UNIT - VI

10. DIELECTRIC PROPERTIES

Introduction: Dielectrics are insulating materials. In dielectrics, all the electrons are bound to their parent molecules and there are no free charges. Even with normal voltage or thermal energy, electrons are not released.

Electric Dipole: A system consisting of two equal and opposite charges separated by a distance is called electric dipole.



Dipole moment: The product of charge and distance between two charges is called dipole moment.

$$\text{i e, } \mu = q \times dl$$

Permittivity: It is a quantity, which represents the dielectric property of a medium. Permittivity of a medium indicates the easily Polarisable nature of the material.

Units: Faraday / Meter or Coulomb / Newton-meter .

Dielectric constant: The dielectric characteristics are determined by the dielectric constant. The dielectric constant or relative permittivity of a medium is defined as the ratio between the permittivity of the medium to the permittivity of the free space.

$$\varepsilon_r = \varepsilon / \varepsilon_0 = C / C_0 \quad \text{where}$$

ε is permittivity of the medium
ε_0 is permittivity of the free space
C is the capacitance of the capacitor with dielectric
C_0 is the capacitance of the capacitor without dielectric

Units: No Units.

Capacitance: The property of a conductor or system of conductor that describes its ability to store electric charge.

$$C = q / V = A \varepsilon / d \quad \text{where}$$

C is capacitance of capacitor
q is charge on the capacitor plate

V is potential difference between plates
A is area of capacitor plate
ε is permittivity of medium
d is distance between capacitor plates

Units: Farad .

Polarizability (α) : When the strength of the electric field E is increased the strength of the induced dipole μ also increases . Thus the induced dipole moment is proportional to the intensity of the electric field.

$\boldsymbol{\mu} = \alpha E$ where α the constant of proportionality is called polarizability .It can be defined as induced dipole moment per unit electric field.

$\alpha = \boldsymbol{\mu} / E$

Units: Farad – meter^2

Polarization Vector (P) : The dipole moment per unit volume of the dielectric material is called polarization vector **P** .if **μ** is the average dipole moment per molecule and N is the number of molecules per unit volume then polarization vector

$$\mathbf{P = N \mu}$$

The dipole moment per unit volume of the solid is the sum of all the individual dipole moments within that volume and is called the polarization of the solid.

Electric Flux Density or Electric Displacement (D): The Electric Flux Density or Electric Displacement at a point in the material is given by

$D = \varepsilon_r \varepsilon_0 E$ ----------(1) where

E is electric field strength
ε_r is relative permittivity of material
ε_0 is permittivity of free space

As polarization measures additional flux density arising from the presence of the material as compared to free space, it has same units as D.

Hence $D = \varepsilon_0 E + \mathbf{P}$ ----------(2)

Since $D = \varepsilon_0 \varepsilon_r E$

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

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

$\mathbf{P} = \varepsilon_0(\varepsilon_r - 1) E.$

Electric Susceptibility (χ_e) : The polarization **P** is proportional to the total electronic flux density E and is in the same direction of E . Therefore, the polarization vector can be written as

$$\mathbf{P} = \varepsilon_0 \chi_e E$$

Therefore $\chi_e = \mathbf{P} / \varepsilon_0 E = \varepsilon_0(\varepsilon_r - 1) E / \varepsilon_0 E$

$$\chi_e = (\varepsilon_r - 1)$$

Dielectric Strength: It can be defined as the minimum voltage required for producing dielectric breakdown. Dielectric strength decreases with raising the temperature, humidity and age of the material.

Various polarization Process: polarization occurs due to several atomic mechanisms. When a specimen is placed in a d.c. electric field, polarization is due to four types of processes. They are

(1) electronic polarization
(2) ionic polarization
(3) orientation polarization and
(4) space charge polarization

Electronic Polarization: the process of producing electric dipoles which are oriented along the field direction is called polarization in dielectrics

Consider an atom placed inside an electric field. The centre of positive charge is displaced along the applied field direction while the centre of negative charge is displaced in the opposite direction .thus a dipole is produced.

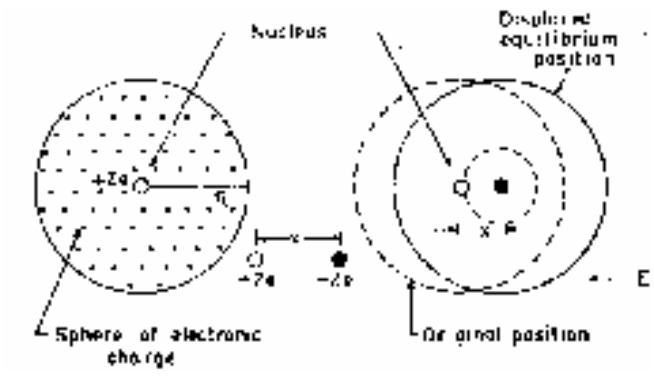
The displacement of the positively charged nucleus and the negative electrons of an atom in opposite directions, on application of an electric field, result in electronic polarization.

Induced dipole moment

$$\boldsymbol{\mu} \alpha E \quad \text{or} \quad \boldsymbol{\mu} = \alpha_e E \quad \text{where } \alpha_e \text{ is electronic polarizability}$$

Electronic polarizability is independent of temperature.

Derivation: Consider the nucleus of charge Ze is surrounded by an electron cloud of charge -Ze distributed in a sphere of radius R.



Charge density ρ is given by

$$\rho = -Ze / ({}^{4}/_{3}\Pi R^3) = - (3/4) (Ze / \Pi R^3) \quad \text{----------(1)}$$

When an external field of intensity E is applied, the nucleus and electrons experiences Lorentz forces in opposite direction. Hence the nucleus and electron cloud are pulled apart.

Then Coulomb force develops between them, which tends to oppose the displacement. When Lorentz and coulomb forces are equal and opposite, equilibrium is reached.

Let x be the displacement

Lorentz force = -Ze E (since = charge x applied field)

Coulomb force = Ze x [charge enclosed in sphere of radius 'x' / 4 Π ε_0 x^2]

Charge enclosed $= (4 / 3) \Pi x^3 \rho$

$= (4 / 3) \Pi x^3 [(- 3 / 4) (Z e / \Pi R^3)]$

$= - Z e x^3 / R^3$

Therefore Coulomb force = $(Ze)(- Z e x^3 / R^3) / 4 \Pi \varepsilon_0 x^2 = - Z^2 e^2 x / 4 \Pi \varepsilon_0 R^3$

At equilibrium, Lorentz force = Coulomb force

⇨ $-Ze E = - Z^2 e^2 x / 4 \Pi \varepsilon_0 R^3$

⇨ $E = -Ze x / 4 \Pi \varepsilon_0 R^3$

⇨ or $x = 4 \Pi \varepsilon_0 R^3 E / Ze$

Thus displacement of electron cloud is proportional to applied field.

The two charges +Ze and -Ze are separated by a distance 'x' under applied field constituting induced electric dipoles .

Induced dipole moment $\boldsymbol{\mu_e} = Ze x$

Therefore $\boldsymbol{\mu_e} = Ze (4 \Pi \varepsilon_0 R^3 E / Ze) = 4 \Pi \varepsilon_0 R^3 E$

Therefore $\boldsymbol{\mu_e} \alpha E$, $\boldsymbol{\mu_e} = \boldsymbol{\alpha_e} E$ where $\boldsymbol{\alpha_e} = 4 \Pi \varepsilon_0 R^3$ is electronic polarizability

The dipole moment per unit volume is called electronic polarization. It is independent of temperature.

$\mathbf{P} = N \boldsymbol{\mu_e} = N \boldsymbol{\alpha_e} E$ where

N is Number of atoms / m^3

$\mathbf{P_e} = N (4 \Pi \varepsilon_0 R^3 E) = 4 \Pi \varepsilon_0 R^3 N E$ where

R is radius of atom

Electric Susceptibility $\chi = \mathbf{P} / \varepsilon_0 E$

Therefore $\mathbf{P} = \varepsilon_0 E \chi$

$\mathbf{P} = (4 \Pi R^3 N) \varepsilon_0 E$ where $\chi = 4 \Pi R^3 N$

Also $\mathbf{P_e} = \varepsilon_0 E (\varepsilon_r - 1) = N \boldsymbol{\alpha_e} E$

Or $\varepsilon_r - 1 = N \boldsymbol{\alpha_e} / \varepsilon_0$

Hence $\boldsymbol{\alpha_e} = \varepsilon_0 (\varepsilon_r - 1) / N$.

Ionic Polarization: It is due to the displacement of cat ions and anions in opposite directions and occurs in an ionic solid .

Consider a NaCl molecule. Suppose an electric field is applied in the positive direction . The positive ion moves by x_1 and the negative ion moves by x_2

Let M is mass of positive ion

M is mass of negative ion

x_1 is displacement of positive ion

x_2 is displacement of negative ion

Total displacement $x = x_1 + x_2$ ----------(1)

Lorentz force on positive ion = + e E ----------(2)

Lorentz force on negative ion = - e E ----------(3)

Restoring force on positive ion = $-k_1 x_1$----------(2 a)

Restoring force on negative ion = $+k_2 x_2$----------(3 a) where k_1, k_2 Restoring force constants

At equilibrium, Lorentz force and restoring force are equal and opposite

For positive ion, $e E = k_1 x_1$
For negative ion, $e E = k_2 x2$] ---------- (4)

Where $k_1 = M \omega_0^2$ & $k_2 = m \omega_0^2$ where ω_0 is angular velocity of ions

Therefore $x = x_1 + x_2 = (e E / \omega_0^2) [1/M + 1/m]$ ----------(5)

From definition of dipole moment

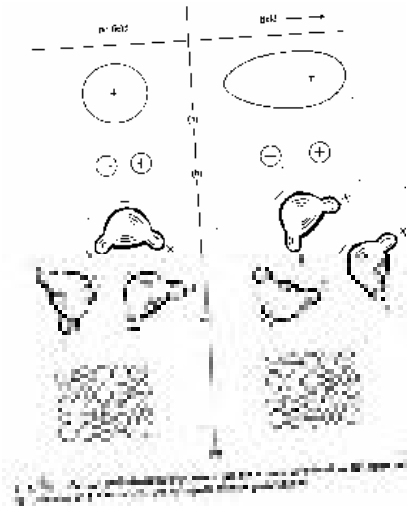
$\boldsymbol{\mu}$ = charge x distance of separation

$\boldsymbol{\mu} = \mathbf{e} x = (e^2 E / \omega_0^2) [1/M + 1/m]$ ----------(6)

But $\mu \alpha E$ or $\mu = \alpha_i E$

Therefore $\alpha_i = (e2 / \omega_0^2)\ [1/M + 1/m]$

This is ionic polarizability.



Orientational Polarization:

In methane molecule, the centre of negative and positive charges coincides, so that there is no permanent dipole moment. On the other hand, in certain molecules such as Ch3Cl, the positive and negative charges do not coincide .Even in the absence of an electric field, this molecule carries a dipole moment, they tend to align themselves in the direction of applied field. The polarization due to such alignment is called orientation polarization. It is dependent on temperature. With increase of temperature the thermal energy tends to randomize the alignment.

Orientational polarization $Po = N\mu = N\mu 2E / 3kT$

$= N \alpha_0 E$

Therefore Orientational polarizability $\alpha_0 = Po / NE = \mu 2 / 3kT$

Thus orintational polarizability α_0 is inversely proportional t absolute temperature of material.

Internal field or Local field or Lorentz field: Internal field is the total electric field at atomic site.

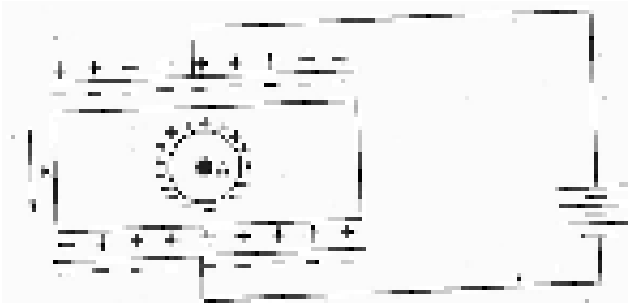
Internal field $A = E_1 + E_2 + E_3 + E_4$ ------- (I) where

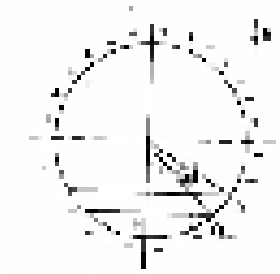
E_1 is field intensity due to charge density on plates

E_2 is charge density induced on two sides of dielectric

E_3 is field intensity due to other atoms in cavity and

E_4 is field intensity due to polarization charges on surface of cavity





Field E_1 : E_1 is field intensity due to charge density on plates

From the field theory

$$E_1 = D / \varepsilon_0$$

$$D = P + \varepsilon_0 E$$

Therefore $E_1 = P + \varepsilon_0 E / \varepsilon_0 = E + P / \varepsilon_0$ ----------(1)

Field E_2 : E_2 is the field intensity at A due to charge density induced on two sides of dielectric

Therefore $E_2 = - P / \varepsilon_0$ ----------(2)

Field E_3 : E_3 is field intensity at A due to other atoms contained in the cavity and for a cubic structure,

$E_3 = 0$ because of symmetry. ---------- (3)

Field E_4: E_4 is field intensity due to polarization charges on surface of cavity and was calculated by Lorentz in the following way:

If dA is the surface area of the sphere of radius r lying between θ and $\theta + d\theta$, where θ is the direction with reference to the direction of applied force.

Then $dA = 2 \Pi (PQ) (QR)$

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

And $d\theta = QR / r \Rightarrow QR = r\, d\theta$

Hence $dA = 2 \Pi (r \sin \theta) (r\, d\theta) = 2 \Pi r^2 \sin \theta\, d\theta$

Charge on surface dA is $dq = P \cos \theta\, dA$ ($\cos \theta$ is normal component)

$$dq = P \cos \theta (2 \Pi r^2 \sin \theta\, d\theta) = P (2 \Pi r^2 \sin \theta \cos \theta\, d\theta)$$

The field due to the charge dq at A, is denoted by $dE_{4\,in}$ direction $\theta = 0$

$$dE_4 = dq \cos \theta / 4 \Pi \varepsilon_0 r2 = P (2 \Pi r^2 \sin \theta \cos \theta\, d\theta) \cos \theta$$

$$dE_4 = P \sin \theta \cos^2 \theta\, d\theta / 2 \varepsilon_0$$

$$\int dE_4 = P / 2 \varepsilon_0 \int_0^{\Pi} \sin \theta \cos^2 \theta\, d\theta = P / 2 \varepsilon_0 \int_0^{\Pi} \cos^2 \theta\, d(-\cos \theta)$$

Let $\cos \theta = x$

$$\int dE_4 = - P / 2 \varepsilon_0 \int_0^{\Pi} x^2\, dx$$

Therefore $E_4 = - P / 2 \varepsilon_0 [x3 / 3]_0^{\Pi}$

$$= - P / 2 \varepsilon_0 [\cos 3 \theta / 3]_0^{\Pi} = - P / 6 \varepsilon_0 [-1 - 1] = P / 3 \varepsilon_0 \quad \text{------- (4)}$$

Local field $Ei = E1 + E_2 + E_3 + E_4$

$$= E + P / \varepsilon_0 - P / \varepsilon_0 + 0 + P / 3 \varepsilon_0$$

$$= E + P / 3 \varepsilon_0$$

Clausius – Mosotti Relation:

Let us consider the elemental dielectric having cubic structure. Since there are no ions and perment dipoles in these materials, them ionic polarizability α_i and orientational polarizability $\boldsymbol{\alpha_0}$ are zero.

i.e. $\alpha_i = \alpha_0 = 0$

Hence polarization $P = N \alpha_e E_i$

$$= N \alpha_e (E + P / 3\varepsilon_0)$$

i.e. $P [1 - N \alpha_e / 3 \varepsilon_0] = N \alpha_e E$

$P = N \alpha_e E / P [1 - N \alpha_e / 3 \varepsilon_0]$ ----------→ **1**

$$D = P + \varepsilon_0 E$$

$$P = D - \varepsilon_0 E$$

Dividing on both sides by E

$$P / E = D / E - \varepsilon_0 = \varepsilon - \varepsilon_0 = \varepsilon_0 \varepsilon_r - \varepsilon_0$$

$$P = E \varepsilon_0 (\varepsilon_r - 1) \text{ ----------} \rightarrow \mathbf{2}$$

From eqn **1** and **2** , we get

$$P = E \varepsilon_0 (\varepsilon_r - 1) = N \alpha_e E / [1 - N \alpha_e / 3 \varepsilon_0]$$

$$[1 - N \alpha_e / 3 \varepsilon_0] = N \alpha_e / \varepsilon_0 (\varepsilon_r - 1)$$

$$1 = N \alpha_e / 3 \varepsilon_0 + N \alpha_e / \varepsilon_0 (\varepsilon_r - 1)$$

$$1 = (N \alpha_e / 3 \varepsilon_0) (1 + 3 / (\varepsilon_r - 1))$$

$$1 = (N \alpha_e / 3 \varepsilon_0)[(\varepsilon_r - 1 + 3) / (\varepsilon_r - 1)]$$

$$1 = (N \alpha_e / 3 \varepsilon_0)[(\varepsilon_r + 2) / (\varepsilon_r - 1)]$$

$$(\varepsilon_r + 2) / (\varepsilon_r - 1) = N \alpha_e / 3 \varepsilon_0$$ Where N – no of molecules per unit volume

This is Clausius – Mosotti Relation.

Dielectric Breakdown : The dielectric breakdown is the sudden change in state of a dielectric material subjected to a very high electric field , under the influence of which , the electrons are lifted into the conduction band causing a surge of current , and the ability of the material to resist the current flow suffers a breakdown .

Or

When a dielectric material loses its resistivity and permits very large current to flow through it, then the phenomenon is called dielectric breakdown.

There are many factors for dielectric breakdown which are (1) Intrinsic breakdown (2) Thermal breakdown (3) Discharge breakdown (4) Electro Chemical breakdown (5) Defect breakdown.

(1) **Intrinsic breakdown**: The dielectric strength is defined as the breakdown voltage per unit thickness of the material. When the applied electric field is large, some of the electrons in the valence band cross over to the conduction band across the large forbidden energy gap giving rise to large conduction currents. The liberation or movement of electrons from valence band is called field emission of electrons and the breakdown is called the intrinsic breakdown or zener breakdown.

The number of covalent bonds broken and the number of charge carriers released increases enormously with time and finally dielectric breakdown occurs. This type of breakdown is called Avalanche breakdown.

(2) **Thermal breakdown:** It occurs in a dielectric when the rate of heat generation is greater than the rate of dissipation. Energy due to the dielectric loss appears as heat. If the rate of generation of heat is larger than the heat dissipated to the surrounding, the temperature of the dielectric increases which eventually results in local melting .once melting starts, that particular region becomes highly conductive, enormous current flows through the material and dielectric breakdown occurs.

Thus thermal breakdown occurs at very high temperatures. Since the dielectric loss is directly proportional to the frequency, for a.c fields, breakdown occurs at relatively lower field strengths.

(3) **Discharge breakdown**: Discharge breakdown is classified as external or internal. External breakdown is generally caused by a glow or corona discharge .Such discharges are normally observed at sharp edges of electrodes. It causes deterioration of the adjacent dielectric medium. It is accompanied by the formation of carbon so that the damaged areas become conducting leading to power arc and complete failure of the dielectric. Dust or moisture on the surface of the dielectric may also cause external discharge breakdown. Internal breakdown occurs when the insulator contains blocked gas bubbles .If large number of gas bubbles is present, this can occur even at low voltages.

(4) **Electro Chemical breakdown:** Chemical and electro chemical breakdown are related to thermal breakdown. When temperature rises, mobility of ions increases and hence electrochemical reaction takes place. When ionic mobility increases leakage current also increases and this may lead to dielectric breakdown. Field induced chemical reaction gradually decreases the insulation resistance and finally results in breakdown.

(5) **Defect breakdown:** if the surface of the dielectric material has defects such as cracks and porosity, then impurities such as dust or moisture collect at these discontinuities leading to breakdown. Also if it has defect in the form of strain in the material, that region will also break on application of electric field.

Frequency dependence of polarizability:

On application of an electric field, polarization process occurs as a function of time. The polarization P(t) as a function of time. The polarization P(t) as a function of time t is given by

$P(t) = P[\ 1- \exp (- t / t_r)]$

Where P – max. Polarization attained on prolonged application of static field.

t_r - relaxation time for particular polarization process

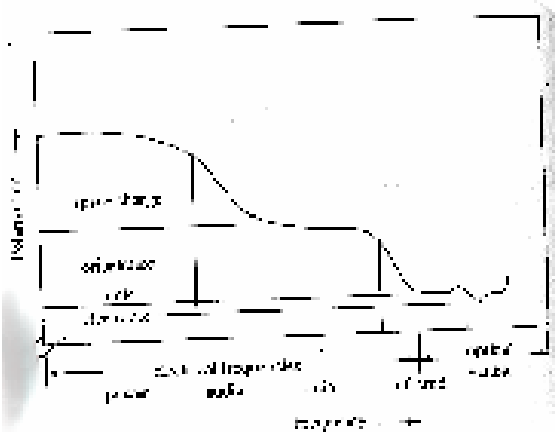
The relaxation time t_r is a measure of the time scale of polarization process. It is the time taken for a polarization process to reach 0.63 of the max. value.

Electronic polarization is extremely rapid. Even when the frequency of the applied voltage is very high in the optical range ($\approx 10^{15}$ Hz), electronic polarization occurs during every cycle of the applied voltage.

Ionic polarization is due to displacement of ions over a small distance due to the applied field. Since ions are heavier than electron cloud, the time taken for displacement is larger. The frequency with which ions are displaced is of the same order as the lattice vibration frequency (≈1013Hz). Hence, at optical frequencies, there is no ionic polarization. If the frequency of the applied voltage is less than 1013 Hz, the ions respond.

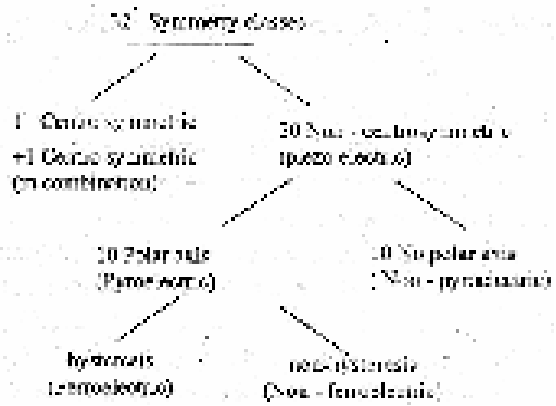
Orientation polarization is even slower than ionic polarization. The relaxation time for orientation polarization in a liquid is less than that in a solid. Orientation polarization occurs, when the frequency of applied voltage is in audio range (1010 Hz).

Space charge polarization is the slowest process, as it involves the diffusion of ions over several interatomic distances. The relaxation time for this process is related to frequency of ions under the influence of applied field. Space charge polarization occurs at power frequencies (50-60 Hz).



Piezo – Electricity: These materials have the property of becoming electrically polarized when mechanical stress is applied. This property is known as Piezo – electric effect has an inverse .According to inverse piezo electric effect, when an electric stress or voltage is applied, the material becomes strained. The strain is directly proportional to the applied field E.

When piezo electric crystals are subjected to compression or tension, opposite kinds of charges are developed at the opposite faces perpendicular to the direction of applied force. The charges produced are proportional to the applied force.



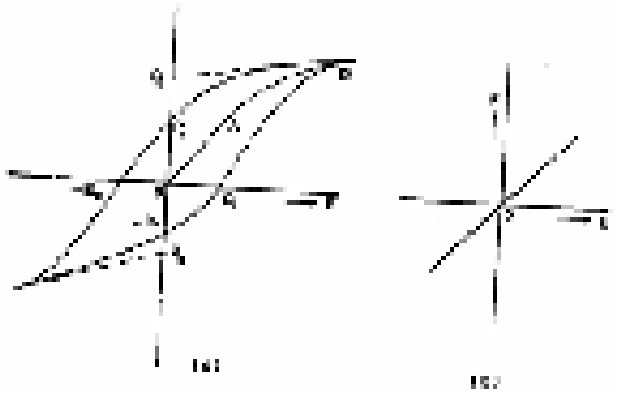
Piezo – Electric Materials and Their Applications: Single crystal of quartz is used for filter, resonator and delay line applications. Natural quartz is now being replaced by synthetic material.

Rochelle salt is used as transducer in gramophone pickups, ear phones, hearing aids, microphones etc. the commercial ceramic materials are based on barium titanate, lead zirconate and lead titanate. They are used for high voltage generation (gas lighters), accelerometers, transducers etc.

Piezo electric semiconductors such as GaS, ZnO & CdS are used as amplifiers of ultrasonic waves.

Ferro electricity: Ferro electric materials are an important group not only because of intrinsic Ferro electric property, but because many possess useful piezo electric, birefringent and electro optical properties.

The intrinsic Ferro electric property is the possibility of reversal or change of orientation of the polarization direction by an electric field. This leads to hysteresis in the polarization P, electric field E relation , similar to magnetic hysteresis. Above a critical temperature, the Curie point T_c, the spontaneous polarization is destroyed by thermal disorder. The permittivity shows a characteristic peak at T_c.



Pyroelectricity: It is the change in spontaneous polarization when the temperature of specimen is changed.



Pyroelectric coefficient 'λ' is defined as the change in polarization per unit temperature change of specimen.

$$\lambda = dP / dT$$

change in polarization results in change in external field and also changes the surface.

Required Qualities of Good Insulating Materials: The required qualities can be classified as under electrical, mechanical, thermal and chemical applications.

i) Electrical: 1. electrically the insulating material should have high electrical resistivity and high dielectric strength to withstand high voltage.
2 .The dielectric losses must be minimum.
3. Liquid and gaseous insulators are used as coolants. For example transformer oil, hydrogen and helium are used both as insulators and coolant.
ii) Mechanical: 1. insulating materials should have certain mechanical properties depending on the use to which they are put.
2. When used for electric machine insulation, the insulator should have sufficient mechanical strength to withstand vibration.
iii) Thermal: Good heat conducting property is also desirable in such cases. The insulators should have small thermal expansion and it should be non-ignitable.
iv) Chemical: 1. chemically, the insulators should be resistant to oils, liquids, gas fumes, acids and alkali's.
2. The insulators should be water proof since water lowers the insulation resistance and the dielectric strength.