UNIT-5
DIELECTRIC PROPERTIES

(1)

Dielectric Properties

Dielectric material is an insulator but consists of two charges (+ve and -ve) separated by a small distance. When electric field is applied to dielectric, +ve charge moves in the direction of applied field and -ve charge will be opposite. This property is called polarisation.

Dielectric material :-

All dielectric materials are insulators but all insulators are not dielectric materials.

Dielectric is an insulator which has temporary or permanant dipoles. It has polarisation property in the presence of electric field.

Ex:- calcite, quartz, perpex.

Dipole :- A system consisting of two equal and opposite charges separated by a small distance dl is defined as dipole

$$-q \;\circ\!\xrightarrow{\;dl\;}\!\circ\; +q$$

Dipole moment :- (μ_d) :-

The product of charge and distance of separation between the charges is defined as electric dipole moment or dipole moment.

$$\mu = q \times dl$$

Units :- coulomb-meter

Permittivity :-

Permittivity of a medium indicates the easily polarisable nature of the material

Units : farad/meter (F/m) $F-m$

Dielectric constant (or) Relative permittivity (ε_r)

The ratio of permittivity of the material in the medium to the permittivity of the material in free space is called as relative permittivity of dielectric constant

$$\boxed{\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}} \qquad \varepsilon_0 = 8.85\times10^{-12} F/m$$

Also $\varepsilon_r = \frac{C}{C_0}$ where C is capacitance of the capacitor with dielectric

C_0 is capacitance of capacitor without dielectric

Dielectric constant will not have any units

Polarisability :- (α)

When the strength of the electric field E is increased, the strength of the induced dipole moment μ also increases ie., μ is proportional to E ($\mu \propto E$)

$$\mu = \alpha E$$

where α is called as polarisability

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

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

Units for polarisability :- farad meter^2 ie., $F\text{-}m^2$

Polarisation Vector ($\vec{P}$)

Polarisation vector is defined as dipole moment per unit volume i.e., $\vec{P} = N\vec{\mu}$

where N is no of molecules per unit volume

& since $\vec{\mu} = \alpha\vec{E}$

$$\therefore \vec{P} = N\alpha\vec{E}$$

Units :- coulomb/(metre)^2 — C/m^2

Electric Flux density :- (or) Electric Displacement (D):-

The number of lines of force passing through unit area is defined as electric flux density or electric displacement

$$\boxed{D = \varepsilon E} \text{ — (1)}$$

We know that $\varepsilon_r = \dfrac{\varepsilon}{\varepsilon_0}$

$$\Rightarrow \varepsilon = \varepsilon_0 \varepsilon_r$$

Substituting in (1)

$$D = \varepsilon_0 \varepsilon_r E \text{ — (2)}$$

Also we have $\boxed{D = \varepsilon_0 E + \vec{P}}$ — (3).

from (2) & (3).

$$\varepsilon_0 \varepsilon_r E = \varepsilon_0 E + \vec{P}$$

$$\vec{P} = \varepsilon_0 \varepsilon_r E - \varepsilon_0 E$$

$$\boxed{\vec{P} = \varepsilon_0(\varepsilon_r - 1)E} \text{ — (4)}$$

Units of Electric flux density :- C/m^2

Susceptibility :- (χ)

$$\chi = \frac{\vec{P}}{\varepsilon_0 E}$$

$$\chi = \frac{\varepsilon_0(\varepsilon_r - 1)E}{\varepsilon_0 E}$$

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$\chi = \varepsilon_r - 1$

$\varepsilon_r = \chi + 1$

No units

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Electronic Polarisation TYPES OF POLARISATION

Different polarisations that occur in dielectric materials are:

1) Electronic polarisation
2) Ionic polarisation
3) Orientation polarisation
4) Space charge polarisation

1) Electronic polarisation

Electronic polarisation occurs in solids. The process of producing electric dipoles along the field direction is known as electronic polarisation.

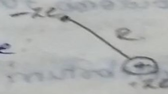
Induced dipole moment μ is proportional to applied electric field

i.e., $\mu \propto E$

$\mu = \alpha_e E$ —— (1)

where α_e is electronic polarisability

Consider the nucleus of charge $+Ze$ is surrounded by an electron of charge $-Ze$ distributed in a sphere of radius R



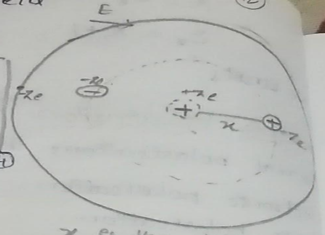
We know that charge density $\rho = \dfrac{\text{charge}}{\text{volume}}$

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

$$\rho = -\frac{3}{4}\frac{Ze}{\pi R^3} \quad (2)$$

Lorentz force = charge × applied field
$= -Ze \cdot E$ —— ③

$$\boxed{\text{Coulomb force} = \frac{+Ze \times \text{charge enclosed in sphere of radius } x}{4\pi\varepsilon_0 x^2}}$$ —— ④



x is the displacement and radius of charged position of atom

We know that density $\rho = \frac{\text{charge}}{\text{volume}}$.

charge $= \rho \times$ volume.

∴ charge enclosed in sphere of radius x $= \frac{-3Ze}{4\pi R^3} \times \frac{4}{3}\pi x^3$

$= \frac{-Ze x^3}{R^3}$ —— ⑤

Substituting ⑤ in ④ we get

coulomb force $= \frac{Ze \times \frac{-Ze x^3}{R^3}}{4\pi\varepsilon_0 x^2}$

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

∴ coulomb force $= \frac{-Z^2e^2 x}{4\pi\varepsilon_0 R^3}$

At equilibrium position, Lorentz force is equal to colomb force.

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

$E = \frac{Ze x}{4\pi\varepsilon_0 R^3}$

∴ Displacement $x = \frac{4\pi\varepsilon_0 R^3 E}{Ze}$

∴ Electric dipolemoment μ is defined as the product of charge and displacement i.e., μ = charge × displacement

$$\mu = Ze \cdot x$$
$$= Ze \cdot \frac{4\pi\varepsilon_0 R^3 E}{Ze}$$
$$\mu = 4\pi\varepsilon_0 R^3 E \quad \text{—— (6)}$$

But $\mu = \alpha_e E$ —— (7)

comparing (6) & (7) we get

electronic polarisability $\alpha_e = 4\pi\varepsilon_0 R^3$

We know that polarisation vector $\vec{P} = N\bar{\mu} = N\alpha_e E$

$$\therefore \vec{P} = N 4\pi\varepsilon_0 R^3 E$$

Susceptibility $\chi = \frac{\vec{P}}{\varepsilon_0 E} = \frac{4\pi N \varepsilon_0 R^3 E}{\varepsilon_0 E}$

$$\chi = 4\pi N R^3.$$

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Ionic polarisation :-

Ionic polarisation occurs only in ionic solids. It is due to the displacement of anions and cations in the opposite direction by the application of electric field.

Consider a sodium chloride molecule. Let +e be the charge on the positive ion and −e be the charge of the positive ion and negative ion, Let M be the mass of positive ion and m be the mass of negative ion

For +ve ion Lorentz force = +eE

Restoring force is proportion to $-x_1$ i.e., $\propto -x_1$

⇒ Restoring force = $-k_1 x_1$

where k_1 – restoring force const

$k_1 = M\omega_0^2$ where M –

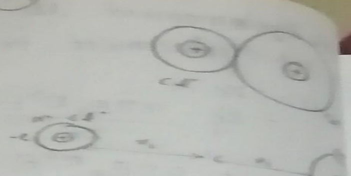
For $-$ve ion

Lorentz force $= -eE$

Restoring force $\propto x_2$

$= K_2 x_2$

$K_2 = m\omega_0^2$



At equilibrium position, the Lorentz force is equal & opposite to the restoring force

For +ve ion,

$$eE = -(-M\omega_0^2 x_1)$$

$$\Rightarrow eE = M\omega_0^2 x_1$$

$$\Rightarrow x_1 = \frac{eE}{M\omega_0^2}$$

For $-$ve ion,

$$-eE = -m\omega_0^2 x_2$$

$$x_2 = \frac{eE}{m\omega_0^2}$$

Total displacement $x = x_1 + x_2$

$$x = \frac{eE}{M\omega_0^2} + \frac{eE}{m\omega_0^2} = \frac{eE}{\omega_0^2}\left[\frac{1}{M} + \frac{1}{m}\right]$$

$\omega \rightarrow$ angular momen

Dipole moment μ = charge $\times$ displacement

$= e \times x$.

$$\mu = e \times \frac{eE}{\omega_0^2}\left[\frac{1}{M} + \frac{1}{m}\right]$$

$$\mu = \frac{e^2 E}{\omega_0^2}\left[\frac{1}{M} + \frac{1}{m}\right] \quad \text{— (1)}$$

But $\mu = \alpha_i E$ — (2) where α_i - ionic polarisability

comparing (1) & (2)

we get ionic polarisability $\alpha_i = \frac{e^2}{\omega_0^2}\left[\frac{1}{M} + \frac{1}{m}\right]$

Polarisation vector $\vec{P} = N\vec{\mu}$

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

Susceptibility $\chi = \frac{\vec{P}}{\varepsilon_0 E} = \frac{Ne^2E}{\omega_0^2\varepsilon_0 E}\left[\frac{1}{M}+\frac{1}{m}\right]$

$$= \frac{Ne^2}{\varepsilon_0\omega_0^2}\left[\frac{1}{M}+\frac{1}{m}\right]$$

Orientation polarisation :-

In methane (CH_4), the centre of the positive charge and the centre of the negative charge coincides and there are no permanant dipoles in methane. Whereas in methylchloride (CH_3Cl) the centre of the positive charge doesnot coincide with the centre of the negative charge and hence there is a permanant dipole in methylchloride. The presence of permanant dipoles is called orientation polarisation.

Orientation polarisation is given by.

$$\boxed{\vec{P} = \frac{N\mu^2 E}{3K_BT}} \quad \text{--- ①}$$

N - No of moles per unit volume
E - Electric field
μ - dipole moment
K_B - Boltzman constant
T - A Temperature

Polarisation vector is

$$\vec{P} = N\alpha_0\bar{E} \quad \text{--- ②.}$$

From ① & ②

$$\alpha_0 = \frac{\mu^2}{3K_BT}$$

where α_0 is orientation polarisability.

Note :- Orientation polarisation is the only one which is dependent on absolute temperature i.e., it is inversely proportional to absolute temperature.

Space charge Polarisation :-

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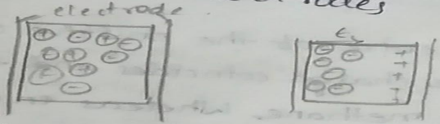
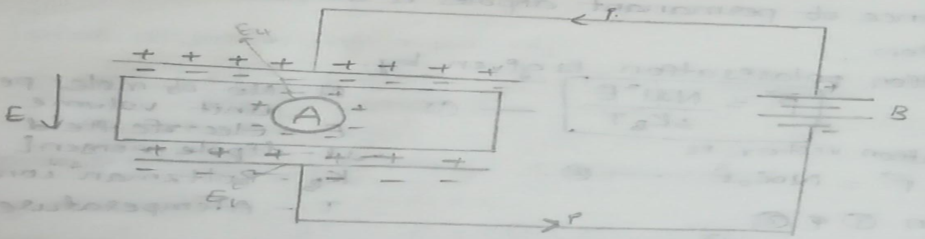
It occurs due to the non uniform distribution of charges in the dielectric material. On the application of electric field, all the +ve charges are aligned along the direction of applied field and the negative charges are aligned in the opposite direction of electric field between the electrodes



Local field (or) Internal field (or) Lorentz field (E_i):



Local field or internal field is defined as the total electric field at the atomic site due to the application of external field and it is given by $E_i = E_1 + E_2 + E_3 + E_4$ — (1)

where E_1 is field intensity on the parallel plate capacitor

E_2 is induced field intensity on the surface of dielectric material

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E_3 is field intensity due to the presence of symmetrical atoms in dielectric material.

E_4 is field intensity on the surface of cavity.

To find E_1 :-

We know that electric flux density (or) electric displacement is given by $D = \varepsilon_0 \varepsilon_r E_A$.

But here $E = E_1$

$$\text{so } D = \varepsilon_0 \varepsilon_r E_1 \quad \text{--- (2)}$$

For dielectric materials $\varepsilon_r = 1$

$$\therefore D = \varepsilon_0 E_1 \Rightarrow E_1 = \frac{D}{\varepsilon_0} \quad \text{--- (3)}$$

Also electric flux density in terms of polarisation is given by $D = \varepsilon_0 E + P$ --- (4)

Substituting (4) in (3) we get $E_1 = \frac{\varepsilon_0 E + P}{\varepsilon_0}$

$$\Rightarrow \boxed{E_1 = E + \frac{P}{\varepsilon_0}} \quad \text{--- (5)}$$

To find E_2 :-

$$E_2 = -\frac{P}{\varepsilon_0} \quad \text{--- (6)}$$

(electric field is applied directly on the plates of the capacitor but not on the dielectric material, so the dielectric has only induced effect, so E is not present in E_2 and negative sign is taken for (5) as the polarity on the dielectric material is opposite to that of the parallel plate capacitor)

To find E_3 :-

$E_3 = 0$ (because there are no symmetrical atoms in dielectric material).

always dielectric dipoles

To find E_4 :-

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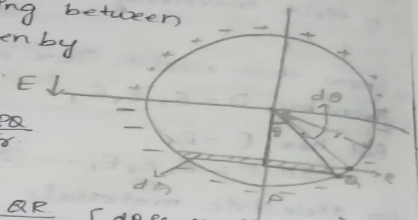
Let dA be the surface area of the sphere of radius 'r' lying between θ and $\theta + d\theta$ and is given by

$$\boxed{dA = 2\pi (PQ)(QR)} \quad \text{— (7)}$$



From figure $\sin\theta = \frac{opp}{hyp} = \frac{PQ}{r}$

$$\Rightarrow PQ = r \sin\theta$$

from fig $\sin d\theta = \frac{opp}{hyp} = \frac{QR}{r}$ [$d\theta$ is small angle so $\sin d\theta \simeq d\theta$]

$$\Rightarrow d\theta = \frac{QR}{r}$$

$$QR = r \cdot d\theta$$

$$\therefore dA = 2\pi (PQ)(QR)$$

$$= 2\pi (r\sin\theta)(r\,d\theta)$$

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

Charge density on surface area dA is given by

$$\boxed{dq = \vec{P} \cos\theta \cdot dA} \quad \text{— (8)}$$

$$\therefore dq = \vec{P} \cdot \cos\theta \cdot 2\pi r^2 \sin\theta \, d\theta$$

$$= \vec{P} \, 2\pi r^2 \sin\theta \cos\theta \, d\theta$$

Field intensity on the surface area dA is given by

$$\boxed{dE_4 = \frac{dq \cdot \cos\theta}{4\pi\varepsilon_0 r^2}} \quad \text{— (9)}$$

$$= \frac{\vec{P}\, 2\pi r^2 \sin\theta \cos\theta \cos\theta \, d\theta}{4\pi \varepsilon_0 r^2}$$

$$dE_4 = \frac{\vec{P}}{2\varepsilon_0} \sin\theta \cos^2\theta \, d\theta$$

∴ field intensity on the surface of small region or cavity in dielectric material is given by

$$E_4 = \int dE_4$$

$$= \int_0^{\pi} \frac{\vec{P}}{2\varepsilon_0} \sin\theta \cos^2\theta \, d\theta$$

$$E_4 = \frac{P}{2\varepsilon_0} \cdot \int_0^{\pi} \sin\theta \cos^2\theta \, d\theta$$

Let $\cos\theta = x$

$\Rightarrow -\sin\theta \, d\theta = dx$

Lower limit i.e., if $\theta = 0$

$\Rightarrow \cos 0 = x \Rightarrow x = 1$

Higher limit i.e., if $\theta = \pi$

$\cos\pi = x \Rightarrow x = -1$

$$E_4 = \frac{P}{2\varepsilon_0} \int_1^{-1} x^2(-dx) = \frac{P}{2\varepsilon_0} \int_{-1}^{1} x^2 dx$$

$$= \frac{P}{2\varepsilon_0} \left[\frac{x^3}{3}\right]_{-1}^{1} = \frac{P}{2\varepsilon_0}\left[\frac{1}{3} - \left(-\frac{1}{3}\right)\right]$$

$$= \frac{P}{2\varepsilon_0} \cdot \frac{2}{3} = \frac{P}{3\varepsilon_0}$$

$$E_4 = \frac{P}{3\varepsilon_0}$$

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

$$= E + \frac{P}{\varepsilon_0} - \frac{P}{\varepsilon_0} + 0 + \frac{P}{3\varepsilon_0}$$

∴ Local field $\boxed{E_i = E + \frac{P}{3\varepsilon_0}}$

Clausius - Mosotte Relation :-

This relation relating the two quantities those dielectric constant ε_r and electronic polarisability α_e

The Clausius Mosotte relation is $\dfrac{\varepsilon_r - 1}{\varepsilon_r + 2} = \dfrac{N\alpha_e}{3\varepsilon_0}$

Proof :-

Consider a dielectric medium with no permanant dipole and no ionic nature.

Therefore orientation polarisation and ionic polarisation be absent in the medium.

When electric field is applied on to such dielectric medium electronic polarisation will takes place

$\alpha_0 = \alpha_i = 0 \quad , \alpha_e \neq 0$

$P = N\vec{\mu}$

But dipole moment $\mu = \alpha E_i$

$\Rightarrow \boxed{P = N\alpha_e E_i}$ —— ①

but $E_i = E + \dfrac{P}{3\varepsilon_0}$

$$P = N\alpha_e \left(E + \frac{P}{3\varepsilon_0}\right)$$

$$P = N\alpha_e E + \frac{N\alpha_e P}{3\varepsilon_0}$$

$$P - \frac{N\alpha_e P}{3\varepsilon_0} = N\alpha_e E$$

$$P\left(1 - \frac{N\alpha_e}{3\varepsilon_0}\right) = N\alpha_e E$$

$$P = \frac{N\alpha_e E}{\left(1 - \frac{N\alpha_e}{3\varepsilon_0}\right)} \quad \text{—— ②}$$

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We know that polarisation $P = \varepsilon_0(\varepsilon_r - 1)E$ —③

From ② & ③

$$\frac{N\alpha_e \cancel{E}}{1 - \frac{N\alpha_e}{3\varepsilon_0}} = \varepsilon_0(\varepsilon_r - 1)\cancel{E}$$

$$\varepsilon_0(\varepsilon_r - 1) = \frac{N\alpha_e}{1 - \frac{N\alpha_e}{3\varepsilon_0}}$$

$$1 - \frac{N\alpha_e}{3\varepsilon_0} = \frac{N\alpha_e}{\varepsilon_0(\varepsilon_r - 1)}$$

$$\frac{N\alpha_e}{\varepsilon_0(\varepsilon_r - 1)} + \frac{N\alpha_e}{3\varepsilon_0} = 1$$

$$\frac{N\alpha_e}{3\varepsilon_0}\left[\frac{3}{\varepsilon_r - 1} + 1\right] = 1$$

$$\frac{N\alpha_e}{3\varepsilon_0}\left[\frac{3 + \varepsilon_r - 1}{\varepsilon_r - 1}\right] = 1$$

$$\frac{N\alpha_e}{3\varepsilon_0}\left[\frac{\varepsilon_r + 2}{\varepsilon_r - 1}\right] = 1$$

$$\therefore \boxed{\frac{N\alpha_e}{3\varepsilon_0} = \frac{\varepsilon_r - 1}{\varepsilon_r + 2}}$$

Piezo electricity :-

With the application of mechanical stress or pressure on the opposite ends of the dielectric material, the voltage or emf is produced or created on the other opposite side of the dielectric material. This is called as piezo electricity.

Inverse piezo electricity :-

On application of voltage or emf on the opposite ends of the dielectric material, compressions or elongation occurs on the other opposite ends of the dielectric material. This is called as inverse piezo electricity.

Pyro Electricity :-

The change in spontaneous polarisation with the change in temperature is called as pyroelectricity. It is represented by $\frac{dP_s}{dT}$.

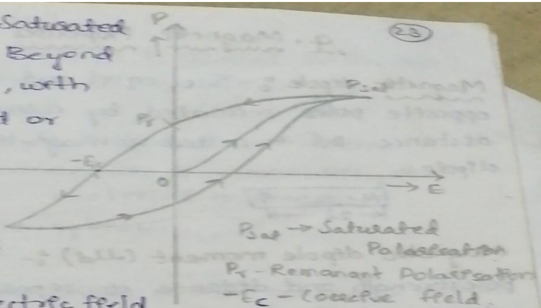
Ferroelectricity :-

The change in polarisation with application of electric field is known as ferroelectricity. The ferroelectric materials exhibit hysteresis curve.

Hysteresis Curve (or) loop : P vs E graph :-

The dielectric hysteresis curve is a graph plotted between polarisation vs applied electric field. As the electric field is increased, the polarisation in dielectric material also increases. At a certain point, with increase of electric field, there is no change

the polarisation i.e., Saturated
polarisation is attained. Beyond
this point of saturation, with
decrease of electric field or
when electric field is
removed, the curve
doesnot retraces its
original path but takes
a new path.



When the external electric field
zero, or removed, there is some amount of polarisation in
the material which is called as remanant polarisation,
represented by P_r. To make the remanant polarisation 0,
negative electric field has to be applied which is called
coercive field represented by $-E_c$. The loop continues but
never reaches to the starting point and hence it is called
hysteresis loop.

Definition of hysteresis curve or loop :-

The lag of polarisation behind the applied electric
field is called as hysteresis loop or hysteresis loss.

Applications: Based on various prop's like insulation, temp dependency, ~~permittivity~~, dielectric strength

1) Used in resonator antenna's for producing & receiving microwaves
2) Used in capacitors for storage of charges
(3) Used as mineral oil in transformers as cooling agent
(4) Used in transducers, spark generators, power transformer.
device which converts one form of energy to another

Thank you

HAVE A NICE DAY