Competing magnetic interactions in perpendicular exchange-biased $[Co/Pt]_y/FeMn$ multilayers

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(Presented on 31 October 2005; published online 21 April 2006)

Perpendicular exchange bias in multilayers arises from a complex interplay between unidirectional anisotropy at the terminating ferromagnet(FM)/antiferromagnet(AFM) interface, the perpendicular anisotropy of the FM/nonmagnet multilayer stack, and the overall magnetostatic energy of the structure. Exchange bias field (H_{eb}) and coercivity (H_c) of $[Co/Pt]_y/FeMn$ with perpendicular anisotropy have been investigated by varying the thickness of a top Co layer in direct contact with the FeMn or number of Co/Pt bilayers. An unusual dependence of H_{eb} and H_c on these parameters has been observed. As the top Co layer thickness of $[Co/Pt]_y/FeMn$ multilayer varies, both H_{eb} and coercivity H_c show a peak in values and decrease when the top Co is too thin or too thick. H_{eb} of $[Co/Pt]_y/FeMn$ is inversely proportional to the number of Co/Pt bilayers, y for $2 \leqslant y \leqslant 5$, while H_c increases. For $y > 5$, H_{eb} increases and H_c decreases with y until both of them reach constant values. These observations have been attributed to the role of the effective perpendicular anisotropy of the FM multilayer, especially the FM layer adjacent to the AFM layer, in maintaining the perpendicular exchange bias. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2165597]

INTRODUCTION

Exchange bias between a ferromagnet (FM) and an antiferromagnet (AFM) layer, observed as a shift in the hysteresis loop when they are cooled through the blocking temperature, has attracted a lot of recent interests because of both intriguing physics and potential applications in information storage technologies.[1,2] Exchange bias has been extensively studied not only on thin-film structure with in-plane magnetization but also with perpendicularly magnetized multilayers.[3–7] It is clear that exchange bias is an interfacial effect between a FM and an AFM arising from a short-range FM-AFM exchange interaction. The magnetic moments of AFM are always along the axis that minimizes their energy of interaction with the FM across the interface. For the Co/FeMn interface it was observed that the induced Fe moment is fully aligned with the Co magnetization.[8] In perpendicular exchange-biased $[Co/Pt]_y/FeMn$ system, the magnetic moments in $[Co/Pt]_y$ and the induced Fe moment at the Co/FeMn interface are believed to be aligned perpendicular to the thin-film plane, along the field-cooled direction. Minimization of the exchange energy requires that the FM magnetization is also aligned perpendicular to the film plane. Hence, perpendicular exchange bias is also dependent on perpendicular anisotropy,[9] which arises from the enhanced perpendicular orbital magnetic moment (m_{orb}) of Co and Co_{3d}–Pt_{5d} interfacial hybridizations,[10] and can be critically dependent on the microstructural parameters, such as multilayer materials, thickness of each layers, etc.

Although exchange bias still remains an intensively studied but incompletely resolved phenomenon, it is generally agreed that H_{eb} is inversely proportional to the ferromagnetic layer thickness, t_{FM}, in in-plane exchange bias system.[11] In addition, when a ferromagnet is grown on an antiferromagnet exchange coupling between the two systems leads to an increased coercivity of the ferromagnet. Experimentally it has been shown that in bilayer Co/FeMn and Co/IrMn structures with in-plane exchange bias, both H_{eb} and H_c are inversely proportional to the thickness of Co.[12] However, in perpendicular exchange-biased $[Co/Pt]_y/FeMn$ systems it has been observed that H_{eb} is inversely proportional to the total number of Co/Pt bilayers, but H_c is proportional to the number of Co/Pt bilayers.[5]

In this article, we investigate the dependence of perpendicular exchange bias on the number of Co/Pt bilayers as well as the thickness of the top Co layer in direct contact with the FeMn. As the top Co layer thickness of $[Co/Pt]_y/FeMn$ multilayer increases, both H_{eb} and H_c increase and then decrease, due to the low effective perpendicular anisotropy when the top FM layer is too thin or too thick. The inverse relationship between H_{eb} and t_{FM} is observed when the number of bilayers y increases from 2 to 5, while H_c increases. As the number of bilayers increases further, H_{eb} increases and H_c decreases a little bit until both of them reach constant values. This relationship can be explained by the complex interplay between unidirectional anisotropy at the terminating FM/AFM interface and the effective perpendicular anisotropy of the FM multilayers.

EXPERIMENT

Two sets of samples were made by ion-beam sputtering at room temperature, with a perpendicular magnetic field of 400 Oe applied during the deposition. The first set of samples $[Co(6\ Å)/Pt(20\ Å)]_4/Co(x\ Å)/FeMn(80\ Å)$ has totally five Co/Pt bilayers, in which the bottom four bilayers have exactly the same Co thickness, and the top layer thickness, which is adjacent to the AFM layer, ranges from 3 to

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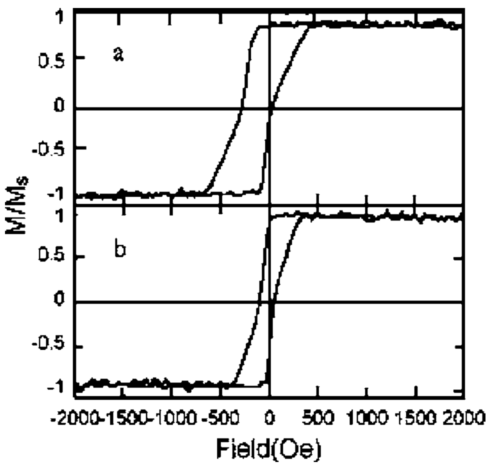

FIG. 1. Perpendicular hysteresis loops of [Co(6 Å)/Pt(20 Å)]$_4$/Co(x Å)/FeMn(80 Å) with x=(a) 6 and (b) 18.

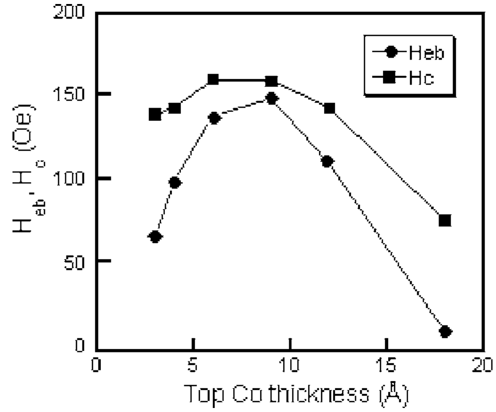

FIG. 2. Exchange bias field (H_{eb}) and coercivity (H_c) vs top Co thickness.

18 Å. The second set of samples is [Co(6 Å)/Pt(20 Å)]$_y$/FeMn(80 Å) with a different number of bilayers, y ranging from 2 to 30.

The chamber base pressure was 9×10^{-9} Torr and the Ar pressure during deposition was 1.2×10^{-4} Torr. The deposition rates for Pt, Co, and FeMn were monitored *in situ* during growth using a crystal thickness monitor, which was calibrated independently by *ex situ* x-ray reflectivity measurements of Pt, Co, and FeMn single-layer films, and subsequently, controlled by deposition time. A thick Pt buffer layer (200 Å) was deposited onto the Si substrate to introduce a Pt (111) growth orientation, the preferred orientation for perpendicular anisotropy of [Co/Pt]. The multilayers were also capped with a thin (~20 Å) Pt layer to prevent oxidization upon exposure to air. The hysteresis loops were measured using a vibrating-sample magnetometer (VSM) with magnetic field perpendicular to the thin-film plane.

RESULTS AND DISCUSSION

Typical perpendicular hysteresis loops of [Co(6 Å)/Pt(20 Å)]$_4$/Co(x Å)/FeMn(80 Å) are shown in Fig. 1, with x=6 and 18 Å. Both of the loops are rather square, because the magnetic behavior is dominated by the bottom layers of Co/Pt multilayer, but the exchange bias is almost nonexistent for x=18 Å. The dependences of H_{eb} and H_c on the top Co layer thickness are shown in Fig. 2. Both H_{eb} and H_c initially increase until the top Co thickness x is about 6–9 Å, then drop rapidly as x increases further. The decrease of H_{eb} and H_c with increasing FM layer thickness is consistent with the changes in effective perpendicular anisotropy. It is well known that the effective perpendicular anisotropy varies with the thickness of the FM layer as $K_{eff}=K_\nu+2K_s/t_{FM}$.[13] If Co is ultrathin (<5 Å), the effective perpendicular anisotropy will also decrease due to the interface roughness effect.[13]

The dependences of H_{eb} and H_c on the top Co layer thickness almost the same as reported earlier in the [Co/Pt]$_y$/IrMn system,[9] except for the critical difference that instead of changing the thickness of all the Co layers we have changed *only one* (the top) Co layer. The exchange bias is an interfacial effect between a FM and an AFM arising from a short-range FM-AFM exchange interaction at the interface. The magnetization direction of the FM layer at the FM/AFM interface determines the magnitude of the exchange bias. As the top Co layer thickness increases, the magnetic anisotropy of this layer turns to lie in plane so that the perpendicular exchange bias decreases very rapidly.

Figure 3 shows selected perpendicular hysteresis loops of [Co(6 Å)/Pt(20 Å)]$_y$/FeMn(80 Å) with y=3, 6, 30. When y=3, the shape of the hysteresis loop is less square and the coercivity is relatively small. As the number of Co/Pt bilayers increases to 6, the hysteresis loop becomes squarer due to more Co/Pt bilayers contributing to the perpendicular anisotropy. When y increases further to 30, the hysteresis loop becomes less square again. But there is still an unusually large H_{eb}, that has not been observed.

The exchange bias field and coercivity versus the number of bilayers (Fig. 4) show that as the number of bilayers increases to 5, H_{eb} is inversely proportional to the number of

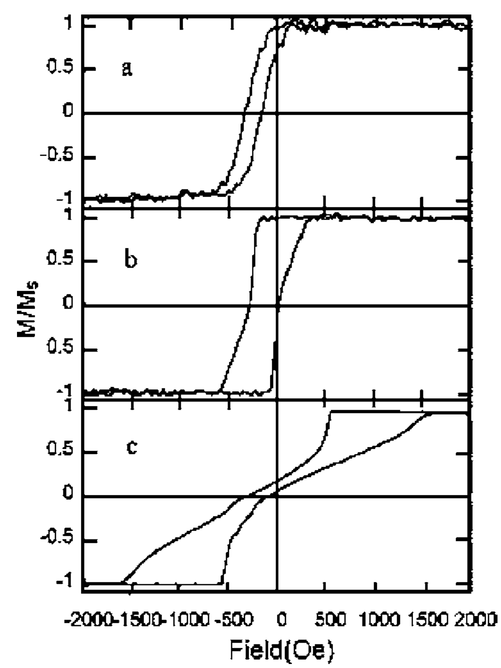

FIG. 3. Perpendicular hysteresis loops of [Co(6 Å)/Pt(20 Å)]$_y$/FeMn(80 Å) with y=(a) 3, (b) 6, and (c) 30.

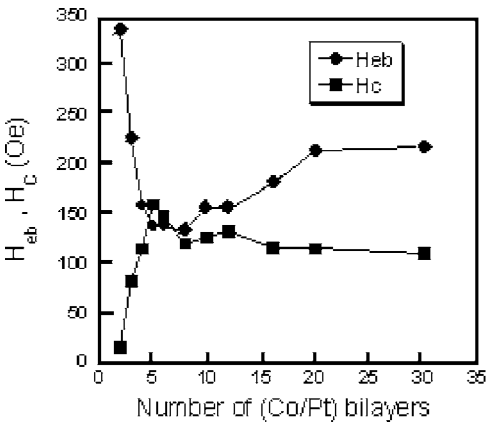

FIG. 4. Exchange bias field (H_{eb}) and coercivity (H_c) vs the number of bilayers.

bilayers or t_{FM}. When the number of Co/Pt bilayers continues to increase, magnetic thin films with perpendicular magnetic anisotropy try to form stripe domains to lower the magnetostatic energy by pulling the magnetization of the FM layer away from the perpendicular direction.[14] But this effect is not strong enough to drive the magnetization to lie in plane compared with the effect of the single top Co layer. Therefore, H_{eb} will not decrease as rapidly as it does when the top Co layer thickness increases. The strong exchange anisotropy energy pins the FM moments at the FM/AFM interface. As the number of Co/Pt bilayers increases further, the magnetostatic energy forces the magnetization in the multilayer stack to lie in plane. Above a critical number of bilayers, these competing energies are best resolved by the formation of a domain wall parallel to the film surface and separating the pinned layers at the interface from the underlying free layers. Because H_{eb} reaches a constant value when $y=30$, and is about the same as the value of H_{eb} when $y=3$, we can infer that the pinned layer corresponds to the top three Co/Pt bilayers.

Although the change of interface roughness could also affect the exchange bias, the root-mean-square (rms) roughnesses measured by atomic force microscope are 1.88, 2.12, and 2.45 Å for samples with $y=3$, 6, 30, respectively, which do not correlate with the change of the exchange bias. It is believed that the effect seen in the measurements of the second series of samples does not arise from an increase in roughness in the Co/Pt multilayer with the number of bilayers.

CONCLUSIONS

The exchange bias field H_{eb} and coercivity H_c of $[\text{Co}(6\ \text{Å})/\text{Pt}(20\ \text{Å})]_4/\text{Co}(x\ \text{Å})/\text{FeMn}(80\ \text{Å})$ and $[\text{Co}(6\ \text{Å})/\text{Pt}(20\ \text{Å})]_y/\text{FeMn}(80\ \text{Å})$ have been investigated. The change in the magnitude of H_{eb} can be explained by the competition between the magnetostatic energy and the exchange bias with perpendicular anisotropy. It has been shown that in the $[\text{Co}(6\ \text{Å})/\text{Pt}(20\ \text{Å})]_4/\text{Co}(x\ \text{Å})/\text{FeMn}(80\ \text{Å})$ system, exchange bias field and coercivity reach a maxima and decrease when the top Co is too thin or too thick. This is due to the effect of the strong magnetostatic energy on single Co layers which decrease the perpendicular anisotropy as well as perpendicular exchange bias. It is also found that H_{eb} of $[\text{Co}(6\ \text{Å})/\text{Pt}(20\ \text{Å})]_y/\text{FeMn}(80\ \text{Å})$ is inversely proportional to the number of Co/Pt bilayers or total Co thickness when y increases until 5. H_{eb} increases a little and then stays constant with a further increase in y. There is an unusually large H_{eb} even when the number of Co/Pt bilayers is 30. This is due to the effect of the weak magnetostatic energy of the whole multilayer with perpendicular anisotropy. The coercivity is basically proportional to the perpendicular anisotropy, which peaks when the number of bilayers is about 5–8. The relation is in contrast with the currently reported inversely proportional relationship between H_{eb} and t_{FM}. A model of separated pinned and free layer regions has been proposed, but there are still more theoretical and experimental works that need to be done to prove it.

ACKNOWLEDGMENTS

This work was supported by DOE Materials Science Division under Grant No. DE-FG03-02ER45987 and by the Campbell Endowment at UW.

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