Available online at www.sciencedirect.com
SCIENCE DIRECT®

Journal of Magnetism and Magnetic Materials 290–291 (2005) 1056–1058

Journal of magnetism and magnetic materials

www.elsevier.com/locate/jmmm

Extraordinary Hall effect in $[Pt/Co]_{15}/AF/[Co/Pt]_{15}$ (AF = NiO, FeMn) multilayers with perpendicular anisotropy

C. Christides[a,b,*], Th. Speliotis[b], D. Niarchos[b]

[a]Department of Engineering Sciences, University of Patras, 26504 Patras, Greece
[b]Institute of Materials Science, National Center for Scientific Research, Demokritos, 15310 Athens, Greece

Abstract

The effect of the metallic antiferromagnet (AF) γ-FeMn and the AF-semiconductor NiO alloys on the polarity of Hall resistivity loops is examined in perpendicularly biased [Pt (2 nm)/Co (0.4 nm)]$_{15}$/AF (3 nm)/[Co (0.4 nm)/Pt (2 nm)]$_{15}$ multilayers.

PACS: 75.47.−m; 75.70.−i; 73.50.−h

Keywords: Exchange biasing; Hall resistivity; Multilayers–metallic

In thin film Co/Pt multilayers that are exchange coupled with antiferromagnetic (AF) layers and exhibit perpendicular magnetic anisotropy (PMA) the extraordinary Hall effect can be used for the measurement of hysteresis loops because the Hall resistivity is proportional to the perpendicular component ($M_\perp$) of magnetization [1]: $\rho_H = \rho_{xy} = R_o H + R_s M_\perp$, where H is the applied field, R_o is the ordinary Hall coefficient, and R_s is the extraordinary Hall coefficient (the demagnetization factor N is equal to 1 due to the geometry of H applied perpendicular to the film plane). In metallic multilayers the $|R_s M_\perp|$ term dominates the ρ_H signal for typical values of H. *Skew scattering* ($\propto \rho_{xx}$) and *side-jump* ($\propto \rho_{xx}^2$) mechanisms give different contributions to $R_s = \alpha\rho_{xx} + \beta\rho_{xx}^2$, where ρ_{xx} is the longitudinal resistivity. In magnetic multilayers [1,2] interface scattering modifies the relationship between R_s and ρ_{xx}. In addition, it was found that the skew-scattering parameter α could be negative [1] whereas the side-jump parameter β is dominated by interface scattering. Thus, the R_s depends on [1,3] the relative magnitude and sign of α and β parameters in multilayers. In this study the effect of the metallic AF γ-FeMn and the AF-semiconductor NiO alloys on the R_s of perpendicularly biased $[Pt/Co]_{15}/AF/[Co/Pt]_{15}$(AF = NiO, FeMn) multilayers is examined.

[Pt (2 nm)/Co (0.4 nm)]$_{15}$/AF (3 nm)/[Co (0.4 nm)/Pt (2 nm)]$_{15}$ (AF = NiO or FeMn), [Pt (2 nm)/Co (0.4 nm)]$_{15}$/FeMn (3 nm)/Pt (2 nm) and [Pt (2 nm)/Co (0.4 nm)]$_{15}$/Pt (2 nm) multilayers were deposited onto thermally oxidized Si(0 0 1)/SiO$_x$ (70 nm) substrates by DC and RF magnetron sputtering from separate targets in 3 mTorr Ar pressure. X-ray diffraction spectra show an average FCC Pt/Co structure, revealing strong (1 1 1)-texture. Isothermal magnetization and EHE loops were measured with a Quantum Design MPMSR2 superconducting quantum interference device (SQUID) magnetometer. The samples were cooled from RT (which is above the observed blocking temperature T_B)

---

*Corresponding author. Department of Engineering Sciences, University of Patras, 26504 Patras, Greece. Tel.:/fax: + 30 2610 997308.

E-mail address: christides@des.upatras.gr (C. Christides).

0304-8853/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmmm.2004.11.365

under a field of 6 kOe, applied perpendicular to the film surface. EHE measurements were performed with the van der Pauw technique using a DC current of 1 mA. All measurements were performed by first applying the maximum positive field $H = 6$ kOe perpendicular to the film surface and then completing the loop.

Fig. 1 shows Hall resistivity (solid line) and magnetization (open circles) hysteresis loops for the [Pt (2 nm)/Co (0.4 nm)]$_{15}$/AF (3 nm)/[Co (0.4 nm)/Pt (2 nm)]$_{15}$ and [Pt (2 nm)/Co (0.4 nm)]$_{15}$/Pt (2 nm) multilayers at 5 K. The polarity of ρ_H loops is negative for NiO and Co/Pt whereas it becomes positive for FeMn. However, the hysteresis loops of magnetization exhibit similar features. These loops are typical of perpendicularly biased Co/Pt multilayers where the reversal of magnetization is characterized by nucleation and domain wall motion before saturation. In addition, a loop-shift towards negative fields appears for AF = FeMn and NiO samples, evidencing an exchange-bias field H_{eb}. The shifted loops are symmetric about the H_{eb}, indicating that the H_{eb} shifts the loop but it cannot alter the reversal pathway because the uniaxial anisotropy in Pt/Co interfaces is so strong that limits potential reversal behavior. Notice that the value of $H_{eb} = -150$ Oe is the same for AF = FeMn and NiO layers. This is an indirect evidence that the magnitude of H_{eb} depends predominantly on the number of [Co/Pt] bilayer repeats and the AF layer thickness. Remarkably, we have observed that the addition of a 3 nm thick FeMn layer on top of [Pt (2 nm)/Co (0.4 nm)]$_{15}$ multilayers changes the polarity of R_s from negative to positive whereas $H_{eb} = 0$ between 5 and 300 K. It shows that the change of the polarity of ρ_H loops with addition of a thin FeMn layer *does not dependent on the presence of exchange-bias effect and the position of the FeMn layer in the stacking sequence* of Co/Pt multilayers. Note that similar measurements have shown an $H_{eb} \neq 0$ when a 20 nm thick FeMn layer was deposited on top of [Pt (2 nm)/Co (0.4 nm)]$_{15}$, indicating that the anisotropy of FeMn layers decreases as AF layer thickness decreases. Thus, the observed $H_{eb} \neq 0$ in Fig. 1c provides an indirect evidence for interlayer coupling between perpendicularly biased [Pt/Co]$_{15}$ sublayers across a common FeMn spacer [4] that stabilizes exchange-bias in a sandwiched AF thin layer whereas the simple [Pt/Co]$_{15}$/FeMn (3 nm) structure does not exhibit exchange bias.

Fig. 2 shows the temperature dependence of the EHE resistance for all the Co/Pt-based samples and for a 70 nm thick Pt film that is used as reference. The resistances, $R(T)$, were measured at zero field (ZF) between 5 and 320 K whereas an $H_{FC} = 3$ kOe was

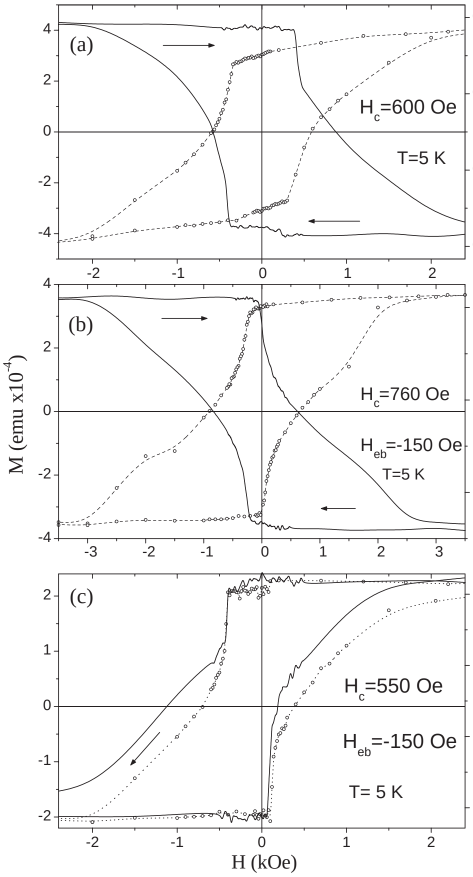

Fig. 1. EHE (solid line) and magnetization (circles) loops for: (a) [Pt/Co]$_{15}$/Pt (2 nm), (b) [Pt/Co]$_{15}$/NiO/[Co/Pt]$_{15}$, and (c) [Pt/Co]$_{15}$/FeMn/[Co/Pt]$_{15}$ multilayers.

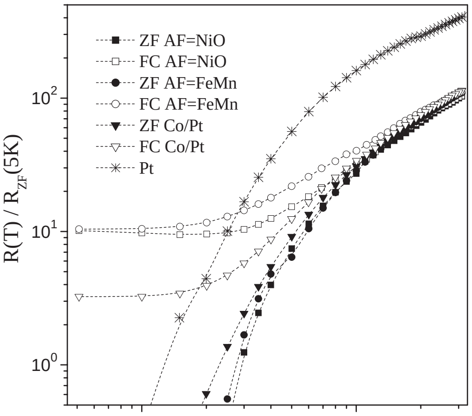

Fig. 2. Normalized ZF (black symbols) and FC (open symbols) $R(T)/R_{ZF}(5\,K)$ vs. T measurements for [Pt (2 nm)/Co (0.4 nm)]$_{15}$/AF (3 nm)/[Co (0.4 nm)/Pt (2 nm)]$_{15}$ (AF = NiO → squares, FeMn→circles), [Pt (2 nm)/Co (0.4 nm)]$_{15}$/Pt (2 nm) (triangles) multilayers and 70 nm thick Pt film. $H_{FC} = 3$ kOe, applied perpendicular to film plane. Both axes are in logarithmic scale with basis 10. To emphasize the behavior at lower temperatures the *decimal logarithms* of the normalized $R(T)/R_{ZF}(5\,K)$ values are plotted.

applied perpendicular to film plane at 320 K and then the $R_{\mathrm{FC}}(T)$ was measured in a field-cooling (FC) process. For each sample the $R(T)$ curves were normalized to the corresponding ZF resistance, $R_{\mathrm{ZF}}(5\,\mathrm{K})$, of the same film at 5 K. Thus, the $R_{\mathrm{ZF}}(5\,\mathrm{K})$ has been used as the residual resistance due to the temperature-independent scattering from defects and impurities. In multilayers with AF = FeMn and NiO layers the $R_{\mathrm{FC}}(T)$ data are above the corresponding $R_{\mathrm{ZF}}(T)$ measurements. In this case the $R_{\mathrm{FC}}(T)$ values below 60 K tend to FC residual resistances which are higher than the corresponding ZF resistances. It can be considered as the manifestation of the exchange bias effect which, in principle, could modify the asymmetric scattering of the conduction electrons in the Co/Pt layers that are responsible for the EHE.

In this study we focus on the induced change of the EHE loop polarities by addition of a very thin FeMn metallic layer. Since, usually, Co/Pt multilayers with PMA exhibit [5] negative polarities in ρ_{H} loops, as in Fig. 1a, it is rather surprising that a 3 m thick FeMn layer reverses the polarity of EHE loops. To understand this effect we write the total Hall resistivity as [6]

$$\rho_{\mathrm{H}} = \rho_{\mathrm{xy}} \simeq -\lambda_{\mathrm{so}} M_{\perp}(A\rho_{\mathrm{xx}} + B\rho_{\mathrm{xx}}^2) + CJ^3\chi_o, \quad (1)$$

where λ_{so} is the spin–orbit coupling constant, A and B are constants that their signs depend on the position of the Fermi level in a band, C is a positive parameter, J is the exchange coupling integral that is positive if the interaction is the *s–d* exchange, and χ_{o} is the total (uniform) chirality. Note that the coefficients in: $R_{\mathrm{s}} = \alpha\rho_{\mathrm{xx}} + \beta\rho_{\mathrm{xx}}^2$, and Eq. (1) imply that: $\alpha = -\lambda_{\mathrm{so}}A$ and $\beta = -\lambda_{\mathrm{so}}B$ (the ordinary Hall coefficient R_{o} does not appear in Eq. (1)). The last term in Eq. (1) has been introduced because chirality-driven EHE contributions might be observed [7] in the three-dimensional noncollinear AF spin structure [4] of γ-FeMn due to lattice distortions perpendicular to (1 1 1) plane [7]. Thus, Eq. (1) indicates that addition of a 3 nm thick FeMn layer is most unlikely to disturb the sign of λ_{so} or the position of the Fermi level (sign of A and B constants) throughout the, much thicker, $[\mathrm{Pt/Co}]_{15}$ sublayer structures used here. The other possibility to explain the observed (Fig. 1) reversal of EHE polarity via the last term of Eq. (1) is to assume that current shunting gives rise to a positive ρ_{H} contribution that surpasses the negative ρ_{H} contribution (Fig. 1a) from the Co/Pt multilayer in the first term of Eq. (1). Furthermore, one may argue that even without reflectivity of electrons at Co/NiO interfaces the impenetrable NiO layer prevents any shunting of current through subsidiary layers (such as FeMn in the metallic case) and it does not affect the negative polarity of ρ_{H} loops in Fig. 1b. However, if the last term of Eq. (1) had such a large contribution to ρ_{H} then a significant EHE would be observed in pure FeMn thin films. To the best of our knowledge this is not reported in the literature and we could not detect an EHE signal in FeMn thin films as well. It shows that the positive polarity in Fig. 1 results from a combination of resistivity effects in both, the Co/Pt multilayer and the FeMn layer. Such an effect may arise from the very short spin-diffusion length [8], $l_{sf} \approx 1.2\,\mathrm{nm}$, of FeMn layers in a multilayered structure. Thus, it can be argued that spin-memory loss at FeMn interfaces reduces the mean-free path of the conducting spin-channels in Co/Pt layers whereas electron reflectivity at NiO interfaces it does not. The former can change the relaxation times of majority and minority electrons in Co/Pt layers but the second cannot do that. This might be a more reasonable explanation for the change of EHE loop polarities in Fig. 1.

In summary, the effect of AF γ-FeMn (metallic) and insulating NiO layers on the polarity of EHE loops of Co/Pt multilayers with PMA has been studied. It was shown that $[\mathrm{Pt}\ (2\,\mathrm{nm})/\mathrm{Co}\ (0.4\,\mathrm{nm})]_{15}/\mathrm{AF}\ (3\,\mathrm{nm})/[\mathrm{Co}\ (0.4\,\mathrm{nm})/\mathrm{Pt}\ (2\,\mathrm{nm})]_{15}$ (AF = NiO, FeMn) multilayers exhibit a negative polarity of ρ_{H} loops for AF = NiO whereas a change of polarity has been observed for AF = FeMn. This can be explained from the very short l_{sf} of spin-up and spin-down channels at FeMn interfaces which modifies the spin-relaxation times in $[\mathrm{Co/Pt}]_{15}$ sublayers and, thus, might change the relative contribution of the spin carriers that participate in the EHE of Co/Pt multilayers. As seen in Fig. 2, the main effect of Co layers into $R(T)$ of pure Pt is to decrease the $\Delta\rho/\Delta T$ rate in the quasilinear part of R vs. T data at higher temperatures. In multilayers with AF = FeMn and NiO layers the $R_{\mathrm{FC}}(T)$ values below 50 K tend to FC residual resistances that are larger than the corresponding ZF resistances, implying that the exchange bias effect may modify the asymmetric scattering of the conduction electrons in the Co/Pt layers which are responsible for the EHE. These results provide a first experimental evidence that addition of a *thin metallic layer with short* l_{sf} in Co/Pt multilayers can change the polarity of ρ_{H} loops.

References

[1] C.L. Canedy, X.W. Li, G. Xiao, Phys. Rev. B 62 (2000) 508.
[2] S. Zhang, Phys. Rev. B 51 (1995) 3632.
[3] S. Honda, Y. Nagata, J. Appl. Phys. 93 (2003) 5541.
[4] W. Kuch, L.I. Chelaru, F. Offi, J. Wang, M. Kotsugi, J. Kirschner, Phys. Rev. Lett. 92 (2004) 017201.
[5] R.A. Hajjar, M. Mansuripur, H.-P.D. Shieh, J. Appl. Phys. 69 (1991) 7067.
[6] G. Tatara, H. Kawamura, J. Phys. Soc. Jpn. 71 (2002) 2613.
[7] R. Shindou, N. Nagaosa, Phys. Rev. Lett. 87 (2001) 116801.
[8] W. Park, D.V. Baxter, S. Steenwyk, I. Moraru, W.P. Pratt Jr., J. Bass, Phys. Rev. B 62 (2000) 1178.