

UNIT-2

Part A: Dielectrics**Syllabus:**

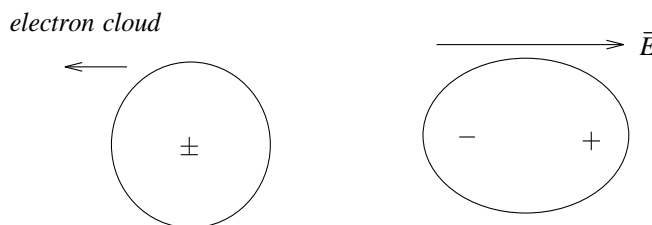
DIELECTRICS: Introduction to Dielectrics-Electric polarization-Dielectric polarizability, Susceptibility and Dielectric constant- Types of polarizations, mathematical derivation for electronic polarizability - Frequency dependence of polarization-Lorentz(internal) field- Claussius -Mossotti equation-Applications of Dielectrics.

Electric Polarization:

When a dielectric is placed in an external electric field, dipole moment is induced by stretching or re-orienting of molecules along the field direction. This is called polarization.

Various Polarization Processes :

1)Electronic Polarization : The displacement of negatively charged electron cloud and positively charged nucleus of an atom in opposite directions, on application of electric field, result in electronic polarization. As the nucleus and the centre of electron cloud are separated by a certain distance, dipole moment is created within each atom.



2) Ionic polarization : The ionic polarization is due to the displacement of cations and anions in opposite directions and occurs in an ionic solid.

3) Orientational Polarization : When an electric field is applied on molecules which possess permanent dipole moment, they tend to align themselves in the direction of applied field. The polarization due to such alignment is called orientation polarization, which is dependent on temperature.

4) Space charge polarization : Space charge polarization occurs due to accumulation of charges at the electrodes or at the interfaces of multiphase materials. The ions diffuse over appreciable distance in response to the applied field, giving rise to redistribution of charges in the dielectric medium.

Polarizability (α):

Polarizability is defined as induced dipole moment per unit electric field.

$$\alpha = \frac{\mu}{E} \quad \text{units: Fm}^2$$

Polarization vector (\bar{P}): It is defined as dipole moment per unit volume.

$$\bar{P} = \frac{\mu}{V} = N\mu \quad \text{where } N \text{ is number of atoms per unit volume.}$$

Electric Displacement (\bar{D}):

When a dielectric is introduced between the plates of capacitor the total electric field can be expressed as

$$\bar{E} = \frac{\sigma_f - \sigma_b}{\epsilon_o} \quad \text{where } \sigma_f \text{ is free charge density and } \sigma_b \text{ is surface charge density. Suffix b}$$

indicates it is bound charge density.

$$\text{Also } \sigma_b = \bar{P}$$

$$\therefore \bar{E} = \frac{\sigma_f - \bar{P}}{\epsilon_o} \quad (\text{or}) \quad \sigma_f = \epsilon_o \bar{E} + \bar{P} = \bar{D}$$

The quantity $\epsilon_o \bar{E} + \bar{P}$ is called electric displacement and is denoted by \bar{D} . The three vectors \bar{P} , \bar{E} and \bar{D} are parallel.

Electric susceptibility χ_e :

In many substances polarization is proportional to the total electric field,

$$\bar{P} = \epsilon_o \chi_e E \quad \text{provided } E \text{ is not too strong.}$$

The constant of proportionality χ_e is called the electric susceptibility of the medium. It is that property of the medium which decides how easily the medium can be polarized.

A factor ϵ_o has been extracted to make χ_e dimensionless. The value of χ_e depends on the microscopic structure of the substance. The materials that obey the above equation are called linear dielectrics.

Dielectric Constant (K):

It is defined as the ratio of the permittivity of the medium to the permittivity of free space.

$$\text{Electric displacement } \bar{D} = (\epsilon_o \bar{E} + \bar{P}) = \epsilon_o \bar{E} + \epsilon_o \chi_e \bar{E} = \epsilon_o (1 + \chi_e) \bar{E}$$

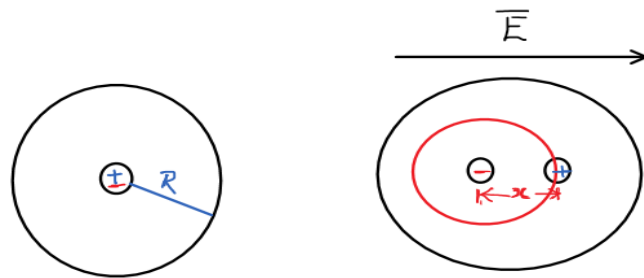
$$\text{or, } \bar{D} = \epsilon \bar{E} \quad \text{where } \epsilon = \epsilon_o (1 + \chi_e) \text{ is called permittivity of the material.}$$

The dimensionless quantity ϵ_r or $K=1+\chi_e=\frac{\epsilon}{\epsilon_o}$ is called relative permittivity or dielectric constant.

Expression for electronic polarizability :

In classical model of an atom, the nucleus of charge ze is surrounded by an electron cloud of charge $-ze$ distributed in a sphere of radius R . The charge density ρ is given by

$$\rho = \frac{-ze}{\frac{4}{3}\pi R^3}$$



When electric field of intensity E is applied, the nucleus and the electrons experience Lorentz forces of magnitude ZeE in opposite directions. Hence nucleus and electron cloud are separated. Now a Coulomb force which tends to oppose displacement develops between them. Equilibrium is reached when Lorentz force and coulomb force are equal and opposite.

Lorentz force on Nucleus is $F_L = ZeE$

$$\text{Coulomb force produced by electron cloud } F_C = -\frac{1}{4\pi\epsilon_o} \frac{Ze \frac{4}{3}\pi x^3 \rho}{x^2}$$

In equilibrium $F_L = F_C$

$$ZeE = -\frac{1}{4\pi\epsilon_o} \frac{Ze \frac{4}{3}\pi x^3 \rho}{x^2}$$

$$ZeE = \frac{1}{4\pi\epsilon_o} \times \frac{Ze \frac{4}{3}\pi x^3}{x^2} \times \frac{ze}{\frac{4}{3}\pi R^3}$$

$$\therefore E = \frac{Ze x}{4\pi\epsilon_0 R^3}$$

\therefore Induced electric dipole moment $\mu_e = Zex$

$$= 4\pi\epsilon_0 R^3 E$$

Electronic polarizability $\boxed{\alpha_e = \frac{\mu_e}{E} = 4\pi\epsilon_0 R^3}$

Also relative permittivity $\epsilon_r = 1 + \chi_e = 1 + \frac{P}{\epsilon_0 E}$

If N is number of atoms/ m^3 , $P = N \alpha_e E$

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

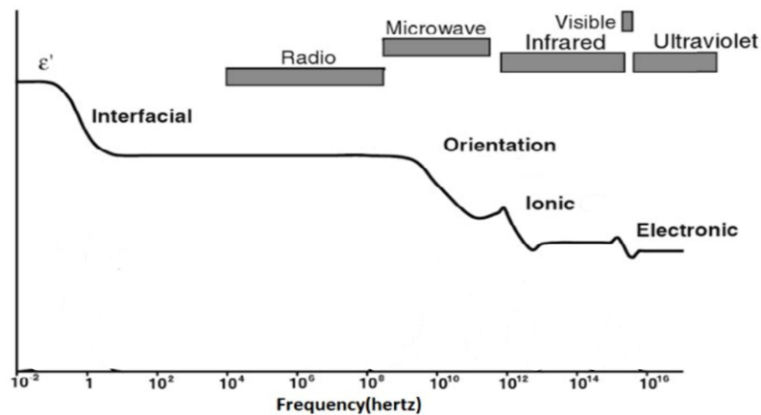
OR

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

Frequency dependence of polarization

On application of electric field, a polarization process occurs as a function of time.

$P(t) = P[1 - \exp(-\frac{t}{t_r})]$ where P is maximum polarization and t_r is relaxation time which is the time taken to reach 63% of maximum polarization. This varies for different polarization processes.



Electronic polarization is extremely rapid and can respond to even high frequencies (optical range $\sim 10^{15} \text{ Hz}$) of applied voltage. Ionic polarization is observed when the frequency is less than 10^{13} Hz . As ions are heavier than electrons the time for displacement is larger. Orientation polarization is slower than ionic polarization and is observed when the frequency of applied voltage is of the audio range (10^6 Hz to 10^{10} Hz). Space charge polarization is slowest of all. It involves diffusion of ions through several interatomic distances. So space charge polarization responds at frequencies less than 10^2 Hz . So all types of polarization are possible at low frequencies.

Local field or Internal field in solid dielectric: (Lorentz field)

The local field at an atom is the sum of the electric field E_1 from external sources and of the field from the dipoles within the specimen.

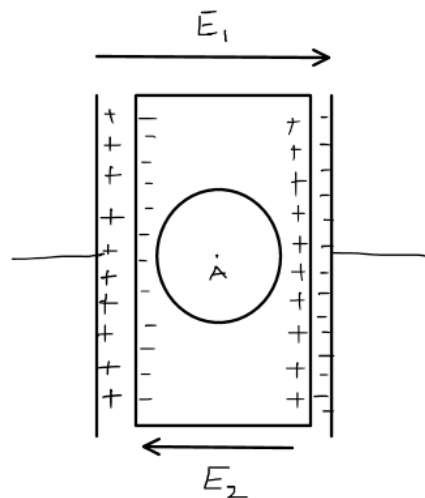
$$\mathbf{E}_{\text{Local}} = \mathbf{E}_1 + \mathbf{E}_2 + \mathbf{E}_3 + \mathbf{E}_4$$

\mathbf{E}_1 = field produced by fixed charges external to the body

\mathbf{E}_2 = depolarization field from surface charge density \bar{P} on the outer surface of specimen

\mathbf{E}_3 = Lorentz cavity field: field from polarization charges on inside of spherical cavity cut out of the specimen with reference atom (at point A) as centre.

\mathbf{E}_4 = field of atoms inside the cavity



Field E_1 :

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

$$E_1 = D/\epsilon_0$$

Field E_2 :

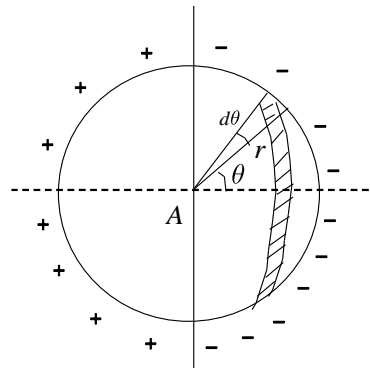
E_2 is the field intensity at A due to the charge density induced on the two sides of the dielectric

Therefore, $E_2 = -P/\epsilon_0$ (2)

$$\text{Let } E_1 + E_2 = E$$

Field E_3 :

Field E_3 due to polarization charges on the surface of fictitious cavity was calculated by Lorentz.



If dA is the surface area of the sphere of radius r lying between θ and $\theta + d\theta$, where θ and $\theta + d\theta$, where θ is the direction with reference to the direction of the applied force,

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

The charge dq on the surface dA is equal to the normal component of the polarization multiplied by surface area.

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

The field due to this charge at A denoted by dE_3 is

$$dE_3 = \frac{1}{4\pi\epsilon_0} \frac{dq}{r^2} \cos\theta$$

\therefore Total field E_3 due to charges on the surface of the entire cavity is obtained by integrating.

$$\begin{aligned} E_3 &= \int dE_3 = \frac{P}{2\epsilon_0} \int_0^\pi \cos^2\theta \sin\theta d\theta = \frac{P}{2\epsilon_0} \int_0^\pi \cos^2\theta d(-\cos\theta) \\ &= \frac{-P}{2\epsilon_0} \left[\frac{\cos^3\theta}{3} \right]_0^\pi = \frac{P}{3\epsilon_0} \end{aligned}$$

Field E_4 due to dipoles within the cavity is the only term that depends on crystal structure. It can be shown that for a reference site with cubic surroundings in a sphere $E_4 = 0$

$$\therefore \text{Internal field or Localfield } E_{\text{Local}} = E_1 + E_2 + E_3 + E_4 = E + \frac{P}{3\epsilon_0}$$

Clausius -Mossotti equation

If α_e is the electronic polarizability per atom, it is related to the bulk polarization P through the relation

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

$$P \left[1 - \frac{N\alpha_e}{3\epsilon_0} \right] = N\alpha_e E$$

$$P = \frac{N\alpha_e E}{\left[1 - \frac{N\alpha_e}{3\epsilon_0} \right]}$$

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

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

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

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

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

OR

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

This is called Clausius Mossotti equation

Applications of Dielectrics

Two most important applications of dielectric materials are as insulating materials and 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.

1. Polymers and ceramics are the widely used solid insulators. Plastics such as polyethylene, polytetrafluoroethylene (PTFE) and polystyrene have lower and practically no dielectric loss.
2. Porcelain towers are used in high voltage power lines because of their high dielectric strength. Porcelain, glass, mica, alumina and asbestos are widely used ceramics.
3. Muscovite mica has good mechanical strength and can be used up to high temperatures of the order of 500°C.
4. Thin plates of glass and linen paper are also used as dielectric in capacitors.
5. Liquid insulating materials like mineral oils have 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.
6. Petroleum oils, silicone oils, and vegetable oils have high thermal stability. They are also used as filling medium for transformers, circuit breakers etc and as impregnants for high voltage cables.