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Cone magnetization state and exchange bias in IrMn/Cu/$[\mathrm{Co/Pt}]_3$ multilayers

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The effects of a Cu interlayer on the perpendicular exchange bias in IrMn/Cu/$[\mathrm{Co/Pt}]_3$ multilayers were investigated by focusing on the correlation between the exchange bias and the magnetic anisotropy. The in-plane magnetization hysteresis loops were interpreted in the framework of a phenomenological model based on the coherent magnetization rotation, indicating that the easy magnetization axis makes an angle of approximately 15° with the normal of the IrMn/$[\mathrm{Co/Pt}]_3$ film. This angle decreases with the introduction of the Cu spacer thickness in the IrMn/Cu/$[\mathrm{Co/Pt}]_3$ system, indicating that the Cu interlayer leads to a predominant perpendicular anisotropy. Although a maximum of the out-of-plane anisotropy is found for Cu layer thickness between 4 and 5 Å, the maximum of the perpendicular exchange bias was found at 3 Å of Cu, which could be attributed to the interplay between two effects, mainly the increase in the effective perpendicular anisotropy with the Cu spacer thickness due to the reorientation of the Co moment toward the normal to the film's plane direction, and the exponential decrease in the ferromagnet/antiferromagnet exchange coupling (and, consequently, of the exchange bias shift field) with the Cu interlayer thickness. © *2009 American Institute of Physics*. [doi:10.1063/1.3270422]

I. INTRODUCTION

Multilayers of Co and Pt (or Pd) have been studies in the past 2 decades due to their perpendicular magnetic anisotropy and potential application in magnetic sensors and read heads.[1,2] The study of the perpendicular exchange bias is more recent and may contribute to a better understanding of the exchange bias phenomenon as well as might also lead to practical applications.[3] For instance, the uniaxial anisotropy of the ferromagnetic (FM) part of a Co/Pt film can be tuned by varying the number of multilayer repetitions[4,5] or the thickness of the Pt (Refs. 6 and 7) or Co layers.[8] Moreover, the coercivity strongly depends on the Pt layer thickness since the coupling between Co layers across Pt could be indirectly associated with the interface anisotropy.[6,7,9] The coercivity can also be greatly lowered if the multilayer is grown onto an ultrathin NiO underlayer.[10]

It has been demonstrated that when the shape and the surface anisotropies are almost compensating each other higher order anisotropy terms become important for the magnetization orientation.[11–14] Stamps *et al.*,[11] using high external field in order to prevent any domain structure, found canting (called cone state) in a certain low-temperature range in Co/Pt multilayers. Recently, it has been shown[14,15] that the reorientation of magnetization from perpendicular to in-plane one occurs via state of canted magnetization.

The influence of the insertion of a thin Pt layer between an antiferromagnet (AF) and the Co/Pt multilayer has been investigated as well.[4,16–19] All these studies show that this insertion leads to the reorientation of the Co moments from a tilted position toward the film's normal. Due to the more perpendicular alignment of these moments and the characteristics of a short range of the AF-FM interaction, a maximum of the perpendicular exchange bias has been found at 3 Å of Pt for IrMn/Pt/$[\mathrm{Co/Pt}]_3$.[17,18]

Most of these studies deal with structures of the $[\mathrm{Pt/Co}]_n$/AF type, where n denote the number of the repetition, referred to as top AF systems. The present work demonstrates that canted anisotropy can be induced at the bottom AF films, i.e., IrMn/$[\mathrm{Co/Pt}]_n$ and IrMn/Cu/$[\mathrm{Co/Pt}]_n$, also showing perpendicular exchange bias with amplitude depending on the Cu layer thickness. Phenomenologically, the canted state anisotropy was introduced by taking into account the FM's first and second order uniaxial anisotropy terms with the corresponding easy magnetization direction allowed one to make a nonzero angle with the film's normal. We show that the presence of the Cu interlayer in IrMn/Cu/$[\mathrm{Co/Pt}]_3$ leads to a predominant perpendicular anisotropy effect opposite to what has been observed in $[\mathrm{Pt/Co}]_3$/Cu/FeMn films.[4]

II. EXPERIMENTAL

The multilayers were deposited by dc magnetron sputtering at room temperature onto thermally oxidized Si(100) substrates. The base pressure was 5.0×10^{-8} Torr and the Ar pressure during deposition was 2.5×10^{-3} Torr. The Pt, Co,

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Cu, and IrMn layers were sputtered at rates of 1.2, 1.2, 1.1, and 2.0 Å/s, respectively, as estimated from the x-ray reflectivity.

In what follows, the films with nominal compositions of Pt(20 Å)/[Co(4.5 Å)/Pt(20 Å)]$_3$ and Pt(20 Å)/IrMn(60 Å)/Cu(t_{Cu})/[Co(4.5 Å)/Pt(20 Å)]$_3$ for the series with $t_{\mathrm{Cu}}=0$, 2, 3, 4, 5, 6, 8, and 10 Å were referred to as [Co/Pt]$_3$ and IrMn/Cu(t_{Cu})/[Co/Pt]$_3$, respectively. The samples were heated at 473 K for 15 min at a pressure of 8.0×10^{-6} Torr and subsequently cooled to room temperature in a magnetic field of 3.0 kOe perpendicular to the film's plane. The structural characterization was made via x-ray diffractometry, employing Cu $K\alpha$ radiation in order to obtain small (reflectivity) and high angle scans. Both in-plane and out-of-plane magnetizations were measured with an alternating gradient-force magnetometer.

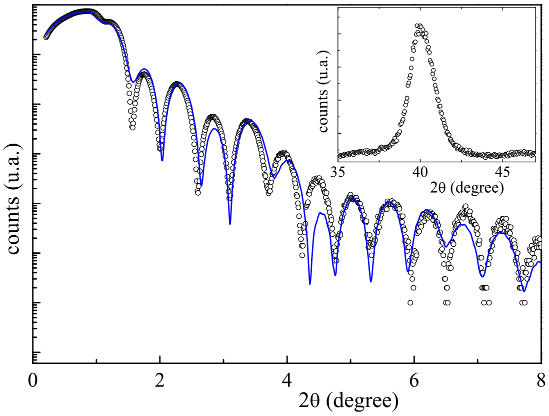

FIG. 1. (Color online) Small-angle reflectivity spectrum (symbols) and simulated curve (lines) for IrMn/[Co/Pt]$_3$; the inset shows the respective high-angle diffraction scan.

III. MODEL

The exchanged-coupled AF/FM systems considered here were assumed to obey the slightly modified rigid AF moment model where the AF moments always point along the original pinning (here, the perpendicular-to-the-plane) direction. The model involves the perpendicular-to-the-plane anisotropy K_P [$=K_S-2\pi M^2$, where K_S is the FM's surface anisotropy constant and $2\pi M^2$ is the demagnetization (for a thin film) one], the FM's first and second order uniaxial anisotropy constants K_1 and K_2, and the AF/FM exchange-coupling constant J_E, as parameters. The FM part of the system is assumed to be of thickness t_{FM} equal to the total thickness of the Co layers with saturation magnetization M. The Pt/Co multilayer is considered as a single FM layer having the same magnetic characteristics as the multilayer. The normalized (to its saturation value) magnetization, i.e., the cosine of the angle between the external magnetic field **H** and **M** was obtained by minimizing the free magnetic energy per unit volume,

$$E = -\mathbf{H}\cdot\mathbf{M} - K_P\frac{(\mathbf{M}\cdot\hat{\mathbf{n}})^2}{M^2} - K_1\frac{(\mathbf{M}\cdot\hat{\mathbf{u}})^2}{M^2} - K_2\frac{(\mathbf{M}\cdot\hat{\mathbf{u}})^4}{M^4} - \frac{J_E}{t_{\mathrm{FM}}}\frac{\mathbf{M}\cdot\hat{\mathbf{n}}}{M}. \qquad (1)$$

The unit vectors $\hat{\mathbf{u}}$ (with polar and azimuthal angles θ and ϕ) and $\hat{\mathbf{n}}$ give the uniaxial anisotropy and the normal to the film's surface directions, respectively. The uniaxial anisotropy terms are attributed to the surface and magnetoelastic anisotropies and $\hat{\mathbf{u}}$ could differ from $\hat{\mathbf{n}}$. Here, the K_2 term has been considered as it could dominate the magnetic properties close to the reorientation transition where interface and shape anisotropies almost cancel each other.[11,12,14] Rectangular distribution ($\pm 50\%$) for ϕ is assumed for fixed θ in order to obtain a cone anisotropy; finally, the total magnetization curve is simulated and compared to the experimental one. Details of the numerical minimization procedure can be found in Refs. 20 and 21.

IV. RESULTS AND DISCUSSION

The reflectivity data and the respective best simulation curve for the IrMn/[Co/Pt]$_3$ multilayer are given in Fig. 1. For the quantitative analysis, the software package WINGIXA by Philips was used; the values of the layer's thickness and the root-mean-square roughness σ are given in Table I. Using this technique, the roughness and interdiffusion are indistinguishable. A rather good agreement was found between the thicknesses determined from the calibration rates and those estimated from reflectivity simulations. The high-angle diffraction scan is also shown in the inset of Fig. 1, where a broad peak is observed at $2\theta=40.00°$, which could be attributed to the (111) texture of the fcc Pt, IrMn, and Co layers.

Figure 2 gives the representative magnetic hysteresis loops for the [Co/Pt]$_3$ and IrMn/Cu(t_{Cu})/[Co/Pt]$_3$ samples. Only for the [Co/Pt]$_3$ multilayer, the easy magnetization axis is actually perpendicular to the film plane, whereas it is canted and the film's plane is not the hard plane for $t_{\mathrm{Cu}}\neq 0$. Evidence for canted magnetization state are the increase in the in-plane coercivity, H_C, and the decrease in the magnetization remanence of the out-of-plane loops with t_{Cu}. Although a certain increase in the out-of-plane remanence is observed for $t_{\mathrm{Cu}}\geqslant 5$ Å, the irreversibility that appears at small fields in the in-plane curves indicates that the easy magnetization axis is not completely normal to the film's plane.

It is worth to note that the in-plane loops are independent of the direction of the magnetic field. Frömter *et al.*[15] esti-

TABLE I. Values of the layer's thicknesses and the root-mean-square roughness σ extracted from the fittings of the x-ray reflectivity patterns of the IrMn/[Co/Pt]$_3$ multilayer.

	Pt	IrMn	[Co/Pt]$_2$	Co	Pt
Thickness (Å)	19.0	51.0	4.5/19.5	4.5	19.8
σ (Å)	4.0	5.0	4.5/5.5	4.5	3.7

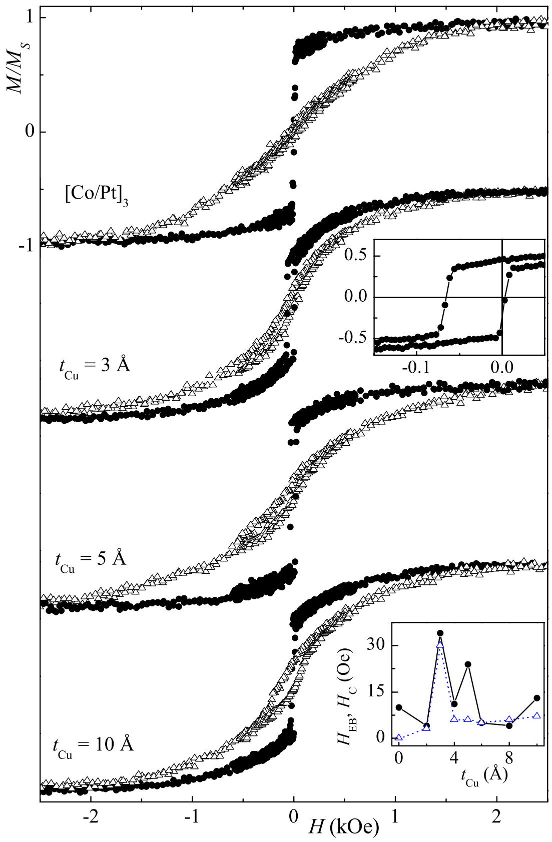

FIG. 2. (Color online) In-plane (empty triangles) and out-of-plane (full circles) hysteresis loops for the $[\mathrm{Co/Pt}]_3$ and $[\mathrm{Co/Pt}]_3/\mathrm{Cu}(t_{\mathrm{Cu}})/\mathrm{IrMn}$ multilayers. The top inset shows the $[\mathrm{Co/Pt}]_3/\mathrm{Cu}$ 3 Å/IrMn out-of-plane loop, and the bottom inset gives the H_{EB} (triangles) and H_C (full circles) vs t_{Cu} for the $\mathrm{IrMn/Cu}(t_{\mathrm{Cu}})/[\mathrm{Co/Pt}]_3$ series, obtained from the out-of-plane loops. The lines are only guides for the eyes.

mated, via scanning electron microscopy with polarization analysis, a canted magnetization phase for a Pt(41 Å)/[Co(5 Å)/Pt(24 Å)]$_7$/Co(5 Å)/Pt(16 Å) film at room temperature with a cone angle of magnetization of 13° apart from the normal of the film. In the present work, the cone angle was obtained from simulations of the in-plane hysteresis loops using the model described in Sec. III, considering coherent magnetization rotation only.

The out-of-plane loops of the $\mathrm{IrMn/Cu}(t_{\mathrm{Cu}})/[\mathrm{Co/Pt}]_3$ series are shifted along the field axis, i.e., they showed perpendicular exchange bias effect (see the top inset of Fig. 2). The corresponding dependencies of the exchange-bias field, H_{EB}, and H_C on t_{Cu} are shown at the bottom inset of Fig. 2. It can be seen that H_{EB} increases significantly for low values of t_{Cu} and reaches a maximum at $t_{\mathrm{Cu}}=3$ Å (see bottom inset of Fig. 2). The H_{EB} increase is accompanied by an enhancement of H_C.

Garcia *et al.*[4] and Sort *et al.*[16] showed that the exchange-bias field of the Pt/Co–FeMn and Pt/Co–IrMn systems can be enhanced by the insertion of a thin Pt layer between the Co and AF layers since Pt reorients the Co moment from a tilted position toward the film's normal. However, they found an exponential decrease in H_{EB} with t_{Cu} when the Pt insertion layer is substituted by Cu for the Pt/Co–Cu–FeMn system and argued that Cu does not favor an effective perpendicular anisotropy in the multilayer.

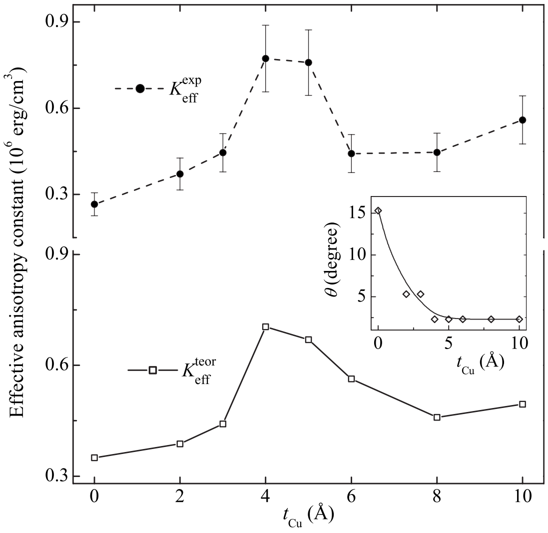

FIG. 3. Effective anisotropy constants obtained by the area method analysis ($K_{\mathrm{eff}}^{\mathrm{expt}}$) and those extracted from the fittings of the in-plane hysteresis loops ($K_{\mathrm{eff}}^{\mathrm{theor}}$) as functions of t_{Cu} for the $\mathrm{IrMn/Cu}(t_{\mathrm{Cu}})/[\mathrm{Co/Pt}]_3$ series. The inset shows $\theta(t_{\mathrm{Cu}})$. The lines are guides to the eyes.

The Cu thickness dependence of the effective perpendicular anisotropy, K_{eff}, calculated by the area method where the two branches of each hysteresis loop is averaged to obtain an anhysteretic curve,[22] is shown at the top panel of Fig. 3. It can be seen that, starting from low t_{Cu} values, K_{eff} increases significantly and reaches a maximum at approximately 4 Å, a value slightly higher than that corresponding to the maximum of H_{EB} (i.e., 3 Å). This difference could be attributed to the interplay between two opposing effects: (i) the role of the Cu spacer for the increase in K_{eff} by reorienting the Co moment toward the perpendicular to the film's plane direction; (ii) the exponential decrease in J_E (and, consequently, of H_{EB}) with the thickness of the nonmagnetic (NM) interlayer in FM/NM/AF films (see, e.g., Ref. 23 and references therein).

The values of $K_1(t_{\mathrm{Cu}})$ were obtained by fitting numerically the in-plane magnetization data; representative experimental curves and the corresponding fitting ones are plotted in Fig. 4, where a reasonable agreement between model and experiment can be seen. In the simulations, it was assumed that [111] is the normal-to-the-film direction (in agreement with the x-ray analysis) together with $K_P=0$, $J_E/t_{\mathrm{Co}}=H_{\mathrm{EB}}M$ (valid for the rigid AF moment model) and a constant value of $K_2=-4.55\times10^5\ \mathrm{ergs/cm^3}$; also, a random distribution of the projections of the easy axes in the film's plane (i.e., equally distributed ϕ) was assumed. In the framework of the present model represented by Eq. (1), it is not possible to obtain a simple expression for the value of K_{eff}. Its maximum value, however, can be estimated by assuming $\hat{\mathbf{u}}$ parallel to $\hat{\mathbf{n}}$ which, after some simple calculations, results in $K_{\mathrm{eff}}^{\max}=J_E/(2t_{\mathrm{FM}})+K_P+K_1+2K_2$. Using the above values of the anisotropy parameters, the $K_{\mathrm{eff}}^{\mathrm{theor}}(t_{\mathrm{Cu}})$ variation was calculated and shown at the bottom panel of Fig. 3. As can be seen, there is a rather good agreement between the top and the bottom curves.

It is worth emphasizing that the out-of-plane loops were not used here for the estimation of the anisotropy parameters

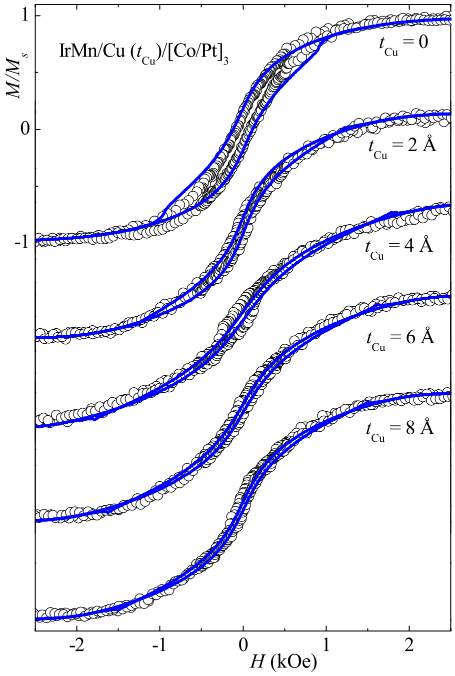

FIG. 4. (Color online) In-plane magnetization curves for IrMn/Cu(t_{Cu})/[Co/Pt]$_3$ multilayers for various t_{Cu}. Symbols: experimental results; lines: best-fitting curves.

since the magnetization rotation is not coherent for this magnetic field orientation, where nucleation and domain-wall motion dominate the magnetization reversal.[7,15,24] Nevertheless, some coherent rotation models have been proposed to explain the magnetic behavior of similar systems by introducing the inhomogeneity of magnetic parameters, such as local coercivity[25] or anisotropy[26] variations. For example, Boukari *et al.*,[13] taking into account both K_1 and K_2 together with a distribution of K_1, were able to fit well some of the out-of-plane loops for their Co/Pt multilayers. Our samples, however, do not show square loops like those of the above cited work, so our attempts to fit the out-of-plane loops with K_1 distribution failed. Therefore, in the present study the anisotropy parameters were obtained by fitting the in-plane loops, where the mechanism for the reversal is the coherent rotation.

The $\theta(t_{Cu})$ variation, also extracted from the fittings of the in-plane magnetization curves and shown in the inset of Fig. 3, indicates that although the Cu spacer reorients the Co moments along the perpendicular to the film's plane direction, the FM anisotropy direction still does not reach the perpendicular configuration. Therefore, in contrast to the [Pt/Co]$_3$/Cu/FeMn system, our results show that the Cu interlayer in the IrMn/Cu/[Co/Pt]$_3$ system leads to predominant perpendicular Co anisotropy.

In summary, we observed canted anisotropy in the IrMn/Cu(t_{Cu})/[Co/Pt]$_3$ multilayers, where the presence of the Cu interlayer leads to a predominant perpendicular anisotropy, in contrast to what has been observed in the [Pt/Co]$_3$/Cu/FeMn films. Phenomenologically, the canted state anisotropy was introduced by taking into account the FM's first and second order uniaxial anisotropy terms with the corresponding uniaxial anisotropy direction allowed to make a nonzero angle with the film's normal. The effective anisotropy constants obtained from the area method analysis are in a rather good agreement with those extracted from the fittings of the in-plane (hard axis) magnetization curves. Also, our multilayers show perpendicular exchange bias which depends on the Cu interlayer thickness.

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