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DIELECTRICS

Introduction to dielectrics:-

A dielectric is an insulator or non conductor of electricity. Its effects are defined in terms of the ratio of the capacitance of a capacitor with a dielectric between the plates to the capacitance of a capacitor without a dielectric between the plates.

Atomic description of dielectrics:-

All the atoms are electrically neutral. The positive charges are located at the center of the atom. The electron revolves around the nucleus. Because of the presence of the negatively charged ions around the nucleus, it appears as though there is a positive charge + a negative charge at the centre of the atom. These equal but opposite charges gives the effect of neutralizing each other and hence the atom does not appear to have any charges and appears neutral. The electric field of the +ve charge is radially outward whereas the average E.F of the -ve charge is radially inward. These equal but opposite average E.F have the effect of neutralizing each other and hence the atom also does not appear to have any E.F associated with it. Because of this basic symmetry of the atom, all atoms are electrically neutral.

If the atom is now placed in an uniform external E.F E_0, we observe a change in this symmetry. The e^- of the atoms finds itself in an external field E_0 and experiences the force.

$$F = qE_0 = -qE_0.$$

Because the electronic charge is -ve, the force on the e^- is opposite to the direction of the external field E_0. They form an electric field (by the effect of dipole formed.)

Polarization :- The process of formation of an electric dipole (or alignment of an existing dipole) under the influence of an external E.F. This causes redistribution of charges.

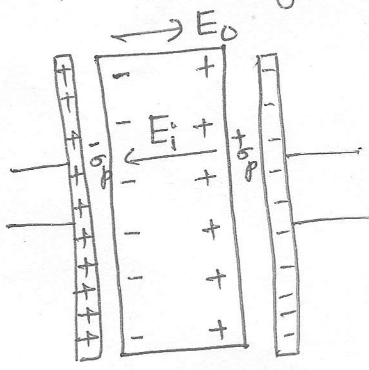
DIELECTRICS :-

They are basically non- conducting materials. There are no free charge carriers in a dielectric. When dielectric materials are placed in an electric field, they modify the E.F and they themselves undergo appreciable changes because of which they act as stores of electrical charges. When charges storage is the main function, the materials are called dielectrics.

In case of dielectrics, the forbidden gap Eg is very large and excitation of electrons from the normally full V.B to the empty C.B is not possible under ordinary conditions. Therefore, conduction can't occur in a dielectric. Even if it contains impurities, extrinsic conduction is not observed. Their resistivity is usually infinitelly high i.e of the order of $10^{10} - 10^{20}\ \Omega m$.

Dielectric Polarization :-

Let us consider an electrically neutral slab of an isotropic dielectric inserted b/w the plates of a charged parallel plate capacitor.



When a dielectric is placed in an E.F electric charges do not flow through the material as they do in an electrical conductor. But only slightly shift from their average equilibrium positions causing dielectric polarization. Because of dielectric polarization, positive charges are displaced towards the field and negative charge shift in the opposite direction. This creates an internal electric field that reduces the overall field with in the dielectric itself. If a dielectric is composed of weakly bonded molecules, those molecules not only become polarized, but also reorient so that their symmetry axes align to the field.

The intensity of polarization is defined as the total dipole moment per unit volume of the material

Thus, $P = \frac{\Sigma d\mu}{V}$

NON-POLAR DIELECTRICS & POLAR DIELECRICS

A molecule is a neutral system in which the algebric sum of all the charges is equal to zero. The spatial arrangement of charges in a molecule may differ from material to material. All +ve charges of a molecule may be replaced by one equivalent positive charge located at the centre of gravity of positive charges. Similarly, all negative charges in it may be replaced with a single equivalent negative charge located at the centre of gravity of all negative charge. The two resultant charges are equal in magnitude. Their points of action in space may coincide or may not coincide. When the points of action coincide the molecule will not possess a permanent dipole moment. Their permittivities are low and range from 1 to 2.2.

If the points of the resultant charges of a molecule do not coincide in space, the molecule possess an intrinsic dipole moment. Such molecules are called polar molecules. In a polar molecules, consisting of several bonds, each bond may carry a permanent dipole moment. The resultant dipole moment of the molecule may be obtained through the vector addition of the moments associated with the different bonds. The permittivities of polar dielectrics are high ranging from 3-8 + more.

POLARIZATION :- AN ATOMIC VIEW

Consider a slab of dielectric located b/w the plates of a parallel plate capacitor. In the absence of an external electric field each elementary volume of the dielectric has no dipole moment.

If the dielectric is a non-polar material the constituent molecules do not possess intrinsic dipole moments and in case the dielectric is a polar material, the individual molecular dipoles are randomly oriented so that in elementary volume $\Sigma\mu = 0$. Hence, polarization is zero.

When the electric field is switched on, dipoles are induced in non-polar molecules, which form chains along the field lines.

The polarization is given by

$$P = N\mu = N\alpha E \quad \text{(Non-polar dielectric)}$$

where N is the no. of molecules / unit volume.

In a polar dielectric, the molecular dipoles experience a torque that tends to align them with the field direction. Total alignment is not achieved because of the disordering effects of thermal agitation. An average alignment $\langle\mu\rangle$ is achieved in the direction of the field.

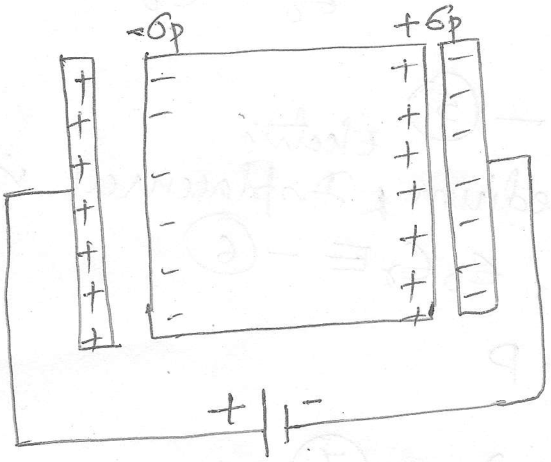
The polarization is therefore given by

$P = N \langle \mu \rangle$ (Polar dielectrics)

Thus, the action of electric fields brings the dipoles into a certain ordered arrangement in space. It is seen that the ends of adjacent dipoles carrying opposite charges neutralize each other.

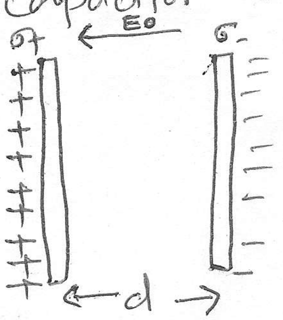
Only the charges of the dipole ends terminating on the opposite faces of the slab remains uncompensated.

Thus, the application of an electric field to a dielectric produces a displacement of charge within the material through a progressive orientation of intrinsic or induced dipoles. This is known as dielectric polarization.



— Relation between Electric field E, Polarization P & Electric displacement D.

Consider the arrangement of a parallel plate capacitor without any medium in between.

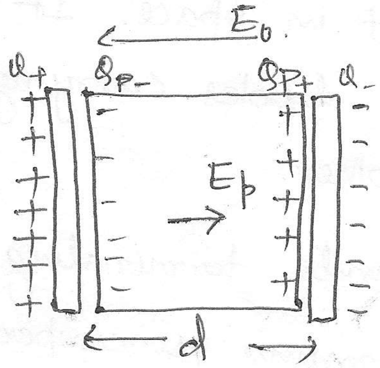


The plate contain charges Q+ & Q- respectively.

According to Gauss law, the E.F is given by

$$E_0 = \frac{q}{\epsilon_0 A} \quad \text{— (1)}$$

when a dielectric slab is placed b/w the parallel plates, the bound charges segregates and forms a dipole, thus giving rise to induced polarization



Because of the induced polarization & accumulation of charges on the slab, an E.F is also observed.

∴ From the Gaussian law of electrostatics E_p due to the presence of dielectrics is given by

$$\vec{E_p} = \frac{Q_p}{\epsilon_0 A} \quad -(2)$$

$$\vec{E_p} = \frac{Q_p \times d}{\epsilon_0 (A \times d)} = \frac{\mu}{\epsilon_0 V} = \frac{P}{\epsilon_0} \quad -(3)$$

∴ Net Electric field is given as

$$\vec{E} = \vec{E_0} - \vec{E_p} \quad -(4)$$

$$\vec{E} = \frac{Q}{\epsilon_0 A} - \frac{P}{\epsilon_0} \Rightarrow E = \frac{D}{\epsilon_0} - \frac{P}{\epsilon_0}$$

$$\Rightarrow \boxed{D = \epsilon_0 E + P} \quad -(5)$$

In the presence of medium, Electric Displacement is given as. $D = \epsilon E = \epsilon_0 \epsilon_r E \quad -(6)$

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

$$P = \epsilon_0 E (\epsilon_r - 1) \quad -(7)$$

$$\epsilon_r - 1 = \chi_r \quad -(8)$$

$$\boxed{P = \epsilon_0 E \chi_r}$$

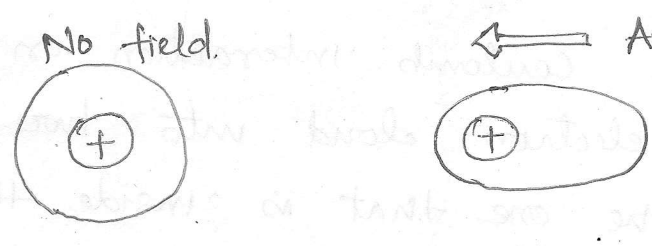
Types of Polarization

Dielectric polarization is classified into four basic types.

(i) Electronic polarization
(ii) Ionic polarization
(iii) Orientation polarization

I :- Electronic polarization

This polarization results from the displacement of the electron clouds of atoms, molecules and ions with respect to heavy fixed nuclei to a distance that is less than the dimensions of the atoms, molecules or ions. This polarization sets in over a very short period of time, of the order of 10^{-14} to 10^{-15} s. It is independent of temperature.



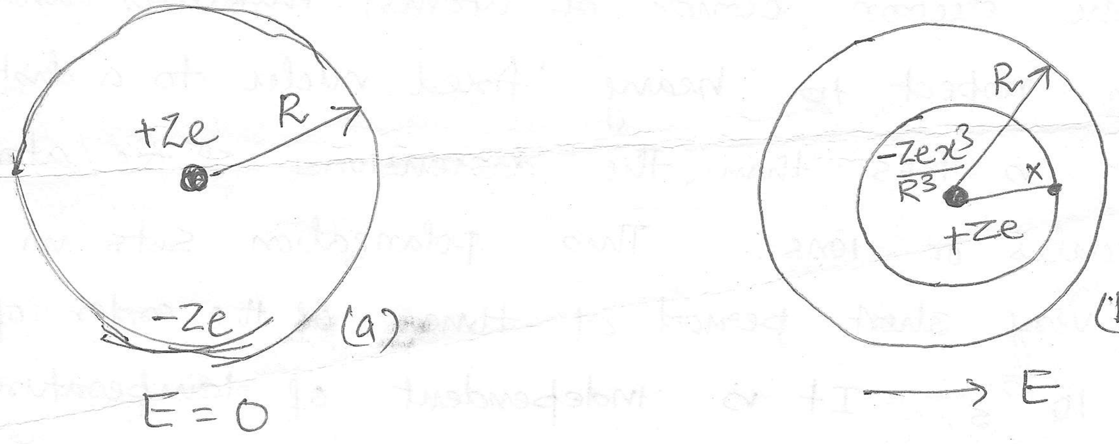
(a) (b).

Expression for Electronic polarization :

Consider a single atom with atomic number Z. The charge on its nucleus is +Ze and Z electrons move around the nucleus.
Let us assume that the nucleus is a point charge and the total negative charge −Ze is homogenously

distributed throughout a sphere of radius, R, when this atom is subjected to an electric field E, the nucleus and the electron cloud will move in opposite directions. The coulomb attractive force opposes the movement, which acts as the restoring force here. Equilibrium condition is attained in which the nucleus is displaced relative to the center of the electron cloud by the amount x.

The force on the nucleus along the field direction is $F = ZeE$



To determine the coulomb interaction on the nucleus we divide the electron cloud into two regions. One region is the one that is inside the sphere of radius x and the other is the annular region lying between the two spherical surfaces of radii x and R.

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

The charge inside the region is given by $-Zex^3/R^3$.

As charge density $\rho = \frac{Q}{Vol.} = \frac{Q}{\frac{4}{3}\pi R^3} = \frac{-Ze}{\frac{4}{3}\pi R^3}$

If we consider the charge lying in an annular ring then, ~~ch~~ magnitude of charge for sphere having radius x is given as

$Q = \rho \times$ volume of the sphere under consideration

$$Q = \frac{-Ze}{\frac{4}{3}\pi R^3} \cdot \frac{4}{3}\pi x^3 = \frac{-Zex^3}{R^3}$$ (charge present in an annular ring of radius x)

The force exerted by this charge on the nuleus is given by

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

Under equilibrium condition, both the forces balances each other.

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

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

Therefore, the displacement of the nucleus is x.

Now, the dipole moment is given as $\mu = Zex$.

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

As $\mu_e = \alpha_e E \Rightarrow \alpha_e = 4\pi\epsilon_0 R^3$

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

N represent the no. of atoms / unit volume

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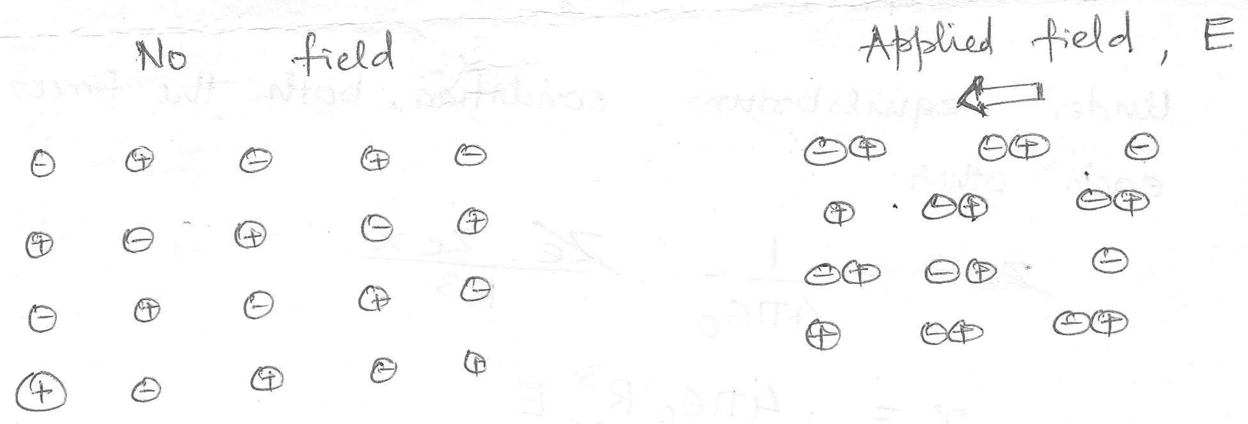
2: Ionic Polarization

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

A sodium chloride molecule consists of Na^+ ions bound to Cl^- ions through ionic bond. If the interatomic distance is d, the molecule exhibits an intrinsic dipole moment equal to 'ed'.

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



When the field direction is reversed the ions move closer & again the dipole moment undergoes a change. Thus, dipoles are induced. The induced dipole moments is proportional to the applied field & is expressed as $\mu_i = \alpha_i E$.

where, α_i = ionic polarizability.

The induced dipole moment $\mu = ex$.

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

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

From the expression it is clear that

I) Ionic polarizability is ~~inversely~~ directly proportional to reduced mass of the molecule.

II) It is inversely proportional to the square of the natural frequency of the molecule.

III) It is independent of temperature.

The ions experience electronic polarization in addition. For most materials, the ionic polarizability is less than the electronic polarizability.

Typically, $\alpha_i = \alpha_e / 10$.

Ionic polarization is given by

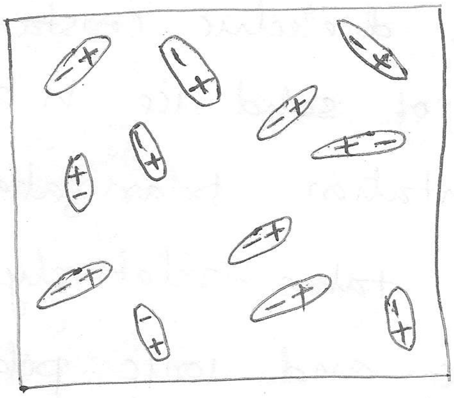
$$P_i = N\alpha_i E$$

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

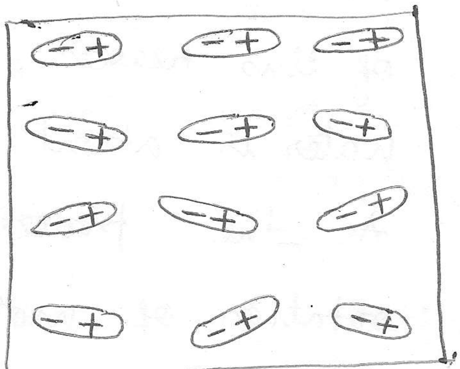
It takes 10^{-11} to 10^{-14} s to build up, and is not influenced by temperature.

3: Orientation Polarization :

The orientation polarization is characteristic of polar dielectrics, which consist of molecules having permanent dipole moment. In the absence of external electric field, the orientation of dipoles is random resulting in a complete cancellation of each other's effect.



No applied field
(a)



Applied field
(b)

When the electric field is impressed the molecular dipoles rotate about their axis of symmetry to align with the applied field.

In case of electronic and ionic polarizations, the force due to the external field is balanced by a restoring force due to coulomb attraction, but for orientation polarization, restoring forces do not exist. However, the dipole alignment is counteracted by thermal agitation.

The dipoles can turn only through a small angle. Even in case of liquids or gases, where molecules are free to rotate, a complete alignment can't be achieved due to the randomizing effect of the temperature.

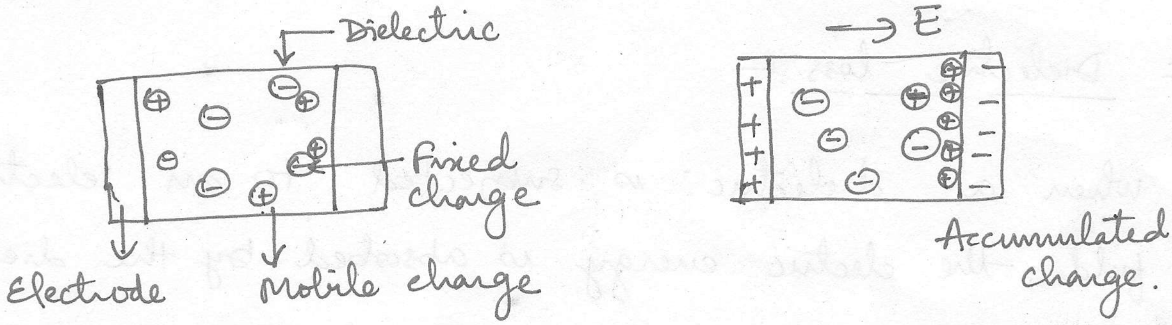
Thus, orientation polarization is strongly temperature dependent. This type of polarization occurs in gases, liquids and amorphous viscous substances. In case of solids, the molecules are fixed in their positions and their rotation is highly restricted by the lattice forces, leading to a great reduction in their contribution to orientation polarization. Because of this reason, while the dielectric constant of water is about 80, that of solid ice is about 10. As the process of orientation polarization involves rotation of molecules, it takes relatively longer time than the electronic and ionic polarizations. The build up time is of the order of 10^{-10} s or more.

$$P_0 = \frac{N\mu^2 E}{3kT} \Rightarrow \alpha_0 = \mu^2/3kT$$

(orientation polarizability)

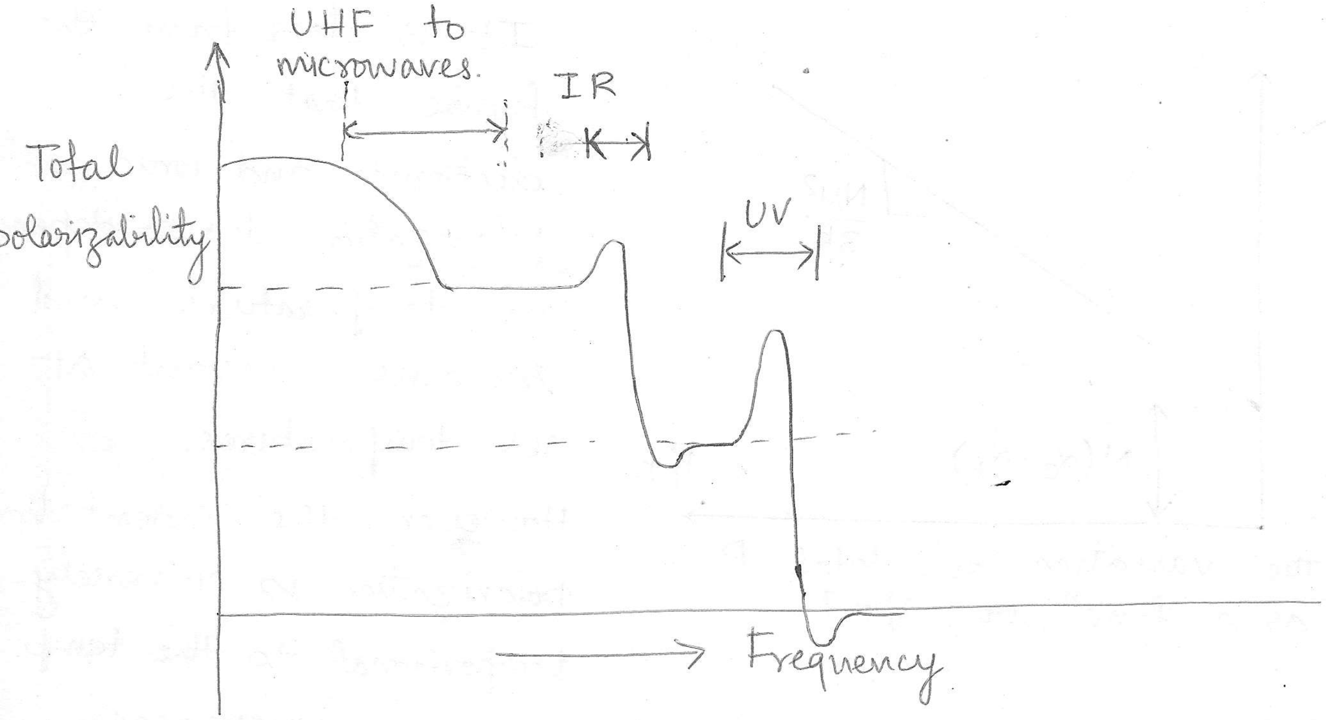
✱. Space - charge Polarization :-

It occurs in heterogenous dielectric material in which there is a change of electrical properties b/w different phases. & in homogenous dielectrics which contains impurities, pores filled with air etc. When an electric field is applied, the electric charges that migrate within the impurity regions store up at the interfaces. The accumulation of charges takes place with opposite polarity on the interface. These takes a longer time & occurs at low frequencies.



This polarization is very small & negligible. Therefore, total polarization in a material may be taken as due to the other three contributions only.

Frequency dependence of Total polarization



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

→ In audio frequency region, all types of polarization are possible and the dielectric is characterized by a polarizability $\alpha = \alpha_e + \alpha_i + \alpha_o$ and the pol^n $P = P_e + P_i + P_o$.

→ At low frequencies, the dipoles will get sufficient time to orient themselves completely along the instantaneous direction of the field. This orientation occurs first in one direction and then the other, following the changes in the direction of the field.

The average time taken by the dipoles to reorient in the field direction is known as the relaxation time τ. The reciprocal of the relaxation time is called the relaxation frequency ν.

→ If $\nu_{E.F} >> \nu_{rel. freq.}$, the dipoles cannot reverse fast enough.

→ If dipole relaxation time τ < than $T/2$ of Electric field, the dipole can easily follow electric field alternations & contribute to orientation polarization.

→ ~~At low frequ~~ The orientation polarization, which is effective at low frequencies, is damped out for higher frequencies ($f_{field} > f_{relax}$).

→ In the rf region or microwave band region, the permanent dipoles fail to follow the field reversals and the polarization falls to a value corresponding to $(P_i + P_e)$. As a result, ϵ_r decreases considerably.

→ In IR region the ionic polarization fails to follow the field reversals due to the inertia of the system and the contribution of ionic polarizability ceases. In this region, only electronic polarization contributes to the total polarization

$\therefore$ $P = P_e$.

→ In the optical region, the electron cloud follows the field variations and the material exhibits the electronic polarizability α_e.

The relative permittivity in the optical region

FERROELECTRICITY :-

Ferroelectric materials are anisotropic crystals that exhibit spontaneous polarization. The dielectric polarization which occurs under the action of the internal processes and without the application of an electric field.

In the absence of an electric field, if the centers of gravity of the positive and negative charges do not coincide, it results in a resultant dipole moment, which is the cause of spontaneous polarization.

The materials which possesses special structure that permits spontaneous polarization are called ferroelectrics and the phenomenon of spontaneous polarization is called ferroelectricity.

Eg: Rochell Salt exhibits ferroelectricity at a temperature ranging from −18°C to 22°C

The main characteristics of ferroelectric substances are as follows :-

1:- They possess very high values of permittivity ε_r of the order of 1000 to 10,000.

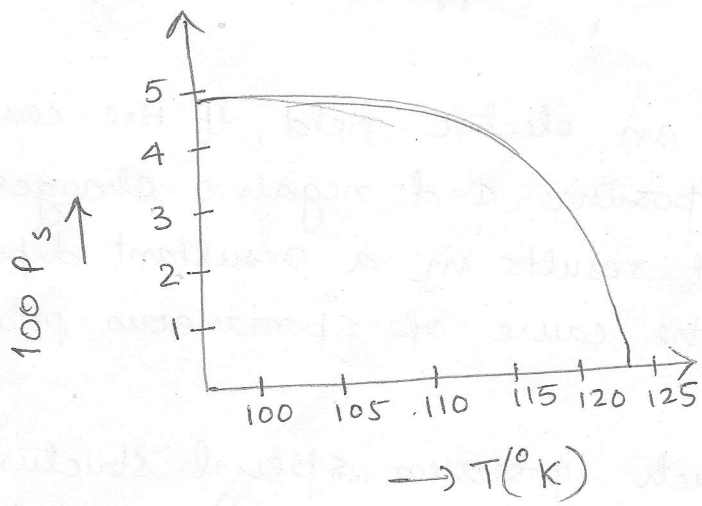
2:- The static dielectric constant of ferroelectric materials change with temperature according to the following relation :

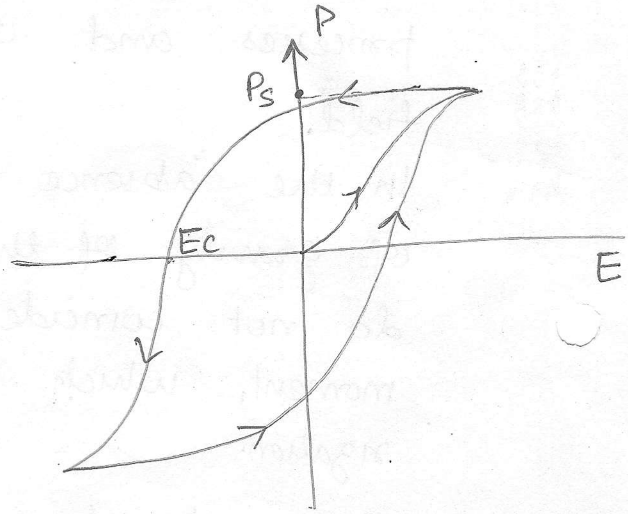
$$\varepsilon = \frac{C}{T - T_c} \quad (T > T_c) \quad \text{Curie-Wiess law}$$

C: Curie Constant

T_c: Curie temperature

3. They possess spontaneous electric polarization, i.e polarization without the help of an external electric field. However, the spontaneous polarization occurs only within a definite temperature range and upto the curie temperature T_c.





4) In a ferroelectric material, the dielectric po'rization depends non-linearly on the applied electric field. In ordinary dielectrics, the polarization varies linearly with the applied electric field. Because of this, ferroelectrics are known as non-linear dielectrics.

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