# Dielectrics

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Conductors – substances that contain unlimited supply of charges that are free to move through the materials

Insulators – which do not have free electrons or number of electrons are too low, the electrons are tightly bound to the atom

Dielectric – when ~~pste~~ certain non-conducting materials are used to fill the space between two conductors of capacitor the capacitance is found to increase. The insulator whose behaviour gets modified in the electric field are called dielectrics

When change in behaviour is dependent ~~of~~ on direction of applied field, it is called as anisotropic

If it is independent of direction of applied field, it is called isotropic.

If you keep dielectrics in presence of electric field, it exerts a force on each charged particle. The positive ones go towards one direction while negative in opposite direction. The relative displacement of charges gives rise to dipole generation and the dielectric is said to be polarized.

$F = qE_0$ force on $e^-$ in EF

Polarization – Process of formation of an electric dipole under influence of EF.

Two types of dielectrics-

i) Polar ii) Non-Polar

i) ~~Polar~~ Non-Polar - Molecule in which centre of gravity of positive and negative charges coincide, and thus for which the inherent dipole moment is zero is non-polar. Permittivity- 1 to 2.2

ii) Polar- If points of resultant charges of molecule do not coincide in space, the molecule possess an intrinsic dipole moment. Such molecules are called polar molecules.
Permittivity- 3 to 8

## Dipole

Dipole moment is the measure of polarity of a system of electric charges.

The electric dipole moment vector points from negative charge to positive charge.

Dipole moment $\mu = q \cdot x$

$q$ is charge , $x$ is distance

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Polarization -

Dielectric contain bound charges which ~~may~~ ay be able to move slightly when EF is applied.

No EF - As centroids of positive and negative coincide there would be no EF external

In EF - the electrons moves in one direction slighty and nucleus in opposite. As centroid doesn't coincide dipole is formed

Polarization - Number of dipole moments per unit volume.

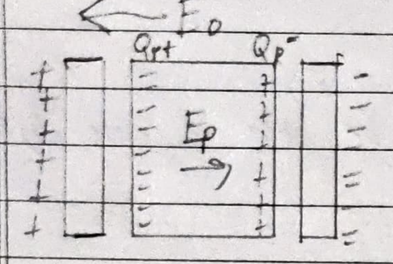
$$P = \frac{\Sigma \mu}{V}$$

Relation between, EF, Polarization and Electric displacement D

when no medium is present

$$E_0 = \frac{q}{\epsilon_0 A}$$

when dielectric slab is placed b/w the plated the bound charges seperate and form dipole.




According to gaussian Law of electrostatics

$$\vec{E_p} = \frac{Q_p}{\epsilon_0 A}$$

$$\vec{E_p} = \frac{Q_p d}{\epsilon_0 V} = \frac{\mu}{\epsilon_0 V} = \frac{P}{\epsilon_0}$$

As i) $Q_p \times d = \mu$ dipole moment
ii) $P = \frac{\mu}{V}$

Net electric field

$$\vec{E} = \vec{E_0} - \vec{E_p}$$

$$= \frac{Q}{\epsilon_0 A} - \frac{P}{\epsilon_0}$$

$$= \frac{D}{\epsilon_0} - \frac{P}{\epsilon_0}$$

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

In presence of medium, Electric displacement is given as

$$D = \epsilon_0 E \epsilon_r$$

$$\epsilon_0 E \epsilon_r = \epsilon_0 E + P$$

$$P = \epsilon_0 E(\epsilon_r - 1)$$

$$\epsilon_r - 1 = \chi_r$$

$$P = \epsilon_0 E \chi_r$$

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Few important Formulae

- Electric Fied $E = \frac{Q}{4\pi\epsilon_0 r^2}$

- Electric displacement is the amount of charge displaced in a given area.

$D = \frac{Q}{4\pi r^2}$ , Hence $E = \frac{D}{\epsilon_0}$

- Dipole moment: Product of charge and the distance between them

$\mu = q \cdot x$

- Surface charge density - The amount of charge induced on a surface

$\sigma = \frac{q}{A}$

- Polarization - Number of dipole moments induced per unit volume

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

- Dipole moment $\propto$ Applied electric field

$\mu = \alpha E$, where $\alpha$ is the constant of proportionality, known as polarizability. It is different for different polarizations.

Dielectric constant of relative permittivity ($K$ or $\epsilon_r$): The ratio of permittivity in given medium to permittivity in free space

$$\epsilon_r = \frac{\epsilon}{\epsilon_0}$$

i) $D = \epsilon_0 E + P$
ii) $P = \epsilon_0 (\epsilon_r - 1) E$
iii) $P = \chi \epsilon_0 E$
iv) $P = N\mu = N\alpha E$

Types of Polarization -
i) Electronic
ii) Ionic
iii) Orientation
iv) Space charge

i) Electronic polarization -
Consider single atom of atomic number Z; +e charge of each proton, -e charge of each electron.
Electron cloud ~~is~~ surround the positive charged nucleus.
We assume the electron cloud is homogenously ~~sprd~~ spread on the positive charged nucleus R. The center of electron cloud and center of positive ~~nucleus~~ nucleus coincide. Thus no dipole moment.
when external electric field is applied on the atom, thus ~~atom~~ nuclear shifts towards negative intensity and electron cloud towards positive intensity. As center of positive and negative is seperated dipole moment is formed. At separation $x$, the forces acting on nucleus or electron cloud due to external field and due to Coulomb become same and opposite.
On nucleus $= +ZeE$, On electron ~~ra~~ cloud $= -ZeE$

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Expression for electronic Polarization -

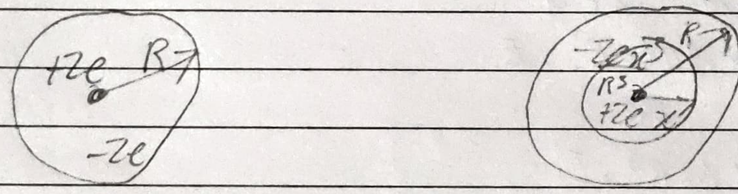
Charge on nulleus $+Ze$ $(-Ze)$

Assume nucleus as point charge and total negative charge spread ove a sphere of radius R. when EF is applied nucleus and electron cloud go in opposite directions.

~~Equib~~ Equilibrium condition is attained in which nucleus is displaced relative to center of ~~atom~~ electron cloud by amount $x$.

The Force on nucleus along field direction

$$F = ZeE$$




E=0 → E

To determine columb interaction on the nulleus we divide the electron cloud in two regions. One is that is inside sphere of radius $x$ and other is circular region lying between two spherical surfaces of radi $x$ and $R$

By applying Gauss theorem, we find the force experienced by nucleus due to negative charge lying within spherical region of radius $x$

$$\text{Charge inside region} = \frac{-Zex^3}{R^3}$$

As charge Density $\rho = \dfrac{Q}{\frac{4}{3}\pi R^3} = \dfrac{-Ze}{\frac{4}{3}\pi R^3}$

So to get charge inside sphere of radius $x$

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

Force by charge on nucleus

$$F = \frac{1}{4\pi\epsilon_0} \cdot \frac{Ze\,(Zex^3/R^3)}{x^2}$$

Under equilibrium condition both force balance each othe

$$ZeE = \frac{1}{4\pi\epsilon_0} \cdot \frac{Ze \cdot Zex}{R^3}$$

$$x = \frac{4\pi\epsilon_0 R^3 \cdot E}{Ze}$$

Therefore displacement of nucleus is $x$

Dipole moment $= Zex$

$$\mu = Ze \times \frac{4\pi\epsilon_0 R^3 \cdot E}{Ze}$$

$$\mu = 4\pi\epsilon_0 R^3 \cdot E$$

$$\mu = \alpha_e E \qquad \text{where } \alpha_e = 4\pi\epsilon_0 R^3$$

$$P_e = N\alpha_e E = 4\pi R^3 \epsilon_0 NE$$

where $N$ is number of atoms/unit volume

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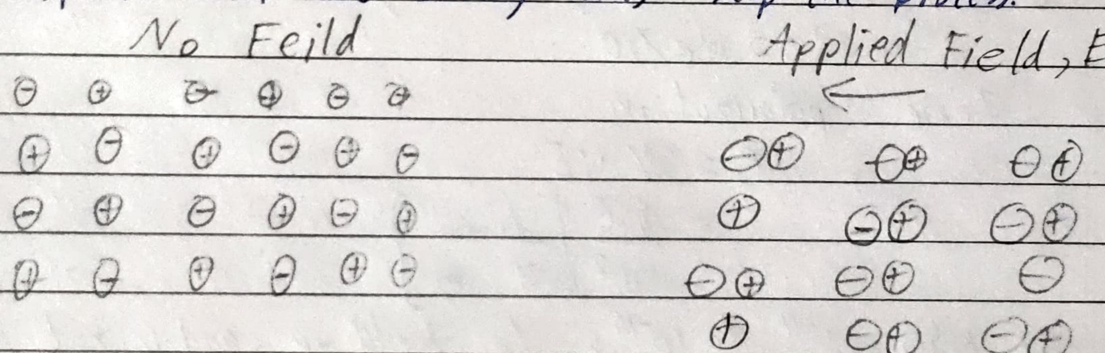
## ii) Ionic Polarization

It occurs in ionic crystals. It happens due to the elastic displacement of positive and negative ions from their equilibrium positions.

$Na^+$ and $Cl^-$ has ionic bond in sodium chloride molecule. If interatomic distance is $d$, the molecule exhibits an intrinsic dipole moment equal to '$ed$'.

When a dc electric field is applied, sodium and chloride ions are displaced until ionic bonding forces stop the process.




When field direction is reversed the ions move closer and again the dipole moment undergoes a change. Thus dipoles are induced. The induced dipole moments is proportional to applied field.

$$\mu_i = \alpha_i E$$

$\alpha$ is ionic polarizability

Induced dipole moment $\mu = ex$

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

The ~~elect~~ ionic polarizability $\alpha_i = \frac{e^2}{\omega_0^2}\left[\frac{1}{M} + \frac{1}{m}\right]$

Points to be noted

i) Ionic polarizability is directly proportional to reduced mass of molecule.

ii) Inversely proportional to square of natural frequency of molecule.

iii) Independent of temperature

Ions also experience electronic polarization. Ionic polarizability is less than electronic polarizability.

$$\alpha_i = \alpha_e/10$$

Ionic polarization

$$P_i = N \alpha_i E$$

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

It takes $10^{-11}$ to $10^{-14}$ s to build up, and is not influend by temperature.

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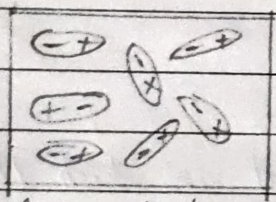
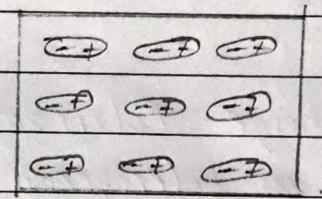
## ii) Orientation Polarization

This is a characteristic of polar dielectrics, as they consist of molecules with permanent dipole moment.
when there is no electric field, orientation of dipole is random and cancell each other's effect.



No applied field



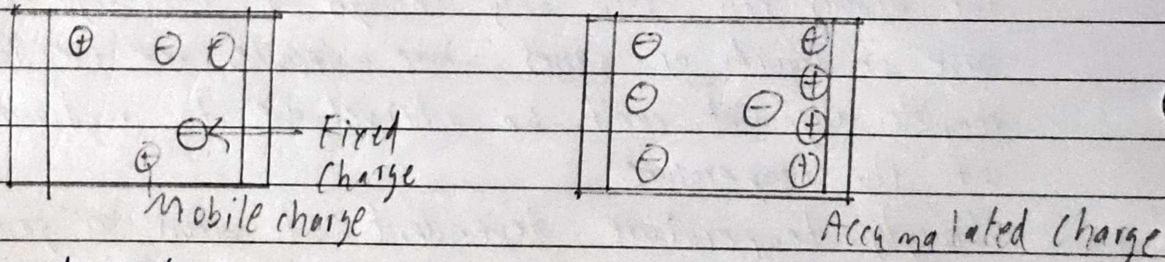
Applied field

when electric field is impresed the molecular dipoles rotate about their axis of symmetry to align with applied field. In case of ionic and electronic polarization the force due to external field is balanced by coulumb attraction, but for orientation polarization, restoring forces do not exist. However the dipole aligment is counteracted by thermal agitation. The dipoles can turn only through a small angle. Even in case of liquids or gasses, where molecules are free to rotate complete alignment can't be acheived due to randomising effect of the temperature.
Strongly temperature dependent. It occurs in gases, liquids and amorphous viscous substances. In case of solids the molecules are fixed in ther position and rotation is highly restricted by lattice forces, leading to great reduction in contribution to orientation polarization.

$$P_o = \frac{N\mu^2 E}{3RT} \qquad \alpha_o = \frac{\mu^2}{3RT}$$

dielectric constant of water is 80 but of soluid ice is 90
As process of orientation polarization involves rotation of moleculs, it takes relatively longer tim than ionic or electronic polarization.
The build up time is of order $10^{-10}s$ or more

iv) Space-Charge Polarization-
It occurs in heterogenous dielectric material in which there is a change of electrical properties b/w different phases. dielectrics which contain impurities, pores filled with air etc. when an electric feild is applied, the electric charges that migrate within impurity region store up at the interfaces. The accumulation of charge takes place with opposite polarity on the interface. These take time and occur at low frequency




This polarization very small and negligible. There for total polarization in a material may be take due to other three polarization only.

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Classius Mosotti $eq^n$

It expresses the dielectric constant of a material in terms of electronic polarizability $\alpha_e$

$$\alpha_e = \frac{P}{NE_i} \quad -① $$

P is polarizability and $E_i$ is local field.

If we substitute value of $E_i$ in above equation, it can be written as

$$\alpha_e = \frac{P}{N[E + \frac{\gamma P}{\epsilon_0}]} \quad -②$$ $\gamma$ is internal field constant

As $$E = \frac{P}{(\epsilon_r - 1)\epsilon_0} \quad -③$$

Value of $\gamma$ is assumed to be $1/3$ for solids

$$\alpha_e = \frac{P}{N[E + \frac{P}{3\epsilon_0}]} \quad -④$$

Substituting ③ in ④

$$\alpha_e = \frac{P}{N\left[\frac{P}{\epsilon_0(\epsilon_r - 1)} + \frac{P}{3\epsilon_0}\right]}$$

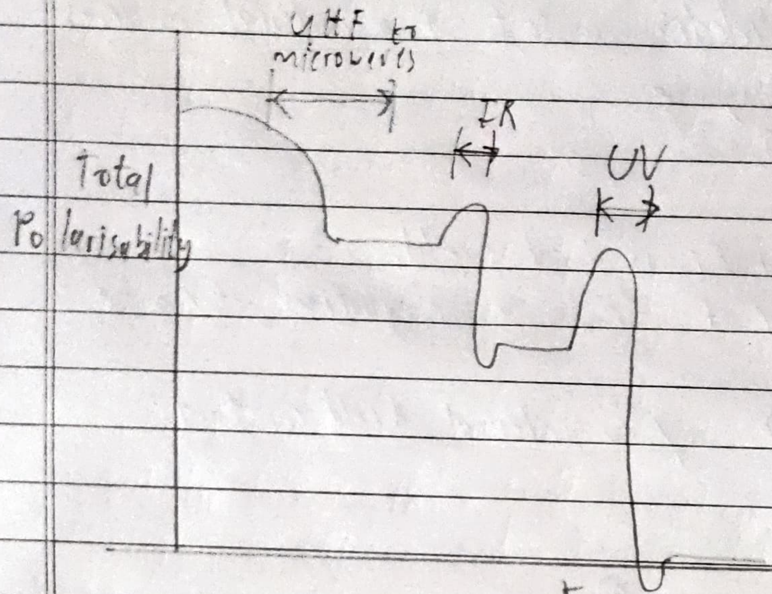
$$N\alpha_e = \frac{1}{\left[\frac{\epsilon_r + 2}{3\epsilon_0 \cdot 3(\epsilon_r - 1)}\right]}$$

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

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

Classius Mosotti equation valid for non polar solids

## Frequency Dependence




In many situations, a dielectric is subjected to an alternating electric field. An AC field changes its direction with tim. With each direction reversal the polarization components are required to follow the field reversal in order to contribute to total polarization.

Electronic polarization persists at - $\sim 10^{13}-10^{15}$ Hz
Ionic persists at $\sim 10^{9}-10^{13}$ Hz
Orientation persists at $\leq 10^{9}$ Hz
Space charge below $< 10$ Hz

The average time taken by the dipole to orient in the field direction is known as relaxation time.

The reciprocal of relaxation time is known as relaxation frequency.

If frequency of applied field >> the relaxation frequency the dipole can't orient

If relaxation time < half time period of electric field then dipole easily follow direction of field.

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→ In audio frequency region → all types of polarization are possible and dielectric is characterised by a polarizability $\alpha = \alpha_e + \alpha_i + \alpha_o$ and Polarization $P = P_e + P_i + P_o$

The orientation polarization is damped out for higher frequencies. ($f_{field} > f_{relax}$)

→ In rf region or microwave band region → the permanent dipoles fail to follow the field reversals. Hence
$\alpha = \alpha_e + \alpha_i$ and $P = P_e + P_i$

→ In IR and optical frequency → ionic polarization fails to follow field reversal due to inertia of the system and contribution of ionic polarizability ceases,
$\alpha = \alpha_e$ and $P = P_e$

The relative permittivity in optical region will be
$\varepsilon_r = n^2$

→ In ultraviolet region : electron cloud fails to follow field reversal and P becomes 0 but $\varepsilon_r = 1$

Dielectric Strength

Dielectrics normally behave as insulators. Their insulating property breaks down and they start to conduct above a given electric field. This is called Dielectric Strength

This limits maximum potential allowed between two conductors and hence $Q = CV$, the maximum charge and energy that can be stored.

Dielectric strength is the voltage a material can withstand before breakdown occurs.
It is measured through thickness of a material. Expressed as voltage gradient.

The voltage that may be applied to a rubber-covered conductor is dependent on the thickness and the quality of rubber covering. Other factors being equal, thicker the insulation the higher maybe applied voltage.

Dielectric strength of few materials.

Air 3MV/m

Paper 16MV/m

Rubber 20MV/m roughly

Water 30MV/m

Teflon 60MV/m

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## Ferroelectricity

- Ferroelectric materials are anisotropic crystals that exhibit spontaneous polarization.

- It occurs without the application of any external field

- It occurs in polar dielectrics, where the centre of gravity of negative and positive charges don't coincide and hence results in a resultant dipole moment.

Characteristics of ferroelectric substance

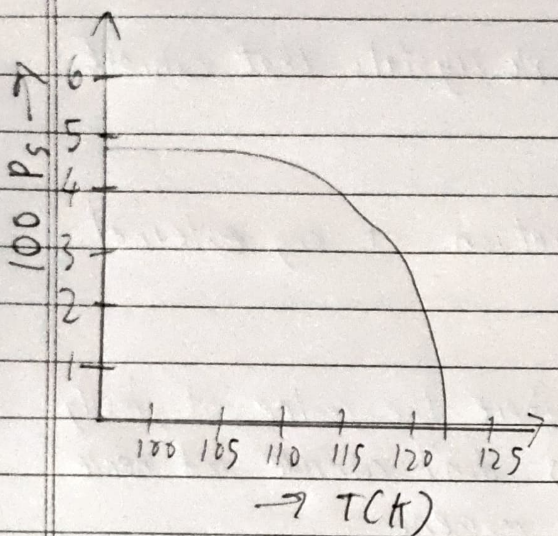
- They posses very high values of permittivity $\varepsilon_r$ of order $10^3$ to $10^4$

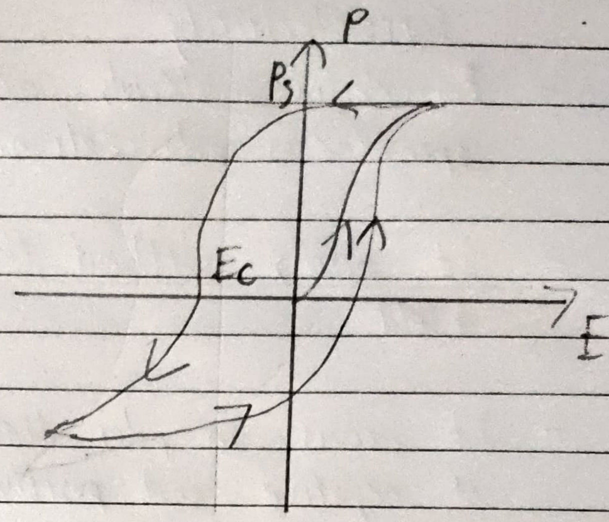
- Static dielectric constant of ferroelectric materials change with temperature according to the following relation

$$\varepsilon = \frac{C}{T-T_c}$$ Curie-Weiss law

C: Curie constant    $T_c$: Curie temperature

- They possess spontaneous electric polarization i.e polarization without the help of external electric field. However spontaneous polarization occurs only within definite temperature rang and upto curie Temperature




- In ferroelectric material dielectric polarization depends non-linearly on applied electric fied, unlike oth ordinary dielectrics Because of this, ferroelectrics are known as non-linear dielectrics

Applications

- Electronic components such as capacitors
- High-k/low-k material widely used in Semiconductors to enhance performance and reduce device size.
- Dielectric material also used in display applications.
- Piezo electrics / Ferroelectrics / MEMs material are also dielectric
- Ceramics and Polymers also often exhibit dielectric properties