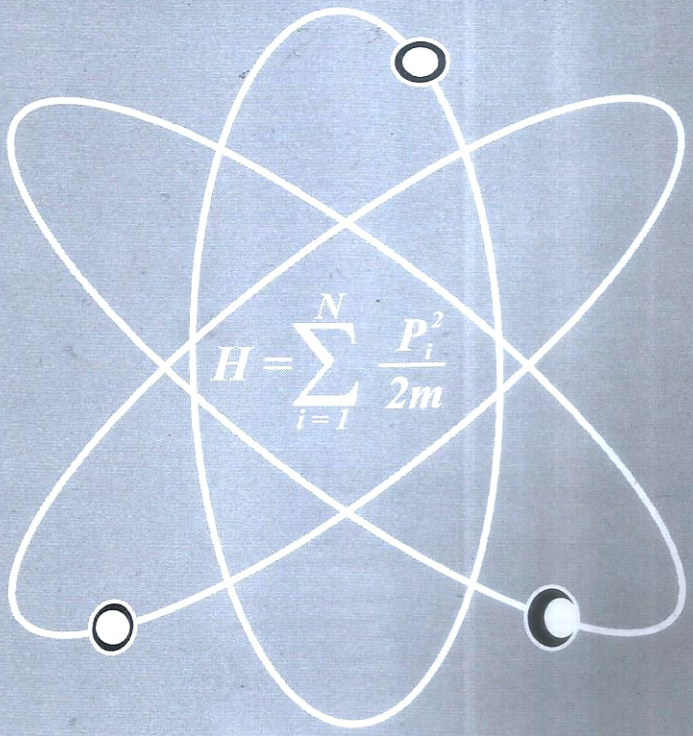
BAYERO JOURNAL OF PHYSICS AND MATHEMATICAL SCIENCES



VOLUME 8, No. 1
SEPTEMBER, 2017.

Published by: THE DEPARTMENTS OF PHYSICS AND MATHEMATICAL SCIENCES, BAYERO UNIVERSITY, KANO.

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BAJOPMAS JOURNAL 8(1): 30 – 36
Printed in Bayero University, Kano - Nigeria.

ANALYSIS OF STRUCTURE, MICROSTRUCTURE AND CHEMICAL COMPOSITION OF SOLID SOLUTIONOF CO-DOPED BARIUM CALCIUM STANNATETITANATE ($Ba_{1-x}Ca_xTi_{0.975}Sn_{0.025}O_3$) ($0 \leq x \geq 0.12$)

U. Ahmadu[1], M. I. Abdullahi[1], Abdulwaliyu B. Usman[1], Uno, E. E[1]. and Moses Agida[1]
[1]Department of Physics, Federal University of Technology, P. M. B. 65, Minna, Nigeria
***Corresponding author*: u.ahmadu@yahoo.com**

ABSTRACT
$Ba_{1-x}Ca_x(Ti_{0.975}Sn_{0.025})O_3(0.00 \leq x \leq 0.12)$ceramics have been synthesized by solid state reaction method. Structural analyses have been carried out to determine the effect of Ca^{2+}substitution on the structural parameters of the ceramic. The average crystallite size decreased from 36.39 nm to 35.39 nm for highly doped Ca^{2+}. Highest increase inc/a ratio was observed at x = 0.06. Microstructural evaluation of the material revealed decrease in grain size from 1 μm to 0.45 μm upon incorporation of Ca^{2+}. Energy Dispersive Spectroscopy (EDS) investigation showed variation in chemical composition but no structural transformation was observed.

Keywords: ceramic; X-ray diffraction; crystallinity; microstructure; grain size

1. Introduction
Lead-basedperovskite ceramics have shown high dielectric and piezoelectric properties which are widely used in piezoelectric devices [1]. Unfortunately, the lead content in such ceramics makes it very toxic and can pollute environment causing damage to the brain and nervous system [2], hence from environmental point of view and human health protection, there is need to replace these materials with lead-free compositions. Over the years, there have been growing researchesin developing lead-free piezoelectric materials which may replace their lead-based counterparts.Perovskite Barium Titanate ($BaTiO_3$ or BT) has been recognized asa promising candidate due to its potential application in multilayer ceramic capacitors, piezoelectric transducers, sensors, Fe-RAM [3], among others. BT is a typical ferroelectric which exhibits a perovskite (ABO_3) structure.However, some of its drawbacks have limited its extensive application in its pure form due to conflict between significant hysteresis in the strain and electric field dependence of the piezoelectricity of the material. These have led to difficulties in controlling the piezoelectric ceramic [3], alongsideits low piezoelectric constant [4]. Thermal instability of its structural phase and other dependent properties are also of major concern. BT exhibits a relatively low transition temperature (T_c=120 °C)at the Curie point and thus suffers structural phase transformation (ferroelectric-tetragonal to paraelectric-cubic phase) at low temperatures [5, 4]. Several attempts at improving its structural stability, ferroelectric and dielectric properties have been made [6. 7. 8]. These include the substitution of Ba^{2+}or $Ti^{4+}$by atoms of different sizes and oxidation states resulting in compounds of different physical and chemical properties, while still retaining the same structural phase [6, 9, 7]. It has been reported that partial substitution of $Ba^{2+}$by Ca^{2+} prevents grain growth, improves electromechanical properties andstructural stability [10, 11, 12].However, the substitution decreased the dielectric constant [11, 13] while the substitution of $Ti^{4+}$by 0.025 mol of Sn^{4+} led to increasedpermittivity, enhanced piezoelectric properties and decreasedT_c [14]. As such, it is expected that simultaneous substitutions of Ba^{2+} by Ca^{2+} and Ti^{4+} by Sn^{4+}(0.025 mol)may offer the possibility of developing a lead-free piezoelectric ceramic.Secondary phases which affect the crystal structure amongst other properties of BT upon substitution of inappropriate Ca^{2+}concentrationhave been reported [11]. Therefore, the appropriate concentration of Ca^{2+} that may improve the structural phase of the ceramic is worth investigating. To the best of

our knowledge, structural and microstructural properties of BT partially substituted by Ca^{2+} and Sn^{4+}(0.025 mol)have not been investigated apart from our earlier work [15].

In the present work,the effect of Ca^{2+}substitution (on the Ba^{2+}site of $BaTiO_3$) on the structural and microstructural properties of $Ba_{1-x}Ca_x(Ti_{0.975}Sn_{0.025})O_3$ceramics($0.00 \leq x \leq 0.12$) have been investigated and the evolution of these properties with doping have been reported.

2. Experimental Procedures

$Ba_{1-x}Ca_x(Ti_{0.975}Sn_{0.025})O_3$ (BCST) ceramics(where$0.00 \leq x \leq 0.12$) weresynthesized by solid state reaction method. Analytical grade $BaCO_3$ ($\geq 99\%$, Kermel, China.), TiO_2 and $CaCO_3$ (99.9 %, Qualikems, India) and SnO_2 (99.99 %, BDH, U.K)were used as the precursors. Stoichiometric amounts of these materials for the required specimens were weighed and dry- mixed thoroughly,followed by wet-mixing with distilled water as the medium. The amount of distilled water used was just enough to form slurry to prevent selective sedimentation of the reagents. The slurry was dried in an oven at 150°C for 1 h. The dried mixture was hand-ground thoroughly for homogeneity using agate mortar and pestle for 4 h. The homogenous mixture was placed in an alumina crucible and calcined at 1050°C for 4 h in a furnace to allow volatilization of bye-product CO_2. The obtained mixed powder was furtherground for 1 h and granulated by adding 4 wt% polyvinyl alcohol (PVA) as binder to reduce brittleness and to have better compactness, and then pressed into 26 mm diameter and 1 mm thickness pellets at a pressure of 10 tons.Finally, the prepared pellets were sintered at 1100°C for 3 h, and furnace-cooled to obtain a crystal phase formation.

X-ray Diffractometer (D8 Advance, BRUKER AXS, 40 kV, 40 mA) with monochromatic Cu-$K_\alpha$radiation (λ = 1.54060 Å)was used to characterize the structural phase composition of the synthesized ceramics over a 2θ range from 20° to 90° with scan step and acquisition time of 0.034° and 88 s, respectively. The morphology and the elemental composition of the ceramics were analyzed using High Resolution Scanning Electron Microscope (HRSEM, Zeiss) coupled with EDS spectrometer working at a voltage of 20 kV with images captured at 5 kV. Prior to the analysis, the samples were placed on a carbon adhesive tape and backed on an aluminium stage. As the samples are non-conducting, a thin layer of AuPd was coated using a sputter coater and then vacuumed in the HRSEM. For measurement of the grain sizes, Imagej software was used.

3. Results and Discussion

3.1 Crystal Structure Analysis

X-ray Diffraction (XRD) patterns of the synthesized $Ba_{1-x}Ca_x(Ti_{0.975}Sn_{0.025})O_3$ ceramics (x = 0.00, 0.06 and 0.12) are depicted in Fig. 1.Thepatterns confirm thatthe ceramics are polycrystalline with single phase perovskite structure which compares well with JCPDS no: 00-005-0626 reference data of tetragonal $BaTiO_3$.The patterns are also in agreement with the reports of other workers who prepared BT-based ceramics using similar method (Kim *et al.*, 2009;Fasasi*et al.*, 2006).

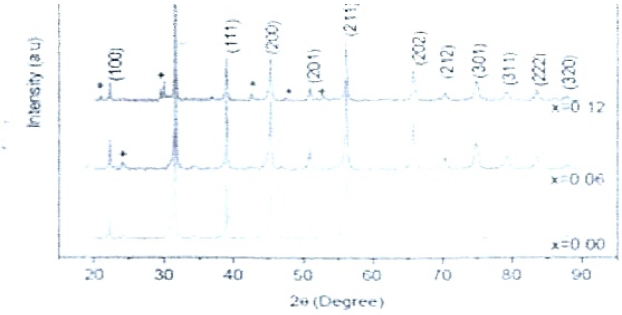

Figure 1: X-Ray Diffraction Pattern of $Ba_{1-x}Ca_x(Ti_{0.975}Sn_{0.025})O_3$ ($0.00 \leq x \leq 0.12$)

However, a minor peak around 47.5° 2θ scan was observed at x = 0.12 which hasbeen identified as orthorhombic $CaTiO_3$ phase (Joint Commission on Powder Diffraction Standards (JCPDS) file no: 00-022-0153) and attributed to the solubility limit of Ca^{2+} inBCST. This suggests that Ca^{2+} is soluble in BCST up to 0.06 mol.There were other diffraction peaks though with very low intensities whose match could not be found as indicated in the XRD spectra. Further, it was observed that the structure sensitive peak (200) slightly shifts towardshigher 2θ angles from 45.246 to 45.261°with increasing Ca^{2+}concentration. This suggests distortion of the ABO_3 unit cell lattice [16] and could lead to changes in the lattice parameters,consistent with fact that the radius of Ca^{2+} ions (0.99 Å) is smaller than that of Ba^{2+}ions (1.34 Å) [13].

Average crystallite size (s) were calculated by eqn. (1) [6] using the Full Width at Half Maximum (FWHM) of the most intense peak.

$$D = \frac{0.9\lambda}{\beta \cos\theta} \qquad (1)$$

Where β is theFWHM of the diffraction peak expressed in radians, θ is the Bragg diffraction angle of the XRD peak, λ is the wavelength of the X-ray used which is 1.54060 Å and D is the crystallite size in nanometers.

The calculated average crystallite size is presented in table 1 where it can be seen that the crystallite size decreased because the FWHMincreased with increase in doping concentration. This is dueto the fact that the smaller Ca^{2+} ions replacedthe larger Ba^{2+}ions and their reactivity with the hostcompounddecreased giving rise to decreased crystallinity.

Table 1: Ca^{2+}concentration (x in mols.), peak position(2θ) and FWHM (β) at (110) and average crystallite size (D)

X	2θ (degree)	$\beta \times 10^{-3}$ (radians)	D (nm)
0.00	31.57	3.61	36.93
0.06	31.59	3.94	33.82
0.12	31.58	3.77	35.39

Lattice parameters*a* and *c*of theceramics were calculated from the XRD spectra using the (100), (200) and (201) diffraction peaks and compared with the JCPDS no: 00-005-0626 data of $BaTiO_3$(table 2).

Table 2: Determined Lattice Constants *a* and *c*, *c/a* and Cell volume of $Ba_{1-x}Ca_x(Ti_{0.975}Sn_{0.025})O_3$ ceramics

x	a (Å)	c (Å)	c/a (Å)	Cell Volume ($Å^3$)
Referenced BT	3.994	4.038	1.0110	64.410
0.00	4.0048	4.0092	1.0011	64.30
0.06	4.0030	4.0149	1.0030	64.30
0.12	4.0020	4.0110	1.0022	64.20

It can be seen that x = 0.00 is weakly tetragonal in comparison with the JCPDS data of $BaTiO_3$prepared at higher temperature. But on substitution of Ca^{2+} for Ba^{2+}, the lattice parameters *a* decreased while *c* increased and consequently*c/a*ratio(tetragonality) increased. However, x = 0.06 is seen to have the highest value and could be attributed to the solubility limit of Ca^{2+}. It has been suggested that the increase of the space available to the Ca^{2+} at the Ba^{2+} site induces ferroelectricity in dielectrics [11] and that this could be the reason for the increase in tetragonality observedon substitution of Ba^{2+} by Ca^{2+}.Also presented in table 2 is the cell volume where it is seen to slightly decrease as the concentration of Ca^{2+} increased. This has been corroborated by the shifting of the (200) peaks to higher angles with increasing Ca^{2+}concentration. Moreover, increase in *c/a* is a desirable characteristic of perovskite titanates because higher *c/a* normally increases the polarizability and the ferroelectric properties [17]. Thus the observed increase in tetragonality of $Ba_{1-x}Ca_x(Ti_{0.975}Sn_{0.025})O_3$ ($0.00 \leq x \leq 0.12$) may lead to improved ferroelectric properties. The most appropriate structural properties of $Ba_{1-x}Ca_x(Ti_{0.975}Sn_{0.025})O_3$ ceramics is obtained with x = 0.06.

3.2 Microstructural Analysis

Fig. 2 depicts HRSEM micrographs of $Ba_{1-x}Ca_x(Ti_{0.975}Sn_{0.025})O_3$ ($0.00 \leq x \leq 0.12$). From Fig 2(a), it can be seen that the particles agglomerate alongside fairly homogeneous and porous microstructure.

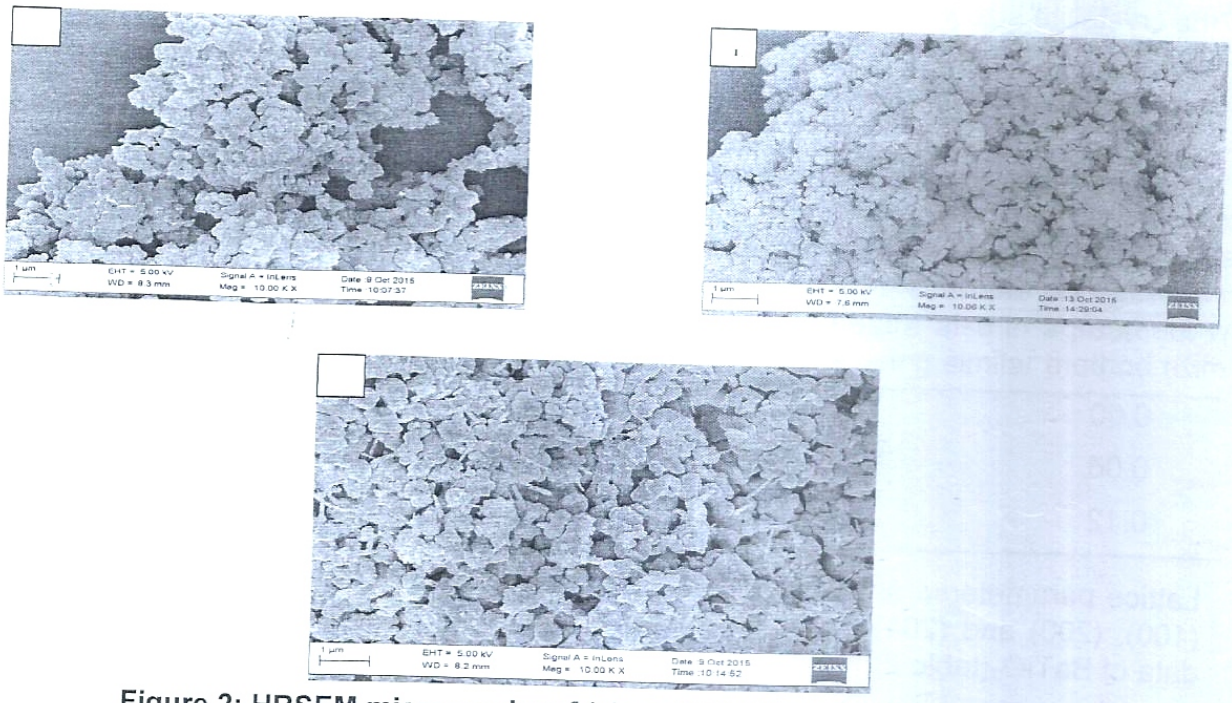

Figure 2: HRSEM micrographs of (a) x = 0.00 (b) x = 0.06 (c) x = 0.12

The average grain size of the ceramics is about 1μm, smaller than those reported in traditional BT ceramics sintered at higher temperature (1450 °C) [18]. The small value of grain size may be due to insufficient sintering temperature. On addition of Ca^{2+} (x = 0.06), closer agglomeration of grainsis observed and the average grain size decreased to about 0.45 μm, eventuallygiving rise to the poor microstructurein Figure 2b. As Ca^{2+}concentration increased (x = 0.12), two regions are distinguishablein their grain size and phase compositions. The first shows a fairly fine-grained microstructure with average grain size of0.7 μm, while the other has rod-like grains (Figure 2c) with porosity. The distinct feature of this sample is the presence of non-homogeneous microstructure.The observed rod-like grains are due to non-uniform distribution of starting powders [12]. It is generally reported that the initial powder preparation process and possibly insufficient mixing of starting powders or insufficient sintering temperaturecould result in poor and non-homogeneous microstructure. The decrease in average grain size of the ceramicupon substitution of $Ca^{2+}$for Ba^{2+} indicates that Ca^{2+} inhibits grain growth [11]. Ferroelectric properties of BT-based ceramicshave been strongly linked to grain size [3] where it is found to decrease when grain size decreases. Decrease in dielectric constant may also be expected because the grain boundary is non-ferroelectric and the dielectric constant of the grain boundary is much smaller than that of the grain [9]. The smaller the grain size, the larger the grain boundary, and the lower the dielectric constant.

3.3 Chemical Composition

Fig. 3 is the Energy Dispersive (EDS) spectrum showing the elemental compositionsof $Ba_{1-x}Ca_x(Ti_{0.975}Sn_{0.025})O_3$ceramics. All the peaks have been identified with thecorresponding elements that match that peak. The spectra clearly reveal the presence of Ba, Ca, Ti, Sn, O, C, Au and Pd,except in the case of x = 0.00 (Fig. 3a) where Al is evident.

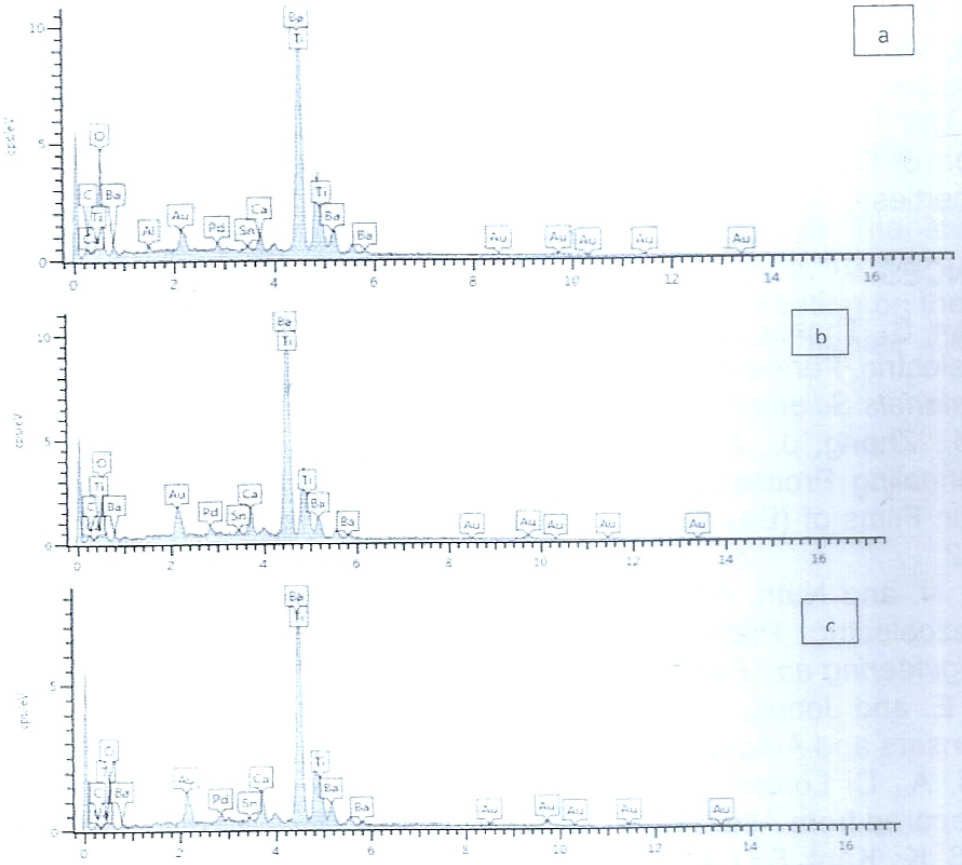

Fig. 3: EDS spectrum of (a) x = 0.00 (b) x = 0.06 (c) x =0.12

The C(carbon) source may have come from the carbon tape.AuPd (Gold-Paladium) is present in the compound in order to make it conducting; while the Al may be attributed to contamination during the preparation of samples for SEM analysis. Table 3gives a quantitative comparison of the nominal compositions and the normalized EDS-derived composition, where the major sources of error have been removed and the remaining elements normalized to 100% to give a representation of the elements present in the compound. The variations in the normalized EDS derived composition in comparison with the nominal composition could be assigned to deficiency of oxygen during sintering in the ambient. The overlap of Ba and Ti is clear in the spectra and makes it difficult to distinguish between them in the quantification results, an observation that has been reported by other workers. However, further investigations are required to elucidate the higher values of the normalized EDS derived results.

Table 3.Nominal and Normalized EDS-derived elemental composition

	Nominal Composition (atomic %)						Normalized EDS Derived Composition (atomic %)					
Sample (x)	Ba	Ca	Sn	Ti	O	Total	Ba	Ca	Sn	Ti	O	Total
0.00	20.00	-	0.50	19.50	60.00	100	18.41	-	0.33	19.11	62.15	100
0.06	18.80	1.20	0.50	19.50	60.00	100	19.59	3.59	0.63	22.97	52.69	100
0.12	17.60	2.4	0.50	19.50	60.00	100	22.31	4.7	0.4	26.64	45.95	100

4. Conclusion

Polycrystalline$Ba_{1-x}Ca_x(Ti_{0.975}Sn_{0.025})O_3$ ($0.00 \leq x \leq 0.12$) ceramics were prepared by solid state reaction method. The results indicate that the FWHM increased, crystallite size and grain size decreased as the concentration of Ca^{2+}increased, all of which lead to reduced crystallinity.Variationsare observed in the lattice parameters which cause lattice distortion and consequently lead to increase in *c/a* ratio alongside slight contraction of unit cell volume. The changes in the structural and microstructural propertiesobserved on substitution of $Ca^{2+}$for Ba^{2+} in BCST ceramic couldlead to changes in the dielectric and other properties.

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