Asymmetric recovery effect of exchange bias in polycrystalline NiFe/FeMn bilayers

X. P. Qiu,1,2,a) Z. Shi,1 S. M. Zhou,1 J. Du,2 X. J. Bai,2 R. Chantrell,3 and L. Sun4

1Department of Physics and Surface Physics Laboratory (National Key Laboratory), Fudan University, Shanghai 200433, China
2National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, China
3Department of Physics, The University of York, York, YO10 5 DD, United Kingdom
4Department of Mechanical Engineering, University of Houston, Houston, Texas 77204, USA

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For exchange bias in polycrystalline NiFe/FeMn bilayers, the hysteretic behavior of the angular dependence and the recovery effect has been studied. In particular, the pinning direction (PD) at the ending remanent state of each hysteresis loop is identified. In the hysteretic behavior, in addition to the coercivity, the PD also demonstrates different angular dependence between clockwise and counterclockwise rotations of the external magnetic field. Measurements of the recovery effect consist of two major steps. In the first step, the PD is deviated from the initial one by using its hysteretic effect and training effect. For polycrystalline NiFe/FeMn bilayers, the rotated PD is located at the maximal angle \( \theta_{\text{PD0}} \) of \( \pm 22^\circ \) with respect to the initial ones. As for the second step, an external magnetic field is applied at a specific orientation \( \theta_{\text{H-RE}} \) and then switched off at the same orientation. For the negative \( \theta_{\text{PD0}} \), the recovery effect only occurs for \( 0 < \theta_{\text{H-RE}} < 180^\circ \) with the maximal effect at \( \theta_{\text{H-RE}} = 90^\circ \) and vanishes for \( 180^\circ < \theta_{\text{H-RE}} < 360^\circ \), and vice versa for the positive \( \theta_{\text{PD0}} \). The recovery effect shows an asymmetric angular dependence on \( \theta_{\text{H-RE}} \). The recovery effect of the PD also depends on the magnitude and the application time of the recovery magnetic field. For the exchange field and the coercivity, similar recovery behaviors are observed and attributed to the recovery effect of the PD. These phenomena clearly show that the motion of antiferromagnet spins not only obeys the thermally activated transition but also strongly depends on the magnetization reversal mechanism of the ferromagnet layer. © 2009 American Institute of Physics. [doi:10.1063/1.3211314]

I. INTRODUCTION

Exchange bias (EB) is known as a phenomenon in which the hysteresis loop is shifted along the magnetic field axis in ferromagnet (FM)/antiferromagnet (AFM) bilayers.1 Many EB-related physical phenomena, including the rotational hysteresis loss, the training effect, the recovery effect, the asymmetry of the hysteresis loop, and the hysteretic behavior of the angular dependence of the EB (ADEB), have been studied extensively.1–20 It is generally believed that the AFM spins play an important role in these phenomena.3–12 For example, in studies of the rotational hysteresis loss, it is suggested that the AFM spins rotate irreversibly during the rotation of the external magnetic field.10,11

For polycrystalline NiFe/FeMn bilayers, the ADEB is different for clockwise (CW) and counterclockwise (CCW) rotations, exhibiting a hysteretic behavior.13 Micromagnetic calculations have suggested that this phenomenon is induced by irreversible rotation of AFM spins. Moreover, the hysteresis loop asymmetry also has different angular dependence for CW and CCW rotations, that is to say, the zero asymmetry is located at different orientations of the external magnetic field for CW and CCW rotations. Since the zero asymmetry indicates parallel alignment of the external field and the pinning direction (PD) of the bilayer,21 it is implicated that the PD is rotated during CW and CCW rotations. Direct measurement of the PD rotation in the ADEB is required to reveal the underlying physics behind the hysteretic behavior.

In the commonly observed EB training effect, the exchange field \( H_E \) and the coercivity \( H_C \) are reduced during consecutive hysteresis loops.14 It is believed that the training effect comes from the switching or rotation of AFM spins as manifested by the PD rotation.17,22 As another EB-related phenomenon, the recovery effect has recently been studied, in which the trained EB can be restored by a full cycle of hysteresis loop perpendicular to the PD.23 Although the rotation of AFM spins has already been predicted theoretically during the recovery procedure,22,23 direct observation of the PD rotation has not been performed yet. Moreover, the recovery procedure is complex, consisting of six segments of applied magnetic field, i.e., 0 to the saturation magnetic field, +HS to 0 to −HS, −HS to 0 to +HS, and +HS to 0. In order to clearly reveal the mechanism of the EB recovery effect, it is essential to simplify the recovery procedure.

In this work, for polycrystalline NiFe/FeMn bilayers, the PD rotation is studied in both the hysteretic behavior of the ADEB and the EB recovery effect. A hysteretic behavior of the PD orientation is found to accompany that of the ADEB between CW and CCW rotations. As the first step of the recovery procedure, the PD can be aligned along either positive or negative angles with respect to the initial PD by exploiting measurements of ADEB and the training effect. As
the second step, an external magnetic field is applied and then switched off at a specific orientation $\theta_{H-RE}$. It is interesting to find that the recovery effect takes the maximum (vanishes) at $\theta_{H-RE}=90^\circ$ and vanishes (takes the maximum) at $\theta_{H-RE}=-90^\circ$ when the rotated PD is located along the negative (positive) angles, respectively. Apparently, the recovery effect shows asymmetric AD on $\theta_{H-RE}$. Both the hysteretic behavior of the ADEB and the EB recovery effect can be explained as a result of the PD rotation. All experimental results can be explained after taking into account the effect of the FM magnetization reversal mechanism on thermally activated transitions of AFM spins.

### II. EXPERIMENTS

A glass/Cu (15 nm)/Ni$_{80}$Fe$_{20}$(3 nm)/Fe$_{50}$Mn$_{50}$ (2.4 nm)/Au(60 nm) sample was grown at ambient temperature by dc magnetron sputtering. The base pressure of the sputtering system was $2 \times 10^{-5}$ Pa and the Ar pressure 0.4 Pa during deposition. The 15-nm-thick Cu buffer layer was deposited to stimulate the fcc (111) preferred growth of FeMn and to enhance the EB. Deposition rates of NiFe, FeMn, Cu, and Au layers were 0.3, 0.1, 0.2, and 1 nm/s, respectively. During deposition of the bottom NiFe layer, a magnetic field of about 130 Oe was applied parallel to the film plane to induce the uniaxial anisotropy in the NiFe layer and the EB in the NiFe/FeMn bilayer, where the magnitude of the deposition magnetic field is large enough to saturate the soft magnetic layer. Similar fabrication procedure was described elsewhere. X-ray diffraction shows that the constituent layers are polycrystalline with fcc (111) and fcc (200) textures. With a vector vibrating sample magnetometer of model 7407 from Lakeshore Co., the magnetic moments $m_x$ (parallel to $H$) and $m_y$ (perpendicular to $H$) were recorded simultaneously. In this system, the $m_y$ pickup coil and the electromagnet are stationary in the laboratory reference with the same common axis, remarked as the (magnetic) field axis. The $m_y$ versus $H$ curve corresponds to the conventional hysteresis loop. For the in-plane configuration, $m_x$ and $m_y$ were both parallel to the film plane. All measurements were performed at room temperature.

For conventional single layer FM films with uniaxial anisotropy, the FM magnetization will be aligned along the easy axis under zero magnetic field $H$, that is to say, $m_x$ has a positive or negative maximum and $m_y$ equals zero when the easy axis of the sample is aligned with the field axis. From the angular dependence of $m_x$ and $m_y$, measured under zero $H$, the orientation of the easy axis can be identified. In a similar way, the PD orientation of the present FM/AFM bilayers is identified as that of the orientation of the magnetization vector at the remanent state. If the uniaxial anisotropy axis and the unidirectional anisotropy direction are colinearly aligned, the PD orientation is parallel to their orientations. In the case of noncollinear alignment, the PD orientation is determined by the equilibrium one of the magnetization vector at the remanent state, depending on the directions and magnitudes of the uniaxial and the unidirectional anisotropies. Therefore, it can be identified by the angular dependence of $m_y$ at zero magnetic field. Here, the initial PD orientation of the sample at the as-prepared state is identified from the angular dependence of $m_x$ and $m_y$ under zero $H$, which was measured by rotating the sample in the film plane. $\theta_{Rm}$ in Fig. 1 refers to the orientation of the magnetic field axis with respect to the initial PD of the sample and $\theta_{PD}$ to that of the rotated PD. For comparison, $\theta_{H-LOOP}$ is defined as that of the external magnetic field to measure hysteresis loops with respect to the initial PD.

For the present NiFe/FeMn bilayers, $m_y$ is equal to zero when the hysteresis loop is measured along the direction of the deposition magnetic field at the as-prepared state. More importantly, it is always equal to zero when the hysteresis loop is measured along the rotated PD at the trained state. Accordingly, the principal axes of uniaxial and unidirectional anisotropies are parallel to each other based on previously reported results, unlike the noncollinear case. Actually, the AFM spins can only experience 180° switching during the hysteresis loop along the PD orientation and the uniaxial anisotropy axis and unidirectional anisotropy direction are not rotated during the hysteresis loop, that is to say, before measurements of the hysteresis loop they are collinear. Since the intrinsic uniaxial anisotropy of the magnetically soft NiFe layers is negligible, the uniaxial and the unidirectional anisotropies are both induced by the AFM spins such that they are possibly collinear. It is noted that the angle between the uniaxial anisotropy axis and the unidirectional anisotropy direction can be simulated from the measured angular dependence of the ferromagnetic resonance field. In the dynamic approach, however, the AFM spins are required to be fixed during the action of the external magnetic field.

### III. RESULTS AND DISCUSSION

Before applications of any external magnetic field, the initial PD was identified as the reference axis, as shown in the figure. The initial PD orientation of the sample is identified from the angular dependence of $m_x$ and $m_y$ under zero $H$, which was measured by rotating the sample in the film plane. $\theta_{Rm}$ in Fig. 1 refers to the orientation of the magnetic field axis with respect to the initial PD of the sample and $\theta_{PD}$ to that of the rotated PD. For comparison, $\theta_{H-LOOP}$ is defined as that of the external magnetic field to measure hysteresis loops with respect to the initial PD. The initial PD orientation of the sample at the as-prepared state is identified from the angular dependence of $m_x$ and $m_y$ under zero $H$, which was measured by rotating the sample in the film plane. $\theta_{Rm}$ in Fig. 1 refers to the orientation of the magnetic field axis with respect to the initial PD of the sample and $\theta_{PD}$ to that of the rotated PD. For comparison, $\theta_{H-LOOP}$ is defined as that of the external magnetic field to measure hysteresis loops with respect to the initial PD.

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![Typical angular distribution of $m_x$ (black) and $m_y$ (red) under $H=0$](image1.png)

**Fig. 1.** (Color online) (a) Typical angular distribution of $m_x$ (black) and $m_y$ (red) under $H=0$ and (b) schematic picture of PD rotation.
Fig. 1. Afterwards, hysteresis loops were measured with CCW rotation of $H$ from $\theta_{H-\text{LOOP}}=-60^\circ$ to $-60^\circ$ and then with CW rotation from $-60^\circ$ to $-60^\circ$. Between neighboring hysteresis loops, the curves of $m_x$ and $m_y$ versus $\theta_{\text{Rtn}}$ under $H=0$ were measured to identify the PD. It is interesting to find that the angular dependence of $\theta_{\text{PD}}$ also shows the hysteretic behavior between CCW and CW rotations, in addition to $H_{C,\text{pd}}$ as shown in Fig. 2. With CCW rotation of $H$ from $-60^\circ$ to $-60^\circ$, the PD first deviates away from and then rotates toward the initial PD, where $\theta_{\text{PD}}$ acquires the positive maximal value of $-22^\circ$. With subsequent CW rotation of $H$ from about $-60^\circ$ to $-60^\circ$, the PD continues to rotate in an opposite way, leading to the negative maximal $\theta_{\text{PD}}$ of $-22^\circ$ and then rotates toward the initial PD. Apparently, the PD rotation exhibits a chirality change during ADEB measurements. It is interesting to find that the maximal $H_{C,\text{pd}}$ is almost located at the same $\theta_{H-\text{LOOP}}$ as that of the positive or negative maximal $\theta_{\text{PD}}$. Furthermore, since $\theta_{\text{PD}} = \theta_{H-\text{LOOP}}$, that is to say, the external magnetic field is parallel to the PD, the coercivity acquires the maximum. Therefore, the hysteretic behavior of $\theta_{\text{PD}}$ between CW and CCW rotations accounts for that of $H_{C,\text{pd}}$ according to the conventional ADEB.\(^{30}\)

In measurements of the recovery effect, two major steps are required. First of all, the PD is aligned along a designated orientation. As shown in Fig. 2(b), the PD can be set at any orientation near the initial PD by measurements of the ADEB of either CW or CCW rotations. Hysteresis loops were measured with CW (CCW) rotation from $\theta_{H-\text{LOOP}}=\pm 60^\circ$ to 0. In this way, the PD is rotated toward negative (positive) angles, as shown in Fig. 2(b). In order to let the PD rotation be saturated, 50 hysteresis cycles were immediately measured at $\theta_{H-\text{LOOP}}=0$ in the training effect, leading to the CW (CCW) rotation of the PD toward more negative (positive) angles.\(^{22}\) Afterwards, the angular dependence of $m_x$ and $m_y$ under zero $H$ was measured to identify the saturated $\theta_{\text{PD}}$. The values of $H_E$ and $H_C$ along the initial PD, which were determined from the last hysteresis loop in the training effect, and $\theta_{\text{PD,0}}$ were obtained. Second, a recovery procedure was performed, in which at a specific $\theta_{H-\text{RE}}$ $H_{\text{RE}}$ was applied and persisted for a time period of $t_{\text{RE}}$ and then switched off at the same orientation. Finally, $\theta_{\text{PD}}$ was identified and $H_E$ and $H_C$ along the initial PD were determined again. Accordingly, the changes of $H_{E,\text{C}}$ and $\theta_{\text{PD}}$ induced by the recovery procedure, i.e., $\Delta H_{E,\text{C}}$ and $\Delta \theta_{\text{PD}}$, are achieved. In experiments done by Brems et al.,\(^{23}\) however, consecutive hysteresis loops were measured along the initial PD before the recovery procedure and thus the PD is expected to be still aligned along the initial PD.

Figures 3(a)–3(c) show the hysteresis loops at zero $\theta_{H-\text{LOOP}}$ and the curves of $m_x$ and $m_y$ versus $\theta_{\text{Rtn}}$ under zero $H$ before and after the recovery procedure, where $H_{\text{RE}}=6.0$ kOe, $t_{\text{RE}}=0$ and $\theta_{H-\text{RE}}=90^\circ$. Before the second step of the recovery measurements, $\theta_{\text{PD,0}}=-22^\circ$ and $H_{\text{Rtn}}=80$ Oe and $H_{C,0}=37$ Oe. After the recovery procedure, $H_{E}=103$ Oe, $H_{C}=60$ Oe, and $\theta_{\text{PD}}=-4^\circ$. Apparently, by the recovery procedure $H_E$ and $H_C$ are enhanced with $\Delta H_{E}=23$ Oe and $\Delta H_{C}=23$ Oe, and the PD is rotated with $\Delta \theta_{\text{PD}}=18^\circ$. At the same time, the asymmetry is also enhanced. However, Figs. 3(d)–3(f) show that at $\theta_{H-\text{RE}}=90^\circ$, no changes take place for $H_E$, $H_C$, the asymmetry, and the PD orientation after the recovery procedure. Apparently, the recovery effect strongly
depends on $\theta_{\text{H-RE}}$. In particular, the present results clearly demonstrate that in the six segments of the work done by Brems et al., the recovery effect acts in at most two segments, i.e., 0 to $H_C$, $+H_S$ to 0.

Figures 4(a)–4(c) show the $(\theta_{\text{H-RE}})$ angular dependence of $\Delta H_E$, $\Delta H_C$, and $\Delta \theta_{PD}$, where $\theta_{PD}=\pm 22^\circ$. With increasing $\theta_{\text{H-RE}}$, all three physical quantities undergo nonmonotonic changes and acquire the maxima at $\theta_{\text{H-RE}}=90^\circ$. It is remarkable that at $\theta_{\text{H-RE}}>180^\circ$, the recovery effect vanishes. Figures 4(d)–4(f) show the results for $\theta_{PD}=\pm 22^\circ$. The recovery effect exits only in the region from $\theta_{\text{H-RE}}=180^\circ$ to $360^\circ$ with a maximum at $\theta_{\text{H-RE}}=270^\circ$, and disappears in the region of $\theta_{\text{H-RE}}=0$ to $180^\circ$. Apparently, the angular dependence of the recovery effect is asymmetric.

Figures 5(a)–5(c) show the dependence of $\Delta H_{EC}$ and $\Delta \theta_{PD}$ on the magnitude of $H_{\text{RE}}$, where $\theta_{PD}=\pm 22^\circ$, $t_{RE}=0$, and $\theta_{H}=90^\circ$. For a small $H_{\text{RE}}$, the recovery effect initially increases sharply and then changes gradually with the magnitude of $H_{\text{RE}}$. This behavior can be understood as follows. Upon applications of $H_{\text{RE}}$ at $\theta_{\text{H-RE}}=90^\circ$, the orientation of the FM magnetization is determined by the magnitude of $H_{\text{RE}}$. When $H_{\text{RE}}$ is smaller than the anisotropic field $H_E$, the FM magnetization is aligned along an orientation between $\theta_{\text{H-RE}}=90^\circ$ and $\theta_{PD}=\pm 22^\circ$. According to the results in Figs. 4(a)–4(c), the recovery effect should be equivalent to the case of $\theta_{\text{H-RE}}<90^\circ$. As the magnitude of $H_{\text{RE}}$ increases, the orientation of the FM magnetization approaches that of $H_{\text{RE}}$, leading to an increase in the recovery effect. For $H$ much larger than $H_E$, the increase in the recovery effect can be attributed to the increase in the time needed to achieve $H_{\text{RE}}$. This assumption is verified by the results in Figs. 5(d)–5(f).

As the application time $t_{RE}$ is increased from zero to about 2.0 s, $\Delta H_E$ and $\Delta H_C$ increase and reach the maximal values. This can be explained by the conventional ADEB. At $t_{RE}=2.0$ s, $\Delta \theta_{PD}=22^\circ$ and thus $\theta_{PD}=0^\circ$, that is to say, the PD is aligned again along the initial PD, resulting in the maximal $\Delta H_E$ and $\Delta H_C$. This is because the external magnetic field is parallel to the PD. With further increasing $t_{RE}$, $\Delta \theta_{PD}$ increases and the PD is deviated from the initial PD, leading to the reductions in $\Delta H_E$ and $\Delta H_C$ because the external magnetic field makes an angle with the rotated PD.

In order to investigate the possible effect of the interface morphology on the training and the recovery effects, two NiFe(3 nm)/FeMn (2.2 nm) bilayers were prepared under base pressures of $2.1 \times 10^{-5}$ and $3.9 \times 10^{-6}$ Pa. For the high vacuum, larger $H_E$ and $H_C$ are acquired. With the high (low) base vacuum, $H_E$ and $H_C$ are 147(90) and 94(68) in the unit of oersted for the first loop at $\theta_{\text{H-LOOP}}=-12^\circ$, respectively. Apparently, it is expected that with high base vacuum, the interface morphology or the AFM grain distribution or both of them are changed, which favors to enhance the EB effect. For the high (low) base pressures, however, the maximal PD rotation is $19(16)^\circ$ in the ADEB measurements of the CW rotation. After the recovery procedure, $\Delta H_{E}=20(24)$ Oe, $\Delta H_{C}=45(35)$ Oe, $\Delta \theta_{PD}=19(18)^\circ$. In a word, $H_E$ and $H_C$ are enhanced by high base vacuum while the PD rotation in either the hysteresis behavior of the ADEB or the recovery effect is almost not influenced. Since the PD rotation is strongly modified by the size distribution of the AFM grains as discussed below, it is also reasonable to suggest that the size distribution of the AFM grains is not influenced by the base vacuum. Furthermore, the interface morphology should be modified by the base vacuum but it has negligible effects on the PD rotation.

The hysteretic behavior of $\theta_{PD}$ in Fig. 2 can be explained using the model of thermally activated switching of AFM spins. In this model, the AFM layer is assumed to consist of exchange-decoupled grains having different activation energies. During hysteresis loops, AFM spins of some grains are switched, resulting in the deviation of the average orien-
rotation of overall AFM spins from the initial PD and the PD rotation, as observed experimentally in CoFe/IrMn bilayers.\textsuperscript{32,33} More remarkably, the PD rotation (CW or CCW) strongly depends on the magnetization reversal channel. As seen from Fig. 6(a), in the CW rotation of $H$ from $\theta_{H-LOOP}=60^\circ$, the FM magnetization is rotated through the channel marked by the arrows in Fig. 6(a) because $\theta_{H-LOOP}>\theta_{PD}$. With the exchange field from the FM layer, the AFM spins of some grains are deviated from the initial PD, leading to the CW rotation of the PD toward negative angles and decreasing $\theta_{PD}$. Due to the exchange coupling from the non-rotatable AFM grains, however, the PD cannot rotate far away from the initial PD, so the continuous CW rotation of $H$ will result in $\theta_{H-LOOP}\leq\theta_{PD}$ at a critical angle. At this moment the FM magnetization will be rotated through another channel as marked by the arrows in Fig. 6(b), the PD rotates in the CCW sense and exhibits a turning point, which can be seen from Fig. 2(b). In a similar way, the PD rotation during the CCW rotation of $H$ from $\theta_{H-LOOP}=-60^\circ$ to $-60^\circ$ can be well understood. It is concluded that for rotations of the PD and the AFM spins, the chirality change and the hysteretic behavior are induced by the channel change of the FM magnetization reversal during hysteresis loops at different $\theta_{H-LOOP}$.

The EB recovery effect in Figs. 3–5 can also be explained in the framework of the thermal activation model. Here we take the negative $\theta_{PD}$ as an example. Before the recovery procedure, the PD has already been set to the negative maximal angle after measurements of the ADEB in the CW sense and training effect. So the PD cannot rotate any more in the CW direction but can rotate back toward the initial PD. In Figs. 3(a)–3(c), with a magnetic field of 6 kOe at $\theta_{H-RE}=90^\circ$, the spins in some AFM grains will be reversed or rotated due to the rotating exchange field from the saturated FM layer and thereby the PD rotates back toward the initial PD, resulting in the recovery of EB. If the field is applied at $\theta_{H-RE}=-90^\circ$, as seen from Figs. 3(d)–3(f), the PD cannot rotate any more toward more negative angles, so the recovery effect vanishes. For $\theta_{H-RE}=90^\circ$ or $-90^\circ$, AFM spins have the highest probability of switching and the strongest recovery effect is obtained, as shown in Fig. 4. For nonzero $\theta_{RE}$, more AFM spins are switched and thus the PD continues to rotate back toward the initial PD, leading to increasing $\Delta \theta_{PD}$, $\Delta H_E$, and $\Delta H_C$. With further increasing $\theta_{RE}$, however, the PD crosses and deviates away from the initial PD. Therefore, although $\Delta \theta_{PD}$ still increases, $\Delta H_E$ and $\Delta H_C$ are reduced due to the ADEB,\textsuperscript{30} as shown in Figs. 5(d)–5(f).

In addition to the EB recovery effect, the thermal activation model can also be used to explain the dependence of the training effect on the AFM layer thickness in NiFe/FeMn and Co/FeMn bilayers.\textsuperscript{22,34–36}

Many theoretical models have been proposed to explain the features of the EB.\textsuperscript{33,37–39} For example, in order to explain the ADEB in Co/IrMn bilayers, a thin spin-disordered layer is assumed to exist at the FM/AFM interface with its uniaxial anisotropy axis making an angle with that of the AFM layer.\textsuperscript{33} The simulated value of the angle is about $20^\circ$, by accident close to the PD rotation of $22^\circ$ for the present NiFe/FeMn bilayers. In order to further verify the validity of the thermal activation model, more experimental and theoretical investigations are required. With the thermal activation model, the recovery and the training effects in the polycrystalline FM/AFM bilayers should disappear near zero temperature. In fact, for FM/AFM bilayers, the training effect is found to become small when decreasing temperature.\textsuperscript{40} On the other hand, however, the training effect is experimentally observed to become pronounced at low temperatures.\textsuperscript{32,41,42} Apparently, the thermal activation model fails to explain the temperature dependence if the uniaxial anisotropy and the energy barrier are assumed to be independent of the temperature. Therefore, the temperature dependence of the uniaxial anisotropy of the AFM layers should be measured in order to explain the temperature dependence of the training effect.

IV. CONCLUSIONS

In summary, in order to deepen the nature of the hysteretic behavior of ADEB and the EB recovery effect in polycrystalline NiFe/FeMn bilayers, the PD rotation at the ending point of each hysteresis loop is identified. The angular dependence of the PD exhibits hysteretic behavior between CW and CCW rotations, in addition to the $H_C$. The chirality change of the PD rotation is induced by the channel change of the FM magnetization rotation. In the EB recovery procedure, with the maximal $\theta_{PD}=\pm 22^\circ$, which can be realized by measurements of the ADEB and training effect, $H_E$ and $H_C$ are enhanced and the PD is rotated toward the initial direction after the recovery procedure with $0^\circ < \theta_{H-RE} < 180^\circ$ ($180^\circ < \theta_{H-RE} < 360^\circ$). The largest recovery effect takes place at $\theta_{H-RE}=90^\circ$ ($270^\circ$). For $180^\circ < \theta_{H-RE} < 360^\circ$ ($0 < \theta_{H-RE} < 180^\circ$), however, the recovery effect disappears. Therefore, the angular dependence of the EB recovery effect is asymmetric. Furthermore, the recovery effect also strongly depends on both the magnitude and the appli-
culation time of $H_{RE}$. The thermal activation model can be used to explained all these phenomena. In particularly, these results have directly confirmed the theoretical prediction of the rotatable anisotropy in polycrystalline FM/AFM bilayers proposed by Stiles and McMichael, and shown the tunability of the PD and accordingly the EB.

Note added in proof. During the review process we became aware of the work done by Jiménez et al., which has studied the magnetization reversal process and the asymmetry of the FM/AFM bilayers with or without misalignment of the unidirectional and the uniaxial anisotropies. In particular, it is found that with collinear alignment of these two anisotropies, $m_\parallel$ is always equal to zero when the external magnetic field is applied parallel to the both of them. It supports the conclusion of that in the present FM/AFM bilayers, the unidirectional anisotropy is always parallel to the uniaxial anisotropy and they are both rotated during the EB training effect and the EB recovery process.

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