Manipulation of Conductive Domain Walls in Confined Ferroelectric Nanoislands

Guo Tian, Wenda Yang, Xiao Song, Dongfeng Zheng, Luyong Zhang, Chao Chen, Peilian Li, Hua Fan, Junxiang Yao, Deyang Chen, Zhen Fan, Zhipeng Hou, Zhang Zhang, Sujuan Wu, Min Zeng, Xingsen Gao,* and Jun-Ming Liu

Conductive ferroelectric domain walls—ultnarrow configurable conduction paths—have been considered as essential building blocks for future programmable domain wall electronics. For applications in high-density devices, it is imperative to explore the conductive domain walls in small confined systems, while earlier investigations have hitherto focused on thin films or bulk single. Here, an observation and manipulation of conductive domain walls confined within small BiFeO$_3$ nanoislands aligned in high-density arrays are demonstrated. Using conductive atomic force microscopy, various types of conductive domain walls, including the head-to-head charged domain walls (CDWs), zigzag domain walls, and typical 71° head-to-tail neutral domain walls (NDWs), are distinctly visualized. The CDWs exhibit remarkably enhanced metallic conductivity with current of μA order in magnitude and 10$^4$ times larger than that inside domains (0.01–0.1 pA), while the semiconducting NDWs allow much smaller current (≤10 pA) than the CDWs. The substantial difference in conductivity for dissimilar walls enables manipulations of various wall conduction states for individual addressable nanoislands via electrical tuning of domain structures. A controllable writing of four distinctive states in individual nanoislands can be achieved, showing application potentials for developing multilevel high-density memories.

1. Introduction

Ferroelectric domain walls (FEDWs),[1,2] which are often viewed as 2D homointerfaces, may possess distinct electronic, magnetic, and optoelectronic properties localized at a 1–10 nm length scale.[3–8] The domain walls can also be created, reshaped, and displaced by external electric field,[9,10] promising for future electronic, spintronic, and optoelectronic devices. In particular, the discovery of enhanced electrical conductivity of FEDWs in otherwise insulating ferroelectrics[3] has open a new avenue for developing wall nanoelectronics and inspired intensive research interests.

In the past decade, enhanced wall conduction has been observed in various proper and improper ferroelectrics,[3,11–15] and numerous intriguing conduction behaviors and the underlying mechanisms have been revealed,[16–27] For instance, a unique feature of quasi-2D electron gas was observed in strongly charged domain walls (CDWs), which exhibit a giant metal-like conductivity up to 10$^9$ times as good as the insulating bulk.[20,24] It was also reported that CDWs can be formed in ultrathin ferroelectric barriers of tunnel junctions, and this approach develops discrete quantum-well energy levels leading to strong quantum oscillations in tunneling conductance.[25,26] These exciting breakthroughs have not only deepened our understanding of new physics related to FEDWs, but also pushed forward their use (e.g., CDWs) toward practical applications in high-density electronic devices. Recently, Nagerajan, Seidel, and coworkers proposed a two-terminal prototype of scalable nonvolatile wall resistive memory with high OFF/ON resistance ratio.[28] Jiang et al. also demonstrated a threeterminal memory device that is able to produce large reading currents along with long retention time, by utilizing retractable partially switched domain walls.[29]

In spite of these fascinating properties in association with wall conduction, major obstacles that hinder their further applications remain and reports on highly promising prototype devices are yet rare. The previously proposed device prototypes based on FEDWs in films and single crystals usually have the lateral architectures with low integration density,[28,29] and it is known that for high-density scaling-up techniques, perpendicular architectures (e.g., ferroelectric/resistive random-access memory) based on nanostructures are much preferred. Besides, it is still a tricky issue to deterministically tailor the wall conduction states for on-demand applications in devices.

G. Tian, W. Yang, X. Song, D. Zheng, L. Zhang, C. Chen, P. Li, H. Fan, J. Yao, Dr. D. Chen, Dr. Z. Fan, Dr. Z. Hou, Prof. Z. Zhang, Dr. S. Wu, Prof. M. Zeng, Prof. X. Gao, Prof. J.-M. Liu
Institute for Advanced Materials (IAM) and Guangdong Provincial Key Laboratory of Quantum Engineering and Quantum Materials
South China Academy of Advanced Optoelectronics
South China Normal University
Guangzhou 510006, China
E-mail: xingsengao@scnu.edu.cn
Prof. J.-M. Liu
Laboratory of Solid State Microstructures and Innovation Center of Advanced Microstructures
Nanjing University
Nanjing 210093, China

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/adfm.201807276.
DOI: 10.1002/adfm.201807276
These issues could be well addressed if the conductive FEDWs can be constrained in small nanodots/nanoislands. Such a strategy does enable the device scaling-up to ultrahigh density, but the size-confinement and surface effects of nanostructures certainly make the wall conduction states very different. If these additives are well understood and controlled, the FEDW conduction as a novel functionality would be offered an additional degree of freedom. In fact, recent studies did reveal some unique exotic domains such as bubble, flux-closure vortex, and center-type topological states in nanoscale ferroelectrics,\(^\text{[30–38]}\) which also add more ingredients into the enthralling DW functionalities. In view of the tantalizing properties in both domain wall conductance and nanoferroelectrics, it is highly promising and extremely important to look into the FEDW conduction behaviors in size-confined nanostructures. This is the major motivation of the present work.

In this work, we report the observation and manipulation of conductive domain walls confined in epitaxial BiFeO\(_3\) (BFO) nanoislands (see Figure 1). The main results can be highlighted from several aspects. First, we have identified various types of conductive domain walls, including zigzag-like walls, head-to-head CDWs, and neutral domain walls (NDWs), inside individual nanoislands. These walls exhibit markedly different conductive behaviors, like quasi-2D metallic behavior for head-to-head CDWs and semiconducting behavior for NDWs. Moreover, both the wall structures and their conduction states can be well tailored using various external electrical biases, allowing predesign control of conduction states in individual nanoislands, highly advantageous for multilevel wall conductivity memory with perpendicular device architecture.

2. Results and Discussion

2.1. Fabrication of BFO Nanoislands

The BFO nanoisland arrays under investigation were patterned from high-quality epitaxial BFO films (\(\approx 35\) nm in thickness) via a nanosphere lithography technique using polystyrene (PS) nanosphere template.\(^\text{[35]}\) A schematic fabrication procedure is illustrated in Figure S1 (Supporting Information). First, the well-packed monolayer of PS spheres was transferred onto the BFO epitaxial film surface, and then these nanospheres were subjected to size shrinkages by oxygen plasma to develop discrete ordered array as template mask for patterning. Subsequently, the as-prepared product was etched by Ar\(^+\) ion beam, and finally the PS mask was lift off by chloroformic solution, generating the well-ordered nanoisland array, as shown in the scanning electron microscopy (SEM) image of Figure 1a. The X-ray diffraction (XRD) \(\theta-2\theta\) spectrum of the sample, given in Figure 1b, shows the good epitaxy structure, reflected by the diffraction peaks from the substrate SrTiO\(_3\) (STO) (002), bottom electrode SrRuO\(_3\) (SRO) (002), and BFO (002), and further confirmed by the (103) reciprocal space map (RSM) shown in Figure 1c. We can also obtain that the in-plane and out-of-plane lattice parameters of the BFO nanoislands are \(a = b = 0.391\) nm.

![Figure 1](image-url)

**Figure 1.** Structures and domain wall conductivity of an array of BFO nanoislands. a) SEM image, b) XRD diffraction pattern, and c) reciprocal space map of nanoislands. d) Simplified schematic diagram of PFM and CAFM characterization of the nanoisland array, and e) an example of CAFM map of conductive domain walls in an array of nanodots, superimposed with their corresponding 3D topographic image.
and $c \approx 0.406$ nm, comparable with those from in-plane compressively strained BFO.[20]

### 2.2. Domain Structures and Wall Conduction

To see the domain conduction behaviors, these nanoislands were examined using conductive atomic force microscopy (CAFM) and piezoresponse force microscopy (PFM), as detailed in the Experimental Section and schematically shown in Figure 1d. An example of the electrical conduction in these nanoislands is given by the CAFM mapping (Figure 1e), superimposed with its 3D AFM topology for better illustration. Clearly, some distinct zigzag-like conduction paths inside the nanoislands can be identified that are related to the conductive walls. By comparing the CAFM image with its corresponding in-plane PFM image (abbreviated as L-Pha), one could see that the most domain walls show high conductivity compared to the domain interior (see Figure S2c,d in the Supporting Information).

To carefully examine the domain structures of the nanoislands, we perform a vector PFM measurement by involving both vertical PFM and lateral PFM scanning before and after a 90° rotation of the sample. These piezoresponse images allow us to construct the 3D piezoresponse vector contour, following the vector PFM analysis method proposed by Rodriguez, Kalinin, and coworkers.[19] An example for the nanoislands in pristine state is shown in Figure S3 (Supporting Information), while two representative domain states for individual nanoislands are given. The most popular state is presented in Figure S3g (Supporting Information) with a clear zigzag domain wall from the lateral component of polarization. The second most popular state exhibits two sets of zigzag walls with intersection to some extent (see Figure S3h in the Supporting Information), wherein the overlapped region forms an antivortex structure. The domain structures of nanoislands can be well switched by using a scanning bias of $-3.5$ V, as reflected by the apparent contrast change in both vertical and lateral PFM images (see Figure S4 in the Supporting Information).

It is also noted that the walls in the pristine state (with downward polarization, shown in Figure S3 in the Supporting Information) exhibit faint CAFM contrast with small conduction close to the noise level (see Figure S2a,b in the Supporting Information). However, once a region of nanoisland array was electrically poled with a $-3.5$ V voltage (with upward polarization), the conducting paths show much better contrast and thus much higher current density. The different conductive levels between the upward and downward polarization states of the nanoislands are likely due to the polarization-modulated resistive switching behavior. As shown in Figure S5 (Supporting Information), the domain walls with downward polarization states show very low conduction level, in contrast to the high conductive FEDWs for upward polarization states. Therefore, we will mainly focus on the domain walls in upward polarization states in the following sections.

To illustrate the one-to-one correspondence between the walls and conduction paths, both the PFM and CAFM images on a nanoisland region that was previously downward switched using a bias of $-3.5$ V are shown in Figure 2. Figure 2a–c demonstrates the PFM images scanned at angles of 0° and 90° (only L-PFM images are shown for simplicity), respectively, along with the corresponding CAFM images. Both the PFM and CAFM images are superimposed with the 3D topographic images for better recognition. From the lateral PFM images, it is revealed that most of the nanoislands show the typical zigzag domain walls, although some others do show wavy or straight head-to-head CDWs and minor amount of straight NDWs. The one-to-one correspondence between the walls and current paths (see Figure 2a–c) can be established, but different types of walls do have very different magnitudes in current density.

To carefully examine the wall conduction, we pick out two nanoislands with typical domain structures (marked with dashed circles in Figure 2a–c) for a detailed discussion. Their CAFM images together with a complete set of PFM images are illustrated in Figure 2d,e, respectively. The first nanoisland (Figure 2d) has one head-to-head CDW along with one 71° NDW. The second nanoisland (see Figure 2e) includes one typical zigzag wall, consisting of two 71° NDWs at the side edges and one very short head-to-head CDW at the zigzag corner. The different types of walls are also reflected by the dissimilar levels of conduction current density shown in the CAFM image. The current profiles across both the NDWs and CDWs are plotted in Figure 2f,g, and one can distinctly identify that the head-to-head CDWs including the straight wall and zigzag wall corner show high current levels on the $\approx$ nA order of magnitude, in contrast to the $\approx$ pA order of magnitude for the 71° NDWs. This difference is further verified by the current–voltage ($I–V$) curves measured at different locations (Figure 2h), which clearly indicate the largest current ($>1$ nA) at the pure head-to-head CDWs, intermediate current ($\approx10$ pA) at the NDWs, and the lowest current ($<0.2$ pA) inside the domains.

### 2.3. Temperature-Dependent Conduction Behaviors

Subsequently, we discuss the conduction mechanisms of these walls by checking the temperature ($T$)-dependent conduction by using in situ temperature control CAFM measurement, as shown in Figure 3. The CAFM maps for the CDWs and NDWs measured at various $T$, as presented in Figure 3a,b, suggest a gradual decrease in current density for the CDWs while a monotonous increase for the 71° NDWs with increasing temperature. This was also verified by the current profiles shown in Figure 3c,d and the $I–T$ curves shown in Figure 3e for both types of walls. It was apparent that the $I–V$ curve for the CDWs exhibits positive temperature coefficient that can be well fit to the metallic conduction relation ($I \sim 1 + a(T – T_0)^{-1}$), while that of NDWs exhibits negative temperature coefficient and conforms to the thermal activation relation ($I \sim \exp(\Delta E/kT)$). It should be mentioned that the results reported here are of generality and applicable to almost all nanoislands of our samples. The metallic conduction of the head-to-head CDWs is somewhat similar to earlier observations on BaTiO$_3$ single crystals and La-doped BFO films.[20,24]

Currently, several mechanisms have been proposed to interpret the wall conductivity, including the band bending, defects, and local lattice distortion, among others, noting that...
no general agreement so far has been reached.\cite{16–20} Here, the identified metallic conduction of these CDWs can be associated with the quasi-2D electron gas of these walls due to the effective compensation of bound polarization charges by the accumulated charges.\cite{20} This can also be understood by the band bending at the CDWs induced by the uncompensated polarization charges, which leads to a dramatic drop of the conduction band below the Fermi level, thus resulting in the metallic behavior. On the other hand, there may also exist built-in potential profiles at the junction between domain wall and surfaces probably due to the recurring of CDWs (or nonohmic contact)\cite{20,24}; hence, tunneling through the barriers becomes important, as supported by the existence of a threshold voltage of \(\approx 1.5 \) V above which the CDWs start to show metallic behavior. The tunneling current can also be enhanced by defect-assisted tunneling; e.g., oxygen vacancies around the domain wall are able to narrow down the barrier width and form trap-assisted tunneling that can greatly enhance the conduction in CDWs.

In contrast, the conduction in NDWs is mainly dominated by thermal activation behavior (e.g., semiconductor-like). This may be due to the slightly lowering of conduction band in NDWs, which increases the density of electron carriers in the conduction band. From the fitting of \(I-V\) curve for NDWs in Figure 3d, one can derive an activation energy of \(\approx 0.22 \) eV, close to the electron hopping between \(\text{Fe}^{2+}\) and \(\text{Fe}^{3+}\) in BFO,\cite{40} implying that the interaction between electrons and \(\text{Fe}^{2+}\) also contributes to the conductive behaviors.

### 2.4. Manipulation of Wall Conduction States

Given the established one-to-one correspondence between the domain wall type and conductivity, it is proper to address how
the wall conduction state can be manipulated by switching the wall from one type to another, which is key for the promising data memory devices. The capability to manipulate the walls and their conduction states by electric field is the most straightforward and simple approach. For realizing this target, various bias-voltage scanning trials were performed on these nanoislands, and the main results are highlighted in Figure 4.

The domain structure and wall conduction for a nanoisland at the pristine state (no electrical bias) are shown in Figure 4a: typical zigzag walls consisting of 71° NDWs and tail-to-tail CDWs, with rather low wall conduction current (<2 pA) over the whole nanoisland. In addition, an electrical bias can change the domain structure remarkably in the repeatable way and thus the domain wall conduction state, allowing programmable and predesignable control of conduction states in individual nanoislands. To illustrate this step-like/processable control, we present the results for several different events.

First, a small bias voltage of −3.5 V switches the vertical polarization component upward completely, while the lateral component retains the similar zigzag wall pattern, as shown in Figure 4b. The new zigzag wall mainly consists of NDWs and head-to-head CDWs at the angle corners (similar to Figure 2e), in which the NDW exhibits a current level of ≈10 pA and the CDW allows a current of ≈100 pA, as mentioned previously. It is worth noting again that the observed different conduction states for the two “zigzag” domain states shown in Figure 4a,b can be attributed to the strong resistive switching behavior between the upward and downward vertical polarization states in individual nanoislands, as illustrated in Figure S5 (Supporting Information).

Second, if the bias voltage is −4.5 V instead of −3.5 V, as shown in Figure 4c, one sees that the zigzag wall now converts to a straight head-to-head CDW, which displays the largest conductive current (≈nA over the whole long wall). Third and more interestingly, if the bias voltage is further increased up to −5.5 V, as shown in Figure 4d, it is surprising to see that the CDW vanishes and it converts to pure stripe pattern consisting of typical 71° NDWs, leading to a sudden drop in the current (≈10 pA).

The above example suggests that both the domain wall pattern and conduction state for a nanoisland can be deterministically controlled by external electrical bias, giving rise to four different conduction states: 1) the initial zigzag-DW state with downward vertical component of polarization, exhibiting smallest current <2 pA; 2) pure 71° NDW state with upward vertical polarization after applying −5.5 V, corresponding to intermediate state with current ≈10 pA; 3) zigzag-DW state with upward vertical component of polarization, created by applying scanning bias of −3.5 V, showing a larger conduction...
(10 pA to 100 nA); and 4) head-to-head CDW state with upward vertical component of polarization, after applying −4.5 V, showing large current >1 nA. The observation of various conduction states in individual nanoislands clearly indicates that the conductive domain walls can be engineered and utilized in multilevel FEDW memory devices, and the schematics of the conceptual devices are illustrated in Figure 4e as one proposal, in which each individual nanoisland is able to store two data bits by using the four programmable conduction states. Such a device has the perpendicular architecture, compatible with ultrahigh-density scaling-up techniques, a noticeable advantage.

Figure 4. Manipulation of various domain wall patterns and corresponding conduction states in individual nanoislands by using external scanning bias voltages. PFM and CAFM images for the four different types of domain wall states: a) zigzag-DW state with downward vertical polarization (pristine state); b) zigzag-DW state with upward vertical polarization (after poling by scanning bias voltage of −3.5 V); c) head-to-head CDW state with upward vertical polarization (bias voltage −4.5 V); and d) purely NDW state with upward vertical polarization (bias voltage −5.5 V). e) Schematic diagrams of conceptual domain wall device utilizing the four domain wall states, which allows to store two data bits in one individual nanoisland cell.
2.5. Discussion

To find out the driving forces for electrical control of different conductive domain wall states, in particular the CDW, we perform a scanning Kelvin potential microscopy (SKPM) measurement to probe the surface potential distribution on a nanoisland. Figure 5a,b shows the surface potential (using SKPM) and corresponding CAFM maps for nanoislands with various conductive domain wall states. Among them, the nanoisland carrying a head-to-head CDW exhibits the lowest surface potential, and the region adjacent to the CDW also shows a relatively low surface potential (negative) in contrast to the remaining region in the same nanoisland (state III in Figure 5a). This suggests that the bias-induced electron injection and trapping, reflected by the lower surface potential, are likely responsible for the CDW formation. The trapped electron charges can compensate the unbalanced polarization bond charge at the CDW and lower the formation energy, and simultaneously assist with the external bias field to trigger the nucleation of CDWs. In contrast, for the nanoislands with less trapped charge density, i.e., relatively higher surface potential, zigzag states with small portion of CDWs or pure NDW states are more favored (states II and IV in Figure 5).

Based on the above analysis, schematic diagrams were also illustrated to help interpret the formation mechanism of the observed domain wall states. One may consider that during the biased scanning of AFM probe on nanoislands, the electron charge from conductive AFM tip can be injected and trapped in the surface of BFO nanoisland, e.g., assisted by charge traps like oxygen vacancies, which can greatly increase the electrostatic energy and possibly lead to local domain changing. Simultaneously, the polarization flipping from downward to upward direction during scanning can further promote the domain rearrangement. For low level of charge trapping, a stripe-like domain texture with pure NDW (see state IV in Figure 5c) forms, similar to stripe domain pattern usually appearing in the BFO film. With increasing level of charge trapping, the electrostatic energy greatly increases, and an electron-rich region due to distribution inhomogeneities tends to attract positive polarization bound charge and reorients the local polarization, forming head-to-head charged domain walls to lower the electrostatic energy. For modulated density of charges (see state II in Figure 5c), very short CDWs appear, and the stripe texture is distorted to form zigzag domain state. At high level of charge trapping, longer head-to-head CDW forms (state III in Figure 5c), and more electrons are attracted inside CDW to balance the bound charge. Similarly, for the initial state, the
zigzag-like domain with downward polarization may be in association with accumulation of oxygen vacancies (with positive charge) at film surface accumulated during film growing stage, which tends to drive the formation of zigzag domain with short tail-to-tail walls in corner (state I in Figure 3c). It was also noted that the in-plane component of electric field from the biased AFM tip can also affect the domain structure, which tends to drive the polarization of domains toward the field direction during scanning (parallel to cantilever in our case). Therefore, concurrent effect of both trap charges and in-plane field from tip would lead to the formation of the observed various domain wall states.

On the other hand, the different levels of electron charge injection/trapping can also be well controlled by bias voltages of scanning AFM probe, as demonstrated in Figure S6 (Supporting Information). Figure S6b (Supporting Information) shows the average surface potential as a function of bias voltage, wherein the surface potential exhibits a monotonic decrease (negative value from trapped electron charge) with increasing bias voltages until reaching a minimum (largest density of trapped charge) at 4.5 V, above which the surface potential increases (reduced trapped charge density) with further increase of voltage. The observed increase in trapped charge density with increasing bias voltage below 4.5 V is likely due to the trap filling process. However, the reduction in trapped charge density at large voltages could be associated with the Coulombic repulsion between trapped charges, which may prohibit further trapping, promote charge migration, and accelerate charge draining through some conduction paths, e.g., CDWs or tunneling. Similar behavior has also been observed in the previous reports by Kim et al.41

This further supports that the above highlighted domain wall states (shown in Figure 4) could also be driven by different levels of charge injection/trapping, which can be easily modulated by external bias. As the domain wall patterns can greatly determine the domain wall conduction state in a nanoisland, our observation provides a simple route to tailor the conduction states of individual nanoislands, via electrical tuning of various domain wall states.

3. Conclusions

In summary, we have observed various types of conductive domain walls confined in high-density arrays of BFO nanoislands, including CDWs, head-to-tail NDWs, and unique zigzag-DWs, which also exhibit much different conductive properties. The head-to-head CDWs demonstrate a metallic conductive behavior and a high conduction level up to two orders in magnitude that of the NDWs and four orders in magnitude that of the domain interior. The dissimilar conductive behaviors also enable the manipulation of various conduction states (e.g., four different conductive levels) in individual nanoislands, via electrical modulation of their domain wall patterns by applying various electrical biases. This creates a new avenue for further engineering the conductive domain walls in ultrahigh-density DW devices, e.g., multilevel nonvolatile memory with perpendicular architecture.

4. Experimental Section

Fabrication of Nanodot Arrays: The fabrication procedure for the nanoisland arrays is illustrated in the schematic flowchart in Figure S1 (Supporting Information), which is based on nanoscale patterning on well-epitaxial BFO thin films. In brief, the epitaxial BiFeO₃ thin film of ~35 nm thickness along with a ~20 nm thick epitaxial SRO layer was deposited on the (100)-oriented STO substrates by pulsed laser deposition using a KrF excimer laser (wavelength $\lambda = 248$ nm) at 680 °C with an oxygen ambient of 15 Pa, a pulse energy of 300 mJ, and a repetition rate of 8 Hz. Then, the nanoscale PS spheres dispersed in a mixture of ethanol and water were transferred onto the as-grown BiFeO₃ film to form a close-packed monolayer template. The nanospheres were then etched to the desired size by oxygen plasma to form a discrete ordered array. This was followed by $\text{Ar}^+$ ion beam etching with appropriate etching time. Finally, the PS layer was removed by chloroformic solution and the periodically ordered BFO nanoisland arrays were obtained. After the patterning, the samples were also annealed at oxygen ambiance at 400 °C for 30 min to reduce the defect and residual strain.

Ion Beam Etching Process: The samples were etched by $\text{Ar}^+$ ion beam etching at a vacuum pressure of 300 V, an ion accelerating voltage of 250 V, a neutralization voltage of 300 V, an anode voltage of 50 V, a plate voltage of 300 V, an ion accelerating voltage of 250 V, a neutralization voltage of 13 A, and a bias current of 1.2 A.

Microstructural Characterizations: The structure of nanodots was characterized by XRD (PANalytical X’Pert PRO), including $\theta$–$2\theta$ scanning and RSM along the (003) diffraction spot. The top-view surface images were obtained by SEM (Zeiss Ultra 55), and the topography images were taken by AFM (Asylum Cypher AFM).

PFM and CAFM Characterizations: The ferroelectric domain structures of these nanodots were characterized by PFM (Cypher, Asylum Research, and Infinity, Oxford) using conductive probes (Arrow EFM, Nanoworld). The local piezoresponse loop measurements were carried out by fixing the PFM probe on a selected nanodot and then applying a triangle square waveform accompanied with AC driven voltage, via the conductive PFM probe. The vector PFM function of the AFM unit allowed simultaneous mapping of the vertical (out-of-plane) and lateral (in-plane) amplitude and phase signals from the nanodot one by one. To reduce the unwanted cantilever flexure (buckling) effect on PFM signal, the laser beam (used to detect the deflection of cantilever) was positioned exactly above the position of AFM tip on cantilever. To determine the 3D domain structures, both the vertical and lateral PFM images were collected for sample rotation at 0° and 90°. Before the rotation, a specific position of the sample was artificially marked, so that the sample region can be tracked after rotation. The CAFM maps and current–voltage ($I$–$V$) measurements were characterized by using platinum- and diamond-coated probes (CONTV-PT of Bruker and CDT-NCHR-10 of Nanoworld, respectively) with an in-situ temperature control accessory.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

The authors would like to thank the National Key Research and Development Program of China (no. 2016YFA0201002), the State Key Program for Basic Researches of China (no. 2015CB921202), the Natural Science Foundation of China (nos. 51431006, 11674108, and 51272078), the Project for Guangdong Province Universities and Colleges Pearl River Scholar Funded Scheme (2014), the Natural Science Foundation of Guangdong Province (no. 2016A030308019), and the Science and Technology Planning Project of Guangdong Province (no. 2015B090927006).
Conflict of Interest

The authors declare no conflict of interest.

Keywords

domain wall memory, ferroelectric domain wall conductivity, ferroelectric nanostructures

Received: October 15, 2018
Revised: March 5, 2019
Published online: May 9, 2019