DIELECTRIC MATERIALS

WHAT ARE DIELECTRICS ?

- Conductors : Substances that contain an unlimited supply of charges that are free to move through the material. Eg. Metals etc.

- Insulators: Substances which do not contain free electrons or the number of free electrons are too low, the electrons are tightly bound to atom. Eg. Plastic, paper etc.

- Dielectrics: When potential difference is applied to certain non-conducting substances, they get polarised. Eg. Mica, glass etc.

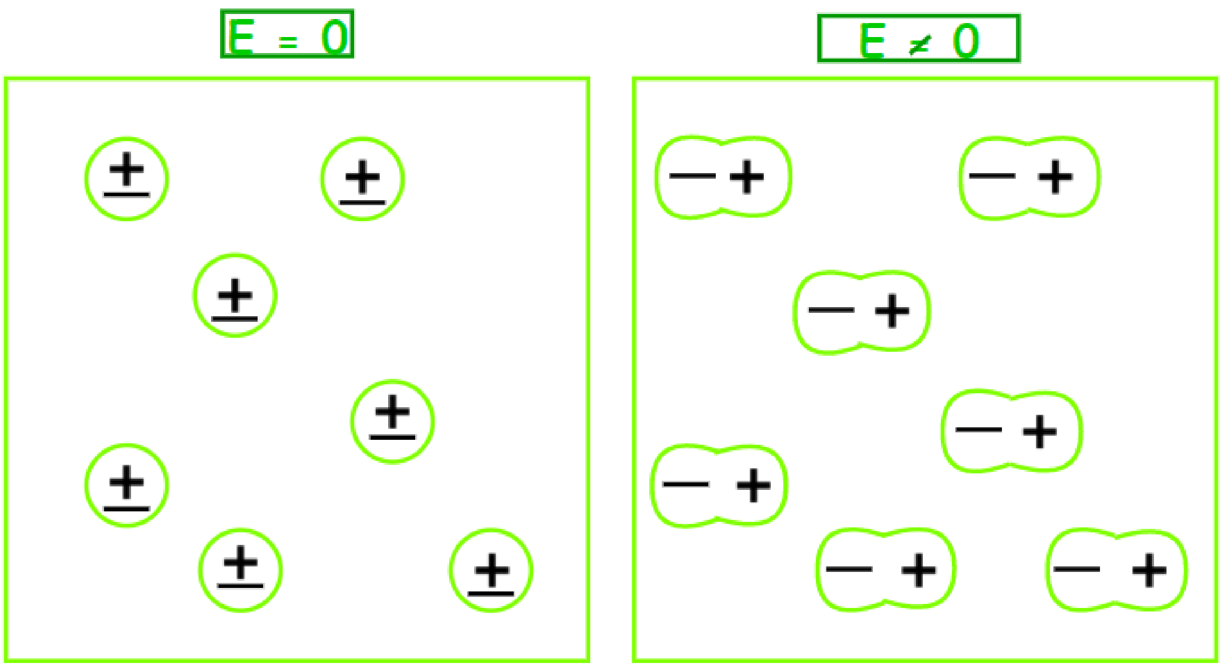
- When these materials are used to fill the space between two conductors of a capacitor the capacitance is found to increase.

- **When change in behaviour of the dielectric is independent of direction of applied field, the dielectric is called as isotropic.**
- **If the change in behaviour of dielectric depends on direction of applied field then the dielectric is called as anisotropic.**
- **If a dielectric is kept in an electric field, then the field exerts a force on each charged particle. The positive particles are pushed in one direction while negative particles in the opposite direction.**
- **Hence, the positive and negative parts of each molecule are displaced from their equilibrium positions in opposite directions.**
- **The relative displacement of charges give rise to dipole generation and the dielectric is said to be polarized.**
- **The dielectrics are classified into two types:**

1) **Non- Polar molecules**
2) **Polar molecules**

NON-POLAR DIELECTRICS

- A molecule in which the centres of gravity of positive and negative charges coincide is called a non polar molecule.
- They have no inherent dipole moment.
- Example: H_2, O_2, CH_4, C_6H_6 etc.

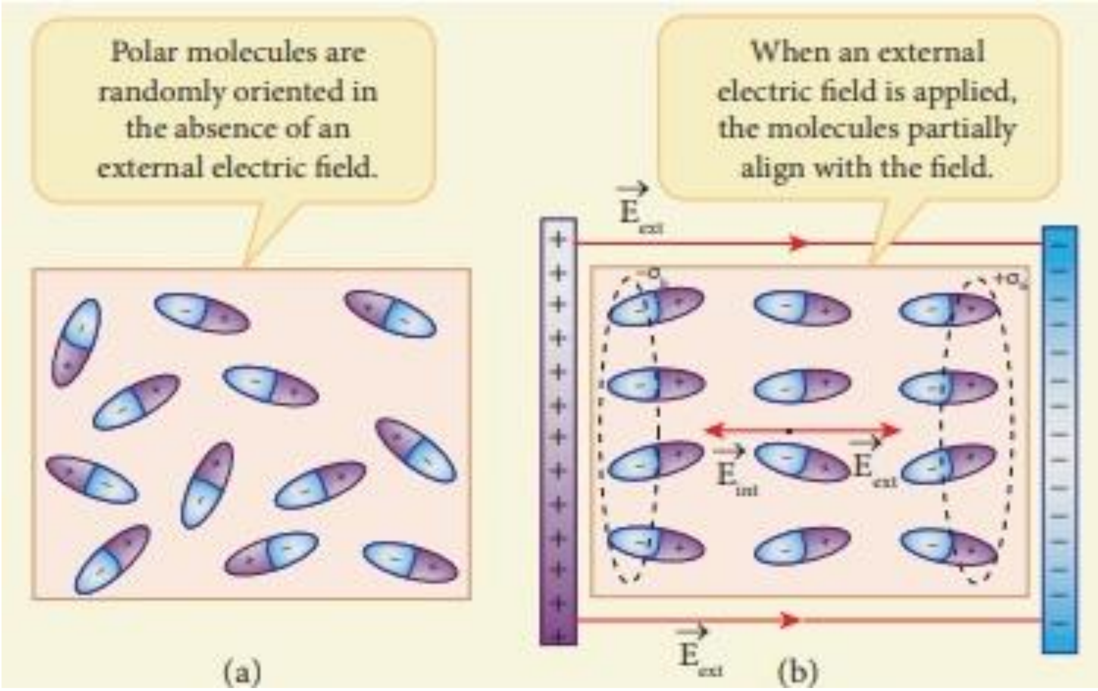


POLAR DIELECTRICS

- Molecule in which the centres of gravity of positive and negative charges do not coincide.
- The positive and negative charges are centred at a point separated by a distance, therefore possess a net dipole moment are called polar molecules.

- Example: H_2O, $CHCl_3$, C_6H_5Cl, C_2H_6OH etc.

- Polar nature of dielectric materials is measured in terms of its permanent dipole moment.



Dielectric materials

Polar molecules

(i) Permanent electric dipole

(ii) Its polarisation is temperature dependent

Non-polar molecules

(i) Induced electric dipole

(ii) Its polarisation independent of temperature

Important Formulae

- Coulomb’s Law
- Electric Intensity
- Electric Potential
- Relation between Electric Intensity and Electric Potential
- Electric Displacement Vector
- Capacity of Capacitor
- Electric dipole and dipole moment

Refer Class Notes

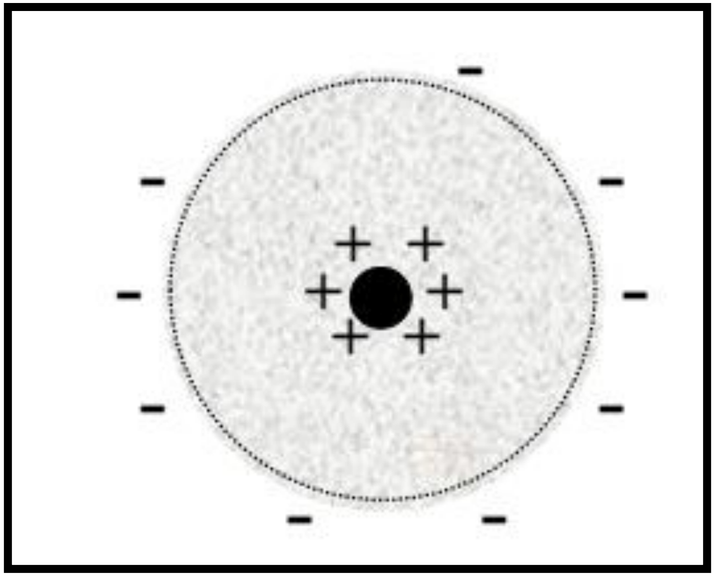
Dielectric Constant (k) or relative permittivity(ϵ_r)

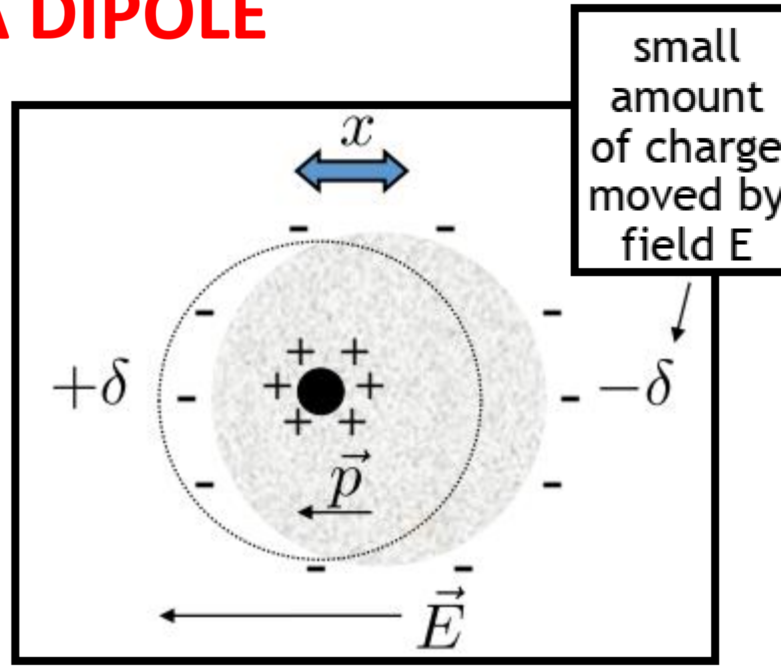
Induced Charges

Expression for induced or polarized surface charge density(σ_p)

Refer Class Notes

WHAT IS A DIPOLE



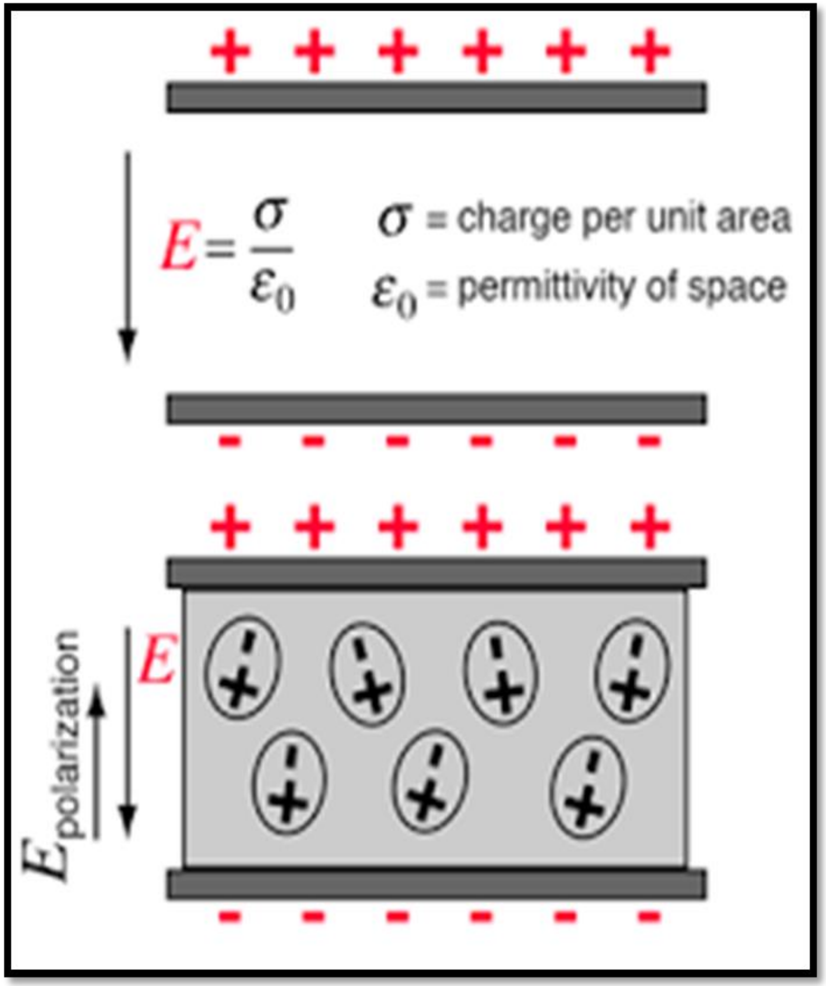


- **Dipole moment is a measure of the polarity of a system of electric charges. It is a quantity that describes two opposite charges separated by a distance *d*.**
- **The electric dipole moment vector points from the negative charge to the positive charge.**
- **The value of dipole moment is given as:** $\mu = (q).(x)$

POLARIZATION

- Dielectrics contain bound charges. The bound charges may be able to move slightly (in opposite directions) when an Electric field is applied.
- No applied field: The centroids of the positive and negative charges coincide → no internal E-field.
- In an Electric field: The electrons move a small distance in one direction and the nucleus moves in the opposite direction.
- Polarization is number of dipole moments induced per unit volume.

$$P = \mu/V$$



❖ Polarization (P)

The electric dipole moment per unit volume is called polarization.

It is denoted by ***P***.

$$P = \frac{\mu}{V}$$

$$P = \frac{(q_p)(d)}{(A)(d)} = \frac{(q_p)}{(d)} = \sigma_P$$

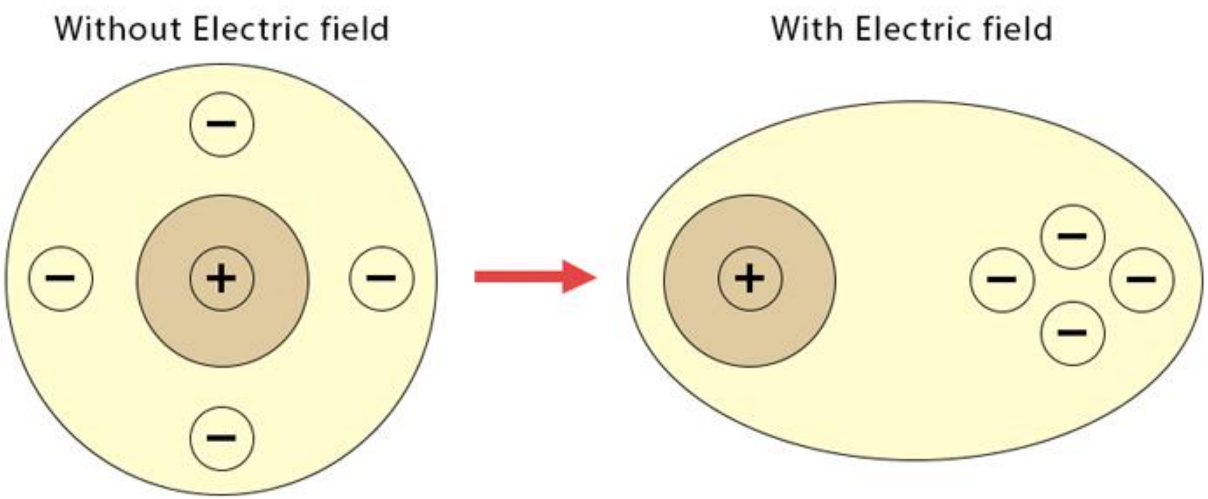
It is numerically equal to surface charge density.

It is a vector quantity and its direction is along the direction of the dipole moment.

Unit: coulomb/metre^2

Polarizability

The tendency of a substance to form dipole moment when an electric field is applied across it



The dipole moment , $\boldsymbol{\mu}$ induced in an atom is proportional to the electric field, $\boldsymbol{E}$ i.e.

$$\mu \propto E$$

$$\mu = \alpha E$$

✓α is the constant of proportionality known as polarizability.

✓If there are N atoms per unit volume, the polarization of the solid is $\boldsymbol{P} = N\boldsymbol{\mu} = N\alpha\boldsymbol{E}$

Field Vectors

1. Relation between D, E and P

2. Relation between ϵ_r and χ

Refer Class Notes

TYPES OF POLARIZATION

- Electronic Polarization
- Ionic Polarization
- Orientation Polarization
- Space charge Polarization

ELECTRONIC POLARIZATION

- ✓ It is defined as an electric strain produced in an atom by the application of electric field.
- ✓ It results from the displacement of nucleus (+Ze) and electrons (-Ze) in opposite direction in the presence of the applied field with the creation of dipole moment.
- ✓ The dipole moment induced is proportional to the strength of field applied

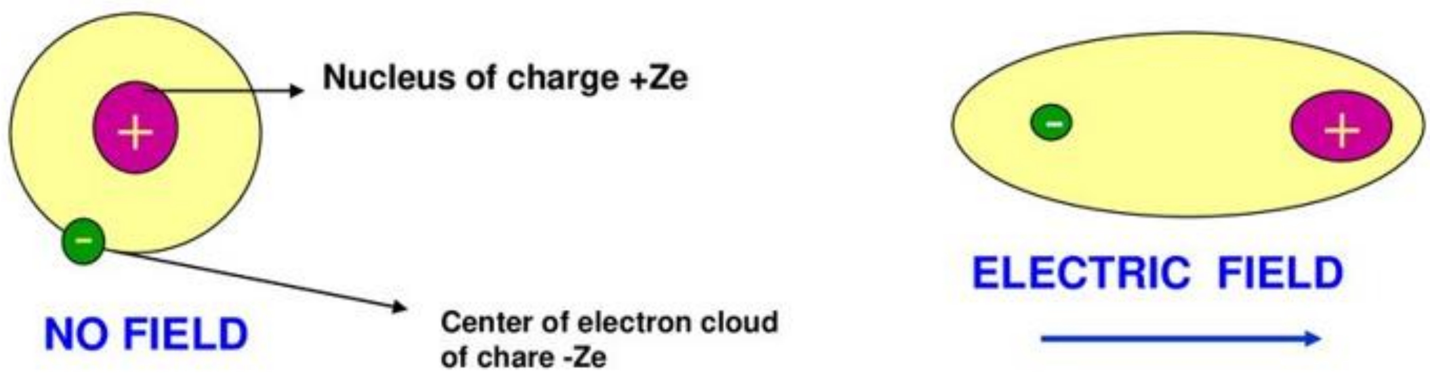
$$\mu_e \propto E$$

$$\mu_e = \alpha_e E$$

where α_e is electronic polarizability of the material which is given by $\frac{\varepsilon_0(\varepsilon_r - 1)}{N}$

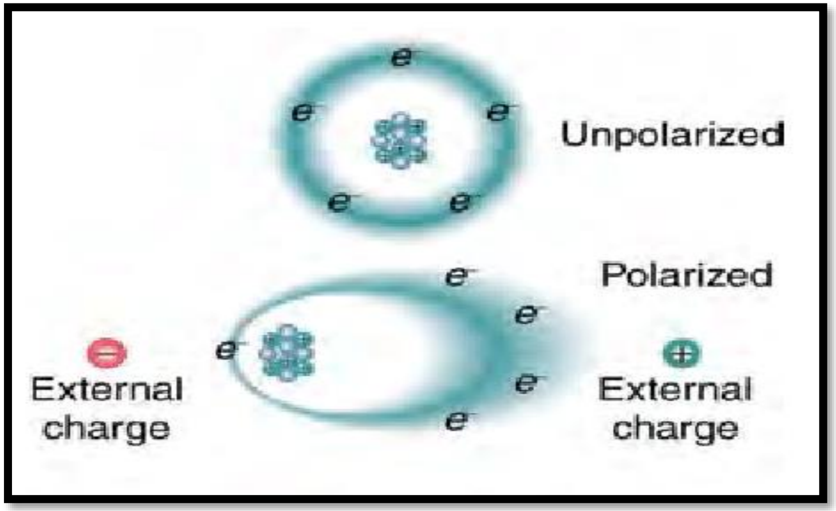
N is number of atoms per cm^3

- ✓ Polarization is $P_e = N\alpha_e E$
- ✓ It is independent of temperature.
- ✓ Monoatomic molecules exhibits this type of polarization.



Electronic polarizability

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



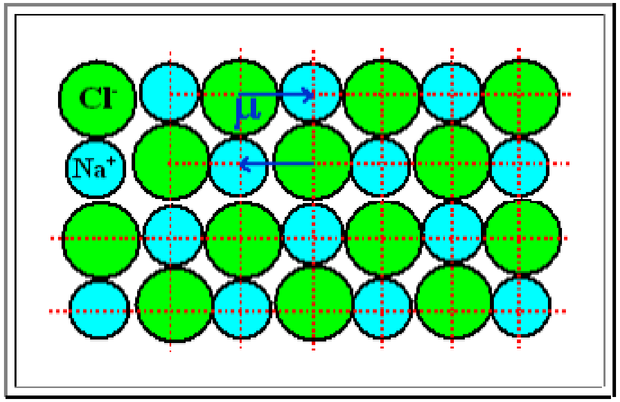
The polarization is defined as the number of dipole moments per unit volume of the material. If N is the number of dipole moments per unit volume, the polarization would be

$$\boxed{P_e = 4\pi\varepsilon_0 R^3 EN}$$

- **Hence, we can say that the electronic polarization is dependent upon the radius of the atom and the number of atoms presents in unit volume of the material.**

Ionic Polarization

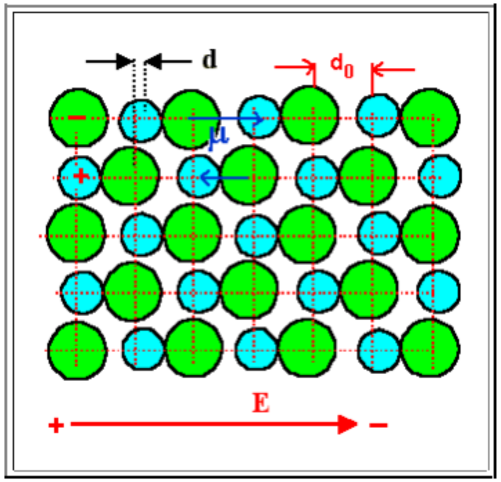
Consider a simple ionic crystal, e.g. **NaCl**.



- The lattice can be considered to consist of **Na^+ - Cl^-** dipoles as shown below.
- Each **Na^+ - Cl^-** pair is a *natural dipole*, no matter how you pair up two atoms.
- The polarization of a given volume, however, is *exactly zero* because for every dipole moment there is a neighboring one with exactly the same magnitude, but opposite sign.
- Note that the dipoles *can not rotate*; their direction is fixed.

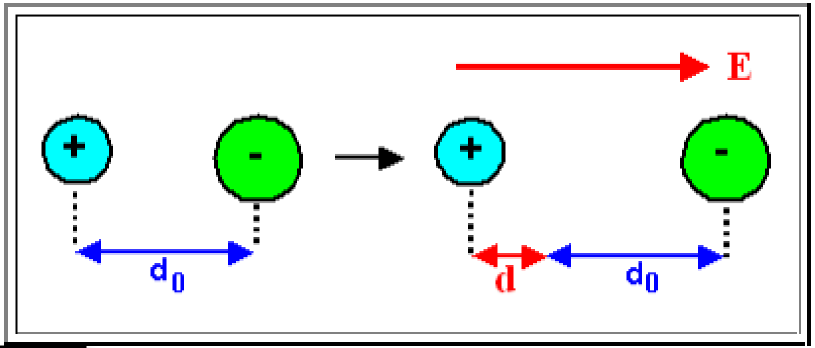
In an electric field, the ions feel forces in opposite directions. For a field acting as shown, the lattice distorts a little bit

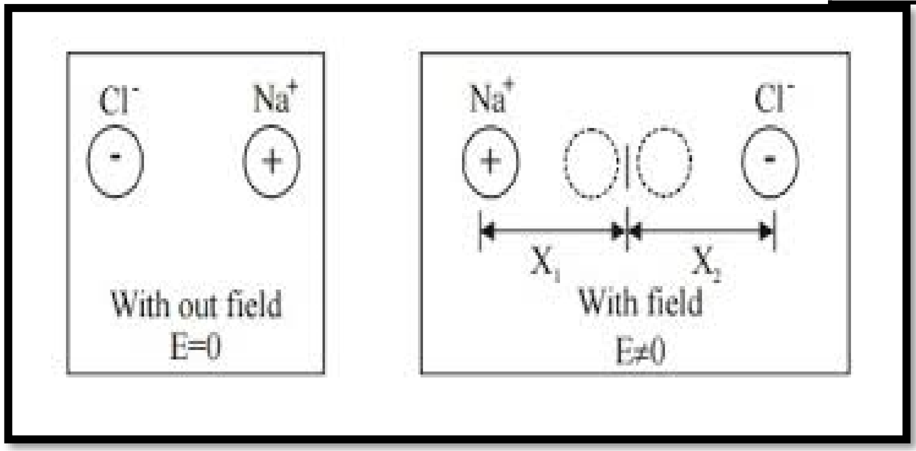
- The **Na^+** ions moved a bit to the right, the **Cl^-** ions to the left.



- The dipole moments between adjacent **NaCl** - pairs in field direction are now different and there is a *net dipole moment* in a finite volume now.

From the picture it can be seen that it is sufficient to consider *one* dipole in field direction. We have the following situation:





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

$$P_i = \frac{Ne^2}{\omega^2}\left[\frac{1}{M} + \frac{1}{m}\right]E$$

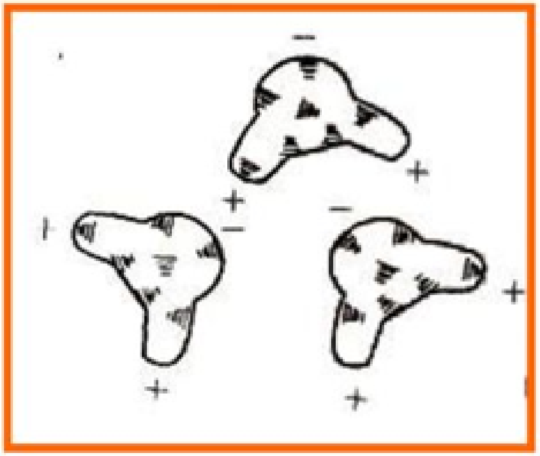
ORIENTATIONAL POLARIZATION

- It is due to the presence of polar molecules in the dielectric material which have permanent dipole moment.
- When electric field is applied on the dielectric material, it tries to align the dipole in its direction that results in the existence of dipole moment in the material.
- It occurs in asymmetric molecules.
- Its depends on the tem

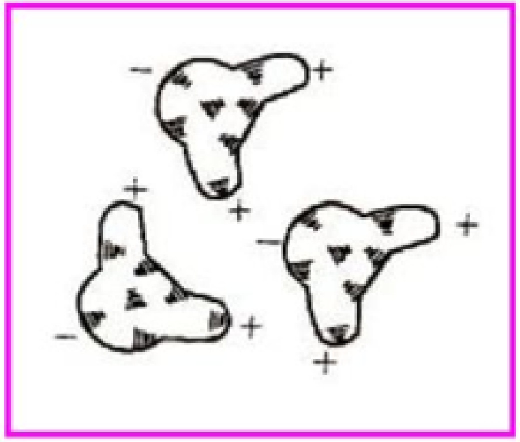
$$\alpha_o = \frac{\mu^2}{3kT}$$

μ is permanent dipole moment

$$P_o = \frac{N\mu^2 E}{3kT}$$



No Field



Electric Field

SPACE POLARIZATION

- It occurs due to the accumulation of electric charges at the interfaceof a multiphased material.
- This is possible when one of the phases present posses much higher resistivity than the other.
- It is found to occur in ferrites and semiconductors.

No Field

Electric Field

The total polarization is $P = P_e + P_i + P_o + P_s$

IMPORTANT FORMULAE

1. Electronic polarization:

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

2. Ionic polarization:

$$P_i = \frac{Ne^2}{\omega^2}\left[\frac{1}{M} + \frac{1}{m}\right]\mathrm{E} \rightarrow \ \alpha_i = \frac{e^2}{\omega^2}\left[\frac{1}{M} + \frac{1}{m}\right]$$

3. Orientation polarization:

$$P_o = \frac{N\mu^2 E}{3kT} \rightarrow \ \alpha_o = \frac{\mu^2}{3kT}$$

Total polarization is given as, $P = P_e + P_i + P_o$

$$\therefore\ P = 4\pi\epsilon_0 N R^3 E + \frac{Ne^2}{\omega^2}\left[\frac{1}{M} + \frac{1}{m}\right]\mathrm{E} + \frac{N\mu^2 E}{3kT}$$

$$P = N\left(4\pi\epsilon_0 R^3 + \frac{e^2}{\omega^2}\left[\frac{1}{M} + \frac{1}{m}\right] + \frac{\mu^2}{3kT}\right)E \leftrightarrow P = N(\alpha_e + \alpha_i + \alpha_o)E$$

Polarization is also mentioned as

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

Therefore, by equating both the equations, we get,

$$\epsilon_0(\epsilon_r - 1)E = N\left(4\pi\epsilon_0 R^3 + \frac{e^2}{\omega^2}\left[\frac{1}{M} + \frac{1}{m}\right] + \frac{\mu^2}{3kT}\right)E$$

$$\rightarrow \epsilon_0(\epsilon_r - 1) = N\left(4\pi\epsilon_0 R^3 + \frac{e^2}{\omega^2}\left[\frac{1}{M} + \frac{1}{m}\right] + \frac{\mu^2}{3kT}\right)$$

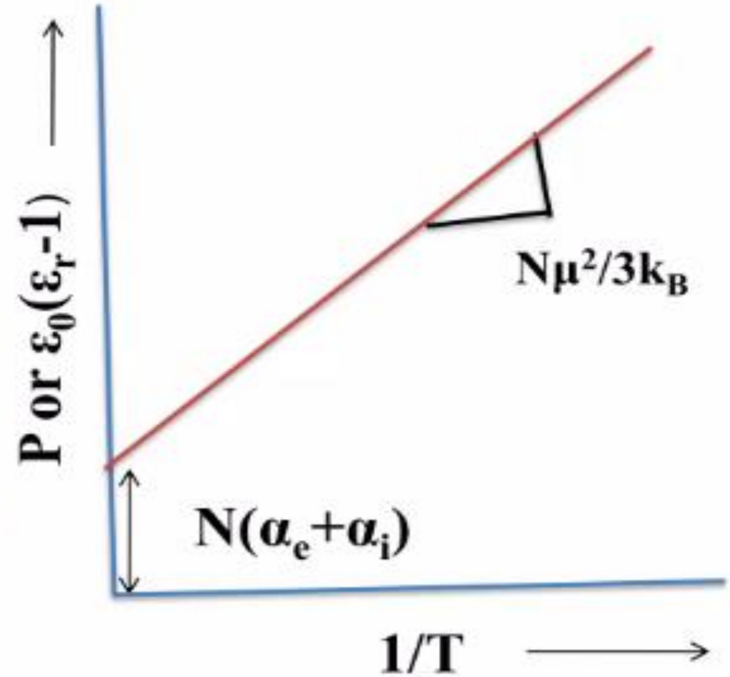
$$\rightarrow \epsilon_r - 1 = \frac{N}{\epsilon_0}\left(4\pi\epsilon_0 R^3 + \frac{e^2}{\omega^2}\left[\frac{1}{M} + \frac{1}{m}\right] + \frac{\mu^2}{3kT}\right)$$

$$\rightarrow \epsilon_r = 1 + \frac{N}{\epsilon_0}\left(4\pi\epsilon_0 R^3 + \frac{e^2}{\omega^2}\left[\frac{1}{M} + \frac{1}{m}\right] + \frac{\mu^2}{3kT}\right)$$

Temperature dependent Polarization

$$P = N[\alpha_e + \alpha_i + \alpha_o]E$$

$$P = N\left[4\pi\varepsilon_0 R^3 + \frac{e^2}{\omega_0^2}\left(\frac{1}{M} + \frac{1}{m}\right) + \frac{\mu^2}{3k_B T}\right]E$$



✓Electronic and ionic polarization do not depend on temperature. However orientation polarization is inversely proportional to temperature.

✓The *P vs 1/T* plot will be a straight line.

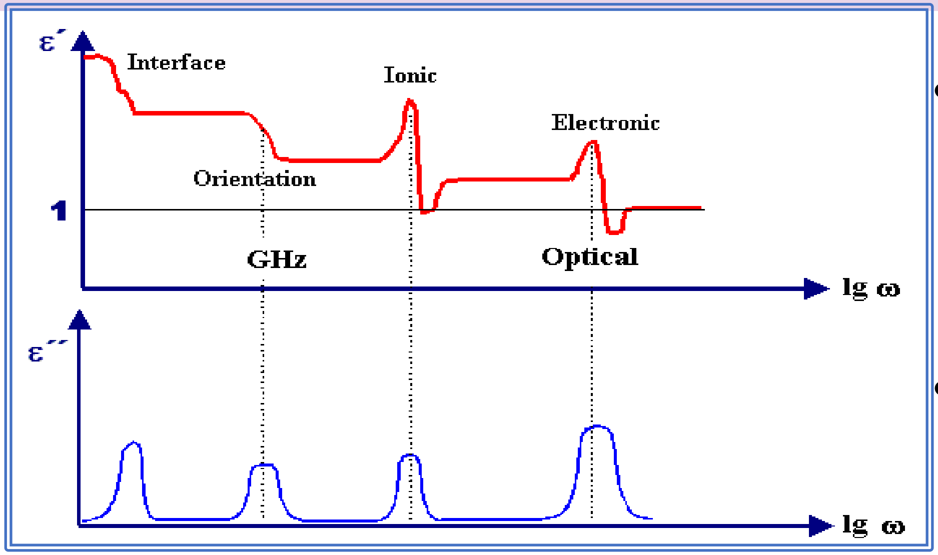
✓Intercept of the line with y axis gives the value of $N(\alpha_e+\alpha_i)$

✓Slope of the straight line will give the value of $N\mu^2/3k_B$

✓So by knowing the slope, value of N i.e the number of molecules per m^3, one can calculate the dipole moment, μ

FREQUENCY DEPENDENCE OF POLARIZATION

- When a dielectric is placed in an alternating field, the dielectric gets polarized → The total polarization depends on the ability of dipole to orient themselves in field direction.
- Electronic polarization is fastest and persists at ~10^{13}-10^{15} Hz.
- Ionic polarization is sluggish; occurs at ~10^{9}-10^{13} Hz.
- Orientation polarization occurs below 10^{9} Hz.
- Space charge polarization occurs at frequencies below 10 Hz



- The average time taken by the dipole to orient in the field direction is known as relaxation time.
- The reciprocal of relaxation time is known as relaxation frequency.

https://www.tf.uni-kiel.de/matwis/amat/elmat_en/kap_3/backbone/r3_3_5.html

- If the frequency of applied electric field >> the relaxation frequency of dipole → the dipole can't orient themselves.
- If the relaxation time of the dipole < the half of the time period of electric field → the dipole easily follows the direction of field.
- At *low frequency (audio frequency):* all type of polarization exists → $P = P_e + P_i + P_o$.
- In *rf frequency or microwave frequency:* orientational polarization ceases off → can't follow the field reversal → $\therefore$ *only* P_e *and* P_i *exists*.
- In *Infrared and optical frequency:* ionic polarization fails to follow the field reversal → ∴ Only electronic polarization contributes.
- The relative permittivity in the optical region will be equal to the square of the refractive index of the dielectric $\epsilon_r = n^2$.
- In *ultraviolet region:* electron cloud fails to follow the field reversal and hence the total polarization becomes zero but ϵ_r=1.

APPLICATION OF DIELECTRICS

DIELECTRIC MATERIALS ARE USED IN MANY APPLICATIONS SUCH AS:

- **Electronic components such as capacitors (responsible for energy storage properties of the device).**
- **High-k / low-k materials widely used in Semiconductors to enhance performance and reduce device size (where k refers to permittivity or dielectric constant).**
- **Dielectric materials are also used in Display applications (e.g. LCD liquid crystal displays).**
- **Piezoelectrics/Ferroelectrics/MEMs materials are also dielectrics.**
- **Ceramics and Polymers also often exhibit dielectric properties.**