

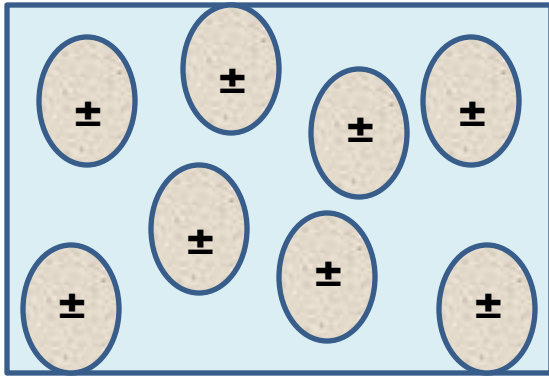
# **DIELECTRIC MATERIALS**

- **Microscopic Displacement of atoms and molecules in an external DC electric field**
- **Polarization and dielectric constant,**
- **Dielectric susceptibility, Temperature and frequency dependence**
- **Dielectric Breakdown.**
- **Ferro-electric material**
- **Piezoelectric Materials**
- **Pyroelectric Materials & Applications**

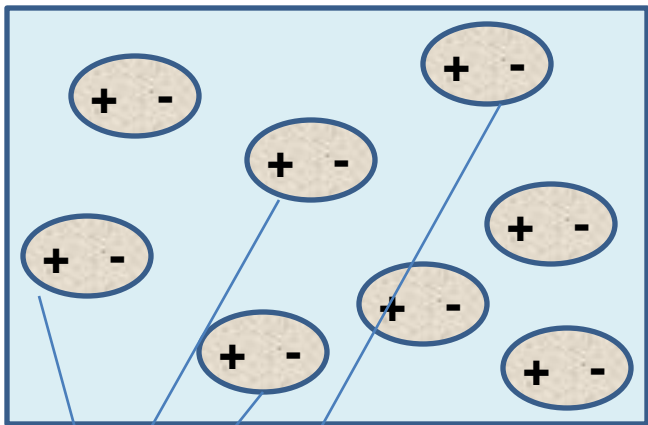
# Dielectrics and Polarisation

- In conductors or semiconductors free mobile carriers conduct electricity through the material, when subject to an electric field.
- In non-conductors, where free carriers are absent, the electrons are bound to the nucleus, but slightly displaced, when an electric field is applied. Positive charges (nucleus) also displaced, but shifting is less as compared to the nucleus as mass is more.

Non-Polar dielectrics  
When  $E=0$



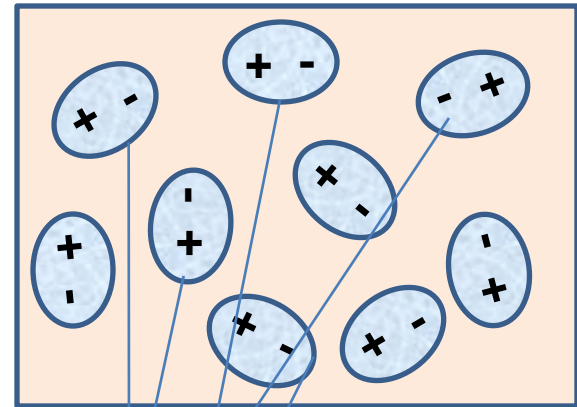
Non-Polar  
When  $E \neq 0$



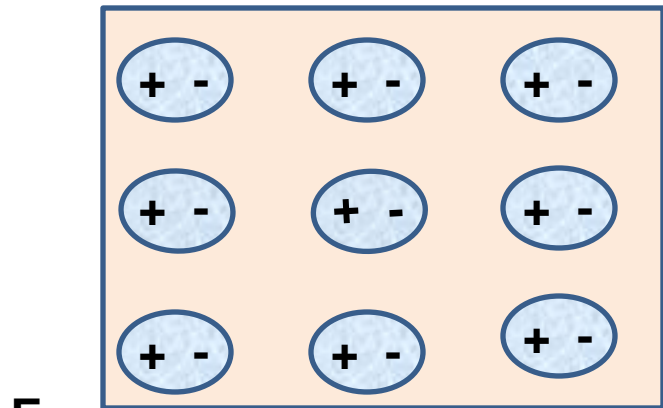
Induced dipoles are set up  
When subjected to EF

## Polarization Effect

Polar dielectrics  
When  $E=0$



Permanent dipoles  
Randomly oriented



Orientation of permanent dipoles  
In the external applied field

# Dielectrics and Polarisation

- **Non-polar:** In some insulators like  $\text{H}_2, \text{O}_2, \text{CCl}_4$  etc., the distribution of electron cloud around the positive nucleus is symmetric, So the CG of negative charges exactly coincide with the positive charge, making the atoms electrically neutral. When electric field is applied, there is a relative shift between the two charges creating **induced dipoles**

# Dielectrics and Polarisation

- **Polar:** if the negative charge distribution is non symmetric around the nucleus, like  $\text{H}_2\text{O}$ ,  $\text{HCl}$ ,  $\text{NH}_3$  etc. the CG of negative charges does not coincide with the positive charge, hence atoms behave like **permanent dipoles** which are randomly oriented . When electric field is applied, these dipoles are oriented in a particular direction

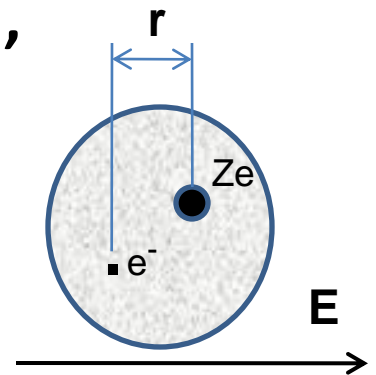
- The setting up of induced dipoles or the orientation of the permanent dipoles in an ext. EF , in the microscopic level results in a net **polarization effect** in the material
- The materials which exhibit polarization effect when subject to an electric field are called **Dielectric Materials** (insulators)

### Microscopic Displacement of atoms and molecules in an external DC electric field

Under a DC electric field the massive nucleus shift a little in the direction of the field, but the light electron cloud shift to a longer distance in the opposite direction.

If the relative displacement between the two is 'r' , the **electric dipole moment** developed is

$$\mu = Ze \cdot r \quad (\text{coul.m})$$



- This dipole moment is proportional to the applied EF
- $\mu \propto E$
- Or,  $\mu = \alpha E$  ,  $\alpha = \mu / E = \text{dipole moment per applied EF}$

**' $\alpha$ ' is the polarisability** of the atom or molecule (**coul-  
m<sup>2</sup>/volt or F-m<sup>2</sup>**)

Net polarization for N no. of atoms/molecules per vol.

$$P = N \mu$$



## Dielectric constant:

for a parallel plate capacitor with plate area 'A'  
and separation between plates 'd'

capacitance of an air capacitor  $C_0 = Q/V = A \epsilon_0 / d$

If a dielectric is inserted then  $C = Q/V = \epsilon_0 \epsilon_r A / d$

Hence,  $C = \epsilon_r C_0$  Or,  $\epsilon_r = C / C_0$

- It indicates that insertion of a dielectric increases the capacitance of a capacitor and **measuring A, d & C we can measure  $\epsilon_r$**

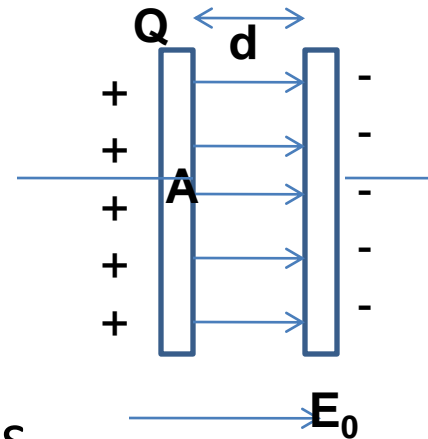
If an air capacitor and a dielectric capacitor are given the same charge 'Q', then potential on the 2<sup>nd</sup> is ,  $V = V_0 / \epsilon_r$

- 'ε<sub>r</sub>' is called the **dielectric constant** of the dielectric
- $\epsilon_r = \epsilon / \epsilon_0$ , is also called as **relative permittivity**
- $\epsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$

### Electric field inside a dielectric

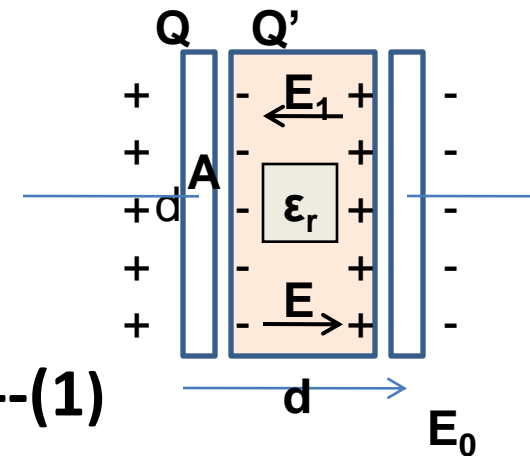
In an air capacitor, let  $E_0$  is the field applied

$Q$  is the charge on capacitor plate



Now if a dielectric is introduced, between the plates, opposite charges are induced on the surfaces of the dielectric and it gets polarized, which creates an EF  $E_1$  within the dielectric opposite to the applied field

Hence, net field inside dielectric is  $E = E_0 - E_1$  -----(1)



- let  $Q'$  is the charge on the surface of the dielectric
- As per Gauss law

$$\epsilon_0 \oint \mathbf{E} \cdot d\mathbf{s} = \epsilon_0 EA = Q - Q' \quad \text{-----}(2)$$

- So,  $E = (Q/\epsilon_0 A) - (Q'/\epsilon_0 A) \quad \text{-----}(3)$

- Comparing (1) & (3)  $E_1 = Q'/\epsilon_0 A \quad \text{-----}(4)$

- Since,  $V = V_0/\epsilon_r$  so,  $E = E_0/\epsilon_r$

- But  $E_0 = Q/\epsilon_0 A$  so,  $E = Q/\epsilon_0 \epsilon_r A$

- In (3),  $Q/\epsilon_0 \epsilon_r A = (Q/\epsilon_0 A) - (Q'/\epsilon_0 A)$

or,  $Q' = Q(1 - 1/\epsilon_r) \quad \text{----}(5)$

- Hence, induced charge in the dielectric is always less than the free charge on the capacitor plate
- Now,  $\epsilon_0 \int \mathbf{E} \cdot d\mathbf{s} = Q - Q' = Q - Q \left(1 - \frac{1}{\epsilon_r}\right) = \frac{Q}{\epsilon_r}$
- Or,  $\epsilon_r \epsilon_0 \int \mathbf{E} \cdot d\mathbf{s} = Q$
- Or,  $\int \mathbf{D} \cdot d\mathbf{s} = Q$  ,
- where,  $\mathbf{D} = \epsilon_r \epsilon_0 \mathbf{E} = \epsilon \mathbf{E}$  -----(6)
- is the electric displacement vector or electric flux density ( C/m<sup>2</sup>) and 'ε' is the permittivity

# Polarisation of a dielectric

- Polarisation effect is the origin of induced charges on the surface of a dielectric
- Polarisation  $\mathbf{P} = \mathbf{Q}'/A$
- ' $\mathbf{P}$ ' is the induced surface charge density on the surface of the dielectric due to polarisation
- $\mathbf{P} = \mathbf{Q}' d / A d$  = Net dipole moment/ volume = Coul.m/m<sup>3</sup>  
= C/ m<sup>2</sup>  
= surface charge density
- If ' $N$ ' is the no. of atoms or molecules per unit volume then
- Polarisation  $\mathbf{P} = \mathbf{N} \boldsymbol{\mu}$
- As  $\mathbf{N} = \rho N_A$  (Avogadro's no.)/  $M$  ( mol. Wt.)

$$\mathbf{P} = \rho N_A \boldsymbol{\mu} / M$$

# Relation between D, E & P

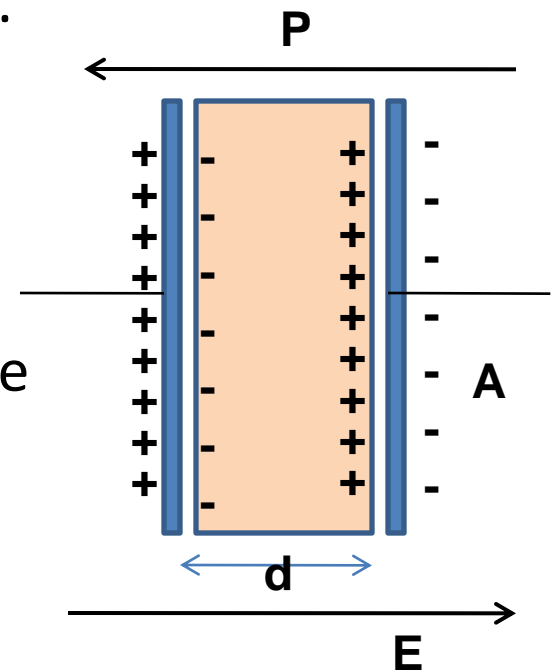
- The charges developed on the plates of capacitor due to external applied field are the **free charges**.
- For an air capacitor, free charges  $Q = C_0 V$



- When a dielectric is introduced in between the plates, it gets polarised; the negative charges shift towards positive plate and positive charge shifts towards negative plate.

- $P = \mu / V = \mu / Ad \rightarrow \mu = PAd$  -----(I)

The dielectric itself behaves as a big single dipole  
 With surface charge density  $\sigma = Q'/A$   
 and its dipole moment is charge X width of the dielectric



- Or,  $\mu = \sigma Ad$  -----(II)

- Comparing (I) & (II) we get  $P = \sigma = Q' / A$

- $\int P.ds = Q'$

- From Gauss law  $\int E.ds = Q - Q' / \epsilon_0 = 1 / \epsilon_0 (Q - \int P.ds)$

- $\int (\epsilon_0 E + P) . ds = Q$

- $\int D.ds = Q$  ; Hence

$$D = \epsilon_0 E + P$$

# Dielectric Susceptibility:

- We have  $\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$
- Also,  $\mathbf{D} = \epsilon \mathbf{E} = \epsilon_r \epsilon_0 \mathbf{E}$
- Hence,  $\mathbf{P} = \mathbf{D} - \epsilon_0 \mathbf{E} = \epsilon_r \epsilon_0 \mathbf{E} - \epsilon_0 \mathbf{E}$
- $\mathbf{P} = \epsilon_0 (\epsilon_r - 1) \mathbf{E}$  ----- (I)
- As  $\mathbf{P} \propto \mathbf{E}$

$$\text{so, } \mathbf{P} = \chi_E \epsilon_0 \mathbf{E} \text{ ----- (II)}$$

Comparing (I) & (II) one gets  $\chi_E = \epsilon_r - 1$  ----- (III)

Where ' $\chi_E$ ' is the dielectric susceptibility of the dielectric and is the measure of the extent to which a material can be polarised by the application of an EF. **It has no unit.** From (III) it is also clear that ' $\epsilon_r$ ' also gives the extent upto which a material can be polarised. The larger the value of ' $\epsilon_r$ ', that easily material can be polarised



## Macroscopic field:

- When  $\mathbf{E}_0$  is external applied field and  $\mathbf{E}_1$  is the field due to induced charges on the surface of the dielectric, which is opposite to  $\mathbf{E}_0$
- The net field  $\mathbf{E} = \mathbf{E}_0 - \mathbf{E}_1$  is called the **macroscopic field** and is uniform throughout the dielectric (a bulk property)
- $\mathbf{E} = \mathbf{E}_0 - Q' / \epsilon_0 A$  or,  $\mathbf{E} = \mathbf{E}_0 - \mathbf{P} / \epsilon_0$
- This is a smoothly varying field, continuous at the boundary
- $\mathbf{E}_0$  &  $\chi_E$  are the macroscopic parameters

## Microscopic field:

- Each atom / molecule inside the material experience a field, which is **due to the surrounding dipoles, their magnitude and arrangement around the atom/ molecule** is called the **microscopic field**.
- If the material is polyatomic, this microscopic field is different at diff. Atom/ mol. site

- The dipole moment at an atom site 'i',  $\mu_i = \alpha_i E_i$

Where, ' $\alpha_i$ ' is the polarisability of the  $i^{\text{th}}$  atom/ mol. It is a measure of the extent upto which an atom can be polarized

- $E_{\text{micro}} = E_0 - E_1 + E_2 + E_3 = E_{\text{macro}} + E_2 + E_3$

- $E_2$  and  $E_3$  are the fields due to various effects of surrounding dipoles

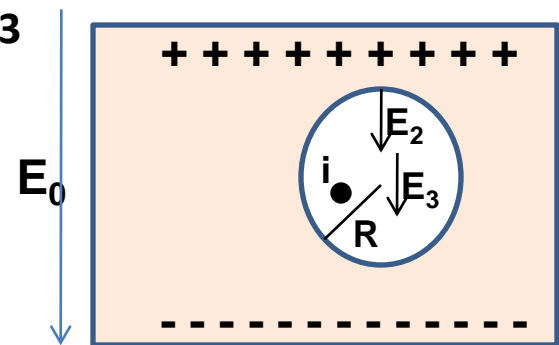
- for cubical symmetry,  $E_3$  is zero

and  $E_2 = P \gamma / \epsilon_0$

with  $\gamma = 1/3$  for cubical symmetry

Hence,  $E_{\text{micro}} = (E_0 - P / \epsilon_0) + P / 3 \epsilon_0$

$$E_{\text{micro}} = E + P \gamma / \epsilon_0$$



## Polarization and polarisability:

- Polarization = net dipole moment per volume  
 $= \sum_i N_i \mu_i$ , with  $N_i$  = no. of 'i' type atom per volume and  
i

$\mu_i$  = dipole moment of  $i^{\text{th}}$  atom

Hence,  $P = \sum N_i \alpha_i E_i$

$P = N \alpha E_{\text{macro}}$  for system with identical atoms  
 $= \epsilon_0 (\epsilon_r - 1) E$

Or,  $\epsilon_0 (\epsilon_r - 1) = N \alpha$  -----(i)

or,  $\epsilon_r = 1 + (N \alpha / \epsilon_0)$  -----(ii)

or,  $\epsilon_r = 1 + (\rho N_A \alpha / M \epsilon_0)$  -----(iii)

## Clausius- Massotti Relation :

- $P = \sum N_i \alpha_i E_i$
- $P = \sum N_i \alpha_i ( E + P \gamma / \epsilon_0 )$   
 $= N \alpha E ( 1 + P \gamma / E \epsilon_0 ) = N \alpha E ( 1 + \chi / 3 )$

Or,  $1 + \chi / 3 = P \epsilon_0 / N \alpha E \epsilon_0$

- $1 + \chi / 3 = \chi \epsilon_0 / N \alpha$
- Or,  $3 + (\epsilon_r - 1) = 3 \chi \epsilon_0 / N \alpha$

- Or,  $(\epsilon_r - 2) = 3 (\epsilon_r - 1) \epsilon_0 / N\alpha$

- Or,  $(\epsilon_r - 1) / (\epsilon_r + 2) = N\alpha / 3 \epsilon_0 \dots\dots\dots(A)$

- this is a relation between macroscopic parameter dielectric constant ' $\epsilon_r$ ', and macroscopic parameter polarisability ' $\alpha$ '  
Called **Clausius- Massotti Relation** . Eq. (A)  
is for cubical symmetry.

- Using Clausius-Mosotti equation, we can measure polarisability, , by measuring relative dielectric constant, and no. of dipoles per unit volume.

# Polarisation Mechanisms:

- There are three types of mechanisms by which dipoles are set up and the material mediums get polarized

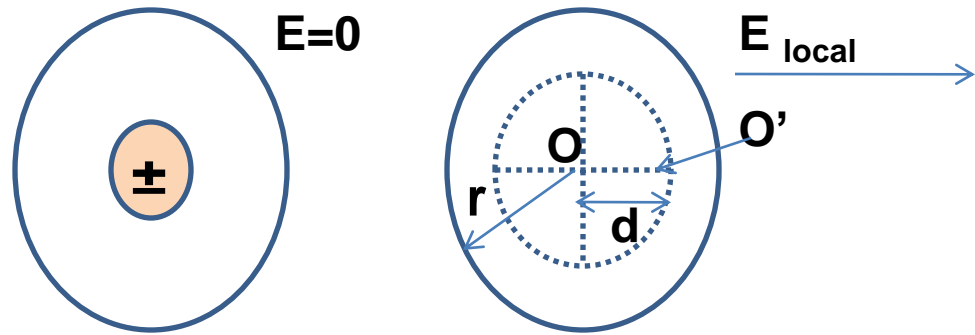
## 1. Electronic polarization

## 2. Ionic polarization

## 3. Dipolar or Orientation polarization

### 1. Electronic polarization:

- This is due to the response of the individual atoms of the dielectric to the microscopic or local field
- The electronic charge cloud shifts in the opposite direction of the field, whereas the positive nucleus shifts in the field direction
- Hence, the atom acquires an induced dipole moment giving rise to electronic polarisation



**Electronic polarization:**

- Under the local field, positive charge shifts to  $O' = Ze$
- Effective negative charge to  $O$ , as seen by the nucleus
- Under local field  $E_{loc}$ , force experienced by the electron cloud is

$$\mathbf{F}_{loc} = -Ze \mathbf{E}_{loc}$$

- The relative shift between the two is 'd'
- Hence, dipole mom. =  $\mu_e = Ze \cdot d$

- Effective negative charge seen at  $O' =$  (total negative charge/ vol. of the atom)  $\times$  (vol. of the sphere of radius 'd')

$$= -Ze / (4\pi / 3) r^3 \times (4\pi / 3) d^3$$

$$\text{or, } Q' = -Ze (d^3/r^3)$$

- Columbic attractive force between the two is
- $F_{\text{col.}} = (1/4\pi\epsilon_0 d^3) \times \{Ze (-Ze (d^3/r^3))\}$   
 $= -Z^2e^2 d / 4\pi\epsilon_0 r^3$
- At eqbm.  $F_{\text{loc}} = F_{\text{col}}$
- so,  $Zed = 4\pi\epsilon_0 r^3 E_{\text{loc}}$

or,  $\mu_e = 4\pi\epsilon_0 r^3 E_{\text{loc}}$

**Electronic Polarisability**

$$\alpha_e = \mu / E_{\text{loc}} = 4\pi\epsilon_0 r^3$$

**Electronic Polarisation**

$$P_e = N \alpha_e E_{\text{loc}} = N 4\pi\epsilon_0 r^3 E_{\text{loc}}$$

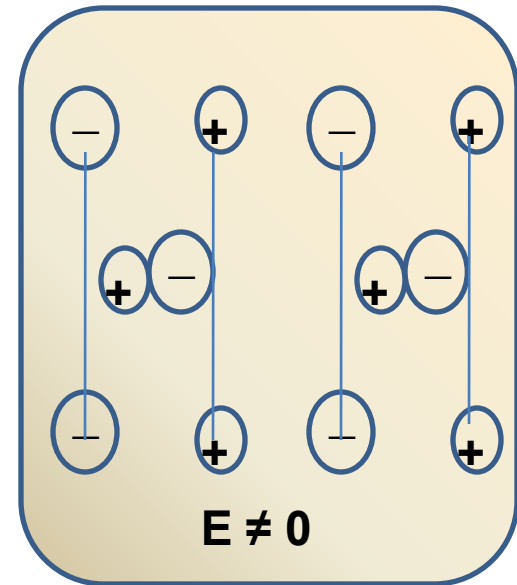
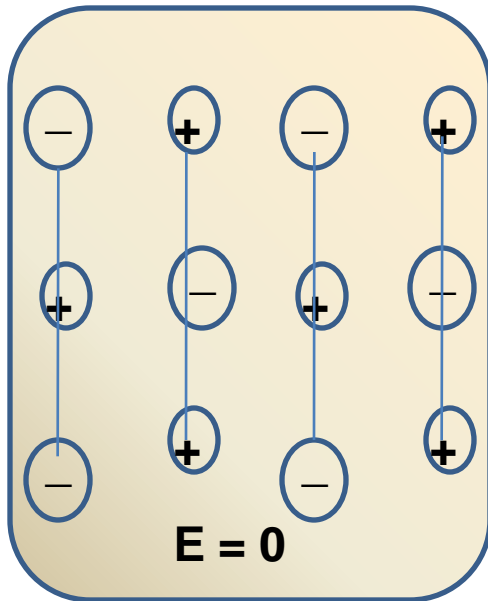
**Electronic Susceptibility**

$$\chi_E = 4\pi N r^3 \text{ and } \epsilon_r = 1 + 4\pi N r^3$$

- Ex;- diamond, phosphorous, inert gases



# Ionic polarization



In dielectrics of ionic bonding the positive and negative ions are displaced under the influence of the local EF near the ions, which induces dipole moment. This induced dipole moment per local field is called **ionic polarisability**.

- On application of an electric field, let the +ve ions move by  $\mathbf{x}_1$  and -ve ions move by  $\mathbf{x}_2$ . Mass of +ve ion is ' $\mathbf{m}$ ', and mass of -ve ion is ' $\mathbf{M}$ '.
- Force on the ions due to applied field,  $\mathbf{F} = \mathbf{qE}$

- Induced dipole moment due to ion displacement,  

$$\mu_i = q(x_1 + x_2)$$
- But a restoring force  $F = m \omega_0^2 x_1$  &  $F = M \omega_0^2 x_2$   
 will act on each ion to bring them back to their mean position. Under the action of these two forces, the ions show an oscillatory motion.
- $qE = m \omega_0^2 x_1 = M \omega_0^2 x_2$
- So,  $x_1 = qE / M \omega_0^2$  &  $x_2 = qE / m \omega_0^2$
- This implies  $\mu_i = q^2 E / \omega_0^2 [ 1/m + 1/ M ]$
- $\alpha_i = \mu_i / E = q^2 / \omega_0^2 [ 1/m + 1/ M ]$
- $P_i = N \alpha_i E = N q^2 / \omega_0^2 [ 1/m + 1/ M ] E$
- find  $\epsilon_r$  &  $\chi$
- Example: Alkali Halides

## Dipolar or orientation polarisation:

- In the polar dielectric system, the permanent dipoles are randomly oriented in the absence of an electric field. When an EF is applied they become oriented in a particular direction, which is called **dipolar or orientation polarisation**
- Orientation polarisation  $\mathbf{P}_o = N\mu_o \mathbf{L}(\mathbf{a})$

Where,  $\mathbf{L}(\mathbf{a})$  is called Langevin's function  $\mathbf{L}(\mathbf{a}) = \{ \coth \mathbf{a} - 1/\mathbf{a} \}$

$$\mathbf{a} = \mu_o \mathbf{E} / k_\beta \mathbf{T}$$

- Usually  $\mathbf{a} \ll 1$ , so  $\mathbf{L}(\mathbf{a}) \approx \mathbf{a}/3$  &  $\mathbf{L}(\mathbf{a}) = \mu_o \mathbf{E} / 3k_\beta \mathbf{T}$
- Hence,  $\mathbf{P}_o = N \mu_o^2 \mathbf{E} / 3k_\beta \mathbf{T}$  &
- $\chi_E = N \mu_o^2 / 3 \epsilon_o k_\beta \mathbf{T} \rightarrow$  is Curie law

- So, orientational polarisation is **inversely proportional to temp. 'T' and depends on the EF 'E'**
- thermal energy tries to randomize the orientation  
but EF tries to orient the dipoles
- **Ex; polymers, organic liquids & solids , water, inorganic oxides, ceramics**
- This type of material is also called Para electric Material.

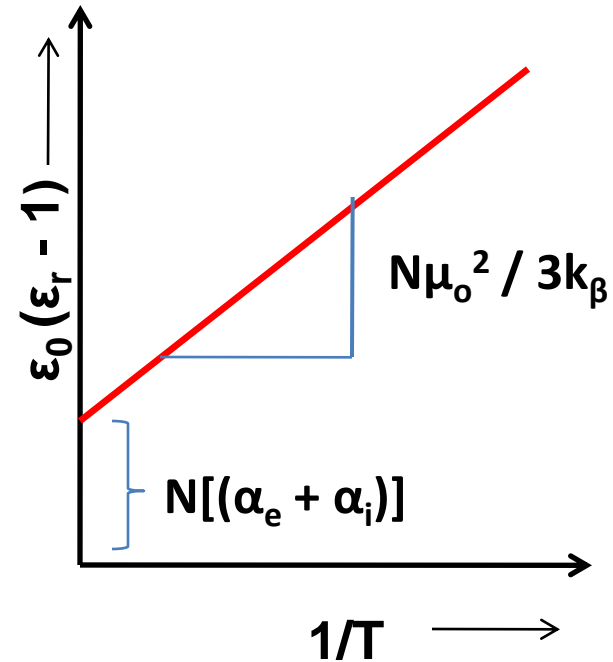
### **Total Polarisation:**

- When a dielectric has neither ionic bonding nor permanent dipoles, they show electronic polarisation
- Ionic crystals having no permanent dipoles show ionic polarisation
- But most of the polyatomic dielectric show all the three type of polarisation

- So, total polarisation  $\mathbf{P}_T = \mathbf{P}_e + \mathbf{P}_i + \mathbf{P}_o$
- Or,  $\mathbf{P}_T = N\{ \alpha_e + \alpha_i + \alpha_o \} \mathbf{E}$
- $= N\{ \alpha_e + \alpha_i + \mu_o^2 / 3k_\beta T \} \mathbf{E}$
- As  $\mathbf{P} = \epsilon_0 (\epsilon_r - 1) \mathbf{E}$
- So  $\epsilon_0 (\epsilon_r - 1)$   
 $= N[(\alpha_e + \alpha_i)] + N\mu_o^2 / 3k_\beta(1/T)$

Graph between  $\epsilon_0 (\epsilon_r - 1)$  &  $1/T$   
 is a straight line, whose slope is  $\frac{N\mu_o^2}{3k_\beta}$   
 & intercept is  $\underline{N[(\alpha_e + \alpha_i)]}$

Hence  $\mu_o, \alpha_e, \alpha_i$  can be found out



# Temperature dependance of dielectric constant

- Total polarisation

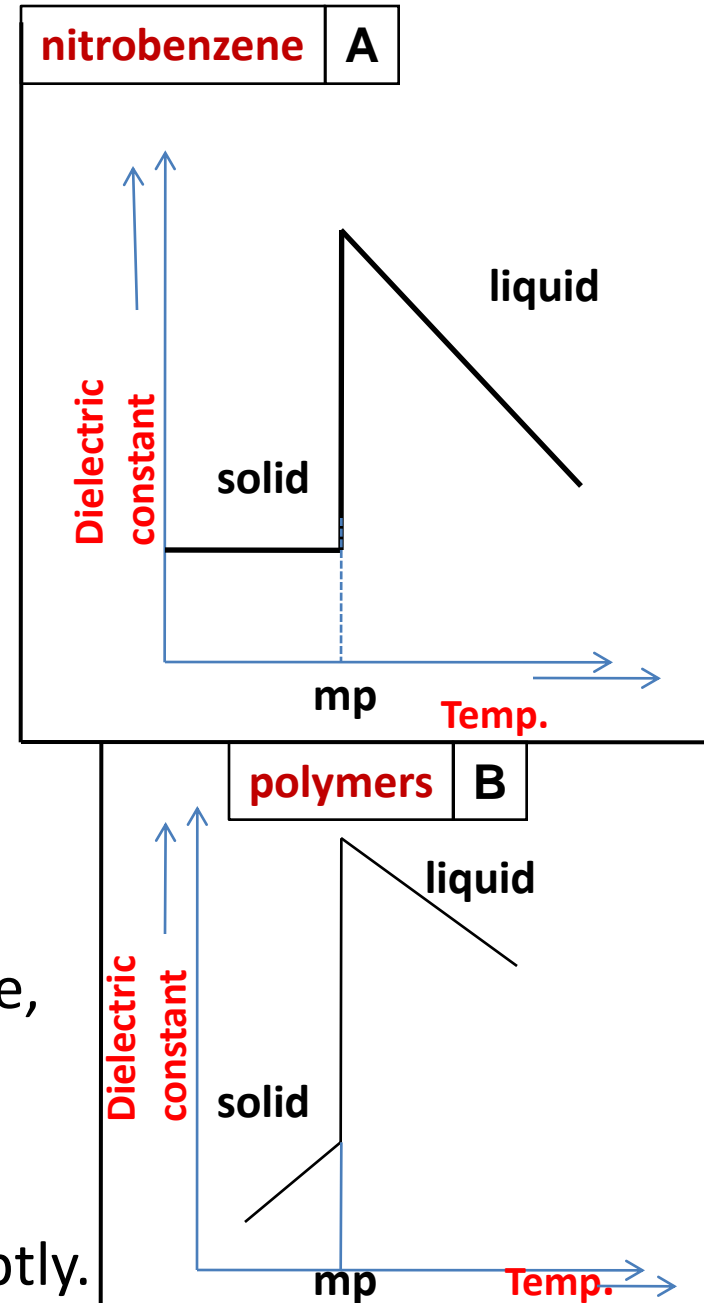
$$P_T = N \{ \alpha_e + \alpha_i + \mu^2 / 3k_\beta T \} E$$

only the third term is temp. dependant  
hence, polar dielectrics with permanent dipoles shows a temp. dependence.

In polyatomic gases & liquids polarisation decreases with increase in temperature

Ex;- fig [A], nitrobenzene, when passes from liquid phase to solid phase,  $\epsilon_r$  increases, as temp. decreases

- At the **mp** when it passes to the solid phase, the permanent dipoles become **frozen**. So orientational polarisation  $P_o$  gradually ceases to contribute, decreasing the value of  $\epsilon_r$  abruptly.

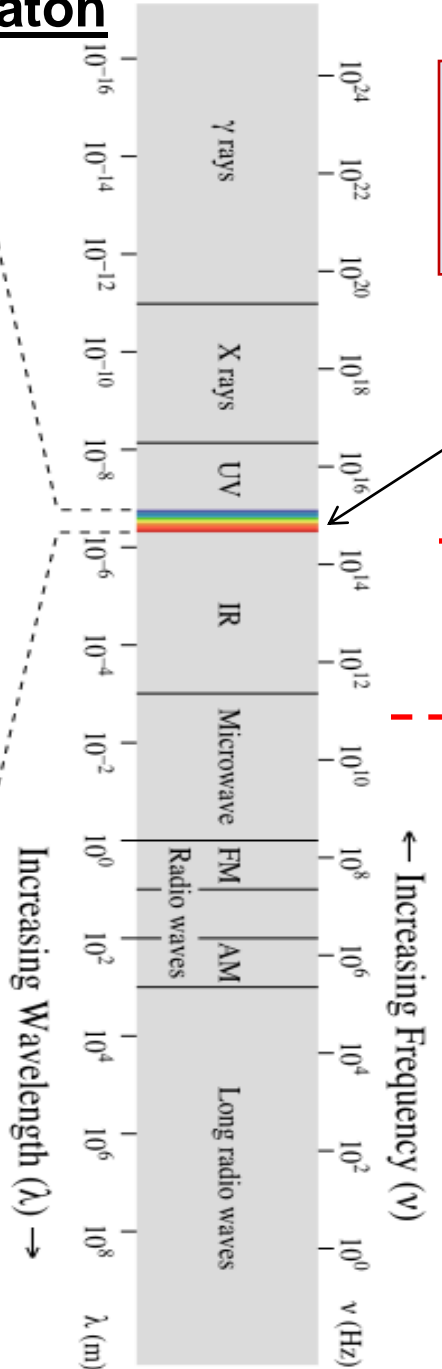
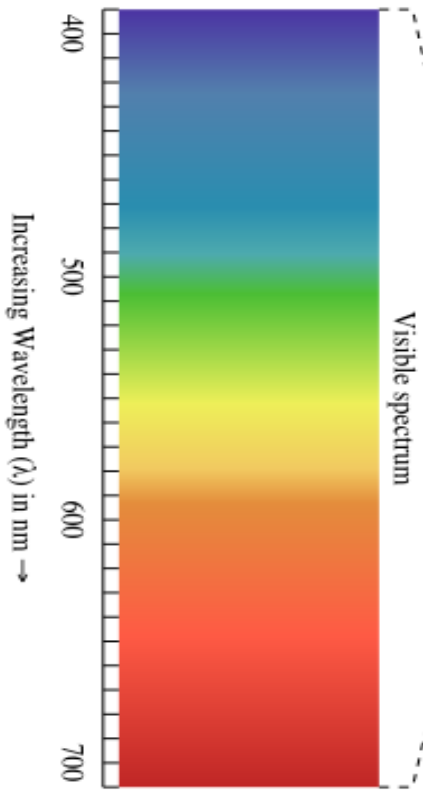


- In the solid phase, the only contributions are due to electronic and ionic polarisation, which are independent of temp. hence, dielectric constant practically remains constant with variation in temp.
- In [B] there are some thermally mobile dipoles even below  $m_p$ , which contribute and there is a little variation in the dielectric constant  $\epsilon_r$  with temp.

### **Frequency dependence:**

- For DC field applied, polarisation or dielectric const. do not depend on frequency
- For AC field applied, displacement of charges, ions or orientation of permanent dipoles should vary periodically with the changing field.
- When the freq. of EF (em radiation) is high, due to fast reversal of the field the switching of dipoles according to the field becomes difficult.
- Due to inertia, the switching of orientational & ionic polarisation is slower than the electronic polarisation ; - dipolar the slowest, ionic slower, but electronic the fastest

# Frequency dependence of polarisation



In optical range value of  $\epsilon_r$  is low as the only contributor is  $P_e$

$P_T = P_e$

$\epsilon_r = n^2$

$P_T = P_e + P_i$

$P_T = P_e + P_i + P_o$

R.I. =  $n = c/v = \sqrt{\mu_r \epsilon_r}$   
 Or,  $\epsilon_r = n^2$   
 as  $\mu_r$  is = 1 for nonmagnetic materials



# Dielectric Loss ,dielectric strength & , dielectric breakdown

## Dielectric loss

In the external AC field the dielectric constant is a complex quantity, the imaginary term implying energy absorption by the dielectric or the power loss . This is called **Dielectric loss**

$$\epsilon_r = \epsilon_r' + i\epsilon_r''$$

## Dielectric strength:

- Dielectric materials are basically insulators. They are used for insulation in electrical & electronics circuits. In the ext. EF they act as insulator upto certain limit (critical field), beyond which they start to conduct and reach the breakdown limit.
- The external electric field at which a dielectric breaks down is called the **Dielectric strength (V/m) [ maximum EF a dielectric can withstand]**

# Dielectric Breakdown:

- When a dielectric material, for some reason starts to conduct, (there is a sudden increase in the current), it loses its dielectric property. This is known as dielectric breakdown. Various breakdown processes are:
  - Avalanche breakdown
  - Thermal breakdown
  - Defect breakdown
  - Discharge Breakdown

## Avalanche Breakdown:

- If electric field is high, some electrons attain sufficient energy to cross the large band gap into conduction band. These high energy electrons collide with other bound electrons and also dislodge them. Process multiplies. This causes a large current to flow through the dielectric causing breakdown called **Avalanche Breakdown**.

## **Thermal Breakdown:**

Losses in the dielectric can produce heat. This is not dissipated due to poor value of thermal conductivity. So the temperature of the dielectric will rise causing more losses. Such a catastrophic process will cause large current to flow giving a breakdown called **Thermal Breakdown.**

## **Defect Breakdown:**

If there are defects like cracks, pores or impurities in a dielectric material, these can be filled with moisture leading to high current flowing through these defect regions. Such a breakdown process is called **Defect Breakdown.**

## **Discharge Breakdown:**

If the material has gas bubble, there will be discharge current through the gas on application of an electric field. Such a breakdown process is called **Discharge Breakdown.**