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Structural evaluation and dielectric behavior of Nb and Nd-doped BaTiO₃ synthesized via mechanical alloying

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Abstract

In this study, barium titanate (BT) with the perovskite structure BaTiO₃ was synthesized via mechanical alloying using TiO₂, BaCO₃, and BaO₂ powders. Commercial barium titanate (CBT) was also employed to investigate and compare the effects of niobium (Nb) and neodymium (Nd) doping. Characterization of the synthesized powder was conducted using XRD, simultaneous thermal analysis (DTA/TGA), BET surface area analysis, Fourier-transform infrared spectroscopy (FT-IR), scanning electron microscopy equipped with energy dispersive spectroscopy (SEM/EDS), and Zetasizer analysis. The electrical properties of the samples were evaluated by determining their dielectric constant and dielectric loss. Zetasizer analysis, SEM images, and crystallite size calculations based on XRD patterns revealed that the particle size of the synthesized barium titanate (SBT) was in the 35 ± 5 nm range, with an average crystallite size of approximately 33 nm, showing good agreement with SEM observations. Dielectric measurements indicated that the 0.3 wt% Nb-doped SBT (S-0.3Nb) exhibited the highest dielectric constant among the Nb-doped variants, while the 0.4 wt% Nd-doped SBT (S-0.4Nd) showed the highest value among the Nd-doped samples. For the CBT samples, the highest dielectric constant was observed in the 0.2 wt% Nb-doped CBT (C-0.2Nb) and 0.3 wt% Nd-doped CBT (C-0.3Nd), suggesting these concentrations as optimal for maximizing dielectric performance. The dielectric constant of the SBT was found to be comparable to that of the CBT, with maximum values of 17000 and 18000, respectively. Furthermore, the apparent density and open porosity of the samples were measured. The apparent density, determined via the Archimedes method, was higher for CBT than for SBT.

Keywords

BaTiO₃ – Niobium – Neodymium – Mechanical alloying – Electrical properties

1. Introduction

Barium titanate (BT) with the perovskite structure BaTiO₃ is classified as a displacive ferroelectric [1]. Among ferroelectric materials, BT has attracted significant attention due to its noncentrosymmetric crystal structure [2], high dielectric constant, wide band gap (3.20 eV), and anisotropic optical behavior [3]. The intrinsic spontaneous polarization in BT induces reversible transitions between distinct polarization states, thereby enabling its functionality as a ferroelectric material in diverse electronic applications [4]. This unique property has positioned BT as a foundational material in the development of various electronic components. It is widely utilized in the manufacture of multilayer ceramic capacitors [5], positive temperature coefficient (PTC) thermistors, PTC resistors [6], piezoelectric transducers, piezoelectric sensors [7], and electro-optical devices [3]. Among its numerous applications, one of the most significant roles of BT as a semiconductor lies in its positive temperature coefficient of resistance (PTCR), which is critical for thermal sensing and circuit protection technologies [8].

The electrical behavior of a material is characterized by its dielectric constant, defined as the ratio of the material's permittivity (ϵ) to the permittivity of vacuum (ϵ_0). This ratio reflects the material's ability to store electric charge relative to vacuum and can be interpreted as the material's response to external electric fields [9, 10]. The dielectric constant in ferroelectric materials increases abnormally near the Curie temperature (T_c), indicating that a large polarization can be induced in the crystal by applying a small electric field [11]. At such a temperature (125 °C), the material's structure changes from ferroelectric to paraelectric, and above that, the spontaneous polarization of the material disappears [12]. Around room temperature, the dielectric constant of BT is 1500-2000, and it increases with temperature, reaching around 6000 near the T_c (about 120°C) [13, 14]. The size of the dipole moment diminishes with increasing temperature due to structural changes, and the hysteresis loop becomes a straight line at the Curie temperature [2, 15]. However, the choice of synthesis method is frequently influenced by both the intended application of the sample and economic considerations [16]. These powders can also be manufactured through solid-state reaction [17], chemical co-precipitation [18], hydrothermal [19], sol-gel [20], spray pyrolysis [21], polymer precursor [22], and combustion methods [23]. BT powder is typically synthesized via the solid-state reaction, which often results in pronounced agglomeration and a broad particle size distribution [24]. In all, the increase in the rate of atom diffusion

and consequently the increase in reaction rate are directly related to the increase in temperature [25]. With the increase in temperature, the reaction between BT and TiO_2 also begins, leading to the formation of Ti-rich compounds. To achieve a fine and uniformly shaped BT powder, it is therefore preferable to reduce the preparation temperature [10]. An alternate technique for improving reaction rates without raising the temperature is mechanical alloying [26]. According to this mechanism, particle size and crystallites are initially reduced, while the surface energy increases as a result of the particle size reduction [27]. The dielectric properties of BT are highly dependent on the grain size [28]. When the grain size in the bulk piece is 0.6-0.8 μm , the dielectric properties are optimal. Due to the particle growth during the sintering process, BT particles of 100-200 nm should be used as the raw material [29]. Most milled BT powders have low tetragonality, which means their crystal lattice is similar to a cubic lattice, with lattice parameters a and c that are relatively close. Lower tetragonality is associated with Ba or Ti vacancies. However, samples heat-treated at high temperatures (solid-state technique) had greater tetragonality [30, 31]. Wang et al. [32] used mechanical alloying to investigate their microstructure and create nanoscale BT powder. They milled barium powder and TiO_2 in a nitrogen gas atmosphere. Based on the findings, a nanocrystalline structure with crystallite sizes of about 14 nm and particle sizes ranging from 20 to 30 nm was measured. Researchers claim that nanoscale structures cause novel phenomena to arise in nanostructured materials as opposed to non-nanostructured materials.

The microstructure and electrical properties of BT also change due to the addition of certain elements [33]. Several additives with different valencies ($3+$ and $5+$), such as Nb, Sr, V, Ce, Sb, and La, when substituted at the Ba^{2+} and Ti^{4+} sites in BT, control the electrical properties and change the system's resistance. Additionally, the substitution of Pb, Ca, and Sr causes changes in the transition temperatures [34-36]. The selection of appropriate dopants during the sintering process is among the key parameters for fabricating BT-based electronic components with optimal dielectric properties [37]. In research by Velasco et al. [38], the increase in the volume of the unit cell was demonstrated by doping Nb. This phenomenon is understandable given that the Nb^{5+} is larger in ionic radius than the Ti^{4+} . The mechanism of electrical conduction in Nb-doped BT alters. At low Nb concentrations (0.1-0.3 at%), electrical conductivity increased, but with the increase in Nb concentration and the change in the conduction mechanism from the electronic state to the cation vacancy state, electrical conductivity decreased significantly. The surplus positive charge can be balanced either by electron compensation or by the formation of cation vacancies.

One key addition for improving the electrical properties of BT is Nd doping, which can replace Ba^{2+} and Ti^{4+} [3]. This rare earth element enhances the dielectric and ferroelectric characteristics of BT. Nd-doped BT ($\text{Ba}_{1-x}\text{Nd}_x\text{TiO}_3$) has emerged as a subject of considerable scientific interest, as evidenced by studies conducted by Sasikumar et al. [39], Yao et al. [40], Sagar et al. [41], Zhang et al. [42], and Ganguly et al. [43]. Sasikumar et al. [39] synthesized compositions with varying Nd concentrations using the conventional solid-state reaction technique. Their investigation revealed a gradual deterioration in ferroelectric properties beyond $x = 0.04$, which was attributed to a structural phase transition from tetragonal to cubic symmetry. Yao et al. [40] found that the Nd^{3+} occupies the Ba^{2+} sites. The addition of Nd has reduced grain size because BT grain growth is restricted. The grain size grew as the Nd content increased to 5 at%, which Sagar et al. [41] attributed to the phase change from tetragonal to cubic. Nd is effective as a barrier to transformation. Some researchers assume that Nd occupies the Ba^{2+} sites in the lattice and compensates for the unoccupied Ti^{4+} , resulting in a considerable drop in T_c as the Nd increases. Others argue that Nd substitution occurs through a double process, allowing it to occupy both positions [44].

This research used the mechanical alloying method to synthesize BT powder and add Nb and Nd dopants. The BT powders obtained by pressing were subsequently sintered. The structure of samples was examined using simultaneous thermal analysis (TGA-DTA), surface analysis by the BET method, Zeta sizer, and XRD. The microstructural characteristics were also evaluated using an SEM equipped with EDS. The apparent density and open porosity of the samples were measured. In addition, the electrical properties, such as the dielectric constant and dielectric loss at various frequencies, were investigated, and the findings of these analyses were correlated.

2. Materials and methods

2.1. Materials

Barium carbonate (BaCO_3), titania (TiO_2), barium oxide (BaO), niobium oxide (Nb_2O_5), and neodymium oxide (Nd_2O_3) were purchased from Merck. Barium titanate (BT) was supplied by Aldrich. All materials used were of standard research grade and were employed without any further purification. The complete specifications of the materials used in this research are reported in Table 1.

Table 1: Physical and Chemical Characteristics of the Raw Materials

Materials	Composition	Suppliers	Molecular	
			Density (g/cm ³)	weight (g/mol)
Barium carbonate	BaCO ₃	Merck	4.43	197.34
Barium titanate	BaTiO ₃	Aldrich	6.08	233.18
Titania	TiO ₂	Merck	3.90	79.90
Barium oxide	BaO	Merck	4.96	153.33
Niobium oxide	Nb ₂ O ₅	Merck	4.50	265.75
Neodymium oxide	Nd ₂ O ₃	Merck	7.24	336.48

2.2. Synthesis and sample preparation

Commercial barium titanate was designated as CBT, while the synthesized barium titanate was referred to as SBT. For the synthesis of SBT via mechanical alloying, the precursor powders were accurately weighed to a precision of 10⁻⁴ grams, using specific weight ratios of BaO/TiO₂ (1.90), BaCO₃/TiO₂ (2.51), and BaO/TiO₂ (1.93). The weighed powders were then combined with zirconia balls at a ball-to-powder ratio of 10:1 and loaded into an aluminum chamber (7 cm in height, 4 cm inner diameter) of the SPEX 8000 milling device. To incorporate Nb or Nd oxides into the BT matrix, the dopant quantities specified in Table 2 were precisely measured and added to the chamber. Mechanical alloying was performed for a duration of 1 h. To prevent powder adhesion to the milling media and chamber walls, 0.02 grams of stearic acid were added to each 1-gram batch of BT and dopant mixture. Subsequently, the milled powders were compacted into tablets with a diameter of 1 cm using a uniaxial press (Tajhiz Ceram, Iran) under a pressure of 300 MPa, followed by sintering. The dimensions and mass of the tablets were recorded at each processing stage to ensure consistency and traceability. Sintering of the pellets was conducted following the pressing stage. The samples doped with Nb₂O₅ were sintered at 1500 °C for 5 hours, and the samples doped with Nd₂O₃ were placed in the furnace for sintering at 1400 °C for 3 hours. The heating rate in both processes was set at 10 °C/min. The sintering of the samples was carried out in an American-made amalgam furnace. Figure 1 shows a schematic of laboratory steps.

Table 2: Atomic and weight percentage of dopants in BT

At %	Wt% - Nd	Wt% - Nb
0.1	0.34	0.26
0.2	0.67	0.53
0.3	1.01	0.80
0.4	1.34	1.06
0.5	1.68	1.32
0.6	2.02	1.60

2.3. Characterization and Analysis

To characterize the phases and crystallite size of the powder samples, a Philips XRG 3100-PW3710 XRD instrument apparatus with an $\alpha = 2^\circ$, step size = 0.04° incidence angle, and Cu-K α radiation ($\lambda = 0.154$ nm) was utilized. Xpert High Score software version 1.0d was used to identify the phases. Table 3 shows the phase identification card numbers, as well as the structural characteristics. The crystallite size was calculated using the Debye-Scherrer equation, which is given by equation 3:

$$D = \frac{57.3k\lambda}{\beta \cos \theta} \quad (\text{Eq3})$$

where D is the average crystallite size in Å, k is the crystallite shape constant ($k = 0.82$ - 0.9), λ is the wavelength of the anode used by the instrument in Å ($\lambda = 1.540598$ Å), β is the full width at half maximum (FWHM) in radians, and θ is the Bragg angle. FT-IR analysis was conducted using the Perkin Elmer Spectrum 400 (USA) to identify chemical bonds in the synthesized powder.

Table 3: phase identification of JCPDS cards using the XRD

Phase	Structure	Lattice Parameter		Signature Peak
		(Å)		
		a	c	
BaTiO ₃	Tetragonal	3.994	4.038	(200) 45.37
BaTiO ₃	Cubic	4.031	4.031	(200) 44.92
BaO	Cubic	5.539	5.539	(111) 27.86
Ti ₂ O ₃	Rhombohedral	5.158	13.611	(116) 53.77
TiO	Hexagonal	3.029	3.228	(101) 44.46
TiO ₂	Tetragonal	3.785	9.514	(101) 25.28

The density of the sintered samples was measured using Archimedes' method by the ASTM C373 standard. In this approach, the dry sample was weighed initially (W_1), then immersed in water at 80 °C for 5 h and weighed (W_2), and finally placed in water at room temperature for 24 h and weighed after extraction (W_3). Equations 1 and 2 were employed to calculate the sample density and the percentage of open porosity, respectively.

$$P = \frac{W_1}{W_2 - W_3} \quad (\text{Eq1})$$

$$\%T = \frac{W_2 - W_1}{W_2 - W_3} \times 100 \quad (\text{Eq2})$$

To prepare the samples for morphology and microstructure analysis, they were first sanded with 800 to 1500 grit sandpaper, then polished, and finally coated with gold using a coater to make the samples conductive. The shape and distribution of particles, the size of agglomerates, and the relationship between powder particles were studied using a scanning electron microscope (TESCAN VEGA II XMU), and chemical composition was determined using an energy-dispersive X-ray spectrometer (EDX, SAMX, DXP-X10P).

Simultaneous thermal analysis (STA) was conducted with a Shimadzu STA-449 instrument to investigate the weight changes and types of reactions occurring in SBT. An accurately weighed amount of SBT powder (20 mg) was placed into an alumina crucible and heated in an air atmosphere at a rate of 10 °C/min until 1200 °C was reached. To measure the particle size distribution, a Zetasizer instrument from the French company Malvern, model HSA 3000, was used. For this purpose, 1 gram of the sample powder was poured into 100 ml of water and placed on a stirrer under mixing (at a speed of 300 rpm) for 2 h. Then, the resulting solution was centrifuged at 3900 rpm for 10 min, and a sample was

taken from the surface of the liquid, which is less dense. The dielectric constant was measured using an LCR meter (Taiwanese company GW Instek, model LCR-8110G). Measurements were taken in the frequency range of 20 Hz to 10 MHz. To perform LCR analysis of the samples, they were coated with gold in two circular cross-sections, one below and one above the sample. Figure 1 shows a schematic of laboratory steps.

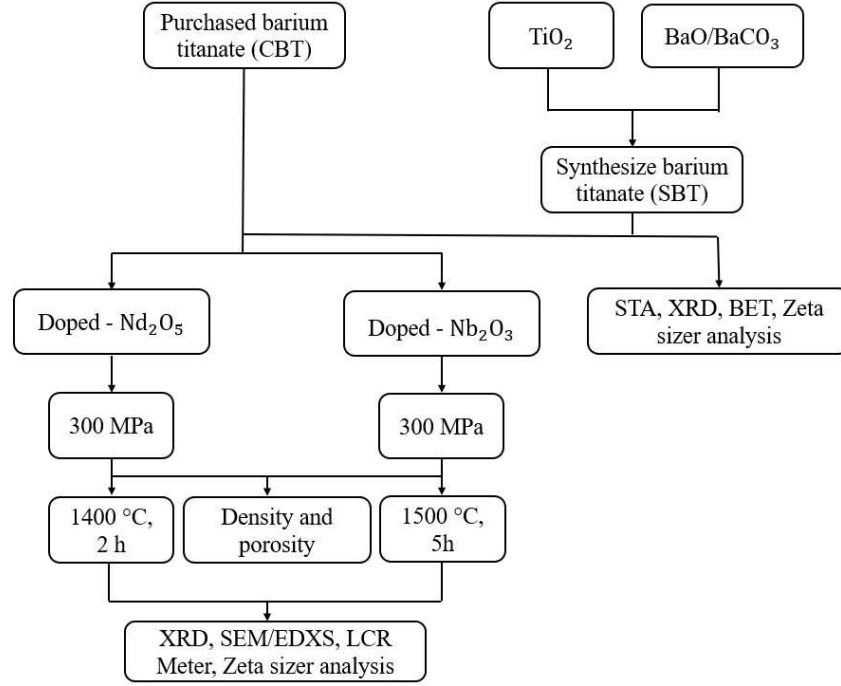


Figure 1: A schematic of laboratory steps.

3. Results and Discussion

3.1. SBT powder study

3.1.1. XRD analysis

Figure 2 shows the XRD patterns of mixed BaO and TiO₂ powders after milling for 6, 9, 12, and 15 h. After 15 h of milling, a pure cubic phase of BT was obtained. According to the standard barium titanate card, SBT powder had a

cubic structure. Table 4 shows the peaks along with the d-spacing. Using equations $a = d \times \sqrt{\frac{4}{3} \times (h^2 + hk + k^2)}$

for (hk0) planes, and $c = l \times d$ for (001) planes, along with equation 3, were applied to calculate the crystallite size of the SBT powder. Based on the calculations, the crystallite size of SBT was approximately 32 nm, confirming the nanostructured nature of the powder.

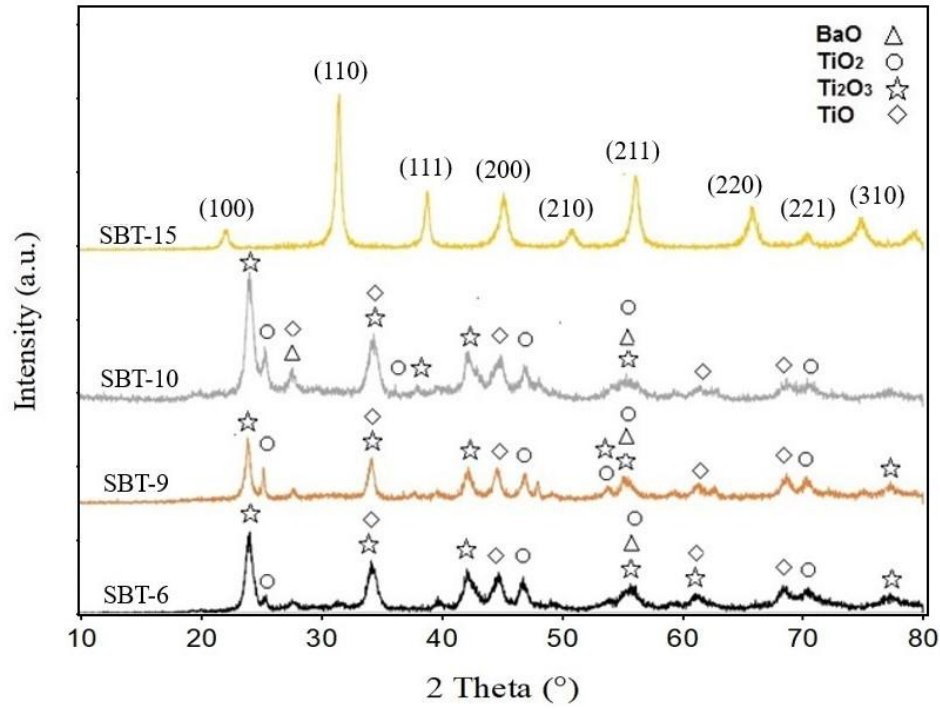


Figure 2: XRD patterns of SBT after 6, 9, 12, and 15 h of mechanical milling.

Table 4: d-spacing for calculating the lattice parameter

Peak Number	(hkl)	d-spacing
2	(110)	2.833
5	(210)	1.794
7	(220)	1.418
9	(310)	1.268

3.1.2. STA analysis

Figure 3 illustrates the STA (DTA/TGA) curves obtained for the SBT powders. The TGA curve indicated no substantial weight change up to a temperature of 1200 °C. Moreover, the DTA curve of SBT reveals no endothermic or exothermic peaks within the specified temperature range, indicating that no phase change occurs in the sample up to 1200 °C. These findings suggest that BT was synthesized in its pure phase, which is also consistent with the results obtained from XRD analysis.

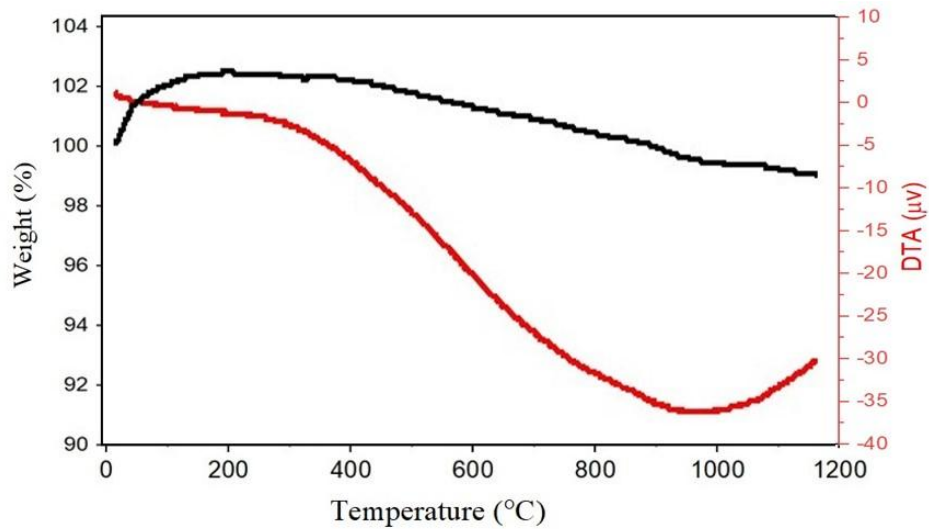


Figure 3: STA (DTA/TGA) curve for SBT.

3.1.3. SEM and Zetasizer analysis

Figure 4 displays the SEM micrographs of the SBT powder. According to the SEM images, some particles are agglomerated and do not have a homogeneous and uniform morphology. At the same time, as shown in Figure 4 (b), there are also particles with dimensions below 100 nm, which could indicate the synthesis of BT nanoparticles. The agglomerated particle shown in Figure 4 (a) was measured to be approximately 316 nm using Image-J software. The results obtained from the Zetasizer analysis also show that the particle size for SBT powder is 35 ± 5 nm, which is in good agreement with the results obtained from the SEM images.

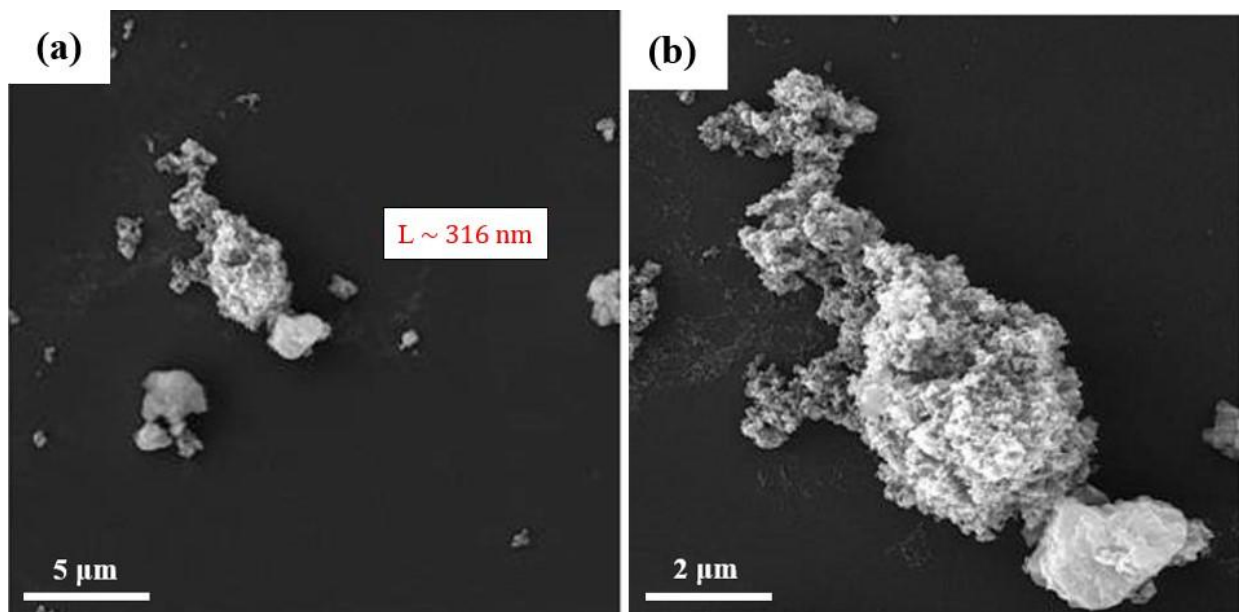


Figure 4: SEM images of SBT.

3.1.4. FT-IR analysis

Figure 5 shows the FT-IR spectrum of the SBT before calcination. The absorption bands at 3446 cm^{-1} and 1634 cm^{-1} correspond to O–H stretching and bending vibrations, typically associated with moisture and structural water. The peak at 1428 cm^{-1} is also likely related to carbonate groups. According to reports from many researchers [45, 46], the peak at 554 cm^{-1} represents the O–Ti–O bond in the octahedral sites within the BT structure. The very strong absorption related to the Ti–O bond indicates that the titanate structural network is fully formed.

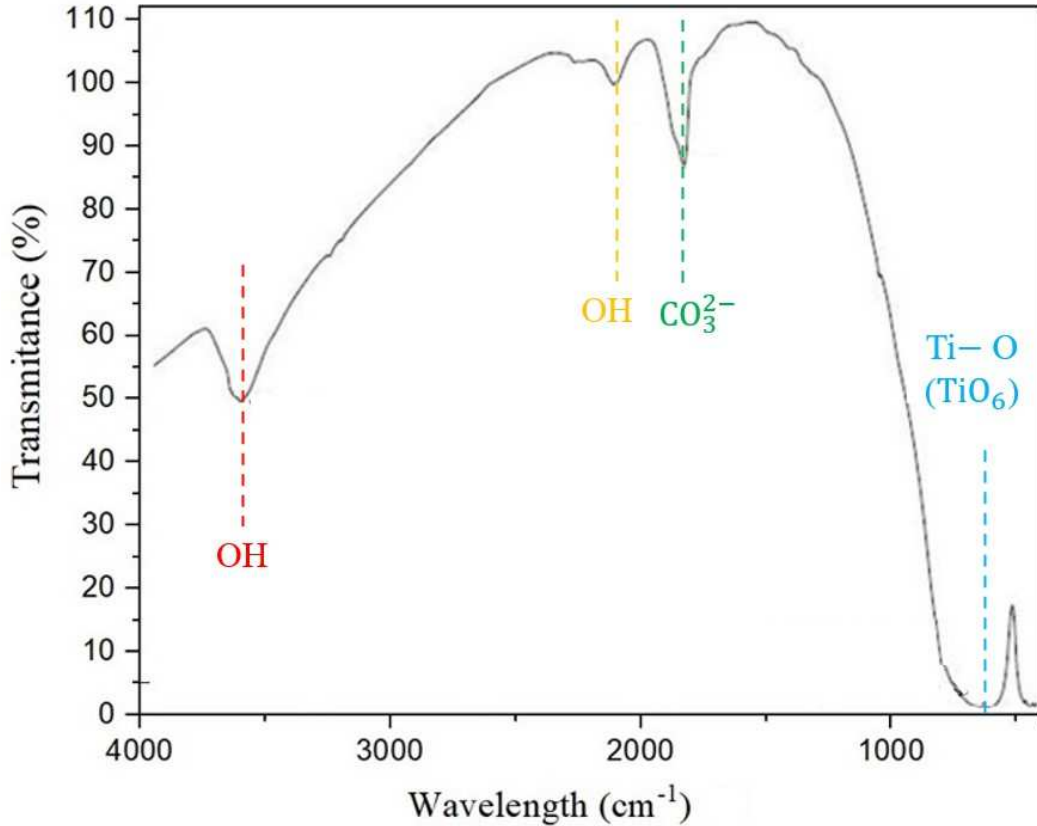


Figure 5: FT-IR spectrum of SBT after mechanical milling and before calcination.

3.1.5. BET analysis

Figure 6 presents the BET analysis graph used to determine the specific surface area, shape, and pore diameter of the synthesized BT powder. According to the N_2 adsorption and desorption isotherm, the rate of N_2 adsorption increases as the gas pressure increases. This curve belongs to the third class of isothermal adsorption and desorption curves established by IUPAC. The pore structure in Type III isotherms is slit-shaped and on the nanometer scale, resulting in weak surface bonding between the gas and the sample surface. The overall pore volume is $0.07\text{ cm}^3/\text{g}$, the pores have a specific surface area of $4.55\text{ m}^2/\text{g}$, and their average diameter is 61.83 nm . Furthermore, using the adsorption

isotherm, the surface pore size of 64.1 nm was determined. The final BET analysis results indicate that the SBT powder exhibits low porosity and limited surface adsorption.

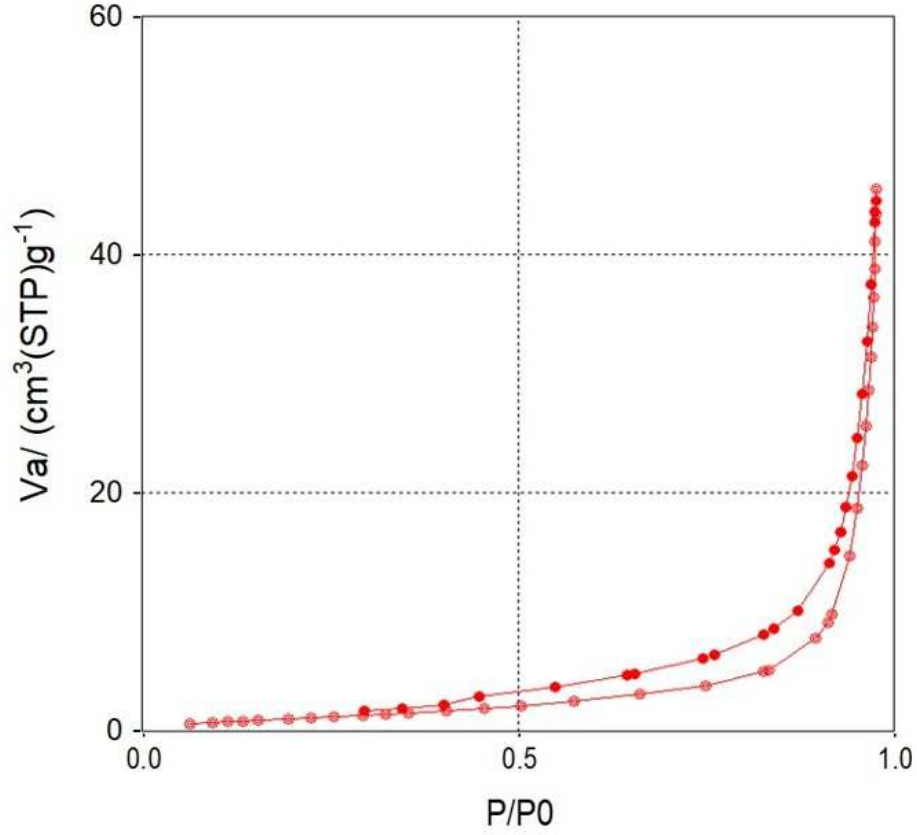


Figure 6: Isothermal adsorption and desorption curve of N₂ (BET) for SBT before calcination.

3.2. Nb and Nd-doped SBT

3.2.1. Dielectric properties

Figure 7 illustrates the variation of dielectric constant with frequency for the SBT doped with different percentages of Nb and Nd, respectively. According to figure 7 (a), the highest dielectric constant is attributed to the sample containing 0.3% Nb (S-0.3Nb), which is considered the optimal percentage for achieving the highest dielectric constant. The dielectric constant of this material at a frequency of 20 Hz is approximately 17000. Figure 7 (b) shows that under comparable conditions, 0.4% Nd-doped SBT (S-0.4Nd) exhibited the highest dielectric constant, which represents the optimal doping level for maximizing the dielectric response.

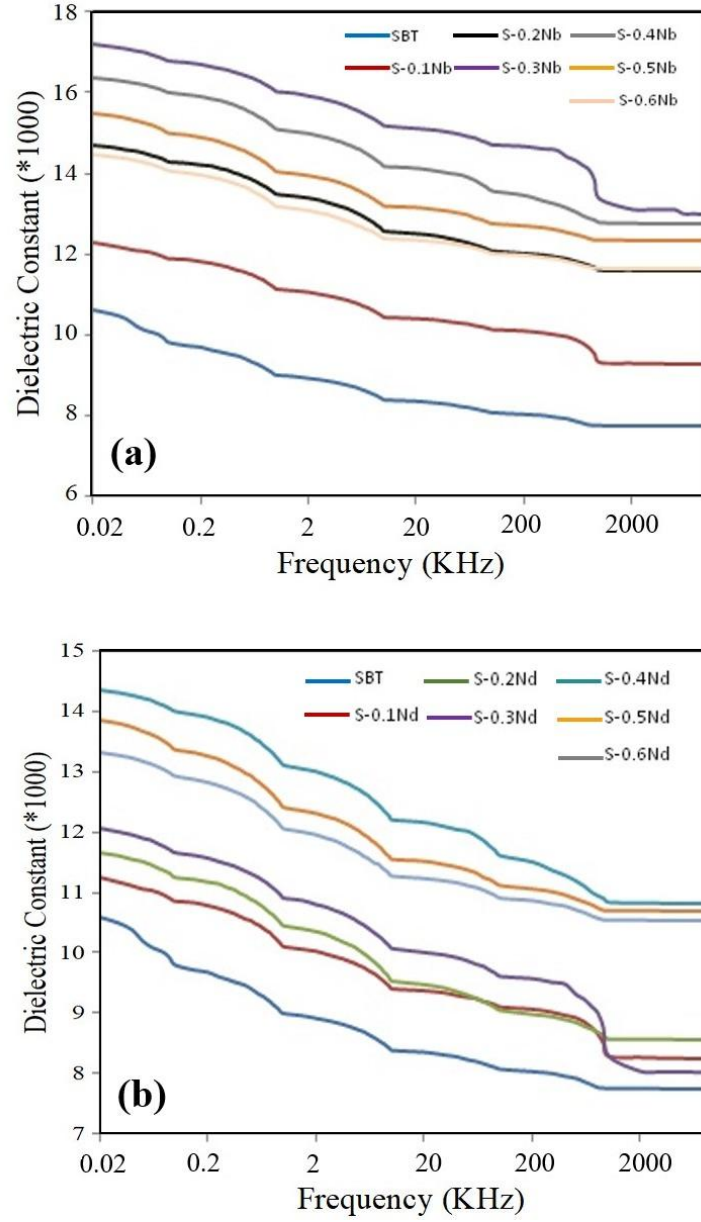


Figure 7: The curves of dielectric constant changes with frequency for the (a) Nb-doped, and (b) Nd-doped SBT.

Figure 8 (a) indicates that the dielectric constant rose to an ideal value of 0.3 at% in Nb-doped SBT. Following that, as expected, the dielectric constant decreases with increasing Nb element. This behavior is explained by a shift in the electrical conduction mechanism from electronic to conduction via cation vacancies at low Nb ratios [47]. Such behavior has also been observed in cerium-doped ceramics. Yasmin et al. [48] attributed this decrease to the limited solubility of cerium in BT, unit cell compression, and reduced polarization within the lattice. Figure 8 (b) indicates that Nd-doped SBT enhances the dielectric constant to an ideal value of 0.4 at%. Beyond this concentration, the

dielectric constant decreases with further Nd incorporation. This event was explained by the following: a small amount of Nd^{3+} ions are fully incorporated into the BT lattice, but the dielectric constant significantly decreases as Nd^{3+} is increased. Tetragonality decreases as the Nd^{3+} content rises, and these alterations are probably caused by high porosity [32, 49].

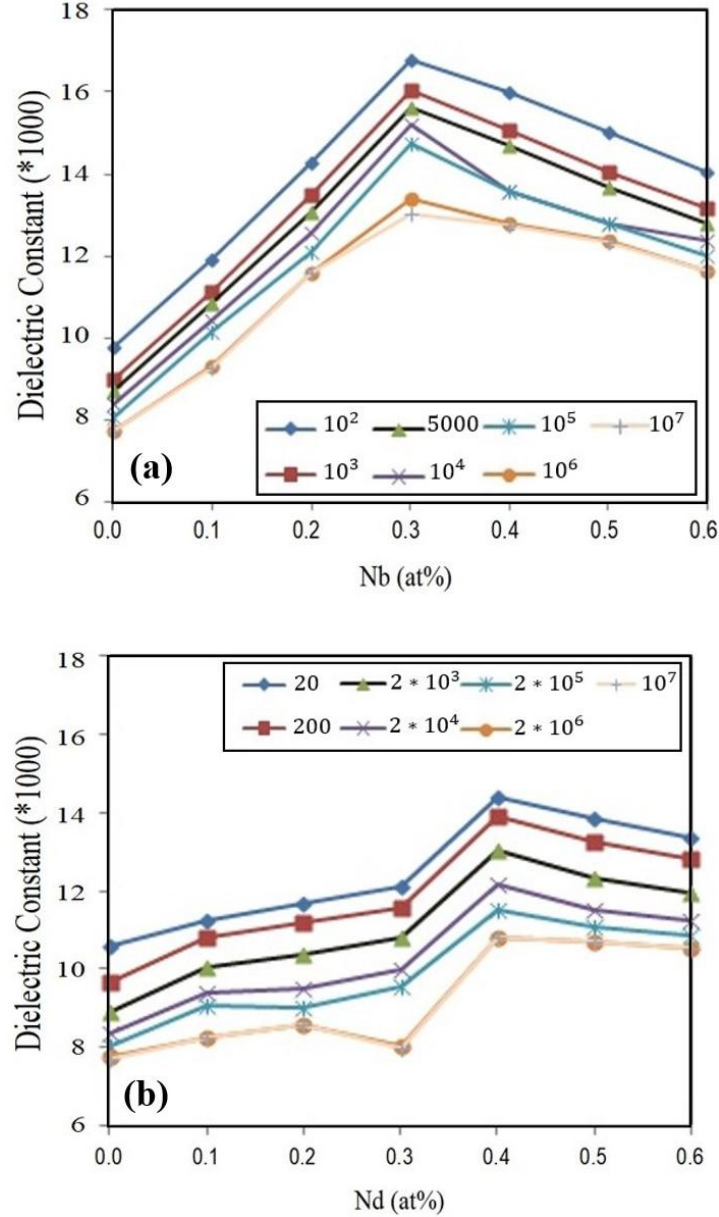


Figure 8: Variation in dielectric constant as a function of (a) Nb, and (b) Nd atomic percentage at various frequencies.

Figure 9 illustrates the variations in dielectric constant as a function of frequency for S-0.3Nb and S-0.4Nd, which represent optimal values for Nb and Nd. S-0.3Nb demonstrates the highest dielectric constant value. Nb appears to be

more efficacious than Nd in enhancing the dielectric constant. This phenomenon is due to the amphoteric characteristics of Nd, which displays varying behavior with Nb when substituted at different sites (Ti or Ba). Nb exclusively replaces Ti in the lattice and diminishes electrical resistance through an electronic conduction mechanism in minimal quantities [47].

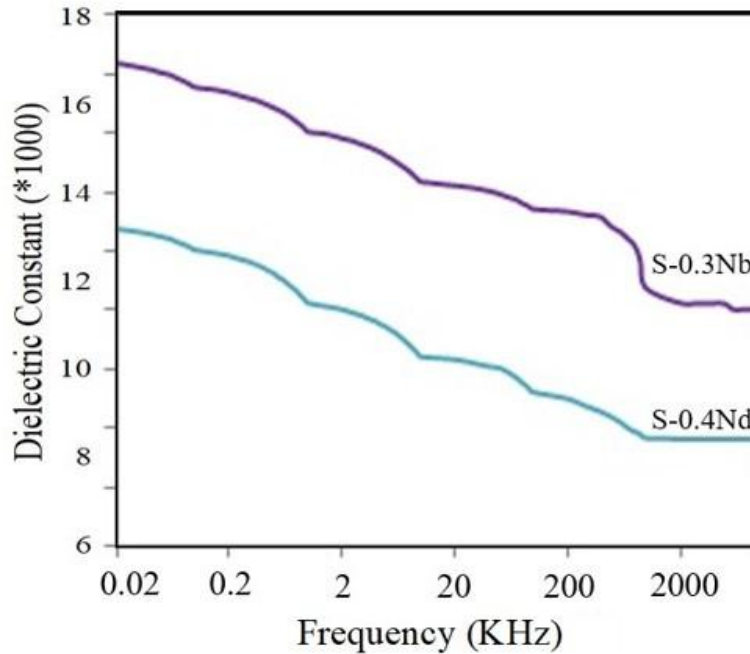


Figure 9: Dielectric constant as a function of frequency for S-0.3Nb and S-0.4Nd.

3.2.2. Microstructure and Zetasizer analysis

Figure 10 shows the SEM images and elemental studies by EDS spectrum of the S-0.3Nb powders. S-0.3Nb resulted in two distinct phases exhibiting different contrasts. The EDS spectrum in Figure 10 (d) indicates that the region depicted in Figure 10 (b) is rich in Nb. Due to Nb's lower atomic weight compared to Ba, this region exhibits a darker appearance. Conversely, the EDS spectrum for the brighter region (Figure 10 (e)) indicates that this area of the sample is abundant in Ba. Figure 10 (c) shows the EDS spectrum for the S-0.3Nb matrix, which demonstrates a high concentration of Ba and a uniform dispersion of Nb particles within the matrix. The dispersed particles exhibit spherical morphology and are uniformly distributed within the matrix phase. The S-0.3Nb Zetasizer analysis showed that the particle size is about 35 ± 5 nm, which is in good alignment with the SEM images of the same condition. The particle size of S-0.3Nb increased slightly compared to SBT, which is due to the incorporation of Nb particles with a larger ionic radius into the barium titanate structure.

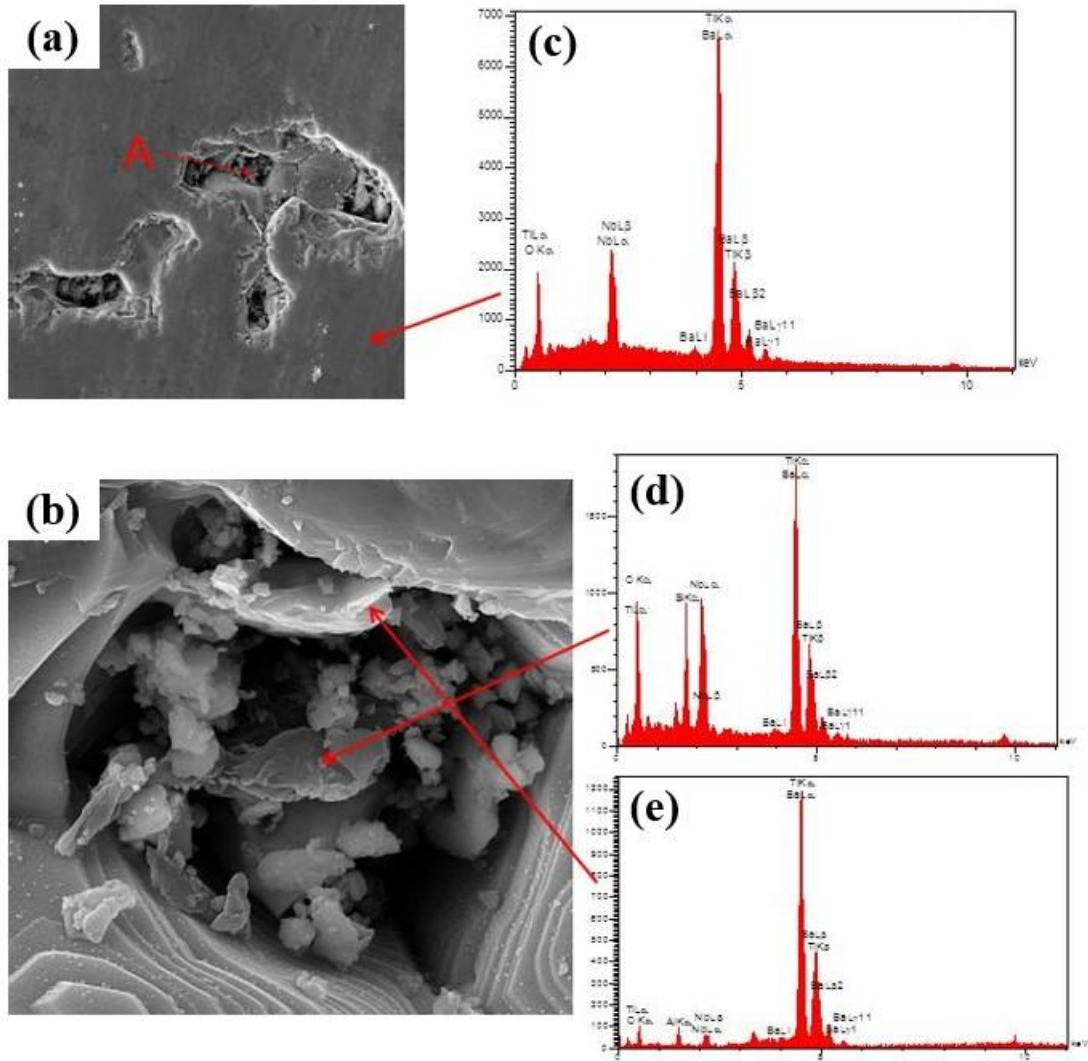


Figure 10: SEM images of S-0.3Nb are shown in (a, b), and the EDS spectrum of the matrix and selected points are presented in (c-e).

According to SEM images in Figure 11, S-0.4Nd created a coarser structure than sample S-0.3Nb (Figure 10), and particle dispersion in the matrix phase was also reduced. The EDS spectrum of the matrix and the area shown in Figure 10 also show that the amount of Ti is higher in the matrix phase, while the amount of Nd is low in both spectra, at 1 wt% in the matrix and 0.6 wt% in the area shown. Zetasizer analysis of sample S-0.4Nd revealed that the particle size in this sample is in the range of 33 ± 4 nm, which is an acceptable match with the SEM images of the same sample. The smaller particle size compared to SBT and S-0.3Nb samples is due to the smaller size of the Nd ion compared to the Ba and Nb ions, which, upon substitution in the lattice, causes lattice contraction and a reduction in particle size.

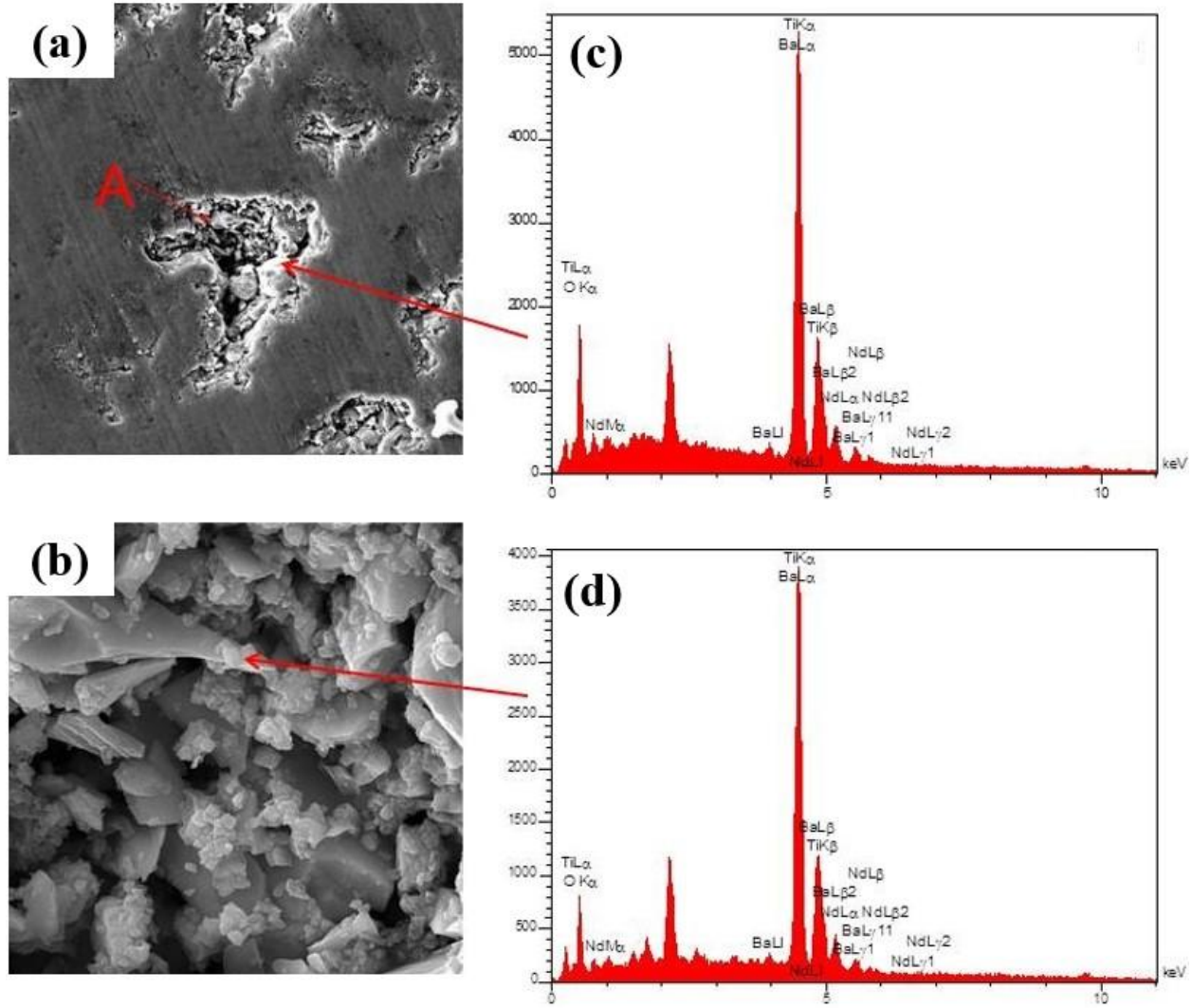


Figure 11: SEM images of S-0.4Nd are shown in (a, b), and EDS spectrum are presented in (c, d).

3.2.3. XRD analysis

Figure 12 shows the main peak range of the XRD pattern in SBT, S-0.3Nb, and S-0.4Nd samples. By doping Nb and Nd into the SBT powder, the main peak angle in BT shifts toward lower angles. This can be explained by Bragg's law. By substituting Nb and Nd with Ti, and due to the difference in the ionic radius of these atoms, and consequently a change in the plane spacing (d), the diffraction angle (θ) changes. The ionic radii of Nb and Nd ions are larger than that of the Ti ion. As a result, the lattice parameter and the d -spacing increase when these ions are used in place of titanium within the crystal structure. According to Bragg's law, an increase in the d -spacing leads to a decrease in the $\sin\theta$, causing the diffraction peaks to shift toward lower angles. The reason for the diffraction peaks of Nd appearing at lower angles compared to Nb is attributed to the larger ionic radius of Nd relative to Nb.

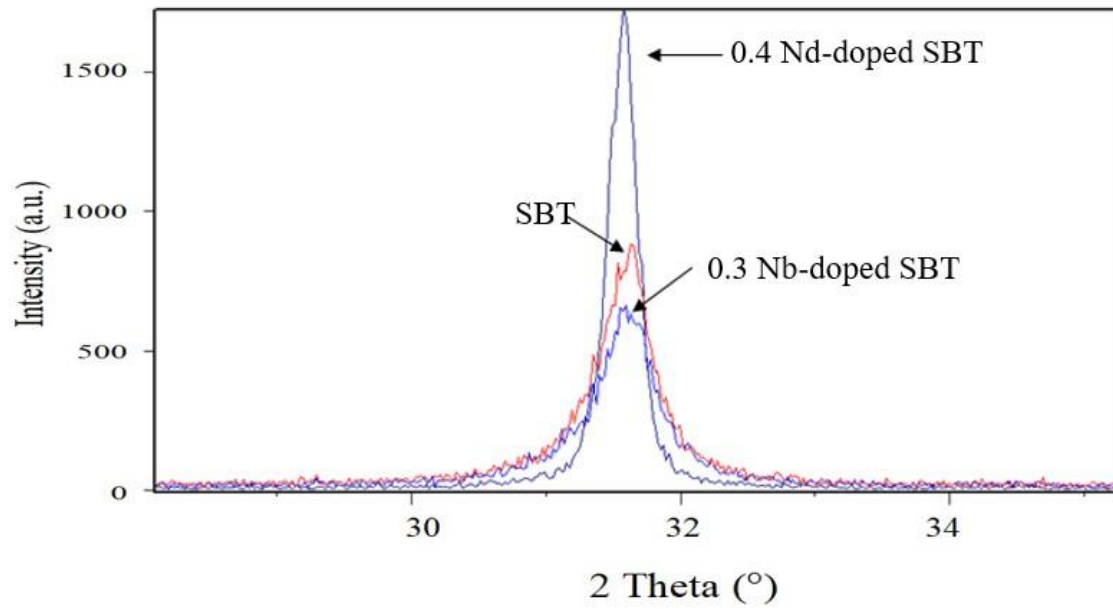


Figure 12: Main peak region of the XRD pattern for SBT, S-0.3Nb, and S-0.4Nd samples.

3.3. CBT powder study

Figure 13 presents the microstructural and EDS analyses of commercial barium titanate (CBT) in its as-received form. As shown in Figure 13 (b), the CBT particles are below 100 nm. According to the EDS spectrum obtained from the marked area, the material composition includes 30 wt% Ti and 33 wt% Ba, with no detectable impurities. These results confirm that the CBT powder is pure and within the nanometric scale.

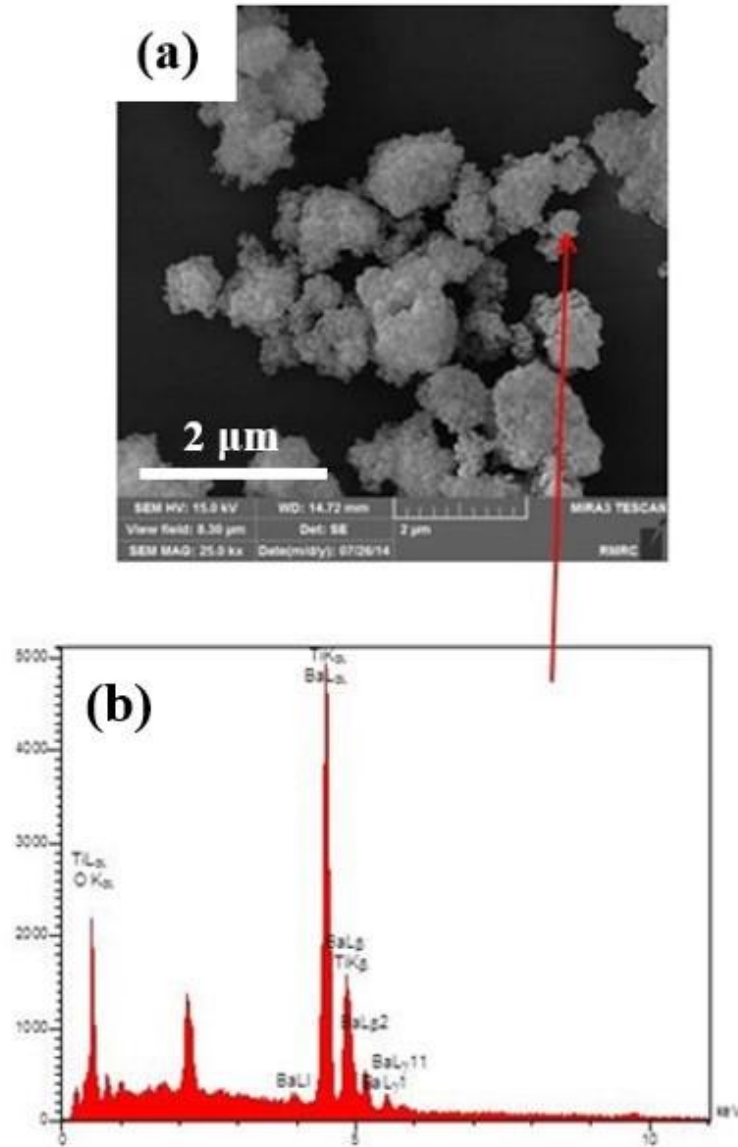


Figure 13: (a) SEM image and (b) EDS spectrum of the CBT.

3.3.1. Density and Porosity

Figure 14 presents the variation in apparent density, determined via the Archimedes method, as a function of Nb and Nd concentrations for both CBT and SBT samples. It is evident that samples derived from CBT powder consistently exhibit higher densities than those produced from SBT powder. In the case of Nb-doped CBT (C-Nb) samples, the density remains relatively unchanged; however, for Nb-doped SBT (S-Nb) samples, the incorporation of Nb results in a marked reduction in density. According to figure 14 (b), the Nd-doped CBT (C-Nd) exhibits higher densities compared to the Nd-doped SBT (S-Nd). Among the SBT samples, S-0.4Nd shows the lowest density, while S-0.2Nd

has the highest. In contrast, C-0.3Nd and C-0.4Nd represent the lowest and highest densities, respectively, among the CBT samples. As observed with Nb-doped specimens, Nd incorporation into SBT significantly reduces the density, whereas CBT samples remain relatively unaffected, whereas the density of the CBT remains relatively unaffected.

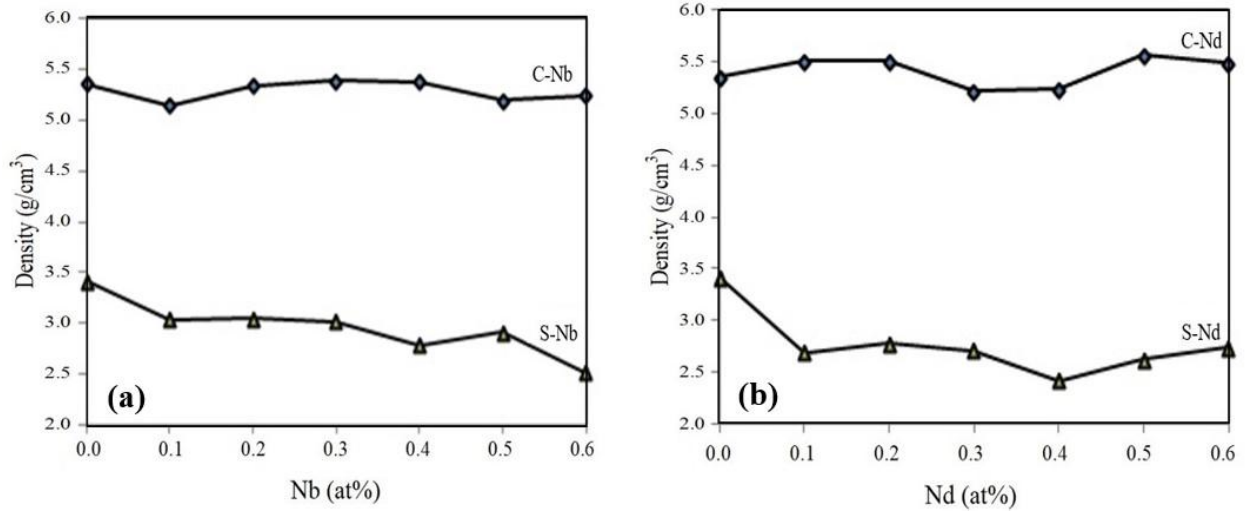


Figure 14: Variation in the apparent density of (a) S-Nb and C-Nb, and (b) S-Nd and C-Nd after sintering.

Figure 15 shows the open porosity percentage as a function of increasing atomic percentages of Nb and Nd for CBT and SBT samples. It can be observed that the overall trend in C-Nb samples indicates an increase in open porosity, whereas in S-Nb samples, the porosity tends to decrease with higher Nb content. Figure 15 (b) displays the open porosity percentage as a function of Nd doping for S-Nd and C-Nd samples. It is observed that in both S-0.1Nd and C-0.1Nd samples, the addition of Nd leads to a sharp decrease in open porosity, reaching its lowest value. Beyond this point, the overall trend shifts toward increasing porosity. Considering the available evidence, it is highly probable that the differences in open porosity trends between CBT and SBT samples upon doping with Nb stem from three main factors: first, variations in the initial powder characteristics such as particle size, specific surface area, and purity, which influence compaction and sintering behavior; second, the distinct roles of dopants (Nb and Nd) in generating lattice defects and secondary phases potentially enhancing densification in synthesized samples while increasing porosity in commercial ones; and third, differing structural responses to thermal conditions and dopant levels, which likely lead to opposing porosity outcomes depending on the powder type and doping concentration.

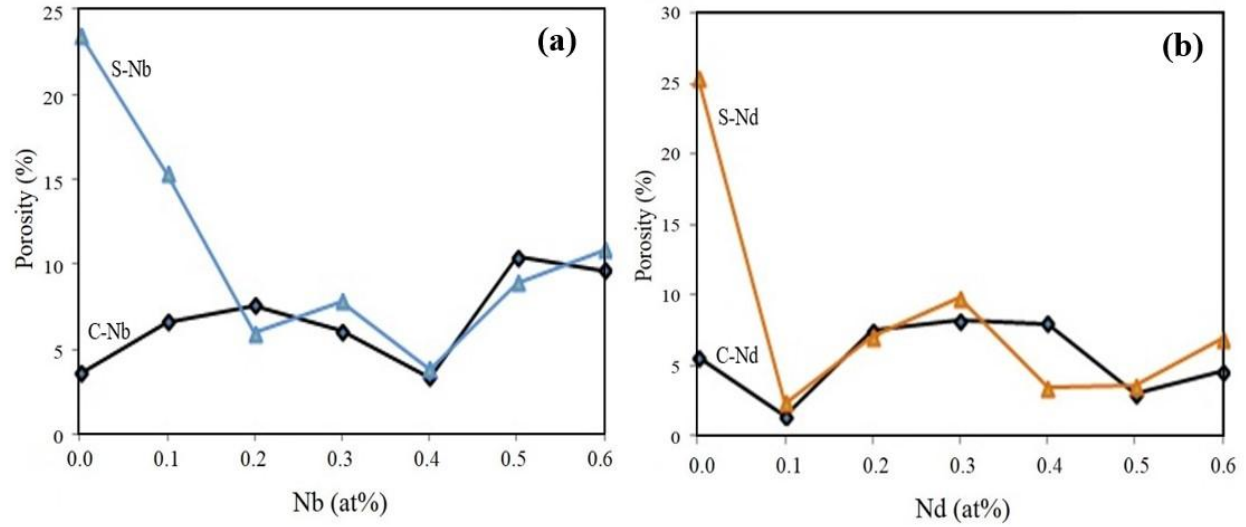


Figure 15: Variation in the open porosity of (a) S-Nb and C-Nb, and (b) S-Nd and C-Nd after sintering.

3.4. Doping effects on CBT

3.4.1. Dielectric properties

The dielectric constant of CBT and samples doped with various concentrations of Nb was measured, and the frequency-dependent behavior is illustrated in Figure 16. The highest dielectric constant was recorded for the sample containing 0.2% Nb (C-0.2Nb), indicating this concentration as optimal for achieving maximum dielectric performance. In comparison, the SBT sample with 0.3% Nb (S-0.3Nb) exhibited a peak dielectric constant of approximately 17000, while the CBT sample reached around 18000 with a lower dopant level. This suggests that the properties of the synthesized powder are comparable to those of the commercial one, as the difference in dielectric constant between the two materials is relatively small. Figure 16 (b) illustrates the relationship between the dielectric constant and Nb, enabling a comparative analysis of dielectric behavior as a function of Nb.

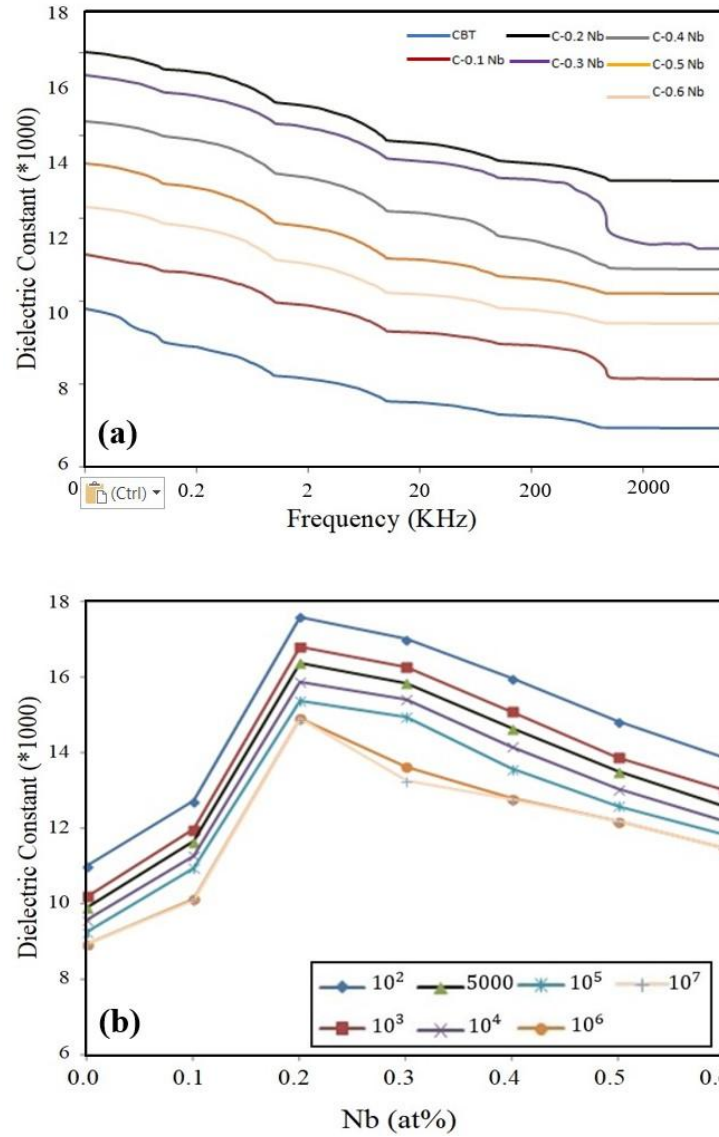


Figure 16: Variation of the dielectric constant as a function of (a) frequency, and (b) Nb-doped CBT.

Figure 17 (a) presents the dielectric constant versus frequency for the CBT sample and those doped with various concentrations of Nd. As shown in the figure, the highest dielectric constant corresponds to the sample containing 0.3 at.% Nd (C-0.3Nd), which is considered the optimal concentration for achieving maximum dielectric performance. Figure 17 (b) further demonstrates that the dielectric constant increases with Nd-doped CBT up to the optimal level of 0.3 at.%. Beyond this point, as expected, the dielectric constant decreases with further Nd doping, which is attributed to microstructural changes in the BT matrix caused by the incorporation of Nd. According to Yao et al. [40], the introduction of Nd^{3+} ions restricts grain growth in BT, resulting in a reduced slope of dielectric enhancement with increasing Nd content up to 0.2 at.%. Some researchers associate this phenomenon with increased porosity and reduced

tetragonality [47]. However, at 0.3 at.% Nd, the highest dielectric constant is achieved, likely due to grain growth facilitated by the complete solubility of low Nd concentrations within the lattice. Nd concentrations exceeding 0.3 at.% lead to a sharp decline in dielectric constant, which is attributed to high porosity and diminished tetragonality.

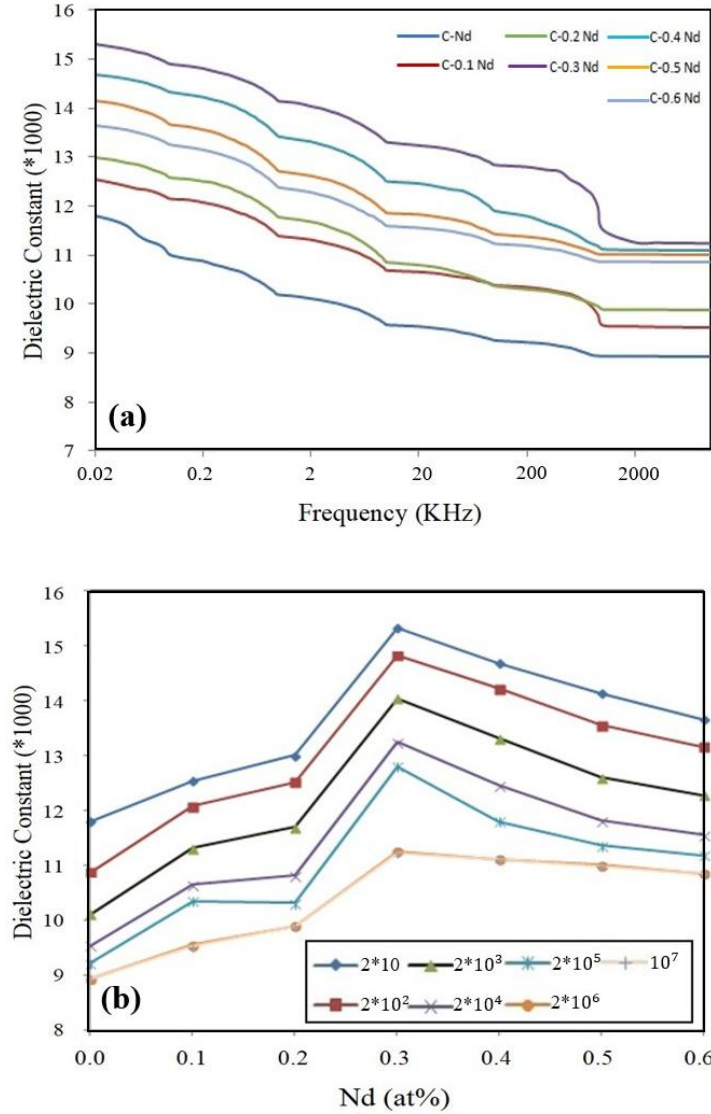


Figure 17: Variation of the dielectric constant as a function of (a) frequency, and (b) Nd-doped CBT.

3.4.2. Microstructure

Figure 18 illustrates the microstructural features and EDS spectrum of the C-0.2Nb sample. The Nb particles are uniformly distributed within the CBT matrix, as evidenced by the EDS analysis of the matrix phase (Figure 18 (c)), which reveals a Nb content of 9.5 wt%. This value slightly exceeds the 6 wt% Nb concentration observed in the region

depicted in Figure 18 (d), suggesting effective dispersion. The absence of additive agglomeration further confirms that mechanical alloying is a highly efficient method for incorporating secondary phases into the CBT matrix. Despite the nanoscale nature of the initial CBT powder, grain growth appears to have occurred during the sintering process following the addition of the secondary phase. This has resulted in particle sizes exceeding 100 nm. Nevertheless, nanoscale dispersed particles remain visible, as shown in Figure 18 (b), indicating partial retention of the nanostructure.

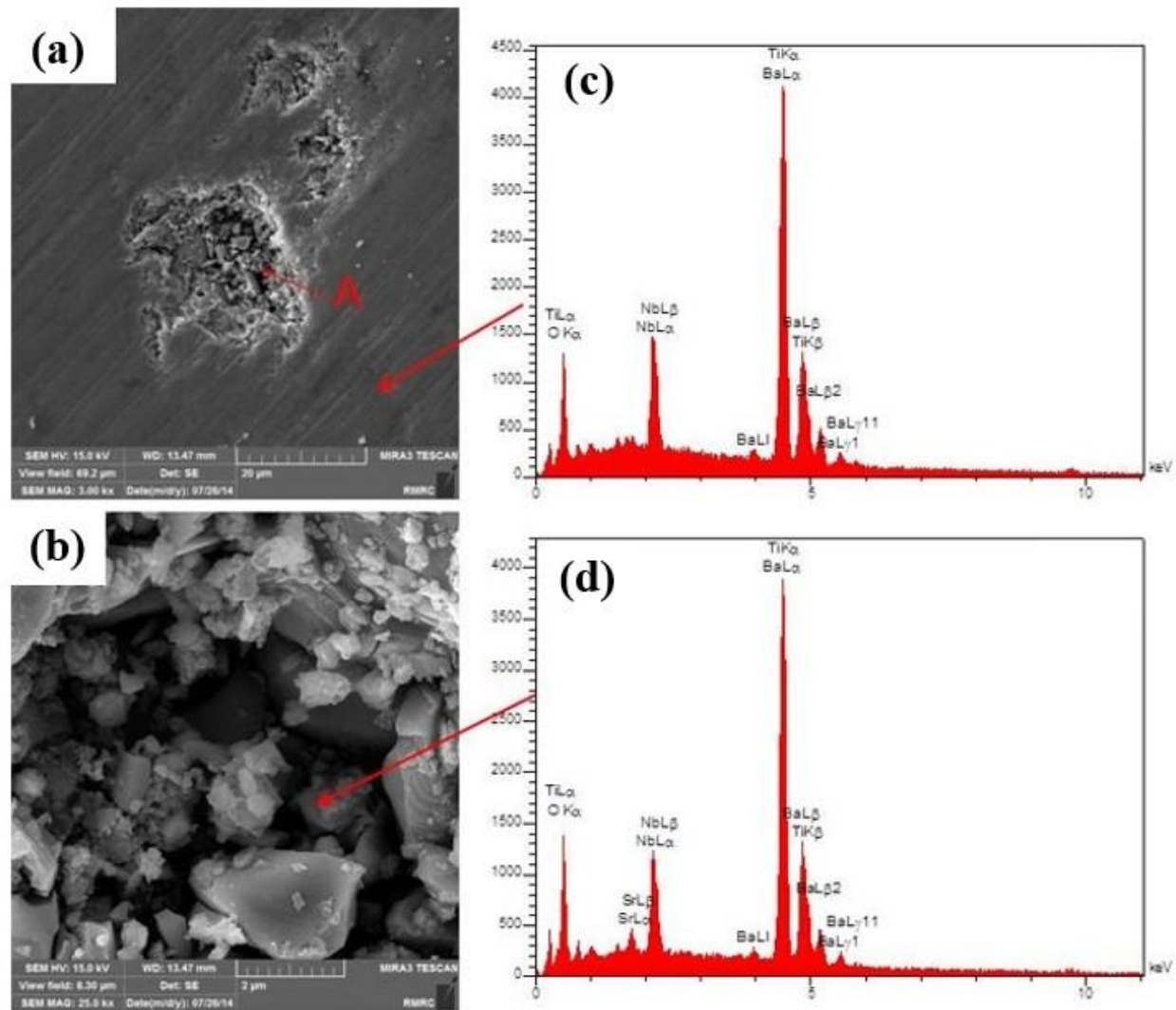


Figure 18: SEM images of C-0.2Nb are shown in (a, b), and EDS spectra are presented in (c, d).

Figure 19 demonstrates the effect of incorporating 0.3 at.% Nd-doped CBT (C-0.3Nd). The Nd content dispersed within the CBT is measured at 1.36 wt%, which is slightly higher than the 0.71 wt% observed in the region highlighted

in Figure 19 (b). As evident from the EDS in Figures 19 (c) and 19 (d), the matrix phase exhibits enrichment in Ti, Ba, and Nd elements. Conversely, the oxygen concentration in the region shown in Figure 19 (b) is higher than that of the matrix, suggesting a lower density of metal-oxygen bonding in the matrix and a greater presence of metal ions. This implies that the structural integrity of Nd and CBT is better preserved in the highlighted region. Furthermore, the data indicate that Nd is not uniformly distributed across the matrix surface.

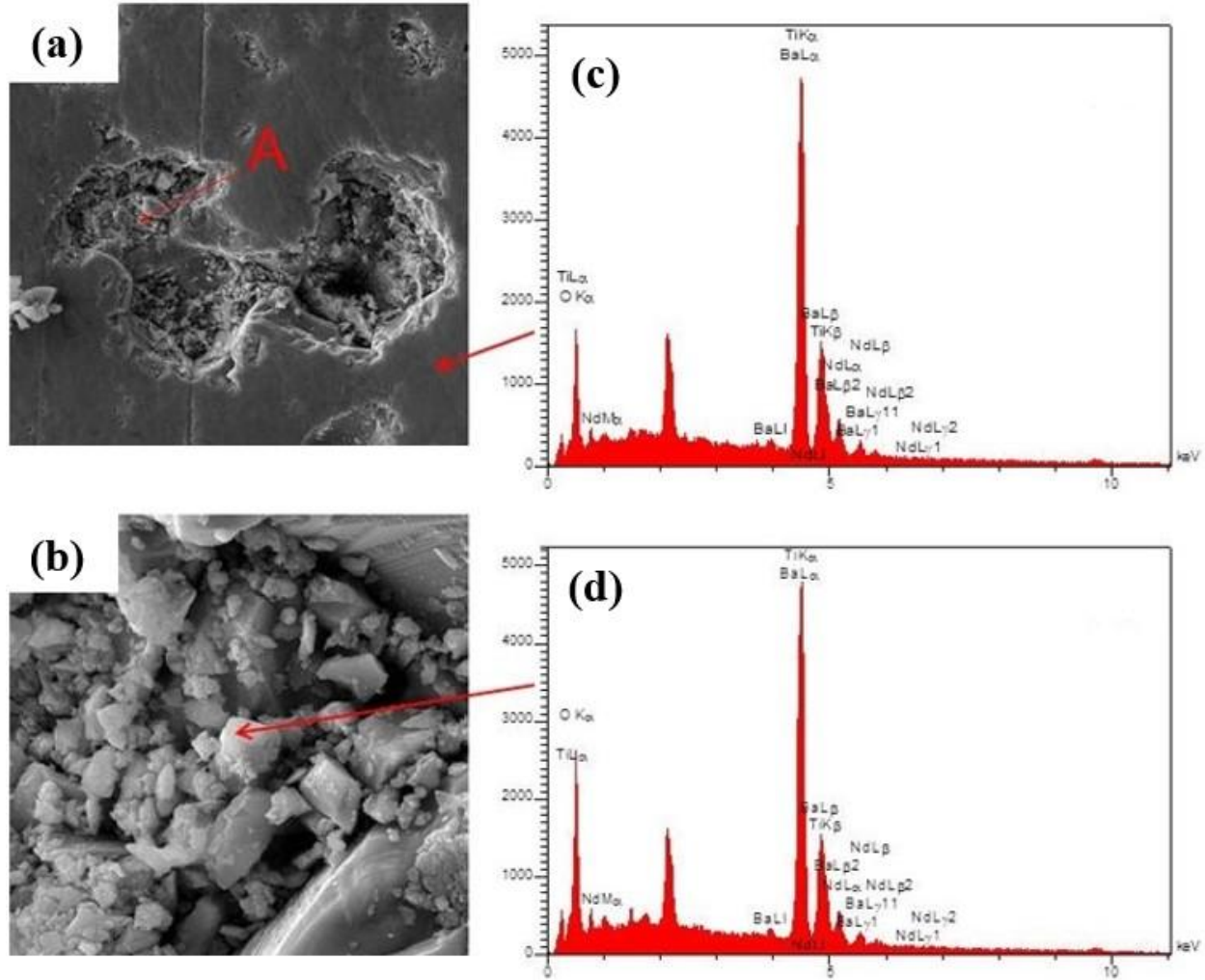


Figure 19: SEM images of C-0.3Nd are shown in (a, b), and EDS spectra are presented in (c, d).

4. Conclusion

In this study, nanostructured barium titanate powder was successfully synthesized via mechanical milling and thoroughly characterized. XRD analysis confirmed the formation of a pure cubic phase after 15 h of milling, with a crystallite size of approximately 32 nm. STA (TGA/DTA) results demonstrated thermal stability up to 1200 °C without

any phase transitions, supporting the structural integrity of the SBT. SEM and Zetasizer analyses revealed particle sizes in the nanometer range ($\sim 35 \pm 5$ nm), with some agglomeration. FT-IR spectra confirmed the presence of Ti–O and O–Ti–O bonds, validating the formation of the titanate network, while BET analysis indicated low specific surface area and minimal porosity, consistent with a compact powder morphology.

The effects of Nb and Nd doping on the structural and dielectric properties of SBT ceramics were investigated. Optimal doping levels were identified as 0.3 at.% for Nb and 0.4 at.% for Nd, with the S-0.3Nb exhibiting the highest dielectric constant ($\sim 17,000$ at 20 Hz). Beyond these concentrations, a decline in dielectric performance was observed, attributed to changes in conduction mechanisms and reduced lattice polarization. Microstructural analyses confirmed uniform dispersion of Nb particles, while Nd-doped samples showed coarser morphology and reduced homogeneity. Zetasizer results supported these findings, with particle sizes of 40 ± 5 nm for S-0.3Nb and 33 ± 4 nm for S-0.4Nd. XRD peak shifts toward lower angles upon doping were consistent with Bragg's law and the substitution of larger Nb and Nd ions for Ti, leading to increased lattice parameters.

Additionally, the structural, dielectric, and microstructural characteristics of CBT and its doped variants were evaluated. CBT powder exhibited high purity and nanoscale particle size (< 100 nm), confirmed by SEM and EDS analyses. CBT-based samples consistently showed higher densities and lower porosity compared to synthesized SBT, indicating superior compaction and sintering behavior. While Nb doping had minimal impact on CBT density, Nd doping led to a slight increase, contrasting with the significant density reduction observed in SBT samples.

Dielectric measurements identified 0.2 at.% Nb and 0.3 at.% Nd as optimal doping levels for CBT, yielding dielectric constants of approximately 18000 surpassing those of similarly doped SBT samples. Microstructural evaluations revealed uniform dopant dispersion, limited agglomeration, and partial retention of nanostructure post-sintering. The observed differences in dielectric behavior and porosity between CBT and SBT are attributed to variations in powder characteristics, dopant interactions, and lattice responses. Overall, mechanical milling proved to be an effective method for synthesizing nanostructured SBT with stable thermal and structural properties. Nb doping, in particular, demonstrated superior performance in enhancing dielectric properties, making it a promising strategy for optimizing barium titanate-based ceramics for advanced electronic applications.

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References

- [1] A. Debnath, S. Lalwani, S. Singh, Improvement in ferroelectric properties of BaTiO₃ film by Mn/Sr doping for non-volatile memory applications, *Micro Nanostruct.* 171 (2022) 207-212. <https://doi.org/10.1016/j.micrna.2022.207421>.
- [2] L. Betancourt-Cantera, F. Sánchez-De Jesús, A. Bolarín-Miró, A. Reyes-Montero, C. Cortes-Escobedo, Synergistic effect of high-energy ball milling and Nb doping on the multiferroicity of BaTiO₃, *Journal of Alloys and Compounds.* 1022 (2025) 1799-1805. <https://doi.org/10.1016/j.jallcom.2025.179930>.
- [3] D. Hamdi, D. Talantikite-Touati, A. Manseri, A. Khodja, A. Souici, Role of Nd doping on the structural, morphological, and optical properties of BaTiO₃ nanoparticles hydrothermally synthesized, *Optical Materials.* 152 (12) (2024) 115387. <https://doi.org/10.1016/j.optmat.2024.115387>.
- [4] J. Shi, R. Dong, J. He, D. Wu, W. Tian, X. Liu, Regulating ferroelectric polarization and dielectric properties of BT-based lead-free ceramics, *Journal of Alloys and Compounds.* 933 (2023) 167746. <https://doi.org/10.1016/j.jallcom.2022.167746>.
- [5] D. Hu, et al., Optimization the energy density and efficiency of BaTiO₃-based ceramics for capacitor applications, *Chemical Engineering Journal.* 409 (2) (2021) 127-135. <https://doi.org/10.1016/j.cej.2020.127375>.
- [6] Y. Shuangjuan, D. Guixia, G. Ruohan, W. Di, Research status and application of BaTiO₃-based positive temperature coefficient thermal ceramics, *Powder of Metallurgy Technology.* 41 (2) (2023) 167–174, 186. <https://dx.doi.org/10.19591/j.cnki.cn11-1974/tf.2020080010>.
- [7] M. Nasui, et al., New approach for oriented BaTiO₃ thin films with piezoelectric properties through chemical synthesis, *Journal of Alloys and Compounds.* 18 (2) (2025) 164-172. <https://doi.org/10.1016/j.jallcom.2025.182008>.
- [8] B. Szafraniak, Ł. Fuśnik, J. Xu, F. Gao, A. Brudnik, A. Rydosz, Semiconducting metal oxides: SrTiO₃, BaTiO₃ and BaSrTiO₃ in gas-sensing applications: A review, *Coatings.* 11 (2) (2021) 185. <https://doi.org/10.3390/coatings11020185>.
- [9] P. Jacobs, W. Brink, R. Reddy, A review of recent developments and applications of high-permittivity dielectric shimming in magnetic resonance, *NMR in Biomedicine.* 37 (4) (2024) 5094. <https://doi.org/10.1002/nbm.5094>.
- [10] A. Prasatkhetragarn, T. Sareein, N. Triamnak, R. Yimnirun, Dielectric and ferroelectric properties of modified-BaTiO₃ lead-free ceramics prepared by solid solution method, *Ferroelectrics.* 586 (1) (2022) 224–241. <https://doi.org/10.1080/00150193.2021.2014274>.
- [11] D. Kuzenko, Critical temperature below the Curie temperature of ferroelectric ceramics PZT, *Journal of Advanced Dielectrics.* 11 (1) (2021) 215–221. <https://doi.org/10.1142/S2010135X21500065>.
- [12] F.Z. Krimech, S. Sayouri, Structure and dielectric behavior of Cu-doped BaTiO₃ ceramics, *Materials. Today Proc.* 30 (2020) 909–917. <https://doi.org/10.1016/j.matpr.2020.04.349>.

- [13] L. Duta, V. Grumezescu, The effect of doping on the electrical and dielectric properties of hydroxyapatite for medical applications: from powders to thin films, *Materials*. 17 (3) (2024) 640. <https://doi.org/10.3390/ma17030640>.
- [14] Y. Adediji, A. Adeyinka, D. Yahya, O. Mbelu, A review of energy storage applications of lead-free BaTiO₃-based dielectric ceramic capacitors, *Energy, Ecology and Environment*. 8 (5) (2023) 401–419. <https://doi.org/10.1007/s40974-023-00286-5>.
- [15] S. Boumous, et al., Electrical and ferroelectric characterization of BaTiO₃ ceramics, dielectric properties and hysteresis behavior, *Journal of Materials Science: Materials in Electronics*. 36 (22) (2025) 1396. <https://doi.org/10.1007/s10854-025-15467-7>.
- [16] S.H. Choi, et al., Enhancement of dielectric properties and microstructure control of BaTiO₃ by seed-induced solid-state synthesis, *Ceramics International*. 49 (11) (2023) 17921–17929. <https://doi.org/10.1016/j.ceramint.2023.02.159>.
- [17] A. Gautam, B.P. Choudhary, M. Kumar, G. Singh, *Manufacturing Methods for Piezoelectric Ceramic Materials*, in: *Piezoelectric Materials*, Jenny Stanford Publishing, Singapore, 2025.
- [18] Y. Iriani, K. Kusumandari, U. Ulfa, D.K. Sandi, Synthesis of BaTiO₃ ceramics using co-precipitation and solid-state reaction method with sintering temperature variation, in *Materials Science Forum*. 1064 (2022) 89–97. <https://doi.org/10.4028/p-de85ci>.
- [19] I. Amaechi, et al., Ultrafast microwave-assisted hydrothermal synthesis and photocatalytic behaviour of ferroelectric Fe³⁺-doped BaTiO₃ nanoparticles under simulated sunlight, *Catalysis Today*. 360 (2021) 90–98. <https://doi.org/10.1016/j.cattod.2019.07.021>.
- [20] J. Zhang, Y. Wu, D. Fu, X. Wang, BaTiO₃ thin films for ferroelectrics and optics synthesized via sol-gel, *Surfaces and Interfaces*. 58 (2025) 105836. <https://doi.org/10.1016/j.surfin.2025.105836>.
- [21] H. El Emam, A. Abdelwahab, S. El-Dek, W. El Roubay, Performance of Ni-doped BaTiO₃ hollow porous spheres supported reduced graphene oxide as an efficient bifunctional electrocatalyst for oxygen evolution reaction and oxygen reduction reaction, *Applied Surface Science*. 618 (11) (2023) 156–163. <https://doi.org/10.1016/j.apsusc.2023.156599>.
- [22] G. da Silva, C. Perdomo, R.F. Klein-Gunnawiek, R. Kiminami, Crystallization kinetic and structural characterization of lead-free piezoelectric 0.94 (Na_{0.5}Bi_{0.5})TiO₃–0.06BaTiO₃ by polymeric precursor method, *Materials Chemistry and Physics*. 277 (3) (2022) 125494. <https://doi.org/10.1016/j.matchemphys.2021.125494>.
- [23] R. Varghese, S. M. Jose, J. Lakshmi, J. Thomas, Investigation of the structural, optical, electrical, and photovoltaic characteristics of nanostructured Ce-doped BaTiO₃ by a modified combustion method, *Optical and Quantum Electronics*. 56 (2024) 118. <https://doi.org/10.1007/s11082-023-05686-9>.
- [24] X. Wang, Y. Fan, G. Luo, R. Tu, Q. Shen, L. Zhang, Effect of yttrium (Y) substitution on the structure and dielectric properties of BaTiO₃, *Ceramics International*. 49 (2023) 9042–9051. <https://doi.org/10.1016/j.ceramint.2022.11.060>.
- [25] M.T. Buscaglia, M. Bassoli, V. Buscaglia, R. Vormberg, Solid-state synthesis of nanocrystalline BaTiO₃: reaction kinetics and powder properties, *Journal of the American Ceramic Society. Soc.* 91 (2008) 2862–2869. <https://doi.org/10.1111/j.1551-2916.2008.02576.x>.
- [26] A.H. Reshak, M.R. Roknabadi, M. Mollaei, M. Zaboli, M. Bedhani, Influence of Mechanical Alloying on Dielectric Features of Ferroelectric BaTiO₃ Microcrystals, *International Journal of Electrochemical Science*. 9 (2014) 720–727. [https://doi.org/10.1016/S1452-3981\(23\)07752-0](https://doi.org/10.1016/S1452-3981(23)07752-0).
- [27] Y. Chen, H. Ye, X. Wang, Y. Li, X. Yao, Grain size effects on the electric and mechanical properties of submicro BaTiO₃ ceramics, *Journal of the European Ceramic Society*. 40 (2020) 391–400. <https://doi.org/10.1016/j.jeurceramsoc.2019.09.033>.
- [28] P. Zheng, J. Zhang, Y. Tan, C. Wang, Grain-size effects on dielectric and piezoelectric properties of poled BaTiO₃ ceramics, *Acta Materialia*. 60 (2012) 5022–5030. <https://doi.org/10.1016/j.actamat.2012.06.015>.

- [29] C. Chang, C. Huang, Y. Wu, C. Su, C. Huang, Synthesis of submicron BaTiO₃ particles by modified solid-state reaction method, *Journal of alloys and Compounds*. 495 (2010) 108–112. <https://doi.org/10.1016/j.jallcom.2010.01.096>.
- [30] M. Niederberger and N. Pinna, *Metal oxide nanoparticles in organic solvents: synthesis, formation, assembly and application*. Springer, 2009.
- [31] H. Xu, Vacancy engineering for high tetragonal BaTiO₃ synthesized by solid-state approaches, *Powder Technology*. 44 (3) (2024) 119–124. <https://doi.org/10.1016/j.powtec.2024.119955>.
- [32] W. Zhang, L. Cao, W. Wang, G. Su, W. Liu, Effects of neodymium doping on dielectric and optical properties of Ba(Nd_xTi_{1.005}O₃) ceramics, *Ceramics–Silikáty*. 57 (2) (2013) 146–150.
- [33] J. Wang, First-principles calculations of electronic and optical properties of A and B site substituted BaTiO₃, *Vacuum*. 193 (12) (2021) 110530. <https://doi.org/10.1016/j.vacuum.2021.110530>.
- [34] M. Tihtih, et al., Role of A-site (Sr), B-site (Y), and A, B sites (Sr, Y) substitution in lead-free BaTiO₃ ceramic compounds: Structural, optical, microstructure, mechanical, and thermal conductivity properties, *Ceramics International*. 49 (2) (2023) 1947–1959. <https://doi.org/10.1016/j.ceramint.2022.09.160>.
- [35] A. Naz, et al., Investigation of Ce doped BaTiO₃ compound for optoelectronic devices, *Physica B: Condensed Matter*. 631 (3) (2022) 413714. <https://doi.org/10.1016/j.physb.2022.413714>.
- [36] T. Nakagawa, M. Menelaou, M. Vrankić, Showcasing the structure and properties of lanthanide-doped BaTiO₃, *Advanced Physics Research*. (2025) 256–264. <https://doi.org/10.1002/apxr.202500006>.
- [37] Y. Huang, C. Zhao, S. Zhong, J. Wu, Highly tunable multifunctional BaTiO₃-based ferroelectrics via site selective doping strategy, *Acta Materialia*. 209 (2021) 1167–1175. <https://doi.org/10.1016/j.actamat.2021.116792>.
- [38] I. Velasco-Davalos, A. Ruediger, J. Cruz-Rivera, C. Gomez-Yanez, Mechanical niobium doping in barium titanate electroceramics, *Journal of Alloys and Compounds*. 581 (2013) 56–58. <https://doi.org/10.1016/j.jallcom.2013.06.187>.
- [39] S. Sasikumar, T. Thirumalaisamy, S. Saravanakumar, S. Asath Bahadur, D. Sivaganesh, I. Shameem Banu, Effect of neodymium doping in BaTiO₃ ceramics on structural and ferroelectric properties, *Journal of Materials Science: Materials in Electronics*. 31 (2) (2020) 1535–1546. <https://doi.org/10.1007/s10854-019-02670-6>.
- [40] Z. Yao, Structure and dielectric behavior of Nd-doped BaTiO₃ perovskites, *Materials Chemistry and Physics*. 109 (2–3) (2008) 475–481. <https://doi.org/10.1016/j.matchemphys.2007.12.019>.
- [41] R. Sagar, S. Madolappa, R. Raibagkar, Electrical, dielectric and pyroelectric behavior of neodymium substituted barium zirconium titanate, *Solid State Sciences*. 14 (2) (2012) 211–215. <https://doi.org/10.1016/j.solidstatesciences.2011.11.006>.
- [42] W. Zhang, L. Cao, G. Su, W. Liu, Influence of microstructure on dielectric properties of Nd-doped barium titanate synthesized by hydrothermal method, *Journal of Materials Science: Materials in Electronics*. 24 (6) (2013) 1801–1806. <https://doi.org/10.1007/s10854-012-1015-z>.
- [43] M. Ganguly, S. Rout, P. Barhai, C. Ahn, I. Kim, Structural, electrical, and optical properties of (Ba_{1-x}Nd_{2x/3})TiO₃ ceramics, *Phase Transitions*. 87 (2) (2014) 157–174. <https://doi.org/10.1080/01411594.2013.798411>.
- [44] F. Wang, et al., Modification of BaTiO₃ for diversified applications by single Nd element substitution with wide doping range, *Journal of Materials Science: Materials in Electronics*. 34 (12) (2023) 1062–1070. <https://doi.org/10.1007/s10854-023-10482-y>.
- [45] R. Upadhyay, A. Argekar, R. Deshmukh, Characterization, dielectric and electrical behaviour of BaTiO₃ nanoparticles prepared via titanium (IV) triethanolaminato isopropoxide and hydrated barium hydroxide, *Bulletin of Materials Science*. 37 (3) (2014) 481–489. <https://doi.org/10.1007/s12034-014-0690-1>.
- [46] A. Haroon, P. Rai, I. Uddin, Synthesis, characterization and dielectric properties of BaTiO₃ nanoparticles, *International Journal of Nanoscience*. 19 (1) (2020) 195–203. <https://doi.org/10.1142/S0219581X19500017>.
- [47] V. Paunovic, V. Mitic, M. Djordjevic, Z. Prijic, Niobium doping effect on BaTiO₃ structure and dielectric properties, *Ceramics International*. 46 (6) (2020) 8154–8164. <https://doi.org/10.1016/j.ceramint.2019.12.043>.

- [48] T. Dechakupt, J. Tangsritrakul, P. Ketsuwan, R. Yimmirun, Microstructure and electrical properties of niobium doped barium titanate ceramics, *Ferroelectrics*. 415 (1) (2011) 141–148.
<https://doi.org/10.1080/00150193.2011.577386>.
- [49] V. Paunović, M. Marjanović, M. Đorđević, V. Mitić, L. Kocić, Electrical characteristics of Nb doped BaTiO₃ ceramics, in: *Proceedings of the III Advanced Ceramics and Applications Conference*, Springer, 34 (2) (2015) 143–158. https://doi.org/10.2991/978-94-6239-157-4_10.