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# High piezoelectric response and polymorphic phase region in the lead-free piezoelectric BaTiO<sub>3</sub>–CaTiO<sub>3</sub>–BaSnO<sub>3</sub> ternary system

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This study attempted to replace Pb-based piezoelectric ceramics with a non-toxic lead-free (Ba,Ca)(Ti,Sn)O<sub>3</sub> substitute, according to current environmental standards. The design of the (Ba<sub>(0.825+x)</sub>Ca<sub>(0.175-x)</sub>)(Ti<sub>(1-x)</sub>Sn<sub>x</sub>)O<sub>3</sub> lead-free piezoceramics reported herein was based on chemical modifications by varying Sn concentrations ( $x = 0.0500-0.1250$ ). The effect of Sn ion modifications on structural evolution and dielectric, ferroelectric and piezoelectric properties was investigated. Partial substitution of Ti with Sn yields a suitable composition with multiphase boundaries near room temperature. As a result, the composition,  $x = 0.1000$ , shows outstanding piezoelectric values of  $d_{33} = 515 \text{ pC N}^{-1}$  and  $d_{33}^* = 1293 \text{ pm V}^{-1}$  at 10 kV, which are higher than those found in commercially available soft PZT. Furthermore, anomalous dielectric relaxation is far below the rhombohedral to orthorhombic phase transition at  $T \approx 90-150 \text{ K}$ , and was found clearly in all compositions. The relaxation fitted the Vogel–Fulcher model with an activation energy of  $E_a \approx 20-70 \text{ meV}$  and freezing temperature of  $T_{VF} \approx 65-85 \text{ K}$ .

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## Introduction

Lead-based perovskite piezoceramics are suitable for universal actuators, sensors and transducers in many electromechanical devices, due to their superiority in both the piezoelectric coefficient ( $d_{33}$ ) and converse piezoelectric coefficient ( $d_{33}^*$ ), as determined by a strain induced electric field.<sup>1</sup> Despite their very useful properties, the impact of lead-containing ceramics on the environment has caused global concern. As a result, three groups of lead-free piezoelectric materials have been developed to replace commercial Pb-based materials completely. These groups include BaTiO<sub>3</sub>-, (K,Na)NbO<sub>3</sub>- and (Bi,Na)TiO<sub>3</sub>-based ceramics.<sup>2</sup> The figure of merit (FOM) for the piezoelectric actuator is determined by the piezoelectric  $d_{33}^*$  coefficient, with its value defined as the  $S_{\text{max}}/E_{\text{max}}$  ratio, where  $S$  is the induced strain and  $E$  the electric field applied. Therefore, it is important to achieve a high strain under minimal electric field.<sup>2-4</sup> Piezoelectric properties of commercial lead-based materials usually

demonstrate  $d_{33} = 400 \text{ pC N}^{-1}$  and  $d_{33}^* = 600 \text{ pm V}^{-1}$  for sensor and actuator modes, respectively.<sup>4,5</sup>

A high strain response in (Bi,Na)TiO<sub>3</sub>-based systems was reported, with  $d_{33}^*$  values of about 300–720  $\text{pm V}^{-1}$ .<sup>6,7</sup> Tan *et al.*<sup>8</sup> recently reported a giant electrostrain of  $\sim 0.70\%$ , with  $d_{33}^* = 1400 \text{ pm V}^{-1}$  in non-textured (Bi,Na)TiO<sub>3</sub>-based ceramics. The outstanding electric field induced strain value in the (Bi,Na)TiO<sub>3</sub>-based ceramics displayed a large  $S$ – $E$  hysteresis loop at a high electrical field ( $>40 \text{ kV cm}^{-1}$ ). Higher  $d_{33}$  and  $d_{33}^*$  values also were obtained in (K,Na)NbO<sub>3</sub>-based ceramics.<sup>9,10</sup> Nevertheless, it is difficult to prepare dense ceramics by using ordinary sintering conditions and also implementing methods such as sintering aids.<sup>11,12</sup> Therefore, numerous binary and ternary BaTiO<sub>3</sub> or simple BT-based systems have been more attractive because of their excellent  $d_{33}$  and  $d_{33}^*$  values, which are greater than those in the two former systems.<sup>13,14</sup> Thus, the BT-based system was suggested as a potential choice for replacing Pb-based piezoelectric materials in some applications. It is well known that compositional design based on chemical modifications is the basic approach for enhancing piezoelectric properties. Cation substitution in the perovskite structure (ABO<sub>3</sub>) can be performed at the A- or B-sites and can induce either the morphotropic phase boundary (MPB), which is similar to the MPB behavior of Pb-based piezoelectric materials,<sup>1,2</sup> or a polymorphic phase transition (PPT), where several structural phases of slightly different chemical compositions can coexist with each other near the ferroelectric–ferroelectric or ferroelectric–paraelectric phase transition temperature. The large  $d_{33}$  value of 697  $\text{pC N}^{-1}$  and dielectric permittivity value of

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around 75 000 were reported in binary  $\text{BaTiO}_3\text{-}x\text{BaSnO}_3$  ceramics by Y. Yao *et al.*,<sup>15</sup> who showed coexistence of quasi-quadruple phases such as the cubic–tetragonal–orthorhombic–rhombohedral (C–T–O–R) phase.

In general, single phase  $\text{BaTiO}_3$  exhibits a tetragonal (T) structure at room temperature ( $\sim 298$  K). The rhombohedral to orthorhombic (R–O) and orthorhombic to tetragonal (O–T) phase transitions occur at  $\sim 183$  K and  $\sim 273$  K, respectively. The  $T_{\text{R-O}}$  and  $T_{\text{O-T}}$  of ceramic shift to a higher temperature by doping  $\text{Sn}^{4+}$  ion in the  $\text{Ti}^{4+}$  site of the  $\text{BaTi}_{1-x}\text{Sn}_x\text{O}_3$  system, while the Curie temperature ( $T_c$ ) decreases.<sup>1,15,16</sup> On the other hand, doping  $\text{Ca}^{2+}$  ion in the  $\text{Ba}^{2+}$  site of  $\text{Ba}_{1-x}\text{Ca}_x\text{TiO}_3$  ceramic tends to lower the  $T_{\text{O-T}}$  transition temperature, but only affects the  $T_c$  temperature slightly, which helps to keep the latter stable for actual piezoelectric application.<sup>1</sup> Furthermore, both  $\text{Ca}^{2+}$  and  $\text{Sn}^{4+}$  ions were doped in Ba- and Ti-sites of the BT structure in order to bring the  $T_{\text{R-O}}$  and  $T_{\text{O-T}}$  close to room temperature and also create a multiphase compound. Li *et al.*<sup>17</sup> reported high piezoelectric properties with  $d_{33} = 510$  pC  $\text{N}^{-1}$  and electromechanical coupling coefficient ( $k_p$ ) = 48% in  $(\text{Ba}_{1-x}\text{Ca}_x)(\text{Ti}_{0.96}\text{Sn}_{0.04})\text{O}_3$ , which resulted from the compound being close to the PPT boundary comprising the O–T phases. They<sup>18</sup> also reported the effect of Ca content on the piezoelectric properties of  $(\text{Ba}_{1-x}\text{Ca}_x)(\text{Ti}_{0.94}\text{Sn}_{0.06})\text{O}_3$  ceramics. Later, Zhu *et al.*<sup>19</sup> showed that the  $(\text{Ba}_{1-x}\text{Ca}_x)(\text{Ti}_{0.92}\text{Sn}_{0.08})\text{O}_3$  system exhibited  $d_{33}$  up to 568 pC  $\text{N}^{-1}$ ,  $k_p = 47.7\%$ , and  $d_{33}^* = 1013$  pm  $\text{V}^{-1}$  near room temperature at the O–T boundary. Furthermore, efforts to form a mixed phase by compositional modifications were attempted in  $(1-x)\text{Ba}(\text{Sn}_{0.12}\text{Ti}_{0.88})\text{O}_3\text{-}x(\text{Ba}_{0.7}\text{Ca}_{0.3})\text{TiO}_3$ ,<sup>20</sup>  $(\text{Ba}_{0.95}\text{Ca}_{0.05})(\text{Ti}_{1-x}\text{Sn}_x)\text{O}_3$ <sup>21</sup> and  $(\text{Ba}_{0.90}\text{Ca}_{0.10})(\text{Ti}_{1-x}\text{Sn}_x)\text{O}_3$ <sup>22</sup> ceramics, where the R–T, R–O–T and O–T phase boundaries were found, respectively, resulting in the enhancement of piezoelectric properties. Based on the literature,<sup>17–22</sup> the structural pseudo-ternary diagram of the  $\text{BaTiO}_3\text{-CaTiO}_3\text{-BaSnO}_3$  (BT–CT–BS) system is shown in Fig. 1. This study focused on the  $(\text{Ba}_{0.825+x}\text{Ca}_{0.175-x})(\text{Ti}_{1-x}\text{Sn}_x)\text{O}_3$  (BT–CT– $x$ BS) compositions,

which traverse the multiphase region, as shown by the “ $\diamond$ ” symbols in Fig. 1. A suitable composition may display multiphase coexistence at room temperature, in which case a high piezoelectric response is expected, based on the MPB or PPT concept.

This study explored the polymorphic phase region of  $(\text{Ba}_{0.825+x}\text{Ca}_{0.175-x})(\text{Ti}_{1-x}\text{Sn}_x)\text{O}_3$  ceramic, with the compositions,  $x = 0.0500, 0.0625, 0.0750, 0.0875, 0.1000, 0.1125$  and  $0.1250$ , being fabricated *via* the conventional solid-state reaction method. Phase transformations and coexistent phases resulted from chemical modifications of the Sn ion at the B-site, and the relationship between the compositions and piezoelectric properties was discussed.

## Experimental

The  $(\text{Ba}_{0.825+x}\text{Ca}_{0.175-x})(\text{Ti}_{1-x}\text{Sn}_x)\text{O}_3$  ceramics with the compositions,  $x = 0.0500\text{--}0.1250$ , were prepared by the conventional solid-state reaction method, with metal oxides and carbonates. Dried  $\text{BaCO}_3$  ( $\geq 98.5\%$ , Sigma-Aldrich),  $\text{CaCO}_3$  ( $\geq 98.5\%$ , Riedel-de Haen),  $\text{TiO}_2$  (99.9%, Sigma-Aldrich), and  $\text{SnO}_2$  (99.9%, Sigma-Aldrich) powders were weighed in accordance with the stoichiometric ratio. All mixed powders were milled with yttria-stabilized zirconia balls for four hours by high-energy vibration milling, and ethanol was used as an intermediary before drying in an oven at  $85$  °C for 24 h. Next, the mixed powders were calcined at  $1200$  °C for 4 h (heating/cooling rate of  $5$  °C  $\text{min}^{-1}$ ). The calcined powders were sieved for uniform particle size and mixed with 5% polyvinyl alcohol (PVA). Circular disks of 10 mm diameter were pressed uniaxially with 2 tons weight for 2 min, and sintered at  $1450$  °C for 2 h in air (heating/cooling rate of  $5$  °C  $\text{min}^{-1}$ ). The density of the samples was examined using Archimedes' principle for the desired relative density of over 95%.

An X-ray diffractometer (Bruker-AXS D 8 Advance) was used to determine the structure of powders obtained after the sintered pellets had been ground using Cu  $\text{K}\alpha_1$  radiation, and data were collected in the  $2\theta$  range from  $20^\circ$  to  $70^\circ$  with a step size ( $2\theta$ ) of 0.02, together with a time per step of 1 s. The sintered samples were polished until they had reached the required smooth surface before the Raman measurement was taken. A Raman spectrophotometer (Dispersive Raman Microscope, SENTERRA, Bruker) was used to support the XRD data, by using the 532 nm exciting line of a He–Ne laser, with recorded wavelength in the range of  $50$  to  $1000$   $\text{cm}^{-1}$  at room temperature.

The ceramic samples were prepared for electrical measurement by polishing both sides of the pellets to a smooth surface, using 600, 1000 and then 2000 series number of grinding paper. The samples were polished down to about 1 mm thickness for dielectric measurement, and  $<0.7$  mm thickness for ferroelectric and piezoelectric measurement. Ag paste electrodes (Heraeus, C1000) were applied and then fired at  $750$  °C for 30 min. Dielectric characterization was performed using an Alpha Impedance Analyzer (Novocontrol, Germany) in conjunction with the physical property measurement system (PPMS, Quantum Design, USA), at a frequency of  $10\text{--}10\,000$  Hz and temperature range from 2 K to 360 K, to determine the phase

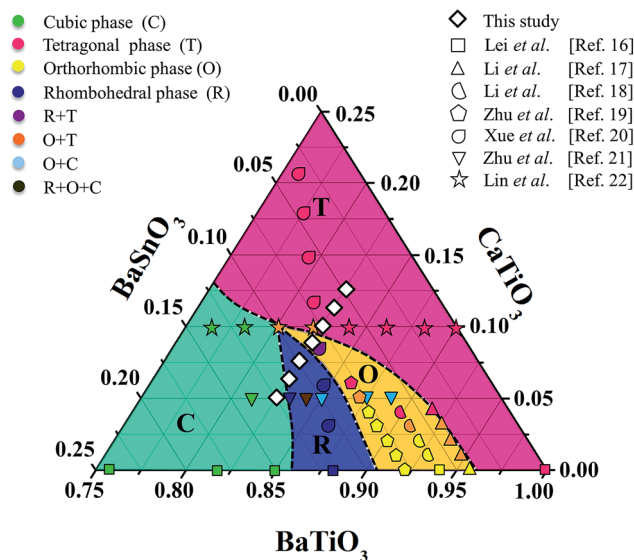


Fig. 1 Ternary diagram of  $\text{BaTiO}_3\text{-CaTiO}_3\text{-BaSnO}_3$  ceramics.



transition temperature. The ferroelectric hysteresis loop was measured by using a ferroelectric tester system (RT66B; Radiant Technologies, Inc., Albuquerque, NM), based on the Sawyer-Tower circuit, with Vision software and high voltage amplifier (Trek) in silicone oil at room temperature, and a frequency of 4 kHz. The unipolar and bipolar strain characteristics were measured for converse piezoelectric measurement, using the MTI-2100 photonic sensor with fiber-optic probes (high-resolution module resolved to 0.01  $\mu\text{m}$ , 2.5 angstroms), in conjunction with the ferroelectric tester system in silicone oil at room temperature. The  $d_{33}^*$  or converse piezoelectric coefficient was calculated from the relationship of maximum strain divided by the maximum electric field ( $S_{\text{max}}/E_{\text{max}}$ ). The ceramic samples were poled in silicone oil under a DC electric field of 30  $\text{kV cm}^{-1}$  for 30 min at room temperature before the direct piezoelectric coefficient ( $d_{33}$ ) was examined. The  $d_{33}$  coefficient was measured using a Berlincourt  $d_{33}$  meter (YE2730A, APC International Ltd., USA).

## Results and discussion

Fig. 2(a) illustrates the XRD patterns of BT-CT-xBS ( $x = 0.0500$ – $0.1250$ ) ceramics at room temperature, which closely match the JCPDS diffraction peaks of pure  $\text{BaTiO}_3$ , as shown by vertical black lines on the plane. JCPDS numbers 05-0626, 81-2200, 85-0368, and 31-0174 belong to tetragonal (T), orthorhombic (O), rhombohedral (R) and cubic (C) symmetry, respectively. All of the samples exhibited a perovskite structure, and no secondary or impure phases were detected. This result indicates that a solid solution was achieved by  $\text{Ca}^{2+}$  and  $\text{Sn}^{4+}$  diffusion at the A- and B-sites of the perovskite structure, respectively. An expanded view of the peaks at  $2\theta = 38.5$ – $39.5^\circ$ ,  $44$ – $46.5^\circ$ , and  $55.5$ – $57^\circ$  is shown in Fig. 2(b). Diffraction peaks for the composition,  $x = 0.0500$ , exhibited tetragonal symmetry, with splitting between the (002) and (200) peaks at  $2\theta \approx 45^\circ$ . The peak intensity of (200) and (211) was slightly higher than that of

(002) and (112), respectively, as observed at  $2\theta \approx 56^\circ$ . The crystal structure at the composition,  $x = 0.0625$ , continued to exhibit T-symmetry, with peak splitting and intensity similar to that of the composition,  $x = 0.0500$ . By increasing the Sn content, the expanded diffraction peaks became broader gradually for the compositions,  $x = 0.0750$ – $0.1000$ , at  $2\theta \approx 45^\circ$  and  $56^\circ$ . Eventually, the peaks were seen to merge into a single one at the compositions,  $x = 0.1125$ – $0.1250$ , as observed at  $2\theta \approx 39^\circ$ ,  $45^\circ$ , and  $56^\circ$ . Each enlarged diffraction peak did not match the T- and O-symmetry exactly at the compositions,  $x = 0.1125$ – $0.1250$ , but rather matched the R- or C-symmetry, due to no splitting at  $2\theta \approx 45^\circ$  and possibly because of its mixture. The structural phase transition of BT-CT-xBS ceramics may change from T- to R- or C-symmetry. The compositions of the phase transition regions were in the range of  $x = 0.0750$ – $0.1000$ . Furthermore, the diffraction peaks shifted to lower angles with increasing  $x$  content, indicating the replacement of  $\text{Ti}^{4+}$  (with an ionic radius of 0.605 Å); and  $\text{Sn}^{4+}$  had a larger ionic radius of 0.69 Å. The detected expansion of the unit cell was similar to the results observed by Singh *et al.* in Sn-doped  $\text{BaTiO}_3$ .<sup>23</sup>

It is known that XRD data provide mainly global macroscopic symmetry of ceramics; the local structure of small cluster regions of different ferroelectric phases may not be evidenced clearly. In contrast, Raman spectroscopy is an informative technique that characterizes lattice dynamics and local structure, and was used to examine local structural distortions and low symmetry ferroelectric phases in many lead-free piezoelectric systems.<sup>24–26</sup> It was used in conjunction with the XRD results of this study to support the presence of different local structures and ferroelectric phase transitions as a function of composition in the ceramics.

Fig. 3(a)–(c) show room temperature Raman spectra of BT-CT-xBS ceramics, with the compositions,  $x = 0.0500$ – $0.1250$ , measured in a frequency range of 50–1000  $\text{cm}^{-1}$ . There are five atoms inside the unit cell of a perovskite structure, which has 12 optical vibrational modes. The optical modes in a cubic symmetry, with  $Pm3m$  space group, belong to  $3F_{1u} + F_{2u}$  irreducible representations. The  $F_{1u}$  modes give  $A_1$  and E modes,

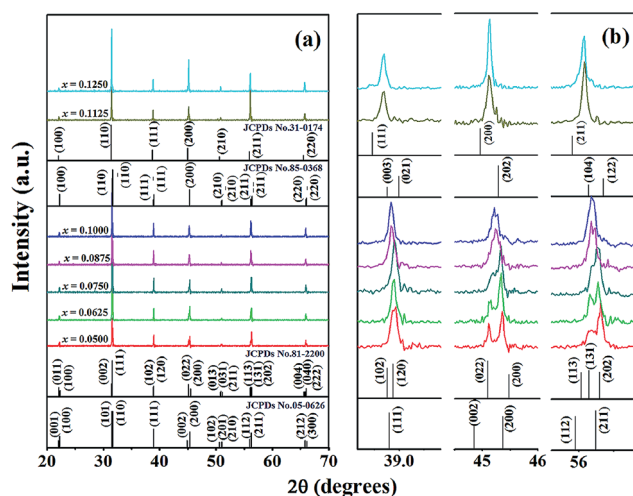


Fig. 2 (a) XRD patterns of BT-CT-xBS ceramics with the compositions,  $x = 0.0500$ – $0.1250$ , and (b) the expanded peak at  $2\theta$  of around  $38.5$ – $39.5^\circ$ ,  $44$ – $46.5^\circ$ , and  $55.5$ – $57^\circ$ .

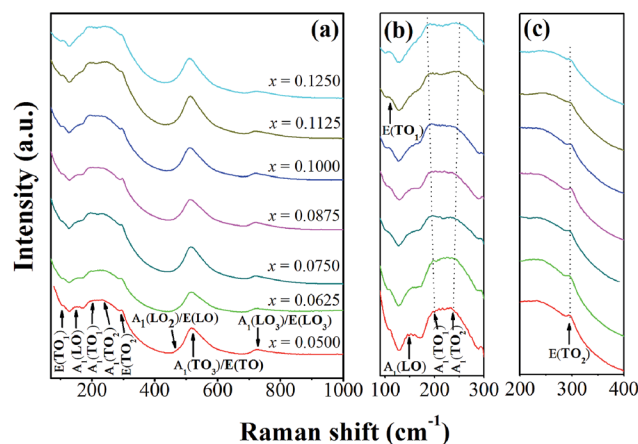


Fig. 3 (a) Raman spectra of BT-CT-xBS ceramics with the compositions,  $x = 0.0500$ – $0.1250$ , and (b) and (c) the expanded peak at around  $100$ – $300$  and  $200$ – $400$   $\text{cm}^{-1}$ .



while the  $F_{2u}$  modes provide  $B_1$  and  $E$  modes when transforming into the T-phase ( $P4mm$ ). The  $A_1$  and  $E$  symbols are Raman-active phonon modes of the T- ( $C_{4v}$ ) phase, which split into transverse (TO) and longitudinal (LO) optical modes when an electrostatic force is induced. All Raman-active modes in Fig. 3 agree well with previous reports.<sup>25,26</sup>

The characteristic peaks of a perovskite ferroelectric phase can be observed in all compositions that consist of a sharp peak at around  $296\text{ cm}^{-1}$ , and broad peaks at around  $520\text{ cm}^{-1}$  and  $724\text{ cm}^{-1}$ , which correspond to the  $E(\text{TO}_2)$ ,  $A_1(\text{TO}_3)/E(\text{TO})$  and  $A_1(\text{LO}_3)/E(\text{LO}_3)$  modes, respectively. Furthermore, an interfering effect between a narrow and broad  $A_1(\text{TO})$  mode presents a dip at around  $176\text{ cm}^{-1}$ , which is attributed to a ferroelectric phase. It is known that  $\text{Ca}^{2+}$  ion can be substituted in either an A- or B-site of the perovskite BT structure. The Ca solubility can reach up to  $x = 0.04$  for B-site substitution in  $\text{BaTi}_{1-x}\text{Ca}_x\text{O}_3$ .<sup>27</sup> Pokorný *et al.*<sup>28</sup> recently reported an  $A_{1g}$  peak mode at  $\sim 800\text{ cm}^{-1}$  that associated with the mixed  $\text{Ti}^{4+}$  and  $\text{Ca}^{2+}$  occupancy of the B-site. In this study, the  $A_{1g}$  peak is absent in the Raman data, which confirms that the  $\text{Ca}^{2+}$  ion prefers to diffuse into an A-site of the perovskite structure in  $(\text{Ba}_{0.825+x}\text{Ca}_{0.175-x})(\text{Ti}_{1-x}\text{Sn}_x)\text{O}_3$  compositions.

The compositions,  $x = 0.0500\text{--}0.0625$ , show the characteristics of a T-phase due to a broad peak at around  $270\text{ cm}^{-1}$ , which corresponds to the  $A_1(\text{TO}_2)$  mode and a minute peak of the  $A_1(\text{LO}_2)/E(\text{LO})$  mode at around  $469\text{ cm}^{-1}$ .<sup>26,28</sup> This result is consistent with the XRD patterns observed for the compositions,  $x = 0.0500\text{--}0.0625$ . Although the main feature of the Raman spectra is consistent with the T-phase for the compositions,  $x = 0.0500\text{--}0.0625$ , there are changes seen in the range of  $100\text{--}300\text{ cm}^{-1}$ . These are associated with the polar  $\text{BO}_6$  vibrations that are characteristic of the O- and R-phases, as Sn content increases in the compositions,  $x = 0.0750\text{--}0.1250$ . Study of the temperature dependent Raman spectra of pure  $\text{BaTiO}_3$  indicates that the peak mode near  $191\text{ cm}^{-1}$  only exists in the O- or R-phase and not in the T- and C-phase.<sup>25,29</sup> The  $A_1(\text{TO}_1)$  mode near  $191\text{ cm}^{-1}$  has been reported as a characteristic of the O-phase,<sup>30</sup> which starts to emerge in the composition,  $x = 0.0500$  until  $x = 0.1250$ , as shown in Fig. 3(b). Three peaks that present at frequencies of  $106$ ,  $155$  and  $191\text{ cm}^{-1}$  correspond to  $E(\text{TO}_1)$ ,  $A_1(\text{LO})$  and  $A_1(\text{TO}_1)$  modes, respectively, which is characteristic of the R-phase.<sup>26,30</sup> Nevertheless, quantity of the R- or O-phase in this study is not significant in the ceramics.

The asymmetric band was made to fit at  $160\text{--}300\text{ cm}^{-1}$  by peak de-convolution with a Gaussian function ( $R^2 \geq 0.97$ ). Fig. 4(a)–(d) show fitted peaks for the composition,  $x = 0.0500$ ,  $x = 0.0750$ ,  $x = 0.1000$ , and  $x = 0.1250$ , respectively. The peak number 1 is located at around  $191\text{ cm}^{-1}$ , which corresponds to the  $A_1(\text{TO}_1)$  mode observed in only the O- or R-phase. Peak number 2 and 3 are around  $232$  and  $260\text{ cm}^{-1}$ , respectively, which corresponds to the  $A_1(\text{TO}_2)$  mode. Perry *et al.* reported that the  $A_1(\text{TO}_2)$  mode is present near  $230\text{ cm}^{-1}$  in the O-phase and transforms to  $267\text{ cm}^{-1}$  in the T-phase.<sup>31</sup> The emergence of both  $A_1(\text{TO}_2)$  modes also was reported in  $\text{Ba}_{1-x}\text{Ca}_x(\text{Zr}_{0.05}\text{Ti}_{0.95})\text{O}_3$  ceramics, with a crossover from the O- to T-phase.<sup>32</sup> The intensity and area under the curve of de-convoluted peak number 1 tend to increase, whereas peak number 3 tends to

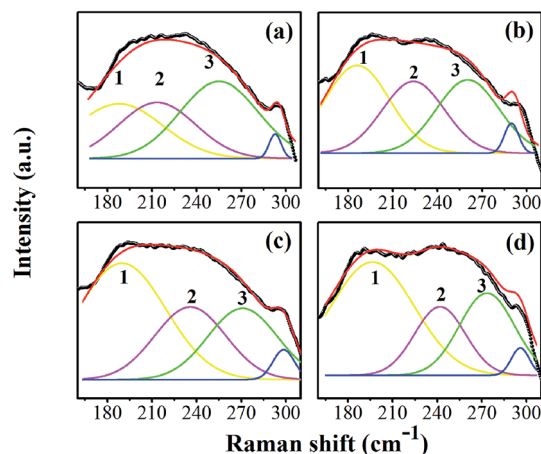


Fig. 4 The peak de-convolution at  $160\text{--}300\text{ cm}^{-1}$  of the compositions,  $x = 0.0500$  (a),  $x = 0.0750$  (b),  $x = 0.1000$  (c), and  $x = 0.1250$  (d), respectively.

decrease, indicating that the R-phase develops and the T-phase is lost. This corresponds to the variable intensities of the  $E(\text{TO}_1)$  peak, suggesting that the volume fraction of the R-phase increases as the peak becomes sharper with increasing Sn content [in Fig. 3(b)]. It is interesting that the Raman spectra in Fig. 4(a)–(d) clearly show the presence of T-, O-, and R-phases in all compositions. It can be concluded, based on the XRD and Raman results, that the global structure of  $x = 0.0500\text{--}0.1000$  ceramics exhibits a T-phase based mainly on XRD data, while the O- and R-phase are present in some local areas of the global T-phase structure, which is supported by the Raman results.

More evidence of local nano-clusters is seen clearly in the presence of the  $E(\text{TO}_1)$  peak at  $106\text{ cm}^{-1}$  in the Raman data. The  $E(\text{TO}_1)$  peak is related to Sn–O motion in the perovskite structure and regarded as an indicator of the presence of the nanometer-sized Sn-rich perovskite phase.<sup>33</sup> The presence of the  $E(\text{TO}_1)$  peak is possible at  $106\text{ cm}^{-1}$  only if Sn-rich domains extend over tens of unit cells, in order that the phonon can give rise to a definite Raman peak. The existence of Sn-rich clusters in the  $\text{Ba}(\text{Ti}_{1-x}\text{Sn}_x)\text{O}_3$  also was confirmed clearly by the synchrotron X-ray Absorption Near-Edge Structure (XANES) results, even though splitting peaks in the XRD patterns were not observed.<sup>34</sup> In addition, the peak intensity of the  $E(\text{TO}_2)$  and  $A_1(\text{LO}_3)/E(\text{LO}_3)$  modes decreases explicitly, and the dip at around  $176\text{ cm}^{-1}$  between the  $A_1(\text{LO})$  and  $A_1(\text{TO}_1)$  mode gradually vanishes with increasing Sn composition of up to  $x = 0.1250$ , as shown in Fig. 3(a)–(c). These results indicated that the relative volume of the ferroelectric phase decreases, due to the appearance of the paraelectric phase in some local areas. The characteristic of the pure cubic phase is supported by two broad bands at around  $250\text{ cm}^{-1}$  and  $520\text{ cm}^{-1}$ .<sup>30</sup> It also corresponded with broader and higher peak intensity of around  $250\text{ cm}^{-1}$  at the compositions,  $x = 0.1125\text{--}0.1250$ . Thus, the C-phase is mixed possibly with the compositions,  $x = 0.1125\text{--}0.1250$ , which correspond with the dielectric data presented below, in that increasing Sn composition shifts the  $T_c$  temperature close to room temperature for the last two compositions.



The Raman findings, based on the combined results of this study, agree well with the XRD data that clarify the crystal structure of the samples.

Fig. 5(a)–(g) illustrate temperature dependence of relative permittivity ( $\epsilon_r$ ) and dielectric loss ( $\tan \delta$ ) of BT-CT-*x*BS ceramics by specifying the acronyms and color bars for different phase transitions. The three pronounced  $\tan \delta$  peaks in the compositions,  $x = 0.0500$ – $0.1000$ , are associated with the three ferroelectric phase transitions: R–O at the temperature of ( $T_{R-O}$ )  $\approx 200$ – $250$  K, O–T at the temperature of ( $T_{O-T}$ )  $\approx 250$ – $300$  K and T–C at the temperature of ( $T_{T-C}$ )  $\approx 300$ – $350$  K. The ferroelectric phase transitions show a significant change of compositions. As expected, the R–O and O–T phase transitions were shifted close to room temperature, while the  $T_{T-C}$  or  $T_c$  decreased slightly with Sn substitution. The  $T_{R-O}$ ,  $T_{O-T}$  and  $T_c$  are evidenced clearly near room temperature at the composition,  $x = 0.1000$ , which is seen clearly in Fig. 5(h), where  $\partial\epsilon_r/\partial T$  is plotted for the composition,  $x = 0.1000$ . As  $x$  increases to over  $0.1000$ , the three phase transition peaks merge into one broad peak at  $T_c$  for the composition,  $x = 0.1125$ . The R–O and O–T phase transitions disappear gradually at the composition,  $x \geq 0.1125$  [Fig. 5(i)], which implies that the O–R–T phase convergence is located in the composition range of  $x = 0.1000$  and  $0.1125$ . Finally, there is only one  $\epsilon_r$  peak left that corresponds to the R–C phase transition at  $T_c$  and the R-phase appears in the composition,  $x \geq 0.1125$ .

The  $T_c$  peak shifts to a lower temperature and broadens gradually with increasing Sn content. This result shows similar behavior to Sn-substituted BaTiO<sub>3</sub>-based ceramics, as reported in the literature.<sup>22,23</sup> By substituting Ti<sup>4+</sup> with Sn<sup>4+</sup>, non-ferroelectric SnO<sub>6</sub> octahedra enter the matrix of the ferroelectric phase. The non-ferroelectric regions disrupt the long-range order of the TiO<sub>6</sub> ferroelectric octahedra, causing unstable off-center displacements of Sn atoms and oxygen ligands, which lead to lowering  $T_c$ . Also, the local  $T_c$  values may vary, due to the random distribution of Sn in the samples, leading to a broad dielectric peak with diffuse phase transition.<sup>35</sup>

According to the modified Curie–Weiss law, diffuse phase transition follows an empirical  $\epsilon_r$  relationship with temperature:<sup>36</sup>

$$\frac{1}{\epsilon} - \frac{1}{\epsilon_m} = \frac{(T - T_m)^\gamma}{C}, \quad 1 \leq \gamma \leq 2 \quad (1)$$

where  $\gamma$  is diffuseness and  $C$  is the Curie–Weiss constant. The  $\gamma$  value is characteristic of the phase transition;  $\gamma = 1$  describes the normal ferroelectric behavior related to a sharp phase transition, whereas  $1 \leq \gamma \leq 2$  denotes a diffuse phase transition. Fig. 6 shows  $\ln[1/\epsilon - 1/\epsilon_m]$  dependence on  $\ln[T - T_m]$  for the dielectric constant measured at 1 kHz. The  $\gamma$  value increases gradually from 1.39 to 1.89 with increasing Sn content, which corresponds to phase transition broadening at  $T_c$ . In other words, the phase transition becomes more diffuse with increasing Sn substitution.

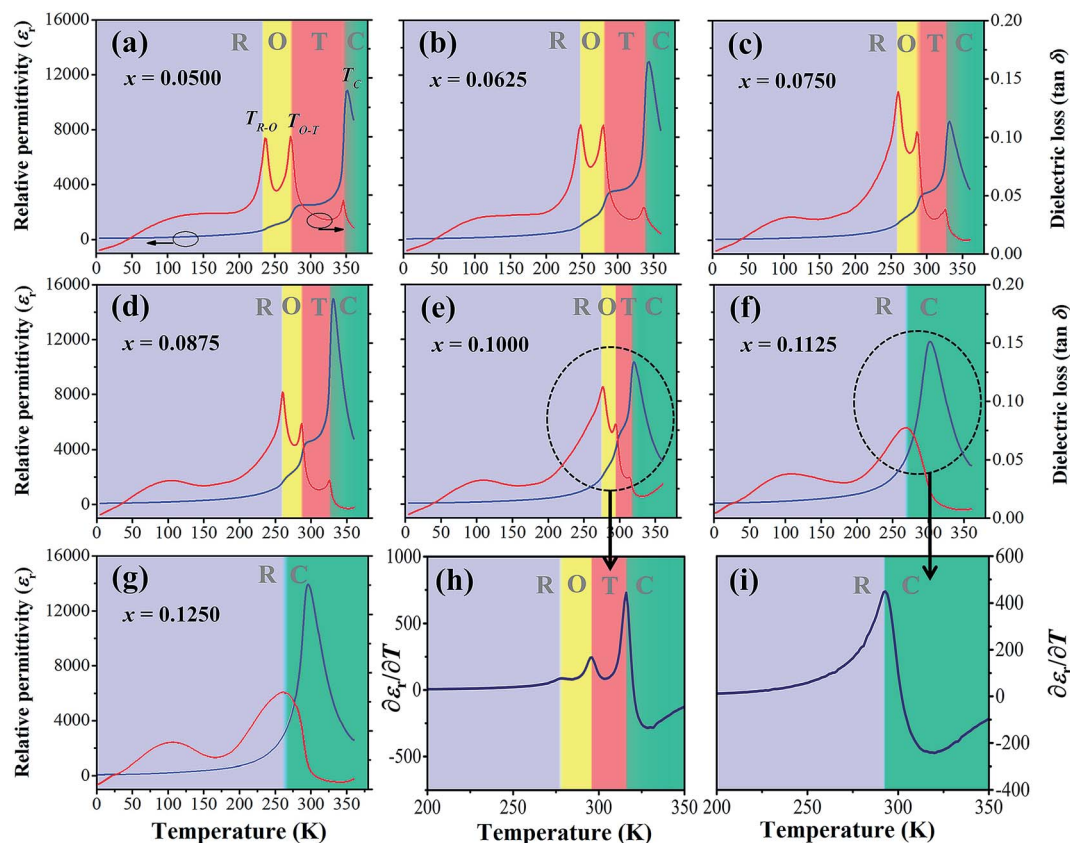


Fig. 5 Dielectric permittivity and dielectric loss versus temperature curves of BT-CT-*x*BS ceramics;  $x = 0.0500$ – $0.1250$  (a)–(g) in the range of 2–360 K at 1 kHz; derivative of the dielectric permittivity versus temperature ( $\partial\epsilon_r/\partial T$ ) for the compositions,  $x = 0.1000$  (h) and  $0.1250$  (i).



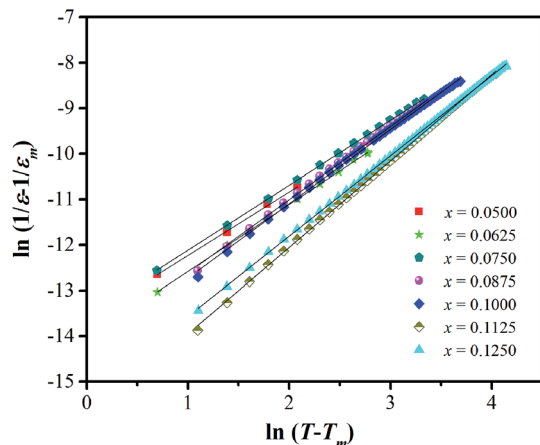


Fig. 6  $\ln(1/\epsilon - 1/\epsilon_m)$  versus  $\ln(T - T_m)$  at 1 kHz for BT-CT-xBS ceramics.

In addition to the three ferroelectric phase transitions, dielectric data in this study show a broad  $\tan \delta$  peak at 100–160 K in all compositions. At the same time, the dielectric permittivity increases gradually from  $\sim 90$  to  $\sim 700$  in  $T = 2$ –180 K, with a small broad kink at  $\sim 125$  K, as shown in Fig. 7. In addition, a small low-temperature shoulder peak in  $\tan \delta$  was found in the compositions,  $x = 0.1125$ – $0.1250$ . Fig. 8 shows the temperature dependence of  $\tan \delta$  at various frequencies for the compositions,  $x = 0.0500$ ,  $x = 0.0750$ ,  $x = 0.1000$ , and  $x = 0.1250$ , respectively, which demonstrates the  $\tan \delta$  peak shifting towards higher temperatures with increasing frequency. In general, this dependence is characteristic of either a simple Arrhenius-type thermally-activated process:

$$f = f_0 \exp\left(\frac{-E_a}{k_B T}\right) \quad (2)$$

or a more complex ‘freezing’ process, as described by the Vogel-Fulcher (VF) model:

$$f = f_0 \exp\left(-\frac{E_a}{k_B(T - T_{VF})}\right) \quad (3)$$

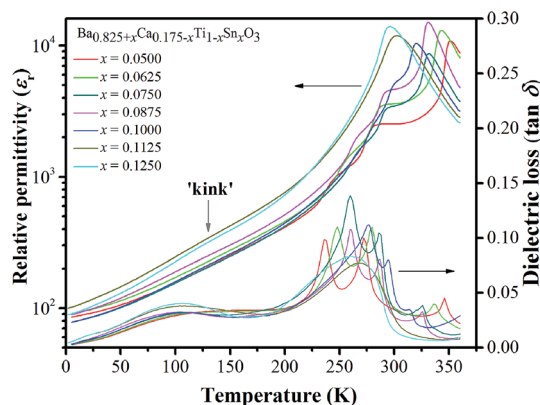


Fig. 7 Temperature dependence of dielectric permittivity and loss tangent measured at 10 Hz for BT-CT-xBS ceramics. A small ‘kink’ in dielectric permittivity at  $T \sim 125$  K is marked by a vertical arrow.

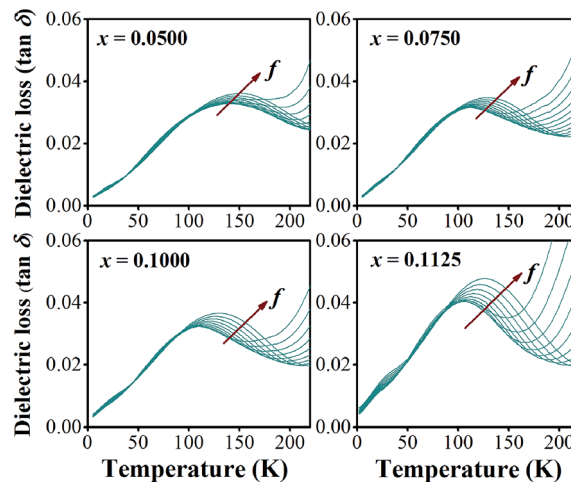


Fig. 8  $\tan \delta$  with varying frequency at a temperature in the range of 2–200 K for BT-CT-xBS ceramics.

In eqn (2) and (3),  $f$  is the applied frequency,  $f_0$  the attempted frequency of dipolar reorientation,  $E_a$  the energy barrier of the reorientation process,  $T$  the maximum temperature of the  $\tan \delta$  peak at an applied frequency,  $T_{VF}$  the ‘static’ dipolar freezing temperature and  $k_B$  the Boltzmann constant. An attempt to fit the data with eqn (2) produced reasonable activation energies of  $E_a$  in the range of 330–625 meV, but unphysical attempts at high frequency  $f_0$  at  $10^{19}$ – $10^{24}$  Hz, were well beyond optical phonons. Results of the fit with the Vogel-Fulcher model of eqn (3) are shown in Fig. 9 for the compositions,  $x = 0.0500$ ,  $x = 0.0750$ ,  $x = 0.1000$ , and  $x = 0.1250$ , respectively. The fitting parameters are listed in Table 1. A good quality fit with physically sound parameters was obtained for the compositions,  $x = 0.0750$ – $0.1250$ , with  $E_a$  ranging from 27 to 71 meV,  $f_0 = 10^7$ – $10^{10}$  Hz and  $T_{VF} = 65$ –86 K. The poor fit for the compositions,  $x = 0.05$ – $0.0625$ , was attributed to a poorly-resolved  $\tan \delta$  peak, probably resulting from several partially overlapping peaks in the  $T = 50$ –150 K range. Indeed, Fig. 8 shows that the main  $\tan \delta$  peak at  $T$

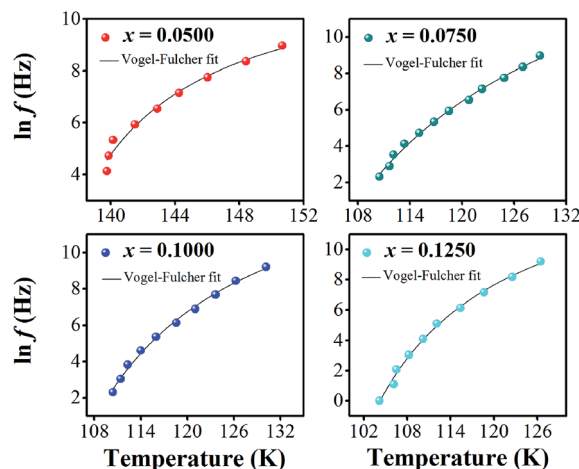


Fig. 9 Natural logarithm of frequency  $\ln(f)$  versus  $1/T$  of BT-CT-xBS ceramics.



Table 1 Parameters and degree of good-fit from the Vogel–Fulcher model for BT–CT–xBS ceramics

Composition	$\ln f_0$ (Hz)	$f_0$ (Hz)	$T_{VF}$ (K)	$E_a$ (meV)	$\chi^2$
$x = 0.0500$	$12.21 \pm 1.44$	$2.01 \times 10^5 \pm 4$	$131.27 \pm 2.77$	$5.6 \pm 3.0$	0.07043
$x = 0.0625$	$9.54 \pm 0.58$	$1.39 \times 10^4 \pm 2$	$123.14 \pm 0.87$	$2.2 \pm 0.7$	0.10293
$x = 0.0750$	$19.14 \pm 2.27$	$2.06 \times 10^8 \pm 10$	$80.46 \pm 6.21$	$43.2 \pm 14.7$	0.02408
$x = 0.0875$	$23.34 \pm 2.01$	$1.37 \times 10^{10} \pm 7$	$65.42 \pm 5.30$	$70.6 \pm 16.3$	0.00807
$x = 0.1000$	$16.54 \pm 1.43$	$1.53 \times 10^7 \pm 4$	$88.38 \pm 3.80$	$26.7 \pm 7.3$	0.02479
$x = 0.1125$	$16.49 \pm 1.60$	$1.46 \times 10^7 \pm 5$	$83.89 \pm 4.75$	$30.0 \pm 9.1$	0.03163
$x = 0.1250$	$16.63 \pm 1.31$	$1.66 \times 10^7 \pm 4$	$85.79 \pm 2.79$	$26.4 \pm 6.0$	0.04949

= 100 K, as well as the low-T shoulder at 30 K, becomes resolved more clearly with increased Sn substituting  $x$ .

It is not inconsequential to identify the source of low-temperature dielectric relaxation explicitly. Both defects and domain walls can cause Vogel–Fulcher relaxation similar to that reported here. Low-frequency (*i.e.*,  $f_0 = 10^5$ – $10^7$  Hz) relaxation is assigned usually to the domain wall motion,<sup>37</sup> whereas high frequency (*i.e.*,  $f_0 = 10^8$ – $10^{12}$  Hz) relaxation is attributed to defect-induced dipolar relaxation.<sup>38</sup> Attempted relaxation at even higher frequency ( $f_0 = 10^{14}$ – $10^{16}$  Hz) may originate in perovskites from small polaron effects.<sup>39</sup> Coupling between the dominant domain-wall and defect-dominant relaxation mechanisms was discussed in ref. 40.

For example, pronounced VF relaxation with  $E_a = 72$  meV,  $f_0 = 10^{12}$  Hz and  $T_{VF} = 90$  K was reported for the BaTiO<sub>3</sub>–0.3BaSnO<sub>3</sub> nonergodic relaxor.<sup>16</sup> The energy scale of this relaxation is similar to that found in this work, but the attempted frequency differs by 2–4 orders of magnitude. Existence of the FE state with the domain walls is not a necessary requirement for dielectric relaxation. In fact, defect relaxation in non-ferroelectric perovskites has been well documented in the literature. For example, relaxation of the Li impurity ion in KTaO<sub>3</sub> has characteristic parameters of  $E_a = 86$  meV and  $f_0 = 8 \times 10^{12}$  Hz;<sup>41</sup> Mn defect on the Sr site in SrTiO<sub>3</sub> relaxes at  $f_0 = 10^{12}$ – $10^{13}$  Hz with  $E_a = 64$ – $78$  meV.<sup>42</sup> In non-stoichiometric BaMg<sub>1/3</sub>Ta<sub>2/3</sub>O<sub>3</sub>, Mg ion misplaced at the Ba site relaxes at  $f_0 = 10^9$  Hz with  $E_a = 38$  meV, whereas oxygen vacancy relaxation occurs at  $f_0 = 5 \times 10^{12}$  Hz and  $E_a = 360$  meV.<sup>43</sup> Other reports on the relaxation of oxygen vacancy in perovskites<sup>44–50</sup> show strong composition dependence of activation energy in the range of 350–910 meV. In view of the literature data discussed, it seems unlikely that the low-temperature relaxation reported here is associated with oxygen vacancy relaxation. It is most plausible that the low-temperature relaxation in the samples of this study is attributed to either defects of impurity or Sn<sup>4+</sup> and Sn<sup>2+</sup> ions misplaced at the A-site because of the rather slow relaxation dynamics (Table 1).

The ferroelectric phase diagram was established according to the dielectric results, as displayed in Fig. 10(a). The diagram consists of three ferroelectric phases; R-, O-, and T-phase and one cubic paraelectric phase.  $T_c$  decreases linearly as the Sn content increases at the rate of 765 K mol<sup>-1</sup> and  $T_{R-O}$  and  $T_{O-T}$  shift close to room temperature for the composition,  $x = 0.1000$ . As a result, ceramics with the composition,  $0.1000 < x < 0.1125$ , are expected to exhibit the O–R–T phase boundary. Fig. 10(b) shows a contour plot of  $\epsilon_r$ , as a function of temperature and

composition related to the phase diagram for BT–CT–xBS ceramics. The maximum  $\epsilon_r$  values are found typically in the neighborhood of the  $T_c$  line, as shown by the yellow-red boundary. Maximum  $\epsilon_r$  is located at 327 K for the composition,  $x = 0.0875$ . It is well known that dielectric and ferroelectric properties contribute to the variation of piezoelectric properties such as  $d_{33} \sim \epsilon_r P_r$ ,<sup>51,52</sup> which has been used to describe the role of identifying direct piezoelectric properties in several KNN-based piezoceramics. In particular, most piezoelectric materials usually operate at room temperature. Thus,  $T_{R-O}$  and  $T_{O-T}$  are important factors that lead to commanding properties. As the phase transition temperatures ( $T_{R-O}$ ,  $T_{O-T}$ , and  $T_c$ ) shift close to room temperature for the compositions,

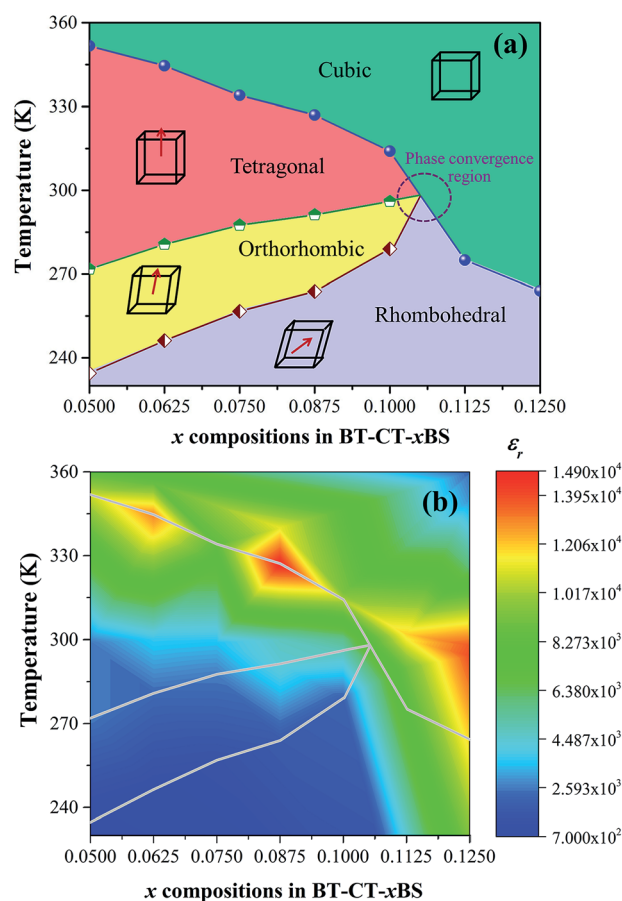


Fig. 10 (a) Phase diagram of BT–CT–xBS ceramics, (b) contour plot of the dielectric constant with temperature and composition of BT–CT–xBS ceramics.



$x = 0.1000$ – $0.1250$ , the room-temperature value of  $\epsilon_r$  is enhanced significantly. Even though the highest composition,  $x = 0.1250$ , is in the orange area ( $\epsilon_r \sim 13\,500$ ) at room temperature, it has a cubic phase and is, therefore, not expected to show outstanding piezoelectric properties. It is interesting that the compositions,  $x = 0.1000$ – $0.1125$ , are inferior to the composition,  $x = 0.1250$ , in terms of  $\epsilon_r$ , but they are expected to show outstanding piezoelectric behavior because of their multiphase composition. However, the composition,  $x = 0.1000$ , could possibly achieve the highest piezoelectric properties because the composition,  $x = 0.1125$ , is located too close to the cubic (paraelectric) phase. In comparison, the relative permittivity value of the composition,  $x = 0.1000$  ( $\epsilon_r \sim 5580$ ), is higher at room temperature than that of soft PZT ( $\epsilon_r \sim 2000$ – $3500$ ) and other BT-based ( $\epsilon_r \sim 3060$ ) ceramics.<sup>13</sup> This is in accordance with a report by Shi *et al.*<sup>35</sup> in that Sn doping causes enhancement of dielectric permittivity, due to the formation of polar nanoregions (PNRs) that are buried in the BT-based matrix.

In order to comprehend the preferable relationship between the constructed phase diagram and electromechanical properties, ferroelectric and piezoelectric properties were measured as a function of Sn compositions. Fig. 11(a) displays room-temperature polarization in an electric field of up to  $50\text{ kV cm}^{-1}$ , measured at a frequency =  $4\text{ Hz}$ . It is seen clearly that all Sn-doped compositions produce a typical ferroelectric (FE) hysteresis loop with remnant polarization ( $P_r$ ), saturated polarization ( $P_s$ ) and coercive field ( $E_c$ ). The Sn-composition dependence of  $P_r$ ,  $P_s$  and  $E_c$  is shown in Fig. 11(b). The  $E_c$  value tends to decrease at higher  $x$  because it is easier to switch the non- $180^\circ$  domain wall in the R-phase, which is mixed with other phases at  $x = 0.1000$ – $0.1250$ , as supported by the XRD, Raman, and dielectric results. This behavior is similar to that observed in other lead-free piezoceramics, which show lower  $E_c$  values in the R-phase.<sup>14,51</sup> Also, the  $P_r$  and  $P_s$  values are likely to decrease with higher Sn concentration. It is evident that  $P_r$  and  $P_s$  values are varied by Sn-substituted compositions, which result from different structural phases. A change in the

hysteresis behavior of the BT–CT–xBS ceramics is represented quantitatively by the FE loop squareness,  $R_{sq}$ , calculated from the following equation:<sup>53</sup>

$$R_{sq} = \frac{P_r}{P_s} + \frac{P_{1.1E_c}}{P_r} \quad (4)$$

where  $P_{1.1E_c}$  is the polarization at an electric field that equals 1.1 times the  $E_c$ .  $R_{sq}$  is equal normally to 2.0 in an ideal hysteresis loop. The  $R_{sq}$  tends to increase with  $x$ ; the first peak of  $R_{sq} = 0.90$  is found at  $x = 0.0750$ , and maximum  $R_{sq} = 1.04$  occurs at  $x = 0.1000$ . Results indicate that the loop features most squareness at  $x = 0.1000$ .

Strain induced by an electric field was measured to investigate the efficiency of BT–CT–xBS ceramics for actuator applications. Fig. 12 displays a unipolar strain *versus*  $E$  for BT–CT–xBS ceramics at room temperature, with the maximum  $E = 10\text{ kV cm}^{-1}$  applied. The strain increases gradually with  $x$  until it reaches the highest value of about  $0.127\%$  at  $x = 0.1000$ , before decreasing to  $0.028\%$  at  $x = 0.1250$ . The normalized strain value or converse piezoelectric coefficient ( $d_{33}^*$ ) was calculated from the relationship of  $S_{\max}/E_{\max}$  in units of  $\text{pm V}^{-1}$ . Fig. 13 shows the  $d_{33}$  and  $d_{33}^*$  dependence of compositions in BT–CT–xBS ceramics. Similar tendencies are seen clearly in both  $d_{33}$  and  $d_{33}^*$  values. The  $d_{33}$  and  $d_{33}^*$  coefficients increase initially at the composition,  $x = 0.0625$ , with  $d_{33} = 385\text{ pC N}^{-1}$  and  $d_{33}^* = 804\text{ pm V}^{-1}$  until maximum values of  $515\text{ pC N}^{-1}$  and  $1293\text{ pm V}^{-1}$  are reached at  $x = 0.1000$ . Eventually, both values drop to  $d_{33} = 104\text{ pC N}^{-1}$  and  $d_{33}^* = 285\text{ pm V}^{-1}$  at  $x = 0.1250$ , due to the cubic phase that dominates the phase mixture. The highest  $d_{33}$  and  $d_{33}^*$  value were observed clearly at the composition,  $x = 0.1000$ . The high piezoelectric response in the composition,  $x = 0.1000$ , is caused by its multiphase transition temperature located near room temperature. The  $T_{R-O}$ ,  $T_{O-T}$ , and  $T_c$  are evident near room temperature.

It is well-known that the dynamic of multiphase transition has preferred oriented polarizations in more than 26 directions at the composition,  $x = 0.1000$ , (*i.e.*, 6, 12 and 8 for the T-, O-, and R-phase, respectively), which confirms the dielectric result. The PPT and MPB region enhance ferroelectric and

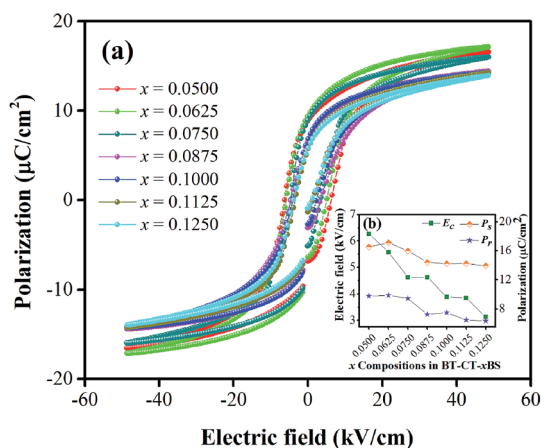


Fig. 11 (a) Composition-dependent  $P$ – $E$  hysteresis loops of BT–CT–xBS ceramics at room temperature, (b)  $P_r$ ,  $P_s$  and  $E_c$ , with composition dependence.

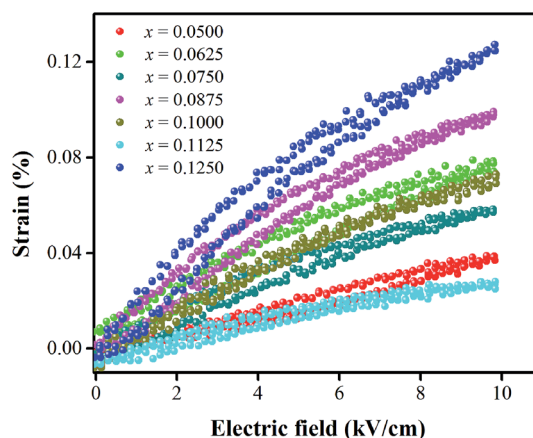


Fig. 12 Unipolar strain with electric-field of BT–CT–xBS ceramics at room temperature.



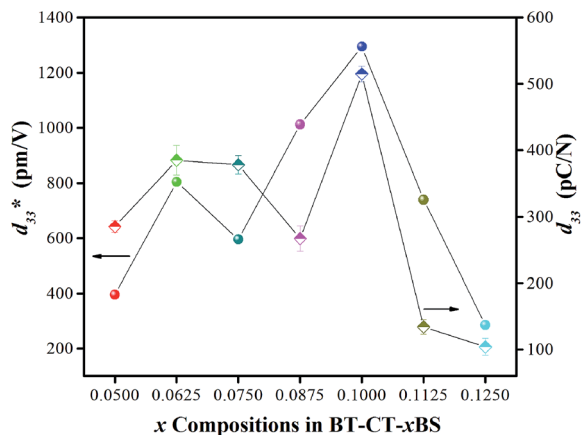


Fig. 13 Dependence of  $d_{33}$  and  $d_{33}^*$  values and  $x$  compositions in BT-CT-xBS ceramics.

piezoelectric properties, due to the intrinsic (compositions, polarized rotation, and polarized elongation/compression) and extrinsic domain wall effect.<sup>54,55</sup> Flattened free energy is caused by being near the Curie temperature, which affects the intrinsic effect.<sup>55</sup> The compositional design based on chemical modifications creates a low  $T_c$  at the composition,  $x = 0.1000$ , which leads to an easy path for polarized rotation and extension at the multiphase boundary that acts on a unit cell scale. This contributes to intrinsic structural instabilities and improved piezoelectricity. Furthermore, the phase boundary makes it easier for domain wall motions<sup>56,57</sup> because of structural instability near the Curie temperature. In particular, the non-180° domain wall motion of O- and R-phase<sup>54</sup> induces piezoelectric properties that show a particularly high strain. As discussed previously in the dielectric result, the composition,  $x = 0.1000$ , exhibits  $T_{R-O}$  and  $T_{O-T}$  phase transition near room temperature. Hence, the electric field has an enormous impact on phase transitions more in this composition than in others. It was reported that polarized rotation from a [111] to [001] direction, induced by an external electric field, can drive the phase transition from R- to T-phase in the perovskite ferroelectrics, BaTiO<sub>3</sub>.<sup>58,59</sup> Polarized rotation with flat free energy can motivate lattice-deformation, leading to a better piezoelectric response. Thus, large piezoelectric coefficients at the composition,  $x = 0.1000$ , are believed to ease polarization of the rotation by enough electric field during strain measurement, due to the nearest R-O-T multiphase transition.

The maximum values of  $d_{33}$  and  $d_{33}^*$  at the composition,  $x = 0.1000$ , in this study were compared to other lead-free piezoelectrics<sup>13,29,60-63</sup> and commercially available soft PZT ceramics, as shown in Fig. 14. The values of  $d_{33}$  and  $d_{33}^*$  are comparable to some BT-based ceramics. However, the best  $d_{33}$  and  $d_{33}^*$  values are higher than those reported for commercially available soft PZT ( $d_{33} = 410$  pC N<sup>-1</sup> and  $d_{33}^* = 600$  pm V<sup>-1</sup>).<sup>4</sup> This Ba<sub>0.925</sub>-Ca<sub>0.075</sub>Ti<sub>0.9</sub>Sn<sub>0.1</sub>O<sub>3</sub> piezoelectric material is devoid of Pb, which is attractive, non-toxic for the environment and follows current legislation. Its use is possible for replacing commercial lead-based piezoelectric ceramics in actuator applications.

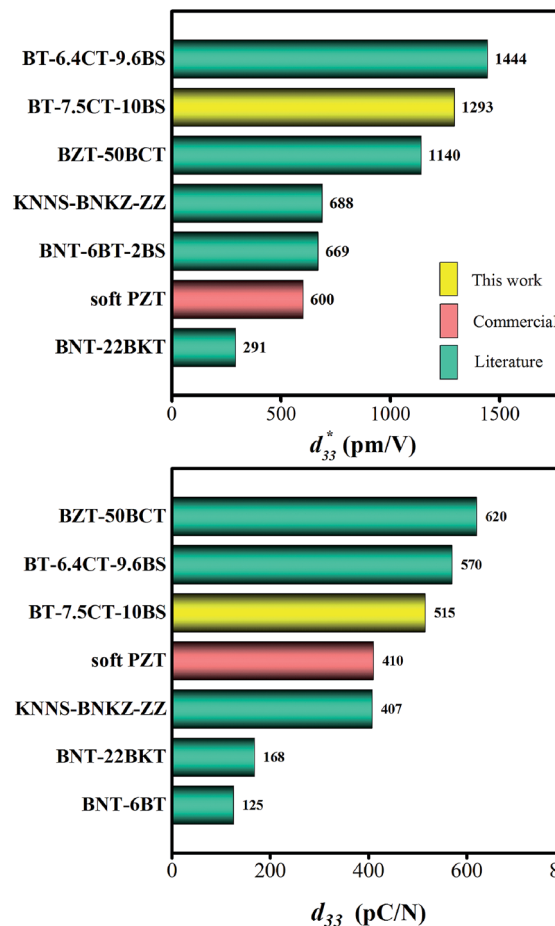


Fig. 14 Comparison of  $d_{33}^*$  (top) and  $d_{33}$  (bottom) coefficient values of Pb and Pb-free piezoelectric ceramics.

## Conclusions

The lead-free Ba<sub>0.825+x</sub>Ca<sub>0.175-x</sub>Ti<sub>1-x</sub>Sn<sub>x</sub>O<sub>3</sub> piezoceramic system was prepared *via* the conventional solid state reaction method. This study found that the substitution of Ti with Sn by structural modification of the perovskite phases improved the dielectric, ferroelectric and piezoelectric properties. The multi-ferroelectric phase transition (R-O, O-T and T-C) near room temperature was found to improve the piezoelectric response of the ceramics significantly. The composition,  $x = 0.1000$ , shows the highest  $d_{33} = 515$  pC N<sup>-1</sup> and  $d_{33}^* = 1293$  pm V<sup>-1</sup> values based on the results of this study. Also, this study reported anomalous dielectric relaxation at below  $T_{R-O}$  phase transition, with activation energy of  $E_a \approx 20-70$  meV and freezing temperature of  $T_{VF} \approx 65-85$  K.

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