

Ultrahigh-temperature piezoelectric polycrystalline ceramics: dramatically enhanced ferroelectricity, piezoelectricity and electrical resistivity in $\text{Ca}_{1-3x}\text{Bi}_{2+3x}\text{Nb}_{2-x}\text{Mn}_x\text{O}_9$

Changbai Long, Wei Ren, Kun Zheng & Huiqing Fan

To cite this article: Changbai Long, Wei Ren, Kun Zheng & Huiqing Fan (2020) Ultrahigh-temperature piezoelectric polycrystalline ceramics: dramatically enhanced ferroelectricity, piezoelectricity and electrical resistivity in $\text{Ca}_{1-3x}\text{Bi}_{2+3x}\text{Nb}_{2-x}\text{Mn}_x\text{O}_9$, Materials Research Letters, 8:4, 165-172, DOI: [10.1080/21663831.2020.1725676](https://doi.org/10.1080/21663831.2020.1725676)

To link to this article: <https://doi.org/10.1080/21663831.2020.1725676>



© 2020 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group



Published online: 14 Feb 2020.



Submit your article to this journal [↗](#)



Article views: 2822



View related articles [↗](#)



View Crossmark data [↗](#)



Citing articles: 11 View citing articles [↗](#)



ORIGINAL REPORT



Ultrahigh-temperature piezoelectric polycrystalline ceramics: dramatically enhanced ferroelectricity, piezoelectricity and electrical resistivity in $\text{Ca}_{1-3x}\text{Bi}_{2+3x}\text{Nb}_{2-x}\text{Mn}_x\text{O}_9$

Changbai Long^{a,b}, Wei Ren^b, Kun Zheng^b and Huiqing Fan^c

^aSchool of Advanced Materials and Nanotechnology, Xidian University, Xi'an, People's Republic of China; ^bElectronic Material Research Laboratory, Key Laboratory of the Ministry of Education & International Center for Dielectric Research, Xi'an Jiaotong University, Xi'an, People's Republic of China; ^cState Key Laboratory of Solidification Processing, School of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an, People's Republic of China

ABSTRACT

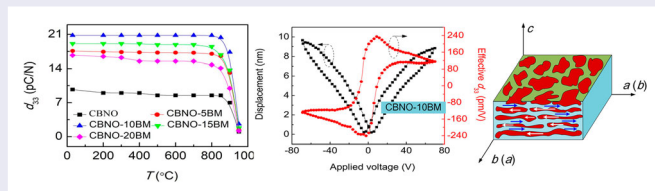
Among Aurivillius-phase ferroelectric ceramics, $\text{CaBi}_2\text{Nb}_2\text{O}_9$ is considered as the best candidate with potential applications in ultrahigh-temperature piezoelectric devices due to the highest T_c ($\sim 940^\circ\text{C}$). This paper reports that BiMn co-substitution at A and B sites gives rise to dramatic enhancements in ferroelectricity, piezoelectricity, and electrical resistivity of $\text{CaBi}_2\text{Nb}_2\text{O}_9$ ceramics. The optimum composition ($\text{Ca}_{0.97}\text{Bi}_{2.03}\text{Nb}_{1.99}\text{Mn}_{0.01}\text{O}_9$) with a T_c of $953 \pm 3^\circ\text{C}$ shows a high ferroelectric remnant polarization (P_r), field-induced strain (S_{33}), piezoelectric activity d_{33} and d_{33}^* with values of $\sim 11.1 \mu\text{C}/\text{cm}^2$, 4.9×10^{-4} , 20.8 and 26.1 pC/N, respectively, which are about two to three times those of $\text{CaBi}_2\text{Nb}_2\text{O}_9$.

ARTICLE HISTORY

Received 17 October 2019

KEYWORDS

Aurivillius-phase ferroelectrics; $\text{CaBi}_2\text{Nb}_2\text{O}_9$ ceramics; piezoelectricity; oxygen vacancy; BiMn substitution



IMPACT STATEMENT

Significant ferroelectric remnant polarization ($P_r = 11.1 \mu\text{C}/\text{cm}^2$), field-induced strain ($S_{33} = 4.9 \times 10^{-4}$), and piezoelectric activity ($d_{33} = 20.8 \text{ pC}/\text{N}$, $d_{33}^* = 26.1 \text{ pC}/\text{N}$) are simultaneously induced in ultrahigh T_c $\text{CaBi}_2\text{Nb}_2\text{O}_9$ piezoceramics by BiMn substitution.

1. Introduction

Piezoelectric materials integrated into high-temperature sensors must take into account two essential application requirements: (1) high Curie temperature (T_c) and (2) high piezoelectric activity (d_{33}), which are desired to meet high operating temperature and high sensitivity, respectively [1–3]. In addition, high electrical resistivity (ρ) is required for ferroelectric materials, which will ensure that they are polarized under large electric fields without breakdown or excessive charge leakage. High ρ is also required during device operating at high

temperatures, because the piezoelectric material has not only the function of generating electric charge under stress or strain but also the ability to maintain the charge for a time long enough to be detected by the electronic system [3]. The maximum operating temperature for ferroelectric materials is at least $\sim 150^\circ\text{C}$ below T_c , because they will be depolarized and most of the piezoelectricity will be lost near this temperature [4]. Single crystals with ultrahigh T_c (~ 1000 – 1400°C) such as LiNbO_3 , GaPO_4 , $\text{La}_3\text{Ga}_5\text{SiO}_{14}$, $\text{YCa}_4\text{O}(\text{BO}_3)_3$, $\text{GdCa}_4\text{O}(\text{BO}_3)_3$ are potential candidates for high-temperature piezoelectric

CONTACT Changbai Long ✉ longchangbai@126.com School of Advanced Materials and Nanotechnology, Xidian University, Xi'an 710071, People's Republic of China; Electronic Material Research Laboratory, Key Laboratory of the Ministry of Education & International Center for Dielectric Research, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China; Wei Ren ✉ wren@xjtu.edu.cn Electronic Material Research Laboratory, Key Laboratory of the Ministry of Education & International Center for Dielectric Research, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China

Supplemental data for this article can be accessed here. <https://doi.org/10.1080/21663831.2020.1725676>

applications [3,5–7]. However, the piezoelectric activity of these single crystals is rather low ($d_{33} = \sim 4\text{--}7$ pC/N) and the cost for them is much high.

The structure of Aurivillius compounds can be described as the intergrowth of $(\text{Bi}_2\text{O}_2)^{2+}$ layers and $(\text{A}_{n-1}\text{B}_n\text{O}_{3n+1})^{2-}$ layers, where n ($n = 1\text{--}6$) is the number of octahedral layers in the perovskite layers [8]. Some Aurivillius ferroelectric ceramics with high T_c of $\sim 650\text{--}940^\circ\text{C}$ show relatively high piezoelectric activity, high resistivity, and low dielectric loss. They have the advantages over the above single crystals of lower cost and the possibility to control their properties by compositional modifications and processing [2]. This makes them more competitive than piezoelectric single crystals applied to high-temperature sensors operating at $500\text{--}800^\circ\text{C}$. Among them, $\text{CaBi}_2\text{Nb}_2\text{O}_9$ ceramic is a promising candidate of high-temperature piezoelectric materials working at high temperature up to 800°C due to the highest T_c of $\sim 940^\circ\text{C}$ [9]. However, the reported d_{33} for ordinarily fired (OF) $\text{CaBi}_2\text{Nb}_2\text{O}_9$ ceramics is only ~ 7.5 pC/N [9]. Yan et al. reported that the value of textured $\text{CaBi}_2\text{Nb}_2\text{O}_9$ ceramic prepared by spark plasma sintering increased to ~ 19.5 pC/N [9]. For Aurivillius-phase ferroelectrics, resistivity in the maximum d_{33} direction (ab plane) is much lower than that in the corresponding perpendicular axis (i.e. along the c -axis direction), which makes the poling process difficult due to high leakage current and limits their integration in high-temperature devices [10]. In addition, it is desirable to obtain high d_{33} in OF ferroelectric ceramics from the viewpoint of commercial applications. In the literature, $\text{CaBi}_2\text{Nb}_2\text{O}_9$ -based ceramics showed increased d_{33} of $12.6\text{--}17.5$ pC/N with appropriate dopants or substitutions at A and/or B sites, e.g. (NaCe) and (LiCePr) substitution at A site and (WTi) substitution at B site [11–15].

In this work, we selected $\text{Bi}^{3+}/\text{Mn}^{2+}$ co-substitution at A and B sites to improve ferroelectric polarization, piezoelectric property, and electrical resistivity of $\text{CaBi}_2\text{Nb}_2\text{O}_9$. Details of the prepared $\text{Ca}_{1-3x}\text{Bi}_{2+3x}\text{Nb}_{2-x}\text{Mn}_x\text{O}_9$ (CBNO-1000xBM, $x = 0, 0.005, 0.01, 0.015$, and 0.02) ceramics and characterizations of their structures and electrical properties are presented in supplemental material. Among all compositions, the optimum composition ($x = 0.01$) with ultrahigh T_c ($953 \pm 3^\circ\text{C}$) shows d_{33} of ~ 20.8 pC/N and d_{33}^* of ~ 26.1 pC/N, which are all higher than those of the above-mentioned piezoelectric single crystals and ceramics with ultrahigh T_c of $> 850^\circ\text{C}$.

2. Results and discussion

Phase purity and microstructure of CBNO-1000xBM were monitored using XRD and SEM, respectively

(Figures S1 and S2). The results reveal that there is no any impurity phase generated in CBNO-1000xBM, indicating Bi and Mn ions diffusing into the lattices of $\text{CaBi}_2\text{Nb}_2\text{O}_9$. Notably, CBNO-15BM and CBNO-20BM both show abnormally strong (00 l) diffraction peaks, e.g. (008) and (0010), being indicative of an increase in the degree of texture in the c -axis direction. This degree of texture expressed by using the Lotgering orientation factor (LOF) is calculated to be $\sim 29.9\text{--}34.3\%$ for them, much higher than that of other compositions with a lower level of BiMn substitution ($\sim 12.5\text{--}16.2\%$) (inset of Figure S1a). Viewed from cross-section SEM images, the average length of grains increases obviously introducing BiMn substitution. The value of modified CBNO-1000xBM compositions is $\sim 12.17\text{--}16.75$ μm , much higher than that of CBNO-0BM (~ 5.36 μm) (Figure S2a). It is presumable that additives of Bi_2O_3 and/or MnO act as effective flux agents functioning as lowering the temperature for ceramics' sintering. In addition, the average aspect ratio t/L (thickness/length of grain) first increases and then decreases with increasing x . This ratio of CBNO-0BM, CBNO-10BM, and CBNO-20BM is about 0.23, 0.49, and 0.29, respectively.

Rietveld structural refinement suggests that CBNO-10BM crystallizes in orthorhombic $A2_1am$ space group with $a = 5.47992(3)$ Å, $b = 5.43959(3)$ Å, $c = 24.88649(6)$ Å, and $V = 741.830(6)$ Å³ (Table S1). Figure 1(a) clearly shows that the refined data well fit with the experimental ones and the final factors, R_{wp} , R_p and reduced χ^2 , are reasonable with values of 8.11%, 5.89%, and 2.015, respectively. Refining the atomic occupancies shows a relatively low degree of cation disordering between the perovskite layer and the $(\text{Bi}_2\text{O}_2)^{2+}$ layer. The occupancy of Ca and Bi at the perovskite A site is 0.8534(8) and 0.1466(8), and the value at the cationic site of the $(\text{Bi}_2\text{O}_2)^{2+}$ layer is 0.0583(5) and 0.9417(5), respectively.

Based on the refined structural parameters (Table S1), the crystal structure of CBNO-10BM is depicted in the inset of Figure 1(a). With $A2_1am$ orthorhombic symmetry, atomic displacements along the polar axis (a -axis) from the corresponding positions in the parent tetragonal ($I4/mmm$) structure cause spontaneous polarization (P_S). Figure 1(b) illustrates atomic displacement along the a -axis of each constituent ion in CBNO-10BM. Clearly, the perovskite cations and anions show significant displacements. Based on these atomic displacements, the total P_S of CBNO-10BM can be calculated with the Sivakumar model in the same manner as reported in Ref. [16]. The calculated P_S of CBNO-10BM is ~ 32.8 $\mu\text{C}/\text{cm}^2$ (Figure 1(c)), much higher than that of CBNO-0BM (~ 24.4 $\mu\text{C}/\text{cm}^2$) [9]. For Aurivillius-phase ferroelectrics, that Bi^{3+} with $6s^2$

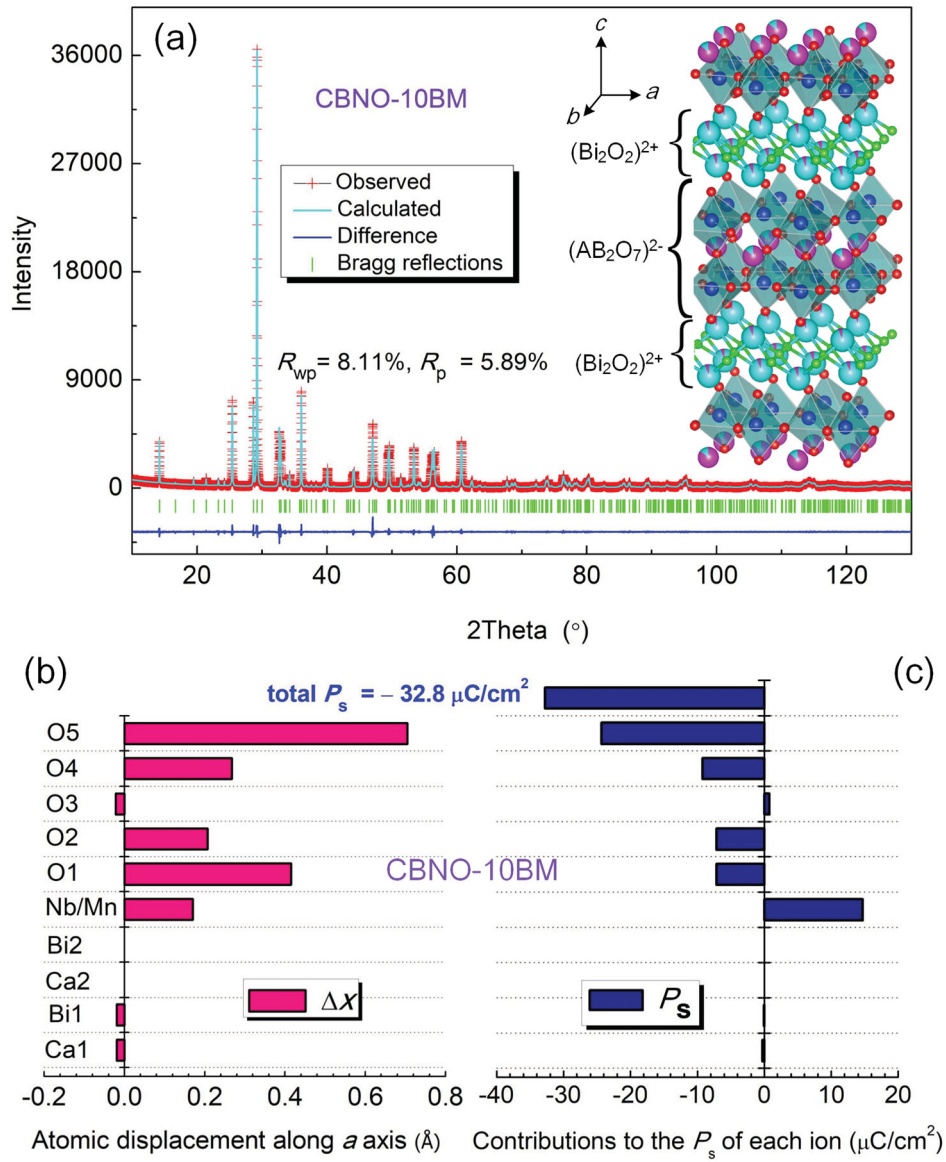


Figure 1. (a) Rietveld refinement for CBNO-10BM with an inset showing its crystal structure at room temperature; (b) ion displacement and (c) contribution to the total spontaneous polarization (P_s) of each constituent ion in CBNO-10BM.

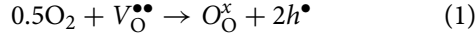
lone pair electrons occupying the perovskite A site can result in an enhancement in orthorhombic distortion and an increase in ferroelectricity [17]. Therefore, increased P_s in CBNO-10BM is probably attributed to the fact that more highly polarizable Bi^{3+} cations occupy the perovskite A sites. Based on the XRD data (Figure S1a), lattice parameters (a , b , c) of other CBNO-1000xBM are also refined. That the unit cell volume (V) increases gradually with increasing x should be the result of the integration of Bi^{3+} into the Ca^{2+} site, because Bi^{3+} with $6s^2$ lone pair electrons relative to Ca^{2+} has a larger polarizability (Bi^{3+} : $6.12 \text{ \AA}^3$ and Ca^{2+} : $3.12 \text{ \AA}^3$) [18].

Figure 2(a) shows the temperature dependence of dielectric permittivity (ϵ') of CBNO-1000xBM. The

maximum ϵ' (ϵ'_{max}) corresponds to the ferroelectric-to-paraelectric phase transition, and the error for extracted T_c is within $\pm 2-3^\circ C$. In the inset of Figure 2(a), T_c of CBNO-1000xBM ranges from $\sim 941 \pm 2^\circ C$ to $\sim 953 \pm 3^\circ C$. T_c first increases and then decreases as x increases from zero to 0.02, which is the same as the change in orthorhombicity defined as $2(a-b)/(a+b)$. This implies that ferroelectricity in CBNO-1000xBM is associated with their structural distortion. It is noted that BiMn substitution gives rise to an obvious decrease in the dielectric loss ($\tan \delta$) in the high-temperature segment ($\sim 400-940^\circ C$) (Figure 2(b)). The loss of CBNO-10BM is lower than 0.1 below $700^\circ C$ (inset of Figure 2(b)), which will be important

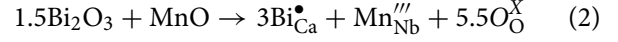
for its high-temperature piezoelectric applications. This decrease in dielectric loss is attributed to an increase in electrical resistivity. Inspection from the impedance spectra of CBNO-1000xBM reveals that the size of high-frequency semicircle associated with bulk resistivity (ρ_b) increases with the BiMn substitution (Figure S3). ρ_b of CBNO-10BM relative to CBNO-0BM increases by about two orders of magnitude at 450–600°C.

CBNO-0BM is a typically mixed p -type ($h^\bullet$) and ionic conductor where holes are created due to the oxidation of oxygen vacancies ($V_O^{\bullet\bullet}$) (Figure S3):



Here, the oxygen vacancies are primarily generated during processing due to the loss of Bi_2O_3 . In particular,

BiMn co-substitution at the A/B sites results in no additional $V_O^{\bullet\bullet}$ in CBNO-1000xBM. In the starting compositions of them, the charge compensation for Mn^{2+} acceptor substitution for Nb^{5+} at the B site involves in Bi^{3+} donor substitution for Ca^{2+} at the A site:



The EPR results indicate that parts of Mn^{2+} ions have been oxidized to Mn^{3+} and Mn^{4+} due to the absorption of $h^\bullet$ (Figure S4):

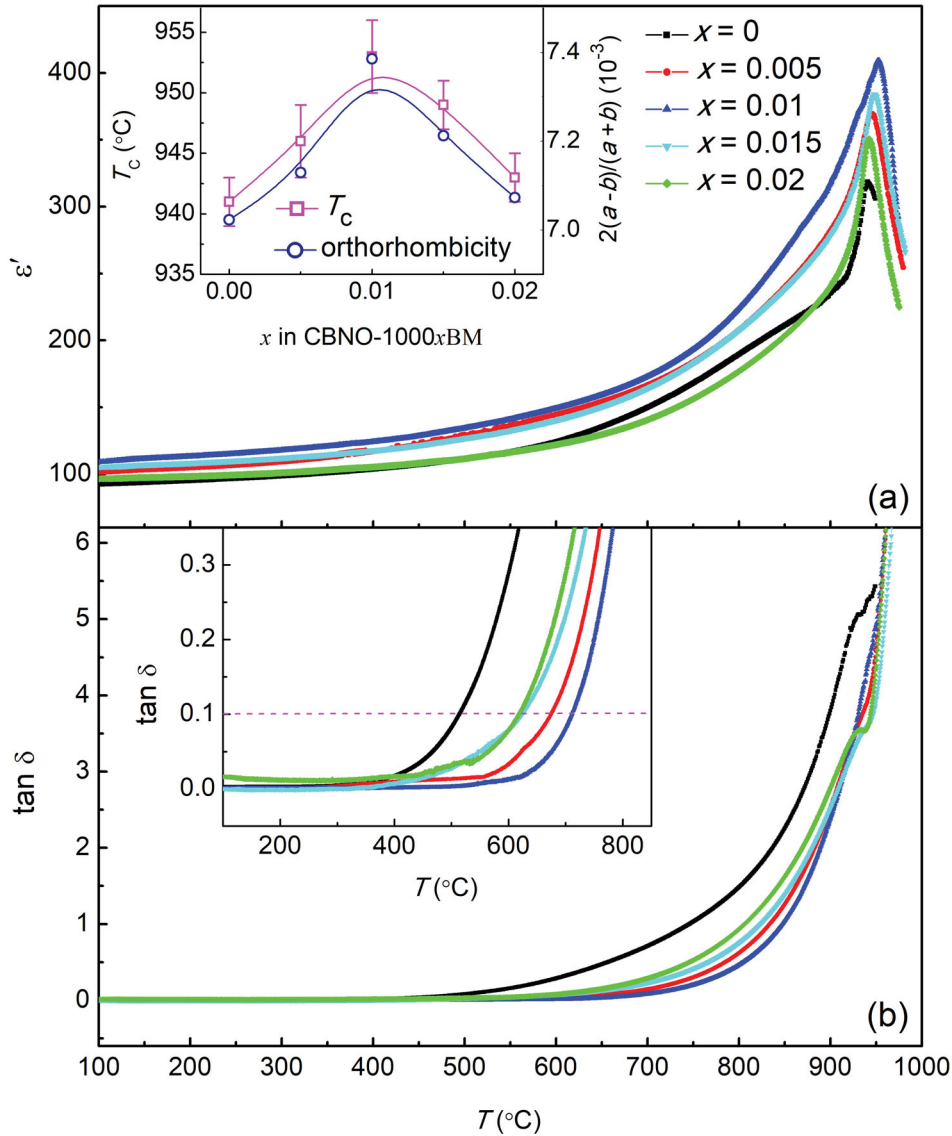
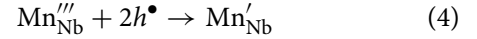
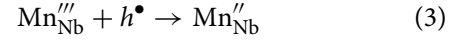


Figure 2. Temperature dependences of dielectric properties at 1M Hz for CBNO-1000xBM: (a) dielectric permittivity (ϵ') with an inset showing extracted T_c and structural orthorhombicity $[2(a-b)/(a+b)]$; (b) dielectric loss ($\tan\delta$) with an inset showing regionally enlarged drawing.

This oxidation of Mn^{2+} promotes the completion of reaction (1). Therefore, the amount of both $V_{\text{O}}^{\bullet\bullet}$ and $h^{\bullet}$ in modified CBNO-1000xBM decreases. This can be confirmed by the fact that CBNO-10BM shows the intrinsic electronic conduction with a high activity energy of 1.75 eV (Figure S3).

CBNO-1000xBM shows saturated P - E loops and butterfly-typed strain curves, which are plotted in Figure 3(a-e). Extracted ferroelectric remnant polarization (P_r) and field-induced strain (S_{33}) of CBNO-1000xBM are

$\sim 3.8\text{--}11.1 \mu\text{C}/\text{cm}^2$ and $\sim 2.6\text{--}4.9 \times 10^{-4}$, respectively (Figure 3(f)). The change trends in P_r and S_{33} are similar to those in T_c , i.e. they first increase and then decrease with increasing x . In addition, inverse piezoelectric coefficient d_{33}^* of the samples can be calculated directly from the slope of the strain versus electric field curves. d_{33}^* of CBNO-1000xBM is $\sim 11.2\text{--}26.1 \text{ pm}/\text{V}$ (pC/N) (Figure 4(a)). Also, piezoelectric coefficients d_{33} and d_{31} of the samples can be measured after DC field poling. d_{33} and d_{31} of CBNO-0BM are ~ 9.7 and $-13.5 \text{ pC}/\text{N}$,

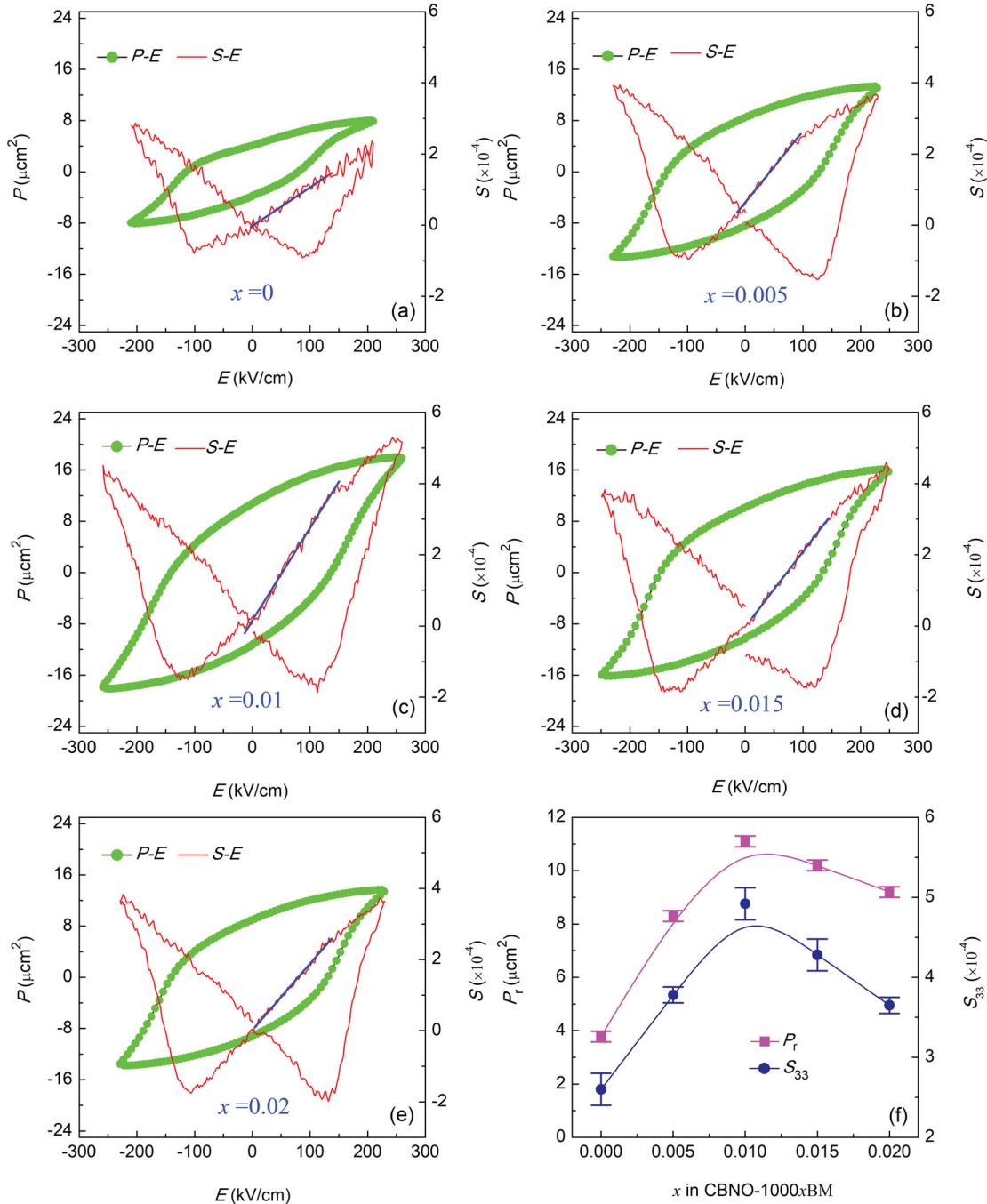


Figure 3. (a–e) P - E loops and (f) extracted P_r and S_{33} of CBNO-1000xBM measured at 140°C and 10 Hz.

and the values of modified composition increases to ~ 16.7 – 20.8 and ~ -20.3 – 26.5 pC/N, respectively. For each composition, the d_{33} value is lower than that of, and the difference in them could be attributed to difficulties accurately determining the slope from the S – E loop.

Figure 4(b) shows the effects of thermal depoling on d_{33} of CBNO–1000xBM. These d_{33} values were measured at room temperature after annealing for 2 h at each x -axis temperature. All the compositions demonstrate good piezoelectric stability against temperature,

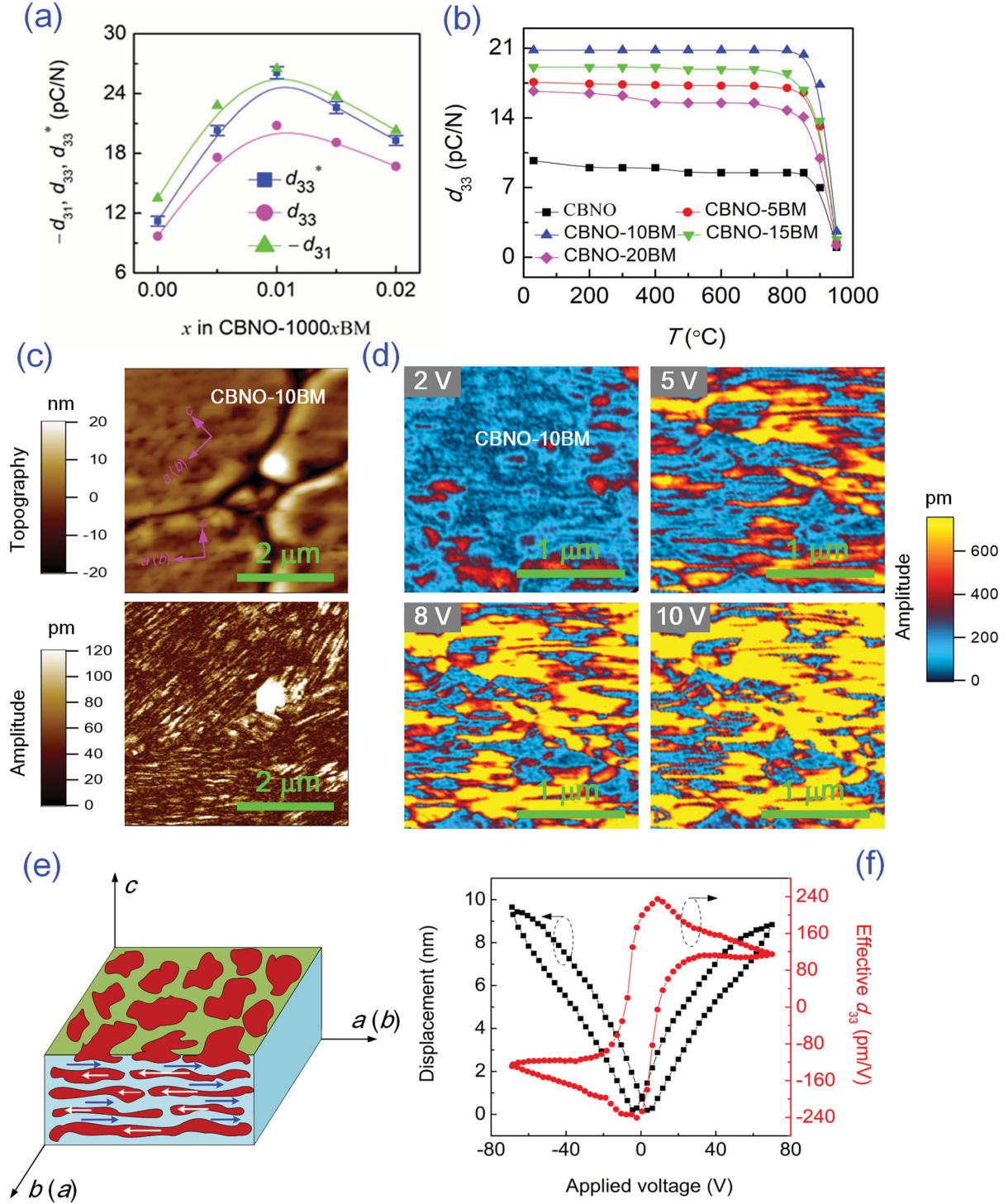


Figure 4. (a) d_{33}^* , d_{33} and d_{31} and (b) effect of thermal temperature (for 2 h) on d_{33} of CBNO–1000xBM. (c) Cross-section topographic and vertical PFM (V-PFM) images of CBNO–10BM. (d) Microscopic piezoelectric response of CBNO–10BM at various voltage. (e) Schematic illustration of the 3D domain structure in CBNO–10BM. (f) Locally microscopic displacement–voltage curve (D – V) and piezoelectric hysteresis loop (d_{33}^* – V) of CBNO–10BM.

and CBNO-10BM and CBNO-15BM still have high d_{33} of ~ 20.6 and 18.5 pC/N after 800°C thermal depoling. A possible reason for this stable d_{33} is a small contribution from the piezoelectrically active non- 180° domain walls. The fraction of the total d_{33} that is due to the irreversible displacement of domain walls is estimated to be $\sim 8.85\%$ and $\sim 18.6\%$ for CBNO-10BM and CBNO-20BM, respectively, in terms of the Rayleigh law (Figure S6). For each composition, d_{33} decreases rapidly when the annealing temperature is near T_c and then becomes almost zero above T_c .

Furthermore, the domain structure of CBNO-1000xBM was characterized by PFM measurements. Figure 4(c) shows cross-section topography and vertical PFM images of CBNO-10BM. Clearly, CBNO-10BM shows a complicated domain configuration with high-density domain walls. Through the PFM image, bright and dark stripes correspond to antiparallel 180° domains and most of domain walls are parallel to the a - b plane and perpendicular to the c -axis. This domain pattern is much less regular than that of $\text{Bi}_4\text{Ti}_3\text{O}_{12}$ but similar to that of $\text{SrBi}_2\text{Ta}_2\text{O}_9$ [19,20]. It is believed that the rod-shaped domains are primarily oriented along the polarization vector (a -axis), and a corresponding 3D domain configuration is schemed in Figure 4(e). The domain regions merge gradually as the voltage increases from 2 to 10 V because the polarization vector of the domains that points into the plane is reversed under a larger voltage (Figure 4(d)). The polarization patterns at 8 and 10 V are much brighter with respect to the ones at 2 and 5 V, indicating that the higher the voltage, the larger the amplitude. In addition, surface displacement was achieved by keeping the PFM tip fixed above the interesting (bright) point and applying a DC voltage from -75 to 75 V, while the piezoelectric response signal was recorded simultaneously. This displacement reflects locally microscopic piezoelectric response of CBNO-10BM nearly parallel to the a - b plane. Viewed from Figure 4(f), displacement-voltage curve (D - V) presents as a typical well-shaped 'butterfly' loop, and CBNO-10BM shows a significant electrostrictive effect with a displacement maximum of 8.9 nm appearing at 75 V. The corresponding piezoelectric hysteresis loop (d_{33}^* - V) derived from the slope of the D - V curve reveals locally microscopic d_{33}^* of ~ 115 – 230 pm/V at 10 – 75 V for CBNO-10BM. In contrast, CBNO-10BM shows much low macroscopic piezoelectricity of ~ 26.1 pm/V (Figure 4(a)), which is the result of a compromise of piezoelectric effects in different crystallographic directions in randomly oriented ceramics. Moreover, giant internal stresses both at the grain boundaries and at the domain boundaries are harmful to achieve significantly macroscopic d_{33}^* .

Among all compositions, CBNO-10BM shows the highest P_r , S_{33} , d_{33} , d_{33}^* , and d_{31} with values of ~ 11.1 $\mu\text{C}/\text{cm}^2$, 4.9×10^{-4} , 20.8 , 26.1 and -26.5 pC/N, respectively. Comparisons in T_c and d_{33} reveal that the obtained T_c ($\sim 953 \pm 3^\circ\text{C}$) and d_{33} of CBNO-10BM are both higher than the reported values ($T_c = \sim 868$ – 939°C , $d_{33} = \sim 12.6$ – 17.5 pC/N) of other modified $\text{CaBi}_2\text{Nb}_2\text{O}_9$ ceramics reported in the literature (see Figure S7). Dramatically enhanced ferroelectric properties and electro-mechanical characteristics of CBNO-10BM can be attributed to three effects induced by BiMn substitution. First, P_s of CBNO-10BM increases significantly from 24.4 (CBNO-0BM) to 32.8 $\mu\text{C}/\text{cm}^2$. Commonly, piezoelectricity of the ferroelectrics is dominated by both intrinsic lattice contribution and extrinsic contribution from movements of non- 180° domain walls [21,22]. For modified CBNO-1000xBM, enhanced piezoelectricity seems to be primarily attributed to the increases in P_s and P_r . Second, BiMn substitution can decrease effectively the $V_{\text{O}}^{\bullet\bullet}$ concentration ($[V_{\text{O}}^{\bullet\bullet}]$) at the perovskite lattices due to the oxidation of Mn^{2+} to Mn^{3+} and/or Mn^{4+} . This is consistent with the results of Mn-substituted $0.62\text{Bi}_{0.5}\text{Na}_{0.5}\text{TiO}_3$ – 0.06BaTiO_3 – 0.32 ($\text{Sr}_{0.7}\text{Bi}_{0.2}[\text{O}_{0.1}]\text{TiO}_3$ ceramics [23]. For CBNO-0BM, ferroelectric polarization is slightly pinched at around $E = 0$ kV/cm (Figures 3(a) and S5(a)) and the measured P - E loop after dc poling (150 kV/cm) is strongly asymmetric with the establishment of a large internal bias field ($E_{\text{ib}} = 35.1$ kV/cm) (Figure S5(b)). It is suggested that one degradation mechanism of its P_r is the pinning of domain walls due to the oxygen vacancies. With decreasing $[V_{\text{O}}^{\bullet\bullet}]$, this pinning effect disappears and the number of available switching domain wall increases; thus, CBNO-10BM shows significant P_r and S_{33} . Simultaneously, relatively high leakage current and electrical conductivity in CBNO-0BM decrease significantly with BiMn substitution (Figure S3). This ensures that CBNO-10BM is sufficient to be poled under higher applied field and thus improves its ferroelectricity and piezoelectricity. Third, CBNO-10BM ceramic shows a sound grain growth with much large size and high t/L ratio, because the additive of BiMn controls the growth of plate-like grains. As a result, there may be more crystallographic directions suitable for polarization [24]. In ferroelectric ceramics, the neighboring grain boundaries have a significant influence on the switching of domains within one grain under electrical poling [7,25]. Lowering the volume of grain boundaries and relieving internal stresses are also beneficial to that the domains switching in the coarse grains of CBNO-10BM. The results also lead to increased P_r , S_{33} , and d_{33} for CBNO-10BM.

The degradations in ferroelectricity and piezoelectricity of CBNO-15BM and CBNO-20BM could be resulted

from a dimensional mismatch between perovskite and bismuth oxide layers [24], due to higher level of BiMn substitutions. It is well known that the electrical properties of layer-structured Aurivillius ferroelectrics are dominant in the a - b plane (normal to c -axis). Therefore, higher c -oriented texture is not in favor of the improvements in ferroelectric and piezoelectric properties for them.

3. Conclusions

Dielectric, ferroelectric, and piezoelectric properties of CBNO-10BM ceramics are characterized. BiMn co-substitution at A and B sites results in an increase in P_S and a decrease in $[V_O^{\bullet\bullet}]$ as well as a sound grain growth. Therefore, modified CBNO-1000xBM compositions relative to CBNO-0BM show dramatically enhanced ferroelectricity, piezoelectricity, and electrical resistivity. CBNO-10BM with T_C of $953 \pm 3^\circ\text{C}$ has P_r , d_{33} , and d_{33}^* with values of $11.1 \mu\text{C}/\text{cm}^2$, 20.8 and $26.1 \text{ pC}/\text{N}$, respectively, which are all higher than those of the reported piezoelectric single crystals and ceramics with ultrahigh T_C of $> 850^\circ\text{C}$. This combined stable d_{33} and high resistivity suggests that it is a very promising material with potential applications in ultrahigh piezoelectric devices.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Natural Science Foundation of China [grant numbers 51502346, 51332003 and 51672220] and China Postdoctoral Science Foundation [grant numbers 2017M623165 and 2019T120904].

References

- [1] Turner RC, Fuierer PA, Newnham RE, et al. Materials of high temperature acoustic and vibration sensor: a review. *Appl Acoust.* 1994;41:299–324.
- [2] Damjanovic D. Materials for high temperature piezoelectric transducers. *Curr Opin Solid State Mater Sci.* 1998;3:469–473.
- [3] Zhang SJ, Yu FP. Piezoelectric materials for high temperature sensors. *J Am Ceram Soc.* 2011;94(10):3153–3170.
- [4] Yan HX, Zhang HT, Reece MJ, et al. Thermal depoling of high Curie point Aurivillius phase ferroelectric ceramics. *Appl Phys Lett.* 2005;8:0829111.
- [5] Zhang SJ, Frantz E, Xia R, et al. Gadolinium calcium oxyborate piezoelectric single crystals for ultrahigh temperature (1000°C) applications. *J Appl Phys.* 2008;104:084103.
- [6] Zhang SJ, Fei Y, Chai B, et al. Characterization of piezoelectric single crystal $\text{YCa}_4\text{O}(\text{BO}_3)_3$ for high temperature applications. *Appl Phys Lett.* 2008;92:202905.
- [7] Yan HX, Ning H, Kan Y, et al. Piezoelectric ceramics with super-high Curie points. *J Am Ceram Soc.* 2009;92(10):2270–2275.
- [8] Aurivillius B. Mixed bismuth oxides with Lauer lattices: I. *Ark Kemi.* 1949;1:463–471.
- [9] Yan HX, Zhang HT, Uvic R, et al. A lead-free high-Curie-point ferroelectric ceramic $\text{CaBi}_2\text{Nb}_2\text{O}_9$. *Adv Mater.* 2005;17:1261–1265.
- [10] Swartz S, Schulze WA, Biggers JV. Fabrication and electrical properties of grain oriented $\text{Bi}_4\text{Ti}_3\text{O}_{12}$ ceramics. *Ferroelectrics.* 1981;38:765–758.
- [11] Peng ZH, Chen Q, Wang Y, et al. Enhancement of piezoelectric properties of (LiCePr)-multidoped $\text{CaBi}_2\text{Nb}_2\text{O}_9$ high temperature ceramics. *Mater Lett.* 2013;107:14–16.
- [12] Zhang XD, Yan HX, Reece MJ. Effect of A site substitution on the properties of $\text{CaBi}_2\text{Nb}_2\text{O}_9$ ferroelectric ceramics. *J Am Ceram Soc.* 2008;91:2928–2932.
- [13] Xing X, Cao F, Peng Z, et al. The effects of oxygen vacancies on the electrical properties of W, Ti doped $\text{CaBi}_2\text{Nb}_2\text{O}_9$ piezoceramics. *Curr Appl Phys.* 2018;18:1149–1157.
- [14] Xie J, Zhong J, Wu C, et al. Enhanced electrical properties related to structural distortion of $\text{CaBi}_2\text{Nb}_2\text{O}_9$ -based piezoelectric ceramics. *J Am Ceram Soc.* 2019;102:1287–1295.
- [15] Liu G, Ren S, Wu C, et al. Enhanced thermal stability of (NaCe)-multidoped $\text{CaBi}_2\text{Nb}_2\text{O}_9$ by A-site vacancies-induced pseudo-tetragonal distortion. *J Am Ceram Soc.* 2018;101:4615–4626.
- [16] Shimakawa Y, Kubo Y, Nakagawa Y, et al. Crystal structures and ferroelectric properties of $\text{SrBi}_2\text{Ta}_2\text{O}_9$ and $\text{Sr}_{0.8}\text{Bi}_{2.2}\text{Ta}_2\text{O}_9$. *Appl Phys Lett.* 1999;74(13):1904–1906.
- [17] Withers RL, Thompson JG, Rae AD. The crystal chemistry underlying ferroelectricity in $\text{Bi}_4\text{Ti}_3\text{O}_{12}$, $\text{Bi}_3\text{TiNbO}_9$, and Bi_2WO_6 . *J Solid State Chem.* 1991;94:404–417.
- [18] Yang F, Wu P, Sinclair DC. Enhanced bulk conductivity of A-site divalent acceptor-doped non-stoichiometric sodium bismuth titanate. *Solid State Ionics.* 2017;299:38–45.
- [19] Katayama S, Noguchi Y, Miyayama M. 3D domain structure in $\text{Bi}_4\text{Ti}_3\text{O}_{12}$ crystals observed by using piezoresponse force microscopy. *Adv Mater.* 2007;19:2552–2555.
- [20] Ding Y, Liu JS, MacLaren I, et al. Ferroelectric switching mechanism in $\text{SrBi}_2\text{Ta}_2\text{O}_9$. *Appl Phys Lett.* 2001;79:1015–1017.
- [21] Zhang QM, Pan WY, Jang SJ, et al. Domain wall excitations and their contributions to the weak-signal response of doped lead zirconate titanate ceramics. *J Appl Phys.* 1988;64:6445.
- [22] Wang CM, Wang JF, Zhang SJ, et al. Electromechanical properties of A-site (LiCe)-modified sodium bismuth titanate ($\text{Na}_{0.5}\text{Bi}_{4.5}\text{Ti}_4\text{O}_{15}$) piezoelectric ceramics at elevated temperature. *J Appl Phys.* 2009;105:094110.
- [23] Li F, Zhai J, Shen B, et al. Simultaneously high-energy storage density and responsivity in quasi-hysteresis-free Mn-doped $\text{Bi}_{0.5}\text{Na}_{0.5}\text{TiO}_3$ - BaTiO_3 - $(\text{Sr}_{0.7}\text{Bi}_{0.2})_{0.1}\text{TiO}_3$ ergodic relaxor ceramics. *Mater Res Lett.* 2018;6:345–352.
- [24] Hou JG, Kumar RV, Qu YF, et al. B-site doping effect on electrical properties of $\text{Bi}_4\text{Ti}_3-2x\text{Nb}_x\text{Ta}_x\text{O}_{12}$ ceramics. *Scr Mater.* 2009;61:664–667.
- [25] Zhang HT, Yan HX, Ning HP, et al. The grain size effect on the properties of Aurivillius phase $\text{Bi}_{3.15}\text{Nd}_{0.85}\text{Ti}_3\text{O}_{12}$ ferroelectric ceramics. *Nanotechnology.* 2009;20:385708.