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.**

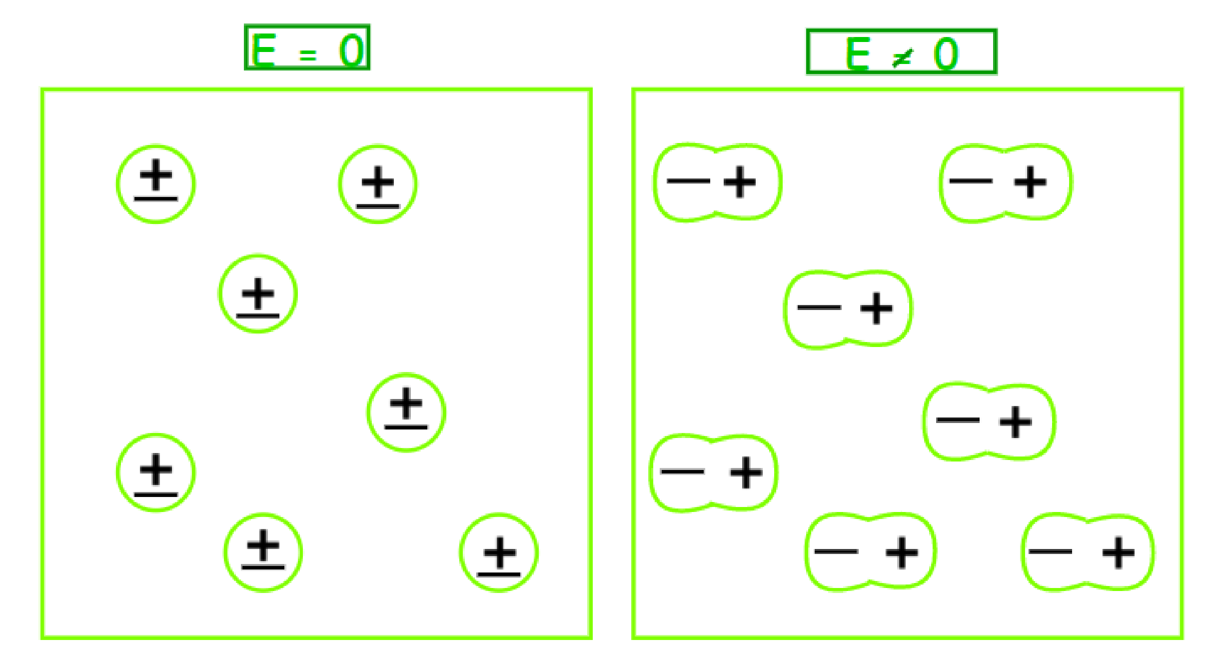
- **When change in behaviour of the dielectric is independent of direction of applied field, the dielectric is called as isotropic.**
- **If the change in behaviour of dielectric depends on direction of applied field then the dielectric is called as anisotropic.**
- **If a dielectric is kept in an electric 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, and thus for which the inherent dipole moment is zero, is called a non polar molecule.

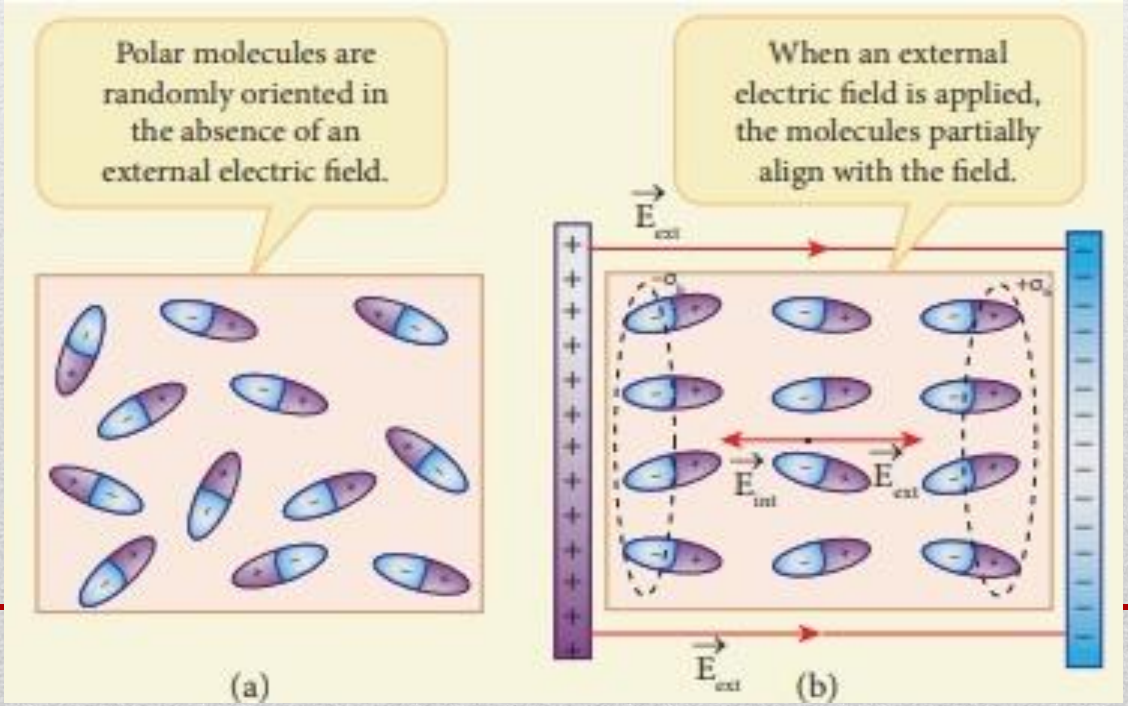
Eg: H_2, O_2, CH_4,C_6H_6 etc.



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. H_2O, $CHCl_3$, C_6H_5Cl, C_2H_6OH etc. are some examples of polar molecules.

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



Dielectric materials

Polar molecules	Non-polar molecules
(i) Permanent electric dipole	(i) Induced electric dipole
(ii) Its polarisation is temperature dependent	(ii) Its polarisation independent of temperature

Important Formulae

- **Coulomb’s Law**
- **Electric Intensity**
- **Electric Potential**
- **Electric Displacement Vector**
- **Capacity of Capacitor**

Refer Class notes

Dielectric Constant or relative permittivity(ϵ_r)

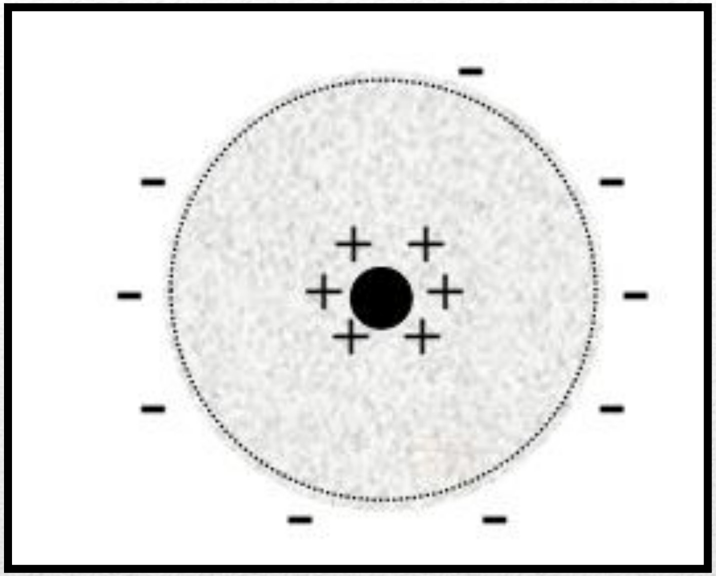
Refer Class notes

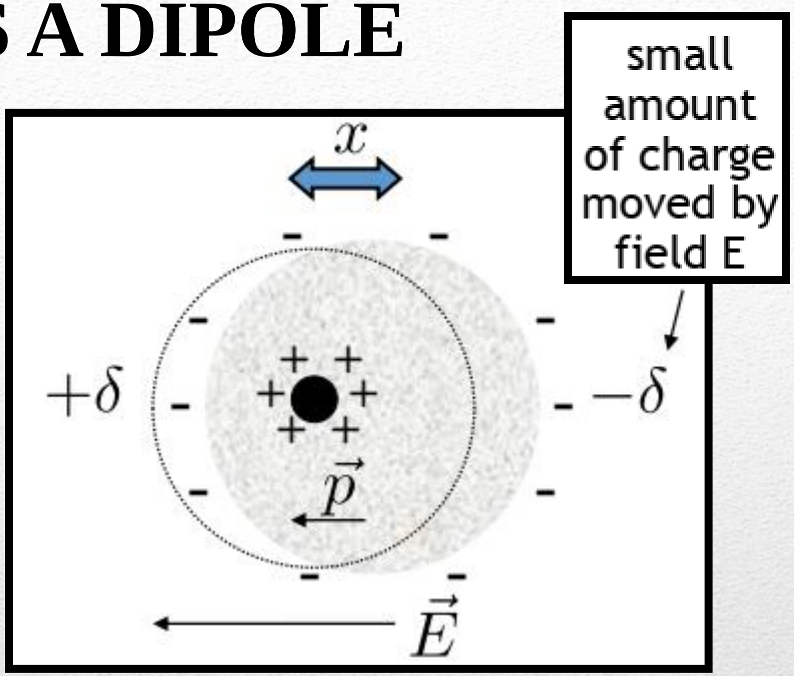
Induced Charges

Expression for induced or polarized surface charge density(σ_p)

Refer Class notes

WHAT IS A DIPOLE



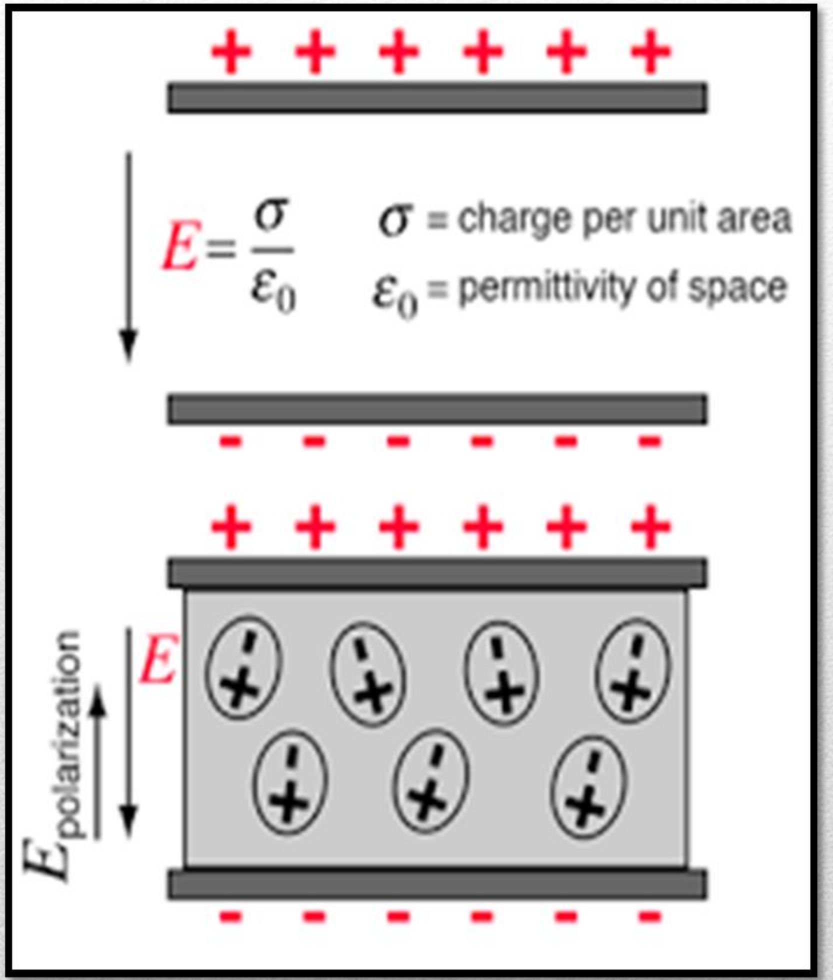


Dipole moment is a measure of the polarity of a system of electric charges. It is a quantity that describes two opposite charges separated by a distance *x*.

The electric dipole moment vector points from the negative charge to the positive charge. It depends on the positions of the charges, not the field lines. 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=µ/V.**



❖ Polarization (P)

✓The electric dipole moment per unit volume is called polarization.

✓It is denoted by ***P***.

$$P = \frac{\mu}{V} = \frac{qd}{Ad} = \frac{q}{A}$$

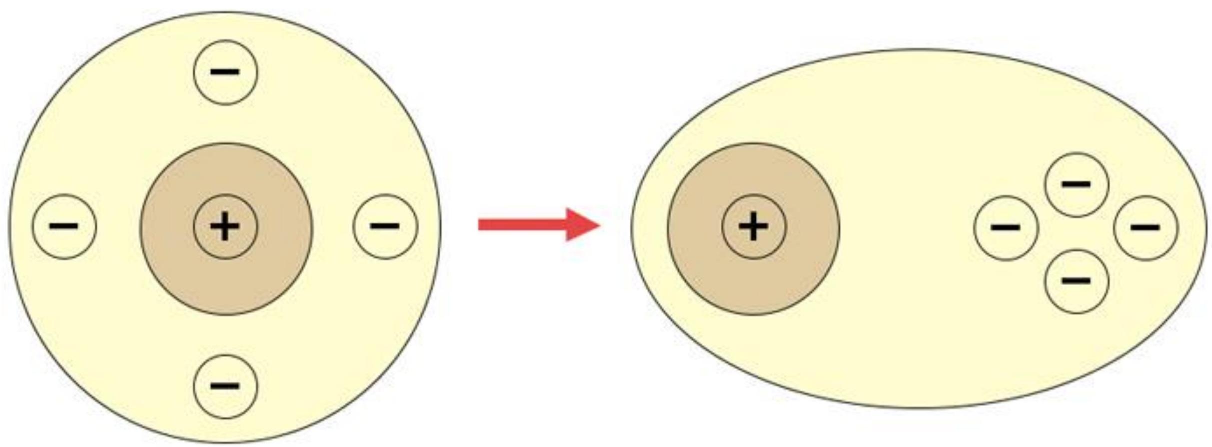
✓It is numerically equal to surface charge density.

✓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

Refer Class notes

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

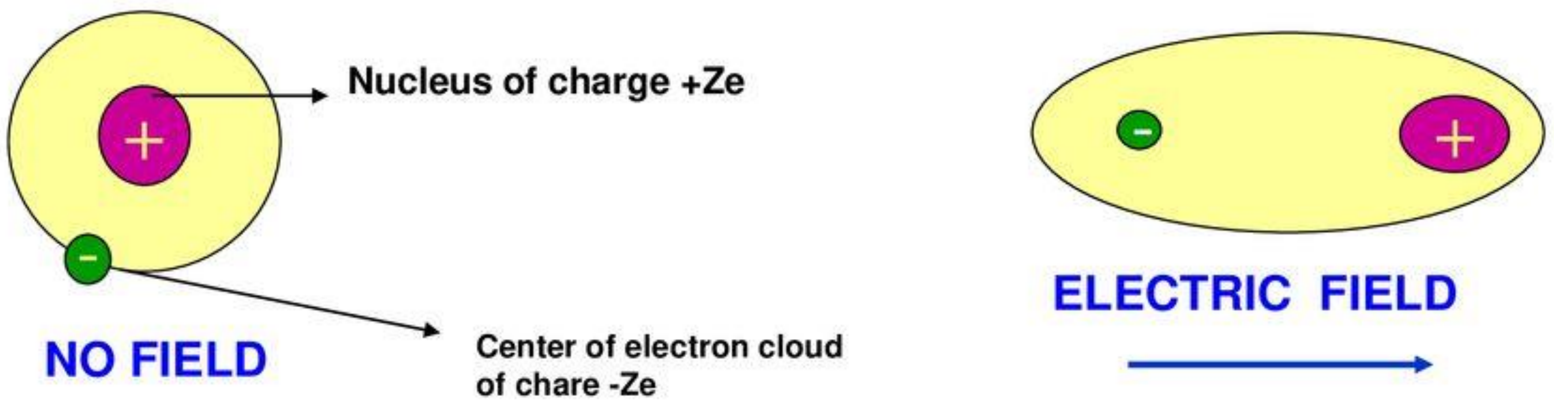
$$\mu_e \propto E$$

$$\mu_e = \alpha_e E$$

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

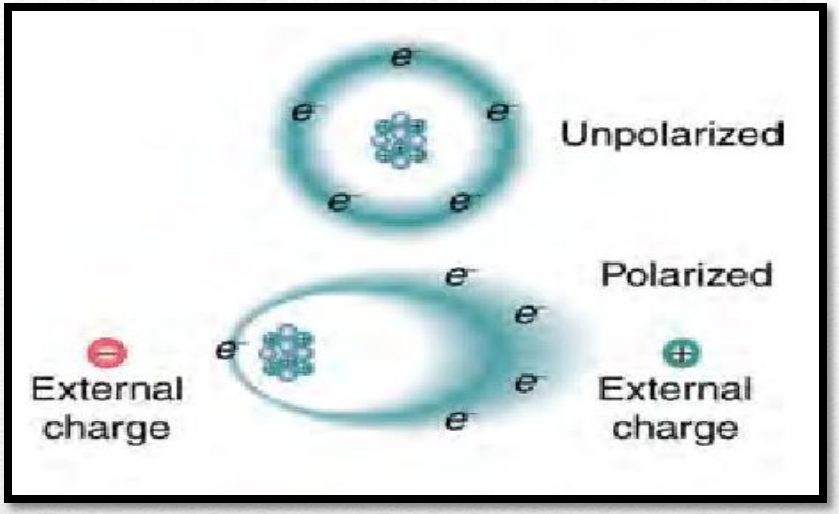
N is number of atoms per cm^3

- ✓ 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

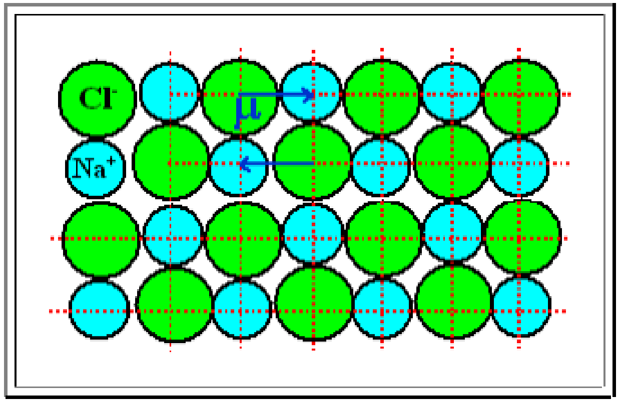
$$\boxed{P_e = 4\pi\varepsilon_0 R^3 EN}$$

- **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**.

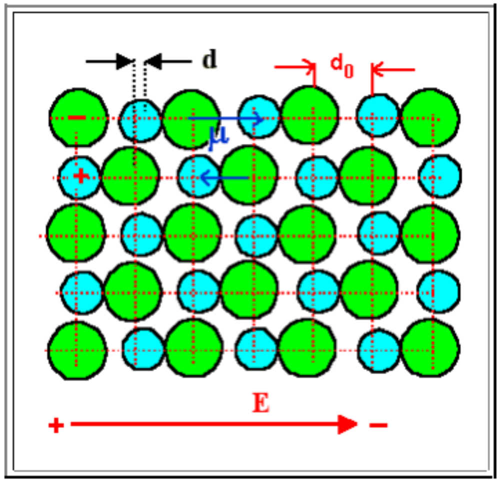
- The lattice can be considered to consist of **Na^+ - Cl^-** dipoles as shown below.



- 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.

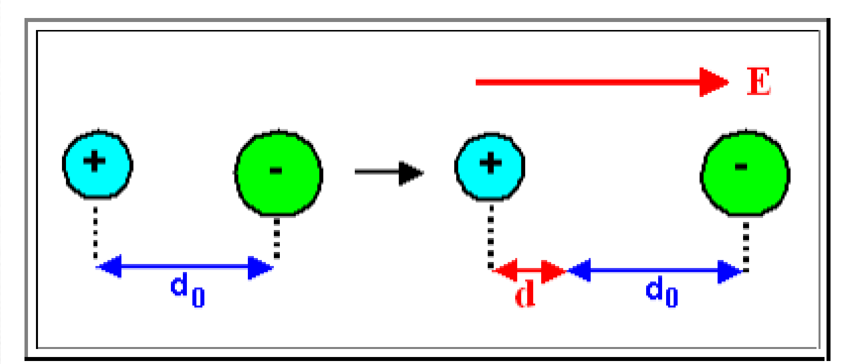
In an electric field, the ions feel forces in opposite directions. For a field acting as shown, the lattice distorts a little bit

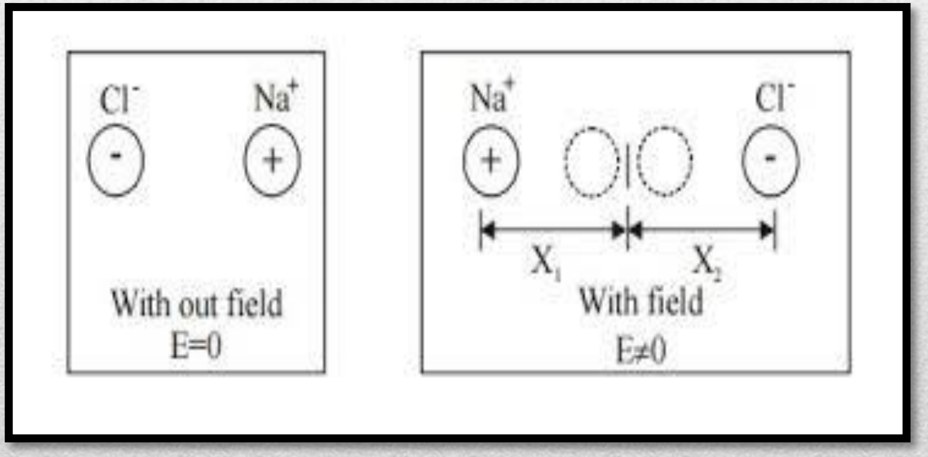
- The **Na^+** ions moved a bit to the right, the **Cl^-** ions to the left.



- 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:





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

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

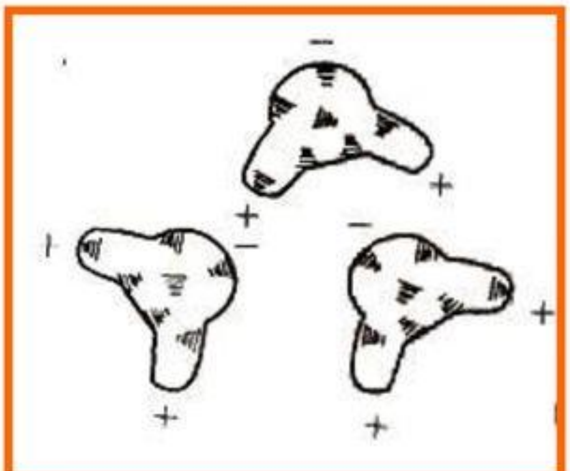
ORIENTATIONAL POLARIZATION

- 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 temperature.

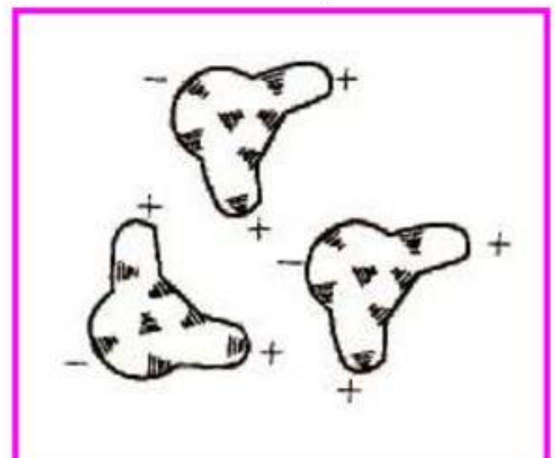
$$\alpha_o = \frac{\mu^2}{3kT}$$

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

μ is permanent dipole moment



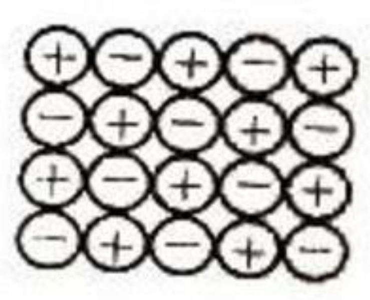
No Field



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,

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

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

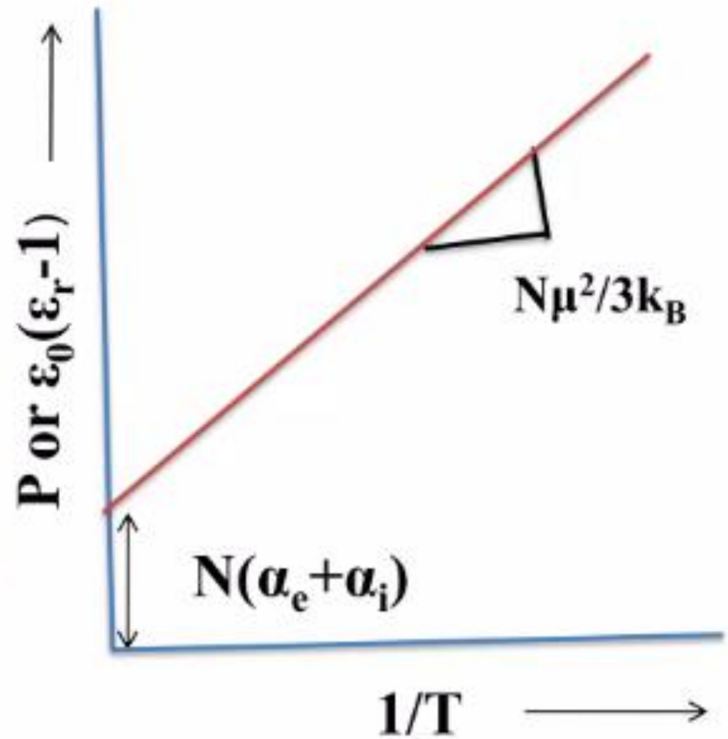
$$\rightarrow \epsilon_r - 1 = \frac{N}{\epsilon_0}\left(4\pi\epsilon_0 R^3 + \frac{e^2}{\omega^2}\left[\frac{1}{M} + \frac{1}{m}\right] + \frac{\mu^2}{3kT}\right)$$

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

Temperature dependent Polarization

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

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



✓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.

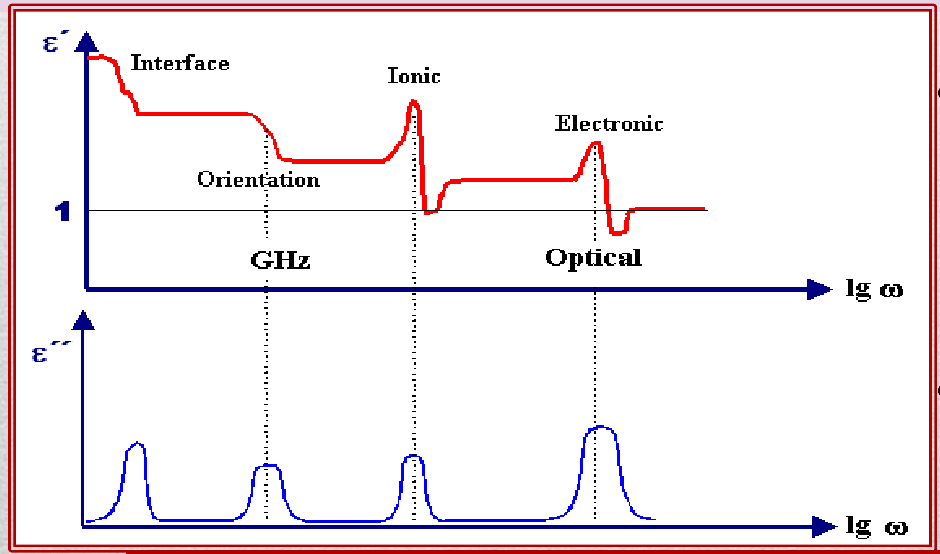
✓Intercept of the line with y axis gives the value of $N(\alpha_e+\alpha_i)$

✓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 → $\therefore$ 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.**