

Observing ferroelastic switching in $H_{0.5}Zr_{0.5}O_2$ thin film

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Observing ferroelastic switching in $Hf_{0.5}Zr_{0.5}O_2$ thin film

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Hafnium zirconium oxides (HZO), which exhibit ferroelectric properties, are promising materials for nanoscale device fabrication due to their high complementary metal–oxide–semiconductor (CMOS) compatibility. In addition to piezoelectricity, ferroelectricity, and flexoelectricity, this study reports the observation of ferroelasticity using piezoelectric force microscopy (PFM) and scanning transmission electron microscopy (STEM). The dynamics of 90° ferroelastic domains in HZO thin films are investigated under the influence of an electric field. Switching of the retentive domains is observed through repeated wake-up measurements. This study presents a possibility of enhancing polarization in HZO thin films during wake-up processes.

Keywords: HfO_2-based ferroelectrics, ferroelasticity, piezoelectric force microscopy (PFM)

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To achieve high compatibility with nanoscale integrated circuit technology, significant efforts have been made to reduce the thickness of ferroelectric materials and overcome the limitations imposed by the size effect.[1] Two-dimensional (2D) ferroelectrics and hafnium oxide (HfO_2)-based ferroelectrics have emerged as competitive alternatives to traditional ferroelectrics in nanoscale electronics.[2,3] The robust ferroelectricity of Si:HfO_2, particularly $Hf_{0.5}Zr_{0.5}O_2$ (HZO), has gained global attention since its discovery in 2011.[4] Due to the advantages of having a relatively large bandgap (5.3 eV–5.7 eV),[5] HfO_2-based ferroelectric devices demonstrate remarkable features, such as high speed and low size scaling,[6] enabling their fabrication as nanoscale transistors with excellent compatibility with complementary metal–oxide–semiconductor (CMOS) technology.[7,8] Nevertheless, several phenomena, including the wake-up effect (increased remanent polarization with cycling for pristine samples),[9] split-up effect (splitting of the *I*–*E* peak into two or more with cycling for woken-up samples),[10] and fatigue issues (decreased remanent polarization with prolonged cycling for woken-up samples),[11] significantly affect the stability and reliability of the device. These phenomena are attributed to domain pinning, electric-induced phase transition, and rearrangement of oxygen vacancies, among others.[6,12–14] However, the intrinsic mechanisms are still under fierce discussion and more research needs to be done.

The ferroelectricity in HfO_2-based films is typically attributed to the non-centrosymmetric structure of the polar orthorhombic phases (space group: $Pca2_1$, $Pmn2_1$),[15] or rhombohedral phase (space group: $R3m$).[16,17] By applying strain or stress through substrates,[18] adopting manipulation strategies involving top-capping electrodes to induce in-plane (IP) stress,[19] adjusting doping concentrations of Zr^{4+}, Y^{3+}, La^{3+}, Gd^{3+},[5,20–22] controlling the grain size,[23] modulating electric fields,[5,24] and selecting suitable fabrication methods,[25,26] and so on,[27,28] a relatively stable ferroelectric phase can be achieved at ambient temperature and pressure. However, there is still a strong need for a thorough microscopic understanding of the domain structure and the associated switching dynamics. In the case of ferroelectric materials, the key physical phenomenon is the motion of domain walls, including both 180° and 90° domain walls. HfO_2-based ferroelectrics are crucial for both theoretical and practical applications due to their ferroelectricity,[29] flexoelectricity,[30] and ferroelasticity.[31] Ferroelasticity is a well-known phenomenon that can exhibit spontaneous strain, which is the deformation of the crystal caused by a phase transition involving different crystal structures or orientations.[32] However, ferroelasticity in HfO_2-based films has received less attention compared to ferroelectricity. This is because identifying spontaneous structural polarization in polycrystalline films with randomly oriented vectors has been challenging.[31] Despite

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several study on the nanoscopic studies of domain structure dynamics in HfO_2-based capacitors,[33–36] in-depth examinations of domain structures and dynamics for HfO_2-based devices remain challenging. This is due to the complex situations involving different phase structures, such as monoclinic and tetragonal phases,[37] and various domain structures, including 180° and 90° domains,[31,38,39] coexisting within a single bulk to minimize electrostatic energy.

This study investigates the kinetics of 90° ferroelastic polarization during wake-up in 12-nm $Hf_{0.5}Zr_{0.5}O_2$ (HZO) ferroelectric films. The polarization switching can be achieved when the electric field is cyclically increased and decreased. The piezoelectric responses obtained using piezoresponse force microscopy (PFM) are consistent with the increased remanent polarization during cycling. This work provides possible explanations and potential insights into the pinched hysteresis phenomenon in HZO ferroelectrics, offering a perspective for fabricating higher-quality nanoscale devices.

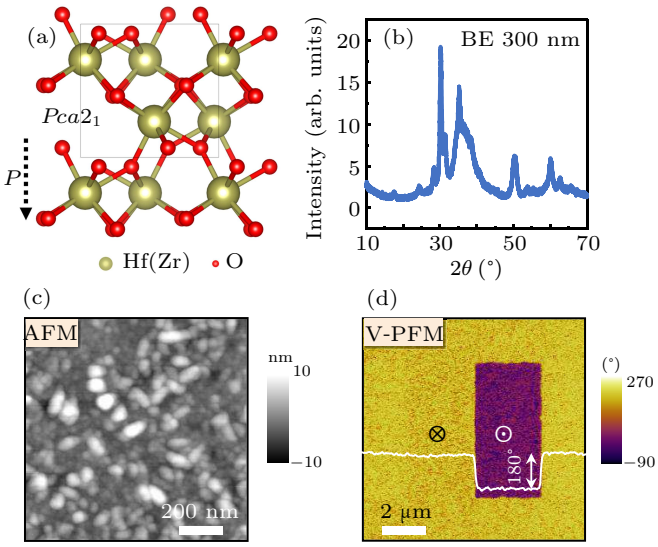


Fig. 1. Ferroelectric HZO thin film: (a) atomic structure of the HZO o-phase region, (b) x-ray diffractometer θ–2θ scans of the HZO thin film, (c) AFM image showing the grain-like topography of the HZO thin film, (d) OP-PFM phase image capturing the bidomain pattern created by electrical writing in the HZO thin film. The white line represents the phase contrast profile following OP polarization switching.

We use atomic layer deposition (ALD) to deposit HZO thin films onto SiO_2 substrates. Additionally, we employ TaN as the bottom electrode to facilitate the formation of HZO films with a ferroelectric phase of $Pca2_1$ (see Fig. 1(a)). The details of the deposition procedure are explained in detail under the methods section, and the microstructural information on the sample structure is given in Fig. S1, supplementary material. As seen in Fig. 1(b), x-ray diffractometer scans of θ–2θ reveal a combination of crystallites with different structures, including tetragonal and orthorhombic (t-phase and o-phase) structures. This is consistent with the results obtained from TEM analysis (Fig. S2, supplementary material). Figure 1(c) shows the surface morphology of the bare thin film, which is covered with grains having a roughness of approximately 2.461 nm over a square area of 1 μm×1 μm. The bipolar domain patterns are conventionally generated by scanning with an electrically biased PFM tip under ±9 V, which exceeds the coercive voltage. The PFM image of the written domain structure is shown in Fig. 1(d), illustrating the initial downward orientation of out-of-plane (OP) polarization and strong polarization retention. These results indicate the high quality of the HZO thin film.

In order to achieve wake-up, HZO thin films fabricated with top electrodes were initially subjected to an electric field cycling. Figures 2(a) and 2(b) demonstrate that the pinched hysteresis of a pristine sample opens, resulting in enhanced current and polarization as the electric field is cyclically increased and decreased. In order to simulate the wake-up process of HZO thin film and observe the corresponding evolution of HZO domains, the OP polarization of the film is repeatedly switched up and down using an OP electric field applied via a conductive tip. Interestingly, a chronological evolution of 90° domains occurs during the wake-up process, as demonstrated in Figs. 2(c)–2(j) through a series of PFM images. During the first few switching cycles, IP PFM phase contrast shows no noticeable change (Figs. 2(c)–2(f)), but gradually becomes mostly uniform with increasing wake-up cycles (Figs. 2(g)–2(i)). The amplitude responses increase during cycling, and this can be summarized by collecting line profiles at the same location indicated in Fig. 2(c) (Fig. S3, supplementary material). The increase in piezoresponse after cycling is consistent with the opened *I*–*E* hysteresis observed after wake-up, as shown in Figs. 2(a) and 2(b). All the states after cycling were examined when the OP polarization was polarized down. Meanwhile, the IP–PFM phase images at the second and the fifth cycles are both shown in a single purple tone throughout the entire region when OP polarization is up (Fig. S4, supplementary material).

Figure 3(a) shows a schematic illustration of how the domain dynamics of HZO thin film can be manipulated and probed using PFM. Figure 3(b) illustrates the bipolar piezoelectric hysteresis loops of HZO thin film obtained from local single-point PFM spectroscopic measurements. The coercive field shows little difference compared to the *I*–*E* loop shown in Figs. 2(a) and 2(b). This could be attributed to unavoidable contact resistance or work function difference between the top and bottom electrodes. By examining the domain behaviors within a single grain, the vertical PFM phase of the pristine sample exhibits a single yellow tone (Fig. 3(c)), while the lateral PFM shows two contrasting tones (Fig. 3(d)) with a 180° difference (Fig. S5, supplementary material) relative to the cantilever's axis. The width of the domain walls is around 0.4 nm, which is largely smaller than the size of the grains. This suggests

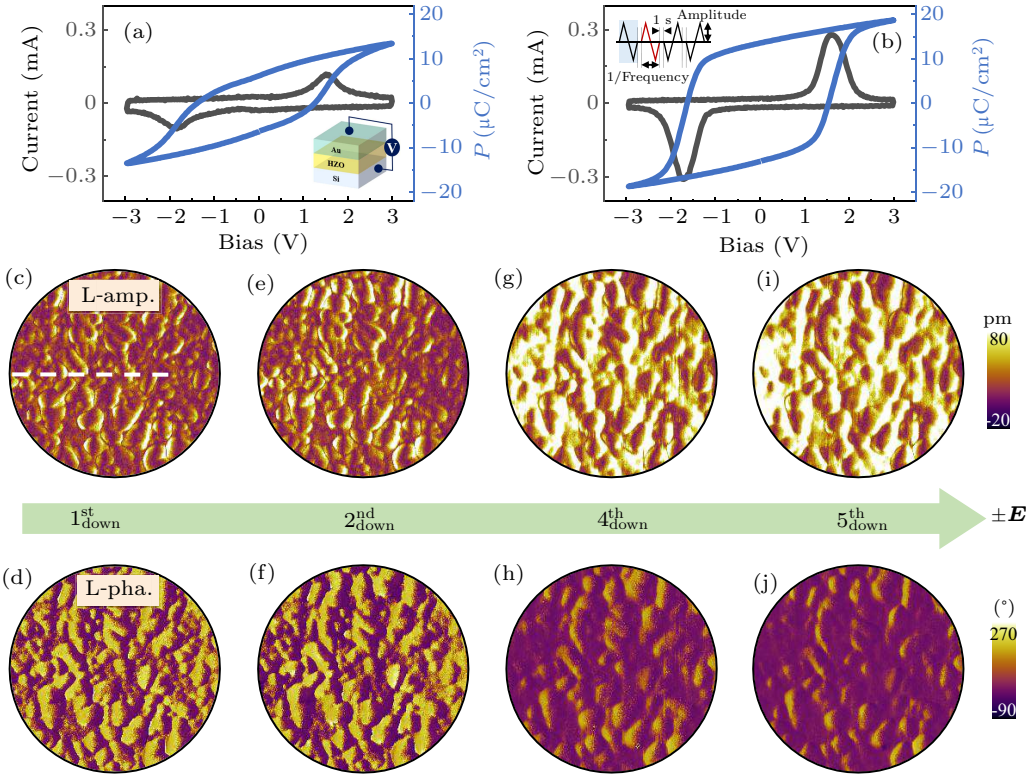


Fig. 2. Domain dynamics during wake-up: (a) characterization of macroscopic polarization before and (b) after wake-up, (c) lateral amplitude and (d) phase images after the first, [(e), (f)] second, [(g), (h)] fourth, and [(i), (j)] fifth wake-up.

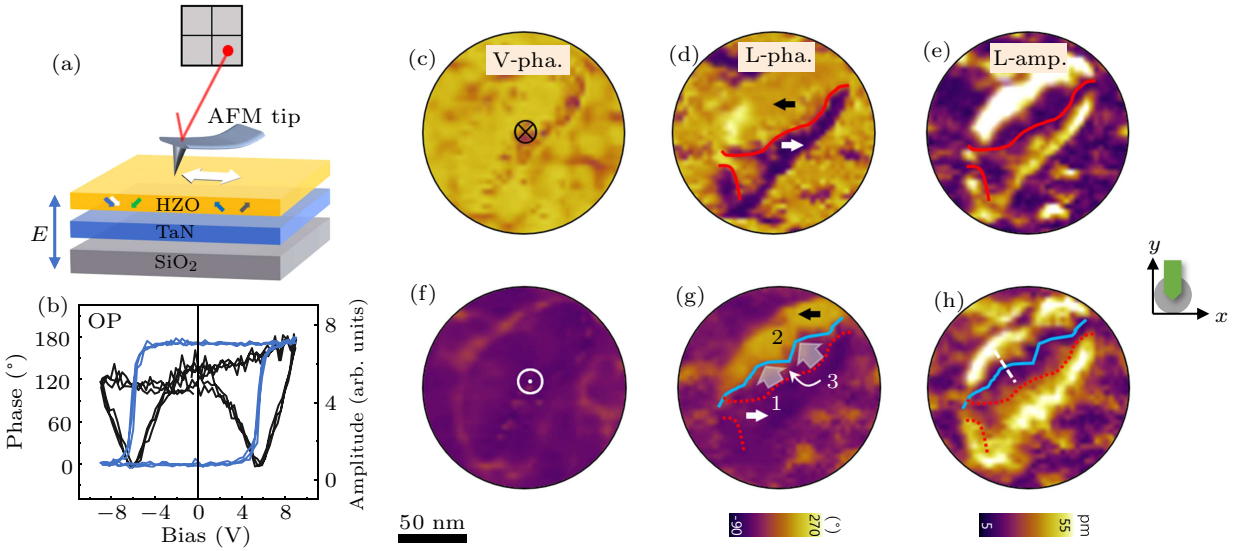


Fig. 3. Ferroelastic domain dynamics of the HZO thin film: (a) schematic diagram of the measurement structure, (b) amplitude and phase hysteresis loops of the HZO thin film using OP-PFM, (c) OP–PFM phase images of the as-prepared state and (d) after vertically poling with negatively biased tip, (e) the corresponding IP–PFM phase images of the same grain before and (f) after switching the OP polarization, (g) the corresponding IP–PFM amplitude images in the same region before and (h) after OP poling.

the presence of favorable downward vertical polarization components (film → bottom electrode) and the presence of domain wall-like characteristics for the lateral polarization components (Fig. 3(e)). After inducing vertical polarization switching using a negatively biased tip, the OP PFM phase contrasts change from yellow (Fig. 3(c)) to purple (Fig. 3(f)), indicating an inversion of the polarization from downward to upward (bottom electrode → film). Meanwhile, after vertical polarization switching (Fig. 3(g)), the boundary of the IP–PFM purple phase tone in the right half of the grain moves from the edge labeled by a red dash to the position marked by a blue curve. Figure 3(h) shows the effective lateral migration of the domain walls in the film under the influence of the OP electric field. The motion path is consistent with that of the phase change. The observed modification of the domain patterns in the IP–PFM after OP poling provides insights into the domain dynamics of HZO thin film. Based on the above results, it is reasonable to speculate that the components within

the film should have an angle with each other, whether in the OP or IP vectors. A detailed analysis of the components is presented in Table S1 of the supplementary material. In addition, IP domains are manipulated by an IP electric field, as shown in Fig. S6 of the supplementary material. In contrast to the motion of domain walls under the influence of the OP electric field and OP polarization switching, only IP ferroelastic switching occurs when an IP electric field is applied.

To reveal the domain structures of the grains, we obtained simpler and more robust high-angle annular dark field (HAADF) imaging using scanning transmission electron microscopy (STEM) from the pristine HZO thin film. Figure 4(a) shows that one of the grains in the film has an orthorhombic *Pca*21 structure with $a = 5.07°$ $b = 5.26°$ $c = 5.08°$. The annular bright field (ABF) image zoomed in squared area reveals that the local ferroelastic phase consists of 90° domains with head-to-tail configurations and aligns at a slight angle to the surface, while the others align with the law line. The polarization direction is confirmed through oxygen displacement. Figure 4(b) shows the equivalent atomic structure with 90° domains. The results coincide with the speculation obtained from PFM characteristics and provide a clear conclusion that the angle between the two domains is 90°, indicating ferroelasticity. The polarization evolution from PFM images confirms that the 90° domain walls undergo a reversible movement, and more uniform domains with the same polarization direction appear as the number of wake-up cycles increases. Moreover, the HAADF image of HZO ferroelastic switching is observed as well after the application of an external electric field. The results shown in Fig. S7 of the supplementary material are consistent with PFM behaviors, verifying the 90° domain switching.

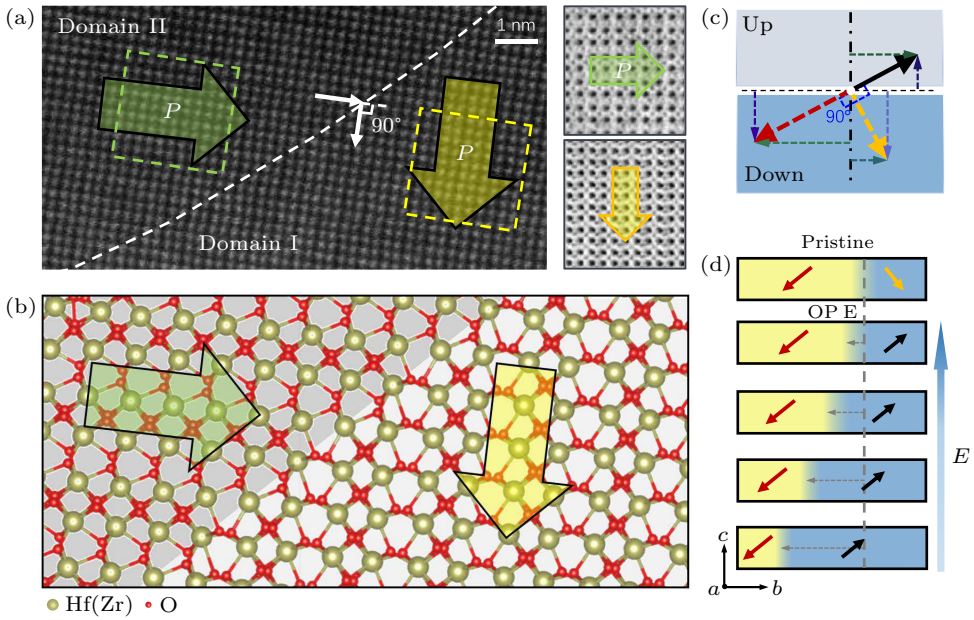


Fig. 4. The atomic structure of HZO thin film: (a) a TEM image showing an o-phase grain with the *c* axis as the polar axis, (b) a diagram depicting the structure of the HZO o-phase with 90° domains, (c) a schematic illustrating the mechanism and (d) movement of 90° ferroelastic domains (walls).

Although the microscopic domain dynamics of the HZO thin film can be observed using PFM and STEM, there are still several important points that need to be highlighted. First, the movement of 90° domain walls would have a significant impact on the ferroelectric and piezoelectric responses of the HZO thin film.[38] It can be inferred from the results that the lateral piezoresponse increases steadily during wake-up (see Figs. 2(e)–2(i) and Fig. S2 in the supplementary material), which may contribute to the increase in remanent polarization after wake-up. Second, the magnitudes of adjacent vectors should not be comparable. If the values of the adjacent piezoelectric components were the same, they would cancel each other out instead of producing signals with increasing amplitude. The possible arrangement of polarization and the evolution of domain structure are schematically depicted in Figs. 4(c) and 4(d) when the film is biased by a negative voltage. In the figure, the black and gray dashed lines represent the pristine vectors, while the solid black line represents the component after poling up. Lastly, although the domain behavior during the cycling process is not clear, the appearance of more lateral components with the same orientation would lead to the formation of larger net perpendicular vectors. These vectors might undergo another ferroelastic switching when an OP downward electric field is applied, similar to the macroscopic behaviors shown in Figs. 2(a) and 2(b).

In summary, a systematic investigation of the mechanisms of the HZO wake-up effect has been performed using PFM and STEM. Instead of the previously proposed domain pinning, charge trapping/de-trapping, and field modification, the movement of 90° domain walls plays a role on the wake-up characteristics. Domains with a 90° orientation are successfully observed by imaging the polarization with atomic reso-

lution via both PFM and STEM techniques, and the movement of 90° ferroelastic domain walls is manipulated by an external electric field. The polarized polarization is retained as domains pointing in the same direction increase and eventually saturate through cycling. The research opens up opportunities to enhance the functionalities of HfO_2-based devices.

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References

[1] Fernandez A, Acharya M, Lee H G, Schimpf J, Jiang Y, Lou D, Tian Z and Martin L W 2022 *Adv. Mater.* **34** 2108841
[2] Dragoman M, Aldrigo M, Dragoman D, Iordanescu S, Dinescu A and Modreanu M 2021 *Rapid Research Letters* **15** 2000521
[3] Guan Z, Hu H, Shen X W, Xiang P H, Zhong N, Chu J H and Duan C G 2020 *Adv. Electron. Mater.* **6** 1900818
[4] Böscke T S, Müller J, Bräuhaus D, Schröder U and Böttger U 2011 *Appl. Phys. Lett.* **99** 102903
[5] Materlik R, Künneth C and Kersch A 2015 *J. Appl. Phys.* **117** 134109
[6] Chen H Y, Zhou X F, Tang L, Chen Y H, Luo H, Yuan X, Chris R Bowen and Zhang D 2022 *Appl. Phys. Rev.* **9** 011307
[7] Müller J, Böscke T S, Müller S, Yurchuk E, Polakowski P, Paul J, Martin D, Schenk T, Khullar K, Kersch A, Weinreich W, Riedel S, Seidel K, Kumar A, Arruda T M, Kalinin S V, Schlösser T, Boschke R, van Bentum R, Schröder U and Mikolajick T 2013 *IEEE International Electron Devices Meeting*, Washington, DC, USA, 2013, pp. 10.8.1–10.8.4
[8] Mulaosmanovic H, Breyer E T, Dünkel S, Beyer S, Mikolajick T and Slesazeck S 2021 *Nanotechnology* **32** 502002
[9] Jiang P F, Luo Q, Xu X X, Gong T C, Yuan P, Wang Y, Gao Z M, Wei W, Tai L and Lv H B 2021 *Adv. Electron. Mater.* **7** 2000728
[10] Li S D, Zhou D Y, Shi Z X, Hoffmann M, Mikolajick T and Schroeder U 2020 *Adv. Electron. Mater.* **6** 2000264
[11] Park M H, Kim H J, Lee G, Park J, Lee Y H, Kim Y J, Moon T, Kim K D, Hyun S D, Park H W, Chang H J, Choi J H and Hwang C S 2019 *Appl. Phys. Rev.* **6** 041403
[12] Pešić M, Fengler F P G, Larcher L, Padovani A, Schenk T, Grimley E D, Sang X H, LeBeau J M, Slesazeck S, Schroeder U and Mikolajick T 2016 *Adv. Funct. Mater.* **26** 4601
[13] Schroeder U, Park M H, Mikolajick T and Hwang C S 2022 *Nat. Rev. Mater.* **7** 653
[14] Lederer M, Lehninger D, Ali T and Kämpfe T 2022 *Rapid Res. Lett.* **16** 2200168
[15] Huan T D, Sharma V, Rossetti G A and Ramprasad R 2014 *Phys. Rev. B* **90** 064111
[16] Wei Y F, Nukala P, Salverda M, Matzen S, Zhao H J, Momand J, Everhardt A S, Agnus G, Blake G R, Lecoeur P, Kooi B J, Íñiguez J, Dkhil B and Noheda B 2018 *Nat. Mater.* **17** 1095
[17] Li X Y, Zhong H, Lin T, Meng F Q, Gao A, Liu Z H, Su D, Jin K J, Ge C, Zhang Q H and Gu L 2023 *Adv. Mater.* **35** 2207736
[18] Estandía S, Dix N, Gazquez J, Fina I, Lyu J, Chisholm M F, Fontcuberta J and Sánchez F 2019 *ACS Appl. Electron. Mater.* **1** 1449
[19] Kim S J, Mohan J, Summerfelt S R and Kim J 2019 *The Journal of The Minerals, Metals & Materials Society (TMS)* **71** 246
[20] Hoffmann M, Pešić M, Chatterjee K, Khan A I, Salahuddin S, Slesazeck S, Schroeder U and Mikolajick T 2016 *Adv. Funct. Mater.* **26** 8643
[21] Müller J, Schröder U, Böscke T S, Müller I, Böttger U, Wilde L, Sundqvist J, Lemberger M, Kücher P, Mikolajick T and Frey L 2011 *J. Appl. Phys.* **110** 114113
[22] Li X F, Li C, Xu Z Y, Li Y S, Yang Y S, Hu H H, Jiang Z Z, Wang J I, Ren J X, Zheng C Y, Lu C J and Wen Z 2021 *Rapid Res. Lett.* **15** 2000481
[23] Kim H J, Park M H, Kim Y J, Lee Y H, Jeon W, Gwon T, Moon T, Kim K D and Hwang C S 2014 *Appl. Phys. Lett.* **105** 192903
[24] Batra R, Huan T D, Jones J L, Rossetti G Jr and Ramprasad R 2017 *J. Phys. Chem. C* **121** 4139
[25] Chernikova A, Kozodaev M, Markeev A, Negrov D, Spiridonov M, Zarubin S, Bak O, Buragohain P, Lu H, Suvorova E, Gruverman A and Zenkevich A 2016 *ACS Appl. Mater. Interfaces* **8** 7232
[26] Shimizu T, Katayama K, Kiguchi T, Akama A, Konno T J and Funakubo H 2015 *Appl. Phys. Lett.* **107** 032910
[27] Mueller S, Mueller J, Singh A, Riedel S, Sundqvist J, Schroeder U and Mikolajick T 2012 *Adv. Funct. Mater.* **22** 2412
[28] Zhong H, Li M Q, Zhang Q H, Yang L H, He R, Liu F, Liu Z H, Li G, Sun Q H, Xie D G, Meng F Q, Li Q, He M, Guo E J, Wang C, Zhong Z C, Wang X Q, Gu L, Yang G Z, Jin K J, Gao P and Ge C 2022 *Adv. Mater.* **34** 2109889
[29] Starschich S, Schenk T, Schroeder U and Boettger U 2017 *Appl. Phys. Lett.* **110** 182905
[30] Guan Z, Li Y K, Zhao Y F, Peng Y, Han G Q, Zhong N, Xiang P H, Chu J H and Duan C G 2022 *Nano Lett.* **22** 4792
[31] Shimizu T, Mimura T, Kiguchi T, Shiraishi T, Konno T, Katsuya Y, Sakata O and Funakubo H 2018 *Appl. Phys. Lett.* **113** 212901
[32] Salje E K H 2012 *Ann. Rev.* **42** 265
[33] Buragohain P, Richter C, Schenk T, Lu H, Mikolajick T, Schroeder U and Gruverman A 2018 *Appl. Phys. Lett.* **112** 222901
[34] Buragohain P, Erickson A, Mimura T, Shimizu T, Funakubo Hiroshi and Gruverman A 2022 *Adv. Funct. Mater.* **32** 2108876
[35] Buragohain P, Erickson A, Kariuki P, Mittmann T, Richter C, Lomenzo P D, Lu H, Schenk T, Mikolajick T, Schroeder U and Gruverman A 2019 *ACS Appl. Mater. Interfaces* **11** 35115
[36] Stolichnov I, Cavalieri M, Colla E, Schenk T, Mittmann T, Mikolajick T, Schroeder U and Ionescu A M 2018 *ACS Appl. Mater. Interfaces* **10** 30514
[37] Richter C, Schenk T, Park M H, Tscharntke F A, Grimley E D, LeBeau J M, Zhou C, Fancher C M, Jones J L, Mikolajick T and Schroeder U 2017 *Adv. Electron. Mater.* **3** 1700131
[38] Nagarajan V, Roytburd A, Stanishevsky A, Prasertchoung S, Zhao T, Chen L, Melngailis J, Auciello O and Ramesh R 2003 *Nat. Mater.* **2** 43
[39] Ding W T, Zhang Y K, Tao L L, Yang Q and Zhou Y C 2020 *Acta Materialia* **196** 556