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Correlation between perpendicular exchange bias and magnetic anisotropy in IrMn/[Co/Pt]$_n$ and [Pt/Co]$_n$/IrMn multilayers

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Perpendicular exchange bias has been observed for IrMn/[Co/Pt]$_n$ and [Pt/Co]$_n$/IrMn multilayers in the as-deposited state. The exchange bias field is largest when the IrMn film is grown on magnetically saturated Co/Pt multilayers (8.12 mT for $n=3$), whereas it is considerably smaller when domain formation in the IrMn film occurs before Co/Pt deposition (3.30 mT for $n=3$). After annealing at 220 °C in an out-of-plane magnetic field the perpendicular exchange bias field and magnetic anisotropy are considerably larger for the Co/Pt multilayers with an IrMn film at the bottom. The apparent correlation between bias and anisotropy is explained by the dependence of the perpendicular exchange bias field on the orientation of the Co spins near the Co/IrMn interface. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1861964]

I. INTRODUCTION

Exchange bias in ferromagnetic (FM)/antiferromagnetic (AFM) bilayer systems is crucial for applications such as read heads, sensors, and magnetic random access memory (MRAM). Although exchange bias has been studied extensively for FM films with in-plane magnetization, a satisfying microscopic description of the phenomenon is still lacking. What is clear, however, is the importance of exchange coupling between the interfacial planes of spins on either side of the FM/AFM interface.[1–3] In an attempt to obtain a better understanding of the role of the interfacial spin structure, exchanged-biased systems with out-of-plane magnetization have been studied recently. Among them are Co/Pt multilayers with CoO (Refs. 4–7) and NiO,[8] Co/Pt, CoFe/Pt, Co/Pd, and FeNi/FeMn multilayers with FeMn,[9–15] and NiFe/CoO multilayers.[16] Although these systems are interesting for fundamental studies of the exchange bias phenomenon, the low blocking temperature of CoO and NiO and the low corrosion resistance of FeMn limit their application potential. IrMn, on the other hand, is an AFM material that is frequently used in magnetic spin valves and magnetic tunnel junctions with in-plane magnetization. IrMn is less corroding than FeMn, and it combines a relatively high interfacial exchange energy ($\sigma \approx 0.2$ mJ/m^2) with a high blocking temperature of about 250 °C.[17–22] Recently, it was shown that IrMn can be successfully used to exchange bias systems with out-of-plane magnetization.[23,24]

In this paper we study perpendicular exchange bias in Co/Pt multilayers with an IrMn film at the bottom or on top. In particular, we focus on the magnetic-field annealing effects and the correlation between perpendicular exchange bias and magnetic anisotropy. These IrMn exchange-biased films are promising building blocks for the fabrication of magnetic spin valves and tunnel junctions with out-of-plane magnetization.

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II. EXPERIMENT

The systems under investigation consist of [Co (4 Å)/Pt (20 Å)]$_n$ multilayers, which are either grown on top of (bottom configuration) or covered by a 100-Å-thick IrMn film (top configuration). The films were deposited by dc magnetron sputtering through a metal shadow mask onto thermally oxidized Si substrates. The shadow mask defined Hall bars with a linewidth of 200 μm and large squares for structural characterization. The Hall bars were used to measure the extraordinary Hall effect (EHE). The exchange bias field and the perpendicular magnetic anisotropy of the multilayers were determined from EHE measurements with an out-of-plane and in-plane applied magnetic fields, respectively. The crystalline texture of the multilayers was studied with x-ray diffraction (XRD). The field annealing experiments were performed in a furnace that was specifically designed to fit in a superconductor magnet. The samples were heated at 220 °C for 1 h and subsequently cooled to room temperature in a magnetic field of 5.5 T.

III. RESULTS

Figure 1 shows hysteresis loops of a SiO_2/[Pt (20 Å)/Co (4 Å)]$_3$/IrMn (100 Å)/Pt (20 Å) multilayer (a) and a SiO_2/Pt (20 Å)/IrMn (100 Å)/[Co (4Å)/Pt (20 Å)]$_3$ multilayer (b) before and after magnetic-field annealing. Both the top and bottom configurations exhibit an out-of-plane magnetization and a clear perpendicular exchange bias after deposition. The exchange bias is largest for the Co/Pt multilayers with an IrMn film on top. For this configuration, domain formation in the IrMn film depends on the net moment on the Co surface. The first magnetization curves that were measured after deposition reveal that the magnetization of the Co/Pt multilayers is already saturated in zero magnetic field. The single-domain state of the Co/Pt multilayer, which is due to stray fields from the magnetron guns, enhances the exchange bias field for the top configuration. For the bottom configuration, domain formation in the IrMn film occurs before deposition of the Co/Pt multilayer and hence it

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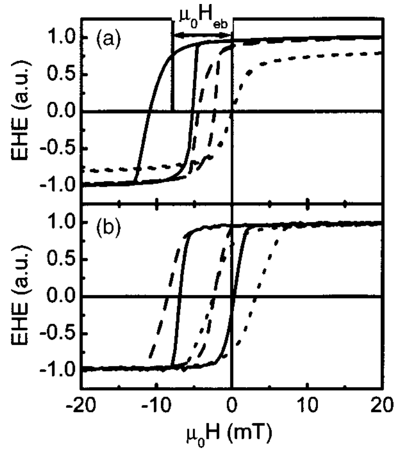

FIG. 1. Out-of-plane EHE hysteresis loops of (a) a SiO_2/[Pt (20 Å)/Co (4 Å)$]_3$/IrMn (100 Å)/Pt (20 Å) multilayer and (b) a SiO_2/Pt (20 Å)/IrMn (100 Å)/[Co (4Å)/Pt (20 Å)$]_3$ multilayer for the as-deposited state (solid line), and after field annealing at 220 °C perpendicular (dashed line) and parallel (dotted line) to the sample plane.

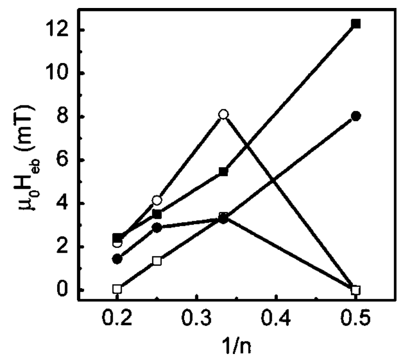

FIG. 3. Exchange bias fields as a function of the number of Co/Pt bilayer repetitions for the as-deposited top (open circles), annealed top (open squares), as-deposited bottom (filled circles), and annealed bottom (filled squares) configurations.

does not depend on the net moment at the IrMn/Co interface. The random domain structure in the IrMn film, however, does still result in a small perpendicular exchange bias because the Co spins couple most strongly to those AFM spins that are aligned parallel.

After annealing the films for 1 h at 220 °C in an out-of-plane field of 5.5 T, the exchange bias field ($\mu_0 H_{\mathrm{eb}}$) for the top configuration has decreased from 8.12 to 3.39 mT, whereas for the bottom configuration it has increased from 3.30 to 5.47 mT. The strikingly different annealing results for the top and bottom configurations are qualitatively similar to those found for IrMn exchange-biased systems with in-plane magnetization. For these structures, differences in (111) texture, grain size, and interface roughness have been suggested as possible explanations.[17–22] Figure 2(c) shows XRD scans on Co/Pt multilayers with IrMn on the top and IrMn at the bottom. In both cases a (111) texture is measured for the Pt and IrMn layers. The Pt and IrMn(111) peak intensities are slightly larger for the bottom configuration and the (111) texture improves upon annealing. The small difference in the (111) film texture is, however, unlikely to explain the perpendicular exchange bias results. Instead, the data in Figs. 1 and 2 suggest that other structural parameters such as grain size and interface roughness have a much greater influence on the exchange bias interactions in the Co/Pt–IrMn system.

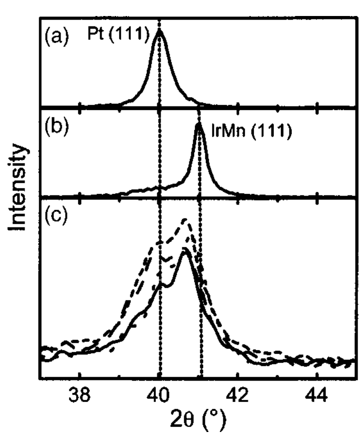

FIG. 2. XRD data for (a) a SiO_2/[Pt (20 Å)/Co (5 Å)$]_{20}$/Pt (20 Å) multilayer, (b) a SiO_2/[Pt (20 Å) /Co (4 Å)$]_3$/IrMn (500 Å)/Pt (20 Å) multilayer, and (c) a SiO_2/[Pt (20 Å)/Co (4 Å)$]_3$/IrMn (100 Å)/Pt (20 Å) and a SiO_2/Pt (20 Å)/IrMn (100 Å)/[Co (4Å)/Pt (20 Å)$]_3$ multilayer. In (c) the solid line, dotted line, dashed line, and short dashed line represent the data for the as-deposited top, annealed top, as-deposited bottom, and annealed bottom configuration, respectively.

As expected, no exchange bias is measured after annealing with an in-plane field of 5.5 T (dotted lines in Fig. 1). In this case the exchange coupling is established in the film plane. The decreased out-of-plane remanence after annealing with an in-plane field indicates a strong reduction of the perpendicular magnetic anisotropy.

Figure 3 summarizes the measured exchange-bias fields for different Co/Pt bilayer repetitions. Since the exchange coupling between FM and AFM films is primarily an interface effect, the exchange bias field does normally scale with the inverse of the FM film thickness. This is also true for exchange-biased Co/Pt multilayers with out-of-plane magnetization. The exchange bias is largest for an annealed film with only two Co/Pt repetitions and IrMn at the bottom. Films with only two Co/Pt repetitions and IrMn on the top do not exhibit perpendicular magnetic anisotropy and the perpendicular exchange bias field is zero. From fits to the data in Fig. 3 the interfacial exchange energy can be calculated. Using $\sigma = \mu_0 H_{\mathrm{eb}} M_s n t_{\mathrm{Co}}$, where M_s is the saturation magnetization of Co and t_{Co} is the Co layer thickness, we find $\sigma = 0.026\ \mathrm{mJ/m^2}$ for the top configuration after deposition and $\sigma = 0.014\ \mathrm{mJ/m^2}$ for the same configuration after magnetic-field annealing. For the bottom configuration the interfacial exchange energy improves from $\sigma = 0.012\ \mathrm{mJ/m^2}$ to $\sigma = 0.019\ \mathrm{mJ/m^2}$ upon annealing. These values for σ are about one order of magnitude smaller than those measured on IrMn exchange-biased systems with in-plane magnetization.[17–22] Although rather small, the perpendicular interfacial exchange energies for the Co/Pt–IrMn system are comparable to those measured on similar CoFe/Pt and Co/Pt multilayers with an AFM FeMn film on top.[9]

To determine the effects of field annealing on the perpendicular magnetic anisotropy of exchange-biased Co/Pt multilayers we measured the EHE voltage with an in-plane

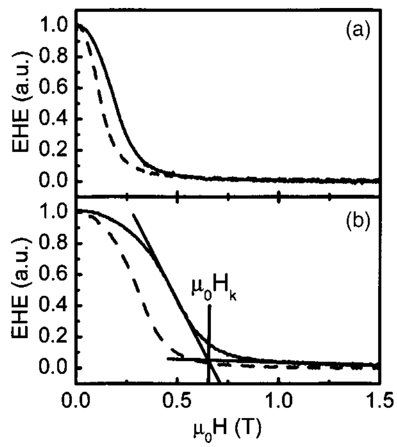

FIG. 4. In-plane EHE hysteresis loops of (a) a SiO_2/[Pt (20 Å)/Co (4 Å)$]_3$/IrMn (100 Å)/Pt (20 Å) multilayer and (b) a SiO_2/Pt (20 Å)/IrMn (100 Å)/[Co (4Å)/Pt (20 Å)$]_3$ multilayer for the as-deposited state (solid line), and after annealing at 220 °C with a magnetic field perpendicular to the sample plane (dashed line).

magnetic field. In this configuration, the applied field will coherently rotate the magnetization direction from perpendicular to parallel to the film plane. The anisotropy field H_k necessary to obtain in-plane magnetization is in a first approximation given by $H_k=2K_{\rm eff}/\mu_0 M_s$, where $K_{\rm eff}$ is the effective magnetic anisotropy. Figure 4 shows the normalized EHE voltage for a SiO_2/[Pt (20 Å)/Co (4 Å)$]_3$/IrMn (100 Å)/Pt (20 Å) multilayer (a) and a SiO_2/Pt (20 Å)/IrMn (100 Å)/[Co (4Å)/Pt (20 Å)$]_3$ multilayer (b) before and after magnetic-field annealing. From these measurements H_k was determined as the intersection of two lines that fit the curves at their maximum slope and at high magnetic field, respectively [see Fig. 4(b)]. For the as-deposited films the anisotropy field and hence the perpendicular magnetic anisotropy are considerably larger for the bottom than for the top configuration. This is most likely due to the fact that the IrMn layer acts as an additional seed layer promoting a higher degree of fcc (111) texture in the Co/Pt multilayer (see Fig. 2).[25,26] In addition, the IrMn film in the bottom configuration might influence the strain and interface roughness in the Co/Pt multilayer. These film properties are known to influence the perpendicular magnetic anisotropy as well.[27,28]

Annealing for 1 h at 220 °C in a field of 5.5 T reduces the perpendicular magnetic anisotropy. Since annealing at 220 °C does not drastically alter the perpendicular magnetic anisotropy of a Co/Pt multilayer without IrMn, the temperature effect is attributed to interdiffusion at the Co/IrMn interface. A similar reduction of the perpendicular magnetic anisotropy has also been found for CoFe/Pt multilayers with an FeMn film on top.[9] Figure 5 summarizes the effective magnetic anisotropy for different Co/Pt bilayer repetitions.

IV. DISCUSSION

As discussed before, the measured difference between the perpendicular exchange bias field of the as-deposited top and bottom structures is partly due to the growth sequence. The magnetic history of both multilayers, however, is similar after magnetic-field annealing. The correlation between perpendicular exchange bias and magnetic anisotropy is therefore studied best by comparing the experimental results on the annealed Co/Pt multilayers. From Figs. 3 and 5 it is clear that the perpendicular exchange bias and the effective magnetic anisotropy are considerably larger for the annealed Co/Pt multilayers with IrMn at the bottom. Although part of the difference between the exchange bias field of the bottom and top structures might be due to the dissimilar grain size or interface roughness, the data suggest that large out-of-plane magnetic anisotropy promotes large perpendicular exchange bias effects. This apparent correlation between bias and anisotropy can be understood by considering the formula of Meiklejohn and Bean for the exchange bias field, $H_{\rm eb}=JS_{\rm AFM}S_{\rm FM}/(\mu_0 a_{\rm AFM}{}^2 M_{\rm FM}t_{\rm FM})$.[29,30] In this formula J is the interface exchange energy, $a_{\rm AFM}{}^2$ is the AFM unit-cell size, $M_{\rm FM}$ is the magnetization of the FM, $t_{\rm FM}$ is the thickness of the FM, and for perpendicular exchange bias $S_{\rm AFM}$ and $S_{\rm FM}$ are the net magnetic moments along the film normal in the AFM and FM interfacial layers. For Co/Pt multilayers with large effective magnetic anisotropy the perpendicular magnetic moment in the FM film will be large, but for structures with small $K_{\rm eff}$ the Co spins might be tilted. This is especially true for the Co/Pt–IrMn system. In this system the interfacial magnetic anisotropy of the Co/IrMn interface is negative and therefore it favors in-plane magnetization.[31] This in-plane anisotropy forces the Co spins to tilt away from the film normal, especially those in the vicinity of the Co/IrMn interface. The resulting average tilt angle is determined by a competition between the out-of-plane anisotropy of the Co/Pt interfaces and the in-plane anisotropy of the Co/IrMn interface. The larger $K_{\rm eff}$, the smaller the misalignment between the Co interfacial moment and the film normal. From the formula of Meiklejohn and Bean it follows that any misalignment between the interfacial Co spins and the film normal reduces the perpendicular exchange bias field. It is therefore not surprising that the measured exchange bias field is largest for those Co/Pt multilayers with a large effective magnetic anisotropy, i.e., the Co/Pt multilayers with IrMn at the bottom. Another indication of a strong correlation between perpendicular exchange bias and magnetic anisotropy can be inferred from the measurements on Co/Pt multilayers with $n=2$ and IrMn on top. These multilayers exhibit an in-plane magnetization and no perpendicular exchange bias.

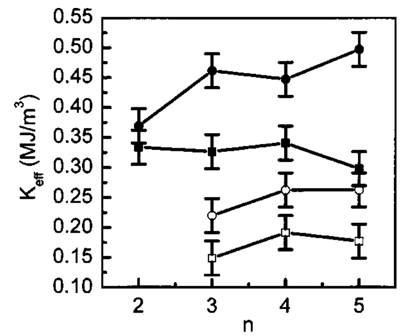

FIG. 5. Effective magnetic anisotropy as a function of the number of Co/Pt bilayer repetitions for the top (open symbols) and bottom (filled symbols) configurations. The circles and squares represent the data for the as-deposited and annealed films, respectively.

Recently, Sort and co-workers also found a correlation between the orientation of the spins in the FM interfacial layers and the magnitude of the perpendicular exchange bias effect. They showed that the exchange bias field of Co/Pt–FeMn and Co/Pt–IrMn systems is enhanced by the insertion of a thin Pt film between the Co and the AFM layer.[12,23] It was argued that the Pt reorients the Co spins from a tilted position (due the in-plane anisotropy of the Co/AFM interface) towards the film normal, leading to a larger perpendicular exchange bias. We measured a similar enhancement of the exchange bias field in SiO_2/[Pt (20 Å)/Co (5 Å)$]_3$/Pt(t)/IrMn (100 Å)/Pt (20 Å) multilayers. In our case a maximum exchange bias field of 16.5 mT was measured for $t_{Pt}=3$ Å, which is a factor of 2 larger than that of Co/Pt multilayers without a Pt spacer layer.[31] Both the Pt insertion experiments and the experiments in this paper clearly show that magnetic anisotropy drastically influences the exchange bias field of systems with out-of-plane magnetization.

V. CONCLUSION

We have shown that IrMn can be successfully used to exchange bias Co/Pt multilayers with out-of-plane magnetization. A clear perpendicular exchange bias is obtained in the as-deposited state for Co/Pt multilayers with an IrMn film on top or at the bottom. The interfacial exchange energy of the Co/Pt–IrMn systems is similar to that of Co/Pt–FeMn, but about one order of magnitude smaller than that of IrMn exchange-biased systems with in-plane magnetization. After annealing at 220 °C in an out-of-plane magnetic field the exchange bias of Co/Pt multilayers with IrMn at the bottom is larger than that of Co/Pt multilayers with IrMn on top. This difference is correlated with the effective magnetic anisotropy of the systems; the perpendicular exchange bias is largest for those multilayers with a large out-of-plane magnetic anisotropy. These results indicate that an out-of-plane spin alignment in the interfacial layers of the ferromagnet is crucial for large perpendicular exchange bias effects.

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