Tailoring perpendicular exchange bias in [Pt/Co]-IrMn multilayers

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(Received 24 September 2004; published 18 February 2005)

In [Pt/Co] multilayers (ML) exchange coupled to IrMn, the magnitudes of the exchange bias field H_E and coercivity H_C measured along the perpendicular to film direction, can be tailored by (i) varying the thickness of the Co layers (t_{Co}) inside the ML and/or (ii) inserting a Pt spacer between the ML and the antiferromagnetic (AFM) layer. An unusual peak in the ferromagnetic (FM) thickness dependence of exchange bias properties is observed. This is ascribed to a reduction of the perpendicular effective magnetic anisotropy for either very small or too large values of t_{Co}. Moreover, for low values of t_{Co}, the insertion of an ultrathin Pt spacer between the [Pt/Co] ML and the IrMn brings about a significant increase of H_E and H_C. However, such an effect is not observed for thicker Co layers. This behavior is explained by the two-fold role of the Pt spacer, i.e., it strengthens the perpendicular orientation of the Co magnetization in the ML but it also tends to reduce exchange bias due to the short-range character of the FM-AFM interactions.

DOI: 10.1103/PhysRevB.71.054411 PACS number(s): 75.70.Cn, 75.30.Gw, 81.15.Cd

I. INTRODUCTION

Exchange coupled ferromagnetic- (FM-) antiferromagnetic (AFM) bilayers typically exhibit a shift of the hysteresis loop along the magnetic field axis, i.e., exchange bias, H_E and an enhancement of coercivity H_C when they are field cooled from above the blocking temperature of the AFM or deposited under the presence of a magnetic field.[1–4] During the last decades, these systems have been extensively investigated mainly due to their technological applications in magnetic sensors based on spin valves or magnetic tunnel junctions structures.[5,6]

Usually, exchange bias is observed in FM-AFM bilayers with in-plane anisotropy. However, recently, exchange bias effects have also been induced along the perpendicular-to-film direction, in both continuous[7–16] and nanostructured[17] multilayers. Some systems can exhibit either in-plane or out-of-plane exchange bias, depending on the field cooling direction. This is of particular interest since it allows probing the three-dimensional spin structure of the AFM layer.[8–11] Remarkably, in some cases, perpendicular exchange bias is observed at room temperature, hence making these structures appealing for the implementation of spin valves or tunnel junctions with perpendicular anisotropy.[11–14]

Among the systems which exhibit perpendicular exchange bias are [Pt/Co] or [Pd/Co] multilayers (ML) exchange coupled to an AFM, such as CoO, $FeCl_2$, FeF_2, NiO, FeMn, or IrMn. The perpendicular anisotropy of these ML depends on several parameters, such as the number of Pt/Co or Pd/Co repeats comprised in the ML, the relative thickness of the Pt, Pd, and Co layers or the thickness of the buffer layer.[18,19] Although the role of these parameters on the magnetic properties of unbiased [Pt/Co] and [Pd/Co] ML (coercivity, remanence to saturation magnetization ratio, nucleation field, etc.) has been extensively investigated,[20,21] a systematic investigation on how these parameters affect the magnitude of exchange bias is still lacking. In particular, it has been shown that perpendicular exchange bias increases with the number of (Pt/Co) repeats, becoming maximum when the loops acquire a complete square appearance, hence suggesting that a well-defined perpendicular magnetic anisotropy is required to maximize exchange bias.[12] In addition, it has been recently shown that a significant increase of H_E can be obtained in exchange biased [Pt/Co] - FeMn ML by inserting an ultrathin Pt layer between the [Pt/Co] ML and the AFM.[13] This behavior has been attributed to the role of the thin Pt spacer in reinforcing the perpendicular orientation of the Co magnetization in the ML leading to an enhanced spin projection between the FM and the AFM after the perpendicular field cooling process.

In this article we investigate perpendicular exchange bias effects in [Pt/Co] ML exchange coupled to IrMn. It is found that, for a fixed number of Pt/Co repeats in the ML, the magnitudes of both H_E and H_C can be tailored by varying the thickness of the Co layers in the ML t_{Co}. Interestingly, the usual inversely proportional relationship between H_E and the FM thickness is only observed for intermediate values of t_{Co}, between 0.6 and 0.9 nm, where a relatively large perpendicular effective anisotropy is preserved. For either very thin ($\leqslant$0.6 nm) or relatively thick ($\geqslant$0.9 nm) Co layers, a decrease of the out-of-plane magnetic effective anisotropy occurs, which drastically reduces perpendicular exchange bias. Moreover, it is observed that by inserting a Pt layer between the [Pt/Co] ML and the AFM, H_E and H_C are only enhanced for low values of t_{Co}, i.e., lower than 0.6 nm. However, as a general trend, for larger t_{Co} values, the insertion of a Pt spacer only leads to decreases in H_E and H_C. This effect is interpreted by taking into account the interplay between the enhancement of the perpendicular orientation of the ML magnetization, brought about by the Pt spacer, and the short-range character of FM-AFM exchange interactions.

II. EXPERIMENTAL PROCEDURE

Several series of multilayers with compositions $[Pt(2\ nm)/Co(t_{Co})]_3/Pt(t_{Pt})/IrMn(5\ nm)/Pt(2\ nm)$, were deposited on thermally oxidized Si wafers by dc magnetron

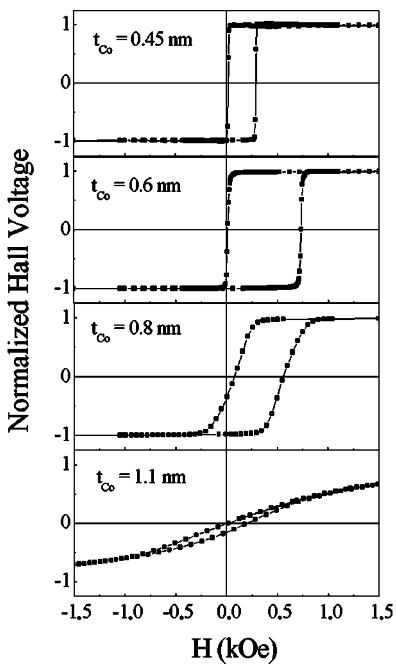

FIG. 1. Hysteresis loops corresponding to the $[\mathrm{Pt}(2\ \mathrm{nm})/\mathrm{Co}(t_{\mathrm{Co}})]_3/\mathrm{IrMn}(5\ \mathrm{nm})/\mathrm{Pt}(2\ \mathrm{nm})$ systems with $t_{\mathrm{Co}}=0.45$, 0.6, 0.8, and 1.1 nm, measured at room temperature along the perpendicular to film direction, by extraordinary Hall effect, after cooling from $T=550$ K in the presence of a -2.4 kOe magnetic field applied along the perpendicular to film direction.

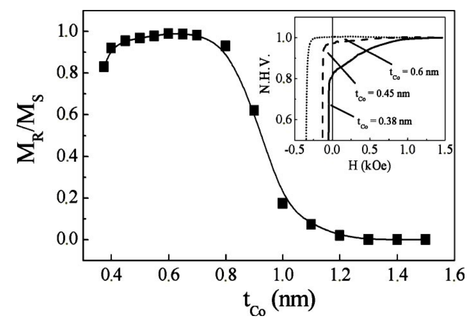

FIG. 2. Dependence of the remanence to saturation ratio M_R/M_S on the Co thickness, t_{Co}, for perpendicular exchange biased multilayers with compositions $[\mathrm{Pt}(2\ \mathrm{nm})/\mathrm{Co}(t_{\mathrm{Co}})]_3/\mathrm{IrMn}(5\ \mathrm{nm})/\mathrm{Pt}(2\ \mathrm{nm})$. Note that, in order to determine M_R/M_S, the loops were centered for the exchange bias field. The inset shows an enlargement of a part of the centered hysteresis loops for $t_{\mathrm{Co}}=0.38$, 0.45, and 0.6 nm. The lines are guides to the eye.

sputtering. The values of t_{Co} ranged from 0.38 to 1.5 nm and those of t_{Pt} from 0 to 1.5 nm. The base pressure was 5.3×10^{-6} Pa, whereas the Ar pressure during deposition was 0.25 Pa. All depositions were performed at room temperature. The samples were annealed at 550 K (above the blocking temperature of all systems) for 1 h and subsequently cooled under a field of -2.4 kOe, applied perpendicular to the film plane, to set the unidirectional exchange anisotropy in this direction. Hysteresis loops, with the magnetic field applied perpendicular to the thin film direction were measured using extraordinary Hall effect (EHE), a technique which is particularly sensitive to the perpendicular component of the magnetization.[22] The magnetic effective anisotropy was determined from the area between the easy and hard axis hysteresis loops recorded either by EHE or using a vibrating sample magnetometer (VSM).[18] Hysteresis loops were also recorded at temperatures above room temperature, up to $T=500$ K, by polar Kerr effect. High resolution transmission electron microscopy images, together with x-ray diffraction, revealed that both the (Pt/Co) ML and IrMn are polycrystalline and exhibit a weak (111) texture.

III. RESULTS AND DISCUSSION

Typical hysteresis loops of the $[\mathrm{Pt}(2\ \mathrm{nm})/\mathrm{Co}(t_{\mathrm{Co}})]_3/\mathrm{IrMn}(5\mathrm{nm})/\mathrm{Pt}(2\mathrm{nm})$ systems measured at room temperature along the perpendicular to film direction by EHE are shown in Fig. 1, for $t_{\mathrm{Co}}=0.45$, 0.6, 0.8, and 1.1 nm. Note that, in these samples, no Pt spacer is introduced between the [Pt/Co] ML and the AFM. For low values of t_{Co} the loops are rather square. However, the remanence to saturation ratio decreases as t_{Co} is progressively increased. For $t_{\mathrm{Co}}=0.8$ nm, the loop becomes tilted and for larger t_{Co} (e.g., 1.1 nm), the out-of-plane loop progressively becomes a hard axis loop. This indicates that for low and intermediate values of t_{Co}, the system exhibits a perpendicular to plane magnetic effective anisotropy, which reorients towards in-plane for sufficiently thick Co layers. In addition, the hysteresis loops are displaced along the magnetic field axis. The loop shift is particularly pronounced for intermediate values of t_{Co}.

The dependence of the remanence to saturation magnetization ratio M_R/M_S, measured from the perpendicular to plane hysteresis loops, on t_{Co} is shown in Fig. 2. The values of M_R/M_S are obtained after recentering the loops for the exchange bias field. As can be seen in the figure, M_R/M_S increases from 0.83 (for $t_{\mathrm{Co}}=0.38$ nm) to 0.99 (for $t_{\mathrm{Co}}\sim 0.6$ nm). For larger t_{Co}, M_R/M_S tends to decrease again and it drastically drops at $t_{\mathrm{Co}}=0.9$ nm, confirming that the perpendicular anisotropy of [Pt/Co] multilayers is lost for exceedingly thick Co layers. The inset of Fig. 2 shows an enlargement of a part of the hysteresis loops (after recentering them along the field axis) for $t_{\mathrm{Co}}=0.38$, 0.45, and 0.6 nm, which illustrates the increase of squareness ratio as t_{Co} is increased to its optimum value.

The dependences of H_E and H_C on t_{Co} are shown in Fig. 3. Similar to M_R/M_S, the magnitudes of H_E and H_C are also maximum for intermediate values of t_{Co}, i.e., $H_E=375$ Oe for $t_{\mathrm{Co}}=0.6$ nm and $H_C=360$ Oe for $t_{\mathrm{Co}}=0.65$ nm. This is in contrast to most exchange bias systems, where, due to the interfacial character of the FM-AFM interactions, H_E is larger for thinner FM layers.[1] It is noteworthy that for the majority of t_{Co} values H_E is larger than H_C and, consequently, only one remanent state is obtained. This is of practical interest in order to use these structures as a reference layer in spin valves or tunnel junctions with perpendicular anisotropy.

In order to get deeper understanding on the dependences of H_C, H_E, and M_R/M_S on t_{Co}, the effective magnetic anisotropy K_{eff} was determined for the different samples, from the area between easy and hard axis hysteresis loops.[18] The dependence of K_{eff} on t_{Co} is shown in Fig. 4. It can be seen that,

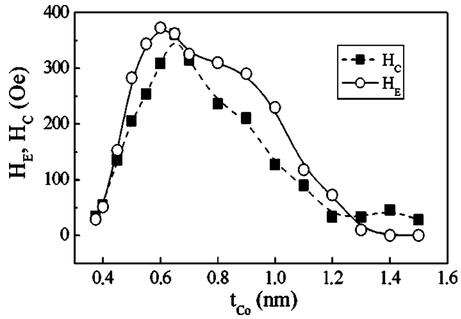

FIG. 3. Dependence of the hysteresis loop shift, H_E(-○-) and the coercivity H_C(-■-) on the Co thickness, t_{Co}, for perpendicular exchange biased multilayers with compositions $[Pt(2\ nm)/Co(t_{Co})]_3/IrMn(5\ nm)/Pt(2\ nm)$. The lines are guides to the eye.

analogously to H_C and M_R/M_S, K_{eff} also exhibits its maximum value around $t_{Co} \sim 0.65$ nm. A similar dependence of K_{eff} on t_{Co} has been reported in [Pt/Co] ML without AFM.[18,19] For unbiased [Pt/Co] ML, the effective anisotropy is, in fact, the result of several anisotropy contributions and it can be expressed as $K_{eff} = K_v + 2K_{surf}/t_{Co} + (3/2)\lambda\sigma - 2\pi M_{s,eff}^2$, where $M_{S,eff} = M_{S,Co}[t_{Co}/(t_{Co}+t_{Pt})]$. The first term is the volume anisotropy, which is mainly related to the crystallographic structure of the ML, the second term is the surface anisotropy, arising from the hybridation between the electronic d states of Pt and Co at the Pt/Co interfaces,[23] the third term is the magnetoelastic contribution (where λ is the magnetostriction constant and σ the stress),[18,24] and the last term is the shape anisotropy contribution, which favors an easy-plane anisotropy. Since in this study the [Pt/Co] ML is exchange coupled to an AFM, additional anisotropy terms are also present, particularly a unidirectional anisotropy term along the perpendicular to film direction, which is responsible for the exchange bias.[25] The decrease of K_{eff} for large values of t_{Co} has been reported in the literature[19,24] and is related to the decrease of the surface anisotropy contribution for larger t_{Co} and the increase of the volume and shape anisotropies. Indeed, for thick Co layers, the easy axis magnetization tilts and tends to fall in the film plane, indicating that the interface anisotropy (responsible for the perpendicular effective anisotropy) is no longer strong enough to overcome the shape anisotropy (see Figs. 1 and 2). More controversial is the decrease of K_{eff} for low values of t_{Co}. Several hypothesis have been reported in the literature. For instance, it has been shown that a crystallographic transition from hcp to fcc occurring in Co for low values of t_{Co}, has an influence on the magnitude of magnetic effective anisotropy.[26] It has been also claimed that for thicker Co layers there would be an improvement of the (111) texture of the ML, which would also bring about an enhancement of K_{eff}.[20,27] Alternatively, some authors have reported the importance of having well defined Pt/Co interfaces parallel to the film plane in order to have a large perpendicular anisotropy. The presence of interface roughness or intermixing between Pt and Co have been shown to play a detrimental role on K_{eff}.[28] If the intermixing is larger, K_{eff} decreases due to a diluted spin density and smaller orbital moments of Co at the interfaces.[29] For low values of t_{Co}, the effects of interdiffusion between Pt and Co are enhanced and in the limit case where a random disordered solid solution of Co and Pt would be formed, this would lead to an fcc matrix which would not support uniaxial anisotropy.[29] Hence, for too thin or too thick Co layers, if the perpendicular anisotropy is not large enough, the out-of-plane hysteresis loops tend to resemble hard axis loops and, consequently, H_C is reduced. However, it should be noted that although H_C is similar for $t_{Co} = 0.4$ nm and $t_{Co} = 1.2$ nm (see Fig. 3), the effective magnetic anisotropy in the two cases is very different (for $t_{Co} = 1.2$ nm, K_{eff} becomes even negative, indicating an in-plane magnetic anisotropy, see Fig. 4). Hence, the relationship between H_C and K_{eff} is not so straightforward in exchange biased [Pt/Co] ML. This could be due to the coupling between the [Pt/Co] ML and the AFM. Namely, if the AFM spins are partially irreversibly dragged during magnetization reversal of the FM, this yields an enhancement of H_C, which is another fingerprint of FM-AFM exchange interactions.[1–4]

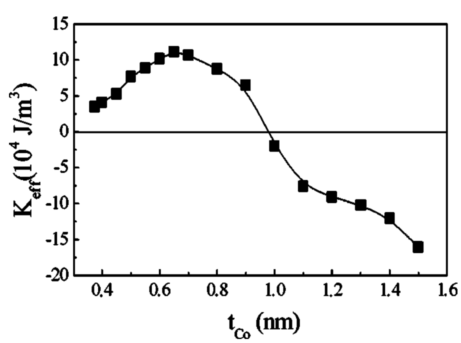

FIG. 4. Dependence of the effective anisotropy K_{eff} on the Co thickness t_{Co} for perpendicular exchange biased multilayers with compositions $[Pt(2\ nm)/Co(t_{Co})]_3/IrMn(5\ nm)/Pt(2\ nm)$. The lines are guides to the eye.

The relationship between K_{eff}, M_R/M_S, and H_E is somewhat complex. In fact, due to the interface nature of FM-AFM exchange interactions it is usual to observe a decrease of H_E for larger FM thickness. An inverse dependence between H_E and the FM thickness (t_{FM}) has been reported in many FM-AFM bilayers.[1] This effect is commonly explained by arguing that when the magnetization of the exchange biased layer switches, the volume Zeeman energy brought by the applied field balances the FM-AFM interfacial coupling energy (σ_{ex}), so that $\sigma_{ex} = H_E M_{S,Co} n t_{Co}$, where n is the number of Pt/Co repeats in the ML and $M_{S,Co}$ the saturation magnetization of Co. The exchange bias energy is a priori expected to be independent of t_{FM} which is indeed confirmed in many systems considering the usually observed $1/t_{FM}$ thickness dependence of H_E. Yet, as can be seen in Fig. 5, σ_{ex} shows a progressive unusual increase with t_{Co}, tending to level off for $t_{Co} = 0.6$ nm and starting to decrease for $t_{Co} \geq 0.9$ nm. It can be argued that during the perpendicular field cooling, as the temperature is reduced to below the blocking temperature, the spins in the different IrMn crystallites will tend to orient along their easy axes closer to the field cooling (FC) direction. However, once at room temperature, when the field is removed, the spins in the Co layers will tend to relax at a certain angle towards in-plane if the perpendicular anisotropy is not large enough. This occurs for either very

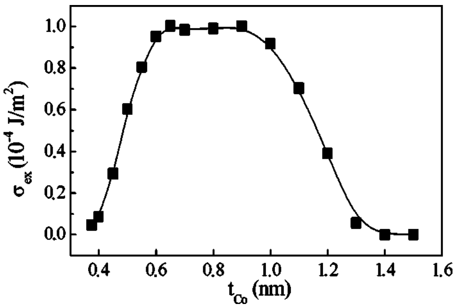

FIG. 5. Dependence of the exchange bias energy σ_{ex} calculated from the shift of the hysteresis loops measured along the perpendicular to film direction, on the Co thickness t_{Co} for perpendicular exchange biased multilayers with compositions $[Pt(2\ nm)/Co(t_{Co})]_3/IrMn(5\ nm)/Pt(2\ nm)$. The lines are guides to the eye.

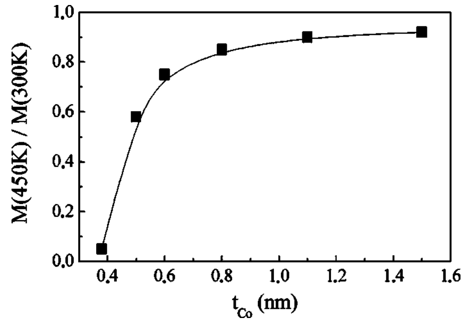

FIG. 6. Dependence of the ratio between the saturation magnetization measured at 450 K, M_S(450 K) and that measured at 300 K, M_S(300 K), on the Co thickness t_{Co} for perpendicular exchange biased multilayers with compositions $[Pt(2\ nm)/Co(t_{Co})]_3/IrMn(5\ nm)/Pt(2\ nm)$. The lines are guides to the eye.

low or relatively large values of t_{Co}. It is well known that exchange bias is roughly proportional to the FM-AFM spin projection at the interface.[30] Hence, H_E is optimised when the FM and AFM easy axes are completely parallel to each other. A situation close to this one is probably accomplished for t_{Co} around 0.6 nm, when the magnetic anisotropy in the ML is sufficiently large to keep M_R/M_S close to 1 (see Fig. 2). For low values of K_{eff}, where M_R/M_S is found to reduce the FM-AFM spin projection (and consequently H_E) will decrease. However, it should be noted that this effect is not the only cause for the difference in H_E for different t_{Co} values. For example, H_E is found to be similar for $t_{Co}=0.45$ nm and $t_{Co}=1.1$ nm (see Figs. 1 and 3), although in the latter case M_R/M_S is much lower. Hence, other mechanisms must be simultaneously influencing exchange bias. Actually, similar to the effective magnetic anisotropy, [Pt/Co] multilayers also exhibit a strong reduction of the Curie temperature T_C for low values of t_{Co} (Ref. 29) basically due to intermixing between Pt and Co at the interfaces. This phenomenon is observed in our case. Namely, for $t_{Co}=0.38$ nm T_C is about 450 K. However, T_C is much higher (larger than the maximum temperature achievable in the polar Kerr setup) for larger values of t_{Co}. In addition, the high-temperature hysteresis loops reveal that the blocking temperature of these systems (i.e., for $t_{IrMn}=5$ nm) is also around 450 K (considering the blocking temperature T_B as the temperature at which H_E vanishes completely upon heating). Figure 6 shows the dependence of the ratio between the saturation magnetization measured at 450 K, and that measured at 300 K, $M_S(450\ K)/M_S(300\ K)$, on t_{Co}. This figure gives an idea of how much magnetic moment in the FM is lost at $T=T_B$ due to thermal activation. It can be seen that, although $M_S(450\ K)/M_S(300\ K)$ practically vanishes for $t_{Co}=0.38$ nm, for $t_{Co}\geqslant 0.65$ nm the saturation magnetization at $T=450$ K is still rather large. Although exchange bias has been occasionally reported in systems with T_C lower than T_B,[31] it is well accepted that H_E is induced by the net FM moment acting during the FC process. Therefore, the condition $T_C > T_B$ is generally required to induce H_E.[1–4] If T_C is lower or about the same order of magnitude as T_B (as it occurs for thin Co layers) the alignment of the AFM spins during the FC is probably less effective and, consequently, H_E is expected to be reduced. Finally, although it was not observed by x-ray diffraction, some structural effects (e.g., improvement of texture in the AFM due to better AFM growth) could also be partially responsible for the H_E enhancement for the H_E enhancement for large FM thickness. It should be noted as well that the maximum of H_C for $t_{Co}\sim 0.65$ nm is also probably related to the enhanced FM-AFM exchange coupling, since an enhancement of H_C is another fingerprint of FM-AFM coupling.

Inserting a Pt spacer between the [Pt/Co] ML and the AFM is another way to significantly modify H_E. This effect was investigated for four series of samples, with $t_{Co}=0.38$, 0.6, 0.8, and 1.1 nm, with the aim of further enhancing H_E. Shown in Fig. 7 are the dependences of H_E and H_C on t_{Pt} (the thickness of the inserted Pt spacer) for the four sets of samples. As can be seen in the figure, completely different behaviors are obtained depending on t_{Co}. Namely, for $t_{Co}=0.38$ nm, large enhancements of H_E and H_C are observed for small Pt thickness, both of them becoming maximum for $t_{Pt}=0.3$ nm and progressively decreasing when t_{Pt} is further increased. Conversely, for $t_{Co}=0.6$ nm, only decreases in H_E and H_C are observed for all values of t_{Pt}. For $t_{Co}=0.8$ nm and low values of t_{Pt} H_E decreases but H_C slightly increases. Finally, for $t_{Co}=1.1$ nm both H_E and H_C decrease with increasing t_{Pt}. The large enhancement of H_E and H_C when an ultrathin Pt spacer is deposited between the [Pt/Co] ML and the AFM has been recently reported in [Pt/Co] - FeMn.[13] However, in the present work we show that this behavior is not universal, but is only observed for low values of t_{Co}. Similar arguments to those given to interpret the variations of H_E and H_C with t_{Co} can be used to understand the role of the Pt spacer in these systems. The H_E and H_C enhancements for $t_{Co}=0.38$ nm can be understood taking into account that when the Pt layer is introduced, the perpendicular orientation of the Co layers in the ML is improved, as can be seen from the 15% increase in M_R/M_S shown in Fig. 8(a). Indeed, when no Pt spacer is inserted, M_R/M_S is reduced because of both a lack of a Pt/Co interface on top of the last Co layer and the fact that the Co/IrMn interface is not so effective in keeping the perpendicular orientation of the last Co layer in the ML. Actually, the M_R/M_S enhancement is accompanied by a slight increase in the perpendicular effective anisotropy

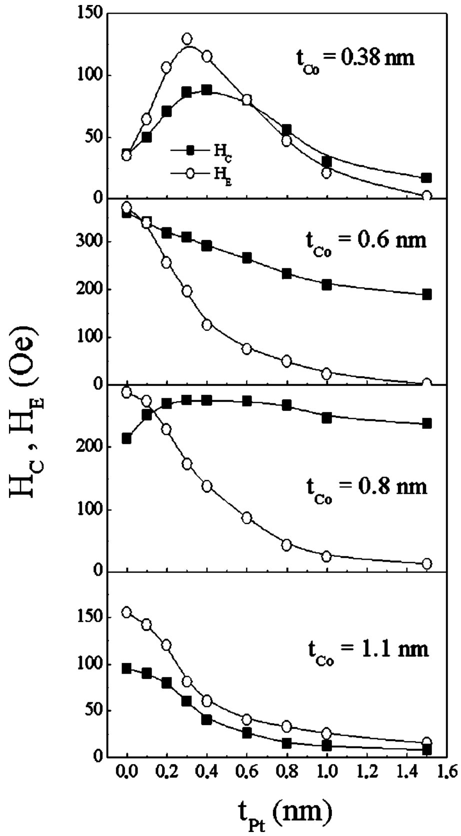

FIG. 7. Dependence of the hysteresis loop shift H_E(-○-) and coercivity H_C(-■-), measured along the perpendicular to film direction, on the thickness of the Pt spacer inserted between the [Pt/Co] multilayer and the AFM layer t_{Pt} for perpendicular exchange biased multilayers with compositions $[Pt(2\ nm)/Co(t_{Co})]_3/IrMn(5\ nm)/Pt(2\ nm)$ for t_{Co}=0.38, 0.6, 0.8, and 1.1 nm. The lines are guides to the eye.

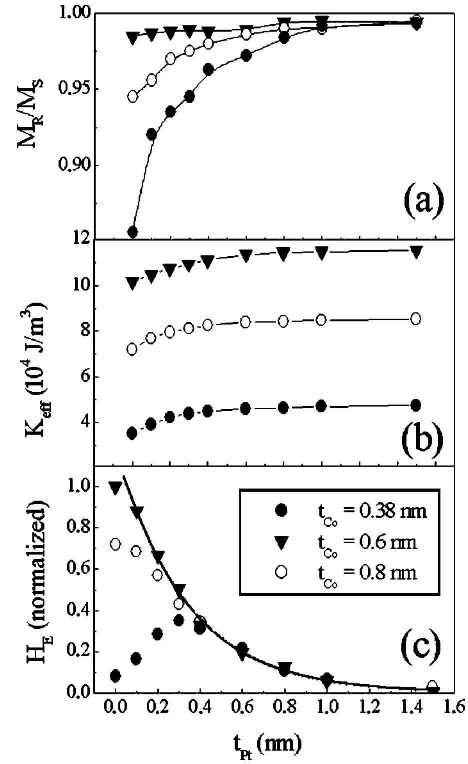

FIG. 8. Dependence of (a) the remanence to saturation ratio M_R/M_S, (b) the effective magnetic anisotropy, K_{eff}, and (c) the normalized hysteresis loop shift, H_E (see text), on the thickness of the inserted Pt spacer layer t_{Pt}, for perpendicular exchange biased multilayers with compositions $[Pt(2\ nm)/Co(t_{Co})]_3/IrMn(5\ nm)/Pt(2\ nm)$ for t_{Co}=0.38(-●-), 0.6 (-▼-) and 0.8 (-○-) nm. Note that in (a) and (b), the lines are guides to the eye, whereas in (c) the line is an exponential fit.

[see Fig. 8(b)]. However, Figure 7 shows that for t_{Co} =0.38 nm, H_E increases from ~40 Oe (for t_{Pt}=0 nm) to 130 Oe (for t_{Pt}=0.3 nm). This means that H_E increases by more than a factor of 3. It should be noted that even in the limit case where the three Co layers were completely uncoupled from each other and that only the last Co layer in the ML was tilted towards in-plane, the observed 15% decrease in M_R/M_S would mean that the tilt of the last Co layer should be of no more than 60° from the perpendicular to plane direction. Hence, assuming that H_E is directly propotional to the FM-AFM spin projection at the interface and that the AFM spins are completely oriented along the perpendicular direction during the field cooling process, this would roughly lead to an H_E enhancement of only a factor of 2 between the value at t_{Pt}=0 and H_E maximum. Since the Co layers in the ML are not completely uncoupled one from another, the three Co layers probably contribute to the 15% decrease of M_R/M_S, i.e., the three of them are somewhat tilted. This implies that the angular tilt is less than 60° and, consequently, the resulting H_E enhancement would be even less than a factor 2. Therefore, since the observed H_E increase is larger, this suggests that other mechanisms should be also considered as partially responsible for the H_E enhancement when the Pt spacer is inserted. For instance, it has been reported that some kind of defects near or at the FM-AFM interface may induce an enhancement of H_E due to local increases of the site anisotropy in the AFM as a consequence of the strains created by these defects, or because of a local decrease of the FM-AFM exchange coupling strength.[32,33] Interestingly, the strain induced anisotropy can be up to an order of magnitude larger than bulk values for strain levels of 1–2 %.[34] Since the Co and Pt cell parameters are not exactly the same, it is indeed likely that the insertion of a Pt spacer at the FM-AFM interface will cause local variations in the IrMn structure, particularly near the interface. Some authors have also observed enhancements of H_E by inserting impurities in the AFM (Ref. 35) or by ion irradiating the FM-AFM structure.[36] In both cases, the effect is to modify the domain configuration of the AFM in such a way that H_E is enhanced, for example creating more AFM domain walls, which enhance the net AFM moment being coupled to the FM. Finally, there could also be some improvement in the texture of the AFM when the Pt is inserted, meaning that the growth of IrMn would improve. However, this effect was not observed by x-ray diffraction.

Contrary to t_{Co}=0.38 nm, for t_{Co}=0.6 nm, H_E and H_C only decrease when the Pt spacer is introduced. Remarkably, although the anisotropy also slightly increases in this case [see Fig. 8(b)], M_R/M_S is already close to 1 for t_{Pt}=0 nm [see Fig. 8(a)]. Hence, for $t_{Co}=0.6$ nm, the Pt spacer does not seem to play a role in reorienting the last Co layer in the ML and it merely causes a decrease of the exchange bias strength due to its short-range character. This result confirms that the H_E enhancement observed for $t_{Co}=0.38$ nm is mainly due to the existing tilt of the Co layers in the ML when no Pt is inserted, rather than simply to the slight increase of perpendicular effective anisotropy. Moreover, since H_C decreases with increasing t_{Pt} in spite of the slight increase in K_{eff}, this demonstrates that FM-AFM exchange interactions play indeed an important role in the observed H_C values of the different samples.

For $t_{Co}=0.8$ nm, H_E also decreases whereas H_C slightly increases for low values of t_{Pt}. For thicker Pt spacers, both H_E and H_C decrease. The dependence of H_C on t_{Pt} is the result of the interplay between the increase of perpendicular orientation of the magnetization (i.e., M_R/M_S) in the ML as t_{Pt} increases [see Fig. 8(a)] and the decrease of FM-AFM exchange interactions (i.e., H_E) with increasing t_{Pt}. Interestingly, if the H_E vs t_{Pt} dependences for $t_{Co}=0.38$, 0.6, and 0.8 nm are plotted together normalizing at the large spacer thickness regime [see Fig. 8(c)], it can be observed that the decrease of H_E is more pronounced for $t_{Co}=0.6$ nm, where the main effect of the Pt spacer is to isolate the FM and the AFM while no improvement of M_R/M_S is observed. The line in Fig. 8(c) is a fit using an exponential law of the decrease of H_E for $t_{Co}=0.6$ nm. As it occurs for other FM-AFM systems where a nonmagnetic spacer is inserted at the FM-AFM interface, the experimental points for $t_{Co}=0.6$ nm are well fitted using this law.[37] However, deviations are observed for lower t_{Co} values which, as already commented, are due to the improvements of the perpendicular orientation of the [Pt/Co] ML magnetization.

Finally, for $t_{Co}=1.1$ nm, the [Pt/Co] ML maintain an in-plane magnetic anisotropy, even when the Pt spacer is introduced, with M_R/M_S values always lower than 0.15 (not shown). This is due to the increasing relative contribution from shape anisotropy when the thickness of the magnetic layer is increased. Therefore, as for $t_{Co}=0.6$ nm, the main role of the inserted Pt spacer is to simply reduce the FM-AFM exchange coupling effects.

IV. CONCLUSIONS

The magnitudes of the exchange bias field and coercivity in [Pt/Co] multilayers exchange coupled to IrMn, measured along the perpendicular to film direction, have been tailored by (i) varying the thickness of the Co layers inside the ML and/or (ii) inserting a Pt spacer between the ML and the AFM layer. An unusual dependence of the exchange bias properties on the FM layer thickness has been observed. Namely, the existence of a peak in the dependence of H_E and H_C on t_{Co} is in contrast with the commonly reported inversely proportional relationship between H_E and the FM thickness. Such atypical behavior is ascribed to the reduction of the FM effective anisotropy and the concomitant reduction of M_R/M_S for either very thin or exceedingly thick FM layers, evidencing that magnetic reorientation transitions in the FM have a strong influence on exchange bias effects. The insertion of a Pt spacer between the [Pt/Co] ML and the AFM layer results in totally different effects depending on the thickness of the Co layers in the ML. Namely, for low values of t_{Co}, H_E and H_C increase and exhibit maximum values for very thin Pt spacers ($t_{Pt}=0.3$ nm), progressively decreasing for larger t_{Pt} values. This is due to the twofold role of the Pt spacer. Namely, it enhances the perpendicular orientation of the Co layers in the ML but, additionally, it tends to reduce exchange bias properties due to the short-range character of the FM-AFM interactions. However, for thicker Co layers, both H_E and H_C mainly decrease when the Pt spacer is introduced. In this case the gain in perpendicular anisotropy brought about by the Pt spacer is not sufficient to overcome the concomitant decrease of the short-range exchange bias properties.

ACKNOWLEDGMENTS

This work was supported by the European Community through the NEXBIAS Grant No. HPRN-CT-2002-00296.

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