

29.1 INTRODUCTION

Dielectric. A dielectric (or an insulator) is a material in which all the electrons are tightly bound to the nuclei of the atoms. Thus there are no free electrons to carry current. Hence the electrical conductivity of a dielectric is very low. (The conductivity of an ideal dielectric is zero). Glass, plastic, mica, oil, etc., are examples of dielectrics.

Nonpolar and Polar Molecules— The molecules of dielectrics may be classified as 'nonpolar' and 'polar'.

A **non-polar molecule** is one in which the centre of gravity of the positive charges (protons) coincides with the centre of gravity of the negative charges (electrons). The non-polar molecules have symmetrical structure and zero electric dipole moment. Examples are: H_2 , N_2 , O_2 , CO_2 , benzene, etc. (Fig. 29.1).

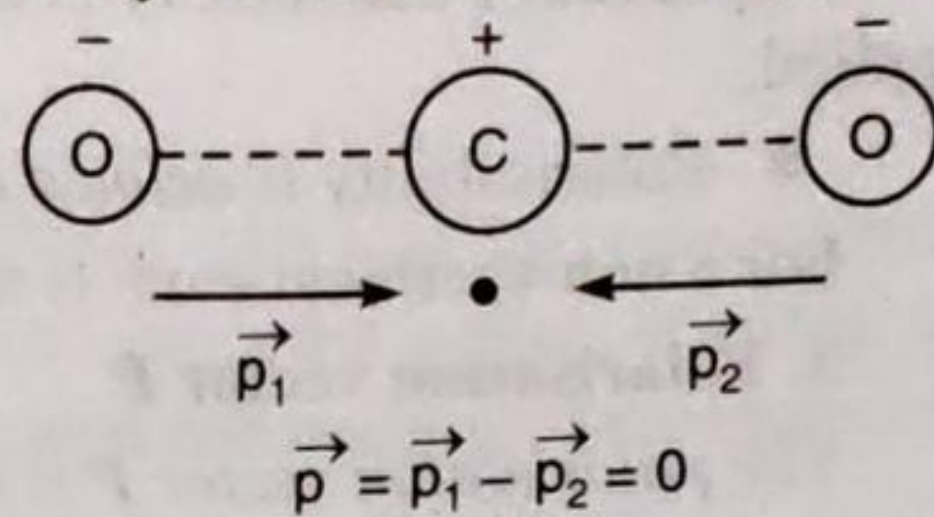


Fig. 29.1

A polar molecule is one in which the centre of gravity of the positive charges is separated from the centre of gravity of the negative charges by a finite distance. The polar molecule is thus an electric dipole and has an intrinsic permanent dipole moment. Examples are: H_2O , HCl , CO , N_2O , NH_3 , etc., (Fig. 29.2). The permanent dipole moment of a molecule of water has the magnitude $p = 6.3 \times 10^{-30}$ Cm and is directed from O^- ion toward the midpoint of the line connecting the H^+ ions.

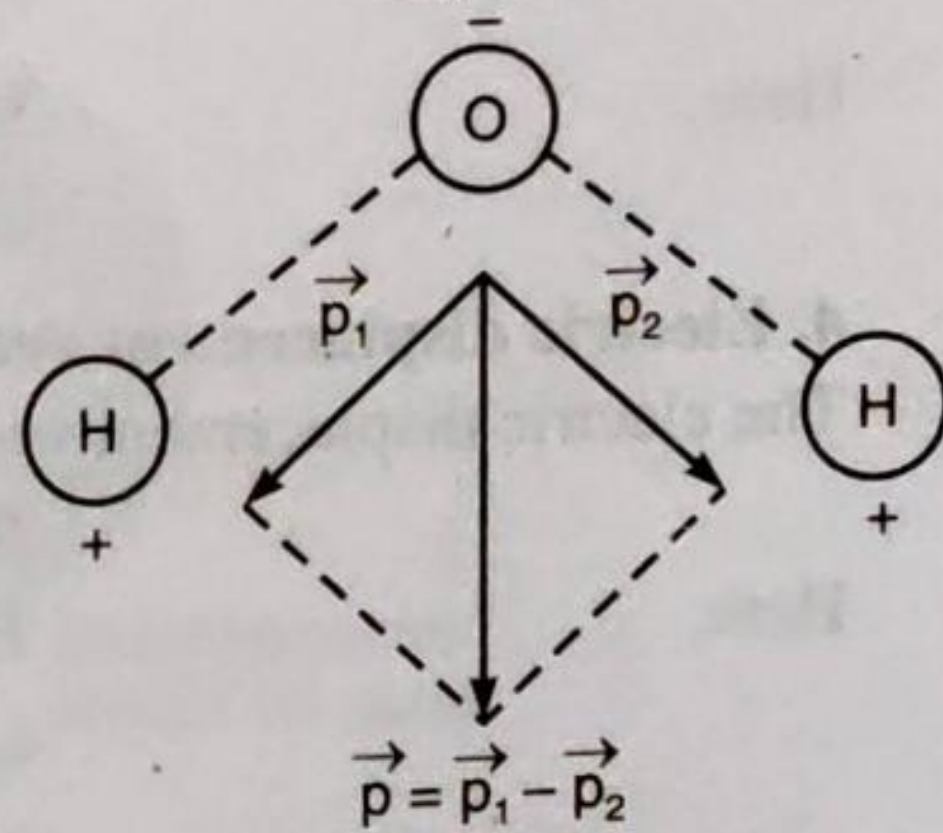


Fig. 29.2

Fundamental definitions in dielectrics

1. Dielectric constant (ϵ_r)

Dielectric constant is the ratio between the absolute permittivity of the medium (ϵ) and the permittivity of free space (ϵ_0)

$$\text{Dielectric constant } (\epsilon_r) = \frac{\text{Absolute permittivity of the medium } (\epsilon)}{\text{Permittivity of free space } (\epsilon_0)}$$

2. Electric polarisation

The process of producing electric dipoles by an electric field is called polarisation in dielectrics.

When an electric field is applied to a crystal or a glass containing positive and negative charges, the positive charges are displaced in the direction of the field, while the negative charges are displaced in the opposite direction. This displacement produces local dipoles throughout the solid.

Electric dipole. A system consisting of two equal and opposite charges $+q$ and $-q$ separated by a distance d is called an *electric dipole* (Fig. 29.3).

Electric dipole moment (μ). The product of the magnitude of the charge (q) and distance between two charges (d) is called *electric dipole moment* (μ).

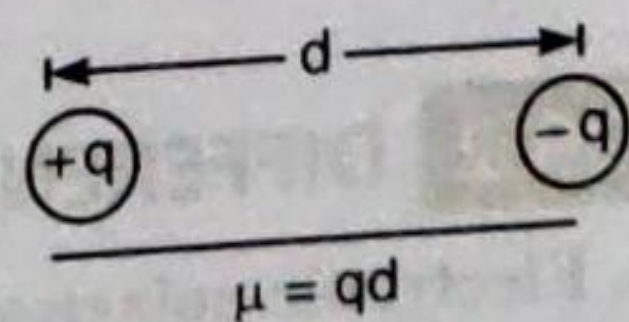


Fig. 29.3

$$\mu = qd.$$

Unit of dipole moment is **coulomb-metre (Cm)**.

The dipole moment is a vector. It points from the negative charge to the positive charge.

3. Polarizability (α). The strength of the induced electric dipole moment (μ) in dielectrics is proportional to the applied electric field (E).

$$\mu \propto E$$

$$\mu = \alpha E.$$

or

Here, α is the constant of proportionality, called the **polarisability**.

$$\alpha = \frac{\mu}{E}$$

Atomic polarisability (α) is defined as the electric dipole moment induced in the atom by an electric field of unit strength. Molecular polarizability (α) is defined as the electric dipole moment induced in the molecule by an electric field of unit strength.

Definition. Polarisability is defined as the ratio of induced dipole moment to the electric field applied.

- Polarisability is defined as induced dipole moment per unit electric field.

For a non-spherical atom α is a tensor.

3. Polarisation vector P

The polarisation vector P is the dipole moment per unit volume of the dielectric material.

$$P = N\bar{\mu}$$

Here,

N = number of molecules per unit volume and

$\bar{\mu}$ = average dipole moment per molecule.

4. Electric displacement vector D

The electric displacement vector D is given by

$$D = \epsilon E = \epsilon_0 \epsilon_r E$$

Here,

E = electric field strength, ... (1)

ϵ_0 = permittivity of free space (i.e., vacuum),

ϵ_r = relative permittivity of the material.

Relation between D and P is

$$D = \epsilon_0 E + P$$

$$\epsilon_0 \epsilon_r E = \epsilon_0 E + P$$

\therefore

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

5. Electric susceptibility (χ_e)

When a dielectric material is placed in an electric field, it becomes electrically polarised. For isotropic dielectrics, the polarisation vector P is proportional to the electric field E . Thus,

$$P = \epsilon_0 \chi_e E$$

The constant χ_e is called the 'electric susceptibility' of the dielectric material.

$$\chi_e = \frac{P}{\epsilon_0 E} = \frac{\epsilon_0 (\epsilon_r - 1) E}{\epsilon_0 E}$$

\therefore

$$\chi_e = (\epsilon_r - 1)$$

29.2 DIFFERENT TYPES OF ELECTRIC POLARISATION

1. Electronic polarisation

The displacement of the positively charged nucleus and the (negative) electrons of an atom in opposite directions on the application of an electric field results in *electronic polarisation*.

Fig. 29.4 shows the electronic polarisation occurring in an atom due to the applied electric field. On applying a field, the electron cloud around the nucleus shifts towards the positive end of the field. As the nucleus and the centre

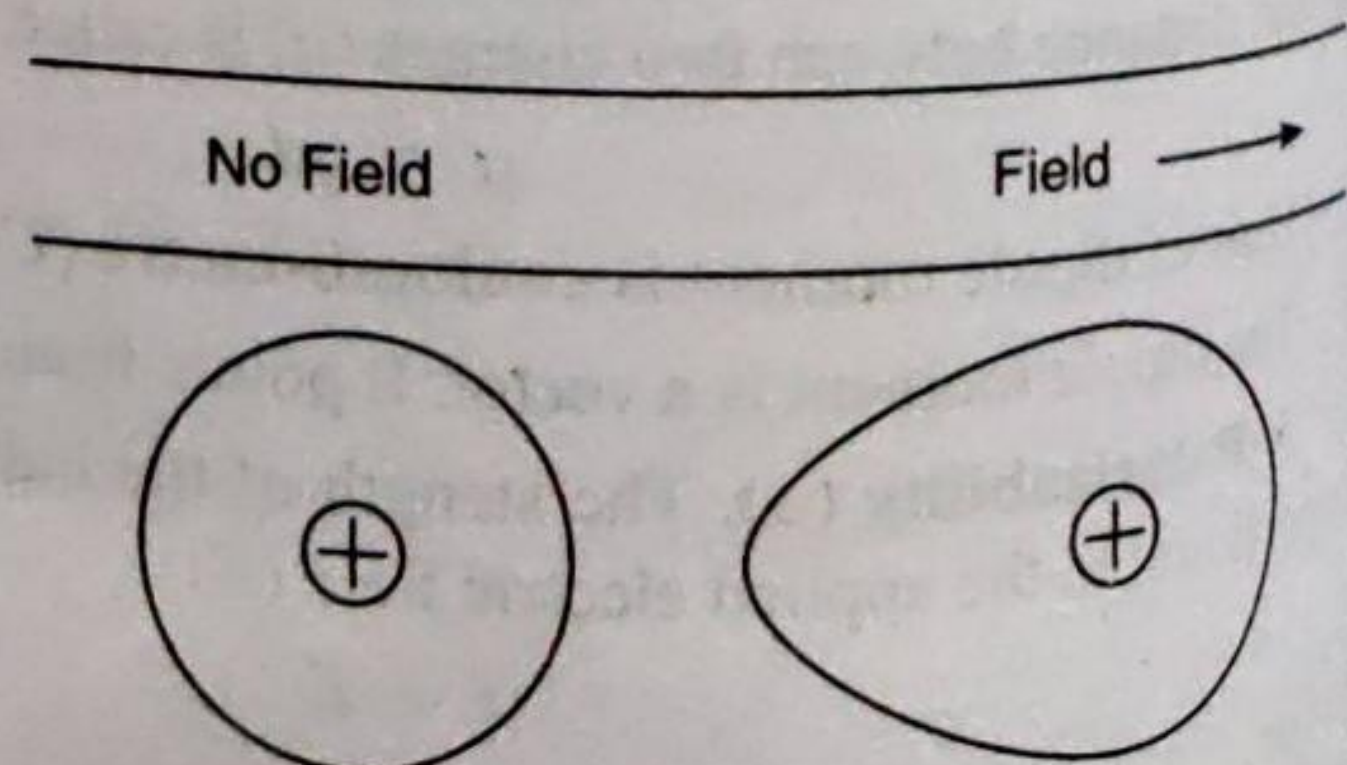


Fig. 29.4

of the electron cloud are separated by a certain distance, dipole moment is created within each atom.

The induced dipole moment (μ) is proportional to the field strength (E).

$$\mu \propto E$$

$$\mu = \alpha_e E$$

or

The constant of proportionality α_e is the electronic polarisability of the atom. The electronic polarisability α_e is proportional to the volume of the atom. It is independent of temperature.

Calculation of electronic polarizability (α_e).

(i) No electric field

Consider an atom of a dielectric material of atomic number Z [Fig. 29.5 (a)]. Ze is the nuclear charge. The electrons of charge $(-Ze)$ are distributed uniformly throughout the sphere of radius R . When there is no external electric field, the centres of the electron cloud and nucleus of the atom are same and one.

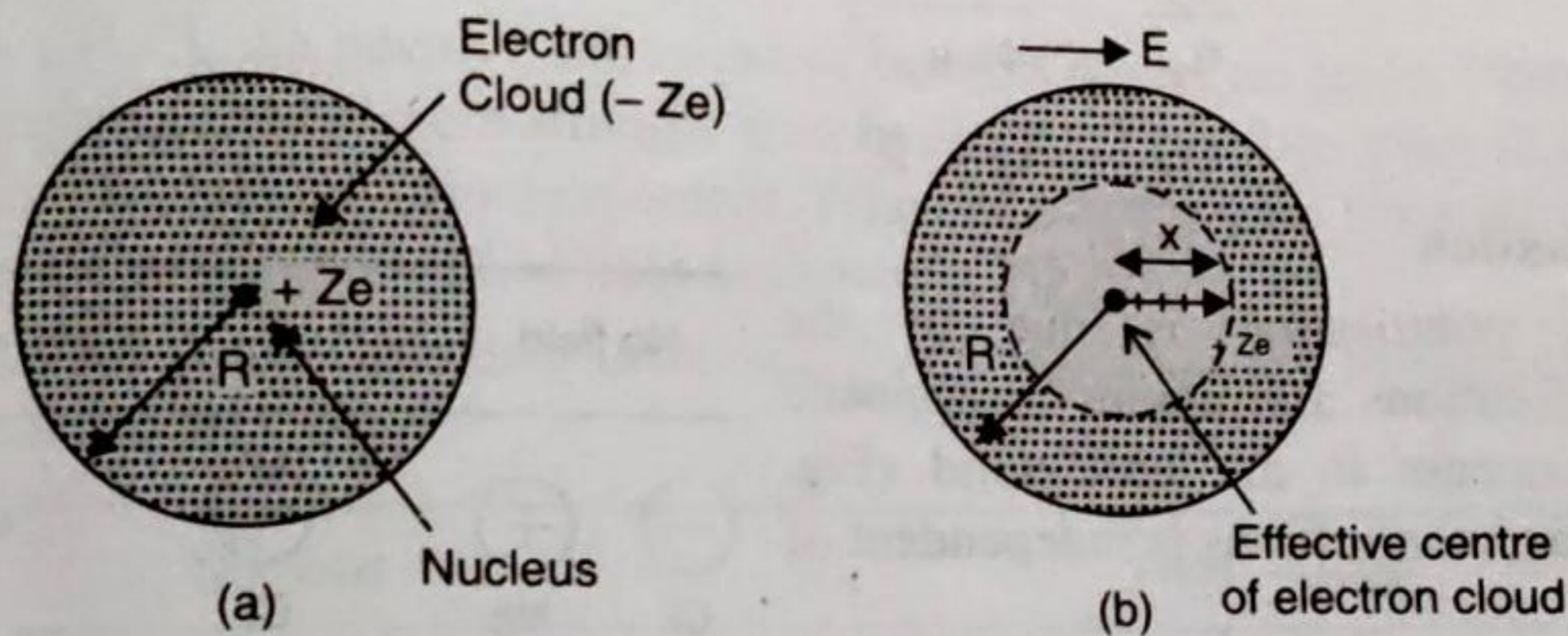


Fig. 29.5

(ii) With electric field

When a d.c. electric field E is applied, the nucleus moves towards the field direction and the electron cloud moves in the opposite direction of the field [Fig. 29.5 (b)]. The electron cloud centre gets a displacement x with respect to the centre of the nucleus. The displacement $x \ll R$. We assume that the spherical shape of the electron cloud is not altered on the application of the electric field.

When the nucleus and electron cloud are shifted from their equilibrium position, an attractive coulomb force is created and it will tend to maintain the original equilibrium position. But the Lorentz force will tend to separate the nucleus and electron cloud of that atom from their equilibrium position. Finally a new equilibrium will be reached when these two forces are equal and opposite.

At equilibrium, *Lorentz force* = *Coulomb force*.

The Lorentz force between nucleus and the electron cloud = $-Ze \times E = -ZeE$... (1)

The charge density of the charged sphere = $\frac{-Ze}{\frac{4}{3}\pi R^3}$

Total number of negative charges in the sphere of radius x } = $\frac{-Ze}{\frac{4}{3}\pi R^3} \times \frac{4}{3}\pi x^3 = -Ze \frac{x^3}{R^3}$... (2)

The coulomb force between the nucleus and the electron cloud } = $\frac{-Ze x^3}{4\pi \epsilon_0 x^2} (Ze) = \frac{-Z^2 e^2 x}{4\pi \epsilon_0 R^3}$

Under equilibrium conditions, the coulomb attractive force and the Lorentz repulsive force are equal and opposite. Thus

$$ZeE = \frac{Z^2 e^2 x}{4\pi \epsilon_0 R^3}$$

or

$$E = \frac{Zex}{4\pi \epsilon_0 R^3} \quad \dots(3)$$

Thus, the displacement of the electron cloud (x) is proportional to the applied electric field E .

$$\text{Induced dipole moment} = \mu = Zex$$

By definition $\mu = \alpha_e E$... (4)

From Eqs. (4) and (5), $E = \frac{Zex}{\alpha_e}$... (5)

From Eqs. (3) and (6), we get

$$\frac{Zex}{\alpha_e} = \frac{Zex}{4\pi \epsilon_0 R^3}$$

$$\therefore \alpha_e = 4\pi \epsilon_0 R^3 \quad \dots(7)$$

2. Ionic polarisation

The ionic polarisation is due to the displacement of cations and anions in opposite directions and occurs in an ionic solid (Fig. 29.6). The displacement of ions is independent of temperature.

Suppose an electric field is applied in the +ve x direction.

Then the +ve ions move to the right by x_1 and -ve ions move to the left by x_2 .

m is the mass of the +ve ion.

M is the mass of the -ve ion.

We assume that there are one cation and one anion in each unit cell of the ionic crystal.

Due to ionic displacement the resultant dipole moment per unit cell,

$$\mu = e(x_1 + x_2) \quad \dots(1)$$

Here, x_1 = shift of +ve ion and x_2 = shift of -ve ion with respect to their equilibrium positions.

When the electric field is applied, the restoring force (F) produced is proportional to the displacement (x).

$$\text{Restoring force on +ve ion, } F = \beta_1 x_1 \quad \dots(2)$$

$$\text{Restoring force on -ve ion, } F = \beta_2 x_2 \quad \dots(3)$$

Here, β_1 and β_2 are restoring force constants. They depend upon the masses of ions and angular frequency of the molecule in which ions are present. Therefore, under equilibrium,

$$F = \beta_1 x_1 = \beta_2 x_2$$

$$x_1 = \frac{F}{\beta_1} = \frac{eE}{m\omega_0^2} \quad \left[\begin{array}{l} \because F = eE \\ \beta_1 = m\omega_0^2 \end{array} \right]$$

Here, ω_0 = natural frequency of the ionic molecule.

Similarly for -ve ion,

$$x_2 = \frac{F}{\beta_2} = \frac{eE}{M\omega_0^2}$$

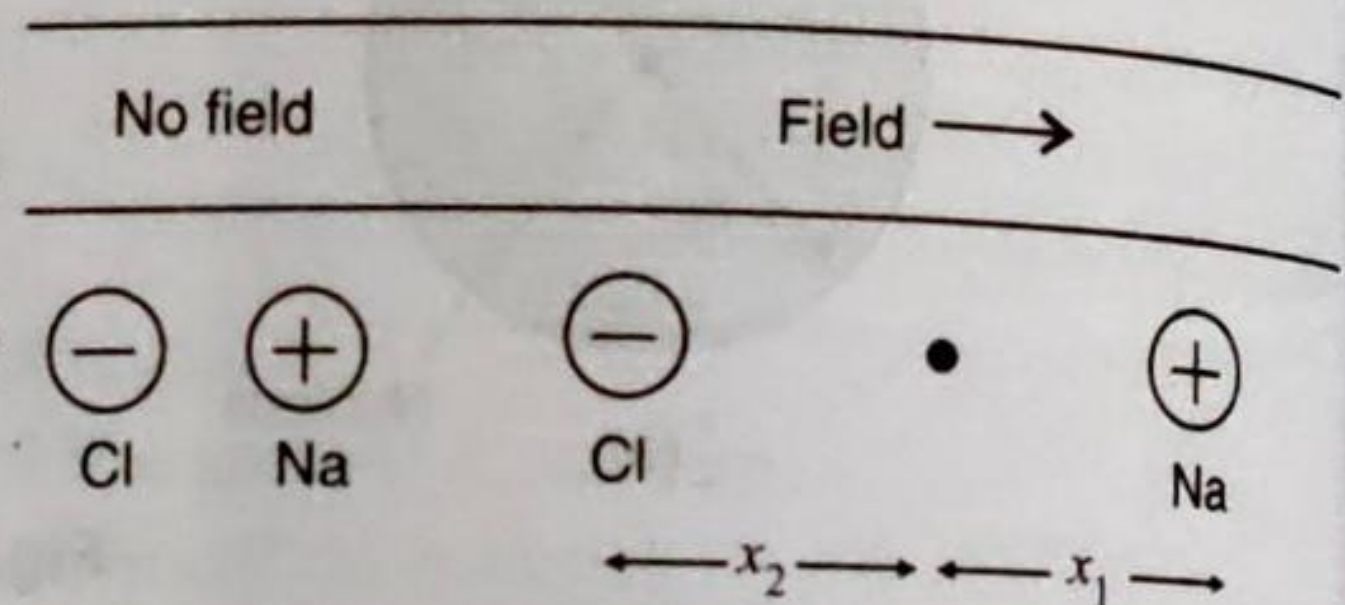


Fig. 29.6

$$x_1 + x_2 = \frac{eE}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right) \quad \dots(4)$$

$$\mu = e(x_1 + x_2) = \frac{e^2 E}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right)$$

$$\alpha_i = \frac{\mu}{E} = \frac{e^2}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{M} \right) \quad \dots(5)$$

Thus the ionic polarisability ' α_i ' is inversely proportional to the square of the natural frequency of the ionic molecule and to its reduced mass. It is independent of temperature.

3. Orientational Polarisation

In methane molecule (CH_4), the centre of the negative and positive charges coincide. It has no permanent dipole moment.

However in CH_3Cl , the positive and negative charges do not coincide. Here chlorine attracts the bonding electrons to itself more strongly than hydrogen. Therefore, even in the absence of an electric field, this molecule has dipole moment. When an electric field is applied, these molecules tend to align themselves in the applied field as shown in Fig. 29.7.

Hence the electric dipole moment increases. The polarisation due to such alignment is called *orientational polarisation*.

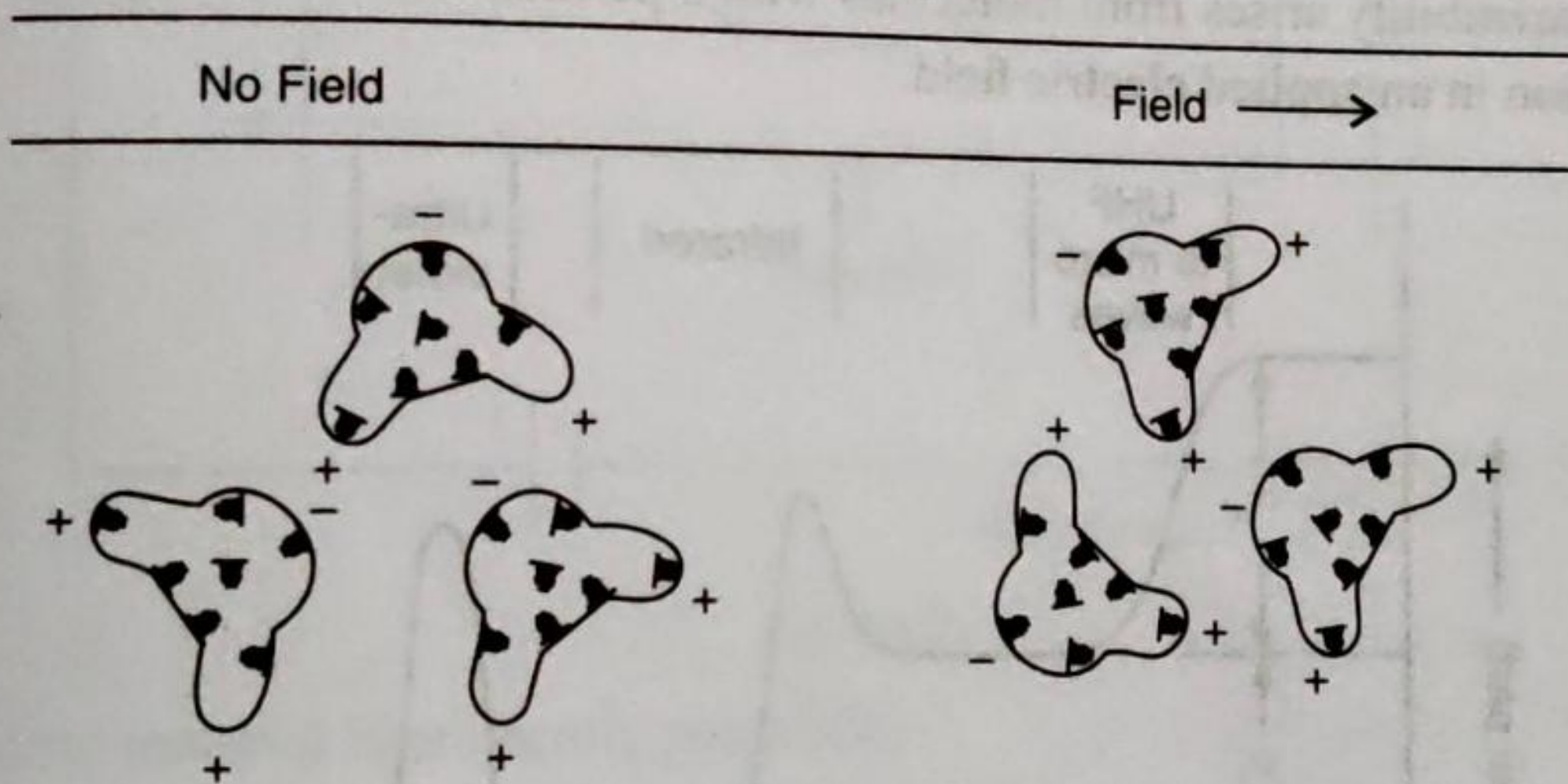


Fig. 29.7

Orientational polarisation can be shown to be

$$P_0 = N \bar{\mu} = N \mu^2 E / 3kT = N \alpha_0 E.$$

$$\therefore \text{orientational polarisability, } \alpha_0 = \frac{P_0}{NE} = \frac{\mu^2}{3kT}.$$

Thus the orientational polarisability α_0 is inversely proportional to absolute temperature of the material.

4. Space-charge polarisation

Space-charge polarisation occurs due to the accumulation of charges at the electrodes or at the interfaces in multiphase dielectrics (Fig. 29.8). It is found in ferrites and semiconductors. The ions diffuse over appreciable distances in response to the applied field, giving rise to a redistribution of charges in the dielectric medium.

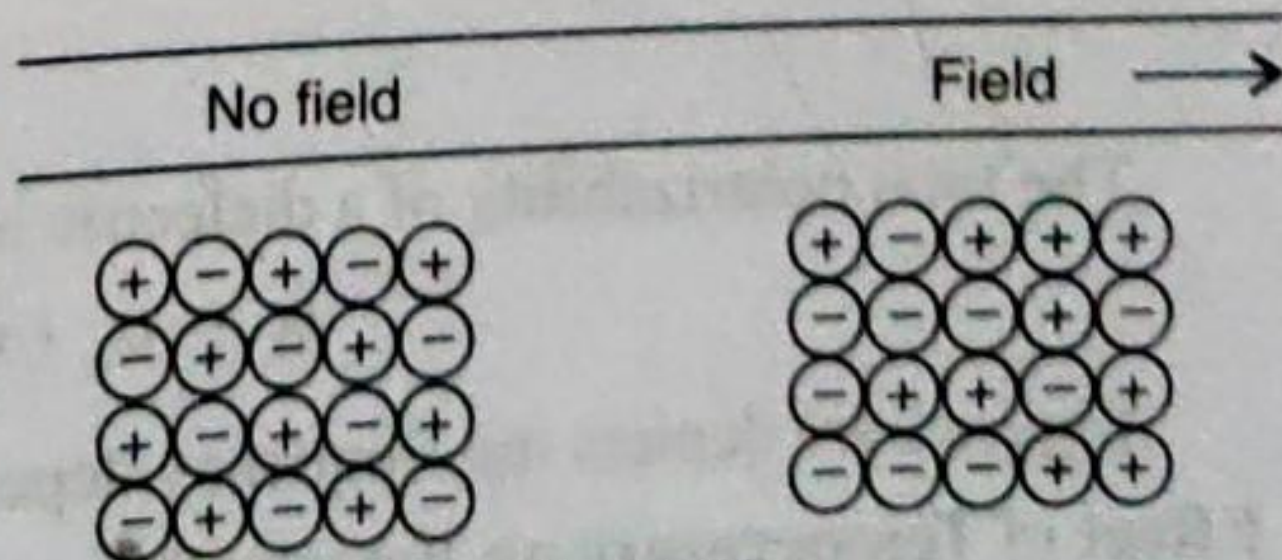


Fig. 29.8

Total Polarisation

Since the value of space-charge polarisability is very small when compared with other types of polarisabilities, it can be neglected.

The total polarisability of a gas ' α ' can be written as

$$\begin{aligned}\alpha &= \alpha_e + \alpha_i + \alpha_0 \\ &= 4\pi \epsilon_0 R^3 + \frac{e^2}{\omega_0^2} \left(\frac{1}{M} + \frac{1}{m} \right) + \frac{\mu^2}{3kT}\end{aligned}$$

The total polarisation P can be written as

$$P = N \alpha E = NE \left\{ 4\pi \epsilon_0 R^3 + \frac{e^2}{\omega_0^2} \left(\frac{1}{M} + \frac{1}{m} \right) + \frac{\mu^2}{3kT} \right\}$$

This equation is known as *Langevin - Debye equation*.

Frequency Dependence of Total Polarizability

The net polarizability of a dielectric material results from three main contributions—the electronic polarizability, ionic polarizability, and dipolar or orientational polarizability. The electronic contribution arises from the displacement of the electron shell relative to a nucleus. The ionic contribution comes from the displacement of a charged ion with respect to other ions. The dipolar polarizability arises from molecules with a permanent electric dipole moment that can change orientation in an applied electric field.

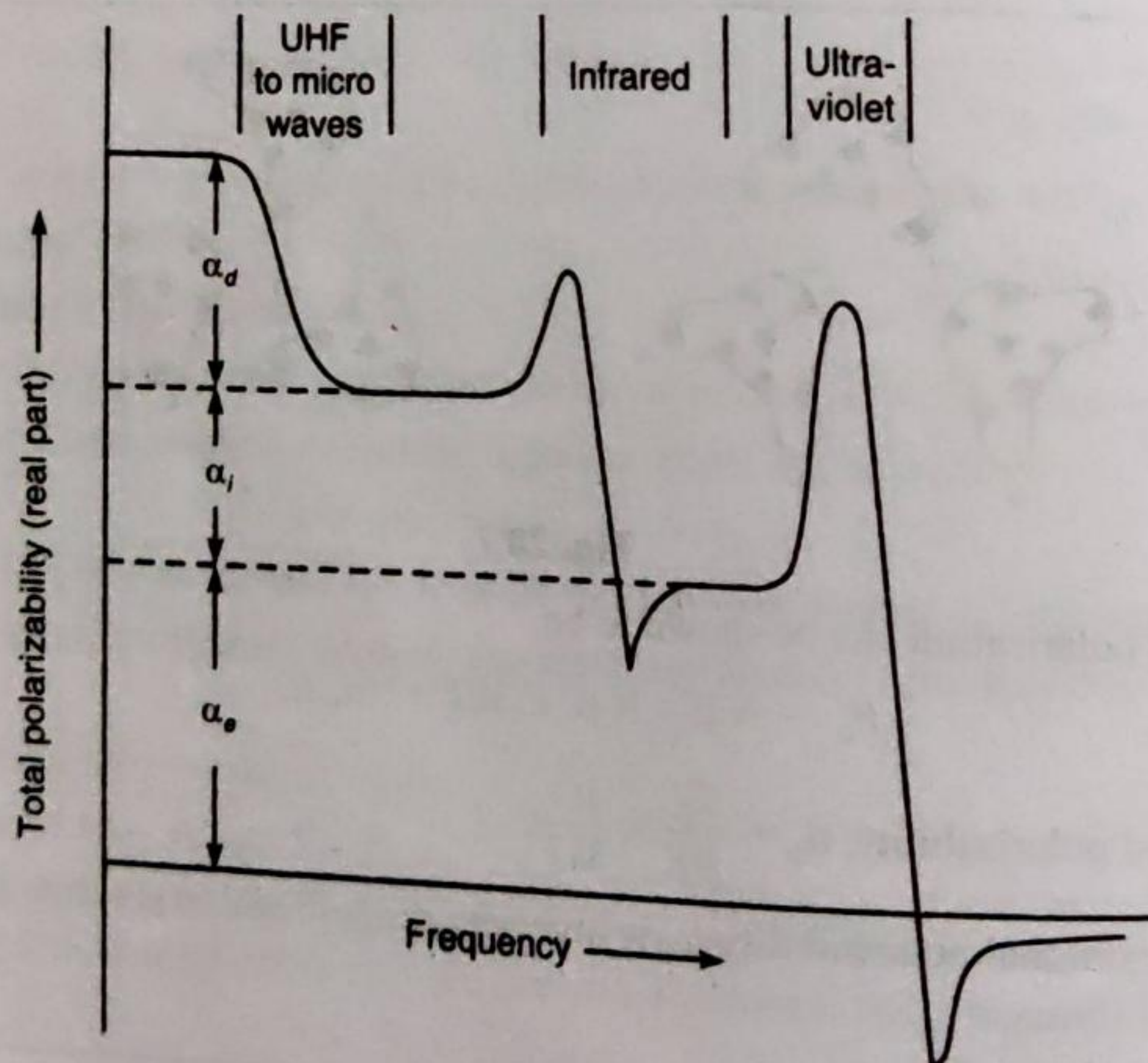


Fig. 29.9

The total polarizability of a dielectric is given by the expression:

$$\alpha = \alpha_e + \alpha_i + \alpha_d \quad \dots(1)$$

Figure 29.9 depicts the frequency dependence of the several contributions to the polarizability.

Effect of Temperature on Polarisation

1. The electronic and the ionic polarisabilities are independent of temperature.

2. The effect of increase of temperature brings about a higher degree of randomness in the molecular orientation in the material. This affects the tendency of permanent dipoles to align along the field direction. Hence, *orientation polarisation decreases with the increase in temperature.*

3. In space charge polarisation, increase in temperature facilitates the diffusion of ions. Thermal energy may also aid in overcoming the activation barrier for the orientation of polar molecules in the direction of the field. Hence, *space charge polarisation increases with increase of temperature.*

29.3 DERIVATION OF CLAUSIUS-MOSSOTTI EQUATION

Lorentz method for finding the internal field for a cubic structure. Consider a slab of a dielectric placed in the uniform electric field between two parallel plates of a capacitor (Fig. 29.10)

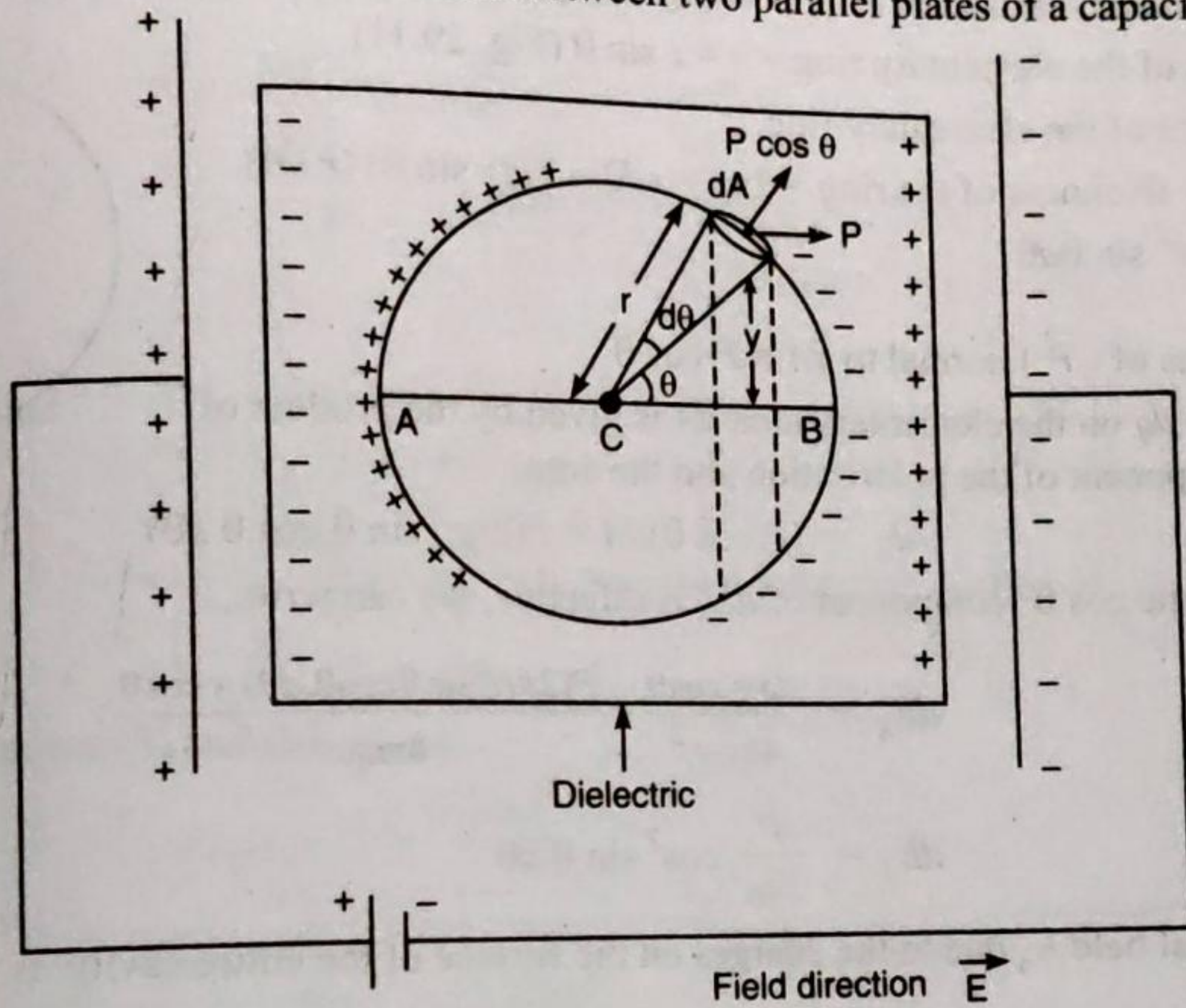


Fig. 29.10

The dielectric material is uniformly polarised.

Let us find the internal field acting on an atom at C.

Consider an imaginary small spherical cavity of radius r around the atom.

The internal field (E_i) at the atom site C is made up of the following four components, namely,

E_1, E_2, E_3 and E_4 .

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

(i) E_1 = Electric field at point C due to charges on the plates of the capacitor in the absence of the dielectric.

E_1 is the field intensity at C due to the charge density on the plates. From the field theory,

$$E_1 = D/\epsilon_0$$

$$D = P + \epsilon_0 E$$

$$E_1 = \frac{P + \epsilon_0 E}{\epsilon_0} = E + \frac{P}{\epsilon_0}$$

... (2)

\therefore

$$E_1 = E + \frac{P}{\epsilon_0}$$

(ii) E_2 = Electric field intensity at C due to the charge density induced on the two sides of the dielectric.

$$E_2 = -\frac{P}{\epsilon_0}$$

(iii) E_3 = Electric field intensity at C due other atoms contained in the cavity.
We are assuming a cubic structure. The lattice has cubic symmetry.

$$E_3 = 0$$

(iv) E_4 = Electric field produced by the polarisation charges on the cavity surface.

Calculation of E_4

Consider an elementary ring of area dA lying between θ and $\theta + d\theta$ from the polarization direction (\vec{P}). The polarization (\vec{P}) is along the applied external field (\vec{E}).

The radius of the elementary ring = $y = r \sin \theta$ (Fig. 29.11).

Surface area of the elementary ring,

$$dA = 2\pi y \times \text{thickness of the ring} = 2\pi y \times r d\theta = 2\pi(r \sin \theta)(r d\theta)$$

$$\therefore dA = 2\pi r^2 \sin \theta d\theta$$

Components of (\vec{P}) normal to $dA = P \cos \theta$

The charge dq on the elementary area dA is given by the product of the normal component of the polarisation and the area.

$$dq = (P \cos \theta)dA = P(2\pi r^2 \sin \theta \cos \theta d\theta)$$

Since only the $\cos \theta$ component of dE_4 is effective, we can write,

$$dE_4 = \frac{dq \times \cos \theta}{4\pi\epsilon_0 r^2} = \frac{P(2\pi r^2 \sin \theta \cos \theta d\theta) \times \cos \theta}{4\pi\epsilon_0 r^2}$$

$$dE_4 = \frac{P}{2\epsilon_0} \cos^2 \sin \theta d\theta$$

Thus the total field E_4 due to the charges on the surface of the entire cavity is

$$E_4 = \frac{P}{2\epsilon_0} \int_0^\pi \cos^2 \theta \sin \theta d\theta$$

$$= \frac{P}{2\epsilon_0} \int_0^\pi \cos^2 \theta d(-\cos \theta)$$

$$= \frac{-P}{2\epsilon_0} \left[\frac{\cos^3 \theta}{3} \right]_0^\pi$$

$$= -\frac{P}{6\epsilon_0} [-1 - 1] = \frac{P}{3\epsilon_0}$$

$$\therefore E_4 = \frac{P}{3\epsilon_0} \quad \dots (5)$$

Now

$$E_i = E_1 + E_2 + E_3 + E_4$$

Substituting the Values of E_1 , E_2 , E_3 and E_4 from Eqs. (2), (3), (4) and (5),

$$E_i = \left(E + \frac{P}{\epsilon_0} \right) - \frac{P}{\epsilon_0} + 0 + \frac{P}{3\epsilon_0}$$

$$E_i = E + \frac{P}{3\epsilon_0} \quad \dots (6)$$

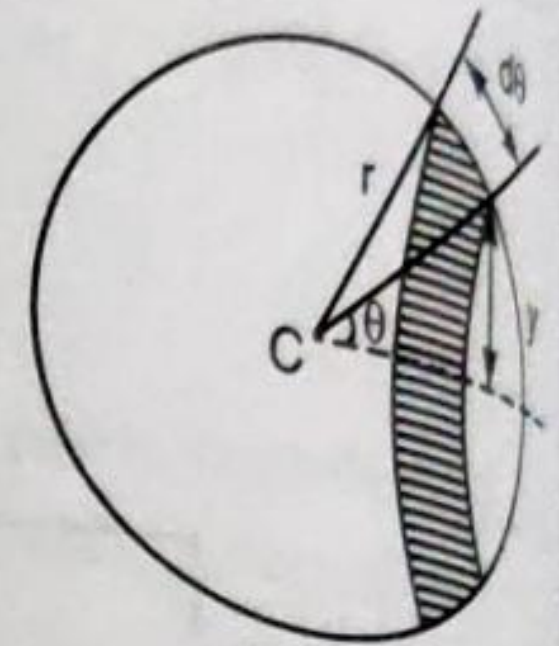


Fig. 29.11

- Eq. (6) is the expression for the local field in a dielectric for a cubic structure.
- Eq. (6) is the expression for the internal field in a dielectric solid material.
- Eq. (6) is the expression for the Lorentz field for elemental dielectrics.

Derivation of the Clausius-Mossotti Relation

Let N be the number of molecules per unit volume and α be the molecular polarisability.

Total polarisation,

$$P = N\alpha E_i \quad \dots (7)$$

Substituting the value of E_i from Eq. (6) in Eq. (7), we get

$$P = N\alpha \left(E + \frac{P}{3\epsilon_0} \right)$$

$$P \left\{ 1 - \frac{N\alpha}{3\epsilon_0} \right\} = N\alpha E$$

$$P = \frac{N\alpha E}{\left(1 - \frac{N\alpha}{3\epsilon_0} \right)} \quad \dots (8)$$

We know that

$$D = P + \epsilon_0 E$$

$$P = D - \epsilon_0 E$$

$$\frac{P}{E} = \frac{D}{E} - \epsilon_0 = \epsilon - \epsilon_0 = \epsilon_0 \epsilon_r - \epsilon_0 = \epsilon_0 (\epsilon_r - 1)$$

\therefore

$$P = E\epsilon_0(\epsilon_r - 1) \quad \dots (9)$$

From equations (8) and (9), we get

$$E\epsilon_0(\epsilon_r - 1) = \frac{N\alpha E}{1 - \frac{N\alpha}{3\epsilon_0}}$$

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

$$1 = \frac{N\alpha}{3\epsilon_0} \left(1 + \frac{3}{\epsilon_r - 1} \right)$$

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

\therefore

$$\left(\frac{\epsilon_r - 1}{\epsilon_r + 2} \right) = \frac{N\alpha}{3\epsilon_0} \quad \dots (10)$$

Equation (10) is the *Clausius Mossotti relation*.

- It relates the dielectric constant to the molecular polarisability.
- It relates the dielectric constant to the atomic polarizability provided the condition of cubic symmetry holds.

29.4 DIELECTRIC LOSS

When a dielectric is subjected to the a.c. voltage, the electrical energy is absorbed by the material and is dissipated in the form of heat. This dissipation of electrical energy in the dielectric is called dielectric loss.

Since this involves heat generation and heat dissipation, this assumes a dominating role in high voltage applications.

Expression for dielectric loss (or loss tangent)

(i) When a.c. voltage is applied to perfect insulator like vacuum or purified gas, there is no consumption of energy and the charging current leads the applied voltage by 90° [Fig. 29.12 (b)].

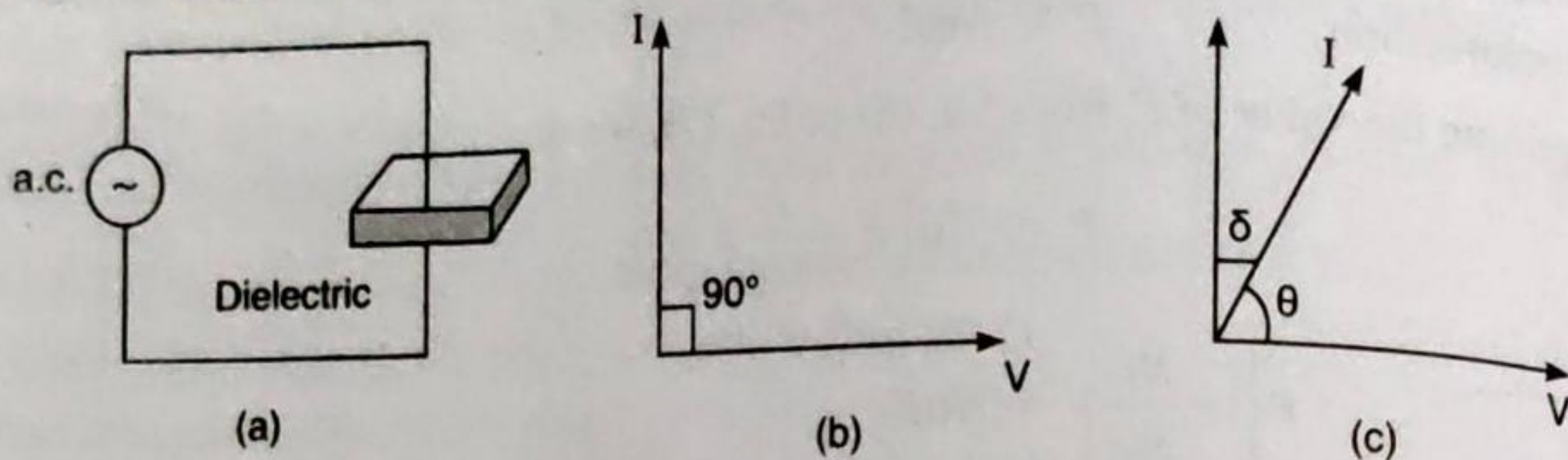


Fig. 29.12

$$\text{Power loss, } P = VI \cos \theta = VI \cos 90^\circ = 0.$$

Thus the ideal dielectrics have no dielectric loss.

(ii) The phase angle between charging current and applied voltage is less than 90° in commercial dielectrics. Complementary angle $\delta = 90 - \theta$ is called the *dielectric loss angle* [Fig. 29.12(c)]. The loss angle is a measure of the power dissipated in each cycle.

For a dielectric having a capacitance of C and having a voltage V applied to it at a frequency f Hz, the dielectric power loss is given by

$$P = VI \cos \theta$$

$$\text{Since } I = \frac{V}{X_c} \text{ where } X_c = \frac{1}{2\pi f C} = \text{capacitive reactance to A.C.}$$

$$\text{and } \cos \theta = \cos (90 - \delta) = \sin \delta,$$

$$P = \frac{V^2}{X_c} \sin \delta = 2\pi f C V^2 \sin \delta$$

Since δ is very small, $\sin \delta = \tan \delta$.

$$\therefore \text{Dielectric power loss, } P = V^2 2\pi f C \tan \delta$$

Here $\tan \delta$ is called *power factor* of the dielectric. The power loss is dependent on $\tan \delta$ as long as the other factors like voltage, frequency and capacitance are constants. Thus the power loss is found to depend on the frequency and value of applied voltage.

29.5 DETERMINATION OF DIELECTRIC CONSTANT OF A DIELECTRIC MATERIAL

The Schering bridge is used for measuring the dielectric constant of dielectric materials.

Principle. It is based on measurement of the capacitance of the capacitor without the dielectric material (C_1) and the capacitance of the capacitor with the dielectric material (C'_1).

The connections are shown in Fig. 29.13.

- C_1 = Capacitor whose capacitance is to be measured
- r_1 = A series resistance representing the loss in the capacitor C_1
- C_2 = Standard capacitor
- R_3 = Non-inductive variable resistance
- R_4 = Non-inductive resistance;
- C_4 = Variable capacitor

D = A.C. null detector;
 S = High frequency oscillator.

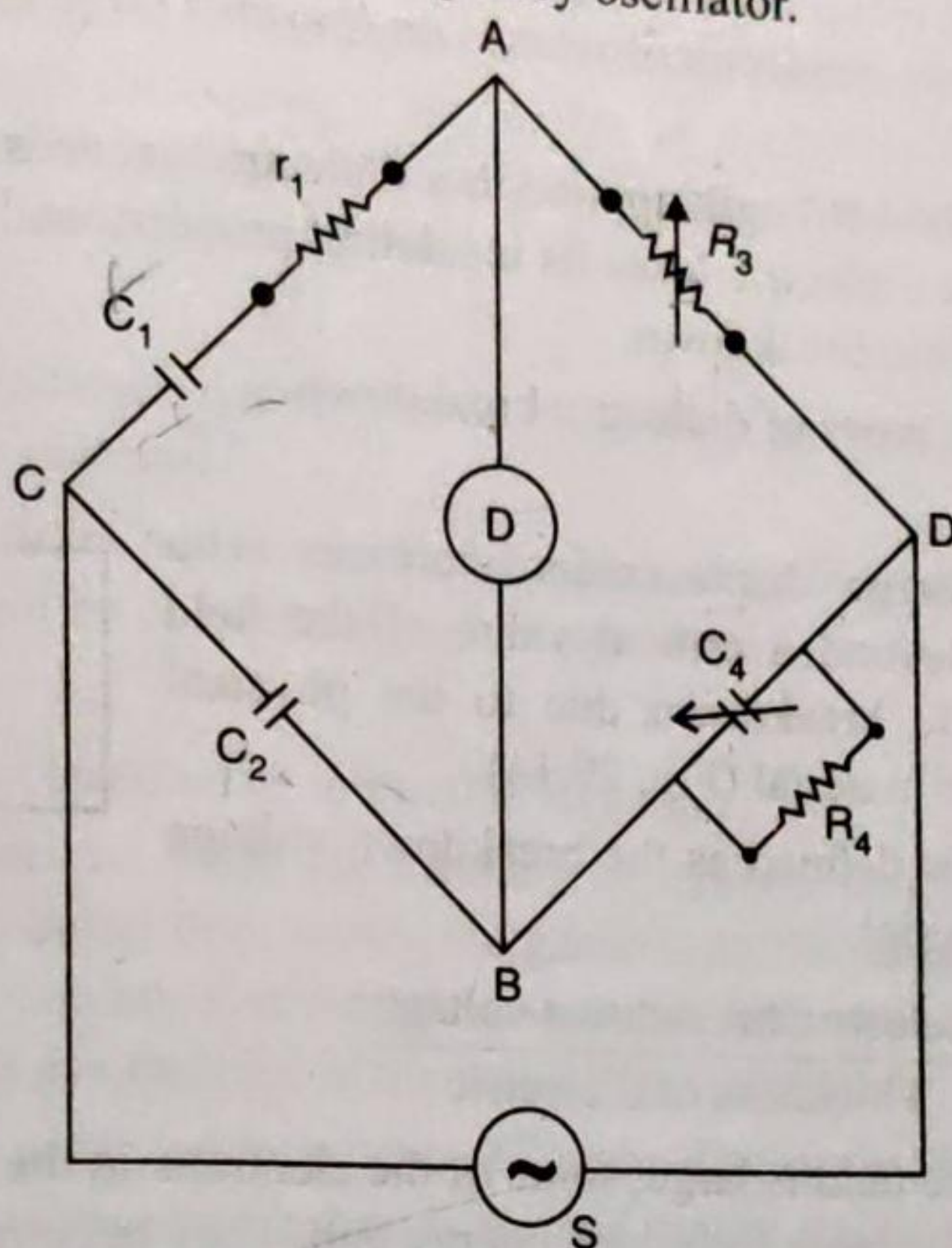


Fig. 29.13

(i) First without inserting dielectric inside C_1 , the bridge is balanced by varying C_4 and R_3 . When current flowing through the detector becomes zero,

$$\frac{\left(r_1 + \frac{1}{j\omega C_1} \right)}{R_3} = \frac{\frac{1}{j\omega C_2}}{\left(\frac{R_4}{(1 + j\omega R_4 C_4)} \right)}$$

$$\left(r_1 + \frac{1}{j\omega C_1} \right) R_4 = \frac{R_3 (1 + j\omega R_4 C_4)}{j\omega C_2}$$

$$r_1 R_4 - \frac{jR_4}{\omega C_1} = \frac{-j R_3}{\omega C_2} + \frac{R_3 R_4 C_4}{C_2}$$

Equating real and imaginary parts, we get

$$r_1 = \frac{R_3 C_4}{C_2}$$

$$C_1 = \frac{C_2 R_4}{R_3}$$

Since R_4 and C_2 are fixed, the dial of R_3 is calibrated to read the capacitance C_1 directly.

(ii) The dielectric specimen should be in the size of C_1 (in its area) and is inserted between the plates of C_1 . Now once again the bridge is balanced. Now the dial reading in R_3 will give the value of new capacitance C'_1 .

Then $\frac{C'_1}{C_1} = \epsilon_r$ = dielectric constant of the specimen.

We can determine the dielectric constant at different frequencies by changing the frequency of the oscillator.

29.6 DIELECTRIC BREAKDOWN

When a dielectric loses its insulation resistance and permits large currents to pass through it, it is said to breakdown.

Whenever the electric field strength applied to a dielectric exceeds a critical value, very large current flows through it. The dielectric loses its insulating property and becomes conducting. This phenomenon is called dielectric breakdown.

There are five important types of dielectric breakdown.

1. Intrinsic breakdown

In a dielectric, the charge displacement increases with increasing field strength. Beyond a critical value of the field strength, there is an electric breakdown due to the physical deterioration of the dielectric material (Fig. 29.14).

The *dielectric strength* is defined as the breakdown voltage per unit thickness of the material.

$$\text{Dielectric strength} = \frac{\text{Dielectric breakdown voltage}}{\text{Thickness of dielectric}}$$

When the applied electric field is large, some of the electrons in the valence band cross over to the conduction band across the large forbidden energy gap. They become conduction electrons and give rise to large conduction currents. The liberation or movement of electrons from valence band is called internal field emission of electrons. This breakdown is called the *Intrinsic breakdown* or *Zener breakdown*.

Avalanche breakdown

Since the electric field is over the order of 10^6 V/cm, the electrons are accelerated to very high velocity, colliding with the other atoms and molecules thereby releasing more electrons and holes breaking covalent bonds between them. The number of bonds broken and hence number of charge carriers released increases enormously with time and finally dielectric breakdown occurs. This type of breakdown is called *Avalanche breakdown*.

This requires relatively large electric fields. Hence this breakdown occurs in thin samples.

Characteristics

1. This kind of breakdown requires relatively large electric fields.
2. Mostly this kind of breakdown occurs in thin samples.

2. Thermal breakdown

Thermal breakdown occurs in a dielectric when the rate of heat generation is greater than the rate of dissipation. Energy due to the dielectric loss appears as heat. If the rate of generation of heat is larger than the heat dissipated to the surrounding, the temperature of the dielectric increases which eventually results in local melting. Once melting starts, that particular region becomes highly conductive, enormous current flows through the material and dielectric breakdown occurs.

Characteristics

1. It occurs only at high temperatures.
2. The strength of the electrical field to create dielectric breakdown depends upon the size and shape of the insulation sample.
3. The breakdown time is of the order of few milliseconds.
4. Since the dielectric loss is directly proportional to frequency, the electric field strength to create dielectric breakdown will be smaller for alternating fields and higher for D.C. fields.

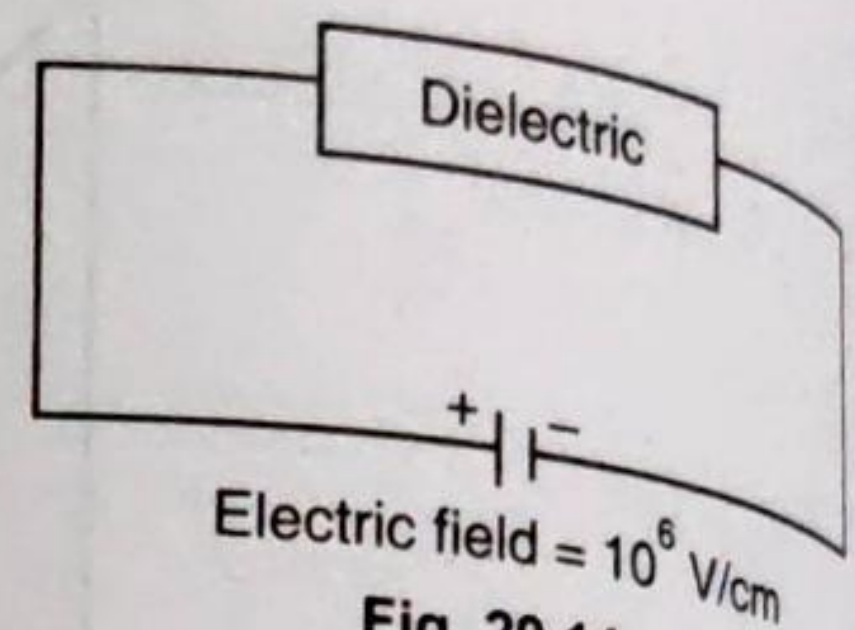


Fig. 29.14

3. Electrochemical breakdown

Electrochemical breakdown has a close relationship with thermal breakdown. When temperature rises, mobility of ions increases. Hence electrochemical reaction takes place. When ionic mobility increases, leakage current also increases. This results in dielectric breakdown. The chemical reaction reduces the insulation resistance and finally creates the dielectric breakdown. This type of breakdown is called *electrochemical breakdown*.

Characteristics

1. Electrochemical breakdown is determined by the leakage current, density of ions, temperature and permanent dipoles in the material.
2. Electrochemical reactions are accelerated by high temperatures. So to avoid breakdown, insulating materials should not be operated at high temperatures.

4. Discharge breakdown

Discharge breakdown is classified as internal or external.

(i) *Internal breakdown* occurs when the insulator contains occluded gas bubbles. Since gases require smaller ionisation potential than solids, the gaseous atoms ionise first and the gaseous ions bombard the solid dielectric causing electrical deterioration. This can occur at low voltages if there are large number of occluded gas bubbles in the insulating material.

(ii) *External breakdown* is caused by a glow or corona discharge. Such discharges are normally observed at sharp edges of electrodes. Carbon is formed on the electrodes due to these discharges. So the damaged areas become conducting leading to power arc and complete failure of the dielectric. Dust and/or moisture on the surface of the dielectric may also cause external discharge breakdown.

When discharge takes place at a point, the surrounding places are burnt and hence their electrical properties are affected. Thus the life of the insulation of an insulating material depends upon the number of discharges which are taking place inside the material. That is, it depends upon the frequency of the applied voltage.

5. Defect Breakdown

The surface of the dielectric materials may have defects such as cracks, porosity and blow holes (Fig. 29.15).

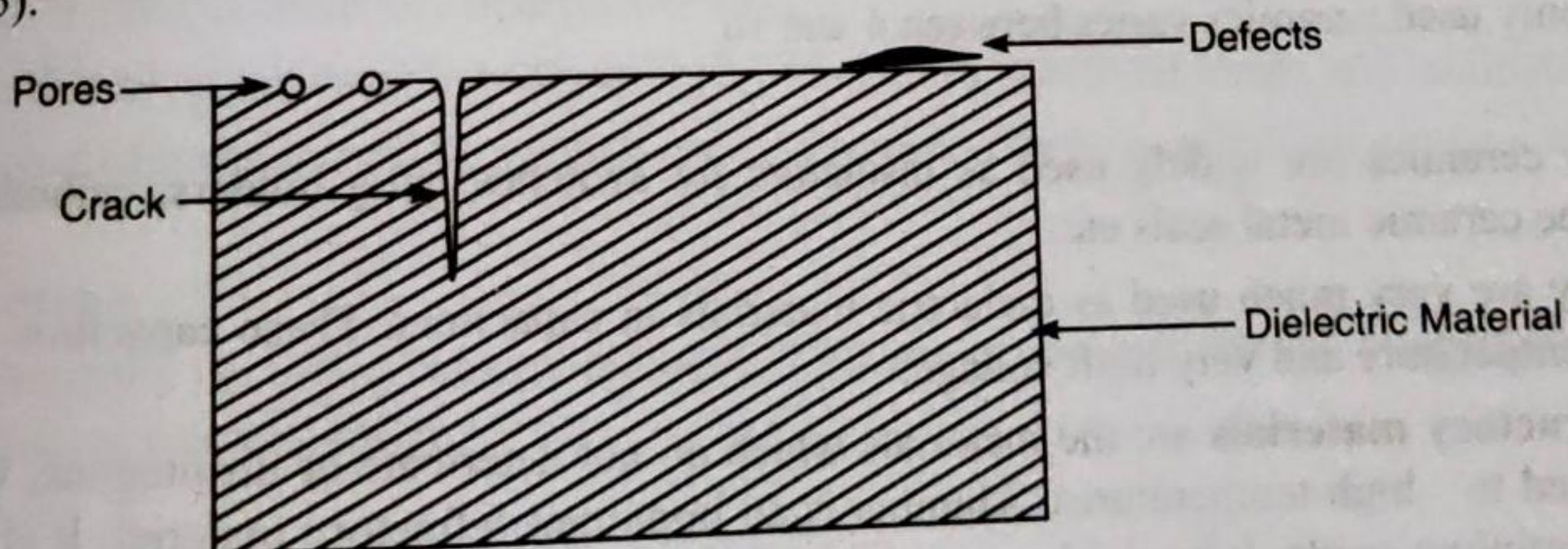


Fig. 29.15

Then impurities like dust or moisture may collect at these discontinuities (defects). This leads to breakdown called *defect breakdown*.

- Glazing is done on ceramic insulators to make the surface nonabsorbent.

29.7 PROPERTIES AND APPLICATIONS OF DIFFERENT TYPES OF INSULATING MATERIALS

Insulating materials are classified into three categories.

1. **Solid insulating materials:** Mica, Porcelain, asbestos, bakelite, rubber, PVC, polythene, glass, cotton, silk, wood and ceramics.

2. **Liquid insulating materials:** Varnish, transformer oil, cable oil, and silicon liquids.

3. **Gaseous insulating materials:** Air, nitrogen, inert gases and sulphur hexafluoride.

1. Solid insulating materials

(i) Mica

It is a mineral compound of silicate of aluminium with silicates of soda potash and magnesia.

Properties:

1. It is crystalline in nature.
2. It can be easily split into very thin flat sheets.
3. It is rigid, tough and strong. It is not affected by moisture .
4. Its dielectric constant varies between 5 and 7.5.
5. Its dielectric strength varies between 700 and 1000 kV / mm .
6. It has high dielectric strength and low power loss.

Uses:

1. Mica sheets are used as insulator between commutator segments.
2. Thick mica tape is used for taping the stator coils of high voltage alternators.
3. It is used in electrical irons, hot plates and toasters for insulation purposes.
4. It is used as a dielectric material for high frequency applications.

(ii) Ceramics

They are generally non-metallic inorganic compounds such as silicates, aluminates, oxides, carbides, borides, nitrides and hydroxides.

Properties:

1. Ceramics are hard, strong, dense and brittle.
2. They are completely stable at high temperatures. They are not affected by moisture and by chemical action except with strong acids and alkalis.
3. They may be either crystalline or amorphous.
4. The ceramics have excellent dielectric and mechanical properties. The dielectric constant of the commonly used ceramics varies between 4 and 10.

Uses:

1. The ceramics are widely used as insulators for switches, plug holders, cathode heaters, vacuum type ceramic metal seals etc.
2. They are very much used as dielectric materials in capacitors. These capacitors withstand very high temperature and very high voltage.
3. **Refractory materials** are the materials which do not deteriorate or disintegrate, when they are subjected to high temperatures. Alumina is an important refractory material. It is primarily made of aluminium oxide. It has high compressive strength, absorbs less moisture and is excellent in heat conduction. It is used in high temperature appliances like furnaces.

(iii) PVC materials

When acetylene and hydrogen chloride are combined in presence of catalyst at temperature of about 50°C, polyvinyl chloride (PVC) resin is produced.

Properties:

1. They have good mechanical and electrical properties.
2. They are non - corrosive.

Uses:

1. They are widely used in insulation for wires and cables.
2. PVC films, tapes, and sheets are commonly used as insulation for dry batteries, conductors and cables.

(iv) Rubber

They are organic polymers and may be natural or synthetic. Natural rubber has limited applications because of its poor stability at wide temperature range. The synthetic rubbers are produced artificially by copolymerisation of isobutylene and isoprene.

Properties:

1. The rubbers have good electrical and thermal properties.
 2. Rubber possesses good dielectric properties and high tensile strength.
- The dielectric constant of rubber varies between 2.5 and 5.

Uses:

1. Rubber is widely used as an insulating material for electric wires, cables, tapes, coatings, transformers, motor winding etc.
2. It is used in the construction of storage battery housings and panel boards.

(v) Glass

Glass is an inorganic material made by the fusion of different oxides like silicon oxide, zinc oxide and magnesium oxide. Silica glass, Pyrex and fibre glass are the important glass insulating materials.

Properties:

1. It is brittle and hard. It is insoluble in water.
2. It has low dielectric loss and has good mechanical strength.
3. It is highly chemical resistant to most corrosive agents. It is a good insulator with good appearance.

Uses:

1. Glass is used as dielectric in capacitors.
2. It is used as an insulator in radio and television tubes, electrical lamps and laminated boards.
3. Toughened glass is used for insulation in extra high voltage lines having voltages above 100 kilovolts.

(vi) Asbestos

It is a naturally occurring mineral material of fibrous structure. Asbestos generally consists of magnesium silicate composition.

Properties:

1. It has high dielectric loss and low dielectric strength.
2. It can withstand very high temperature (400°C).

Uses:

1. Asbestos finds extensive use in electrical machines because of its ability to withstand very high temperature.
2. It is used for making of cloth tapes and paper boards for insulation purposes.
3. It is used for covering/insulating the wire in electric heating devices, ovens, electric irons, etc.

2. Liquid insulating materials

Liquid insulating materials can be divided into three groups.

- (i) *Mineral insulating oils* : Transformer oil, cable oil, capacitor oil, etc.
 (ii) *Synthetic insulating oils* : Askarels, aroclors, sovol and sovtol.
 (iii) *Miscellaneous insulating oils* : Vegetable oils, vaseline and silicon liquids.

(i) **Mineral insulating oils**

These oils are obtained from crude petroleum by distillation and have high oxidation resistance and good thermal stability.

Properties and uses

Transformer oil is the important mineral insulating oil with high dielectric strength, viscosity and cooling properties. This oil is used for insulation and cooling of transformer. It transfers heat from windings and core to the cooling surfaces by convection. It maintains the insulation of the windings.

(ii) **Synthetic insulating oils**

Now-a-days synthetic oil is used as an insulator in transformers in the place of transformer oil (mineral oil) because synthetic oils are very much resistant to oxidation and to fire hazards. Due to longer life and safety in operating conditions, synthetic oil is used as coolant and insulator in H. V. transformers. Particularly askarels have thermal stability upto 110°C and are manufactured from chlorinated hydrocarbons.

(iii) **Miscellaneous insulating oils**

Silicon liquids have stability upto 200°C and are costly. The dielectric strength of these liquids is same as that of mineral oils and power factor is very low. They are used in H.V. Transformers. Further these are used to increase the surface resistivity of ceramic insulators. Vaseline has high viscosity and high dielectric constant. It is used for impregnation of papers used in capacitors.

3. Gaseous insulating materials

(i) **Air**

It is the most important insulating material available in nature. The dielectric constant of air increases linearly with the increase of pressure. It is used in air capacitors. The power loss is practically zero. It is used for insulation between the two conductors of high voltage transmission lines. Air can be used as insulation only in the low voltage applications since at higher field strengths air may get ionised.

(ii) **Nitrogen**

Nitrogen is chemically inert. It prevents oxidation and reduces the rate of deterioration. In oil filled transformers, the nitrogen is used to replace oxidizing atmosphere. This is also used in capacitors and in cables under pressure.

(iii) **Inert gases**

They are used in electronic tubes and discharge tubes as insulators.

(iv) **Sulphur hexafluoride**

It is produced when sulphur is burnt in fluorine atmosphere. It has high dielectric strength. It has superior cooling properties than those of air and nitrogen. It has high chemical stability upto 100°C and is used in transformers and electric switches. Further it is also used in Van de Graff generator, Voltage stabilizer and X-ray apparatus for insulation purposes.

FERROELECTRIC CRYSTALS

29.8 INTRODUCTION

- (A ferroelectric crystal exhibits an electric dipole moment even in the absence of an external electric field. In the ferroelectric state, the center of positive charge of the crystal does not coincide with the centre of negative charge.)

Applications of Ferroelectricity

- (i) The dielectric constant of ferroelectrics is very high (thousands or many thousands in a number of cases) and so they are used in manufacture of small size high capacity capacitors.
- (ii) The property of hysteresis makes it possible to use them as memory devices for computers.
- (iii) Piezoelectric acoustic transducers and pyroelectric infrared detectors are the devices based also on ferroelectrics.
- (iv) The piezoelectric constants of quartz are quite small, but the great mechanical and thermal strengths of this solid have made it pre-eminent for highly stable piezoelectric oscillators. These devices control the frequencies of radio transmitters and quartz clocks, particularly quartz wrist watches.

EXERCISE

- The displacement vector is _____.
 (a) $D = \epsilon_0 E$ (b) $D = \epsilon_0 E + P$ (c) $D = \frac{1}{\epsilon_0} E$ (d) $D = \epsilon_0 E - P$
 - _____ polarizability is produced by opposite displacement of positive nucleus and negative electrons within the same atom.
 (a) ionic (b) electronic (c) dipolar (d) orientation
 (B.U. 2013)
 - Ionic polarizability is _____ to the square of the natural frequency of the ionic molecule.
 (a) inversely proportional (b) directly proportional
 (c) equal to (d) twice
 (B.U. 2012)
 - The Lorentz field (E_L) is given by
 (a) $E_L = E + \frac{P}{\epsilon_0}$ (b) $E_L = E + \frac{P}{3\epsilon_0}$ (c) $E_L = 2E + \frac{P}{\epsilon_0}$ (d) $E_L = 3E + \frac{P}{\epsilon_0}$
 (B.U. 2013)
 - The Clausius-Mossotti equation relates
 (a) conductivity and dielectric constant (b) conductivity and polarizability
 (c) polarizability and dielectric constant (d) polarizability and dipole moment
 (B.U. M.Sc. 2006)
 - $\frac{n\alpha}{3\epsilon_0} = \frac{(\epsilon_r - 1)}{(\epsilon_r + 2)}$ is known as _____ relation.
 (a) Debye (b) Clausius-Mossotti (c) Einstein-Debye (d) Bose-Einstein
 (B.U. 2013)
 - Dielectric materials are those which are used to store _____ energy.
 (a) potential (b) kinetic (c) total (d) electrical
 (B.U. 2011)
- [Ans. 1(b), 2(b), 3(a), 4(b), 5(c), 6(b), 7(d)]
 (B.U. 2010)
- What are polar and nonpolar molecules in dielectrics? Give examples. (Madras 2006)
 - Define polarization. (B.U. 2013)
 - (i) Explain molecular polarizability. (B.U. 2013)
 (ii) Explain atomic polarizability. (B.U. 2012)
 - Discuss the electronic polarization in Dielectrics. (B.U. 2011)
 - Discuss in detail the different types of polarisation mechanisms in dielectrics.

13. Give a schematic sketch of the variation of the total polarizability of an atom as a function of the frequency, explaining the physical origin of the various contributions and the relevant frequency ranges. (B.U. 2015)
14. Derive the Clausius-Mossotti relation. (B.U. 2012)
15. Derive the Clausius-Mossotti relation for electronic polarizability and describe an experiment to determine the dielectric constant. (B.U. 2010)
16. Discuss local field in solid dielectrics. Deduce the Clausius-Mossotti equation. (Madras 2006)
17. Write a note on dielectric breakdown. (Madras 2006)
18. Discuss the properties of any five insulating materials. (B.U. 2011)
19. Give the general properties of Dielectric materials. (B.U. 2013)
20. Explain the ferroelectric crystals. (B.U. 2011)
21. What is ferroelectricity? Explain.
22. Explain dielectric relaxation and dielectric loss in solids. Give an idea of dielectric constant and loss angle for some insulating materials.