ELECTRICAL PROPERTIES

Introduction
The objective of this chapter is to explore the electrical properties of materials, i.e. their responses to an applied electric field. We begin with the phenomenon of electrical conduction: the parameters by which it is expressed, the mechanism of conduction by electrons, and how the electron energy band structure of a material influences its ability to conduct. These principles are extended to metals, semiconductors and insulators. Particular attention is given to the dielectric characteristics of insulating materials. The final sections are devoted to the peculiar phenomena of Ferro electricity and piezoelectricity.

The electrical conductivity is one of the properties of materials that vary most widely and the best conductors such as copper and silver have values of about $10^8 \Omega^{-1} m^{-1}$ and a good insulator such as polystyrene has conductivity $10^{-15} \Omega^{-1} m^{-1}$. In a metal, the current is carried by conduction electrons, and hence the name electronic conduction.

30 Minutes

ENERGY BAND STRUCTURES IN SOLIDS (Board Teaching & PPT)
In an isolated atom electron occupy well defined energy states, when atoms come together to form a solid, their valence electrons interact with each other and with nuclei due to Coulomb forces. Inter atomic spacing is small in solids compared with liquids and gases. Due to this closeness of atoms, energy levels of the atoms are disturbed. Energy levels of the valence electrons are most affected. Each energy level splits up into a number of closely spaced levels. These split energy levels form a continuous band called energy band as shown in fig 3.13.

Energy level is the discrete energy of an electron in an atom. But energy band is the energy of the same electron when it is in a solid. At large separation distances, each atom is independent of all the others, so they have energy levels. But the atoms come close to each other, electrons respond to the influence of other nuclei and electrons. So each atomic level splits into N levels each of which may be occupied by pairs of electrons of opposite spins. The extent of splitting depends on inter atomic separation.
Firstly outer most electron shells are disturbed.
In each energy band, energy levels are discrete; the difference between adjacent states is infinitesimally small. At the equilibrium spacing, band formation may not occur for electron sub shells nearest the nucleus as shown in fig 3.13. Further gaps exist between adjacent bands. The electron does not have any energy within energy gap.

![Figure 3.13: Electron energy versus inter atomic separation for an aggregate of atoms](image)

**ENERGY BAND STRUCTURES AND CONDUCTIVITY**

There are four types of band structures which are possible at 0 K. The highest filled state at 0 K is called Fermi Energy (E_F). The two important energy bands are:

**Valence band:** Valence band is the wide range of energies possessed by the valence electrons. The highest filled energy band where the electrons are present at 0 K.

**Conduction band:** Conduction band is the wide range of energies possessed by the conduction electrons. A partially filled or empty energy band where the electrons can increase their energies by going to higher energy levels within the band when an electric field is applied.

**Energy Band Structures and Conductivity for metals**

In metals (conductors), highest occupied band is partially filled or bands overlap. Conduction occurs by promoting electrons into conducting states that starts right above the Fermi level. The conducting states are separated from the valence band by an infinitesimal amount. Energy provided by an electric field is
sufficient to excite many electrons into conducting states.

Ex: Copper atomic number is 29, its electronic configuration is \(1s^22s^22p^63s^23p^63d^{10}4s^1\). Each copper atom has one 4s electron. For a solid consisting of \(N\) atoms, the 4s band can accommodate \(2N\) electrons. Thus only half of the 4s band states are filled. This is shown in fig 3.14(a).

For the second band structure, there is an overlap of filled band (valence band) and empty band (conduction band). Ex: Magnesium atomic number is 12, its electronic configuration is \(1s^22s^22p^63s^2\). Each magnesium atom has two 3s electrons. In a solid of magnesium, the 3s and 3p bands are overlapped. This is shown in fig 3.14(b).

![Energy Band Structures and Conductivity](image)

**Figure 3.14:** The various possible electron band structures in solids at 0 K. (a) The electron band structure found in metals such as copper, in which there are available electron states above and adjacent to filled states, in the same band. (b) The electron band structure of metals such as magnesium, wherein there is an overlap of filled and empty outer bands. (c) The band structures of insulators. (d) The band structure of semiconductors.

**Energy Band Structures and Conductivity for Semiconductors and insulators:**

As shown in fig 3.14, (c) and (d) band structures are similar. The valence band is completely filled with electrons. There is large energy gap between filled valence band and empty conduction band. Ex: Insulators. If the energy gap between valence and conduction band is small than i.e. semiconductor.

Electrical conduction requires that electrons be able to gain energy in an electric field. To become free, electrons must be promoted (excited) across the band gap. The excitation energy can be provided by heat or light. In semiconductors and insulators, electrons have to jump across the band gap into conduction band to find conducting states above \(E_f\). The energy needed for the jump may come from heat or from irradiation at sufficiently small wavelength (photo excitation).

The difference between semiconductors and insulators is that in semiconductors electrons can reach the
conduction band at ordinary temperatures, where in insulators they cannot. An electron promoted into the conduction band leaves a hole (positive charge) in the valence band, that can also participate in conduction. Holes exist in metals as well, but are more important in semiconductors and insulators.

10 Minutes

Verify

1. In terms of electron energy band structure, discuss reasons for the difference in electrical conductivity between metals, semiconductors, and insulators.

2. Explain formation of energy band structure considering decrease in inter atomic spacing in to account.

3. Define equilibrium spacing.

Session 11

Process of electrical conduction in metals, conductivity, mobility and Matthiessen's rule

30 Minutes

Process of electrical conductivity in metals (Board Teaching)

It is defined as the voltage apply to a conductor which is equal to the product of current passing through the conductor times its resistance. This law is independent of size and shape of the conductor under consideration. However, it can also be expressed in terms of current density J and electric field E. The current density in the direction of electric field is defined as the amount of charge flowing across a unit area of cross section per unit time in a conductor. If n is a number of electrons crossing a unit area in unit time then the amount of charge is equal to “- ne”. Average velocity of electrons is the drift velocity. The flow of charge per unit time through unit area of the conductor is equal to the product of electron charge times the drift velocity of the electrons which is current density

\[ J = -ne v_d. \]

\[ J = \frac{ne^2 \tau}{m} E \]

Or
\[ J = \sigma E \]

It follows that the electric current density is proportional to the applied electric field. This equation is known as Ohm’s law and proportionality constant is called electrical conductivity \( \sigma \).

(iv) Electrical conductivity

In general the electrical conductivity is a property of a conducting material which allows the flow of current.

\[
\sigma = \frac{ne^2 \tau}{m}
\]

This is one of the central results of the classical free electron theory of metals. This formula is not useful for calculating the conductivity of a given metal, since it contains an unknown term called relaxation time. The theory itself has important implications. This picture of electron gas undergoing constant scattering and is still used. For a particular metal \( n, e \) and \( m \) are constants. Therefore, the electrical conductivity depends on the relaxation time ‘\( \tau \)’. Thus in the absence of collision process the relaxation time is infinite and hence the conductivity becomes infinite. The electrical conductivity can also be expresses in terms of mobility.

\[ \sigma = ne\mu \]

Thus in general the electrical conductivity of a metal depends on two factors. They are \( n \) and \( \mu \).

(v) Electrical Resistivity (\( \rho \))

Electrical resistivity is a measure of how strongly a material opposes the flow of electric current. A low resistivity indicates a material that readily allows the movement of electric charge. The S.I. unit of electrical resistivity is \( \Omega \)-m. It is commonly represented by a Greek letter \( \rho \).

(vi) Electrical conductivity (\( \sigma \))

It is the ability of a substance to conduct an electric current. It is the inverse of the resistivity.

Ohms law

Ohm's law can be rewritten in terms of the current density \( J = I/A \) as: \( J = \sigma E \). Ohm’s law can be expressed in both microscopic and macroscopic forms.

(Macroscopic form)

(Microscopic form)

Electrical conductivity varies between different materials by over 27 orders of magnitude.
Metals: $\sigma > 10^5 \text{ (}\Omega\text{.m})^{-1}$

Semiconductors: $10^{-6} < \sigma < 10^5 \text{ (}\Omega\text{.m})^{-1}$

Insulators: $10^{-6} \text{ (}\Omega\text{.m})^{-1} < \sigma < 10^{-20} \text{ (}\Omega\text{.m})^{-1}$

One of the best materials for electrical conduction (low resistivity) is silver, but its use is restricted due to the high cost. Most widely used conductor is copper: inexpensive, abundant, high $\sigma$, but rather soft – cannot be used in applications where mechanical strength is important.

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Table 3.1: Room temperature electrical conductivities for eight common metals and alloys

Solid solution alloying and cold working improve strength but decrease conductivity. If hardening is preferred, Cu-Be alloy is used. When weight is important one uses aluminum, which is half as good as Cu and more resistant to corrosion. Heating elements require low (high $R$), and resistance to high temperature oxidation: nickel chromium alloy.

Drift velocity of electrons:

When an electric field $E$ is applied to a conductor, the electrons modify their random motion and move with an average drift velocity $v_d$ in a direction opposite to that of the electric field and an electric current is established in the conductor. The flow of current in a conductor is an indication that the electron in it moves in a specific direction. As a result, Maxwell-Boltzmann distribution function of the electrons in the conductor undergoes a change. The directional motion of the electrons is due to the applied electric field. The group of electrons within the conductor drifts in the direction opposite to the applied electric field. This motion is called a drift motion and the associated velocity of the electron is called drift velocity.
Due to the electric field $E$ an electron inside the metal experiences a force and this force $F$ is equal to the product of electric charge and electric field.

$$F = -e \times E$$

where ‘$-e$’ is the charge of the electron. As a result, the electron acquires acceleration. According to newton's second law of motion, the force experienced by the electron is given by

$$F = m \times a$$

where ‘$a$’ is the acceleration of the electron and $m$ is the mass of the electron. Eliminating $F$ from the above equations gives the acceleration of the electron under the influence of electric field $-eE = ma$.

$$a = \frac{-eE}{m}$$

It is clear from the above equation that the electrons are accelerated indefinitely because of growth of their velocity due to electric field i.e. its drift velocity $v_d$ increases with time. However the electrons are not accelerated indefinitely because during their motion the electrons collide with impurities and lattice imperfections in the crystal. Here Drude assumed that the conduction electron acquires random motion after collision with impurities and lattice imperfections. In the collision process the electron loses the energy and after collision it again gains energy from the electric field. The velocity of the electrons after collision does not depend upon its velocity before collision. When the electron collides with the lattice imperfection it stops momentarily and moves in another direction with a new velocity. Thus electrons acquire random motion even in the presence of electric field. This problem can be solved by considering these collisions are similar to the collision process of an ideal gas in a container. The collision process introduces the concept of relaxation time, which influences the conductivity in the metals. The average time between successive collisions of electron with the lattice imperfection is called relaxation time and is denoted by $\tau$.

The acceleration of the electron due to collision with impurities is given by $-v_d/\tau$ (negative sign is due to the acceleration is opposite to the direction of electric field). Now, the acceleration is equal to sum of the acceleration due to electric field and acceleration due to collision with impurities.

$$a = \frac{-eE}{m} - \frac{v_d}{\tau}$$

After sometime the acceleration of the electrons due to the electric field and acceleration due to collision should compensate with each other but leads to steady state condition of the electron gas. As a result the acceleration of electron becomes zero.
\[
\frac{-eE}{m} - \frac{vd}{\tau} = 0
\]

The drift velocity of the electron is then obtained by arranging the above equation.

\[
v_d = -\frac{e\tau E}{m}
\]

Thus the electrons in a conductor attain a constant drift velocity under the application of the electric field. The drift velocity is proportional to applied electric field and the proportionality constant is called the electron mobility \( \mu \).

(ii) Electron Mobility (\( \mu \)):

The electron mobility is defined as the drift velocity \( v_d \) per unit applied electric field \( E \).

\[
\mu = \frac{v_d}{E}
\]

Substituting the value of drift velocity in the above equation we get

\[
\mu = \frac{-e\tau}{m}
\]

The above equation shows that mobility of an electron depends on the relaxation time and hence it depends on temperature.

10 Minutes

Verify

1. Draw energy band structure for Copper and Magnesium.
2. Write microscopic and macroscopic forms of Ohm’s law
3. Define drift velocity and mobility of electron and write the expression of electrical conductivity in metals.

30 Minutes

ELECTRICAL RESISTIVITY OF METALS:

The resistivity \( \rho \) is defined by scattering events due to the imperfections and thermal vibrations. Total resistivity \( \rho_{\text{tot}} \) can be described by the Matthiessen’s rule:

\[
\rho_{\text{total}} = \rho_{\text{thermal}} + \rho_{\text{impurity}} + \rho_{\text{deformation}},
\]

Where \( \rho_{\text{thermal}} \) - from thermal vibrations, \( \rho_{\text{impurity}} \) - from impurities, \( \rho_{\text{deformation}} \) - from deformation-induced defects resistivity increases with temperature, with deformation, and with alloying.
Graphical explanation to electrical resistivity in metals:

One of the best materials for electrical conduction (low resistivity) is silver, but its use is restricted due to the high cost. Most widely used conductor is copper: inexpensive, abundant, high σ, but rather soft – cannot be used in applications where mechanical strength is important.

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temperature oxidation: nickel chromium alloy.

10 Minutes

Verify

1) Discuss the origin of electrical resistance in metals.
2) Explain variation of electrical resistance of a metal with change of temperature?
3) Compare the influence of temperature, impurity concentration and deformation on electrical resistance of metals.

Session 12: Semiconductors and conductivity

30 Minutes

Classification - conductivity (Board Teaching)

SEMI CONDUCTORS

INTRODUCTION (10 min)
The electrical conductivity of the semiconducting materials is not as high as that of the metals. Nevertheless they have some unique electrical characteristics that render them especially useful. The electrical properties of these materials are extremely sensitive to the presence of even minute concentrations of impurities.

Intrinsic Semiconductors (20 min):

Intrinsic semiconductors - electrical conductivity is defined by the electronic structure of pure material.

Extrinsic semiconductors - electrical conductivity is defined by impurity atoms.

Intrinsic semiconductors

Highly pure semiconductors with no impurities are called intrinsic semiconductors. In such a material there are no charge carriers at 0K. Since the valence band is filled and the conduction band is empty. At higher temperatures, the electrons reaching the conduction band due to thermal excitation leave equal number of holes in valence band. In intrinsic semiconductor, the number of free electrons is equal to the number of holes. The bond structure and band structures of intrinsic semiconductors are shown in below fig 3.15.

Examples: Si, Ge, GaP, GaAs, InSb, CdS, ZnTe
Figure 3.15: (a) For a semiconductor, occupancy of electron states after an electron excitation from the valence band into the conduction band in which both a free electron and a hole are generated. (b) Electron bonding model of electrical conduction in intrinsic silicon after excitation.

Number of electrons in the conduction band increases exponentially with temperature. $E_g$ is the band-gap width. In an electric field, electrons and holes move in opposite direction and participate in conduction. Since both electrons and holes are charge carriers in an intrinsic semiconductor, the conductivity is

$$\sigma = n|e|\mu_e + p|e|\mu_h$$

where $p$ is the hole concentration and $\mu_h$ the hole mobility.

Electrons are more mobile than holes, $\mu_e > \mu_h$. In an intrinsic semiconductor, a hole is produced by the promotion of each electron to the conduction band. Therefore, $n = p$ and (only for intrinsic semiconductors)

$$\sigma = n|e|\mu_e + p|e|\mu_h = p|e|\mu_e + p|e|\mu_h$$

$n$ (and $p$) increase exponentially with temperature, whereas $\mu_e$ and $\mu_h$ decrease (about linearly) with temperature. The conductivity of intrinsic semiconductors is increasing with temperature (different from metals)

$$\sigma = n|e| \mu_e + \mu_h$$

**Extrinsic semiconductors**

The application of intrinsic semiconductors is restricted due to its low conductivity. In electronic devices, high conducting semiconductors are more essential. The concentration of either electrons or holes in a semiconductor should be increased depending upon the requirements in the electronic devices.
This can be carried out simply by adding impurities (one atom in $10^7$ host atoms) to the intrinsic semiconductors. The process of adding impurity to the intrinsic semiconductors is called doping. The doped semiconductor is called as extrinsic semiconductor. The concentration of electrons and holes are not equal in an extrinsic semiconductor.

Usually the doping material is either penta-valent atoms (P, AS, Sb, Bi) or trivalent atoms (B, Al, Ga, In). The penta-valent atom is called donor atom because it donates one electron to the conduction band of pure semiconductor. The trivalent doping atom is called acceptor atom because it accepts one electron from semiconductor atom. The added impurity is called dopant.

In Extrinsic semiconductors, electrical conductivity is defined by impurity atoms.

Example: Si is considered to be extrinsic at room T if impurity concentration is one impurity per $10^{12}$ lattice sites (remember our estimation of the number of electrons promoted to the conduction band by thermal fluctuations at 300 K) unlike intrinsic semiconductors, an extrinsic semiconductor may have different concentrations of holes and electrons. It is called p-type if $p > n$ and n-type if $n > p$.

Thus there are two types of extrinsic semiconductors depending on the type of impurity added (10 min).

1. N-type extrinsic semiconductors
2. P-type extrinsic semiconductors

**N-type extrinsic semiconductors:**

Excess electron carriers are produced by substituting impurities that have more valence electron per atom than the semiconductor matrix.

Example: phosphorus (or As, Sb) with 5 valence electrons, is an electron donor in Si since only 4 electrons are used to bond to the Si lattice when it substitutes for a Si atom. Fifth outer electron of P atom is weakly bound in a donor state (~ 0.01 eV) and can be easily promoted to the conduction band. Impurities which produce extra conduction electrons are called donors, Elements in columns V and VI of the periodic table are donors for semiconductors in the IV column, Si and Ge.

The hole created in donor state is far from the valence band and is immobile. Conduction occurs mainly by the donated electrons thus n-type.
Figure 3.16: Extrinsic n-type semi conduction model (electron bonding). An impurity atom such as phosphorus, having five valence electrons, may substitute for a silicon atom.

Figure 3.17: (a) Electron energy band scheme for a donor impurity level located within the band gap and just below the bottom of the conduction band. (b) Excitation from a donor state in which a free electron is generated in the conduction band.

P-type extrinsic semiconductors:
Excess holes are produced by substituting impurities that have fewer valence electrons per atom than the matrix. A bond with the neighbors is incomplete and can be viewed as a hole weakly bound to the impurity atom. Elements in columns III of the periodic table (B, Al, Ga) are donors for semiconductors in the IV column, Si and Ge. Impurities of this type are called acceptors.
Figure 3.18: (a) Energy band scheme for an acceptor impurity level located within the band gap and just above the top of the valence band. (b) Excitation of an electron into the acceptor level leaving behind a hole in the valence band.

Figure 3.19: Extrinsic p-type semi conduction model (electron bonding). An impurity atom such as boron having three valence electrons, may substitute for a silicon atom.

The energy state that corresponds to the hole (acceptor state) is close to the top of the valence band. An electron may easily jump from the valence band to complete the bond leaving a hole behind. Conduction occurs mainly by the holes (thus p-type). For extrinsic p-type semiconductors

\[ \sigma = p |e| \mu_p \]

10 Minutes
Verify

1) Explain the conductivity and resistivity of different types of semiconductors.
2) Compare the temperature dependence of the conductivity for metals and intrinsic semiconductors. Briefly explain the difference in behavior.

3) Draw energy band structure of n-type and p-type semiconductors.

4) Compare the temperature dependence of the conductivity for metals and intrinsic semiconductors. Briefly explain the difference in behavior.

30 Minutes

**Factors effecting conductivity of semiconductors**

1) Temperature effect on concentration of charge carrier in intrinsic and extrinsic semiconductors.

2) Effect of concentration of charge carriers on mobility of charge carriers.

3) Effect of temperature on mobility of charge carriers

(Please refer Callister's Materials science and engineering - An Introduction)

10 Minutes

**Verify**

1. State the reason for increase of electrical conductivity with increase of temperature in intrinsic semiconductor.

2. State the reason for decrease of mobility with increase of concentration of charge carriers and temperature.

3. Explain the reasons for no change in carrier concentration with increase of temperature in extrinsic region.

**Session 13: Basic definitions in Dielectrics, relations and Polarization**

30 Minutes

**DIELECTRICS (Board Teaching)**

All dielectric materials are electrical insulators. But all electric insulators need not be dielectrics. Ex: Vacuum is an insulator but it is not dielectric. The distinction between a dielectric material and an insulator lies in the application. The insulating materials are used to resist the flow of current through
it, when a potential difference is applied across its ends. On the other hand the dielectric materials are used to store electric energy.

Dielectrics are the materials having electric dipole moment permanently or temporarily by applying the electric field. In dielectrics all the electrons are bound to their parent molecules and there are no free charges. Further at the ordinary temperatures, the electrons cannot be dislocated either by thermal vibrations or by ordinary applied voltages. Generally the dielectrics are non-metallic materials of high resistivity and have negative temperature coefficient of resistance.

A dielectric material is an insulator in which electric dipoles can be induced by the electric field (or permanent dipoles can exist even without electric field), that is where positive and negative charge are separated on an atomic or molecular level with \( \varepsilon_r = 81 \) for water, 20 for acetone, 12 for silicon, 3 for ice, etc.

**FUNDAMENTAL DEFINITIONS**

**Dielectric constant \( (\varepsilon_r) \)**

The dielectric characteristic of a material are determined by the dielectric constant or relative permittivity \( \varepsilon_r \) of that material. The dielectric constant determines the share of the electric stress which is absorbed by the material. It is the ratio between the permittivity of the medium and the permittivity of free space.

\[
\varepsilon_r = \frac{\varepsilon}{\varepsilon_{\text{free}}}
\]

The dielectric constant \( \varepsilon_r \) has no unit and it is a measure of the electric polarization in the dielectric material.

**Electric polarization**

When an electric field is applied to a crystal or a glass containing positive and negative charges, the positive charges are displayed in the direction of field, while the negative charges are displaced in the opposite direction. This displacement produces local dipoles throughout the solid. Thus the process of producing dipoles by an electric field is called polarization in dielectrics.

**Polarization vector \( (P) \)**

It is found that the strength of the induced electric dipole moment is proportional to the applied electric field.

\[
\mu = \alpha E
\]

Where \( \alpha \) is the constant of proportionality, called the polarizability. If \( \mu \) is the average dipole moment
per molecule and \( N \) is the number of molecules per unit volume then the polarization the solid is given by the polarization vector ‘\( P \)’ and it can be written as

\[
P = N \mu
\]

So the polarization vector ‘\( P \)’ is the dipole moment per unit volume of the dielectric material.

**Electric displacement vector ‘\( D \)’:**

The electric displacement vector (or) electric induction ‘\( D \)’ is a quantity which is a very convenient function for analyzing the electrostatic fields in the dielectric and is given by

\[
D = \varepsilon E = \varepsilon \varepsilon_0 E + P
\]

From this one can get

\[
\frac{P}{E} = \varepsilon - \varepsilon_0 = \varepsilon_0 (\varepsilon_r - 1)
\]

This quantity ‘\( D \)’ is similarly to the magnetic induction ‘\( B \)’ in the magnetism. Further the electric displacement vector ‘\( D \)’ has the remarkable property that its sources are only the free electric charges. The dielectric constant of vacuum is 1 and is close to 1 for air and many other gases. But when a piece of a dielectric material is placed between the two plates in capacitor the capacitance can increase significantly.

\[
C = \varepsilon_r \varepsilon_0 \frac{A}{L}
\]

Magnitude of electric dipole moment is \( \mu = q d \)

**DIELECTRIC MATERIALS IN CAPACITORS :**

Dipole formation and/or orientation along the external electric field in the capacitor causes a charge redistribution so that the surface nearest to the positive capacitor plate is negatively charged and vice versa. The process of dipole formation/alignment in electric field is called polarization and is described by \( P = Q^1/A \). Dipole formation induces additional charge \( Q^1 \) on plates: total plate charge \( Q_t = |Q + Q^1| \).

Therefore, \( C = \frac{Q_t}{V} \) has increased and dielectric constant of the material \( \varepsilon_r = C / C_{vac} > 1 \).

In the capacitor surface charge density (also called dielectric displacement) is

\[
D = Q/A = \varepsilon_r \varepsilon_0 E = \varepsilon_0 E + P
\]

Polarization is responsible for the increase in charge density above that for vacuum.

10 Minutes

**Verify**

1) Define and explain (i) dielectric constant (ii) electric susceptibility (iii) electric polarization and
(iv) polarizability.
2) What is meant by local field in a dielectric material? Explain how the local field could be calculated for a cubic dielectric crystal.
3) Explain the polarization mechanism in dielectric materials.
4) Establish a relation between the electronic polarizability ($\alpha_e$) and relative permittivity ($\epsilon_r$) using the concept of internal field.
5) With usual notations show that $P = \varepsilon_0 (\epsilon_r - 1) E$.
6) Obtain an expression for the internal field seen by an atom in an infinite array of atoms subjected to an external field.

30 Minutes

TYPES OF POLARIZATION:

Polarization is the alignment of permanent or induced atomic or molecular dipole moments with an external applied electric field. There are three types of polarization (fig. 3.21).

1. Electronic polarization
2. Ionic polarization
3. Molecular (orientation) polarization

Figure 3.21: (a) Electronic polarization that results from the distortion of an atomic electron cloud by an electric field. (b) Ionic polarization that results from the relative displacements of electrically charged ions in response to an electric field. (c) Response of permanent electric dipoles (arrows) to an applied electric field, producing orientation polarization.
Electronic (induced) polarization: Applied electric field displaces negative electron “clouds” with respect to positive nucleus. It occurs in all materials.

Ionic (induced) polarization: In ionic materials, applied electric field displaces cations and anions in opposite directions.

Molecular (orientation) polarization: Some materials possess permanent electric dipoles (e.g. H₂O). In absence of electric field, dipoles are randomly oriented. Applying electric field aligns these dipoles, causing net (large) dipole moment.

\[ P_{\text{total}} = P_e + P_i + P_o \]

Session 14: Frequency dependence of polarization, piezoelectricity and Ferroelectricity

FREQUENCY DEPENDENCE OF POLARIZATION:

For alternating currents, an applied voltage or electric field changes direction with time. Now, consider a dielectric material which is connected to ac supply. With each direction reversal, the dipoles attempt to reorient with the field as shown in below fig 3.22.
**Figure 3.22:** Dipole orientations for (a) one polarity of an alternating electric field and (b) for the reversed polarity.

As shown in above fig.in a process requires some finite time. For each type of polarization some minimum reorientation time exists, which depends on the ease with which the particular dipoles are capable of realignment. A relaxation frequency is taken as a reciprocal of this minimum reorientation time.

Electrons have much smaller mass than ions, so they respond more rapidly to a changing electric field. For electric field that oscillates at very high frequencies ($10^{15}$Hz) only electronic polarization can occur. Compared with electrons, ions have large mass so ionic polarization can’t occur at optical frequencies. It requires large time to displace ions. At smaller frequencies ($10^{13}$ Hz) ionic polarization also occur in addition to electronic polarization.

**Figure 3.23:** Variation of dielectric constant with frequency of an alternating electric field. Electronic, ionic and orientation polarization contributions to the dielectric constant are indicated.

Now third type is orientation polarization. Orientation of permanent dipoles which require the rotation of a molecule can occur only if the oscillation is relatively slow. So at low frequencies ($10^6 – 10^{10}$ Hz) the orientation polarization occurs in addition to electronic and ionic polarization. Space charge polarization is the slowest process and occurs only at power frequencies ($10^2$ Hz).

Thus at low frequencies the value of total polarization is very high and at high frequencies the value of total polarization is very small. If polarization is large, dielectric constant is also large from formulae $D=\varepsilon_0 E+P$ and $D=\varepsilon E$. Dielectric constant versus frequency graph is as shown in fig 3.23.

**TEMPERATURE DEPENDENCE OF POLARIZATION**
Electronic and ionic polarizations are practically temperature independent at normal temperatures. But orientation polarization and space charge polarization are affected by temperature. In orientation polarization, the sum of dipoles in presence of electric field is opposed by thermal vibrations of atoms. So polarization decreases with increasing temperature. In contrast to this in some polar substances, normal temperatures will oppose the permanent dipoles to align in the field direction. But higher temperatures facilitate the movement of dipoles. So polarization increases with increasing temperature. For example:

1. Dielectric constant of solid HCl decreases from 19 to 14 when temperature is increased from 100 to 160 K. This shows that the number of molecules per unit volume decreases due to the expansion on melting.

2. Solid nitrobenzene is a polar molecule, but it does not exhibit orientation polarization in its solid state because the rotation of molecules is prevented under an applied field. But in liquid state, the molecules have sufficient energy to reorient themselves in the applied field. The relative dielectric constant increases from 3 to 37 on melting. This is in contrast with the results obtained for solid HCl.

**DIELECTRIC STRENGTH (OR) DIELECTRIC BREAKDOWN**

Very high electric fields (>10^8 V/m) can excite electrons to the conduction band and accelerate them to such high energies that they can, in turn, free other electrons, in an avalanche process (or electrical discharge). The field necessary to start the avalanche process is called dielectric strength or breakdown strength.

**DIELECTRIC LOSS**

When an ac electric field is applied to a dielectric material, some amount of electrical energy is absorbed by the dielectric material and is wasted in the form of heat. This loss of energy is called dielectric loss. This loss is at the electric field frequencies in the vicinity of the relaxation frequency for each of the operative dipole types for a specific material. A low dielectric loss is desired at the frequency of utilization.

**10 Minutes**

**Verify**

1. Explain relation between dielectric constant and polarization.
2. Explain the reasons decay of dielectric constant with increase in frequency of applied field.
3. Define dielectric loss.
Ferro electricity is defined as the spontaneous alignment of electric dipoles by the mutual interaction in the absence of an applied electric field. It arises from the fact that the local field increases in proportion to the polarization. Thus, ferro-electric materials must possess permanent dipoles. Ex.: BaTiO$_3$, Rochelle salt (NaKC$_4$H$_4$O$_6$.4H$_2$O), potassium di hydrogen phosphate (KH$_2$PO$_4$), Potassium niobate (KNbO$_3$). These materials have extremely high dielectric constants at relatively low applied field frequencies. Thus, capacitors made from ferro electric materials are smaller than capacitors made of other dielectric materials.

Properties of Ferro electric Materials:

1. Ferro electric materials can be easily polarized even by very weak electric fields.
2. They exhibit dielectric hysteresis. Lagging of polarization behind the applied electric field is called dielectric hysteresis. Ferro electricity is a result of dielectric hysteresis.
3. Ferro electric materials possess spontaneous polarization, which is a polarization that persists when the applied field is zero.
4. Ferro electric materials exhibit ferro-electricity when the temperature $T < T_c$ where $T_c$ is ferroelectric curie temperature when $T > T_c$, they are converted into para electric materials.
5. They exhibit domain structures as in the case of ferromagnetic materials.
6. Ferro electric materials exhibit piezo electricity and pyro electricity. Piezo electricity means the creation of electric polarization by mechanical stress. Pyro electricity means the creation of electric polarization by thermal stress.

Spontaneous polarization and domains in BaTiO$_3$:

The structural changes in BaTiO$_3$ crystal due to lattice variation give rise to ferro electricity. Above 120°C BaTiO$_3$ has a cubic crystal structure with the titanium ions exactly at the body centre, Barium ions are at the body corners and oxygen ions are at the face centers as shown in fig 3.25. At those temperatures, there is no spontaneous dipole moment.

If the crystal is cooled below 120°C the titanium ions shift to one side of the body centre. This
displaces the neighboring ions along one of the crystal directions which become elongated. This gives the tetragonal structure due to the shifting of the titanium ion. This displacement of the titanium ion creates electric dipoles and all the dipoles of the adjacent unit cells get aligned in one direction. Below $120^\circ$C temperatures there is an enormous value for dielectric constant. The dielectric constants of these materials are some three orders of magnitude larger than that in ordinary dielectrics. Since ferroelectric materials are similar to ferromagnetic materials. They exhibit domain structure.

**Applications of Ferroelectric Materials:**

1. In optical communication, the ferroelectric crystals are used for optical modulation.
2. The high dielectric constant of ferroelectric crystals is also useful for storing energy in small sized capacitors in electrical circuits.
3. These are used in electro acoustic transducers such as microphone.

**PIEZO ELECTRICITY (10 min):**

In some ceramic materials, application of external forces produces an electric (polarization) field and vice-versa. Applications of piezoelectric materials is based on conversion of mechanical strain into electricity (microphones, strain gauges, sonar detectors) stress-free with applied stress. Examples: barium titanate $\text{BaTiO}_3$, lead zirconate $\text{PbZrO}_3$, quartz.
Figure 3.24: (a) Dipoles within a piezoelectric material. (b) A voltage is generated when the material is subjected to a compressive stress.

10 Minutes

Verify

1. Define piezoelectricity and ferroelectricity

2. Write important characteristics of ferroelectric materials?

3. Discuss some of the important applications of the piezoelectrics.