1 INTRODUCTION

Dielectrics are the insulating materials having electric dipole moment permanently or temporarily by applying the electric field. These are mainly used to store electrical energy and used as electrical insulators. All dielectrics are electrical insulators, but all electrical insulators need not to be dielectrics.

Dielectrics are non - metallic materials of high specific resistance and have negative temperature coefficient of resistance.

2 BASIC DEFINITIONS

2.1 Electric flux density (D)

The number of electric lines passing through the unit area of cross section.

$D = [\phi / A]$ ***Unit:*** Coulomb m^{-2}

2.2 Permittivity

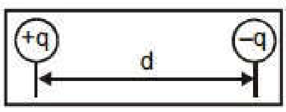
It is the ratio of electric displacement in a dielectric medium to the applied electric field strength.

$\varepsilon = \frac{D}{E}$ for a dielectric medium $\varepsilon_r >> 1$

2.3 Dipole moment

Dipole moment is defined as the product of charge and distance between two changes.

$\mu = q \times d$



Unit : Coulomb meter.

2.4 Polarization

The separation of negative and positive charges is called polarization. i.e., the i.e., process of producing electric dipoles by an electric field is called polarization

$$P = \frac{N\mu}{V} = N\mu \qquad \text{[for unit volume V=1]}$$

2.5 Polarization vector

If " " is the average dipole moment per molecule and "N" is the number of molecules per unit volume then the polarization of the solid is given by the polarization vector P and it can be written as

$$P = \frac{N\mu}{V} = N\mu \qquad \text{[for unit volume V=1]}$$

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

2.6 Polar and Non-polar Molecules

Polar Molecules

Polar Molecules which are having permanent dipole moment even in the absence of an applied field are called polar molecules.

Example: H_2O, HCl, CO.

Non-polar Molecules

Molecules which do not have permanent dipole moment, but they have induced dipole moment in the presence of applied electric field are called non - polar molecules.

Example: O_2, H_2, N_2

2.7 Dielectric Constance (Or) Relative Permittivity

The dielectric characteristics of a material are determined by the dielectric constant (or) relative permittivity of the material

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

$$\varepsilon_r = \frac{\text{Permitivity of the medium}}{\text{Permitivity of free space}}$$

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \qquad \text{where} \qquad \varepsilon_0 = 8.854 \times 10^{-12}\ \text{F/m.}$$

2.8 Electric Susceptibility

The polarization vector P is proportional to the total applied electric field intensity E and is in the same direction of E. Therefore, the polarization vector can be written as

$$P = \varepsilon_0 \chi_e E$$

Where χ_e is electric susceptibility

Relation between Electric Susceptibility and relative permittivity

Relation between Electric Susceptibility (χ) and relative permittivity (ε_r)

We know that $P \propto E$

$$P = \varepsilon_0 \chi_e E$$

$$\chi_e = \frac{P}{\varepsilon_0 E}$$

But $\varepsilon_r = 1 + \chi_e$

$$\chi_e = \varepsilon_r - 1$$

$\therefore$ We can write $P = \varepsilon_0 E(\varepsilon_r - 1)$

It is a measure of characteristic of every dielectric.

2.9 Different between Polar and Non - Polar molecules

S.No	*Polar molecules*	*Non - Polar molecules*
1.	These molecules have permanent dipole moment even in the absence of on applied field.	These molecules do not have permanent dipole moment
2.	The polarization of polar molecules is highly temperature dependent.	The polarization in these type of molecules is independent of temperature.
3.	There is absorption or emission in the infrared range for these molecules ***Example:*** H_2O, HC1, CO	There is no absorption of emission in infrared range for these molecules ***Example:*** O_2, H_2, N_2

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3 POLARIZATION MECHANISMS INVOLVED IN A DIELECTRIC MATERIAL

There are four different types of polarization.

Electronic (or) induced polarization

Ionic (or) atomic polarization

Orientation (or) dipolar polarization

Space - Charge (or) interfacial polarization

3.1 Electronic Polarization

Electronic Polarization occurs due to the displacement of positively charged nucleus and negatively charged electron in opposite directions by an external electric field. It creates a dipole moment in the dielectric. This is called electronic polarization.

The induced dipole moment, $\mu_e = \alpha_e E$ ...(1)

where α_e - Electronic polarisability.

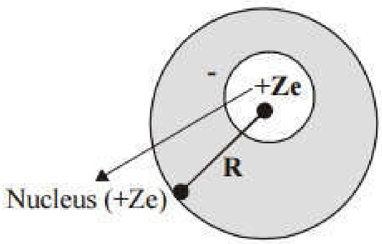
E - Electric field Strength.

It is proportional to volume of the atoms and is independent of temperature.

3.2 Calculation of electronic polarization(α_e)

Consider an atom of a dielectric material of nuclear charge (Ze). The electrons of charge (–Ze) are distributed uniformly throughout the atom (Sphere) of radius R as shown in figure.

With out field



(a) Without Field

Fig.4.1 Electronic polarization

$$\left.\begin{array}{r}\text{Charge density of the charged}\\ \text{sphere (electrons)of radius R}\end{array}\right\} = \frac{\text{Total charge of sphere with radius R}}{\text{Volume}}$$

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

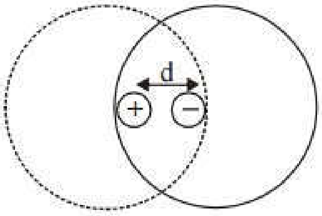
$$= \frac{-3Ze}{4\pi R^3} \quad \dots(1)$$

With field

When the atom of the dielectric is placed in an electric field (E), two types of forces are arise.

Lorentz force: Force which separates electrons and positive nucleus due to applied field.

Coulomb force: An attractive force which is produced after separation.



(b) With Field

Fig.4.2 Electronic polarization

At equilibrium

Lorentz force = Coulomb force

Lorentz force = (charge of the electron) × (intensity of applied Field)

= (–Ze) (E) ... (2)

$$\text{Coulomb force} = \frac{\begin{bmatrix}\text{Charge of the}\\ \text{positive nucleus}\end{bmatrix} \times \begin{bmatrix}\text{Total negative charges}\\ \text{enclosed in the sphere}\end{bmatrix}}{4\pi\varepsilon_0 d^2} \quad ..(3)$$

$$\left.\begin{matrix}\text{The total number of}\\ \text{negative charges enclosed}\\ \text{in the sphere of radius 'd'}\end{matrix}\right\} = \begin{bmatrix}\text{Charge density}\\ \text{of electrons}\end{bmatrix} \times \begin{bmatrix}\text{volume of the}\\ \text{sphere}\end{bmatrix}$$

$$= \left[\frac{-3Ze}{4\pi R^3}\right]\left[\frac{4\pi d^3}{3}\right]$$

$$= \frac{-Zed^3}{R^3} \quad ...(4)$$

Substitute equation (4) in equation (3),

$$\text{Coulomb force} = \frac{Ze \times \left[\frac{-Zed^3}{R^3}\right]}{4\pi\varepsilon_0 d^2}$$

$$= \frac{-Z^2e^2d}{4\pi\varepsilon_0 R^3}$$

$$\text{Coulomb force} = \frac{-Z^2e^2d}{4\pi\varepsilon_0 R^3} \quad ...(5)$$

At equilibrium, coulomb force and Lorentz force must be equal and opposite.

Lorentz force (eqn (2)) = Coulomb force (eqn (5))

$$(-Ze)(E) = \frac{-Z^2e^2d}{4\pi\varepsilon_0R^3}$$

$$E = \frac{Zed}{4\pi\varepsilon_0R^3}$$

$$d = \frac{4\pi\varepsilon_0R^3E}{Ze} \qquad \ldots(6)$$

The displacement (d) of electron cloud is proportional to applied field (E).

Now the two electric charges +Ze and –Ze are displaced by a distance *d* under the influence of the field and form an induced dipole moment which is given by

Induced dipole moment (μ_e) = Charge of the electron × displacement

$$\mu_e = Z_ed$$

Substituting the value of 'd' from eqn (5)

$$\mu_e = \frac{Ze4\pi\varepsilon_0R^3E}{Ze}$$

$$\mu_e = 4\pi\varepsilon_0R^3E$$

$$\mu_e \;\alpha\; E$$

$$\mu_e = \alpha_e E$$

Where $\alpha_e = 4\pi\varepsilon_0R^3$

is called electronic polarization which is proportional to volume of the atom.

Conclusion:

Electronic polarization is independent of temperature.

Electronic polarization occurs in all dielectric materials.

It is proportional to the volume of atoms in the material.

3.3 Electronic polarization in terms of ε_0 and ε_r

P_e is the total number of dipoles per unit volume [V=1]

$$P_e = \frac{N\mu_e}{V} = N\mu_e$$

Where N is the number of atoms per m^3

But $\mu_e = \alpha_e E$

$$P_e = N\alpha_e E$$

We know that, $P_e = \varepsilon_0 E(\varepsilon_r - 1)$

$$N\alpha_e E = \varepsilon_0 E(\varepsilon_r - 1)$$

$$\alpha_e = \frac{\varepsilon_0(\varepsilon_r - 1)}{N}$$

This is called electronic Polarisability

4.3.4 Ionic Polarization

Ionic Polarization which arises due to the displacement of cations (+ve) and anions (-ve) in opposite directions and occurs in ionic solids in the presence of electric field, is called ionic polarization.

Example : NaCl, KCl crystal.

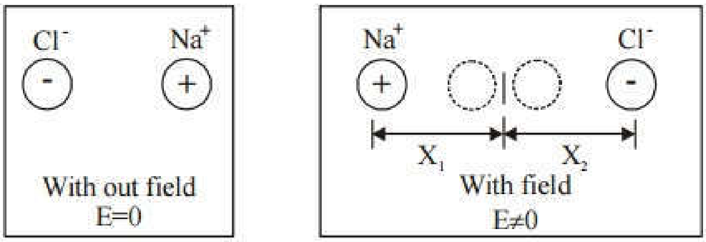


Fig. 4.3 Ionic polarization

Let us assume that there is one cation and one anion present in each unit cell of the ionic crystal (Nacl). When an electric field is applied let $X_1$and X_2 be the distance to which positive and negative ions move from their equilibrium positions.

The Resultant dipole moment per unit volume due to ionic displacement is given by,

Dipole moment i = Charge × Displacement

Dipole moment μ_i = Charge × Displacement

$$\mu_i = e[x_1 + x_2] \quad \ldots (1)$$

When the field is applied, the restoring force produced is proportional to the displacement.

For +ve ion Restoring force $F \propto x_1$

$$F = \beta_1 x_1 \qquad \dots (2)$$

For –ve ion Restoring force $F \propto x_2$

$$F = \beta_2 x_2 \qquad \dots (3)$$

Here β_1 and β_2 are restoring force constants, which depends on the mass of the ions and angular frequency of the molecule in which ions and present.

If **m** is mass of positive, ion, **M** is mass of negative ion, and ω_0 is angular frequency we can write,

$$\beta_1 = m\,\omega_0^2 \qquad \dots (4)$$

$$\beta_2 = M\,\omega_0^2 \qquad \dots (5)$$

Equation (2) and (3) can be written as,

$$F = m\,\omega_0^2 x_1 \qquad \dots (6)$$

$$F = M\,\omega_0^2 x_2 \qquad \dots (7)$$

We know, $$F = eE \qquad \dots (8)$$

Equation equations (6), (7) with (8)

$$m\,\omega_0^2 x_1 = eE$$

$$x_1 = \frac{eE}{m\,\omega_0^2} \qquad \dots (9)$$

$$M\,\omega_0^2 x_2 = eE$$

$$x_2 = \frac{eE}{M\,\omega_0^2} \qquad \dots (10)$$

$$x_1 + x_2 = \frac{eE}{\omega_0^2}\left[\frac{1}{m} + \frac{1}{M}\right] \qquad \dots (11)$$

Substitute equation (11) in equation (1)

$$\mu_i = \frac{e^2 E}{\omega_0^2}\left[\frac{1}{m} + \frac{1}{M}\right] \qquad \dots (12)$$

We know that $\mu_i = \alpha_i E$

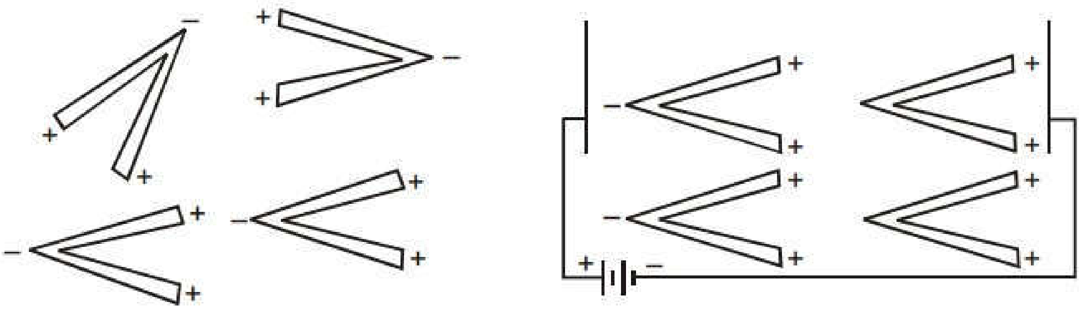
where α_i is ionic polarisability

$$\boxed{\alpha_i = \frac{e^2}{\omega_0^2}\left[\frac{1}{m} + \frac{1}{M}\right]}$$

Conclusion:

Ionic polarisability (α_i) is inversely proportional to the square of angular frequency of the ionic molecule.

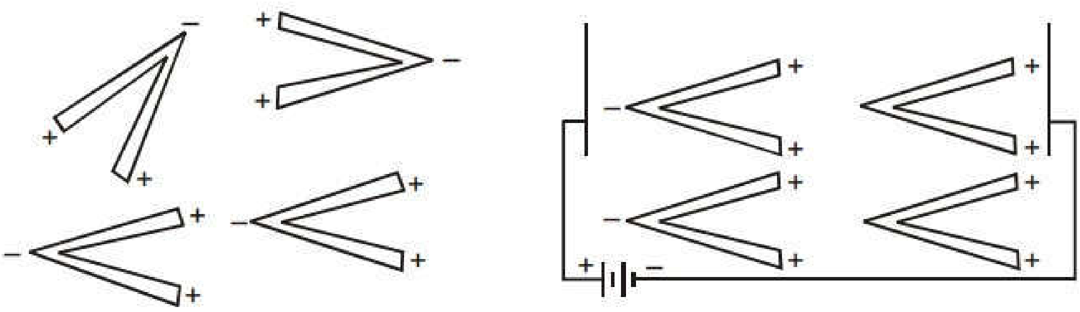
It is independent of temperature.



(a) Without field (b) With field

3.5 Orientation Polarization

The orientation polarization is due to the existence of a permanent dipole moment (polar molecule) in the dielectric medium. Polar molecules have permanent dipole even in the absence of an electric field.



(a) Without field **(b) With field**

Fig.4.4 Orientation polarization

When an electric field is applied on the dielectric medium with polar molecules, the electric field tries to align these dipoles along its field direction as shown in figure. Due to this there is a resultant dipole moment in that material and this process is called orientation polarization.

This polarization depends on temperature. When the temperature is increased, the dipoles are aligned in random directions.

Orientation polarization $P_o = \frac{N\mu^2 E}{3KT}$

Where N - Number of atoms.

Orientation polarization $P_o = N\alpha_o E$

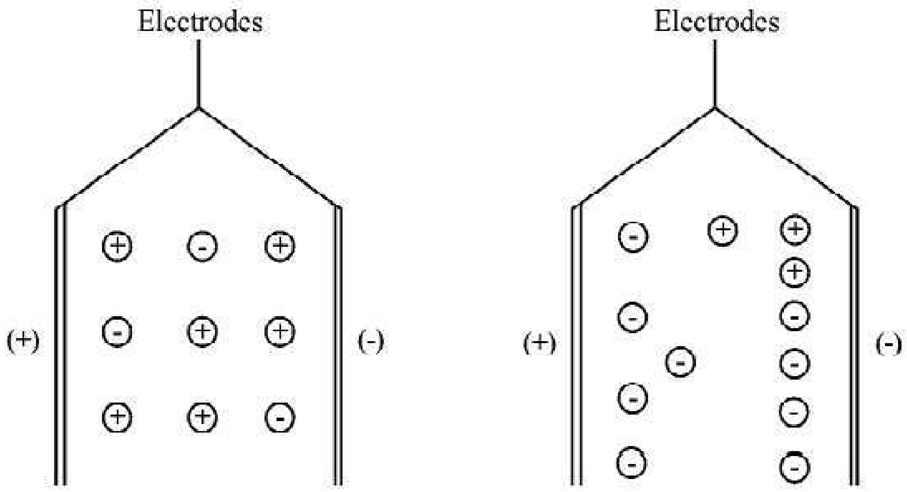
$$\alpha_o = \frac{P_o}{NE}$$

Here $\alpha_o \propto \frac{1}{T}$ i.e., α_o is inversely proportional to temperature of the material.

3.6 Space Charge Polarization

The space charge polarization occurs due to the diffusion of ions along the field direction giving rise to redistribution of charges in the dielectric.

Normally this type of polarization occurs in ferrites and semiconductors and it is very small when compared to other types of polarization.



(a) Without field **(b) With field**

Fig.4.5 Space Charge polarization

3.7 Total Polarization

The total polarization is the sum of the electronic, ionic orientational and space charge polarization.

Orientation polarization $P_o = N\alpha_o E$

Total polarization $P_{total} = P_e + P_i + P_o + P_s$

The total polarisability $\alpha = \alpha_e + \alpha_i + \alpha_o + \alpha_s$

Here α_s is very small and it can be neglected.

$$\alpha = \alpha_e + \alpha_i + \alpha_o$$

$$\alpha = 4\pi\varepsilon_o R^3 + \frac{e^2}{\omega_0^2}\left[\frac{1}{m} + \frac{1}{M}\right] + \frac{\mu^3}{3KT}$$

$$P = N\,E\,\alpha$$

$$P = N\,E\left[4\pi\varepsilon_o R^3 + \frac{e^2}{\omega_0^2}\left[\frac{1}{m} + \frac{1}{M}\right] + \frac{\mu^3}{3KT}\right]$$

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

FREQUENCY AND TEMPERATURE DEPENDENCE OF POLARIZATION MECHANISM

4.1 Frequency dependence

On application of an alternating field across the material, the polarization occurs as function of time

i.e., $P(t) = P_m\left[1 - \exp[-t/t_r]\right]$

Where P_m is the maximum polarization attained due to applied field and t is the relaxation time. Which is the time taken for a polarization process to reach 0.63 of the maximum value. The relaxation times are different for different kinds of polarization mechanisms.

Electronic polarization is very fast and is completed at any instant of time even when the frequency of the voltage is very high in the optical range (10^{15} Hz). Thus it occurs at all frequencies.

Ionic Polarization is slower and the ions do not respond when the voltage corresponds to visible optical frequencies, i.e., the electric field changes in polarity at very fast, so that the ions are not able to reorient themselves due up to the field. So the ionic polarization does not occur at visible optical frequencies. It occurs only at frequencies less than 10^{13} Hz.

Orientation Polarization is even slower than ionic polarization and occurs only at electrical frequencies (audio and radio frequencies 10^6 Hz).

Space-charge polarization is the slowest process because the ions have to diffuse (jump) over several inter atomic distances. This occurs at very low frequencies of 50 - 60 Hz (power frequencies).

Thus at low frequencies all the four polarizations will occur and the total polarization is very high, but at high frequencies, the value of the total polarization is very small. The following graphs show the frequency dependence of polarization mechanism and the corresponding power losses at those frequencies.

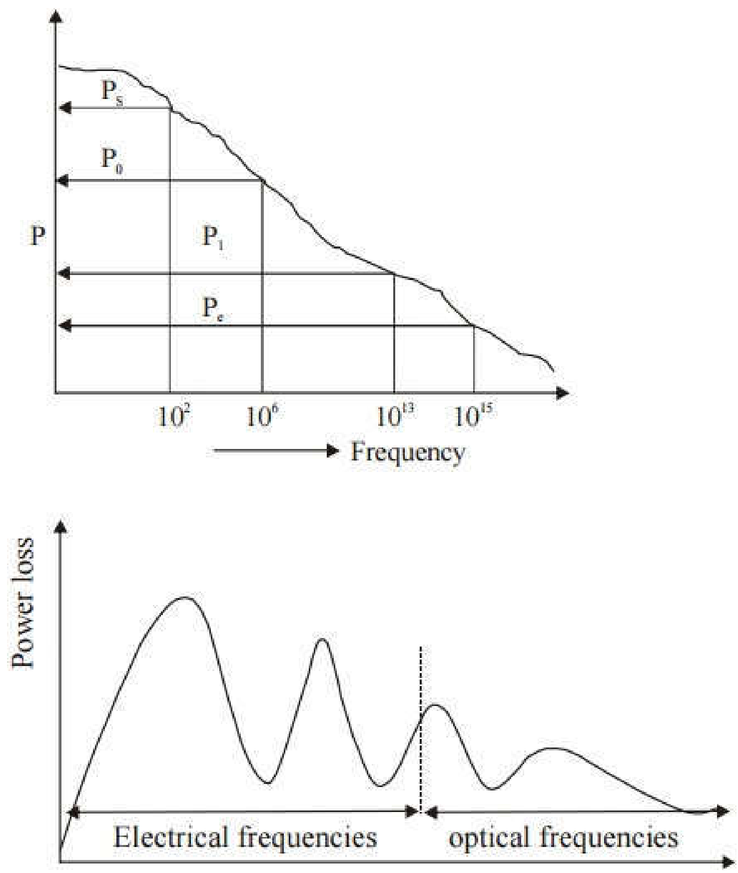


Fig.4.6 Polarization Mechanisms

4.2 Temperature dependence

Electronic and ionic polarizations are independent of temperature and the orientation and space charge polarizations are dependent of temperature. Orientation polarization is inversely proportional to the temperature.

Orientation polarization decreases when temperature increases. Because the random nature decreases the tendency of permanent dipoles to align along the field direction. Thus the dielectric constant increases.

Space charge polarization is directly proportional to the temperature. The space charge polarization increases with increase the temperature. It is because of the fact that the thermal energy helps to overcome the activation barrier and the ions diffuse easily, this results in decrease of dielectric constant.

5 COMPARISION OF TYPES OF POLARISATION

S. N	*Factor*	P_e	P_i	P_o	P_s
1	**Definition**	Electron clouds are shifted from nucleus	Cations and anions are shifted	Regular alignment of random molecules takes place.	Ion diffusion takes place.
2	**Examples**	Inert gases	Ionic crystals	Alcohol, methane, CH_3Cl	Semi conductors, Ferrites.
3	**Temperature dependence**	Independent	Independent	Dependent	Dependent
4	**Relaxation time**	Very fast	Slow	Slower	Slowest
5	**Power loss**	Low	High	Higher	Highest
6	**Frequency range**	10^{15} Hz	10^{13} Hz	10^{6} Hz	10^{5} Hz
7	**Polarisability**	$\alpha_e = \frac{\varepsilon_0 (\varepsilon_r - 1)}{N}$	$\alpha_i = \frac{e^2}{\omega_0^2}\left[\frac{1}{m} + \frac{1}{M}\right]$	$\alpha_o = \frac{\mu^2}{3KT}$	α_s is negligible

6 INTERNAL FIELD (OR) LOCAL FIELD

When a dielectric material is placed in an external electric field, it exerts a dipole moment in it. Therefore two fields are exerted.

Due to external field.

Due to dipole moment

This long range of coulomb forces which is created due to the dipoles is called as **Internal field (or) local field**. This field is responsible for polarizing the individual atoms (or) molecules.

Lorentz method to find the internal field

The dielectric material which is placed in between two plates of a parallel plate capacitor is uniformly polarized as shown in Figure.