Magnetoelectric coupling in λ' -Fe₄N/ Pb(Mg_{1/3}Nb_{2/3})_{0.7}Ti_{0.3}O₃ multiferroic heterostructures

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ABSTRACT

Epitaxial γ' -Fe₄N films with different thicknesses were fabricated on Pb(Mg_{1/3}Nb_{2/3})_{0.7}Ti_{0.3}O₃ (PMN-PT) substrates by facing-target reactive sputtering. The magnetoelectric coupling (MEC) in the samples was systematically investigated. Firstly, the magnetization along different in-plane directions is tunable by the electric field. It was found that MEC in the films on PMN-PT(011) is stronger than that on PMN-PT(001) due to the different in-plane magnetic anisotropy. Moreover, the magnetoelectric coupling is strongly related to the γ' -Fe₄N film thickness, which can be ascribed to the competition between the strain and spin-dependent screening effect induced MEC. Additionally, the electric-field tailored remanent magnetization of the samples gradually increases with temperature due to the thermal agitation. Besides, the electric-field effect on the out-of-plane magnetic hysteresis loops is consistent with the in-plane cases. The results are of benefit to the development of the electric-field controlled spintronic devices.

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I. INTRODUCTION

Effective electric-field control of magnetization is very important in spintronic devices with small size, fast access speed, and low energy consumption.^{1–3} Multiferroic materials are the most popular materials to achieve magnetoelectric coupling (MEC). Besides the single-phase multiferroic materials, more research focuses on the artificial ferromagnetic (FM)/ferroelectric (FE) multiferroic heterostructures, which have the potential applications due to their strong MEC. In the last decade, the piezoelectric material Pb(Mg_{1/3}Nb_{2/3})_{0.7}Ti_{0.3}O₃ (PMN-PT), which is a promising FE layer in FM/FE heterostructures, has attracted much attention due to its large electrostriction.^{4–17} The mechanism of the MEC in PMN-PT based multiferroic heterostructures is that the FM layer will suffer a strain from PMN-PT to which an electric field was applied and then the strain can modulate the magnetization of the FM layer because of the converse magnetostriction effect.^{4–11} However, the clamping effect is crucial in the strain-induced MEC from the substrate. In this case, a thick FE substrate is needed, which can hardly be applied to the thin-film spintronic devices.²¹ Recently, much effort

has been focused on MEC induced by the charge screening effect in FM/FE heterostructures.^{18–21} Nevertheless, the effective electric control of magnetization is difficult to realize because the conventional electrostatic screening effect only appears at the depth of a few angstroms in the FM layer.^{21–23} The spin-dependent charge induced MEC, named as spin-dependent screening effect (SSE), in FM/FE heterostructures has been proposed.^{24–26} In the FM/FE heterostructures, the spiral spins at the FM interface can be mediated by an electric field due to the *s-d* exchange interaction, so the magnetization can be modulated.²³ The SSE-induced MEC can penetrate the FM layer within tens of nanometers,^{25–29} which is a promising way to control magnetization. However, the experimental research on the SSE-induced MEC is still at the early stage, which needs further investigation.

Previously, we demonstrated that a large electric-field control of magnetization in epitaxial γ' -Fe₄N/PMN-PT(011) heterostructures could be induced by an SSE.³⁰ Here, the effects of film thickness, temperature, and lattice orientation on the MEC in γ' -Fe₄N/PMN-PT heterostructures were investigated

systematically. MEC in γ' -Fe₄N/PMN-PT(011) heterostructures is stronger than that in γ' -Fe₄N/PMN-PT(001) heterostructures due to the different in-plane magnetic anisotropy. MEC is strongly dependent on the γ' -Fe₄N film thickness because of the strain and spin-dependent screening effect induced MEC. The electric-field tailored remanent magnetization of the heterostructures gradually increases with temperature.

II. EXPERIMENT

Epitaxial γ' -Fe₄N films with different film thicknesses ($t = 5, 8.5, 12, 17, 25.5$, and 34 nm) were fabricated by a facing-target reactive sputtering method on the 0.2 -mm thick PMN-PT (001) and (011) substrates. The substrate temperature was kept at 450°C during the γ' -Fe₄N film deposition. The pressure in the chamber was kept at 1 Pa, where the gas flow rates of pure Ar and N₂ were fixed at 100 and 20 sccm, respectively. The ferroelectric domains of PMN-PT substrates were measured by a piezoelectric force microscopy (PFM). The ferroelectric hysteresis loops (P - E curves) of PMN-PT substrates were measured by a TF analyzer. The film thicknesses were determined by a Veeco Dektak 6M surface profiler and confirmed by high-resolution transmission electron microscopy (HRTEM). The microstructure was analyzed by an X-ray diffraction (XRD) θ - 2θ scans (Cu K_α source, $\lambda = 1.5406$ Å), φ scans (Beijing Synchrotron Radiation Facility, $\lambda = 1.5491$ Å), and HRTEM. The surface morphology was measured by atomic force microscopy (AFM). The magnetic hysteresis loops were measured by a Quantum Design magnetic property measurement system (SQUID-VSM). The anisotropic magnetoresistance (AMR) and planar Hall effect (PHE) were measured by a physical property measurement system (PPMS). An electric field was applied on the samples by a Keithley 2400 source meter instrument, where the Ag layers were used as the top and bottom electrodes. The resistance can be monitored when the electric field is applied, which can help insure that the electric field works.

III. RESULTS AND DISCUSSION

A. Structural characterization

Figure 1(a) shows the XRD θ - 2θ scan of γ' -(001) with a 34 -nm-thick γ' -Fe₄N film. Here, γ' -(001) and γ' -(011) refer to the γ' -Fe₄N/PMN-PT(001) and γ' -Fe₄N/PMN-PT(011) heterostructures, respectively, which will be used hereafter. In Fig. 1(a), the γ' -Fe₄N(001) and (002) peaks at 23.44° and 47.97° appear, indicating that the γ' -Fe₄N film is [001] oriented. Based on Bragg's law, the calculated lattice constant is $c = 3.792$ Å, which is consistent with the value (3.795 Å) of bulk γ' -Fe₄N.³¹ The calculated lattice constant indicates that the growth of the γ' -Fe₄N films is fully relaxed due to the misfit dislocations at the interface, which has also been observed at the γ' -Fe₄N/MgO interface.³² In Fig. 1(b), the γ' -Fe₄N(011) and (022) peaks appear at 33.40° and 70.18° . The calculated out-of-plane lattice spacing is 2.681 Å, which is also consistent with the bulk value (2.683 Å). Figures 1(c) and 1(d) show the X-ray φ scan of γ' -(001) and γ' -(011), respectively, where the peaks from γ' -Fe₄N(111) were detected. The 4-fold and 2-fold symmetric peaks of γ' -(001) and γ' -(011) indicate the epitaxial growth of γ' -Fe₄N films on PMN-PT(001) and (011) substrates.

Figure 1(g) shows the AFM images of γ' -(001) and γ' -(011) with different γ' -Fe₄N film thicknesses. The average surface roughness R_a is defined as³³

$$R_a = \frac{1}{L} \int_{x=0}^{x=L} |y| dx, \quad (1)$$

where x is the displacement along the lateral scan direction, y is the vertical fluctuation, and L is the assessment value of x . In Fig. 1(g), R_a of γ' -(001) is smaller than that of γ' -(011). The R_a of the samples with the film thickness of 5 and 8.5 nm ($R_a = 1.14$ – 1.45 nm) is larger than those of thicker ones ($R_a = 0.867$ – 1.23 nm), which can be attributed to the relatively large R_a of the PMN-PT substrates ($R_a = 0.853$ and 0.893 nm), as shown in Figs. 1(e) and 1(f).

Figure 2 shows the TEM images of γ' -(001) and γ' -(011) with γ' -Fe₄N film thicknesses of 34 nm. Figures 2(a) and 2(d) show the low-magnification TEM images, where a sharp interface between the film and substrate can be seen. Figures 2(b) and 2(e) show the high-resolution TEM images, where the insets show the Fast Fourier Transform (FFT) diffraction images of the area labeled by red squares. In Figs. 2(b) and 2(e), the clear lattice fringes and FFT images further confirm the epitaxial growth of the γ' -Fe₄N films on PMN-PT substrates. Figures 2(c) and 2(f) show the inverse FFT images of the areas labeled by red squares in Figs. 2(b) and 2(e), respectively. The ordered atoms indicate that the γ' -Fe₄N films are crystals with good quality. In Figs. 2(c) and 2(f), the in-plane and out-of-plane lattice spacings are consistent with bulk γ' -Fe₄N, which is in good agreement with the XRD results. The FFT and inverse FFT operations on the HRTEM images were performed by Gatan's DigitalMicrograph™ software.^{34,35}

Figures 3(a) and 3(b) show the P - E curves of PMN-PT(001) and (011) substrates at room temperature, respectively. The two kinds of substrates show ferroelectric hysteresis loops. The remanent polarization and coercive field of PMN-PT(001) are $29 \mu\text{C}/\text{cm}^2$ and $3.14 \text{ kV}/\text{cm}$, while those of PMN-PT(011) are $25 \mu\text{C}/\text{cm}^2$ and $2.90 \text{ kV}/\text{cm}$, respectively. The coercive fields of PMN-PT are much smaller than that of BiFeO₃ and Pb(Zr_{0.2}Ti_{0.8})O₃,^{36,37} which makes its ferroelectric polarization easier to be switched by a relatively small electric field. Figures 3(c) and 3(d) show the PFM images of the PMN-PT(001) and (011) substrates after a positive tip bias ($+10$ V) in a $3 \times 3 \mu\text{m}^2$ area. The polarization state in PFM images points to the same direction after applying an electric field due to its ferroelectricity. The ferroelectric polarization switching of both PMN-PT(001) and (011) substrates is also confirmed by phase hysteresis loops and amplitude butterfly loops, as shown in Figs. 3(e) and 3(f). The PFM phase change by 180° of the PMN-PT(001) and (011) substrates is consistent with the P - E curves.

B. Influence of film thickness on MEC

In order to clarify the MEC mechanisms, two kinds of MEC mechanisms in FM/FE heterostructures need to be mentioned. One is the strain-induced MEC. Figures 4(a) and 4(c) show the unit cells of PMN-PT(001) and (011) substrates, where the blue arrows refer to the ferroelectric polarization and the red arrows

FIG. 1. X-ray θ - 2θ scans of epitaxial γ' - Fe_4N films on (a) PMN-PT (100) and (b) (110) substrates. φ scan of epitaxial γ' - Fe_4N films on (c) PMN-PT (100) and (d) (110) substrates. AFM images of (e) PMN-PT(011) and (f) (001) substrates. (g) AFM images of $\gamma'_{(011)}$ and $\gamma'_{(001)}$ with $t = 5, 8.5, 12, 17, 25.5,$ and 34 nm.

FIG. 2. Low-magnification TEM images of (a) $\gamma'_{(001)}$ and (d) $\gamma'_{(011)}$. HRTEM images of (b) $\gamma'_{(001)}$ and (e) $\gamma'_{(011)}$, where the insets are the FFT diffraction images of the areas in (a) and (d) labeled by red squares. (c) and (f) are the inverse FFT images of the areas labeled by red squares in (b) and (e).

refer to the electric field. By applying a large electric field, the ferroelectric polarization will switch to the red arrows, and then the in-plane strain can be triggered, as shown in Figs. 4(b) and 4(d). The violet arrows show the in-plane strain directions of PMN-PT

(001) and (011) under an electric field. The in-plane [100] and [010] directions of PMN-PT(001) suffer a compressive strain.³⁸ In the PMN-PT(011) substrate, an in-plane compressive strain along the [100] direction and a tensile strain along the [01-1] direction

FIG. 3. P - E curves of (a) PMN-PT(001) and (b) PMN-PT(011) substrates. PFM images of (c) PMN-PT(001) and (d) PMN-PT(011) substrates after a positive tip bias switching (+10 V) applied in a $3 \times 3 \mu\text{m}^2$ area. PFM ramp curves (phase and amplitude) of (e) PMN-PT(001) and (f) PMN-PT(011) substrates. (g) The schematic of the epitaxial γ' - Fe_4N /PMN-PT heterostructure with an applied electric field.

FIG. 4. The unit cell and spontaneous polarization of (a) PMN-PT(001) and (c) PMN-PT(011) substrates. The schematics of the in-plane strain of (b) PMN-PT(001) and (d) PMN-PT(011) substrates at a large electric field. (e) The schematic of the electric-field induced SSE at the γ' -Fe₄N/PMN-PT interface.

will be generated.^{14,38} So, the magnetization of the γ' -Fe₄N films could be mediated due to the strain and its converse magnetostriction effect. Another MEC mechanism is the spin-dependent screening effect. Figure 4(e) shows the illustration of the electric-field induced spin screening at the γ' -Fe₄N/PMN-PT interface. The spin density near the interface is larger, which can be changed by the ferroelectric polarization. The SSE-induced MEC can be even stronger than the strain effect.^{27–30}

The magnetic hysteresis (M - H) curves of $\gamma'_{(001)}$ and $\gamma'_{(011)}$ with different γ' -Fe₄N film thicknesses were measured by SQUID-VSM, where an *in situ* electric field was applied to the samples. Figures 5–7 show the in-plane M - H curves of the $\gamma'_{(011)}$ along [100] and [01-1] directions and $\gamma'_{(001)}$ along the [100] direction. In Fig. 3(g), the electric field is +10 and -10 kV/cm, where the direction is downward and upward, respectively. In Fig. 5(f), it is seen that the electric field of -10 kV/cm can hardly affect the M - H curves, which is also demonstrated in the previous work.³⁰ Therefore, only the electric field of +10 kV/cm is considered in this work.

The easy axis of γ' -Fe₄N films is along the [100] direction and the hard axis is along the [110] direction.³² In Fig. 5, the magnetization switching of $\gamma'_{(011)}$ along the [01-1] direction becomes easier by applying an electric field of 10 kV/cm at $t \geq 12$ nm because the easy axis turns into the hard axis under the electric field due to the SSE-induced MEC.^{26–30} However, at $t = 5$ and 8.5 nm, the magnetization change becomes harder, which is different from that of the thicker ones. As mentioned above, the γ' -Fe₄N films suffer a tensile strain along the [01-1] direction under an electric field, so the magnetization becomes harder because of the negative magnetostriction coefficient of γ' -Fe₄N.^{39,40} The strain from PMN-PT substrates will induce an opposite effect to the SSE in the

γ' -Fe₄N/PMN-PT heterostructures, where the SSE is dominant.³⁰ Why does the SSE decrease sharply and almost vanish at $t = 5$ and 8.5 nm? In Fig. 5, the coercivity of the samples with $t = 5$ and 8.5 nm is several hundred oersted at a zero electric field, which is much larger than that of the thicker ones (less than 100 Oe). The surface roughness of the samples with $t = 5$ and 8.5 nm is larger than that of the thicker ones, which can enlarge the coercivity.^{41,42} Meanwhile, the large surface roughness of the films can also reduce the spin diffusion length, so the electric-field control of the magnetization by the spin-dependent charge will be restrained in a thinner film.^{26–29} Accordingly, the electric-field control of the magnetization in $\gamma'_{(011)}$ with $t = 5$ and 8.5 nm comes from the strain rather than the SSE, which is contrary to the case of thicker ones ($t = 12, 17, 25.5$, and 34 nm). It should be noted that the electric-field control of magnetization by the SSE is the largest so far, where the remanent magnetization change is as large as 984 emu/cm³ (from 0.3 emu/cm³ to 984.9 emu/cm³) at $t = 17$ nm, as shown in Fig. 5(d). In previous results, the magnetization change is 800 emu/cm³ in the CoFeB/PMN-PT(011) heterostructure,¹⁰ while the values in the Co/PMN-PT(011) and Fe/PMN-PT(100) heterostructures are 300 and 200 emu/cm³, respectively.^{17,28} In order to verify the reversible control on the magnetization, the magnetization change along the [01-1] direction was measured at a magnetic field of 100 Oe and different electric fields (M - t curves), as shown in Figs. 5(g)–5(i). The different magnetization states at different electric fields are stable and repeatable. In Figs. 6 and 7, the M - H curves of the $\gamma'_{(011)}$ and $\gamma'_{(001)}$ along the in-plane [100] direction are similar to that in Fig. 5. In Fig. 6, the magnetization switching of $\gamma'_{(011)}$ along the in-plane [100] direction (easy axis) becomes harder by applying an electric field at $t \geq 12$ nm because of an SSE-induced MEC. At $t = 5$ and 8.5 nm, the results are different because the compressive strain of

FIG. 5. M - H curves of $\gamma'_{(011)}$ with different γ' -Fe₄N layer thicknesses along the in-plane [01-1] direction at 300 K and different electric fields: (a) 5 nm, (b) 8.5 nm, (c) 12 nm, (d) 17 nm, (e) 25.5 nm, and (f) 34 nm. (g)–(i) The repeatable magnetization states of $\gamma'_{(011)}$ along the [01-1] direction at an electric field.

FIG. 6. M - H curves of $\gamma'_{(100)}$ with different $\gamma'-Fe₄N layer thicknesses along the in-plane [100] direction at 300 K and different electric fields: (a) 5 nm, (b) 8.5 nm, (c) 12 nm, (d) 17 nm, (e) 25.5 nm, and (f) 34 nm.$

FIG. 7. M - H curves of $\gamma'_{(001)}$ with different γ' - Fe_4N layer thicknesses along the in-plane $[100]$ direction at 300 K and different electric fields: (a) 5 nm, (b) 8.5 nm, (c) 12 nm, (d) 17 nm, (e) 25.5 nm, and (f) 34 nm. M - H curves of $\gamma'_{(001)}$ measured along the in-plane $[110]$ direction at 300 K and different electric fields: (g) 17 nm and (h) 25.5 nm. (i) The schematic of the in-plane direction of $\gamma'_{(001)}$.

the PMN-PT(011) substrates orients along the in-plane $[100]$ direction and the magnetostriction coefficient of γ' - Fe_4N is negative. Figures 7(a)–7(f) show the M - H curves along the in-plane easy axis $[100]$ direction of $\gamma'_{(001)}$. The measurement schematic is shown in Fig. 7(i). At $t \geq 12$ nm, the magnetization switching becomes harder by applying an electric field due to SSE, which is similar to that of $\gamma'_{(011)}$. At $t = 5$ and 8.5 nm, the SSE decreases dramatically, where the PMN-PT(001) substrates and the negative magnetostriction coefficient of γ' - Fe_4N make the magnetization switching a little easier at an electric field of 10 kV/cm. Figures 7(g) and 7(h) show the M - H curves along the in-plane $[110]$ direction of $\gamma'_{(001)}$ with $t = 17$ and 25.5 nm. It is clearly seen that the magnetization changes at an electric field, which is much smaller than that of $\gamma'_{(011)}$. Above all, for both $\gamma'_{(001)}$ and $\gamma'_{(011)}$, the electric-field control of magnetization does not change regularly with the thickness of γ' - Fe_4N films. The magnitude of the electric-field tailored magnetization first increases and then decreases as t increases, which reaches its maximum at $t = 17$ nm. As t increases from 17 to 34 nm, the spin-dependent charge density decreases due to the limit of the spin diffusion length.^{28,29} As t decreases from 17

to 5 nm, the large surface roughness diminishes the spin diffusion length greatly, which weakens the SSE-induced MEC, so the strain effect has an opposite influence with SSE. The electric-field controlled magnitude of magnetization from SSE increases as t decreases from 34 to 17 nm and decreases as t decreases from 17 to 5 nm.

In addition, it is obvious that the electric-field control of magnetization of $\gamma'_{(001)}$ is much smaller than that of $\gamma'_{(011)}$. In $\gamma'_{(001)}$, the angle between the in-plane easy axis $[100]$ and hard axis $[110]$ is 45° with a 4-fold symmetry. In $\gamma'_{(011)}$, the angle between the in-plane easy axis $[100]$ and hard axis $[01-1]$ is 90° with a 2-fold symmetry. Therefore, the magnetic anisotropy between the easy axis and hard axis of $\gamma'_{(001)}$ is smaller than that of $\gamma'_{(011)}$. Accordingly, the magnetic anisotropy change of $\gamma'_{(001)}$ induced by an electric field can hardly be pronounced. The different magnetic anisotropy of $\gamma'_{(011)}$ and $\gamma'_{(001)}$ can be confirmed by M - H curves at a zero electric field, as shown in Figs. 5–7. In Fig. 5, the magnetization switching of $\gamma'_{(011)}$ along the in-plane $[01-1]$ direction at a zero electric field is much harder than that along the in-plane $[100]$ direction, while the magnetization switching of $\gamma'_{(001)}$ along the in-plane $[110]$ direction at a zero electric field is similar to that along the in-plane $[100]$ direction.

C. Influence of temperature on MEC

As demonstrated above, the magnitude of the electric-field controlled magnetization reaches the maximum at $t = 17$ nm, so $\gamma'_{(001)}$ and $\gamma'_{(011)}$ with $t = 17$ nm were selected to investigate the influence of the temperature on MEC. Figure 8 shows the in-plane M - H curves of the samples with $t = 17$ nm at different temperatures by applying the electric fields. It was found that the magnitudes of the electric-field controlled magnetization along different in-plane directions of $\gamma'_{(001)}$ and $\gamma'_{(011)}$ increase gradually as the temperature increases from 5 to 300 K. The change of the remanent magnetization, $\Delta M_r = [M_r(10 \text{ kV/cm}) - M_r(0 \text{ kV/cm})]/M_r(0 \text{ kV/cm})$ was calculated, as shown in Figs. 8(i)–8(l), where $M_r(10 \text{ kV/cm})$ and $M_r(0 \text{ kV/cm})$ represent the remanent magnetizations at 10 and 0 kV/cm, respectively. It was found that ΔM_r increases monotonously from 2.4% to 189.5% as temperature increases from 5 to 200 K. Besides, one can also see that the coercivity of $\gamma'_{(001)}$ and $\gamma'_{(011)}$ decreases with the increase of temperature due to the thermal agitation.^{43,44} The electric-field control of the magnetization in the γ' -Fe₄N/PMN-PT heterostructure is induced by the SSE, where an electric field can control the direction of spiral spin density in the FM layer.^{26–29} Accordingly, as the temperature decreases, the spin direction can hardly be affected because of the decreased thermal agitation. Moreover, in Figs. 8(a), 8(e), and 8(i), the M - H curves at 5 K distort dramatically near 0 Oe. The largest

magnetization at the distorted part is as large as 2680 emu/cm³, which is much larger than the largest theoretical saturation magnetization of γ' -Fe₄N (1669 emu/cm³).⁴⁵ Therefore, the distortion of the M - H curve should not be the intrinsic property of γ' -Fe₄N, which should be a combination of the normal M - H curve and extra signals. Besides, the distortion does not appear above 50 K. The distortion looks like a typical superconducting signal, which is similar to previous results.^{46,47} This phenomenon is fascinating and promising, which deserves further investigation.

D. Electric-field control of the out-of-plane magnetization

Figures 9(a)–9(f) show the out-of-plane M - H curves of $\gamma'_{(011)}$ with different γ' -Fe₄N layer thicknesses at 10 and 0 kV/cm. The out-of-plane magnetization switching becomes easier by applying an electric field of 10 kV/cm. The change of remanent magnetization ΔM_r first increases, then decreases as t increases, which reaches the maximum at $t = 17$ nm. The in-plane and out-of-plane magnetizations can be controlled simultaneously, which indicates that the out-of-plane direction of the spin density can also be mediated.²⁶ At $t = 17$ nm, the change of the out-of-plane remanent magnetization ΔM_r of $\gamma'_{(011)}$ is as large as 295.9%, which is much larger than previous results.^{48,49} The M - H curves are almost unchanged at $t = 5$ and 8.5 nm while the electric field is applied,

FIG. 8. M - H curves of $\gamma'_{(001)}$ along the in-plane $[100]$ direction at an electric field and different temperatures: (a) 5 K, (b) 50 K, (c) 100 K, and (d) 200 K. M - H curves of $\gamma'_{(011)}$ along the in-plane $[100]$ direction at an electric field and different temperatures: (e) 5 K, (f) 50 K, (g) 100 K, and (h) 200 K. M - H curves of $\gamma'_{(011)}$ along the in-plane $[01-1]$ direction at an electric field and different temperatures: (i) 5 K, (j) 50 K, (k) 100 K, and (l) 200 K.

FIG. 9. Out-of-plane M - H curves of $\gamma'_{(011)}$ with different t at 300 K, (a) 5 nm, (b) 8.5 nm, (c) 12 nm, (d) 17 nm, (e) 25.5 nm, and (f) 34 nm. (g) Out-of-plane M - H curves of $\gamma'_{(001)}$ with $t = 17 \text{ nm}$ at 300 K by applying an electric field. (h) The repeatable out-of-plane magnetization of $\gamma'_{(001)}$ at different electric fields, where $M(E)$ is the magnetization at an electric field of E .

FIG. 10. (a) AMR and (b) PHE of $\gamma'_{(011)}$ with $t = 17 \text{ nm}$ by applying the electric field pulse of +10 and -10 kV/cm.

which is consistent with the in-plane results. Besides, the out-of-plane magnetization switching becomes easier at 10 kV/cm, indicating that the SSE-induced MEC can generate a perpendicular magnetic anisotropy in the FM layer by optimizing the experimental conditions. The out-of-plane M - H curve of $\gamma'_{(001)}$ with $t = 17$ nm is also investigated at an electric field, as shown in Fig. 9(g). It is obvious that the magnetization switching becomes harder at 10 kV/cm, which is opposite to that in $\gamma'_{(011)}$. Figure 9(h) shows the change of the out-of-plane magnetization of $\gamma'_{(001)}$ at a magnetic field of 1 T and different electric fields, where the reversible and stable magnetization states are observed.

E. Electric-field control on AMR and PHE

The electric-field controlled AMR and PHE of $\gamma'_{(011)}$ with $t = 17$ nm were measured by PPMS. Pulsed electric fields were applied to the samples before the electric transport measurements. Figures 10(a) and 10(b) show the AMR and PHE after applying the electric field pulses of +10 kV/cm and -10 kV/cm, where the magnetic field was 1000 Oe. After applying the electric field pulses, the phases of AMR are almost the same, but the magnitudes change. Similarly, the magnitudes of PHE are influenced by applying the electric field pulses, but the phases are not affected. Although the magnitudes of AMR and PHE can be affected by the electric field pulses, these results indicate that the electric field pulses can slightly modulate the magnetic anisotropy of γ' -Fe₄N film. Accordingly, the non-volatile control is proved to be valid in the samples, which can also be confirmed from the difference of magnetizations after removing the electric field of +10 and -10 kV/cm, as shown in Figs. 5(g)–5(i).

IV. CONCLUSION

The SSE-induced MEC was investigated systematically in the $\gamma'_{(001)}$ and $\gamma'_{(011)}$ heterostructures with different γ' -Fe₄N film thicknesses. Strong MEC was observed in $\gamma'_{(011)}$, where the electric-field controlled in-plane magnetization is as large as 984 emu/cm³. The electric-field control of the magnetization does not change regularly with the γ' -Fe₄N layer thickness, which is attributed to the competition between the strain and SSE-induced MEC. Besides, MEC in $\gamma'_{(001)}$ is weaker than that in $\gamma'_{(011)}$. As temperature decreases from 300 to 5 K, MEC in $\gamma'_{(001)}$ and $\gamma'_{(011)}$ gradually weakens. The electric-field control of the out-of-plane M - H curves of $\gamma'_{(011)}$ with different t are similar to the in-plane ones.

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