Effect of orientation on polarization switching and fatigue of Bi$_{3.15}$Nd$_{0.85}$Ti$_{2.99}$Mn$_{0.01}$O$_{12}$ thin films at both low and elevated temperatures

Wanli Zhang 1, Yanhu Mao 1, Shaoan Yan 2,3*, Minghua Tang 4,5*, Yongguang Xiao 4,5, Suihu Dang 1, Wenxi Zhao 1 and Guangzhao Wang 1

Abstract
Bi$_{3.15}$Nd$_{0.85}$Ti$_{2.99}$Mn$_{0.01}$O$_{12}$ (BNTM) thin films with (200)-orientations, (117)-orientations, and mixed-orientations were prepared by sol-gel methods. The influence of orientations on polarization fatigue behaviors of BNTM thin films were systematically investigated at both low and elevated temperatures. It was found that the changed trends of the polarization fatigue of (200)-oriented and (117)-oriented BNTM thin films at elevated temperatures were opposite. The fatigue properties become exacerbated for the (200)-oriented ones and become improved for the (117)-oriented ones, while the reduction of remanent polarization first decreases and then increases for the mixed-oriented ones. It can be assumed that the different roles played by domain walls and interface layer with increasing $T$ in these thin films have caused such differences, which was certified by the lower activation energies (0.12–0.13 eV) of (200)-oriented BNTM thin films compared to those of BNTM thin films (0.17–0.31 eV) with other orientations through the temperature-dependent impedance spectra analysis. With the aid of piezoresponse force microscopy (PFM), the non-neutral tail-to-tail or head-to-head polarization configurations with greater probabilities for (117)-oriented and mixed-oriented thin films were found, while a majority of the neutral head-to-tail polarization configurations can be observed for (200)-oriented ones.

Keywords: Polarization switching, BNTM, Domain pinning, Temperature-dependent fatigue

Background
Bi$_4$Ti$_3$O$_{12}$ (BIT)-based layered ferroelectric thin films have always been one of the most potential ferroelectric materials to replace the commercial (Pb, Zr)TiO$_3$ (PZT)-based ferroelectric random access memory (FRAM) for its high curie temperature, large remanent polarization, and good anti-fatigue properties [1–3]. The lattice constants of BIT crystal along the c-axis, a-axis, and b-axis were 3.284 nm, 0.544 nm, and 0.541 nm at 300 K, respectively. BIT thin films also show anisotropic polarizations, which are about 4 and 50 μC/cm$^2$ along its c- and a-axis, respectively [4]. There are numerous factors such as layer thickness, precursor solution, and annealing condition that affect the orientation of Nd-substituted BIT (Bi$_{3.15}$Nd$_{0.85}$Ti$_3$O$_{12}$, BNT) films [5–7]. Hu discovered that different thicknesses of each spin-on coating layer can favor BNT films with different orientations [5]. Yu et al. proposed that 0.10 M precursor solution for BNT showed the best ferroelectric and dielectric properties [6]. Zhong et al. reported that Bi$_{3.15}$Nd$_{0.85}$Ti$_{2.99}$Mn$_{0.01}$O$_{12}$ (BNTM) thin film with an annealing temperature of 750 °C showed higher tunability and dielectric constant than BNT thin film annealing under a temperature of 700 °C [7]. But high leakage current and poor fatigue properties can be caused by the evaporation of bismuth under high annealing temperatures. Moreover, it has also reported that BNT thin films with different orientations exhibit varying polarization...
fatigue behaviors [8]. However, the reason for why different orientations showed varying fatigue characteristics at elevated temperatures was still not very well understood.

Ferroelectric-based memories may operate in temperature range from −40 to 125 °C, which can be elusive to understand the temperature-dependent change of fatigue behaviors of ferroelectric materials. It has been reported that the fatigue endurance for BNT thin films showed improved fatigue resistance from 25 to 125 °C, which can be attributed to the fact that the effect of domain unpinning enhanced more rapidly with increasing temperature than that of domain pinning. [9]. However, an opposite fatigue behavior has been reported. [9]. However, an opposite fatigue behavior has been observed during the polarization fatigue tests [10]. It can be elucidated that lots of affecting factors get together to decide the trend of fatigue behaviors at elevated temperatures as reported in our previous work [11]. Zhang et al. have studied the polarization switching properties of BNT thin films at elevated temperatures and concluded that the enhanced effect of electron injection can produce more highly mobile defect charges due to a lower Schottky barrier at high temperatures compared to that at low temperatures, which can induce pinned domain walls and serious fatigue [12]. However, earlier reports mainly studied on macroscopic performance tests and neglected microscopic domain dynamics which are considered to mainly affect the polarization switching and fatigue behaviors. With the aid of impedance spectra techniques, PFM and first-principles theory, the microscopic domain evolution and activation energies of oxygen vacancies of BiFeO3 thin films can be successfully observed during the polarization fatigue tests [13]. Thus, the studies of microscopic domain dynamic and transport law of oxygen vacancies will be helpful to further understand the fatigue behaviors of anisotropic BNTM thin films at an elevated temperature (T).

In the following section, polarization switching and fatigue properties of BNTM thin films with (200)-orientations, (117)-orientations, and mixed-orientations were studied at elevated temperatures from 200 to 475 K. The temperature-dependent fatigue behaviors of these thin films were also illuminated. The combination of temperature-dependent impedance spectra and PFM tests was made to learn the transport mechanisms of oxygen vacancies and microscopic evolution of domains. Different transport mechanisms of carriers of BNTM thin films with varying orientations for fatigue behaviors at elevated T will be discussed in detail.

**Methods**

All chemicals and reagents were supplied by Sinopharm Chemical Regent, Co., Ltd. The starting precursor materials were Bi(NO₃)₃·5H₂O (purity ≥ 99.0%), Nd(NO₃)₃·6H₂O (purity ≥ 99.0%), Ti(OCH₃)₄ (purity ≥ 99.0%) and Mn(CH₃COO)₂·4H₂O (purity ≥ 99.0%). The solvents were 2-methoxyethanol (purity ≥ 99.0%) and glacial acetic acid (purity ≥ 99.5%) with acetyl acetone (purity ≥ 99.0%) as a chelating agent. Ten percent excess of bismuth nitrate was added to compensate for possible bismuth loss during the high-temperature process. The precursor solutions were adjusted to 0.04 M, 0.08 M, and 0.1 M, which correspond to BNTM-1, BNTM-2, and BNTM-3 thin films, respectively.

These detail works can be found in our previous studies [14, 15]. The spin-on films were repeated ten times at 700 °C for 2.5 min in O₂ for BNTM-1 and were repeated four times at 700 °C for 5 min in O₂ for BNTM-3, while the annealing processes were repeated for four times at 650 °C for 2.5 min in O₂, and the final layer was given an extra thermal process at 720 °C for 5 min in O₂ for BNTM-2. Pt top electrodes were deposited with a diameter of 200 μm through DC sputtering.

X-ray diffraction (XRD) with Cu-Kα radiation was used to study texturing state and crystallographic structure of such thin films. Scanning electron microscope (SEM, Japan, Hitachi S4800) was conducted to characterize the surface and cross-sectional morphologies of these films. Ferroelectric test systems (USA, Radiant Technologies Precision workstations) were used to measure temperature-dependent dielectric properties and AC impedance spectra of such films. A commercially available Z-view software was used to analyze the impedance results. Ferroelectric test systems (USA, Radiant Technologies Precisions workstations) were used to measure the polarization fatigue properties. PFM (piezoresponse force microscopy) tests were conducted by using AFM (atomic force microscopy) system (MFP-3D, USA, Asylum Research) under an ambient condition. A platinum-coated silicon cantilever (radius 15 nm, spring constant 2 N/m) was used to scan with a tip lift height of 30 nm at 35 kHz.

**Results and Discussion**

XRD patterns of BNTM-1, BNTM-2, and BNTM-3 thin films were shown in Fig. 1. To quantify the texturing state, the degrees of orientation are defined as α_{hkl} = I_{(hkl)}/(I_{(006)} + I_{(117)} + I_{(200)}), where I_{(hkl)} is the XRD peak intensity of (hkl) crystal plane. The degrees of α_{200} and α_{117} of BNTM-1, BNTM-2, and BNTM-3 thin films were found to be 63.50% and 29.23%, 43.22% and 48.5%, and 32.11% and 60.2%, respectively. A (200)-oriented growth of BNTM-1 and (117)-oriented growth of BNTM-3 were observed, while a mixed-preferred growth was presented in BNTM-2. The surface and cross-section of such thin films are observed through SEM methods as shown in Fig. 2a–g. The surface of BNTM-1, BNTM-2, and BNTM-3 thin films is mainly composed of bullet-shaped grains, a mixture of plate-like grains, and rod-like grains through the observation in Fig. 2a–c, respectively, which was also reported in others’ works [16]. Film thicknesses of
BNTM-1, BNTM-2, and BNTM-3 were estimated to be 470 nm, 454 nm, and 459 nm through the cross-sectional SEM images (as shown in Fig. 2d–g), respectively. As mentioned above, layer-by-layer crystallization was adopted in the preparation of BNTM thin films. The growth of (117)-oriented crystals was favored by the thicker spin-coating layer, while the growth of (200)-oriented crystals was not restricted by the layer thickness owing to the geometrical effect as shown in Fig. 1b and c. The thicknesses of each spin-coating layer of BNTM-1, BNTM-2, and BNTM-3 thin films were estimated to be 47 nm, 91 nm, and 115 nm, respectively, which favor the (200)-oriented, the mixed-oriented, and the (117)-oriented BNTM thin films. These results have also been reported by Hu and Wu [5, 17].

The $P-V$ hysteresis loops of BNTM-1, BNTM-2, and BNTM-3 thin films from 200 to 400 K measured with the maximum voltage ($V_{m}$) of 16 V were exhibited in Fig. 3a–c. The remanent polarization $2P_{r}$ and coercive voltage $2V_{c}$ of such films strongly depend on $T$ as shown in Fig. 3d–f, where the average coercive voltage $V_{c}$ ($V_{c} = (V_{c}^{+} - V_{c}^{-})/2$) and $2P_{r}$ as a function of $T$ under different $V_{m}$. It can be concluded that $2P_{r}$ of BNTM-1 first increases as $V_{m}$ is less than 10 V, and decreases when $V_{m}$ is more than 10 V with increasing $T$, while $2P_{r}$ of BNTM-2 and BNTM-3 always first increases from 220 to 300 K and then decreases from 300 to 400 K under the whole range of $V_{m}$. It can be explained by the larger depolarization field at film/electrode interfaces of BNTM-2 and BNTM-3 which is caused by the higher density of domain walls, while its amounts at interfaces are lower for BNTM-1. The values of $V_{c}$ of BNTM-1 decrease with increasing $T$ as the values of $V_{m}$ increase from 6 to 16 V, while its values of BNTM-2 and BNTM-3 first increase and then decrease with increasing $T$ under the values of $V_{m}$ from 8 to 10 V. It should be triggered by the competition of the nucleation rate of domains and domain pinning-unpinning with increasing $T$, where the nucleation rate of domains ($n$) and the activation electric field ($a$) can be expressed as

$$n \propto \exp(-a/E).$$

Thus, $n$ plays a decisive role to determine the values of $V_{c}$ at low $T$ and small $V_{m}$, and an increasing $V_{c}$ will be increased with a

---

**Fig. 1.** XRD patterns of BNTM-1, BNTM-2, and BNTM-3 thin films (a) and schematic diagram of (200)-grain growth (b) and (117)-grain growth of thin films (c).

**Fig. 2.** SEM surface and cross-section images: a, d BNTM-1; b, e for BNTM-2; c, f for BNTM-3.
higher nucleation rate of domains. The domain wall velocity has strongly determined the probability of domain wall pinning after reaching the saturation point of nucleation rate of domains at high $V_m$ and $T$. Domain wall velocity ($v$) and the energy barrier for domain growth ($U_0$) can be expressed as $v \propto \exp(-U_0/k_B T)$, where $k_B$ means the Boltzmann constant [18]. With the increasing $T$, the domain unpinning effect has been strongly enhanced by the increasing $v$. Thus the fact that $V_c$ decreases with the increasing $T$ at the saturation value of $V_m$ can be due to the higher $v$.

The fatigue characteristics of BNTM-1, BNTM-2, and BNTM-3 from 300 to 400 K were displayed in Fig. 4a–c. The pulse amplitudes were 10 V and 8 V for the reading and fatigue process, respectively. The relationship of $\pm \Delta P_N = (\pm P_r)^N - (\pm P_r)^N$ can be described that $N$ is the number of switching cycles, $P_N$ is the total polarization, $P_r^+$ is the switched remanent polarization between the two opposite polarity pulses, and $P_r^-$ is the non-switched remanent polarization between the same two polarity pulses. After $1 \times 10^9$ cycles pulse switching, the reductions of $\Delta P_N$ of BNTM-1, BNTM-2, and BNTM-3 were 0%, 32.5%, and 41.2% at 300 K, 7.4%, 51.4%, and 31.2% at 350 K, and 11.3%, 34.5%, and 15.7% at 400 K, respectively. The fatigue characteristics of BNTM-1 become more serious and those of BNTM-3 show a reverse trend from 300 to 400 K, while the fatigue characteristics of BNTM-2 become more serious from 300 to 350 K, and get improved from 350 to 400 K. At first, the improved fatigue properties of BNTM-3 from 300 to 400 K should be due to the enhanced effect of domain wall unpinning [11, 18–20]. It can be consumed that the competition between domain pinning and the growth of dead layer has always been an obvious effect on polarization fatigue [21, 22]. As for BNTM-1, the growth of the dead layer is the dominant factor, and the long-range diffusion of oxygen vacancies becomes enhanced with increasing $T$ and contributes to the increase of the thickness of the dead layer, which can be also certified by the decrease of dielectric response after fatigue process from Fig. 4d. As for BNTM-2, the effect of dead layer growth first plays a major role with $T$ from 300 to 350 K during the fatigue tests, and then the enhanced domain unpinning effect leads to improved fatigue properties from 350 to 400 K. It was also discussed in some other works [22, 23].

The plots of dielectric constant ($\varepsilon_r$) vs frequency before and after the fatigue process were further conducted to investigate the dead layer growing effect as shown in Fig. 4d–f. The values of $\varepsilon_r$ of such thin films increase with increasing $T$, which indicates that the domain unpinning effect becomes stronger with the increasing $T$. The change in the values of $\varepsilon_r$ of BNTM-1 and BNTM-3 after fatigue process increases with increasing $T$. It can be explained by the combined effect of long-range diffusion of removable carriers and the dead layer’s growth at elevated $T$. As for BNTM-1 and BNTM-3, the thickness of the dead layer increases with increasing $T$ and becomes the main influence on the value of $\varepsilon_r$, which leads to the reduction of $\varepsilon_r$ of BNTM-1 and BNTM-3. However, the change in the $\varepsilon_r$ of BNTM-2 showed a weak correlation, which was explained that a large amount of charged...
domain wall formed by oxygen vacancies’ migration during the fatigue process had taken part in the dielectric response, which caused the increase of $\varepsilon_r$ for BNTM-2.

AC impedance spectra tests were used to study the conductance mechanism before and after the fatigue process with the temperature range from 300 to 475 K. Fig. 5a–c shows the real and imaginary impedance ($Z'$ and $Z''$) as frequency decreases from 1 MHz to 1 kHz. The grain contribution can be reflected by high-frequency arcs. The nonlinear least square fitting were conducted to estimate resistances of grains ($R_g$) of BNTM films, which was also reported by Bai et al. [24]. The $R_g$ follows Arrhenius’ relationship as $R_g \propto \exp(-E_a/k_B T)$, where $E_a$ represents average activation energy of carriers during conductance process and $k_B$ means Boltzmann’s constant [25]. The curves of $\ln(R_g)$ vs $1000/T$ were shown in Fig. 5d–f. It has been found

Fig. 4. Plots of polarization fatigue curves and dielectric constant ($\varepsilon_r$) vs frequency at both fresh and fatigued condition: a, d for BNTM-1; b, e for BNTM-2; c, f for BNTM-3

Fig. 5. Impedance diagrams at elevated temperature and $\ln(R_g)$ vs $1000/T$ Arrhenius plots at both fresh and fatigued condition: a, d for BNTM-1; b, e for BNTM-2; c, f for BNTM-3
that the value of $R_k$ increases a little after $1.6 \times 10^9$ pulse cycles, which can be elucidated that the population of carriers increased with increasing $T$ and a part of oxygen vacancies or injected electrons was trapped by charged domain walls during the fatigue process [26, 27]. The values of $E_a$ for BNTM-1 were 0.12-0.13 eV from 425 to 475 K and much smaller than the values of BNTM-2 and BNTM-3. The large values of $E_a$ (0.12-0.31 eV) are generally considered as the contribution of migration of oxygen vacancies within their clusters [25]. It can be estimated that long-range diffusion of oxygen vacancies happens more easily in BNTM-1 thin film, which was further accounted for that the density of domain walls of (200)-oriented thin films was less than that of (117)-oriented and mixed-oriented thin films. The schematics of domains and the domain walls of (200)-oriented and (117)-oriented BNTM thin films were made as shown in Fig. 6a–b. It can be seen that the (200)-oriented thin films mainly consist of 180°-domain and, the width of domain wall is much smaller than that of (117)-oriented domains, which have strong horizontal component of polarization. The tail-to-tail or head-to-head polarization configurations which can induce the pinning effect for domain walls can happen more easily with (117)-oriented domains. Thus the question why (200)-oriented BNTM thin films show the opposite fatigue behaviors with increasing $T$ compared to that in (117)-oriented BNTM thin films can be explained. For BNTM-1 mainly consisted of (200)-oriented domains, the diffusion of oxygen vacancy should be a determined role for the fatigue behaviors with increasing $T$. And for BNTM-3 with a majority of (117)-oriented domains, domain walls with larger width which depend on the temperature should be the main cause. The intense diffusion of oxygen vacancies with increasing $T$ can facilitate the growth of a dead layer which makes serious fatigue, while the width of domain wall can be smaller with increasing $T$. Thus an improved fatigue properties can achieve.

In order to verify our correctness of aforementioned models, the microscopic domain structures of BNTM-1, BNTM-2, and BNTM-3 thin films were studied through the PFM method. AFM surface topography, OP (out-plane) PFM amplitude images, OP PFM phase images, IP (in-plane) PFM amplitude images, IP PFM phase images, and zoomed-in PFM images of a specific region in the red solid square of such films were shown in Fig. 7a–o. The regions with bright yellow and dark colors in OP phase images correspond to vertically up or down 180°-domains, while the regions with rich yellow and dark colors in IP image correspond to laterally left or right 90°-domains. It can be seen that the phases of laterally right or left 90°-domains are more obvious for BNTM-2 and BNTM-3 than those of BNTM-1 as shown in Fig. 7p–r, which has further elucidated that (117)-oriented domains have a strong horizontal component of polarization. IP PFM images of the zoomed-in specific region with red solid squares were shown in Fig. 7p–r. The cyan dotted lines correspond to the boundaries of vertically up and down 180°-domains in OP phase images as shown in Fig. 7p–r, while the blue dotted lines correspond to the boundaries of laterally left and right 90°-domains in IP images. When cyan dotted lines are just located at the boundaries of dark and bright regions in IP phase images which are marked with blue dotted lines, the polarization configurations with tail-to-tail or head-to-head structures which were marked with red dotted lines in Fig. 7p–r will be formed and lead to the accumulation of opposite charge for domain walls. It can be concluded that the non-neutral tail-to-tail or head-to-head polarization configurations can happen with greater probabilities for BNTM-2 and BNTM-3 thin films compared to those for BNTM-1 thin films as shown in Fig. 7p–r. Therefore, the density of pinned domain walls and width of domain wall have determined the temperature-dependent fatigue behaviors for (117)-oriented thin films. Thus domain walls with higher velocity and less possibility to capture oxygen vacancies can realize the improved fatigue at elevated temperatures as compared to those at lower temperatures [28].

Conclusions

In conclusion, the mechanisms of orientations on temperature-dependent polarization switching and fatigue properties of BNTM thin films were systematically expounded. It was found that the fatigue properties become exacerbated for (200)-oriented thin films and become improved for (117)-oriented ones with increasing $T$. The accumulation of oxygen vacancies at the interface and domain walls with larger width should be the determined roles for the fatigue behaviors of (200)-oriented and (117)-oriented thin films with increasing $T$, respectively. The intense diffusion of oxygen vacancies with increasing $T$ can facilitate the growth of a dead layer which makes serious fatigue, while the width of domain wall becomes smaller and brings improved fatigue properties affected by an enhanced domain unpinning effect with increasing $T$. A lower activate energy of 0.12–0.13 eV was found for (200)-oriented BNTM thin films as compared to those of 0.17–0.19 eV for (117)-oriented
ones. The non-neutral tail-to-tail polarization configurations with greater probabilities for (117)-oriented and mixed-oriented thin films were found, while a majority of the neutral head-to-tail polarization configurations can be observed for (200)-oriented ones. Therefore, the intense diffusion of oxygen vacancies and the properties of domain walls have determined the differences of temperature-dependent fatigue behaviors of BNTM thin films with different orientations.

Abbreviations
AFM: Atomic force microscopy; BIT: Bi$_4$Ti$_3$O$_{12}$; BNT: Nd-substituted BIT; BNTM: Bi$_{3.15}$Nd$_{0.85}$Ti$_{2.99}$Mn$_{0.01}$O$_{12}$; $E_a$: Average activation energy of carriers; FRAM: Ferroelectric random-access memory; IP: In plane; PFM: Piezoresponse force microscopy; $P_r$: Remanent polarization; $P_{r*}$: Switched remanent polarization; $P_{r^*}$: Non-switched remanent polarization; PZT: (Pb, Zr)TiO$_3$; $R_g$: Resistances of grains; SEM: Scanning electron microscope; $U_0$: Energy barrier for domain growth; $V_c$: Coercive voltage; $V_m$: Maximum voltage; XRD: X-ray diffraction; $Z'$: Real impedance; $Z''$: Imaginary impedance; $\alpha$: Activation electric field; $\varepsilon_r$: Dielectric constant.

Acknowledgements
The authors acknowledge the contributions of Dr. Gang Li in the theoretical analysis.

Funding
This work was supported from the National Natural Science Foundation of China (11,835,008, 51,472,210, 61,804,130, 51,872,250), the National Key R&D
The authors declare that they have no competing interests.

Competing Interests

WaZ and SY conceived and designed the experiment. YX and SD helped

modify this paper. All authors read and approved the final manuscript.

Contributions

Authors

Availability of Data and Materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Availability of Data and Materials

Received: 29 October 2018 Accepted: 18 March 2019

References

1. Lee HN, Hesse D, Zakhvor N, Gosele U (2002) Ferroelectric Bi 3.25La0.75Ti3O12

films of uniform a-axis orientation on silicon substrates. Science 296:2006–2009. https://doi.org/10.1126/science.1069956

2. Chon U, Jang HM, Kim MG, Chang CH (2002) Layered perovskites with giant spontaneous polarizations for nonvolatile memories. Phys Rev Lett 89(8):–. https://doi.org/10.1103/PhysRevLett.89.087601

3. Xie D, Luo YF, Han XG, Ren TL, Liu LT (2009) Characterization of PrBi1.1Nd0.9TiO3 thin film structure using a halium oxide as buffer layer for ferroelectric-gate field effect transistors. J Appl Phys 106(11):114117–114117. https://doi.org/10.1063/1.3267153

4. Rae AD, Thompson JG, Withers RL, Willis AC (1990) Structure refinement of commensurately modulated bismuth titanate, Bi 2Ti 2O 7. Acta Cryst B 46:474–487. https://doi.org/10.1107/S01087681900003251

5. Hue GD (2006) Orientation dependence of ferroelectric and piezoelectric properties of Bi 5–xSrxTiO 3 thin films on Pt(100)/TiO 2/SiO 2/Si substrates. J Appl Phys 100:096109 (1–3). https://doi.org/10.1063/1.2364668

6. Yu J, Yang B, Li J, Liu YM, Zheng CD, Wu YY, Guo DY, Zhang DM (2008) Effect of precursor solution concentration on the grain orientation of Bi 3.15Nd0.85Ti3O12 thin films. J Phys D Appl Phys 41(5):033304 (1–5). https://doi.org/10.1088/0022-3727/41/5/033304

7. Zhong XL, Wang JF, Luo M, Tan CB, Shu HB, Zhou YC (2008) Effect of Mn doping on the microstructures and dielectric properties of Bi 3.15Nd0.85Ti3O12 thin films. Thin Solid Films 516(23):6240–6243. https://doi.org/10.1016/j.tsf.2008.03.004

8. Yang F, Guo YC, Li LY, Tang MH (2016) Anisotropic polarization fatigue in Bi 1.15Nd0.85TiO 3 thin films. J Phys D Appl Phys 49(19):195305 (1–7). https://doi.org/10.1088/0022-3727/49/19/195305

9. Zhao C, Wu D, Li AD, Xia YD (2008) Fatigue characteristics of Nd-substituted Bi2Ti2O 6 ferroelectric thin films at elevated temperatures. J Phys D: Appl Phys 41(2):22003 (1–4). https://doi.org/10.1088/0022-3727/41/2/22003

10. Cheng ZQ, Wang XL, Dou SX, Ozawa K, Kimura H (2007) Ferroelectric properties of Bi 3.15Nd0.85Ti3O12 thin film at elevated temperature. Appl Phys Lett 90(22):220902 (1–3). https://doi.org/10.1063/1.2734390

11. Zhong WL, Tang MH, Xiong Y, Yan SA, Cheng CP, Li G, Xiao YG, Li Z (2017) Polarization switching and fatigue characteristics of highly (117)-oriented Bi 3.15Nd0.85Ti3O12 ferroelectric thin films at both low and elevated temperatures. RSC Adv 7:20929–20935. https://doi.org/10.1039/C7RA02523H

12. Zhang Y, Zhong XL, Chen ZH, Wang JB, Zhou YC (2011) Temperature dependence of polarization switching properties of Bi 3.15Nd0.85Ti3O12 ferroelectric thin film. J Appl Phys 110(1):014102–1–5. https://doi.org/10.1063/1.3600237

13. Ke QQ, Kumar A, Lou XJ, Feng YF, Zeng KY, Cai YQ, Wang J (2015) Microstructural evolution of charge defects in the fatigue process of polycrystalline BiFeO 3 thin films. Acta Mater 82:190–197. https://doi.org/10.1016/j.actamat.2014.08.059

14. Zhang WL, Tang MH, Xiong Y, Wang K, Wang ZP, Xiao YG, Yan SA, Li Z, He J (2016) Influence of the annealing temperature of the Bi 3.15Nd0.85Ti3O12 seed layer on the structural and electrical properties of Bi 3.15Nd0.85Ti3O12 thin films. RSC Adv 6:88668–88673. https://doi.org/10.1039/C6RA13718

15. Zhang WL, Tang MH, Xiong Y, Wang ZP, Xiao YG, Yan SA, Li Z, He J (2016) Improvement of nucleation and electrical properties of Bi 3.15Nd0.85Ti3O12 thin films with an upper Bi 2Ti 2O 7 buffer layer. J Sol-Gel Sci Technol 80:853–859. https://doi.org/10.1007/s10971-016-4715-0

16. Chen YC, Sun YM, Lin CP, Gan JY (2004) Enhanced a–axis-oriented crystal growth of Nd-substituted bismuth titanate thin films with layer-by-layer crystallization. J Cryst Growth 268:1210–1214. https://doi.org/10.1016/j.jcrysgro.2004.05.010

17. Wu D, Li AD, Ming NB (2004) Structure and electrical properties of Bi 3.15Nd0.85Ti2.99Mn0.01O12 thin films. J Phys D Appl Phys 41(12):122003 (1–7). https://doi.org/10.1088/0022-3727/41/12/122003

18. Yuan GL, Liu JM, Wang YP, Wu D, Zhang SG, Shao QY, Liu JG (2004) Temperature-dependent fatigue behaviors of ferroelectric Bi 2O 2O 4 and layer-perovskite oxide thin films. Appl Phys Lett 84(17):3352–3354. https://doi.org/10.1063/1.1734685

19. Wang Y, Wang KF, Zhu C, Liu JM (2006) Polarization fatigue of ferroelectric PbO 2TiO 3 thin films: temperature dependence. J Appl Phys 99(4):–. https://doi.org/10.1063/1.2172847

20. Guo DY, Wang CB, Shen GD, Zhang M, Li MY, Liu J (2009) Effect of measuring factors on ferroelectric properties of Bi 3.15Nd0.85Ti3O12 thin films prepared by sol-gel method for non-volatile memory. Appl Phys A Mater Sci Process 97(4):877–881. https://doi.org/10.1007/s00339-009-5349-1

21. Zhong N, Xiang Y, Li Y, Zhang YY, Xu J, Wang XD, Yang P, Duan CG, Chu JH (2015) Polarization fluctuation behavior of lanthanum substituted Bi 3.15Nd0.85Ti3O12 thin films. J Appl Phys 118(10):104102–5–. https://doi.org/10.1063/1.4930041

22. Li, Dong X, Remeis D, Li T, Chen Y, Wang G (2014) Effect of polarization switching cycles on the dielectric response and Rayleigh constant in Bi 2Sr 2CaCu 2O 8 thin films. J Appl Phys 115(6):064102–1–4. https://doi.org/10.1063/1.4864761

23. Bai W, Chen C, Zhu Y, Yang J, Lin T, Meng XJ, Tang XD, Duan CG, Chu JH (2012) Dielectric responses and scaling behaviors in Aurivillius Bi 2Ti 2O 7 multiferroic thin films. Appl Phys Lett 100(8):082902–1–4. https://doi.org/10.1063/1.3669033

24. Kumar N, Ghosh A, Choudhury RNP (2011) Electrical behavior of PbZr 0.52TiO 3thin films grown on polycrystalline BiFeO 3 substrates. Mater Chem Phys 130(1-2):381–386. https://doi.org/10.1016/j.matchemphys.2011.06.059

25. Zhou X, You Y, Chen W, Deng H, Wu D, Wu T, Chen L, Wang JL (2012) Mechanism of polarization fatigue in BiFeO 3. ACS Nano 6:9897–9904. https://doi.org/10.1021/nn303080k

26. Kitanaka Y, Nojuchi Y, Miyajama M (2010) Oxygen-vacancy-induced 90°domain clamping in ferroelectric BiFeO 3 single crystals. Phys Rev B 81(9):094114–1–8. https://doi.org/10.1103/PhysRevB.81.094114

27. Zhang WL, Mao YH, Yan SA, Xiao YG, Tang MH, Li G, Peng QX, Li Z (2018) Temperature-dependent domain dynamics and electrical properties of Nd-doped Bi 3.15Nd0.85Ti3O12 thin films in fatigue process. Materials 11(12):–. https://doi.org/10.3390/ma11122418