CHAPTER-1

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1.1 Dielectric

In electromagnetism, a dielectric (or dielectric material or dielectric medium) is an electrical insulator that can be polarised by an applied electric field. When a dielectric material is placed in an electric field, electric charges do not flow through the material as they do in an electrical conductor, because they have no loosely bound, or free electrons that may drift through the material but instead, they shift only slightly from their average equilibrium positions, causing dielectric polarisation. Because of dielectric polarisation, positive charges are displaced in the direction of the field and negative charges shift in the direction opposite to the field (for example, if the field is moving parallel to the positive x-axis, the negative charges will shift in the negative x direction). This creates an internal electric field that reduces the overall field within the dielectric itself. If a dielectric is composed of weakly bonded molecules, those molecules not only become polarised but also re-orient so that their symmetry axes align to the field.[1]

The study of dielectric properties concerns the storage and dissipation of electric and magnetic energy in materials.[2][3][4] Dielectrics are important for explaining various phenomena in electronics, optics, solid-state physics, and cell biophysics.[5][6] Although the term insulator implies low electrical conduction, dielectric typically means materials with a high polarisability. The latter is expressed by a number called the relative permittivity. The term insulator is generally used to indicate electrical obstruction while the term dielectric is used to indicate the energy-storing capacity of the material (using polarisation). A common example of a dielectric is the electrically insulating material between the metallic plates of a capacitor. The polarisation of the dielectric by the applied electric field increases the capacitor's surface charge for the given electric field strength.[1]

The dielectric constant (ε′) decreases rapidly with the increase in frequency. This decrease is due to the reduction of the space charge polarization effect. Then, it remains nearly constant but, increases with increasing temperature at a given frequency. However, at low frequency the dielectric constant was high. At frequencies used in PCBs and microwave components, the amount of energy absorbed by the dielectric generally increases with frequency until you get into the high GHz range. Loss gets larger with frequency because the changing Electro Magnetic field causes the molecules in the dielectric to vibrate. Dielectric relaxation as a whole is the result of the movement of dipoles (dipole relaxation) and electric charges (ionic relaxation) due to an applied alternating field and is usually observed in the frequency range 10^2-10^{10} Hz. A dielectric permittivity spectrum over a wide range of frequencies is given in figure 1.1.

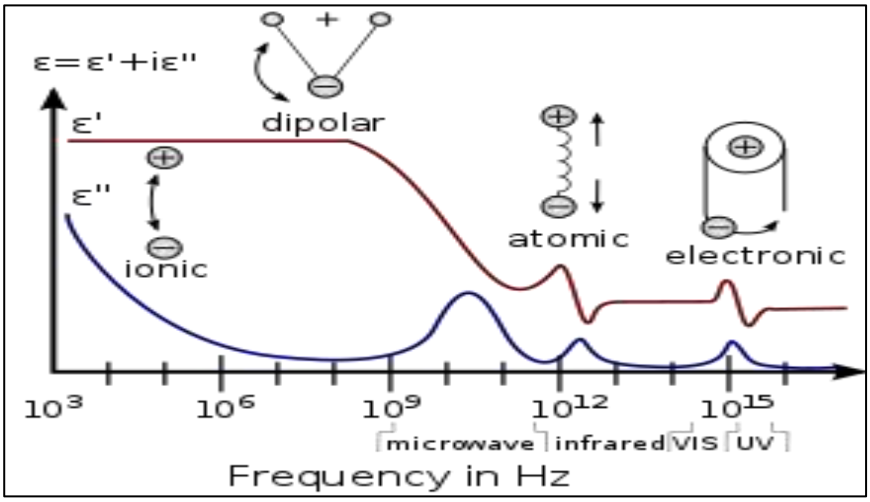
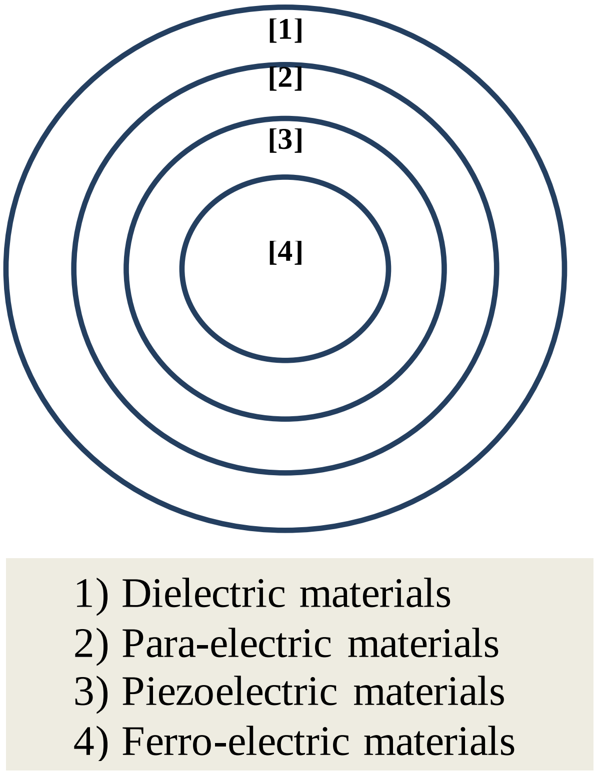


Figure 1.1 A dielectric permittivity spectrum over a wide range of frequencies. (Figure is taken from open access internet source: https://en.wikipedia.org/wiki/Dielectric_spectroscopy#/media/File:Dielectric_responses.svg)

The term dielectric was coined by William Whewell (from dia + electric) in response to a request from Michael Faraday.[7][8] A perfect dielectric is a material with zero electrical conductivity (cf. perfect conductor infinite electrical conductivity),[9] thus exhibiting only a displacement current; therefore it stores and returns electrical energy as if it were an ideal capacitor. There are several classes of dielectrics such as para-electric, piezoelectric, and ferroelectrics depending on the structural relation with the polarization.



1) Dielectric materials
2) Para-electric materials
3) Piezoelectric materials
4) Ferro-electric materials

Figure 1.2 Schematic representations of Sets of dielectric materials

1.2 Electric Susceptibility:

The electric susceptibility (χ_e) of a dielectric material is a measure of how easily it polarises in response to an electric field. This, in turn, determines the electric permittivity of the material and thus influences many other phenomena in that medium, from the capacitance of capacitors to the speed of light.

It is defined as the constant of proportionality (which may be a tensor) relating an electric field E to the induced dielectric polarisation density P such that

$$P = \varepsilon_0 \chi_e E \tag{1}$$

Where ε_0 is the electric permittivity of free space.

The susceptibility of a medium is related to its relative permittivity ε_r by

$$\chi_e = \varepsilon_r - 1 \tag{2}$$

So in the case of a vacuum,

$$\chi_e = 0 \tag{3}$$

The electric displacement D is related to the polarisation density P by

$$D = \varepsilon_0 E + P = \varepsilon_0 (1 + \chi_e) E = \varepsilon_0 \varepsilon_r E \tag{4}$$

1.3 Dielectric Polarization:

Dielectric Polarization occurs when an external electric field is applied to a dielectric substance. When an electric field is applied, it causes charges (both positive and negative) to be displaced. The primary goal of dielectric polarisation is to connect macroscopic and microscopic characteristics.

In the classical approach to the dielectric, the material is made up of atoms. Each atom consists of a cloud of negative charge (electrons) bound to and surrounding a positive point charge at its center. In the presence of an electric field, the charge cloud is distorted, as shown in the top right of Figure 1.3.

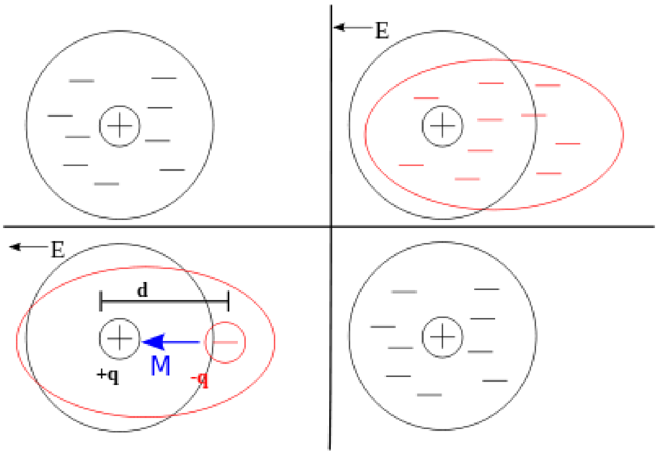


Figure 1.3 Electric field interactions with an atom under the classical dielectric model

This can be reduced to a simple dipole using the superposition principle. A dipole is characterized by its dipole moment, a vector quantity shown in the figure as the blue arrow labeled M. It is the relationship between the electric field and the dipole moment that gives rise to the behavior of the dielectric. (Note that the dipole moment points in the same direction as the electric field in the figure. This isn't always the case, and is a major simplification, but is true for many materials.) When the electric field is removed the atom returns to its original state. The time required to do so is the so-called relaxation time; an exponential decay.

1.4 Ionic polarisation:

Ionic polarisation is polarisation caused by relative displacements between positive and negative ions in ionic crystals (for example, NaCl). If a crystal or molecule consists of atoms of more than one kind, the distribution of charges around an atom in the crystal or molecule leans to positive or negative. As a result, when lattice vibrations or molecular vibrations induce relative displacements of the atoms, the centers of positive and negative charges are also displaced. The locations of these centers are affected by the symmetry of the displacements. When the centers don't correspond, polarisation arises in molecules or crystals. This polarisation is called ionic polarisation.

Ionic polarisation causes the ferroelectric effect as well as dipolar polarisation. The ferroelectric transition, which is caused by the lining up of the orientations of permanent dipoles along a particular direction, is called an order-disorder phase transition. The transition caused by ionic polarisations in crystals is called a displacive phase transition.

1.5 High k dielectric

"High-k" stands for high dielectric constant, a measure of how much charge a material can hold. The term high-κ dielectric refers to a material with a high dielectric constant (κ, kappa), as compared to silicon dioxide. Sometimes these materials are called "high-k" (pronounced "high kay"), instead of "high-κ" (high kappa). High-κ dielectrics are used in semiconductor manufacturing processes where they are usually used to replace a silicon dioxide gate dielectric or another dielectric layer of a device. The implementation of high-κ gate dielectrics is one of several strategies developed to allow further miniaturization of microelectronic components, colloquially referred to as extending Moore's Law. The highest dielectric constant material is Calcium Copper Titanate. The dielectric constant of Calcium Copper Titanate (CCTO) is over 10,000 and goes deeper at higher frequencies. It is used to develop super-capacitors. However, there are some limitations to its application, and it may take some time.

Representative examples of High k dielectrics include Al_2O_3, HfO_2, ZrO_2, $HfZrO_4$, TiO_2, Sc_2O_3, Y_2O_3, La_2O_3, Lu_2O_3, Nb_2O_5, Ta_2O_5, ZnO and their simple mixtures. PZT-type perovskite shows ferroelectric behavior. Several investigations of M^*TiTaO_6 (M*= Al, Cr, Fe) have indeed revealed a strong relaxor ferroelectric behavior for $FeTiTaO_6$.[10]

1.6 Requirement of high k dielectric

Silicon dioxide (SiO_2) has been used as a gate oxide material for decades. As metal–oxide semiconductor field-effect transistors (MOSFETs) have decreased in size, the thickness of the silicon dioxide gate dielectric has steadily decreased to increase the gate capacitance (per unit area) and thereby drive current (per device width), raising device performance. As the thickness scales below 2 nm, leakage currents due to tunneling increase drastically, leading to high power consumption and reduced device reliability. Replacing the silicon dioxide gate dielectric with a high-κ material allows increased gate capacitance without the associated leakage effects.

Many materials systems are currently under consideration as potential replacements for SiO_2 as the gate dielectric material for sub-0.1μm complementary metal–oxide–semiconductor (CMOS) technology. A systematic consideration of the required properties of gate dielectrics indicates that the key guidelines for selecting an alternative gate dielectric are (a) permittivity, band gap, and band alignment to silicon, (b) thermodynamic stability, (c) film morphology, (d) interface quality, (e) compatibility with the current or expected materials to be used in processing for CMOS devices, (f) process compatibility, and (g) reliability. Many dielectrics appear favorable in some of these areas, but very few materials are promising concerning all of these guidelines. A review of current work and literature in the area of alternate gate dielectrics is given. Based on reported results and fundamental considerations, the pseudo-binary materials systems offer large flexibility and show the most promise toward successful integration into the expected processing conditions for future CMOS technologies, especially due to their tendency to form at interfaces with Si (e.g. silicates). These pseudo-binary systems also thereby enable the use of other high-κ materials by serving as an interfacial high-κ layer. While work is on-going, much research is still required, as it is clear that any material which is to replace SiO_2 as the gate dielectric faces a formidable challenge. The requirements for process integration compatibility are remarkably demanding, and any serious candidates will emerge only through continued, intensive investigation. [11]

1.7 Dielectric Relaxation:

In physics, dielectric relaxation refers to the relaxation response of a dielectric medium to an external, oscillating electric field. This relaxation is often described in terms of permittivity as a function of frequency, which can, for ideal systems, be described by the Debye equation. On the other hand, the distortion related to ionic and electronic polarisation shows the behavior of the resonance or oscillator type. The character of the distortion process depends on the structure, composition, and surroundings of the sample.

1.8 Requirement of relaxor ferroelectrics

Relaxor ferroelectrics are ferroelectric materials that exhibit high electrostriction. As of 2015, although they have been studied for over fifty years,[12] the mechanism for this effect is still not completely understood and is the subject of continuing research.[13][14][15]

Relaxor Ferroelectric materials find application in high-efficiency energy storage and conversion as they have high dielectric constants, orders-of-magnitude higher than those of conventional ferroelectric materials. Like conventional ferroelectrics, Relaxor Ferroelectrics show permanent dipole moment in domains. However, these domains are on the Nano-length scale, unlike conventional ferroelectrics domains that are generally on the micro-length scale, and take less energy to align. Consequently, Relaxor Ferroelectrics have very high specific capacitance and have thus generated interest in the fields of energy storage.[16] Furthermore, due to their slim hysteresis curve with high saturated polarization and low remnant polarization, Relaxor ferroelectrics have high discharge energy density and high discharge rates. BT-BZNT Multilayer Energy Storage Ceramic Capacitors (MLESCC) were experimentally determined to have very high efficiency (>80%) and stable thermal properties over a wide temperature range.[17]

1.9 Materials:

1.9.1 Perovskite

Perovskite structures are adopted by many oxides that have the chemical formula ABO_3. The idealized form is a cubic structure (space group Pm3m, no. 221) which is rarely encountered. The orthorhombic (e.g. space group Pnma, no. 62, or Amm2, no. 68) and tetragonal (e.g. space group I4/mcm, no. 140, or P4mm, no. 99) phases are the most common non-cubic variants. Although the perovskite structure is named after $CaTiO_3$, this mineral forms a non-idealized form. $SrTiO_3$ and $CaRbF_3$ are examples of cubic perovskites. Barium titanate is an example of a perovskite that can take on the rhombohedral (space group R3m, no. 160), orthorhombic, tetragonal, and cubic forms depending on temperature.[18]

Perovskite materials exhibit many interesting and intriguing properties from both the theoretical and the application point of view. Colossal magneto resistance, ferroelectricity, superconductivity, charge ordering, spin-dependent transport, high thermo-power, and the interplay of structural, magnetic, and transport properties are commonly observed features in this family. These compounds are used as sensors and catalyst electrodes in certain types of fuel cells[19] and are candidates for memory devices and spintronics applications.[20] Many superconducting ceramic materials (the high-temperature superconductors) have perovskite-like structures, often with 3 or more metals including copper, and some oxygen positions left vacant. One prime example is yttrium barium copper oxide which can be insulating or superconducting depending on the oxygen content. Chemical engineers are considering a cobalt-based perovskite material as a replacement for platinum in catalytic converters for diesel vehicles.[21]

1.9.2 Perovskite-Based Relaxor Ferroelectrics

Ferroelectrics (FE) are polar materials with spontaneous polarization that can be reoriented by changing the direction of the external applied electric field. In general, the overall polarization of the ferroelectric crystal is zero because of the equal number of domains oriented in random directions. As electric field (E) increases, the cations obtain sufficient energy to overcome the local electrical potential barrier and will be able to jump from one random potential well position to another permissible well position most closely aligned with the field, which results in the switching of domains. At strong enough E (E_{max}), switching will result in a domain saturation state (i.e., at the field above which no further domain reorientation in field direction is possible) at which the exhibited polarization is the Ps. Upon reducing and reversing E, the converse process takes place but traces along a new path consistent with the creation of new domains in the opposite direction. The polarization exhibited at zero fields after field reduction is Pr, which is not equal to zero in an FE material. The required E that can switch the ferroelectric material domains back and forth is the coercive field (Ec). Once poled, the material continues to follow the hysteresis loop and will return to zero net polarization at −Ec or if the material is raised above Tc, but not at E = 0 [22]. This phenomenon is called polarization-electric field (PE) hysteresis; shown in Figure 1.4 for a ferroelectric material.[23-25]

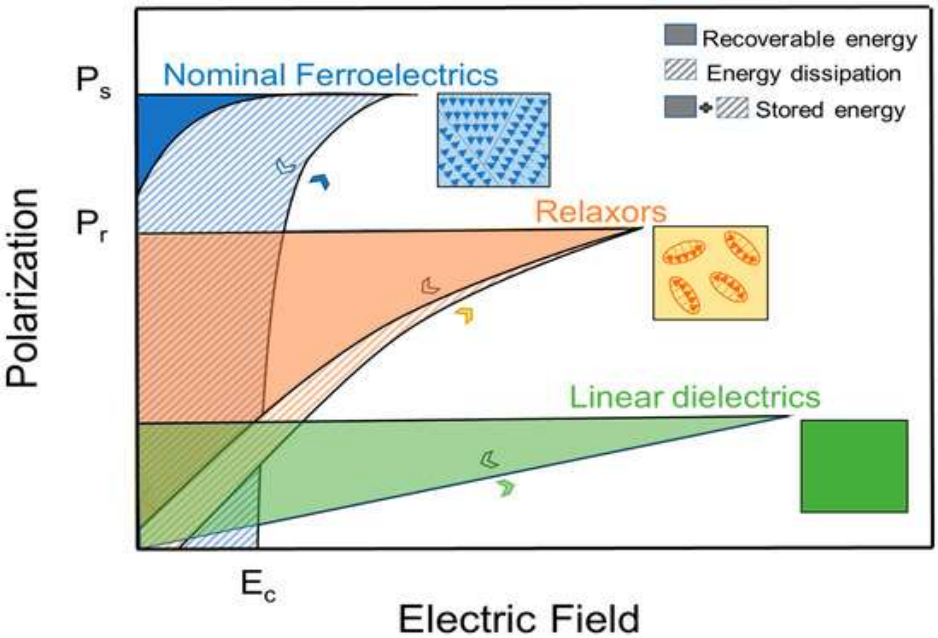


Figure 1.4 Polarization versus electric field (P−E) for typical ferroelectrics, relaxors, and linear dielectrics[26]

Perovskite-phase metal oxides exhibit a variety of interesting physical properties which include ferroelectric, dielectric, pyroelectric, and piezoelectric behavior.[27-29] Specifically, linear dielectric materials exhibit linear polarization behavior as a function of an applied field. Ferroelectric ceramics are dielectrics with a permanent electric dipole, which can be oriented upon the application of an electric field. Pyro-electric materials yield spontaneous polarization, but the direction of such polarization cannot be reversed upon application of an electric field. Piezo-electrics either exhibit an electrical charge when mechanically stressed or undergo mechanical deformation upon the application of an electric field. In general, these various properties arise from the crystal symmetry adopted by these materials.[30,31]

Though Perovskite-phase metal oxides have lots of studies in the area of high dielectric materials, several similar types of structured material are showing incipient ferroelectric behavior and high dielectric constant materials

1.9.3 Simple Oxides:

Representative examples of High k dielectrics include Al_2O_3, HfO_2, ZrO_2, TiO_2, Sc_2O_3, Y_2O_3, La_2O_3, Lu_2O_3, Nb_2O_5, Ta_2O_5, ZnO and their simple mixtures. The dielectric constant is a very important factor of a material that determines its applications in the electronic industry as a capacitor, thin-film transistor, memory devices, high-speed IC packaging, and EMI shielding. ZnO is one of the most demanded materials in the electronic industry due to its very attractive properties like wide availability, nontoxicity, and cost-effectiveness. Nano composites of ZnO have been explored by various researchers. Zinc oxide (ZnO) is a versatile material that can be used as a dielectric in various electronic applications. ZnO is widely employed as a dielectric material in capacitors. Due to its high dielectric constant, ZnO allows for increased charge storage capacity, leading to capacitors with higher energy density. ZnO-based capacitors are used in power electronics, energy storage systems, and other applications where high capacitance is required. ZnO thin films can be used as gate dielectrics in transistors and integrated circuits. ZnO films exhibit excellent electrical properties, such as low leakage current, high breakdown voltage, and good thermal stability. These properties make ZnO a suitable choice for high-performance transistors and ICs. ZnO-based varistors are electronic components used to protect sensitive circuits from voltage surges or transient voltages. The ZnO-based varistor utilizes the nonlinear behavior of ZnO as a dielectric material to provide high resistance at normal operating voltages and low resistance when subjected to high voltage spikes. ZnO possesses piezoelectric properties, meaning it can generate an electric charge when subjected to mechanical stress or vice versa. ZnO-based piezoelectric devices, such as sensors, actuators, and resonators, utilize this property. ZnO thin films are commonly used as a dielectric layer in these devices to enhance their performance. ZnO thin films can also function as dielectric layers in optoelectronic devices, including light-emitting diodes (LEDs), solar cells, and photo detectors. By using ZnO as a dielectric, it is possible to improve the device's performance by enhancing charge transport, reducing leakage currents, and increasing light absorption.

The unique combination of electrical, optical, and piezoelectric properties of ZnO makes it a versatile dielectric material with applications across a wide range of electronic devices and systems. On-going research and development continue to explore new ways to utilize ZnO's properties and improve its performance in various applications.

ZnO is a wide-band gap semiconductor of the II-VI semiconductor group. The native doping of the semiconductor due to oxygen vacancies or zinc interstitials is n-type.[32] Other favorable properties include good transparency, high electron mobility, wide band gap, and strong room-temperature luminescence. Those properties make ZnO valuable for a variety of emerging applications: transparent electrodes in liquid crystal displays, energy-saving or heat-protecting windows, and electronics such as thin-film transistors and light-emitting diodes.

1.9.4 Crystal Structure of ZnO

Zinc oxide crystallizes in two main forms, hexagonal wurtzite[33] and cubic zinc blende. The wurtzite structure is most stable at ambient conditions and thus most common. The zinc blende form can be stabilized by growing ZnO on substrates with cubic lattice structure. In both cases, the zinc and oxide centers are tetrahedral, the most characteristic geometry for Zn(II). ZnO converts to the rock salt motif at relatively high pressures about 10 GPa.[33] The many remarkable medical properties of creams containing ZnO can be explained by its elastic softness, which is characteristic of tetrahedral coordinated binary compounds close to the transition to octahedral structures.[34]

Hexagonal and zinc-blende polymorphs have no inversion symmetry (the reflection of a crystal relative to any given point does not transform it into itself). This and other lattice symmetry properties result in piezoelectricity of the hexagonal and zinc-blende ZnO, and pyro-electricity of hexagonal ZnO.

The hexagonal structure has a point group of 6 mm (Hermann–Mauguin notation) or C_{6v} (Schoenflies notation), and the space group is $P6_3mc$ or C_{6v}^4. The lattice constants are $a = 3.25$ Å and $c = 5.2$ Å; their ratio $c/a \sim 1.60$ is close to the ideal value for hexagonal cell $c/a = 1.633$.[35] As in most group II-VI materials, the bonding in ZnO is largely ionic ($Zn^{2+}O^{2-}$) with the corresponding radii of 0.074 nm for Zn^{2+} and 0.140 nm for O^{2-}. This property accounts for the preferential formation of wurtzite rather than zinc blende structure,[36] as well as the strong piezoelectricity of ZnO. Because of the polar Zn−O bonds, zinc and oxygen planes are electrically charged. To maintain electrical neutrality, those planes reconstruct at the atomic level in most relative materials, but not in ZnO^-, its surfaces are atomically flat, stable, and exhibit no reconstruction.[37] However, studies using wurtzite structures explained the origin of surface flatness and the absence of reconstruction at ZnO wurtzite surfaces[38] in addition to the origin of charges on ZnO planes.

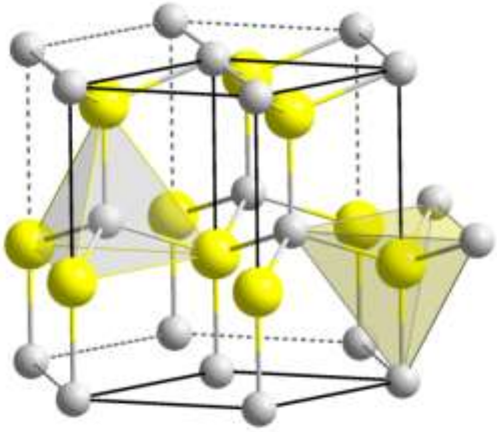


Figure 1.5 ZnO Wurtzite structure (Figure is taken from open access internet source: https://en.wikipedia.org/wiki/Zinc_oxide#/media/File:Wurtzite_polyhedra.png)

1.9.5 $CoNb_2O_6$

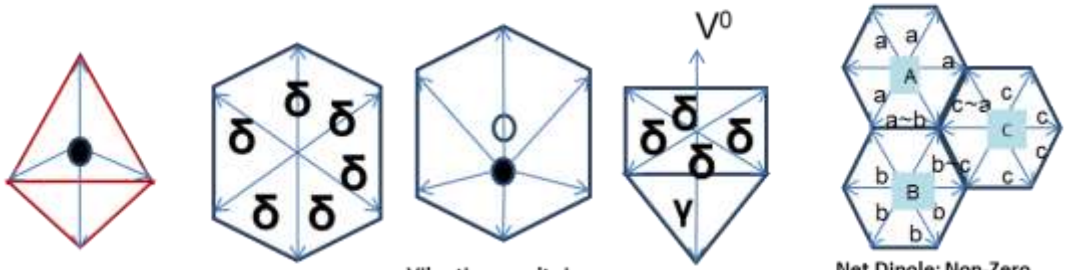
$CoNb_2O_6$ refers to Cobalt Niobate, which is a compound composed of cobalt (Co), niobium (Nb), and oxygen (O). It belongs to the family of complex metal oxides and has attracted interest due to its intriguing physical properties.

Thermodynamic characteristics such as entropy, heat capacity, or susceptibility of the ferroic materials (ferromagnets or ferroelectrics) having quantum phase transitions (QPT) are studied intensively to comprehend their specific nature.[39-41] Quantum criticality near the quantum critical point (QCP) is observed firstly in ferroelectrics where the ferroelectric transition temperature is suppressed to zero by tuning parameters [42]. The tuning parameters, which control the systems from ordered phase to quantum para-magnetic (QPa) or quantum para-electric states in different cases, can be hydro-static pressure, atomic substitution, a transverse magnetic field in ferromagnets or an electric field in ferroelectrics. The non-classical behavior of the inverse susceptibility χ^{-1} (equivalent to the inverse dielectric function ϱ^{-1}) of $SrTiO_3$ and related compounds is proportional to T^2 close to the QCP [43]. To convince of the weight of the finite temperature quantum criticality [44], Kinross et al. have specified the quantum critical properties of a quasi-one-dimensional Ising ferromagnet $CoNb_2O_6$ sustaining up to high temperature.

The anisotropy of the heat capacity and the susceptibility of $CoNb_2O_6$ has also been investigated experimentally since 1994 by Hanawa et al. [45]. They confirm that the magnetic moment of Co in this compound is 5.05 µB and the Co+2 (3d7) ion prefers a high spin (HS) state with s=3/2 rather than a low spin (LS) state with s=1/2 which is normally used in the exact fermion solution for the TIM. Recent first-principle calculations of Molla and Rahaman [46] have indicated that the magnetic moment at the cobalt site is 2.89 µB, thus the cobalt ion favors an HS state. The specific heat of $CoNb_2O_6$ exhibits the maximum peak which gradually reduces and moves to higher temperatures while increasing the field.[47] Ferroelectricity is primarily caused in semiconducting materials by the delicate balance between a long-range dipole interaction and a short-range interaction. This delicate balance is its characteristic appearance which gives ferro-electricity. Dipole moments are created whenever there is even a little distortion of the electron cloud as a result of structural changes in dielectrics. Therefore, new materials with a simple structure are not only preferable for understanding the microscopic origin of ferroelectricity, but they are also important for integrating into modern ferroelectric devices with the utilization of novel Pb and Bi free ferroelectric/piezoelectric/relaxor and multiferroic materials. This is because it is easier to understand the microscopic origin of ferroelectricity when the structure of the material is simpler. The purpose of this study was to create a novel lead-free high-k relaxor dielectric that has the potential for great performance as well as a high Curie temperature.

1.10 Aim of the present work:

To understand the origin of dielectricity, we have to understand polarization in polyhedra.



Net Dipole: Non-Zero (a)

Net Dipole: Zero (b)

Vibration results in Net dipole (c)

Net Dipole: Non-Zero (d)

Net Dipole: Non-Zero (e)

Figure 1.6 Representation of Change in dipole in various types of Structures.

As can be seen from Figure 1.6 (a) if we see the tetrahedral, the net dipole moment is there which will result in dieletricity. In figure (b) if we see the perfect octahedra, the net dipole is zero, but if we see Figures (c, d, and e) there is a net dipole moment because in figure (c) the vibration of cation from its mean position result in net dipole, in figure (d) the vacancy in octahedra is generating the net dipole, in figure (e) if there are different type of cations connected will lead the change in ionic strength in M-O bond and interconnected polyhedral (face shared) it can also result in the net dipole moment in the lattice and this type of dielectricity is because of high entropy and presence M-O bond of different ionic strength or polarization that result in net polarization in the lattice.

In this thesis, I attempted the Synthesis of various high entropy ZnO structures by doping various cations in the wurtzite lattice.

- Cu^{+} doped ZnO (**$Zn_{1-x}Cu_xO_{1-\delta}$**)
- Cu^{2+} and Li^{+} doped ZnO (**$Zn_{0.92}Cu_{0.05}Li_{0.03}O_{1-\delta}$ and $Zn_{0.9}Cu_{0.05}Li_{0.05}O_{1-\delta}$**)
- Fe^{3+} and Li^{+} doped ZnO (**$Zn_{1-2x}Li_xFe_xO$**)

Further, Ti^{4+} substitution on the Nb site in $CoNb_2O_6$ was contemplated in this study to develop innovative high k dielectric/ferroelectric properties as a result of decreased oxidation. Both smaller cations (Co^{3+} and Ti^{4+}) can lead to net dipole moment in each octahedron from the deviation from the mean position in octahedra and can generate high k dielectricity or it may turn the material into lead-free ferroelectricity. That is why we did the Synthesis of Ti^{4+} substitution on the Nb site in $CoNb_2O_6$ and studied to develop innovative high k dielectric/ferroelectric properties.

The focus of my work is to understand the variation of Oxygen ion vacancy and the electronic state of ions to deliver different ionicity in the chemical bonding resulting in the net polarization in the lattice to alter the dielectric constant of the material.

(i) The thesis study focuses on the synthesis and characterization of materials, as well as various types of applications such as high k dielectric and magnetic characteristics.

(ii) Grain and grain boundaries, morphological structure, particle analysed, temperature, and frequency influence on dielectric and electrical characteristics have been investigated extensively.

(iii) To improve the dielectric constant and magnetic properties of ceramic materials that are useful in the field of microelectronic devices and permanent magnets, sol-gel, and solid-state chemical route was used to observe and monitor the homogeneous mixing of metal ions and material synthesized. The objective of the present work is to synthesize the following ceramic materials:

- Synthesis of Cu-doped ZnO by sol-gel route reaction method. (hexagonal, Wurtzite)
- Synthesis of Cu and Li doped ZnO by sol-gel route reaction method. (hexagonal, Wurtzite)
- Synthesis of Fe and Li doped ZnO by sol-gel route reaction method. (hexagonal, Wurtzite)
- Synthesis of Ti-doped $CoNb_2O_6$ by solid-state reaction method. (Orthorhombic, Rutile)

Different types of physiochemical characterization of the following above materials in the sequential steps:

i. X-ray powder diffraction (XRD) study was used for the identification of phase formation and the crystal structure of the materials.
ii. Scanning electron microscope (SEM) analysis has been performed for the detailed morphological study of the fractured surface of the materials.
iii. Energy Dispersive X-Ray Spectroscopy (EDAX) analysis has been performed for the elemental analysis of the materials.
iv. The magnetic properties of the ceramics studied.
v. The oxidation state of the element was to be examined with the help of X-ray Photoelectron Spectroscopy (XPS).
vi. The impedance spectroscopy was carried out at a variable temperature in the air to study the dielectric behavior of the material.
vii. The P-E Loop study was done by the P-E Loop tester.

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