Angular dependence of magnetization reversal in exchange-biased Co/Pt multilayer with perpendicular magnetic anisotropy

Y. Nie,[1,2] W. W. Lin,[1] M. Huang,[1] K. X. Xie,[1] J. Du,[1] H. Sang,[1,a)] and G. Xiao[3]
[1]*National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing 210093, People's Republic of China*
[2]*College of Science, Liaoning Technical University, Fuxin 123000, People's Republic of China*
[3]*Department of Physics, Brown University, Providence, Rhode Island 02912, USA*

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The magnetization reversal in exchange-biased $(Co/Pt)_5/Co/FeMn$ multilayer with perpendicular magnetic anisotropy has been studied depending on the angle between an applied field and the easy axis (the normal of the film plane). The results show different characters from that in most in-plane exchange bias systems. In a large angular range, the magnetization rotates first toward the adjacent direction of easy axis for both descending and ascending branches because perpendicular magnetic anisotropy is much larger than unidirectional exchange anisotropy. With increasing the angle from 0° to 90°, the magnitude of the exchange bias field decreases, but the coercivity increases due to domain nucleation and propagation included in the magnetization reversal process. The angular dependence of magnetization reversal shows no hysteresis between clockwise and counterclockwise rotations. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2840904]

In exchange bias (EB) system,[1] magnetization reversal of the ferromagnetic (FM) layer can be influenced by the antiferromagnetic (AF) layer due to the FM-AF interfacial interaction.[2–8] In certain EB systems, magnetization reversal exhibits asymmetry for the descending and ascending field branches.[2–4,7,8] The magnetization reversal process depends on the relative orientation and magnitudes of the uniaxial anisotropy and unidirectional exchange anisotropy, as well as the applied field.[4–8] The angular dependence of magnetization reversal in EB system has been studied with the applied field in the film plane.[7–10] These results show that the coercivity H_C exhibits uniaxial symmetry, whereas the EB field H_{EB} exhibits unidirectional symmetry.[7–10] H_C decreases when the applied field direction changing from the easy magnetization direction of the FM layer to the hard, and H_{EB} decreases when the applied field direction rotated away from the exchange field direction.[7–10] Also, there was a report on the angular dependence of EB with the applied field rotated out of the film plane. In this case, the hysteresis loops shifts not only along the field axis but also along the magnetization axis.[11] However, most works were carried in FM/AF systems with a ferromagnetic in-plane easy axis,[7–11] seldom in the system with a perpendicular easy axis.[2,3,12–15] Recently, there were reports that the angular dependence of EB shows hysteresis between clockwise (CW) and counter-CW (CCW) rotations of Co/FeMn (Ref. 16) and NiFe/FeMn (Ref. 17) bilayers. However, this phenomenon was not observed in exchange-biased NiFe/MnPt bilayers.[8] It should be noted that these measurements were performed with in-plane rotation, but no result with out-of-plane rotation was reported.

In this paper, we investigate the angular dependence of magnetization reversal in an exchange-biased Co/Pt multilayer with perpendicular magnetic anisotropy (PMA), varying the angle between the applied field and the normal of the film plane. Also, the out-of-plane CW and CCW rotation measurements were performed. Due to strong PMA in Co/Pt multilayer, the magnetization reversal in perpendicular exchange-biased $(Co/Pt)_5/Co/FeMn$ multilayer has some characters different from that in most in-plane EB systems.

The multilayer Ta (60 Å)/Pt (100 Å)/[Co(4.8 Å)/Pt(9 Å)$]_5$/Co (7 Å)/FeMn (80 Å) was deposited on the Si(100) wafer at room temperature (RT) using a dc magnetron sputtering system. The base pressure of the sputtering system was 1.2×10^{-8} Torr, and the Ar pressure during sputtering was about 4 mTorr. During deposition, a magnetic field of about 1 kOe was applied perpendicular to the sample plane to induce the EB. X-ray diffraction indicated a preferential (111) texture in the sample.

Magnetic measurements were performed in a vibrating sample magnetometer with vector pickup coils. As shown in Fig. 1, the direction of the applied field **H** is denoted as the *x*

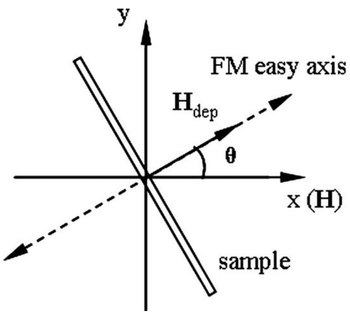

FIG. 1. A scheme in which the direction of the applied field **H** is defined as *x* axis and that of the depositing-field $\mathbf{H}_{dep}$ (solid line with arrow) is along the easy axis (dashed line with arrows) of the FM layer (the normal of the film plane), and θ is the angle between the direction of positive applied field and the depositing-field direction.

[a)] Author to whom correspondence should be addressed. Electronic mail: haisang@nju.edu.cn.

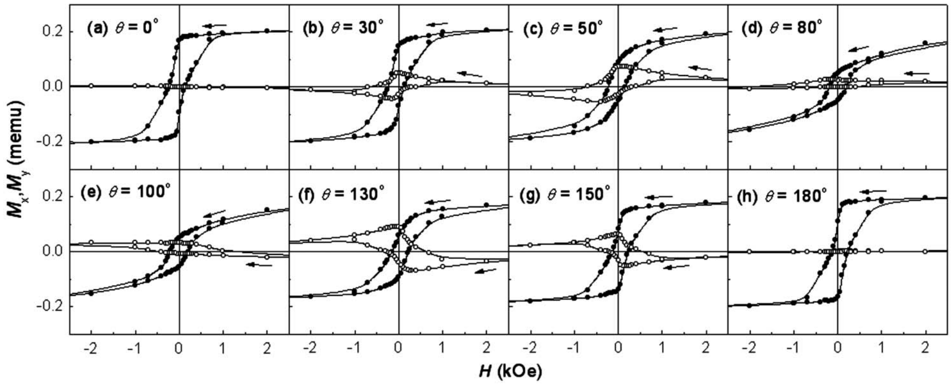

FIG. 2. Hysteresis loops measured at θ=(a) 0°, (b) 30°, (c) 50°, (d) 80°, (e) 100°, (f) 130°, (g) 150°, and (h) 180°, in which solid circles and open circles correspond to M_x and M_y (low field part), respectively. The arrows show the beginning of the loops.

axis, and the depositing-field direction is along the normal of the film plane (the easy axis of the FM layer). The angle between the direction of positive applied field and the depositing-field direction, θ, can be changed by rotating the sample. The hysteresis loops of the sample were measured at RT up to 10 kOe field, and the magnetization components parallel (M_x) and perpendicular (M_y) to the applied field direction were recorded. The hysteresis loops of the sample were measured with the sample rotated CCW from 0° to 180° and CW from 180° to 0°. The hysteresis loops of both M_x and M_y at the same angle in the CW rotation display no difference from that in the CCW rotation, indicating that the hysteresis behavior of angular dependence, reported in Refs. 16 and 17, does not appear in our sample for the out-of-plane rotations.

Figure 2 partly shows typical hysteresis loops of both M_x and M_y measured at different angles of the applied field with the normal of the film plane. The magnetization reversal process and its asymmetric behavior can be displayed more clearly from both M_x and M_y loops. When the magnetic field is applied along the depositing-field direction ($\theta=0°$) [Fig. 2(a)], the M_x loop exhibits a negative shift with an EB field of about −60 Oe, and M_y loop is flat, showing the absence of the net magnetization perpendicular to the applied field during the magnetization reversal. For $\theta=30°$, one can see from Fig. 2(b) that M_y increases to the positive and falls to the negative, and then approaches zero for large negative field when decreasing the applied field from a positive maximum (descending branch). When increasing the applied field from a negative maximum (ascending branch), M_y decreases to the negative, and then raises to the positive, finally approaches zero for large positive field. M_y has a larger magnitude at $\theta=50°$ [Fig. 2(c)], and the peak of M_y in the descending branch is larger than that in the ascending branch. The shape of M_y curve exhibits slight asymmetry for the descending and ascending branches. For $\theta=80°$, the shift of the M_x loop almost vanishes [Fig. 2(d)], and M_y has a slight swell in the descending branch and is flat in the ascending branch, indicating that the incoherent magnetization rotation is included in the magnetization reversal. Both M_x and M_y of $\theta=100°$, 130°, 150°, and 180° were shown in Figs. 2(e)–2(h). For $\theta=130°$ shown in Fig. 2(f), the M_x loop exhibits a positive shift, and M_y decreases initially to the negative in the descending branch of the loop and increases initially to the positive in the ascending branch.

One may find that the feature of M_y loop in our case is different from that in most EB systems.[6–8,16] The peaks of M_y are usually of the same sign, i.e., either positive or negative, for the descending and ascending branches.[6–8,16] The magnetization reversal process in the EB system depends on the competition between the uniaxial anisotropy and the unidirectional exchange anisotropy,[4–8] which could be deduced from the coherent rotation model. Assuming that the uniaxial anisotropy field of the FM layer is collinear to the exchange field, the energy E in an EB system can be written as

$$E = -HM_S \cos(\theta - \alpha) + K_U \sin^2 \alpha - K_E \cos \theta, \tag{1}$$

where M_S is the saturation magnetization of the FM layer, α is the angle between the magnetization and the easy axis of the FM layer, and K_U and K_E are the uniaxial anisotropy of the FM layer and the unidirectional FM-AF exchange anisotropy, respectively. For the most cases in the literature,[6–8,16] the uniaxial anisotropy is smaller than the unidirectional exchange anisotropy, i.e., $K_U < K_E$, so the magnetization usually rotates first toward the unidirectional anisotropy direction for both descending and ascending branches and thus, the peaks of M_y are usually of the same sign for the descending and ascending branches.[6–8,16] Due to FM-AF exchange coupling, the pathway of magnetization rotation in the EB systems behaves differently from the FM layer without AF layer.

For our case, because perpendicular anisotropy of the FM layer K_U, which is in the order of 10^6 erg/cm^3, is much larger than the FM-AF exchange anisotropy, i.e., $K_U > K_E$, the effect of the uniaxial magnetic anisotropy in the FM layer on the magnetization rotation is dominant.[6,8] Shown in Fig. 3 is the pathway of the magnetization rotation illustrated by plotting experimental data of M_y vs M_x. As $\theta=50°$ [see Fig. 3(a)], for the descending branch, the magnetization first rotates CCW toward one direction of the easy axis (the unidirectional anisotropy direction) from the direction of positive applied field. Next, irreversible reversal process takes place when the applied field reaches the critical field. Finally, the magnetization rotates CW to the direction of negative applied field. For the ascending branch, the magnetization first rotates CCW toward another direction of the easy axis (*opposite* to the unidirectional anisotropy direction) from the direction of negative applied field, and after the irreversible reversal process, the magnetization rotates CW to the direction of negative applied field. As $\theta=130°$ [see Fig. 3(b)], the

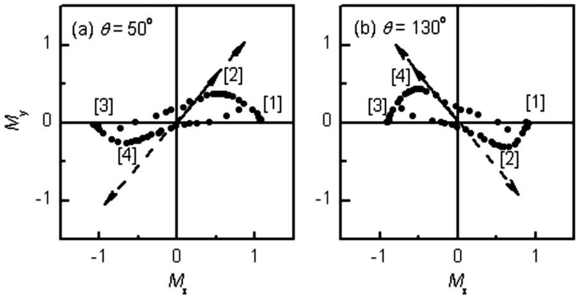

FIG. 3. The process of the magnetization rotation plotted as M_y vs M_x at θ=(a) 50° and (b) 130°. The solid line with arrow shows the depositing-field direction and dashed line with arrows the easy axis of the FM layer. The numbers nearby the data points are guides for the eyes.

magnetization rotates first CW toward one direction of the easy axis (opposite to the unidirectional anisotropy direction) for the descending branch, and the magnetization rotates CCW toward another direction of the easy axis (the unidirectional anisotropy direction) for the ascending branch. That is to say, the magnetization rotates first toward the closest direction of easy axis for both descending and ascending branches and thus, the magnetization can rotate in the whole *xy* plane, following the behavior in FM layer without AF layer.

The angular dependences of the coercivity H_C and the EB field H_{EB} of $(Co/Pt)_5/Co/FeMn$ sample are shown in Fig. 4. H_C which exhibits a uniaxial symmetry, increases with the angle θ increasing from 0° to 90°, while decreases from 90° to 180°, as shown in Fig. 4(a). The increase of H_C with the applied field direction changing from the easy magnetization direction to the hard one is different from most systems and has been observed in Co/Pt multilayer,[18] which is due to the magnetization reversal involving domain nucleation and propagation for strong PMA in Co/Pt multilayer.[2] H_{EB} exhibiting a uniaxial symmetry is of negative (positive) and varies flatly when $0° < \theta < 30°$ ($150° < \theta < 180°$), as shown in Fig. 4(b), increases with θ increasing from 30° to 80° (from 100° to 180°), and is almost zero when $80° < \theta < 100°$. The tendency of H_{EB} is similar to most EB systems,[7–11] but the flatness for $80° < \theta < 100°$ was seldom observed, which needs further study.

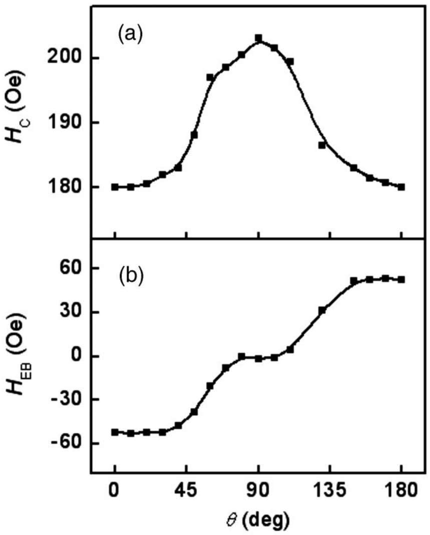

FIG. 4. The dependence of (a) H_C and (b) H_{EB} on the angle θ.

In summary, we have studied magnetization reversal in perpendicular exchange-biased $(Co/Pt)_5/Co/FeMn$ multilayer with the applied field at different angles with respect to the normal of the film plane. Due to strong PMA in Co/Pt multilayer which is much larger than the unidirectional exchange anisotropy, in a large angular range, the magnetization in the exchange-biased multilayer always rotates toward the adjacent direction of easy axis when the applied field decreases and thus, the magnetization can rotate in the whole *xy* plane, following the behavior in Co/Pt multilayer without FeMn. The coercivity H_C and the EB field H_{EB} exhibit uniaxial and unidirectional symmetries, respectively. The magnitude of the EB field decreases with increasing the angle θ from 0° to 90°, but the coercivity increases due to domain nucleation and propagation included in the magnetization reversal process. The angular dependence of magnetization reversal shows no hysteresis between CW and CCW rotations in our case.

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