Structure and Dielectric Studies of Sn\(^{4+}\)/Er\(^{3+}\) co-doped BaTiO\(_3\) Nano-Powders

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1. Introduction

Barium titanate (BTO\(_3\)) has been considered as one of the ferroelectric materials most frequently used in manufacturing various microelectronic devices due to its unique electrical properties, mechanical and chemical stability [1]. Much attention has been paid to prepare such ceramics with an average grain size below 100 nm to improve their electrical properties to be used in fabricating multilayer ceramic capacitors (MLCCs) with high efficiency. However, MLCCs based BTO\(_3\) have still some drawbacks originating from the degradation of ferroelectric and dielectric properties when the grain size decreases [2]. Many attempts were made to overcome such problems and to prepare BTO\(_3\) sample with fine particle size, controlled stoichiometry, and uniformity. Currently, there are two methods for synthesizing BTO\(_3\) sample: solid-phase [3] and liquid-phase methods [4]. The traditional solid phase method of high sintering temperatures still has some drawbacks such as serious agglomeration and coarse grains. Instead, the sol–gel method of low sintering temperature provides a new approach to the preparation of high purity, uniform, and ultrafine metal oxide nanoparticles in a few steps [2]. Thus, in the current study, the sol–gel method has been used to prepare pure (BTO\(_3\)) and Sn\(^{4+}\)/Er\(^{3+}\) co-doped barium titanate (BTSO\(_3\):2Er) nanopowders.

The doping mechanism and influence of the large rare-earth ions on structural and electrical properties of BTO\(_3\) ceramics have been extensively studied [5, 6]. By definition, the relaxor ferroelectrics are well characterized by broad relaxation peaks in their dielectric spectra which shifted to higher temperatures with increasing frequency [7, 8]. The relaxor phenomenon was first evidenced in Ba(Ti\(_{1-x}\)Sn\(_x\))\(_2\)O\(_3\), and is currently ascribed to the development of polar nanoregions (PNRs) [9, 10]. On the other hand, the polarized domains in pure BaTiO\(_3\) exhibit a sharp relaxation peak at the phase transition temperature, i.e. the Curie temperature (\(T_C \sim 130\,^\circ\)C) [11]. Several types of research reported a diffused phase transition in Ba(Tio\(_{0.7}\)Sn0.3)\(_2\)O\(_3\) that achieves complete relaxor characteristics [12]. This results in increase of permittivity, tunability under biasing field, as well as a reduction of the low-frequency dielectric losses. The addition of rare-earth (RE\(^{3+}\)) elements to BTO\(_3\) was found to be useful for producing semiconducting materials which in turn enables the development of positive temperature coefficient resistors (PTCR) [13]. The special interest is given for rare-earth cations because some of them exhibit amphoteric behavior when they incorporated into the BTO\(_3\) structure. For instance, lanthanide ions from Sn\(^{3+}\) to Er\(^{3+}\), having a particle size between Ba\(^{2+}\) and Ti\(^{4+}\), can be accommodated either at A or B lattice sites, depending on their concentrations and stoichiometry of the hosting structure [12, 14, 15]. Erbium (Er\(^{3+}\)) has been widely used because of its great technological interest [16]. As its particle size (0.89 Å) value lies between Ba\(^{2+}\) (1.61 Å) and Ti\(^{4+}\) (0.605 Å),
it would occupy Ti-site to improve the stability of BTO$_3$ at this location [17, 18]. Based on the above, the main objective of the current study is to investigate two subjects, BTO$_3$ and BTSO$_3$:2Er. The first is to prepare these ceramics on the nanoscale having sufficiently high permittivity to be useful for electrical capacitors and relaxors fabrication. The second concerns the effect of Sn$^{4+}$/Er$^{3+}$ co-doping on their microstructure, crystalline structure, and dielectric properties. Sample’s structure was characterized using X-ray diffraction (XRD) and field emission scanning electron microscopy (FESEM) whereas their dielectric properties were studied over a temperature range (-50°C to 200°C) at different frequencies.

2. Materials and methods

2.1. Synthesis procedure

The chemical starting materials used in the present study were barium acetate Ba(CH$_3$COO)$_2$ (Aldrich 99%), titanium(IV) $n$-butoxide Ti(OC$_3$H$_7$)$_4$ (Alfa Aesar 99%+%), 35 ml acetyl acetone C$_5$H$_8$O$_2$ (Aldrich 99%+%) and 20 ml acetic acid (C$_2$H$_4$O$_2$) diluted with distilled water (HAc)-H$_2$O were selected as solvents of 6.662 g titanium(IV) $n$-butoxide and 5 g barium acetate, respectively. Barium titanate (BTO$_3$) was obtained by reacting to two solutions of barium acetate and titanium(IV) $n$-butoxide (Sol 1) for 1 h on the stirrer. To obtain BTSO$_3$:2Er (BaTi$_{0.88}$Sn$_{0.1}$Er$_{0.02}$O$_3$) Sol 1 was mixed with tin solution (10 mol.% SnCl$_4$·5H$_2$O (Strem Chemicals, Incorporated), dissolved in 16 ml isopropanol) for 15 min on the stirrer (Sol 2), and then added erbium solution (2 mol.% Er(NO$_3$)$_3$·5H$_2$O (Aldrich 99%+) dissolved in 5 ml distilled water), and then the mixture was stirred on hotplate for 50 min (Sol 3). As a result, gel was formed at 130°C which was then annealed in air for 4 h at 1050°C (using Muffle furnace type Carbolite CWF1200) and finally small crystalized samples of BTO$_3$ and BTSO$_3$:2Er were obtained.

For dielectric measurements, the fine ceramic sample was pressed into samples-shaped pellets having a diameter of 10 mm and a thickness of 2.4 mm under pressure of 40 MPa at room temperature. Then, both surfaces of each sample were coated with a silver paste to ensure good contacting.

2.2. Characterization of nanopowders

To examine the crystal structure of BTO$_3$ and BTSO$_3$:2Er nanopowders, XRD measurements were performed. Philips X-ray diffractometer having monochromatized Cu $K_{α1}$ ($λ = 1.5406$ Å) of power 40 kV × 30 mA, was used. The crystallite size ($G$) was calculated from the Scherrer equation [19]:

$$G = \frac{Kλ}{D \cos(θ)},$$

(1)

where $K = 0.89$ is the Scherrer constant, $λ$ is the wavelength, $D$ is the full width (in radians) of the peak at half maximum (FWHM) intensity, and $θ$ is the diffracted angle. FESEM together with energy dispersive X-ray (EDX) analysis were provided with a variable pressure FESEM instrument (FEI, model: Quanta 250 FEG) to determine the crystalline phases and elements. To achieve this, the samples were gold-sputtered using Edwards S150A Sputter coater to make the images more obvious. The sample’s chemical structure was characterized using the Fourier transform infra-red spectroscopy using Thermo Nicolet, FT-IR, and NEXUS in the range from 400 up to 4000 cm$^{-1}$.

The dielectric measurements were carried out by inserting the sample between two conducting parallel plates forming a capacitor. The sample temperature was controlled by thermometer contact to the sample and temperature controller. A computerized Impedance Analyzer IM3570 was used to measure the dielectric properties of the prepared samples at a temperature range between (-50) and 200°C over a wide frequency range from 10$^2$ up to 10$^6$ Hz. The permittivity $ε’$ and AC conductivity $σ_{AC}$ were calculated from the output parameters like capacitance $C$ and loss tangent $\tan(δ)$ as follows:

$$ε' = \frac{Cd}{ε_0A},$$

(2)

$$σ_{AC} = \frac{ωε_0ε’}{tan(δ)},$$

(3)

where $ε_0$ is the permittivity of free space (8.854 × 10$^{-12}$ F/m), $d$ is the sample thickness, and $A$ is the sample surface area. The measurement uncertainty reported to be ±1% and ±3% in $ε'$ and $\tan(δ)$, respectively. The measurement reproducibility was tested by re-measuring $ε'$ and $\tan(δ)$ after experimenting once again.

3. Results and discussion

3.1. Structure and morphology study

Figure 1 illustrates XRD patterns for BTO$_3$ and BTSO$_3$:2Er powders annealed in air at 1050°C for 4 h. It can be seen that all the observed peaks corresponding to BTO$_3$ tetragonal perovskite structure were presented in all patterns according to ICDD number [74-2491]. It is evident that the BTSO$_3$:2Er sample contains traces of SnO$_2$ without secondary phases results from Er$^{3+}$ doping; referring to Er$^{3+}$ nominally substitute for Ti$^{4+}$ site and well soluble in host material due to its lower concentration. In BTSO$_3$:2Er, a preferential substitution Er$^{3+}$ for B sites is postulated in 0 ≤Er$^{3+}$ ≤ 0.03 composition range as well as the non-total stabilization of these parameters for 0.03 ≤Er$^{3+}$ ≤ 0.30 [20]. Figure 1b shows the expanding area between 2θ = 40° and 2θ = 49° for both samples, which highlighted the splitting of (002) and (200) orientations at around 45° in 2θ scale, exploring the tetragonal feature for BTO$_3$ [21]. The splitting taken as 2θ distance between the peaks is large enough to confirm tetragonality for BTO$_3$ whereas it decreased for BTSO$_3$:2Er, referring to tetragonality decrease as confirmed by the calculations listed in Table I.
Fig. 1. XRD patterns of nano-crystalline BTO$_3$ and BTSO$_3$:2Er samples sintered in air for 4 h at 1050$^\circ$C (a), and those for expanding area between 2$\theta$ = 44$^\circ$ and 46$^\circ$ (b).

| Samples        | CS [nm] | a [Å]     | c [Å]     | c/a   |
|----------------|---------|-----------|-----------|-------|
| BTO$_3$        | 64      | 3.9888    | 4.020     | 1.0078|
| BTSO$_3$:2Er   | 57.11   | 4.0000    | 4.0052    | 1.0013|

To calculate the tetragonality factor, the lattice parameters (a, c) should be calculated at first from the following equation:

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + (\frac{l}{2})^2}}$$

where $d_{hkl}$ is the d-spacing for the (hkl) plane. Table I shows the crystallite sizes, lattice parameters (a, c) and tetragonal factor for BTO$_3$ and BTSO$_3$:2Er using the planes (200) and (002). The average crystallite size was found to be 64 and 57.11 nm for BTO$_3$ and BTSO$_3$:2Er, respectively, confirming that the samples were successfully prepared in the nanoscale.

FESEM microphotographs and the corresponding EDX images for BTO$_3$ and BTSO$_3$:2Er samples, are together illustrated in Figs. 2 and 3. It turns out that both samples show free uniform grains. Inset of Fig. 3 and Table I show that the compensation mode of Sn$^{4+}$/Er$^{3+}$ ions in BaTiO$_3$ can suppress grain growth, forming a uniform and fine-grained microstructure with an average grain size of 57.11 nm. Further, the surface morphology of BTSO$_3$:2Er shows different microstructure features due to doping with Sn$^{4+}$ and Er$^{4+}$ ions which have larger ionic radii than Ti$^{4+}$. Accordingly, BTSO$_3$:2Er has higher densification than pure BTO$_3$. To identify the purity of nanoparticle samples, dispersive X-ray analysis (EDX) is investigated. BTO$_3$ has high-intensity peaks corresponding to oxygen, Ba, and Ti elements, confirming the absence of any impurities. Similar peaks with lower intensities and additional peaks corresponding to Sn and Er elements are noticed for BTSO$_3$:2Er sample (Fig. 3).

FTIR spectra for BTO$_3$ and BTSO$_3$:2Er samples, are shown in Fig. 4. For BTO$_3$ spectra, the weak band at 549 cm$^{-1}$ is assigned to M–O stretching vibration of
Assignment for FTIR data of BTO$_3$ and BTSO$_3$:2Er

| No. | Frequency [cm$^{-1}$] | Band assignment |
|-----|----------------------|-----------------|
| 1   | 549                  | T-O stretching vibration |
| 2   | 852                  | Ti–O or Sn–O or Er–O stretching vibration |
| 3   | 1037                 | CO$_3^-$ bending vibration |
| 4   | 1388, 1436          | CO$_3^-$ stretching vibration |
| 5   | 1629                 | O–H bending vibration |
| 6   | 2857                 | C–H stretching vibrations (CH$_2$ group) |
| 7   | 2925                 | C–H stretching vibrations (CH$_3$ group) |
| 8   | 3432                 | O–H stretching vibration |

The permittivity (Fig. 5b) was investigated for BTO$_3$ (Fig. 5a) and BTSO$_3$:2Er samples over a wide temperature range (−50 to 200°C) and a frequency range (10$^2$–10$^5$ Hz). As a general description, $\varepsilon'$ for both samples exhibits high values in the low-frequency region, followed by a significant decrease at high frequencies, in agreement with the result reported for the compounds based relaxor ferroelectric materials [12, 20]. Further, the decrease in permittivity with frequency increase is commonly due to decrease in the total polarization components, i.e., space charge, dipolar, ionic, and atomic polarization. The last two polarizations are excluded from further discussion because their mechanisms are determined at very high frequencies ($>10^4$ Hz) out of our frequency window. In Fig. 5a, $\varepsilon'$ of BTO$_3$ shows three successive relaxation peaks corresponding to three structural transitions. The first is the sharpest and highest intensity peak whose maximum is determined at 125°C, revealing the tetragonal-cubic phase transition temperature, i.e., the Curie temperature ($T_C$) [31]. The second is a relatively broad and low-intensity peak, determined at 30°C, that specifies tetragonal-orthorhombic phase transition temperature ($T_{T-O}$), while the last one is a weaker relaxation peak whose maximum positioned at −35°C corresponds to orthorhombic-ribbonodral phase transition temperature ($T_{O-R}$), as shown in Table III. These transitions have been typically found for all classical ferroelectric materials [32].

### Phase transition temperatures for BTO$_3$ and BTSO$_3$:2Er

| Sample | $T_D$ | $T_{T-O}$ | $T_C$ ($T_C$—$T_{T-O}$) | $>T_C$ |
|--------|-------|-----------|--------------------------|--------|
| BTO$_3$ | −35   | 30        | 125                      | ND*    |
| BTSO$_3$:2Er | ND* | −6        | 100                      | 174    |

*non-detected
Fig. 5. Temperature dependence of permittivity ($\varepsilon'$) at different frequencies for BTO$_3$ (a) and BTSO$_3$:2Er (b), sintered in air for 4 h at 1050°C.

For BTSO$_3$:2Er sample (Fig. 5b), the shape of $\varepsilon'$ curves significantly changed and the phase transition temperatures shifted to lower values. Similar behavior has been reported previously upon the incorporation of Sn ions or/and addition of more than 2 mol.% Er into the stoichiometric BTO$_3$ [33, 34]. Therefore, Er-doped samples reported no changes in $T_C$ when the concentration of Er ions is lower than 2 mol%. As a result, one may attribute the changes occurring in $T_C$ of BTSO$_3$:2Er sample to the presence of Sn$^{4+}$ ions instead of less effective Er$^{3+}$ ions at low concentrations.

Accordingly, doping with Sn$^{4+}$ results in a remarkable permittivity increase as compared to that reported for pure BTO$_3$ sample, i.e., it is 1151 at room temperature and 24221 at $T_C$. This reveals enhanced dielectric properties upon doping BTO$_3$ with Sn$^{4+}$ ions. The degree of enhancement is larger than those reported for BaTiO$_3$ doped with other ions, i.e., Co$^{2+}$, Bi$^{3+}$, La/Mn, and Y$^{3+}$/Nb$^{5+}$ [35–39]. The possible reasons for that would be explained based on a specific amount of space charge sites produced inside the grain boundaries and domain walls. Therefore, the space charge itself creates an opposite electric field hindering the polarization that originates from movements of domain walls and grain boundaries. However, as the densification of BaTiO$_3$ is increased, the space-charge fields would be easily reduced by space charge of the surrounding grains. Thus, the domain walls become quite free in denser ceramics, causing a polarization increase that results in a considerable permittivity increase. Another reason may come from the large bond length in the case of Er–O and Sn–O than Ti–O.

Furthermore, $\varepsilon'$ of BTSO$_3$:2Er sample exhibits an unexpected relaxation peak whose maximum is positioned at a temperature higher than $T_C$ (∼174°C). Less attention has been paid to discuss the possible reason for such a peak and therefore it is still an open point for future discussion. According to our knowledge, we suggest that the orientation polarization of aggregated SnO$_2$ inside the ceramic whose traces appeared in XRD analysis (Fig. 1a), is responsible for such a peak. It can also be noticed from Fig. 5b that $T_C$ of doped samples shifts to higher temperatures with increasing frequency which may reveal the relaxor ferroelectrics [7, 8].

3.2.2. Temperature and frequency dependence of conductivity

To investigate the relation between the observed relaxation peaks and transportation of free charge carriers through the crystalline lattice, AC conductivity ($\sigma_{AC}$) for both BTO$_3$ and BTSO$_3$:2Er samples is studied at first as a function of temperature at 10$^2$ Hz (Fig. 6a) and then as a function of frequency at 100°C (Fig. 6b). In Fig. 6a, $\sigma_{AC}$ for both samples starts to slightly increase with increasing temperature and then shows anomalous behavior near the structure transition temperatures. Thus, it exhibits also three pronounced relaxation peaks confirming the phase transition feature for the investigated samples. It can also be noticed that a peak position shifts to higher values for BTSO$_3$:2Er sample. The conduction at temperatures below $T_C$, within the tetragonal ferroelectric may originate from the presence of impurities or defects. Oxygen vacancies as most mobile ionic defects in
perovskite could be responsible for the conduction process [4]. At a temperature higher than $T_C$, within the cubic paraelectric phase, the electrical conduction could be due to thermally activated ionic hopping of oxygen vacancies in $\text{BTSO}_3:2\text{Er}$. 

On the other side, the frequency-dependent conductivity (Fig. 6b) for both samples displays an increase with a frequency increase, obeying the universal power-law $A \omega^n$ [41, 42]. This arises from the long-range movements and alignments of free charge carriers towards the electric field, resulting in a net flow of charge through samples. The conductivity value of $\text{BTSO}_3:2\text{Er}$ is $\sim 10^4$ times higher than that for barium titanate sample, due to formation of excess oxygen vacancies.

4. Conclusion

Nano-powdered pure and $\text{Sn}^{4+}/\text{Er}^{3+}$ co-doped $\text{BTO}_3$ ceramics have been successfully synthesized using the modified sol–gel method. The obtained gel converted to crystalline tetragonal powder upon annealing in air at $1050^\circ\text{C}$ for 4 h. Upon co-doping with $\text{Sn}^{4+}/\text{Er}^{3+}$ ions, microstructure and dielectric properties significantly changed as follows:

1. Grains became denser and their sizes decreased from 64 to 57.11 nm.
2. The Curie temperature ($T_C$) shifted from 125 to 103$^\circ\text{C}$.
3. The permittivity of $\text{BTSO}_3:2\text{Er}$ sample increased to become approximately ten times greater than that of pure $\text{BTO}_3$.
4. AC conductivity value was found to be $\sim 10^3$ times higher than that for pure $\text{BTO}_3$, leading to possibility of using $\text{BTSO}_3:2\text{Er}$ in the field of electrical capacitor fabrication.
5. An unexpected relaxation peak whose maximum was positioned beyond $T_C(174^\circ\text{C})$ in the permittivity and AC conductivity spectra. It may have originated from the orientation polarization of aggregated SnO$_2$ inside the ceramic.

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