} + 1} \left( \frac{8\sqrt{2}\pi(m_e^*)^{3/2}}{h^3} \right) E^{1/2} dE$$

where  $m_e^* = \text{effective mass of electron.}$

On integration we can show that

$$n_e = 4\sqrt{2} \left( \frac{\pi m_e^* kT}{h^2} \right)^{3/2} e^{\left(\frac{E_F - E_g}{kT}\right)}$$

Similarly, the concentration of hole charge carriers is given by

$$n_h = 4\sqrt{2} \left( \frac{\pi m_h^* kT}{h^2} \right)^{3/2} e^{\left(\frac{-E_F}{kT}\right)}$$

**Describe Fermi level in intrinsic semiconductor and hence obtain the expression**

At 0K, all the energy levels of valence band are completely filled and all the levels of conduction band are empty. But at ordinary room temperature and above some of the electrons from valence band excite and fill bottom levels of conduction band. As a result bottom levels of conduction band and top levels of valence band are filled. Due to this the average energy of the conduction electrons is  $\frac{1}{2}E_g$ , where  $E_g$  is the energy gap.

Thus for an intrinsic semiconductor the Fermi Level lies at the middle of the energy gap/band.

WKT,

The concentration of electron charge carriers is given by

$$n_e = 4\sqrt{2} \left( \frac{\pi m_e^* kT}{h^2} \right)^{3/2} e^{\left( \frac{E_F - E_g}{kT} \right)} \dots (1)$$

Similarly, the concentration of hole charge carriers is given by

$$n_h = 4\sqrt{2} \left( \frac{\pi m_h^* kT}{h^2} \right)^{3/2} e^{\left( \frac{-E_F}{kT} \right)} \dots (2)$$

But for an intrinsic semiconductor,  $n_e = n_h \dots (3)$

From equns 1,2 &3, we get  $(m_e^*)^{3/2} e^{\left( \frac{E_F - E_g}{kT} \right)} = (m_h^*)^{3/2} e^{\left( \frac{-E_F}{kT} \right)}$

$$e^{\left( \frac{2E_F - E_g}{kT} \right)} = \left( \frac{m_h^*}{m_e^*} \right)^{3/2}$$

Taking logarithms on both sides, we get

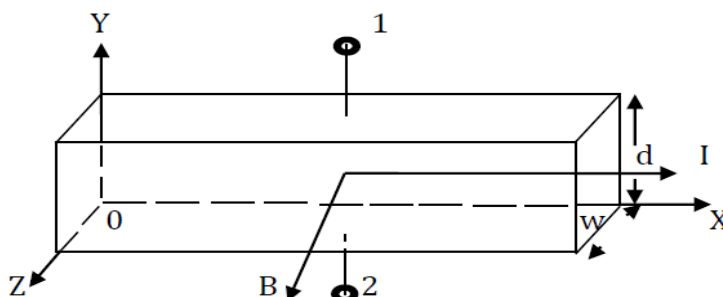
$$\left( \frac{2E_F - E_g}{kT} \right) = \frac{2}{3} \ln \left( \frac{m_h^*}{m_e^*} \right)$$

$$E_F = \frac{3}{4} kT \ln \left( \frac{m_h^*}{m_e^*} \right) + \frac{E_g}{2} \quad \text{Practically, } m_e^* = m_h^*, \ln \left( \frac{m_h^*}{m_e^*} \right) = \ln(1) = 0$$

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

**Hall Effect:** When magnetic field is applied perpendicular to the direction of the current in a conductor, a potential difference develops along a direction perpendicular to both current and magnetic field. This effect is known as **Hall effect**. The potential difference developed is known as Hall voltage.

**Hall voltage and Hall coefficient:**





Consider a rectangular conductor of cross section  $w \times t = a$  in which current "I" flows along x-axis. when a magnetic field 'B' is applied along z-axis, Hall voltage  $V_H$  develops along y-axis between the terminals 1 & 2.

If  $E_H$  be the Hall electric field and 'v' be the drift velocity (of charges)

Then under equilibrium conditions,

Force on charges due to Hall electric field = Force on charges due to magnetic field

$$\text{ie: } qE_H = qvB$$

$$\therefore E_H = vB \text{ also } E_H = \frac{V_H}{d}$$

$$\therefore \frac{V_H}{d} = vB \text{ or } V_H = vBd \dots\dots(1)$$

$$\text{Wkt, } I = nqav \text{ or } v = \frac{I}{nqa} \dots\dots(2)$$

$$\therefore \text{ from eqns 1 \& 2, we get } V_H = \frac{IBd}{nqa} \text{ but } a = w \times d$$

$$\therefore V_H = \frac{IB}{nqw} \dots\dots(3)$$

The quantity  $\frac{1}{nq}$  is the reciprocal of charge density and is called the **Hall coefficient** ' $R_H$ '

$$\text{ie; } R_H = \frac{1}{nq} \dots\dots(4)$$

$$\text{From eqns 3 \& 4 we get } V_H = R_H \frac{IBd}{a} \text{ or } R_H = \frac{V_H a}{IBd} \dots\dots(5)$$

$R_H$  and charge density can be determined as  $V_H$ , B, d and a are all measurable quantities.

**Electrical Conductivity( $\sigma$ ), resistivity( $\rho$ ) and Hall angle( $\theta_H$ ):**

Let 'V' be the voltage applied along X-axis to produce the electric field 'E' and current 'I'. If 'L' be the length of the conductor along X-axis, then wkt,  $E = \frac{V}{L}$

$$\text{Also, } E_H = vB = \frac{IB}{nqa}$$

$$\therefore \frac{E_H}{E} = \frac{IB}{nqa} \times \frac{L}{V} \text{ but } R = \frac{V}{I}$$

$$\therefore \frac{E_H}{E} = \frac{B}{nqa} \times \frac{L}{R} \text{ also resistivity } \rho = \frac{Ra}{L}$$

$$\therefore \frac{E_H}{E} = \frac{B}{nq\rho} \text{ or } \frac{E_H}{E} = \frac{B\sigma}{nq}$$

Charges in the conductor are under the influence of applied electric field 'E' along x-axis and Hall electric field ' $E_H$ ' along y-axis. The angle made by the resultant of these two fields with x-axis is called Hall angle ( $\theta_H$ ) and is given by

$$\tan \theta_H = \frac{E_H}{E} = \frac{B}{nq\rho} \dots\dots(1)$$

The mobility ( $\mu$ ) of charge carriers can be determined if the charge density ( $n$ ) is known using the relation

$$\sigma = nq\mu \quad \text{also } \sigma = \frac{\mu}{R_H}$$

$$\therefore \text{resistivity, } \rho = \frac{R_H}{\mu}$$

$$\therefore \text{From eqn 1, } \tan \theta_H = \frac{B\sigma}{nq} = B\mu \quad \therefore \mu = \frac{\sigma}{nq}$$

**Uses of Hall effect:**

1. Hall effect is used to find the nature of the charges (Positive or Negative) which in turn determine whether the semiconductor is N-type or P-type.
2. Hall effect is used to find the density of charge carriers.
3. Hall effect is used to find the mobility of charge carriers.
4. Hall effect is used to find Hall voltage, Hall angle & Hall coefficient.
5. Hall effect sensors work on the principle of Hall effect used to detect/sense magnetic fields ranging from  $1\mu T$  to  $1 T$ . (Earth's mag. field  $50\mu T$ )
6. Hall effect device is used as multipliers as Hall voltage is the product of current and magnetic field..

**Fleming's Right Hand Rule:**

It states that if the thumb, fore finger and middle finger of a right hand are stretched out mutually perpendicular to each other, if thumb points in the direction of current, fore finger points in the direction of magnetic field, then middle finger points in the direction of force acting on the charge and hence the motion of the charge.

It is clear that opposite polarity of Hall voltage will be developed for two types of charge carriers for the same directions of current and magnetic field. This is used to find the nature of charges and hence to find the nature of a given semiconductor. (N-type or P-type)

## DIELECTRICS

**DIELECTRICS** are the dielectric/non-conducting materials whose main function is to store electrical charges.

Ex: Glass, Ceramics, Polymers, Paper etc

**Insulators** are the dielectric/non-conducting materials whose main function is to provide electrical insulation.

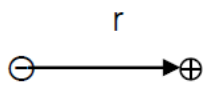
**Dielectric constant/Relative permittivity( $\epsilon_r$ )** is defined as the ratio of the capacitance of a capacitor with dielectric as medium( $C_m$ ) to the capacitance of the same capacitor with air as medium( $C_a$ ). **ie;**  $\epsilon_r = \frac{C_m}{C_a}$ ,  $\epsilon_r$  describes the ability of the dielectric material to store charges.

The permittivity of the medium is given by  $= \epsilon_0 \epsilon_r$ ,  $\epsilon_0 = 8.854 \times 10^{-12} \text{F/m}$ , called permittivity of free space.

Dielectric materials are the insulating materials used to store electrical charges. In Insulators all the states are completely occupied by electrons.

Dielectric materials has very few electrons for electrical conductivity.

Electric dipole is defined as any two equal and opposite charges separated by a small distance.


 Note:  $-Q$  and  $+Q$  charges separated by a small distance 'r' form electric dipole.

The dipole is represented by an arrow which starts from **-ve charge and ends at +ve charge**.

Electric dipole moment is defined as the product of the either of the charge and distance between the charges of the dipole.

Electric dipole moment,  $\mu = Q \cdot r$  .....C m (Coulomb metre)

For a system of charges,  $\mu = \sum_{i=1}^n Q_i \cdot r_i$

Where  $Q_i = \text{charge of } i^{\text{th}} \text{ particle}$  &  $r_i = \text{distance of } i^{\text{th}} \text{ particle from reference charge}$ .

Electric flux density(D) is defined as the electric flux ( $\phi$ ) per unit area of cross section.  $D = \frac{\phi}{A}$

From Gauss law  $D = \frac{Q}{4\pi r^2}$ , where  $Q = \text{charge enclosed in the sphere of radius } r$

Also  $D = \epsilon_0 \epsilon_r E$ ,  $\epsilon = \epsilon_0 \epsilon_r$  and  $D = \epsilon_0 E + P$

Where  $E = \text{Electric field intensity}$ ,  $P = \text{Polarisation}$ ,  $\epsilon_0 =$

**Permittivity of free space,**

$\epsilon_r = \text{dielectric constant/Relative permittivity of the medium}$ ,  $\epsilon =$

**Permittivity of the medium**

Electric field strength( $E$ ) is defined as the force experienced by a unit positive charge at a point in an electric field.  $E = \frac{F}{q}$  .... N/C or V/m

Dielectric polarizability( $\alpha$ ) is defined as the induced dipole moment of an atom per unit electric field intensity.  $\alpha = \frac{\mu}{E} = \frac{P}{NE}$

where  $N = \text{Number of dipoles per unit volume}$ .

**Polarisation(P)** is defined as displacement of the charges in atoms/molecules of the dielectrics under the influence of external electric field resulting in dipole moment.

or

**Polarisation(P)** is defined as the electric dipole moment per unit volume.

$$P = \frac{\text{Electric dipole moment}}{\text{Volume}} = \frac{\mu}{V} \dots \text{C/m}^2$$

$$P = \frac{\alpha E}{V} \therefore \mu = \alpha E$$

$$P = N \alpha E \text{ where } N = \text{Number of dipoles per unit volume.}$$

$$\text{Also } P = \epsilon_0(\epsilon_r - 1)E$$

$$\text{But electric susceptibility, } \chi = \frac{P}{\epsilon_0 E} = (\epsilon_r - 1)$$

$$\text{Dielectric constant/Relative permittivity of medium, } \epsilon_r = \frac{C_m}{C_o}$$

Where  $C_m = \text{capacitance of the capacitor with medium as dielectric}$

$C_o = \text{capacitance of the capacitor with vacuum as dielectric}$

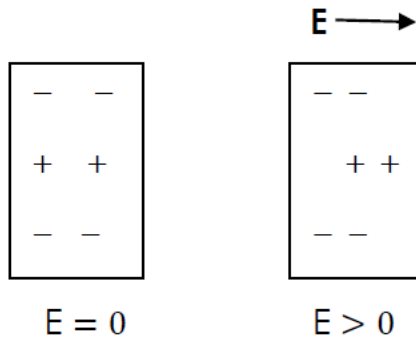
## POLAR DIELECTRICS and NON-POLAR DIELECTRICS

There are two types of dielectrics namely:

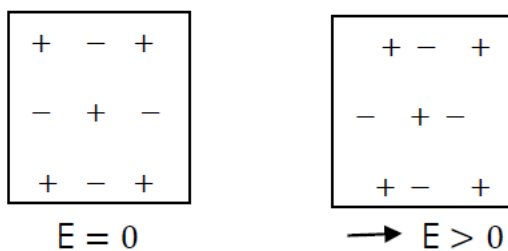
- 1) **Nonpolar dielectrics** are the dielectrics in which the centres of gravity of positive and negative charges of the molecules coincide with each other.  
Ex: Symmetric molecules like (monoatomic)He, Ne, Ar, Xe etc and  $H_2, N_2, Cl_2$  etc
- 2) **Polar dielectrics** are the dielectrics in which the centres of gravity of positive and negative charges of the molecules do not coincide with each other.  
Ex: NaCl, HC

There are four types of dielectric polarization namely,

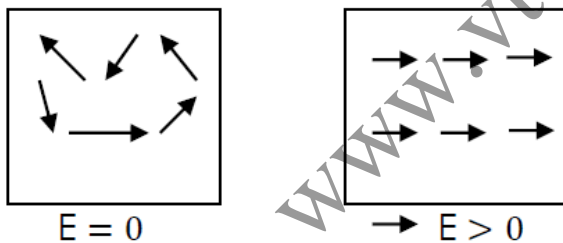
- 1) **Electronic polarization( $P_e = N\alpha_e E$ )** is the polarization in dielectrics due to displacement of the positive and negative charges under the influence of external electric field.



- 2) Ionic polarization** ( $P_i = N\alpha_i E$ ) is the polarization in dielectrics having ionic bonds like NaCl. Under external electric field displacement of ions takes place resulting in polarization.



- 3) Orientation polarization** ( $P_o = N\alpha_o E$ ) is the polarization in dielectrics having molecules of permanent dipole moment. Under external electric field randomly oriented dipoles are aligned along the field resulting in polarization.



- 4) Space charge polarization (migrational or interfacial polarization)  $P_s = 0$  as it is very small.

Total polarization  $P_T = P_e + P_i + P_o + P_s$ , as  $P_s$  is very small and negligible,  

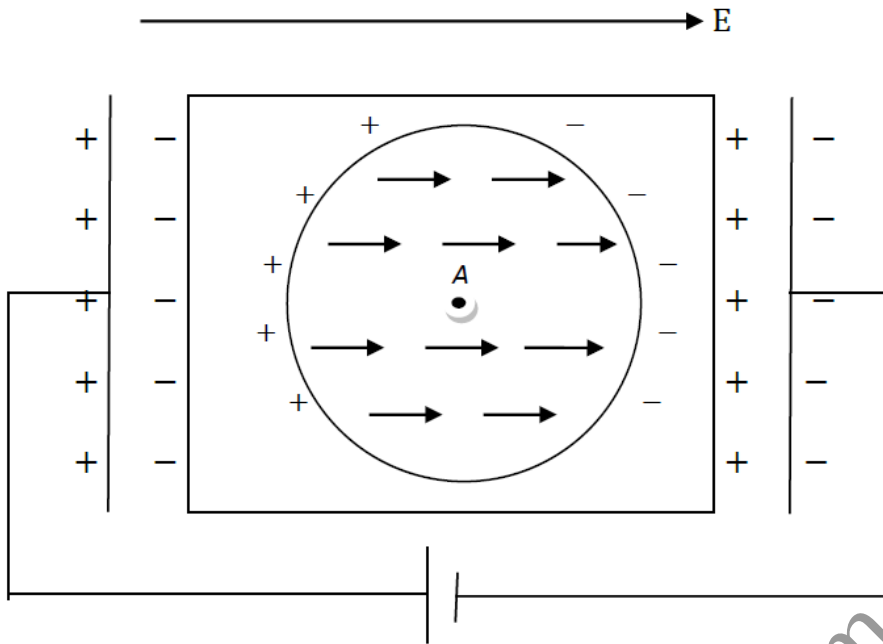
$$P_T = N(\alpha_e + \alpha_i + \alpha_o)E$$

### INTERNAL FIELD/LOCAL FIELD/LORENTZ FIELD

The total electric field at an atom site in a dielectric material due to applied external electric field and induced various fields is called 'internal field'



### Expression for internal field by Lorentz method:



Consider an atom/dipole 'A' at the centre of an imaginary spherical cavity of large radius compared to intermolecular distance in a dielectric placed between the plates of a parallel plate capacitor.

The electric field at 'A' is called the internal field ' $E_i$ ' given by Lorentz

$$E_i = E_1 + E_2 + E_3 + E_4 \quad \dots\dots(1)$$

Where  $E_1 = \text{Field}$  due to charge density on the plates of the capacitor given by

$$E_1 = E + \frac{P}{\epsilon_0} \quad \dots(2) \quad P = \text{Polarisation}, \epsilon_0 = \text{Permittivity of free space}$$

$E_2 = \text{Field}$  due to polarized charges induced on the plane ends of dielectric given by

$$E_2 = -\frac{P}{\epsilon_0} \quad \dots(3)$$

$E_3 = \text{Field}$  due to polarized charges induced on the surface on the spherical cavity given by

$$E_3 = \frac{P}{3\epsilon_0} \quad \dots\dots(4)$$

$E_4 = \text{Field}$  due to all dipoles inside the spherical cavity given by

$$E_4 = 0 \quad \dots\dots(5)$$

From equations 1 to 5, we get

$$E_i = E + \frac{P}{\epsilon_0} - \frac{P}{\epsilon_0} + \frac{P}{3\epsilon_0} + 0$$

$$E_i = E + \frac{P}{3\epsilon_0}$$

### EXPRESSIONS FOR INTERNAL FIELDS IN 1D & 3D DIELECTRICS AND LORENTZ FIELD.

Internal field in 1D dielectric material,  $E_i = E + \frac{1.2 \mu_{ind}}{\pi \epsilon_0 a^3}$



Where  $E$  = applied electric field,  $\mu_{ind}$  = induced dipole moment,  
 $\epsilon_0$  = permittivity of free space and  $a$  = inter atomic distance.

**Internal field in 3D dielectric material**,  $E_i = E + \frac{\gamma P}{\epsilon_0}$

Where polarizability,  $P = \frac{\mu_{ind}}{a^3}$  and Internal field constant  $\gamma = \frac{1.2}{\pi}$

**Lorentz field**,  $E_L = E + \frac{P}{3\epsilon_0}$  where  $\gamma = \frac{1}{3}$  for cubic dielectric

**Note: Internal field for 3D cubic material is called Lorentz field.**

### INTERNAL FIELD(LOCAL FIELD)/LORENTZ FIELD IN SOLIDS

**Internal(Local) field** is the resultant field experienced by a molecule/an atom in a solid due to the external field and the fields produced by dipoles.

Internal field is the sum of the applied field and the induced field.

#### CLAUSIUS-MOSOTTI EQUATION

WKT, If  $P_e, P_i$  &  $P_o$  are the electronic, ionic and orientation polarizations respectively, then total polarization of the dielectric material,  $P = P_e + P_i + P_o$

But for an elemental dielectric material  $P_i$  &  $P_o$  are equal to zero.

$$\therefore P = P_e, \text{ also } P_e = N\alpha_e E_i,$$

where  $\alpha_e$  = electronic polarizability,  $E_i$  = Internal electric field

$$\text{ile; } P = N\alpha_e E_i \text{ but } E_i = (E + \frac{P}{3\epsilon_0})$$

$$\therefore P = N\alpha_e (E + \frac{P}{3\epsilon_0}) \dots (1)$$

$$\text{Also } P = \epsilon_0 (\epsilon_r - 1) E \dots (2)$$

$$\text{From eqns 1 \& 2, we get, } \epsilon_0 (\epsilon_r - 1) E = N\alpha_e (E + \frac{\epsilon_0 (\epsilon_r - 1) E}{3\epsilon_0})$$

$$\text{on simplification } \epsilon_0 (\epsilon_r - 1) = N\alpha_e (1 + \frac{(\epsilon_r - 1)}{3})$$

$$\epsilon_0 (\epsilon_r - 1) = N\alpha_e (\frac{3 + (\epsilon_r - 1)}{3})$$

$$3\epsilon_0 (\epsilon_r - 1) = N\alpha_e (\epsilon_r + 2)$$

Rearranging, we can show that,

$$\frac{(\epsilon_r - 1)}{(\epsilon_r + 2)} = \frac{N\alpha_e}{3\epsilon_0}, \text{ this is the Clausius-Mosotti equation}$$

used to obtain the value of dielectric constant of an elemental dielectric material.

### **DIELECTRIC MATERIALS:**

1. Dielectric materials are mainly used as Insulating materials and to store electrical charges in capacitors.
2. The dielectrics in general must have high resistivity, high/low dielectric constant, low dielectric loss, adequate chemical stability, high moisture resistance and suitable mechanical properties.

Dielectrics may be solids, liquids or gases .

#### **Solid dielectrics:**

1. Solid dielectrics are used as dielectric materials in capacitors for storing electrical charges. Ex:Polymers, ceramics, mica,barium titanate etc
2. **Quartz crystal** is used in ultrasonic transducer, crystal oscillator, filters etc
3. **Lead zirconate titanate** is used in the –preparation of microphone, spark generator, ear phones etc

#### **Liquid dielectrics(LDs):**

1. Liquid dielectrics are used as a cooling medium in transformers and some electronic equipments.
2. Liquid dielectrics are used as filling medium in capacitors, bushings etc
3. LDs are used as an insulating and arc-quenching medium in switchgear.
4. LDs impregnated with solid materials like paper etc are used in transformers, switch gears, capacitors and cables.

#### **Gaseous dielectrics:**

1. Compressed air is used as a dielectric insulation in air blast circuit breaker.
2. Air is used as arc-extinguishing medium.

#### **Application of dielectrics in Transformers**

1. Transformer oil is special mineral oil with high dielectric strength used for insulation and cooling of transformer.
2. It transfer heat by convection from windings and core to cooling surface.
3. It also maintains the insulation of the windings.

Sludge formation takes place in the oil due to moisture, dirt or some foreign matter in the oil which is harmful. Sludge formation reduce the rate of heat transfer ,Ducts are clogged and operating temperature increases. The oil must undergo dehydration periodically and tested at regular intervals.