Angular Dependence of Exchange Bias and Coercive Field in CoFe/MnIr Epitaxial Bilayers

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We have measured the hysteresis loop and torque curves at various applied magnetic field angle in CoFe/MnIr epitaxial bilayers on single crystal MgO (001), (111), and (011) samples. The (001) samples show double shifted magnetization curves, which are dominant as the MnIr thickness increases. It suggests that the unidirectional anisotropy and cubic anisotropy of CoFe (001) layer plays a key role in the formation of double shifted magnetization reversal. The angular variation of exchange bias (Hex) and coercive field (Hc) depend on the orientation of MgO substrates. The measured results are compared with calculated data, which are fitted using the crystalline anisotropy, unidirectional and uniaxial anisotropy induced by the field annealing. The calculated Hex and Hc as a function of measuring angles show similar trend as the measured ones. Theses energy contributions play an essential role in the angle dependent magnetization process in epitaxial CoFe/MnIr bilayers.

Index Terms—**Crystalline anisotropy, domain pattern, epitaxial bilayer, exchange bias and coercive field.**

I. INTRODUCTION

EXCHANGE coupling in ferromagnetic/antiferromagnetic (F/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. Despite extensive experimental and theoretical study, the nature of the exchange coupling such as the exchange bias field and enhanced Hc in F/AF bilayers is not well understood. Recently, the angular dependence of the exchange bias Hex and coercive field Hc has been explained using a simple Stoner–Wohlfarth (S–W) model under the condition of uniaxial anisotropy and unidirectional exchange coupling [1], [2]. The complex angular dependence of the Hex and Hc in the NiFe/CoO bilayer film had been explained by the higher order terms in the Fourier expansions [3], however, the origin of the higher order energy corresponding to the higher order Fourier terms is not clear.

In the present paper, we have investigated the angular dependence of the Hex and Hc in the CoFe/MnIr epitaxial bilayers on single crystal MgO (001), (111), and (011) samples. The Hex and Hc behavior as a function of field angle has been analyzed in terms of the unidirectional, uniaxial, and crystalline anisotropies of CoFe/MnIr bilayers.

II. SAMPLE PREPARATION AND EXPERIMENTAL TECHNIQUES

The $Co_{70}Fe_{30}/Mn_{75}Ir_{25}$ bilayers were deposited onto a 20-nm Cu buffer layer epitaxially grown on single crystal MgO (110), (111), and (001) substrates at room temperature by dc magnetron sputtering method [4]. The MnIr thickness was varied from 0 to 20 nm and CoFe thickness was 100 nm. A magnetic field of 30 Oe was applied during the deposition of bilayers, parallel to the film plane along MgO [1–10] for (110) and (111) substrates and along MgO [100] for (001) substrates, respectively. The easy axis ($\theta = 0°$) were defined as direction of the applied field during deposition. The Mn-Ir/Co-Fe bilayers were annealed at 200 °C for 1 h in a magnetic field of 1 kOe in vacuum less than 5×10^{-6} Torr along the same direction of the applied field during the deposition. Magnetization curves with magnetic field angle from $\theta = 0°$ to $\theta = 180°$ were measured with a vibrating sample magnetometer and magnetooptic Kerr effect (MOKE) instrument. The Hex and Hc at each measuring field angle θ are determined as a shift of the center and half width of the magnetization curve along the field axis, respectively. The domain patterns of the F layer were observed using MOKE microscope on the longitudinal Kerr effect. The magnetic torque curves were measured with a null method torque magnetometer. All measurements were performed at room temperature.

III. RESULTS AND DISCUSSIONS

A. Magnetization Reversal and Torque Curves Dependence on Crystalline Orientations

The hysteresis loops and torque curves of the epitaxial CoFe (100 nm)/MnIr (20 nm) deposited on single crystal MgO (001), (111), and (011) are shown in Fig. 1(a) and (b), respectively. The entire hysteresis loop measured along $\theta = 0°$ shows a square shape and exhibits the Hex. In Fig. 1(a), the (001) sample shows a double shifted hysteresis loop measured at hard axis. Recent study indicates that the double shifted hysteresis loop in NiFe/NiO exchange bilayers is caused by cubic anisotropy induced by the F-AF interface coupling and magnetization reverses by incoherent rotation for the field applied along the hard axis and through the nucleation and growth of domain walls for fields applied along the easy axis [5], [6].

Digital Object Identifier 10.1109/TMAG.2005.854762

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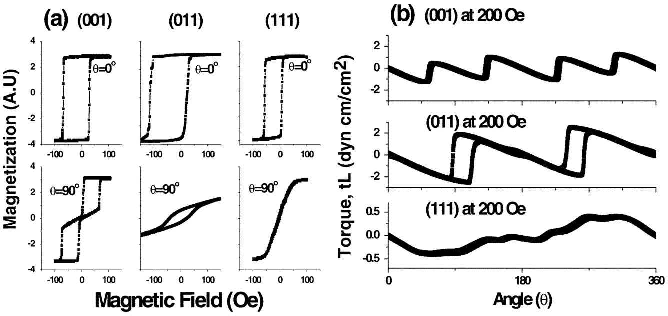

Fig. 1. (a) Hysteresis loops at $\theta = 0^\circ$ (easy axis) and $\theta = 90^\circ$ (hard axis) and (b) torque curves at 200 Oe of CoFe (100 nm)/MnIr (20 nm) epitaxial bilayers in the (001), (111), and (011) samples.

For (011) and (001) samples, the torque curves clearly shows the two- and four-fold symmetry, respectively. In the case of the (111), six-fold symmetry is negligibly small. These torque responses correspond well with the respective crystallographic symmetries. The dominant four-fold symmetry in the (001) sample confirms the extent of the cubic crystalline anisotropy. The magnetization reversals and magnetic anisotropies depend on the MgO crystallographic orientation.

Table I summarizes the magnetic parameters of Hex and Hc at $\theta = 0^\circ$ and anisotropy constants obtained from Fig. 1(a) and (b). The Hex is propositional to the unidirectional anisotropy constant K^θ such as $Hex = K^\theta/tM_s$, where M_s is the saturation magnetization of CoFe. The K^θ of the (011) sample shows extra large value of 0.75 erg/cm^2, which is nearly three times higher than that of the (001) sample. The Hc is dominantly affected by uniaxial and cubic crystalline anisotropy of the CoFe epitaxial layers.

B. Hysteresis Loop and Domain Patterns for Double-Shifted Magnetization Process

The hysteresis loops for various MnIr thicknesses in the (001) sample at $\theta = 90^\circ$ are shown in Fig. 2. The single (001) CoFe layer (x = 0 nm) shows the square hysteresis loop at $\theta = 90^\circ$, however, the double shifted magnetization change is more and more dominant as the MnIr thickness increases. The unidirectional anisotropy constant also increases with AF thickness [4]. These results indicate that the change of first and second shifted field, [$\mathrm{H_{s1}}$ and $\mathrm{H_{s2}}$ indicated in Fig. 2(b)] in the double shifted loop is due to the increase of the induced unidirectional anisotropy in the (001) sample having the cubic crystalline anisotropy.

We are focused on the domain pattern in the (001) sample in order to obtain better information for the double-shifted magnetization process. Each domain pattern of the (001) sample at $\theta = 90^\circ$ is corresponding to each stage of the magnetization process indicated in Fig. 2(c). The magnetization direction indicated by arrow on each domain is confirmed by the degree of contrast change and the magnetization value. At stage 2 and 4, the domain pattern shows the 45° and 135° inclined strip domains with 90° domain wall. However, the hard axis domains show reversed direction of 0° (black arrow) and 180° (white arrow) at stage 2 and 4, respectively. At stage 3, the magnetic moment is nearly zero in hysteresis loop and there is no domain pattern, like a single domain. The overall domain pattern change during double shifted magnetization process shows that magnetization reversal has occurred discontinuously from 0° to 90° (stage 2) and 90° to 180° to (stage 4). It is maintaining the continual stable state at 90° (stage 3) during intermediate field range between stage 2 to stage 3.

TABLE I
EXCHANGE COUPLING PARAMETERS AND MAGNETIC ANISOTROPY ENERGIES

MgO plane	Hex (Oe) at 0°	Hc (Oe) at 0°	K^θ (erg/cm^2)	$tK^{2\theta}$ (erg/cm^2)	$tK^{4\theta}$ (erg/cm^2)
(001)	18.6	44.4	0.27	0.41	0.64
(011)	46.4	69.1	0.75	1.26	0.42
(111)	23.3	33.1	0.34	0.10	0.02

The K^θ, $tK^{2\theta}$ and $tK^{2\theta}$ are corresponding to the single-, two- and four-fold anisotropy energies per unit area in Fig.1 (b), respectively.

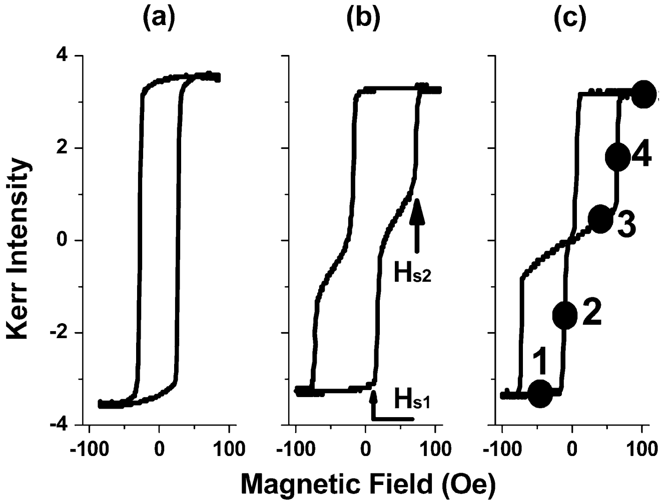

Fig. 2. Hysteresis loop of CoFe (100 nm)/MnIr (x nm) at $\theta = 90^\circ$ in the (001) sample with (a) x = 0 nm, (b) x = 2 nm, and (c) x = 20 nm.

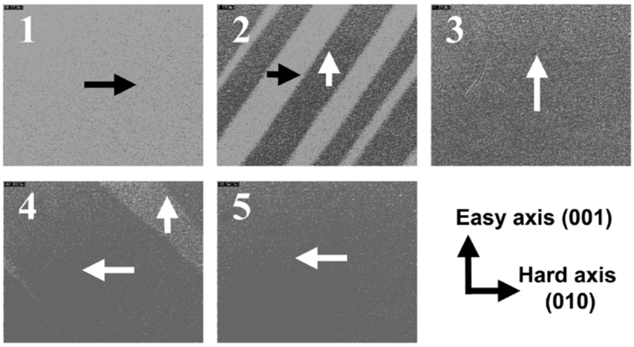

Fig. 3. Domain patterns of the CoFe (100 nm)/MnIr (20 nm) in the (001) sample at $\theta = 90^\circ$. The arrows indicate the magnetization directions of each domain.

C. Angular Dependence of Hex and Hc

Fig. 4 shows the angular dependence of the Hex and Hc for (001), (011), and (111) samples, respectively. The angular variation of the Hex and Hc shows the symmetry about the axis at 90°. In the (001) sample, the Hc and Hex changes through three steps, in which the abrupt change occurred at about $\theta = 45^\circ$ and $\theta = 75^\circ$. Before $\theta = 45^\circ$ range, the uniaxial anisotropy is

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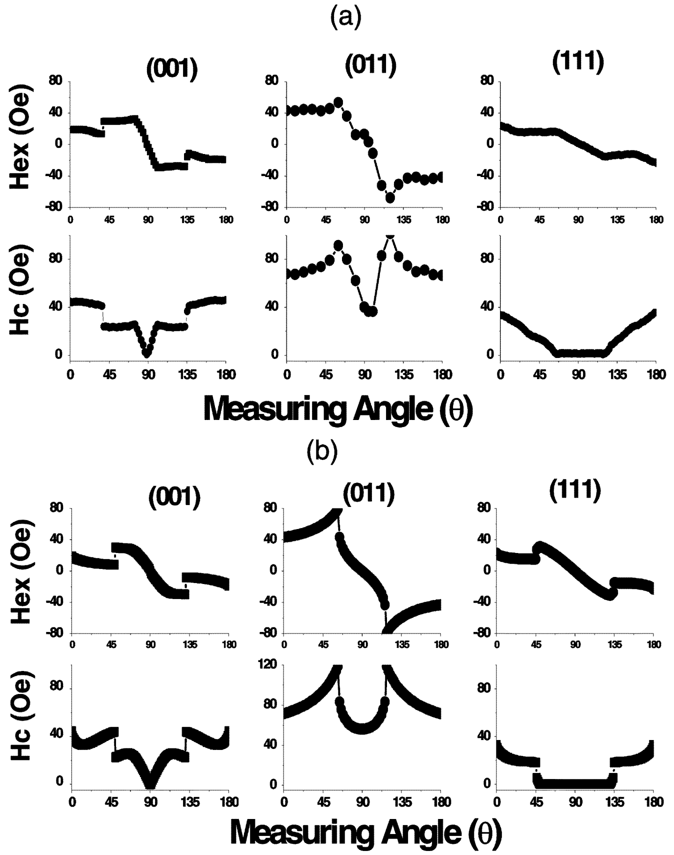

Fig. 4. (a) Measured and (b) calculated angular dependence of Hex and Hc in CoFe (100 nm)/MnIr (20 nm) on single crystal MgO (001), (111), and (011).

dominant and the Hc and Hex slightly changed. At $\theta = 45^\circ$ the cubic crystalline anisotropy is comparable with the uniaxial anisotropy, thus the hysteresis loop drastically change from the normal magnetization process to the asymmetric double shifted one. From $\theta = 75^\circ$ to 90, the asymmetric double shifted loop move to symmetric one as shown in Fig. 1. The largest Hc and Hex were observed at near $\theta = 60^\circ$ in (011) sample. The angular variation of the (111) sample shows similar behavior as in the case of uniaxial polycrystalline F/AF bilayers [1], [2].

The qualitative analyses by using the S–W model provide a preliminary understanding for the magnetization reversal in the F/AF bilayers. The total energy per unit area, tE including the Zeeman energy, unidirectional, K_{ex}, uniaxial, K_u, and crystalline anisotropy, E_C can be expressed as

$$tE_t = -tHM_s\cos(\phi-\theta) - K_{\mathrm{ex}}\cos\phi + tK_u\sin^2\phi + tE_C \quad (1)$$

where t is the thickness of the CoFe layer. The ϕ and θ are the magnetization and measuring field angles from the annealing field direction, respectively. The crystalline anisotropy, K_c for the (001), (111), and (011) samples are modified as in the following equations, which are based on the fitting results:

$$E_C = K_c\sin^2 2\phi \quad \text{for } (001) \quad (2)$$

$$E_C = 0, \quad \text{for } (111) \quad (3)$$

$$E_C = K_c\cos^2\phi(\sin^2\phi - 1/4\cos^2\phi), \quad \text{for } (011). \quad (4)$$

The calculated angular dependences in Fig. 4(b) are fitted using $\mathrm{Hex} = K_{\mathrm{ex}}/M_s t, tK_u/K_{\mathrm{ex}}$, and tK_c/K_{ex} for each samples. The fitting parameters of tK_u/K_{ex} and tK_c/K_{ex} are 1.5 and 3.4 for (001) sample, 0.7 and 0 for (111) sample, and 0 and 2.3 for (011) sample, respectively. The fitting results show reasonable agreement with experimental measurements for the Hex and Hc depending on measuring field angle. In the (111) sample, the 6-fold crystalline anisotropy is negligible and uniaxial anisotropy contribution is dominant. Meanwhile, the cubic crystalline anisotropy is dominant in the (011) sample, however, the angular dependence can be only explained in the case of $45^\circ < \theta < 135^\circ$.

Therefore, the crystalline anisotropy is not simple and these complex anisotropies involved in F/AF bilayers are induced from the interfacial contribution and during field annealing. The induced complex anisotropies in CoFe/MnIr epitaxial bilayers can be estimated through the numerical fittings for the angular dependence of the Hc and Hex based on the measured results. Therefore, the angular dependence of the Hex and Hc is important for understanding of the overall magnetization reversal process.

In summary, we have investigated the hysteresis loop and torque curves in CoFe/MnIr epitaxial bilayers. The double shifted magnetization curves measured at hard axis in the (001) sample are dominant as the MnIr thickness increases. It suggests that the unidirectional anisotropy plays a key role in the formation of double shifted magnetization reversal in the (001) sample having cubic crystalline anisotropy. The angular variation of exchange bias and coercive field depends on the MgO crystallographic orientation as well as the crystalline anisotropy, unidirectional and uniaxial anisotropy induced by the field annealing. These energy contributions play an essential role in the angular dependent magnetization process.

ACKNOWLEDGMENT

This work was supported by the Korea Science and Engineering Foundation through the Research Center for Advanced Magnetic Materials, Chungnam National University.

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Manuscript received January 7, 2005.

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