Critical Angle Behavior of Exchange Bias and Coercivity in CoFe/MnIr Bilayers

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Angular dependence of H_{ex} and H_c, and the critical angle behavior are measured in CoFe/MnIr bilayers annealed at 200°C and 340°C. The interfacial exchange coupling anisotropy and the antiferromagnet anisotropy at $t_{AF} < t_{AF}^c$ are estimated from the best fitting of angular dependence of H_{ex} and H_c using Stoner–Wohlfarth (S–W) model. These results confirm existence of interfacial exchange coupling anisotropy between F and AF layers for $t_{AF} < t_{AF}^c$. The measured critical angles for $t_{AF} > t_{AF}^c$ as well as for $t_{AF} < t_{AF}^c$ are well explained using S–W model.

***Index Terms*—Critical AF thickness, critical angle, exchange bias and coercivity, Stoner–Wohlfarth model.**

I. Introduction

EXCHANGE coupling between ferromagnetic (F) and antiferromagnetic (AF) bilayers has attracted a great deal of attention in recent years because of its applications to the magnetic recording head for high areal density and magnetoresistive random access memory. In view of the great technical interest of these materials, efforts are being put simultaneously on a large scale to utilize the effects of exchange bias in real application systems in one hand and also to carry out extensive experimental and theoretical investigations on the other to explain the mechanism of exchange coupling. As a result, a number of unusual properties were reported such as the asymmetry in the magnetization reversal. In exchange coupled F/AF bilayers, the exchange bias field (H_{ex}) appeared only for a thick enough AF layer whose thickness exceeds a critical AF thickness $(t_{AF} > t_{AF}^c)$. Besides, the angular dependence of the exchange bias (H_{ex}) and coercive field (H_c) have been explained using Stoner–Wohlfarth (S–W) model for $t_{AF} > t_{AF}^c$ under the conditions of uniaxial anisotropy and unidirectional exchange coupling [1]–[3]. The critical angle, which is the offset angle of coercivity with respect to field angle, has also been analyzed for $t_{AF} > t_{AF}^c$ [4], [5]. However, it appears a little attention has been paid toward a study of H_{ex} and H_c for the condition of $t_{AF} < t_{AF}^c$.

In this work, we measured the H_{ex} and H_c with field angle in the case of $t_{AF} > t_{AF}^c$ as well as $t_{AF} < t_{AF}^c$. The angular dependence of H_{ex} and H_c, and the critical angle behavior in CoFe/MnIr bilayers were systematically analyzed by using the S–W model.

II. Sample Preparation and Experimental Techniques

The $Co_{70}Fe_{30}(t_F = 100$ nm$)/Mn_{75}Ir_{25}$ (t_{AF} nm) bilayers with $t_{AF} = 0, 2, 4, 10$ and 20 were deposited onto a Ta 5 nm/Cu 10 nm/NiFe 2 nm/Cu 5 nm buffer layer grown on thermally oxidized Si wafer substrates at room temperature by dc magnetron sputtering method. A magnetic field of 30 Oe was applied during the deposition of bilayers. Post deposition annealing was done on the samples at 200°C and 340°C for 1 h under 1 kOe. The structural analysis was performed by x-ray diffraction and grazing incident x-ray diffraction with Cu$K\alpha$ radiation source [6]. The easy axis $(\theta = 0°)$ was defined as direction of the applied field during deposition. Magnetization curves with magnetic field angle from $\theta = 0°$ to 180° were measured using a Magneto-Optic Kerr Effect (MOKE) instrument. The H_{ex} and H_c at each measuring field angle θ are determined as a shift of the center and half width of the magnetization curve, respectively.

III. Results and Discussion

A. AF Thickness Dependence of H_{ex} and H_c

Fig. 1 shows the variations in measured H_{ex} and H_c of CoFe/MnIr bilayers with antiferromagnetic layer thickness for both the annealing temperatures. The H_{ex} becomes nonzero when t_{AF} exceeds about 3 nm and rapidly rises. On the other hand, the H_c shows a peak response at $t_{AF} = 2$ nm. These results indicate that the critical thickness (t_{AF}^c) of MnIr layer to display exchange bias was about 3 nm in these materials, as depicted in Fig. 1(a). The unidirectional exchange coupling constants $(J = M_s t_F H_{ex})$ are estimated from measured H_{ex} values for three samples with different AF thicknesses while considering the $t_F = 100$ nm and its $M_s = 1700$ emu/cm^3. The estimated values of J for $t_{AF} = 4, 10$ and 20 nm thicknesses are 0.34, 0.24, and 0.23 erg/cm^2, respectively, in case of 200°C annealed samples, and 0.46, 0.51, and 0.41 erg/cm^2, respectively, for 340°C annealed samples.

B. Angular Dependence of H_{ex} and H_c in $t_{AF} < t_{AF}^c$

The measured angular dependence of H_{ex} and H_c in F/AF bilayers was used for explaining the magnetization reversal behavior, which has also been analyzed theoretically using S–W

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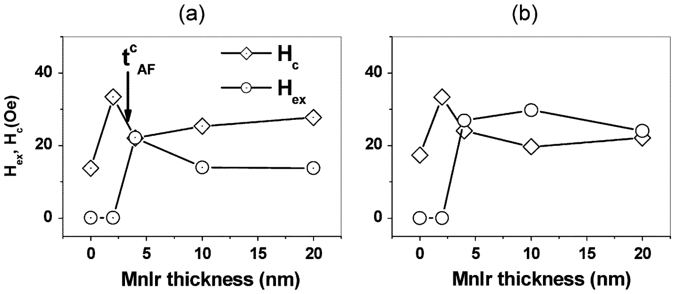

Fig. 1. AF thickness dependence of $H_{\rm ex}$ and H_c in CoFe 100 nm/MnIr ($t_{\rm AF}$ nm) bilayers with $t_{\rm AF} = 0, 2, 4, 10$ and 20 annealed at (a) 200°C and (b) 340°C.

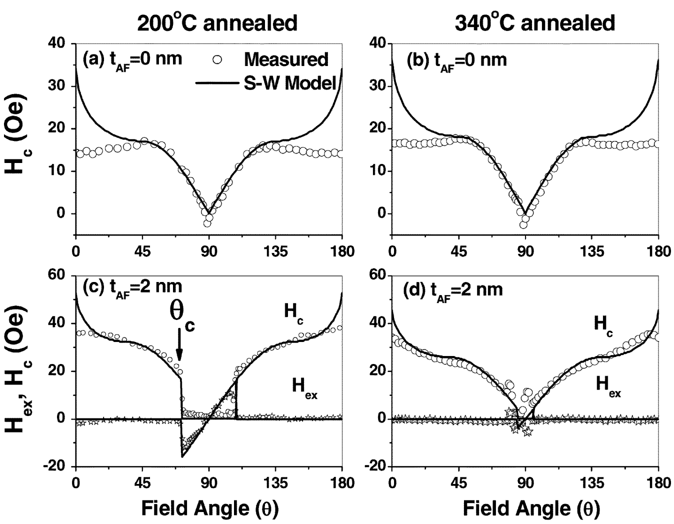

Fig. 2. Angular dependence of $H_{\rm ex}$ and H_c in CoFe 100 nm/MnIr ($t_{\rm AF}$ nm) bilayers with $t_{\rm AF} = 0$ and 2 annealed at (a) and (c) 200°C and (b) and (d) 340°C. The lines are calculated using S–W model.

model [1], [2]. Especially, the asymmetric magnetization reversal in Co/IrMn bilayers was theoretically predicted using S–W model [4]. Therefore, qualitative analysis of $H_{\rm ex}$ and H_c by S–W model provides scope for understanding the magnetization reversal in F/AF bilayers. The total magnetic energy per unit area of exchange biased F and AF layers with thickness t_F and $t_{\rm AF}$, respectively, can be written as follows:

$$E_T = t_F H M_s \cos(\phi_F - \theta) + t_F K_F \sin^2\phi_F + t_{\rm AF} K_{\rm AF} \sin^2\phi + J\cos(\phi_F - \phi_{\rm AF}) \quad (1)$$

where K_F and $K_{\rm AF}$ are the uniaxial anisotropy constants for the F and AF layers, J is the unidirectional exchange coupling energy, θ is the magnetic field angle from easy axis, and ϕ_F and $\phi_{\rm AF}$ are the orientation angles of F magnetization and AF spins, respectively. The angular dependence of $H_{\rm ex}$ and H_c are calculated from the minimum condition of the total magnetic energy in (1).

Fig. 2 shows the measured and calculated angular dependence of $H_{\rm ex}$ and/or H_c in CoFe/MnIr bilayers for $t_{\rm AF} = 0$ and 2 nm ($t_{\rm AF} < t^c_{\rm AF}$) samples annealed at 200°C and 340°C, respectively. In Fig. 2(a) and (b), the significant deviation between measured and calculated H_c near the easy axis ($\theta = 0°$) may be due to domain nucleation and annihilations processes. However, in the field angles between $45° < \theta < 135°$, the measured and calculated H_c values agreed very well. This agreement could be due to the dominant magnetization rotation behavior, which is related to the anisotropy energy; thus facilitates to obtain $t_F\ K_F$ value of the ferromagnetic CoFe layer from the best fitting the angular dependence of H_c in the angle range of $45° < \theta < 135°$. The estimated uniaxial anisotropy constants of $t_F\ K_F$ for the $Co_{70}Fe_{30}$ layer, having $t_F = 100$ nm and $M_s = 1700$ emu/cm^3, are 0.29 and 0.31 erg/cm^2 at 200°C and 340°C annealed samples, respectively. These $t_{\rm F}K_{\rm F}$ values are used for the calculation of angular dependence of $H_{\rm ex}$ and H_c in CoFe/MnIr bilayers.

Fig. 2(c) and (d) show the angular dependence of $H_{\rm ex}$ and H_c for $t_{\rm AF} = 2$ nm ($t_{\rm AF} < t^c_{\rm AF}$) samples annealed at 200°C and 340°C, respectively. The $H_{\rm ex}$ values at easy axis ($\theta = 0°$) show 0 Oe. However, as the field angle increases a negative $H_{\rm ex}$ appears at a certain angle and correspondingly the H_c abruptly approaches to zero at this angle, as shown in Fig. 2(c) and (d). Most of the experimental results, reported in the literature, regarding the angular dependence of $H_{\rm ex}$ and H_c in exchange biased F/AF bilayers have been focused on $t_{\rm AF} > t^c_{\rm AF}$ samples. In the present work, our results show a first clear observation of the angular dependence of $H_{\rm ex}$ and H_c on $t_{\rm AF} < t^c_{\rm AF}$ samples. We define the critical angle (θ_c) at the kinks observed in $H_{\rm ex}$ and at the abrupt decrease in H_c, as shown in Fig. 2(c). At the critical angle, there observed a transition in the magnetization reversal process from reversible to irreversible behavior [4].

The angle of the ferromagnetic magnetization depends on the direction of the external field due to the Zeeman-term in (1). Due to the coupling between ferromagnetic and antiferromagnetic layers, the direction of the antiferromagnetic magnetization also depends on the external field. Thus, both the anisotropy energy $t_{\rm AF}K_{\rm AF}\sin^2(\phi_{\rm AF})$ of the AF layer and the coupling energy $J\cos(\phi_{\rm F} - \phi_{\rm AF})$ between F/AF bilayers depend on the direction of external field, such that the ratio of these two terms is sometimes smaller than zero (in which case, both layers rotate simultaneously) and sometimes larger than zero (in which case, exchange bias can be observed).

Therefore, the interfacial exchange coupling energy (J) and the anisotropy energy of the AF layer ($t_{\rm AF}K_{\rm AF}$) can also be predicted from the best fitting of angular dependence of $H_{\rm ex}$ and H_c for $t_{\rm AF} < t^c_{\rm AF}$. The estimated values of J and $t_{\rm AF}K_{\rm AF}$ for this condition are 0.51 and 0.39 erg/cm^2, respectively, for 200°C-annealed samples, and 0.35 and 0.20 erg/cm^2, respectively, for 340°C-annealed samples. It may be a noteworthy as the annealing temperature increases, the values of J and $t_{\rm AF}K_{\rm AF}$ for $t_{\rm AF} < t^c_{\rm AF}$ decrease, which could be due to inter-diffusion of Mn atoms during annealing at elevated temperature.

Generally, the unidirectional anisotropy J has been calculated from the measured $H_{\rm ex}$ in the case of $t_{\rm AF} > t^c_{\rm AF}$. However, in the case of $t_{\rm AF} < t^c_{\rm AF}$, the J could not be estimated because of $H_{\rm ex} = 0$, as shown in Fig. 1. In this work, we estimated the J value and $t_{\rm AF}K_{\rm AF}$ at $t_{\rm AF} < t^c_{\rm AF}$ through the best curve fitting of angular dependence of the $H_{\rm ex}$ and H_c.

C. Angular Dependence of $H_{\rm ex}$ and H_c in $t_{\rm AF} > t^c_{\rm AF}$

Fig. 3 shows the measured and calculated angular dependence of $H_{\rm ex}$ and H_c in CoFe/MnIr (10 nm) bilayers annealed at 200°C and 340°C, respectively. In these samples, the $H_{\rm ex}$ and H_c with angle shows normal behavior, except the abrupt change of $H_{\rm ex}$ and H_c at critical angle (θ_c), as shown in Fig. 3(a). The

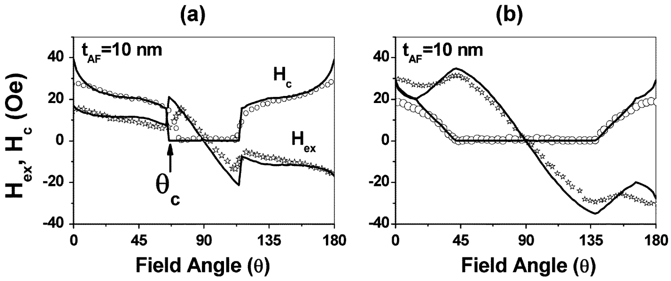

Fig. 3. Angular dependence of $H_{\rm ex}$ and H_c in CoFe 100 nm/MnIr 10 nm bilayers annealed at (a) 200°C and (b) 340°C. The lines are calculated using the S–W model.

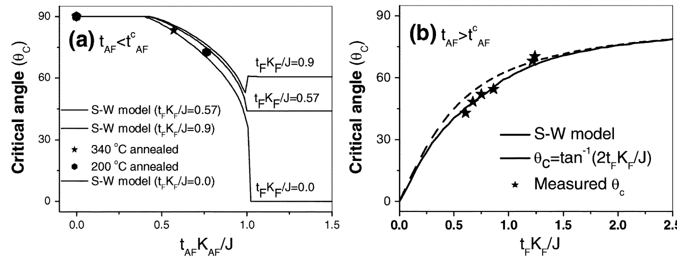

Fig. 4. The critical angle with (a) $t_F K_F/J$ at $t_{\rm AF}K_{\rm AF} > J$ and (b) $t_{\rm AF}K_{\rm AF}/J$ at $t_{\rm AF}K_{\rm AF} < J$. The star marks are measured one and the solid lines are calculated one using the S–W model. The dashed line in (b) is calculated by (2).

kinks in $H_{\rm ex}$ and abrupt decrease in H_c at θ_c are dominantly appeared on the conditions of $H_c > H_{\rm ex}$, which is explained by using the S–W model. Xi *et al.* [1] were able to well fit and explained the angular dependence of $H_{\rm ex}$ and H_c of exchange coupled NiFe/CrMnPt bilayers. However, they could not expect the abrupt change of $H_{\rm ex}$ and H_c by using the S–W model in spite of the conditions of $H_c > H_{\rm ex}$.

D. Critical Angle Behaviors

The critical angle (θ_c) is one of the transition phenomena between reversible and irreversible magnetization reversal where the coercive field vanishes. Recently, the critical angle was measured at only $t_{\rm AF} > t^c_{\rm AF}$ samples and analyzed using the geometrical asteroid method such as [4], [5]

$$\theta_c = \tan^{-1}\left(\frac{2t_F K_F}{J}\right). \qquad (2)$$

The critical angle at $t_{\rm AF} > t^c_{\rm AF}$ is only dependent on the $t_F K_F$ and J. In this work, we measured the critical angles (θ_c) from the angular dependence of $H_{\rm ex}$ and H_c. Also, the θ_c are calculated by using the S–W model. The measured θ_c are separately compared with calculated one as a function of $t_{\rm AF}K_{\rm AF}/J$ and $t_F K_F/J$ for each case of $t_{\rm AF} < t^c_{\rm AF}$ and $t_{\rm AF} > t^c_{\rm AF}$, respectively. This was because the critical angle depends on $t_{\rm AF}K_{\rm AF}/J$ as well as $t_F K_F/J$ in the case of $t_{\rm AF} < t^c_{\rm AF}$, whereas it only depends on $t_F K_F/J$ for the case of $t_{\rm AF} > t^c_{\rm AF}$. The critical angle is found to decrease with $t_{\rm AF}K_{\rm AF}/J$ at $t_{\rm AF} < t^c_{\rm AF}$, while it increases with $t_F K_F/J$ at $t_{\rm AF} > t^c_{\rm AF}$.

Fig. 4(a) shows the measured critical angles at $t_{\rm AF} < t^c_{\rm AF}$, which are compared with the calculated ones under the conditions of $t_F K_F/J = 0.57$ and 0.9 for comparison between 200°C and 340°C annealed samples. The calculated critical angle at $t_{\rm AF} < t^c_{\rm AF}$ under the condition of $t_F K_F/J = 0.0$ however shows the low limit values. The values of $t_F K_F/J$ are obtained from $t_F K_F$ and J values, which are estimated from the best fitting of angular dependence of $H_{\rm ex}$ and H_c in Fig. 2. The critical angle in the samples of $t_{\rm AF} < t^c_{\rm AF}$ can be predicted by using the S–W model. Fig. 4(b) shows the measured and calculated critical angles with $t_F K_F/J$ at $t_{\rm AF} > t^c_{\rm AF}$. The measured critical angles at $t_{\rm AF} > t^c_{\rm AF}$ showed excellent agreement with calculated ones by using S–W model the (2). The reversible magnetization behavior is generally well explained by the coherent rotation model. Therefore, the critical angle behavior, which is the transition angle from reversible to irreversible magnetization reversal, can also be well predicted by the S–W model.

In summary, we have investigated the angular dependence of $H_{\rm ex}$ and H_c, and the critical angle behavior in CoFe100 nm/MnIr ($t_{\rm AF}$ nm) bilayers with $t_{\rm AF} = 0, 2, 4, 10$ and 20 annealed at 200°C and 340°C. The measured $H_{\rm ex}$ and H_c with angle are compared with calculated ones. The interfacial exchange coupling energy and the antiferromagnet anisotropy at $t_{\rm AF} < t^c_{\rm AF}$ are estimated from the best fitting of angular dependence of $H_{\rm ex}$ and H_c. These results confirm the existence of interfacial exchange coupling anisotropy between F and AF layer at $t_{\rm AF} < t^c_{\rm AF}$. The measured critical angles both for $t_{\rm AF} > t^c_{\rm AF}$ and $t_{\rm AF} < t^c_{\rm AF}$ are well explained by using the S–W model.

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