

# LEARNING MATERIAL OF ELECTRICAL ENGINEERING MATERIALS (EEM) (3<sup>RD</sup> SEM)



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## **MODULE-I**

### **CONDUCTIVITY OF METALS**

#### **INTRODUCTION:**

The most important properties of metals are their high thermal and electrical conductivities. Silver has the highest electrical conductivity. Copper comes next and is similar to silver from the point of view of atomic structure ; both belonging to the same group of periodic table. The conductivity of copper is less than that of silver. Since supplies of copper are not abundant in nature, aluminium which is light and has a high conductivity is rapidly becoming more important as a conductor material. Gold which has a conductivity higher than that of aluminium but lower than that of silver or copper does not find use in electrical industry because it is expensive. Metals having complex structures such as As, Sb, Bi, Sn, Hg have lower conductivities which lie between those of ideal metal (very high conductivity) and of insulators (negligible conductivities).

#### **FACTORS AFFECTING THE RESISTIVITY OF ELECTRICAL MATERIALS**

1. Temperature : The electrical resistance of most metals increases with increase of temperature while those of semiconductors and electrolytes decreases with increase of temperature. Many metals have vanishing resistivity at absolute zero of temperature which is known as superconductivity.
2. Alloying : A solid solution has a less regular structure than a pure metal. Consequently, the electrical conductivity of a solid solution alloy drops off rapidly with increased alloy content. The addition of small amount of impurities leads to considerable increase in resistivity.
3. Cold Work : Mechanical distortion of the crystal structure decrease the conductivity of a metal because the localized strains interfere with electron movement.
4. Age Hardening : It increases the resistivity of an alloy.

#### **MOTION OF AN ELECTRON IN AN ELECTRIC FIELD**

In a conductor, the electrons are moving about with random velocity , the magnitude of which depends upon the temperature. There are two comonents of motion, as follows :

1. Random motion , due to thermal effects.
2. Directed motion , the direction being determined by the polarity of the electric field.

#### **EQUATION OF MOTION OF AN ELECTRON**

When no electric force is applied , the free electrons move about through the conductor in a random manner in such a way that the number of electrons moving from right to left is the same as the number moving from left to right and the resultant current is nil. If an electric force is

applied to the conductor, each electron has superposed on to its random motion, a motion impressed on it by electric force, and the electrons as a whole are driven through the conductor by the continued action of this electric force.

### THE CURRENT CARRIED BY ELECTRONS

In a current carrying conductor, the electrons drift along with an average velocity which is generally small compared with their random velocity due to thermal agitation. Let a current  $I$  be carried along a conductor of cross section  $A$  by electrons of charge  $-e$  and of average drift velocity  $v$ . In time  $dt$  the electrons will travel a distance  $vdt$  and the number of electrons crossing any cross section  $A$  in time  $dt$  will be the number contained in the volume  $Avdt$ . Thus if there are  $N$  electrons per unit volume of the conductor the total charge flowing through the section in time  $dt$  is  $dq = -e.N.A.v.dt$

$$I = dq/dt = -eNAv$$

And current density

$$I/A = -e Nv = +e^2 N E t/m$$

Since,

$$v = -eEt/m$$

The expression for current density shows that the current density does not depend on the size of the conductor. It is a general property of the material. Finally, the current density is proportional to the electric field strength and the constant of proportionality  $e^2 N t/m$  is called conductivity of the material and is denoted by  $\sigma = e^2 N t/m$ .

Ohm's law follows as an immediate consequence of the relation  $J = \sigma E$ ; because

$$I = J.A$$

$$= \sigma E.A$$

$$= (\sigma V/l).A$$

Where  $l$  is the length of conductor and  $V$  is the voltage applied to the conductor ends. Since  $\sigma A/l = R$  where  $R$  is the resistance of the conductor.

### MOBILITY :

It has been noted that the average drift velocity of the electrons in an applied field is proportional to the field, the absolute magnitude of the proportionality factor  $et/m$ , being called the mobility of the electrons which is denoted by  $u$ . The mobility may thus be defined as the magnitude of average drift velocity per unit field.

The mobility and the conductivity are related by the equation  $\sigma = NeU$ .

Thus the mobility of the electrons can be determined by knowing the conductivity of the material and estimating the number of free electrons.

Mobility,  $U = \sigma/Ne = 1/\rho Ne$

$$= 1/(1.73 \times 10^{-8} \times 8.5 \times 10^{28} \times 1.6 \times 10^{-19})$$

$$= 4.25 \times 10^{-3} \text{ m}^2/\text{volts-sec}.$$

The order of magnitude of collision time for copper atoms may be determined from the relation  $t = m/Ne^2\rho$ .

In the absence of an electric field no electric current is observed in the conductor. When an electric field is applied to the conductor the electrons moving in the direction of the electric force

acting on them retarded. Thus the movement of electrons in the direction of the field force predominates over that which proceeds in the opposite direction, the result being an electric current. Taking account of fact that only quantum states of motion are possible for electrons, the acceleration may be conceived as the transfer of an electron into a new quantum state of greater velocity and the deceleration as the transfer of an electron into a state of less velocity. The electric current may thus be treated as the predominance of states that corresponds to the motion of electrons from one end to another over the opposite states.

In actuality, the movement of electrons among the atoms of a solid is far more complex than in vacuum and could be taken account. In a perfectly built crystal the electrons can move in nearly the same way as in vacuum. But crystal irregularity due to impurities and thermal agitation distorts the regular flow of charges and produces a electric field that force the electrons out of their initial path. The electrons move freely only in undistorted section of the crystal. Here they accumulate energy with the increase in speed.

### **ENERGY LEVELS OF THE MOLECULE:**

The energy of an atom changes only by a single means, i.e., a change occurs when one electron passes from one quantum states to another. However, the energy of a molecule is likely to change in either one or all of the following three ways:

1. The energy changes of a molecule may take place like that of an atoms.
2. Since the atoms of a molecule vibrate with respect to one another, the vibrational energy of molecule may also assume discrete values.
3. Furthermore since the molecule rotates as a whole, the rotational energy is also quantised and a change in the state of a molecule may result in a change in rotational energy.

The energy states of a molecule are therefore described by indicating the state of its electronic cloud (electron level) the state of its vibrational motion (vibrational level) and the state of its rotational motion (rotational level).

The difference between the rotational levels are smaller than those between the vibrational levels. Further differences between the vibrational levels are smaller than those between the electronic levels. This corresponds to a type of house numbering system.

Suppose the electronic levels in a molecule are at 100, 200, 300, ... units, the vibrational levels are at 10, 20, 30, ... units and the rotational levels are at 1, 2, 3, ... units. In such case, a molecule in the first electronic level, the second vibrational level and the third rotational level will have a total energy of 123 units.

### **EMISSION OF ELECTRONS FROM METALS**

If an electron acquires excess energy at least to the work function by some mean, it will escape from the metal and will travel to a nearly electrode held at a positive potential with respect to the emitting surface. A continuous flow of such electrons constitutes the thermionic emission of vacuum tubes. Electrons may acquire sufficient energy to escape from the metal in either of the following ways:

- I. By heating of the metal: Thermionic emission

- II. By projecting light of sufficiently small wavelength on the metal: photoelectric emission.
- III. By applying an intense electric field to the metal: Field emission ,and
- IV. By bombarding the metal surface with electrons: secondary emission.

## THERMIONIC EMISSION

Thermionic emission is a process of evaporation which takes place when some of the conduction electrons in the cathode have enough kinetic energy to escape through its surface. The emission therefore, depends upon the distribution of energy among the free electrons in the cathode. This distribution of energy is a function of temperature.

To escape from the metal, an electron must have a component of velocity  $\mu$  at right angles to the surface, and the corresponding kinetic energy,  $\frac{1}{2}m\mu^2$  must be at least equal to the work done in passing through the surface. This is denoted by  $E_e$ , the energy corresponding to the escape level. Since the free electrons in a metal move at random, not all of those whose total kinetic energies exceed the  $E_e$ , will have sufficient energy in the right direction to escape. Only a certain proportion will do so and these will constitute the thermionic emission.

In the figure the number of electrons having kinetic energies equal to or greater than  $E_e$  is the number occupying the energy levels of that value and all higher values. The number is proportional to the area under the corresponding part of the distribution curve, which has been heavily shaded in the figure. Consequently, the thermionic emission from the metal is proportional to the heavily shaded area, i.e., at a given temperature, the number of electrons represented by the shaded area will be able to leave the metal surface. If the 'tail' of the curve does not exceed beyond the value  $E_e$  the thermionic emission will be zero. Once this point has been reached the emission rapidly increases with temperature.

Since even at the absolute zero temperature many electrons in the metal have high energies, up to the value  $E_f$ , the minimum excess energy necessary for thermionic emission is given by  $\phi = E_e - E_f$ . The quantity  $\phi$  is called the work function of the metal. The existence of a work function implies that there are forces which restrain an electron from escaping as it approaches the surface of a metal. The emission current is strongly dependent upon the work function. The larger the values of work function, more difficult it is for the electrons to escape from the metal. In other words, if the difference between Fermi level and the escape level is large, the emission is relatively small. The value of work function can be estimated from measurements of emission current as function of temperature.

The choice of cathode material in vacuum tubes is based on ease of electron emission (or low electron affinity) so that an adequate supply of electrons is obtained with low operating temperatures. The close parallel between thermionic emission and evaporation was recognised by Richardson who showed that the current emitted per unit area of the metal should be given by

$$j = AT^2 e^{-(\phi/KT)}$$

Where  $\phi$  is the work function of the metal, K is the Boltzmann constant and T is the absolute temperature. A is called the thermionic emission constant and should be a universal constant for all metals, equal to  $120 \text{ Amp/cm}^2/\text{deg}^2$ , but its value are found to vary considerably, an effect which is generally attributed to partial reflection of electrons at the surface of the metal. The emission obtained from different faces of a metal is also found to vary and the value of A for polycrystalline materials is quite low.

The number of material available for use as cathodes in thermionic values is greatly limited by the requirement of high electron emission at temperatures where the material does not disintegrate. The temperature at which adequate emission is obtained is determined primarily by the value of the work function  $\phi$ . The common materials used for cathodes are tungsten, thoriated tungsten and a mixture of barium oxide-strontium oxide. In order to obtain a current density of about  $1 \text{ A/cm}^2$  the operating temperatures for these materials are approximately  $2500^\circ$ ,  $1900^\circ$  and  $1100^\circ \text{K}$  respectively. Tungsten is resistant to 'poisoning' by residual gas and gives long life to transmission tubes. Thoriated tungsten is not so resistant to 'poisoning' but has considerable advantage because of lower operating temperature. The barium strontium oxide cathode is also liable to be 'poisoning' by the presence of residual gas. It is therefore necessary to maintain high vacuum in tubes where it is used.

Table 3.1 gives values of the thermionic emission constant, A, work function  $\phi$  and Fermi energy,  $E_f$  for a number of metals, semi conductors oxide coated cathodes.

## PHOTOELECTRIC EMISSION

This involves the interaction of light with electrons showing that light has quantum qualities. In photoelectric emission, a beam of light of frequency,  $\nu$  interacts with the electrons only in discrete quantities of energy,  $h\nu$  where h is planck's constant.

The electrons have to acquire additional energy in order to reach the escape level,  $E_e$ . In other words, emission is possible only if an individual quantum of light has sufficient energy above the escape energy. The necessary condition of emission is  $h\nu \geq e\phi$  where  $\phi$  is expressed in electron volts.

For copper, the work function,  $\phi$  is very high and potassium it is very small. Hence, in the case of potassium, photoelectric emission is possible for relatively low light frequencies. Measurement of the minimum frequency (given by  $h\nu = e\phi$ ) for which photoelectric emission can occur gives a method of estimating the work function. When the frequency is greater than the minimum, the maximum energy which the electrons may possess outside the metal is  $(h\nu - e\phi)$  joules. In practice, a frequency greater than the minimum is usually used, a retarding potential being applied to the collecting anode.

The quantity of energy transferred to an electron in the material is determined only by the frequency of the light vibrations and is independent of the intensity of light ray. As the intensity of light is increased, the number of light absorbing electrons increases, but the energy absorbed by each of the electrons remains unchanged.

Light is capable of transferring electrons to the free state inside a material thus increasing the electrical conductivity of the material. When the energy imparted to the electrons is quite large, the later may be emitted from the material into the surrounding medium. This phenomenon is known as the photoemissive effect, or photoemissivity, whereas the increased electrical conductivity produced by light is called the photoconductive effect, or photoconductivity.

The study of photoelectric phenomena provides us with information about the properties of electrons in materials such as the amount of energy required to transfer an electron into the free state.

A part from photoconductive and photoemissivity cells, a third type-the photovoltaic or barrier layer cell exists. In the photovoltaic cell, light establishes an emf between two substances such as a layer of cuprous oxide on copper or of selenium or iron. Photovoltaic cells are widely used in illumination and exposure meters.

Photoemissive cells or photo-tubes are two-elements tubes whose cathodes emit electrons when exposed to light. The anode current resulting from a given amount of incident light is a function of the wavelength of light, which gives rise to a number of useful application. These include door openers, counters, position and temperature control and colour analysis.

The materials most commonly used for photoconductive cells in the visible part of the spectrum are selenium, cadmium sulphide and thallic sulphide and those for infrared rays are lead sulphide, lead selenide and lead telluride. Such cells are widely used in automation and for remote control industrial processes.

## **FIELD EMISSION**

Field emission and cold emission occurs when the direction of the applied electric field is such that it attracts electrons out of the metal. The potential energy at the surface of the metal is  $(\phi + E_F)$ . This is the energy required for the extraction of the electron from the metal.

When the external field is large, the energy required to extract the the electrons from the metal is small, which shows the variation of potential energy with distance.

## EFFECT OF TEMPERATURE ON THE ELECTRICAL CONDUCTIVITY OF METALS

As the temperature is increased there is a greater thermal motion of the atoms which decreases the regularity in the atom spacings with a consequent decrease in the mobility of the electrons. The resistivity of most metals therefore increases with an increase in the temperature.

The electrical conductivity of a metal on the basis of the free electron model is given by  $\sigma = N \left( \frac{e^2}{m} \right) \tau = \frac{N e^2}{m c} \lambda$ , where  $\lambda$  is the mean free path and equals  $c \tau$  where  $c$  is the mean velocity of the electrons. The value of  $c$  corresponds to the Fermi energy  $E_F$  because only those electrons which are at top of the Fermi distribution curve can be accelerated and can gain energy. This velocity is of the order of  $10^8$  cm/sec for most metals and since  $\tau = 10^{-14}$  sec at room temperature, the mean free path is of the order of  $10^{-6}$  cm, or about 100 times the atomic spacing in solids. Since the number and the energy of the electrons at the top of the Fermi distribution curve vary insignificantly with temperature, the change in temperature must be associated with a change in the mean free path. Ideally the mean free path of an electron in a perfectly regular lattice, each electron will exist in a particular energy state and thus will have a fixed velocity indefinitely. Practical metals do not have a perfect lattice because of impurities and because of the deviation of atoms about their mean position due to lattice oscillations (Debye waves). Thus the mean free path for an imperfect lattice is finite. This accounts for the lower conductivities of alloys which have a disordered lattice.

The lattice imperfections due to impurities and atomic oscillations cause scattering of the electron waves which is analogous to the scattering of light waves in an imperfect crystal. The scattering is independent of temperature giving rise to the constant resistance which is characteristic of alloy materials. Since the lattice oscillations decrease at low temperature the scattering of electron waves falls and the conductivity therefore increases rapidly as the temperature approaches absolute zero. There is a limiting value beyond which the conductivity will not increase, the limit being determined by the previous history of the metal. In general, the purer the specimen, the higher is the limiting conductivity.

The conductivity of many metals decreases linearly as the temperature is increased above the room temperature but below this temperature the conductivity increases markedly and with a higher power of the absolute temperature ( $T^5$ ).

## ELECTRICAL CONDUCTING MATERIALS

**COPPER:** Pure annealed copper is used for the winding of electrical machines. High purity copper is obtained by electrolytic refining. Traces (0.1%) of iron, silicon or phosphorous seriously reduce the conductivity of copper. The conductivity of copper is also decreased when it is hard drawn into wires for use in machines. Annealing is therefore necessary before the material can be used in machines.



Hard drawn copper because of its increased mechanical strength compared with annealed copper is used for conductors in low voltage overhead distribution lines. Long span lines of thin cross section require conductors of higher mechanical strength. This is achieved by adding a small percentage of cadmium to copper. Cadmium increases the mechanical strength of copper without affecting its conductivity adversely. The usual addition of cadmium are between 0.8% and 1%.

Copper conductors having a steel core are also employed for long span transmission lines, where a combination of high conductivity, small sag and minimum cross section are desired. In such conductors, an insulating tape over the wire has to be provided in order to prevent the corrosive action of steel on copper.

For ordinary insulated stranded cables V.I.R insulation is almost universally employed. In such cables the conductor strands are tinned in order to protect the copper from the sulphur of the V.I.R. The tinning process assists in soldering and operations.

Copper is employed in machine windings because it is easily workable without any likelihood of fracture. Further, it can be soldered easily thus simplifying the jointing operation.

**ALUMINIUM:** Aluminium conductors are particularly suitable for operations in very high ambient temperatures. Use of aluminium as an electrical material particularly in the aircraft industry has considerable advantages because of the saving in weight involved. Again electrochemical plants are enormous user of aluminium bush bars. This is because electrolytic cells operate with heavy current with low voltages and to carry these currents massive bars are required. Aluminium because of its lightness is being used more and more for such bush bars. The current carrying capacity of aluminium being 75% that of copper and its density being approximately one-third that of copper an aluminium bush bar is only half the weight of copper bush bar of equal current carrying capacity. Since aluminium costs a little less than copper, an aluminium bush bar will cost only about half as much as its copper counterpart.

The steel reinforced aluminium conductor (A.C.S.R.) is extensively being used for long span transmission lines.

In the commercial form aluminium is obtainable with a purity of about 99% but it is generally alloyed with small quantities of copper, zinc, nickel or magnesium to improve its hardness and strength.

Aluminium is not easily solderable but fluxes have been devised to make soldering easy. Mechanical clamping and screwing methods have also been developed.

**TUNGSTEN:** Tungsten has the highest melting point among metals. It is therefore suitable for applications requiring high operating conditions, such as lamp and valves filaments. The resistivity of tungsten is  $5 \mu\Omega\text{-cm}$  which is twice as poor as that of aluminium. However the great hardness and the high boiling point and melting points of tungsten coupled with its

resistance to abrasion. Establish this metal as an outstanding material for electrical contacts in certain applications. It is extremely resistant to the destructive forces of arcing. Typical operating conditions for tungsten contacts are:

Voltage a.c. or d.c. upto 230V

Current                      upto 15A

Typical applications of tungsten contacts are in battery ignition systems, vibrators are electric razors.

**CARBON AND GRAPHITE:** The severity of sparking and the rate of commutator wear in electrical machines is greatly reduced by using brushes made of carbon. Carbon is also used in automatic voltage regulators for making the pressure sensitive pile resistors. Among other uses of carbon are for making arc welding electrodes, fixed and variable resistors for light currents and contacts of certain classes of d.c. switchgear which are subjected to arcing. The action of carbon in a microphone is that of providing a material, the resistance of which decreases when it is compressed. The resistance temperature coefficient of carbon is negative.

**IRON AND STEEL:** Steel is employed as conductor rail in traction on account of its cheapness and rigidity. Galvanised steel and iron wires which are generally used for earth conductor in low voltage distribution system may also be used for the phase conductors in rural areas where cheapness is the main consideration. Such lines will however have large voltage drops because of the high resistance and inductance. Addition of manganese has a hardening effect on steel and manganese steel (about 13% manganese) has the further property of being practically non magnetic. Steel alloyed with chromium and aluminium is used for making starter rheostats where lightness combined with robustness and good heat dissipation are important considerations.

Cast iron is used in the manufacturing of “resistance grids” to be used in the starting of the large dc motors.

**NICKEL:** The material is used extensively for making the electrodes of thermionic valves, and sparking plugs. It is also, used to form the positive plate of the NiFe accumulator which has distinct advantages over the ordinary lead acid accumulator.

**LEAD:** Lead has two important electrical applications. It is used to form (a) cable sheaths and (b) the plates of lead acid accumulator. Lead sheaths are required to protect the insulation of the cable from effects of moisture.

**TIN:** The important electrical use of tin is in the manufacture of low current fuses.

**ALLOYS:** Alloy materials are used for making resistors for laboratory instruments and for laboratory standards where a high constancy of resistance is desirable. They are also used for making heater and thermo-couple elements. The important alloys are:

- a. Constantan or Eureka[(55-60%) Cu, (45-40%) Ni]
- b. German silver (an alloy of Cu,Zn and Ni)
- c. Manganin (86% Cu, 2% Ni , 12% Mn)
- d. Nichrome (60% Ni, 15% Cr, 24% Fe)

### **ELECTRICAL CONTACT MATERIALS:**

Several elements, in their relatively pure form such as copper, molybdenum , nickel, palladium, silver and tungsten are acceptable make and break contact materials. Alloys and heterogeneous mixtures which are, in general, combinations of the elements mentioned above are also used in electrical contacts. Silver is an important contact material. Copper added to silver reduces the cost of the contact material, whereas a combination of tungsten and silver results in a contact material having the advantages of the individual metal. A silver tungsten contact material will have high thermal and electrical conductivity, low contact resistance and high resistance to oxidation due to the presence of silver and a high melting point and high resistance to electrical erosion due to the presence of tungsten.

The principal deficiencies of copper as a contact material are its poor resistance to oxidation and the relative ease with which it forms other chemical compounds (e.g.,sulphides) that interface with its performance. If however, the frequency of operation is not too low, and if there is some wiping action between the contacts, copper contacts may be used at currents (a.c. or d.c.) of up to about 500A and voltages (a.c. or d.c.) of up to about 600 volts. Typical applications of copper contacts are in control relays, motor starter switches and tap changers.

Contacts made of silver and silver alloys are possibly the most widely used in electrical industry. Silver is far superior to copper in its resistance to oxidation and it exhibits low contact resistance. Silver and silver alloy contacts may be used for voltage(a.c. or d.c.) upto 600 volts and direct currents upto 50A and alternating currents upto 200A. Such contacts are used in all types of industrial, relays, generator cut outs, thermal overload devices and thermostatic control.

### **NON-LINEAR CONDUCTORS:**

Certain conducting materials do not obey Ohm's law and the resistance of such materials may vary with the applied voltage. Such material are said to possess non linear resistance. There are other classes of materials in which the resistance varies not only with the applied voltage but also with the polarity of the applied voltage. Such materials are said to possess rectifying properties.

## THERMAL CONDUCTIVITY OF METALS :

It is observed that metals which are good conductors of electricity are also good conductors of heat.

When a homogenous isotropic materials is subjected to a temperature gradient, a flow of heat results in a direction opposite to the gradient. Thus if  $dT/dx$  represents the temperature gradient, the quantity of heat flowing per second is found from the expression.

$$Q = K.A \, dT/dx$$

If  $Q$  is expressed in watts,  $dT/dx$  in K per metre and the area of cross section  $A$  in sq.metres, then the coefficient of thermal conductivity,  $K$  is given in watts/metre x K.

In insulating solids, the heat is carried by the lattice vibrations. This in part is also the case in metals, but the thermal conductivity due to the conduction electrons predominates in both insulators and conductors.

The electrons in the hot end has a higher thermal energy. They move to the cold end where the excess energy is released to the atoms whereby the thermal agitation of the atoms and the temperature increase. The electrons of the cold end have less kinetic energy; so in passing to the hot end they decrease the thermal agitation and the temperature. Since the same electrons also conduct electric current, the transfer of heat and the conduction of current must be closely related processes.

Finally, the total energy transferred across a cross-section is dependent upon

1.  $N$ , the number of electrons/ $m^3$
2.  $V$ , the average velocity of the electrons
3.  $dW/dx$ , the energy gradient
4.  $\lambda$ , the mean free path
5.  $A$ , the area of cross-section or  $Q \propto NV.dW/dx \times A \times \lambda$ .

$$Q = \text{constant} \times N.V. \times dW/dx.\lambda A$$

Further, since energy is a function of temperature which in turn is a function of position.

$$Q = \text{constant} \times N.V.\lambda \, dW/dT.dT/dx .A$$

$$K = \text{constant} \times NV\lambda dW/dT .$$

$dW/dT$  is the rate at which the average energy of an electron increases with temperature. It is called the specific heat of an electron in the metal.

## THERMO ELECTRIC EFFECT :

The basis of the study of thermo electric effects arises from the fact that electron motion is altered by the flow of current or by the application of temperature gradient.

1. Thomson Effect:

If a piece of metal is made to have a temperature gradient between its two ends, an emf is observed to exist between those ends. This effect is known as Thomson effect, arise since electrons at the hot end tend to move to the cold end. A space charge is established in the metal producing an electric field the direction of which is from the hot end tend to move

to the cold end. This electric field tends to drive the electrons from the cold end to hot end. When equilibrium is reached the two effects are cancelled. Under these conditions the electric field is proportional to the temperature gradient. The temperature gradient is negative, because as the distance from the hot end increases, the temperature decreases. Thus the electric field is in opposition to the temperature gradient.

$$E = -\sigma \frac{dT}{dx}$$

Where  $\frac{dT}{dx}$  is the temperature gradient, and  $\sigma$  is the Thomson coefficient which is expressed in units of volts/°C.

## 2. Seebeck Effect :

The thermocouple was discovered by Seebeck in 1822 when he demonstrated that a loop composed of two dissimilar metals could be made to carry a continuous current simply by maintaining the two junctions at different temperatures. The magnitude of the current depends on the resistance of the metals. When the two metals are placed in contact, then a contact potential equal to the difference in work function of the two metals is established at the junction. The work function is defined as the difference between the escape level and the Fermi level. The Fermi level is subjected to a small temperature change of order of  $10^{-5}$  -  $10^{-4}$  eV/K. This causes a difference in the contact potentials at the two junctions due to the different temperatures at the two ends and the result is an emf which is free to drive the current.

## 3. Peltier Effect :

In 1834, Peltier discovered the converse effect and showed that when a current is passed through the junction of two different metals, heat is absorbed or liberated depending on the direction of the current. Thus if the Seebeck emf is from metal A to metal B at the hot junction, an external emf applied in this direction will produce a cooling effect at this junction. The heat is referred to as "Peltier heat" and it is equal to the work done in transferring a charge  $q$  from metal A to metal B or  $\pi_{A-B}$  joules, where  $\pi$  is the Peltier coefficient.

## CHAPTER - II

### INTRODUCTION

Insulators or dielectrics as distinct from conductors have no free electrons. Hence when a source of e.m.f is connected across a dielectric no current flows. However, since no dielectric is perfect it contains a small number of free electrons and a very small current flows through it when an electric field is applied. Capacitors therefore have a small leakage conductance.

### EFFECT OF A DIELECTRIC ON THE BEHAVIOUR OF A CAPACITOR

Suppose that two large plane parallel plates separated by a distance  $d$  (meters) in vacuum are maintained at a potential difference  $V$ . The plates will become charged positively and negatively with charges  $= Q_0$  and a uniform electric field intensity  $E = V/d$  (volts/m) will be created between the plates. The magnitude of the charge accumulated on each plate is proportional to the applied potential difference, i.e.  $Q_0 \propto V$  or  $Q_0 = C_0 V$ , where  $C_0$  is defined as the capacitance.

By applying Gauss theorem, the magnitude of flux density  $D$  within the plates is given by

Since the electric field strength  $E$  is related to the flux density by the relation  $D = \epsilon_0 E$ , the field strength in the region between the plates is given by  $E = D/\epsilon_0 = Q_0/A\epsilon_0$ . Since  $V = Ed$ , the capacitance of the system is given by  $C_0 = \epsilon_0 A/d$  where  $\epsilon_0$  is termed as the absolute permittivity of free space.

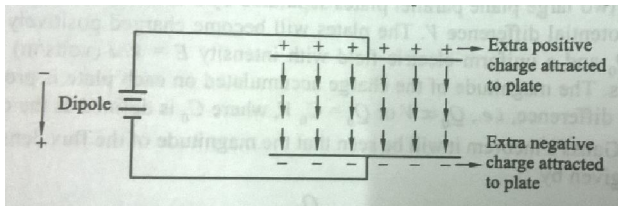
If the space between the plates is now filled with a dielectric and  $V$  is kept constant, it is found that the value of the charge is increased to  $Q = CV$ .

It follows that the new capacitance is given by  $C = \epsilon A/d$  where  $\epsilon$  is defined as the absolute permittivity of the dielectric and the ratio  $\epsilon_r = C/C_0 = \epsilon/\epsilon_0$  is called the relative permittivity, specific inductive capacity or the dielectric constant of the material. The dielectric constant of a medium is constant if the state of the medium doesn't vary from point to point. At the boundary between two media the dielectric constant changes abruptly, and bodies that are non-homogeneous with respect to density and other properties are usually non-homogeneous with respect to the dielectric constant.

### POLARISATION

A dielectric consists of molecules the atomic nuclei of which are effectively fixed, relative to each other. In absence of any external field the electrons are distributed symmetrically round the nucleus at any instant. When an electric field is applied the electrons of the atoms are acted upon by this field. This causes a movement of the electrons which are displaced in a direction opposite to that of the field. The resultant effect is to separate the positive and negative charges in each molecule so that they behave like electric dipoles. The strength of each dipole is given by the dipole moment which in its simplest form consists of two point charges of opposite sign  $\pm Q$  separated by a distance  $d$ . The dipole moment has magnitude  $Qd$  and is represented by a vector pointing from the negative charge in the direction of the positive charge. The dipole moments are expressed in terms of the Debye unit.

When the dipoles are created the dielectric is said to be polarized or in state of polarization. When the field is removed and the atoms return to their normal or unpolarised state, the dipole disappear. The polarized dielectric consists of a layer of dipole as shown in fig below



There is an induced negative charge on the surface of the dielectric near the positive plate and a similar induced positive charge on the surface near negative plate. There is no resultant charge density at any point within the dielectric because all individual dipole are aligned parallel to the field, each negative charge of the one dipole being next to the positive charge of the next dipole.

Consider the dielectric to be composed of a large number of elementary cylinder each of length  $l$  in the direction of the applied field and of cross section  $\delta A$ . Let a uniform field of strength  $E$  be applied normal to the plates. This polarizes the dielectric inducing dipoles in each elementary cylinder and charges  $\delta q$  appear on either end of the cylinder. The charge density,  $\sigma$  on the surface  $\delta A$  of the cylinder given by

$$\begin{aligned}\sigma &= \delta q / \delta A \\ &= l \cdot \delta q / l \cdot \delta A \\ &= m / \delta V\end{aligned}$$

Where  $m$  is the dipole moment and  $\delta V$  is the volume of the elementary cylinder. If the number of dipoles per unit volume be  $N$  i.e., if  $N = l / \Delta v$ ; then  $\sigma = Nm$ . The product  $Nm$  is called the polarization ( $P$ ) of the dielectric and is the total dipole moment established within unit volume of the insulating medium. Thus a dielectric subjected to a homogenous field carries a dipole moment  $P$  per unit volume which may be written as  $P = Nm$

The charge density  $\sigma$  is a scalar quantity but the polarization  $P$  is a vector quantity because it involves direction. For any dielectric,  $\sigma$  is equal to the normal component of the polarization. For an isotropic dielectric, the direction of polarization is perpendicular to the plates. Hence we may write  $\sigma = P_n$ , where  $P_n$  is the component of polarization perpendicular to the plates.

The electric polarization of a dielectric maybe conceived as a forced state of the medium caused by the action of an electromotive force and which disappear when that force is removed. In other words, it is a displacement of charge produced by an electromotive intensity. When emf acts on a conducting medium it produces a current through it, but if the medium is a non-conductor or dielectric, the current cannot continues so flow through the medium but electric charge would be displaced within the medium in the direction of the electromotive intensity.

If  $\sigma_0$  represent the charge density on the plates of a condenser containing no dielectric and if  $\sigma_1$  represent the charge density on the plates of the condenser filled with a homogenous dielectric then

$$\sigma_0 = Q_0/A = C_0 V/d = \epsilon_0 V/d = \epsilon_0 E_n$$

Where  $E_n$  is the normal component of the electric field strength,

$$\text{Similarly } \sigma_1 = Q/A = C V/d = \epsilon V/d = \epsilon E_n$$

i.e there is an increase in charge density. The increase may be observed experimentally. On removal of the dielectric, this additional charge return to the source. The additional attraction of charge to the condenser plates is explained by assuming that charges of opposite sign having a density  $\epsilon_0 E_n (\epsilon_n - 1)$  are formed on the surface of the dielectric next to the condenser plates,

Thus we may write,

$$\sigma_1 > \sigma_0$$

Where  $\sigma_{pol}$  is the charge density due to polarization or  $\epsilon E_n = \epsilon_0 E_n + P_n$  Where  $P_n = \epsilon_0 E (\epsilon_r - 1)$ .

The above expression may be written in the generalized form as,

$$\epsilon E = \epsilon_0 E + P$$

$$P = (\epsilon - \epsilon_0) E$$

$$= \epsilon_0 E (\epsilon_r - 1)$$

Or  $P \propto E$ , stating that the polarization  $P$  of a substance is proportional in magnitude to the applied field  $E$ , at all ordinary field strength, provided that the dielectric constant  $\epsilon_r$  is independent of the applied field which it is for normal dielectrics below the breakdown field. The magnitude of polarization is expressed in coulombs/m<sup>2</sup>.

Since polarization  $P$  is proportional to the dipole moment  $m$ , the latter must be proportional to the electric field strength or  $m = \alpha E$ .  $\alpha$  is proportionality constant and is called the polarizability of the elementary dipole volume.

In deriving  $P = \epsilon_0 E (\epsilon_r - 1)$  the physical state of the dielectric was not considered.

Consider a gas containing  $N$  atoms/m<sup>3</sup> subjected to a homogenous field  $E$ , Neglecting any interaction between the dipoles induced in the atoms, which is an odd approximation for a gas, we find for the polarization of a gas,

$$P = Nm = N\alpha E$$

Comparing this expression with the macroscopic expression for  $P$ , We have

$$\epsilon_r = 1 + N\alpha/\epsilon_0$$

When two plates in vacuum are charged initially to potential  $V$ , a uniform field is created between them and the intensity of the field is given by  $V/d$ . When a slab of permittivity  $\epsilon$  is interposed between the plates, the capacity of the system is reduced by the factor  $\epsilon$ . But since the potential difference between the plates is maintained by the battery, the charge on the plates should increase by a factor  $\epsilon$ . Hence the charge per unit area is given by

$$D_n = \epsilon E_0$$



In accordance with the ideas of displacement a further quantity of charge is displaced per unit area between the plates. The additional charge displaced per unit area at any point is represented by the normal component of the polarization vector  $P$ .

Hence,

$$D_n = \epsilon_0 E_n + P_n$$

In general, the total displacement  $D$  at any point is now given by

$$D = D_0 + P$$

Or

$$D = \epsilon_0 E + p$$

The above equation is valid for even anisotropic media where the polarization vector is not necessarily parallel to the electric field vector.

Since

$$P = N\alpha E$$

$$\begin{aligned} D &= E (\epsilon_0 + N\alpha) \\ &= [\epsilon_0 + (\epsilon_r - 1) \epsilon_0] \end{aligned}$$

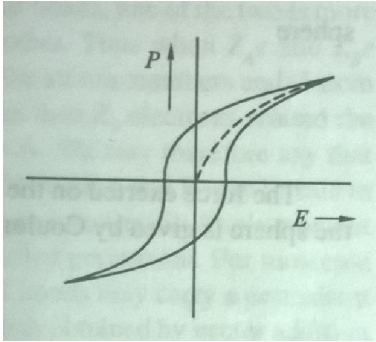
$$\epsilon_r = 1 + (N/\epsilon_0)$$

$$D = \epsilon_0 \epsilon_r E$$

The above equation is valid only for isotropic material where the permittivity  $\epsilon_r$ , remains constant in all directions. In crystals  $\epsilon_r$ , generally depends on the direction along which it is measured relatively to the crystal axes. In polycrystalline materials, on the other hand, with a random distribution of grains, the directional effects disappear.

The essence of all electrostatic problems in the presence of dielectric materials is the determination of polarization  $P$ . All dielectric application depends upon the ability to vary  $P$  in some manner.  $P$  may be varied by changing the electric field, temperature, or mechanical strain. In most problems, it is required to find out the manner in which  $P$  varies with the electric field  $E$ . In an anisotropic material, the relationship between  $P$  and  $E$  may be very complex because the resultant polarization in a given direction may be a function of electric fields in all three mutually perpendicular directions. The simplest case is the three  $P$  is directly proportional to  $E$  i.e.  $P = K\epsilon_0 E$ .  $K$  is a dimensionless scalar quantity and is defined as the dielectric susceptibility of the medium. Under these conditions,  $\epsilon_r = 1 + K$ .

In case of isotropic materials, the relation between  $P$  and  $E$  may exhibit hysteresis in which case  $D \neq \epsilon_0 \epsilon_r E$ . Such materials are non-linear and are called ferroelectric materials. The figure below shows the polarization curve for such a material.



Here it is possible to define a number of dielectric constants. The initial dielectric constant may be defined as the slope of the normal polarization curve at  $E = 0$ . The incremental dielectric constant is defined as the limit of

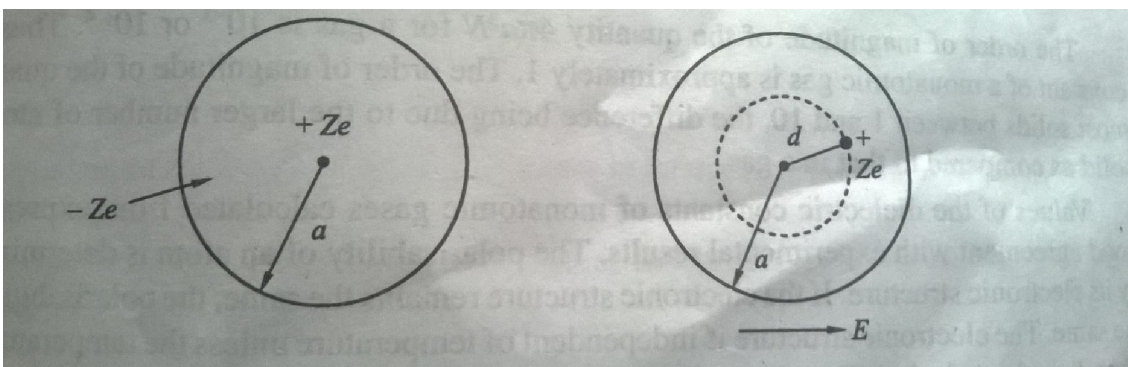
$$\frac{\Delta P}{\Delta E} \text{ as } \Delta E \rightarrow 0.$$

In ferroelectric materials the electric flux lags behind the electric force producing it such that under varying electric forces a dissipation of energy occurs. The energy is dissipated as heat. The energy loss due to this case is called the dielectric hysteresis loss.

The dissipation of energy may be explained by assuming a continual charge in the orbital paths of the electron in the atomic structure due to a varying or alternating electric stress in the dielectric. Dielectric hysteresis, however, cannot be measured as a separate quantity and in practice the total dielectric losses (including losses due to a small conduction current) are usually measured by means of an a.c bridge.

## THE DIELECTRIC CONSTANT OF MONOATOMIC GASES

In a gas the average distance between the atoms or molecules is large enough so that one neglect interaction between them and the individual atom can be studied independently. Consider a single atom consisting of a positive nucleus of charge  $Ze$  with  $Z$  electrons moving around the nucleus. Let us assume that the total negative charge  $-Ze$  is distributed homogeneously throughout a sphere of radius “a”.



When this atomic model is placed in a field  $E$  as shown in figure above, there is no translational force on the atoms as a whole, since it is electrically neutral. But the nucleus and the electron cloud will evidently try to move in opposite direction because of opposite signs of their charges. However as they are pulled apart, a force will develop between them tending to bring the nucleus back to the centre of the sphere. Consequently, an equilibrium condition will be obtained in which the nucleus is displaced relative to the centre of the electron cloud in the direction of  $E$ . the displacement of nucleus may be calculated as follows: assume that the nucleus is shifted by an amount “ $d$ ” as shown in the figure. The force on the nucleus in the direction of the field equals  $ZeE$ . The electron cloud can be divided into two regions- one inside an imaginary sphere of radius “ $d$ ” and other between the two spherical surfaces of radii “ $d$ ” and “ $a$ ”. From Gauss’s theorem the charge in the latter region does not exert any force on the nucleus. The only force exerted on the nucleus is the one produced by the negative charge which is distributed inside the smaller sphere of radius “ $d$ ”. The charge inside this sphere is equals to

$$= -Ze \times \frac{\text{Volume of sphere with radius } d}{\text{Volume of sphere with radius } a}$$

The force exerted on the nucleus by this charge assuming it to be concentrated in the centre of the sphere is given by Coulomb’s law. In equilibrium condition, one obtains

$$ZeE = \frac{1}{4\pi\epsilon_0} \frac{(Ze)(Zed^3/a^3)}{d^2}$$

Hence, the displacement of the nucleus relative to the centre of the sphere is given by

$$d = 4\pi \frac{\epsilon_0 a^3}{Ze} \cdot E$$

This shows that the displacement is proportional to the field strength- a situation akin to the one is in which a mechanical force is exerted on a particle bound with an elastic force to a certain equilibrium position.

On the application of an electric field the atom still remains neutral but has a non-zero dipole moment due to displacement of nucleus relative to the centre of the electron cloud. The magnitude of the dipole moment is given by

$$m = Ze \cdot d = 4\pi \epsilon_0 a^3 E$$

This expression shows that the dipole moment is proportional to the volume of the electron cloud. The polarizability  $\alpha$  is thus equation to  $4\pi \epsilon_0 a^3$ .

Finally using the equation the dielectric constant of a monoatomic gas may be expressed as

$$\epsilon_r = 1 + 4\pi \alpha^3 N$$

The order of magnitude of the quantity  $4\pi a^3 N$  for a gas is  $10^{-3}$  or  $10^{-4}$ . Thus the dielectric constant of a monoatomic gas is approximately 1. The order of magnitude of the quantity  $4\pi a^3 N$  for most of the solids lies between 1 and 10, the difference being due to large number of atoms per  $m^3$  in a solid as compared to that in a gas.

Values of the dielectric constants of monoatomic gases calculated from the expressions are in good agreement with the experimental results. The polarizability of an atom is determined completely by its electronic structure. If the electronic structure remains the same, the polarizability also remains the same. The electronic structure is independent of the temperature unless the temperature is very high. Hence if the number of atoms per unit volume is constant, the dielectric constant of monoatomic gases is independent of temperature for normal operating temperatures.

### FREQUENCY DEPENDENCE OF PERMITTIVITY

$$\epsilon_r^* = \epsilon_s' - j\epsilon_r''$$

Where  $\epsilon_s'$  and  $\epsilon_r''$  are the real and imaginary parts of the permittivity.

$$\epsilon_r' = 1 + \frac{Ne^2}{m\epsilon_0} \left( \frac{(\omega_0^2 - \omega^2)}{(\omega_0^2 - \omega^2)^2 + \frac{4B^2\omega^2}{m^2}} \right)$$

$$\epsilon_r'' = -\frac{Ne^2}{m\epsilon_0} \left( \frac{2B\omega/m}{(\omega_0^2 - \omega^2)^2 + \frac{4B^2\omega^2}{m^2}} \right)$$

For  $\omega=0$ , the imaginary part  $\epsilon_r''$  vanishes, the real part  $\epsilon_r'$  being then equal to static value  $1 + (Na_s/\epsilon_0)$ . The real part is positive for all value of  $\omega$  less than  $\omega_0$  and negative for all values of  $\omega$  greater than  $\omega_0$ . The reason for complex value in general of  $\epsilon_r$  is that polarizability  $\alpha$  is a complex quantity. It is complex because the induced dipole moment  $\alpha E$  and therefore the polarisation is no longer in phase with the applied field,  $E$ .

### FREQUENCY DEPENDENCE OF IONIC POLARISABILITY

The difference between the frequency dependence of ionic polarizability and that of electronic polarizability is of qualitative nature only. Since the masses of the particles involved in ionic polarization are those of atoms rather than those of electrons, the natural frequencies of ionic vibration lies in the infra-red part of the electromagnetic spectrum corresponding to  $\omega_0=10^{14}$  rad/sec. Hence even for the rapidly varying fields encountered in microwaves, the ionic polarizability may be considered as instantaneous and frequency independent.

Thus the complex dielectric constant of a non-dipolar, solid or liquid, considering both electronic and ionic polarisation and applying the Lorentz correction for the internal field will be given by

$$\frac{\epsilon_r^* - 1}{\epsilon_r^* + 2} = \frac{1}{3\epsilon_0} N(\alpha_e^* + \alpha_i^*)$$

Where  $\alpha_e^*$  and  $\alpha_i$  are real and therefore the dielectric constant of non-dipolar solids or liquids is real and the behaviour of such materials is same as in static fields. However, such materials may contain ions, which may be displaced over one or more interatomic distances under the influence of an external electric field (cf.glass). This would lead to an imaginary part of the dielectric constant and hence to dielectric losses.

## DIELECTRIC LOSSES

Consider a parallel plate condenser filled with dielectric material characterised by  $\epsilon_r^*$ . Let the electrode area be 'A' and the plate separation be 'd'. The admittance  $\bar{Y}$  of the capacitor for any angular frequency  $\omega$  is given by  $\bar{Y}=G+jB$  where G and B are the conductance and susceptance respectively.

$$\bar{Y} = G + j\omega C$$

Where C is the capacitance which may depend on frequency, because  $C=\epsilon_r^* A/d$ . The conductance G equals  $\sigma A/d$ , where  $\sigma$  is an effective conductivity at the angular frequency  $\omega$ . The conductance G arises because of the conversion of part of the electrical energy into heat, but mainly because of the complex dielectric constant.

$$\begin{aligned}\bar{Y} &= \frac{A}{d}(\sigma + j\omega \epsilon_r^*) \\ &= \frac{A}{d} j\omega \epsilon_r^* \text{ (say)}\end{aligned}$$

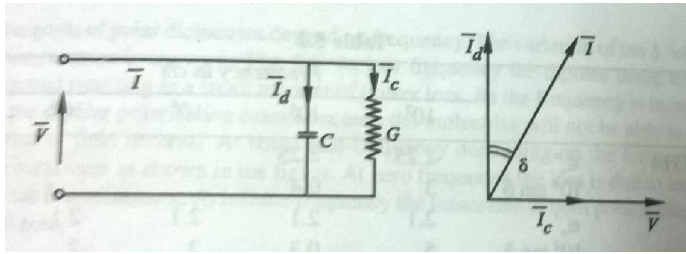
Where  $\epsilon_r^*$  is the complex permittivity such that

$$\begin{aligned}j\omega \epsilon_r^* &= \sigma + j\omega \epsilon_r' \\ \epsilon_r^* &= \epsilon_r' - j\sigma/\omega = \epsilon_r' - j\epsilon_r'' \\ &= |\epsilon_r^*|/\delta \\ \epsilon_r^* &= \frac{\sigma}{\omega}\end{aligned}$$

Thus the absorption of energy by the material in an alternating field is proportional to the imaginary part of the dielectric constant. The dielectric is said to have losses which are characterised by the loss tangent.

$$\tan \delta = \frac{\epsilon_r''}{\epsilon_r'} = \frac{\sigma}{\omega \epsilon_r'} = \frac{G}{B} = \frac{G}{\omega C} = \frac{1}{\omega CR}$$

We may thus represent a condenser containing a lossy dielectric by an equivalent circuit which consists of a pure capacitance and parallel resistance, the latter being inversely proportional



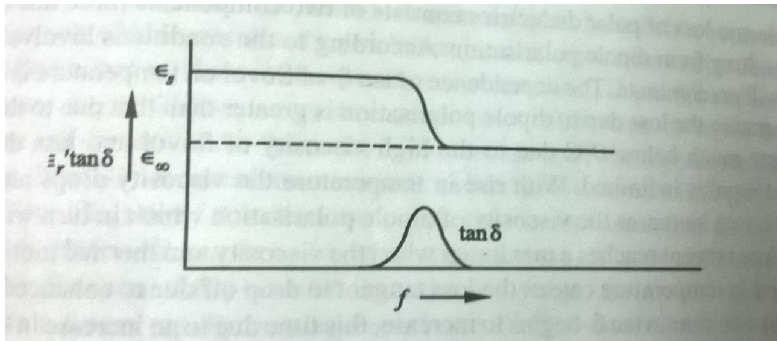
In this circuit  $\bar{I}_c$  is the conduction current which is responsible for the dielectric losses and is in phase with the applied voltage.  $\bar{I}_d$  is the displacement current which is in phase quadrature with the applied voltage.  $\bar{I}$  is the phasor sum of  $\bar{I}_c$  and  $\bar{I}_d$ .

If there are no losses,  $\epsilon_r''$  is zero and the current  $\bar{I}$  leads the applied voltage by  $90^\circ$  under these circumstances.

### SIGNIFICANCE OF THE LOSS TANGENT

The loss tangent has a very small value for free space. For solid materials  $\tan\delta=0.0003$ , which is equivalent to a Q of 3000. A fairly good value of Q for a coil is around 300. That is why we attach importance to losses in a coil and ignore those in capacitors.

The variation of  $\tan\delta$  with the frequency will show a normal resonance like behaviour. This is shown in figure below.



The curve of  $\tan\delta$  has largest value in the region of frequencies where there is a sharp change in the dielectric constant. In case of ionic resonance this change in dielectric constant occurs from microwave to infrared regions of frequencies. The dielectric losses associated with ionic vibrations are usually referred to as infrared absorption. Similarly, the losses in the optical region associated with electronic vibrations are referred to as optical absorption. Hence it is possible to predict whether the dielectric properties are due to ionic or electronic polarisation. The occurrence of absorption in the optical region is the source of colour in materials, e.g., NaCl is transparent in the visible region which means that there is negligible absorption for the corresponding frequencies. Under X-rays, NaCl turns yellow-brown.

### DEPENDENCE OF THE LOSS TANGENT ON TEMPERATURE AND FREQUENCY

The dielectric loss of polar dielectrics consists of two components those due to leakage current and those resulting from dipole polarisation. According to the conditions involved one or the other component will predominate. The dependence of  $\tan\delta$  of Sovol on temperature is shown in figure.

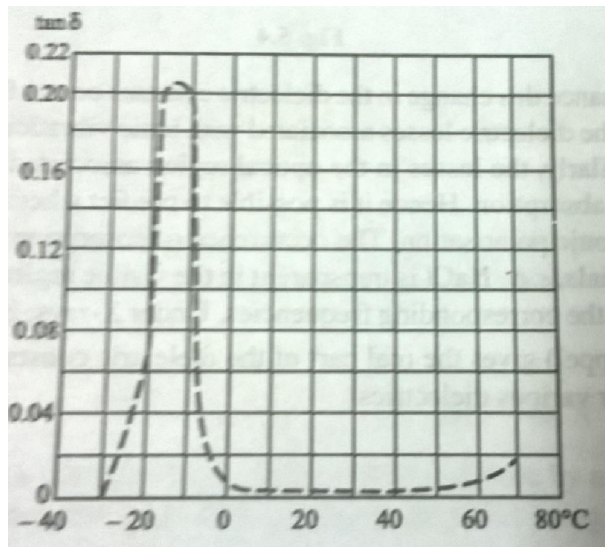
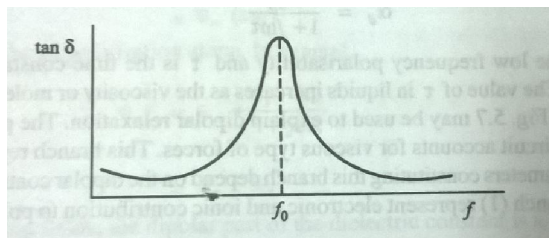


Fig-Temperature dependence of  $\tan \delta$

At low temperature the loss due to dipole polarisation is greater than due to leakage current. At low temperature much below  $0^{\circ}\text{C}$  due to high viscosity of Sovol and less thermal motion the orientation of dipoles is limited. With rise in temperature the viscosity drops and acquires greater mobility and hence increase the viscosity of dipole polarisation which in turn will increase the loss tangent. The loss tangent reaches the maximum when the viscosity and thermal motion are optimum. A further increase in temperature causes the loss tangent to drop off due to enhanced thermal agitation. After falling to a minimum  $\tan \delta$  begins to increase, this time due to an increase in the leakage current.

The loss tangents of dielectric depends on frequency. The variation of  $\tan \delta$  with frequency at a constant temperature is shown in figure below.



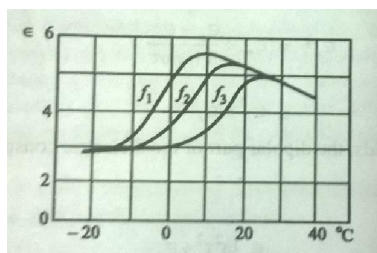
At low frequency the dipoles make less number of rotations per second resulting in a small amount of power loss. As the frequency is increased beyond a certain limit the dipolar polarisation ceases because the molecules will not be able to keep up with the increased rate of field reversal. At some mid-frequency depending on the temperature the loss tangent will be maximum as shown in the figure above. At zero frequency loss is due to leakage current only and hence  $\tan \delta$  is minimum. At infinite frequency the losses due to both polarisation and leakage current become zero.

#### FREQUENCY AND TEMPERATURE DEPENDENCE OF THE DIELECTRIC CONSTANT OF POLAR DIELECTRIC

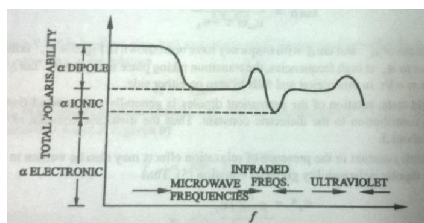
The temperature rise has double effect on the dipolar polarisation. It weakens the intermolecular forces and hence enhances the orientation and, it increases the thermal



agitation and hence strongly disturbs the orientation. The higher intermolecular forces and lesser thermal agitation, at very low temperature reduces the orientational polarisation. At sufficiently high temperature the dielectric constant is again reduced due to the strong thermal motion which disturbs the orientation of the dipoles. Within this limiting temperatures the dielectric constant reaches a maximum value when the condition are optimum. The figure below shows the dependence of dielectric constant upon temperature at different frequencies.



The dielectric constant of a polar material depends on frequency. Upto a certain frequency the dielectric constant remains practically constant corresponding to the d.c value; but at very high frequency it drops to a low value. When the frequency is sufficiently high the dipoles become unable to align with the field and hence no orientational polarisation, which means smaller dielectric constant. Figure shown below shows the total polarisability of a substance determined as a function of frequency.



## DIELECTRIC PROPERTIES OF POLYMERIC SYSTEM

Polymers can be divided into two general classes having distinctive properties. Firstly, there are nonpolar polymers which have no permanent dipole moments and which generally show fairly low electric constants, practically no dielectric loss and very slight frequency dependence of either of three quantities. Polyethylene and Teflon are examples of such polymers. The polarisation which these materials exhibit is chiefly due to distortions of the electronic and atomic structures. The small but measurable dielectric loss exhibited by these materials has not been satisfactorily explained.

Secondly, the vast majority of polymers have structures containing permanent dipoles and, as in the case of monomeric liquids and glasses, they exhibit dielectric dispersion (i.e., frequency dependent dielectric constant and loss) superposed on atomic and ionic polarisation. In these materials the behaviour is similar to that in polar liquids.

In some microwave application it is desirable to have dielectric with a low dielectric constant. According to the Clausius-Mossotti equation this is achieved by designing non-ionic compounds of atoms of small atomic polarisabilities and no free dipoles. Polymeric compounds of the first category like polystyrene, polyethylene, etc. are suitable for this purpose.



## IONIC CONDUCTIVITY IN INSULATORS

The conductivity  $\sigma$  of insulators is very small but not zero. It is associated with the motion of ions and is therefore called ionic conductivity. The resistance temperature coefficient of insulators is negative and cannot be expressed even approximately by a straight line relation as in the case of metals. The variation of conductivity of insulators with temperature is often given by formula.

$$\sigma = \sigma_0 e^{-\frac{\phi}{2KT}}$$

Where  $\phi$  is a kind of activation energy. At elevated temperatures an insulators may therefore become a conductor.

In loose structures such as are found in glasses, there are a large number of interstices that are only partially occupied by ions. Conduction takes place when the ions move from an occupied site to an unoccupied site; the activation energy involved in the process explain the exponential dependence of  $\sigma$  upon  $T$ . Most ionic crystals are, however, much more rigid and therefore the ionic conductivity is much smaller. Ionic conductivity exists because of two types of defects in the crystals namely the Frankel defects and Schottky defects. Frankel defects occur when ions jump into interstitial positions, leaving vacant sites behind. Schottky defects occur when a positive ion vacancy and a negative ion vacancy are created simultaneously.

Under the influence of an applied field both types of vacancy move through the lattice giving rise to ionic conductivity. It may be shown with the help of thermodynamics that the number of these vacancies increases with increase in temperature. The activation energy  $\phi$  represents the energy required to move the ions into the vacant sites.

## INSULATING MATERIALS

The resistance of an insulator falls as the temp. Increases. In some cases there is a marked decreases in resistance. Thus, by raising the temp. Of India rubber by 15°C, the resistance is found to be halved. The presence of moisture has the adverse effect of lowering the resistivity of insulator. The important properties of insulator for d.c use two other properties, via: dielectric losses and permittivity become important. The permittivity is an important especially with materials used for cable construction and for H.V. power distribution work.

### Breakdown in Dielectric Materials

The electric strength at breakdown is defined as the minimum electric stress usually expressed in KV/cm, waveform, frequency and the type of electrodes. The electric breakdown strength of a material depends on its composition, thickness, temperature, moisture content and to some extent on the time of application voltage. It is also affected by the shape of the waveform and the steepness of the waveform of the applied voltage. There is no definite relationship between these variables, but in general for sheet materials, the electric strength is an inverse function of the thickness and time and decreases with increases temp. And moisture content. At breakdown, the high electric stress is assumed to cause an

interatomic displacement of the orbital electrons which alters the atomic structure causing heating and a conducting path in the material.

The breakdown mechanism of gaseous, liquid and solid dielectrics are different in nature.

#### **(a) Breakdown in Gaseous Dielectrics**

Breakdown in gases begins with the ionization due to collision of electron. In strong electric field the kinetic energy acquired by the accelerating free electron will be greater than the ionization energy of the gas. Collision ionization is started by the most of the mobile electron. The dielectric strength of gaseous dielectric depends on many factors. The electric strength is higher at very high and at very low pressure. The electric strength also depends on the uniformity of the applied electric field. When the electrodes have different shapes the breakdown voltage depends on the polarity of the electrodes. The breakdown voltage depends on the frequency of the applied field.

The other factors which influence the breakdown voltage of gas dielectric are the distance between the electrode and the chemical composition of the gas.

#### **(b) Breakdown in Liquid Dielectric**

The breakdown mechanism of liquid dielectric depends on the purity of the dielectric. In the contaminated dielectric the breakdown occurs due to the formation of conducting bridge between the electrode by droplet of emulsified water and suspended particles especially fibrous particles. The time taken to form the bridge depends on the extent of combination, the shape of the electrodes and gap between them. In technically pure liquid dielectric the breakdown is initiated by the ionisation of the gases in the liquid. All liquids dissolve a certain quantity of gas especially air. In degassed high purity liquid dielectric breakdown is evidently due to the collision ionization initiated by secondary electron emitted from the cathode due to the strong electric field.

#### **(c) Breakdown in solid dielectric**

Three kinds of breakdown are possible in solid dielectric—electro thermal, purely electrical and electrochemical. In practice electro thermal and purely electrical breakdown are of major importance. Electro thermal breakdown is due to the heating produced by the dielectric loss which is proportional to the intensity of electrostatic field and the frequency. Purely electrical or intrinsic breakdown mechanism in many solid dielectrics, especially crystalline type is due to collision ionization by electron. Electrochemical breakdown usually occurs at very high temperature and high humidity of the surrounding air. The permittivity has an important bearing on the voltage gradient and electric stresses when dissimilar insulating materials are arranged in series, the individual voltage gradient being inversely proportional to the respective permittivities.

#### **Important Requirements of Good Insulating Materials**

The requirement of good insulating material can be classified as electrical, mechanical, thermal and chemical. Electrically the insulating material should have high resistivity to

reduce the leakage current and high dielectric strength to enable it to withstand higher voltage without being punctured or broken down. Since the insulator are used on the basis of volume and not weight a low density is preferred.

Liquid and gaseous insulator are also used as coolant for e.g transformer oil, hydrogen and helium are used both as insulation and cooling purpose. The insulator should also have small thermal expansion to prevent mechanical damage.

Chemically the insulator should be resistant to oil, liquid, gas flumes, acid and alkalis. Insulating material should have certain mechanical properties depending on the use of which they are put. Materials with large electronic and ionic Polaris abilities and therefore large permittivity are used for making dielectrics capacitor. The use of molecules with a permanent dipole moment is not desirable because of possibility of large dielectric losses at high frequencies.

- I. **Mica:** Mica sheets are used for the insulating leaves between commutator segments. Micanite is used for slot linings of H.V machines and for making bushes. Mica is usually avoided for slot lining L.V machines because its space factor is low.
- II. **Porcelain:** Porcelain is produced in two ways. The “dry” process produces a low voltage porcelain, which is used for switch bases, fuses, etc. The product is usually hygroscopic and porous unless well glazed. The “wet” produces a non-hygroscopic porcelain which is used for H.V transmission line insulator, conductor, rail support on railways and high voltage switch parts.
- III. **Marble and Slate:** These are employed for switch boards and panels. Slate is generally coated with an insulating varnish to make it non-hygroscopic.
- IV. **Polythene:** The low power factor and therefore low dielectric losses of Polythene has made it particularly attractive for high frequency application, such as cable and Insulator Wire for Radio Frequency work.
- V. **Bakelite:** The most common type of phenol formaldehyde is Bakelite. It is a hard, thermosetting, dark colour material widely used for small moulded parts such as lamp holder, terminal blocks and small panels.
- VI. **Polyvinylchloride (PVC):** PVC is replacing rubber to a greater extent in many application. PVC insulated (non sheathed) or PVC insulated and sheathed cable for general purpose wiring is now well established and the choice between VIR and PVC is often largely a matter of relative price or personal preference on the part of the user. PVC insulation are not effected by oils and petrol and are therefore widely used in aircraft and factories.
- VII. **Asbestos:** Asbestos in insulation can be used in very high temperature surrounding.
- VIII. **Rubber:** The material used for cable insulation are pure rubber, vulcanised rubber impregnated paper and vulcanized bitumen.
- IX. **Cotton and Silk:** Cotton is hygroscopic and has low electric strength show that it must be impregnated with varnish or wax after winding.
- X. **Silk** is more expensive than cotton but takes up less space and is therefore used for winding in fractional horse power machine. The operating

temperature of cotton and silk is about 100 degree C and the material will carbonised above this temperature.

- XI. Glass:** Ordinary glass is a good insulator but is too brittle to be used for anything but scientific instrument parts, accumulator container and for certain other special purposes.
- XII. Paper and Boards:** Paper usually impregnated with oil or varnish is an essential insulator in all high voltage cables.
- XIII. Wood:** Typical applications of wood are **for** terminal blocks, **wedges** for armature windings, operating rod in H.V switch gear and L.V distribution line supports.
- XIV. Enamel Covering :** This consist of a thin film of either oil base or synthetic base varnish applied by drawing the conductor through a trough of varnish and then through a heated chamber so as to bake the varnish into a tough and elastic film of high dielectric strength .
- XV. Transformer Oil:** Transformer cores and chokes are commonly immersed in oil known as transformer oil which act to some extent as an insulator but chiefly as a cooling medium.

### ***Properties and Testing of Transformer Oil***

The properties of transformer oil should fully comply with the standards and rules in force in the country where it is used. The most important specification are dielectric strength, viscosity and flash point.

### ***Contamination and Purification of Transformer Oil***

Many impurities such as water, fibre, resins, carbon particles etc. may get into the oil due to imperfect purification at the plant.

The oil is boiled to evaporate the water contain in the oil. Since the impurities including water are heavier then oil this can be removed from the oil by quickly rotating the oil in a centrifuge.

**(I) Polymers:** Polymeric materials or plastics comprise a large group of organic or organometallic high molecular compound.

Plastic are synthetic resin obtain by linear polymerisation and by poly condensation.

The no. of monomer molecule in a single polymer molecule is known as degree of polymerisation.

Synthetic resin are widely used in electrical industries as insulating and structural component. They have almost replace the nature resin. Some of the synthetic resin commonly used in electrical engineering are listed below.

**Polystyrene:** Polystyrene is produced either with a direct polymerisation of liquid styrene or with water styrene emulsion. Product obtain from polymerisation of chlorinated styrene possess a higher heat resistance.

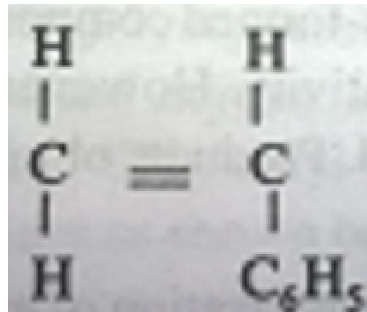
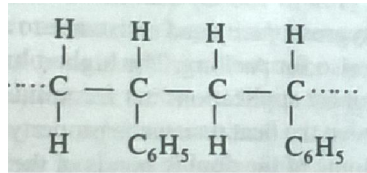


Fig – Polystyrene

**Polythylene:** This is obtained from polymerisation of ethylene. The polymerisation is done with a special catalyst at atmospheric pressure and at temperature not exceeding 100 degree C. It is used in high voltage power cables.

**Polyvinyl chloride (PVC):** This is obtained from polymerisation of gaseous vinyl chloride.

PVC is widely used for making various plastic and rubber like articles.

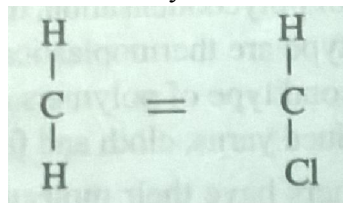


Fig- Vinyl chloride molecular structure

**Polymethylmethacrylate:** This is a polymer of methyl methacrylate which is a transparent, colourless material, and is widely used in tool making.

**Polytetrafluoroethylene (PTFE):** This is obtained through the polymerisation of tetrafluoroethylene. Its electrical strength drops sharply when subjected to a continuous ac voltage. PTFE has a low radiation resistance. The applications of PTFE are as capacitor dielectric.

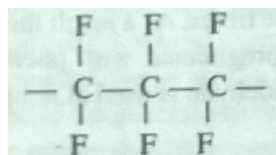


Fig-Linear molecular structure of (PTFE)

**Polyster Resin:** There are many resin in this group with divergent composition and properties. They are all obtain from poly hydric alcohols which contain two or more hydroxyl group OH. The thermo setting polyester resin are used as protective sheath for electrical apparatus.

Silicon resin are organic compound of silicon with a structure of alternating atoms of silicon and oxygen (Siloxane).

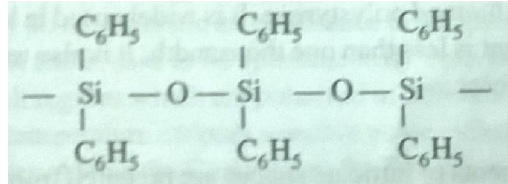


Fig- Molecular structure of phenylpolysiloxane

**Cellulose Easters:** This are obtain by chemically processing the natural polymer cellulose. Cellulose Easters are less hydroscopic, flexible and have high mechanical strength. They are thermoplastic.

**Stocks Plastics:** The stocks plastics prepared from laminateand certain kind of resin are used for various kind of electrical insulating components. They are available in moulded form. Paper base laminate have relatively good mechanical and electrical properties as well as low hygroscopicity. They are used as insulator in electrical apparatus, machine etc.

**Foamed Plastics:** Synthetic resin can be foamed by heating a mixture of resin with suitable foaming agent. It is widely used in high and ultra-high frequency since its loss tangent is less than 1000.

**Moulded plastics:** Plastic article and component of intricate shape are prepared from moulding compound. The binding agent used for binding electrical goods are thermoplastics organic resin, organopolysiloxanes and resin of the polytetrafluoroethylene type, celluloseeaster. The binding agent will allow the plastic to be moulded in any desire shape.

Plasticizers are used to make the moulded plastic less brittle.

Mould plastic find wide application as insulating and structural components. They are used in the manufacture of low voltage electrical equipment.

### Ferro Electricity

Ferro electric material have a high dielectric constant which is nonlinear i.e it depends to a considerable extent on the intensity of electric field. Such material exhibit hysteresis loops. If the centre of gravity of the positive and the negative charges in a body do not coincide in the absence of an applied electric field, the substances has an electric dipole moment and is said to be spontaneously polarised. Such a substance is ferroelectric. It contains small regions which are polarised in different directions even in absence of an electric field. When the temperature exceed a certain value called the Curie point the substance loses its Ferro electric properties. Example of Ferro electric material are Rochelle salt.

Ferro electricity bears a close analogy to Ferro magnetism. The lower the temperature and stronger the electric field the more pre dominant is effect of the letter over the random thermal agitation.

### Piezoelectricity

Piezoelectricity provide us with a means of converting electrical energy to mechanical energy and vice versa.

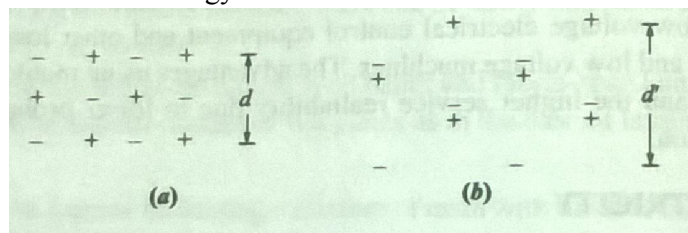


Fig- 1

When an electric field is applied to a substance it become polarise, the electron and nuclei assume a new geometric position and the mechanical dimension of the substance are altered. The phenomenon is called electrostriction.

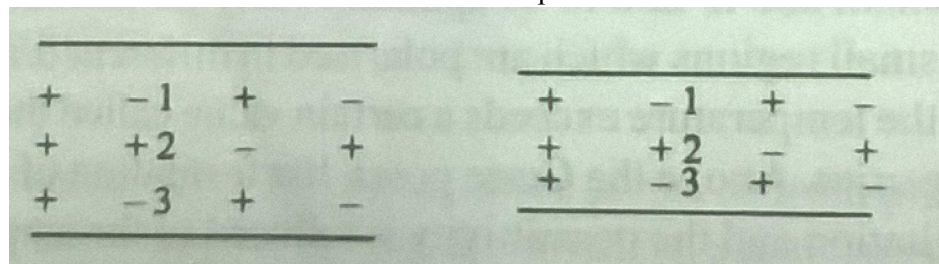


Fig-2

The reverse effect i.e. the production of polarisation by the application of mechanical stress can take place only if the lattice has no centre of symmetry, the phenomenon being known as piezoelectricity.

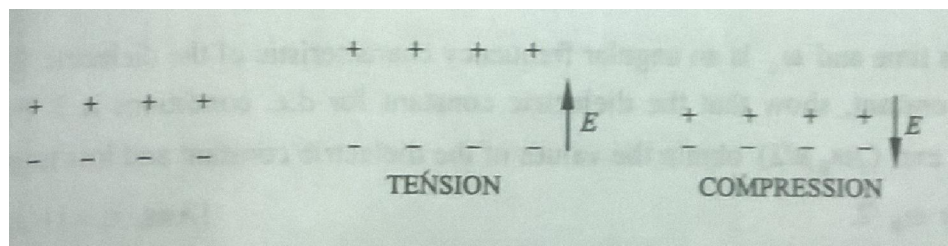


Fig-3

Figure 1(a) shows a two dimensional unit cell. When a field is applied as in Figure 2(b) the charges assume new position and linear dimension of the sample changes.

When mechanical force is applied to the unit cell in which the second row of the charges is a line of symmetry as in Figure 1(b) the distance between the first and the second row is equal to the distance between the second and the third row; hence there is no change in the electric moment of the charge array because new dipoles moments of equal magnitude but opposite sense are induced.

However if the array of the charges has no centre of symmetry as in Figure 3 the dipole moment is increased or decreased depending upon the field direction. The dipole moment

again increases or decreases depending upon the type of mechanical forces, which is tension or compression.



## MODULE-III

### MAGNETIC PROPERTIES OF MATERIALS

#### INTRODUCTION-

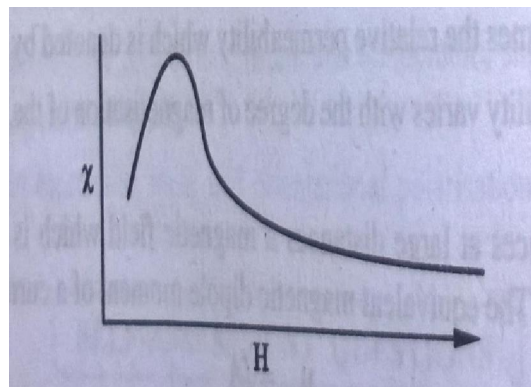
Materials in which a state of magnetisation can be induced are called magnetic materials. When magnetised, such materials create a magnetic field in the surrounding space.

All the molecules of a material contain electrons orbiting around the nucleus. These orbits are therefore equivalent to circulating currents and so develop an m.m.f. Depending on whether any unneutralised orbit exists or not, specimens can be said to be magnetised or unmagnetised. The readiness of a material to accept magnetism is expressed by its permeability.

For most of the materials, magnetic permeability is equal to that of free space  $\mu_0$  and is constant; but for magnetic materials, the permeability equals  $\mu_0$  times the relative permeability which is denoted by  $\mu_r$ . the relative permeability varies with the degree of magnetisation of the material and may have a value as high as 2500.

$$\chi = \mu_r - 1$$

Where  $\chi$  is a dimensionless quantity defines as the magnetic susceptibility of the medium. The magnetic susceptibility depends on the nature of the magnetic material and on its state (temperature, etc.). The susceptibility of a material may change on cold working. For example, if copper is cold worked, the susceptibility may change from negative to a positive value, and again on annealing after cold work, the susceptibility may become negative again.



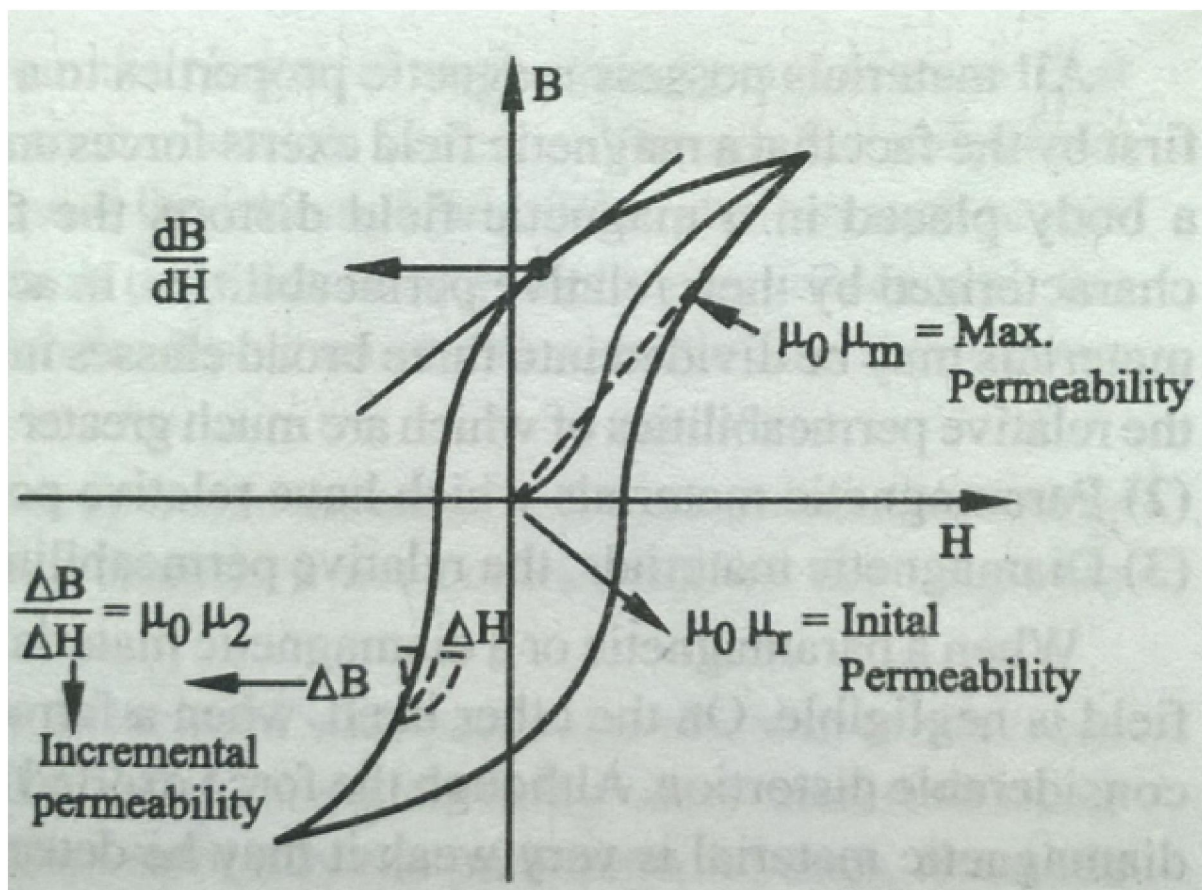
The susceptibility may be determined by measuring the force exerted on a magnetic material

when it is placed in a magnetic field, the susceptibility of a ferromagnetic substance is very strongly dependent on the field strength.

Fig. 1. Susceptibility versus Field strength (Ferromagnetic materials)

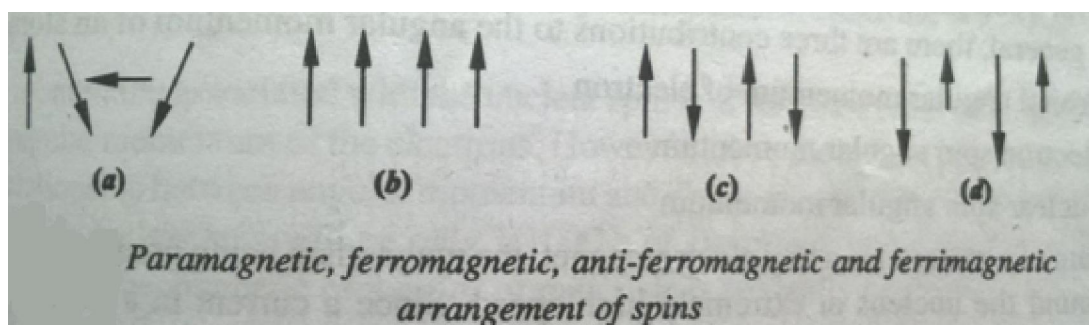
### CLASSIFICATION OF MAGNETIC MATERIALS-

Magnetic material for which a linear relationship between  $M$  and  $H$  exists are divided into classes depending upon the sign of  $\chi$ . Materials which have a negative value of  $\chi$  of the order of  $10^{-4}$  to  $10^{-6}$  are called diamagnetic and those which have a positive value of  $\chi$  of about the same order of magnitude are called paramagnetic. The materials in which the resultant magnetisation is one to several orders of magnitude greater than  $\mu_0 H$  are called ferromagnetic. The following figure shows a number of permeabilities.



Another classification of magnetic materials is based on the presence or absence of permanent magnetic dipoles. Materials which lack permanent magnetic dipoles are called diamagnetic. If permanent magnetic dipoles are present in the atoms of a material, it may be paramagnetic, ferromagnetic, antiferromagnetic or ferromagnetic depending on the interaction between the individual dipoles. If the interaction between the atomic permanent dipole moments is zero or

negligible and the individual dipole moments are oriented at random as shown in fig 3(a), the material will be paramagnetic. If the dipoles tend to line up in parallel, as shown in fig 3(b), the material will be ferromagnetic. When neighbouring moments are aligned in antiparallel as in fig 3(c), the phenomenon is called as antiferromagnetism. When the order of the magnetic moments is as shown as in fig 3(d), the phenomenon is known as ferrimagnetism. The molecular moments in ferromagnetic materials will have the values in between the values for ferromagnetic and antiferromagnetic materials.



The magnetic properties of materials are characterised by their relative permeabilities. Based on this, magnetic materials can be divided into 3 categories viz. 1) ferromagnetic materials, the relative permeabilities of which are much greater than unity and are dependent on the field strengths 2) paramagnetic materials, which have relative permeabilities slightly greater than unity 3) diamagnetic materials, the relative permeabilities of which are slightly less than unity

When a paramagnetic or a diamagnetic material is placed in a magnetic field, the distortion of the field is negligible. On the other hand, when a ferromagnetic material is placed on the field, there is a considerable distortion. Diamagnetism is a universal property of all materials. The diamagnetic properties, however are weaker than the paramagnetic ones and still weaker than the ferromagnetic properties. The peculiarities of ferromagnetic behaviour are due to a very specific property, viz. the formation within the ferromagnetic material of vast regions or domains within which the magnetic moments of a large number of atoms are arranged parallel to on another giving magnetic saturation in each domain.

## DIAMAGNETISM-

The magnetic moments of diamagnetic materials are mainly due to the orbital angular momentum of the electrons. A steady current flowing in the orbit produces a magnetic field equivalent to that set up by a dipole perpendicular to the plane of orbit (Ampere's law). By Lenz's law, the induced magnetic moment and hence the susceptibility will be negative and  $M$  will be in opposite direction to  $H$ .

From the table above, it can be observed that permeability of such materials is approximately equal to unity. The diamagnetic susceptibility is very small and negative as can be verified by the small repulsion experienced by such materials in presence of external magnetic field.

Diamagnetism is associated with all the elements since it affects all electrons. In the electrical polarisation, the induced moment lies along the direction of external applied electric field giving a positive electrical susceptibility whereas in the magnetic case, the induced moment gives a negative susceptibility.

Particles which do not have a net magnetic moment include in the first place atoms and ions with completed shells, e.g.,  $F^-$ ,  $Cl^-$ ,  $Na^+$  and atoms of the noble gases. The diamagnetic effect becomes observable only when the net paramagnetic atomic moment is zero in zero field. The diamagnetic susceptibility arises due to a change in magnitude of the electronic orbital moments. Due to the small value of diamagnetic susceptibility, diamagnetism is of little importance.

Material	$\chi = \mu_r - 1$	$\mu_r$
Diamond	$-2.1 \times 10^{-5}$	0.999979
Graphite	$-12 \times 10^{-5}$	0.999880
Copper	$-0.9 \times 10^{-5}$	0.999991
Gold	$-3.6 \times 10^{-5}$	0.999964
Germanium	$-0.8 \times 10^{-5}$	0.999992
Silicon	$-1.7 \times 10^{-5}$	0.999983
Benzene	$-0.75 \times 10^{-5}$	0.999993
Bismuth	$-17.6 \times 10^{-5}$	0.999824
Glass	$-1.3 \times 10^{-5}$	0.999987
Hydrogen	$-0.006 \times 10^{-5}$	0.999999
Quartz	$-1.5 \times 10^{-5}$	0.999985
Water	$-0.9 \times 10^{-5}$	0.999991
$Al_2O_3$	$-0.5 \times 10^{-5}$	0.999995
NaCl	$-1.2 \times 10^{-5}$	0.999988

## PARAMAGNETISM-

A material has paramagnetic properties if permanent magnetic dipoles exist in its atoms, ions or molecules. On the application of an external magnetic field, the permanent magnetic dipoles line

up and thus produce a positive induced magnetic moment. This is due to the shift in positions of electrons such that the total energy is kept to a minimum. The formation of permanent dipole moments is due to the orbital motion and spin of electrons.

Paramagnetic atoms and ions include particles having one electron over and above a completed shell (e.g. atoms of the alkaline metals), atoms of the transition elements, etc.

On the application of magnetic field, the atoms (or molecules) tend to rotate in such a way that their magnetic moment coincides with the direction of field. As a result, equilibrium is established between two tendencies, viz. the ordering action of the field and the tendency to thermal randomness.

The relationship between paramagnetic susceptibility and magnetic moment of an atom is given by

$$\chi = m^2 / 3KT$$

Where  $m$  is the magnetic moment,  $K$  is the Boltzmann's constant and  $T$  is the absolute temperature. In general, the magnitude of  $m$  is of the order of 1 Bohr Magneton.

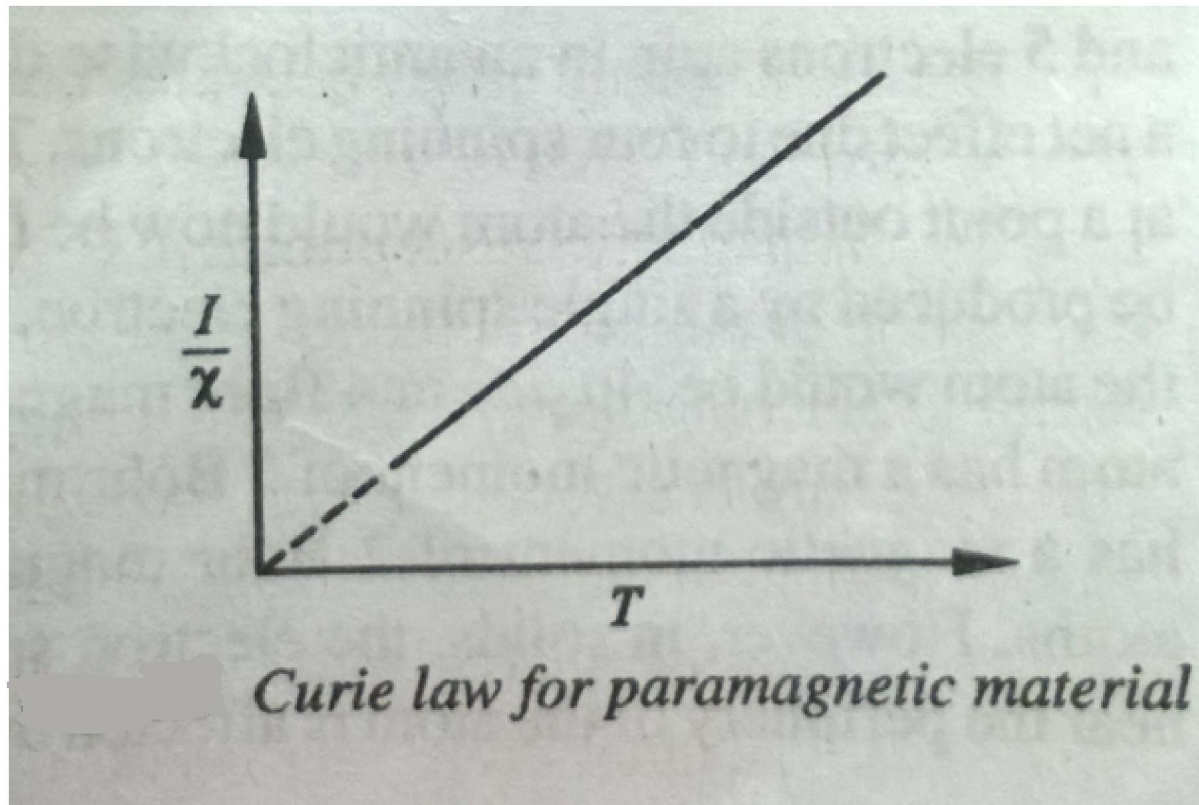
The paramagnetic susceptibility varies inversely with the absolute temperature for ordinary fields and temperatures

Or,  $\chi = C/T$

This law is known as the Curie Law of paramagnetism and the constant  $C$  is called the Curie constant. For large fields at low temperatures, the magnetisation tends to a constant value. From the table below, we can say that the relative permeability of paramagnetic substances equal to unity.

Paramagnetic salts have been used to obtain very low temperatures by adiabatic demagnetisation. Other applications include in the solid state MASER.





### **FERROMAGNETISM-**

The magnetisation of a ferromagnetic sample depends on the magnetic history of the sample in addition to the field intensity. Ferromagnetics are solids, generally crystalline in nature, which are magnetised independent of any external field. This can be explained in terms of the uncompensated electron spins. When the number of electrons spinning in clockwise and anticlockwise direction are unequal, then the magnetic moment is equal to magnetic field produced due to single spinning electron times the difference in number of electrons spinning in each direction. On this basis, Cobalt has a magnetic moment of 3 bohrmagnetons while Nickel has that of 2 bohrmagnetons and iron has that of 4 bohrmagnetons. The actual magnetic moments are smaller than those given above due to the electron spin being affected by the proximity of other atoms.

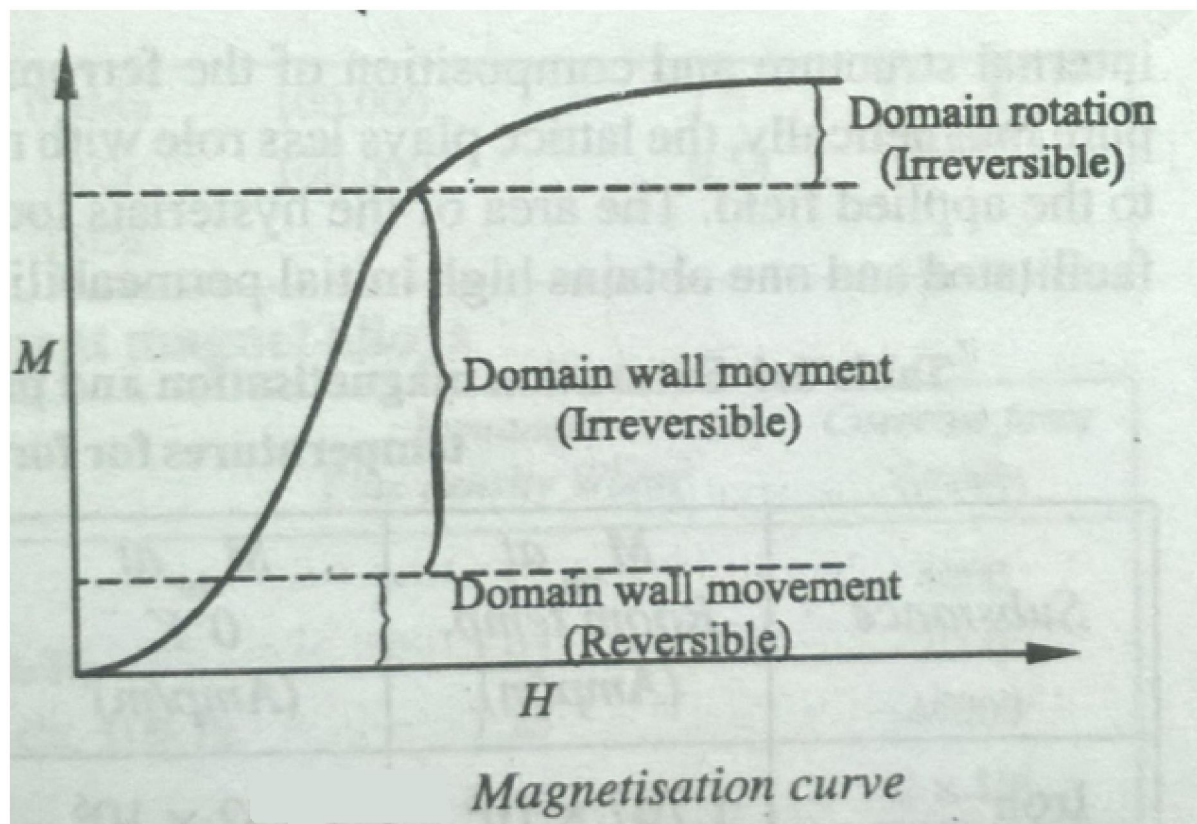
When the temperature exceeds the ferromagnetic Curie temperature or transition temperature  $T_F$ , the susceptibility becomes independent of field strength and the behaviour of a ferromagnetic material becomes similar to that of a paramagnetic material.

### **THE MAGNETISATION CURVE-**

Every crystal of a ferromagnetic substance has a perpendicular crystallographic direction along which it is most easily magnetised. Hence, higher fields are required to magnetise single crystals along some direction than others which are referred to as 'easy' and 'hard'. The energy of

magnetisation is given by the area  $\int H \cdot dm$  between the magnetisation curve and the M axis ( $H=0$ ) as shown in fig. below. The excess energy required to magnetise a specimen in the hard direction is known as anisotropy energy which is less for Fe and Ni (since cubic symmetry) than for Co (only axial symmetry).

With small external fields, the domain wall movements are mostly reversible, owing to the initial portion of the magnetisation curve. In higher fields, these boundary movements continue but are often larger and irreversible finally resulting in all favourable oriented domains reaching their maximum size. Application of still higher fields results in domain rotation which is a difficult process and hence the increase in magnetisation is therefore slow. This explains the ferromagnetic hysteresis effect. Finally the magnet is saturated, i.e., all the domains point in the direction of  $H$ .

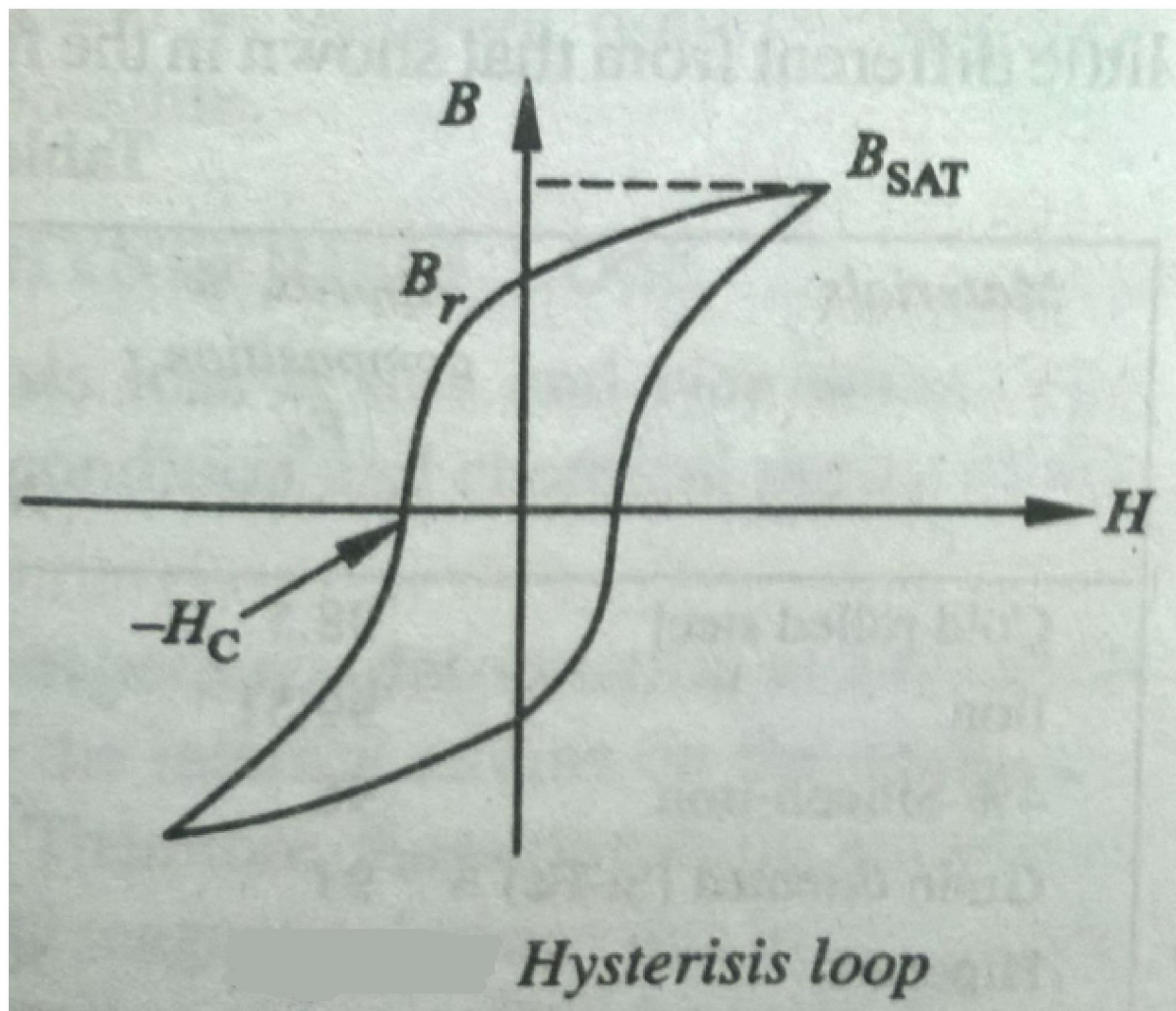


### THE HYSTERESIS LOOP-

Below the Curie temperature all ferromagnetic materials exhibit the well-known hysteresis in the  $B$  versus  $H$  curves. Starting with an unmagnetised specimen,  $B$  varies reversibly with  $H$  for small fields. Since there is no hysteresis in this region, one defines the initial permeability  $\mu_r$ , in the same way as the permeability of a paramagnetic material. As the field  $H$  is increased,  $B$  begins to increase rapidly and ultimately approaches a saturation value  $B_{sat}$ . upon reducing the value of  $H$  from the saturation region to zero, it is observed that there remains a flux density,  $B_r$ , called the

remanent flux density. Since  $H=0$ , the material must be permanently magnetised; in fact, the magnetisation corresponding to  $B_r$  is equal to  $B_r/\mu_0$ . the field  $-H_c$  required to reduce the flux density to zero is called the coercive force.

Coercive force and remanent flux density depend on the imperfections in the material while the saturation value of the flux density depends on the chemical constitution and temperature. The area contained in the hysteresis loop equals the work needed to reverse the direction of magnetisation. As the material becomes more pure magnetically, the area of the hysteresis loop becomes smaller, the domain wall movement is facilitated and one obtains high initial permeability.



#### **FACTORS AFFECTING PERMEABILITY AND HYSTERESIS LOSS-**

If the initial permeability is high, the hysteresis loss is low and vice-versa. Both depend on the chemical purity and the physical condition of the sample. The crystals of a ferromagnetic material when cold worked, experience deformation and so a greater magnetic field is required to



give a definite magnetisation. Therefore the permeability decreases and the hysteresis loss is increased. A cold worked material when subsequently subjected to heat treatment, the magnetic properties will be restored. Impurities like carbon, sulphur, oxygen and nitrogen affect the regular geometric pattern of the crystals and are harmful to the magnetic properties.

### **COMMON MAGNETIC MATERIALS-**

- 1) Iron and silicon iron alloys- Addition of silicon from 0.3 to 4.5% by weight to iron greatly improves the magnetic properties of the latter. Silicon increases the electrical resistivity of iron thus decreasing the iron loss due to eddy currents in the material. Addition of silicon also decreases the hysteresis loss. However, as the silicon content in iron is increased, the saturation magnetisation decreases. Therefore, in small machines, iron losses are of secondary importance and hence a material of low silicon content(0.5%) may be used. On the other hand, in large turbo-generators where the magnitude of losses may be a considerable fraction of output, materials of high silicon content are used.
- 2) Nickel-iron alloys- A group of iron alloys containing between 40 and 90 % nickel have, when given appropriate heat treatment during manufacture, much higher permeabilities at low flux densities and much lower losses than ordinary iron. The important alloys are permolloy and mumetal. Addition of cobalt to such alloys reduces hysteresis, manganese reduces coercivity, and molybdenum increases initial permeability and reduces the iron losses. These alloys are widely used in transformer cores and loading coils for telephone circuits, instrument transformers, for the magnetic circuits of measuring instruments and for magnetic screens of electronic equipment.
- 3) Permanent magnet materials and design of permanent magnets- While for transformers, coils and relays, “soft” magnetic materials having low remanence are used, for permanent magnets “hard” magnetic materials which have high remanence are usually preferred. Materials with carbon added were used in the earlier times, but now permanent magnet steels are used with tungsten as an important constituent. Other alloys such as of iron and platinum, cobalt and platinum, etc. are also used.

### **MAGNETIC RESONANCE-**

An electron having a mass and spin will give rise to both magnetic moment and kinetic moment. If  $m$  is the magnetic moment and  $P$  is the magnetic moment then the gyromagnetic ratio is given by

$$Y=M/P$$

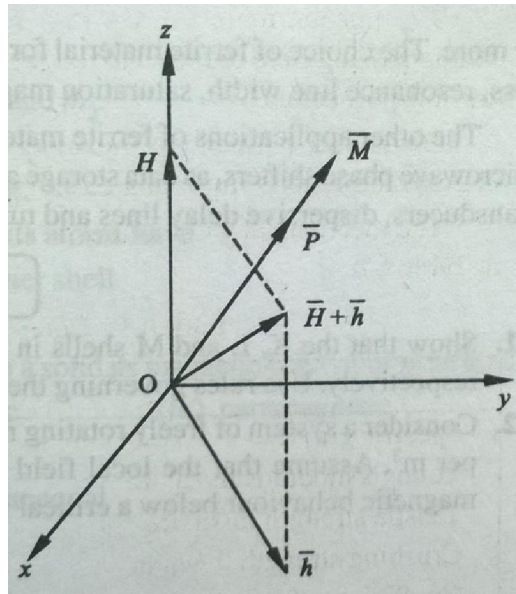
The electron will rotate in a fixed direction along the axis OC shown in fig, when an external field is applied. If an external field  $H$  is applied along the z-axis, this magnetic field exerts a couple of moment  $M$ ,

$$C = dP/dt = M \times H$$

$$\text{Also, } dP/dt = -(1/Y) dM/dt = M \times H$$

The tip of the  $M$  vector will rotate in a circle lying in a plane perpendicular to  $z$ -axis. The angular frequency is given by  $\omega = 2\pi f$

Now if a circularly polarised high frequency field  $h$  is applied this field will rotate in the field of magnetic polarisation (plane  $XOY$ ). If the sense of rotation of  $h$  is such that the resultant vector  $(H+h)$  rotates in the same sense as that of the precession and if the frequency of  $h$  is the same as that of the precession then there will be a synchronisation of the two phenomena and we have the magnetic resonance. This will cause absorption of energy from the high frequency field. This phenomena is known as gyromagnetic resonance.



## MODULE-IV

### SEMI-CONDUCTORS

#### INTRODUCTION

The resistivity of metallic conductors at room temperature lies between  $1.6 \times 10^{-6}$  to  $100 \times 10^{-6}$  ohm cm and that of the insulators between  $10^9$  to  $10^{18}$  ohm cm. the corresponding value for semi-conductors is between those for conductors and insulators. It is of the order of 0.01 to 50 cm at room temperature.

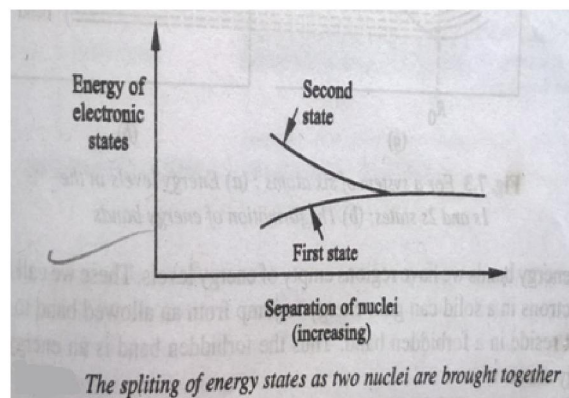
The variation of resistance of a semiconductor with temperature is nonlinear and the resistance temperature coefficient may have a positive or a negative value at room temperature. Small amount of impurities about 1ppm have an appreciable effect on the resistance value of a semiconductor. Examples of elements which are semiconductors are B, C, Si, Ge, Sn, P and As etc.

The major difference between a conductor and a semiconductor relates to the dependence of their electrical conductivity on the degree of purity of the crystal. The conductivity of a good conductor increases with purification whereas that of a semiconductor generally decreases with purification. There are changes in energy levels that occur when a large number of atoms are brought together to form a solid. It can be seen that energy levels in single atoms break up to form energy bands when a solid is formed. This helps in classification of solids into three distinct groups' i.e. conductors, semi-conductors and insulators.

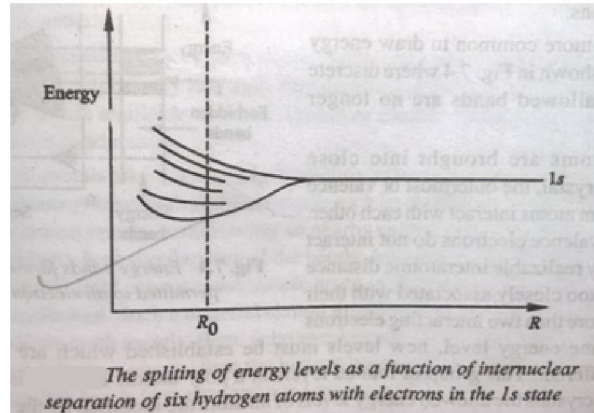
#### ENERGY BANDS IN SOLIDS

When two nuclei each having an electron at  $n=1$  state are brought closer, they still offer two low energy states to the electrons. These states do not correspond to their initial energy states. There will now be an energy difference between the two electronic states of the new system.

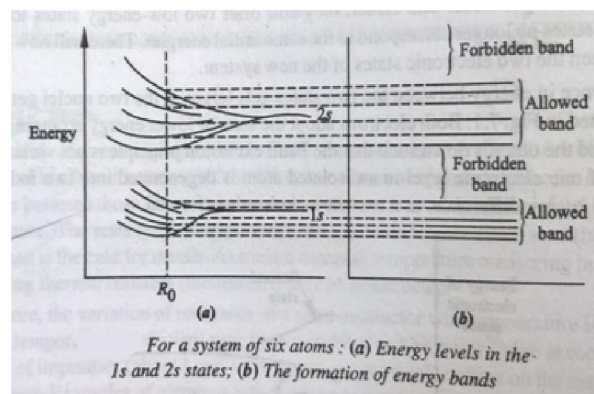
The difference in energy states gets larger as the two nuclei get closer to each other as illustrated in the figure below.



Considering 6 hydrogen atoms individually, one 1s level occurring in each of the atoms. As the atoms are grouped together the system comprising of 6 atoms will now have six energy levels as shown in the illustrated dig. In an individual hydrogen atom there are two quantum states of opposite spins i.e.  $+1/2$  and  $-1/2$ . Hence there would be twelve quantum states in 1s group for the 6-atom system. However as these pairs of wave functions differ only in spin, they make a very small energy difference making the twelve appear only six.

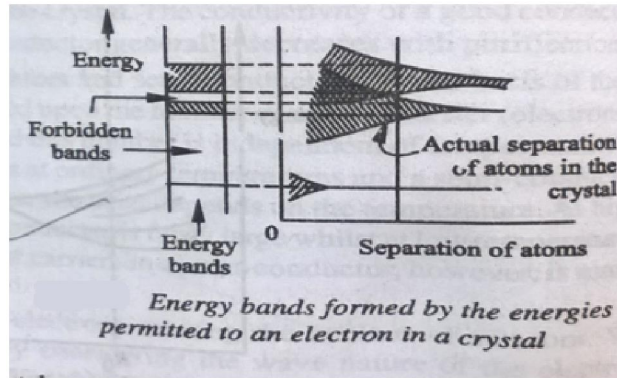


The possible 1s and 2s wave functions are called energy bands. The band in a solid comprises of the total number of energy levels each of which was originally associated with one atom only. Each energy band corresponds to one of the energies permitted in an isolated atom. For a crystal of N atoms, there would be N energies in each band.



In between the energy bands there are regions empty of energy levels. They are called the forbidden band. Electrons can jump from one allowed band to other allowed bands but no electron can exist in the forbidden bands.

When atoms are brought into close proximity as in a crystal, only the valence electrons of adjacent atoms interact with each other. The inner electrons are too closely associated to their nuclei. Hence they do not interact with each other. Since no more than two electrons can have the same energy level, new levels must be established which are discrete but only infinitesimally. This group of related poly atomic material is called an energy band.

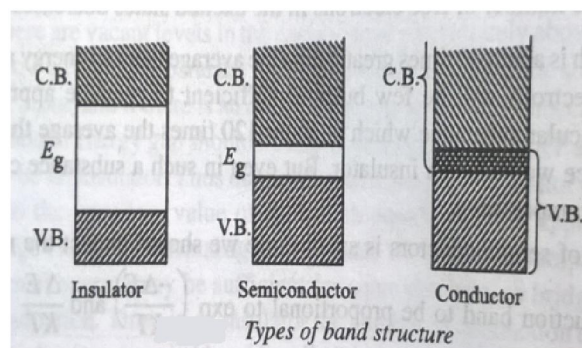


In an  $N$  atomic solid, there are  $N$  possible levels such that two electrons of the opposite spin may occupy the the same state. Thus the solid can accommodate  $2N$  electrons.

## CONDUCTORS SEMI CONDUCTORS AND INSULATORS

Most of the electrical properties of a material are related only to the upper bands of the energy levels, specifically two energy bands called the conduction band and the valence band. Valence band contains energy of same levels as the valence electrons. Electrons in this band are attached to individual atoms and are not free to move about.

The conduction bands are high enough such that electrons attaining these levels are loosely bound to the parent atoms and hence can move easily under the effects of an external electric field. Electrons in the valence band can leave their bands to join the conduction bands if given sufficient energy to jump the forbidden energy gap. The size of band gap determines whether a solid is a conductor, an insulator or a semiconductor.



Conductors contain a large number of electrons in the conduction band at room temperature. No energy gap exists and valence and conduction bands overlap.

An insulator is a material in which the energy gap is so large that no electron can gain enough energy to jump to the conduction band.

A semiconductor is a solid with little energy gap existing between the valence and the conduction bands, small enough for the electrons to cross over. At room temperature, sufficient energy is available for a few valence electrons to bridge the energy gap to the conduction band. Hence material sustains some electric current.

## **TYPES OF SEMI-CONDUCTORS**

### **Intrinsic type**

Since semiconductors have small energy gaps, some electrons may from the highest filled band can be excited to the conduction band, giving the semiconductors, its conducting property. Such materials are called intrinsic semiconductors.

In the intrinsic semiconductors, current are carried by two types of carriers, the electrons in the conduction band and the holes in the valence band which are created when the electrons are excited from the valence to the conduction band. For each electron in the conduction band, one hole is formed in the valence band. A hole is considered as a positive charge carrier.

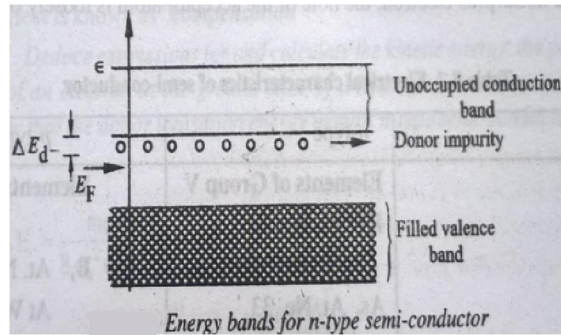
When a hole is created, it is possible that a covalent bond of the nearest electrons breaks and the electron fills in the holes, thus creating a new hole. In this manner the current is supported by electrons which are not in the conduction bands and whose energies are that of the valence band.

The holes may be considered as a positively charged particle similar to that of the electron, but having definite mass. The mobility of hole is approximately half that of the mobility of electrons. In conduction of holes, the electron movement is restricted whereas in the conduction by electrons, the electrons are free to move about the entire crystal.

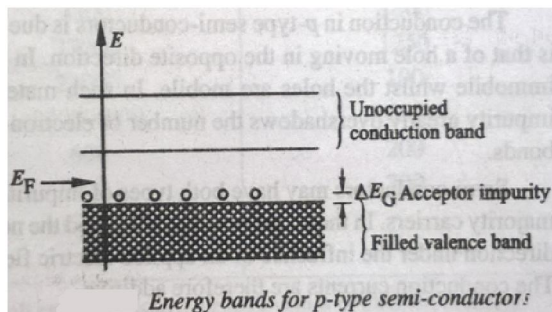
### **Extrinsic semi conductors**

The presence of small quantities of impurities, especially if the impurities have either 3 or 5 valence electrons, modifies the characteristics of a semiconductor and such types of semiconductors are called extrinsic type. The role of impurity atoms or other lattice imperfections contribute to the system of energy levels. They create their own level, a narrow energy band between the filled and the unfilled bands.

In case of penta-valent impurities, the impurity atom replaces one of the tetra-valent semiconductor atoms contributing four electrons for covalent bond formation and leaving one extra. The energy level of this extra electron is just less than the conduction band energy level. Thermal energy can easily bring this electron to the conduction level thus helping in the conduction process. This type of impurity is called a donor. The conductivity in this case is much more than the conductivity of the intrinsic type semiconductor. This type of semiconductor is called an n-type semiconductor.



When a trivalent impurity replaces a tetra-valent atom, it forms three bonds with neighbouring atoms' electrons and thus fall short of one electron for the fourth bond. This gives rise to a hole. Conduction now occurs by means of the hole and it is called a p type semiconductor. The impurity in this case is an acceptor atom since it accepts electrons from the parent atom.



Semiconductors may have both kinds of impurities and are named after the majority carriers. In these cases the positive holes and the negative electrons help carry the current in the direction of the applied electric field although they may move in the opposite directions. The conduction currents therefore are additive.

If a semiconductor contains nearly equal amount of n-type and p-type impurities, electrons from the n-type and holes from the p-type may merge to complete the bonds. Such a process doesn't lead to increase in the conductivity since electrons and holes are no longer available for conduction. This effect is called as "compensation".

The various types of lattice defects in solids are:

1. Substitutional : the semiconductor atom is replaced by an occasional foreign atom. The imperfections can be deliberately controlled or can be created in transistor materials.

2. Vacancies: lattice vacancies are created when certain atoms in a semiconductor are missing, this being called schottky defect. These are essential in copper oxide operations. This procedure decreases the crystal densities due to increase in volume without increase in mass.

3. Interstitial: these are the extra atoms between the regular atoms of the crystal. These called the frenkel defects. The density remains un altered.

4. Dislocation: these are the irregularities in the crystals and are used to make non rectifying junctions by polishing or sand blasting. They act as the sources of mechanical weaknesses in real crystals. Their presence is responsible for slip at very low stress applied.

## 7.8 DIFFUSION

Mobility of carriers in semiconductors is greater than that of the metals but the conductivity of the latter is much greater than the former due to abundance of carriers. The conductivity is so less that the random motion of the electrons due to the unequal carrier density plays greater role in conduction rather than the drift caused due to applied electric fields. Diffusion arises from density differences and the resulting current is called the diffusion current.

The defining equations for diffusion currents in one direction are

$$J_n = eD_n\left(\frac{\partial n}{\partial x}\right) \text{ for electrons}$$

$$J_p = eD_p\left(\frac{\partial p}{\partial x}\right) \text{ for the holes}$$

$J_n$ =diffusion current density of electrons

$J_p$ =diffusion current density of holes

$D_n$ = diffusion constant of electrons

$D_p$  = diffusion constant of holes and  $\frac{\partial n}{\partial x}$ =gradient of electron density and  $\frac{\partial p}{\partial x}$ = gradient of hole density.

The diffusion current due to random carrier motion is proportional to the gradient of carrier density with distance. The coefficient of proportionality is called the diffusion constant and is denoted as D. The total current in a semiconductor is the sum of the conduction current and the diffusion current.

Thus the total current density of electrons is  $J_n = eU_n \cdot nE_x + eD_n\left(\frac{\partial n}{\partial x}\right)$

And for the holes is  $J_p = eU_p \cdot pE_x + eD_p\left(\frac{\partial p}{\partial x}\right)$  where  $E_x$  is the applied electric field.

## THE EINSTEIN RELATION

There exists an important relation between the diffusion constant and the mobility. This is called as the Einstein relation and can be deduced as follows:



Consider a semiconductor in which there exists an electric field  $E_x$  and a concentration gradient such that the resultant current is zero. Under these conditions the system is in thermal equilibrium and the Boltzmann statistics applies. Consider a potential  $V(x)$  producing at  $x$  an electric field given as  $E(x) = -dv/dx$ .

The Boltzmann expression for the density of holes as a function of  $x$  in thermal equilibrium is

$$P(x) = Ce^{-eV/KT} \text{ where } C \text{ is a constant.}$$

The gradient of the hole density is therefore given by

$$\begin{aligned} \frac{dp}{dx} &= \left( -\frac{e}{KT} \right) p \cdot \frac{dv}{dx} \\ &= \left( \frac{e}{KT} \right) \cdot p \cdot E(x) \end{aligned}$$

The hole current vanishes in thermal equilibrium, therefore from the total hole current density equation

$$\begin{aligned} 0 &= peu_p E_x - eD_p \cdot dp/dx \\ &= peu_p E_x - (e^2/KT) D_p \cdot p \cdot E_x \end{aligned}$$

Or  $D_p = (KT/e) U_p$  (the Einstein relation)

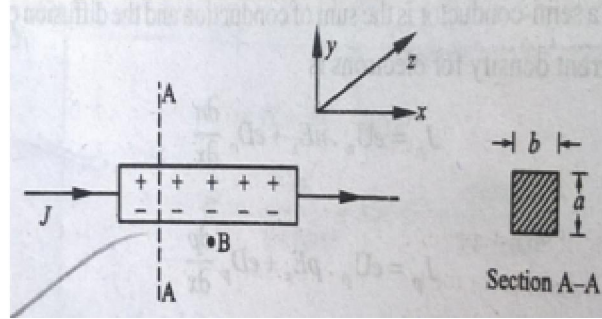
Similarly for the electrons

$$D_n = (KT/e) U_n$$

Thus  $D/u = 0.02586 \text{ Volt (at } 300^0\text{K)}$

## HALL EFFECT

Consider a slab of material in which there is a current density  $J$  resulting from an applied electric field  $E_x$  in the  $x$  direction. The electrons will drift with an average velocity of  $V_x$  in the  $x$  direction. When a magnetic field of flux density  $B_z$  ( $\text{wb/m}^2$ ) is super posed on the applied electric field in the  $z$  direction, the electrons will experience a Lorentz force perpendicular to  $V_x$  and  $B_z$ . The magnitude of this force will be given by  $B_z \cdot (u_z) e$ .



Thus the electrons are driven towards one face in the sample material resulting in an excess of electrons near one face and a deficiency of electrons near the other face. These charges in turn will create a counter acting current field  $E_y$  in the  $y$  direction.  $E_y$  builds up until it has sufficient magnitude to compensate the Lorentz force exerted on the electrons due to the magnetic field.

$$eE_y = B_z e(V_x).$$

In the steady state a Hall Voltage is set up in the  $y$  direction which is given by:

$$V_H = E_y \cdot a = B_z(V_x) \cdot a$$

Current density in the sample is given by :  $J_x = N \cdot e \cdot (V_x)$

Where  $N$  = number of conduction electrons per unit volume

$$J_x = \frac{I}{a} b = Ne(V_x)$$

$$I = Ne(V_x) a \times b$$

And thus  $V_H = 1/(N \cdot e \cdot b)$

$$= (1/Ne) \cdot (B_z I / b)$$

Hence the ratio  $\pm \frac{1}{Ne} = \frac{E_y}{J_x B_z}$  must be a constant. It is called the Hall coefficient and is denoted by  $R_H$ . it varies from metal to metal and the +ve and -ve signs denote the charge of the carriers.

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

$$R_H = \pm \frac{I}{e} \left[ \frac{NeU_e^2 - NhU_h^2}{NeU_e + NhU_h} \right]$$

## THERMAL CONDUCTIVITY OF SEMICONDUCTORS

Heat conduction occurs in two ways:

1. by the electrons

2. by the thermal vibration of atoms

Random thermal vibrations of all the atoms in a semiconductor may be regarded as the sum total of the total vibrations of individual atoms, atoms in pairs.....body as a whole. The higher the temperature the greater are these vibrations.

The coefficient of thermal conductivity of a semiconductor has two parts i.e. the thermal conduction due to electrons and the thermal conduction due to the thermal vibration of atoms.

When concentration of free electrons in the semiconductor varies, the thermal conductivity due to electrons also varies in direct proportion to the electrical conductivity, whereas thermal conductivity due to vibrations remains practically constant. The WIEDEMANN-FRANZ law for metals is  $K/\sigma = A_m T$  where  $A_m$  is a constant for all metals. This law can be applied to semiconductors and states that

$K = A_s T \cdot \sigma + K_{lh}$  where  $A_s$  is the constant corresponding to the semiconductor and  $K_{lh}$  is the contribution to thermal conductivity due to vibration.

## ELECTRICAL CONDUCTIVITY OF DOPED MATERIALS

A semiconductor may be doped with donors and acceptors in which case the density of one type of carriers predominates. Thus in the presence of donor levels, the electrons are majority carriers and in presence of acceptor levels, holes are the majority carriers. The free carrier concentration given by impurity atoms whose valence electrons have energy less by  $\Delta E$  than their energy in free state is

$$n_e = A_1 \cdot e^{(-\Delta E/2KT)}$$

The valence band also always contains a certain no. of holes. It may be shown that electrons and holes concentration are related as

$$n_e n_h = n_i^2$$

Where  $n_i = e^{(-\Delta E/2KT)}$  is the concentration of either electrons or holes when no impurities are added and  $\Delta E$  = forbidden energy gap.

The product of two concentrations doesn't depend upon number of impurity atoms nor on electron energies of such atoms. It always equals to the square of free electrons or the hole concentration of pure semiconductor at that temperature.

If impurity atoms are electronegative the hole concentration will be

$n_h = A_2 e^{(\Delta E/2KT)}$  and the electron concentration will be  $n_e = n_i^2/n_h$