Ac conductivity and ferroelectric phase transition of Bi$_{0.7}$(Ba$_{0.8}$Sr$_{0.2}$)$_{0.3}$Fe$_{0.7}$Ti$_{0.3}$O$_3$ ceramic

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Abstract

The Bi$_{0.7}$(Ba$_{0.8}$Sr$_{0.2}$)$_{0.3}$Fe$_{0.7}$Ti$_{0.3}$O$_3$ ceramic is synthesized by a solid state reaction method and characterized by X-ray diffraction (XRD), SEM, Raman spectra and impedance spectroscopy. Besides, the XRD pattern shows perovskite phase with rhombohedral structure (R3c space group) at room temperature. Furthermore, the ferroelectric-paraelectric phase transition ($T_C$) and G-type antiferromagnetic Neel temperature ($T_N$) is detected by Raman spectroscopy. Meanwhile, the electrical conductivity of the sample is investigated in the temperature and the frequency range 713–773 K and 100–1000 kHz respectively by means of impedance spectroscopy. The Nyquist plots ($-Z'$ versus $Z''$) frequency plots are well fitted to an equivalent circuit model. The ac conductivity data obey the universal power law. The nature of variation of dc conductivity suggests Arrhenius type of electrical conductivity. The temperature dependence of the alternative current conductivity ($\sigma_a$) and direct current conductivity ($\sigma_{dc}$) confirm the presence of the ferroelectric–paraelectric phase transition.

Keywords: D. Perovskite; Ferroelectric; Raman spectroscopy; ac conductivity; Phase transition

1. Introduction

Multiferroics are rare multifunctional materials that exhibit more than one ferroic order in the same phase. Bismuth ferrite (BFO) is one of the most interesting members of multiferroic family [1]. Such class of materials exhibits a magnetoelectric coupling that is of high technological relevance, due to the promising industrial applications and because of interesting physics as well [2–4]. BFO is an attracting material has a high Curie temperature ($T_C$=1103 K) and G-type antiferromagnetic Neel temperature ($T_N$=643 K) [5]. The structure and properties of BFO single crystal reveal that it has rhombohedral-distorted perovskite structure (with the cell parameters; $a_0=5.6343$ Å and $a_0=95.348$) with space group R3c at room temperature [6]. Even though BFO antiferromagnetic (AFM) often a weak ferromagnetism (FM) is observed due to canting of Fe$^{3+}$ spins at room temperature [7]. Doping changes cycloidal spin structure of BFO to a canted spin structure [8] which can be the reason behind the enhancement in leakage current due to oxygen vacancies or impurities is the major problem in BFO. It is observed that doping [6,7,9] with lone-pair active ions at A-sites and magnetic transition metals at B-sites reduce the leakage current in BFO and enhance the multiferroic properties. Many attempts had been made to improve the ferroelectricity and ferromagnetism in BFO. An effective way to improve the magnetic properties is ion substitution. Rare earth (RE) ion doping at Bi site [8–16] can enhance the dielectric and magnetic properties.

In this framework to improve the electrical resistivity, others such as the perovskite PbTiO$_3$, BaTiO$_3$ and SrTiO$_3$ [17,18] were dissolved with BiFeO$_3$. Among other materials, barium strontium titanate, (BaSr)TiO$_3$ or BST, is the most extensively
studied perovskite ferroelectric oxide. This material is invaluable for the electronics industry, due to its high dielectric constant, low dielectric loss, and good thermal stability and high frequency characteristics [19]. Moreover, the importance of the behavior of phonons in multiferroic materials is being recently undertaken. For example, the study of HoMnO₃ [20] and Bi₁₋ₓDyₓFeO₃ [21] by Raman and IR spectroscopy, LuMnO₃ by transmittance and reflectance measurements [22] revealed the importance of the phonons in multiferroic materials. Coming to the BiFeO₃, which is considered to be the only multifunctional material at room temperature, the study of phonon behavior is recently reported in epitaxial BiFeO₃ films and single crystal BFO sample [23,24] establishing the importance of spin–phonon coupling. Singh and al. first reported the room temperature Raman spectra of epitaxial thin films with phonon mode assignment [23], Haumont et al. observed anomalies in the phonon spectra of BiFeO₃ across the magnetic transition (Tₛ) and suggested that multiferroic character might be playing a key role in the strong phonon anomaly observed [25]. However, Haumont et al. discuss no specific phonon mode assignment. Fukumura and al. reported all the 13 Raman modes predicted by group theory for single crystal BiFeO₃ and pointed out the discrepancy in the results of Haumont et al. [24]. This is the only report in literature, which showed the presence of all 13 Raman modes predicted by theory. To the best of our knowledge, no Raman data is reported in the literature for polycrystalline BiFeO₃ samples.

In this paper, the main objective of our research work is to study the preliminary structural, and detailed vibrational and electric properties of single-phase Bi₀.₇(Ba₀.₈Sr₀.₂)₀.₃Fe₀.₇Ti₀.₃O₃ to get information for selection material for some meaningful applications. Thus, the study of the frequency dependence of ac conductivity suggests that this material obey Jonscher’s universal power law. Therefore, Bi₀.₇(Ba₀.₈Sr₀.₂)₀.₃Fe₀.₇Ti₀.₃O₃ ceramic is synthesized by solid state reaction and studied by X-ray diffraction, Raman and impedance spectroscopy in order to determine the structure and to understand the ion conductivity of this material.

2. Experimental

2.1. Synthesis

The Bi₀.₇(Ba₀.₈Sr₀.₂)₀.₃Fe₀.₇Ti₀.₃O₃ ceramic is prepared using the solid state reaction method. High purity Bi₂O₃, Fe₂O₃, TiO₂, BaCO₃ and SrCO₃ powders were carefully weighed in stoichiometric proportions and thoroughly mixed in agate mortar for 2 h. Bismuth oxide was taken in 5% mole excess to compensate bismuth loss during sintering process. To reveal characteristic features of the synthesis of Bi₀.₇(Ba₀.₈Sr₀.₂)₀.₃Fe₀.₇Ti₀.₃O₃ ceramic the stoichiometric mixture of powders corresponding to the chemical solid-phase reaction given below by Eq. (1):

$$0.35\text{Bi}_2\text{O}_3 + 0.24\text{BaCO}_3 + 0.06\text{SrCO}_3 + 0.35\text{Fe}_2\text{O}_3 + 0.3\text{TiO}_2$$

$$\rightarrow \text{Bi}_0.7\text{(Ba}_{0.8}\text{Sr}_{0.2})_0.3\text{Fe}_{0.7}\text{Ti}_{0.3}\text{O}_3 + 0.3\text{CO}_2$$

(1)

is thoroughly prepared.

In order to obtain single phase sample, the powder is then pressed into discs and calcined at 600 °C for 1 h and later at 800 °C for 2 h with intermediate grindings. After calcination, sample is ground for 2 h and pressed into pellets, then heated at 830 °C for 1 h in air with a high heating rate. The sintered sample is then leached with dilute nitric acid to get rid of any impurity phase. The compactness value C defined as the ratio between the experimental density $d_{\text{exp}}$ and theoretical density $d_{\text{theor}}$ of ceramic disks. This value is 93%.

2.2. X-ray diffraction

The crystal structure of the sintered sample is examined by an X-ray diffraction (XRD, XPERT-PRO). CuKα radiation ($\lambda = 1.5406$ Å) is used to collect the diffraction data in a broad range of Bragg angles $20 \leq 2\theta \leq 72$. The data is analyzed by the Rietveld method using the “Fullprof” software [26] to assess phase purity and the crystal structures of the material.

2.3. Scanning electron microscopy

The grain morphology is studied by scanning electron microscopy (SEM, Philips XL30). The SEM micrograph of the compound shows the distribution more uniform of grains with some small size of voids suggesting the formation of high-densification homogeneous sample. Optimum calcination and sintering strategy for obtaining pure perovskite phase, presence of all elements, and homogeneous microstructures have been determined. The surface morphology of the compound reveals the average grain size of the order of 1 µm.

2.4. Raman measurements

Raman spectra of sintered samples are recorded from 100 to 700 cm⁻¹ in a micro-Raman Spectrometer (LABRAM HR-800), working in a backscattering configuration, equipped with an He⁺ ion ($\lambda = 633$ nm) laser. The spectral resolution of the system is 3 cm⁻¹. The deconvoluted Raman active modes for Bi₀.₇(Ba₀.₈Sr₀.₂)₀.₃Fe₀.₇Ti₀.₃O₃ are determined by fitting using the LabSpec5 software with a combined Lorentzian–Gaussian band shape.

2.5. Impedance study

The finely grained sample is pressed into pellets of 8 mm diameter and 1 mm thickness using a hydraulic press and then placed between two parallel platinum electrodes. The dielectric properties of this compound are measured from 713 K to 773 K and in the 100–1000 kHz frequency range. Temperature is measured using a thermocouple with 2 K accuracy.

3. Results and discussion

3.1. X-ray characterization

Fig. 1 shows the XRD pattern of Bi₀.₇(Ba₀.₈Sr₀.₂)₀.₃Fe₀.₇Ti₀.₃O₃ ceramic at room temperature. A profile matching of the XRD spectra is made using the “Fullproof” software [26]. The Bragg peaks are modeled with Thompson–Cox–Hastings pseudo-
Voigt function and the background is estimated by linear interpolation between selected background points. The analyses of the XRD pattern confirm a single phase formation without any impurity phase. The rhombohedral distorted perovskite structure of BiFeO$_3$ with R3c space group is conserved. Moreover, there is structural distortion in many multiferroic materials. Similarly, the ionic radius of Ba$^{2+}$ and Ti$^{4+}$ are larger and also the slightly smaller ionic radius of Fe$^{3+}$ in comparison with that of Fe$^{3+}$ results in an increase in the tolerance factor from 0.840 for BiFeO$_3$ to 0.875 for our sample. The Rietveld refinement is a method in which the profile intensities obtained from step scanning measurements of ceramics allow to estimate an approximate structural model for the real structure. It is well known that room temperature phase of BFO is rhombohedrally distorted perovskite structure described by space group R3c [3]. The obtained rhombohedral unit cell parameters for Bi$_{0.7}$(Ba$_{0.8}$Sr$_{0.2}$)$_{0.3}$Fe$_{0.7}$Ti$_{0.3}$O$_3$ are $a_m=5.6428$ Å, $a_m=59.758^\circ$ and $V=126.350$ Å$^3$. The rhombohedral unit cell parameters of BiFeO$_3$ are $a_m=5.6343$ Å, $a=59.348^\circ$ and $V=124.601$ Å$^3$ [6]. The increase of the lattice parameters and the volume compared to BiFeO$_3$ can be related to the arithmetic radius to site A. The ionic radius of Ba$^{2+}$ (1.36 Å) and Sr$^{2+}$ (1.18 Å) are larger than that of Bi$^{3+}$ (1.03 Å), while the radius of Ti$^{4+}$ (0.605 Å) is smaller than that of Fe$^{3+}$ (0.645 Å) [29].

### 3.2. Surface morphology

Fig. 2 shows the SEM photograph of Bi$_{0.7}$(Ba$_{0.8}$Sr$_{0.2}$)$_{0.3}$Fe$_{0.7}$Ti$_{0.3}$O$_3$ ceramic. It is seen that the grain size of this ceramic is the minimum (0.5 µm) and the maximum (3 µm). Moreover, the substitution of BiFeO$_3$ by Ba$_{0.8}$Sr$_{0.2}$TiO$_3$ reduces the grain size and increases the volume fraction of grain boundaries and the microstructure is relatively homogenous. The grain shapes become more regular, the grain sizes present a little decrease and the size distribution is more uniform [30]. The Ti$^{4+}$ ions play a role of donor because of its higher valence than that of Fe$^{3+}$ ions. This substitution requires charge compensation which can be achieved by suppression of oxygen vacancies. The decrease in grain size can be interpreted as a result of the suppression of oxygen vacancies, which slows oxygen ions motion and consequently grain grown rate [31].

In the energy dispersive analysis of X-ray “EDAX” spectrum at room temperature of Bi$_{0.7}$(Ba$_{0.8}$Sr$_{0.2}$)$_{0.3}$Fe$_{0.7}$Ti$_{0.3}$O$_3$ sample shown in Fig. 3, any additional peaks related to factors other than the voters are revealed. This spectrum reveals the presence of all Bi, Ba, Sr, Ti, Fe and O elements, which confirms that there is elemental composition of the sample does not contain foreign elements and phases if the parasites are there, there must be some form of Bi, Ba, Fe, Sr, Ti and...
oxygen only during sintering. The sample shows the exact for standard peak position for Bi, Fe, Sr, Ti and Oxygen. In addition, quantitative analysis (see Table 1) shows that the atomic composition of Bi, Ba, Sr, Ti, Fe and O is very close to a 1:1 stoichiometry.

4. Temperature evolution of the Raman spectra

Looking at Fig. 4, the sample Bi$_{0.7}$(Ba$_{0.8}$Sr$_{0.2}$)$_{0.3}$Fe$_{0.7}$Ti$_{0.3}$O$_3$ exhibits 11 modes of all 4A1 + 9E phonon modes that are allowed in the non-centre symmetrical R3c in part of the spectra until 700 cm$^{-1}$. A comparison of Raman peak positions for pure BFO obtained from this study and other works is provided in Table 2 for reassurance of the presence of the R3c phase in BFO. So, we noted that the peak positions of doped sample coincide with the R3c phase consistent with our XRD result.

However, the changes in the low frequency A1 modes are associated to the change in the occupation level of Bi atoms of perovskite unit, whereas the high frequency E modes is induced by internal vibration of Fe atoms in the FeO$_6$ octahedra [32]. Among these modes the first three A1 and the E mode at 322 cm$^{-1}$ are governed by the Bi–O covalent bonds, which are the origin of ferroelectric distortion.

Raman spectra in the frequency range 100–700 cm$^{-1}$ is collected for several temperatures (from 523 to 773 K) around the transition evidenced at 751 K by dielectric measurement [6]. Fig. 5 shows the Temperature-dependent Raman spectra of 0.7BiFeO$_3$–0.3Ba$_{0.8}$Sr$_{0.2}$TiO$_3$ compound.

In this study, the Raman peak at 162 and 203 cm$^{-1}$ expanded gradually until the complete disappearance with the increase in temperature which is related primarily to the Bi–O vibrations. In fact, we observed that these modes at 322 and 378 cm$^{-1}$ nearly disappears just near at $T_C$ as presented in Fig. 2. This transition ferro-paraélectrique ($T_C$) will be discussed in paragraph pro. These clear changes can be explained by the existence of oxygen vacancies in our sample. Because of the different valence states of (Ba$^{2+}$, Sr$^{2+}$) and Bi$^{3+}$ ions, addition of (Ba$^{2+}$, Sr$^{2+}$) to BFO requires charge compensation which can be achieved by the formation of oxygen vacancies.

In this context, a clear change in the spectral shape is observed. Mainly due to the disappearance of anomaly near the Neel temperature in Raman phonon modes 451 cm$^{-1}$ contribution when passing through the antiferromagnetic–paramagnetic phase transition. The latter phenomenon is not detected by measuring impedance. Indeed, the spin-phonon coupling is caused by the integral of the modulation by the exchange network, in fact the anomaly is attributed to a spin-reorientation. The behavior of phonon modes appear to be influenced by the appearance of the magnetic order of iron ions. Spin frustration causes a change in the exchange energy between the ions. This large energy variation is probably due to the fact that the phonon generates an angular deformation of Fe–O bonds, which has an impact on the direction of spin iron ions in the magnetic plane [22]. Recently, through temperature Raman measurements, this study report the existence of coupling between ferroelectric and magnetic order parameters in polycrystalline 0.7BiFeO$_3$-0.3Ba$_{0.8}$Sr$_{0.2}$TiO$_3$.

Table 1

<table>
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<th>Elements</th>
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Fig. 3. The EDAX spectrum of the Bi$_{0.7}$(Ba$_{0.8}$Sr$_{0.2}$)$_{0.3}$Fe$_{0.7}$Ti$_{0.3}$O$_3$ ceramic.

Fig. 4. Measured spectra, simulated spectra of the deconvoluted (decomposed) Raman active modes for Bi$_{0.7}$(Ba$_{0.8}$Sr$_{0.2}$)$_{0.3}$Fe$_{0.7}$Ti$_{0.3}$O$_3$. 
5. Impedance analysis

The complex impedance spectra ($Z''$ versus $Z'$) of the Bi$_{0.7}$(Ba$_{0.8}$Sr$_{0.2}$)$_{0.3}$Fe$_{0.7}$Ti$_{0.3}$O$_3$ compound at several temperatures are reported in Fig. 6. They exhibit some dispersion instead of a centered semicircle on the real axis, which indicates a non-Debye type of relaxation [36]. As temperature increases, the radius of the arc corresponding to the bulk resistance of the sample decreases, indicating an activated thermal conduction mechanism [37]. The impedance data is fitted to an equivalent circuit consisting of series combination of grains, grains boundary and electric-electrode interface elements. The first, consists of parallel combination of resistance ($R_g$) and capacitance ($C_g$), the second consists of parallel combination of resistance ($R_{gb}$) and a constant phase element CPE$_{gb}$ whereas the third consists of a constant phase element CPE$_e$. Impedance of the capacity of the fractal interface CPE which is given by following equation:

$$Z_{CPE} = \frac{1}{Q(\omega)^\alpha}$$

(4)

where $Q$ indicates the value of the pseudo-capacitance of the CPE element and $\alpha$ the degree of deviation with respect to the value of the pure capacitor [38].
These real and imaginary components of the whole impedance are calculated according to following expressions:

$$Z' = \frac{R_g}{1 + (\omega R_1 C)} + \frac{R_g Q_g \omega \alpha_{gb} \sin(\alpha_{gb} \pi/2)}{(1 + R_{gb} Q_g \omega \alpha_{gb} \cos(\alpha_{gb} \pi/2))^2 + (R_{gb} Q_g \omega \alpha_{gb})^2} \sin(\alpha_{gb} \pi/2) + \frac{\cos(\alpha_{gb} \pi/2)}{Q_g \omega \alpha_{gb} \alpha_{gb}^2}$$

(5)

$$-Z'' = \frac{R_g^2 \omega}{1 + (\omega R_1 C) + \frac{R_g Q_g \omega \alpha_{gb} \sin(\alpha_{gb} \pi/2)}{(1 + R_{gb} Q_g \omega \alpha_{gb} \cos(\alpha_{gb} \pi/2))^2 + (R_{gb} Q_g \omega \alpha_{gb})^2} \sin(\alpha_{gb} \pi/2) + \frac{\sin(\alpha_{gb} \pi/2)}{Q_g \omega \alpha_{gb} \alpha_{gb}^2}}$$

(6)

The angular frequency dependence of the experimental and simulated (solid line) of the real part $Z'$ of impedance at several temperatures is shown in Fig. 7. Indeed, the magnitude of $Z'$ becomes independent of frequency. This behavior is observed semicircle represented the bulk, the grain boundary and the electric-electrode interface elements response of the system [44]. The capacitance values for the high and the low frequency semicircles are found to be in the range of $10^{-11}$ to $10^{-8}$ and $10^{-6}$ F, respectively, proving that the observed semicircles represent the bulk, the grain boundary and the electric-electrode interface elements response of the system, respectively [45].

In order to understand the conduction phenomena, we used the Arrhenius modeling equation:

$$\sigma_g T = A \exp\left(\frac{-E_a}{k_B T}\right)$$

(7)

where $E_a$ is the activation energy, $A$ is the pre-exponential factor, $k$ is the Boltzmann constant, and $T$ is the temperature. The temperature dependence of the electrical conductivity $\sigma_g = e/R_g S$ (with $e$ and $S$ are respectively the thickness and the area of the pellet) is represented in Fig. 9 in the form of Ln ($\sigma_g * T$) versus reciprocal temperature. Two regions are observed and separated by a discontinuity in the around temperature 751 K. This discontinuity is an agreement with the ferroelectric–paraelectric phase transition detected by dielectric measurement [46] and spectroscopy Raman in function several temperatures. According to the Arrhenius law, the obtained activation energy are $E_{a1} = 1.19$ eV in region I ($T < T_C$) and $E_{a2} = 1.07$ eV in region II ($T > T_C$).
6. Ac conductivity analysis

Electrical conductivity is a prominent factor which reveals reliable information about the transport phenomenon in materials. The frequency–temperature dependence of ac conductivity for the Bi$_{0.7}$(Ba$_{0.8}$Sr$_{0.2}$)$_{0.3}$Fe$_{0.7}$Ti$_{0.3}$O$_3$ sample is shown in Fig. 10. In fact, the conductivity curves reveal two distinct regions: the low-frequency region and high-frequency region. At low frequencies, a plateau which characterizes the direct current conductivity (dc) is present, while at high frequencies, the conductivity increases gradually with the increase in frequency. Besides, the transition region from dc to ac conductivity shifts to higher frequencies with the increase in temperature. The dependence of the ac conductivity on frequency can be expressed by the following equation [47]:

$$\sigma_{ac}(\omega) = \sigma_{dc} + A\omega^s$$  \hspace{1cm} (8)

where $\sigma_{dc}$ is the total conductivity, $\sigma_{dc}$ is the frequency independent part of conductivity, $A$ is a temperature dependent parameter and $s$ is the temperature dependent exponent in the range of $0 \leq s \leq 1$. The exponent $s$ represents the degree of interaction between mobile ions with the lattices around them and the prefactor exponent $A$ determines the strength of polarizability [48].

Fig. 11 shows the variation of Ln($\sigma_{dc}$*T) versus 1000/T in bulk of Bi$_{0.7}$(Ba$_{0.8}$Sr$_{0.2}$)$_{0.3}$Fe$_{0.7}$Ti$_{0.3}$O$_3$. The phase transition is confirmed by the change of the curve slope at 751 K. The activation energy calculated from linear fit to the data points is $E_a=1.19 \text{ eV}$, in the ferroelectric region, and $E_a=0.98 \text{ eV}$, in the paraelectric region. The value of $s$ obtained from the fitted data are plotted as functions of temperature in Fig. 12. It can be deduced that the $s$ value is temperature dependent. Besides, a change in the slope of the curve was observed at 751 K which is close to the temperature of the transition detected by diffusion Raman.
Bi$_{0.7}$$(B_a_{0.8}S_r_{0.2})_{0.3}$Fe$_{0.7}$Ti$_{0.3}$O$_3$ ceramic sample is performed.

7. Conclusion

In conclusion, solid-state synthesis and investigation of Bi$_{1-x}$(Ba$_{0.8}$Sr$_{0.2}$)$_{1+x}$Fe$_{1-x}$Ti$_{1+x}$O$_3$ ceramic sample is performed. A correlation between the structural, vibrational, and electrical properties behavior of the compounds is found. Besides, X-ray structural analysis confirms the material show rhombohedral structure with R3c space group at room temperature. Furthermore, the phase transition ferroelectric-paraelectric ($T_C$) and antiferromagnetic Neel temperature ($T_N$) is detected by Raman spectroscopy. The complex impedance spectroscopic studies also show relaxation effects which are non-Debye type. The frequency dependent conductivities for the title compound suggest two distinct linear regions, associated with two activation energies $E_{a1} = 1.19$ eV in region I ($T < T_C$) and $E_{a2} = 1.07$ eV in region II ($T > T_C$).

References


[34] G.L. Yuan, S.W. Or, H.L.W. Chan, Raman scattering spectra and ferroelectric properties of Bi$_{1-x}$Nd$_x$FeO$_3$ ($x$=0–0.2) multiferroic ceramics, J. Appl. Phys. 101 (2007) 064101.


[38] A. Zaafouri, M. Megdiche, M. Gargouri, AC conductivity and dielectric behavior in lithium and sodium diphosphate LiNa$_3$P$_2$O$_7$, J. Alloy. Compd. 584 (2014) 152.


[40] P.C. Sati, M. Arora, S. Chauhan, M. Kumar, S. Chhoker, Structural, magnetic, vibrational and impedance properties of Pr and Ti codoped BiFeO$_3$ multiferroic ceramics, Ceram. Int. 40 (2014) 7805.


