AIP | Applied Physics Letters

Using exchange bias to extend the temperature range of square loop behavior in [Pt Co] multilayers with perpendicular anisotropy

J. Sort, F. Garcia, S. Auffret, B. Rodmacq, B. Dieny, V. Langlais, S. Suriñach, J. S. Muñoz, M. D. Baró, and J. Nogués

Citation: Applied Physics Letters **87**, 242504 (2005); doi: 10.1063/1.2139840
View online: http://dx.doi.org/10.1063/1.2139840
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/87/24?ver=pdfcov
Published by the AIP Publishing

Using exchange bias to extend the temperature range of square loop behavior in [Pt/Co] multilayers with perpendicular anisotropy

J. Sort[a)]
Institució Catalana de Recerca i Estudis Avançats (ICREA) and Department de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain

F. Garcia, S. Auffret, B. Rodmacq, and B. Dieny
SPINTEC (URA 2512 CNRS/CEA), CEA/Grenoble, 17 Av. Martyrs, 38054 Grenoble Cedex 9, France

V. Langlais, S. Suriñach, J. S. Muñoz, and M. D. Baró
Department de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain

J. Nogués[b)]
Institució Catalana de Recerca i Estudis Avançats (ICREA) and Department de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain

(Received 10 August 2005; accepted 10 October 2005; published online 6 December 2005)

The temperature dependence of the magnetic properties of [Pt/Co] multilayers (ML), exhibiting perpendicular anisotropy, with and without exchange biasing with an antiferromagnet (AFM) has been investigated. Upon heating, a loss of the out-of-plane anisotropy and, consequently, of the remanence to saturation ratio is observed in these systems. However, such effect occurs at higher temperatures in the [Pt/Co] ML exchange coupled to the AFM than for the unbiased ML. This is attributed to the additional anisotropy induced to the ML by the ferromagnetic-antiferromagnetic exchange coupling. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2139840]

Exchange interacting ferromagnetic (FM)-antiferromagnetic (AFM) materials exhibit a shift in the hysteresis loop (i.e., exchange bias) and an enhancement of coercivity when they are field cooled through the blocking temperature, T_B, of the AFM.[1] The shift of the hysteresis loops has been technologically exploited in devices based on spin valves or tunnel junctions.[2] Additionally, the H_C enhancement has been proposed to improve the hard magnetic properties of permanent magnetic materials.[3] Recently, the coupling of FM nanoparticles embedded in an AFM matrix has been shown to increase their superparamagnetic blocking temperature.[4]

Usually, exchange bias is observed in FM-AFM bilayers with in-plane anisotropy. However, exchange bias effects have also been induced along the perpendicular-to-film direction.[5–10] Most of the studied systems exhibiting out-of-plane exchange bias are based on [Pt/Co] or [Pd/Co] multilayers, ML, (as FM) coupled to an AFM. 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.[7–9,11] Moreover, these ML have potential applications in magneto-optic storage technology.[12,13] However, one of the features commonly observed in multilayers with perpendicular anisotropy is that, upon heating, a two-stage transition towards in-plane anisotropy occurs.[14,15] First, at a temperature called T^*, the out-of-plane uniaxial anisotropy decreases, giving rise to multidomain structures (with out-of-plane domains), which results in a complete loss of squareness, i.e., remanence to saturation ratio, $M_R/M_S=0$. Upon further heating, the easy axis of the multilayer rotates from out-of-plane to in-plane at a temperature denoted as reorientation transition, T_{Reo}.[14–21] This loss of squareness can be a limiting factor for the application of ML with out-of-plane anisotropy.

In this letter we demonstrate that it is possible to extend the temperature range where [Pt/Co] ML maintain $M_R/M_S=1$ by exchange coupling them, along the perpendicular direction, with an AFM with high T_B (IrMn and FeMn). This effect is linked to the uniaxial anisotropy, induced by the FM-AFM interface coupling, resulting also in coercivity enhancement, rather than to the unidirectional anisotropy which generates the loop shift.

Two series of multilayers with compositions:

(i) $[\mathrm{Pt}(2\ \mathrm{nm})/\mathrm{Co}(0.4\ \mathrm{nm})]_5/\mathrm{Pt}(2\ \mathrm{nm})$; $[\mathrm{Pt}(2\ \mathrm{nm})/\mathrm{Co}(0.4\ \mathrm{nm})]_5/\mathrm{Pt}(0.5\ \mathrm{nm})/\mathrm{IrMn}(5\ \mathrm{nm})/\mathrm{Pt}(2\ \mathrm{nm})$ and

(ii) $[\mathrm{Pt}(2\ \mathrm{nm})/\mathrm{Co}(0.3\ \mathrm{nm})]_5/\mathrm{Pt}(2\ \mathrm{nm})$; $[\mathrm{Pt}(2\ \mathrm{nm})/\mathrm{Co}(0.3\ \mathrm{nm})]_5/\mathrm{Pt}(0.5\ \mathrm{nm})/\mathrm{FeMn}(13\ \mathrm{nm})/\mathrm{Pt}(2\ \mathrm{nm})$

were deposited at room temperature onto thermally oxidized Si wafers by dc magnetron sputtering. The samples were annealed at 500 K for 1 h and subsequently cooled either in $H_{\mathrm{FC}}=0$ or $H_{\mathrm{FC}}-2.5$ kOe, applied perpendicular to the film plane. Hysteresis loops were measured along the perpendicular to film direction using a vibrating sample magnetometer at temperatures ranging from 300 to 420 K.

Note that the ultrathin Pt layer between the [Pt/Co] ML and the AFM was introduced to enhance the perpendicular orientation of the [Pt/Co] ML and, consequently, the magnitude of exchange bias.[7] Moreover, the presence of the interface Pt layer ensures that the top Co layer in both MLs is in contact with a Pt layer, rather than in direct contact with the AFM layer. This avoids the possible effects that different capping layers have on the out-of-plane anisotropy of ML.[22] The Pt layer has to be chosen thin enough not to deteriorate the exchange bias,[7] but thick enough to elude the effects of

[a)]Electronic mail: jordi.sort@uab.es.
[b)]Electronic mail: josep.nogues@uab.es

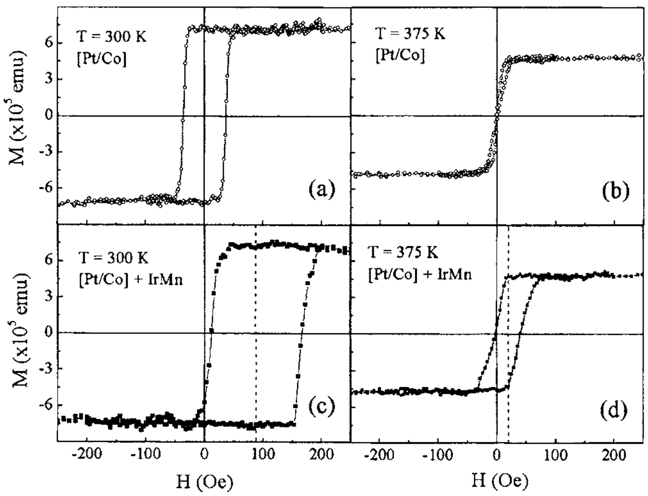

FIG. 1. Hysteresis loops corresponding to [Pt/Co] and [Pt/Co]/IrMn measured at $T=300$ K and $T=375$ K.

the thickness of the capping layers on the out-of-plane anisotropy. Since such effects saturate for $t_{\text{Capping}}=0.5$ nm,[22] this thickness was chosen for the interface Pt layer.

Shown in Fig. 1 are the hysteresis loops of the [Pt/Co] and [Pt/Co]/IrMn systems, measured at $T=300$ and $T=375$ K. At room temperature, the loop corresponding to [Pt/Co]/IrMn is shifted along the magnetic field axis by an amount $H_E=90$ Oe (where H_E designates the hysteresis loop shift). Moreover, the loops exhibit a square shape, with $M_R/M_S=1$ [note that the squareness ratio is evaluated after recentering for the hysteresis loop shift], confirming that both systems exhibit a perpendicular effective magnetic anisotropy. Remarkably, the coercivity of the exchange coupled [Pt/Co]/IrMn system is significantly larger than for the unbiased [Pt/Co] ML, i.e., the presence of the AFM also induces a coercivity enhancement. At $T=375$ K, although the [Pt/Co]/IrMn system still preserves a large squareness ratio, the uncoupled [Pt/Co] ML exhibits a virtually zero remanent magnetization. This suggests that at high temperatures the out-of-plane effective magnetic anisotropy is exceedingly weak to maintain the $M_R/M_S=1$ ratio. The central constriction observed in the hysteresis loop of Fig. 1(b), at $T=375$ K is typical of the instability of the single-domain configuration (i.e., the formation of out-of-plane domains),[14,17] probably indicating that for the uncoupled ML $T^* < 375\text{ K} < T_{\text{Reo}}$.

The temperature dependence of H_C for both [Pt/Co] and [Pt/Co]/IrMn systems and the loop shift, H_E, for [Pt/Co]/IrMn, after perpendicular field cooling, is shown in Fig. 2(a) and its inset, respectively. H_E progressively decreases with temperature vanishing at about $T_B \sim 400$ K. As expected, the [Pt/Co] ML without AFM exhibits no exchange bias. The coercivity also decreases with temperature in both systems. In the unbiased [Pt/Co] ML the reduction of H_C is due to the decrease of perpendicular anisotropy with temperature. In the ML/IrMn system the reduction of the coercivity originates both from the weakening of the out-of-plane anisotropy and from the decrease of the strength of the FM-AFM exchange interactions with temperature. This exchange coupling reduction is due to the decrease of anisotropy in IrMn. Fig. 2(a) also reveals that H_C vanishes at $T=380$ K for the unbiased [Pt/Co] ML and at $T=410$ K for

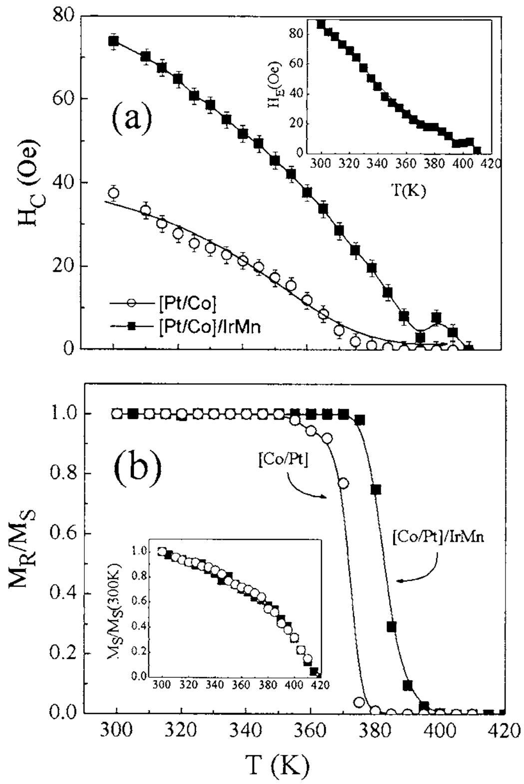

FIG. 2. (a) Temperature dependence of the coercive field, H_C, for unbiased [Pt/Co] (-O-) and exchange coupled [Pt/Co]/IrMn (-■-) multilayers. The inset shows the temperature dependence of the hysteresis loop shift, H_E, for [Pt/Co]/IrMn. (b) Temperature dependence of the remanence to saturation ratio, M_R/M_S, for [Pt/Co] and [Pt/Co]/IrMn multilayers. The inset shows the temperature dependence of the normalized saturation magnetization, M_S/M_S(300 K) for both systems. The lines are guides to the eye.

the exchange biased [Pt/Co]/IrMn system. The loss of coercivity indicates that the out-of-plane anisotropy is exceedingly weak to keep the out-of-plane homogeneous state. Hence, the loss of out-of-plane anisotropy occurs at a lower temperature for the single [Pt/Co] ML without AFM. This is more clearly evidenced in Fig. 2(b), where the temperature dependence of M_R/M_S is shown. The transition is found to occur at approximately 20 K higher temperature for [Pt/Co]/IrMn. In fact, in multilayered structures with perpendicular anisotropy, T^* and T_{Reo} can be tailored by varying the thickness of the different layers conforming the ML or the number of Pt/Co repeats.[16,18,20,21] However, since in our case both samples were deposited in the same run, the thicknesses of the Co, t_{Co}, and Pt, t_{Pt}, layers are the same. The inset of Fig. 2(b) shows the temperature dependence of $M_S(T)/M_S(300\text{ K})$. It can be observed that, for both systems, $M_S(T)/M_S(300\text{ K})$ vanishes at $T=420$ K, which is the Curie temperature, T_C, of the systems. Similar to T^* and T_{Reo}, T_C also depends on t_{Co} and t_{Pt}.[18,23] Hence, the fact that the temperature dependence of $M_S(T)$ is the same for both systems is a confirmation that t_{Co} and t_{Pt} in the two samples do not differ. Therefore, the enhancement of the $M_R/M_S=1$ temperature range is attributed to the exchange coupling between the [Pt/Co] ML and IrMn. It is worth noting that the ML/IrMn system after zero field cooling exhibits no loop shift, although the coercivity enhancement with respect to the single ML remains unchanged (not shown). Remarkably, the temperature dependence of the coercivity, M_R/M_S and M_S of the field cooled and zero field cooled ML/IrMn layers

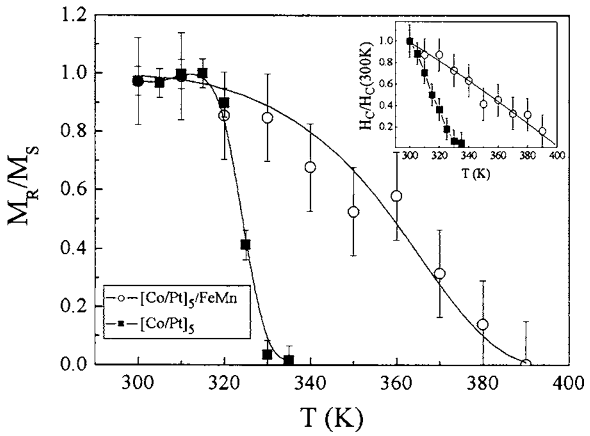

FIG. 3. Temperature dependence of the remanence to saturation ratio, M_R/M_S, for [Pt/Co] and [Pt/Co]/FeMn multilayers. The inset shows the normalized temperature dependence of the coercive field, H_C, for unbiased [Pt/Co] and exchange coupled [Pt/Co]/FeMn systems.

remains exactly the same. Hence, the enhancement of the transition temperature is not associated with the loop shift itself but, rather, to the coercivity enhancement induced by the AFM-FM coupling.

This enhancement of the transition temperature is exacerbated in exchange biased [Pt/Co] multilayers with thinner Co layers provided that the T_B of the AFM is sufficiently high (e.g., 13-nm-thick FeMn, where $T_B \sim 400$ K). This is illustrated in Fig. 3, where the temperature dependence of M_R/M_S is plotted for both [Pt/Co] and [Pt/Co]/FeMn. Note that since t_{Co} is smaller (0.3 nm) the loss of remanence for the unbiased [Pt/Co] ML occurs at lower temperatures, i.e., $\sim$330 K (Fig. 3) than for the [Pt/Co] ML with $t_{\text{Co}}=0.4$ nm (Fig. 2). The larger difference between T_B and the temperature of the loss of remanence for the unbiased ML results in a larger enhancement of the range of out-of-plane stability. The presence of the AFM also increases the temperature range for which $H_C>0$ (inset of Fig. 3). However, the transitions for FeMn are somewhat more rounded than for IrMn. This could be ascribed to the different spin structure of the AFMs when field cooled out of plane.

It has already been reported that exchange AFM-FM coupling can be used to enhance the Néel temperature of the AFM phase[24] or even the Curie temperature of the FM phase.[25] The former was explained by using a mean field model in which two disparate ordering temperatures approach each other as a function of the relative thickness of the layers. Moreover, exchange bias effects can induce a 30-fold increase in the superparamagnetic blocking temperature of FM nanoparticles.[4] This has been explained by the extra anisotropy provided to the FM by the interface FM-AFM exchange coupling.[4,26] It is well known that in FM-AFM systems the interface coupling induces a unidirectional anisotropy, which causes the loop shift and extra uniaxial (or higher order) anisotropies, which result in a coercivity enhancement.[27] Hence, the enhancement of the transition temperature at which M_R/M_S becomes 0 in [Pt/Co]/AFM can be interpreted by considering that the AFM induces an additional out-of-plane anisotropy to the ML after cooling. The extra anisotropy makes the ML more stable against thermal fluctuations. Hence, provided that the exchange bias blocking temperature in the [Pt/Co]/IrMn or [Pt/Co]/FeMn systems is higher than T^* and T_{Reo} of [Pt/Co] ML, the FM-AFM coupling extends the temperature range in which the FM preserves a perpendicular effective orientation. This finding may have important implications for perpendicular recording media or spin valves or tunnel junctions with out-of-plane anisotropy since it would extend the temperature range of applicability.

In conclusion, it has been shown that the temperature at which the perpendicular magnetic anisotropy of a [Pt/Co] ML loses its $M_R/M_S=1$ state can be enhanced by exchange coupling the ML along the perpendicular to film direction with an AFM with T_B higher than T^* and T_{Reo} of the single [Co/Pt] ML. The phenomenon can be understood considering that the AFM induces an extra- anisotropy in the FM, along the perpendicular to film direction, which persists at temperatures higher than T^* and T_{Reo}.

Financial support from the NEXBIAS (HPRN-CT 2002-00296), the 2005-SGR-00401 and the MAT-2004-01679 research projects is acknowledged.

[1] J. Nogués and I. K. Schuller, J. Magn. Magn. Mater. **192**, 203 (1999).
[2] B. Dieny, V. S. Speriosu, S. S. P. Parkin, B. A. Gurney, D. R. Wilhoit, and D. Mauri, Phys. Rev. B **43**, 1297 (1991).
[3] J. Sort, S. Suriñach, J. S. Muñoz, M. D. Baró, J. Nogués, G. Chouteau, V. Skumryev, and G. C. Hadjipanayis, Phys. Rev. B **65**, 174420 (2002).
[4] V. Skumryev, S. Stoyanov, Y. Zhang, G. C. Hadjipanayis, D. Givord, and J. Nogués, Nature (London) **423**, 850 (2003).
[5] B. Kagerer, Ch. Binek, and W. Kleemann, J. Magn. Magn. Mater. **217**, 139 (2000).
[6] S. Maat, K. Takano, S. S. P. Parkin, and E. E. Fullerton, Phys. Rev. Lett. **87**, 087202 (2001).
[7] F. Garcia, J. Sort, B. Rodmacq, S. Auffret, and B. Dieny, Appl. Phys. Lett. **83**, 3537 (2003).
[8] L. Sun, S. M. Zhou, P. C. Pearson, and C. L. Chien, J. Appl. Phys. **93**, 6841 (2003).
[9] C. H. Marrows, Phys. Rev. B **68** 012405 (2003).
[10] J. Sort, B. Dieny, M. Fraune, C. Koenig, F. Lunnebach, B. Beschoten, and G. Güntherodt, Appl. Phys. Lett. **84**, 3696 (2004).
[11] F. Garcia, G. Casali, S. Auffret, B. Rodmacq, and B. Dieny, J. Appl. Phys. **91**, 6905 (2002).
[12] W. B. Zeper, H. W. van Kesteren, B. A. J. Jacobs, J. H. M. Spruit, and P. F. Carcia, J. Appl. Phys. **70**, 2264 (1990).
[13] S. Uba, L. Uba, A. N. Yaresko, A. Ya. Perlov, V. N. Antonov, and R. Gontarz, Phys. Rev. B **53**, 6526 (1996).
[14] A. Berger and H. Hopster, J. Appl. Phys. **79**, 5619 (1996).
[15] P. Poulopoulos, M. Farle, U. Bovensiepen, and K. Baberschke, Phys. Rev. B **55**, R11961 (1997).
[16] D. P. Pappas, K. P. Kämper, and H. Hopster, Phys. Rev. Lett. **64**, 3179 (1990).
[17] D. Pescia and V. L. Pokrovsky, Phys. Rev. Lett. **65**, 2599 (1990).
[18] Y. Xiao, J.-H. Xu, and K. V. Rao, J. Appl. Phys. **79**, 6267 (1996).
[19] A. Berger and H. Hopster, Phys. Rev. Lett. **76**, 519 (1996).
[20] O. Shulte, F. Klose, and W. Felsch, Phys. Rev. B **52**, 6480 (1995).
[21] R. P. Cowburn, J. Ferré, J.-P. Jamet, S. J. Gray, and J. A. C. Bland, Phys. Rev. B **55**, 11593 (1997).
[22] B. N. Engel, M. H. Wiedmann, and C. M. Falco, J. Appl. Phys. **75**, 6401 (1994).
[23] Y. E. Wu, C. W. Su, C. S. Shen, and M. T. Lin, Chin. J. Phys. (Taipei) **39**, 182 (2001).
[24] P. J. van der Zaag, Y. Ijiri, J. A. Borchers, L. F. Feiner, R. M. Wolf, J. M. Gaines, R. W. Erwin, and M. A. Verheijen, Phys. Rev. Lett. **84**, 6102 (2000).
[25] X. Liu, Y. Sasaki, and J. K. Furdyna, Appl. Phys. Lett. **79**, 2414 (2001).
[26] D. Givord, V. Skumryev, and J. Nogués, J. Magn. Magn. Mater. **294**, 111 (2005).
[27] T. Mewes, H. Nembach, M. Rickart, S. O. Demokritov, J. Fassbender, and B. Hillebrands, Phys. Rev. B **65**, 224423 (2002); I. N. Krivorotov, C. Leighton, J. Nogués, I. K. Schuller, and E. D. Dahlberg, Phys. Rev. B **65**, 100402 (2002).