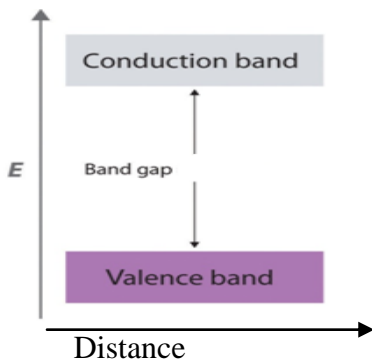


### Introduction:

Materials such as glass, ceramics, polymers, and paper are non-conducting materials. They prevent the flow of current through them. Therefore, they can be used for insulation purposes. When the main function of non-conducting materials is to provide electrical insulation, they are called **Insulators**.



**Figure 1: Band diagram of an insulator**

When non-conducting materials are placed in an electric field, they undergo appreciable changes because of which they act as stores of electric charges. When charge storage is the main function, the materials are called **Dielectrics**. For a material to be a good Dielectric, it must be an insulator.

The forbidden energy gap ( $E_g$ ) between the valence band and conduction band is very large (fig.1) in dielectrics and excitation of electrons from valence band to conduction band is not possible under ordinary conditions. Therefore, conduction cannot occur in a dielectric. Even if the dielectric contains impurities, extrinsic conduction cannot occur as observed in case of extrinsic semiconductors. The resistivity of an ideal dielectric is infinity, in practise dielectrics conduct electric current to a negligible extent and their resistivity range from  $10^{10}$  to  $10^{20} \Omega\text{m}$ .

### **Polar and Non-polar dielectrics:**

A dielectric material doesn't possess any free electrons. All the electrons are bound very strongly to the respective nuclei of the parent molecules. Each molecule consists of equal amount of positive and negative charges. All the positive charges are concentrated in the nuclei, which are surrounded by electron clouds in which all the negative charges are distributed.

In the molecules of some dielectric materials, the effective centre of the negative charge distribution coincides with the effective centre of the positive charges. Such materials are called non-polar dielectrics. eg Hydrogen, carbon dioxide etc.

In some dielectric materials, the effective centres of the negative and positive charges in the molecules do not coincide with each other even in the absence of any external field. Each molecule behaves as though it consists of a pair of equal negative and positive charges separated by a small distance. Such a pair is referred to as a permanent dipole and the materials comprising of such dipoles are called polar dielectrics. HCl, H<sub>2</sub>O etc.

### **Induced dipole:**

If an atom is placed in an electric field of strength 'E', the electron cloud will be displaced in the direction opposite to 'E' by a distance 'd' with respect to the nucleus. The centres of gravity of positive and negative charges in the atom no longer coincide.

The atom is equivalent to the system of charges,  $q = Ze$  of equal magnitude but opposite in sign separated by a distance 'd'. Such a system is called an **electric dipole**. The dipole is induced in the atom due to the action of external electric field. Though a dipole is electrically neutral, the induced dipole sets up its own electric field

which is opposite in direction to the external field. The dipole moment  $\mu$  is a vector, directed along the axis of the dipole from the negative charge to the positive charge.

When an atom or molecule is placed in an electric field, the field tends to displace the equilibrium position of the bound charges because of which dipole moment is induced in the molecule. The molecule is then said to be polarized.

When the molecule is polarized, restoring forces due to coulomb attraction come into play which tends to pull the displaced charges together. The charges separate until the restoring force balances the force due to the electric field.

The induced dipole moment is proportional to the field strength. The larger the field, greater the displacement of charges and hence larger the induced dipole moment. The induced dipole moment is given by.

$$\mu = \alpha E \quad \alpha \text{ is the polarizability of the molecule.}$$

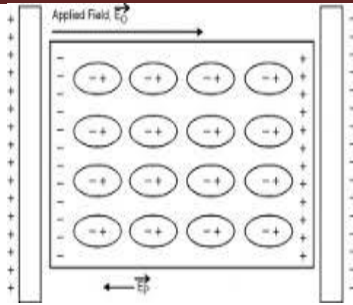
It characterizes the capacity of electric charges in a molecule to suffer displacement in an electric field. The unit of polarizability is  $\text{Fm}^2$ . The induced dipole moment vanishes as soon as the electric field is switched off.

### **Permanent dipole**

In some molecules known as polar molecules, the centres of gravity of the charges of opposite sign are separated even in the absence of external field. Such molecules are said to have intrinsic dipole moment and carry permanent dipoles.

### **Polarization**

Displacement of positive and negative charges in the molecules of a dielectric under the action of applied electric field leading to the development of dipole moment is known as dielectric polarization.



Consider an electrically neutral slab inserted between the plates of a parallel plate capacitor as shown in figure. Dielectric is imagined to be divided into large number of identical cells of volume  $dv$ . Under the action of external electric field, charges are induced in each cell and each cell acquires a dipole moment  $d\mu$ .

Then intensity of polarization “P” is defined as the total dipole moment per unit volume of the material.

$$P = \sum \frac{d\mu}{dv} = \frac{\mu}{v}$$

### **Dielectric constant**

For isotropic materials the electric flux density  $E$  and the electric induction (or electric displacement)  $D$  are related by the equation

$$D = \epsilon_0 \epsilon_r E$$

Where  $\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$ , is the dielectric constant of vacuum and  $\epsilon_r$  is the relative dielectric constant or relative permittivity for the material. It has no units.

### **Dielectric susceptibility**

The magnitude of polarization is directly proportional to the intensity of the electric field.

$$\text{Thus,} \quad P = \chi \epsilon_0 E \quad (\text{for linear dielectrics})$$

$\chi$  (chi) is the proportionality constant and is called the dielectric susceptibility of the material. It characterizes the ease with which the dielectric material can be influenced by an external field.  $P$  is a

measure of the polarization produced in the material per unit electric field.

### Relation between $\epsilon_r$ and $\chi$

To describe the combined effects of the applied electric field  $\mathbf{E}$  and electric polarization  $\mathbf{P}$ , an auxiliary vector  $\mathbf{D}$  called **Electric displacement vector** is introduced.

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$$

Substituting for  $\mathbf{P} = \chi \epsilon_0 \mathbf{E}$  in the above equation

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \chi \epsilon_0 \mathbf{E}$$

$$\mathbf{D} = (1 + \chi) \epsilon_0 \mathbf{E}$$

$$\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E} = \epsilon \mathbf{E}$$

$$\text{where } \epsilon_r = 1 + \chi$$

$\epsilon_0$  and  $\epsilon$  are the permittivity of the free space and the dielectric material respectively.  $\epsilon_r$  is the relative permittivity or the dielectric constant.

### Types of Polarization

#### i) Electronic or Atomic Polarization:

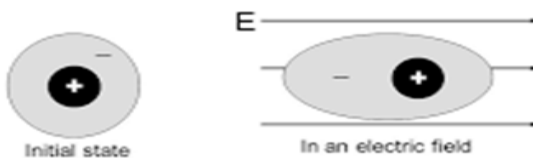


Figure 2: Electronic Polarization

This is the polarization that results from the displacement of electron clouds of atoms or molecules with respect to the heavy fixed nuclei to a distance that is less than the dimensions of atoms or molecules (figure 2). This polarization sets in over a very short period, of the order of  $10^{-14}$ - $10^{-15}$ s. It is independent of temperature.

The polarization is given by  $P_e = N\alpha_e E \dots (1)$

Where  $N$  is the number of atoms/unit volume,  $\alpha_e$  is electronic polarizability.

$$\text{We have } P = \chi \epsilon_0 E \text{ or } \chi = \frac{P}{\epsilon_0 E} \dots (2)$$

$$\text{Dielectric constant } \epsilon_r = 1 + \chi \dots (3)$$

Substituting eqn. (2) in eqn. (3)

$$\epsilon_r = 1 + \frac{P_e}{\epsilon_0 E} \dots (4)$$

Substituting for  $P_e$  from eqn (1) in eqn (4)

$$\epsilon_r = 1 + \frac{N \alpha_e E}{\epsilon_0 E}$$

$$\epsilon_r = 1 + \frac{N \alpha_e}{\epsilon_0} \dots (5) \text{ or } \alpha_e = \frac{\epsilon_0 (\epsilon_r - 1)}{N}$$

$\epsilon_r$  is the dielectric constant of a non-polar gaseous dielectric. The above equation indicates that the dielectric constant depends on the polarizability of a molecule and the number of molecules in a unit volume of the dielectric.

## **ii) Ionic Polarization:**

Ionic polarization occurs in ionic crystals. It is brought about by the elastic displacement of positive and negative ions from their equilibrium position. Eg: Sodium chloride crystal.

A NaCl molecule consists of  $\text{Na}^+$  ion bound to  $\text{Cl}^-$  ion through ionic bond. If the interatomic distance is 'd', the molecule exhibits an intrinsic dipole moment equal to "qd" where q is the charge of the electron and d is the distance of separation.

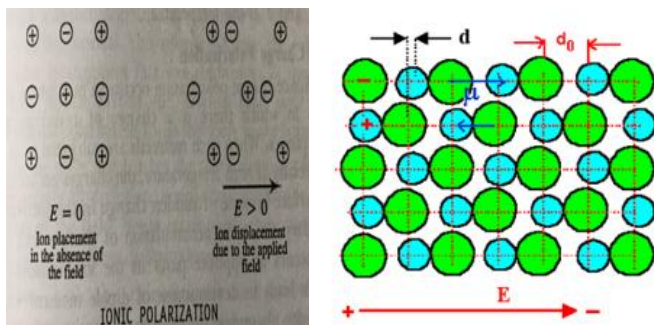


Figure 3: Ionic Polarization

When ionic solids are subjected to an external electric field, the adjacent ions of opposite sign undergo displacement (figure 3). The displacement causes an increase or decrease in the distance of separation between the atoms depending upon the location of the ion pair in the lattice. This polarization takes  $10^{-11}$ - $10^{-14}$ s to build up and is independent of temperature.

Ionic polarization is given by  $P_i = N\alpha_i E$

For most materials, the ionic polarizability is less than electronic polarizability. Typically,  $\alpha_i = \frac{1}{10} \alpha_e$

### iii) Orientation or dipole Polarisation

This polarization is a characteristic of polar dielectrics which consists of molecules having permanent dipole moment. In the absence of external electric field, the orientation of dipoles is random resulting in a complete cancellation of each other's effect.

When the electric field is applied, the molecular dipoles rotate about their axis of symmetry and tend to align with the applied field and the dielectric acquires a net dipole moment and it is orientation polarization.

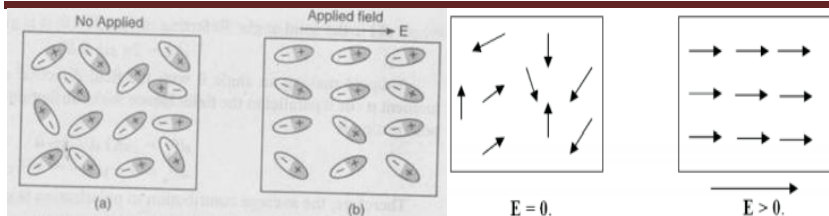


Figure 4: Orientation Polarization

The dipole alignment is counteracted by thermal agitation. Higher the temperature, the greater is the thermal agitation. Hence, orientation polarization is strongly temperature dependent.

In case of solids, the rotation of polar molecules may be highly restricted by the lattice forces, leading to a great reduction in their contribution to orientation polarization. Because of this reason, while the dielectric constant of water is about 80, that for solid ice is only 10.

As the process of orientation polarization involves rotation of molecules, it takes relatively longer time than other two polarisations.

The build up time is of the order of  $10^{-10}$ s or more.

The orientation polarizability  $\alpha_0 = \frac{\mu^2}{3kT}$  and

$$\text{orientation polarization } P_0 = \frac{N\mu^2 E}{3kT}$$

Orientation polarization is inversely proportional to temperature and proportional to the square of the permanent dipole moment.

#### **4. Space charge or Interface polarization:**

This polarisation occurs in multiphase dielectric materials in which there is a change of resistivity between different phases, when such materials are subjected to an electric field, especially at high temperatures, the charges get accumulated at the interface, because of sudden change in conductivity across the boundary. Since the



accumulation of charges with opposite faces occurs at opposite parts in the low resistivity phase, in effect it leads to the development of dipole moment within the low resistivity phase domain. E.g. Non-homogenous materials such as composites.

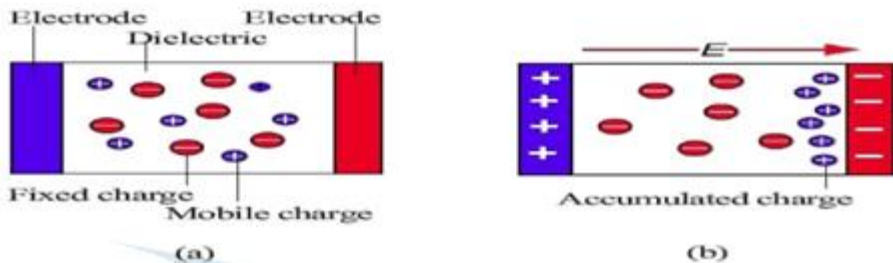


Figure 5: Space charge polarization

### Internal field in a solid for one dimensional infinite array of dipoles

When a dielectric material, either solid or liquid is subjected to an external electric field, each of the atoms develops a dipole moment and acts as an electric dipole. Hence the resultant field at any given atom will be the sum of applied electric field and the electric field due to the surrounding dipoles. The resultant local field is called the internal field ( $E_i$ ) and is defined as the electric field that acts at a site of any given atom of a solid or liquid dielectric subjected to an external electric field and is the resultant of the applied field ( $E$ ) and the field due to all the surrounding dipoles ( $E'$ ).

$$E_i = E + E'$$

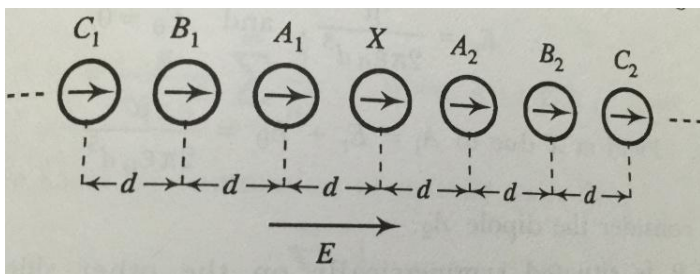


Figure 6: Linear array of atoms in an electric field

The total field at 'X' which is the internal field  $E_i$ , is the sum of the applied field ( $E$ ) and the field due to all the dipoles ( $E'$ )

$$E_i = E + E' = E + \frac{1.2\mu}{\pi\epsilon_0 d^3}$$

Thus, the combined effect of induced dipoles of neighbouring atoms is to produce a net field at the location of a given atom, which is larger than the applied field.

### **Clausius-Mosotti Equation:**

Let us consider a solid dielectric, which exhibits electronic polarizability. If  $\alpha_e$  is the electronic polarizability per atom, it is related to the bulk polarization  $P$  through the relation.

$$P = \alpha_e N E_i$$

$$\text{Therefore } \alpha_e = \frac{P}{N E_i} \dots (1)$$

Where  $N$  is the number of atoms per  $m^3$  and  $E_i$  is the local field.

$$\text{From Lorentz field equation } E_i = E + \frac{P}{3\epsilon_0} \dots (2)$$

Substituting equation (2) in equation (1) we get

$$\alpha_e = \frac{P}{N \left[ E + \frac{P}{3\epsilon_0} \right]}$$

$$\text{We have } E = \frac{P}{\epsilon_0 (\epsilon_r - 1)}$$

Substituting for  $E$  in the above equation, we obtain

$$\alpha_e = \frac{P}{N \left[ \frac{P}{\epsilon_0 (\epsilon_r - 1)} + \frac{P}{3\epsilon_0} \right]}$$

$$\frac{N\alpha_e}{\epsilon_0} = \frac{1}{\left[ \frac{1}{\epsilon_r - 1} + \frac{1}{3} \right]} = \frac{1}{\left[ \frac{\epsilon_r + 2}{3(\epsilon_r - 1)} \right]}$$

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

The above equation is known as Clausius Mosotti equation.

### **Solid, Liquid and Gaseous Dielectrics**

#### **Solid dielectrics:**

Most dielectric materials are solids and are used as insulation in capacitors, high voltage transformers, switches, overhead lines and cabling. Solid dielectrics have a moderate dielectric constant.

Examples of solid dielectric materials include: Inorganic materials such as ceramic and glass, Plastic films (e.g. Kapton), Rigid fibrous reinforced laminates, Resins, varnishes and silicones, Vulcanized adhesive tapes, Mica, Textiles and fibres (e.g. Nomex), Elastomers and rubber-like materials (PVC, MDPE, XLPE)

Solid dielectric materials have their own physical, electrical and thermal properties that make them suited to a specific type of application. Some are obviously more flexible, durable, absorb more or less moisture, and have different thermal insulating properties.

#### **Liquid dielectrics:**

The common uses of liquid dielectrics are insulation and cooling of transformers, reactors, capacitors and rheostats (variable resistors used to control currents). Dielectrics in liquid form are used to

prevent or slow down electric discharges. Primary disadvantage of many liquid dielectrics is that they are highly flammable. While alternatives to mineral oil have been tested, such as polychlorinated biphenyls (PCBs), silicone and fluorocarbon oils – these are highly toxic and very expensive.

Examples of liquid dielectric materials include: Mineral oil hydrocarbons, Silicone fluids, Synthetic esters

### **Gas dielectrics:**

Gas dielectrics are commonly used in sealed transformers, gas-insulated lines (GILs), voltage switchgears, circuit breakers and gas-insulated transformers (GIT). The most common insulating gas, sulphur hexafluoride, is high in fluorine, which is excellent at quenching discharge and has good cooling properties. However, decomposition can produce di-sulphur decafluoride, which is highly toxic. Some gas dielectrics include: Sulphur hexafluoride, Nitrogen, Air, Carbon dioxide, Hydrogen

### **Frequency dependence of Dielectric constant:**

Dielectric constant ( $\epsilon_r$ ) remains unchanged when the material is subjected to a dc voltage. But  $\epsilon_r$  changes when the material is subjected to the influence of an ac voltage, the changes depend on the frequency of the applied voltage. In addition,  $\epsilon_r$  becomes a complex quantity and is expressed as

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

where  $\epsilon_r'$  and  $\epsilon_r''$  are the real and imaginary parts of the dielectric constant.

$\epsilon_r'$  represents part of the dielectric constant that is responsible for the increase of capacitance.

$\epsilon_r''$  represents the loss

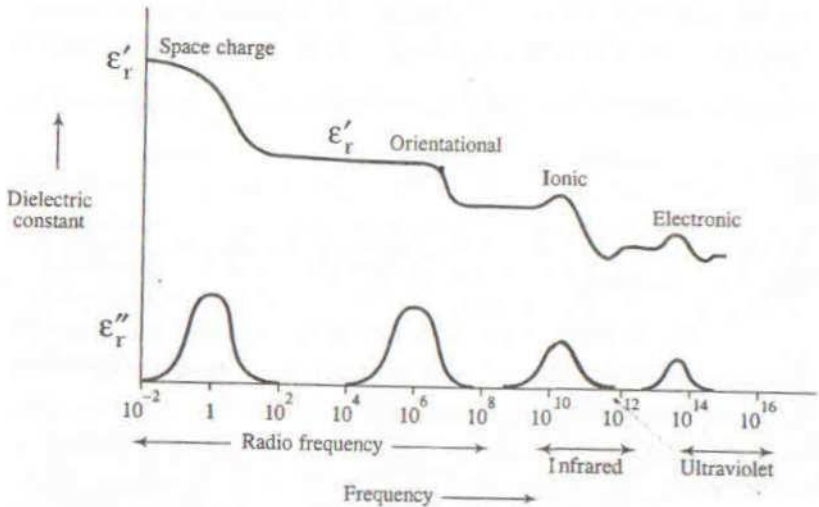


Figure 7: Variation of dielectric constant with frequency

All the four polarization mechanisms that occur in a dielectric material will be effective in static field conditions. But, each of them respond differently at different frequencies under alternating field conditions, since the relaxation frequency of different polarization processes are different as shown in figure 7. If  $\tau_e$ ,  $\tau_i$  and  $\tau_o$  are the relaxation times for electronic, ionic and orientation polarisations, then in general

$$\tau_e < \tau_i < \tau_o$$

When the frequency of applied field matches the relaxation frequency of a given polarisation mechanism, the absorption of energy from the field becomes maximum.

When the frequency of applied field becomes greater than the relaxation frequency for a particular polarisation mechanism, the

switching action of the dipoles cannot keep in step with that of changing field and the corresponding polarization mechanism is halted. Thus as the frequency of applied ac is increased, different polarization mechanisms disappear in the order- interface, orientation, ionic and electronic.

$$f_0 < f_i < f_e$$

The loss that occurs in a dielectric material is essentially due to the phase lag of voltage behind current in the capacitor between the plates of which dielectric material lies. Such a loss in a capacitor is expressed by a factor called  $\tan \delta$ . A large value of  $\tan \delta$  signifies higher dielectric loss. It is also referred to as tangent loss

$$\tan \delta = \frac{\epsilon_r''}{\epsilon_r'}$$

### **Dielectric Loss:**

When a conductor is subjected to an AC/DC electric field, it dissipates part of the electrical energy into heat energy. Power loss denotes the average electrical power dissipated in a material during a certain interval of time; it is also called as  $I^2R$  loss or Joules heat.

This power loss ( $I^2R$ ) in dielectrics is very small due to high resistance of dielectric materials to DC voltages and vice-versa to AC voltages. The absorption of electrical energy by a dielectric subjected to an alternating electric field is known as the dielectric loss. The origin of dielectric loss can be explained as follows:

“An AC field changes its direction with time. With each direction reversal, the molecules are required to follow the field reversals to contribute to the dielectric polarization.” A capacitor once charged in one half-cycle, the molecules of the dielectric medium are polarized. When the capacitor is discharged in the second half cycle, the molecules revert to their initial condition. During this process of returning to their initial state, the molecules jostle with each other

and lose energy due to friction. The energy lost due to friction takes the form of heat. This energy loss increases with increase in frequency.

### **Application of dielectrics in transformers:**

A transformer consists of two insulated coils wound on an insulated core. The amount of insulation to the coils and core are dependent on the voltage and hence in case of high voltage transformers insulation is required between individual windings of the coil and between the core and coils. The common materials used as insulation are paper, mica or cloth. The paper is impregnated with varnish or wax to fill the air gaps. Since the permittivity of air is less, the chances of ionization at high voltages exists which ultimately leads to excessive heating and damage to the insulation. This effect is called as corona. Mica is used to guard against corona. For operating voltages greater than 3 kV and up, a kind of oil based on minerals known as transformer oil is used. The role of the oil is to not only keep the transformer cool, but also guard against corona to upto 100 kV. A more conventional approach to keeping a large voltage transformer cool is by circulating cool water through it.

### **Dielectric Breakdown:**

When a dielectric is under the influence of a very high electric field, a considerable number of covalent bonds may be torn away and electrons may get excited to energies within the conduction band. These electrons acquire a large kinetic energy and cause localized melting, burning, vaporization of material leading to irreversible degradation and eventual failure of the material. This results in high electrical conductivity and total loss of the charge storage property of the dielectric. The formation of such conducting paths in a dielectric under the action of an applied electric field is termed **dielectric breakdown**.

### **Breakdown Mechanisms in Solid Dielectrics:**

The physical pattern of breakdown of solid dielectrics may differ in various cases. However, the fundamental breakdown mechanisms are as follows.

#### **1. Intrinsic Breakdown:**

- a. It occurs at large electric fields
- b. It occurs at ordinary temperatures.
- c. It occurs in thin samples.
- d. The breakdown time is of the order of microseconds.

#### **2. Thermal Breakdown:**

- a. It occurs at high temperatures.
- b. The breakdown time is of the order of milliseconds.
- c. In AC fields, the breakdown strength is lower.
- d. The breakdown strength depends on the size and shape of the material.

#### **3. Discharge Breakdown:**

- a. There are two types of breakdowns: External and Internal breakdown.
- b. It occurs at low electric fields.
- c. It depends on the frequency of the applied voltage.

#### **4. Electrochemical Breakdown:**

- a. It depends on the concentration of ions and magnitude of leakage current.
- b. It occurs at ordinary temperatures.

#### **5. Defect Breakdown:** If the surface of the dielectric material has defects such as cracks and porosity, impurities such as dust or moisture may deposit at these defects. These impurities lead to breakdown.



## **ELASTICITY:**

### **Introduction:**

Materials are classified as Rigid, Elastic and Plastic based on the behavior of the material on the application of external force also called as applied force or deforming force.

A rigid body is one which does not undergo any deformation when external forces act on it. When forces are applied on a rigid body the distance between any two particles of the body will remain unchanged however large the force may be. In actual practice no body is perfectly rigid. For practical purposes solid bodies are taken as rigid bodies.

When a body acted upon by a suitable force undergoes a change in form then this change in form is called Deformation. The change could be either in shape or size or even both. If the body recovers its original state on the removal of deforming force, then it is called as an Elastic material. eg. Quartz

**“Elasticity is the property of the material of a body by virtue of which it regains its original shape and size after the deforming forces are removed”.**

If the body does not show any tendency of returning back to its original or initial state and stays in the changed form after the withdrawal of external force, then it is said to be in Plastic state. Eg Clay.

**“Plasticity is the property of the material of a body by virtue of which it fails to regain its original shape and size after the deforming forces are removed”.**

### **Deforming Force:**

Consider a body which is not free to move and is acted upon by external force. Due to the action of external forces the body changes its shape or size. Now the body is said to be deformed. Thus, the applied external force which causes deformation is called deforming force.

### **Restoring force:**

When deforming force is applied to a body then molecules of body tend to displace from their position. As a result of this, a reaction force is developed within the body which tries to bring the molecules back to its equilibrium position. This reaction force which is developed in the body is called internal force or restoring force.

### **STRESS:**

Under the action of external force, the body changes its form because the molecules inside it are displaced from their previous positions. While they are displaced, the molecules develop a tendency to come back to their original positions, because of intermolecular binding forces. The aggregate of the restoration tendency exhibited by all the molecules of the body manifests as a balancing force or restoring force counteracting the external force. This restoring force is equal in magnitude but opposite to that of the applied force. Therefore, **stress is given by the ratio of Restoring force to the area of its application. Unit of stress is  $\text{Nm}^{-2}$ .**

**Normal stress:** Restoring force per unit area perpendicular to the surface is called normal stress.

**Tangential stress:** Restoring force parallel to the surface per unit area is called tangential stress.

## **STRAIN:**

The deformation produced by the external force accompanying a change in dimensions or form of the body is called strain. It is the **ratio of change in dimensions of the body to its original dimensions.**

The way in which the change in dimensions is produced depends upon the form of the body and the manner in which the force is applied. Deformation is of three types, resulting in three types of strains, defined as follows:

**i) Linear strain or Tensile strain:** If the shape of the body could be approximated to the form of a long wire and if a force is applied at one end along its length keeping the other end fixed, the wire undergoes a change in length.

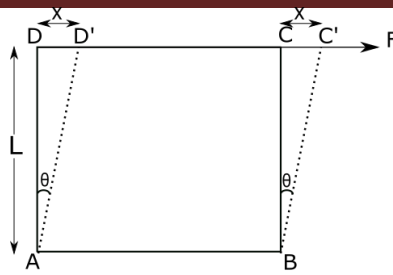
If  $x$  is the change in length produced for an original length  $L$  then,

$$\text{Linear strain} = \frac{\text{change in length}}{\text{original length}} = \frac{x}{L}$$

**ii) Volume strain:** If a uniform force is applied all over the surface of a body, the body undergoes a change in its volume (however the shape is retained in case of solid bodies). If  $v$  is the change in volume to an original volume  $V$  of the body then,

$$\text{Volume strain} = \frac{\text{change in volume}}{\text{original volume}} = \frac{v}{V}$$

**iii) Shear strain:** If a force is applied tangentially to a free portion of the body, another part being fixed, its layers slide one over the other; the body experiences a turning effect and changes its shape. This is called **shearing** and the angle through which the turning takes place is called **shearing angle ( $\theta$ )**.



$$\text{Shearing strain } (\theta) = \frac{x}{L}$$

### **HOOKE'S LAW:**

There is a relation between stress and strain and the relation between the two is given by Hooke's law.

It states that “**stress is proportional to strain**” (provided strain is small), so that the ratio of stress to strain is a constant, called the **modulus of elasticity or coefficient of elasticity**. i.e., **stress  $\propto$  strain**,

$$\text{Or, } \frac{\text{stress}}{\text{strain}} = \text{a constant (E)}$$

### **STRESS - STRAIN RELATIONSHIP IN A WIRE**

When the stress is continually increased in the case of a solid, a point is reached at which the strain increases rapidly. The stress at which the linear relationship between stress and strain ceases to hold good is referred to as the *elastic limit of the material*. Thus, if the material happens to be in the form of a bar or a wire under stretch, it will recover its original length on the removal of the stress so long as the stress is below the elastic limit, but if this limit is exceeded, it will fail to do so and will acquire what is called as ‘*permanent set*’.

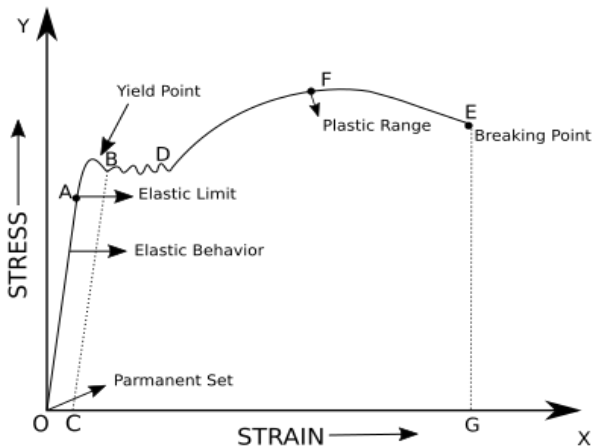


Figure 8: Stress-Strain diagram.

The relationship between stress and strain is studied by plotting a graph for various values of stress and the accompanying strain. The straight and sloping part OA of the curve shows that the strain produced is directly proportional to the stress applied or the Hooke's law is obeyed perfectly up to A and that, therefore, on the removal of the stress, it will recover its original condition of zero strain, represented by O.

As soon as the elastic limit is crossed, the strain increases more rapidly than the stress, and the graph curves along AB, the extension of the wire now being partly elastic and partly plastic. Hence, on being unloaded here, say, at the point B, it does not come back to its original condition along AO, but takes the dotted path BC, so that there remains a residual strain OC in it, which is *permanent set acquired by the wire*. **The strain left behind in the material even after the removal of the applied load is called residual strain.**

Beyond the point B, for practically little or no increase in stress (or the load applied) there is a large increase in strain (i.e., in the extension produced) up to D, so that the portion BD of the graph is an irregular wavy line, the stress corresponding to D being less than

that corresponding to B. This point B where the large increase in strain commences is called the **yield point**, the stress corresponding to it being known as the **yielding stress**. The yielding ceases at D and further extension, which now becomes plastic, (being mainly due to shear stress rather than simple tension) can only be produced gradually increasing the load so that the portion DF of the graph is obtained, the cross-section of the wire decreasing uniformly with extension (or strain) upto F and hence volume remaining constant. *The maximum load (or force) to which the wire is subjected divided by its original cross-sectional area is called the **ultimate strength** or the **tensile strength** of the wire and is also termed as **breaking stress**.*

The extension of the wire goes on increasing beyond F without any addition to the load, even if the load is reduced a little, and wire behaves as though it were literally ‘flowing down’. This is because of a faster rate of decrease of its cross-sectional area at some section of its length where local constriction, called a “neck” begins to develop, with the result that, even if the load is not increased, the load per unit area or the stress becomes considerably greater there, bringing about corresponding increase in strain or extension in the wire. The load is there, decreased, i.e., the stress reduced at this stage and the wire finally snaps or breaks at E, which thus represents the breaking point for it.

**Elastic Fatigue:** We recall that, if the maximum stress in the specimen does not exceed the elastic limit of the material, the specimen returns to its initial condition when the load is removed. Such a conclusion is correct for loadings repeated a few dozen or even a few hundred times. However, it is not true when loading is repeated thousands or millions of times. In such cases rupture will occur at a stress much lower than the static breaking strength, this phenomenon is known as Fatigue. A fatigue failure is of a brittle nature even for materials that are normally ductile.

A body subjected to repeated strains beyond its elastic limit, has its elastic properties greatly impaired, and may break under a stress less than its normal breaking stress even within its elastic limit. This is called elastic fatigue.

Fatigue must be considered in the design of all structural and machine components that are subjected to repeated or to fluctuating loads. The number of loading cycles that may be expected during the useful life of a component varies greatly. For example, a beam supporting an industrial crane may be loaded as many as two million times in 25 years (about 300 loadings per working day) an automobile crankshaft will be loaded about half a billion times if the automobile is driven 320,000 km, and an individual turbine blade may be loaded several hundred billion times during its lifetime.

**Strain Hardening:** When a metal is stressed beyond its elastic limit, it enters the plastic region (region in which the residual strain remains upon unloading). When the load is further increased, the material hardens and becomes stronger, i.e. it's more difficult to deform the material as the strain increases and hence it's called "strain hardening". This tends to increase the strength of the material and decreases its ductility. It is region between yield point and ultimate tensile strength.

**Strain softening:** Strain softening is defined as the region in which the stress in the material is decreasing with an increase in strain. It is observed after the yield point. This is due to brittleness and heterogeneity of the material.

**Corresponding to the three types of strain, we have three types of elasticity:**

**a) Linear Elasticity or Elasticity of length called Young's modulus, corresponding to linear or tensile strain:**

When the deforming force is applied to the body, along a particular direction, the change per unit length in that direction is called longitudinal, linear or elongation strain, and the force applied per unit area of cross section is called longitudinal or linear stress. **The ratio of longitudinal stress to linear strain within elastic limit is called the coefficient of direct elasticity or Young's modulus and is denoted by Y or E.**

If F is the force applied normally, to a cross-sectional area a, then the stress is F/a. If L is original length and x is change in length due to the applied force, the strain is given by x/L, so that,

$$Y = \frac{\text{Normal stress}}{\text{Longitudinal strain}} = \frac{F/a}{x/L} = \frac{FL}{ax} \text{ N/m}^2$$

**b) Elasticity of volume or Bulk modulus:**

When the deforming force is applied normally and uniformly to the entire surface of a body, it produces a volume strain (without changing its shape in case of solid bodies). The applied force per unit area gives the normal stress or pressure. **The ratio of normal stress or pressure to the volume strain without change in shape of the body within the elastic limits is called Bulk modulus.**

If F is the force applied uniformly and normally on a surface area (a) the stress or pressure is F/a or P and if v is the change in volume produced in an original volume V, the strain is given by v/V and, therefore,

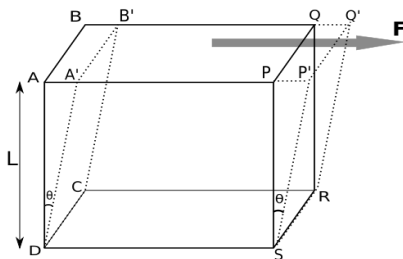
$$K = \frac{\text{Normal stress}}{\text{Volume strain}} = \frac{F/a}{v/V} = \frac{FV}{av} = \frac{PV}{v} \text{ N/m}^2$$

**Bulk modulus is referred to as incompressibility and hence its reciprocal is called compressibility (strain per unit stress).**



**c) Modulus of Rigidity (corresponding to shear strain) :**

In this case, while there is a change in the shape of the body, there is no change in its volume. It takes place by the movement of contiguous layers of the body, one over the other. There is a change in the inclinations of the co-ordinates axes of the system or the body. Consider a rectangular solid cube whose lower face DCRS is fixed, and to whose upper face a tangential force  $F$  is applied in the direction as shown. Under the action of this force, the layers of the cube which are parallel to the applied force slide one over the other such that point  $A$  shifts to  $A^1$ ,  $B$  to  $B^1$ ,  $P$  to  $P^1$  and  $Q$  to  $Q^1$  that is the planes of the two faces  $ABCD$  and  $PQRS$  can be said to have turned through an angle  $\theta$ . This angle  $\theta$  is called the angle of shear or **shearing strain**. Tangential stress is equal to the force  $F$  divided by area of the face  $APQB$ .



Hence **tangential stress** =  $\frac{F}{a}$

Shearing strain ( $\theta$ ) =  $\frac{PP^1}{PS} = \frac{x}{L}$

**The rigidity modulus is defined as the ratio of the tangential stress to the shearing strain.**

**Rigidity modulus  $\eta$**  =  $\frac{\text{tangential stress}}{\text{shearing strain}} = \frac{F/a}{\theta} = \frac{F/a}{x/L} = \frac{FL}{ax} \text{ N/m}^2$

## RELATION BETWEEN THE ELASTIC CONSTANTS

$$\frac{9}{Y} = \frac{3}{\eta} + \frac{1}{K}$$

### Relation between $K$ , $\eta$ and $\sigma$

$$\sigma = \frac{3K - 2\eta}{2\eta + 6K}$$

### **Poisson's Ratio ( $\sigma$ ):**

In case of any deformation taking place along the length of a body like a wire, due to a deforming force, there is always some change in the thickness of the body. This change which occurs in a direction perpendicular to the direction along which the deforming force is acting is called **lateral change**.

**Within elastic limits of a body, the ratio of lateral strain to the longitudinal strain is a constant and is called Poisson's ratio.**

If a deforming force acting on a wire of length  $L$  produces a change in length  $x$  accompanied by a change in diameter of 'd' in it which has an original diameter of 'D', then lateral strain  $\beta = \frac{d}{D}$  and

Longitudinal strain  $\alpha = \frac{x}{L}$ ,

$$\therefore \text{Poisson's ratio, } \sigma = \frac{\beta}{\alpha} = \frac{Ld}{xD}$$

**There are no units for Poisson's ratio. It is a dimensionless quantity.**

### Strain Gauge:

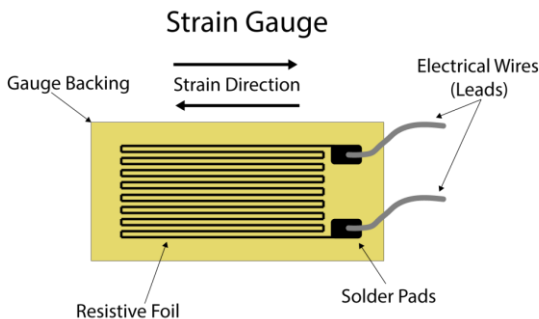


Figure 9: A generic strain gauge

A strain gauge is a sensor whose measured electrical resistance varies with changes in strain. Strain is the deformation or displacement of material that results from an applied stress. Stress is the force applied to a material, divided by the material's cross-sectional area. Strain gauges convert the applied force, pressure, torque, etc., into an electrical signal which can be measured. Force causes strain, which is then measured with the strain gauge by way of a change in electrical resistance. Then the voltage measurement is gathered using data acquisition.

The strain gauge must be connected to an electrical circuit that is capable of accurately responding to the minute changes in resistance associated with strain. Multiple strain gauges can be used in a divided bridge circuit to measure small changes in electrical resistance. This is called a Wheatstone bridge. In a Wheatstone bridge configuration, an excitation voltage is applied across the circuit, and the output voltage is measured across two points in the middle of the bridge. When there is no load acting on the load cell,

the Wheatstone bridge is balanced and there is zero output voltage. Load cells are designed to focus stress through beam elements where strain gauges are located. Any small change in the material under the strain gauge results in a change in the resistance of the strain gauge as it deforms with the material. This causes the bridge to be thrown out of balance, resulting in a change in the output voltage. As stated earlier, the resistance change is minute, which means that signal amplification is often needed to properly determine changes. The amplification process strengthens the strain signal changes; however, it also leads to more unwanted noise also being detected in the signal. Signal conditioning filters out the excess noise, ensuring accurate and understandable data.

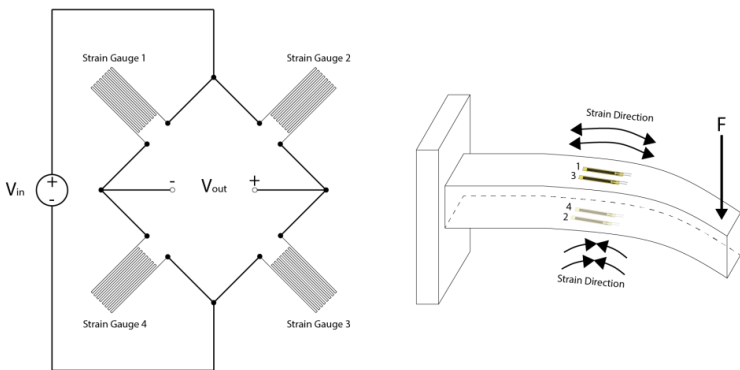


Figure 10: Wheatstone bridge and location of strain sensor

### **Transducers:**

A transducer is an electrical device that is used to convert one form of energy into another form. In general, these devices deal with different types of energies such as mechanical, electrical energy, light energy, chemical energy, thermal energy, acoustic energy, and electromagnetic energy.

For instance, consider a mike used in telephones, mobile phones, etc. It converts sound into electrical signals and the signal then amplified into the preferred range. The ensuing electrical signals are converted back into audio signals at the output of the loudspeaker. LED lights are also a kind of transducer that converts electrical into light energy. The best transducer examples are loudspeakers, microphones, position, thermometers, antenna, & pressure sensor. Likewise, there are different kinds of transducers used in electrical and electronic projects.



Figure 11: Transducer working principle

### **Transducer Types and Its Applications:**

There are a variety of transducer types like pressure transducer, piezoelectric transducer, ultrasonic transducer, temperature transducer, and so on. Let us discuss the use of different types of transducers in practical applications. Some transducer types like

active transducer and passive transducers are based on whether a power source is required or not.

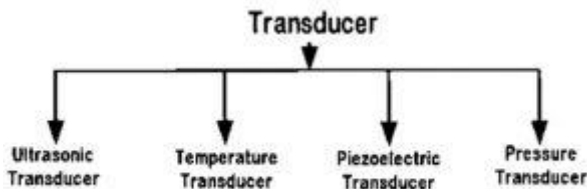


Figure 12: Types of Transducer

Active transducers don't require any power source for their operation and work on the principle of energy conversion. They generate an electrical signal that is proportional to the input. Passive transducers require an external power source for their operation and generate an output in the form of capacitance, or resistance. The signal is then converted into an equivalent voltage or current signal.

### **Piezoelectric Transducer:**

A piezoelectric transducer or piezoelectric sensor is a device that uses the piezoelectric effect to measure changes in acceleration, pressure, strain, temperature or force by converting pressure energy into an electrical charge. When a force or pressure is applied on a piezoelectric material, the transducer converts this energy into voltage. This voltage, a function of the force or pressure applied can be easily measured by using a voltmeter and a precise value of the force/pressure from the voltage reading can be inferred. In this way, physical quantities like mechanical stress or force can be measured directly using a piezoelectric transducer.

A generic piezoelectric transducer consists of a quartz crystal which is made from silicon and oxygen arranged in crystalline structure ( $\text{SiO}_2$ ). Generally, a unit cell (basic repeating unit) in all crystals is symmetrical; but in piezoelectric quartz crystal, the arrangement of atoms is not symmetrical. Though the atoms inside

them may not be symmetrically arranged, yet their electrical charges are balanced so that the positive charges cancel out negative charges. The quartz crystal has the unique property of generating electrical polarity when mechanical stress applied to it along a certain plane.

Basically, there are two types of stress. One is compressive stress and the other is tensile stress. In unstressed quartz no charges are induced on it. In the case of compressive stress, positive charges are induced on one side and negative charges are induced in the opposite side. The crystal size gets thinner and longer due to compressive stress. In the case of tensile stress, charges are induced in reverse and the quartz crystal gets shorter and thicker. The rate of charge produced will be directly proportional to the rate of change of mechanical stress applied on the crystal.

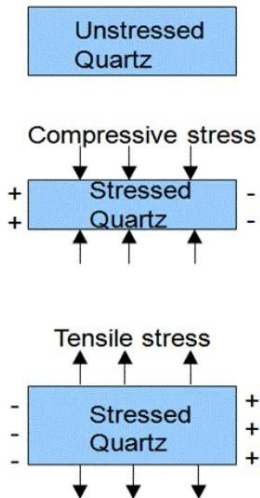


Figure 13: Stressed and Unstressed Quartz crystal

One of the unique characteristics of the piezoelectric effect is that it is reversible, which means when voltage is applied to them,

they tend to change dimension along with the direction of the field applied i.e. quartz crystal when placed in an electric field will deform by an amount proportional to the strength of the electric field.

### **Piezoelectric Transducer Formula:**

The orientation of the crystal also affects the amount of voltage generated. Crystal in a transducer can be arranged in longitudinal position or transverse position. In the longitudinal arrangement, the charge generated is given by

$$Q = F * d$$

Where F is the applied force, d is the piezoelectric coefficient of the crystal ( $d_{\text{quartz}} = 2.3 * 10^{-12} \text{ C/N.}$ )

In the transverse effect, the charge generated is given by

$$Q = F * d * (b/a)$$

When the ratio b/a is greater than 1 the charge produced by transverse arrangement will be greater than the amount generated by longitudinal arrangement.

### **Piezoelectric Ultrasonic Transducer:**

The ultrasonic piezoelectric transducer works on the principle of the converse piezoelectric effect. In this effect when electricity is applied to a piezoelectric material, it undergoes physical deformations proportional to applied charge. The circuit of the ultrasonic transducer is given below.



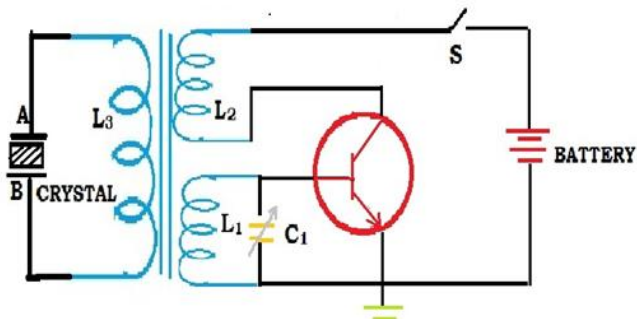


Figure 14: Ultrasonic piezoelectric transducer

The quartz crystal is placed between two metal plates A and B which are connected to the primary  $L_3$  of the transformer. The primary of the transformer is inductively coupled to the electronic oscillator. The coils  $L_1$  and  $L_2$ , which forms secondary of the transformer, are connected to the electronic oscillator.

When the battery is turned ON, the oscillator produces high-frequency alternating voltage pulses with a frequency  $f = \frac{1}{2\pi\sqrt{L_1 C_1}}$ . Due to this, an e.m.f is induced in  $L_3$  which is transferred to the quartz crystal through plates A and B. Due to converse piezoelectric effect the crystal starts contracting and expanding alternatively thus creating mechanical vibrations. Resonance takes place when the frequency of the electronic oscillator is equal to the natural frequency of the quartz. At this point, quartz produces longitudinal ultrasonic waves of large amplitude.

### **Piezoelectric Transducer Applications:**

As piezoelectric materials cannot measure static values they are primarily used for measuring surface roughness, in accelerometers and as a vibration pickup.

- Used in seismographs to measure vibrations in rockets.
- In strain gauges to measure force, stress, vibrations etc...
- Used by automotive industries to measure detonations in engines.
- Used in ultrasonic imaging in medical applications.

### **Temperature Transducer: Thermocouple:**

A thermocouple is a device for measuring temperature. It comprises two dissimilar metallic wires joined together to form a junction at one end and terminated at the other. The joined end is called the sensing junction or hot junction and the terminated end is called the reference junction or cold junction. The temperature at the reference junction is always maintained at a constant value. When the sensing junction is heated or cooled, a variation in temperature occurs between the junctions resulting in the development of a potential difference causing a flow of current in the circuit. The thermoelectric voltage produced is due to the different binding energies of the electrons to the metal ions. This voltage depends on the metals themselves, and in addition on the temperature. The thermal voltage is produced only because of the closed circuit between the two metals. This phenomenon is called “Seebeck Effect”.

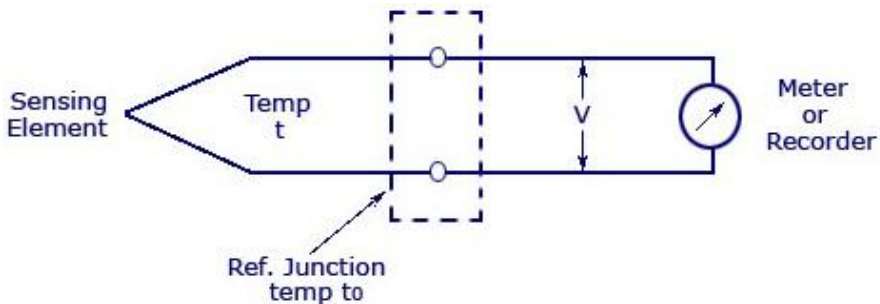


Figure 15: Schematic of a thermocouple

In theory, any two metals can be used to make a thermocouple but in practice, there are a fixed number of types that are commonly used. They have been developed to give improved linearity and accuracy and comprise specially developed alloys like Chromel, Alumel, Constantan, etc. Thermocouples can be made to be robust, fast responding and measure a very wide temperature ranges and applications.

Depending on an application's process temperature range, accuracy specifications, and material compatibility, thermocouple sensors are available in different types like K, J, E, Type T thermocouples, Type S thermocouples, Type R thermocouples, and other dissimilar metal combinations.

### **SOLVED NUMERICALS**

1. Calculate the dielectric constant of NaCl, if a NaCl crystal is subjected to an electric field of 1000 V/m and the resulting polarization is  $4.3 \times 10^{-8} \text{ C/m}^2$ .

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

$$(\epsilon_r - 1) = \frac{P}{\epsilon_0 E} = \frac{4.3 \times 10^{-8}}{8.856 \times 10^{-19} \times 10^3} = 0.0049$$

$$\epsilon_r = 1.0049$$

2. The dielectric constant of Helium at  $0^\circ\text{C}$  is 1.000074. The density of atoms is  $2.7 \times 10^{25} / \text{m}^3$ . Calculate the dipole moment induced in each atom when the gas is placed in an electric field of  $3 \times 10^4 \text{ V/m}$ .

Dipole moment induced in each atom is  $\alpha_e E$  where the electronic

$$\text{polarizability } \alpha_e = \frac{\epsilon_0 (\epsilon_r - 1)}{N} = \frac{8.854 \times 10^{-12} \times 0.000074}{2.7 \times 10^{25}} = 2.4255 \times 10^{-41}$$

$$\text{Dipole moment} = 2.4255 \times 10^{-41} \times 3 \times 10^4 = 7.2767 \times 10^{-37} \text{ Cm}$$

3. An elemental solid dielectric material has a polarizability  $7 \times 10^{-40} \text{ Fm}^2$ . Assuming the internal field to be Lorentz field, calculate the dielectric constant for the material if the material has  $3 \times 10^{26} \text{ atoms/m}^3$ .

$$\frac{(\epsilon_r - 1)}{(\epsilon_r + 2)} = \frac{N\alpha_e}{3\epsilon_0} = \frac{3 \times 10^{26} \times 7 \times 10^{-40}}{3 \times 8.854 \times 10^{-12}} = 0.7906$$

$$(\epsilon_r - 1) = (\epsilon_r + 2) \times 0.7906$$

$$\epsilon_r = \frac{2.5812}{0.2094} = 12.33$$

4. A monoatomic gas contains  $3 \times 10^{25} \text{ atoms/m}^3$  at a certain temperature at one atmosphere pressure. The radius of the atom is 0.19 nm. What is the relative permittivity of the gas at the given pressure and temperature? What is the polarizability of the atom?

**Answer:**  $1^{26}$ ;  $7.66 \times 10^{-40} \text{ F.m}$

5. A metallic cube of side 100 cm is subjected to a uniform force acting normal to the whole surface of the cube. The pressure is  $10^6 \text{ Pascal}$ . If the volume changes by  $1.5 \times 10^{-5} \text{ m}^3$ , calculate the bulk modulus of the material.

$$\text{By definition, } K = \frac{\frac{F}{A}}{\frac{\Delta V}{V}} = P \frac{V}{\Delta V}$$

$$K = \frac{10^6 \times 1}{1.5 \times 10^{-5}} = 6.67 \times 10^{10} \text{ N m}^{-2}$$

6. A metal cube of side 0.20 m is subjected to a shearing force of 4000 N. The top surface is displaced through 0.50 cm with respect to the bottom. Calculate the shear modulus of elasticity of the metal.

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$$\eta_R = \frac{F}{A} \times \frac{L}{x} = \frac{4000}{0.04} \times \frac{0.20}{0.005} = 4 \times 10^6 \text{ N m}^{-2}$$

7. A bar subjected to a tensile load 55 KN. Bar diameter=31 mm; Gauge length=300mm; extension=.115mm; change in diameter=.00367mm. Find: Poisson's ratio, Young's modulus, Bulk modulus, and modulus of rigidity.
- 1) Poisson's ratio=lateral strain/longitudinal strain  $\Rightarrow \sigma=0.308$
  - 2) Young's modulus=stress/strain;  $Y=190.09 \times 10^3 \text{ N/mm}^2$
  - 3)  $Y=3K (1-2\sigma) \Rightarrow 190.09 \times 10^3 = 3K (1-2 \times 0.308) \Rightarrow$  Bulk modulus (K)= $165 \times 10^3 \text{ N/mm}^2$
  - 4)  $Y=2\eta(1+\sigma) \Rightarrow 190.09 \times 10^3 = 2 \times \eta(1+0.308) \Rightarrow$  Modulus of rigidity ( $\eta$ )= $72.664 \times 10^3 \text{ N/mm}^2$

S. No	Sample Questions
1.	Define polarization? Explain the four types of polarization.
2.	Arrive at Clausius-Mosotti equation.
3.	Define dielectric polarizability and dielectric susceptibility.
4.	Derive an expression for the internal field in a one dimensional array of atoms in a dielectric solid?
5.	Write a short note on dielectric loss. Show that dielectric loss is given by $\tan \delta = \frac{\epsilon''_r}{\epsilon'_r}$
6.	Discuss the stress-strain curve with a neat figure.
7.	What are the different moduli of elasticity? Discuss their relationships?
8.	What are transducers? Explain the different types of transducers.
9.	Explain the construction and working of a ultrasonic piezoelectric transducer.

10.	Discuss the construction and working of a strain gauge.
11.	Explain the construction and working of a thermocouple.

## Appendix

### Lorentz field

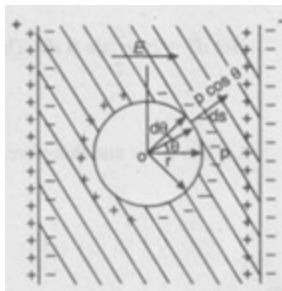


Figure 16

The local field in a three dimensional solid is determined by the structure of the solid.

Let us consider a dielectric slab kept in a uniform electric field,  $E$  (Figure 15 ). Let a molecule be at the point  $O$  and is surrounded by a spherical cavity of radius  $r$ . Let  $r$  be arbitrary but sufficiently large compared to molecular dimensions and sufficiently small compared to the dimensions of the dielectric slab. The spherical cavity contains many molecules within it. The molecule at  $O$  experiences three electric fields acting on it.

- i) The external electric field  $E$ .
- ii) The field  $E_1$  due to induced charges on the surface of the spherical cavity.
- iii) The field  $E_2$  due to the molecular dipoles present in the spherical cavity.

Therefore, the total internal field intensity,  $E_i$  is given by

$$E_i = E + E_1 + E_2$$

To calculate  $E_1$ , let us imagine that the dielectric is removed from the sphere. For the actual pattern of the electric field not to be distorted,

a surface electric charge should be placed on the spherical surface. At each point of the sphere, the surface charge density is given by

$$\sigma = P \cos \theta$$

where  $\theta$  is the angle between radius vector  $\mathbf{r}$  and the direction  $\mathbf{E}$ . The charge on the element  $dS$  of the surface of the sphere will be  $dq = \sigma dS = P \cos \theta dS$

This charge will produce electric field intensity  $dE_1$  at the centre of the sphere

$$dE_1 = \frac{dq}{4\pi\epsilon_0 r^2} = \frac{P}{4\pi\epsilon_0 r^2} \cos \theta dS$$

This electric field can be resolved into two components: one component  $dE_1 \cos \theta$  parallel to the direction of  $\mathbf{E}$  and the other  $dE_1 \sin \theta$  perpendicular to the direction of  $\mathbf{E}$ .

$$dE_1 \cos \theta = \frac{P}{4\pi\epsilon_0 r^2} \cos^2 \theta dS$$

$$dE_1 \sin \theta = \frac{P}{4\pi\epsilon_0 r^2} \cos \theta \sin \theta dS$$

It is obvious that the perpendicular components of the upper and lower half of the sphere cancel each other and only the parallel components contribute to the total intensity  $E_1$ .  $E_1$  is obtained by integrating  $dE_1$  over the whole surface area of the sphere. Thus,

$$E_1 = \int_0^\pi dE_1 \cos \theta dS = \frac{P}{4\pi\epsilon_0 r^2} \int_0^\pi \cos^2 \theta dS$$

But  $dS = 2\pi r^2 \sin \theta d\theta$ . Therefore,

$$E_1 = \frac{P}{2\epsilon_0} \int_0^\pi \cos^2 \theta \sin \theta d\theta$$

Let  $\cos \theta = x$  and therefore,  $-\sin \theta d\theta = dx$ .  
 when  $\theta = 0$ ,  $\cos \theta = 1$  and  $\theta = \pi$ ,  $\cos \pi = -1$

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$$E_1 = -\frac{P}{2\epsilon_0} \int_1^{-1} x^2 dx = -\frac{P}{2\epsilon_0} \left[ \frac{x^3}{3} \right]_1^{-1} = -\frac{P}{2\epsilon_0} \left[ \frac{-1}{3} - \frac{1}{3} \right] = \frac{-P}{2\epsilon_0} \left( \frac{-2}{3} \right) = \frac{2P}{6\epsilon_0} = \frac{P}{3\epsilon_0}$$

As there exists symmetrical distribution of molecular dipoles around the molecules at O within the cavity, their contribution cancel each other.

Therefore  $E_2=0$ .

Hence the total internal field is given by  $E_i = E + E_1$

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

The field given by the above equation is called **Lorentz field** or **local field**.