Unit – III

MAGNETIC AND DIELECTRIC PROPERTIES OF MATERIALS

DIELECTRIC PROPERTIES OF MATERIALS

3.7 Introduction

Dielectrics are the materials for which all the electrons are tightly bounded to their parent molecule. All dielectrics are insulators, but it slightly differs from insulators because dielectrics are used to store electrical energy.

Examples: Glass, Mica, Rubber, Paper, Wood,
Ceramic, Ebonite

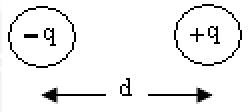
Properties of dielectrics

1. Dielectrics are non-metals with high resistivity
2. They have very large energy gap of more than 3eV
3. The electrical conductivity of dielectric is very low because there are no free electrons to carry charges
4. They have negative temperature coefficient of resistance and high insulation resistance

Basic definitions

Electric Dipole

Two equal and opposite charges (+*q*, -*q*) separated by a small distance (*d*) is called electric dipole.



Dipole moment (μ)

The product of the magnitude of the charge (q) and distance between two charges (d) is called as dipole moment

Dipole moment μ = q. d

Its unit is Coulomb- meter

Permittivity (ε)

Permittivity represents the dielectric property of the medium. Permittivity of free space is $\varepsilon_0 = 8.854 \times 10^{-12}$ Farad/meter

Electric displacement vector (D)

The electric displacement vector (D) is a quantity which is a convenient function for analyzing the electrostatic fields in the dielectrics. It is given by

$$D = \varepsilon E = \varepsilon_0 E + P$$

Dielectric Constant(ε_r)

It is the ratio between the permittivity of a medium (ε) and the permittivity of free space (ε_o).

$$\varepsilon_r = \varepsilon / \varepsilon_o$$

Polarization

The process of producing electric dipoles by the application of an external electric field is called polarization in dielectrics.

Polarisability

We know that average dipole moment (μ) is proportional to the applied electrical field (E)

$$\bar{\mu} \, \alpha \, E$$

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

Where α is the polarisability

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

Polarisability is defined as the ratio of the average dipole moment per unit electrical field applied. Its unit is Farad-metre^2

Polarization vector (p)

It is defined as the dipole moment per unit volume

$$\vec{P} = \frac{\mu}{V}$$

Its unit is Coulomb – meter^{-2}

Polar molecules

Molecules have permanent dipole moment even in the absence of an applied field is called polar molecules.

Example: $CHCl_3$, H_2O,HCl

Non polar molecules

Molecules do not have permanent dipole moment is called non-polar molecules. Example: CCl_4, CO_2, H_2

Active dielectrics

When a dielectric is subjected to an external electric field, if the dielectric actively accepts the electricity, then they are termed as active dielectrics. Thus active dielectrics are the dielectrics which can easily adopt itself to store the electrical energy in it.

Example: Piezoelectric, ferroelectrics, pyro electrics

Passive dielectrics

These dielectrics are also called insulating materials. As the name itself suggests conduction will not take place through these dielectrics. Thus passive dielectrics are the dielectrics which restrict the flow of electrical energy in it.

Example: Glass, Mica, Plastic

3.8 Various polarization mechanisms in dielectrics

.The application of an electric field to a dielectric material creates the dipoles resulting in polarization. There are four different types of polarization namely

(i) Electronic (or) Induced polarization
(ii) Ionic (or) atomic polarization
(iii) Orientation polarization
(iv) Space-charge (or) Interfacial polarization

3.8.1.Electronic (or) Induced polarization

Electronic polarization occurs due to the displacement of positively charged nucleus and negatively charged electrons in opposite directions, when an external electric field is applied**.**

Induced dipole moment is

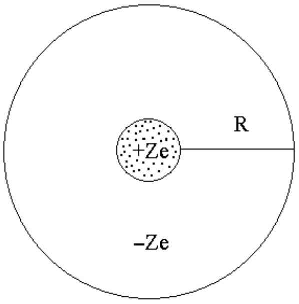
$$\mu = \alpha_e E \qquad \text{--------} \ (1)$$

Where, α_e is known as electronic polarizability. Monoatomic gases exhibit this kind of polarization. It is proportional to the volume of the atoms and independent of temperature.

Calculation of electronic polarizability (α_e)

a) Without field

Let us consider a classical model of an atom. Assume the charge of nucleus of that atom is (+Ze).The nucleus surrounded by an electron cloud of charge(-Ze), which is distributed throughout the sphere (atom) of radius R.



The charge density 'ρ' of the electrons

$$\rho = \frac{Total\ negative\ charge}{Volume\ of\ the\ atom}$$

The charge density 'ρ' of the electrons = $\frac{-Ze}{\frac{4}{3}\pi R^3}$

$$\text{Charge density} = \frac{-3\ Ze}{4\ \pi R^3} \ \ldots\ldots\ldots\ldots\ldots \ (2)$$

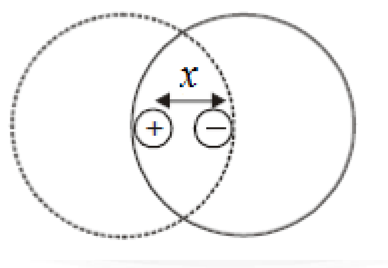
b) With field

If the dielectric material is placed in an electric field of strength E, two phenomena occurs,

Lorentz force:which is tends to separate the nucleus and the electron cloud from their equilibrium position. The positive nucleus will move towards the field direction and the electron cloud will move in the opposite direction of field.

Coulomb force: It arises between the nucleus and the electron cloud which will tend to maintain the original equilibrium position.

Let '*x*' be the displacement made by the electron from the positive core as shown in figure.



Here the displacement of electron cloud is proportional to applied electric field (E)

Induced dipole moment (μ_e) = Magnitude of charge x Displacement

$$= Z\ e\ x \ \text{------------------} \ (3)$$

Since the core is heavy, it will not move when compared to the movement of electron cloud. Here, $x \ll R$. Since Lorentz and coulomb forces are equal and opposite in nature, equilibrium is reached.

At equilibrium,

Lorentz force = Coulomb force

We know that,

Lorentz force (F_L) = Charge x Electric field

= - ZeE ………(4)

Coulomb force (F_C) = $\frac{QZe}{4\pi\epsilon_0 x^2}$ (5)

Total number of negative charges (Q) enclosed in the sphere of radius x = charge density charges of electrons x Volume of the sphere

$$Q = \frac{-3\,Ze}{4\pi R^3} \times \frac{4}{3}\pi x^3$$

$$Q = \frac{-Zex^3}{R^3} \text{ ………….} \quad (6)$$

Substitute eqn. (6) in (5) we get,

$$\text{Coulomb force (Fc)} = \frac{Ze}{4\pi\epsilon_0 x^2} \times \frac{-Zex^3}{R^3}$$

$$F_c = \frac{-Z^2 e^2 x}{4\pi\epsilon_0 R^3} \text{ ………} \quad (7)$$

At equilibrium position,

Equation (4)= equation (7)

Therefore by substitution we get

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

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

$$x = \frac{4\pi\epsilon_0 R^3 E}{Ze} \text{………….. } (8)$$

Substitute the value of 'x' in eqn. (3) we get

$$\mu_e = \frac{Ze 4\pi \in_0 R^3 E}{Ze}$$

$$\mu_e = 4\pi \in_0 R^3 E \quad ----- (9)$$

Compare eqn. (9) and (1) we get,

$$4\pi \in_0 R^3 E = \alpha_e \mathrm{E}$$

$$\alpha_e = 4\pi \in_0 R^3 \quad \text{--------------} \; (10)$$

Where $\alpha_e$is called electronic polarization

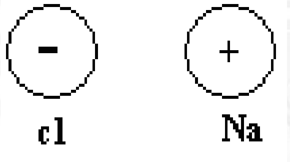
Conclusion:

- Electronic polarization is independent of temperature.
- It is proportional to the volume of atoms in the material
- Electronic polarization takes place in all dielectrics

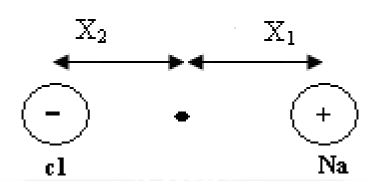
3.8.2 Ionic polarization

Ionic polarization occurs due to the displacement of positive and negative ions in opposite directions, when an external electric field is applied. This type of polarization is produced in ionic molecules such as NaCl, KBr, and KCl etc.

Let us now consider a NaCl crystal. Each Na^+ and Cl^- is a natural dipole as shown in figure.



In the presence of electric field, the ions are separated in an opposite directions as shown in given figure.



The Na $^+$ ion moved a bit right for a distance say 'x_1', and Cl^- moved a bit left for a distance say 'x_2'.

Induced dipole moment = $Charge \ \times displacement$

$$\mu_i = e(x_1 + x_2) \text{ ---------------- } (1)$$

When the field is applied, the restoring force produced is proportional to the displacement of the positive ion

For positive ion

Restoring force $F \ \alpha \ x_1$

Or $F = \beta_1 x_1$ ………………. (2)

For negative ion

Restoring force $F \ \alpha \ x_2$

Or $F = \beta_2 x_2$ …………………(3)

Here $\beta_1$and $\beta_2$are restoring force constants, which depend on the masses of the ions and the angular frequency of the molecule.If m is the mass of positive ion and M is the mass of negative ion and is the angular frequency

$$\beta_1 = m\omega_0^2 \ldots\ldots\ldots\ldots\ldots (4)$$

$$\beta_2 = M\omega_0^2 \ldots\ldots\ldots\ldots\ldots (5)$$

Where ω_0 = angular frequency

Substituting for $\beta_1$in equation (2), the restoring force for positive ion can be written as

$$F = m\omega_0^2 x_1 \ldots\ldots\ldots\ldots..(6)$$

We know that

$$F = eE \ldots\ldots\ldots.(7)$$

Equating eqn.(6) and (7) we get

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

Therefore,

$$x_1 = \frac{eE}{m\omega_0^2} \ldots\ldots\ldots\ldots\ldots\ldots.. (8)$$

Similarly for the negative ion we can write

$$x_2 = \frac{eE}{M\omega_0^2} \ldots\ldots\ldots\ldots\ldots\ldots.. (9)$$

Adding eqn.(9) and (10) we get

$$x_1 + x_2 = \frac{eE}{\omega_0^2}\left(\frac{1}{m} + \frac{1}{M}\right) \ldots\ldots\ldots\ldots (10)$$

Substitute equation(11) in eqn. (1) we get

$$\mu_i = \frac{e^2E}{\omega_0^2}\left(\frac{1}{m} + \frac{1}{M}\right) \text{ ------}(11)$$

But, from definition,

$$\mu_i = \alpha_i E \text{ -----------} (12)$$

Compare equation (12) and (13) we get,

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

$$\alpha_i = \frac{e^2}{\omega_0^2}\left(\frac{1}{m} + \frac{1}{M}\right) \text{-------} (13)$$

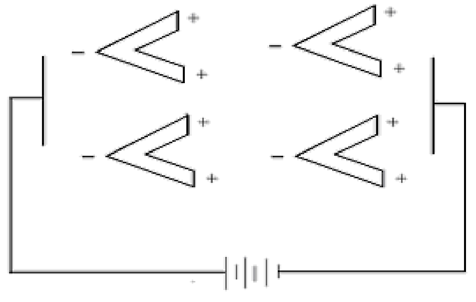
Conclusion

- So the ionic polarizability is inversely proportional to the square of the natural frequency of the ionic molecule
- It is directly proportional to reduced mass
- It is independent of temperature

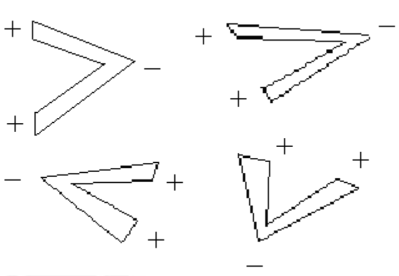
3.8.3 Orientation polarization

This polarization takes place only in the polar dielectrics. Polar dielectrics have molecules with permanent dipole moments even in the absence of electric field as shown in figure.

When field is applied, positive align with the direction of field and the negative side align with the direction as shown figure.



At H=0



At magnetic field

From the Langevin's theory of Para magnetism, net intensity of magnetization is given by

$$\text{M} = \frac{N\mu^2 B}{3K_B T}$$

Since same principle can be applied to the application of electric field in dielectrics.

Orientation polarization

$$P_0 = \frac{N\mu^2 E}{3K_B T} \text{ ----------- (1)}$$

$$P_0 = N\alpha_0 E \text{ -------------- (2)}$$

Where, N represents the no of atoms and compare equations (1) and (2) we get,

$$N\alpha_0 E = \frac{\mu^2 E}{3K_B T}$$

$$\alpha_0 = \frac{\mu^2}{3K_B T} \text{-------- (3)}$$

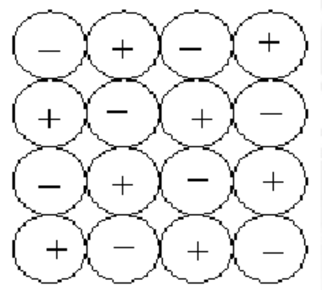
Conclusion

- The orientation polarizability is inversely proportional to absolute temperature of the material

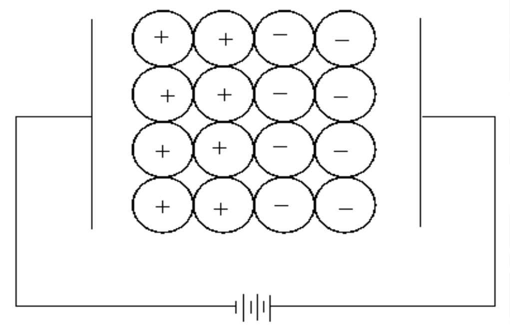
3.8.4 Space charge polarization (or)

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

Consider a dielectric medium placed between any two electrodes. When no field is applied to the electrode the positive and negative charges are not separated as shown in figure.



When an electric field is applied, the positive charges are accumulated near the negative electrode as shown in figure.



Therefore a dipole moment is induced due to the displacement of the ions. Then the induced dipole moment per unit volume gives the induced polarization. This polarization is known as Space charge polarization

Total Electric polarization

The Total Electric polarization is the sum of electronic polarization, ionic polarization, orientation polarization, and space charge polarization. Among these, the space charge polarization is very small compared to others. So it can be neglected

Therefore the total polarizability is given by

$$\alpha = \alpha_e + \alpha_i + \alpha_0$$

$$\alpha = 4\pi \in_0 R^3 + \frac{e^2}{\omega_0^2}\left(\frac{1}{m} + \frac{1}{M}\right) + \frac{\mu^2}{3K_BT} \text{ ----- } (1)$$

We know that the total polarization**is**

$$P = NE\alpha \text{ ---------- } (2)$$

Substitute equation (1) in (2) we get,

$$P = NE\left[4\pi \in_0 R^3 + \frac{e^2}{\omega_0^2}\left(\frac{1}{m} + \frac{1}{M}\right) + \frac{\mu^2}{3K_BT}\right]$$

This equation is called Langevin- Debye equation