Angular dependence of magnetization reversal process in exchange biased epitaxial MnPd/Fe bilayers

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(Presented 19 January 2010; received 27 October 2009; accepted 9 December 2009; published online 19 April 2010)

We investigated the angular dependence of magnetization reversal in epitaxial MnPd/Fe bilayers grown on MgO(001) using combined longitudinal and transverse magneto-optical Kerr effect. Square loops, asymmetrically shaped loops, and double-shifted loops were observed as the field orientation was varied from parallel to perpendicular to the bias direction. Additionally, including the effect of an induced uniaxial anisotropy in the ferromagnetic layers, an improved effective field model was used to interpret the complex angular dependence of the magnetic switching fields. The fitting shows good agreement with the experimental results for the samples with different thicknesses. © *2010 American Institute of Physics*. [doi:10.1063/1.3340449]

Angular dependent magnetic measurements have been widely adopted in investigating the interfacial exchange coupling between ferromagnetic (FM) and antiferromagnetic (AFM) layers.[1–3] Numerous studies on polycrystalline bilayers demonstrated that the angular dependence of the exchange field and the coercive field can be described by Fourier cosine series with odd and even terms, respectively.[4,5] Considering a unidirectional anisotropy and an induced uniaxial anisotropy, the hysteresis loops and the value of exchange bias and coercivity could be numerically fitted by the Stoner–Wohlfarth model.[6,7] In epitaxial exchange biased systems, the intrinsic magnetocrystalline anisotropy needs to be further considered, which results in a more complex angular dependent behavior. Square and double-shifted loops are observed when measuring parallel and perpendicular to the bias direction, respectively.[8–10] However, only few works systematically studied the angular dependence of exchange coupling and switching field.[11,12] In this paper, we focused on the angular dependence of the magnetic behavior of single crystalline MnPd/Fe bilayers. Square, asymmetrically shaped, and double-shifted loops were observed at different field orientations. Additionally, including the effect of the induced uniaxial anisotropy, we extended the effective field model to explain the complex angular dependence of the switching fields.

MnPd/Fe bilayers were grown on MgO(001) substrates in an ion beam sputtering system. The substrates were annealed at 500 °C for 1 h and held at 310 °C during deposition. The c-axis oriented MnPd/Fe bilayers were epitaxially grown on the substrates according to the relationships: MnPd(001)‖Fe(001)‖MgO(001) and MnPd[100]‖Fe[110]‖MgO[100]. The thickness of the MnPd layer was fixed at 45 nm and the thickness of the Fe layer, t_{Fe}, was varied from 9 to 20 nm. An external magnetic field of 300 Oe along the Fe[010] direction was applied during growth. A protective Pt layer with a thickness of 2 nm was deposited on top of the films.

A typical θ-2θ x-ray diffraction measurement shown in Fig. 1(a) confirms that the films are grown on the substrates with (001) growth orientation for Fe layers and c-axis normal orientation for MnPd layers.[13–15] The magnetic properties were characterized at room temperature by combined measurements of the longitudinal and transverse magneto-optical Kerr effect (MOKE) for different field orientations, ϕ, as defined in Fig. 1(b).

Figure 2 shows the typical MOKE loops for the MnPd(45 nm)/Fe(13 nm) bilayer obtained at different ϕ. When the applied field is parallel to the bias direction, i.e., $\phi=0°$, the longitudinal magnetization component shows a square loop with an exchange bias field of 37 Oe [Fig. 2(a)]. The transverse MOKE signal is always null, which indicates that the reversal of Fe magnetization is mediated by domain nucleation and propagation for both sides of the loop. The square loops can be observed up to $\phi=\pm 10°$. This is in contrast to the previous work on Fe/MnF_2 bilayer where the square loop was obtained only at $\phi=0°$.[2] We ascribe this difference to a strong induced uniaxial anisotropy caused by the exchange coupling in MnPd/Fe bilayers.[16] The induced uniaxial anisotropy has the same direction with the exchange bias,[7,8] as marked in Fig. 1(b).

Asymmetrically shaped loops with a distinct kink on the descending branch are observed for $15° \leq \phi \leq 35°$ [Fig.

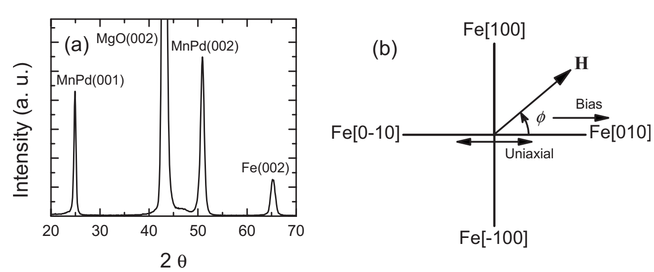

FIG. 1. (a) Typical x-ray diffraction patterns for the c-axis oriented MnPd/Fe bilayer. (b) Definition of the exchange coupling direction and the field orientation in an epitaxial exchange biased film.

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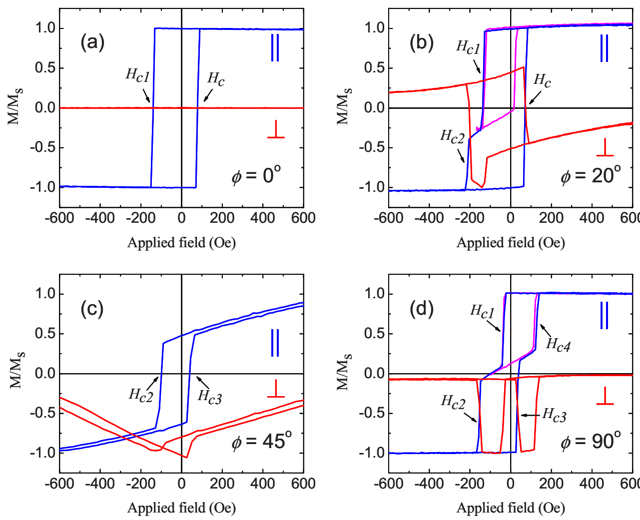

FIG. 2. (Color online) Representative longitudinal (∥) and transverse (⊥) MOKE loops for MnPd/Fe bilayer with $t_{Fe}=13$ nm obtained at (a) 0°, (b) 20°, (c) 45°, and (d) 90° of the applied field referred to the bias direction. The minor loops for $\phi=20°$ and 90° are also plotted in (b) and (d), respectively.

2(b)]. The transverse MOKE loop indicates that the kink is an intermediate state at the $[\bar{1}00]$ direction when the magnetization switches from the [010] to $[0\bar{1}0]$ directions. For the ascending branch, the magnetization transitions smoothly from the $[0\bar{1}0]$ to [010] direction without staying at the intermediate Fe easy directions, suggesting that the magnetization reversal occurs by domain nucleation. Similar asymmetric loops were first reported in Fe/MnF_2 system, in which the coherent rotation processes for the descending branch were demonstrated by the minor loops being full reversible.[17] However, for MnPd/Fe bilayers, the minor loop in Fig. 2(b) is irreversible. This behavior is believed to result from the crystal structure of Fe layers. After the magnetization switches from the [010] to $[\bar{1}00]$ directions, if the field direction is reversed, the induced uniaxial and unidirectional anisotropies are not strong enough to overcome the Fe magnetocrystalline anisotropy to reverse the magnetization back to the [010] direction unless a small positive field is applied.

For the field applied around the Fe [110] hard axis, i.e., $40° \le \phi \le 60°$, both branches of the loops show only one irreversible magnetic transition between the [010] and $[\bar{1}00]$ directions [Fig. 2(c)]. Except for the obvious exchange bias, the two branches are similar in shape, but the previous imaging work in our group has demonstrated the magnetic reversal is dominated by coherent rotation for the descending branch but by domain nucleation for the ascending branch.[15]

Double-shifted hysteresis loops with two-stage magnetic transitions occurring on both branches are observed for $65° \le \phi \le 115°$ [Fig. 2(d)]. The transverse MOKE loop indicates the switching routes are from the [100] to the [010] and finally to the $[\bar{1}00]$ directions for decreasing field and the reverse one for increasing field. The minor loop in Fig. 2(d) is also irreversible and almost overlaps with the upper side of the major loop because of the same switching path.

The switching fields for different kinds of loops are defined in Figs. 2(a)–2(d) and are measured for different ϕ. The

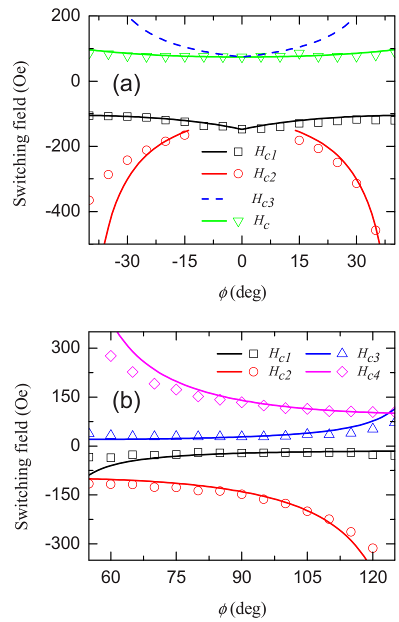

FIG. 3. (Color online) Experimental switching fields (symbols) as a function of the field orientation ϕ and the theoretical fitting (continuous lines) by the revised effective field model close to (a) parallel and (b) perpendicular to the bias direction. The dashed blue curve is produced by the model before improvement.

angular dependence of switching fields is symmetric about the bias direction, which confirms that the induced uniaxial anisotropy is collinear with the exchange bias. The switching fields close to parallel and perpendicular to the bias direction are displayed in Figs. 3(a) and 3(b), respectively. Herein, we adopt an effective field model, originally developed by Arenholz *et al.*,[2] to quantitatively interpret the complex angular dependent switching fields. This model considers three contributions to the effective field, H_{eff}, acting on the FM layer during magnetization reversal. They are the exchange field H_X, the external magnetic field, H_{ext}, and the anisotropy field, H_A, aligned with the Fe easy axis. H_A depends on the projection of the FM magnetization onto the easy axis and the strength of the anisotropy.[18] For our system, the symmetry of cubic anisotropy in FM layer is broken by the induced uniaxial anisotropy. Therefore, we assign different anisotropy fields, H_{A1} and H_{A2}, for Fe moments aligned with the easy axes parallel and perpendicular to the bias direction, respectively.

By comparing the effective field at different Fe easy axis involved in a magnetic transition, the switching fields can be estimated. In the case of $0° \le \phi < 45°$, the effective field component along the [010] direction for the deceasing field before the reversal sets in can be expressed as $H_{eff}^{[010]} = H_{ext}\cos\phi + H_X + H_{A1}$, while the effective field along the $[\bar{1}00]$ direction is $H_{eff}^{[\bar{1}00]} = -H_{ext}\sin\phi$, where $H_{ext} < 0$. When $H_{eff}^{[\bar{1}00]} \ge H_{eff}^{[010]}$, the Fe moments switch from the [010] to the $[\bar{1}00]$ directions at $H_{c1} = -(H_X + H_{A1})/(\cos\phi + \sin\phi)$. On further reducing the applied field, the relevant effective fields are changed to $H_{eff}^{[\bar{1}00]} = -H_{ext}\sin\phi + H_{A2}$ and $H_{eff}^{[0\bar{1}0]} = -H_{ext}\cos\phi - H_X$, so the magnetization reorients to the $[0\bar{1}0]$ direction at $H_{c2} = -(H_X + H_{A2})/(\cos\phi - \sin\phi)$. If $|H_{c1}| \ge |H_{c2}|$, the intermediate state along the $[\bar{1}00]$ direction is

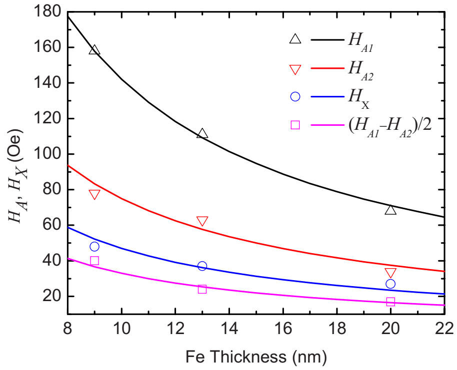

FIG. 4. (Color online) The anisotropy fields H_{A1} and H_{A2} and the bias field H_X obtained from the fitting for the angular dependence of switching fields for MnPd/Fe bilayers with different t_{Fe}. The difference between H_{A1} and H_{A2} is also plotted. The full curves correspond to a $1/t_{Fe}$ dependence.

unstable, so the magnetization favors a direct transition from the [010] to $[0\bar{1}0]$ directions. Consequently, the descending branch of hysteresis loop shows only one step. When $|H_{c1}| < |H_{c2}|$, the magnetization is aligned along the $[\bar{1}00]$ direction between H_{c1} and H_{c2}, thus the descending branch has the feature of two stages. The critical angle separating the two kinds of magnetization reversal satisfies $\tan \phi_{crit} = (H_{A1} - H_{A2})/(H_{A1} + H_{A2} + 2H_X)$. Obviously, a stronger uniaxial anisotropy induces a larger difference between H_{A1} and H_{A2}, and a larger ϕ_{crit}.

For the ascending branch at $0° \le \phi < 45°$, H_X is antiparallel to H_{A1}, the effective field is more aligned with the magnetization, which favors the reversal mode of domain nucleation. Similarly, the magnetic transitions from the $[0\bar{1}0]$ to [100] and finally to [010] directions can be estimated to take place at $H_{c3} = (H_{A1} - H_X)/(\cos \phi - \sin \phi)$ and $H_{c4} = (H_{A2} - H_X)/(\cos \phi - \sin \phi)$, respectively. Because $H_{c3} > H_{c4}$, a direct magnetic transition from the $[0\bar{1}0]$ to [010] directions can be expected. However, if the magnetization reversal is mediated by 180° domain wall nucleation, only the effective field component parallel to the bias direction, which is $H_{eff}^{\parallel} = H_{ext} \cos \phi + H_X - H_{A1}$, needs to be taken into account. If $H_{eff}^{\parallel} > 0$, the magnetization will switch from the $[0\bar{1}0]$ to [010] directions via 180° domain wall nucleation at $H_c = (H_{A1} - H_X)/\cos \phi$. Both reversal mechanisms can interpret the direct magnetic transition on the ascending branch in Figs. 2(a) and 2(b), but, in practice, the magnetization reversal will follow the path which gives lower coercivity. Due to $H_c < H_{c3}$, the reversal mechanism of 180° domain wall nucleation is preferred. It should be noted that for the descending branch we discussed above, the absolute value for the switching field derived by 180° domain wall nucleation is larger than the one by considering the intermediate state, thus the two-stage magnetic transition is dominant.

For the external field applied close to perpendicular to the bias direction, i.e., $45° < \phi < 135°$, the switching fields for the double-shifted loops can be similarly predicted as $H_{c1} = -(H_{A2} - H_X)/(\sin \phi - \cos \phi)$, $H_{c2} = -(H_{A1} + H_X)/(\sin \phi + \cos \phi)$, $H_{c3} = (H_{A2} - H_X)/(\sin \phi + \cos \phi)$, and $H_{c4} = (H_{A1} + H_X)/(\sin \phi - \cos \phi)$.

Using the above-derived expressions, the angular dependence of the switching fields for MnPd/Fe bilayers with $t_{Fe} = 13$ nm can be nicely fitted [Figs. 3(a) and 3(b)]. For the external field near the bias direction, the theoretical curve of H_c except H_{c3} shows an excellent agreement with the experimental observations. The $1/\cos \phi$ dependence of the experimental value of H_c can be linked to the Kondorsky model, which was developed to describe the magnetization reversal by 180° domain nucleation in samples with strong uniaxial anisotropy.[19] The fitting for the experimental data gives the parameters $H_{A1} = 111$ Oe, $H_{A2} = 63$ Oe, and $H_X = 37$ Oe. Then, the critical angle ϕ_{crit} separating the occurrence of the square loops and the asymmetric loops can be predicted at 11°, which agrees well with the experimental value.

Similar fitting parameters for MnPd/Fe bilayers with different t_{Fe} are plotted in Fig. 4. H_{A1}, H_{A2}, and H_X depend inversely on t_{Fe}. Using the relation $J_{ex} = H_X t_{Fe} M_{Fe}$ and the magnetization for bulk Fe $M_{Fe} = 1700$ emu/cm^3, the exchange coupling energy J_{ex} between Fe and MnPd layers is obtained as 0.082 erg/cm^2. The difference between H_{A1} and H_{A2} is proportional to the strength of the induced uniaxial anisotropy. The $1/t_{Fe}$ thickness dependence of $(H_{A1} - H_{A2})/2$ confirms the uniaxial anisotropy results from the interfacial exchange coupling.

This work was supported by DoE/BES under Grant No. ER45987.

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