Orientational dependence of exchange anisotropy of Mn-Ir/Co-Fe epitaxial bilayers

doi: 10.1063/1.1669116

Orientational dependence of exchange anisotropy of Mn-Ir/Co-Fe epitaxial bilayers[a)]

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(Presented on 9 January 2004)

The exchange anisotropy of pseudo-single crystalline Mn-Ir/Co-Fe bilayers with different crystallographic orientations, such as (110), (001), and (111), was investigated. As a result, we found that the unidirectional anisotropy constant J_K strongly depends on the crystallographic orientation, while the critical thickness of the antiferromagnetic layer $d_{\mathrm{AF}}^{\mathrm{cr}}$ is similarly ~3 nm. As a notable result, the J_K of the (110)-epitaxial bilayer with $d_{\mathrm{AF}}=4$ nm shows extra large value of 0.73 erg/cm^2. The magnetic anisotropy of the Mn-Ir layer determined from the saturation torque amplitude was 8.5×10^5 erg/cm^3 for the (110) bilayer, 5.0×10^4 erg/cm^3 for the (001) bilayer, and 10^3-10^4 erg/cm^3 for (111) bilayer, respectively. From the correlation between the exchange anisotropy and the magnetic anisotropy of the Mn-Ir layer, we conclude that the domain wall model is inadequate to explain these experimental results and the single spin model can do it qualitatively, assuming that the interfacial exchange coupling energy differs in the respective crystallographic orientation. [DOI: 10.1063/1.1669116]

I. INTRODUCTION

The exchange anisotropy of ferromagnetic (FM)/antiferromagnetic (AFM) bilayers has been practically used in spin valves (SVs) as a reproducing head element of hard disk drives (HDDs) and in magnetic tunnel junctions as memory cells of magnetic random access memories (MRAMs). With increasing the track density of HDDs, dimensions of SV elements become smaller, ~0.1 μm nowadays, and will be comparable to typical grain diameter of thin films, ~20 nm, in the near future. In such a case, a SV element is composed of a single crystalline and its magnetic/transport properties might be different from those of the present polycrystalline SV elements. One of the issues that should be discussed for the forthcoming single crystalline nanoscaled SVs is the effect of crystallographic orientation on the exchange anisotropy, in order to provide sufficiently large pinning field. However, the orientational dependence of exchange anisotropy has been limitedly reported for the cases of Ni-Fe/$Fe_{50}Mn_{50}$,[1] NiO/Ni-Fe,[2] and Ni-Fe/Mn-Ni (Ref. 3) systems. In the present study, we fabricated epitaxially grown pseudo-single-crystalline Mn-Ir/Co-Fe bilayers on single crystal MgO substrates with respective crystallographic orientation, and compared the exchange anisotropy of the respective bilayers. We then examined the correlation between the exchange anisotropy and the magnetic anisotropy of the Mn-Ir layers determined by the magnetic torque analysis.[4]

II. EXPERIMENTAL PROCEDURE

The $Mn_{75}Ir_{25}/Co_{70}Fe_{30}$ bilayers and $Mn_{75}Ir_{25}$/Ni-Fe bilayers were deposited onto a 20-nm-thick Cu buffer layer eptaxially grown on single crystal MgO substrates with respective crystallographic orientation at room temperature by dc magnetron sputtering method. In order to achieve the epitaxial growth on MgO substrates, the Cu buffer layer was deposited with applying the adequate substrate bias. The Mn-Ir layer thickness d_{AF} was varied from 2 to 20 nm. A magnetic field of 30 Oe was applied during the deposition of bilayers, parallel to the film plane along MgO$[1\bar{1}0]$ for (110) and (111) substrates and along MgO[100] for (001) substrate. The Mn-Ir/Co-Fe bilayers were annealed at 240 °C for 0.5 h in a magnetic field of 1 kOe along the same direction of the applied field during the deposition.

The structural analysis was performed by x-ray diffraction (XRD) and grazing incident x-ray diffraction (GID) with Cu$K\alpha$ radiation source. The magnetization curves were measured with a vibrating sample magnetometer (VSM). The magnetic torque curves were measured with a null method torque magnetometer having a sensitivity of about 1×10^{-3} dyn cm. All measurements were performed at room temperature. The unidirectional anisotropy constant J_K was calculated with the equation $J_K=M_s d_F H_{\mathrm{ex}}$, where $M_s d_F$ is the areal saturation magnetization of the FM layer, and H_{ex} is the exchange biasing field determined as a shift of the center of the magnetization curve along the field axis.

III. RESULT

A. Structural analysis

Figure 1 shows the Mn-Ir{111} pole figures of Mn-Ir/Co-Fe bilayers with respective crystallographic orientation. Hereafter, we call an epitaxial bilayer with (*hkl*) orientation

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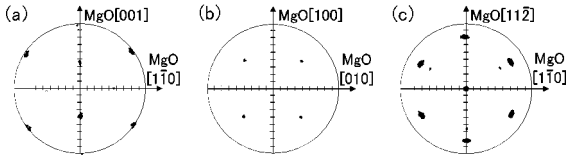

FIG. 1. Mn-Ir{111} pole figure of Mn-Ir 10 nm/Co-Fe 4 nm bilayers fabricated on single crystal substrates of (a) MgO (110), (b) MgO (001), and (c) MgO (111).

as a (*hkl*) bilayer. In Figs. 1(a) and 1(b), the epitaxial feature of Mn-Ir layer is confirmed by the two- and fourfold symmetry for the (110) and (001) bilayer, respectively. The sixfold symmetry observed for the (111) bilayer, as shown in Fig. 1(c), indicates twinning of the crystals. The obtained epitaxial relationships are stated as MgO(110)//Cu(110)//Mn-Ir(110) and MgO[001]//Cu[001]//Mn-Ir[001] for the (110) bilayer, MgO(001)//Cu(001)//Mn-Ir(001) and MgO[100]//Cu[100]//Mn-Ir[100] for the (001) bilayer, and MgO(111)//Cu(111)//Mn-Ir(111) and MgO[$1\bar{1}0$]//Cu[$1\bar{1}0$]//Mn-Ir[$1\bar{1}0$] for the (111) bilayer. The epitaxial relationship of the Mn-Ir layers in the respective orientation is schematically summarized in Fig. 2. The crystallographic structure of Mn-Ir was separately determined by x-ray diffraction (XRD) and grazing incidence x-ray diffraction (GID) as fct ($c/a = 0.99$) for the (110) bilayer, fct ($c/a = 1.01$) for the (001) bilayer, and fcc for the (111) bilayer.

The vertical grain diameter of Mn-Ir, evaluated from XRD profile with Scherrer's formula, corresponds to the designed Mn-Ir layer thickness for the respective bilayer. The lateral grain diameter of Mn-Ir, determined with atomic force microscopy, is sufficiently large (>20 nm) because of the epitaxial growth on the thick Cu under layer and is comparable with each other for the respective bilayer. It means that we need not consider the thermal effect[5] on magnetic properties of bilayers in following sections. The interfacial roughness R_a of the respective bilayer, determined with atomic force microscopy, is dispersed in the range of 0.25–0.35 nm for the (110) bilayer, 0.1–0.2 nm for the (001) bilayer, and 0.3–0.5 nm for the (111) bilayer. These R_a values are mainly dominated by the surface roughness of MgO substrate, and do not show a clear relation with the exchange anisotropy within the same crystallographic orientation. Therefore, we can also neglect the effect of the interfacial roughness in the following sections.

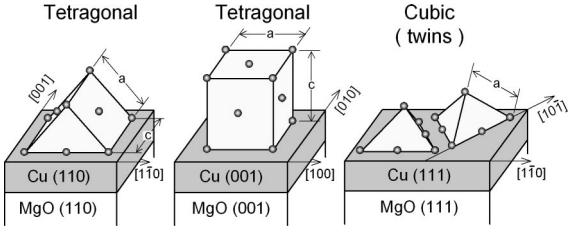

FIG. 2. Schematic model of the epitaxial relationship of Mn-Ir/Co-Fe bilayers fabricated on MgO single crystal substrate with various orientations.

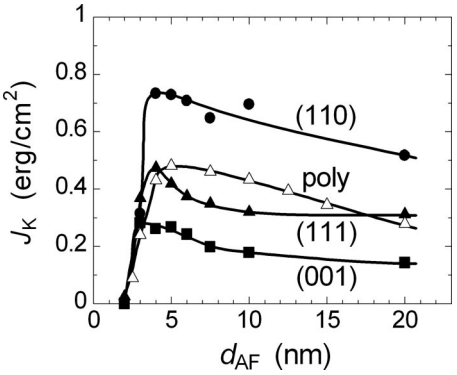

FIG. 3. Changes of the unidirectional anisotropy constant J_K of the (110)-, (001)-, (111)-epitaxial Mn-Ir d_{AF}/Co-Fe 4 nm bilayers and polycrystalline Mn-Ir d_{AF}/Co-Fe 4 nm bilayers with (111) preferred orientation as a function of Mn-Ir thickness d_{AF}.

B. Exchange anisotropy

Figure 3 shows the d_{AF} dependencies of unidirectional anisotropy constant J_K of epitaxial bilayers with respective crystallographic orientation. For comparison, the case of polycrystalline bilayers with (111) preferred orientation, annealed at 250 °C for 0.5 h, is also shown. While the critical thickness of the AF layer d_{AF}^{cr}, beyond which the exchange anisotropy is induced, is similarly ~3 nm for the respective bilayer, the J_K strongly depends on the crystallographic orientation. The J_K of the (110) bilayer shows extra large value of 0.73 erg/cm^2 at $d_{AF}=4$ nm, which is nearly three times of that of the (001) bilayer. The J_K of the (111) bilayers showed a similar value to that of the polycrystalline bilayers. From the application point of view, (110) orientation is most favorable for nanoscaled SVs to induce large exchange anisotropy.

C. Magnetic anisotropy of antiferromagnetic layer

The magnetic anisotropy of Mn-Ir layers were evaluated with magnetic torquemetry of the bilayers whose AFM layer is thinner than the critical thickness. According to the single spin model (SSM), established by Meiklejohn and Bean,[6] the saturation amplitude of torque curve $(tL)_{sat}$ corresponds to $nK_{AF}^{n\theta}d_{AF}$, where n is the number of symmetry and $K_{AF}^{n\theta}$ is the magnetic anisotropy of AFM layers with n-fold symmetry.[4] Figure 4 shows saturated magnetic torque curves under high magnetic field (>400 Oe) for Mn-Ir/Ni-Fe bilayers with respective crystallographic orientation. The d_{AF} is less than the critical thickness of 3 nm: 2 nm for the (110) bilayer and 1.5 nm for (001) and (111) bilayers. The applied field angle θ was measured from the applied field direction during the film deposition.

For (110) and (001) bilayers the torque curve clearly shows the two- and fourfold symmetry, respectively. In the case of the (111) bilayer, although the amplitude is not so large, the sixfold symmetry can be recognized. These torque responses correspond well with the respective crystallographic symmetries. We otherwise confirmed that the specimens without a Mn-Ir layer, namely MgO/Cu/Ni-Fe/Cu, show sufficiently low magnetic torque responses. It means that the magnetic torque curves shown in Fig. 4 originate in the magnetocrystalline anisotropy of Mn-Ir. Table I summa-

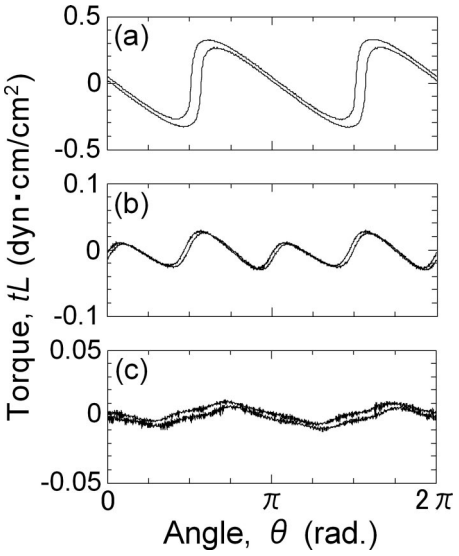

FIG. 4. Measured magnetic torque curves under high magnetic field for (a) (110)-, (b) (001)-, and (c) (111)-epitaxial Mn-Ir/Ni-Fe bilayer whose antiferromagnetic layer is thinner than the critical thickness.

rizes the $K_{\mathrm{AF}}^{n\theta}$ value, calculated with the formula $(tL)_{\mathrm{sat}} = nK_{\mathrm{AF}}^{n\theta} d_{\mathrm{AF}}$. We should notice here that the present evaluation method is based on the assumption of the SSM: the moments in the antiferromagnet are locked together under the magnetization process of the exchange-coupled bilayers. If the domain wall model,[7] which assumes the presence of a relative rotation of the AFM moments, is more appropriate than the SSM for exchange bias phenomena, the obtained $K_{\mathrm{AF}}^{n\theta}$ values do not exactly correspond with the magnetic anisotropy energy of the antiferromagnet. However, even in the case of the domain wall model, the experimentally obtained $K_{\mathrm{AF}}^{n\theta}$ values in the present study provide the *effective* magnetic anisotropy energy of the antiferromagnet, which determines the magnetization process of the FM/AFM bilayers.

IV. DISCUSSION

In this section we will discuss the physical reason for the difference of the exchange anisotropy of Mn-Ir/Co-Fe bilayers with respective orientation.

According to the domain wall model proposed by Mauri,[9] the following relations are deduced:

$$J_K = 2\sqrt{AK_{\mathrm{AF}}} \quad \text{and} \quad d_{\mathrm{AF}}^{\mathrm{cr}} \propto \sqrt{A/K_{\mathrm{AF}}},$$

where A is the stiffness constant of AFM. It is clear that the domain wall model is inadequate to elucidate the experimental results. Namely, the relation of J_K for respective crystallographic orientations $[(110)>(111)>(001)]$ does not correspond to that of K_{AF} $[(110)>(001)>(111)]$. In addition, $d_{\mathrm{AF}}^{\mathrm{cr}}$ is almost constant 3 nm, while K_{AF} changes against the crystallographic orientation.

On the other hand, the SSM gives the relation

$$J_K \sim J \quad \text{and} \quad d_{\mathrm{AF}}^{\mathrm{cr}} = J/nK_{\mathrm{AF}}^{n\theta},$$

TABLE I. Magnetic anisotropy of energy of $Mn_{72}Ir_{25}$ film, determined from magnetic torque analysis of exchange coupled Mn-Ir/Ni-Fe bilayers.

	Crystal plane	Symmetry	Anisotropy energy
K_{AF}^{20}	(110)	two-fold	8.5×10^5 erg/cm^3
K_{AF}^{40}	(001)	four-fold	5.0×10^4 erg/cm^3
K_{AF}^{60}	(111)	six-fold	$10^3\sim10^4$ erg/cm^3

where J is the exchange coupling energy at the FM/AFM interface. The experimental results can be qualitatively explained by this model, assuming that J for the respective bilayer with different crystallographic orientations is not the same. However, the SSM has another problem: J calculated from $K_{\mathrm{AF}}^{n\theta}$ and $d_{\mathrm{AF}}^{\mathrm{cr}}$ with the equation $J = nK_{\mathrm{AF}}^{n\theta} d_{\mathrm{AF}}^{\mathrm{cr}}$ does not correspond to J_K obtained by the measurements. The calculated J values, 0.5 erg/cm^2 for (110), 0.06 erg/cm^2 for (001), and $0.002\sim0.02$ erg/cm^2 for (111), differ from the maximum J_K values obtained in Fig. 3. Further investigation is needed to answer this problem.

V. SUMMARY

The exchange anisotropy of the pseudo-single-crystalline $Mn_{75}Ir_{25}$ d_{AF} $(=2-20$ nm$)/Co_{70}Fe_{30}$ 4 nm bilayers with respective crystallographic orientations [(110), (001), and (111)] was investigated. The critical thickness $d_{\mathrm{AF}}^{\mathrm{cr}}$ is similarly ~3 nm regardless of the crystallographic orientation. On the other hand, the unidirectional anisotropy constant J_K strongly depends on the crystallographic orientation. As a notable result, the J_K of the (110) epitaxial bilayer with $d_{\mathrm{AF}}=4$ nm shows an extra large value of 0.73 erg/cm^2 and is three times larger than that of the (001) bilayer. The anisotropy energy of the Mn-Ir layer was also determined from the saturation amplitude of the magnetic torque curve of bilayers with $d_{\mathrm{AF}} < d_{\mathrm{AF}}^{\mathrm{cr}}$. The K_{AF} value is 8.5×10^5 erg/cm^3 for the (110) bilayer, 5.0×10^4 erg/cm^3 for the (001) bilayer, and 10^3-10^4 erg/cm^3 for the (111) bilayer, respectively. We conclude that the domain wall model is inadequate to explain the experimental results and the single spin model can do it qualitatively, assuming that the interfacial exchange coupling energy differs in the respective crystallographic orientations.

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