B.Sc. Physics (SECOND YEAR)

Paper II Electromagnetics

UNIT-III

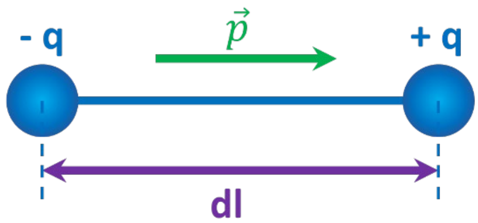
Dielectric Materials

- Dielectric materials are a type of electrical insulators that can be polarized through an external applied electric filed.
- These materials, generally, do not contain any free charge carriers for conduction.
- In such dielectric materials, positive and negative charge entities are bounded together.
- The behaviour of dielectric materials can be modified by an external electric field through reorienting the charges within the atom or molecules.
- Generally, these materials do not have any net dipole moment in absence of external electric field.
- As a consequence of applied electric field, positive charge of dielectric is pushed in direction of the field while negative the opposite way. The overall effect is a displacement of entire positive charge in the dielectric relative to the negative charge, formed induced electric dipoles.
- Dielectric materials are classified into two categories, named as polar molecules and non-polar molecules.

Electric Dipole and Electric Dipole Moment

An electric dipole is an entity in which equal positive (+q) and negative (-q) charges are separated by a small distance (dl) and the resultant electric dipole moment ($\vec{p}$) due to it is given by,

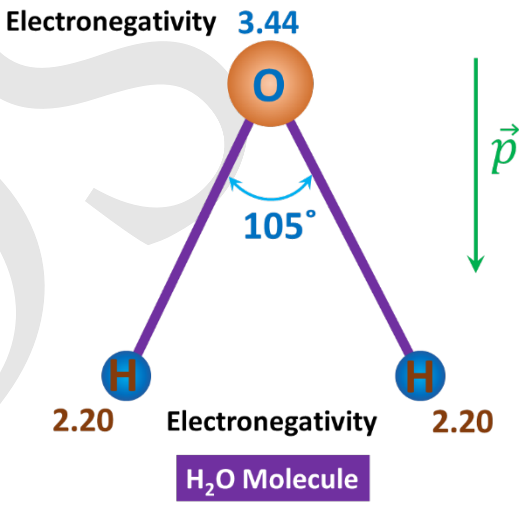
$$\vec{p} = q\,\overrightarrow{dl}$$

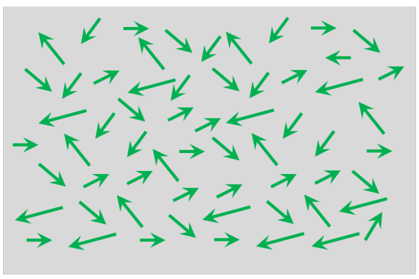


The electric dipole moment is a vector quantity and it is directed from negative charge to positive charge as shown in adjacent figure.

Non-polar and Polar Molecules

If the centre of gravity of the positive and negative charges in a molecule are separated by a short distance, such molecules are known as ***Polar Molecules***. It behaves as an electric dipole with direction of dipole moment from negative charge to positive charge. These have permanent electric dipole moment. Examples of polar molecule substance are water molecules (H_2O), ammonia (NH_3), sulphur dioxide (SO_2), hydrogen sulphide (H_2S), and ethanol (C_2H_6O).





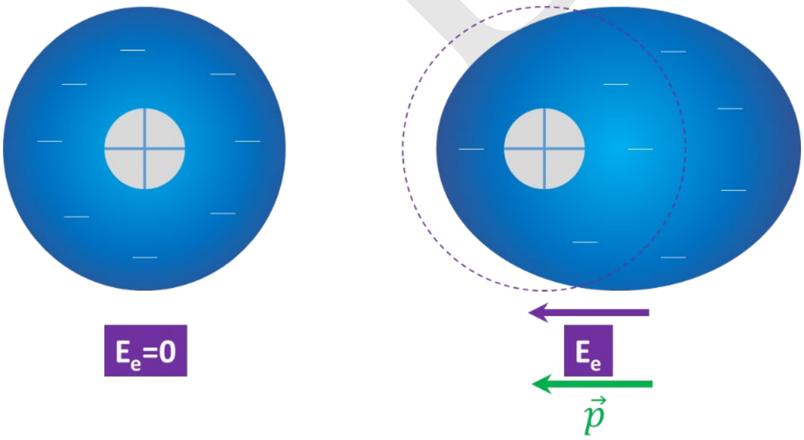
Net electric dipole moment = 0
when external electric field E = 0

In absence of external electric field, the net electric dipole moment of polar dielectric is zero due to random orientation of various dipoles inside the material.

If the centre of gravity of the positive and negative charges in a molecule coincide with each other, the molecule is called ***Non-polar Molecule***. These materials do not have electric dipole moment. Examples of non-polar molecules are noble gases (He, Ne, Ar, Kr, Xe), H_2, N_2, O_2, Cl_2, CO_2, C_2H_6, CH_4, and C_2H_4.

Dielectric Polarization

Generally, dielectric materials do not have any net dipole moment in absence of external electric field. As a consequence of applied electric field, positive charge of dielectric is pushed in direction of the field while negative the opposite way. The overall effect is a displacement of entire positive charge in the dielectric relative to the negative charge, formed induced electric dipoles. The relative displacement of the charges in dielectric is called ***Polarization***, leaving the material polarized.



Dielectric polarization is a *relative shift* of positive and negative electric charge in opposite directions within a material, which is induced by application of an external electric field.

The phenomenon of *appearance of the charges on the surfaces* of the dielectric in presence of an external electric field is known as ***polarization*** or ***dielectric***

polarization. Charge induced on the surfaces of the dielectric is called ***bound charges***.

Electric dipoles align themselves along the external electric field in presence of applied external electric field and such process of *electric dipole alignment* in a dielectric is also known as ***dielectric polarization***.

Dielectric material has net non-zero electric dipole moment in presence of external electric field. Dipole moment ($\vec{p}$) points in the same direction as external electric field ($\vec{E}$).

$$\vec{p} = \alpha\vec{E}$$

where, constant of proportionality α is called ***polarizability***. It depends on the detailed structure of the atom/molecule.

$$\alpha = \frac{\vec{p}}{\vec{E}}$$

Each permanent dipole in dielectric material experiences a torque which tends to line it up along the electric field direction, then material is said to be ***polarized***.

$$\text{P} = \text{dipole moment per unit volume}$$

$$\vec{P} = n\,\vec{p}$$

$$\vec{P} = n\,\alpha\vec{E}$$

where, n is number of molecules per unit volume.

Polarization vector ($\vec{P}$) is defined as the induced surface charge per unit area i.e. surface density of bound charge in dielectric.

$$P = \frac{q^{/}}{A} = \sigma_b$$

$$P = \frac{q^{/}d}{Ad} = \frac{induced\ dipole\ moment}{volume}$$

Types of Polarization

(i) Electronic Polarization (P_e)

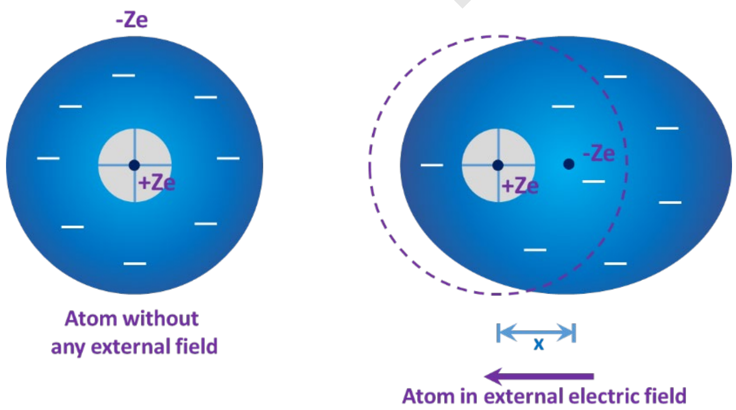
(ii) Ionic Polarization (P_i)

(iii) Orientation Polarization (P_o)

(iv) Interfacial or Space-charge Polarization (P_s)

(i) Electronic Polarization (P_e)

It is due to displacement of the centre of the negatively charged electron cloud relative to the positively charged nucleus of an atom by an external electric field.



Monoatomic gases exhibit only this type of polarization.

This type of polarization is temperature independent.

(Over-simplified model) In case of rare gas atoms (in which it is assumed that interaction among atoms is negligible), volume charge density of the electron is given by;

$$\rho = -\frac{Q}{V}$$

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

$$\rho = -\left(\frac{3}{4}\frac{Ze}{\pi R^3}\right)$$

Lorentz force (F) is given by;

$$F = -QE$$

$$F = -ZeE$$

*Lorentz forces of magnitude ZeE in opposite directions, experienced by nucleus and electron when placed in external electric field E.

As electron and nucleus are displaced, a Coulomb force develops between them.

$$F_c = \frac{Ze\ (charge\ enclosed\ in\ sphere\ of\ radius\ x)}{4\pi\epsilon_0 x^2}$$

$$F_c = \frac{Ze\left(\frac{4}{3}\pi x^3\rho\right)}{4\pi\epsilon_0 x^2}$$

Putting the value of ρ,

$$F_c = \frac{Ze\left(\frac{4}{3}\pi x^3\right)\left(-\frac{3}{4}\frac{Ze}{\pi R^3}\right)}{4\pi\epsilon_0 x^2}$$

$$F_c = -\frac{Z^2e^2x}{4\pi\epsilon_0 R^3}$$

At equilibrium position,

$$F = F_c$$

Putting the values of F and F_c ,

$$-ZeE = -\frac{Z^2e^2x}{4\pi\epsilon_0 R^3}$$

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

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

which shows that displacement x depends on applied external electric field (E), i.e.

$$\vec{x} \propto \vec{E}$$

Induced electric dipole moment ($\overrightarrow{p_e}$),

$$\vec{p}_e = Zex$$

Putting the value of x and simplify it,

$$\vec{p}_e = 4\pi\epsilon_0 R^3 \vec{E}$$

$$\vec{p}_e \propto \vec{E}$$

$$\vec{p}_e = \alpha_e \vec{E}$$

where, electronic polarizability is,

$$\alpha_e = 4\pi\epsilon_0 R^3$$

Dipole moment for unit volume is called electronic polarization.

$$\vec{P_e} = n\,\vec{p_e}$$

$$\vec{P_e} = n\alpha_e\vec{E}$$

where, n is the number of atoms per unit volume.

But,

$$\vec{P_e} = \varepsilon_0(\varepsilon_r - 1)\vec{E}$$

$$\varepsilon_0(\varepsilon_r - 1) = n\alpha_e$$

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

(ii) Ionic Polarization (P_i)

Ionic polarization occurs in ionic materials when an electric field is applied to an ionic material. Cation and anion get displaced in opposite directions and result into a net electric dipole moment.

It is also type of temperature independent polarization.

$$\vec{P_i} = \alpha_i\vec{E}$$

(iii) Orientation Polarization (P_o)

In orientation polarization, tiny electric dipoles aligned by an external electric field in direction of electric field.

Orientation polarization is dependent on temperature. It decreases with increasing temperature. At low temperature, dipole orientation by electric field is opposed by frictional forces.

$$\vec{P}_o = \alpha_o \vec{E}$$

(iv) Interfacial or Space-charge Polarization (P_s)

It occurs due to the accumulation of charges at the interfaces in a multiphase dielectric material. Such polarization is possible when one of the phase present has much higher resistivity than the other phase. It is observed in ferrites, semiconductors, and in composite insulators at elevated temperatures.

$$\vec{P}_s = \alpha_s \vec{E}$$

Total polarization P of a substance is equal to the sum of different types of polarizations, i.e.

$$P = P_e + P_i + P_o + P_s$$

Total polarizability α is given by,

$$\alpha = \alpha_e + \alpha_i + \alpha_o + \alpha_s$$

where, α_e is electronic polarizability, α_i is ionic polarizability, α_o is orientation polarizability and, α_s is the space-charge polarizability.

Dielectric constant and electric susceptibility

$$P \propto E$$

$$P = \varepsilon_0 \chi_e E$$

where, χ_e is dimensionless constant and is known as electric susceptibility.

Electric susceptibility measures the amount of polarization which a given electric field produced in a dielectric.

Relative permittivity (ε_r)

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

ε_r is also known as dielectric constant (k) of the medium and measures the charge storing capacity of the dielectric.