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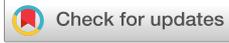
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Correlation between structural quality and magnetic properties of IrMn-based multilayers

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Structural and magnetic characterizations have been performed on exchange-biased multilayers, namely, Ta/*X*/IrMn/*Y*/Ta where *X* and *Y* are Py and/or Co. In agreement with earlier calculations, magnetic hysteresis loops reveal a clear correlation between the structural quality of the IrMn layer and the variation of the surface exchange energy constant versus its thickness. Moreover, we observe a direct link between the exchange bias variation with temperature and the magnetic disorder. © 2005 American Institute of Physics. [DOI: 10.1063/1.2136233]

I. INTRODUCTION

The exchange bias phenomenon occurs at the boundary between ferromagnetic (FM) and antiferromagnetic (AFM) materials. It is mainly characterized by a hysteresis loop of the FM material shifted along the magnetic-field axis. Although it has been discovered half a century ago¹ and that many researches have already been done in this field, the fundamental mechanism of the exchange bias is still unclear and the microscopic magnetism details remain puzzling.² It is well known that the exchange bias is an interfacial phenomenon^{3,4} but the full understanding of the phenomenon is complex because of the significant number of parameters involved. It has been shown that the exchange bias is strongly influenced, for example, by crystal structure,^{5,6} by AFM grain size,⁷⁻⁹ by interface roughness,¹⁰⁻¹² or by magnetic domains.¹³ In this paper, we show a clear correlation between the interface exchange coupling and the crystalline texture of the AFM pinning layer.

II. EXPERIMENTAL DETAILS

In our sample, an antiferromagnetic IrMn layer is located in between two ferromagnetic layers, either Co or Permalloy. Three distinct structures have been grown and studied, namely, glass/Ta₅/Py₁₀/IrMn_{*t*_{IrMn}}/Py₅/Ta₅, glass/Ta₅/Py₁₀/IrMn_{*t*_{IrMn}}/Co₅/Ta₅, and glass/Ta₅/Co₁₀/IrMn_{*t*_{IrMn}}/Co₅/Ta₅. The layer thicknesses are given in nanometers; and for the three structures, the thickness of the AFM layer *t*_{IrMn} has been varied from 2.5 to 24 nm. The multilayers were deposited onto float-glass substrates by sputtering Ir₂₀Mn₈₀ (IrMn), Py (Fe₂₀Ni₈₀), and Ta targets mounted on rf magnetron cathodes and a Co target mounted on a dc magnetron cathode. The operating Ar pressure was fixed to 5.10⁻³ mbars and the substrate was maintained at room temperature. In order to set exchange bias, the samples were annealed after growth for 30 min. at 200 °C with a 300 Oe magnetic field applied along the ferromagnetic layer easy axis. Microstructural studies have been carried out by x-ray diffraction (XRD) using the cobalt radiation on a Philips ex-

periment spectrometer. $\theta/2\theta$ high angle x-ray-diffraction and grazing incidence scattering (GIS) experiments were done to check the crystal structure. In the $\theta/2\theta$ scan mode, the detected diffraction peaks arise from the crystallographic planes parallel to the surface while the GIS scans inform about the crystallite distribution of crystallographic axes. Texture can be highlighted by combining these two experiments.

Exchange bias parameter at the top interface has been extracted from magnetic hysteresis loops performed by using a standard superconducting quantum interference device (SQUID) magnetometer. The surface exchange coupling energy is then conventionally defined by $J_{EX} = H_{EX} M_S t_{FM}$ where H_{EX} is the shift of the top FM layer hysteresis loop, and M_S and t_{FM} are the magnetization and the thickness of the considered FM layer.

III. CRYSTALLINE QUALITY

Figure 1 shows the XRD patterns obtained in (a) the $\theta/2\theta$ high angle geometry and (b) the grazing incidence ge-

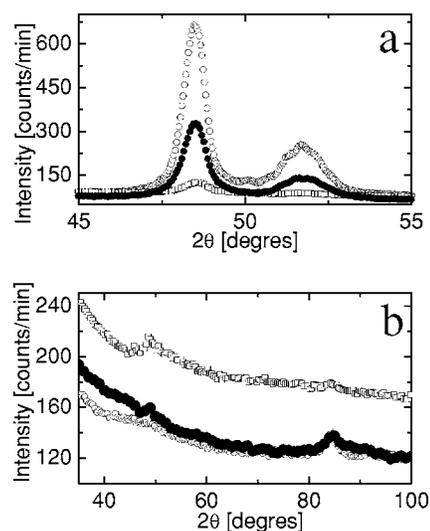


FIG. 1. X-ray-diffraction patterns measured in (a) $\theta/2\theta$ and (b) GIS geometries on glass/Ta₅/Py₁₀/IrMn₂₀/Py₅/Ta₅ (○), glass/Ta₅/Py₁₀/IrMn₂₀/Co₅/Ta₅ (●), and glass/Ta₅/Co₁₀/IrMn₂₀/Co₅/Ta₅ (□) multilayers.

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ometry, for the three sample structures with a 20-nm-thick IrMn layer. As we showed in a previous study,¹⁴ when the IrMn layer is sandwiched between two Py layers, Py and IrMn are well crystallized with the (111) planes parallel to the surface [Fig. 1(a)]. In this case, we can see more than one diffraction peak around the peak corresponding to the Py (111) planes. These additional peaks have been shown to arise from the x-ray interferences at each atomic plane, attesting the high structural quality and texture in those multilayers. In the $\theta/2\theta$ geometry, only the IrMn (111) peak can be observed while only the (220) planes diffract in GIS [Fig. 1(b)]. This is a second proof of a high crystalline texture along the growth direction. We have also shown in this previous study that the crystalline quality of our sample does not change when the IrMn thickness varies. When the top Py layer is replaced by a Co layer, both Py and IrMn layers are still well crystallized. However, this is not the case for the Co upper layer and, as a consequence, this last one destroys previously observed interference patterns in the $\theta/2\theta$ geometry. Moreover, in GIS, even if the (220) IrMn plane diffraction peak is still present, the (111) IrMn plane diffraction peak appears. This is due to some IrMn grains that have their (111) planes disoriented compared to the sample surface. When both Py layers are replaced by Co layers, the IrMn layer is less textured because of the amorphous structure of the Co underlayer. This results in a clear reduction of the (111) IrMn peak intensity in the $\theta/2\theta$ geometry. On the GIS spectra, only the (111) IrMn diffraction peak can be observed. The IrMn layer is still textured but the (111) planes in each grain are randomly oriented. Thus, the IrMn crystalline texture depends on the layers in contact with it. In conclusion, the IrMn layer crystalline texture is the best when sandwiched between two Py layers, is reduced when the top Py layer is replaced with Co, and is poor when sandwiched with two Co layers.

IV. IMPACT OF THE CRYSTALLINE QUALITY ON THE EXCHANGE BIAS

Obviously, structural disorder in the IrMn layer induces magnetic disorder in the volume and at the interface. We have the three sets of samples with increasing structural disorder in order to study the influence of the IrMn layer structural quality on the magnetic properties, the exchange-biased multilayers. The IrMn thickness dependence of the exchange coupling energy at the top interface, J_{EX} , is shown in Fig. 2 for the three sets of samples.

In all cases, J_{EX} falls sharply to zero for IrMn thicknesses less than 5 nm. In this thickness range, the anisotropy energy of the IrMn layer is lower than J_{EX} . Then, when the FM magnetization rotates, the IrMn resulting magnetization follows the FM layer one resulting in zero exchange bias. More interesting are the results for IrMn thickness higher than 5 nm. In this thickness range, the three sets of samples show different behaviors. Let us consider first the Py/IrMn/Py trilayer for which J_{EX} is maximum for $t_{IrMn} = 5$ nm. It strongly decreases when t_{IrMn} increases and tends to a constant value for thick IrMn layers. The second set of sample with Co/IrMn/Co trilayer shows a completely different variation of J_{EX} with IrMn thickness. The maximum is

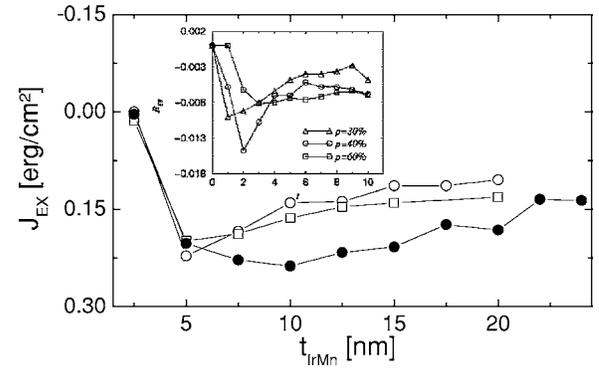


FIG. 2. Surface exchange coupling energy J_{EX} evaluated from equation $J_{EX} = H_{EX} M_{SFM}$ for the top IrMn interface in glass/Ta₅/Py₁₀/IrMn _{t_{IrMn}} /Py₅/Ta₅ (○), glass/Ta₅/Py₁₀/IrMn _{t_{IrMn}} /Co₅/Ta₅ (●), and glass/Ta₅/Co₁₀/IrMn _{t_{IrMn}} /Co₅/Ta₅ (□) multilayers with t_{IrMn} varying from 2.5 to 24 nm. The inset shows calculations made in Ref. 15 with the domain state model for 30%, 40%, and 60% of defects.

achieved for $t_{IrMn} = 10$ nm. Moreover, the maximum is less pronounced because of the round shape of the curve. And finally, when t_{IrMn} increases, J_{EX} decreases more slowly than in Py/IrMn/Py trilayers. In the case of Py/IrMn/Co multilayers, the variation of J_{EX} is similar to the Py/IrMn/Py set, with a maximum for $t_{IrMn} = 5$ nm. Nevertheless, J_{EX} decreases more slowly when the IrMn thickness is increased. In fact, concerning the J_{EX} variation, we observe for Py/IrMn/Co an intermediate evolution between the one of Py/IrMn/Py and of Co/IrMn/Co.

Indeed, structural defects induce magnetic disorder, so our experimental data show a clear correlation between the IrMn structural properties and the variation of J_{EX} with the IrMn thickness. These results are in good agreement with the numeric calculation done by Nowak *et al.*¹⁵ By using Monte Carlo technique the authors obtained a domain state model. They considered one monolayer variable thickness. To include a certain amount of structural disorder, the AFM layer was diluted; a fraction of randomly chosen atoms were left without spin. Then some exchange interactions were broken at random sites in the AFM layer, and consequently the energy cost of domain-wall formation was reduced. The inset of Fig. 2 shows the dependence of the bias field on the AFM thickness measured in atomic layers, for different dilutions of the AFM layer, calculated with the domain state model. These results are similar to our experimental data when 30%, 40%, and 60% dilutions are, respectively, associated with our Py/IrMn/Py, Py/IrMn/Co, and Co/IrMn/Co multilayers.

Nowak *et al.* explained the variation of the exchange field or of J_{EX} variation with the AFM thickness starting from the magnetic domain size. For very thin films, the surface exchange coupling energy is greater than the anisotropy energy, $J_{EX} \geq K_{AFM} t_{AFM}$. The net magnetization carried by the magnetic domains is unstable and follows the one of the FM layer during a hysteresis cycle. When the AFM thickness is such as both energies are equal, the magnetic domain configuration becomes stable and the magnetic domain size is equal to the domain-wall width: the exchange field is non-zero. When the IrMn thickness increases, the magnetic domain size increases, leading to a decrease of the net domain magnetization and thus to the decreases of the exchange bias.

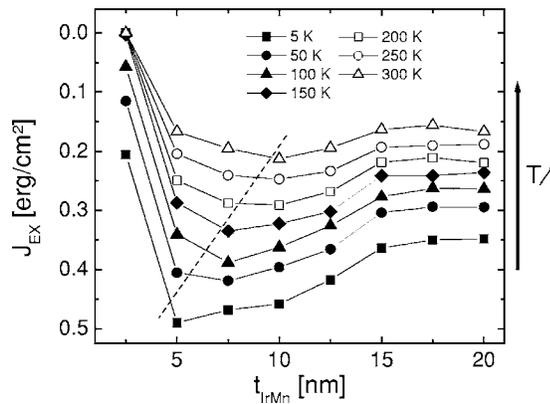


FIG. 3. Surface exchange coupling energy J_{EX} evaluated from equation $J_{EX} = H_{EX} M_S t_{FM}$ for the top IrMn interface in glass/Ta₅/Co₁₀/IrMn_{t_{IrMn}}/Co₅/Ta₅ multilayers at temperatures from 5 to 300 K.

Above a certain IrMn thickness, the magnetic domain size reaches a limit and the exchange field or the surface exchange coupling energy does not evolve anymore.

Moreover, Nowak *et al.* showed¹⁶ that the magnetic domain size depends on the AFM layer dilution; the smaller the dilution, the coarser the domains. Thus, for higher dilution which corresponds to Co/IrMn/Co multilayers, magnetic domains are smaller and the minimum AFM thickness to get exchange bias is increased. In addition, the smaller the domains size is, the greater is the net domain magnetization and so the surface exchange coupling energy. This explains why the surface exchange coupling energy is a little bit greater for Co/IrMn/Co. These results confirm that the structural quality of the IrMn layer has a strong impact on the surface exchange energy variation with IrMn thickness.

V. IMPACT OF THE TEMPERATURE ON THE EXCHANGE BIAS

We have also studied the variation of the coupling between the FM and AFM layers with temperature. Our results are shown on Fig. 3 where the variation of the surface exchange coupling energy with the IrMn thickness is reported for different temperatures in Glass/Ta₅/Co₁₀/IrMn_x/Co₅/Ta₅. Whatever the IrMn thickness, we observe an increase of the surface exchange coupling energy when temperature decreases. Moreover, the maximum of the $J_{EX}(t_{IrMn})$ curve shifts toward smaller IrMn thicknesses when the temperature decreases. Furthermore, as the temperature decreases, the shape of the curve is then similar to what we have measured at room temperature for the low disorder case, i.e., for Py/IrMn/Py samples. Thus, what we observe is an obvious link between temperature and number of defects in the AFM layer.

The same evolution of the curve slope with temperature has been observed by Ali *et al.*¹⁷ in Ta_{7.5}/Co₄/Cu_{2.3}/

Co_{2.5}/IrMn_x/Ta_{2.5} and has been reproduced by calculations based on the domain state model. In an intuitive way, it is easy to understand the shift of the maximum value of J_{EX} when the temperature changes. When the temperature increases, the interface becomes more and more unstable because of the enhanced thermal fluctuations. Thus, in order to stabilize the interface, a higher value of AFM thickness is needed. Consequently, the peak is shifted towards higher values of IrMn thickness at higher temperature. Nevertheless, a quantitative description requires the development of a model including temperature effects and giving the stability conditions of the domain magnetization with temperature, thickness, and AFM anisotropy.

VI. CONCLUSION

To conclude, we have studied the structural and the magnetic properties and their interplay in IrMn-based multilayers. The surface exchange coupling energy variation with IrMn thickness is closely dependant on the structural quality of the IrMn layer. This result is in a perfect agreement with earlier calculations made by Nowak *et al.* In addition, we show that the evolution of the exchange bias with temperature and defect number in the IrMn layer is strongly correlated.

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