Dielectric Properties of Insulating Materials

1

Insulators

The insulating material is a substance which prevents the leakage of electric current in unwanted directions. In other words, when the main function of nonconducting materials is to provide electrical insulation they are called insulators.

Dielectrics

Dielectrics is a nonconducting materials which can be polarized in the presence of electric field. In other words materials which form charged dipole instantaneously under the influence of electric field are known as dielectrics i.e. they have ability to store energy when external electric field is applied. The dielectrics are of two types i.e. polar and non-polar.

Remember:

A dielectric is always an insulator.

Dielectrics Parameter

1. Permittivity ($\in$)

The term permittivity or dielectric constant is the measurement of electrostatic energy store within it and therefore depends on the material.

$$\boxed{\in = \in_r \in_0}$$

where, $\in_r$ = Relative permittivity

$\in_0$ = Permittivity of vacuum

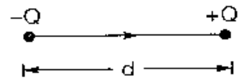
$\in_0 = 8.854 \times 10^{-12}$ Farad meter^{-1}

Note:

- Unit of permittivity is farad meter^{-1}.
- Relative permittivity of vacuum is equal to 1.
- $\in_r$ is a dimension less quantity for construction of condenser the relative permittivity should be as high as possible
- Materials used for capacitor (ceramic) have higher dielectric constant than polymer.

2. Dipole Moment

Two charge of equal magnitude but opposite in polarity placed distance d apart constitute a dipole moment.



$\boxed{\bar{p} = Q\bar{d}}$ Debye

Note:

- Dipole moment is a vector quantity and pointing from the negative charge to the positive charge.
- 1 Debye = 3.33×10^{-30} Coulomb - meter

3. Polarization

The electric dipole moment per unit volume is called as polarization.

$\boxed{P = Np}$ Coulomb / m^2

Where, N = Number of dipoles per unit volume.

In many dielectric materials the polarization vector is proportional to the electric field E, as

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

Where, E = Electric field intensity

χ_e = Electrical susceptibility

$$\boxed{\chi_e = \epsilon_r - 1}$$

Note:

χ_e is a measure of the ability of the material to become polarized.

$$\boxed{\chi_e = \frac{\text{Bound charge density}}{\text{Free charge density}}}$$

4. Polarizability

The elemental dipole moment is proportional to electric field strength E, that acts on the particle so that,

$$\boxed{p = \alpha E}$$

Where, α = Polarizability, Farad-m^2

E = Electric field intensity, V/m

p = Dipole moment, Coulomb-m

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

Note:

α represents the extent of degree of polarization.

5. Electric Flux Density

$\boxed{\bar{D} = \epsilon \bar{E}}$ ... for isotropic materials.

Remember:

- In isotropic materials ϵ is independent of the direction.
- Electric flux density when an electric field is applied.

$$\boxed{D = \epsilon_0 E + P}$$

- The stored energy per unit volume in a dielectric medium due to polarization.

$$\boxed{W = \frac{1}{2}PE}$$

Mechanism of Polarization

1. Electronic polarization

The electronic polarizability of a molecule can be define as the dipole moment induced per unit field strength resulting only from shift of the electron clouds relative to nuclei.

$$\boxed{P_e = N\alpha_e E}$$

Where, α_e = Electronic polarizability

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

Where, R = Radius of atom

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

$\boxed{\epsilon_r = 1 + 4\pi N R^3}$ ...for rare gases

2. Ionic polarization

When in a molecule some of the atoms have excess positive and negative charges resulting from ionic character of the bonds, an electric field will tend to shift positive ions relative to nuclei.

$$\boxed{P_i = N\alpha_i E}$$

Where α_i = ionic polarizability

Note:

- $\alpha_i = \frac{1}{10} \times \alpha_e$.
- Ionic polarization is independent of temperature.

3. Orientational polarization

When an internal field is applied to a molecule carrying a permanent dipole moment, the external field will tend to align the dipole along the direction of external field by applying a torque.

$$\boxed{P_0 = \frac{NP_p^2}{3KT}E}$$

Where,
N = Number of permanent dipoles
P_p = Permanent dipole moment
E = Applied external electric field intensity
K = Boltzman constant
T = Temperature in Kelvin

Orientational polarizability

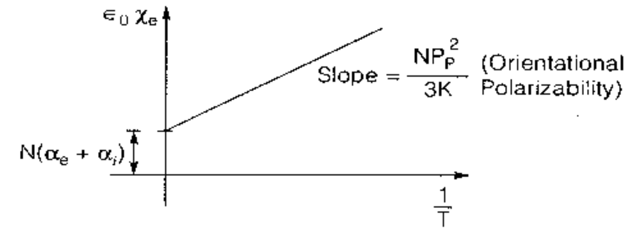
$$\boxed{\alpha_0 = \frac{P_p^2}{3KT}} \text{ ... Curie law}$$

Total polarization of a polygamic gas

$$\boxed{P = P_e + P_i + P_0}$$

$$\boxed{P = N\left(\alpha_e + \alpha_i + \frac{P_p^2}{3KT}\right)E}$$

$$\boxed{\epsilon_0 \, x_e = N(\alpha_e + \alpha_i) + \left(\frac{NP_p^2}{3K}\right)\frac{1}{T}}$$



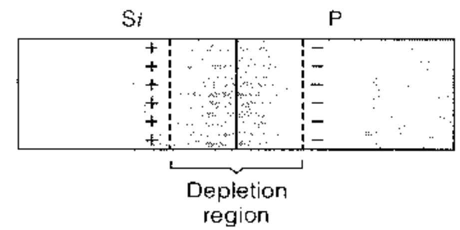
Plot of $\epsilon_0 \chi_e$ Vs 1/T

Note:

- Orientational polarization is dependent on temperature and frequency.
- Orientational polarization is applied only to polar dielectrics.

4. Interfacial Polarization or Space charge polarization

This type of polarization occurs due to accumulation of charges at the interfacing in a multiphase material.



Net polarization

$$\boxed{P = P_e + P_i + P_0 + P_s}$$

Where, P_s = Interfacial polarization

Note:

For single phase material, value of P_s become zero.

Internal Field in Solids and liquids

The internal field

$$\boxed{E_i = E_{ext} + \frac{\gamma}{\epsilon_0}P}$$

Where,
P = Dipole moment per unit volume
γ = Internal field constant

$\because\ \gamma, \epsilon_0$, P are positive quantity. Thus

$$\boxed{E_i > E_{ext}}$$

Note: ....

For cubic lattice $\gamma = 1/3$ and internal field is called Lorentz's internal field and given by

$$\boxed{E_{i(Lorentz's)} = E_{ext} + \frac{P}{3\epsilon_0}}$$

Types of Dielectric Materials

1. Elemental Solid Dielectrics

These are the materials consisting of single type of atoms. Such materials contains neither ions nor permanent dipoles.

$$\boxed{\epsilon_r = (\chi_e + 1) = \frac{1-(1-\gamma)\frac{N\alpha_e}{\epsilon_0}}{1-\frac{\gamma N\alpha_e}{\epsilon_0}}}$$

Remember: ....

- In elemental solid dielectric only electronic polarization exhibit.
- Diamond, sulphur, germanium etc. are example of elemental dielectric materials.

2. Ionic Nonpolar Solid Dielectrics

These solids contains more than one type of atoms, but no permanent dipoles. In ionic crystals the total polarization is electronic and ionic in nature.

3. Polar Solid

In these solids molecules possess permanent dipole moments. The total polarization has all the three components, i.e., ionic, electronic and orientational polarization.

Clausius-Mosotti relation

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

where N = Number of molecules per unit volume

α_e = Electronic polarizability

Maxwell's relation for index of refraction

$$\boxed{\epsilon_{re} = n^2} \quad (\text{assuming } \mu = \mu_0)$$

where ϵ_{re} = Dielectric constant at optical frequencies

n = Refractive index

μ = Magnetic permeability of material

μ_0 = Magnetic permeability of vacuums

In Clausius-Mosotti relations, for gases at low pressure

$\epsilon_r = 1$ or $\epsilon_r + 2 = 3$

So, $$\boxed{\frac{N\alpha_e}{\epsilon_0} = \epsilon_r - 1 = \chi_e}$$

Debye's generalization of Clausius-Mosotti relation

- Polarizability per kilogram molecule

$$\boxed{\pi = \frac{N_A\alpha}{3\epsilon_0} = \frac{\epsilon_r - 1}{\epsilon_r + 2}\cdot\frac{M}{\rho}}$$

where π = Molar polarizability

N_A = Avogadro's number

$= 6.023 \times 10^{26}$

α = Polarizability which includes effect of orientational polarization

M = Molecular weight of material, kg

ρ = Density, kg/m^3

- Maxwell's relation for optical frequencies or Lorentz-Lorentz equation

$$\boxed{\pi = \frac{N_A\alpha}{3\epsilon_0} = \frac{n^2 - 1}{n^2 + 2}\cdot\frac{M}{\rho}}$$

where n = Refractive index

Note: ....

Lorentz-Lorentz equation will apply only for the case $\alpha = \alpha_e$.

- Condition for spontaneous polarization

$$\frac{N\alpha\gamma}{\epsilon_0} = 1$$

where, N = Number of molecules per unit volume, m^{-3}
α = Polarizability, Farad-m^2
γ = Internal field constant

Curie-Weiss Law

$$\chi_e = \epsilon_r - 1 = \frac{C}{T - \theta}$$

where, C = Curie constant
θ = Characteristic temperature which is usually a few degree smaller than the ferroelectric Curie temperature θ_f.
T = Temperature

Note:

Above temperature θ, the spontaneous polarization vanishes and the material becomes piezoelectric from ferroelectric.

Classification of Dielectric Material Based on the Dielectric Behavior in the Presence of Electric Field

1. Piezoelectric Material

Piezo electric materials are those which get polarized when they are subjected to mechanical stress. Piezo electric material also get strained when subjected to electrical stress.

Example:

Quartz crystal, $BaTiO_3$ crystal, $BaTiO_3$ ceramic modified lead zirconate titanae ceramic, Rochelle salt.

Piezoelectricity

- Direct Effect: The application of stress to a crystal produces a strain which results in a net polarization.
- Inverse Effect: The application of an electric field produces a strain whose sign depends on the field direction
- These are both linear effects. Such materials obey the following equations:

$$\left.\begin{array}{l} T = cS \\ S = sT \end{array}\right\} \quad \text{...(i)}$$

$$P = dT \quad \text{...(ii)}$$

- A stress T results in a strain S in a material and c is an elastic stiffness constant; s is reverse of c. The stress T will produce a polarization; d is called piezoelectric strain constant.
- The dielectric displacement, in the presence of stress.

$$D = \epsilon E + dT \quad \text{...(iii)}$$

and the inverse effect is given by the relation

$$S = sT + dE \quad \text{...(iv)}$$

2. Ferroelectric Material

A ferroelectric material is one which exhibits an electric dipole moment and is said to be spontaneously polarised even in the absence of an electric field. Ferroelectric shows a hysteresis in polarization.

Example:

Rochelle salt, KDP, Barium titanate, sodium nitrite, lead titanate.

Note:

- The direction of polarization can be reversed by applying an external field in reverse direction of spontaneous polarization.
- Curie weiss law only applicable for ferroelectric material.

3. Pyroelectric Material

Pyroelectric material are those which exhibits spontaneous polarization in the absence of external electric field and changes its polarization on heating.

$$\Delta P = \lambda \Delta T$$

where, ΔP = Change of polarization
λ = Pyroelectric constant
ΔT = Change in temperature

Example:

Tourmaline and polyvinylidene fluoride.

4. Anti-ferroelectric Material

These are materials in which the dipole moment are aligned in anti-parallel direction therefore net spontaneous polarization is zero.

parallel direction therefore net spontaneous polarization is zero.

Example:

ADP, Lead Zirconate, Sodium Nibate.

Remember:

- All ferroelectric can be piezoelectric and pyroelectric
- All pyroelectric are piezo electric
- All piezoelectric are not pyroelectric
- All pyroelectric are not Ferroelectric.