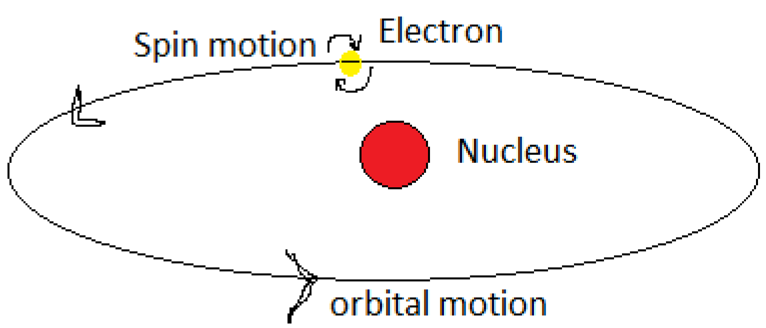
Unit 3
Types of Magnetic materials

Introduction

All substances show some kind of magnetic behaviour. After all, they are made up of charged particles: electrons and protons. It is the way in which electron clouds arrange themselves in atoms and how groups of these atoms behave that determines the magnetic properties of the material. The atom (or group of atoms) in effect becomes a magnetic dipole or a mini bar magnet that can align according to the magnetic field applied. The net effect of all these dipoles determines the magnetic properties of the magnetic materials.
Electricity is the movement of electrons, whether in a wire or in an atom, so each atom represents a tiny permanent magnet in its own right. The circulating electron produces its own orbital magnetic moment, and there is also a spin magnetic moment because the electron itself spins, like the earth, on its own axis.



In most materials these magnetic moments, measured in Bohr magnetons (μB), cancel each other out with each electronic magnet negating the field produced by another. In certain magnetic materials the magnetic moments of a large proportion of the electrons align, producing a unified magnetic field. The field produced in the material (or by an electromagnet) has a direction of flow, and any magnet will experience a force trying to align it with an externally applied field, just like a compass needle. These forces are used to drive electric motors, produce sounds in a speaker system, control the voice coil in a CD player, and so on. The interactions between magnetism and electricity are therefore an essential aspect of many devices we use every day.

MAGNETIC MATERIALS - TERMS

Magnetic Susceptibility: Ratio of intensity of magnetisation produced in the sample to the magnetic field intensity which produces magnetization. It has no units. χ = □/□

Magnetization: The process of converting a non magnetic material to a magnetic material.

Intensity of magnetization: It is magnetic moment per unit volume. • Relative permeability: The ratio of flux density produced in a material to the flux density produced in vacuum by the same magnetising force.

Magnetic flux (Φ): The total no: of magnetic lines of force in a magnetic field (unit- Weber)

Magnetic flux density (B): Magnetic flux per unit area at right angles to the direction of flux. (Wb/□^{2})

Magnetic field intensity (H): Magneto motive force per unit length of the magnetic circuit. It is also called magnetic field strength or magnetizing force. (A-turns/m)

Permeability (*μ*): The ability of a material to conduct magnetic flux through it. (H/m)

CLASSIFICATION OF MAGNETIC MATERIALS

Diamagnetic – materials which lack permanent dipoles are called diamagnetic Paramagnetic – if the permanent dipoles do not interact among themselves, the material is paramagnetic

Ferromagnetic – if the interaction among permanent dipoles is strong such that all the dipoles line up in parallel, the material is ferromagnetic

Antiferromagnetic – if the permanent dipoles line up in antiparallel direction, the material is antiferromagnetic

Ferrimagnetic – antiparallel with unequal magnitude

DIAMAGNETIC MATERIALS

• No permanent dipoles are present so net magnetic moment is zero.

• Dipoles are induced in the material in presence of external magnetic field.

• The magnetization becomes zero on removal of the external field.

• Magnetic dipoles in these substances tend to align in opposition to the applied field.

• Hence, they produce an internal magnetic field that opposes the applied field and the substance tends to repel the external field around it.

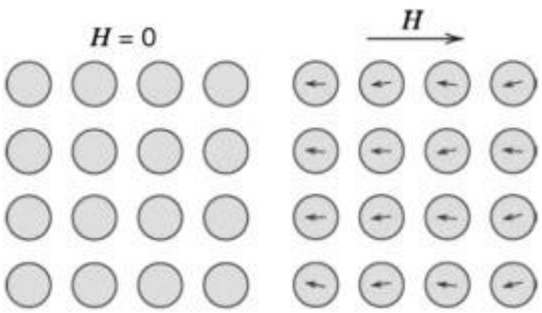
• This reduces the magnetic induction in the specimen.

Magnetic susceptibility is small and negative.

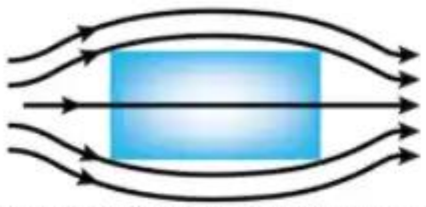
• Relative permeability is less than one.

• It is present in all materials, but since it is so weak it can be observed only when other types of magnetism are totally absent.

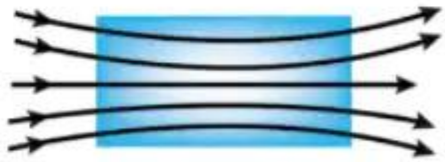
• Ex: Gold, water, mercury, B, Si, P, S, ions like Na^+, Cl^- and their salts, diatoms like H_2, N_2.



They repel the magnetic lines of force. The existence of this behaviour in a diamagnetic material is shown



Magnetic Field lines through Diamagnetic material



Magnetic Field lines through paramagnetic material

PARAMAGNETIC MATERIALS :

If the orbital's are not completely filled or spins are not balanced, an overall small magnetic moment may exist.

• The magnetic dipoles tend to align along the applied magnetic field and thus reinforce the applied magnetic field. • Such materials get feebly magnetised in the presence of a magnetic field i.e. the material allows few magnetic lines of force to pass through it.

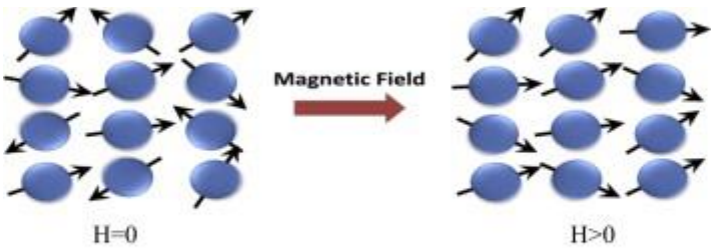
• The magnetization disappears as soon as the external field is removed.

The magnetization (M) of such materials was discovered by Madam Curie and is dependent on the external magnetic field (B) and temperature T as: $\chi = C/T$ where, C= Curie Constant

• The orientation of magnetic dipoles depends on temperature and applied field. • Relative permeability μr >1

• Susceptibility is independent of applied magnetic field and depends on temperature.Susceptibility is small and positive • These materials are used in lasers.

• Ex: Liquid oxygen, sodium, platinum, salts of iron and nickel, rare earth oxides



FERROMAGNETIC MATERIALS

• They exhibit strongest magnetic behaviour.

• Permanent dipoles are present which contributes a net magnetic moment.

• Possess spontaneous magnetization because of interaction between dipoles

• Origin for magnetism in Ferro magnetic materials are due to Spin magnetic moment. All spins are aligned parallel & in same direction

• When placed in external magnetic field it strongly attracts magnetic lines of force

• The domains reorient themselves to reinforce the external field and produce a strong internal magnetic field that is along the external field.Most of the domains continues to be aligned in the direction of the magnetic field even after removal of external field.

• Thus, the magnetic field of these magnetic materials persists even when the external field disappears.

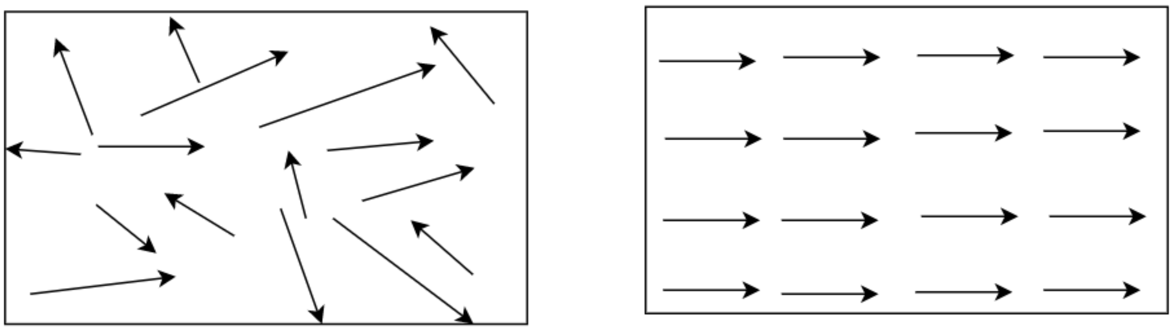
• This property is used to produce Permanent magnets.

• Transition metals, iron, cobalt, nickel, neodymium and their alloys are usually highly ferromagnetic and are used to make permanent magnets.

Susceptibility is large and positive, it is given by Curie Weiss Law; $\chi = C/T-\theta$ where, C is Curie constant & θ is Curie temperature.

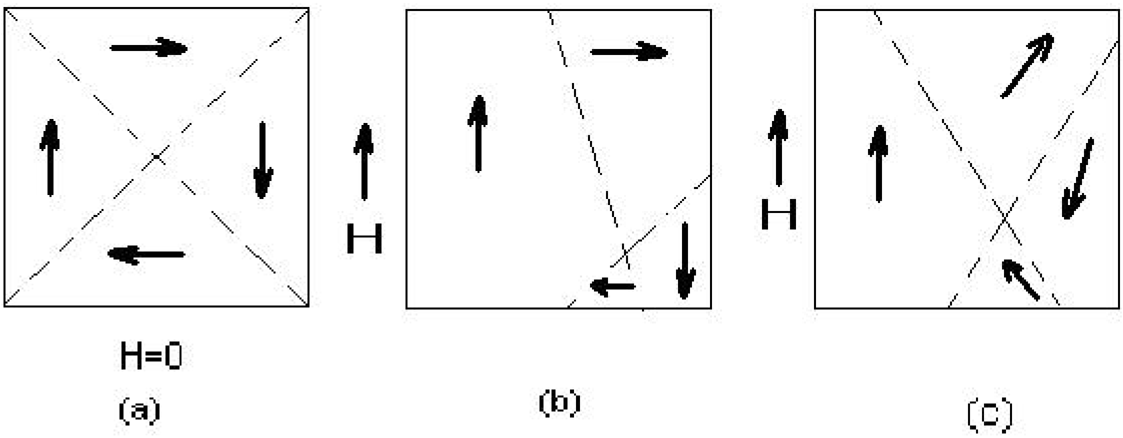
• When temperature is greater than Curie temperature then the material gets converted into paramagnetic.

• They possess the property of Hysteresis.



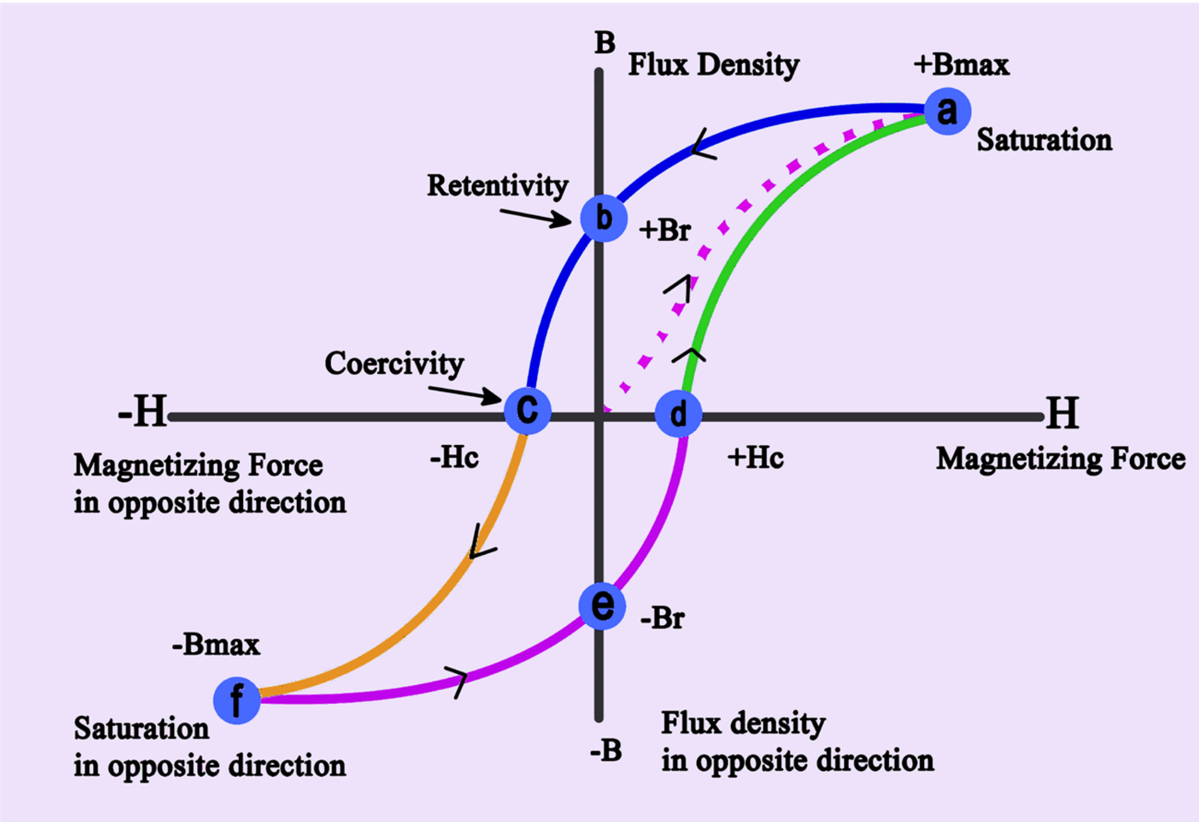
Domain theory of ferromagnetic materials:

A magnetic domain is a region within a magnetic material in which the magnetization is in a uniform direction. Ferromagnetic materials tend to form magnetic domains. Each domain is magnetized in a different direction. Applying a field changes domain structure. Domains with magnetization in the direction of the field grow. (Domain growth) Domain structure minimises energy due to stray fields. Domains with magnetization in the direction of the field grow while other domains shrink. Applying very strong fields can saturate magnetization by creating a single domain. (Domain rotation)



Hysteresis: The property of Ferromagnetic materials which gives the relation between Magnetization and the strength of Magnetic field is called Hysteresis. The magnetization of the specimen increases from zero to higher values and attains its maximum value at a point referred to as Saturation Magnetization. When we further increase Magnetic field H there is no further increment in magnetic moment.When we decrease Magnetic field H to Zero, the Magnetization M attains point Q referred to as Residual Magnetization. Further if we change the magnetic field from zero to negative values, the magnetization of material becomes zero at a point R, where magnetic field Hc is referred to as Coercivity of the specimen. If we increase Magnetic field H in reverse direction Magnetization of material reaches its peak value at a point S. The area of loop indicates the amount of energy wasted in one cycle of operation

Hysteresis loop - The loop traced out by magnetization in a ferromagnetic or ferrimagnetic material as the magnetic field is cycled.



ANTIFERROMAGNETIC MATERIALS

• The spin alignment is in antiparallel manner.

• Susceptibility is small and positive and it depends on temperature.

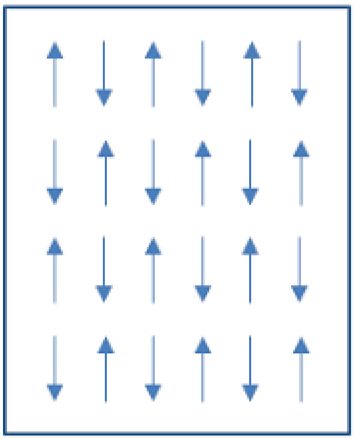
• Initially susceptibility increases with increase in temperature and beyond Neel temperature the susceptibility decreases with temperature.

• The antiparallel alignment exists in material below a critical temperature known as Neel temperature

• At Neel temperature susceptibility is maximum.

Susceptibility, χ = □ /□+θ

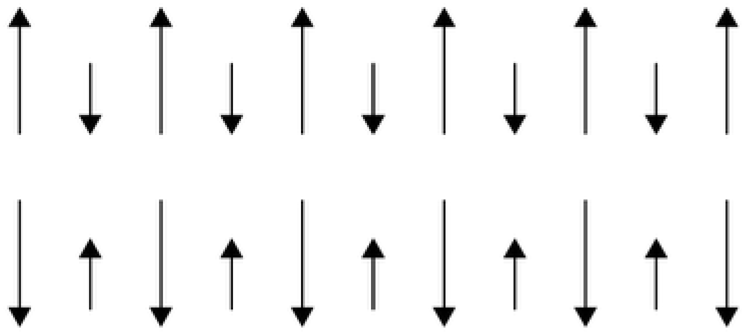
• Examples: Mn, Cr, FeO, MnO, Cr_2O_3 and salts of transition elements



Antiferromagnetic ordering

FERRI MAGNETIC MATERIALS

- The spin alignment is antiparallel but have different magnitude.
- So they possess net magnetic moment which produce a large magnetization even for a small applied external field.
- It is also called ferrites.
- Susceptibility is very large and positive.
- Examples: ferrous ferrite, nickel ferrite



Comparison:

S. N	Properties	Diamagnetic	Paramagnetic	Ferromagnetic
1	Definition	It is a material in which there is no permanent magnetic moment.	It has permanent magnetic moment.	It has enormous (more) permanent magnetic moment.
2	Spin or magnetic moment or dipole alignment.	No spin alignment.	Random alignment	Parallel and orderly alignment.
3	Behavior	Repulsion of magnetic lines of force from the centre of the material.	Attraction of magnetic lines towards the centre.	Heavy attraction of lines of force towards the centre.
4	Magnetized direction	Opposite to the External magnetic field.	Same direction as the External magnetic field.	Same direction as the External magnetic field.
5	Permeability	It is very less	It is high	It is very high
6	Relativity permeability	$\mu_r < 1$	$\mu_r > 1$	$\mu_r >> 1$
7	Susceptibility	Negative	Low positive	High positive
8	Magnetic phase transition	At 0 K, diamagnetic material is Superconductor. When we increase its temperature it becomes a normal conductor.	When temperature is less than the curie temp, it is converted in to Diamagnetic.	When temperature of the material is greater than it Curie temperature it is converted into Paramagnet.

SOFT MAGNETIC MATERIALS

Properties:

• These magnetic materials can be easily magnetized and demagnetized, but they cannot be permanently magnetized

• Less energy is required to magnetize and demagnetize a soft magnetic material.

• These are used to make electromagnets.

• Eg: Iron silicon alloys, Ferrous nickel alloy, Iron-cobalt alloys, Ferrite and garnets • Low Hysteresis loss and low coercivity.

• These materials have large values of permeability and susceptibility

Applications:

• Soft magnetic materials have relatively small and narrow hysteresis loop and hence small energy loss per cycle of magnetization. They are widely used for the construction of cores of electrical rotating machines, transformers, and for making electro-magnets, reactors, relays

• Soft magnetic materials are mostly used where changing magnetic flux is associated, such as magnetic core of electric motors, alternators, DC generators, electrical transformers, protective relays, inductors.

• Used for making a path for flux in permanent magnetic motors

• Used for magnetic shielding, electromagnetic pole-pieces, to activate the solenoid switch

• Permanent magnet uses soft magnetic material to make a path for flux

Examples:

• Nickel Iron Alloys - It is used in communication equipment such as audio transformer, recording heads and magnetic modulators. Since it has high initial permeability in feeble fields, low hysteresis and low eddy current losses.

• Grain oriented sheet steel: used to make transformer cores.

• Mu-metal: used in miniature transformers meant for circuit applications.

• Ceramic magnets: used for making memory devices for microwave devices and computer.

HARD MAGNETIC MATERIALS

Properties:

• These magnetic materials cannot be easily magnetized and demagnetized, but they can be permanently magnetized.

• The reason is that the domain walls are motionless owing to crystal defects and imperfections.

• Hard magnetic materials have large hysteresis loss due to large hysteresis loop area

• These are used to make permanent magnets.

• High remnant magnetization

• The shape of BH loop is nearly rectangle.

• Small initial permeability.

• Relatively low permeability and susceptibility

• These materials have high Coercivity and retentivity. Hence, cannot be easily magnetized and demagnetized.

• High magnetizing force is required to attain magnetic saturation.
• Eg: Alnico alloy, Copper nickel iron alloy, Copper nickel cobalt alloy
Applications:
• Hard magnetic materials (such as carbon steel, tungsten steel, cobalt steel and hard ferrites) have large hysteresis loop area and consequently large energy loss per cycle of magnetization and are used in making all kinds of instruments and devices requiring permanent magnets.
Various other applications are; • Automotive: motor drives for fans, wipers, injection pumps, starter motors, Control for seats, windows etc.
• Telecommunication: Microphones, Loud Speakers, Telephone Ringers etc. • Data processing: Printers, Stepping Motors, Disc Drives and Actuators.

S. No	Hard Magnetic Materials	Soft Magnetic Materials
1.	Cannot be easily magnetized	Can be easily magnetized.
2.	It can be produced by heating and sudden cooling	It can be produced by heating and slow cooling.
3.	Domain wall does not move easily and require large value of H for magnetization.	Domain wall move easily and requires small value of H for magnetization.
4.	Hysteresis loop area is large Susceptibility and Permeability values are small.	Hysteresis loop area is small Susceptibility and Permeability values are high.
5.	Retentivity and Coercivity are large	Retentivity and Coercivity are small.
6.	High eddy current loss	Low eddy current loss
7.	Impurities and defects will be more	No impurities and defects
8.	**Examples:** Alnico, Chromium steel, tungsten steel, carbon steel.	**Examples:** Iron-silicon alloy, Ferrous nickel alloy, Ferrites Garnets.
9.	**Uses:** Permanent magnets, DC magnets.	**Uses:** Electro magnets, computer data storage. Transformer core.

Ferrites are compounds of iron oxides with oxides of other metal.
• A ferrite is a type of ceramic compound composed of iron(III) oxide (Fe_2O_3) combined chemically with one or more additional metallic elements.
• They are both electrically nonconductive and ferrimagnetic, meaning they can be magnetized or attracted to a magnet.

• Based on their magnetic coercivity and resistance to being demagnetized, ferrites are of two types; soft and hard ferrites

• Hard ferrites have high coercivity, hence they are difficult to demagnetize. They are used to make permanent magnets, for devices such as refrigerator magnets, loudspeakers and small electric motors.

Soft ferrites have low coercivity. They are used in the electronics industry to make ferrite cores for inductors and transformers, and in various microwave components.

• Ferrite compounds have extremely low cost, being made of iron oxide (i.e. rusted iron), and also have excellent corrosion resistance. • They are very stable and difficult to demagnetize, and can be made with both high and low coercive forces.

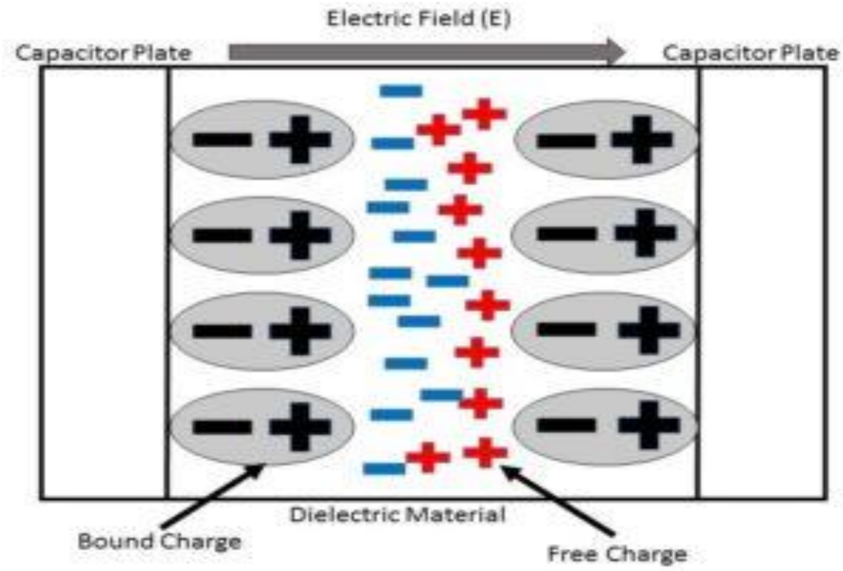
• It is used for high frequency applications.

Properties

• Hard
• Brittle
• Iron-containing
• Polycrystalline
• High electrical resistivity
• Low electrical losses
• Significant saturation magnetization
• Very good chemical stability
• Generally grey or black

Dielectrics

A dielectric (or dielectric material) is an electrical insulator that can be polarized by an applied electric field. When a dielectric is placed in an electric field, electric charges do not flow through the material as they do in an electrical conductor but only slightly shift from their average equilibrium positions causing dielectric polarization. Eg: Glass, mica, paraffin, papers, Bakelite etc.



Electric dipole: Two equal and opposite charges +Q and –Q which are separated by a vector distance dx is called an electric dipole. Electric dipole moment is a measure of the separation of positive and negative electrical charges within a system, that is, a measure of the system's overall polarity. The SI units for electric dipole moment are coulomb-meter (C· m) It is defined as the product of either of the charges and the distance between them. It is given by $\mu = Q \times dx$ and is directed from negative charge to positive charge.

Polar dielectrics

If the effective centers of positive and negative charges in the molecules do not coincide with each other (i.e. the effective centres of positive and negative charges are separated by a small distance) even in the absence of any external field, then, such materials are called polar dielectrics. They possess a permanent dipole moment. Eg. H_2O, N_2O …..

Non – polar dielectrics

If the effective centers of the negative charge distribution coincide with the effective center of the positive charges then the effect is to neutralize each other. Such materials are called non – polar dielectrics.

They do not possess permanent dipole moment. Eg. H_2, N_2, O_2,…..

Permittivity : Permittivity is defined as the ratio of electric displacement vector (D) in a dielectric medium to the applied electric field strength (E).

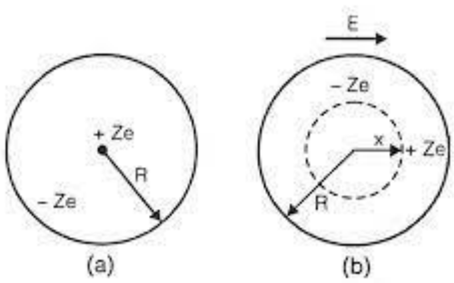
Permittivity (ε) is a measure of the ability of a material to be polarized by an electric field. Static dielectric constant ε_r is the ratio of the permittivity of the material medium to the permittivity of free space. $\varepsilon_r = \varepsilon/\varepsilon_0$.

1. It is independent of shape or dimensions of the material and it is characteristic of the dielectric medium.
2. Dielectric constant of a material is a macroscopic quantity that measures how effective electric field is, in polarizing the material.

Dielectric polarization (Electrical polarization) : The displacement of charges in the molecules of a dielectric under the action of an applied electric field, leading to development of dipole moment is called dielectric polarization. Because of dielectric polarization, positive charges are displaced in the direction of the field and negative charges shift in the opposite direction. This creates an internal electric field that reduces the overall field within the dielectric itself. From the macroscopic point of view, sum of the dipole moments in a given volume is given by ∑ □□ = □ □□= □ Δ□ □Δ□ □=1 where N is the number of molecules per unit volume, □□is the average dipole moment and P is the diploe moment per unit volume called electric polarization.

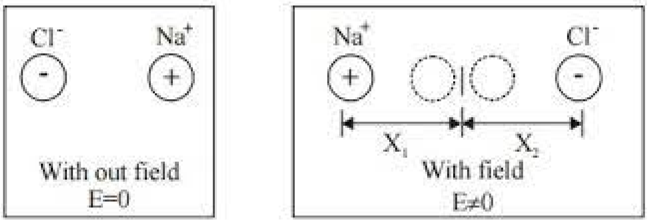
Types of Electric polarization
There are four different mechanisms through which electrical polarization can occur in dielectric materials when they are subjected to an external electric field. They are 1.Electronic polarization, 2.Ionic polarization 3.Orientation polarization 4.Space charge polarization

1. Electronic polarization The electronic polarization occurs due to the displacement of the positive and negative charges in a dielectric material due to the application of an external electric field as shown. The development of dipole moment occurs throughout the material, so whole material will be polarized.



Atomic model for electronic polarization

2.Ionic polarisation This occurs only in materials which are ionic. An applied field acts to displace positive charges in one direction (cation) which gives rise to a net dipole moment. When an Electric field is applied to the molecule, the positive ions are displaced by X1 to the negative side of electric field and negative ions are displaced by X2 to the positive side of field. The resultant dipole moment μ = q (X1 + X2).. This polarization occurs at frequency 1013 Hz (IR). It is a slower process compared to electronic polarization. It is independent of temperature. The ionic polarisation is given by □□ = □□□□ where □□ is the ionic polarisability.

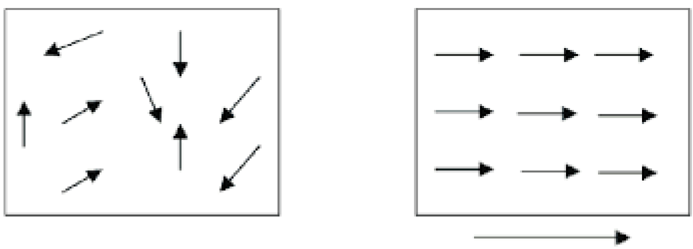


3. Orientational polarisation This is found only in substances that possess permanent dipole moments. Polarization results from a rotation of the permanent dipoles in the direction of the applied field. It is strongly temperature dependent and decreases with increase of temperature.

It is also called dipolar or molecular polarization. The molecules such as H2, N2, O2, Cl2, CH4, CCl4 etc., does not carry any dipole because centre of positive charge and centre of negative charge coincides. On the other hand molecules like CH3Cl, H2O, HCl, ethyl acetate (polar molecules) carries dipoles even in the absence of electric field.

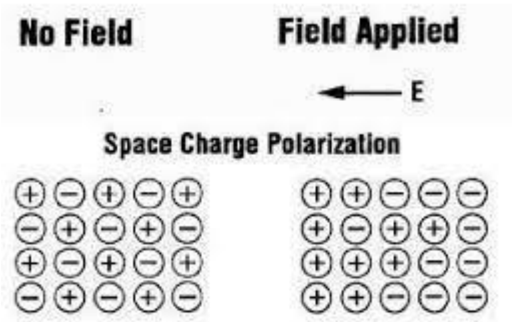
In the case of a CH_3Cl molecule, the positive and negative charges do not coincide. The Cl- has more electro negativity than hydrogen. Therefore, the chlorine atoms pull the bonded electrons towards them more strongly than hydrogen atoms. Therefore, even in the absence of field, there exists a net dipole moment. In the presence of he field there is alignment of dipoles leading to polarization.

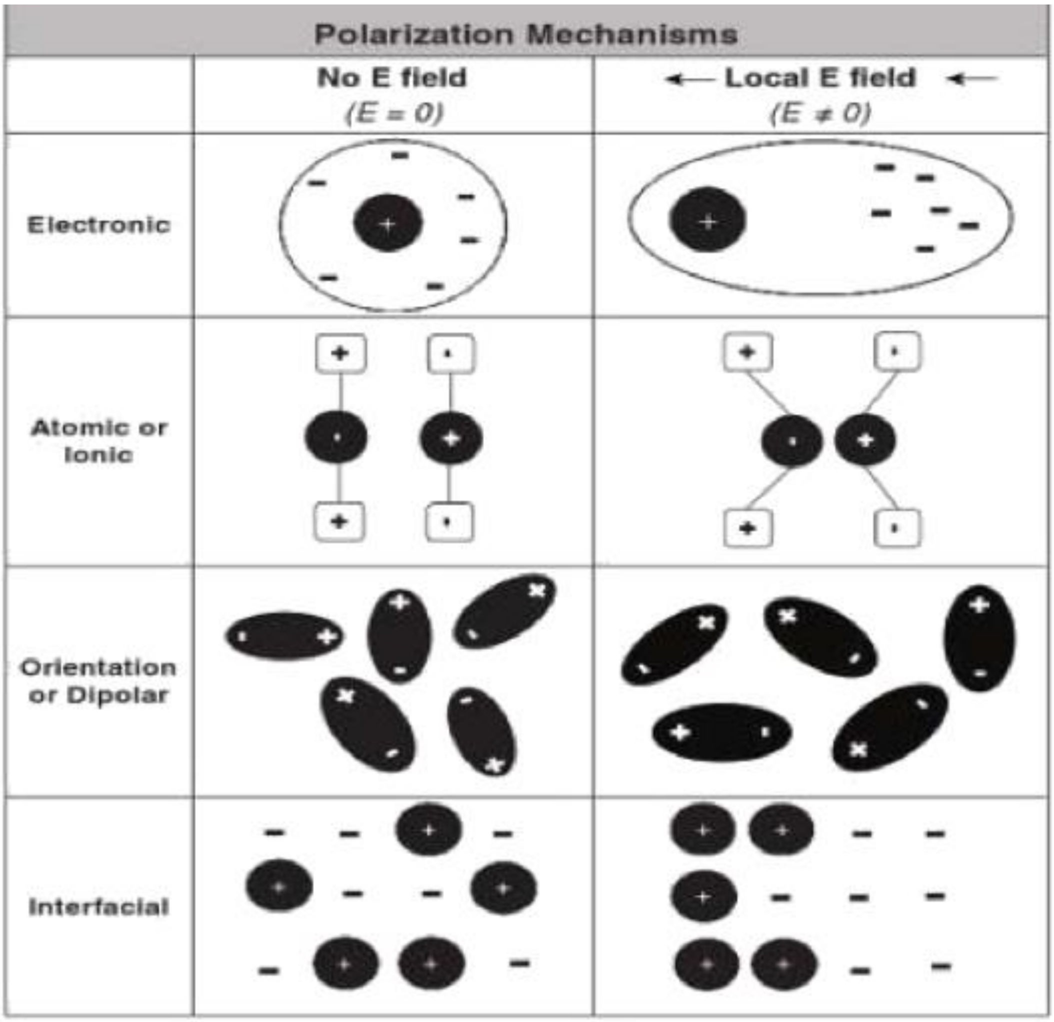
It occurs at a frequency 10^6 Hz to 10^{10}Hz. It is slow process compared to ionic polarization. It greatly depends on temperature. The orientational polarisation is □□ = □□□□ where □□ is the orientational polarisability given by □□ = □ ^{2} /3□ □ .



E = 0. E > 0.

4. Space charge polarisation The space-charge polarization occurs due to the diffusion of ions, along the field direction, thereby giving rise to redistribution of charges in the dielectrics.
Space charge polarization occurs in multiphase dielectric materials in which there is a change of resistivity between different phases. The space charge polarization is not an important factor in most common dielectrics.
Interfacial or space charge polarization occurs when there is an accumulation of charge at an interface between two materials or between two regions within a material because of an external field. This can occur when there is a compound dielectric, or when there are two electrodes connected to a dielectric material. This polarization is usually observed in amorphous or polycrystalline solids. The electric field will cause a charge imbalance. Mobile charges in the dielectric will migrate over to maintain charge neutrality. This then causes interfacial polarization.





Total polarisation is given by $P = P_e + P_i + P_o$.