Investigation of dielectric relaxations and conduction mechanism in Aurivillius ceramic Bi$_5$Ti$_3$FeO$_{15}$

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Abstract:

Aurivillius Bi$_5$Ti$_3$FeO$_{15}$ (BTFO) ceramic is synthesized by the generic solid-state reaction route. The room temperature X-ray diffraction (XRD) study confirms that the compound is having single-phase without any impurity. Surface morphology of the prepared sample ensures that the presence of microstructural grains with size around 0.2 to 2 µm is observed. Dielectric properties of sample are investigated as a function of frequency of about 100 Hz to 1 MHz at various temperatures (303 K $\leq$ T $\leq$ 773 K). The Nyquist plots of impedance data exhibit a semi-circular arc in high temperature region, which is explained by the equivalent electrical circuit ($R_1C_1$) ($R_2Q_{C_2}$). Our results indicate that resistance as well as capacitance of grain boundary is more prominent over the grains. Analysis of ac conductivity data is done by using Jonscher universal power law ($\sigma_{ac} = \sigma_{dc} + A\omega^n$) which confirms that the conduction process is dominated by the hopping mechanism. The activation energies calculated for relaxation and conduction processes are very close to each other (0.32 eV to 0.53 eV) by which we conclude that the same type of charge carriers are involved in both the processes.

Keywords: Nyquist plot; impedance spectroscopy; activation energy; ac conductivity; hopping.

1. Introduction

Aurivillius crystal structure is discovered by B. Aurivillius in the year of 1949 by observing ferroelectricity in Bi$_2$WO$_6$ [1]. The crystal structure of Bi$_2$WO$_6$ consists of the ABO$_3$ pervoskite blocks interlinked by the Bi$_2$O$_2$ blocks. In the recent years, layered structure of Aurivillius family have much attention because of its remarkable ferroelectric properties, low fatigue effects, and high Curie temperature (T$_c$) [2-4]. Various researchers have tailored its properties by inserting the additional number of perovskite layers and controlling the concentration of magnetic/nonmagnetic ions at the magnetic sites. Among them bismuth based Aurivillius compound Bi$_5$Ti$_3$FeO$_{15}$ (BTFO) is the most important member due to its well ferroelectro-magnetic and high chemical flexibility properties [5,6]. The Aurivillius structured
compounds have great potential to be used in non-volatile random access memory, high temperature pizeo-electrics and photoluminescence [7-11]. The general expression for the Aurivillus compound is $(Bi_2O_2)^{2+}(A_{n-1}B_nO_{3n+1})^{2-}$, where $A$ is the twelve coordinated cations such as Na, Bi, K, Ca, Pb, Sr, Ba etc., $B$ is the octahedral coordinated cations e.g., Ti, Cr, Ta, Nb etc., and $n$ is the number of the corner sharing of $BO_6$ octahedral sheets. This Aurivillius structure is composed of the alternative stacking of the fluorite-like layer $(Bi_2O_2)^{2+}$ and perovskite-like layer $(A_{n-1}B_nO_{3n+1})^{2-}$ oriented along the crystallographic c-axis [12-14]. For $n=4$, BTFO sample consists of alternating sequence of $(Bi_3Ti_3FeO_{13})^{2-}$ and $(Bi_2O_2)^{2+}$ layers along the [001] direction.

Orthorhombic BTFO sample is reported to possess $A2$_1$am$ space group [15] with ferroelectric transition temperature ($T_c$) $\sim 1003$K and antiferromagnetic transition temperature (Néel temperature) $\sim 80$K [16,17]. The structural, magnetic, and transport properties of BTFO are highly dependent on synthesis conditions. Electrical properties of this compound is reported to show significant variations under the influence of temperature, pressure, magnetic field, and frequency. To the best of our literature survey, only few researchers have focused on the dielectric properties, relaxation behavior, and conduction mechanisms of the BTFO [18-20]. For better understanding of the microstructural behavior of grain and grain boundaries, studies of the electrical properties are highly essential. The observed relaxation in the material cannot be concluded from the dielectric measurement. In order to characterize the dielectric relaxation behavior, the complex impedance spectroscopy (CIS) modulus analysis, and conductivity studies are promising techniques. Besides, ac conductivity gives the concise idea about the long range hopping mechanism of charge carriers [21-23].

In this study, preparation of $Bi_5Ti_3FeO_{15}$ sample is followed by the standard solid-state sintering process. The materials are subjected to the comprehensive investigations of microstructure, dielectric, impedance, and modulus. Complex impedance spectroscopy, modulus, and conductivity plots are fitted by using the electrical equivalent circuit ($R_1C_1$) ($R_2QC_2$), theoretical Bergman modified KWW (Kohlraush–Williams–Watts) function, and Johnscher’s single power law respectively to understand the relaxation behavior. Analysis of conductivity data provides a clear insight of the contribution of direct current conductivity, nature of polarizability, and strength of interaction of mobile charge ions with neighbouring lattices.

2. Experimental techniques

The synthesis of BTFO ceramic is followed the conventional solid state reaction process by using the high purity oxide materials (>99.9%) namely $Bi_2O_3$, $Ti_2O_3$ and $Fe_2O_3$ (Sigma-Aldrich made). These oxides are used as a precursor, weighted in desired proportions and mixed thoroughly with the help of Agate mortar and pestle in stoichiometric ratio. The above mixture is grinded for two hours, pelletized and calcined at an optimized temperature of 800 ºC for 8 hours.
in a PID controlled programmable silicon carbide tubular furnace. Again the pre-treated pellets are grinded, pelletized and finally sintered at 850 °C for 8 hours with a ramping rate of 4°C/minute. The crystalline structure and phase of the material are confirmed from the X-ray diffraction (XRD) measurement at room temperature, which is carried out by using the RIGAKU JAPAN and ULTIMA-IV diffractometer of Cu-Kα radiations (λ = 1.5406 Å). The experimental data is performed in the broad diffraction angle 20° ≤ 2θ ≤ 60° with step size 0.02° per second and the scan rate 3° per minute. The microstructure of BTFO sample is determined from the Scanning electron microscopy (SEM) image via JEOL/EO JSM-6480 LV system with an operated accelerating voltage of 30 kV. All the electrical measurements are taken by considering the parallel plate capacitor configuration. The disk shaped pellets of both sides are coated with silver paste, and ohmic contact were made using electrical probes. The frequency dependent dielectric parameters such as capacitance, dissipation factor, impedance and phase factor are characterized with the help of Wayne Kerr 6500B impedance analyser with drive ac voltage of amplitude 1V over a wide temperature (303 K ≤ T ≤ 773 K) and frequency (100 Hz ≤ f ≤ 1 MHz) range.

3. Results and discussion

3.1 X-ray diffraction.

XRD characterization is carried out to ensure the proper phase formation and to know the crystal structure of the prepared sample. The room temperature XRD pattern of Bi$_5$Ti$_3$FeO$_{15}$ is shown in figure 1, which reveals the formation of single phase material without any additional impurity phases. All Bragg peaks are well consistent with standard JCPDS card no. (ICSD: 074037) which signifies the orthorhombic phase with space group $A2_{1}am$ [24]. To extract the concise information about the structural parameters, we have done the Rietveld refinement of experimental XRD data using the FULLPROF Suite software by considering the various parameters such as background, zero shift, scale factor, atomic positions, thermal factors, lattice parameters, FWHM, shape parameters, and preferred orientation. Peak shape parameters and background points are refined by considering the Pseudo-Voigt function and linear interpolation between a set of background points with refinable heights respectively [25]. After a series of refinement cycles, the fit converged to $\chi^2 = 4.27$. The lattice parameters obtained from the refinement are $a = 5.4435$ Å, $b = 5.4652$ Å, $c = 41.3482$ Å with cell volume $V = 1230.12$ Å$^3$. The quality of fitting is estimated from the GOF = $R_{wp}$/$R_{exp}$ and found to be 2.1, which indicates the good quality of the fit. Furthermore, highest intensity diffraction peak corresponds to (119) orientation, which is accordance with the general formula of Aurivillius compound (112n+1) [26].
3.2 Morphological study by SEM

The microstructural behavior of the BTFO is determined from the scanning electron micrograph (SEM) shown in the figure 2(a). SEM micrograph illustrates that bulk BTFO consists of plate like grains, overlapping to each other without having any microscopic defects such as cracks and micro cracks etc. The grains are not compactly packed to each other and the larger grains are separated from the smaller grains by grain boundary. The non-homogeneous plate like grains of size varies from 0.2 to 2µm are distributed throughout the whole surface of bulk material. Figure 2(b) represents the energy dispersive X-ray (EDX) spectrum of BTFO sample, which ensure that within the limit of experimental error, all the elements i.e., Bi, Ti, Fe, and O are present with proper atomic percentages.

3.3 Dielectric Relaxation properties

Figure 2: (a) and (b) SEM micrograph and energy dispersive spectrum of BTFO sample respectively.
The variation of dielectric permittivity ($\varepsilon'$) and loss spectra (tan$\delta$) as a function of frequency over the different temperatures from 303 K to 773 K as shown in the figure 3(a) and (b). The values of $\varepsilon'$ and tan$\delta$ increases remarkably with decreasing the frequency and increasing the temperature, and then stabilized with further increase of the frequency. This is due to the contribution of both extrinsic and intrinsic polarization. The extrinsic polarization arises because of the defects, dislocation of charge carriers, space charge polarization and electrode interface (i.e. Maxwell Wagner effect), while intrinsic polarization arises due to the different kind of polarization such as electronic, ionic and dipolar [27]. In the low frequency regime, high dielectric dispersion is noticed which may be due to the extrinsic contribution. In Bi-based Aurivillius compounds fluctuation of valence state of different ions Fe$^{2+}$, Fe$^{3+}$, Ti$^{3+}$, Ti$^{4+}$ is also reported to exist causing high dielectric dispersion. Fluctuation of various valence state originates due the presence of Bi-lone pair electrons (6s) diminishing the oxygen percentage in the material. Fluctuation of valence state causes electron hopping which increases with increasing temperature. The gradual decrease of $\varepsilon'$ with increase in frequency is mainly due to the reduced dispersion of space charges [28]. An increase leakage current at low frequency and high temperature results the high dielectric loss which will be further correlated with our conductivity study.

Figure 3: (a) and (b) variation of dielectric dispersion ($\varepsilon'$) and loss (tan$\delta$) with the frequency at different temperatures from 303 to 773 K. Inset images of (a) and (b) are the magnified and loss (ln tan$\delta$) dispersions respectively.

3.4 Impedance spectroscopy

To investigate the different relaxation mechanisms, present in the ceramic sample, we have performed the impedance spectroscopy. It gives us more insight about the homogeneous and nonhomogeneous distribution of grains and grain boundaries present in the material. Various relaxations are arising because of the contribution of grains, grain boundaries, and electrode-interface phenomena. In order to have better understanding of different relaxation mechanisms present in BTFO, we have done Cole-Cole analysis [29]. Figure 4(a) illustrates the complex impedance
spectrum (Nyquist plot) of the impedance data plotted against the imaginary impedance \(Z'\) versus real impedance \(Z'\) at fixed different temperatures. To extract the correlation between the observed and experimental data, we have fitted the experimental data (inset of fig. 4) with the help of the equivalent electrical circuit \((R_1C_1) (R_2QC_2)\) with the ZSIMP WIN software (version 3.21). The symbols \(R_1\) and \(R_2\) are marked for the resistances associated with the grains and grain boundaries, while \(C_1\) and \(C_2\) are the respective capacitances and \(Q\) represents the constant phase element (CPE) which accounts for the non-Debye type of behavior. The mathematical relation of CPE impedance is given in the equation [2]

\[
Z_{\text{CPE}} = \frac{1}{[B(j\omega)^n]}
\]

where \(B\), \(\omega\), and \(n\) \((0 \leq n \leq 1)\) are the pre-exponential factor, angular frequency, and empirical exponent accordingly. For \(n = 1\) CPE is regarded as an ideal capacitor, whereas for \(n = 0\) corresponds to actual resistance [30]. The fitted impedance parameters \(R_1\) and \(R_2\) are the resistances of grain and grain boundary at different temperatures are summarized in the Table 1. In the low temperature regime (below 400K), the Cole-Cole plot look like incomplete semi-circular arcs (303K and 363K) for low \(Z'\) values, then for high \(Z'\) value nearly straight lines with large slopes is observed which indicates the high insulating nature of the sample. With the gradual increase of temperature the straight line bends towards the real part of the impedance \(Z'\) and forms a distorted semi-circular arcs. Further increase of the temperature causes the centre of semi-circular arcs to be shifted to the complex impedance origin. Eventually maxima and diameter of the respective semi-circular arcs decreases, which indicates the pronounced increase of dc conductivity in the samples [31]. The obtained result from the fitted impedance data indicates the resistance of grain boundary \((R_2)\) is larger than the resistance of grains \((R_1)\) and the gross resistance in the material is due to the contribution of grain boundary. Both the resistances \(R_1\) and \(R_2\) are found to be decreased with the increase in temperature demonstrating negative temperature coefficient of resistance (NTCR) i.e., semiconducting behaviour of the sample [32]. The activation energy of both \(R_1\) and \(R_2\) are calculated from the Arrhenius plot as illustrated in the figure 4(b). It reveals that the activation energy of \(R_2\) \((= R_{gb})\) \((E_a = 0.35 \text{ eV})\) is found to be larger than \(R_1\) \((= R_g)\) \((E_a = 0.34 \text{ eV})\).
Figure 4: (a) Cole-Cole or Nyquist plot of BTFO sample at fixed various temperatures fitted with an equivalent circuit shown in the inset. (b) The activation energies of both grain and grain boundary are calculated from the linear fit (solid red line) of the logarithmic $R_g$ and $R_{gb}$ versus $10^3/T$ plot.

TABLE 1. Resistance of grain ($R_1$) and grain boundary ($R_2$) at various temperatures obtained from the fitting of impedance semi-circular arcs with the electrical equivalent circuit.

<table>
<thead>
<tr>
<th>$T$ (K)</th>
<th>$R_1 \times 10^4 \Omega$</th>
<th>$R_2 \times 10^4 \Omega$</th>
<th>CPE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B$</td>
</tr>
<tr>
<td>303</td>
<td>143.6</td>
<td>452.5</td>
<td>$1.70 \times 10^{-9}$</td>
</tr>
<tr>
<td>363</td>
<td>31.37</td>
<td>474.4</td>
<td>$2.54 \times 10^{-9}$</td>
</tr>
<tr>
<td>423</td>
<td>7.009</td>
<td>107.7</td>
<td>$4.02 \times 10^{-9}$</td>
</tr>
<tr>
<td>483</td>
<td>1.329</td>
<td>10.93</td>
<td>$5.41 \times 10^{-9}$</td>
</tr>
<tr>
<td>543</td>
<td>1.137</td>
<td>1.609</td>
<td>$2.93 \times 10^{-5}$</td>
</tr>
<tr>
<td>603</td>
<td>0.344</td>
<td>0.599</td>
<td>$2.51 \times 10^{-11}$</td>
</tr>
<tr>
<td>663</td>
<td>0.169</td>
<td>0.303</td>
<td>$8.00 \times 10^{-9}$</td>
</tr>
</tbody>
</table>
3.5 Modulus analysis

The electric modulus formalism distinguishes the microscopic processes which are associated with conduction mechanism and localised dielectric relaxations. As the impedance is obtained from the resistance of the sample in the same way, modulus is dictated from the inverse permittivity of the sample. The mathematical relation of complex modulus in terms of impedance is expressed as:

\[ M^* = \frac{1}{\varepsilon} = j\omega\varepsilon_0 Z^* \]  \hspace{1cm} (3)

\[ M^* = M' + jM'' = j\omega\varepsilon_0 (Z' - jZ'') \]  \hspace{1cm} (4)

So, the real and imaginary part of the complex modulus is written as

\[ M' = \omega\varepsilon_0 Z' \]
and
\[ M'' = \omega\varepsilon_0 Z'' \]

where \( Z', Z'', \omega (= 2\pi f) \), and \( \varepsilon_0 (= \frac{\varepsilon_0 A}{d}, \varepsilon_0 \) is the free space permittivity, \( A \) is the surface area and \( d \) is thickness of the sample) are the real, imaginary part of modulus, angular frequency and free space capacitance respectively. The difference of real (\( M' \)) and imaginary (\( M'' \)) modulus with respect to the frequency is illustrated in the figure 5(a) and (b) up to a large range of frequency and fixed temperature ranges from 303 K to 773 K. We note that maxima of \( M' \) is displaced to the high frequency regime with the increase of temperature and most of the peaks gone out of the frequency
window from the right side. In the low frequency region the value of $M'$ is very low nearly equal to zero, but it increases with increasing the frequency. This conduction mechanism is due to the characteristic behavior of short range mobility of charge carriers. $M''$ versus frequency plot indicates that, with an increase of temperature relaxation peaks are migrating to the higher frequency region. The frequency region below the maximum peak determines the range in which charge carriers are mobile over the long distances. At the high frequency, above the highest peak charge carriers are confined to the potential well, being mobile over the short distances [33]. This type of behavior of the modulus spectra suggest that an activation process is thermally activated where long range hopping is taking place at high temperature. Experimental data of $M''$ is fitted by using the theoretical modified Bergman KWW (Kohlraush–Williams–Watts) function [34], then an imaginary modulus is given by:

$$M'' = \frac{M''_{\text{max}}}{[1 - \beta + (\beta/1 + \beta)\beta(\omega_{\text{max}}/\omega) + (\omega/\omega_{\text{max}})^{\beta}]}$$  \hspace{1cm} (5)

here, $M''_{\text{max}}$ is the maximum value of imaginary modulus, $\omega_{\text{max}}$ is the maximum angular frequency of the respective modulus, $\beta$ is the exponent denotes deviation from an ideal Debye type of behavior and related to the full width half maxima (FWHM) of the $M''$ versus frequency curve. The values of the $\beta$ are found from the fitted data. The variation of $\beta$ at different temperature is illustrated in the inset figure 4(b), which demonstrates that $\beta = 1$ corresponds to the ideal Debye type of behavior with distinct relaxation time whereas $\beta = 0$ relates to the utmost number of dipolar interaction. The figure 5(c) depicts the scaling behavior of the sample, where normalised modulus $M'/M''_{\text{max}}$ versus the frequency $f/f_{\text{max}}^\prime$ is plotted against the selected temperatures i.e., 303, 363, 423 and 483 K. Which signifies that almost all the peaks collapse into the one master curve at different temperatures and the dynamic processes are temperature independent at low frequency region. It is interesting to note that with an increase in frequency transition from long-range to short-range occurs. Figure 5(d) shows the $ln\tau$ versus $1000/ T$, where the dielectric relaxation time ($\tau^m$) can be derived from the relation $\tau^m = \frac{1}{f^m} = 2\pi f^m$, $f^m$ is the maximum frequency at the highest value of $M''$. The dynamics of relaxation process can be analyzed from the Arrhenius law, which is expressed in terms of relaxation time $\tau^m$ as; $\tau^m = \tau_0 \exp\left(\frac{E_a}{k_BT}\right)$ [35]. Here, $\tau_0$, $E_a$, $k_B$, and $T$ are the pre-exponential factor, an activation energy of the charge carriers, Boltzmann constant, and absolute temperature respectively. The activation energy ($E_a = 0.32$ eV) of modulus is extracted from the linear fitting of Arrhenius plot. Thus, the activation energies of impedance and modulus are 0.34, 0.35, and 0.32 eV comparable, which signify that the same type of charge carriers are participate in both relaxation and conduction processes [36].
3.6 Electrical conductivity analysis

Electrical conductivity in the material is a thermally activated process in which bound charge carriers move in the order way with an application of external electric field. It is one of the crucial properties of the material to characterize the behavior of the charge carriers. Figure 6(a) shows the ac conductivity ($\sigma_{ac}$) versus frequency plot in the selected temperature range 483 K to 773 K. Equation of ac conductivity in terms of empirical impedance can be represented by [37]:

$$\sigma_{ac} = \frac{Z' \times t}{A[(Z')^2 + (Z'')^2]}$$

(6)

where, $A$ and $t$ correspond to the surface area and thickness of the sample. Conductivity plot possess the following set of characteristics such as: (i) at the low frequency region plateau like behavior is observed due to the long range translational motion of ions in the direct current conductivity $\sigma_{dc}$ region. We observed that conductivity $\sigma_{dc}$ increases with increase in temperature indicating that the electrical conductivity in the material is mainly due to the thermally activated process. (ii) At the high frequency region, conductivity depends on $A\omega^n$ of Johnscher’s power law given as [38]:

$$\sigma(\omega) = \sigma_{dc} + A\omega^n$$

(7)
where, \( \sigma(\omega) \) is the total conductivity \( i.e. \), the sum of the ac and dc conductivity of the material, \( \sigma_{dc} \) is the direct current conductivity, \( A\omega^n \) is the pure dispersive term of the ac conductivity, \( A \) is the pre-exponential factor which determines the strength of the polarizability, \( \omega \) \( (= 2\pi f) \) is the angular frequency, and \( n \) is the exponent \( (0 \leq n \leq 1) \) which signifies the degree of interaction between the mobile charge ions with lattice surrounding them. According to the Johnscher, the frequency dispersion conductivity arises because of the relaxation phenomenon of the ionic atmosphere arises from the mobile charge carriers [39]. The experimental conductivity plot is well fitted up to the high frequency range \( (~10^5 \text{ Hz}) \) using the equation (7). The fitted parameters of the ac conductivities are noted in the Table 2. Inset figure 6(a) illustrates that the exponents \( n \) and \( A \) are obtained from the fitted data as a function of temperature. The values of \( n \) define the motion of charge carriers \( i.e. \), translational motion and localization. If the values of \( n < 1 \), the motion of the charge carrier is translational, and if \( n > 1 \), motion is localized. We examined that values of \( n \) increases with increasing the temperature around 663 K, but after decreases up to 773 K. This indicates the hopping conduction of charge carriers are present in the sample. Different hopping mechanisms are reported in the various literature at different temperature and frequency. The values of \( n \) increases with the temperature, represents the small polaron hopping, while \( n \) decreases with increasing the temperature, indicates the large polaron hopping [40]. The figure 6(b) represents the variation of dc conductivity with an inverse temperature. It is observed that the \( \sigma_{dc} \) increases with increase in temperature, and follow the thermally activated of Arrhenius type of relation:

\[
\sigma_{dc} = \sigma_0 \exp\left(-\frac{E_a}{k_BT}\right)
\]

where \( \sigma_0, E_a, k_B, \) and \( T \) are the pre exponential factor, activation energy, Boltzmann constant, and absolute temperature accordingly [41]. From the slope of the linear fitting of dc conductivity data, we can obtain the activation energy of about 0.53 eV. Thus, all the extracted activation energy of the BTFO material is lie within the range 0.32 to 0.53 eV. This results, the long range hopping of polarons are responsible for the electrical conductivity in the material. Eventually, the activation energies are calculated from the both relaxation and electrical conduction process become very close, confirm that the both dielectric relaxation and conduction process are assigned by the same type of charge carriers.
Figure 6: (a) Temperature dependence ac conductivity ($\sigma_{ac}$) versus frequency in the range of 483 to 773 K. The solid lines (red) represent the Johnsher’s power law fit. Inset figure is the variation of fitting parameters ($n, A$) with temperature. (b) Logarithmic dc conductivity ($\sigma_{dc}$) versus inverse temperature of BTFO ceramic and red solid line is the linear fit of the data.

**TABLE 2.** Various parameters $A$ and $n$ of ac conductivity at selected temperatures are listed in below.

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>ac conductivity $\sigma_{ac}$</th>
<th>$A$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>483</td>
<td>$4.96 \times 10^{-7}$</td>
<td>$0.647$</td>
<td></td>
</tr>
<tr>
<td>543</td>
<td>$6.75 \times 10^{-9}$</td>
<td>$0.915$</td>
<td></td>
</tr>
<tr>
<td>603</td>
<td>$3.95 \times 10^{-9}$</td>
<td>$0.947$</td>
<td></td>
</tr>
<tr>
<td>663</td>
<td>$2.30 \times 10^{-9}$</td>
<td>$0.970$</td>
<td></td>
</tr>
<tr>
<td>723</td>
<td>$3.33 \times 10^{-10}$</td>
<td>$0.420$</td>
<td></td>
</tr>
<tr>
<td>773</td>
<td>$5.31 \times 10^{-9}$</td>
<td>$0.435$</td>
<td></td>
</tr>
</tbody>
</table>

4. Conclusion

In this work, single phase Bi$_5$Ti$_3$FeO$_{15}$ sample is synthesized by using the generic solid state sintering method. XRD data at room temperature ensures that the BTFO material having an orthorhombic crystal structure with space group $A2\alpha m$. SEM and EDX spectrum are confirmed the growth in the grain size and presence of all the constitutes in the sample respectively. The electrical properties, studied over wide temperature and frequency range, reveal NTCR
behavior of BTFO ceramic. Our impedance analysis confirms the contribution of grain boundaries to the electrical properties and the resistance and capacitance of the grain boundaries are more prominent over the contribution due to grain. We also show that the both grain and grain boundaries follow the non-Debye relaxation behaviour. The electrical conductivity spectra are found to obey the Jonscher universal power law in an entire temperature range. The remarkable decrease of exponent $n$ above 663 K suggests that two kinds of hopping mechanism are involved in BTFO ceramic. Below 663 K long-range hopping mechanism is applicable whereas neighbouring site hopping mechanism is applicable above 663 K. Eventually, activation energy ($E_a$) extracted from impedance, modulus and dc conductivity analysis are very close to each other ($0.32 \text{ eV} \leq E_a \leq 0.53 \text{ eV}$), which reveals that the same kind of charge carriers are responsible in both dielectric relaxation and electrical conductivity process in the sample.

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