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EFFECT OF Bi_2O_3 EXCESS ON MORPHOLOGY AND STRUCTURE OF BiNbO_4 CERAMICS

WPLYW NADMIARU Bi_2O_3 NA MORFOLOGIĘ I STRUKTURĘ CERAMIKI BiNbO_4

Goal of the present research was to fabricate BiNbO_4 ceramics from the mixture of powders by the solid state reaction route and pressureless sintering at various temperatures ($T_S = 870^\circ\text{C}$ and $T_S = 910^\circ\text{C}$) and study microstructure, phase composition and crystalline structure of BiNbO_4 ceramics. Four batches were fabricated and examined, namely the one fabricated from the stoichiometric mixture of reagent – grade oxide powders, viz. Bi_2O_3 and Nb_2O_5 as well as the ones with an excess of 3%, 5% and 10% by mole of Bi_2O_3 . It was found that apart from the main orthorhombic α - BiNbO_4 phase additional phases, namely tetragonal $\text{Bi}_5\text{Nb}_3\text{O}_{15}$, and cubic Bi_3NbO_7 are possible to form from the mixture of bismuth oxide and niobium oxide. It was found that α - BiNbO_4 ceramics exhibited the orthorhombic symmetry identified as *Pnma* (52). However, small differences in elementary cell parameters were found for the samples sintered from stoichiometric and non-stoichiometric mixture of initial powders.

Keywords: BiNbO_4 ceramics, pressureless sintering, X-ray diffraction, phase analysis, crystal structure

Celem niniejszej pracy było wytworzenie ceramiki BiNbO_4 z mieszaniny proszków metodą reakcji w fazie stałej z następującym spiekaniem swobodnym przeprowadzonym w temperaturze $T_S = 870^\circ\text{C}$ i $T_S = 910^\circ\text{C}$. Ponadto zbadano wpływ zawartości Bi_2O_3 na mikrostrukturę, skład chemiczny, fazowy i strukturę krystaliczną ceramiki BiNbO_4 . Mieszaniny tlenków wyjściowych Bi_2O_3 i Nb_2O_5 przygotowano zarówno w ilości stechiometrycznej, jak i z nadmiarem tlenu bizmutu odpowiednio 3%mol, 5%mol i 10%mol. Na podstawie rentgenowskiej fazowej analizy stwierdzono, że oprócz głównej fazy rombowej α - BiNbO_4 wytworzona ceramika zawiera niewielkie domieszki fazy tetragonalnej $\text{Bi}_5\text{Nb}_3\text{O}_{15}$ i regularnej Bi_3NbO_7 . Stwierdzono, że faza α - BiNbO_4 wykazuje symetrię rombową opisywaną jako *Pnma* (52), natomiast niestechiometryczność mieszaniny proszków wyjściowych powoduje niewielkie różnice parametrów komórki elementarnej

1. Introduction

Applications of microwave dielectric ceramics in the mobile communication system, such as resonators and band-pass filters duplexers, have been tremendously increasing in the last decade, due to their high reliability, high integration potential, good dielectric properties [1]. Most of the known commercial microwave dielectrics such as complex perovskite compounds: $\text{Sn}_x\text{Zr}_{1-x}\text{TiO}_3$, $\text{Ba}(\text{Zn}_{1/3}\text{Ta}_{2/3})\text{O}_3$ (BZT) and $\text{Ba}(\text{Mg}_{1/3}\text{Ta}_{2/3})\text{O}_3$ (BMT) exhibit excellent microwave dielectric properties. However, they can be sintered only at very high temperatures greater than 1400°C [1,2].

The so-called passive integration, i.e. integration of passive components such as capacitors, resistors, inductors and line resonators into the substrate carrying the integrated circuits is used for miniaturization. This passive integration is performed using multilayer ceramics technology, whereby green ceramic tapes of different materials – corresponding to the different passive functions – are laminated and co-fired usually at rather low temperatures with low loss and low melting point electrode such as Ag or Cu [1]. Therefore, it

is necessary to find the microwave dielectric ceramics with low sintering temperatures and excellent microwave dielectric properties.

Bismuth-based dielectric ceramics were well known as low-fired materials and had been investigated for the application as multilayer ceramics capacitors [2]. Recently, bismuth niobate (BiNbO_4) has been reported to be a promising microwave dielectric ceramics due to its high quality factor ($Q = 14000$), small temperature coefficient of resonance frequency (~ 50 ppm/ $^\circ\text{C}$), and relatively low dielectric constant (~ 45) [1,2,4,3].

Goal of the present research was to fabricate BiNbO_4 ceramics from the mixture of powders by the solid state reaction route and pressureless sintering at various temperatures and study thermal and mass effects taking place on heating the mixture of powders (by simultaneous thermal analysis), revise the morphology (SEM), crystalline structure and phase composition of sintered ceramics (by X-ray diffraction method and EDS) as well as to reveal the influence of Bi_2O_3 excess (used in the course of ceramics fabrication) on final properties of bulk ceramics.

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2. Experimental

The samples of BiNbO₄ chemical composition were synthesized using the solid state reaction method. An appropriate amount of reagents – grade oxide powders, viz. Bi₂O₃ and Nb₂O₅ were thoroughly weighted in stoichiometric amount to provide conditions for formation of the desired composition, given in Eq. (1):



Also three sets of experiments with non-stoichiometric mixture of bismuth oxide and niobium oxide have been performed. Namely, an excess of 3%, 5% and 10% by mole of Bi₂O₃ has been utilized. Then the mixture of oxides was ground with an agate mortar and pestle first. After that the chemicals were wet ground in polyamide bottles using zirconia balls and ethanol as a medium for 24 h to get proper mixing and surface active fine powder. The planetary ball mill was utilized for wet grinding of the powders. A small amount of ethyl alcohol and zirconia balls as grinding medium were used in the milling/homogenizing treatment that lasted for $t = 24$ h. After milling the powders were subjected for drying. Then the dried mixture of powders was compacted into pellets of 20 mm in diameter by pressing under pressure of $p = 30$ MPa in a stainless – steel die. The green bodies were then placed in an alumina crucible and fired with air at $T = 800^\circ\text{C}$ (the heating rate $5^\circ\text{C}/\text{min}$, the soaking time $t = 2$ h) to conduct the solid state reaction. After thermal treatment the pellets were crushed in a mortar and the synthesized material was subjected to wet milling and drying again. Phase composition of the synthesized powder was checked with X-ray diffraction method. Apart from α -BiNbO₄ phase a small amount of additional phases like Bi₅Nb₃O₁₅, Bi₃NbO₇ and Bi₃Nb₁₇O₄₇ was detected. Before sintering the compacts were formed in a stainless – steel die of 10 mm in diameter. Sintering was performed by pressureless sintering under ambient air in a furnace at temperature $T = 870^\circ\text{C}$ and $T = 910^\circ\text{C}$ and soaking time $t = 2$ h. Then the fabricated BiNbO₄ ceramics were characterized in terms of phase composition, microstructure and crystal structure.

Microstructure and chemical composition of the final ceramics were investigated by scanning electron microscope (SEM) HITACHI S-4700 equipped with an energy dispersive spectrometer (EDS) NORAN Vantage.

The crystal structure of ceramics was studied by X-ray diffraction method at room temperature (XPert-Pro diffractometer, $\Theta - 2\Theta$ mode, CoK α radiation, detector scan step $\Delta 2\Theta = 0.01^\circ$ and a counting time $t = 100$ s). Phase analysis of X-ray diffraction patterns of BiNbO₄ powders was carried out using Match! (Crystal Impact) computer program [4]. As the diffraction data were raw (profile) data, the so-called "raw data processing" had to be carried out. That included: stripping of the alpha-2-radiation, data smoothing, peak searching, profile fitting, and correction for errors. The goal was to obtain a list of peaks (2Θ and intensity values) with highest possible precision. It is extremely important that this step is performed as accurate as possible in order to obtain reasonable results in the search-match process later on.

The structural analysis was performed with X'pert High-Score Plus software (PANalytical B.V). The latest available

ICSD [7], ICDD [7] and IUCr/COD/AMCSD [7], databases were utilized. Refinement of the structural parameters of BiNbO₄ ceramics was performed with the Rietveld method [e.g.7].

3. Results and discussion

3.1. Thermal behavior of the powders

Simultaneous thermal analysis (STA), in which both thermal analysis (DTA) and mass change effects (TG) are measured concurrently on the same sample was used to investigate synthesis effects in the stoichiometric mixture of powders (viz. Bi₂O₃ and Nb₂O₅). The measurements were obtained with Netzsch STA409 thermal analyzer and results of STA of the oxides forming BiNbO₄ compound are given by us elsewhere [5, 6]. Let us only mention that the main mass change effects took place within the temperature range $T = 200^\circ\text{C} - 500^\circ\text{C}$. At temperature $T = 500^\circ\text{C}$ the total mass change was $\Delta m = -0.78\%$. Further increase in temperature was not accompanied with any mass change effects. DTA analysis revealed an existence of an exothermic peak at $T \approx 860^\circ\text{C}$ (formation of α -BiNbO₄, i.e. orthorhombic form of bismuth niobate) [11] as well as two endothermic peaks that appeared at $T \approx 1067^\circ\text{C}$ and $T \approx 1186^\circ\text{C}$ [12]. Taking into consideration published phase diagrams of Bi₂O₃-Nb₂O₅ system [e.g. 7 and references cited therein] one can conclude that the first peak corresponds to decomposition of the possible minor phase Bi₅Nb₃O₁₅ into Bi₃NbO₇ and transformation of low temperature α -BiNbO₄ into high temperature β -BiNbO₄ phase. It is worth noting that structural phase transition from α - to β -BiNbO₄ takes place at $T \approx 1020^\circ\text{C}$ whereas, Bi₅Nb₃O₁₅ is unstable at $T = 1050^\circ\text{C}$ [13]. At temperature $T > 1020^\circ\text{C}$ Bi₃NbO₇ is likely to exist as a minor phase together with β -BiNbO₄. Above $T > 1110^\circ\text{C}$ only high temperature BiNbO₄ phase is possible to exist in bismuth-rich Bi₂O₃-Nb₂O₅ system [13]. Therefore, one can suppose that the second above-mentioned endothermic peak at $T \approx 1186^\circ\text{C}$ corresponds to decomposition of Bi₃NbO₇ and melting of β -BiNbO₄ phase.

3.2. Morphology and chemical composition of ceramics

SEM pictures of BiNbO₄ ceramics obtained by pressureless sintering from stoichiometric and non-stoichiometric mixtures of oxides are shown in Fig. 1.

One can see from Fig. 1 that neither an excess of Bi₂O₃ (Fig. 1a, c or Fig. 1b, d) nor an increase in temperature (Fig. 1a, b or Fig. 1c, d) change the morphology of ceramics in a substantial way. Grains of about $1\mu\text{m}$ in diameter constitute relatively porous ceramics. Application of an excess of Bi₂O₃ does not improve porosity of ceramic samples under study.

Results of the calculations performed on the basis of the EDS measurements spectra for BiNbO₄ ceramics sintered at $T_s = 870^\circ\text{C}$ and $T_s = 910^\circ\text{C}$ from both stoichiometric mixture of oxides and from mixtures including an excess of Bi₂O₃ are shown in Fig. 2. One can see from Fig. 2 that an increase in the sintering temperature from $T_s = 870^\circ\text{C}$ to $T_s = 910^\circ\text{C}$ does not influence significantly the chemical composition of ceramics. On the other hand, all traces shown in Fig. 2 exhibit 'sigmoidal' shape in relation to Bi₂O₃ excess in the initial

mixture. This can be explained in terms of thermal behavior of Bi_2O_3 [8]. The higher is an amount of Bi_2O_3 excess in the initial mixture of oxides the smaller is the deviation from the stoichiometric BiNbO_4 composition (dashes straight lines in Fig. 2) after sintering. One can estimate from Fig. 2 that for achieving the stoichiometric composition of BiNbO_4 ceramics subjected to pressureless sintering in ambient air at $T_s = 910^\circ\text{C}$ an excess of 10 mol% of Bi_2O_3 oxide is necessary while if sintering is performed at $T_s = 870^\circ\text{C}$ an excess of Bi_2O_3 of about 9 mol% is required.

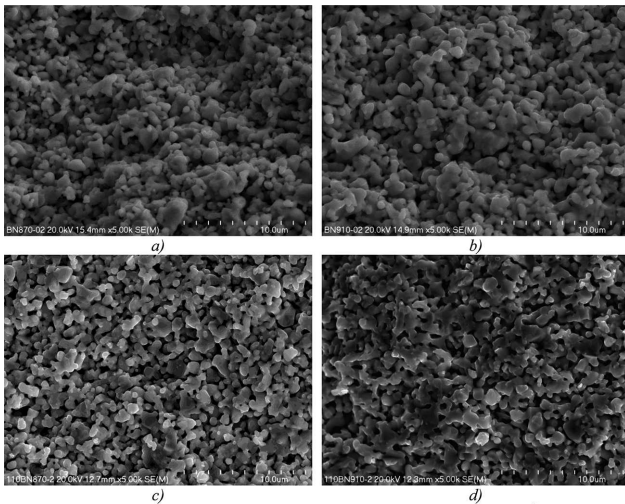


Fig. 1. Morphology of BiNbO_4 ceramics sintered at $T_s=8700\text{C}$ (a,c) and $T_s=9100\text{C}$ (b,d) from stoichiometric mixture of oxides (a,b) and with 10mol% excess of Bi_2O_3 (c, d)

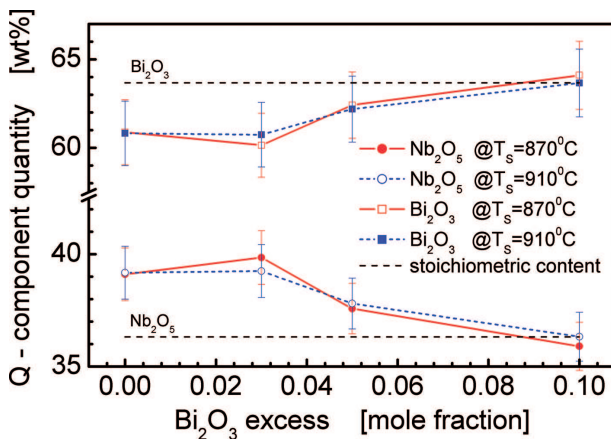


Fig. 2. Composition of BiNbO_4 ceramics sintered at temperature $T_s=8700\text{C}$ and $T_s=9100\text{C}$ expressed in the mole fraction of constituting oxides, viz. Bi_2O_3 and Nb_2O_5

3.3. Crystal structure

As an example, X-ray diffraction patterns of BiNbO_4 ceramics sintered at $T_s = 870^\circ\text{C}$ and $T_s = 910^\circ\text{C}$ from stoichiometric mixture of Bi_2O_3 and Nb_2O_5 oxides as well as from a mixture with an excess amount of 10 mol% of Bi_2O_3 are shown in Fig. 3 (raw data). Also diffraction lines of the possible phases (BiNbO_4 and $\text{Bi}_5\text{Nb}_3\text{O}_{15}$) are shown. One can see from Fig. 3 that diffraction peaks present in the pattern could

matched the appropriate phase. The search-match procedure was performed after raw data processing.

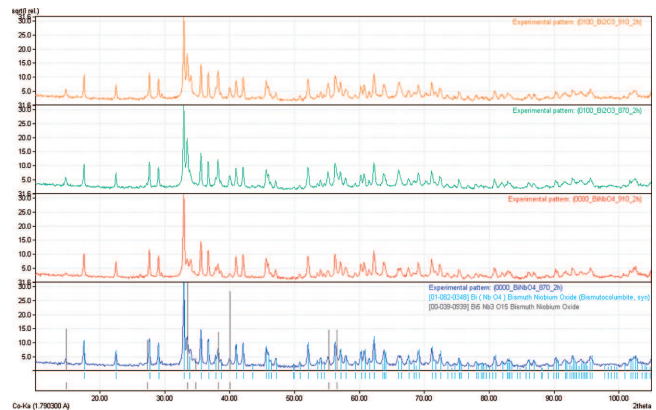


Fig. 3. Comparison of X-ray diffraction patterns of BiNbO_4 ceramics with diffraction lines positions of major ($\alpha\text{-BiNbO}_4$) and minor ($\text{Bi}_5\text{Nb}_3\text{O}_{15}$) phases

Phase analysis of X-ray diffraction patterns has shown that BiNbO_4 ceramics fabricated during the present study was multiphase and apart from the major phase of bismutocolumbite BiNbO_4 (PDF card No 01-082-0348; total number of peaks 124; 109 peaks in the range, matched 93 peaks; Figure-of-Merit, i.e. a number which is calculated from the various measures of agreement between database and unknown pattern, $FoM=0.871$) a small amount of minor phases like $\text{Bi}_5\text{Nb}_3\text{O}_{15}$ (PDF card No 00-039-0939; total number of peaks 8; 8 peaks in the range; matched 8 peaks; $FoM=0.694$) and Bi_3NbO_7 (PDF card No 01-086-0875; total number of peaks 9; 8 peaks in the range; matched 8 peaks; $FoM=0.737$). Unfortunately, only qualitative phase analysis was possible due to fact that crystallographic information files mentioned above did not contain enough data necessary to perform semi-quantitative analysis using the "Reference Intensity Ratio method"[9].

Detailed structural analysis of X-ray diffraction patterns was performed with Rietveld method. A model structure of $\alpha\text{-BiNbO}_4$ (orthorhombic symmetry, $Pnma(52)$ space group) according to the ICSD database (code 97422) was taken as an initial structure for structural parameters refinement. Results of the calculations are shown in Fig. 4-Fig. 6. It was found that the elementary cell parameters change slightly in the following range: $a = 5.679\text{-}5.680\text{\AA}$, $b = 11.710\text{-}11.712\text{\AA}$ and $c = 4.982\text{-}4.983\text{\AA}$.

Dependence of the calculated elementary cell volume on an excess amount of Bi_2O_3 (Fig. 4) show that after initial increase, the volume decreases with an increase in Bi_2O_3 . Taking into consideration that the ionic radius of $\text{Bi}^{3+} = 1.2\text{\AA}$ is almost two times larger than the ionic radius of $\text{Nb}^{5+} = 0.7\text{\AA}$ an increase in bismuth amount in BiNbO_4 compound (Fig. 2) can stand for an increase in the elementary cell volume. Further decrease in $\alpha\text{-BiNbO}_4$ elementary cell may be due to increase in an amount of $\text{Bi}_5\text{Nb}_3\text{O}_{15}$ impurity phase which can cause deficiency in bismuth ions in BiNbO_4 compounds. This can be seen in Fig. 3 as an increase in intensity of the diffraction line at the angle $2\theta = 14.75^\circ\text{-}14.80^\circ$. However, more detailed measurements (and/or calculations) should be performed to justify the above mentioned hypothesis.

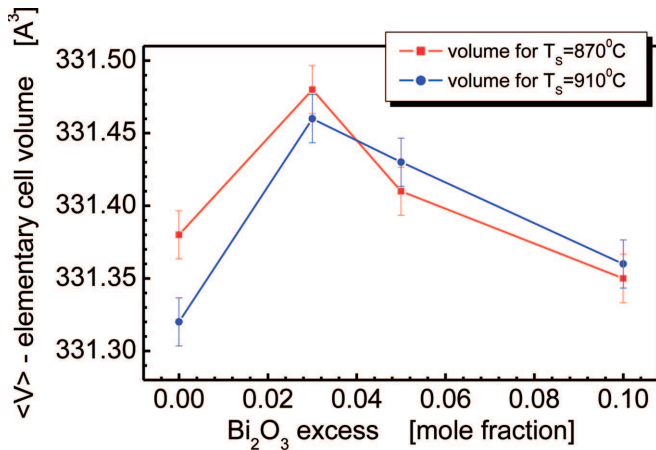


Fig. 4. Dependence of the elementary cell volume on excess amount of Bi₂O₃ oxide

Effect of sintering temperature on the elementary cell volume also changes with an increase in Bi₂O₃ amount. One can estimate from Fig. 4 that for an excess amount of Bi₂O₃ less than c.a. 4 mol% higher sintering temperature causes the smaller elementary cell volume of α -BiNbO₄ compound whereas for Bi₂O₃ excess amount >4 mol% higher sintering temperature leads to an increase in the elementary cell volume.

Dependence of the average crystallite size of α -BiNbO₄ compound on an excess amount of Bi₂O₃ at different sintering temperatures is shown in Fig. 5. Higher sintering temperature causes larger mean dimensions of crystallites (expected phenomenon). One can also see in Fig. 5 that the higher is an amount of Bi₂O₃ in the mixture of initial oxides the smaller is the difference in mean dimensions of crystallites caused by the sintering temperature and both curve runs tend to achieve a value of c.a. $\langle D \rangle \approx 900 \text{ \AA}$.

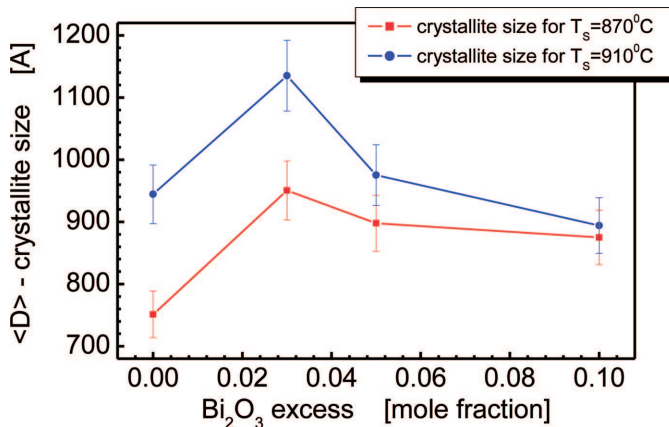


Fig. 5. Dependence of the average crystallite size on excess amount of Bi₂O₃ oxide

Dependence of the average micro strain on excess amount of Bi₂O₃ shown in Fig. 6 proves quality of the crystalline structure of fabricated α -BiNbO₄ compound. One can see in Fig. 6 that in case of lower sintering temperature (i.e. T_s = 870°C) micro deformations calculated for orthorhombic structure of α -BiNbO₄ compound decrease with a local minimum (i.e. non-monotone) at 3mol% of Bi₂O₃. On the other hand, ceramic samples sintered at higher temperature, (i.e. T_s = 910°C) exhibited an increase of the average micro strain with an in-

crease in an excess amount of Bi₂O₃. Both curve runs tend to achieve value of c.a. $\langle \Delta d/d \rangle \approx 0.04\%$.

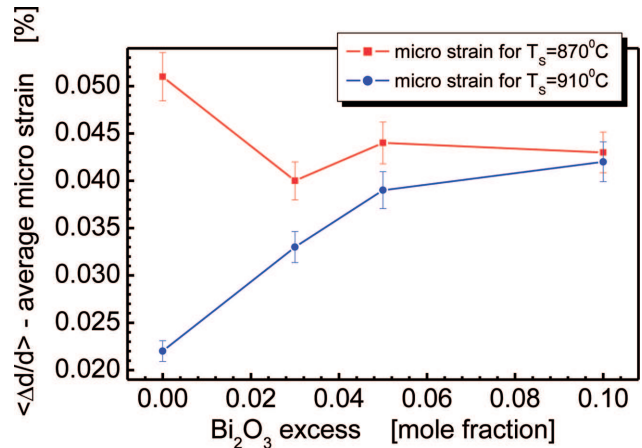


Fig. 6. Dependence of the average strain on excess amount of Bi₂O₃ oxide

4. Conclusions

By means of the mixed oxide method followed by pressureless sintering BiNbO₄ ceramics was successfully fabricated from both stoichiometric and non-stoichiometric mixture of Bi₂O₃ and Nb₂O₅ powders, via the solid state reaction route. It was found that BiNbO₄ ceramics sintered in ambient air exhibited multiphase composition i.e. apart from the major α -BiNbO₄ phase the tetragonal Bi₅Nb₃O₁₅ and cubic Bi₃NbO₇ phases were present. The chemical composition of the sintered ceramics changes with composition of the initial mixture of powders. It was revealed that an excess of 10 mol% or 9 mol% of Bi₂O₃ is necessary for achieving the theoretical composition of BiNbO₄ when sintering is performed at T_s = 910°C or T_s = 870°C, respectively. However, an excess of Bi₂O₃ in amount of 3-10mol% did not improve density of ceramics.

It was found that BiNbO₄ ceramics, adopted the orthorhombic crystal structure described as *Pnna* (SG 52) (α -BiNbO₄) with the elementary cell parameters differing in $\pm 0.02\%$, namely: $a = 5.679\text{--}5.680 \text{ \AA}$, $b = 11.710\text{--}11.712 \text{ \AA}$ and $c = 4.982\text{--}4.983 \text{ \AA}$. Average crystallite size of α -BiNbO₄ changed within the range $\langle D \rangle = 751\text{--}951 \text{ \AA}$ and $\langle D \rangle = 894\text{--}1135 \text{ \AA}$ at T_s = 870°C and T_s = 910°C, respectively, whereas microdeformations $\langle \Delta d/d \rangle = 0.04\text{--}0.051\%$ and $\langle \Delta d/d \rangle = 0.022\text{--}0.042\%$ for samples sintered at T_s = 870°C and T_s = 910°C, respectively.

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