Examination of the influence of cobalt substitution on the properties of barium titanate ceramics

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Abstract

Cobalt (Co) doped Barium titanate (BaTiO₃) powders, with Co concentration (0,5 and 10 mol%), are synthesized by the sol-gel technique and characterized by Thermogravimetric analysis (TGA), and Differential thermal analysis (DTA), X-Ray diffraction (XRD), Fourier Transform Infrared (FT-IR) and scanning electron microscopy (SEM). X-ray diffraction (XRD) patterns of the obtained powders, calcined at a relatively low temperature (1000 °C/3 h), found their crystallization in the pure perovskite structure without the appearance of secondary phases. XRD results reveal that the Co decreases the lattice parameters, the volume of the unit cell and the crystallite size of BaTiO₃. The investigations carried out by FT-IR spectroscopy allow the investigation of the substitution procedure behavior associated to the Co incorporation into BaTiO₃ lattice. The evolution of the physical parameters as functions of the dopant content have been examined based on XRD and FT-IR results. Furthermore, the morphology and the shape variation of particle size were studied through SEM.

Keywords: barium titanate, co-doping, ferroelectrics, synthesis, XRD, SEM

Kulcsszavak: bárium-titanát, co-dopping, ferroelektromos, szintézis, XRD, SEM

1. Introduction

Recently, the research progression in the area of technical ceramics [1]–[7] has drawn great attention [4], [8]–[17]. Perovskite ferroelectric materials (ABO₃) have had great interest due to the presence of a ferroelectric phase, their relatively simple structure which can allow theoretical interpretations and finally the feasibility of modifying their physical properties by numerous ionic substitutions. In addition, these materials exhibit high-physical performance, dielectric, electro-optical, and electronic properties [18]–[23], which make the materials widely used in various applications in different areas.

Barium titanate (BaTiO₃) is one of the most important perovskite materials. It is a ferroelectric material, with piezoelectric properties and photorefractive effect. As a solid, it has five phases ranging from low to high temperature: rhombohedral, orthorhombic, tetragonal, cubic and hexagonal crystal structure. Indeed, all of the crystal structures show the ferroelectric effect except cubic structure. It has the appearance of a transparent powder or white crystals. It is soluble in concentrated sulfuric acid perhaps not in water.

Interesting and exotic properties are theoretically expected in doped BaTiO₃ like ferromagnetism at room temperature enhanced dielectric properties etc. [24]. Moreover the

synthesis technique also influences the level of doping and physical properties. Based on this fact, several studies are made adopting various synthesis methods such as solid state ceramic technique, laser ablation, sol-gel and chemical routes etc. [25]–[27]. In response to these reports, various types of doping have been attempted for BaTiO₃ including Fe, Mn, Co etc. [24]–[28].

In the present paper, Co-doped BaTiO₃ (BTCox) ceramics, with x = (0, 5 and 10%) were prepared using the sol-gel technique, the choice of this method of processing was based on its various advantages, low processing temperature, high purity, homogeneity and an excellent control of the stoichiometry of the products [29]. We have investigated the phase and structural properties of the prepared samples

using X-ray diffraction (XRD), Fourier Transform Infrared (FT-IR) spectrometer and Scanning Electronic Microscopy (SEM). Experimental results are analyzed and then discussed as function of the doping concentration and compare the obtained values to those of the literature.

2. Experimental methods

2.1 Materials and synthesis method

Crystalline powders BTCo_x were synthesized and obtained using sol-gel method [30] through the destabilization of colloidal solution (DCS). This process provides numerous advantages such as an excellent control of the stoichiometry and a good homogeneity of the powders in spite of crystallization at relatively low temperature [8], [10], [29].

The powders were prepared using barium acetate trihydrate (Ba(CH₃COO)₂ · 3H₂O) (99.9% purity), titanium isopropoxide Ti[OCH(CH₃)₂]₄ (97% purity) and Cobalt acetate Co(CH₃CO₂)₂ · 4 H₂O (99.9% purity) as precursors, lactic acid (CH₃CH(OH)COOH) as peptizing agent and distilled water as solvent. The different steps relating to the preparation of BTCo_x powders are shown schematically in the flowchart in Fig. 1. A white sol with adequate proportions was obtained, which was dried in an oven at 80 °C for 72 h to obtain a dry gel. The raw powders, after grinding, were calcined in air in a programmable oven at the temperature of 1000 °C for 3 h.

The samples in pellet shapes were obtained by pressure with an uniaxial pressure equal to 10 tonnes/cm². Then, the pellets were sintered 1200 °C for 6 h reached with a heating rate 5 °C/min.

2.2 Characterization

Thermal study using Thermogravimetric analysis (TGA), and Differential thermal analysis (DTA) were performed on the sample BTCo_{0.15}. The crystallinity and phases of the ceramic powders were examined using X-ray diffraction. The powder X-ray pattern was recorded for all samples with various cobalt concentrations by using an X-ray diffractometer equipped with [XPERT-PRO diffractometer with Cu-Kα radiation (λ = 1.5405980 Å)]. XRD spectrum was recorded in the 2θ range of 20 to 80°. The morphology of the ceramic powders was characterized by Scanning electron microscopy (SEM). Moreover, the functional groups in powders were detected by using of a Bruker-Tensor 27 spectrophotometer FT-IR spectroscopy in the wave number range 450- 4000 cm⁻¹.

3. Results and discussion

3.1 Thermal analysis

Fig. 2 shows the thermal analysis (TGA and DTA) of the sample 15% doped BaTiO₃, performed in air up to 1200 °C with a temperature rate 5° C / min. The TGA curve reveals three steps of decomposition (corresponding to an overall mass loss of approximately 28mg). The first step (33-320 °C), represents a weight loss which attributed to the elimination of water and excess lactic acid. This mass loss is accompanied by an endothermic peak in the DTA curve. The second stage (320–631 °C), represents a progressive mass loss, accompanied

by several peaks endothermic and the other exothermic peaks in the DTA curve which can be attributed to the decomposition of the organic matter and the elimination of CO₂. In this temperature range, rearrangements of chemical bonds in the gel occur and the gel is converted to polymers [31]. The last stage of mass loss located in the range of (631–1000 °C) was detected, accompanied by an endothermic peak in the DTA curve, which is attributed to the decomposition of organic polymers and the formation of inorganic substances (the starting formation of BTCo_{0.15}). No reaction or mass loss was noticed above 1000 °C, showing complete crystallization of the ceramic powders. This relatively low temperature compared to other reported from other works using different synthetic techniques [32] is due to the sol gel preparation method [8], [30].

Fig. 1 Flow chart of the sol-gel processing of (x= 0, 0.05 and 0.1) powder ceramics
1. ábra A (x= 0, 0.05 és 0.1) kerámia porok szol-gél eljárásának folyamata

Fig. 2 TG/DTA curves of the ceramic sample
2. ábra A (kerámiaminta TG/DTA görbéi

3.2 Structural study

XRD patterns of the as-prepared powders were investigated, and they are reported as function of the Cobalt concentrations in Fig. 3. It shows that the BTCo crystallize in the perovskite phase without any secondary phase. The peaks are indexed as

the respective planes on the basis of JCPDS cards. Phan et al.[33] prepared BTCo usnig classical solid state reaction method, after annealing at 1300 °C—4h, but with the presence of the secondary phases. The diffractograms reveal well-resolved peaks, which are a clear indication of the good particles's crystallinity. These peaks are assigned in pure sample, i.e., x=0% to the perovskite structure with the tetragonal phase, which exists throughout the whole concentration ranges. This is supported by the presence of well resolved (002)-(200) doublet peaks around 2θ of 44-46° on the diffractogram.

The lattice parameters (a and c) were determined from XRD data analysis considering tetragonal phase with an accuracy of ±0.002 Å using the following relations;

$$\frac{1}{d^2} = \frac{h^2 + k^2}{a^2} + \frac{l^2}{c^2} \quad (1)$$

Where a is the lattice constant, d is interplanar spacing and (hkl) are Miller indices.

The fitted and calculated parameters are given in Table 1. The values of lattice constants (a and c) are given in Table 1 and were found that the lattice constant *a* increase while *c* decreases with Co concentration. Lattice parameters of pure the BaTiO₃ sample are in good agreement with reported values *a* = *b* = 3.988 Å and *c* = 4.026 Å (*α* = *β* = *γ* = 90°) [33]. Moreover, the decrease in lattice parameters can be attributed to Co²⁺ ions (0.58 Å) replacing the Ti⁴⁺ (0.605 Å), having higher ionic radii.

Fig. 3 XRD patterns of Co-doped BaTiO₃ powder samples calcined at 1000°C for 3h
3. ábra Az 1000 °C-on 3 órán át kalcinált Co-adalékolt BaTiO₃ porminták XRD mintája

Sample	Lattice parameters				Crystal- lite size (nm)	Lattice strain (×10 ⁻³)
	<i>a</i> (Å)	<i>c</i> (Å)	<i>V</i>	Tetra-go- nality		
BaTiO ₃	3.9917	4.0247	64.1304	1.0082	42.2725	1.38
BaTi _{0.95} Co _{0.05} O ₃	3.9945	4.0146	64.0594	1.0050	56.3634	2.87
BaTi _{0.9} Co _{0.1} O ₃	3.9948	4.0113	64.0136	1.0041	59.0017	2.56

Table 1. Lattice parameters, tetragonality, unit cell volume (*V*), Lattice strain and Crystallite size of Co-doped BaTiO₃

1. táblázat A Co-adalékolt BaTiO₃ rácsparaméterei, tetragonitása, egységnyi térfogata (*V*), rácsfeszítése és kristálymérete

The unit cell volume (*V*) is known to be most basic characteristic of the solid-state structure and the values of the unit cell volume are given in Table 1. The unit cell volume decreases as Co concentration increases. The decrease in unit cell volume can be attributed to changes in the crystal structure.

Scherrer formula takes into account only the influence of crystallite size on the XRD peak broadening, however, it doesn't provide anything about the sample's microstructures of the lattice i.e., regarding the intrinsic strain, which gets developed in the nanocrystals due to the grain boundary, point defect, stacking faults and triple junction [34]. Many approaches exist, such as Warren-Averbach and Williamsons Hall method, etc., which takes into account the effect of the strain induced XRD peak broadening and can be used to calculate the intrinsic strain along with the particle size. Among these approaches, Williamson–Hall (W–H) method is a very simple and The Williamson–Hall (W–H) approach is a simple and straightforward one. [34], [35].

The crystallite size and micro-strain was calculated using Williamson–Hall (W–H) plot which explains x-ray diffraction peak broadening [36].

$$\beta = \beta_{size} + \beta_{strain} \quad (2)$$

$$\beta = \frac{0.94\lambda}{D \cos \theta} + 4\epsilon \tan \theta \quad (3)$$

Where, *β* is the full width of half maximum, *ε* is the strain, and *D* is the crystallite size. Figures 4(a), (b) and (c) show the linear plots, the intercepts and the slopes pointing out the crystallite size, as well as the strain of the prepared plotted samples as plotted by Williamson–Hall method. The crystallite size and the strain of single-phase samples are shown in Table 1. The nature of the strain formed was determined by the nature of the slope, that is, with a positive slope indicating a tensile strain and the negative slope indicating a compressive strain [37].

The results revealed that all the samples had a positive slope and were subjected to tensile strain. The strain values of BTCo0.05 compound was found to be higher than the value of the other samples (Pure BaTiO₃ and BTCo0.1). The higher value of lattice strain induced in the BTCo0.05 sample is considered due to the creation of oxygen vacancies [38]. Table 1 illustrates the obtained crystallite size and the deviation of strain values BTCo_x (*x*=0, 5 and 10%) samples. In addition, the crystallite size was found in the range of 42.27-59 nm (from W–H plot).

3.3 Morphological investigation

Fig. 5 shows the evolution of the morphology and grain size of the BaTi_{1-x}Co_xO₃ (*x*=0, 0.05 and 0.1) powders as a function of the cobalt concentrations. Fig. 5a shows that the microstructure is completely anarchic, this is due to the shape of the precursors which have not yet reacted with each other, while the SEM image of the BTCo0.05 powder (Fig. 5b) we notice the start of the incorporation of the precursors together, which is in good agreement with the results of the previous characterizations. Concerning Fig. 5c, we obtained a fine microstructure of average size less than 1 μm, homogeneous and of regular and well-defined shape, which indicates that the powder crystallizes in the perovskite phase without the presence of impurities.

Fig. 4 Williamson-Hall plot of pure and Co doped BaTiO_3 samples

4. ábra A tiszta és a Co adalékolt BaTiO_3 minták Williamson - Hall diagramja

Fig. 5 Morphology images of pure and Co-doped BaTiO_3 samples. a) BaTiO_3 , b) $\text{BaTi}_{0.95}\text{Co}_{0.05}\text{O}_3$, c) $\text{BaTi}_{0.9}\text{Co}_{0.1}\text{O}_3$

5. ábra A tiszta és a Co adalékolt BaTiO_3 minták mikroszerkezete. a) BaTiO_3 , b) $\text{BaTi}_{0.95}\text{Co}_{0.05}\text{O}_3$, c) $\text{BaTi}_{0.9}\text{Co}_{0.1}\text{O}_3$

3.4 FT-IR study

IR spectra of the as prepared (BTCox) powders, heat treated at 1000 °C for 3 h, were recorded in a wavelength range of 400 cm⁻¹ to 4000 cm⁻¹. Indeed, the above XRD results is supported by FTIR spectra, as shown in Fig. 6. The peak of absorption at 990 cm⁻¹ attributed to the vibration of the Ti-OR bond [39] diminishes slightly in intensity and is transformed into a single band indicating the disappearance of the alkoxide groups. The characteristic absorption at the range of 1455 cm⁻¹ to 1457 cm⁻¹ are assigned to the stretching vibrations of carboxylate as there is a small amount of BaCO₃ [40]. In addition, Indeed, we can always observe the appearance of a single absorption bands at around 493, 480 and 490 cm⁻¹ respectively, which can be assigned to the stretching and bending vibrations of the Ti-O bond in [TiO₆]²⁻ octahedron. The obtained results are therefore in good agreement with those of X-ray diffraction.

Fig. 6 FT-IR spectra of BaTi_{1-x}Co_xTiO₃ (x=0, 5 and 10%) ceramics calcined at 1000 °C/4h.

6. ábra Az 1000 °C-on 4 óra alatt kalcinált BaTi_{1-x}Co_xTiO₃ (x=0, 5 és 10%) kerámiák FT-IR spektrumai

4. Conclusions

Cobalt doped barium titanate powders (BTCO) ceramics, with Co contents (0, 5, and 10 mol%), were successfully synthesized by the sol-gel method and characterized by X-Ray diffraction (XRD), scanning electron microscopy (SEM) and FT-IR spectroscopy. XRD results show that the cobalt diminishes the lattice tetragonality of BaTiO₃. The XRD pattern confirms that the successful formation of the single-phase (tetragonal) perovskite structure of the all presented ceramic samples. Moreover, the corresponding XRD spectra are exempt of any extra secondary phase indicating a complete incorporation of Co²⁺ in the BaTiO₃ structure then confirmed by FT-IR analysis. The line broadening of BaTiO₃ is attributed to small lattice strain and crystallite size. This broadening was examined by W-H plot and size-strain plot. According to SEM characterizations, BTCO ceramics were well synthesized, and particle size decreases as dopant concentration increase. In addition, the presented powders samples are relatively

homogeneous, consisting of regularly oriented grains in the form of anarchic for 0% and 5% of Co and spherical for 10% Co doped BaTiO₃. For further understanding more samples with mediate composition will be prepare and studied for structural and physical properties.

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