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Z. Shi, J. Du, R. W Chantrell, S. Mangin, S. M Zhou. Torque approach for tuning exchange bias training effect in polycrystalline NiFe/FeMn bilayers. *Applied Physics Letters*, 2011, 98 (12), pp.122507. 10.1063/1.3569140 . hal-02085981

HAL Id: hal-02085981

<https://hal.univ-lorraine.fr/hal-02085981v1>

Submitted on 1 Apr 2019

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Torque approach for tuning exchange bias training effect in polycrystalline NiFe/FeMn bilayers

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(Received 31 January 2011; accepted 1 March 2011; published online 25 March 2011)

In order to tune the exchange bias training effect, a torque approach is proposed. Torque loops are performed between two consecutive hysteresis loops by clockwise and counterclockwise rotation of the sample within an angular range under an in-plane external magnetic field. For the angular range from 0° to 180° , the coercivity H_C and the exchange field H_E are both reduced and the pinning direction (PD) orientation is changed, exhibiting the first type training effect. For the angular range from -20° to 380° , H_C and the PD orientation are almost unchanged although H_E is reduced, exhibiting the second type training effect. © 2011 American Institute of Physics.

[doi:10.1063/1.3569140]

Exchange coupling at the interface of ferromagnetic (FM) and antiferromagnetic (AFM) layers can induce a unidirectional anisotropy in the FM layer. In the exchange bias (EB) effect,¹ the center of the hysteresis loop shifts and the coercivity (H_C) often increases. Since its discovery, extensive research work has been done due to not only the abundant physics properties but also to the potential applications in spintronics.¹⁻³

Among various effects of EB, training effect has been studied extensively in various FM/AFM, and ferrimagnet/ferrimagnet, and FM/FM systems.⁴⁻¹⁹ In the training effect, H_C and exchange field (H_E) decrease with the cycling number n . Abrupt changes in H_E and H_C occur between $n=1$ and $n=2$.¹⁰ For $n > 2$, an empirical power law between EB (H_E and H_C) and n occurs.^{4,7,8,11,15} With respect to the behaviors of the coercive fields, two major types of training effect have been observed.^{6,16} For the first one, the coercive field of the descent branch changes very much whereas that of the ascent branch almost does not change. For the second one, the changes in the coercive fields of the two branches are close to each other, which is observed in either in-plane and out-of-plane EB systems.^{6,16,17} H_C almost does not change during cycling although H_E changes gradually. Up to date no mechanism explains the difference between the two training types. Since the shrinkage of H_E and H_C is strongly related to the pinning direction (PD), where the magnetization is aligned with zero H (the external magnetic field), the training effect can in principle be tuned by controlling the PD. In this letter, we show that the type of training effect can be tuned by a special torque training procedure in which the torque loop is measured between two consecutive hysteresis loops. By rotation θ_H (the angle between H and the initial PD) from 0° to 180° (from -20° to 380°) one can observe the first (the second) type of training effect. Furthermore, motion of AFM spins is mapped out during both the conventional training and the torque training procedures.

Two samples of substrate/Cu(20 nm)/Ni₈₀Fe₂₀(=NiFe) (6 nm)/Fe₅₀Mn₅₀(=FeMn)(t_{AFM})/Au(11 nm) with t_{AFM}

=11 nm and 20 nm were deposited on Si wafers by magnetron sputtering at ambient temperature. The base pressure of the system is 1.8×10^{-5} Pa and the Ar pressure 0.5 Pa during deposition. The deposition rates of constituting layers are about 0.1 nm/s. A magnetic field of about 170 Oe is set in the film plane to induce a unidirectional anisotropy during deposition. X-ray diffraction in the high angle region shows that constituent layers are of (111) preferred orientation. In-plane M - H loops are measured using vibrating sample magnetometer with vector coil, in which the magnetic moment parallel (m_x) and perpendicular (m_y) to H are recorded simultaneously. The PD can be identified by angular variation in m_x and m_y under zero H . When $m_y=0$ and m_x takes the maximum value, $\theta_H=0$ is set. In the conventional approach, consecutive hysteresis loops were measured without break. In the torque approach, torque loops were performed between two consecutive hysteresis loops by clockwise and counterclockwise rotation of samples in a specific H . θ_H changes from 0° to 180° or from -20° to 380° . All the measurements are carried out at room temperature.

For the NiFe/FeMn (11 nm) sample, the initial PD and $\theta_H=0^\circ$ are first identified. Then 10 torque loops are performed within the angular region from 0° to 180° in a magnetic field of 1 kOe, followed by a hysteresis loop at $\theta_H=0^\circ$. In comparison, the conventional training effect is measured for another sample at $\theta_H=0^\circ$. Figures 1(a) and 1(b) show the results. For the $n=1$ loop (solid line) in the conventional training effect and the loop after $n'=10$ (dot line) torque loops, H_E/H_C equals 93/89 and 59/43 in the unit of oersted, respectively. For the $n=1$ loop m_y is almost equal to zero, indicating the collinear alignment of the unidirectional and the uniaxial anisotropic axes before the torque training, and appears after the torque training, indicating the noncollinear alignment.²⁰ Figure 1(c) shows the m_y versus θ_H curves under $H=0$ of the as-deposited state (solid line), after $n'=10$ torque loops (dot line), and after $n=1$ hysteresis loop (dash line). The PD is rotated from 0° to 24° after the torque training procedure, which coincides with nonzero m_y in Fig. 1(b).

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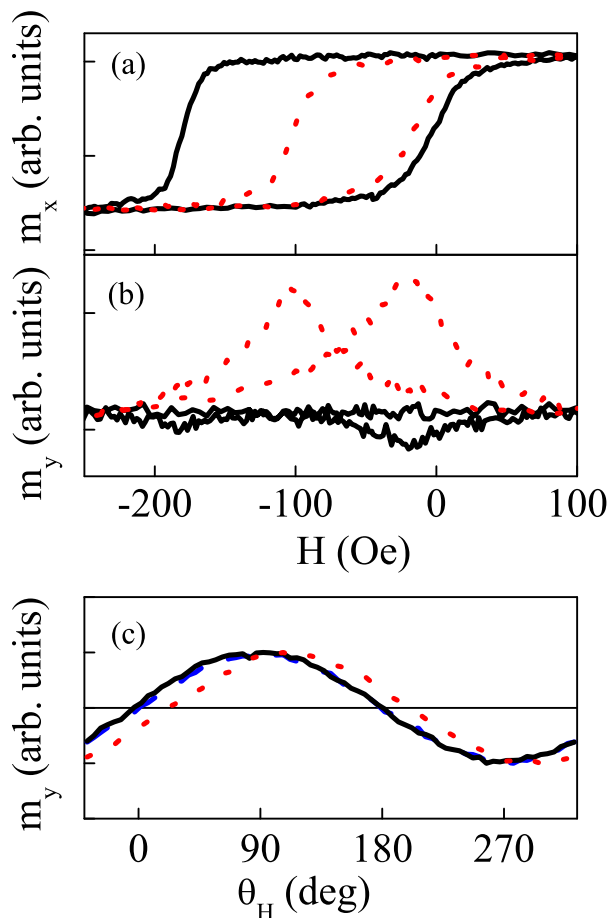


FIG. 1. (Color online) (a) m_x and (b) m_y vs H of $n=1$ (solid line) in the conventional approach and after $n'=10$ within the angular range from 0° to 180° (dot line). In (c) m_y vs θ_H under $H=0$ at the as-prepared state (solid line), after ten torque loops (dot line), and after the $n=1$ hysteresis loop (dash line).

It is essential to reveal the effect of the angular rotation on the torque training effect. For the NiFe/FeMn (20 nm) sample, $n'=20$ torque loops are measured within the angular region from -20° to 380° and then hysteresis loop is measured at $\theta_H=0^\circ$. In comparison, the conventional training effect is also measured. Figures 2(a) and 2(b) show the results. H_E/H_C equals 38.5/21.5 Oe after $n'=20$ and 46.5/20.5 Oe for $n=1$. Apparently H_E is reduced whereas H_C is almost unchanged and the reversal fields of the two branches is shifted by a similar amount. To obtain this second type of training effect the training torque procedure is needed. It is noted that the first type of training effect is caused by the conventional approach,⁶ as demonstrated by $n=1$ and $n=10$ hysteresis loops. Figure 2(c) shows that the PD orientation does not change significantly after both the torque training and the conventional consecutive training procedure when all hysteresis loops are measured at $\theta_H=0^\circ$. It shows that the torque loop performed between -20° and 380° has no effect on the PD orientation. The angular rotation range is proved to have strong effects on the torque training effect.

To better understand the effect of the torque training procedure, it is essential to reveal the n' effect on the EB. Figure 3(a) shows the hysteresis loops of the NiFe/FeMn (11 nm) bilayer after different n' . Several features can be found. First of all, although H_E decreases gradually from 93 to 74 Oe with increasing n' , H_C almost does not change. Second,

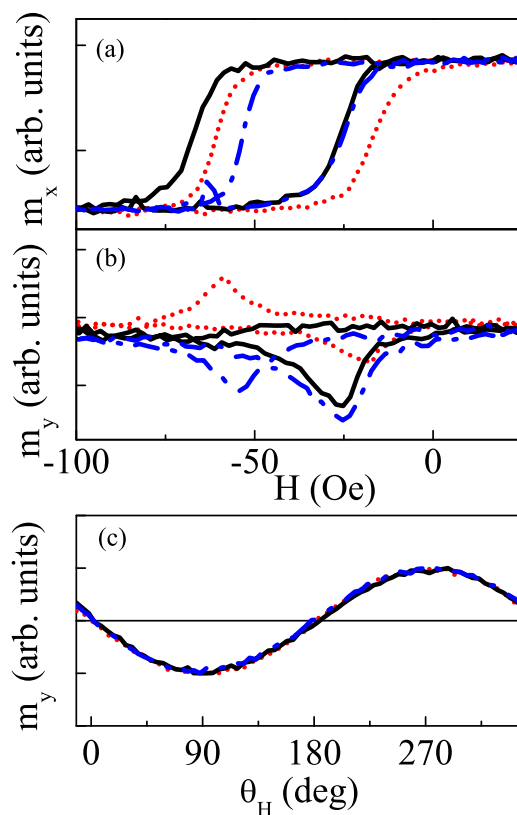


FIG. 2. (Color online) (a) m_x and (b) m_y vs H for $n=1$ (solid line) and $n=10$ (dash line) in the conventional approach and after $n'=20$ within the angular region from -20° to 380° (dot line). In (c) m_y vs θ_H under $H=0$ at the as-prepared state (solid line), after $n'=20$ within the angular region from -20° to 380° (dot line), and $n=1$ (dash line) in the conventional approach.

the m_y values of two branches are almost fixed, as shown in Fig. 3(b), which is different from the observed results in the conventional training effect.¹⁹ Moreover, as shown in Fig. 3(c), the PD is not rotated during the torque training procedure, which agrees with the behavior of m_y as shown in Fig. 3(b). Furthermore, H_E and H_C depend on n' , as shown in Fig. 3(d).

The behaviors of H_E , H_C , and the PD can be understood as follows. In AFM grains, AFM spins may be thermally stable or instable at finite temperatures, depending on the energy barrier which is equal to the product of the uniaxial anisotropy constant and the grain volume.^{21,22} In some stable AFM grains, AFM spins are fixed whereas AFM spins in other grains are rotated during the FM magnetization reversal process. Nonrotatable and rotatable grains, therefore, correspond to H_E and H_C , respectively. During deposition under magnetic fields or magnetic field cooling procedure, the unidirectional and the uniaxial anisotropies are established. In the present NiFe/FeMn bilayers, their axes are collinearly aligned at the as-prepared state as demonstrated by the fact that m_y is always equal to zero when $\theta_H=0^\circ$.²⁰ During the training effects, the AFM spins in rotatable grains, the average orientation of AFM spins in all rotatable grains, and thus the uniaxial axis move to new equilibrium orientations. Similarly, the unidirectional axis may deviate from the initial PD. Therefore, the axes of the uniaxial anisotropy and the unidirectional one may be noncollinearly aligned and the PD orientation may be different from the initial one. At the same time, the magnitude of both the uniaxial and the unidirectional anisotropies may also be reduced. It is noted that the

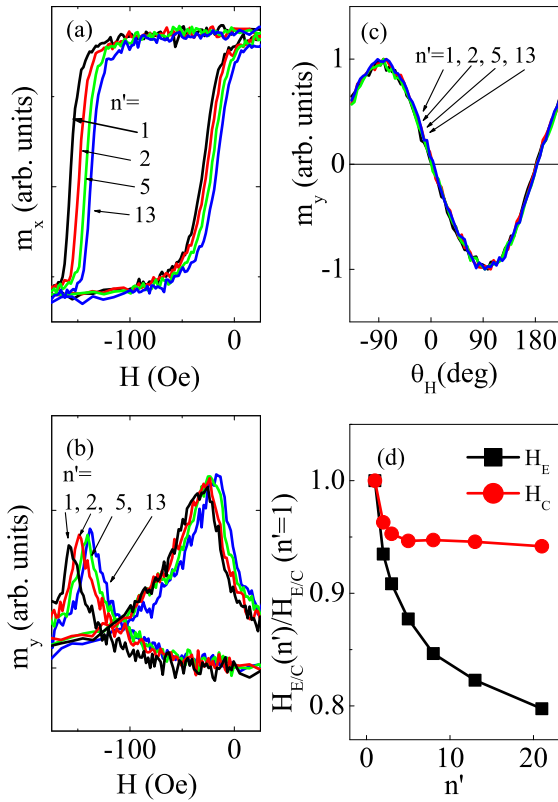


FIG. 3. (Color online) (a) m_x and (b) m_y vs H , and (c) m_y vs θ_H under $H=0$ with torque loops of $n'=1, 2, 5$, and 13 within the angular region from -20° to 380° . In (d), the dependence of H_E and H_C on n' .

rotation of AFM spins depends on the motion of the FM magnetization.

For the torque training procedure taking place between 0° to 180° , the AFM spins in both rotatable and nonrotatable grains are deviated from the initial PD and orientated between 0° to 180° , leading to the reduction in H_E and H_C , and to the PD rotation. For the torque training procedure taking place between -20° and 380° , AFM spins in the rotatable grains are finally orientated along the initial PD after CW rotation from -20° and 380° and subsequent CCW rotation from 380° and -20° , leading to the recovery of the axis and the magnitude of the uniaxial anisotropy. Meanwhile, the transition of AFM spins in the nonrotatable grains may still be triggered. Therefore, H_C and the PD orientation are not changed much but H_E is reduced. Similar results in the conventional training effects of Pt/Co/Pt/IrMn multilayers and (110) epitaxially grown NiFe/FeMn bilayer can be understood in the same way.^{16,17} For the Pt/Co/Pt/IrMn multilayers with pinned domain wall motion, the magnetization of all domains is aligned along the film normal direction near coercive fields and thus the AFM spins can only be aligned along the film normal direction. Accordingly, the axis and the magnitude of the uniaxial anisotropy are not changed and the PD is not rotated either. Since AFM spins in nonrotatable grains may experience 180° switching, H_E is reduced. It should be noted that above discussion is only valid for poly-

crystalline FM/AFM bilayers. For epitaxially grown FM/AFM bilayers, new features occur in the EB training effect. For epitaxially grown FM/AFM bilayers, the EB training effect is much smaller than that of polycrystalline FM/AFM bilayers.¹⁶ The second type training effect occurs in epitaxially grown NiFe/FeMn bilayers by conventional procedure possibly due to the smaller fraction of the rotatable AFM grains compared with that of polycrystalline ones.

In short summary, the torque training procedure is proposed to tune the EB training effect. When the angular rotation covers the 0° to 180° range, a first type training effect is induced,⁶ where H_C and H_E are both reduced, and the PD orientation changes. For the angular rotation range from -20° to 380° , a second type training effect is induced,⁶ where H_C and the PD orientation are almost unchanged even so H_E is reduced. Apparently, besides H_E and H_C , the PD orientation is also of crucial importance to map out the motion of AFM spins during the training effect and to tune the EB training effect.

This work was supported by the National Natural Science Foundation of China under Grant Nos. 50871030, 11074112, and 10974032 and the National Basic Research Program of China under Grant No. 2009CB929201.

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