



Perpendicular exchange bias in IrMn/Pt/[Co/Pt]₃ multilayers with cone magnetization

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ABSTRACT

The perpendicular exchange bias and magnetic anisotropy were investigated in IrMn/Pt/[Co/Pt]₃ multilayers through the analysis of in-plane and out-of-plane magnetization hysteresis loops. A phenomenological model was used to simulate the in-plane curves and the effective perpendicular anisotropies were obtained employing the area method. The canted state anisotropy was introduced by taking into account the first and second uniaxial anisotropy terms of the ferromagnet with the corresponding uniaxial anisotropy direction allowed to make a nonzero angle with the film's normal. This angle, obtained from the fittings, was of approximately 15° for IrMn/[Co/Pt]₃ film and decreases with the introduction of Pt in the IrMn/Pt/[Co/Pt]₃ system, indicating that the Pt interlayer leads to a predominant perpendicular anisotropy. A maximum of the out-of-plane anisotropy was found between 0.5 and 0.6 nm of Pt, whereas a maximum of the perpendicular exchange bias was found at 0.3 nm. These results are very similar to those obtained for IrMn/Cu/[Co/Pt]₃ system; however, the decrease of the exchange bias with the spacer thickness is more abrupt and the enhancement of the perpendicular anisotropy is higher for the case of Cu spacer as compared with that of Pt spacer. The existence of a maximum in the perpendicular exchange bias as a function of the Pt layer thickness was attributed to the predominance of the enhancement of exchange bias due to more perpendicular Co moment orientation over the exponential decrease of the ferromagnetic/antiferromagnetic exchange coupling and, consequently, of the exchange-bias field.

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1. Introduction

During the past decades, studies of the magnetic anisotropies in Co/Pt and Co/Pd multilayers have been made from both theoretical and experimental points of view. Aside from their potential practical use for high-density computer data storage [1,2], these systems are also fascinating for studying the spin reorientation [3] and cone magnetization states [4–9]. 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 [10]. Several reviews on exchange-bias can be found in the literature [11–14].

It has also been demonstrated that, in this type of multilayers, when the shape and the surface anisotropies almost compensate each other, higher order anisotropy terms become important for the magnetization orientation [6–9]. Frönter et al. [15] estimated, via scanning electron microscopy with polarization analysis, a canted magnetic phase for a Co/Pt multilayer with a cone angle magnetization of 13° apart from the normal of the film. Recently, Castro et al. [5] showed that the canted state anisotropy can be phenomenologically introduced by taking into

account the first and second uniaxial anisotropy term of the ferromagnet (FM) with the corresponding uniaxial anisotropy direction allowed to make a nonzero angle with the film's normal.

The influence of the insertion of a thin Pt layer between an antiferromagnet (AF) and the Co/Pt multilayer has been investigated by several groups [16–20]. They all agree that the Pt layer reorients the Co moment from a tilted position towards the film's normal. Due to the more perpendicular alignment of these moments and the short range AF/FM interaction, a maximum of the perpendicular exchange bias field has been found at 0.3 nm of Pt for [Co/Pt]₃/Pt/IrMn [18,19]. In contrast to the [Pt/Co]₃/Cu/FeMn [16], the Cu interlayer in the IrMn/Cu/[Co/Pt]₃ system [5] leads to a predominant perpendicular Co anisotropy. It is well known that the exchange bias effect is strongly influenced by the interfaces roughness and the chemical intermixing at the interfaces. Zarefy et al. [21] studied the interface of a [Pt/Co]₃/IrMn multilayer by laser-assisted tomographic atom probe and showed more diffusion at the Co/IrMn interfaces than at the IrMn/Pt one.

The present work reports on the anisotropy and perpendicular exchange bias of IrMn/Pt/[Co/Pt]₃ multilayers. These films were deposited exactly at the same conditions used in a previous work of ours [5]. This allows us to compare the variations of the perpendicular anisotropy and the decrease of the perpendicular exchange bias with

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the spacer (Pt or Cu) thickness. Phenomenologically, the canted state anisotropy was introduced by taking into account the FM first and second order uniaxial anisotropy terms with the corresponding easy magnetization direction allowed to make a non-zero angle with the film's normal.

We assume, for these multilayers, that all the Co layers are perfectly coupled to each other. This assumption is supported by Robinson et al. [22] for [Co 0.4 nm/Pt 1.1 nm]₅, where it has been observed through in-situ magneto-optical images that the Co layers switch as a single ferromagnet, for magnetic field applied perpendicular to the film's plane. This result has been attributed by these authors to the strong ferromagnetic coupling between the adjacent Co layers. Moreover, Baltz et al. [23] showed that the Co layers for [Co 0.6 nm/Pt 1.8 nm]₅ are ferromagnetically coupled ($J_{\gamma} > 3 \times 10^{-6} \text{ J/m}^{-3}$) and are also uniformly magnetized. For our samples, where the Pt thickness is about 2.0 nm, we expect similar magnetic behaviour, i. e., all Co layers rotating like a single ferromagnetic layer.

2. Experimental details

The multilayers were deposited by dc magnetron sputtering at room temperature onto thermally oxidized Si(100) substrates in an AJA sputter deposition system. The base pressure was 6.7×10^{-6} Pa and the Ar pressure during deposition was 0.33 Pa. The Pt, Co, and IrMn layers were sputtered at rates of 0.12, 0.12, and 0.20 nm/s, respectively, as estimated from the X-ray reflectivity.

In what follows, the films with nominal compositions Pt(2.0 nm)/[Co(0.45 nm)/Pt(2.0 nm)]₃ and Pt(2.0 nm)/IrMn(6.0 nm)/Pt(t_{Pt})/[Co(0.45 nm)/Pt(2.0 nm)]₃ for the series with $t_{\text{Pt}} = 0, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8$ and 1.0 nm, were referred as to [Co/Pt]₃ and IrMn/Pt(t_{Pt})/[Co/Pt]₃, respectively. Each sample was heated at 473 K for 15 min at pressure of 1.1×10^{-3} Pa and subsequently cooled down to room temperature in an external magnetic field of 2.39×10^5 A/m perpendicular to the film's plane. The structural characterization was made via conventional X-ray diffractometry performed on a Philips X'Pert machine, employing Cu $K\alpha$ radiation as well as by small-angle reflectivity. Both in-plane and out-of-plane magnetizations were measured with a home-made alternating gradient-force magnetometer.

3. 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 with respective constant K_p [$=K_s - 2\pi M^2$, where K_s and $2\pi M^2$ are the FM surface anisotropy and the demagnetization constants, respectively], 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 was obtained by minimizing the free magnetic energy per unit volume

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

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, and J_E is the AF/FM exchange-coupling constant. The uniaxial anisotropy terms, being K_1 and K_2 the FM first and second order uniaxial anisotropy constants, respectively, are attributed to the surface and magnetoelastic anisotropies and $\hat{\mathbf{u}}$ could differs from $\hat{\mathbf{n}}$. Here, the K_2 -term has been considered as it could dominate the magnetic properties close to the reorientation transition

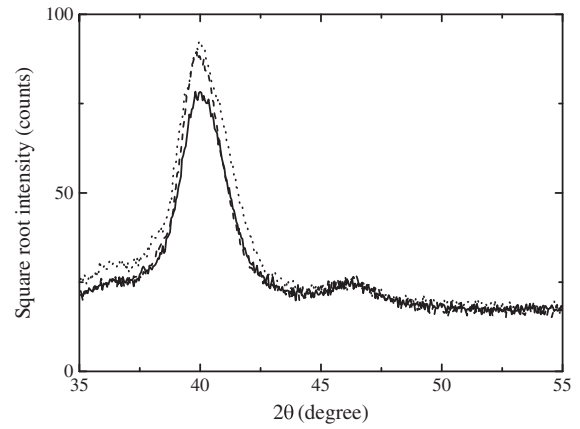


Fig. 1. (Color online) High angle X-ray diffraction profiles for IrMn/[Co/Pt]₃ (full line), IrMn/Pt(1.0 nm)/[Co/Pt]₃ (dash line) and IrMn/Cu(1.0 nm)/[Co/Pt]₃ (dot lines).

where interface and shape anisotropies almost cancel each other [6,7,9]. 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 with the experimental one.

4. Results and discussion

The high-angle diffractions scans show a (111) texture of the fcc Pt, IrMn and Co layers at $2\theta = 40.00^\circ$ (Fig. 1) and the reflectivity data are similar to the spectra plotted in Fig. 1 of ref. [5]. The in-plane and out-of-plane magnetic hysteresis loops for [Co/Pt]₃ and for some representative IrMn/Pt(t_{Pt})/[Co/Pt]₃ samples are shown in Fig. 2. Only for the [Co/Pt]₃ multilayer, the easy magnetization axis is actually perpendicular to the

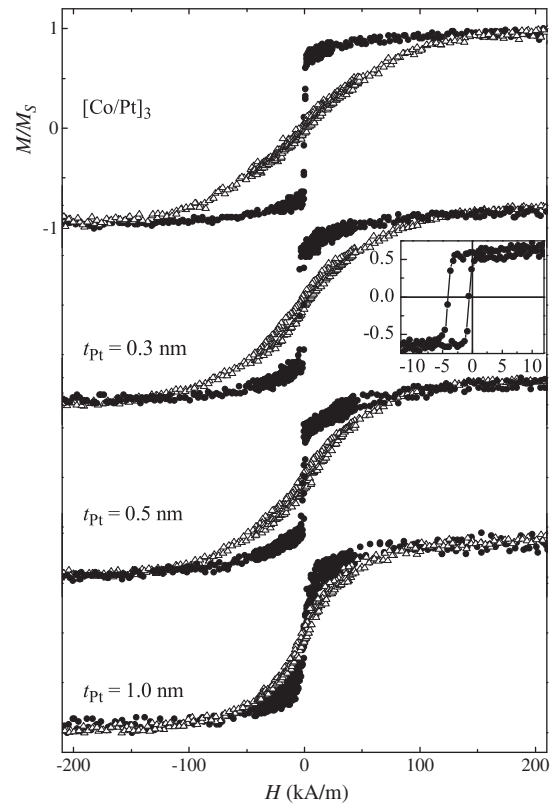


Fig. 2. (Color online) In-plane (empty triangles) and out-of-plane (full circles) hysteresis loops for [Co/Pt]₃ and IrMn/Pt(t_{Pt})/[Co/Pt]₃ multilayers. The inset shows the IrMn/Pt(0.3 nm)/[Co/Pt]₃ out-of-plane loop. The lines are only guides to the eyes.

film plane, whereas it is canted and the film's plane is not the hard magnetization plane for $t_{Pt} \neq 0$. Therefore, similarly to the IrMn/Cu/[Co/Pt]₃ system [5], the magnetization is canted for all samples, and the cone angles are extracted from the fits of the in-plane loops.

A shift of the out-of-plane loop along the field axis can be clearly seen in the inset of Fig. 2. The dependencies of the perpendicular exchange-bias field, H_{EB} on t_{Pt} are shown in Fig. 3(a). The dependence of H_{EB} as a function of t_{Cu} , extracted from Ref. 5 is also included. It can be seen that H_{EB} increases significantly for low values of t_{Pt} and reaches a maximum at $t_{Pt} = 0.3$ nm. Therefore, the $H_{EB}(t_{Pt})$ variation is in agreement with the results obtained by Garcia et al. [16] and Sort et al. [17] that showed that the exchange bias field of 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.

In contrast to the t_{Cu} dependence where an abrupt decrease of H_{EB} was obtained, in the present work a smoother dependence of H_{EB} with t_{Pt} is found. The H_{EB} increase is accompanied by an enhancement of H_C [see Fig. 3 (b)], where $H_C(t_{Cu})$ and $\theta(t_{Cu})$, represented by open circles, are also obtained from Ref. 5. Moreover, the maxima of H_{EB} occur for the same spacer thickness and have almost the same value (≈ 29 Oe). It is worth to note that the decreases of $H_{EB}(t_{Pt})$ and $H_{EB}(t_{Cu})$ are not exponential and are influenced by the maxima of K_{eff} that occur at thicker Pt or Cu spacer layers, as it will be discuss below.

The $\theta(t_{Pt})$ variation, extracted from the fittings of the in-plane magnetization curves and shown in Fig. 3(c), indicates that although the Pt 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. This result is similar to the $\theta(t_{Cu})$ variation except that the saturation value is obtained for thicker Pt layer.

The top panel of Fig. 4 shows the effective perpendicular anisotropy, K_{eff}^{exp} , as a function of the Pt thickness calculated by the area method,

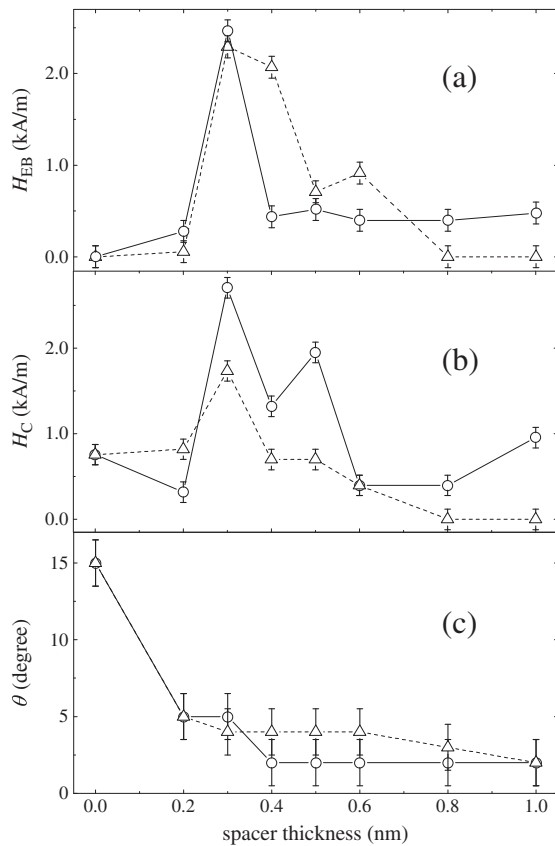


Fig. 3. (Color online) H_{EB} (a), H_C (b) and θ (c) as function of t_{Pt} (triangles) or t_{Cu} (circles) for IrMn/Pt(t_{Pt})/[Co/Pt]₃ and IrMn/Cu(t_{Cu})/[Co/Pt]₃, extracted from Ref. 5, series. The lines are only guides to the eyes.

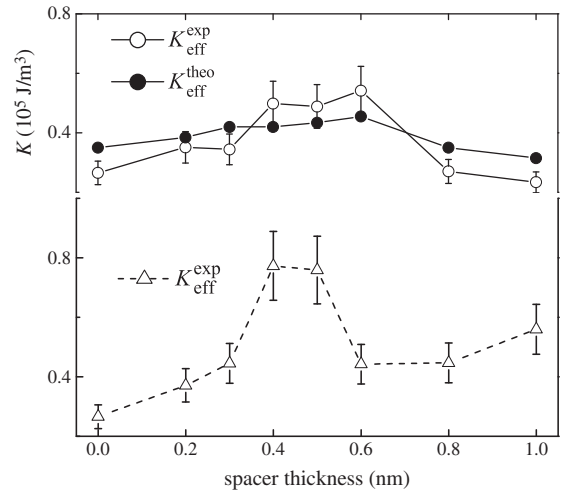


Fig. 4. Top: effective anisotropy constants obtained by the area method analysis (K_{eff}^{exp}) and those extracted from the fittings of the in-plane hysteresis loops (K_{eff}^{theo}) as functions of t_{Pt} for IrMn/Pt(t_{Pt})/[Co/Pt]₃ films; bottom: K_{eff}^{exp} as function of t_{Cu} for IrMn/Cu(t_{Cu})/[Co/Pt]₃ films [5]. The lines are guides to the eyes.

where the two branches of each hysteresis loop are averaged in order to obtain an hysteretic curve [24]. A maximum of K_{eff}^{exp} is obtained between 0.5 and 0.6 nm of Pt, a value higher than that corresponding to the maximum of H_{EB} (i.e., 0.3 nm). The presence of the maximum of H_{EB} is a consequence of the enhancement of perpendicular exchange bias due to the reorientation of the Co moment towards the perpendicular to the film's plane direction over the exponential decrease of J_E (and consequently, of H_{EB}) with t_{Pt} .

Representative in-plane loops and best simulation loops are given in Fig. 5, where a reasonable agreement between model and experiment

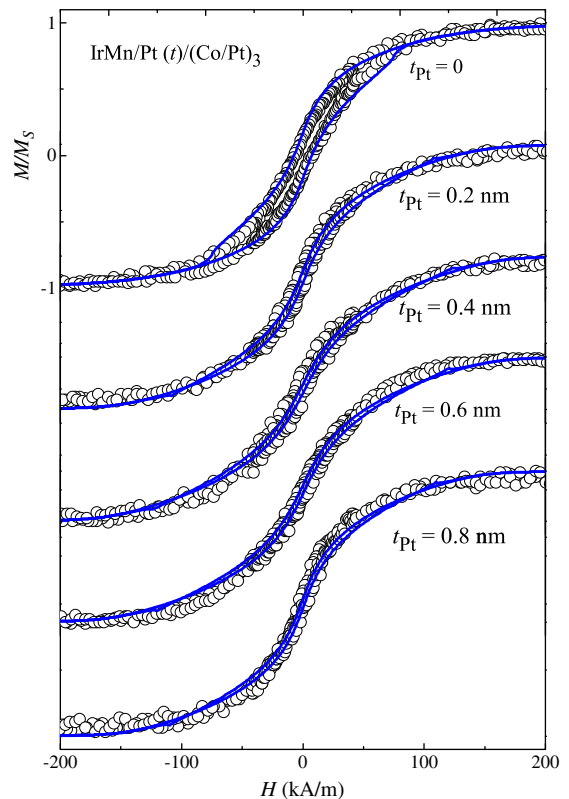


Fig. 5. (Color online) In-plane magnetization curves for IrMn/Cu(t_{Pt})/[Co/Pt]₃ multilayers for various t_{Pt} . Symbols: experimental results; lines: best-fitting curves.

can be seen. In this configuration, the predominant mechanism for the magnetization rotation is the coherent rotation [26] and the theoretical model described in the Section 3 could be used for the estimation of the anisotropy parameters. However, the magnetization rotation is not coherent for out-of-plane loops (see Fig. 2), where the nucleation and domain wall motion dominate the magnetization reversal [23,27,28] and the model is not valid.

In the simulations, it was assumed that [111] is the normal-to-the-film direction (in agreement with the X-ray analysis) together with $K_P=0$, $J_E/t_{Co}=H_{EB}M$ (valid for the rigid AF moment model) and a constant value of $K_2=-4.55\times 10^4\text{J/m}^3$; also, a random distribution of the projections of the easy axes in the film's plane (i.e., equally distributed ϕ) was assumed. The maximum values of the anisotropy parameters [$K_{\text{eff}}^{\text{theo}}=J_E/(2t_{FM})+K_P+K_1+2K_2$] were calculated and their variations are shown in the upper panel of Fig. 4, represented by full circles. As can be seen, there is a rather good agreement between $K_{\text{eff}}^{\text{theo}}$ and $K_{\text{eff}}^{\text{exp}}$ as function of t_{Pt} .

It is worth to note that the maximum values of K_{eff} obtained in this work ($0.54\times 10^5\text{J/m}^3$) are lower than the value obtained for IrMn/Cu/[Co/Pt]₃ samples ($0.77\times 10^5\text{J/m}^3$) shown in the bottom panel of Fig. 4. This result is unexpected since the Co/Pt interfaces contribute to the perpendicular anisotropy [19] and the Co/Cu (111) interfaces add to in-plane anisotropy [25]. However, it is well known that the IrMn layer is not the best buffer for promoting a (111) texture [21] and the Cu spacer layer may promote a better (111) texture than the Pt spacer layer would do. This argument is supported by the intensity of the (111) X-ray peak, which increases 30% and 39% for IrMn/Pt (1.0 nm)/[Co/Pt]₃ and IrMn/Cu (1.0 nm)/[Co/Pt]₃, respectively, when compared to the one obtained for the IrMn/[Co/Pt]₃ sample (see Fig. 1). Therefore, these minor structural changes can influence the higher perpendicular anisotropy found for the Cu spacer layer series. Moreover, the smoother decrease of H_{EB} with t_{Pt} as well as the weaker enhancement of the perpendicular anisotropy indicate a much smoother exponential decrease of the exchange constant with t_{Pt} when compared with the respective variations for the t_{Cu} case.

In summary, we observed canted anisotropy in IrMn/Pt(t_{Pt})/[Co/Pt]₃ multilayers, where the presence of the Pt interlayer leads to a predominant perpendicular anisotropy. Phenomenologically, the canted state anisotropy was introduced by taking into account the FM first and second order uniaxial anisotropy terms with the corresponding uniaxial anisotropy direction allowed to make a non-zero 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. Comparison between these results and those obtained for IrMn/Cu(t_{Cu})/[Co/Pt]₃ multilayers showed that both Cu

and Pt interlayers reorient the Co moments along the perpendicular to the film's plane direction. However, the main difference is the smoother decrease of H_{EB} with t_{Pt} in contrast to the abrupt decrease of H_{EB} with t_{Cu} .

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