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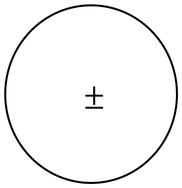
Name of Program –Physics (Hons), Part II
Paper –IV, Group A

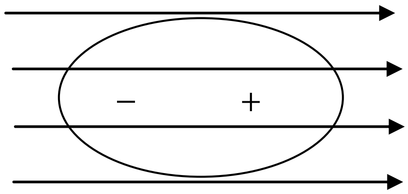
Dielectric Polarization

Non polar dielectric in electric field:-

The phenomenon of stretching of dielectric molecule in external electric field so that the centre of positive charge does not coincide with the centre of negative charge in called dielectric polarization.



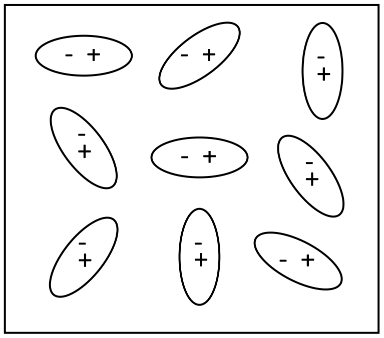
$\overrightarrow{E_0} = 0$



$\overrightarrow{E_0}$ =Applied

Polar dielectric in absence of electric field:-

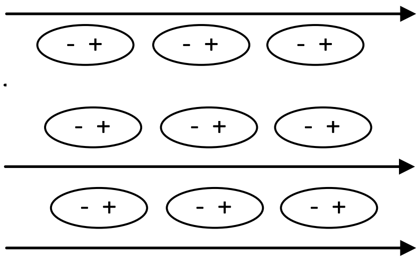
When no eclectic field is applied the different individual permanent dipoles of such a dielectric are randomly oriented due to thermal agitation. So total dipole moment is zero.



Polar dielectric in presence of electric field:-

When an electric field is applied the individual dipole moment tend to align in the direction of external electric field. So net dipole moment in the direction of external field i.e. the dielectric is polarized.

Thus each molecule becomes a tiny electric dipole with a dipole moment parallel to external electric field.



$\overrightarrow{E_0}$ =Applied

q_i =Induced positive/ negative charge

$\overrightarrow{dl}$ = separation between centre of positive and negative charge

Induced dipole moment

$$\vec{p} = q_i \overrightarrow{dl}$$

Torque experienced by each molecule $\vec{\tau} = \vec{p} \times \overrightarrow{E_0}$

Atomic polarisability:-

The induced dipole moment of an atom/ molecule is directly proportional to the strength of applied electric field $\overrightarrow{E_0}$

$$\vec{p} \propto \overrightarrow{E_0}$$

$$\vec{p} = \propto \varepsilon_\circ \overrightarrow{E_0}$$

Where ∝ is a constant of proportionality and is called atomic /molecular polarisability and depends upon the dielectric constant of material.

Atomic polarizability

$$\propto = \frac{P}{\varepsilon_\circ \overrightarrow{E_0}}$$

Unit of $\propto = m^3$

For most of atoms ∝ is of the order of 10^{-29} to 10^{-30} m^3.

Dielectric polarization :-

q_i = induced positive or negative charge in dielectric

dl = separation between the centre of charges

Dipole moment of each atom

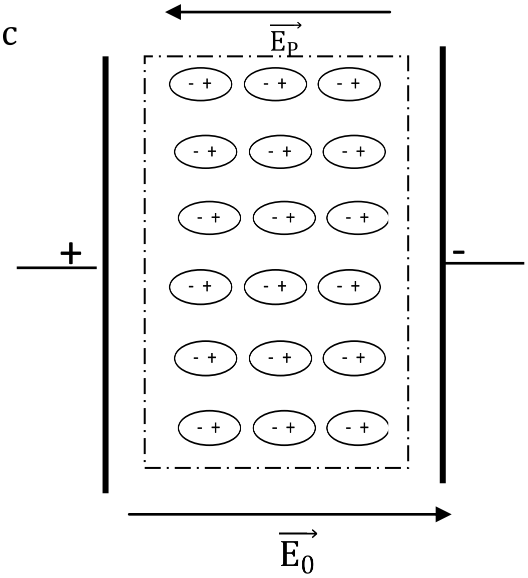
$$\vec{p} = q_i \overrightarrow{dl}$$

If N = Number of atoms per unit volume.

Total dipole moment density

$$\vec{P} = N\vec{p}$$

$$\vec{\mathbf{P}} = N q_i \overrightarrow{dl}$$



This total induced dipole moment density **P** is called Dielectric polarization

Dielectric polarization = Total induced dipole moment density .

$$\text{Unit} = \frac{\text{coulomb metre}}{(\text{metre })^3} = \frac{\text{couomb}}{(\text{metre })^2} = cm^{-2}$$

$$\text{Dipole moment per unit volume} = \frac{\text{Dipole moment}}{\text{Volume}}$$

$$P = \frac{\mathbf{q_i dl}}{\mathbf{A;dl}}$$

$$P = \frac{q}{A} = \sigma_p$$

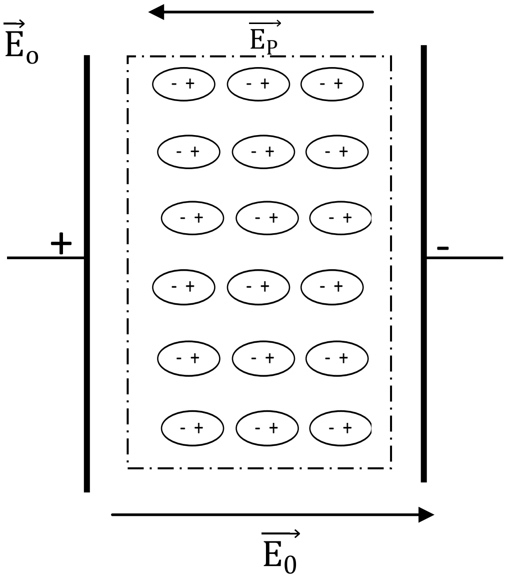
Dielectric polarization is numerically equal to induced surface charge density.

Electric Displacement Vector

$\vec{E}_o$ =Applied (i.e External) electric field

$\vec{E}_p$ = Electric field due to polarization , opposite to $\vec{E}_o$

Net electric field inside dielectric



$$\vec{E} = \vec{E}_o - \vec{E}_p$$

$$\vec{E} = \vec{E}_o - \frac{\sigma_p}{\varepsilon_o}$$

$$\vec{E} = \vec{E}_o - \frac{\vec{P}}{\varepsilon_\circ} \qquad [\because \vec{P} = \sigma_p]$$

$$\vec{E}_o = \vec{E} + \frac{\vec{P}}{\varepsilon_\circ}$$

$$\vec{E}_o = \frac{\varepsilon_\circ\vec{E}+\vec{P}}{\varepsilon_\circ}$$

$$\varepsilon_\circ\vec{E}_o = \varepsilon_\circ\vec{E} + \vec{P}$$

The quantity $\varepsilon_\circ\vec{E}_o$ within the dielectric is called electric displacement vector and is denoted by $\vec{D}$ i.e. $\vec{D} = \varepsilon_\circ\vec{E}_o$

$$\vec{D} = \varepsilon_\circ\vec{E}_o + \vec{P}$$

The electric displacement vector is also known as dielectric displacement. It is vector field in a non conducting medium (i.e. dielectric)

$\vec{D}$ = Electric displacement vector

$\vec{E}$ = Electric field vector

$\vec{P}$ = Electric polarization vector

$$\vec{D} = \varepsilon_\circ\vec{E}_o + \vec{P}$$

In free space/ vacuum there is no polarization

$$\vec{P} = 0\ \vec{D} = \varepsilon_\circ\vec{E}_o$$

Gauss's a law for dielectric

The differential from of Gauss's law is given by $\vec{\nabla}.\vec{E} = \frac{\rho}{\varepsilon_\circ}$

Where ρ is the net volume charge density.

When a charge is present within a dielectric in addition to free (external) charge density (ρ_f) and an induced charge density (ρ_p) is developed due to polarisation.

Net charge density

$$\rho = \rho_f + \rho_p$$

$$\vec{\nabla}.\vec{E} = \frac{\rho}{\varepsilon_\circ}$$

$$\vec{\nabla}.\vec{E} = \frac{\rho_f}{\varepsilon_\circ} + \frac{\rho_\rho}{\varepsilon_\circ}$$

The volume charge of polarization ρ_p is given by

$$\rho_p = -\vec{\nabla}.\vec{P}$$

$$\vec{\nabla}.\vec{E} = \frac{\rho_f}{\varepsilon_\circ} - \frac{\vec{\nabla}.\vec{P}}{\varepsilon_\circ}$$

$$\vec{\nabla}.\vec{E} + \frac{\vec{\nabla}.\vec{P}}{\varepsilon_\circ} = \frac{\rho_f}{\varepsilon_\circ}$$

$$\vec{\nabla}\left[\vec{E} + \frac{\vec{P}}{\varepsilon_\circ}\right] = \frac{\rho_f}{\varepsilon_\circ}$$

$$\vec{\nabla}\left[\frac{\varepsilon_\circ\vec{E} + \vec{P}}{\varepsilon_\circ}\right] = \frac{\rho_f}{\varepsilon_\circ}$$

$$\vec{\nabla}\left[\varepsilon_\circ\vec{E} + \vec{P}\right] = \rho_f$$

But $\varepsilon_\circ\vec{E} + \vec{\rho} = \vec{D}$ is called electric displacement vector

$$\vec{\nabla}.\vec{D} = \rho_f \text{ ------------------ } (1)$$

This equation shows that divergence of displacement vector is equal to density of free charge.

But $\vec{D} = \varepsilon_\circ\varepsilon_r\vec{E}$

$$\vec{D} = \varepsilon\,\vec{E}$$

$$\vec{\nabla}.\vec{D} = \vec{\nabla}.\varepsilon\,\vec{E}$$

From eqn. (1)

$$\vec{\nabla}.\varepsilon\,\vec{E} = \rho_f$$

$$\vec{\nabla}.\vec{E} = \frac{\rho_f}{\varepsilon}$$

This is known as differential form of Gauss's law for dielectric.

For free space/ vacuum

Gauss Law $\vec{\nabla}.\vec{E} = \frac{\rho}{\varepsilon_\circ}$

Dielectric Constant :-

$$K = \frac{E_0}{E} = \frac{\varepsilon_0 E_0}{\varepsilon_0 E} = \frac{D}{\varepsilon_0 E}$$

$$\varepsilon_r = \frac{D}{\varepsilon_0 E}$$

$$D = \varepsilon_0\varepsilon_r E = \varepsilon E$$

$$\because K = \frac{E_0}{E} = \frac{\frac{\sigma}{\varepsilon_0}}{\frac{\sigma - \sigma_\rho}{\varepsilon_0}} = \frac{\sigma}{\sigma - \sigma_\rho}$$

For metals – $\sigma_\rho = \sigma$ $\quad\therefore K = \infty$

For vacuum – $\sigma_\rho = 0$ $\quad\therefore K = 1$