Orissa Journal of Physics
ISSN 0974-8202

Vol. 31, No. 1
February 2024
pp. 29 -42

Review on LCR measurement of dielectrics and analysis of various parameters

B. BISWAL and D. K. MISHRA

Department of Physics, Faculty of Engineering and Technology (ITER), Siksha 'O' Anusandhan Deemed to be University, Khandagiri Square, Bhubaneswar 751030, Odisha, India

Received: 26.11.2023 ; *Accepted : 29.01.2024*

Abstract : Dielectric materials find numerous applications in electronic devices due to their insulating behavior and charge storing capacity. A material fabricated for any practical purpose need to be analyzed accordingly. Likewise the dielectric and electrical properties of the dielectric materials are analyzed using an LCR meter. This review article basically incorporates brief discussion about dielectrics, different dielectric parameters, polarization mechanisms observed inside a dielectric due to application of external electric field, different forms of dielectric materials used for LCR analysis and important information that can be obtained from the AC parameters measured by the LCR meter. Dielectric spectroscopy or complex impedance spectroscopy deals with sufficient information on the structure of matter, ion displacement, dipole orientation, charge accumulations at interfaces, conduction mechanisms, defect/vacancy distributions and resistances from grain and grain boundary regions of a dielectric material.

Keywords: Dielectrics, LCR analysis, resistive properties, electric modulus

1. Introduction

Modern technology is based upon highly efficient electronic materials. The dielectric as well as multiferroic materials are extensively used in sensing devices, electronic circuit elements such as electronic substrates, high frequency circuit packaging materials, filters, actuators, resonators and in memory devices. For application in electronic/semiconductor industries, dielectric materials with high permittivity and low loss are required. These dielectric materials are analyzed by using an LCR meter. Before going to the LCR measurement part let us discuss briefly about the dielectric materials.

1.1 Dielectrics

Dielectrics are basically electrical insulators. Dielectrics are of two types: polar dielectrics and non-polar dielectrics. Polar dielectrics have spontaneous dipole moments as the center of positive charges and negative charges don't coincide in these materials. Non-polar dielectrics don't have any dipole moment without application of any external electric field. Since the dielectric don't have free electrons like metals, thus can't conduct effectively. However, when the dielectric is placed in an electric field the displacement of positive charges inside the dielectric along the field direction and the shifting of negative charges in a direction opposite to the electric field make the dielectrics polarized. Due to this electrical polarization, the electric field inside the dielectric decreases. The concept of storing charge or electrical energy in a dielectric material is realized considering capacitors (basically a parallel plate capacitor). A parallel plate capacitor with air in between the plates has a capacitance of $C_0=\epsilon_0 A/d$, where, ϵ_0 is the permittivity of free space, A is the area of the plate and d be the separation between the plates. The capacitance of the parallel plate capacitor increases when a dielectric material is inserted between the plates and is given by: $C= \epsilon_0\epsilon_r A/d$ $(=\epsilon A/d)$, where, ϵ_r is the dielectric constant or relative permittivity of the dielectric and ϵ is the permittivity of the dielectric. The dielectric constant of a dielectric material being a macroscopic parameter is the measure of its electric permeability that can be expressed as the ratio of capacitance of a parallel plate capacitor with the dielectric in between the plates to the ratio of capacitance of the capacitor with vacuum as its dielectric.

Thus, $\epsilon_r= C/C_0$ ……………………………………..……………………….(1)

The dielectric constant can also be represented as the ratio of permittivity of the dielectric material to the permittivity of free space.

i.e., $\epsilon_r=\epsilon/\epsilon_0$ …………………………………………………………………….(2)

1.2 Electrical circuit representation of Dielectrics

A parallel plate capacitor with vacuum or air in between the plates can be connected in an electrical circuit and an alternating voltage of $V=V_0 \exp(j\omega t)$ with an angular frequency $\omega=2\pi f$ (f is the frequency) is applied as shown in

Figure 1(a). If the charge developed on the capacitor plates is Q then the capacitance of the air filled capacitor

$$C_0=Q/V \quad \ldots\ldots (3)$$

The current in the circuit

$$I_{C0}=\frac{dQ}{dt}=\frac{d(C0V)}{dt}=\frac{d}{dt}(C_0V_0\exp(j\omega t)) = j\omega C_0V = C_0\omega V_0 \exp[j(\omega t+\pi/2)] \quad (4)$$

This represents that the current in this capacitive circuit leads the applied voltage by a phase angle of $\phi=\pi/2$ as depicted in Figure 1(b).

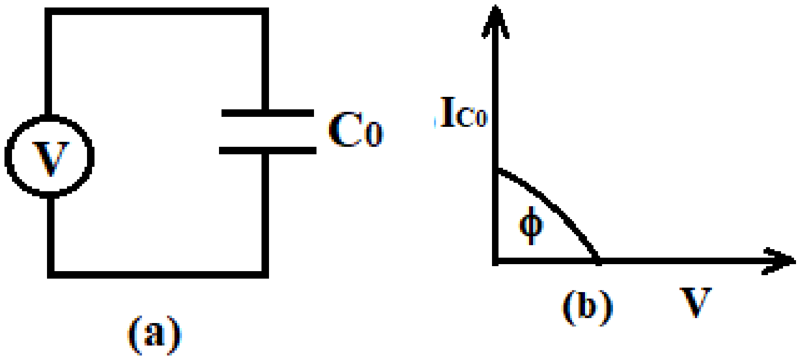

Figure 1. (a) Equivalent circuit diagram of an air capacitor (b) Phasor diagram showing current leads voltage by phase of $(\frac{\pi}{2})^{\circ}$.

The dielectrics were explained on the basis of electrical circuit concepts in 1965 by Nelson [1]. A parallel plate capacitor with a dielectric material in between the plates, when supplied the same voltage $V=V_0 \exp(j\omega t)$ the capacitance of the capacitor with the dielectric is given as $C=\epsilon_r C_0$ and the total current in the circuit (I) is a vector sum of charging current (I_C) and loss current (I_R). The charging current in the circuit is expressed as

$$I_C=j\omega CV \quad \ldots\ldots (5)$$

Since, no dielectric is an ideal insulator small loss current arises due to conductance through the dielectric. The loss current is expressed as

$$I_R=GV=V/R \quad \ldots\ldots (6)$$

Where, G is the conductance and R is the equivalent resistance of the dielectric inside the parallel plate capacitor.

This conductance effect of the dielectric can be represented in the electrical circuit as a resistance connected in series or parallel with the capacitor as shown in Figure 2(a). The conductance effect arises in dielectrics due to motion of some charge carriers or due to presence of defects/ impurity phases in the dielectric material under consideration. Thus, the total current is

$I = I_C + I_R = (j\omega C + \frac{1}{R})V$ ……………………………………………………………(7)

Thus the total current having a real part makes an angle with the imaginary axis known as the loss angle (δ). Hence, in case of a parallel plate capacitor filled with a dielectric material, the current (I) leads voltage by a phase angle $\phi = \frac{\pi}{2} - \delta$ which is depicted in Figure 2(b). This total current (I) containing both real and imaginary component gives the idea of complex dielectric constant for any dielectric material.

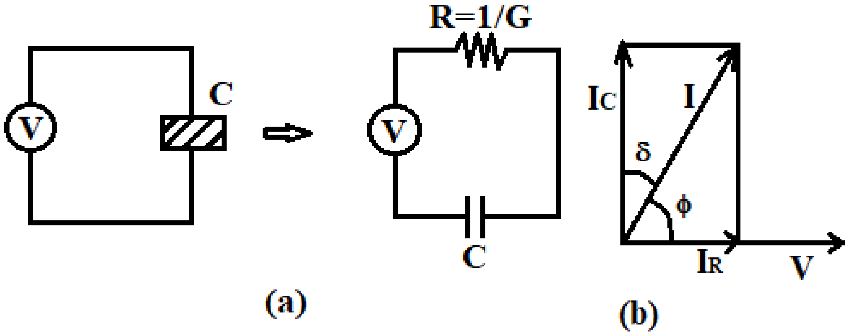

Fig. 2. (a) Equivalent circuit diagram of a capacitor with a dielectric between the plates (b) Phasor diagram showing current leads voltage by ($\frac{\pi}{2}$-δ)^o.

1.3 Complex Dielectric Constant

The total current in the dielectric circuit can be written as

$I = I_C + I_R = (j\omega C + \frac{1}{R})V = j\omega\epsilon_r C_0 V + \frac{V}{R}$ ………………………………………………(8)

Let's use ϵ_r' in place of ϵ_r and loss current (I_R) can be written as

$I_R = \omega\epsilon_r'' C_0 V$ (real component of current) ……………………………………………(9)

Thus,

$I = j\omega(\epsilon_r' - j\epsilon_r'')C_0 V = j\omega\epsilon_r C_0 V$ ……………………………………………………(10)

Hence, the complex dielectric constant is expressed as

$$\epsilon_r = \epsilon_r' - j\epsilon_r'' \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

The real part of the complex dielectric constant accounts for the relative permittivity of the dielectric, whereas the imaginary part accounts for the energy loss in the dielectric. The ‘dielectric loss’ or ‘dissipation factor’ for the dielectric material is expressed as the tangent of the loss angle δ i.e.,

$$\tan\delta = I_R/I_C = \epsilon_r''/\epsilon_r' \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

The relative permittivity or dielectric constant and the loss factor of any dielectric depends on the polarization mechanisms arising inside the dielectric due to externally applied electric field. The electrical polarizations are of four types (atomic/ionic polarization, dipolar/orientational polarization, electronic polarization and interfacial polarization) and these are frequency and temperature dependent processes [2]. Therefore, dielectric constant (ϵ_r) and the dielectric loss (tanδ) are also dependent on frequency and temperature. Let’s discuss about the dielectric polarizations.

1.4 Polarization mechanisms in Dielectrics

Electric polarization in homogeneous dielectric materials consists of three polarization processes: electronic, ionic and dipolar polarization [3]. ***Electronic polarization*** arises from the slight shifting of negatively charged electron cloud from the positively charged nucleus due to application of external electric field. Having very light mass electrons can respond to high frequency electric fields and thus electronic polarizability (α_{el}) contributes up to the optical frequency range ($>10^{12}$ Hz). However, electronic polarization is independent of temperature. ***Atomic or ionic polarization*** in dielectrics is observed due to finite separation of different atomic nucleus or positive and negative ions in presence of external electric field. Ions are nearly thousand times heavier than electrons and hence they can be polarized up to infrared frequency range (up to 10^{12} Hz). Beyond this frequency range ionic polarizability (α_{ion}) is absent in dielectric materials. Some dielectrics have permanent dipoles randomly oriented inside it and application of electric field make these dipoles to get oriented along the electric field direction giving rise to the ***dipolar or orientational polarization***. This orientation of dipoles are restricted to the microwave frequency range and at higher frequencies ($>10^9$ Hz) dipolar polarizability (α_{dip}) can’t contribute to the total polarizability of the dielectric material.

For inhomogeneous dielectric materials, along with these three polarizations (electronic, ionic and dipolar) another polarization effect come into picture, known as ***interfacial/space charge polarization***. The space charge polarization arises due to the inhomogeneity across different phases present inside the dielectric material and across the sample-electrode interface. Space charge effects are limited up to the kHz frequency range. At low frequency, the accumulation of charges at the interface regions gives rise to interface polarizability (α_{int}). The frequency spectrum of all these polarizations occurring in a dielectric is shown in Figure 3.

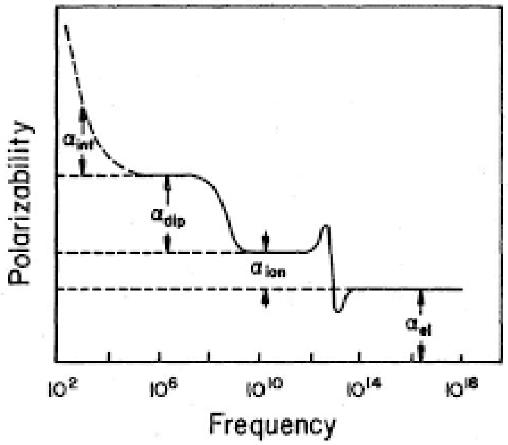

Figure 3. Frequency spectrum of different polarizations contributing to the dielectric constant [4].

At low frequencies presence of all four type of polarizations results in high value of dielectric constant (ϵ_r) in all dielectric ceramics. At high frequencies the relaxation time of dipolar polarization is maximum and hence at large applied frequencies dipolar polarization vanishes first and then the ionic polarization disappears. Only electronic polarization exists in high frequency region. Therefore, with increase in frequency a decreasing trend is observed for both dielectric constant and dielectric loss of any dielectric material.

Depending on the values of dielectric constant and loss factor the dielectrics are used in different applications in electronic industries in the required range of frequencies. Dielectrics are mostly used as insulators in various electrical circuits to isolate different electronic components from each other and also from the ground and as capacitors for energy storage or memory devices. High K (dielectric constant) dielectrics with higher optical band gap (>4ev) are basically used for fabrication of metal-insulator-metal (MIM) capacitors generally having capacitance of the order of hundreds of fF or hundreds of pF [5-6]. Metal oxides (ZrO_2, HfO_2, GeO_2, TiO_2, Al_2O_3, La_2O_3, Y_2O_3, Sc_2O_3, Lu_2O_3, $HfZrO_4$, Nb_2O_5, Ta_2O_5 etc) with high dielectric constant values are used in resistive RAM memories, dynamic random access memories (DRAM), metal oxide semiconductors (MOS) as well as in ferroelectric logic and memory devices [7-8]. Bismuth ferrite ($BiFeO_3$) and bismuth ferrite based compounds ($BiFeO_3$-$PbTiO_3$, $BiFeO_3$-$BiScO_3$, $BiFeO_3$-$BaTiO_3$ etc) having high dielectric constant and low dielectric loss are highly used in memory devices as supercapacitors [9-12]. Low K dielectrics are basically used as electronic substrates, high frequency electronic circuit packaging materials and frequency resonators.

Thus, for application of dielectric materials their dielectric (dielectric constant and dielectric loss) and electrical (ac conductivity, impedance, electric modulus and admittance) properties should be investigated with the help of LCR meter/impedance analyzer.

2. Types of material:

Powder samples, pellets (bulk) and thin film form of materials are taken to measure the dielectric properties of materials. Dielectric properties of the *powder* samples of any dielectric ceramic material can be measured by a transmission line measurement technique having a network analyzer along with waveguide setup. The dielectric constant of well known ceramic powders of yttria stabilized zirconia (Y_2O_3-ZrO_2), zinc oxide (ZnO), titanium dioxide (TiO_2), barium titanate ($BaTiO_3$) etc are measured using this technique [13]. The dielectric constant of these ceramics is also measured in their *bulk* form taking the shape parameters (area and thickness of the pellet prepared from powders by pressing the powders into thin pellets using hydraulic press) into consideration. The pellets of these ceramics are silver pasted on its opposite surfaces to make them conductive and placed inside a user designed sample holder that is connected to a LCR meter through waveguide setup. Finally, the observed dielectric constants of the ceramics powders are found to be nearly equal to the dielectric constant values of the bulk ceramic samples. Similarly *thin films* of any dielectric material are used to measure its dielectric properties using an experimental setup consisting of metal-dielectric-metal parallel plate structure, a LCR meter and a network analyzer [14].

3. Parameters measured by LCR meter:

LCR meter is an electronic equipment used to measure the parameters like inductance (L), capacitance (C) and resistance (R) of an electronic component. The digital LCR meter that we have used for analyzing the dielectric properties of our synthesized aluminosilicate ceramics is NF model ZM2376. The primary parameters that can be measured by the LCR meter are : inductance (L), capacitance (C), resistance (R), magnitude of complex impedance (Z), magnitude of complex admittance (Y) and the conductance (G). The secondary parameters measured by the LCR meter are: dielectric loss factor (D), quality factor (Q), phase angle (θ) etc. Variation of these parameters with frequency of the applied electric field is analyzed at room temperature as well as at high temperatures by placing the sample holder inside a furnace. The frequency can be varied from 100Hz to 1MHz and temperature can go up to 500℃.

The complex dielectric functions: permittivity (ϵ^*), impedance (Z^*) and modulus (M^*) along with the AC conductivity of the dielectric material can be estimated from the capacitance (C) and loss tangent values obtained directly from the LCR meter readings using related formulae.

Dielectric parameters:

The complex permittivity is given as:

$\epsilon^*(\omega) = \epsilon'(\omega) - j\epsilon''(\omega)$ [ϵ' : real part, ϵ'' : imaginary part] ………….(13)

$\epsilon'(\omega) = \frac{Cd}{\epsilon 0 A}$ = dielectric constant (ϵ_r)

d: the thickness of pellet,

A: surface area of pellet

ϵ_0: absolute permittivity/permittivity of free space

Dissipation factor: $\tan\delta = \epsilon''/\epsilon' = \frac{1}{RC\omega} = \sigma_{AC}/\omega\epsilon'$ [ω=2Лf, angular frequency] .(14)

Electrical parameters:

AC conductivity: $\sigma_{AC}(\omega) = \omega\epsilon_0\epsilon''(\omega) = \sigma_{DC} + A\omega^n$ ………………………….(15)

Where, σ_{DC}: frequency independent (DC) conductivity part

$A\omega^n$: frequency dependent conductivity part

From the AC conductivity measurements, the low frequency static (DC) conductivity can be obtained for the dielectric specimen. The frequency dependent conductivity behavior usually follows the universal Jonscher power law showing increase in AC conductivity with increase in frequency due to hopping of charge carriers into nearest neighbouring sites.

Complex impedance:

Complex impedance spectroscopy (CIS) is used to analyze the resistive properties of dielectric materials and the complex impedance is given by:

$$Z^*(\omega) = 1/j\omega C_0\epsilon^* = Z'(\omega) - jZ''(\omega) \qquad \text{……………………. …………………..(16)}$$

Where, $Z'(\omega) = |Z| \cos\theta$: real part of complex impedance

$Z''(\omega) = |Z| \sin\theta$: imaginary part of complex impedance

The polycrystalline solid materials are highly used as efficient dielectric in semiconductor/electronic industries. Basically, the polycrystalline solids consist of grain and grain boundary regions. The grain (bulk) properties are quite different from the grain boundary characteristics. Thus, the charge transport mechanism, resistivity and the macroscopic dielectric constant in polycrystalline materials represent the cumulative contribution of sample-electrode interface, grain and grain boundary characteristics. These contributions can be represented as equivalent parallel RC circuits connected in series as depicted in Brick Layer Model of polycrystalline solid in Figure 4. The resistance of each RC circuit represents the leakage current characteristics of the dielectric material and C represents the charge storing characteristic [15]. The overall impedance of the polycrystalline dielectric is the sum of individual impedances of each RC circuits corresponding to grain (bulk), grain boundary and sample-electrode contributions.

However, ideal RC circuits always can't account for the different contributions from different regions of a polycrystalline solid. To analyze the non-ideal behavior of each contribution a constant phase element (CPE) is used to replace the ideal capacitor in the RC equivalent circuits. All intrinsic grain interiors should have similar dielectric properties to be represented as a single RC circuit for the entire sample grain contribution. Similarly all the extrinsic grain boundary regions and sample-electrode interfaces should possess similar dielectric behavior to be depicted as a single RC element for the total specimen under consideration. In general the grain capacitances (C_b) are of the order of pF, the grain boundary capacitances (C_{gb}) are of the order of nF and the electrode interface capacitances (C_{el}) are of the order of μF. Again, the resistances of grain, grain boundary and electrode interfaces should be different in order to distinguish the contributions from each region.

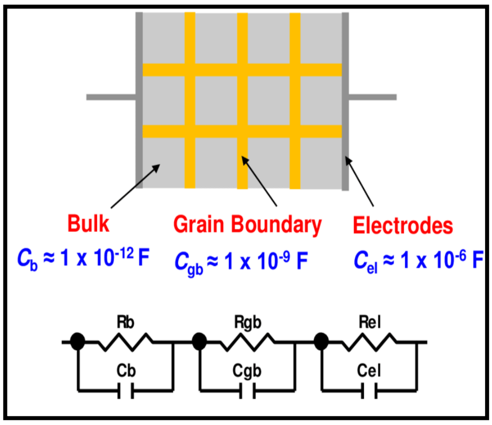

Fig. 4. Brick Layer Model [15]

The complex impedance data is represented as *Nyquist plots* taking real part (Z′) of complex impedance in the X-axis and imaginary part (Z″) of complex impedance in the Y-axis. In the Nyquist plot the grain, grain boundary and electrode interface contributions towards the electrical transport mechanism are depicted as semicircles whose diameters give the time constant (τ=RC) of each RC circuit associated to the semicircle as shown in Figure 5. The semicircle at the high frequency side represents the grain contribution and the semicircle at the low frequency side represents the grain boundary/electrode interface contribution towards the transport phenomena of the dielectric [15]. The maximum frequency of each semicircle is equal to 1/RC i.e., for semicircle representing grain contribution $\omega_b = \frac{1}{RbCb}$, for the semicircular arc representing grain boundary contribution $\omega_{gb} = \frac{1}{RgbCgb}$ and for the semicircle depicting electrode contribution $\omega_e = \frac{1}{ReCe}$. Fitting of these semicircles with equivalent RC circuits can be done using the ZSimpWin software and the fitting parameters: grain resistance/capacitance (R_g/C_g), grain boundary resistance/capacitance (R_{gb}/C_{gb}), electrode resistance/capacitance (R_e/C_e) and the constant phase element (CPE) can also be obtained. The use of CPE in place of ideal capacitor in the RC equivalent circuits give rise to depressed semicircles inclined more towards the Z′ axis signifying Non-Debye type relaxation mechanisms in dielectric materials [16].

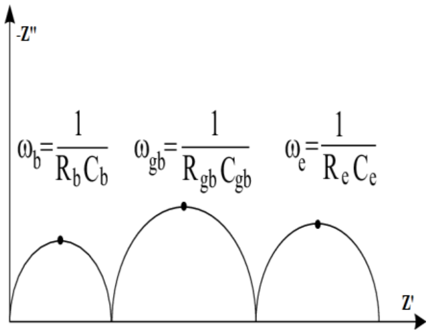

Fig. 5. Semicircular arcs in Z′ versus Z″ plot representing grain (bulk), grain boundary and electrode contribution [16].

Complex modulus:

The complex modulus analysis also distinguishes the contribution of grain, grain boundary and electrode interface towards the electrical properties of the dielectrics. The complex modulus is equal to the reciprocal of the complex permittivity and is given by:

$$M^*(\omega)=1/\epsilon^*(\omega)=M'(\omega)+M''(\omega) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(17)$$

Where, $M'(\omega)=(-1)\omega C_0 Z''(\omega)$: the real part of complex modulus

$M''(\omega)=\omega C_0 Z'(\omega)$: the imaginary part of complex modulus

The electric modulus analysis is used to eliminate the electrode effect. In general, for dielectrics at low frequency region the frequency versus M′ plots tend towards zero signifying the negligible electrode polarization effect [17]. The loss modulus spectrum (frequency versus M″ plot) consists of broad peaks symbolizing the dielectric relaxation processes exhibiting in dielectric materials [18]. The region towards the low frequency side of the M''_{max} peak represents the long range translational motion of charge carriers, the high frequency side of the M''_{max} peak represents the short range localized hopping of charge carriers and the peak region shows the transition from long range to short range motion of charge carriers leading to the relaxation processes in these ceramics [19].

4. LCR analysis of aluminosilicates:

The aluminosilicate materials, known as mullite (3Al2O3.2SiO2) are synthesized with different concentrations of alumina and silica. The mullite ceramics with two different concentrations: $Al_{0.60}Si_{0.40}O$ and $Al_{0.75}Si_{0.25}O$ are synthesized using pyrophoric technique, a nano material synthesis technique. Basically, aluminosilicate ceramics are insulators at room temperature and show semiconducting behavior at high temperatures. These ceramics are frequently used as dielectric substrates, electronic circuit packaging materials and for heat and current insulation in electronic circuits. However, the detail analysis of electrical characteristics of these ceramics is rarely found in literature. Thus, we have performed dielectric and electrical measurements of these two stoichiometric mullites using LCR meter and network analyzer.

The room temperature dielectric constant values calculated using the capacitance (C) value recorded from the LCR meter reading are found to be 110 and 2665 for $Al_{0.60}Si_{0.40}O$ and $Al_{0.75}Si_{0.25}O$ respectively with dielectric loss of 2.04 and 2.29 at 100Hz frequency. At 1MHz frequency the dielectric constant of $Al_{0.60}Si_{0.40}O$ and $Al_{0.75}Si_{0.25}O$ ceramics are estimated to be 6.03 and 5.08 with a loss factor of 0.07 and 0.05. This result agrees well with the existing literature which states that the dielectric constant of mullite ceramics varies in between 5-7 at 1MHz frequency. Thus, measurement of dielectric properties with the help of LCR meter following the parallel plate capacitor concept is expected to give valid results.

The electrical conductivity, complex impedance and complex modulus analysis of these ceramics are also performed using the data obtained from LCR readings. The AC conductivity of the order of 10^{-5}-10^{-6} is observed in these ceramics. The temperature dependent conductivity behavior shows increase in conductivity with the rise in temperature, thereby validating the semiconducting nature of these mullite ceramics. The frequency dependent conductivity obeys the universal Jonsher power law and the conductivity mechanism is governed by the correlated barrier hopping (CBH) model. The impedance analysis of these ceramics confirms the contribution of grain and grain boundaries towards the electrical transport mechanism of these ceramics and two overlapping semicircles are thus observed in the Nyquist plot of these ceramics. The modulus analysis shows the presence of single electrical relaxation phenomena in these ceramics which is a Non-Debye type relaxation [20].

5. Conclusion:

Dielectric spectroscopy is a fundamental to analyze the dielectric (capacitive) and electrical (resistive) characteristics of a dielectric material. Dielectrics with low relative permittivity or high relative permittivity are used in specific applications of semiconductor/electronic devices. Measurement of dielectric parameters using the LCR meter is found to be an effective technique for analyzing the electrical properties of the materials. The frequency-temperature dependent dielectric properties of several ceramics like bismuth ferrite ($BiFeO_3$), lead titanate ($PbTiO_3$), composite perovskites ($BiFeO_3$-$BaTiO_3$, $BiFeO_3$-$PbTiO_3$ etc), oxide ceramics (ZrO_2, TiO_2, SiO_2 etc) are well analyzed using the LCR meter and network analyzer. Our work based on the dielectric properties of aluminosilicate ceramics also confirms the reliability of this measurement technique. Thus, LCR analysis using the capacitance method is an effective technique to examine the capacitive and resistive properties of any kind of dielectric material.

References:

[1] S O Nelson, *J. Microw. Power. Electromagn. Energy.* 44(2), 98 (2010)

[2] E A Campo, Selection of polymeric materials||Electrical properties of polymeric materials (William Andrew Publishing, 2008)

[3] M. Choudhury, M. Shafiq, I. Kiitam, A. Hussain, I. Palu and P. Taklaja, Energies. 15, 3408 (2022)

[4] M J Kadhim, A K Abdullah, I A Al-Ajaj, A S Khalil, *Int. J. Appl. Innov. Eng. Manag.* 3(1), 468 (2014)

[5] J A Kittl, K Opsomer, M Popovici et al., *Microelectron. Eng.* 86, 1789 (2009)

[6] C Poole, I Darwazeh, Microwave Active Circuit Analysis and Design||Microwave transistors and MMICs (Academic Press, 2016), https://doi.org/10.1016/B978-0-12- 407823-9.00012-3

[7] R D Clark, Materials. 7, 2913 (2014)

[8] J Oh, K Jeon, S H Lee et al., *Microelectron. Eng.* 97, 26 (2012)

[9] V Jadhav, R S Mane, Bismuth-Ferrite-Based Electromechanical Supercapacitors (Springer International Publishing, 2020), https://doi.org/10.1007/978-3-030-16718-9

[10] R Gerson, PC Chou, WJ James, *J. Appl. Phys.* 38, 55 (1967)

[11] A Pokalniskis, A Lukowiak, G Niaura et al., *J. Alloy. Comp.* 830, 154632 (2020)

[12] R Ranjan, KA Raju, *Phys. Rev. B.* 82, 054119 (2010)

[13] B. D. Graber, A. P. Iliopoulos, J. G. Michopoulos, J. C. Steuben, A. J. Birnbaum, R. P. Fischer, L. A. Johnson, P. A. Bernhardt, J. M. Coombs, E. P. Gorzkowski, E. A. Patterson, Vol 9: 40th Computers and Information in Engineering (CIE) (2020), https://doi.org/10.1115/DETC2020-22482

[14] R. Estrada, N. Djohan, G. C. Rundupadang, A. Kurniawan, ARPN. J. Eng. Appl. Sci. 12, 3813-3816 (2017)

[15] R. Schimdt, In ‘CRC Concise Encyclopedia of Nanotechnology’, Eds., CRC Press Taylor & Francis Group: Boca Raton, USA (2015). ISBN: 978-1-46658-034-3

[16] A. Bendahhou, K. Chourti, R. El. Bouayadi, S. El. Barkany, M. Abou-Salama, *RSC Adv.* 10, 28007-28018 (2020)

[17] G. R. Gajula, L. R. Buddiga, K. N. Chidambara Kumar, M. Dasari, *Res. Phys.* 17, 103076 (2020)

[18] C. Heng Lee, J. Hassan, M. hashim, R. s. aziz, N. M. Saiden, *J. Adv. Diel*. 4, 1450034 (2014)

[19] M. Belal Hossen, A. K. M. Akther Hossain, *J. Adv. Ceram.* 4, 217-225 (2015)

[20] B. Biswal, D. K. Mishra, S. N. Das, S. Bhuyan, Ceram. Int. 47, 32252-32263 (2021)