

Dielectrics

INTRODUCTION

All dielectric materials are insulators. The distinction between a dielectric material and an insulator lies in the application to which one is employed. Insulating materials are used to resist the flow of current through it when a difference of potential is applied across its ends. On the other hand, dielectric materials are used to store electrical energy.

A dielectric material is one which stores electrical energy with a minimum dissipation of power, since the electrons are bound to their parent molecules and hence, there is no free charge.

(1) Electric Field Intensity or Electric Field Strength Consider a point charge dq in the region of an electric field. Let F be the force acting on the point charge dq .

The force per unit test charge dq is known as electric field strength (E), given by

$$E = \frac{F}{dq} = \frac{Q}{4\pi\epsilon r^2}$$

From Coulomb's law, when two point charges Q_1 and Q_2 are separated by a distance r , the force of attraction or repulsion between the two charges is

$$F = \frac{Q_1 Q_2}{4\pi\epsilon r^2} \hat{n}$$

where ϵ is the permittivity or dielectric constant of the medium in which the charge is placed. For vacuum, $\epsilon = \epsilon_0 = 8.854 \times 10^{-12} \text{ F m}^{-1}$.

(2) Electric Flux Density or Electric Displacement Vector The electric flux density or electric displacement vector D is the number of flux lines crossing a surface normal to the lines, divided by the surface area.

The electric flux density at a distance r from the point charge Q can be written as,

$$D = \frac{Q}{4\pi\epsilon r^2}$$

where, $4\pi r^2$ is the surface area of a sphere of radius r .

From above Eqs we get

$$D = \epsilon E = \epsilon_0 E + P$$

where P is the polarisation and it has the same unit as D , i.e., coulomb per square metre (Cm^{-2}).

(3) Dielectric Parameters The dielectric parameters are as follows.

- a. Dielectric constant (ϵ_r)
- b. Electric dipole moment (μ)
- c. Polarisation (P), and
- d. Polarisability (α).

a. Dielectric Constant: The dielectric constant (ϵ_r) of a material is defined as the ratio of the permittivity of the medium (ϵ) to the permittivity of free space (ϵ_0),

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

where ϵ_r is the dielectric constant, which is a dimensionless quantity. The measure of dielectric constant or relative permittivity gives the properties of a dielectric material. The dielectric constant of air is one.

b. Electric Dipole Moment: Consider two charges of equal magnitudes but of opposite polarities separated by a distance r , as shown in the below Figure.

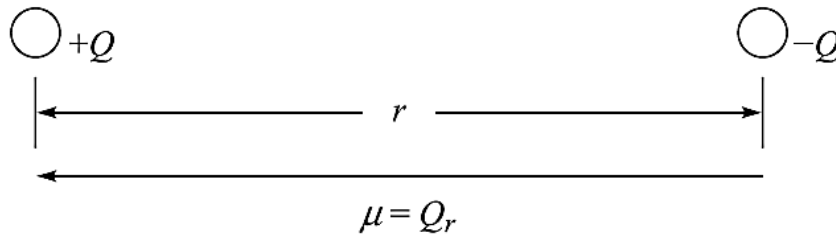


Fig. Electric dipole

The arrangement of two equal and opposite charges $+Q$ and $-Q$, separated by a distance r is known as electric dipole. The product of magnitude of the charge and the distance of separation is known as electric dipole moment (m).

$$\mu = \text{charge} \times \text{distance} = Q \cdot r$$

where m is the dipole moment and its unit is coulomb metre (Cm). Since the dipole moment is a vector, it points from the negative to the positive charges as shown in above Figure.

The total dipole moment of a system constituting of point charges $Q_1, Q_2, Q_3, \dots, Q_n$ and the distances of separation r_1, r_2, \dots, r_n is

$$\mu_{total} = \sum_{i=1}^n Q_i r_i$$

c. Polarisation: When an electric field is applied to a solid material consisting of positive and negative charges, the positive charges are displaced opposite to the direction of the field, while the negative charges are displaced in the direction of the field. The displacement of these two charges create a local dipole in the solid. This type of displacement of positive and negative charges by the application of electric field leads to polarisation.

$$P = \frac{\mu}{\text{volume}}$$

where, P is the polarisation in Cm^{-2} . The term, ‘polarisation’ is defined as the induced dipole moment per unit volume.

d. Polarisability: When a dielectric material is placed in an electric field, the displacement of electric charges gives rise to the creation of dipole in the material. The polarisation P of an elementary particle is directly proportional to the electric field strength E

$$P \propto E$$

$$P = \alpha E$$

where α is a proportionality constant known as polarisability. The unit of α is F m^2 .

If the solid material contains N number of particles per unit volume, then the polarisation can be written as,

$$P = N \alpha E$$

where $\alpha = \alpha_e + \alpha_i + \alpha_o$. Here α_e , α_i and α_o are the electronic, ionic and orientation polarisability, respectively. In the following sections, the above three polarisations are discussed in detail

DIFFERENT TYPES OF POLARISATIONS

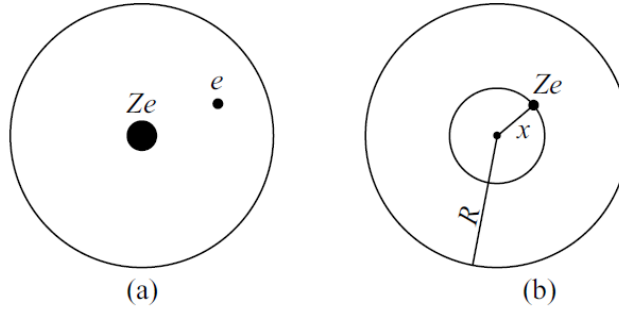
The application of an electric field to a dielectric material creates or realigns the dipoles resulting in polarisation. There are four different types of polarisations. They are listed below.

- (1) Electronic or induced polarisation (P_e)
- (2) Atomic or ionic polarisation (P_i)
- (3) Orientation polarisation (P_o), and
- (4) Interfacial or space charge polarization

1. Electronic or Induced Polarisation

A dielectric material consists of a large number of atoms. Let us consider a dielectric material consisting of only one atom, as shown in Fig. (a). The nucleus is at its centre while the electrons are revolving around the nucleus. When an electric field is applied to this atom, the nucleus

moves away from the field while the electrons move towards the field. Therefore, there is a displacement between the nucleus and the electrons. This displacement produces an induced dipole moment, and hence, polarisation. The polarisation produced due to the displacement of electrons is known as electronic polarisation.



Electronic polarization

Let Z and R be the atomic number and radius of an atom, respectively. Similarly, let e be the charge of an electron. If E is the electric field intensity applied to the atom, then the force acquired by the nucleus is ZeE . Due to the application of the electric field, there is a displacement x of the nucleus from its position. If a sphere is drawn by taking x as the radius, then the entire portion of the atom is splitted into two. From Gauss's theorem it can be proved that the electron cloud present outside the small sphere of radius x has no impact on the nucleus. Therefore, the nucleus exerts force only due to the electron cloud present in the inner portion of the sphere of radius x .

Let the nucleus be present at the centre of the sphere of radius x and the electron clouds are present throughout this sphere

$$\begin{aligned}\text{The charge inside the sphere} &= \frac{\frac{4}{3}\pi x^3}{\frac{4}{3}\pi R^3} Ze \\ &= \frac{x^3}{R^3} Ze\end{aligned}$$

The Coulomb force acting between the nucleus and the electron clouds inside the sphere of radius x is given by,

$$F = \frac{Ze \left[-\frac{x^3}{R^3} Ze \right]}{4\pi\epsilon_0 x^2}$$

At equilibrium, the nucleus is balanced and hence, the total force on the nucleus is zero. Therefore,

$$ZeE = \frac{Ze \left[-\frac{x^3}{R^3} Ze \right]}{4\pi\epsilon_0 x^2}$$

Simplifying the above equation, we get

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

The induced dipole moment is given by

$$\mu_{ind} = Ze x$$

Substituting the value of x from above Eq. in the above equation, we get

$$\mu_{ind} = 4\pi\epsilon_0 R^3 E$$

$$\mu_{ind} = \alpha_e E$$

where, α_e is the electronic polarisability and is equal to

$$\alpha_e = 4\pi\epsilon_0 R^3 \quad (1)$$

It is clear from above Eq. that the electronic polarisability is directly proportional to R^3 . From above Eq, the electronic polarisation can be written as

$$P_e = N \alpha_e E \quad (2)$$

Substituting the value of α_e from Eq. (1) in the above equation, we get

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

i.e.,

$$\epsilon_0(\epsilon_r - 1)E = 4\pi\epsilon_0 R^3 E$$

$$\epsilon_r - 1 = 4N\pi R^3$$

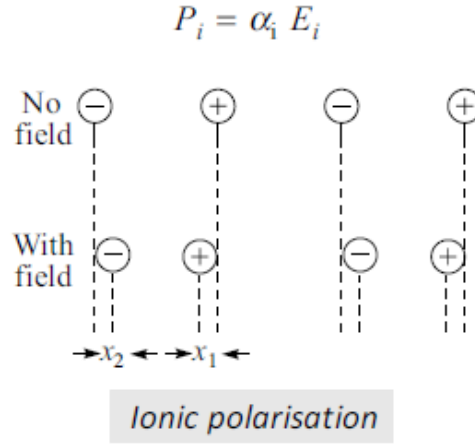
where ϵ_r is the dielectric constant of the material.

2. Atomic or Ionic Polarisation

When an electric field is applied to an ionic crystal, the polarisation that arises due to the displacement of the positive ions away from the field and the displacement of the negative ions towards the field is known as atomic or ionic polarisation. This type of polarisation is produced in ionic molecules such as NaCl, KBr, KCl and LiBr.

Consider the arrangement of ionic molecules as shown in Fig.. In the absence of electric field, there is no displacement of ions. When an electric field is applied, there is a displacement of the

positive and negative ions which produces an induced dipole moment μ_i . This induced dipole moment in turn produces an induced polarisation. The induced average ionic polarisation produced per ionic dipole is given by



The polarisation produced for a crystal having N number of dipoles per unit volume is given by,

$$P_i = N \alpha_i E_i \dots \dots \dots (1)$$

Let x_1 and x_2 be the displacements of the positive and negative ions, produced due to the application of an electric field. The dipole moment induced is given by,

$$\mu_i = e(x_1 + x_2) \dots \dots \dots (2)$$

Let F be the force experienced by the ions due to the application of the electric field. The restoring force acting on the ions is directly proportional to their displacements

$$\begin{aligned} F &\propto x_1 \\ F &\propto x_2 \\ &= \beta_1 x_1 = \beta_2 x_2 \dots \dots \dots (3) \end{aligned}$$

where, β_1 and β_2 are the proportionality constants and they are directly proportional to the mass and angular frequency of the respective ions.

i.e.,

$$\begin{aligned} \beta_1 &\propto m \text{ and } \beta_2 \propto M \\ &\propto \omega_0^2 \end{aligned}$$

From Eq. (3), the force experienced by the positive and negative ions is given by,

$$F = eE = m\omega_0^2 x_1 = M\omega_0^2 x_2$$

Therefore,

$$x_1 = \frac{eE}{m\omega_0^2} \quad \text{and} \quad x_2 = \frac{eE}{M\omega_0^2}$$

Substituting the values of x_1 and x_2 , the induced dipole moment can be written as,

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

The ionic polarisability

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

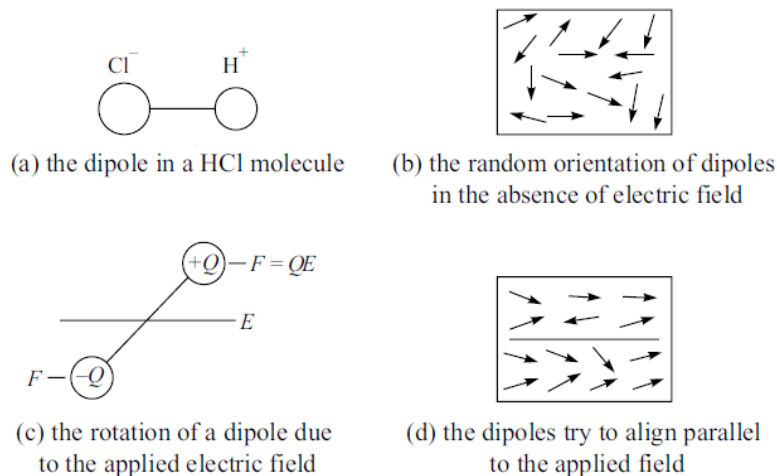
Using Clausius–Mosotti equation, the dielectric constant for an ionic crystal can be written

$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{N\alpha_i}{3\epsilon_0}$$

In addition to ionic polarisation, an ionic molecule also possesses electronic polarisation due to the displacement of electron clouds. The electronic polarisation of an ionic molecule will be in the order of $1/10^{\text{th}}$ of ionic polarisation. Hence, its magnitude is much smaller than the ionic polarisation.

3. Dipolar or Orientation Polarisation

The dipolar or orientation polarisation is produced only in case of polar molecules such as H_2O , HCl and nitrobenzene. When an electric field is applied to a polar molecule, the dipoles experience a torque and try to align parallel to the applied field, which results in a rotation of the dipoles. The mechanism of dipolar polarisation is shown in below Fig.



Dipolar polarisation

Consider a polar molecule is subjected to an electric field of strength E. Let θ be the angle of rotation of the dipoles.

Then the torque produced by the field on the dipole is

$$\tau = \mu_p E \sin \theta \dots \dots \dots (1)$$

where μ_p is the permanent dipole moment.

The maximum work is done when the dipole is rotated through an angle of $\theta = 180^\circ$. When the dipole is already parallel to the applied field, i.e., when $\theta = 0^\circ$, the work done is minimum.

Therefore, the maximum energy is given by

$$\begin{aligned} E_p &= \int_0^\pi \mu_p E \sin \theta d\theta \\ &= 2\mu_p E \end{aligned}$$

The average dipole energy E_{dip}

$$E_{dip} = \mu_p E$$

The ratio of the average dipole energy to average thermal energy is, given by

$$\frac{\text{Average dipole energy}}{\text{Average thermal energy}} = \frac{\mu_p E}{\frac{5}{2}KT}$$

If this ratio is greater than unity, then the orientation polarisation is said to be effective. The average orientation polarisation is

$$\begin{aligned} P_o &\propto \frac{\text{Permanant dipole moment} \times \text{Average dipole energy}}{\text{Average thermal enegry}} \\ P_o &\propto \mu_p \frac{\mu_p E}{\frac{5}{2}KT} \end{aligned}$$

If the calculation for average dipole energy is properly done using Boltzmann's statistics, then the average orientation polarisation is

$$P_o = \frac{1}{3} \frac{\mu_p^2 E}{kT}$$

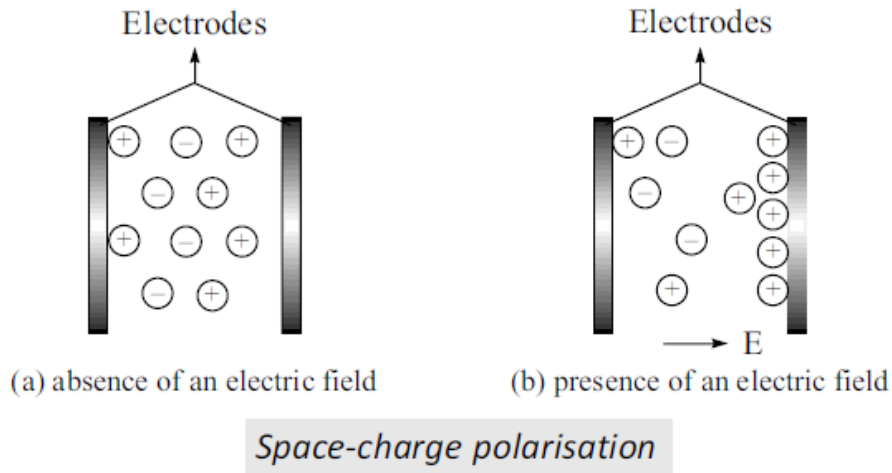
Therefore, the orientation polarisability can be written as,

$$\alpha_o = \frac{\mu_p^2}{3kT}$$

It is clear from above Eq. that the orientation polarisation is temperature dependent

4. Interfacial or Space Charge Polarisation

Consider a dielectric medium is placed between any two electrodes, as shown in below Fig. When no field is applied to the electrode, the positive and negative charges are not separated and there are fixed number of charges. On the other hand, when an electric field is applied, the charges are separated. The positive charges are accumulated near the negative electrode. Therefore, a dipole moment is induced due to displacement of the ions. Then, the induced dipole moment per unit volume gives the induced polarisation. This polarisation is known as interfacial polarisation.



Total Polarisation:

In the calculation of total polarisation, the space charge polarisation is not taken into account, since it occurs at interfaces and it is very small and hence negligible. In addition to this, the fields are not well defined at interfaces.

Therefore, the total polarisation is the sum of the electronic, ionic and orientation polarisation.

Therefore, total polarisation is given by

$$P = P_e + P_i + P_o$$

Substituting the values of P_e , P_i and P_o , in above eq. we get

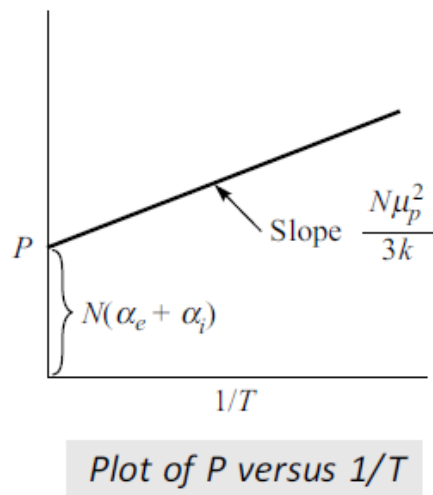
$$P = N \alpha_e E_i + N \alpha_i E_i + N \alpha_o E_i$$

Substituting the values of α_e , α_i and α_o in above equation we get

$$P = N E_i \left[4\pi \epsilon_o R^3 + \frac{e^2}{\omega_0^2} \left(\frac{1}{M} + \frac{1}{m} \right) + \frac{\mu_p^2}{3kT} \right]$$

When a plot is drawn between P and $1/T$, a straight line is obtained, as shown in below Fig. The straight line makes an intercept at the y-axis, when $1/T = 0$. The value of the temperature

independent portion in the plot is $NE_i(\alpha_e + \alpha_i)$. Therefore, by drawing a plot between P and $1/T$, one can determine the orientation polarisation and the sum of electronic and ionic polarisation.



TYPES OF DIELECTRIC MATERIALS

The dielectric materials are classified into three types as given below.

- (1) Solid dielectric
- (2) Liquid dielectric, and
- (3) Gaseous dielectric

1. Solid Dielectric

There are three types of solid dielectric materials. They are

(i) Elemental Solid Dielectrics Solid materials consisting of single type of atoms, such as diamond, sulphur, germanium, etc., are said to be elemental solid dielectric materials. These materials exhibit electronic polarisability only.

(ii) Ionic Nonpolar Solid Dielectrics In ionic crystals such as alkali halides, the total polarization is ionic and electronic in nature. These solids contain more than one type of atoms, but no permanent dipoles. These types of dielectric materials are said to be ionic nonpolar dielectric materials.

(iii) Polar Solid Dielectrics In solids, whose molecules possess permanent dipole moments, the total polarisation has all the three components, i.e., it is the sum of electronic, ionic and orientation polarisations. These types of materials are known as polar solid dielectric, e.g., solid $C_6H_5NO_2$

2. Liquid Dielectric Materials.

Liquid dielectric materials are also classified into three types as given below.

(i) Mineral Insulating Oils Transformer oil, capacitor oil and cable oil are said to be mineral insulating oils. They are directly obtained from crude petroleum by distillation. They are used as coolant in transformers and capacitors.

(2) Synthetic Insulating Oils Synthetic insulating oils are also used for the purpose of cooling in high-tension transformers. Compared to mineral insulating oils, synthetic oils are inferior. Also, they are very cheap, e.g., karels, sovol, etc.

(3) Miscellaneous Insulating Oils Silicone liquid and vegetable oil are said to be miscellaneous insulating oils. The silicone liquid is costly compared to synthetic insulating oils. It is used in high tension transformers.

Gaseous Dielectrics

Air, nitrogen, hydrogen, sulphur hexafluoride are some of the gaseous dielectric materials used.

(1) Air Air is one of the most important and naturally available gas used for electrical insulation. Its resistivity is infinity under normal conditions, when there is no ionisation. The relative permittivity of air is 1. It is used as a dielectric in long-distance electrical transmissions, and in air-capacitors. Compressed air is used as an arc-extinguishing medium which provides dielectric insulation in air-blast circuit breakers.

(2) Nitrogen Nitrogen is chemically inert and is used as a dielectric medium to prevent oxidation. It is used in gas-filled high-voltage cables as an inert medium to replace air in the space above the oil. It is also used in transformers and in low-loss capacitors for high-voltage testing, and so on.

(3) Sulphur Hexafluoride It is an electronegative gas and is used as a dielectric in X-ray equipment, waveguides, coaxial cables, transformers and as an arc-quenching medium in circuit breakers. Its dielectric strength is nearly 2.3 times higher than that of air or nitrogen. It sublimates at about 209 K and may be used up to a temperature of 423 K. It is nontoxic, non-inflammable and chemically inert.

(4) Hydrogen The dielectric strength of hydrogen is about 65% higher than that of air. It is used as a cooling medium in large turbo-generators and synchronous motors. The injurious effects of hydrogen gas are considered to be negligibly small, since during the discharge it does not

produce ozone or oxides of nitrogen. Further, the high voltage discharge of hydrogen is not so severe.

CLAUSIUS-MOSOTTI EQUATION

Elemental solid dielectrics like germanium, silicon, diamond, sulphur, etc., have no permanent dipoles or ions and will have only cubic structure, thereby exhibiting only electronic polarisation.

The total polarisation is written as,

$$P = N \alpha E_i$$

$$\text{Where, } \alpha = \alpha_e + \alpha_i + \alpha_0$$

Elemental solid dielectrics have only electronic polarisation and the remaining polarisation namely, ionic and orientation, are equal to zero, since there is no ionic character or permanent dipoles.

the total polarisation

$$P = N \alpha_e E_i$$

where $\alpha_i = \alpha_0 = 0$, and N is the number of atoms per unit volume

$$\text{Internal field } E_i = E + \frac{P}{3\epsilon_0}$$

Substituting the value of internal field from Eq. in above equation, we get

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

We know that,

$$D = \epsilon_0 E + P$$

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

From the definition of electric displacement vector,

$$D = \epsilon E$$

Therefore,

$$\frac{P}{E} = \epsilon - \epsilon_0 = \epsilon_r \epsilon_0 - \epsilon_0$$

Where

$$\epsilon_r = \epsilon_r \epsilon_0$$

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

Or,

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

Substituting P value in Eq. (1), we get

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

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

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

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

Simplifying the above equation, we get

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

where, N is the number of dipoles per unit volume. Equation (2) is known as Claussius–Mosotti equation. In this equation, by substituting the values of ϵ_r , ϵ_0 and N, one can determine the electronic polarisability α_e .

For a dielectric material consisting of N number of dipoles

$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{1}{3\epsilon_0} \sum_i N_i \alpha_{ei}$$

where N_i and α_{ei} are the appropriate quantities for the types of atoms or molecules.

DIELECTRIC LOSS

When an AC field is applied to a dielectric material, some amount of electrical energy is absorbed by the dielectric material and is wasted in the form of heat. This loss of energy is known as dielectric loss. The dielectric loss is a major engineering problem. In an ideal dielectric, the current leads the voltage by an angle of 90° is shown in below Fig. But in case of a commercial dielectric, the current does not exactly lead the voltage by 90° . It leads by some other angle ϕ that is less than 90° . The angle $\phi = 90 - \theta$ is known as the dielectric loss angle. For a dielectric having capacitance C and voltage V applied to it at a frequency f Hz, the dielectric power loss is given by

$$P = VI \cos \theta$$

Since $I = V/X_c$ where, X_c is the capacitive reactance and is equal to $1/j\omega C$.

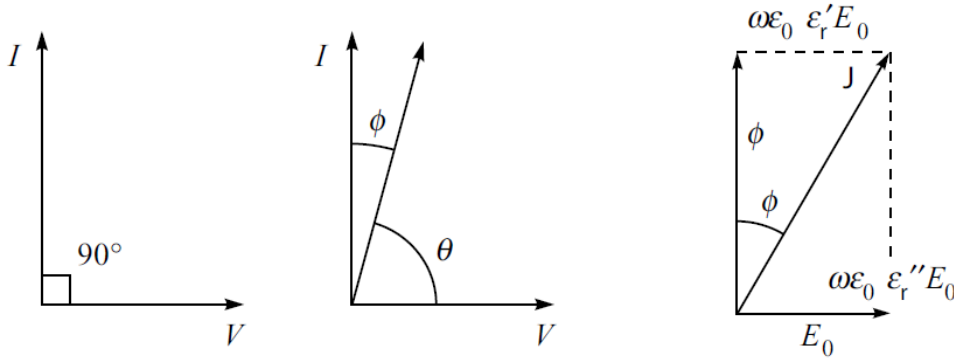
Therefore,

$$P = \frac{V^2}{X_c} \cos (90 - \phi) = V^2 j\omega C \sin \phi$$

Since θ is very small,

$$\sin \Phi = \tan \Phi \text{ and } P = j V^2 \omega C \tan \Phi,$$

where $\tan \Phi$ is said to be the power factor of the dielectric. The power loss depends only on the power factor of the dielectric as long as the applied voltage, frequency and capacitance are kept constant.

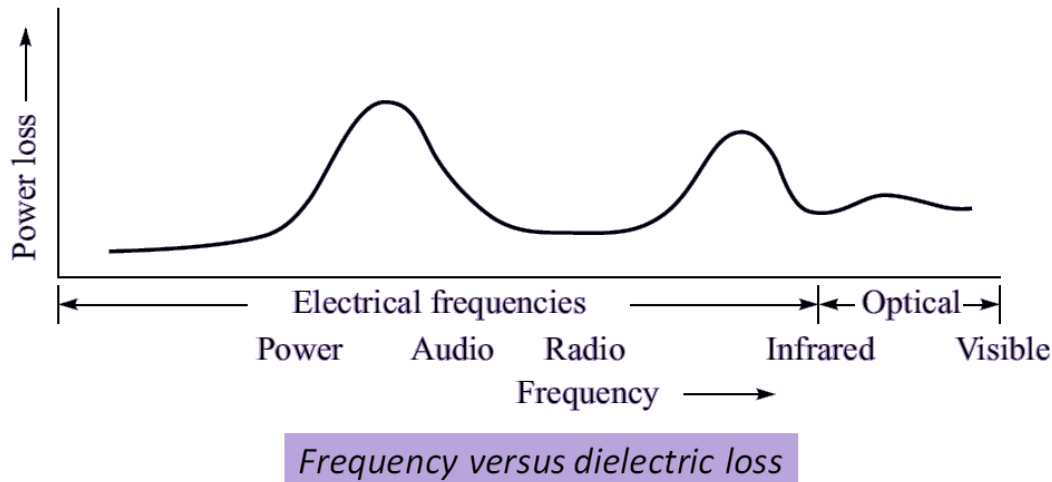


Relation between current and voltage in dielectrics

The dielectric loss is increased by the following factors:

- (1) High frequency of the applied voltage
- (2) High value of the applied voltage
- (3) High temperature, and
- (4) Humidity

The frequency dependence of the dielectric loss is shown in below Fig. The dielectric losses in the radio frequency region are usually due to dipole rotation. The dielectric losses at lower frequencies are mainly due to dc resistivity. The dielectric losses in the optical region are associated with electrons and they are known as optical absorption.



PIEZOELECTRIC MATERIALS

Dielectric materials may be divided into the two following categories:

- (i) **Linear dielectrics** are those materials in which the polarization \mathbf{P} and displacement \mathbf{D} are directly proportional to the intensity of the electric field \mathbf{E} ; and relative permittivity ϵ_r and susceptibility χ do not depend on the intensity of electric field. They are also known as **passive dielectrics**.
- (ii) **Nonlinear dielectrics** are those materials in which relative permittivity ϵ_r and susceptibility χ depend on the intensity of electric field. These materials are known as **active dielectrics**.

eg. Piezoelectrics, pyroelectrics, ferroelectrics and some of the optical media.

- Piezoelectric crystals provide a relation between electrical and mechanical forces and hence serve as **transducers** which produce or detect electrical or mechanical signals.
- Hence they are used to detect very small mechanical displacements and small amounts of electric charge.
- All commercial piezoelectric materials used today are **ferroelectrics**.

Piezoelectric Effect

- The French physicists Pierre Curie and Paul-Jean Curie discovered the piezoelectric effect in 1880.
- When one pair of opposite faces of certain asymmetric crystals such as quartz is compressed, opposite electric charges appear on the other pair of opposite faces of the crystal.

- If the crystals are subjected to tension, the polarities of the charges are reversed. The development of charges as a result of the mechanical deformation is known as the **direct piezoelectric effect**. Crystals that exhibit piezoelectric effect are called **piezoelectric crystals**. If an electric field is applied across one pair of faces of a piezoelectric crystal, it gets deformed along the direction of the other opposite pair of faces. If an alternating voltage is applied between the two opposite faces of the crystal, it vibrates with the frequency of the field. The mechanical deformation of piezoelectric materials caused by an external electric field is known as the **inverse piezoelectric effect**.

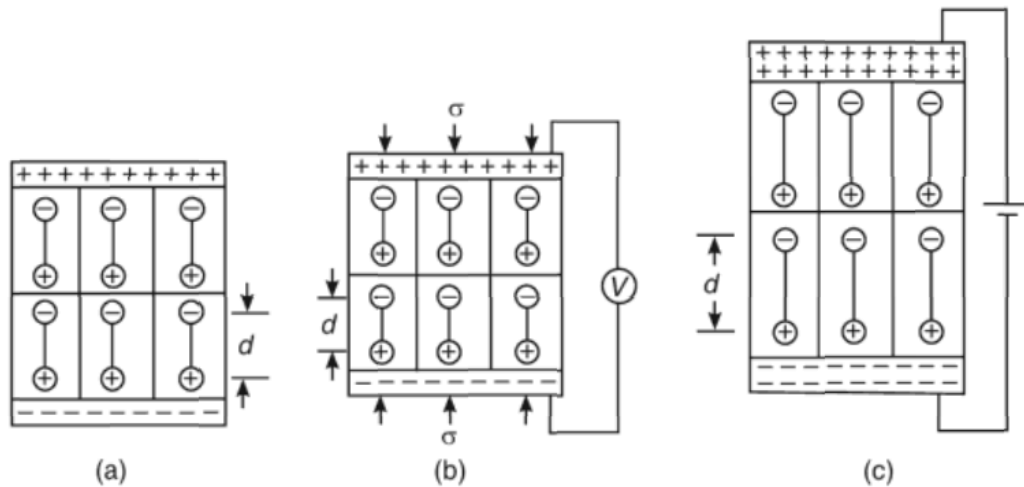


Fig. (a) Electric dipoles in a piezoelectric crystal. (b) Mechanical forces cause appearance of polarization charges (c) An external voltage applied across ends of the crystal causes dimensional changes.

- In ordinary solids, a stress causes a proportional strain 's' related by an elastic modulus. Piezoelectricity is the additional creation of the **electric charge** by an **applied stress**.
- The induced polarization P, in direct piezoelectric effect, is directly proportional to the applied mechanical stress, σ .

$$P = d\sigma$$

where d is the proportionality constant and is known as **piezoelectric coefficient** and is expressed in Coulombs/Newton. It may be defined as the charge developed per unit force. A change in sign of s, reverses the sign of polarization. The value of d should be high for practical applications.

- In the inverse piezoelectric effect, an electric field E produces a proportional strain,

$$s = dE$$

Thermodynamics proves that the piezoelectric coefficient d of direct and inverse piezoelectric effects are equal for the same dielectric.

electromechanical coupling factor, k is used to describe the piezoelectric effect in actual piezoelectric elements. Energy can be given to a piezoelectric element either mechanically by stressing it or electrically by charging it. All the energy given to it is not converted in producing the effect. Therefore, the piezoelectrics are characterized by strength of piezoelectric effect. This strength is measured by the electromechanical coupling factor, k .

In case of **direct piezoelectric effect**, the external force is expended not only on the deformation of the element but also on its polarization. The square of the piezoelectric coupling factor is defined as the ratio of the electrical energy generated by the piezoelectric element to the total energy expended on the deformation

$$K^2 = \frac{\text{Mechanical energy converted to electrical energy}}{\text{Total input mechanical energy}}$$

In case of **inverse piezoelectric effect**, the external voltage is expended not only on charging the element but also on its deformation. The square of the piezoelectric coupling factor is defined as the ratio of the electrical energy generated by the piezoelectric element to the total energy expended on the deformation.

$$K^2 = \frac{\text{Electrical energy converted to mechanical energy}}{\text{Total input electrical energy}}$$

Electrostriction

Electrostriction is a property of all electrical non-conductors, or dielectrics, that causes them to change their shape under the application of an electric field.

FERROELECTRIC MATERIAL

In certain dielectric materials, polarisation is not a linear function of applied electric field. Such materials exhibit hysteresis curve similar to that of ferromagnetic materials and are known as ferroelectric materials. The hysteresis curve exhibited by a ferroelectric material is shown in below Fig.. Hysteresis Properties When an increasing electric field is applied to a ferroelectric material, it results in an increase in polarisation and it reaches a maximum value for a particular field strength. On the other hand, if we decrease the electric field, the polarisation decreases. When the field strength is zero, i.e., $E = 0$, a small amount of polarisation exists in the material. This polarisation is known as remanent polarisation.

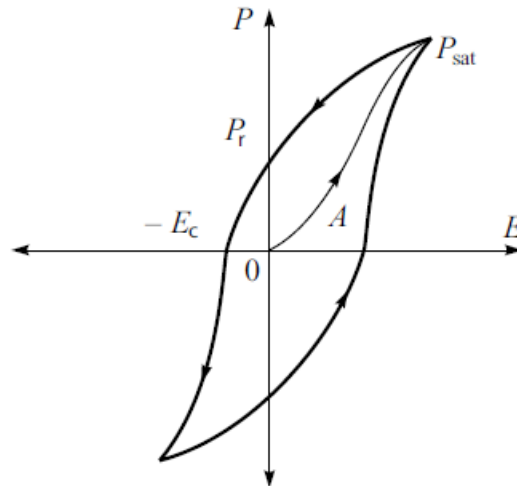


Fig. Hysteresis curve for ferroelectric material

Now the ferroelectric material is said to be spontaneously polarised. In order to reduce the value of polarisation to zero, an electric field strength ($-E_c$) should be applied. This field is known as coercive field. The hysteresis loop of a ferroelectric material is explained on the basis of the domain concept. Domain is experimentally observed by applying polarised light, which makes the domain visible. Figure 18.13 explains the domain structure of barium titanate crystal.

Domains which are opposite in direction to the applied field decrease in size and domains which are parallel to the field direction increase in size in the form of needles of approximately 10^{-6} m width. Substances like Rochelle salt (sodium-potassium salt of tartaric acid; $\text{NaKC}_4\text{H}_4\text{O}_{21} \cdot 4\text{H}_2\text{O}$), potassium dihydrogen phosphate (KH_2PO_4), barium titanate (BaTiO_3), etc., are typical examples. Ferroelectric crystals lack centre of symmetry.

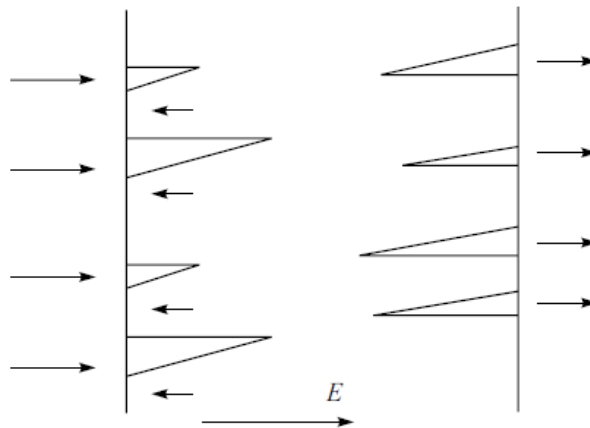


Fig. Domain structure of barium titanate

Classification of Ferroelectric Crystals Ferroelectric crystals are classified into three groups namely,

- (1) Rochelle salt
- (2) Potassium dihydrogen phosphate, and
- (3) Barium titanate

(1) Rochelle Salt It behaves as a ferroelectric material in the temperature range from 255 to 296 K, i.e., it possesses two transition temperatures (Curie temperature). The crystal structure is orthorhombic above upper curie temperature. Below this transition temperature, the crystal structure is monoclinic in nature. A plot of polarisation versus temperature is shown in below Fig.

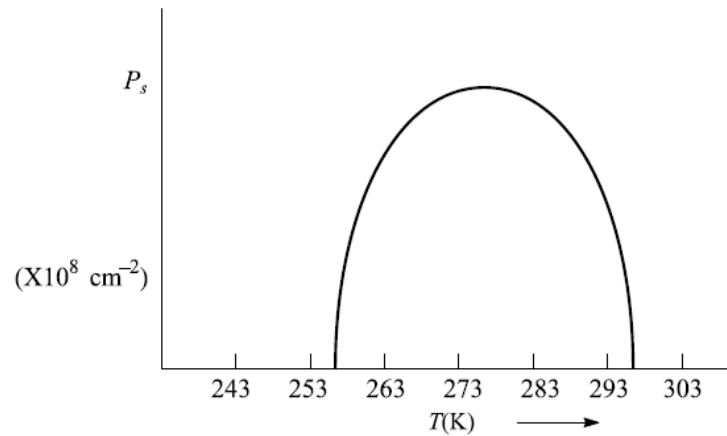


Fig. Temperature versus polarisation of Rochelle salt.

(2) Potassium Dihydrogen Phosphate It has only one Curie temperature and its value is 123 K. It possesses ferroelectric property below this temperature. Above Curie temperature, its crystal structure is tetragonal. Below Curie temperature, the crystal structure is orthorhombic. Other ferroelectric crystals belonging to this family include KD_2PO_4 , RbH_2PO_4 , CsH_2AsO_4 , CsD_2AsO_4 . The variation of polarization with respect to temperature is shown in below Fig.

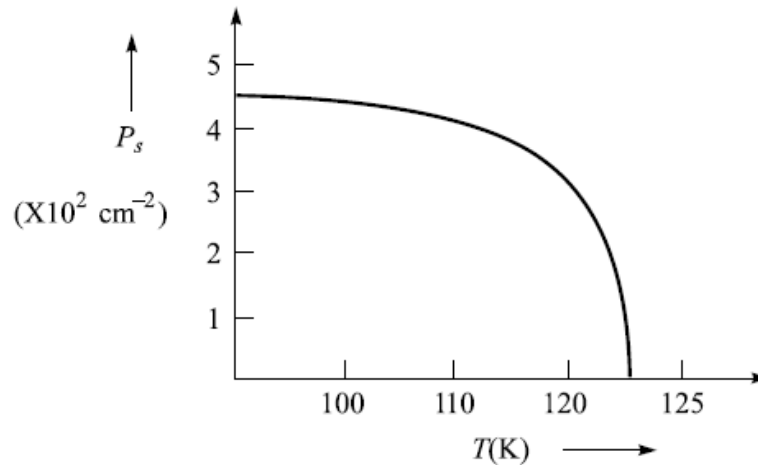


Fig. Polarisation versus temperature in potassium dihydrogen phosphate

(3) Barium Titanate This crystal exhibits three different ferroelectric phases. The transition temperatures of barium titanate are 278 K, 193 K and 393 K. The structure of barium titanate is cubic above 393 K. It has orthorhombic structure when the temperature lies between 278 K and 193 K. Below 193 K, it has rhombohedron structure. The structure of BaTiO₃ above 393 K and the variation of polarisation with temperature are given, respectively, in Figs a and b.

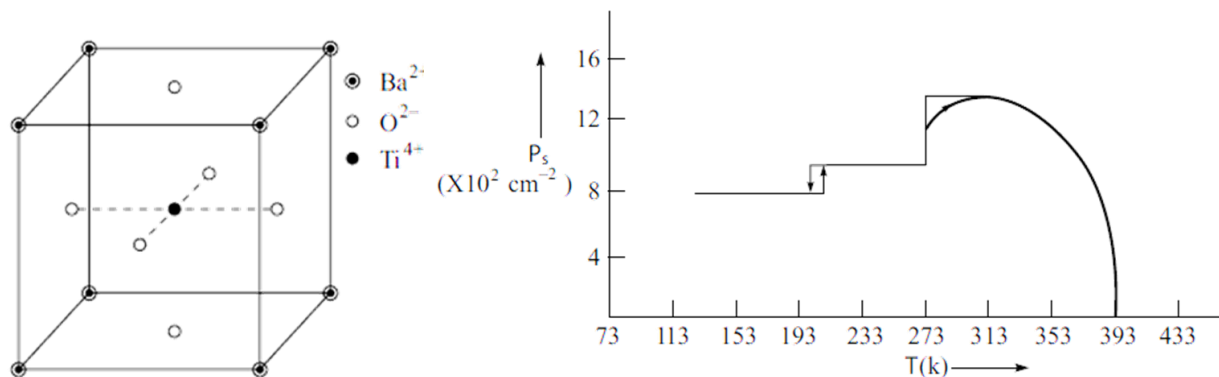


Fig. (a) Crystal structure of barium titanate (above 393 K) (b) Polarisation versus temperature in barium titanate

Applications of dielectric materials

1. Quartz crystal is used for the preparation of ultrasonic transducers, crystal oscillators, delay lines, filters, etc.
2. Barium titanate is used for the preparation of accelerometers.

3. Lead zirconate titanate ($\text{PbZr}_x\text{Ti}_{1-x}\text{O}_3$) is used for the preparation of earphones, microphones, spark generators (gas lighter, car ignition, etc.), displacement transducer, accelerometers, etc.
4. The insulating dielectric liquids are used in transformers, switchgears and generators.
5. Dielectric materials are used as insulating material in power cables, signal cables, electric motors, electric iron, etc.
6. Dielectric materials are used in radiation detectors, thermoionic valves, strain gauges, capacitors, resistors and many other electric devices
7. The electro-optic devices are prepared using dielectric material.