Thickness dependence of Co anisotropy in TbFe/Co exchange-coupled bilayers

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The orientation of element-specific moments was determined by using x-ray magnetic circular dichroism spectroscopy to explore exchange anisotropy of TbFe/Co bilayers. Perpendicular anisotropy of 15 Å Co was induced by TbFe through exchange coupling, resulting in the out-of-plane Co moments. With increasing the thickness, Co moments were gradually tilted to the in-plane orientation because of increasing planar anisotropy. In the bilayer with thick Co, interfacial Fe moments were unidirectionally aligned in the plane, leading to in-plane exchange bias of Co. The coercivity and exchange bias field of Co in the bilayers exhibited a strong dependence on Co thickness. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1689911]

Extensive effort has been devoted to investigate the physical mechanisms of the exchange bias because of the fundamental interest and important technical applications.[1] Most of the research focused on the investigation of the exchange interaction between ferromagnetic (FM) and antiferromagnetic (AFM) bilayers applied for storage industry. The planar exchange anisotropy was also found in the bilayers composed of ferromagnetic layer with in-plane anisotropy and ferrimagnetic rare-earth–transition-metal (RE–TM) alloys with perpendicular anisotropy.[2] Since RE–TM films are amorphous with strong exchange anisotropy coupled to FM, these bilayers can potentially replace the FM–AFM for applications.[3–6] Cain and Smith proposed that the strong exchange coupling between RE–TM and FM resulted from the existence of a homogeneous and continuous interface in the bilayers.[3,4] However, the biasing mechanism was only described by indirect results because of difficulties in analyzing the orientation of magnetic moments in the films.[6] Over the last few years, the x-ray magnetic circular dichroism (XMCD) technique has evolved into an important magnetometry tool.[7] It possesses high sensitivity to element-specifically determine spin and orbital magnetic moments and their anisotropy in ferromagnets or ferrimagnet systems.[8–10] In this work, we deposited thin Co layers with various thicknesses on the TbFe to quantitatively derive the orientation of the moments at the interface from the XMCD measurement. By observing the variation of canting angle of Co and Fe with the thickness, we can concretely build up a scheme to clarify the source of exchange bias in the bilayers with perpendicular and longitudinal anisotropies.

The $Tb_{21.3}Fe_{78.7}$ 300 Å/Co x Å were deposited by magnetron sputtering at a base pressure of 3×10^{-7} Torr onto Si substrates, where x varied from 5 to 150. The bilayers were sandwiched by SiN_x layers to prevent oxidation. An in-plane field of 150 Oe was applied during the deposition to induce the exchange-biasing field. The single layer of $Tb_{21.3}Fe_{78.7}$ possessed the coercivity of 16.2 kOe in the out-of-plane direction and low magnetization of 15 emu/cm^3. The low magnetization was chosen to suppress the effect of dipole–dipole interaction on exchange bias. A vibrating sample magnetometer and Kerr-effect tracer were used for measuring the magnetic properties. XMCD spectroscopy was utilized to derive the effective canting angles of Fe and Co in the bilayers through the total electron yield measurement. L-edge absorption spectra of Fe and Co were, respectively, obtained within the energy range of 695–740 and 770–810 eV. The energy resolution and degree of polarization at the Co, Fe edges are 0.2 eV and 60%. All of the XMCD measurements were performed at room temperature without applied fields.

As 15 Å Co with in-plane anisotropy was deposited on 300 Å TbFe with the perpendicular anisotropy, not only the planar hysteresis loop disappeared but the remanence magnetization was reduced as well, as shown in Fig. 1(a). In contrast, a square out-of-plane loop was obtained and its product of remanence magnetization and thickness (M_rt) was approximately equal to the M_rt sum of TbFe and Co. It implied that Co moments were aligned in the perpendicular direction and coherently rotated with the TbFe under the applied fields due to the strong exchange interaction between the bilayer. Similar to the effect of exchange coupling between soft and hard magnetic films, the effective coercivity of TbFe decreased from 16.2 kOe of single layer to 5.7 kOe in the bilayer. As the Co thickness increased to more than 25 Å, in-plane shifted loops were observed in the film plane. As shown in Fig. 1(b), the in-plane loops of 50 Å Co in the

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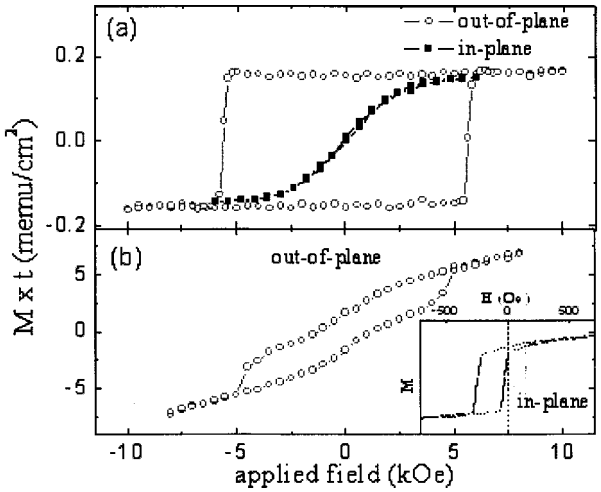

FIG. 1. In-plane and out-of-plane hysteresis loops of the bilayers with the Co of: (a) 15 and (b) 50 Å.

bilayer exhibited a biasing field of 145 Oe and an enhanced coercivity of 106 Oe. The oblique out-of-plane loop indicated Co has a significant planar anisotropy in the bilayer.

The in-plane coercivity (H_c) and biasing field (H_b) of Co also depended strongly on the Co thickness in the bilayer, as shown in Fig. 2. The Co in the bilayer possessed higher H_c than that in the single layer because of exchange interaction between TbFe and Co. With increasing thickness, the in-plane anisotropy of Co became dominant because surface anisotropy was weakened.[11] As the Co increased from 25 to 40 Å, the in-plane anisotropy of Co was enhanced, which forced TbFe moments at the interface to align toward the in-plane orientation and led to the increased in-plane H_c and H_b. With further increasing Co thickness, the in-plane anisotropy of Co was less changed; therefore, H_c and H_b were inversely proportional to Co thickness due to the characteristic of interfacial coupling of exchange bias, as observed in the in-plane FM/AFM bilayers.

XMCD spectroscopy was utilized to clarify the dependence of the Co and Fe moment orientation on Co thickness in the bilayers. Because of strong antiparallel exchange coupling between the TM and heavy RE moments,[12] the orientation of Tb was considered to be aligned in the opposite direction of Fe moments. In the XMCD measurement, the polarized x ray was incident to the samples at an angle of 65° from the surface normal, as illustrated in Figs. 3(a) and 3(b). If the direction of the in-plane component of the incident x ray is along the direction of the applied field during the deposition, we define it as the parallel (*P*) incidence, indicated in Fig. 3(a). The opposite is the antiparallel (*A*) incidence, shown in Fig. 3(b). Right and left circular polarized x rays were sequentially illuminated to the bilayers to obtain *L*-edge absorption spectra of Fe and Co. All of the XMCDs of Co and Fe in the experiments were derived by subtracting the spectrum of the right circularly polarized x ray from that of the left. Taking sampling depth (~8 nm) into the consideration, the XMCD signal of Co averaged over the entire the film, with the preponderance of the signal coming from the near-surface layers. On the other hand, the Fe signal came mainly from the interface region. As shown in Figs. 4(a) and 4(b), the normalized XMCDs of Co in *P* and *A* incidences are similar in the bilayer with 15 Å Co, but are almost reversed in the bilayer with 50 Å Co. In principle, the XMCD

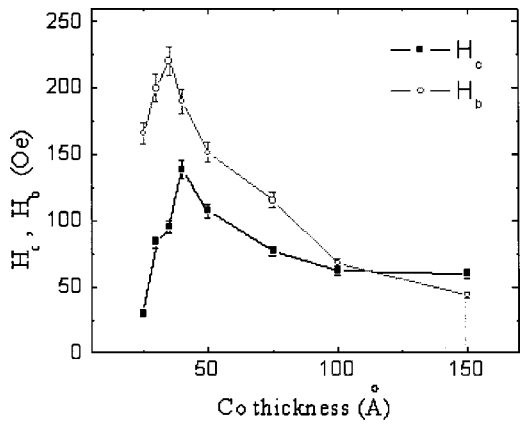

FIG. 2. Dependence of coercivity H_c and exchange bias H_b on Co thickness in the bilayers.

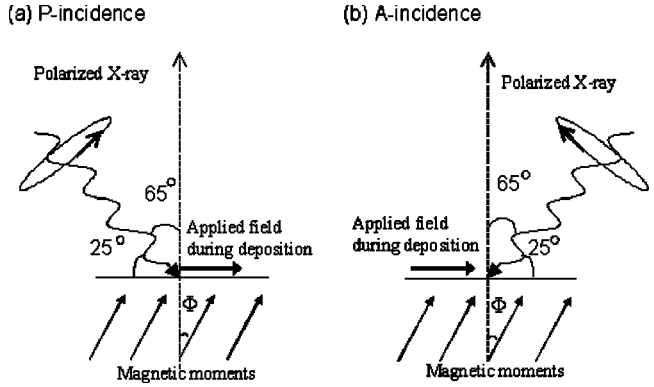

FIG. 3. Illustration of (a) *P* incidence and (b) *A* incidence in XMCD measurement.

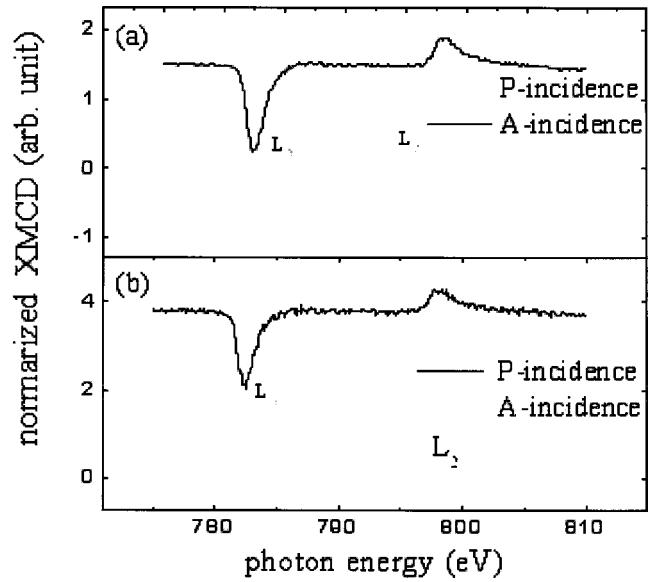

FIG. 4. Normalized XMCDs of *P* and *A* incidence in the TbFe/Co bilayer with the Co of: (a) 15 Å and (b) 50 Å.

effect is quantitatively related to the amounts of magnetic moments and to the anisotropies of the spin density and orbital moments.[7,8] The dichroism effect in XMCD spectroscopy reaches the maximum if the photon spin and the magnetization directions are parallel or antiparallel, and becomes zero if their directions are perpendicular to each other. Therefore, we can consider the XMCD intensity I of Co as

$$I = I_0 \cos\Theta, \tag{1}$$

where I_0 is the maximum intensity related to the amount of spin and orbital moments and Θ is the angle between the magnetization orientation and the incident x-ray direction. If the Co moments were entirely perpendicular to the surface, the XMCD intensity of P and A incidences should be identical because the two incident x rays had the same angle of 65° from perpendicular moments. Therefore, the similarity of the dichroisms of P and A incidences in Fig. 4(a) implies that the perpendicular anisotropy of 15 Å Co in the bilayer was induced by strong exchange coupling from TbFe. In contrast, the reversed dichroism signals observed in 50 Å Co indicated that the Co moments in the bilayer preferred the in-plane alignment.

Furthermore, the orientation of Co moments near the surface and Fe moments near the interface of Co and TbFe in the bilayer can be quantitatively derived by XMCD measurements to concretely explore the origin of exchange bias in the TbFe/Co bilayers. As depicted in Fig. 3, if the orientation of the specific moment is aligned at an angle Φ from the surface normal, the dependence of XMCD intensity on the angle Φ can be given by

$$I_{L3,P} = I_0 \cos(180° - 65° - \Phi) = -I_0 \cos(\Phi + 65°) \tag{2}$$

and

$$I_{L3,A} = I_0 \cos(180° + 65° - \Phi) = -I_0 \cos(\Phi - 65°). \tag{3}$$

Here, $L_{L3,P}$ and $I_{L3,A}$, respectively, expressed the XMCD intensity of the L_3-edge of P and A incidences. Combining Eqs. (2) and (3), the effective canting angle Φ of Co and Fe moments can be obtained by the following formula:

$$\tan\Phi = \cot 65° \times (L_{L3,A} - I_{L3,p})/(I_{L3,A} + I_{L3,p}). \tag{4}$$

Figure 5 shows the variation of the Φ of Co and Fe with the Co thickness in the bilayers. Since the majority of the XMCD effect comes from the regions close to the surface, the derived Φ of Co and Fe in the bilayers particularly indicated the orientation of Co moments near the surface and the Fe moments in the interface region. The orientation of near-interface Co can be reasonably assumed being parallel to near-interface Fe because of strong exchange interaction between Fe and Co moments. From Fig. 5, the canting angles of Co and the near-interface Fe are quite similar, implying that the orientation variation of the Co magnetization across the film thickness is negligible. In the bilayer with 15 Å Co, both Co and Fe moments preferred the out-of-plane alignment because of their small Φ of 15.4° and 13.1° from the surface normal. With increasing thickness, the Co and near-interface Fe gradually lie in the plane. The moment orientation of Co and Fe at the interface is determined by the energy terms of spin–spin coupling, in-plane, and perpendicular anisotropy. With decreasing thickness, the in-plane anisotropy of Co is reduced because surface anisotropy becomes significant in the thin films.[11] Therefore, perpendicular anisotropy of TbFe dominated the orientation of moments at the interface in the bilayer with 15 Å Co, which induced the out-of-plane Co moments through exchange coupling to TbFe. As the Co thickness increased, in-plane anisotropy of Co became dominant, which led to the in-plane alignment of interfacial Fe moments through the exchange coupling. Consequently, the existence of in-plane TbFe moments near the interface was responsible for the in-plane exchange bias in the TbFe/Co bilayers.

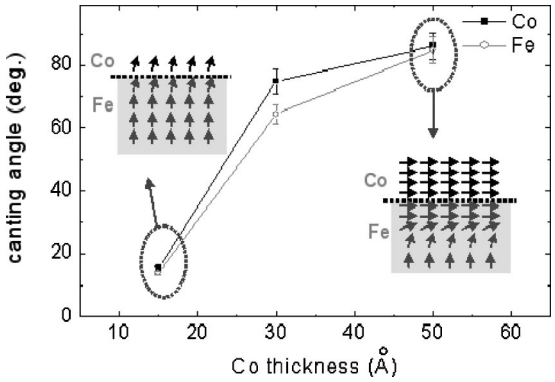

FIG. 5. Variations with Co thickness of canting angles of Co and interfacial Fe from the surface normal.

In conclusion, by utilizing XMCD spectroscopy, we quantitatively determined the orientation of moments in the TbFe/Co exchange-biased bilayers. Through the mechanism of exchange coupling, the perpendicular anisotropy of 15 Å Co was induced by TbFe. With increasing Co thickness, in-plane anisotropy of Co became dominant, resulting in the preferred in-plane moments of Co and TbFe near the interface. The existence of in-plane TbFe moments near the interface led to the in-plane exchange-bias fields.

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