...microphones, etc.

9.1 POLARIZATION AND SUSCEPTIBILITY

When a dielectric is placed in an external electric field $\mathbf{E}_0$, the positive and negative charges are displaced from their equilibrium positions by very small distances (less than an atomic diameter) throughout the volume of the dielectric. This results in the formation of a large number of dipoles each having some dipole moment in the direction of the field. The material is said to be polarized with a *polarization* **P** defined as the dipole moment per unit volume of the material. As shown in Fig. 9.1, the effect of polarization is to reduce the magnitude of the external field $\mathbf{E}_0$. Thus the magnitude of the resultant field is less than the applied field, i.e., $E < E_0$. In vector notation, we may write

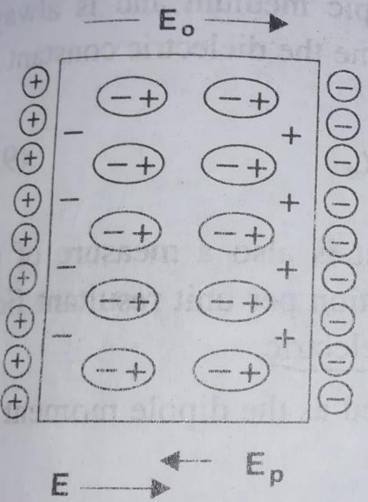

Fig. 9.1. A dielectric slab placed in an electric field $\mathbf{E}_0$ *produced by fixed charges (encircled) outside the slab. The internal polarization field* $\mathbf{E}_p$ *is assumed to be due to fictitious bound charges at the surface of the slab and is directed opposite to* $\mathbf{E}_0$.

$$\mathbf{E} = \mathbf{E}_0 + \mathbf{E}_p \tag{9.1}$$

The field $\mathbf{E}_p$ is called the *polarization field* as it tends to oppose the applied field E_0 within the material. For ordinary electric fields, the polarization **P** is proportional to the macroscopic field **E**. In SI units, it is expressed as

$$\mathbf{P} = \varepsilon_0 \chi_e \mathbf{E} \tag{9.2}$$

where ε_0 is the permittivity of free space and χ_e is the electric susceptibility. Thus, except for a

9.2 THE LOCAL FIELD

The electric field acting at the site of an atom or molecule is, in general, significantly different from the macroscopic electric field **E** and is called the *local field*. This field is responsible for polarization of each atom or molecule of a solid. For an atomic site with cubic symmetry, the local field is given by the *Lorentz relation,* i.e.,

$$\mathbf{E}_{\mathbf{loc}} = \mathbf{E}_{\mathbf{o}} + \mathbf{E}_{\mathbf{p}} + \frac{\mathbf{P}}{3\varepsilon_0} = \mathbf{E} + \frac{\mathbf{P}}{3\varepsilon_0} \tag{9.3}$$

Thus, apart from the macroscopic field, the local field also contains a term which represents the field due to polarization of other atoms in the solid. The expression (9.3) gets modified with shape of the specimen.

9.3 DIELECTRIC CONSTANT AND POLARIZABILITY

The electric displacement vector for an isotropic or cubic medium can be defined as

$$\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E} = \varepsilon_0\mathbf{E} + \mathbf{P} \tag{9.4}$$

where ε_r is called the *relative permittivity* or *dielectric constant* of the dielectric. It is a scalar quantity for an isotropic medium and is always dimensionless. The Eq. (9.4) can be used to define the dielectric constant as

$$\varepsilon_r = \frac{\varepsilon_0\,\mathbf{E}+\mathbf{P}}{\varepsilon_0\,\mathbf{E}} = 1 + \chi_e \tag{9.5}$$

Thus, like susceptibility, the dielectric constant is also a measure of the

Dielectric constant

the size or shape of the dielectric.

→ ε_r describes the ability of the dielectric material to store electric charges.

define in another way.

A/c to coulomb's law, the force of attraction (or) repulsion b/n two electric charges of magnitudes q_1 and q_2 separated by a distance 'r' is given by $F_0 = \frac{1}{4\pi\varepsilon_0} \times \frac{q_1 q_2}{r^2}$.

When charges are placed in some other medium

$$F = \frac{1}{4\pi\varepsilon} \times \frac{q_1 q_2}{r^2}$$

$$\frac{\text{Force in dielectric field} \rightarrow F}{\text{,, in vacuum} \rightarrow F_0} = \frac{\varepsilon_0}{\varepsilon} = \frac{1}{K} \Rightarrow \boxed{K = \varepsilon_r = \frac{\varepsilon}{\varepsilon_0}}$$

ε_r = Dielectric constant

...tric constant may be defined as the ratio of permittivity of the ...m to the permittivity of free space.

Can be defined as

$$D = \varepsilon_0 E + P \quad —①$$

E → electric field

D → electric Displacement

P → polarization

} → vectors

$(\because D = q/A)$

or

The electric displacement vector D in terms of electric field strength $D = \varepsilon E \quad —②$

ε_0 = permittivity of free space.

from ① & ②

$$\varepsilon E = \varepsilon_0 E + P \Rightarrow \varepsilon E = \varepsilon_0 E + \varepsilon_0 \chi E$$

$$= \varepsilon_0 E(1+\chi) —③$$

χ = electric susceptibility of the dielectric medium.

$$\frac{\varepsilon}{\varepsilon_0} = (1+\chi)$$

$$\boxed{\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = 1+\chi}$$

ε_r → relative permittivity (or) dielectric constant by dielectric

from ③ & ②

$$D = \varepsilon_0 E \varepsilon_r \quad —④$$

from ① & ④.

$$\varepsilon_0 E \varepsilon_r = \varepsilon_0 E + P \Rightarrow \boxed{\varepsilon_r = \frac{\varepsilon_0 E + P}{\varepsilon_0 E} = 1 + \frac{P}{\varepsilon_0 E} = 1 + \chi_e} —⑤$$

also $\boxed{P = \varepsilon_0 E(\varepsilon_r - 1)} —⑥$

$$\boxed{E = \frac{P}{\varepsilon_0(\varepsilon_r - 1)}} —⑦$$

After Types of polarizations:

orentz field.

12.13 CLAUSIUS MOSSOTTI EQUATION

We have studied that the molecules of non-polar dielectrics do not possess permanent dipole moment. However, when an external electric field is applied, dipole moment is induced. The polarization P_i is proportional to local electric field E_i, *i.e.*,

$$P_i = \alpha_e E_i \qquad \ldots(1)$$

where α_e is the electronic polarizability per atom.

If there are N molecules per unit volume of the dielectric, then polarization P is given by

$$P = \sum_i P_i = N \alpha_e E_i$$

or

$$\alpha_e = \frac{P}{N E_i} \qquad \ldots(2)$$

The local field E_i is the Lorentz field and is given by

$$E_i = E + \frac{P}{3\varepsilon_0} \qquad \text{(see eq. (6) of previous article)} \quad \ldots(3)$$

Substituting the value of E_i from eq. (3) in eq. (2), we get

$$\alpha_e = \frac{P}{N\left[E + \frac{P}{3\varepsilon_0}\right]}$$

But $$P = \varepsilon_0 (\varepsilon_r - 1) E$$

or $$E = \frac{P}{\varepsilon_0 (\varepsilon_r - 1)}$$

From eqs. (4) and (5), we get

$$\alpha_e = \frac{P}{N\left[\frac{P}{\varepsilon_0 (\varepsilon_r - 1)} + \frac{P}{3\varepsilon_0}\right]}$$

or $$N\alpha_e = \frac{\varepsilon_0}{\left[\frac{1}{(\varepsilon_r - 1)} + \frac{1}{3}\right]}$$

or $$\frac{N\alpha_e}{\varepsilon_0} = \frac{1}{\left[\frac{1}{(\varepsilon_r - 1)} + \frac{1}{3}\right]} = \frac{1}{\left[\frac{(\varepsilon_r + 2)}{3(\varepsilon_r - 1)}\right]}$$

or $$\frac{N\alpha_e}{\varepsilon_0} = \frac{3(\varepsilon_r - 1)}{(\varepsilon_r + 2)}$$

or $$\frac{(\varepsilon_r - 1)}{(\varepsilon_r + 2)} = \frac{N\alpha_e}{3\varepsilon_0}$$

This is known as Clausius-Mossotti equation.

In general, $$\boxed{\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{N\alpha}{3\varepsilon_0}}$$

where α = total polarisability.

9.6 FERROELECTRICITY

Ferroelectricity is the phenomenon which refers to the state of *spontaneous polarization*, i.e., polarization of the meterial in the absence of an electric field. It is thus analogous to ferromagnetism which represents the state of spontaneous magnetization of the material. The crystals exhibiting ferroelectricity are called the *ferroelectric crystals*. In such crystals, the centres of positive and negative charges do not coincide with each other even in the absence of the field, thus producing a non-zero value of the dipole moment. The variation of polarization with electric field is not linear for such crystals but forms a closed loop called the *hysteresis loop*. The ferroelectricity disappears above a certain critical temperature called the ***transition temperature*** or the *Curie point*, T_C, when the material gets transformed from ferroelectric to paraelectric state as indicated by a rapid decrease in the dielectric constant

12.16 PYROELECTRICITY

When the temperature of the specimen is changed, there is a change in spontaneous polarisation. This effect is known as ***pyroelectric effect.*** This branch of phsyics is known as pyroelectricity. The pyroelectric coefficient λ is defined as the change in polarisation per unit temperature change of the specimen. Therefore,

$$\lambda = \frac{dP}{dT}$$

Due to the change in polarisation, there will be a corresponding change in external field. This results a change of charge on the surface. It is possible to detect a charge of 10^{-16}°C using a suitable electrometer. Therefore, a temperature changes as small as 10^{-6} °C can be measured using pyroelectric effect.

The pyroelectric materials such as $BaTiO_3$, $LiNibO_3$, etc., are used to make very good infra-red detectors which can operate at room temperature.

Such ... constant with temperature is close to that observed experimentally in the paraelectric state.

9.7 PIEZOELECTRICITY

In cetain crystals, the application of an external stress induces a net dipole moment which produces the electric polarization with the polarization charges appearing on the surfaces of the crystals. Such crystals are called the *piezoelectric crystals* and the phenomenon is known as the *piezoelectricity*. Some examples of such crystals are quartz, the Rochelle salt and tourmaline. The inverse effect is also observed, i.e., the application of an electric field produces strains in the crystal.

In schematic one-dimensional notation, the piezoelectric equations are

$$\left.\begin{aligned} P &= Zd + \varepsilon_0 E \chi \\ e &= Zs + Ed \end{aligned}\right] \qquad (9.39)$$

where P represents the polarization, Z the stress, d the piezoelectric strain constant, E the electric field, χ the dielectric susceptibility, e the elastic strain and s the elastic compliance constant. The first one of the equations (9.39) exhibits the development of polarization by an applied stress and the second one shows the development of elastic strain by an applied electric field. Generally, very large electric fields are needed to produce very small strains. In quartz, for example, an electric field of about 10^4 Vm^{-1} produces a strain of about 1 in 10^8 only.

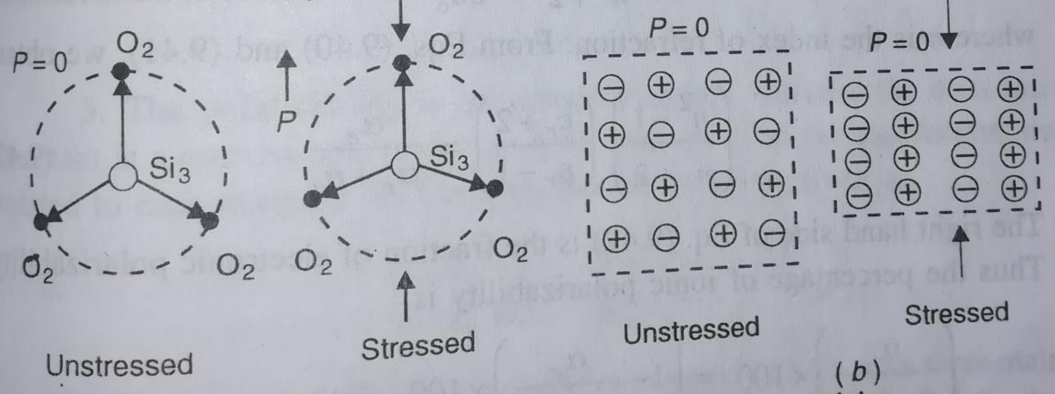

Fig. 9.6. *Effect of crystal symmetry on piezoelectricity.*
(a) Quartz crystal with no centre of inversion shows piezoelectricity.
(b) A crystal with centre of inversion shows no piezoelectricity.

The occurrence of piezoelectricity is the result of displacement of ions in certain crystals under the effect of the applied stresses. In such crystals, the ions are so displaced that their charge distribution loses the original symmetry as shown in Fig. 9.6a. In certain other crystals (Fig. 9.6b), where the symmetry of the charge distribution is not disturbed even after distortion, no piezoelectricity is observed. The latter type of crystals are those which ... *of inversion*. Thus the absence of the centre of inversion

(v) **Defect breakdown** ... porosity, impurities for instance dust or moisture ... breakdown.

40.21 APPLICATIONS OF DIELECTRIC MATERIALS

Two most important applications of dielectric materials are: (*i*) as insulating materials and (*ii*) as medium in capacitors. For insulating materials application the dielectric is required to have low dielectric constant, low dielectric loss, high resistance and high dielectric strength. Further, they should possess adequate chemical stability, high moisture resistance, and suitable mechanical properties for particular service condition.

(*i*) **Solid Insulating Materials:** Polymers and ceramics are the widely used solid insulators. A variety of plastics, rubbers, waxes, paper, synthetic fibres and fabrics are applied in the form of films, sheets, slabs, tapes, sleeving, tubing, rods and moulding. Plastics such as polyethylene, polytetrafluroethylene (PTFE) and polysterene have low ε_r and practically no dielectric loss. Porcelain towers are used in high voltage power lines because of their high dielectric strength. The dielectric strength of porcelain bodies is enhanced by glazing their surfaces. Porcelain, glass, mica, alumina and asbestos are widely used ceramics.

Capacitors: A capacitor is an electronic component that stores energy in the form of electric field. Basically, it consists of two conducting plates separated by a dielectric. Capacitors are widely used in electrical and electronic equipments.

(*a*) **Paper Capacitors:** In this type of capacitors, one or more layers of extremely thin kraft or linen paper are used as the dielectric medium. The paper is kept between aluminium foils which act as the metal plates. The whole assembly is rolled into a cylindrical element. The dielectric is impregnated with mineral oil or waxes to prevent absorption of moisture.

(*b*) **Plastic Capacitors:** Plastics can be formed in thin, uniform and non-porous films. Such thin plastic films are used as dielectric medium in these capacitors. Some of the materials used are polyester, polycarbonate, polyethylene, polystyrene, polypropylene, poly tetrafluoroethylene (PTFE) and polythene Terephthalate films.

(*c*) **Ceramic Capacitors:** These capacitors use ceramic as the dielectric medium. Low loss low permittivity capacitors are made from steatite which formed in the form of a thin plate or foil. High permittivity capacitors use barium titanate as the dielectric material.

(*d*) **Mica Capacitors:** Muscovite mica is a naturally occurring material and can be laminated into very thin sheets. This material has good mechanical strength and can be used up to high temperatures of the order of 500°C. Impregnants like polystyrene improve the properties of mica.

(e) **Glass Capacitors:** Very thin plates of glass are used as dielectric in these capacitors. The plates are interleaved with aluminium foil and fused together to form a solid block.

(f) **Electrolytic Capacitors:** In electrolytic capacitors, a metallic anode has oxide film grown over it and this oxide layer acts as a dielectric. The anode is surrounded by an electrolytic solution of ammonium borate or sodium phosphate which acts as cathode. Etched aluminum foil is used as anode in aluminum electrolytic capacitors. Aluminum oxide film is grown over the aluminum foil and it acts as a dielectric film. A liquid electrolyte is held in contact with dielectric film. Another etched aluminum foil is used as the cathode. The assembly is sealed in an aluminum can.

(ii) **Liquid Insulating materials:** Liquid insulating materials are mainly mineral oils and synthetic oils, which are used for the *purpose of insulation* as well as *cooling* in transformers. **Transformers:** A transformer is a device used for transmitting power from one circuit to another or from one place to another place. It consists of two windings, primary and secondary windings, linked by a common magnetic flux. During the construction of transformers, the windings are impregnated by varnishes. In case of H.V. transformers used in distribution of power where very high voltages are present, proper provisions are to be provided to distribute away the heat produced and to provide high dielectric strength. These transformers are usually immersed in liquid dielectrics.

(a) **Mineral insulating oil:** Mineral oil has very high dielectric strength and is highly viscous. It transfers heat from the transformer windings and core to the outer shield and enables dissipation of the heat generated. The oil should be perfectly free from moisture to maintain its high dielectric strength. Even small traces of water significantly reduce the dielectric strength. Therefore, the oil is periodically dehydrated. Secondly, sludge formation takes place in the oil due to constant heating of the oil during its working and it also should be removed periodically to maintain its initial quality.

(b) **Synthetic insulating oil:** Nowadays, synthetic oils are being used in place of mineral oils because synthetic oils are much more resistant to oxidation and fire hazards. Sovol, sovotol etc are some of the synthetic oils widely used in H.V. transformers.

(c) **Miscellaneous insulating oils:** Petroleum oils, silicone oils, and vegetable oils belong to this category. They have high thermal stability. They are mainly used as filling medium for transformers, circuit breakers etc and as impregnants for high voltage cables.

(*iii*) Dielectric heating: Insulating materials can be efficiently heated up by subjecting them to a high voltage of suitable frequency, namely the frequency at which dielectric loss is maximum. The dielectric loss manifests in the form of heat. Adequate heating may be obtained at high voltages of the order of 20 kV having a frequency of about 30 MHz. The chief advantage of this method is that the material is heated up quickly as the heat is produced in the insulating material itself.

Cooking in microwave oven is one of the popular examples of dielectric heating. Water invariably exists in all articles of food, which exhibits dielectric loss in microwave region. In a oven, microwaves produced by a source are distributed by reflection from the metal walls. They pass through the glass-cooking dish and are absorbed by water molecules. The food is cooked due to the heat produced in the absorption process.

Dielectric heating is widely employed in dehydration of food, tobacco etc. Wooden sheets are preferred to be glued by this method. The heat produced in the glue due to the dielectric absorption leads to binding of the wooden sheets. The advantage of this method is that the moisture content of wooden sheets remains unaltered.