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Magnetization reversal in perpendicular exchange-biased multilayers

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Abstract. Co/Pt multilayers with perpendicular magnetic anisotropy exhibit an exchange bias when covered with an IrMn layer. The exchange bias field, which is about 7 mT for 3 Co/Pt bilayer repetitions and a Co layer thickness of 5 Å, can be increased up to 16.5 mT by the insertion of a thin Pt layer at the Co/IrMn interface. The interfacial magnetic anisotropy of the Co/IrMn interface ($K_S^{Co/IrMn} = -0.09$ mJ/m^2) favours in-plane magnetization and tends to tilt the Co spins away from the film normal. Dynamical measurements of the magnetization reversal process reveal that both thermally activated spin reversal in the IrMn layer and domain wall nucleation in the Co/Pt multilayer influence the interfacial spin structure and therefore the strength of the perpendicular exchange bias field.

PACS. 75.70.-i Magnetic properties of thin films, surfaces, and interfaces – 75.50.Ee Antiferromagnetics – 75.30.Gw Magnetic anisotropy

1 Introduction

In the past decades, exchange bias has been intensively studied because of its applications in the magnetic recording industry. Since its discovery by Meikeljohn and Bean in 1956 [1], many exchange-biased systems have been grown and characterized. Bilayers of ferromagnetic (FM) and antiferromagnetic (AFM) materials are particularly interesting. The interfacial exchange coupling between both layers leads to a shift in the hysteresis loop (commonly called exchange bias) and this shift is often accompanied by an increase in the coercive field of the FM layer. In-plane magnetized bilayers such as CoFe/IrMn have been studied for a long time and are already incorporated in magnetic sensors and read heads. However, although exchange bias effects are extensively used in commercial products its micromagnetic origin is still the topic of an intense scientific debate. The study of exchange bias in systems with perpendicular magnetic anisotropy might contribute to a better understanding of the exchange bias phenomenon and since the storage industry is expected to switch to perpendicular magnetic media in the near future it might also lead to practical applications.

Perpendicular exchange bias has been studied during the last 4 years. Co/Pt multilayers with out-of-plane magnetization have been coupled to CoO [2–5], and NiO [6] and Co/Pt, CoFe/Pt and Co/Pd multilayers have been coupled to FeMn [7–11]. Although these systems are interesting for fundamental investigations of exchange bias effects, low blocking temperatures (CoO and NiO) and low corrosion resistance (FeMn) limit their application potential. On the other hand, IrMn exhibits good corrosion resistance, relatively high interfacial exchange energy ($\sigma \approx 0.2$ mJ/m^2) and a high blocking temperature of about 250 °C [12–16].

In this paper we present a study of exchange bias effects in perpendicular magnetized systems with IrMn as the AFM. The ferromagnetic film consists of a [Co (5 Å)/Pt (20 Å)]$_3$ multilayer with perpendicular magnetic anisotropy. The IrMn is grown on top of the Co/Pt multilayer and it is capped with Pt to prevent oxidation. In some films the IrMn layer is directly contacted to the outermost Co layer, while in others these two materials are separated by a thin Pt insertion layer. Although both configurations exhibit perpendicular exchange bias, the largest effects are obtained for a 3 Å thick Pt insertion layer. Dynamical measurements of the magnetization reversal process corroborate the influence of the interfacial spin configuration on the strength of the perpendicular exchange coupling.

2 Experiment and results

The multilayers were deposited by dc magnetron sputtering through a metal shadow mask onto thermally oxidized Si substrates. The shadow mask defined Hall bars with a line width of 200 μm. The Hall bars were used to measure the extraordinary Hall effect (EHE) in a perpendicular

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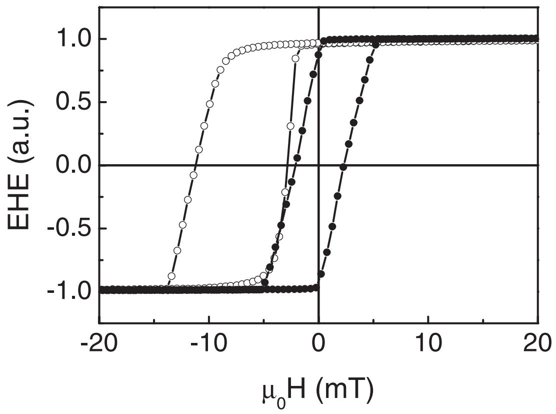

Fig. 1. Out-of-plane EHE hysteresis loops for SiO_2/[Pt (20 Å)/Co (5 Å)$]_3$/Pt (20 Å) (filled circles) and SiO_2/[Pt (20 Å)/Co (5 Å)$]_3$/IrMn (100 Å)/Pt (20 Å) (open circles) multilayers.

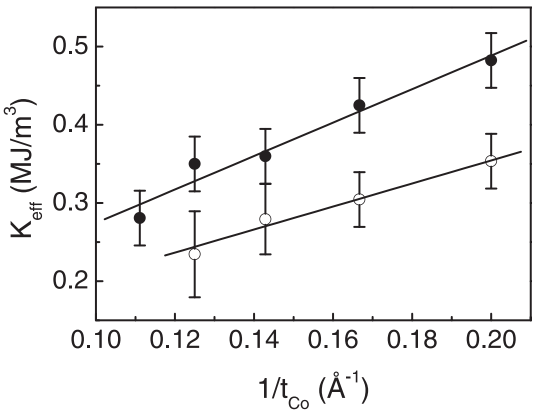

Fig. 2. Effective magnetic anisotropy as a function of the inverse Co layer thickness for SiO_2/[Pt (20 Å)/Co (t Å)$]_3$/ Pt (20 Å) (filled circles) and a SiO_2/[Pt (20 Å)/Co (t Å)$]_3$/ IrMn (100 Å)/Pt (20 Å) (open circles) multilayers.

magnetic field. These measurements are quasi-static and the results for unbiased and biased Co/Pt multilayer are shown in Figure 1. The Co/Pt multilayer with a 10 nm thick IrMn on top exhibits a perpendicular exchange bias of about 7 mT and an enhanced coercivity with respect to the unbiased film. In addition, contact between the IrMn and the Co/Pt multilayer induces an asymmetry in the ascending and descending branches of the hysteresis loop. This asymmetry, which also occurs in systems with in-plane magnetization [17–19], indicates that magnetization reversal proceeds differently for a switch into and away from the exchange bias direction. This difference is due to exchange coupling induced shifts in the energy barriers for magnetization reversal leading to a dissimilar domain nucleation density in the two branches of the hysteresis loop [20].

The deposition of an IrMn layer on top of the outermost Co layer drastically changes the effective magnetic anisotropy. In perpendicular systems, the film magnetization is out-of-plane because the interfacial anisotropy K_S compensates the demagnetization energy. For Co/Pt multilayers with three bilayer repetitions ($n = 3$) the effective anisotropy K_{eff} can be written as [8,21]:

$$K_{eff} = K_V + \frac{5K_S^{\mathrm{Co/Pt}}}{3t_{\mathrm{Co}}} + \frac{K_S^{\mathrm{top}}}{3t_{\mathrm{Co}}}. \qquad (1)$$

Here K_V is the volume anisotropy of the Co layers and $K_S^{\mathrm{Co/Pt}}$ is the interfacial anisotropy of the Co/Pt interface. For the unbiased and exchange-biased Co/Pt multilayers, K_S^{top} represents the interfacial anisotropy of the top Co/Pt interface ($K_S^{\mathrm{Co/Pt}}$) and the Co/IrMn interface ($K_S^{\mathrm{Co/IrMn}}$), respectively. Following this definition the magnetization of the multilayer is out-of-plane when $K_{eff} > 0$.

When a magnetic field is applied in the film plane, the magnetization coherently rotates away from the film normal. The field that is necessary to saturate the magnetization in the film plane, H_S, can be measured by EHE. For a crystalline magnetic anisotropy of second order, H_S equals the anisotropy field $H_k = 2K_{eff}/\mu_0 M_S$. We measured the saturation field as a function of the Co layer thickness and used this information to calculate the effective magnetic anisotropy. The results are shown in Figure 2. As expected from equation (1), K_{eff} decreases with increasing Co layer thickness. From the slopes of the fits to the data we infer $K_S^{\mathrm{Co/Pt}} = 0.11$ mJ/m^2 and $K_S^{\mathrm{Co/IrMn}} = -0.09$ mJ/m^2. The negative interfacial magnetic anisotropy of the Co/IrMn interface indicates that the contribution of this interface to the effective anisotropy favours in-plane magnetization. Although the magnitude of $K_S^{\mathrm{Co/IrMn}}$ is not enough to reorient the magnetization of the entire Co/Pt stack (K_{eff} is still positive), it may tilt the Co spins away from the film normal in the vicinity of the Co/IrMn interface. Since the exchange bias depends critically on the net out-of-plane interface moment, a misalignment between the Co spins and the film normal will reduce the perpendicular exchange bias field (see next section).

In order to reduce the tilt of the interfacial spins, we inserted a thin Pt layer at the Co/IrMn interface [9,22]. The result is a large enhancement of the exchange bias field as shown in Figure 3. The dependence of the perpendicular exchange bias on the Pt insertion layer thickness for patterned films is summarized in Figure 4. A maximum exchange bias field of 16.5 mT is obtained for $t_{Pt} = 3$ Å.

The results in Figure 4 indicate that the perpendicular exchange bias is very sensitive to the spin configuration at the Co/IrMn interface. To investigate how thermal activation and field sweep rate effects influence the perpendicular exchange bias we conducted dynamical magneto-optical Kerr effect (MOKE) measurements on samples with a size of about 0.5×0.5 cm (i.e. continuous films). In the MOKE set-up, a ferrite electromagnet produced high frequency magnetic fields with field sweep rates between 1 mT/s and 40 T/s. Dynamical hysteresis

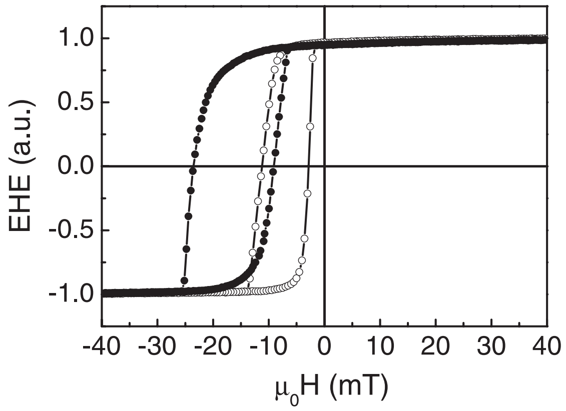

Fig. 3. Out-of-plane EHE hysteresis loops for SiO_2/[Pt (20 Å)/ Co (5 Å)]$_3$/Pt (t Å)/IrMn (100 Å)/Pt (20 Å) multilayers with t = 0 Å (open circles) and t = 3 Å (filled circles).

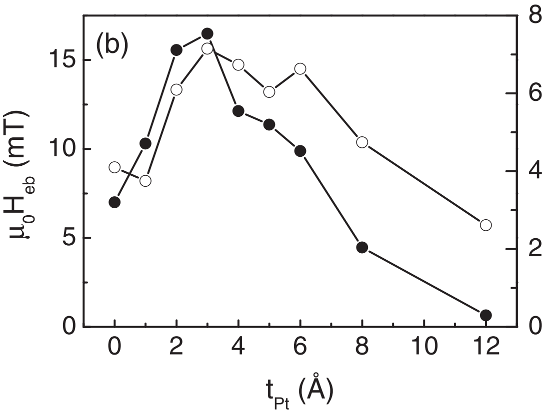

Fig. 4. Dependence of the exchange bias field (filled circles) and the coercive field (open circles) on the thickness of the Pt insertion layer. The data is extracted from EHE measurements with a line width of 200 μm.

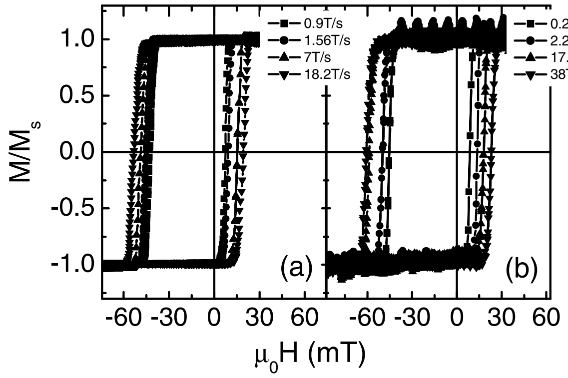

Fig. 5. Dynamical MOKE hysteresis loops for (a) SiO_2/[Pt (20 Å)/ Co (5 Å)]$_3$/IrMn (100 Å)/Pt (20 Å) and (b) SiO_2/[Pt (20 Å)/Co (5 Å)]$_3$/Pt (3 Å)/IrMn (100 Å)/ Pt (20 Å) at different field sweep rates.

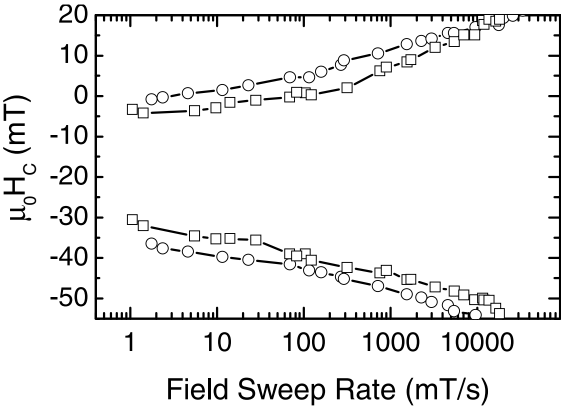

Fig. 6. Variation of the coercive fields as a function of the field sweep rate for the ascending and descending branches of the hysteresis loop. The squares and circles are measured on Co/Pt multilayers without and with a 3 Å thick Pt insertion layer, respectively.

loops were measured on exchange-biased Co/Pt multilayers with and without Pt insertion layers. A selection of hysteresis loops is shown in Figure 5. The evolution of the coercive field for the ascending and descending branches of the hysteresis loop are summarized in Figure 6. The energy necessary to reverse the magnetization increases with increasing field sweep rate. The change in switching field, however, is slightly different for the ascending and descending branches of the hysteresis loop. As a result, the perpendicular exchange bias field varies with the field sweep rate as shown in Figure 7. The dependence of the exchange bias on the field sweep rate is different for the Co/Pt multilayer with and without a Pt insertion layer. Whereas the perpendicular exchange bias field increases for the multilayer with a 3 Å thick Pt insertion layer at high field sweep rates, it decreases for the multilayer with a direct contact between the Co and IrMn layers.

A similar exchange-biased Co/Pt stack with only 4 Å thick Co layers was also measured (see Fig. 8). In this case the perpendicular exchange bias field decreases drastically above a field sweep rate of 1 T/s.

3 Interpretation

The spin structure at the Co/IrMn interface is the key to the perpendicular exchange bias phenomenon. According to Meiklejohn and Bean the exchange bias field can be written as [23,24]:

$$H_{eb} = \frac{J S_{\mathrm{AFM}} S_{\mathrm{FM}}}{\mu_0 a_{\mathrm{AFM}}^2 M_{\mathrm{FM}} t_{\mathrm{FM}}}. \tag{2}$$

In this formula J is the interface exchange energy, a_{AFM}^2 is the AFM unit cell size, M_{FM} is the magnetization of the FM, t_{FM} is the thickness of the FM, and for perpendicular exchange bias S_{AFM} and S_{FM} are the net magnetic moments along the film normal in the AFM and FM interfacial layers. A tilt of the Co spins away from the surface normal reduces S_{FM} and therefore it limits the perpendicular exchange bias field. The insertion of a thin Pt layer at the Co/IrMn interface reorients the Co spins to a more perpendicular position and this enhances the bias (see Figs. 3 and 4). However, the exchange interaction between the IrMn film and the Co/Pt multilayer

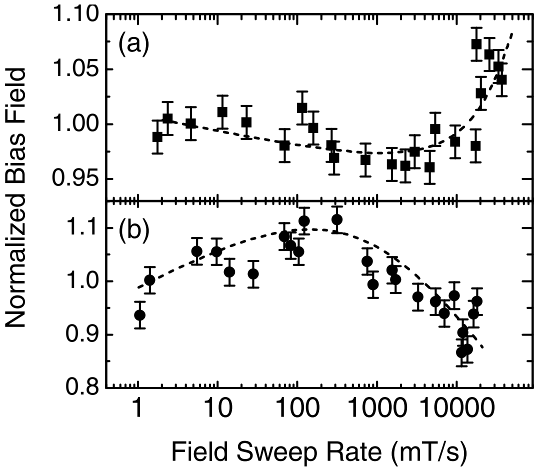

Fig. 7. Normalized perpendicular exchange bias field as a function of the field sweep rate for (a) SiO_2/[Pt (20 Å)/Co (5 Å)]$_3$/ Pt (3 Å)/IrMn (100 Å)/Pt (20 Å) and (b) SiO_2/[Pt (20 Å)/ Co (5 Å)]$_3$/IrMn (100 Å)/Pt (20 Å). The dashed lines are guides to the eye.

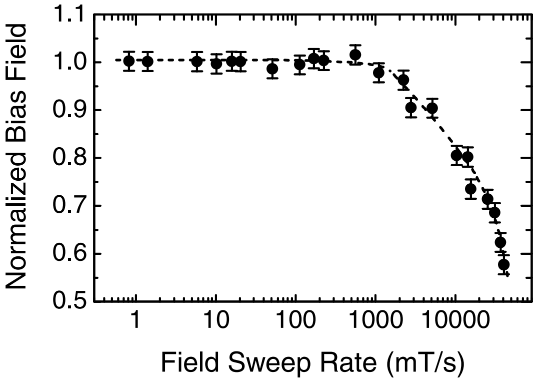

Fig. 8. Normalized perpendicular exchange bias field as a function of the field sweep rate for SiO_2/[Pt (20 Å)/Co (4 Å)]$_3$/IrMn (100 Å)/ Pt (20 Å).

decays exponentially with their separation distance and this leads to a decrease of the exchange bias field for thick Pt insertion layers [25,26]. Similar results on Pt insertion layers have been obtained for Co/Pt multilayers with a FeMn layer on top [9,22]

The dynamical evolution of the exchange bias field depends on thermally activated spin reversal in the IrMn film and the magnetization reversal process in the Co/Pt multilayer. XMCD spectroscopy experiments by Ohldag et al. on Co/IrMn bilayers reveal that the exchange bias originates from a small amount of pinned uncompensated spins at the IrMn interface [27]. The pinned spins do not rotate in an external magnetic field and the coupling between these uncompensated spins and the interfacial Co spins shifts the hysteresis loop away from zero field. The majority of the uncompensated interfacial spins in the IrMn film, however, are not pinned. These spins are dragged along with the magnetization reversal process in the Co layer and although they do contribute to an enhanced coercivity (with respect to the unbiased system) they are not responsible for the exchange bias effect. For small field sweep rates the reversal of AFM spins is supported by thermal activation [28–32]. At high field sweep rates, however, thermally activated spin reversal in the AFM is reduced and this enhances the number of pinned uncompensated spins and hence the exchange bias field. This is observed for Co/Pt multilayers with a Pt insertion layer at the Co/IrMn interface (see Fig. 7(a)). However, the perpendicular exchange bias field of the other Co/Pt multilayers decreases at high field sweep rates. This discrepancy is due to the influence of the magnetization reversal process in the Co/Pt multilayers. At low field sweep rates only a few inverse domains nucleate and magnetization reversal predominantly proceeds through domain wall motion. At high field sweep rates, however, domain wall propagation becomes relatively slow compared to the variation of the applied magnetic field and therefore more domains do nucleate in the Co/Pt multilayers [34]. In other words, with increasing field sweep rate the magnetization reversal mechanism changes from domain wall propagation to domain wall nucleation. The domain walls that nucleate in the FM film exert a torque on the AFM spin structure [33]. This torque promotes spin reversal in the IrMn film and hence it reduces the perpendicular exchange bias field. Since the magnitude of the torque effect is proportional to the density of domain wall nucleation sites it only becomes significant at high field sweep rates. At elevated frequencies the torque effect opposes the effect thermal activation. The influence of domain wall nucleation in the FM is especially strong for Co/Pt multilayers in which the outermost Co layer is directly contacted to the IrMn film. In this case direct exchange coupling between the FM and AFM interfacial moments results in a large torque effect and hence a decrease of the perpendicular exchange bias field at large field sweep rates. For multilayer with a Pt insertion layer at the Co/IrMn interface, on the other hand, the net Co moment along the film normal SFM is larger leading to an enhanced bias, but the interface exchange coupling J is smaller due to the separation of the FM and AFM layers. As a result, the dynamic response of the IrMn spins depends more on thermal activation than on domain wall nucleation and therefore the perpendicular exchange bias field increases at large field sweep rates.

4 Conclusions

In this paper we showed that it is possible to grow perpendicular exchange-biased structures using IrMn as the antiferromagnetic layer. The exchange bias field is maximized by the insertion of a 3 Å thick Pt layer at the Co/IrMn interface. Dynamical measurements of the magnetization reversal process in these perpendicular exchange-biased multilayers reveal the importance of the interfacial spin structure in both the FM and the AFM. The dependence of the perpendicular exchange bias on the field sweep rate is determined by a competition between reduced thermally activated spin reversal in the IrMn film (which increases the bias) and enhanced domain wall nucleation in the Co/Pt multilayers (which decreases the bias) at high frequencies. For Co/Pt multilayers with and without a Pt insertion layer we find that changes in thermal activation and domain wall nucleation dominate, respectively.

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References

1. W.H. Meiklejohn, C.P. Bean, Phys. Rev. **102**, 1413 (1956)
2. S. Maat, K. Takano, S.S.P. Parkin, E.E. Fullerton, Phys. Rev. Lett. **87**, 087202 (2001)
3. O. Hellwig, S. Maat, J.B. Kortright, E.E. Fullerton, Phys. Rev. B **65**, 144418 (2002)
4. T.L. Kirk, O. Hellwig, E.E. Fullerton, Phys. Rev. B **65**, 224426 (2002)
5. P. Kappenberger, S. Martin, Y. Pellmont, H.J. Hug, J.B. Kortright, O. Hellwig, E.E. Fullerton, Phys. Rev. Lett. **91**, 267202 (2003)
6. Z.Y. Liu, S. Adenwalla, J. Appl. Phys. **94**, 1105 (2003)
7. F. Garcia, G. Casali, S. Auffret, B. Rodmacq, B. Dieny, J. Appl. Phys. **91**, 6905 (2002)
8. F. Garcia, F. Fettar, S. Auffret, B. Rodmacq, B. Dieny, J. Appl. Phys. **93**, 8397 (2003)
9. F. Garcia, J. Sort, B. Rodmacq, S. Auffret, B. Dieny, Appl. Phys. Lett. **83**, 3537 (2003)
10. C.H. Marrows, Phys. Rev. B **68**, 012405 (2003)
11. L. Sun, S.M. Zhou, P.C. Searson, C.L. Chien, J. Appl. Phys. **93**, 6841 (2003)
12. H. Fuke, K. Saito, Y. Kamiguchi, H. Iwasaki, M. Sahashi, J. Appl. Phys. **81**, 4004 (1997)
13. A.J. Devasahayam, P.J. Sides, M. Kryder, J. Appl. Phys. **83**, 7216 (1998)
14. J. van Driel, R. Coehoorn, K.-M.H. Lenssen, A.E.T. Kuiper, F.R. de Boer, J. Appl. Phys. **85**, 5522 (1999)
15. J. van Driel, F.R. de Boer, K.-M.H. Lenssen, R. Coehoorn, J. Appl. Phys. **88**, 975 (2000)
16. G. Anderson, Y. Huai, L. Miloslawsky, J. Appl. Phys. **87**, 6989 (2000)
17. B. Beckmann, U. Nowak, K.D. Usadel, Phys. Rev. Lett. **91**, 187201 (2003)
18. D. Spenato, S.P. Pogossian, H. Le Gall, J. Magn. Magn. Mater. **262**, 294 (2003)
19. V.I. Nikitenko, V.S. Gornakov, A.J. Shapiro, R.D. Shull, K. Liu K, S.M. Zhou, C.L Chien, Phys. Rev. Lett. **84**, 765 (2000)
20. Magneto-optical Kerr effect measurements on continuous films exhibit a much smaller asymmetry and larger exchange bias (see Fig. 5). We attribute these differences to a variation in the nucleation process near the edges of the Hall bar structure. The influence of patterning on perpendicular exchange bias will be discussed elsewhere
21. F.J.A. den Broeder, H.C. Donkersloot, H.J.G. Draaisma, W.J.M. de Jonge, J. Appl. Phys. **61**, 4317 (1985)
22. J. Sort, F. Garcia, B. Rodmacq, S. Auffret, B. Dieny, J. Magn. Magn. Mater. **272-276**, 355 (2004)
23. W.H. Meiklejohn, C.P. Bean, Phys. Rev. **102**, 1413 (1956)
24. W.H. Meiklejohn, J. Appl. Phys. **33**, 1328 (1962)
25. N.J. Gökemeijer, T. Ambrose, C.L. Chien, Phys. Rev. Lett. **79**, 4270 (1997)
26. L. Thomas, A.J. Kellock, S.S.P. Parkin, J. Appl. Phys. **87**, 5061 (2000)
27. H. Ohldag, A. Scholl, F. Nolting, E. Arenholz, S. Maat, A.T. Young, M. Carey, J. Stöhr, Phys. Rev. Lett. **91**, 017203 (2003)
28. E. Fulcomer, S.H. Charap, J. Appl. Phys. **43**, 4184 (1972); **43**, 4190 (1972)
29. M.D. Stiles, R.D. McMichael, Phys. Rev. B **60**, 12950 (1999)
30. R.L. Stamps, Phys. Rev. B **61**, 12174 (2000)
31. A.F. Khapikov, J.W. Harrell, H. Fujiwara, C. Hou, J. Appl. Phys. **87**, 4954 (2000)
32. H. Xi, R.M. White, S. Mao, Z. Gao, Z. Yang, E. Murdock, Phys. Rev. B **64**, 184416 (2001)
33. M. Labrune, S. Andrieu, F. Rio, P. Bernstein, J. Magn. Magn. Mater. **80**, 211 (1989)
34. M.D. Stiles, R.D. McMichael, Phys. Rev. B **59**, 3722 (1999)