UNIT- III

DIELECTRIC PROPERTIES OF MATERIALS

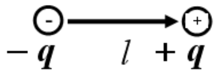
Materials which are electrically insulating (non-metallic) exhibit or made to exhibit an electric dipole structure are called dielectrics. All dielectric materials are insulators. The distinction between a dielectric material and an insulator lies in the application to which one is employed. The insulating materials are used to resist the flow of current through it when a difference of potential is applied across it ends. On the other hand, the dielectric materials are used to store electrical energy.

A dielectric material is an electrical insulator that can be polarized by an applied electric field. When a dielectric is placed in an electric field, electric charges do not flow through the material as they do in a conductor, but only slightly shift from their average equilibrium positions causing dielectric polarization. Because of dielectric polarization, positive charges are displaced toward the field and negative charges shift in the opposite direction. This creates an internal electric field that reduces the overall field within the dielectric itself

Ex: Glass, mica, paraffin, papers, Bakelite etc.

Electric dipole, dipole moment and polarization

A pair of equal and opposite charges whose distance of separation is small is known as electric dipole.



Product of the magnitude of one of the charges and the distance of separation between them is called as dipole moment.

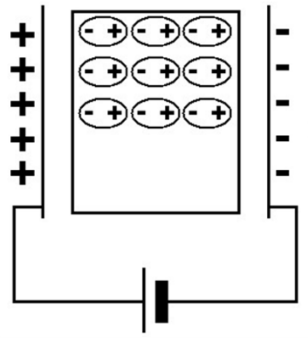
$$\mu = ql$$

Where μ - dipole moment (Cm^{-1})

q- magnitude of the charge

l- distance of separation of charges

Polarization (P):



It can be defined as vibration confined to single direction or alignment confined to one direction also it is the dipole moment per unit volume

Definition:

The displacement of charges in the atom or molecules of a dielectric under the action of an applied field leading to the development of dipole moment is called polarization or electric polarization.

The charges appearing separated are called polarized charges.

$\mathbf{P = \varepsilon_o(\varepsilon_r - 1)E}$ unit of P is Coulomb/meter^2

Polarizability (α):

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 polarization P of an elementary particle is directly proporational to the electric field strengt

$$P \propto E$$

$$P = \alpha E$$

Where α is the proportionality constant called Polarizability of the atom or molecule. The unit of α is Fm^2.

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

$$P = N\alpha E$$

Where $\alpha = \alpha_e + \alpha_i + \alpha_o$. Here α_e, α_i and α_o are respectively the electronic, ionic and orientation polarizability.

Polarizability is the property of the individual atom or molecule.

Dielectric constant (ε_r):

The dielectric constant of a material is defined as the ratio of the permittivity of the medium (ε) to the permittivity of free space (ε_o).

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o}$$

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.

Dielectric losses:

It is the loss of energy in the form of heat by a dielectric medium due to the internal friction developed as a consequence of switching action of molecular dipoles under certain A C conditions.

Dipolar relaxation:

Relaxation time is the time required for the dipole to reach the equilibrium orientation from the disturbed position in alternating field conditions.

The reciprocal of the relaxation time is the relaxation frequency.

Dielectric strength:

"Dielectric strength is the maximum electric field that the dielectric material can withstand without suffering electrical breakdown".

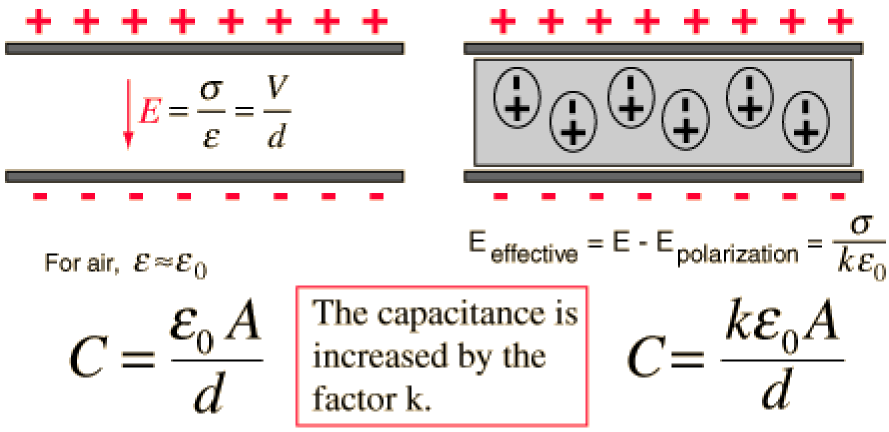
Spontaneous polarization:

Polarization in the absence of an electric field is called spontaneous polarization. The groups of dielectric materials which exhibit spontaneous polarization are called **ferroelectrics.**

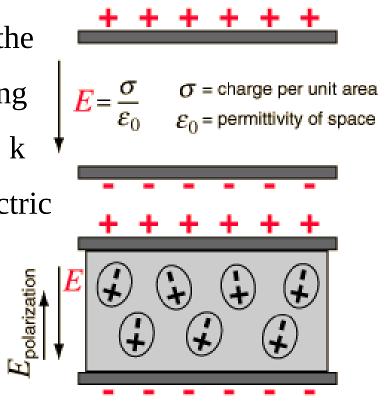
The term 'Ferro electricity' is applied to certain crystalline materials that exhibit a permanent electric polarization which is analogous in many ways to the permanent magnetization exhibited by ferromagnetic materials.

Parallel Plate with Dielectric:

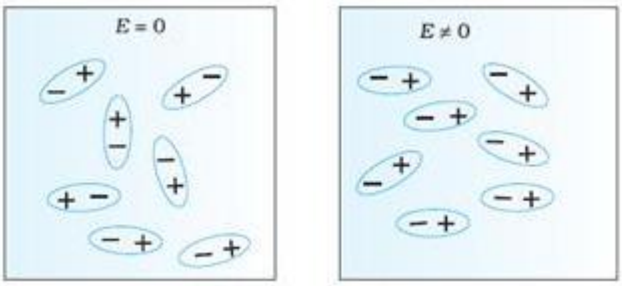
The capacitance of a set of charged parallel plates is increased by the insertion of a dielectric material. The capacitance is inversely proportional to the electric field between the plates, and the presence of the dielectric reduces the effective electric field. The dielectric is characterized by a dielectric constant k, and the capacitance is multiplied by that factor.



When a dielectric is placed between charged plates, the polarization of the medium produces an electric field opposing the field of the charges on the plate. The dielectric constant k is defined to reflect the amount of reduction of effective electric field as shown below. The permittivity is a characteristic of space, and the relative permittivity or "dielectric constant" is a way to characterize the reduction in effective field because of the polarization of the dielectric. The capacitance of the parallel plate arrangement is increased by factor k.



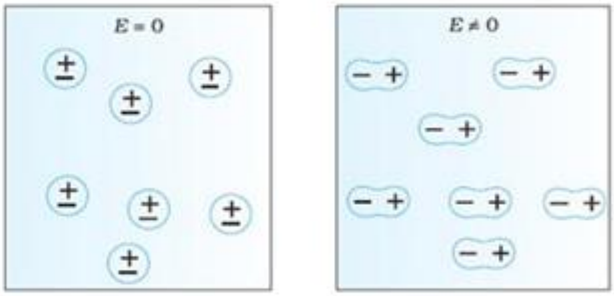
Polar Dielectrics: Polar dielectrics are those in which the possibility of center coinciding of the positive as well as negative charge is almost zero i.e. they



Polar molecules

don’t coincide with each other. The reason behind this is their shape. They all are of asymmetric shape. Some of the examples of the polar dielectrics is NH_3, HCL, water etc.

Non Polar dielectrics: In case of non polar dielectrics the centres of both positive as well as negative charges coincide. Dipole moment of each molecule in non polar system is zero. All those molecules which belong to this category are symmetric in nature. Examples of non polar dielectrics are: methane , benzene etc.



Non-polar molecules

Electrical polarization mechanisms:

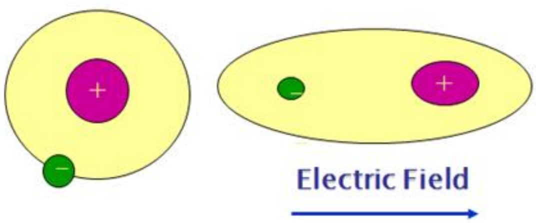
There are four different mechanisms through which electrical polarization can occur in dielectric materials when they are subjected to an external electric field. They are

1. Electronic or induced polarization
2. Ionic or atomic polarization
3. Orientation polarization and
4. Space charge or Interfacial polarization.
5.

1. Electronic polarization (P_e)

The electronic polarization occurs due to the displacement of the positive and negative charges in a dielectric material owing to the application of an external electric field. As electrons are very light they have a rapid response to the field changes; they may even follow the field at optical frequencies. It occurs in monoatomic gases and is independent of temperature.

∴ Development of dipole moment occurs throughout the material, so the whole material will be polarized.

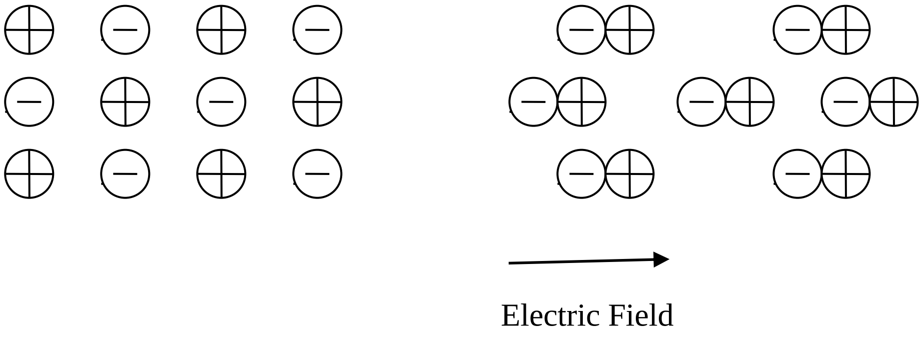


$$\alpha_e = \frac{\varepsilon_0(\varepsilon_r - 1)}{N}$$

N is the number of atoms/unit volume

2. Ionic polarization (P_i)

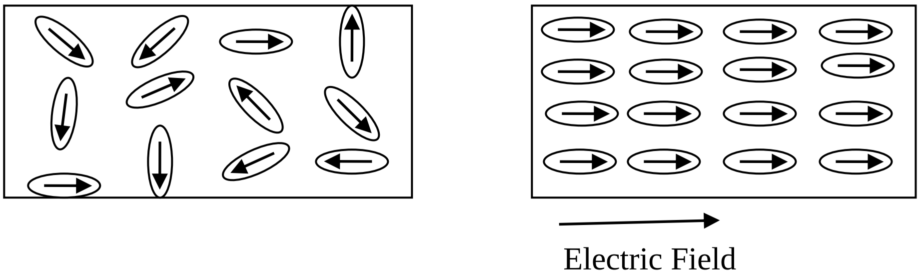
Ionic polarization occurs only in those dielectrics which contains ionic bonds. Example: NaCl. In ionic lattice, the positive ions are displaced in the direction of an applied field while the negative ion are displaced in the opposite direction, giving rise to the resultant dipole moment to the whole body and is independent of temperature.



3. Orientation polarization (P_o)

This is found only in substances that possess permanent dipole moments. Polarization results from a rotation of the permanent dipoles into the direction of the applied field.

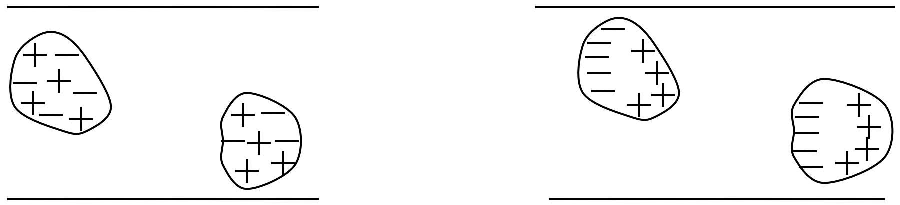
It is strongly temperature dependent and decreases with increase of temperature.



4. Space charge polarization (P_s)

Space charge polarization occurs in multiphase or heterogeneous dielectric materials in which there is a change of resistivity between different phases. Space charge polarization is also called as interfacial polarization or Migrational polarization. The Migrational polarization takes longer time and is therefore occurs at low frequency

The space charge polarization is not an important factor in most common dielectrics.



The total polarization ‘α’ of a material is thus given by the sum of electronic, ionic and orientation polarization.

$$\text{i.e., } \alpha = \alpha_e + \alpha_i + \alpha_o$$

Internal fields in Liquids and solids:

The internal field or the local field is the electric field that acts at the site of any given atom of a solid or a liquid dielectric subjected to an external electric field and it is the resultant of the applied field and field due to all the surrounding dipoles’.

Consider a dielectric material, either liquid or solid, kept in an external uniform electric field of strength E. In the material let us consider an array of equidistant atomic dipoles arranged parallel to the direction of the field as shown in fig. below.

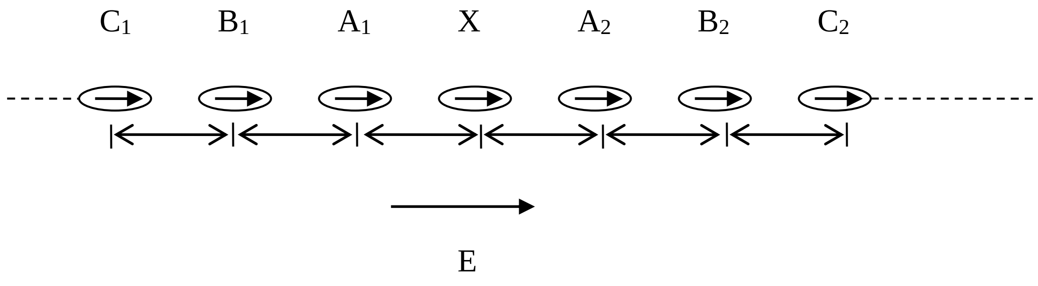


Fig. Linear array of atoms in an electric field.

Let d → interatomic distance

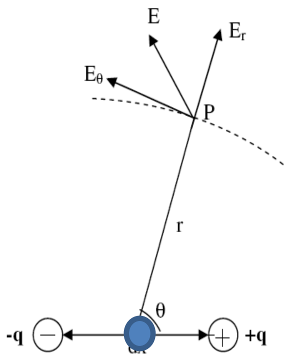
μ → dipole moment of each atomic field

the total field at 'X' due to all the other dipoles and applied field can be found as follows.

We know that the components of the electric field at a point 'P' due to an electric dipole, are given in polar form as

$$Er = \frac{\mu \cos\theta}{2\pi\varepsilon_o r^3} \text{--------------(1)}$$

And $$E_\theta = \frac{\mu \sin\theta}{4\pi\varepsilon_o r^3} \text{------------(2)}$$



Using the above, let us calculate the electric field at 'X' due to the dipole A_1.

Since the distance of 'X' from A_1 is 'd' and since the directions of dipole moments of both are collinear.

r = d and $\theta = 0$

$$\therefore \quad E_r = \frac{\mu}{2\pi\varepsilon_o d^3} \quad \text{and} \quad E_\theta = 0$$

$\therefore$ field at 'X' due to A_1 = $E_r + E_\theta = \dfrac{\mu}{2\pi\varepsilon_o d^3}$

Now consider the dipole A_2

Since it is situated symmetrically on the other side of 'X', its field at x will also be

$$= \frac{\mu}{2\pi\varepsilon_o d^3}$$

$\therefore$ The field E_1 at 'X' due to both dipole A_1 and A_2 is

$$E_1 = 2\left[\frac{\mu}{2\pi\varepsilon_o d^3}\right] = \frac{\mu}{\pi\varepsilon_o d^3}$$

If we consider the two dipoles B_1 and B_2, each of which is located at a distance of 2d, then the field E_2 at x due to both of them is

$$E_2 = \frac{\mu}{\pi\varepsilon_o (2d)^3}$$

Similarly the field at'X'due to the dipoles C_1 and C_2 is

$$E3 = \frac{\mu}{\pi\varepsilon_o (3d)^3}$$

∴ The total field E induced at 'X' due to all the dipoles in the linear array is

$$E^1 = E_1+E_2+E_3+\ldots\ldots\ldots\ldots$$

$$= \frac{\mu}{\pi\varepsilon_o d^3} + \frac{\mu}{\pi\varepsilon_o (2d)^3} + \frac{\mu}{\pi\varepsilon_o (3d)^3} + \ldots\ldots\ldots\ldots\ldots\ldots$$

$$= \frac{\mu}{\pi\varepsilon_o d^3}\left[1+\frac{1}{2^3}+\frac{1}{3^3}+\ldots\ldots\ldots\ldots\ldots\ldots\right]$$

$$= \frac{\mu}{\pi\varepsilon_o d^3}\,\Sigma_{n=1}^{\infty}\frac{1}{n^3} \qquad \text{where } n = 1, 2, 3\ldots\ldots\ldots\ldots\ldots\ldots$$

But w.k.t $\Sigma \frac{1}{n^3} = 1.2$

$$\therefore\; E^1 = \frac{(1.2)\mu}{\pi\varepsilon_o d^3} \text{------------------(3)}$$

∴ The total field at 'X' which is the internal field 'E_i' is the sum of the applied field E and the field due to all the dipoles i.e., E'

$$\therefore E_i = E + E^1 = E + \frac{(1.2)\mu}{\pi\varepsilon_o d^3} \text{--------------(4)}$$

If α is the polarisation for the material, then

$$\mu = \alpha E \text{--------------(5)}$$

$$\therefore E_i = E + \frac{1.2\ \alpha\ E}{\pi\varepsilon_o d^3} \text{-------------(6)}$$

since α, E, ε_o *and d* are all +ve quantities.

$$E_i > E$$

Equation (6) is only for one-dimensional array of atoms. But in 3-dimensional cases, the general equation for internal field is expressed as

$$E_i = E + \left(\frac{\gamma}{\varepsilon_o}\right)P \qquad \text{where } P=(1/d^3)\alpha E = N\alpha E \text{ and } \gamma = \frac{1.2}{\pi}$$

Where P is the dipole moment / unit volume of the material and γ is the proportrionality constant called internal field constant.

In 3-d case, if it is cubic lattice, then it can be shown that $\gamma = \frac{1}{3}$ in which event, the internal field is named as Lorentz field given by

$$E_{Lorentz} = E + \frac{P}{3\varepsilon_o}$$

Relation between polarization P, susceptibility χ and the static dielectric constant ε_r:

Consider a parallel plate capacitor with plates between which an electric field E_o exist, if 'σ'is the charge per unit area on the plates, then from Gauss law we have

$$E_o = \frac{\sigma}{\varepsilon_o} \text{--------------(1)}$$

After the introduction of slab in between the plates the field developed inside is E_i. The field due to polarization will be in a direction opposite to that of E_o.

∴The resultant field 'E' in the material can be written as

$$E = E_o - E_i \text{-----------------(2)}$$

If σ_p is the charge/unit area on the slab surfaces then by following equation (1) we write

$$E_i = \frac{\sigma_P}{\varepsilon_o} \text{---------------(3)}$$

From equation (1) (2) and (3)

$$E_i = \frac{\sigma}{\varepsilon_o} - \frac{\sigma_P}{\varepsilon_o}$$

Or $$\varepsilon_o E = \sigma - \sigma_P \text{----------------(4)}$$

Since magnitude of polarization P =charge/unit area

$$P = \sigma_p$$

Also by Gauss law, we know that

$$D = \sigma$$

Where D → electric flux density

Equation (4) can be written as $\varepsilon_o E = D - P$

Or $$D = \varepsilon_o E + P \text{----------------(5)}$$

But we know that

$$D = \varepsilon_o \varepsilon_r E$$

$\therefore$ equation (5) $\rightarrow \varepsilon_o \varepsilon_r E = \varepsilon_o E + P$

or $\quad P = \varepsilon_o (\varepsilon_r - 1) E$

or $\quad P = \varepsilon_o x E$

where $\quad \chi = (\varepsilon_r - 1)$ is the dielectric susceptibility of the material.

Clausius – Mossotti Relation:

Consider an elemental solid dielectric material of dielectric constant ε_r. If 'N' is the number of atoms/unit volume of the material, 'μ' is the atomic dipole moment, then we have,

Dipole moment / unit volume = N μ --- (1)

Here the field experienced by the atoms is the internal field E_i. Hence, if α_e is the electronic polarizability of the atoms, we can write the equation for μ as,

$$\mu = \alpha_e E_i \qquad \text{--- (2)}$$

Equation (1) becomes,

Dipole moment / unit volume = N $\alpha_e E_i$ --- (3)

In equation (3) left side is same as Polarization P.

$$P = N \alpha_e E_i \qquad \text{--- (4)}$$

Or $$E_i = \frac{P}{N\alpha_e} \qquad \text{--- (5)}$$

But we have the relation for P as,

$P = \varepsilon_o (\varepsilon_r - 1) E$ Where E is the applied field

Or $$E = \frac{P}{\varepsilon_0 (\varepsilon_r - 1)} \qquad \text{--- (6)}$$

Also we have the equation for the internal field as,

$$E_i = E + \left(\frac{\gamma}{\varepsilon_o}\right) P \qquad \text{--- (7)}$$

Where, γ is the internal field constant.

Substituting for E_i and E from equations (5) and (6) in equation (7), we have

$$\frac{P}{N\alpha_e} = \frac{P}{\varepsilon_0(\varepsilon_r - 1)} + \left(\frac{\gamma}{\varepsilon_o}\right)\text{P}$$

Or $$\frac{1}{N\alpha_e} = \frac{1}{\varepsilon_0}\left[\frac{1}{(\varepsilon_r - 1)} + \gamma\right]$$

Considering the internal field in the material to be Lorentz field, we have $\gamma = 1/3$. Substituting the same in the above equation, we get,

$$\frac{1}{N\alpha_e} = \frac{1}{\varepsilon_0}\left[\frac{1}{(\varepsilon_r - 1)} + \frac{1}{3}\right] = \frac{1}{\varepsilon_0}\left[\frac{3 + \varepsilon_r - 1}{3(\varepsilon_r - 1)}\right] = \frac{1}{\varepsilon_0}\left[\frac{\varepsilon_r + 2}{3(\varepsilon_r - 1)}\right]$$

By rearranging the above we have,

$$\frac{(\varepsilon_r - 1)}{(\varepsilon_r + 2)} = \frac{N\alpha_e}{3\varepsilon_0} \qquad \text{--- (8)}$$

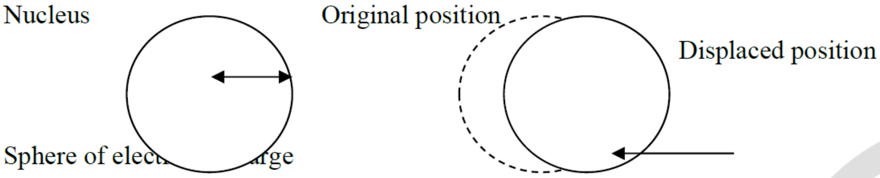
Equation (8) is called Clausius – Mossotti equation, and it holds good for crystals of high degree of symmetry. The equation provides a relation between ε_r the dielectric constant which is a macroscopically measurable quantity, and α_e the electronic polarizability which is an atomic property i.e., microscopic.

Derivation of electronic polarizability (α_e)

The polarization 'P' of a non-polar gas is given by P = N α_e E

Where α_e is called the electronic polarizability

Consider a monochromatic dielectric material as shown. Let the charge on the nucleus is 'Ze' and let this be surrounded by an electronic cloud of '– Ze' in a shere of radius 'R' as shown.



The charge density 'ρ' is given by

$$\rho = \frac{charge}{volume} = \frac{-Ze}{\frac{4}{3}\pi R^3}$$

$$\rho = \frac{-3Ze}{4\pi R^3} \qquad \text{----(1)}$$

Let an external electric field 'E be applied to the atom.

The nucleus and the electron experience Lorentz force = ZeE in opposite directions. Thus the nucleus and electron cloud are pulled apert. But because of Coulomb force the displacement will be very small. Let it be 'x'.

Lorentz force = - ZeE

Coulomb force = $\frac{Ze \times charge\ enclosed\ in\ the\ sphere\ of\ radius\ x}{4\pi\varepsilon_0 R^3}$

$$= \frac{Ze \times \left(\frac{4}{3}\pi x^3 \rho\right)}{4\pi\varepsilon_0 x^2}$$

Therefore, Coulomb force $= \frac{Ze \times \left(\frac{4}{3}\pi x^3 \left[\frac{-3Ze}{4\pi R^3}\right]\right)}{4\pi\varepsilon_0 x^2}$

$$= \frac{Ze \times \left(\frac{-Zex^3}{R^3}\right)}{4\pi\varepsilon_0 x^2}$$

Therefore, Coulomb force $= \frac{-Z^2 e^2 x}{4\pi\varepsilon_0 R^3}$

At equilibrium Lorentz force = Coulomb force

$$- ZeE = \frac{-Z^2 e^2 x}{4\pi\varepsilon_0 R^3}$$

Therefore $x = \frac{4\pi\varepsilon_0 R^3}{Ze} E$

Because of the displacement, dipole moments are produced.
Therefore the dipole moment $\mu = Z\,e\,x$

Therefore $\mu = Z\,e\,\dfrac{4\pi\varepsilon_0 R^3}{Ze}E = 4\pi\varepsilon_0 R^3 E$ ----(2)

By definition $\mu = \alpha_e E$ ----(3)

Comparing equations (1), (2) and (3)

$$\alpha_e = 4\pi\varepsilon_0 R^3$$

This gives the expression for electronic polarizability.

By definition $P = N\mu = N\alpha_e E$

But, $P = \varepsilon_o(\varepsilon_r - 1)E$

$N\alpha_e E = \varepsilon_o(\varepsilon_r - 1)E$

$\alpha_e = \dfrac{\varepsilon_o(\varepsilon_r - 1)}{N}$

The electronic polarizability can also be given by the above expression. Here N is the number of atoms / unit volume. The Unit of α_e is $F\text{-}m^2$.

Applications of dielectric materials

Dielectric materials are used in capacitors to increase charge storage capacity. Quartz, Lead Zirconate titanate, Rochelle salt, Barium titanate and poly vinylidene fluoride are piezoelectric materials. Quartz is piezoelectric but not ferroelectric. It is in the form of SiO2. Piezoelectric crystals used in Electronics industry in frequency control of oscillators. A properly cut piezoelectric crystal is placed in between the plates of a capacitor of a circuit whose frequency is same as the natural frequency of mechanical vibration of the crystal. The circuit acts as a tuned circuit of very high Q-value and possesses excellent frequency stability. They are also used as electro-acoustic transducers (to convert electrical energy into mechanical and vice versa). Transducers are used in ultrasonic’s for Sound Navigation and Ranging (SONAR), in ultrasound imaging of human body, non-destructive testing of materials, measurement of velocity of ultrasound in solids and liquids.

Lead Zirconate titanate (Pb Ti1-x Zrx O3) or (PZT) are used in accelerometers, earphones etc., PZT piezoelectric crystals are used in gas lighters, car ignition.

Rochelle salt (Na KC4 H4O6 4H2O) is both piezoelectric and ferroelectric, it is hygroscopic and could be used in the range of temperature of 180 to 240c. It is highly sensitive.
Barium titanate (Ba Ti O3) is less sensitive than Rochelle salt. It has an advantage of serving over a wide range of temperature. It can withstand atmospheric corrosion. It is used in accelerometers. Polyvinylidene fluoride (PVDF) is inexpensive.

Solid Dielectrics

- Jacketing Materials
- Moulding Materials
- Filling Materials

•Moulding Materials : These are used for mechanically rigid forms of insulation, for example, insulators, bushings and so on e.g. are ceramics, glass (toughened glass), fiberglass reinforced plastics and epoxy - resins .
•Jacketing Materials : Jacketing on a conductor for insulation. Polymers have been found suitable for providing extruded insulating jackets to the conductors. For example, polyethylene (PE), polyvinylchloride (PVC), natural and synthetic (ethylene propylene) rubber are extruded on the conductor in power cables. Polypropylene and paper are used in capacitors and transformers. Mica and fiberglass based polypropylene tapes are used in electrical machines.
•Beside oils, wax - based draining and non - draining impregnating compounds of different types are used to impregnate paper used in power cables, transformers, capacitors, and instrument transformers. Insulating Mechanical Support : In the form of plates, pipes and ledges, insulating supports are required in transformers, circuit breakers and isolators. The products, such as pressboards, hard paper (thin paper laminates), wood (yellow teak) are used in transformers and Bakelite..
•Unlike gaseous and liquid dielectrics, any damage caused to solid dielectrics due to excessive electrical, thermal or mechanical stresses is often irreversible .
•Their thermal and mechanical properties play a very sensitive role since these considerably affect the electrical properties .

•Solid Dielectrics are more exposed to atmosphere, hazards of weather (rain, storm, hail, ice deposits etc.), ultra violet radiation from the sun and pollution (dust, salts etc.)

Liquid Dielectrics

•Insulating oils are used in power and instrument transformers, power cables, circuit breakers, power capacitors, and so on. Liquid dielectrics perform a number of functions simultaneously, namely- insulation between the parts carrying voltage and the grounded container, as in transformers
•impregnation of insulation provided in thin layers of paper or other materials, as in transformers, cables and capacitors, where oils or impregnating compounds are used
•cooling action by convection in transformers and oil fi lled cables through circulation
•filling up of the voids to form an electrically stronger integral part of a composite dielectric
•arc extinction in circuit breakers
•possess a very high electric strength and their viscosity and permittivity vary in a wide range.

Gaseous Dielectrics

By applying a sensible electrical field, the dielectric gases can be polarised. Vacuum, Solids, Liquids and Gases can be a dielectric material. A dielectric gas is also called as an insulating gas. It is a dielectric material in gaseous state which can prevent electrical discharge. Dry air, Sulphur hexafluoride (SF6) etc are the examples of gaseous dielectric materials. Gaseous dielectrics are not practically free of electrically charged particles. When electric field is applied to a gas, the free electrons are formed. A few gases such as SF6 are strongly attached (the electrons are powerfully attached to the molecule), some are weakly attached for e.g., oxygen and some are not at all attached for e.g. N2. Examples of dielectric gases are Ammonia, Air, Carbon dioxide, Sulphur hexafluoride (SF6), Carbon Monoxide, Nitrogen, Hydrogen etc. The moisture content in dielectric gases may alter the properties to be a good dielectric.

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