

# **SVR ENGINEERING COLLEGE**

## **PHYSICS OF ELECTRONIC MATERIALS & DEVICES**

by

**N. DIVYA MANJIRA**

### **4.Dielectric Materials and their applications**

#### **Introduction :**

A dielectric material, also known as an insulating material, is a substance that does not conduct electric current easily. It is characterized by its ability to store and release electrical energy in the form of an electric field. Dielectric materials are used in a wide range of applications, including capacitors, transformers, insulators, and electrical cables.

Dielectric materials have high resistivity, which means they offer a high resistance to the flow of electric current. This property allows them to effectively isolate and separate electrical conductors, preventing unwanted current leakage. Dielectric materials are typically used to insulate conductive components and prevent short circuits or electric shocks.

One of the key properties of dielectric materials is their dielectric constant (also known as relative permittivity). The dielectric constant represents the material's ability to store electrical energy in an electric field compared to a vacuum. Materials with higher dielectric constants can store more electrical energy. Dielectric materials are often used in capacitors, where they are placed between the conductive plates to increase the capacitance of the device.

Common examples of dielectric materials include:

Ceramic materials: Ceramic materials, such as porcelain, alumina, and titanates, are widely used as dielectric materials due to their high resistivity and stability at high temperatures.

Polymers: Many polymers, such as polyethylene, polypropylene, and polystyrene, exhibit good dielectric properties and are used in various electrical applications.

Glass: Certain types of glass, like borosilicate glass, can act as good dielectric materials due to their high resistivity and low electrical conductivity.

Mica: Mica is a naturally occurring mineral that is often used as a dielectric material in capacitors and insulators due to its excellent electrical insulation properties.

Paper: In some applications, paper treated with insulating materials is used as a dielectric material. It is commonly used in electrical cables and power transformers.

### **Dielectric Properties :**

Dielectric properties refer to the electrical characteristics and behaviours of dielectric materials when subjected to an electric field. These properties play a crucial role in determining the performance and suitability of dielectric materials for various applications. Here are some key dielectric properties:

1.Dielectric Constant/Relative Permittivity: The dielectric constant ( $\epsilon_r$ ) or relative permittivity of a material represents its ability to store electrical energy in an electric field compared to a vacuum. It is a dimensionless quantity that indicates the material's capacitance relative to vacuum. Dielectric materials with higher dielectric constants can store more electrical energy.

2.Dielectric Strength/Breakdown Voltage: The dielectric strength of a material is the maximum electric field strength it can withstand without experiencing electrical breakdown. It is typically measured as the voltage at which dielectric breakdown occurs, leading to electrical conduction or insulation failure. Dielectric materials with higher

dielectric strength are more resistant to breakdown and are suitable for high-voltage applications.

3.Dielectric Loss: Dielectric loss, also known as dissipation factor or loss tangent ( $\tan \delta$ ), is a measure of the energy lost as heat when an electric field is applied to a dielectric material. It represents the ratio of the energy dissipated to the energy stored in the material. Materials with low dielectric loss are preferred for applications where energy efficiency is crucial.

4.Dielectric Breakdown/Electric Strength: Dielectric breakdown refers to the failure of a dielectric material due to excessive electric field stress, leading to a sudden increase in electric current. It is typically characterized by a rapid drop in insulation resistance. Dielectric breakdown strength is the measure of the electric field strength at which dielectric breakdown occurs.

5.Dielectric Polarization: When an electric field is applied to a dielectric material, its molecules or atoms can become polarized, causing the alignment of positive and negative charges within the material. This polarization creates an induced dipole moment, resulting in the storage of electrical energy. Dielectric polarization is responsible for the ability of dielectric materials to store and release electrical energy.

6.Dielectric Relaxation: Dielectric relaxation refers to the time-dependent response of a dielectric material to an alternating electric field. It occurs due to the reorientation or realignment of polar molecules or ions within the material. Dielectric relaxation is characterized by relaxation time, which represents the time required for the dielectric material to reach a steady-state polarization after the electric field is applied or removed.

These dielectric properties are important considerations when selecting dielectric materials for specific applications, such as capacitors, insulators, transformers, and electronic components. The choice of dielectric material depends on factors such as operating

voltage, frequency, temperature, dielectric constant requirements, and desired electrical behaviour in the presence of an electric field.

### **Electronic Polarizability :**

Electronic polarizability is a property of atoms, molecules, or materials that describes their response to an external electric field by developing an induced dipole moment. It quantifies how easily the electron cloud around the atoms or molecules can be distorted under the influence of an electric field. The extent of electronic polarizability determines how much the charge distribution within the system changes in response to the electric field.

When an electric field is applied to a material, the positive and negative charges within the atoms or molecules experience a force that tends to separate them, causing a temporary deformation of the electron cloud. This leads to the development of an induced dipole moment, which creates an opposing electric field. The induced dipole moment is proportional to the applied electric field and is determined by the electronic polarizability of the system.

The electronic polarizability of a system depends on various factors, including the nature of the atoms or molecules, their electronic structure, and the arrangement of the system in space. It can be influenced by factors such as bond type, bond length, molecular shape, and the presence of functional groups.

The electronic polarizability is typically represented by a tensor quantity because it may vary depending on the direction of the applied electric field relative to the system. In some cases, such as isotropic materials or spherically symmetric atoms, a scalar polarizability is sufficient to describe the response to the electric field.

The electronic polarizability plays a significant role in various areas of science and technology. It is particularly relevant in the study of dielectric materials, where it determines the ability of a material to store electrical energy in the presence of an electric field. Materials

with high electronic polarizability tend to exhibit high dielectric constants and can store more electrical energy in capacitors.

Furthermore, electronic polarizability affects the optical properties of materials, such as their refractive index and response to light. It also influences the intermolecular forces and interactions between molecules, which are important in fields like chemistry, biology, and materials science.

### **Electronic Susceptibility :**

Electronic susceptibility, also known as electric susceptibility, is a measure of the response of a material's electronic structure to an external electric field. It quantifies the degree to which the polarization of the material changes in the presence of an electric field. In other words, electronic susceptibility relates the induced polarization to the strength of the applied electric field.

The electronic susceptibility is mathematically defined as the ratio of the induced polarization per unit volume to the applied electric field strength. It is typically denoted by the symbol  $\chi_e$ . The relationship between polarization (P) and the electric field (E) is given by the equation:

$$P = \chi_e \epsilon_0 E,$$

where  $\epsilon_0$  is the vacuum permittivity.

The electronic susceptibility depends on the electronic structure of the material and can vary for different substances. It is related to the electronic polarizability, which describes the ease with which the electron cloud can be distorted. In fact, the electronic polarizability ( $\alpha$ ) and the electronic susceptibility ( $\chi_e$ ) are related through the equation:

$$\chi_e = (N / \epsilon_0) \alpha,$$

where N is the number density of polarizable entities (atoms or molecules) in the material.

The electronic susceptibility is an important parameter in the study of dielectric materials. It determines the material's response to electric fields and is related to other dielectric properties, such as the dielectric constant and dielectric loss. Materials with higher electronic susceptibility tend to exhibit greater polarization and higher dielectric constants, indicating their ability to store more electrical energy in the presence of an electric field.

### **Dielectric Constant :**

The dielectric constant, also known as relative permittivity, is a fundamental property of a dielectric material that quantifies its ability to store electrical energy in an electric field compared to a vacuum. It represents the ratio of the capacitance of a capacitor with the dielectric material to the capacitance of the same capacitor with a vacuum as the dielectric.

Mathematically, the dielectric constant ( $\epsilon_r$ ) is defined as:

$$\epsilon_r = C/C_0,$$

where  $C$  is the capacitance of the capacitor with the dielectric material and  $C_0$  is the capacitance of the same capacitor with vacuum as the dielectric.

The dielectric constant is a dimensionless quantity and varies for different materials. A dielectric constant of 1 indicates that the material has the same capacitance as a vacuum, while a dielectric constant greater than 1 indicates that the material can store more electrical energy.

The dielectric constant depends on the electronic structure, composition, and arrangement of atoms or molecules within the dielectric material. It is influenced by factors such as molecular polarizability, dipole moments, and the presence of free charges. Dielectric materials with high dielectric constants typically have a

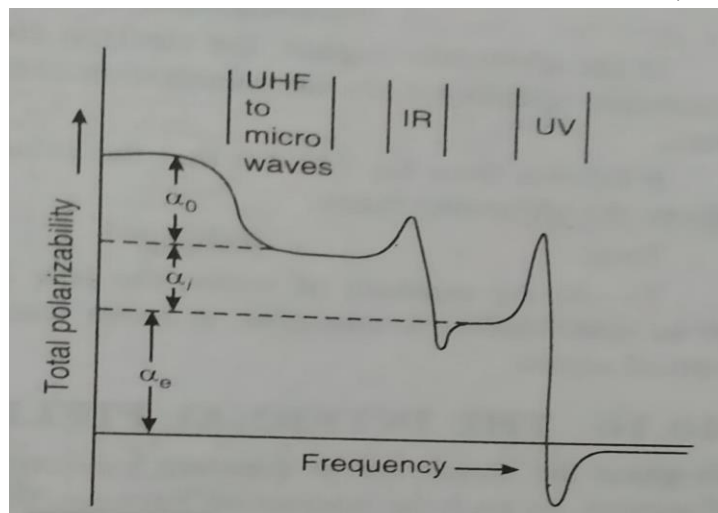
greater ability to polarize under the influence of an electric field and store more electrical energy.

The dielectric constant is an important parameter in the design and analysis of various electrical and electronic devices. It affects the performance of capacitors, where the dielectric constant determines the capacitance value. Higher dielectric constants allow for increased energy storage in capacitors. Additionally, the dielectric constant influences the behaviour of dielectric materials in terms of their electrical insulation properties, permittivity, and impedance matching in transmission lines.

It is important to note that the dielectric constant may vary with frequency and temperature. Materials can exhibit frequency-dependent dielectric constants, particularly at higher frequencies. The dielectric constant is a measure of a dielectric material's ability to store electrical energy compared to a vacuum. It is determined by the material's composition, structure, and electronic properties. The dielectric constant has significant implications for the design and performance of electrical and electronic devices that utilize dielectric material

### **Frequency dependence of polarization :**

In many practical situations, a dielectric is subjected to an alternating electric field. With each direction reversal of ac field, the polarization



component also reverses. The total polarization depends on the ability of dipoles to orient themselves in the direction of the field during each alternation of the field. The above fig. illustrates the dependence of P on frequency of the electric field for a polar dielectric.

In **audio frequency region**, all types of polarization are possible and the dielectric is characterized by a polarizability,  $\alpha = \alpha_e + \alpha_i + \alpha_o$  and the polarization  $P = P_e + P_i + P_o$ .

At low frequencies, the dipoles will get sufficient time to orient themselves completely along the instantaneous direction of the field. This orientation occurs first in one direction and then in the other, following the changes in the direction of the field. The average time taken by the dipoles to reorient in the field direction is known as the **relaxation time**  $\tau$ . The reciprocal of the relaxation time is called the **relaxation frequency**  $\nu$ . The orientation polarization, which is effective at low frequencies, is damped out for higher frequencies.

In the **radio frequency or microwave band region**, the permanent dipoles fail to follow the field reversals and the polarization falls to a value corresponding to  $(P_i + P_e)$ . As a result,  $\epsilon_r$  decreases considerably.

In the **infrared region** the ionic polarization fails to follow the field reversals & the contribution of ionic polarizability ceases, only electronic polarization contributes to the total polarization. Therefore,  $P = P_e$ .

In the **optical region**, the electron cloud follows the field variations and the material exhibits an electronic polarizability  $\alpha_e$ . The relative permittivity in the optical region will be equal to the square of the refractive index 'n' of the dielectric.

$$[\epsilon_r]_{\text{optical region}} = n^2$$

In the **ultraviolet region**, the electron cloud too fails to follow the field alternations and the electronic contribution to the polarization ceases. Consequently, the total polarization becomes zero.



## **Dielectric Strength :**

Dielectric strength refers to the maximum electric field strength a dielectric material can withstand without experiencing electrical breakdown or insulation failure. It is a measure of the material's ability to resist the flow of electric current and maintain its insulating properties under high voltage conditions.

When the electric field strength exceeds the dielectric strength of a material, the insulating properties break down, resulting in the occurrence of electrical discharge or breakdown. Electrical breakdown can lead to the formation of an electric arc or spark, which may cause damage to the material, equipment, or even pose safety hazards.

Dielectric strength is typically specified in units of volts per unit thickness (e.g., volts per millimetre). It represents the voltage gradient required to cause electrical breakdown, divided by the thickness of the dielectric material.

Several factors can influence the dielectric strength of a material:

1.Material Properties: The inherent properties of the dielectric material, such as its composition, molecular structure, purity, and density, can affect its dielectric strength. For example, materials with higher resistivity, stronger bonding, and fewer defects or impurities tend to exhibit higher dielectric strengths.

2.Thickness: The dielectric strength is inversely proportional to the thickness of the material. Thicker materials generally have higher dielectric strengths, as they provide a larger insulation barrier.

3.Temperature: The dielectric strength of a material can decrease with increasing temperature. Elevated temperatures can lead to thermal degradation or ionization of the material, reducing its ability to withstand high electric field stresses.

4.Moisture and Contaminants: Moisture, humidity, and contaminants can significantly reduce the dielectric strength of a material. Moisture

and impurities can introduce conductive paths, allowing electric current to flow and causing breakdown at lower electric field strengths.

Dielectric strength is an important parameter when selecting materials for high-voltage applications, such as power transmission, electrical insulation, and high-voltage capacitors..

It is crucial to design electrical systems and select dielectric materials with dielectric strengths that exceed the anticipated operating voltage to ensure safety, reliability, and efficient performance. Compliance with applicable industry standards and regulations is essential for the proper selection and use of dielectric materials with appropriate dielectric strength ratings.

### **Dielectric Loss :**

Dielectric loss, also known as dielectric dissipation factor or  $\tan \delta$ , is a measure of the energy loss that occurs in a dielectric material when subjected to an alternating electric field. It quantifies the efficiency with which the dielectric converts electrical energy into heat energy.

When an alternating voltage is applied to a dielectric material, the electric field alternates direction at the frequency of the applied voltage. As the electric field oscillates, the dielectric molecules or dipoles within the material attempt to realign themselves with the changing field. However, due to molecular friction and internal resistance within the material, energy is dissipated in the form of heat during the realignment process. This dissipation of energy leads to dielectric loss.

Mathematically, the dielectric loss tangent ( $\tan \delta$ ) is defined as the ratio of the power dissipated in the dielectric ( $P_{\text{diss}}$ ) to the product of the applied voltage (V) and the current (I):

$$\tan \delta = P_{\text{diss}} / (VI).$$

The dielectric loss is commonly expressed as a small angle in radians ( $\tan \delta = 0.01$  corresponds to a loss angle of 0.57 degrees).

The dielectric loss factor depends on several factors, including the properties of the dielectric material and the frequency of the applied electric field.

Some key factors influencing dielectric loss include:

1. Material Properties: The molecular structure, composition, and purity of the dielectric material play a significant role in determining the dielectric loss. Materials with high molecular mobility, strong intermolecular interactions, or impurities tend to exhibit higher dielectric losses.

2. Frequency: The dielectric loss typically increases with increasing frequency. At low frequencies, dielectric loss is mainly associated with relaxation processes, such as dipolar relaxation or molecular reorientation. At higher frequencies, additional loss mechanisms, such as electronic and ionic conduction, may contribute to dielectric loss.

3. Temperature: Dielectric loss is often temperature-dependent. Increasing temperature can enhance molecular motion and lead to increased dielectric loss in many materials.

Dielectric loss has practical implications in various applications. In electrical insulation systems, dielectric losses can lead to inefficiencies, increased heating, and reduced overall performance. In power systems and high-frequency applications, minimizing dielectric loss is crucial to ensure efficient energy transfer and reduce power losses.

Dielectric loss is often characterized through measurements, such as the measurement of the loss tangent ( $\tan \delta$ ), which provides insight into the dielectric behavior and performance of materials. Different measurement techniques, such as dielectric spectroscopy or impedance analysis, are employed to quantify and analyse dielectric losses over a range of frequencies.

Dielectric loss represents the energy dissipation that occurs in a dielectric material when subjected to an alternating electric field. It is quantified by the dielectric loss tangent ( $\tan \delta$ ) and is influenced by material properties, frequency, and temperature. Understanding and managing dielectric losses are important in various applications where efficient energy transfer and minimal energy losses are desired.

### **Piezoelectric properties :**

Piezoelectric properties refer to the ability of certain materials to generate an electric charge or voltage when subjected to mechanical stress or deformation, and conversely, to undergo mechanical strain or deformation when subjected to an electric field. This phenomenon is known as the piezoelectric effect and is exhibited by certain crystals, ceramics, polymers, and composites.

Piezoelectric materials have a crystal structure that lacks a center of symmetry, which allows for the piezoelectric effect to occur. When an external force is applied to a piezoelectric material, it causes a displacement of charged ions within the material, leading to the generation of an electric potential difference across the material. This phenomenon is called direct piezoelectric effect.

Conversely, when an electric field is applied to a piezoelectric material, it induces a mechanical strain or deformation due to the repositioning of charged ions. This is known as the inverse piezoelectric effect.

The piezoelectric effect can be quantified by two main parameters:

1. Piezoelectric Coefficient (d): The piezoelectric coefficient represents the magnitude of the coupling between the applied stress or strain and the resulting electric charge or voltage. It quantifies the sensitivity of the material to mechanical stress or deformation. The value of the piezoelectric coefficient depends on the crystallographic orientation of the material and the specific type of piezoelectric material.

2.Piezoelectric Modulus (e): The piezoelectric modulus relates the induced strain or deformation to the applied electric field. It represents the ability of the material to undergo mechanical displacement in response to an electric field. Like the piezoelectric coefficient, the piezoelectric modulus depends on the crystallographic orientation and the material properties.

Piezoelectric materials find a wide range of applications due to their ability to convert mechanical energy into electrical energy and vice versa. Some common applications of piezoelectric materials include:

1.Sensors and Actuators: Piezoelectric materials are used in various sensors to detect and measure physical quantities such as pressure, force, acceleration, and vibration. They are also employed as actuators in devices for precise positioning, sound generation, ultrasonic cleaning, and fuel injection.

2.Energy Harvesting: Piezoelectric materials can be used to convert mechanical vibrations or ambient vibrations into electrical energy. This energy harvesting capability is utilized in applications such as self-powered sensors and wireless sensor networks.

3.Medical Imaging: Piezoelectric materials are a crucial component in ultrasound transducers used for medical imaging. They generate and detect ultrasonic waves to produce images of internal body structures.

4.Piezoelectric Devices: Piezoelectric materials are utilized in various devices such as piezoelectric motors, inkjet printers, ultrasonic cleaners, and acoustic wave filters.

It is important to note that not all materials exhibit piezoelectric properties. The most commonly known piezoelectric materials include quartz, tourmaline, lead zirconate titanate (PZT), and certain ceramics and polymers that are engineered to exhibit piezoelectric behavior.

Piezoelectric properties refer to the ability of certain materials to generate an electric charge or voltage in response to mechanical stress

and undergo mechanical deformation in response to an electric field. These materials find widespread applications in sensing, actuation, energy harvesting, medical imaging, and various other technological fields.

### **Applications of Dielectric Materials :**

Dielectric materials play a crucial role in various applications across multiple industries. Their unique electrical properties make them valuable for insulation, energy storage, and electronic device design. Here are some common applications of dielectric materials:

1. Insulation: Dielectric materials are extensively used for electrical insulation to prevent the flow of electric current and protect conductive components. They are used in power cables, transformers, motors, capacitors, printed circuit boards (PCBs), and other electrical equipment.

2. Capacitors: Dielectric materials are a fundamental component of capacitors, which store electrical energy. The dielectric material separates the capacitor's conductive plates, allowing the storage of charge and energy. Different dielectric materials are chosen based on factors such as dielectric constant, breakdown voltage, and temperature stability to suit specific capacitor applications.

3. Printed Circuit Boards (PCBs): Dielectric materials are essential in the construction of PCBs. They provide electrical insulation between conducting traces and layers, allowing the formation of complex circuitry. Dielectric materials with low dielectric constant and good dimensional stability are preferred for high-frequency applications to minimize signal loss and impedance mismatch.

4. Integrated Circuits (ICs): Dielectric materials are used in the fabrication of ICs for insulation and isolation purposes. They help to define and separate different components and layers, such as transistors, interconnects, and capacitors, within the integrated circuit.

5.Optical Devices: Dielectric materials are employed in various optical applications, such as lenses, mirrors, waveguides, and thin films. Dielectric coatings on optical surfaces enhance reflectivity, transmission, and anti-reflective properties, enabling the manipulation and control of light in optical systems.

6.Microwave and RF Components: Dielectric materials with specific electrical properties, such as low loss tangent and high dielectric constant, are used in microwave and radio frequency (RF) components. These materials enable efficient energy transfer, impedance matching, and signal propagation in antennas, filters, resonators, and waveguides.

7.Energy Storage: Dielectric materials are utilized in energy storage systems such as electric double-layer capacitors (supercapacitors) and dielectric energy storage devices. Their ability to store electrical energy as an electric field provides high-power density and fast charge-discharge characteristics compared to traditional batteries.

8.Piezoelectric Devices: Certain dielectric materials exhibit piezoelectric properties, which are used in applications such as sensors, actuators, ultrasound transducers, and energy harvesting devices. Piezoelectric materials convert mechanical energy into electrical energy and vice versa, enabling precise measurement, actuation, and energy conversion.

9.Thermal Management: Dielectric materials with high thermal conductivity and electrical insulation properties are employed in thermal management applications. They are used as heat sinks, thermal interface materials, and insulating layers in electronic devices to dissipate heat efficiently and prevent thermal damage.

These are just a few examples of the wide-ranging applications of dielectric materials. The selection of specific dielectric materials depends on the desired electrical, thermal, and mechanical properties required for a particular application.

## **Differences between Insulators and Dielectrics :**

Insulators and dielectrics are both materials that exhibit high electrical resistance, but there are some key differences between them.

Here are the main differences:

Definition: Insulators are materials that have extremely high electrical resistance, which means they impede the flow of electric current.

Dielectrics, on the other hand, are a specific subset of insulating materials that are used for their unique electrical properties in the presence of an electric field.

Response to Electric Field: When an electric field is applied to an insulator, it does not significantly alter the material's electrical properties. Insulators simply prevent the flow of electric current. In contrast, dielectrics exhibit polarization and other electrical effects in the presence of an electric field, such as the ability to store electric charge and the phenomenon of dielectric breakdown.

Dielectric Constant: Dielectrics have a property called the dielectric constant or relative permittivity, which is a measure of how well they can store electrical energy in an electric field compared to a vacuum. Insulators may or may not have a defined dielectric constant, as it depends on their specific composition and structure.

Capacitance: Dielectrics are commonly used in capacitors to store electric charge. The presence of a dielectric material between the conductive plates of a capacitor increases its capacitance by enhancing the ability to store charge. Insulators, on the other hand, do not typically play a direct role in increasing capacitance.

Breakdown Voltage: Insulators have a high breakdown voltage, which refers to the electric field strength at which they experience electrical breakdown and allow electric current to flow. Dielectrics also have a breakdown voltage, but it may be lower than that of insulators, as dielectrics can undergo dielectric breakdown at higher electric field strengths.



Applications: Insulators are commonly used for electrical insulation in various applications, such as power transmission, electrical wiring, and insulating coatings. Dielectrics have specific applications that take advantage of their electrical properties, such as in capacitors, electrical energy storage, piezoelectric devices, and electrical insulation with additional benefits provided by polarization effects.

Both insulators and dielectrics exhibit high electrical resistance, dielectrics have specific electrical properties related to their behavior in an electric field, such as polarization and energy storage capabilities. Insulators, on the other hand, simply prevent the flow of electric current without significant electrical effects. The distinctions between the two arise from their different applications and the unique electrical behaviors exhibited by dielectrics.