Dielectric Materials

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Materials Based on electrical resistivity

Resistivity range in Ohm m ⇨ *25 orders of magnitude*

Metallic materials ⟷ Semi-conductors

10^{-9}		10^{-7}		10^{-5}		10^{-3}		10^{-1}		10^{-1}		10^{3}	
Ag Cu Al Au		Ni Pb		Sb Bi Graphite		Ge (doped)		Ge				Si	

Insulators

10^{5}		10^{7}		10^{9}		10^{11}		10^{13}		10^{15}		10^{17}	
Window glass *Ionic conductivity*				Bakelite		Porcelain Diamond Rubber Polyethylene		Lucite Mica		PVC		SiO_2 (pure)	

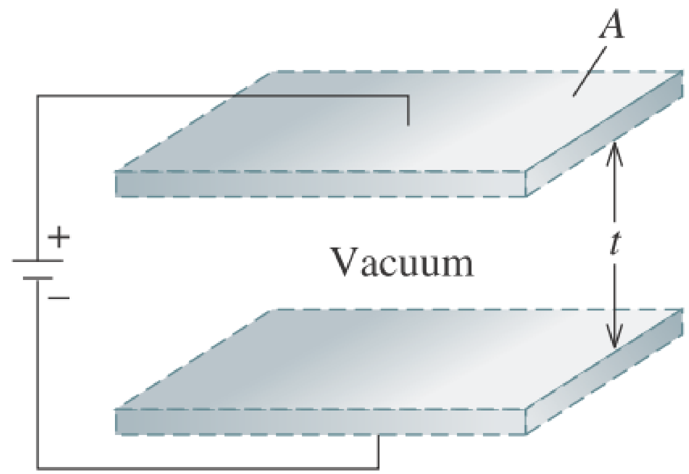
Dielectric materials

Class of insulators which polarizes on application of electric field

- Difficult to excite electrons from valence to conduction band by thermal means or by applied electric field.
- Very poor conductor of electricity.
- Exhibits or may be made to exhibit an electric dipole structure;
- Separation of positive and negative charged entities on a molecular/ atomic level.

Capacitance

When a voltage is applied across a capacitor, one plate becomes positively charged, the other negatively charged, with the corresponding electric field directed from the positive to the negative.



$$C = \frac{Q}{V}$$

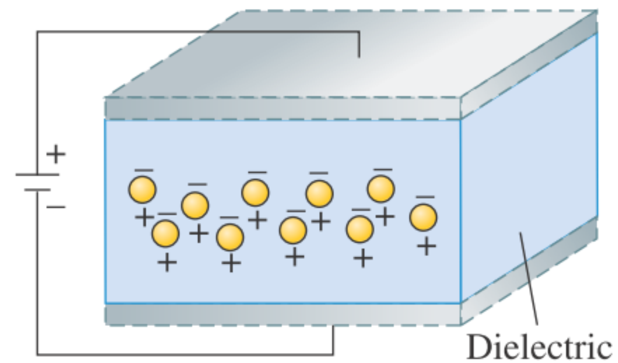
For a parallel plate with area A and distance t, in vacuum, C is given by

$$C_0 = \frac{\varepsilon_0 A}{t}$$

$$\varepsilon_0 = 8.85x10^{-12}\ F/m$$

Relative permittivity of a free space

Dielectric permittivity/constant



For a given dielectric material with plates having area A and thickness t, C is given by

$$C = \frac{\varepsilon A}{t}$$

ε - Relative permittivity of a medium

The relative permittivity ε_r , often called the dielectric constant, is equal to the ratio

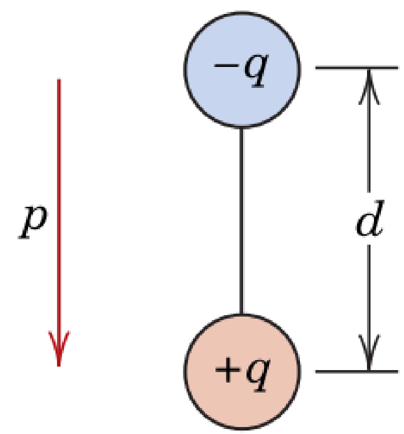
$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \frac{C}{C_0}$$

Dielectric constant – Charge storage capacity of the material

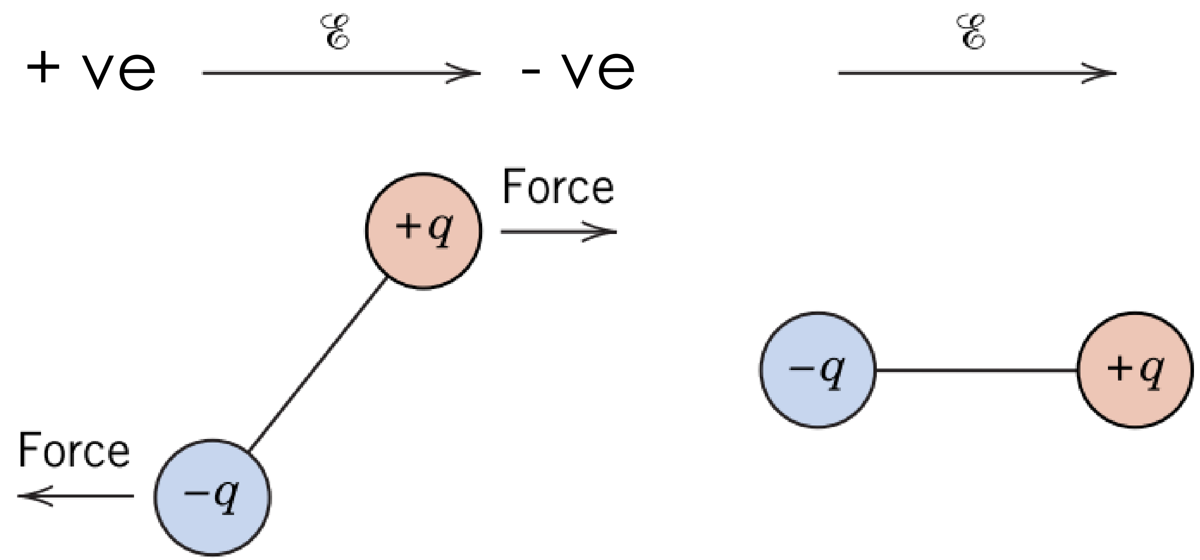
Polarization

Electric dipole, there is a separation between a + ve and a - ve electric charge.

Electric dipole moment $p = q.d$



No electric field



In presence of an electric field

In presence of an electric field E, there will be a force (or torque) on the electric dipole to orient it with the applied field;

The process of dipole alignment is termed Polarization.

Polarization

Polarization is total dipole moment per unit volume

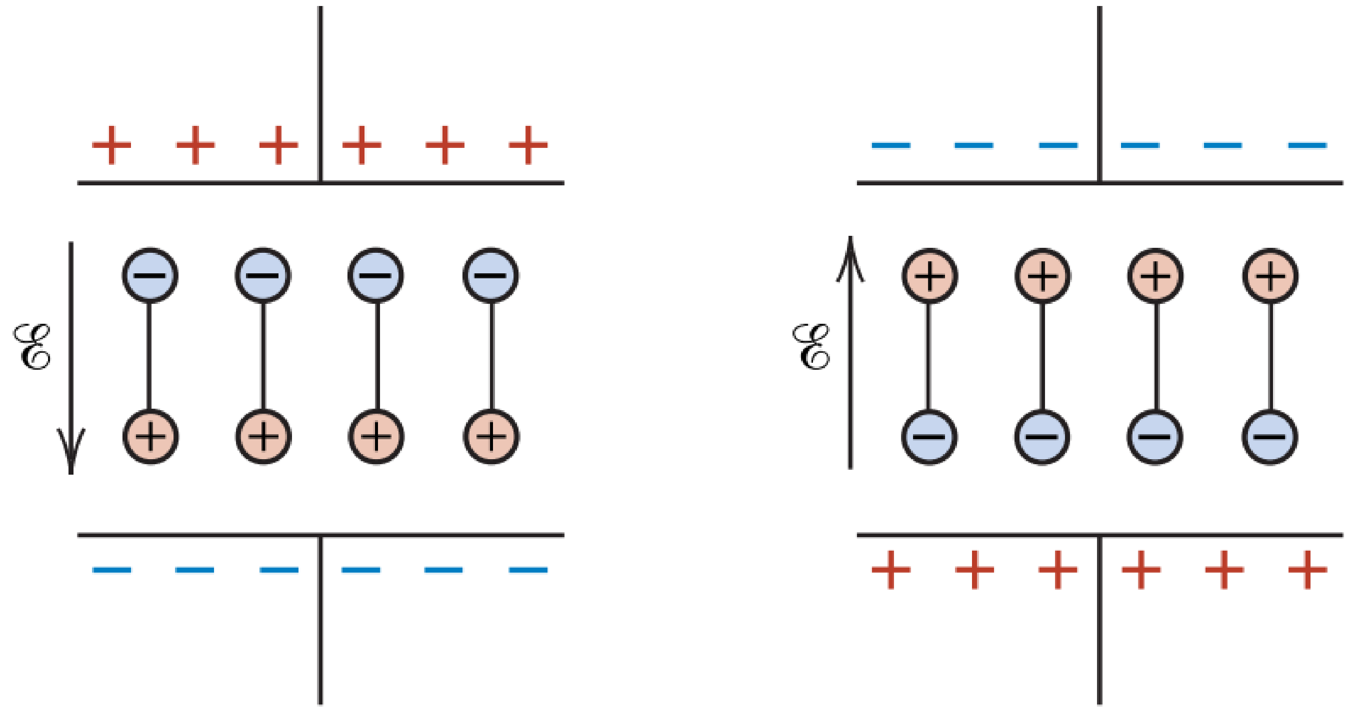
Polarization electric field within the dielectric that results from the mutual alignment of the many atomic or molecular dipoles with the externally applied field *E*.

For many dielectric materials, *P* is proportional to *E* through the relationship

$$P = \varepsilon_0 (\varepsilon_r - 1) E$$

Polarization vs AC field

For many practical applications AC field is necessary



So, Dipoles has to reorient with the field

How much time does it take?

Polarization vs AC field

- For each polarization type, some minimum reorientation time exists.
- This time depends on the ease with which the particular dipoles are capable of realignment.
- This time is called as relaxation time.

$$P(t) = P_0\left[1 - e^{-t/t_r}\right]$$

P_0 = Maximum polarization attained on prolonged application of a static field.

$P(t)$ = Polarization attained in time t.

t_r = relaxation time.

- Relaxation frequency = Reciprocal of the relaxation time.

Dielectric loss/Power loss

Absorption of electrical energy by a dielectric material that is subjected to an alternating electric field.

Dielectric loss is the dissipation of energy through the movement of charges in an alternating electromagnetic field as polarization switches direction.

The dipoles could not follow the AC field and get relaxed or lose energy to become stable.

Types of Polarization

A dielectric material can have more than one polarizations present

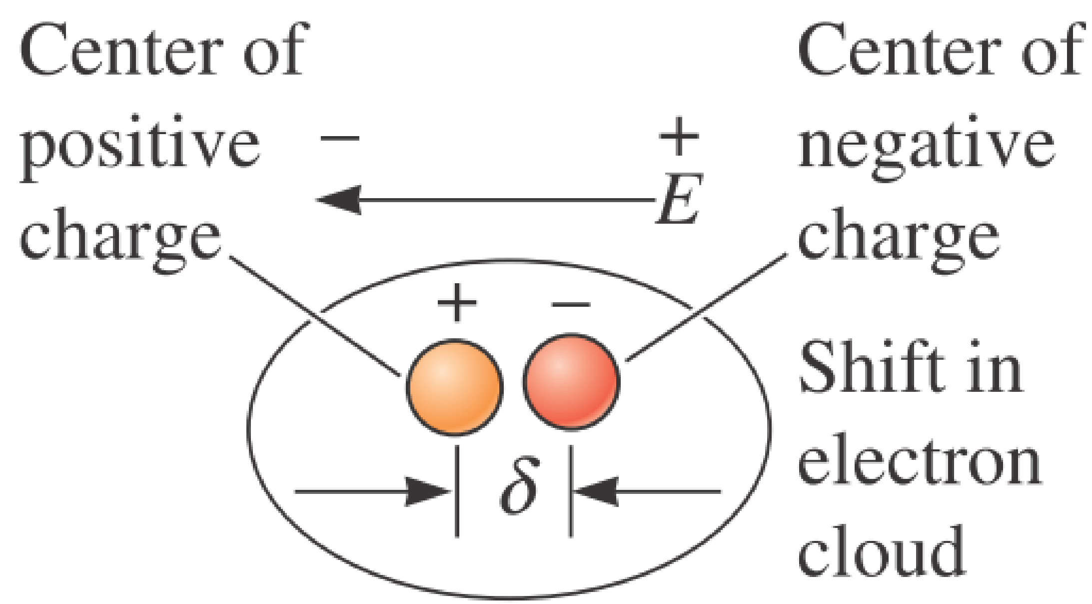
1. Electronic polarization (P_e)
2. Ionic polarization (P_i)
3. Orientation/Dipolar polarization (P_o)
4. Space charge polarization (P_s)

The total polarization P of a substance is equal to sum of all types of polarizations

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

1. Electronic polarization

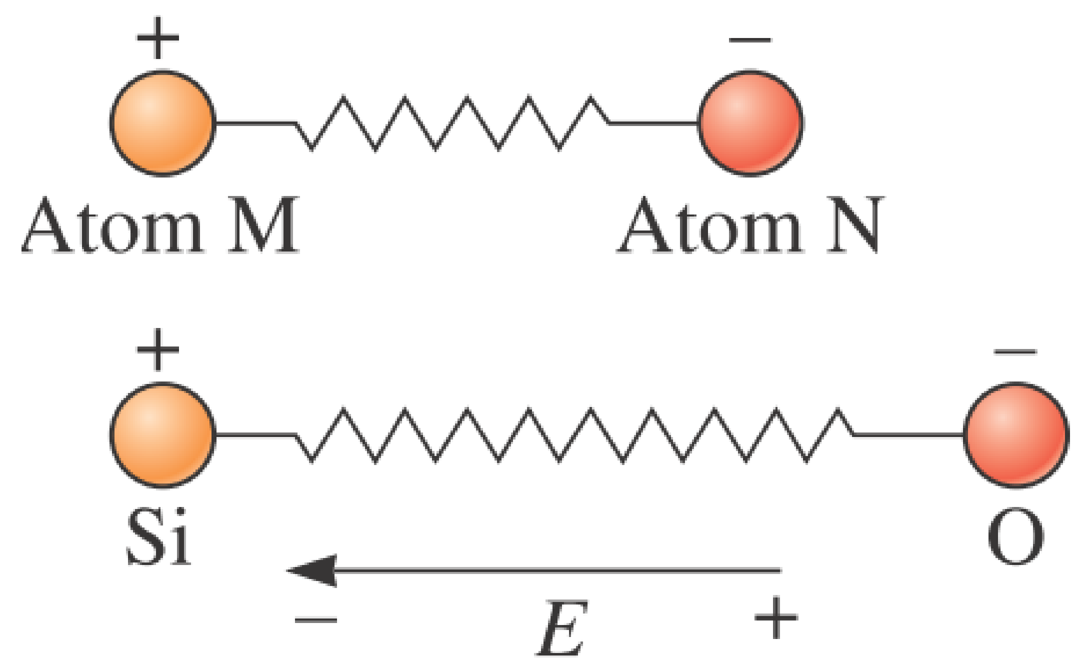
1. May be induced to one degree or another in all atoms.
2. Results from a displacement of the center of the negatively charged electron cloud relative to the positive nucleus of an atom by applied field.
3. Present in all dielectric materials and only when an electric field is applied.
4. Independent of temperature.
5. Relaxation frequency: ~ 10^{15} Hz.



2. Ionic polarization

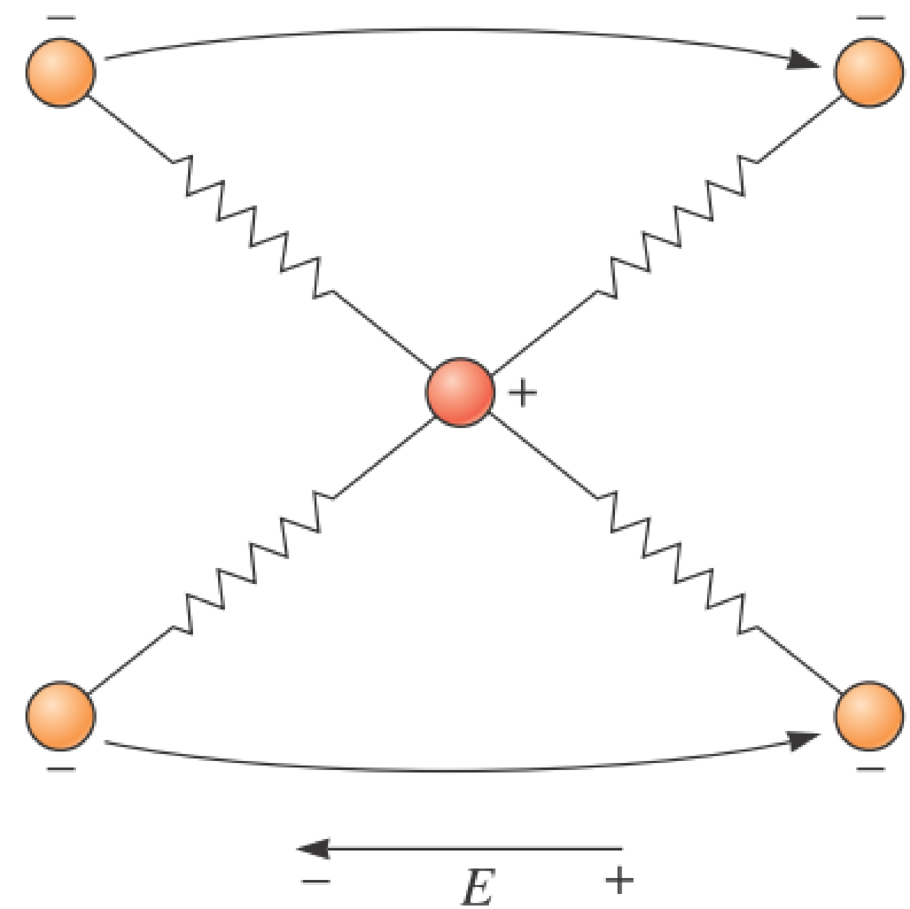
1. Occurs only in ionic materials.
2. Cations & anions are displaced in opposite direction due to field.
3. Magnitude of dipole moment for each ion pair.

   $p_i = qd_i$; d_i is relative displacement
4. Independent of temperature.
5. Relaxation frequency: ~ 10^{13} Hz.



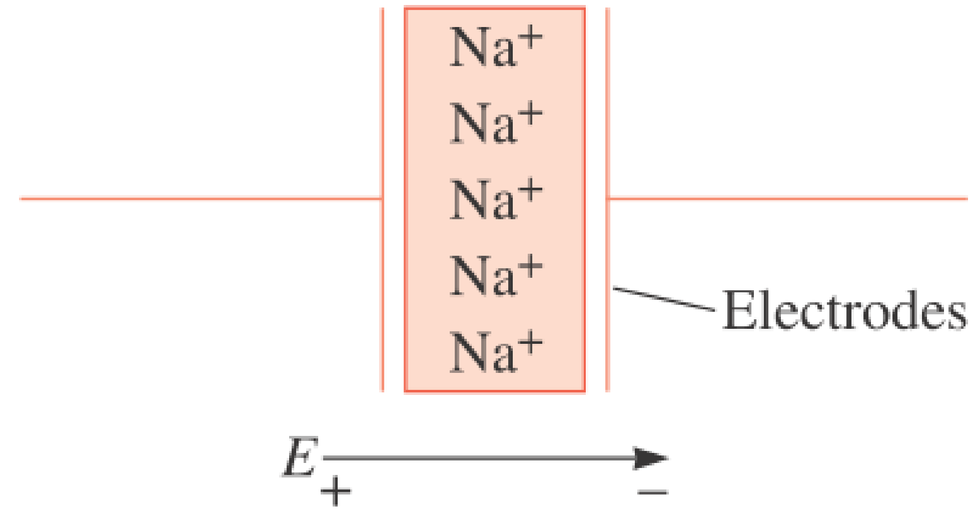
3. Orientation/Dipolar polarization

1. Found only in materials with permanent dipole moments.
2. Results from a rotation of the permanent moments into the direction of the applied field.
3. This alignment tendency is counteracted by the thermal vibrations of the atoms, such that polarization decreases with increasing temperature.
4. Relaxation frequency: ~ 10^{10} Hz.



4. Space charge polarization

1. Occurs due to accumulation of charges at electrodes, grain boundaries or at interfaces in a multiphase materials.
2. Ions diffuse over appreciable distance in response to the applied electric field → redistribution of charges in the dielectric medium.
3. Increases with temperature.
4. Relaxation frequency: ~ 10^2 Hz.



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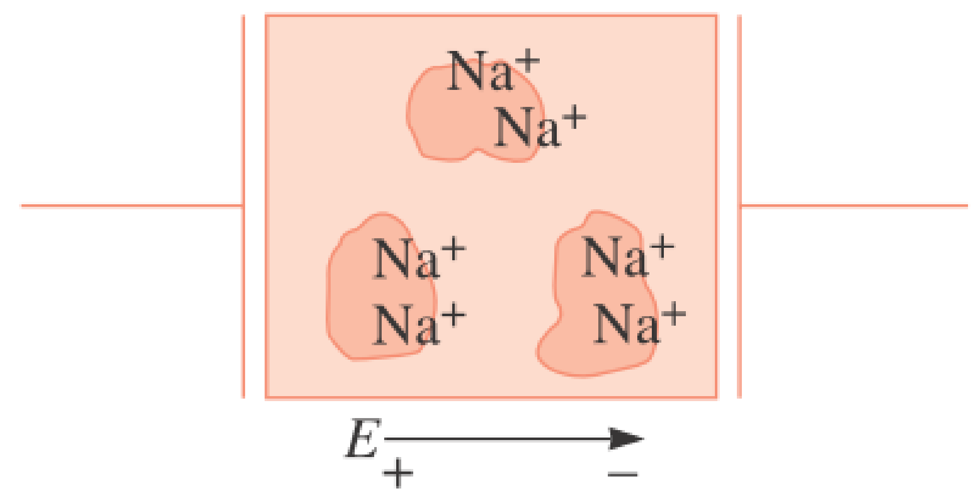
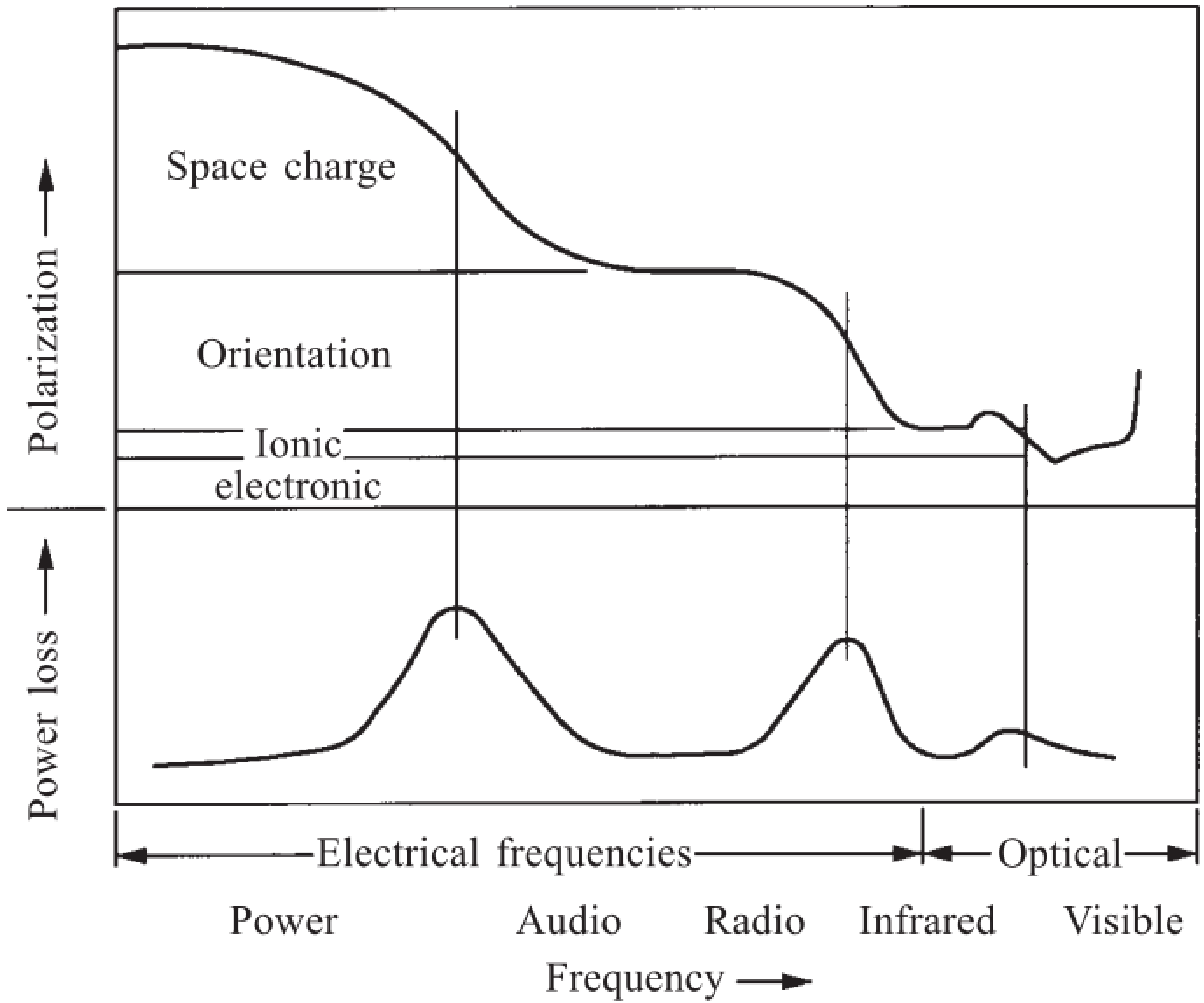


Dielectric polarization vs frequency

The polarization decreases with frequency



Dielectric field strength

Upper limit of the applied electric field

When very high electric fields are applied across dielectric materials, large numbers of electrons gets excited to energies within the conduction band.

As a result

1. The current increases through the dielectric dramatically
2. Localized melting,
3. burning,
4. or vaporization

This causes irreversible degradation and even failure of the material.

This phenomenon is known as dielectric breakdown.

The dielectric strength, sometimes called the breakdown strength, represents the magnitude of an electric field necessary to produce breakdown.

Selected dielectric materials

Material	ε_r 60 Hz	ε_r 10^6 Hz	$\tan\delta$, 10^6 Hz	Dielectic strength, 10^6 V m^{-1}
Electrical porcelain	6	6	0.02	5
Steatite, $MgO{\cdot}SiO_2$	6	6	0.001	12
Fused silica	4	3.8	0.0001	10
Soda-lime-glass	7	7	0.005	10
Mica	8	5	0.0005	100
Nylon 6, 6	4	3.5	0.02	15
Polyethylene	2.3	2.3	0.0004	4
Polyvinylchloride (plasticized)	7	3.4	0.05	2
Vulcanized rubber	4	2.7	0.003	25
Bakelite	4.4	4.4	0.028	15
Transformer oil	5	2.5	0.0001	10

Summary

1. Dielectric materials are a class of insulator which gets polarizes on application of electric field.
2. Dielectric constant represents charge storage ability of the material.
3. Dipoles cannot reorient with applied AC field and lose some energy called as polarization loss.
4. Electronic polarization is fast while space charge polarization is slow.
5. Dielectric field strength is the ability to sustain electric field.