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Tuning the coercive field of $CoFe_2$ in hard/soft $CoFe_2O_4/CoFe_2$ bilayers

R Sayed Hassan, C Mény, N Viart[1], C Ulhaq, G Versini, J L Loison and G Pourroy

Institut de Physique et Chimie des Matériaux de Strasbourg, UMR 7504, 23 rue du Loess, BP 43, 67034 Strasbourg Cedex 2, France
E-mail: viart@ipcms.u-strasbg.fr

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Abstract. The sensitivity of magnetoresistive devices, i.e. their ability to be switched by very small fields, depends on the softness of their soft electrode. In this paper, we show the possibility to tune the coercive field of the $CoFe_2$ alloy, commonly used as a soft electrode, from intrinsic values down to zero, by varying the pulsed laser ablation conditions of $CoFe_2/CoFe_2O_4$ bilayers. This tuning possibility relies on the existence of a frustration of the spins of the $CoFe_2$ layer originating from both the ferrimagnetic nature of the $CoFe_2O_4$ layer and the oxide/metal interface roughness.

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[1] Author to whom any correspondence should be addressed.

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1. Introduction

Spintronics-based devices have attractive applications in sensors and magnetic random access memories (MRAM). Their operation requires two electrodes of different magnetic hardness. In the majority of the studies presented in the literature [1, 2], this is obtained by the use of electrodes of different chemical compositions. Still, some works use electrodes of the same nature for the soft and the hard magnetic layers [3]–[7]. The different hardnesses are then obtained either by simply using different thickness for each electrode or by using a pinning layer in the form of an antiferromagnetic material [3, 4]. The hardness of the electrode may thus be increased but not decreased below its intrinsic value. It is, however, of crucial interest to control the softness of the electrodes, as well as their hardness because this softness controls the ability of the electrode to be sensitive to magnetic fields as weak as possible. In this paper, we show the possibility to tune the hardness of a magnetic $CoFe_2$ layer in the $CoFe_2O_4/CoFe_2$ system from an ultra soft magnetic material to a hard magnetic material by varying the elaboration conditions. One major advantage of this system is that the $CoFe_2O_4$ layer, being insulating, will not shunt the current away from the active layers in current-in plane configurations.

2. Experimental

The $CoFe_2O_4/CoFe_2$ systems were grown on Si (100) substrates heated at 300 °C by pulsed laser deposition using an excimer laser: XeCl ($\lambda = 308$ nm) (samples OM1) and KrF ($\lambda = 248$ nm) (samples OM2) with a fluency of about 2 and 3 J cm^{-2} respectively. The pulse length of the laser was 20 ns at a repetition rate of 10 Hz. The two layers $CoFe_2$ and $CoFe_2O_4$ were deposited by ablating a $CoFe_2$ metallic target. The oxide was first deposited under $O_2 : N_2$ (20 : 80) at a deposition pressure of 6.5 Pa for the samples (OM1) [8] and 5 Pa for the samples (OM2), respectively [9]. The laser was stopped during the evacuation of the reactive atmosphere down to a ground pressure of around 10^{-6} Pa for the deposition of the $CoFe_2$ layer. The thickness of the $CoFe_2O_4$ layer was fixed at 150 nm while that of the metal was varied between 5 and 54 nm. The bilayers were characterized by cross-sectional transmission electron microscopy. The magnetization of the films was measured by using a commercial Quantum Design superconducting quantum interference device (SQUID) magnetometer.

3. Results and discussion

A magnetization hysteresis loop typical for all samples is shown in figure 1. We observe two magnetic contributions of different hardness corresponding to the soft metallic layer and the hard oxide one. The samples were polarized in the plane of the bilayer to +50 kOe. The insert corresponds to the minor loop, where the field is traced from +1 kOe to −1 kOe and back to +1 kOe. This minor loop witnesses the reversal of the magnetization of the soft $CoFe_2$ layer without affecting the hard $CoFe_2O_4$ layer.

The hardness of the $CoFe_2$ layer may be evaluated from the coercive field of these minor loops. Its variation with the inverse $CoFe_2$ thickness for all samples is shown in figure 2. It is linear, which indicates that the coercive field variation has an interfacial origin. However, two different behaviors are observed: the coercive field either increases with the inverse of the $CoFe_2$ thickness for samples (OM1) (figure 2(a)) or decreases for samples (OM2) (figure 2(b)).

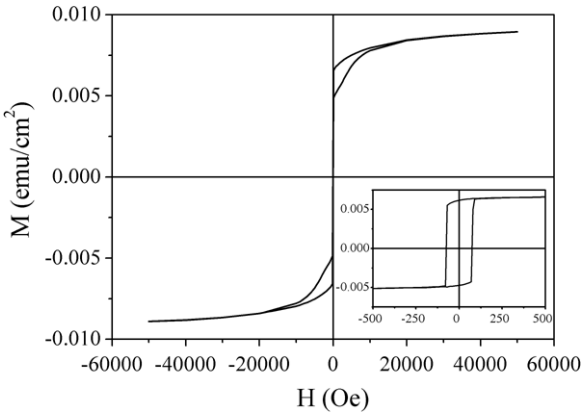

Figure 1. In-plane hysteresis loop for a sample (OM2):$(CoFe_2O_4)_{150\,nm}$/$(CoFe_2)_{54\,nm}$ deposited on to Si (100) with the KrF laser. Insert: the minor loop for the same sample.

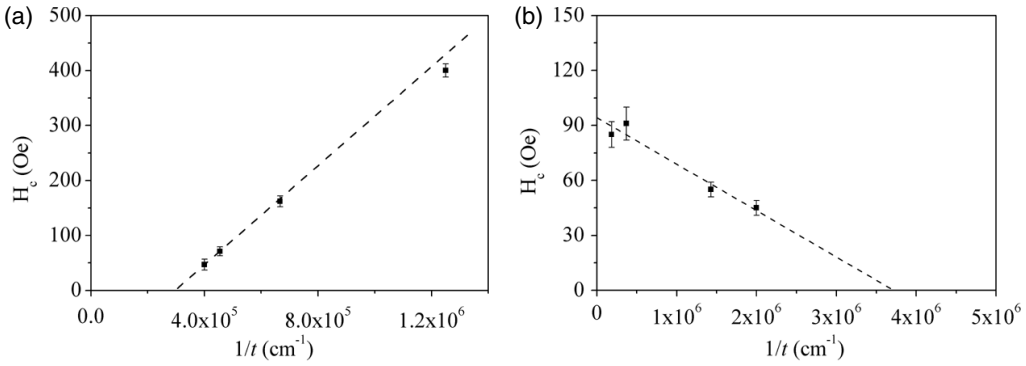

Figure 2. Variation of the coercive field of the $CoFe_2$ layer with the inverse of this layer thickness: (a) for samples (OM1) and (b) for samples (OM2).

The effective anisotropy K of the $CoFe_2$ layer of thickness t may be written as the sum of a volume K_V and interface K_S terms according to [10]:

$$Kt = K_V t + K_S, \tag{1}$$

and may be estimated from the linear variation of the coercive field with the inverse thickness of the metallic layer through the following relationship [11]:

$$H_C = \left|\frac{K}{M_S}\right| = \left|\frac{K_S}{M_S}\left(\frac{1}{t}\right) + \frac{K_V}{M_S}\right|, \tag{2}$$

where M_S is the saturation magnetization of the $CoFe_2$ layer (the measured value is about 1600 emu cm^{-3}, close to the 1800 emu cm^{-3} observed for the bulk $CoFe_2$ alloy).

The values of the volume and surface anisotropies deduced from figures 2(a) and (b) are $K_V = 170$ kerg cm^{-3} and $K_S = -0.6$ erg cm^{-2} for samples (OM1) and $K_V = 150$ kerg cm^{-3} and $K_S = -0.04$ erg cm^{-2} for samples (OM2). For all samples (OM1 and OM2), the product $K_S K_V$ is negative. This means that the two anisotropy contributions are perpendicular to each other. It is therefore possible to observe a thickness value (36 and 3 nm extrapolated from

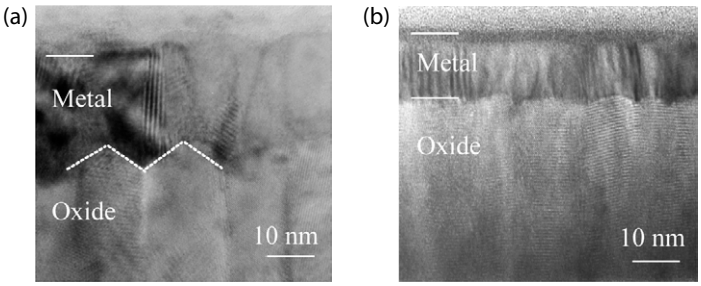

Figure 3. HR-TEM cross-section observations of samples (OM1) (a) and (OM2) (b).

figures 2(a) and (b) respectively) for which the surface and volume terms cancel. The anisotropy then vanishes and the material, having a zero coercive field, is ultra soft.

A perpendicular anisotropy term can be found at surfaces or interfaces, but, when observed, it is pointing out of the sample plane [12]–[14]. In our measurements, the magnetization curves are performed in the plane of the samples, therefore only the in-plane anisotropies are probed. As a consequence, the anisotropy term that is shown to be perpendicular to the applied field is not actually pointing out of plane but is confined in the plane of the film. However, it must be remembered that our samples are polycrystalline and therefore are not supposed to show well-defined anisotropy directions. This leads us to think that the observed perpendicular anisotropy is not a real anisotropy but reflects the tendency of the magnetization to align in a direction perpendicular to the direction of the applied magnetic field. This can be explained if we take into account the establishment of magnetic frustrations at the $CoFe_2O_4/CoFe_2$ interface. Indeed, $CoFe_2O_4$ is a ferrimagnetic layer constituted by two sub-lattices having opposite magnetization directions. Therefore, the roughness of the $CoFe_2O_4$ layer, observed on cross-sections by transmission electronic microscopy (figure 3), results in the creation of frustrations: a part of the ferromagnetic layer is willing to be parallel with the net magnetization of the ferrimagnet while another part is willing to be antiparallel. For the ferromagnetic layer the only way to solve these frustrations is to align perpendicularly to the ferrimagnet magnetization direction (as schematized in figure 4), which results in a perpendicular coupling [15]. However, due to the ferrimagnetic nature of $CoFe_2O_4$, the interface is not magnetically compensated, therefore a purely perpendicular coupling is not observed but is represented by the surface anisotropy term K_S that is perpendicular to the applied field direction. When the interface is very rough, the value of K_S is large because the degree of magnetic frustration is high. This is the case for samples (OM1) (figure 3(a)). For samples (OM2) deposited with the energetic excimer laser (KrF), the interface roughness is much smaller and the $CoFe_2O_4$ layer, while still being polycrystalline, presents a strong crystallographic (111) texture (figure 3(b)). This leads to lower frustrations and to a smaller value of K_S. The magnitude of the K_S value is therefore a measure of the degree of magnetic frustration in the $CoFe_2$ layer.

4. Conclusion

We have shown that in the $CoFe_2O_4/CoFe_2$ system, the coercive field of the soft layer $CoFe_2$ may be tuned and even decreased to zero. That may be explained by a magnetic frustration existing in the soft metallic layer and originating from the ferrimagnetic nature of the oxide

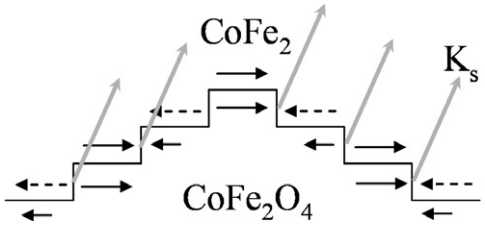

Figure 4. Schematic side view of the spin configurations in a $CoFe_2O_4/CoFe_2$ sandwich with a frustration of the $CoFe_2$ spins by the roughness of the $CoFe_2O_4$ layer.

layer coupled to the roughness of the oxide/metal interface. This frustration induces the fact that the surface anisotropy term is perpendicular to the bulk term. The total soft layer anisotropy term may then be tuned by the choice of its thickness. The values measured for the surface and bulk terms of the soft layer anisotropy are such that the total anisotropy may even be completely cancelled. This $CoFe_2O_4/CoFe_2$ system therefore offers a precious way to obtain an ultra soft magnetic layer.

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References

[1] Tripathy D and Adeyeyea A O 2007 *J. Appl. Phys.* **101** 09J505
[2] van Dijken S, Fain X, Watts S M and Coey M D 2004 *Phys. Rev.* B **70** 052409
[3] Egelhoff W F, Chen P J, Powell C J, Stiles M D, McMichael R D, Judy J H, Takano K, Berkowitz A E and Daughton J M 1997 *IEEE Trans. Magn.* **33** 3580
[4] Sousa J B, Ventura J O, Salgueira da Silva M A, Freitas P P and Veloso A 2002 *J. Appl. Phys.* **91** 5321
[5] Ji Y, Hoffmann A, Pearson J E and Bader S D 2006 *Appl. Phys. Lett.* **88** 052509
[6] Djayaprawira D D, Tsunekawa K, Nagai M, Maechera H, Yamagata S and Watanabe N 2005 *Appl. Phys. Lett.* **86** 092502
[7] Ku J, Chang J, Han S H, Ha J G and Eom J 2006 *J. Magn. Magn. Mater.* **304** e273
[8] Viart N, Rebmann G, Pourroy G, Loison J L, Versini G, Huber F, Ulhaq-Bouillet C, Mény C, Panissod P and Saviot L 2004 *Thin Solid Films* **471** 40
[9] Sayed Hassan R, Viart N, Ulhaq-Bouillet C, Loison J L, Versini G, Vola J P, Crégut O, Pourroy G, Muller D and Chateigner D 2007 *Thin Solid Films* **515** 2943
[10] Néel L 1954 *J. Physique Radium* **15** 225
[11] Viart N, Sayed Hassan R, Loison J L, Versini G, Huber F, Panissod P, Mény C and Pourroy G 2004 *J. Magn. Magn. Mater.* **279** 21
[12] Zana I and Zangari G 2004 *J. Magn. Magn. Mater.* **272–6** 1698
[13] Belmeguenai M, Devolder T and Chappert C 2006 *J. Magn. Magn. Mater.* **307** 325
[14] Yang J H, Kim M J, Cho S H, Kim H T, Kim Y B, Kim D H, Kapustin G A and Lee K H 2002 *J. Magn. Magn. Mater.* **248** 374
[15] Koon N C 1997 *Phys. Rev. Lett.* **78** 4865