

Chapter - 3

Dielectric Material

We know, Conductors are required for the conduction of current whereas dielectric are required to have insulation at various high voltage applications and unwanted current.

* What is dielectric material?

A dielectric material is an electrical insulator that can be polarized by an applied electric field.

When a dielectric is placed in an electric field, electric charges do not flow through the material as they do in a conductor, but only slightly shift from their average equilibrium positions causing dielectric polarization. Because of dielectric polarization, positive charges are displaced toward the field and negative charge shift in opposite direction.

Parallel Plate capacitor

$$C = \frac{\epsilon_0 A}{d} \quad \text{where, } \epsilon_0 = \text{absolute permittivity}$$

A = Plate area

d = distance of separation

If there is a material medium between the plates, then capacitance (the charge storing ability per unit voltage), increases by a factor ϵ_r , where ϵ_r is called the dielectric constant of the medium or Relative permittivity.

The increase in capacitance is due to the polarization of the medium in which positive and negative charges are displaced with respect to their equilibrium positions.

The opposite surfaces of the dielectric medium acquire opposite surface charge densities that are related to the amount of polarization in the material.

Electric dipole moment P , which is measure of electrostatic effects of a pair of opposite charges $+Q$ & $-Q$ separated by a finite distance ' a ',

so defined by

$$P = Qa$$

Terms

$$D = \epsilon E$$

where,

D = dielectric flux density.

E = Electric field strength.

ϵ = permittivity of medium

$\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$ for free space

$\epsilon = \epsilon_0 \epsilon_r$ for other material

$\epsilon_r \Rightarrow$ Relative permittivity.

Insulator :> The term insulator is generally used to indicate electrical obstruction.

Dielectric :> The term dielectric is generally used to indicate energy storing capacity of material by means of polarization.

*Electric Susceptibility (χ_e): χ_e of dielectric is the measure of how easily it polarizes in response to an electric field.

$$\chi = \frac{\text{Polarization (P)}}{\epsilon_0 \times \text{Electric field (E)}}$$

$$\therefore \chi = \frac{P}{\epsilon_0 E}$$

*Relative Permittivity $\Rightarrow \epsilon_r = \chi + 1$.

Macroscopic Approach of permittivity \Rightarrow

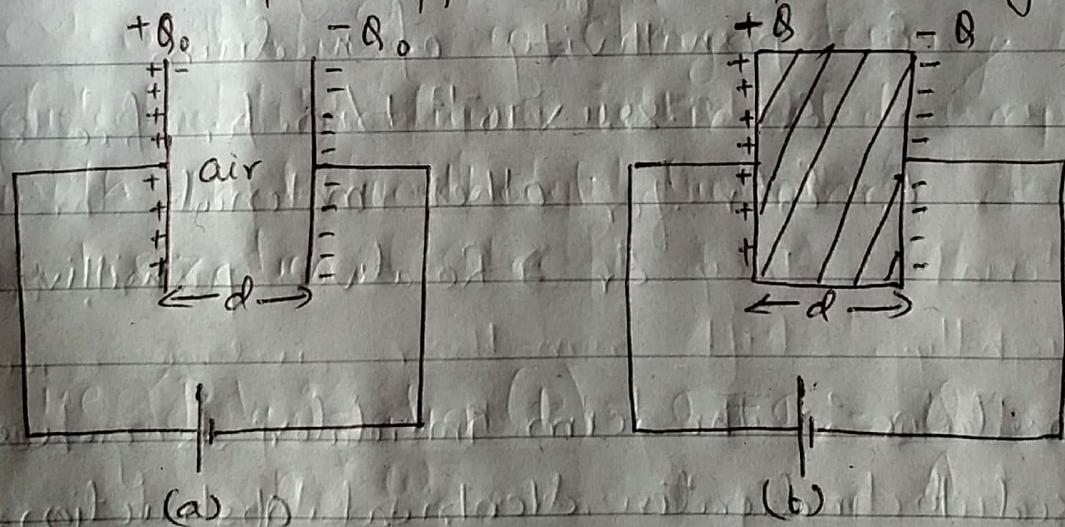


Fig: Parallel plate capacitor (a) without material
b) with material.

Case (a)

$$\text{Capacitance } (C_0) = \frac{\sigma_0}{V} \quad \textcircled{1}$$

After insertion of dielectric between the plates, then the charges on the surface of plate get increased due to appearance of the charge on the surface of the dielectric near to the capacitor plates.

Case (b)

$$\text{Capacitance } (C) = \frac{\sigma}{V} \quad \textcircled{2}$$

from case (a) & (b)

$$C_0 = \frac{\sigma_0}{V} \quad \text{and} \quad C = \frac{\sigma}{V}$$

$$\text{or } C_0 V = \sigma_0$$

$$\text{or } V \times \frac{\epsilon_0 A}{d} = \sigma_0$$

$$\text{or, } \frac{V \epsilon_0}{d} = \frac{\sigma_0}{A} = \sigma_0 \quad \text{L } \textcircled{3}$$

$$\text{or } C V = \sigma$$

$$\text{or, } V \cdot \frac{\epsilon_0 \epsilon_r A}{d} = \sigma$$

$$\text{or, } \frac{V}{d} \cdot \epsilon_0 \epsilon_r = \frac{\sigma}{A} = \sigma \quad \text{L } \textcircled{4}$$

where, σ = surface charge density.

Now, dividing eqn (4) by (3) we get,

$$\left[\frac{\sigma}{\sigma_0} = \frac{Q}{Q_0} = \frac{C}{C_0} = \epsilon_r \right]$$

∴ Therefore dielectric constant or relative permittivity is defined as the increase in charge stored on capacitor plates due to insertion of dielectric medium compared to the charge without dielectric medium.

Now, defining polarization,
Increase in ^{Surface} charge density when dielectric medium is inserted compared with that without dielectric is called polarization.

$$\text{i.e., Polarization (P)} = \sigma - \sigma_0 = \frac{Q}{A} - \frac{Q_0}{A}$$

$$\text{or, } P = \epsilon_0 \epsilon_r \frac{V}{d} - \epsilon_0 \frac{V}{d}$$

$$\text{or, } P = \epsilon_0 \frac{V}{d} (\epsilon_r - 1)$$

$$\therefore P = \epsilon_0 \chi_e E$$

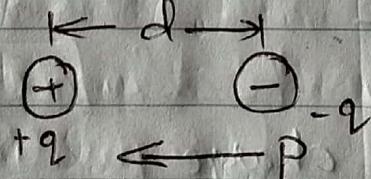
where,

$E = V/d \rightarrow$ electric field strength.

$\chi_e = \epsilon_r - 1 \rightarrow$ dielectric susceptibility
 $P \Rightarrow$ polarization vector of material.

Q) Define dipole moment, polarization vector, and polarizability.

* When a positive charge and a negative charge is separated by a certain distance 'd' then the vector pointing from negative charge to positive charge is called dipole moment and is given by product of charge and mean distance between their centre.



$$\text{dipole moment } (P) = q \cdot d$$

* The charges in a dielectric material won't experience bulk motion in presence of an external electric field, but they will rearrange themselves in more suitable manner. This process is known as polarization, and a dielectric material so stressed is said to be polarized.

* Polarizability is the relative tendency of a charge distribution like the electron cloud of an atom or molecule to be distorted from its normal shape by an external field.

Polarizability α_e is the Induced dipole moment (P) of an atom in Electric field (E).

$$\alpha_e = \frac{Ze^2}{m_e^* \omega_0^2}$$

where, e = electronic charge

ω_0 = Oscillation frequency of centre of electron cloud around nucleus

Z = atomic number

m_e^* = effective mass of electron

Q) Show that magnitude of surface polarization charge density is equal to polarization vector.

Ans \Rightarrow

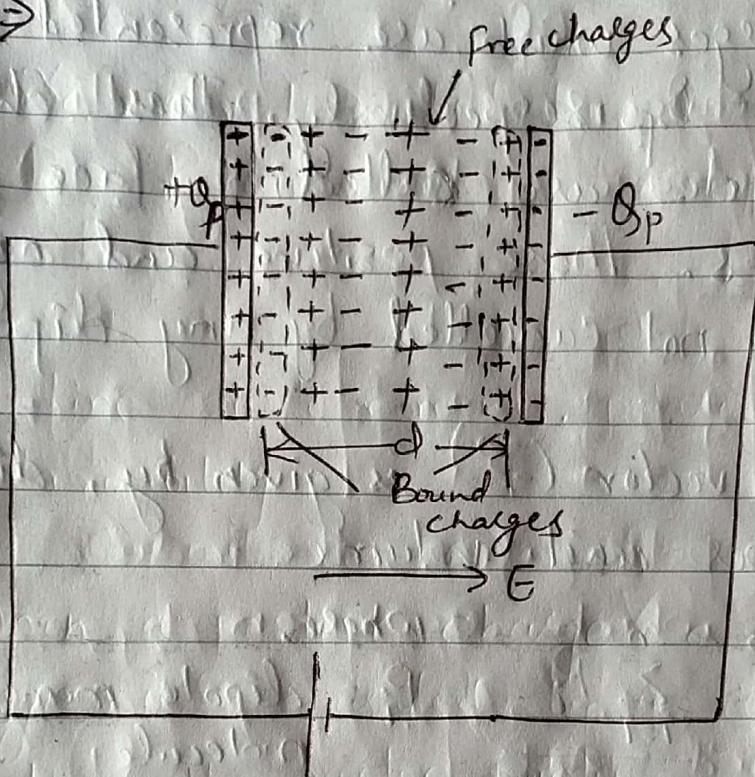


Fig: Polarization of dielectric in influence of electric field

When an electric field is applied, then electronic cloud moves in opposite direction to field and polarization takes place. As shown as in figure above, there is no net charge within the material, but the negative and

positive charge is on far side of material are found to the surface charge on the the plate. So there are positive and negative surface charges which are represented as $+\delta_p$, $-\delta_p$ respectively. These charges on the far sides are called surface polarization charges. These positive and negative charges are not cancelled by any dipoles.

Polarization vector (\vec{P}) is given by, dipole moment per unit volume.

$$\vec{P} = \frac{\sum_{i=1}^n P_i}{V} \quad \text{where, } P_i = \text{dipole moment of } i^{\text{th}} \text{ molecule.}$$

V

$n = \text{no. of molecules}$

$V = \text{Volume of dielectric material.}$

Let $+\delta_p$ and $-\delta_p$, be surface charges and d be the distance of separation between them. Then total dipole moment,

$$P_{\text{total}} = \delta_p \cdot d$$

Polarization = $\frac{\text{Total dipole moment}}{\text{Volume}}$

or, $\vec{P} = \frac{Q_p \cdot d}{V}$

or, $\vec{P} = \frac{Q_p \cdot d}{A \cdot d}$

or, $\vec{P} = \frac{Q_p}{A}$

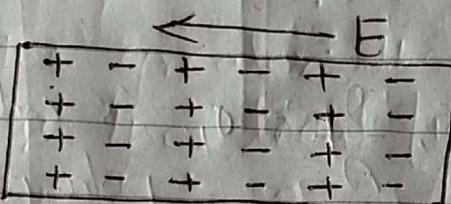
$\therefore \vec{P} = \sigma_p$, $\frac{Q_p}{A} = \sigma_p$ is called surface polarization charge density.

Hence, it is proved that polarization vector is equal to the surface polarization charge density.

Q) How the macroscopic parameters are related to microscopic parameters in dielectric materials? Show.

OR

Relation between relative permittivity (ϵ_r) and electronic polarizability (α_e)



During polarization, the induced dipole moment which is given by,

$$P_{\text{ind}} = \alpha_e E \quad \text{--- (1)}$$

we know,

$$\text{Dielectric polarization } (P) = \chi_e \epsilon_0 E \quad \text{--- (2)}$$

α_e is the electronic polarizability per unit volume, then total induced dipole moment per unit volume (P) = $N \cdot P_{\text{in}}$

$$P = N \alpha_e E \quad [\text{from (1)}] \quad \text{--- (3)}$$

where, N = No. of atoms.

From eqⁿ ② and ③ we get,

$$\frac{E}{\epsilon_0} \chi_e = N \alpha_e f$$

$$\therefore \chi_e = \frac{N \alpha_e}{\epsilon_0}$$

$$\text{and } E_r + 1 = \frac{N \alpha_e}{\epsilon_0}$$

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

This expression relates the macroscopic property of dielectric material i.e. Relative permittivity to microscopic property i.e. electronic polarizability.

Clausius-Mossotti Equation \rightarrow

The actual field experienced by a molecule in dielectric is defined as local field (E_{loc}) which depends not only on the free charges on the plates but also on the arrangement of all the polarized molecules around this point. The greater the polarization, the greater is the local field is given by,

$$E_{loc} = E + \frac{P}{3\epsilon_0} \quad \text{--- (1)}$$

Induced polarization of molecule/atom is given by,

$$P_{ind} = \alpha_e \cdot E_{local}$$

Now, Polarization of whole material is sum of induced polarization of each atom.

$$\therefore \text{Polarization}(P) = N P_{ind}$$

$$= N \alpha_e E_{loc}$$

$$\text{or, } P = N \alpha_e \left(E + \frac{P}{3\epsilon_0} \right) \quad [\text{From (1)}]$$

$$\text{or, } P = N \alpha_e E + \frac{N \alpha_e P}{3\epsilon_0}$$

$$\text{or, } P - \frac{NdeP}{3\epsilon_0} = NdeE$$

$$\text{or, } P \left(1 - \frac{Nde}{3\epsilon_0} \right) = NdeE$$

$$\therefore P = \frac{NdeE}{\left(1 - \frac{Nde}{3\epsilon_0} \right)} \quad \text{--- (ii)}$$

Also, we have,

$$\text{Polarization (P)} = \chi_e E \epsilon_0 \quad \text{--- (iii)}$$

$$\text{or, } \frac{NdeE}{\left(1 - \frac{Nde}{3\epsilon_0} \right)} = \chi_e E \epsilon_0 \quad [\text{From (ii)}]$$

$$\text{or, } \chi_e \epsilon_0 = \frac{Nde}{\left(1 - \frac{Nde}{3\epsilon_0} \right)}$$

$$\text{or, } \chi_e \epsilon_0 \left(1 - \frac{Nde}{3\epsilon_0} \right) = Nde$$

$$\text{or, } \chi_e \epsilon_0 + \frac{Nde \chi_e}{3} = Nde \quad \text{(iv)}$$

$$\text{or, } \chi_e \epsilon_0 = \frac{Nde \chi_e + Nde}{3} \quad \text{(v)}$$

$$\text{or } X_e E_0 = \frac{Nde}{3} (X_e + 3)$$

$$\text{or } \frac{X_e}{3 + X_e} = \frac{Nde}{3E_0}$$

$$\text{or } \frac{\epsilon_r - 1}{3 + \epsilon_r - 1} = \frac{Nde}{3E_0} \quad \begin{array}{l} \text{[using } X_e = \epsilon_r - 1] \\ \text{or } \epsilon_r = X_e + 1 \end{array}$$

$$\therefore \frac{\epsilon_r}{\epsilon_r + 2} = \frac{Nde}{3E_0}$$

The above equation is known as clausius Massotti equation. It relates relative permittivity with electronic polarizability.

Types of Polarization :-

- (i) Electronic Polarization or Dielectric polarization
- (ii) Ionic polarization
- (iii) Orientational / Dipolar polarization
- (iv) Interfacial polarization.

① Electronic polarization :-

Basic atomic model

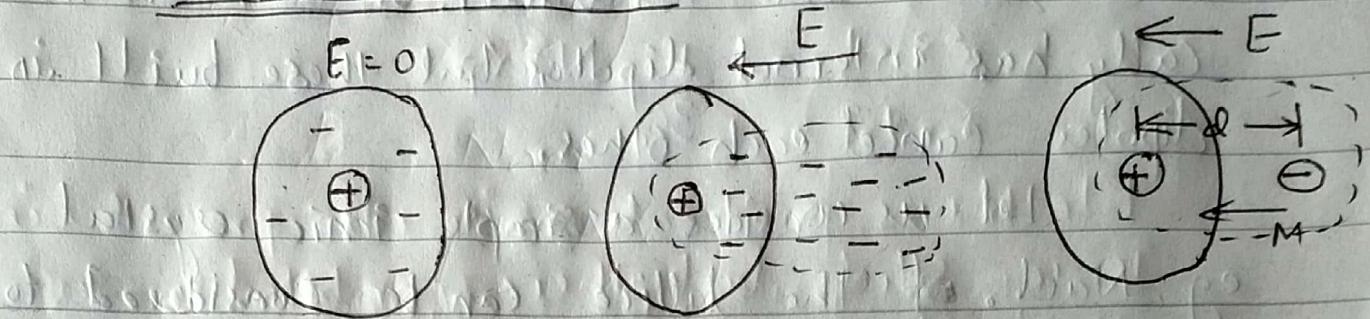


Fig: Electric field

A material is made up of atoms. Each atom consists of a cloud of negative charge (electrons) bound to and surrounding a positive point charge at its center. In the presence of an electric field the charge cloud is distorted as shown in the top right of figure.

This can be reduced to simple dipole using superposition theorem. A dipole is characterized by its dipole moment. A dipole moment is a vector quantity pointing from negative to positive charge.

$$\text{i.e } M = q \times d$$

[This is the answer to question \rightarrow How electronic polarization takes place in an atom?]

(ii) Ionic polarization

In this case, a solid material must have some ionic character. It then automatically has internal dipoles but these built-in dipoles cancel each other.

Let us consider a simple ionic crystal e.g. NaCl. The lattice can be considered to consist of Na^+ and Cl^- dipoles as shown in the diagram.

* In the absence of external Electric field:

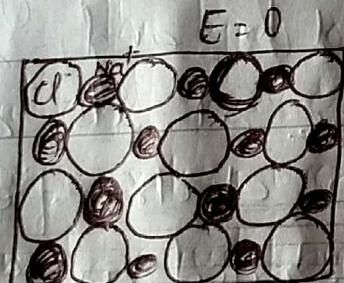


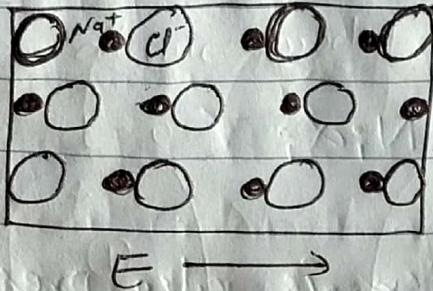
Fig : crystal of NaCl

Each Na^+ - Cl^- pair is a natural dipole, no matter how you pair up two atoms.

Polarization of a given volume, however, is exactly zero, because for every dipole moment, there is a neighbouring one with exactly the same magnitude but opposite sign.

Note : The dipoles cannot rotate, their direction is fixed.

* In the presence of Electric field



In an electric field ions feel forces in opposite directions. For a field acting as shown, the lattice distorts a little bit. Na^+ ions move a little bit to the right, Cl^- ions to the left.

The dipole moments between adjacent NaCl pairs in field direction are now different and there is net dipole moment in a finite volume.

$\text{Par} = \alpha_i E_{\text{elec}}$ where, α_i = ionic polarizability

which is greater than α_e .

Generally, $\alpha_i > 10\alpha_e$.

Total Polarization (P) = $N_i \text{Par}$

$$= N_i \alpha_i E_{\text{elec}}$$

where, N_i = No. of ions.

$$E_{\text{loc}} = E + \frac{P}{3\epsilon_0} \quad \text{and} \quad P = X\epsilon_0 E$$

we obtain,

$$\frac{E_r - 1}{E_r + 2} = \frac{1}{3\epsilon_0} Nid^2$$

Electronic polarization is also present in ionic solids but their contribution is negligible compared to ionic polarization.

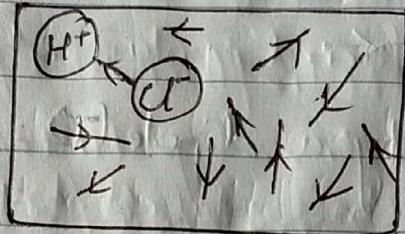
III

Orientational Polarization/ Dipolar polarization:

This type of polarization is observed in liquid and gases. In these material natural dipoles exist which are free to rotate. In thermal equilibrium, the dipoles will be randomly oriented and thus carry no net polarization. The external field aligns these dipoles to some extent and thus induces a polarization of the material.

The prime example is liquid HCl, where every HCl molecule is little dipole that can have any orientation with respect to

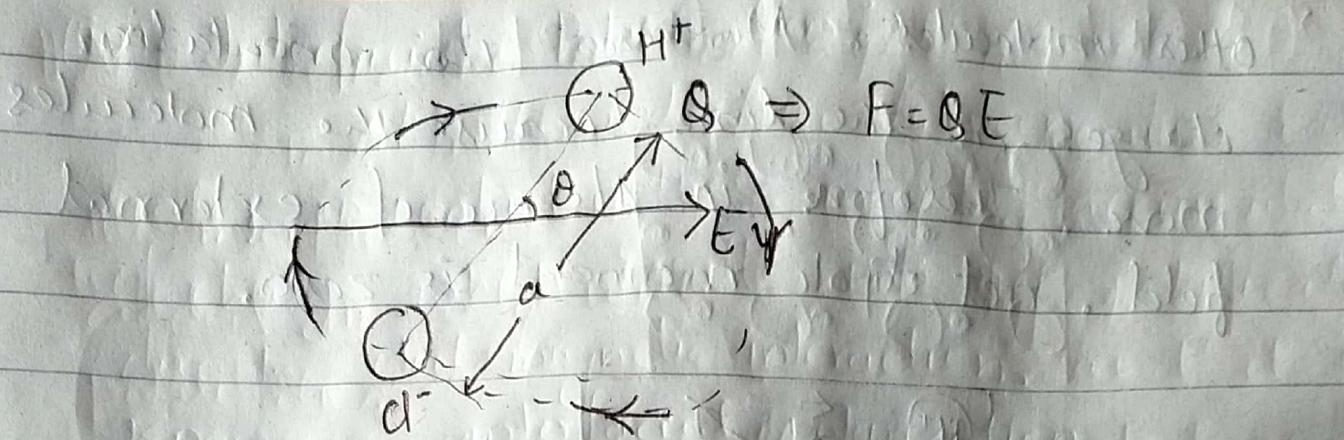
other molecules. Moreover the orientation changes all the time because the molecules move. Therefore in absence of external field, net dipole moment is zero.



If we introduce electric field, dipoles would have tendency to turn into field because that would lower their energy.

In reality, orientation of dipole into the field direction would be counterbalanced by random collision with other dipoles and this process is energized by the thermal energy KT .

So, the orientation of dipole is little bit shifted so that an average orientation in the field direction results.



Torque experienced by a dipole ($\tau = F \sin \theta \times a$)
 $= E Q \sin \theta \cdot a$
 $= E a \sin \theta (\vec{Q} \cdot \vec{a})$

$= E a \sin \theta P_0$

where, P_0 = dipole moment = Qa

If PE = 0 at $\theta = 0$ and PE = P_{\max} at $\theta = 180^\circ$

then,

$$P_{\max} = \int_0^{180^\circ} E a \sin \theta P_0 d\theta$$

$$\therefore P_{\max} = EP_0 \int_0^{180^\circ} \sin \theta d\theta$$

$$\therefore P_{\max} = EP_0 [-\cos \theta]_0^{180^\circ}$$

$$\therefore P_{\max} = EP_0 [-\cos 180 + \cos 0]$$

$$\therefore P_{\max} = 2EP_0$$

$$\text{Average dipole potential energy} = \frac{PE_{\max}}{2}$$

$$= \frac{2EP_0}{2}$$

$$= EP_0$$

$$\text{Average dipole energy} \propto P_0 \times \frac{\text{Average dipole P-E}}{\text{Average thermal energy}}$$

$$\text{Average dipole energy} \propto P_0 \times \frac{P_0 E}{\left(\frac{5KT}{2}\right)}$$

$$\text{Average dipole energy} \propto \frac{P_0^2 E}{\left(\frac{5KT}{2}\right)}$$

$$\text{Using Boltzmann statistics, Average dipole moment per molecule} = \frac{P_0^2 E}{3KT} = \alpha_d E$$

where,

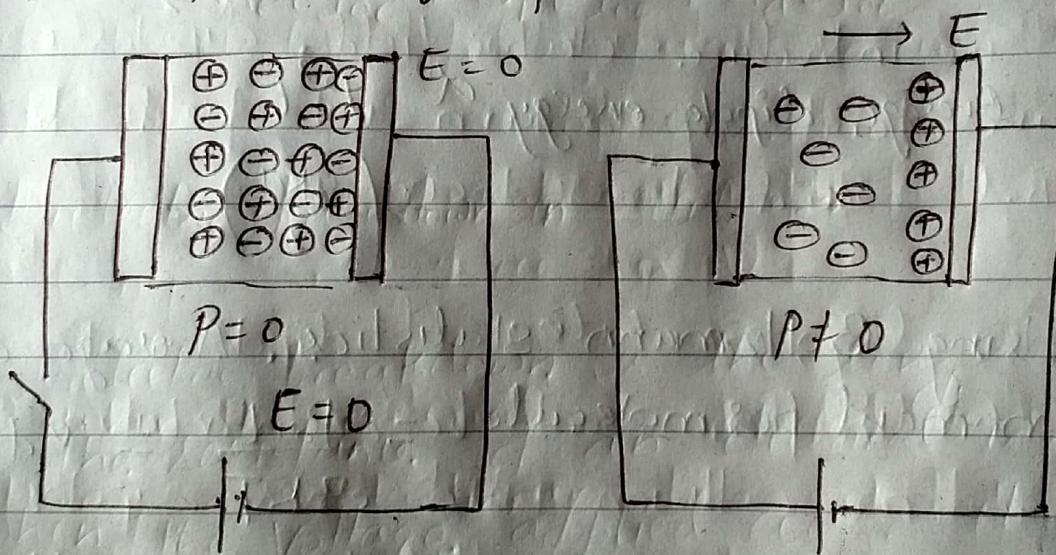
$$\alpha_d = \text{dipolar or orientational polarizability}$$
$$= \frac{P_0^2}{3KT}$$

$$\text{and } (\alpha_d \propto \frac{1}{T})$$

(iv) Interfacial Polarization \Rightarrow

At the interface between two materials, in contact, there may be accumulation of charge which results into net polarization due to electromagnetic interaction, and it is known as interfacial polarization.

Consider a dielectric placed between two parallel plates of capacitor as shown below:



a) $E = 0$

b) E is applied

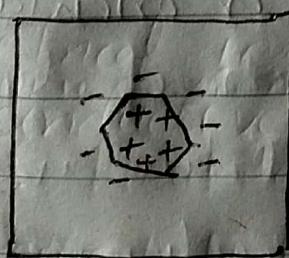


Fig: Trapping of charges at defects.

Defects and impurities present inside dielectric material contribute free charge carriers. In absence of electric field, there is uniform distribution of positive and negative ions giving net zero polarization. When electric field is applied, mobile lighter positive ions H^+ , etc. migrate near the negative plate of capacitor. They cannot leave the dielectric material, even if they leave they cannot enter into metal plate, so there is accumulation of charges at the interface between the plate and dielectric. As a result, the surface charge density on a capacitor plate increases. Due to separation of +ve and -ve charges, the net polarization is finite.

Trapping of mobile charge at the crystal defects is another example of interfacial polarization.

Net Polarization and net dipole moment :-

Since interfacial polarization occurs at the interfaces (mostly) so it cannot be added linearly with other types of polarization.

So, under the influence of electronic, ionic and orientational polarization, Induced dipole moment per molecule/atom

$$I = \alpha_e E_{loc} + \alpha_i E_{loc} + \alpha_d E_{loc}$$

Dielectric breakdown in solids :-

Dielectric breakdown is the long reduction in the resistance of an electrical insulator when the voltage applied across it exceeds the breakdown voltage. This results in the electrical insulator becoming electrically conductive.

→ Maximum electric field that can be applied to the insulating medium without causing dielectric breakdown is called dielectric Strength.

→ Dielectric Strength depends on impurities or material, sample geometry, temperature, ambient conditions, duration and frequency of applied field, nature of electrodes, etc.

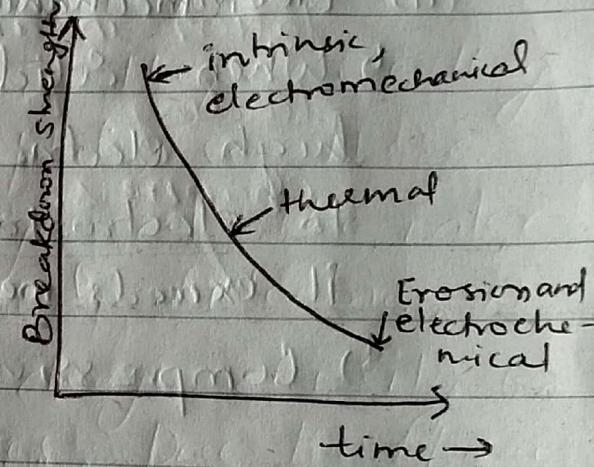
Mechanism of Dielectric Breakdown in Solid's

(i) Intrinsic Breakdown:

When a large voltage is applied for short duration intrinsic breakdown takes place.

Intrinsic breakdown depends upon the presence of free electrons which are capable of migration through the lattice of dielectric.

Usually small number of conduction electrons are present in solid dielectric, these electrons get multiplied with the application of high field.



↳ When an electric field is applied electrons gain energy from electric field and cross the band gap to reach conduction band.

↳ This process is repeated, more and more electrons are available in conduction band eventually leading to breakdown.

(ii) Electromechanical breakdown ↳

↳ When solid dielectrics are subjected to high electric fields, failure occurs due to electrostatic compressive force strength if it exceeds mechanical withstand of the material.

↳ Compressive force $\propto V^2$

↳ When the material is subjected to high stress theory of elasticity does not hold good and plastic deformation has to be considered.

↳ Mechanical compression may also cause thermal breakdown, shearing of internal cracks, crack propagation and eventually dielectric failure.

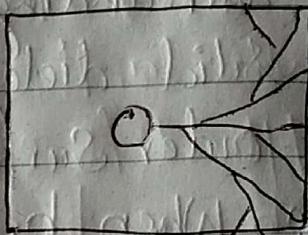
(iii) Thermal Breakdown \Rightarrow

- ↳ When an electric field is applied to a dielectric conduction current flows through the material. (however it may be small).
(Joule heating σE^2 or dielectric loss $V^2 W \tan \delta$)
- ↳ The current heats up the specimen and temperature rises.
- ↳ Heat generated is transferred to the surrounding medium by conduction through solid dielectric and by radiation from its outer surfaces.
- ↳ When heat generated exceeds heat lost, the electrical conductivity of dielectric increases due to increase in temperature.
- ↳ Many local hot spots may ~~deform~~ form permanent conduction channel leading to dielectric breakdown.

(iv) Breakdown due to Internal Storage.

Solid insulating materials contain void or cavities within the medium or at the boundaries between the dielectric and the electrodes.

- ↳ These voids have lower dielectric strength as compared to the material.
- ↳ Hence even under the normal working voltage the field in the voids may exceed their breakdown value and breakdown may occur.
- ↳ Breakdown channel spreads through the insulation in an irregular tree like fashion leading to the formation of conducting channels.



Ferroelectricity

- ↳ Certain crystals like Barium titanate (BaTiO_3) which have permanent polarization even in the absence of an applied field called as ferroelectric crystals and the phenomenon ferroelectricity.
- ↳ The temperature above which the ferroelectricity is lost is called Curie Temperature (T_c). The Curie temperature of BaTiO_3 is 130°C .
- ↳ Below Curie temperature the center of mass of positive and negative charges do not coincide and thus net polarization exist. But above Curie temperature the centre of mass of positive and negative charges coincide & thus net polarization is zero.
- ↳ Below T_c whole specimen gets spontaneously polarized and above T_c , disorderliness of dipole increases which is called as pyroelectric state.

↳ Ferroelectric crystals have large dielectric constants.

↳ Above T_c , the dielectric constant usually follows Curie-Weiss behaviour which is given by,

$$\epsilon_r = \frac{C}{T - T_0}, \text{ where}$$

C = Curie constant

T_0 = Curie-Weiss temperature

↳ The variation of polarization with electric field is not linear for such crystals but forms a closed loop called as ferromagnetic loop which is similar to hysteresis loop.

The ferroelectric crystals may be classified into two main groups

(i) order-disorder group

(ii) displacive group.

In order-disorder group, the ferroelectric transition is associated with individual ordering of ions. e.g. KH_2PO_4 , RbH_2PO_4 , etc.

4) The displacive group of ferroelectric ~~trans~~ materials is one in which the ferroelectric transition is associated with displacement of sub-lattice of ions of one type relative to sub-lattice of another type.

Piezo-electricity :-

↳ Certain crystals become polarized in response to an applied mechanical stress. It is called direct piezoelectric effect.

↳ Materials exhibiting direct piezoelectric effect also exhibit the reverse piezoelectric effect (i.e. The internal generation of mechanical strain resulting from applied electric field.)
→ These two effects are commonly known as piezo-electricity.

↳ Only certain crystals which has no center of symmetry exhibit piezo-electricity. In absence of external force centre of mass of positive and negative charges coincide. But when external force is applied center of mass of positive and negative charges get

shifted giving rise to net polarization.

- ↳ The polarization direction depends on the direction of applied force too.
- ↳ Similarly, an electric field applied to ~~piezoelectric~~ piezoelectric material results in the generation of mechanical strain and if the direction of applied field is ~~reversed~~ reversed then the strain developed is also is shifted in another direction.

Let T_j be applied mechanical stress in j direction, P_i is the induced polarization along i direction then,

$$P_i = d_{ij} T_j$$

d_{ij} \Rightarrow piezo-electric co-efficient

Similarly for reverse piezo-electric effect,

$$S_j = d_{ij} E_i$$

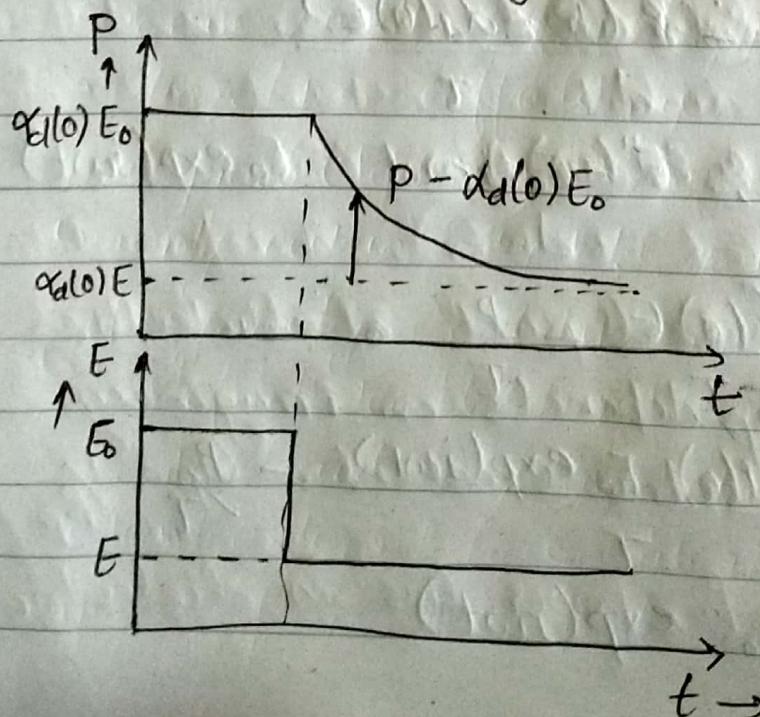
Where, S_j = induced strain along j direction.

E_i = applied electric field along i direction.

d_{ij} = Piezoelectric co-efficient.

Dielectric losses, frequency and Temperature effect :

When a dielectric material is placed in an ac electric field, the field tries to polarize the material in different direction in each half cycle. But the thermal motion and intermolecular interactions try to randomize the orientation. So, the dipoles cannot respond instantaneously to the changes in field. At low frequency, dipoles can respond to the change in field, so dipolar polarizability is maximum in this region. At high frequency, its value decreases.



In the above figure, the dielectric is applied by a dc field E_0 for long time before the field is reduced to E .

$\alpha_{dd}(0)$ corresponds to polarizability at zero frequency.

Assume T as the average relaxation time between molecular collisions. If p is the induced dipole moment then $P - \alpha_{dd}(0)E_0$ is the excess moment which must disappear as t tends to infinity. T is the average time to eliminate the excess dipole moment. Rate of change of dipole moment is,

$$\frac{dp}{dt} = -\frac{(P - \alpha_{dd}(0)E)}{T}$$

In case of ac, $E = E_0 \sin \omega t = E_0 \exp(i\omega t)$

Then,

$$\frac{dp}{dt} = \frac{\alpha_{dd}(0)E}{T} - \frac{P}{T}$$

$$\therefore \frac{dp}{dt} = \frac{\alpha_{dd}(0) E_0 \exp(i\omega t)}{T} - \frac{P}{T}$$

$$\therefore P = \alpha_{dd} E_0 \exp(i\omega t)$$

where,

$$\alpha_d(\omega) = \frac{\alpha_d(0)}{1 + j\omega T}$$

where, $\alpha_d(\omega)$ represents dipolar polarizability under ac conditions.

Thus, we observe that polarizability is the function of frequency.

The ac dipolar polarizability of any liquid is complex, so we can obtain complex dielectric constant.

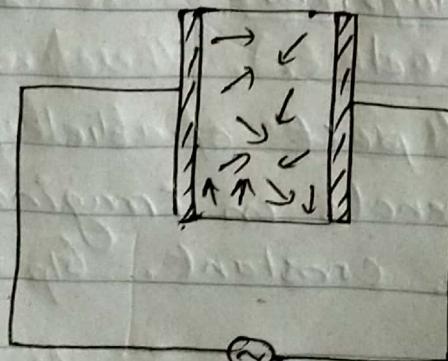
$$\epsilon_r = \epsilon_r' - j\epsilon_r''$$

Where,

ϵ_r' = real part of dielectric constant

ϵ_r'' = imaginary part of dielectric constant

ϵ_r' and ϵ_r'' are frequency dependent.



$$V = V_0 \sin \omega t$$

Capacitor with dielectric

The capacitance of a capacitor is given by,

$$C = \frac{\epsilon_0 \epsilon_r(\omega) A}{d}$$
$$= \frac{\epsilon_0 (\epsilon_r'(\omega) - j\epsilon_r''(\omega)) A}{d}$$

The capacitive Susceptance $Y = j\omega C$.

$$\therefore Y = j\omega \left[\frac{\epsilon_0 \epsilon_r'(\omega) - j\epsilon_0 \epsilon_r''(\omega)}{d} A \right]$$
$$= \frac{j\omega \epsilon_0 \epsilon_r'(\omega) A}{d} + \frac{\omega \epsilon_0 \epsilon_r''(\omega) A}{d}$$
$$= j\omega C + G_p$$

where, $C = \frac{\epsilon_0 \epsilon_r'(\omega) A}{d}$

$$G_p = \frac{\epsilon_0 \epsilon_r''(\omega) A \omega}{d}$$

C depends on
 C represents real part of dielectric constant G_p depends on imaginary part of dielectric constant. $G_p = 1/R_p$

is responsible for power loss in dielectric medium.

G_p is called conductance of the capacitor.

The capacitor can be represented by an ideal capacitor with capacitance C and a resistor with resistance $R = \frac{1}{G_p}$ in parallel to represent the power loss in the dielectric medium.

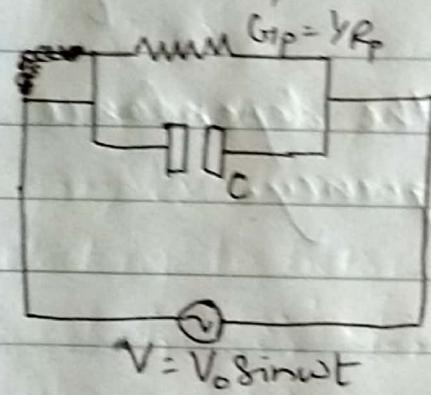


fig: Equivalent circuit diagram of real capacitor.

$$\begin{aligned} \text{Total input power to dielectric (P}_{in}\text{)} &= VI \\ &= V \cdot VY \\ &= V^2(G_p + j\omega C) \\ &= V^2G_p + j\omega CV^2 \end{aligned}$$

$$\text{Real power dissipation} = V^2G_p = P_{loss}$$

loss tangent or loss factor is given by,
 $\tan \delta = \epsilon_r''/\epsilon_r'$

Power loss per unit volume, $P_{vol} = \frac{P_{loss}}{\sqrt{}}$

$$\text{or } P_{vol} = \frac{V^2 G_p}{A \cdot d} = V^2 \cdot \frac{\omega \epsilon_0 \epsilon_r''}{d} \cdot \frac{1}{A \cdot d}$$

$$= \frac{V^2}{d^2} \omega \epsilon_0 \epsilon_r''$$

$$= E^2 \omega \epsilon_0 \epsilon_r' \tan \delta \left[\tan \delta = \frac{\epsilon_r''}{\epsilon_r'} \right]$$

The expression relates the dependence of dielectric loss on frequency.

$$\text{Also, } dd = \frac{1}{T}$$

so at higher temperature polarization of material is randomized by increased thermal vibrations. so, dielectric constant also decreases at higher temperature (since ϵ_r is linearly related with ϵ_r'). Therefore dielectric strength of material is lower at higher temperature.