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MAGNETIZATION AND MAGNETORESISTANCE CORRELATION IN NiFe/Au/Co/Au MULTILAYERS

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Abstract: The magnetic and magnetotransport properties of $(Ni_{83}Fe_{17}/Au/Co/Au)_N$ multilayers with $t_{Co} = 0.6$ nm and different thicknesses of Au ($1 \le t_{Au} \le 3$ nm) layers were investigated. Co layer thickness used ensures its perpendicular anisotropy. We show that in hysteretic region of $R(H)$ and $M(H)$ dependencies the reorientation of Py layers is strongly influenced by magnetic stray fields originating from domain structure of Co layers.

1. INTRODUCTION

In our previous paper [1] we have demonstrated that at remanence, in sputtered Py/Au/Co/Au ($Py = Ni_{83}Fe_{17}$) multilayers (ML), the alternating in-plane (Py layers) and out-of-plane (Co layers) magnetization configuration in neighboring ferromagnetic layers can be realized. The linear and almost unhysteretic dependence of electrical resistance on magnetic field ($R(H)$) observed for such structures seems to be attractive for particular applications. On the other hand nearly independent (distinct) magnetization reversal of permalloy and cobalt layers together with the dense labyrinth domain structure of Co layers enables investigations of the domain wall coupling [2-5] and its influence on magnetoresistance effect. In this contribution we show the detailed analysis of the correlation between $M(H)$ and $R(H)$ dependencies in NiFe/Au/Co/Au structure in order to identify the mechanism responsible for the observed $R(H)$ behaviour in the hysteretic range.

2. EXPERIMENTAL

The MLs with the sequence of glass/[Py(2 nm)/Au(t_{Au})/Co(0.6 nm)/Au(t_{Au})]$_N$ with $1 \le t_{Au} \le 3$ nm were deposited in Ar atmosphere using the UHV magnetron sputtering. The sputtering rates were 0.06, 0.05, and 0.045 nm/s, for Au, Py, and Co, respectively. The low angle X-ray diffraction patterns gave evidence of periodic structure and allowed the determination of a modulation wavelength and a total thickness of MLs. The magnetization reversal processes were studied at room temperature with a vibrating sample magnetometer (VSM). Magnetoresistance was measured at room temperature in a four-point configuration in fields up to 2 T. A magnetic force microscopy (MFM) was used to visualize the domain structure of MLs. All measurements reported were performed with magnetic field applied perpendicularly to a film plane.

3. RESULTS AND DISCUSSION

Exemplary hysteresis loops, shown in Fig. 1, suggest that magnetization reversals of Py and Co layers in our structure take place independently of each other. Cobalt layers, with thickness

t_{Co} < 1.2 nm, sandwiched between gold poses perpendicular anisotropy [6], therefore for magnetic field applied perpendicularly they are magnetically saturated in relatively small fields. Indeed, in investigated structures one can easily distinguish two regions in $M(H)$ dependence. In the first one, in the vicinity of null field, changes in magnetization are dominated by hysteretic reversal of Co layers magnetized in easy direction. In the second region (125 kA/m ≤ $|H_{\perp}|$ ≤ 440 kA/m) magnetization changes linearly with H indicating a hard axis reversal. We attribute this region to Py layers reversal with saturation field determined by the shape anisotropy ($H_S = M_{S\text{Py}} \approx 480$ kA/m [7]). A closer look at hysteretic part of $R(H)$ and $M(H)$ dependencies (see Fig. 2) reveals that they are well correlated. The characteristic magnetic fields corresponding to nucleation ($H_{N\text{Co}}$) and annihilation of the Co domain structure (saturation of Co layers, $H_{S\text{Co}}$) can be well recognized both in $M(H)$ and $R(H)$ dependencies. The existence of the stripe and labyrinth domain structure at remanence was confirmed by MFM measurements. Neglecting the hysteretic region, the Au spacer with thickness $t_{Au} \geq 1.5$ nm assures negligibly small interlayer coupling [8]. Therefore, in the first approximation of $R(H)$ dependence modeling we have considered independent magnetic reversal of Co and Py layers in the whole range of magnetic fields. For such an assumption the magnetization reversal of Co layers $M_{Co}(H)$ can be determined from the magnetization changes of the whole sample $M_{total}(H)$ (see, *e.g.*, left panel of Fig. 1) by subtracting the contribution related to Py layers ($M_{Co} = M_{total}$ M_{Py}, where $M_{Py}/M_{S\text{Py}} = H/H_{S\text{Py}}$ for $|H| \leq H_{S\text{Py}}$).

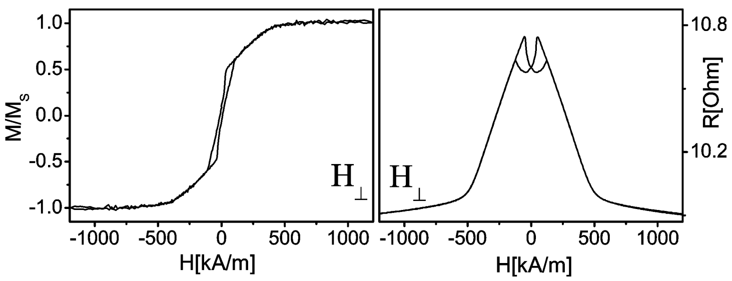

Fig. 1. Exemplary $M(H)$ and $R(H)$ (right panel) dependencies obtained for glass/[Py(2 nm)/Au(1.5 nm) / Co(0.6 nm)/Au(1.5 nm)]$_{15}$ multilayer with magnetic field applied perpendicularly to the sample plane

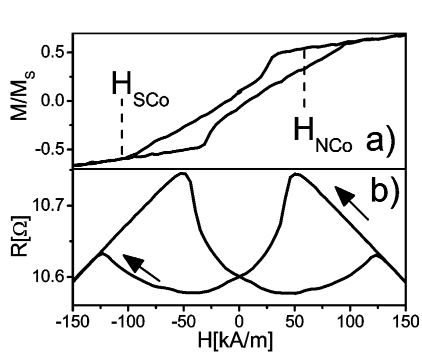

Fig. 2. Magnetization and resistance (bottom panel) dependencies for [NiFe(2 nm)/Au(1.5 nm)/Co(0.6 nm) / Au(1.5 nm)]$_{15}$ multilayer. $H_{S\text{Co}}$ and $H_{N\text{Co}}$ are saturation and domain nucleation fields of Co layers

Considering nearly independent magnetization reversal of Py and Co layers in Py/Au/Co/Au multilayers the observed magnetoresistance effect, similarly to spin valve structures, can be described in the form:

$$R(H) = r_0 - dr\cos(\phi_V), \tag{1}$$

where r_0 and dr are parameters from a general equation describing giant magnetoresistance [9] with (r_0 dr) and ($r_0 + dr$) being the resistance for parallel and antiparallel configuration of magnetic layers respectively and ϕ_V the angle between their magnetization vectors. In calculations of $R(H)$ dependencies performed for the magnetic field range corresponding to the existence of magnetic domains in Co layers two different magnetic configurations (related to the domains magnetized parallel and antiparallel to the field direction) should be considered. For magnetization of Co layers along their easy axes $M(H)$ is related to domain wall motion. In such a case the surface fraction of Co layers magnetized parallel to the initial direction of magnetic field is proportional to magnetization and can be determined as follows: $a(H) = (M(H)/M_S + 1)/2$. Using parameter a calculated above we can determine the $R(H)$ dependence as:

$$R(H) = a\left(r_0 - dr\cos(\phi)\right) + (1-a)\left(r_0 + dr\cos(\phi)\right), \tag{2}$$

where ϕ is the angle between magnetic moments of Py layers and a normal to the sample plane (the normal is directed along the initial magnetic field direction – model curves start at $H > H_{SPy}$):

$$\cos\phi = \begin{cases} H/H_{S\,\mathrm{Py}} & \text{if } |H| \le H_{S\,\mathrm{Py}} \\ |H|/H & \text{if } |H| \ge H_{S\,\mathrm{Py}} \end{cases}. \tag{3}$$

Equation (2) can be written this way because of 200 nm domain sizes in Co layers: electrons scattered from a given area of Py layer will most probably experience the next scattering in Co domain facing that area.

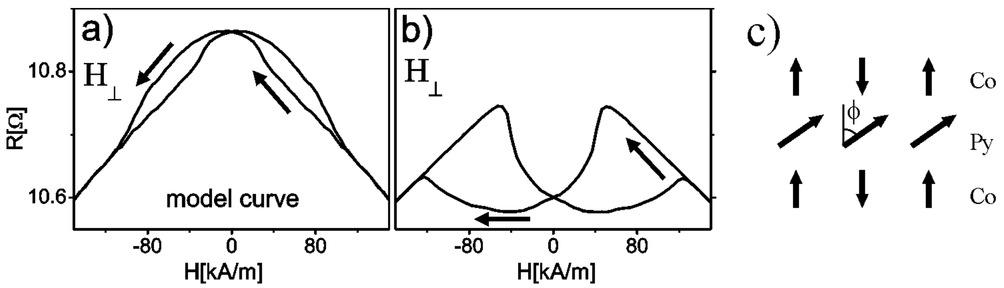

Fig. 3. A comparison between a model curve (a) obtained from equation (2) and a corresponding experimental $R(H)$ dependence (b) for [NiFe(2 nm)/Au(1.5 nm)/ Co(0.6 nm)/Au(1.5 nm)]$_{15}$ multilayer. For calculation it was assumed that r_0 = 10.86 Ω and dr = 0.907 Ω. The arrows indicate a field sweep direction (c). A cartoon showing that in this calculation it was assumed that Py layer magnetization direction does not depend on the state of neighboring Co domain

The comparison of the $R(H)$ dependence calculated according to Eq. (2) with the measured one (Fig. 3) reveals that there is a serious discrepancy between them in the hysteretic region. The model curve, contrary to the real one, displays higher R values in unsaturated (multi-domain) as in saturated (single-domain) state of Co layers. We believe that it invalidates our preliminary assumption of independent reversal of Co and Py layers and suggests that the coupling between neighboring magnetic layers should be considered. As an estimate of coupling strength we took the field value, H_x, for which the resistance in single-domain state of Co layers (*i.e.*, for $a = 1$ or 0) has the same value as in remanence. The choice of H_x as a quantity describing magnetic interaction between Co and Py layers caused by the domain structure can be explained as follows. In remanence the only external field acting on Py layers originates from Co layers domain structure (see Fig. 4a). To the contrary, for single-domain state at $H = H_x$ the magnetostatic fields of Co layers are negligible and the magnetization direction of Py layers is determined only by the applied magnetic field. The same value of electrical resistance for $H = 0$ and $H = H_x$ indicates that the mutual magnetic configuration of Py and Co layers is the same (ϕ_V value), however, the distribution of magnetic moments in both cases is different (see Fig. 4c). The same deviation from in-plane alignment of permalloy layers magnetization indicates that stray fields acting on Py layers at remanence are effectively equal H_x. As expected the H_x value decreases with increasing the thickness of spacer layer (Fig. 4b).

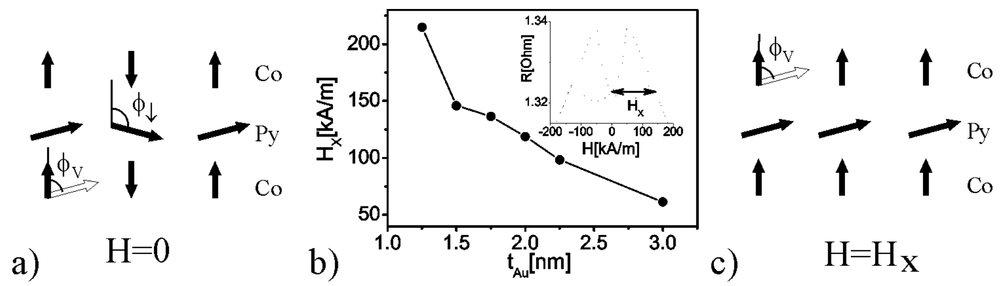

Fig. 4. a) A cartoon of the multilayer geometry used in calculating $R(H)$ dependence showing the situation with no external field applied. A local magnetization direction of Py layer depends on local Co domain polarization; b) Estimated values of magnetic field strength, H_x, of Co layers acting on Py layers *versus* Au layers thicknesses. H_x values were obtained from $R(H)$ dependencies (see the text and an inset of a central panel) of [NiFe(2 nm)/Au(t_{Au})/Co(0.6 nm/Au(t_{Au})]$_{15}$ MLs; c) The cartoon of the ML geometry for $H = H_x$, *i.e.*, in single-domain state of Co layers. Note that the value of ϕ_V is the same in a) and c)

To determine the effective magnetic field of Co domain structure acting on Py layers we have transformed Eq. (2). In its new form not only the existence of the domain structure in Co layers but also non-collinear magnetization distribution in Py layers (caused by stray fields originated from Co domain) is considered. We assumed ϕ to have different values ($\phi_\uparrow$ and $\phi_\downarrow$) depending on domain state of a given Co layer region (see Fig. 4a). Consequently, in Eq. (3) we substitute $H \equiv H + H_x(H)$ and $H \equiv H\ H_x(H)$ to calculate $\cos(\phi_\uparrow)$ and $\cos(\phi_\downarrow)$, respectively. Equation (2) takes the form:

$$R(H) = a\left(r_0 - dr\cos(\phi_{\uparrow})\right) + (1-a)\left(r_0 - dr\cos(\phi_{\downarrow})\right) . \tag{4}$$

It should be noted that it was assumed that Co reversal is not influenced by stray fields of Py layers so $M(H)$ dependence of Co layers used for modeling with Eq. (2) was used for Eq. (4) too (see the parameter a in Fig. 5a). $H_x(H)$ dependence was calculated according to Eq. (4) from $M_{\mathrm{Co}}(H)$, $M_{\mathrm{Py}}(H)$ and $R(H)$ dependencies taking into account that for H values far from $\pm H_{S\mathrm{Py}}$ the relation $\cos(\phi_{\uparrow})$, $\cos(\phi_{\downarrow}) = 2H_x/H_{S\mathrm{Py}}$ is fulfilled. $M_{\mathrm{Co}}(H)$ and $R(H)$ dependencies of [NiFe(2 nm)/Au(1.5 nm)/Co(0.6 nm)/Au(1.5 nm)]$_{15}$ ML used in calculation are shown in Fig. 5a. Figure 5b shows applied field dependence of H_x value obtained from Eq. (4). For the structure with t_{Au} = 1.5 nm the maximum of H_x is 155 kA/m which is very close to the value of 146 kA/m from Fig. 4b (for ML with t_{Au} = 3 nm the values are 46 and 61 kA/m, respectively). Since the maximum value of H_x depends on the exact shape of $M(H)$ dependence of Co taken for calculation the obtained values must be treated as an approximation. Nevertheless for Fig. 5 changing $a(H)$ dependence to the linear in H (in the hysteretic range) diminishes maximum of H_x by only 3%. Finally it should be noted that in this contribution we have assumed that the observed magnetoresistance is of the GMR type [9] (*i.e.* is correlated with changes of the angle between magnetization directions of Py and Co layers) and other effects such as anisotropic magnetoresistance or the scattering of electrons by domain walls [10] can be neglected.

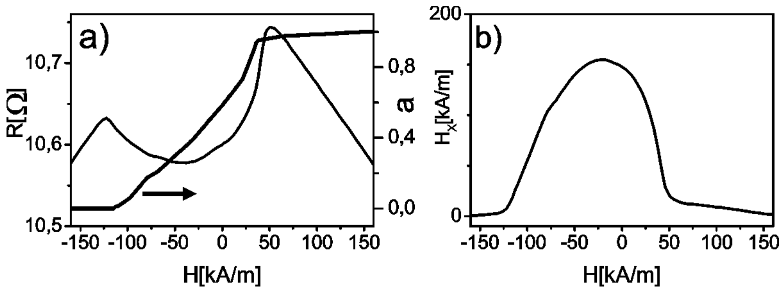

Fig. 5. (a) The $R(H)$ dependence of [NiFe(2 nm)/Au(1.5 nm)/Co(0.6 nm/Au(1.5 nm)]$_{15}$ ML and the corresponding $M_{\mathrm{Co}}(H)$ dependence (shown in form of $a(H)$ dependence – for the definition of a see the text) and (b) the corresponding $H_x(H)$ dependence calculated from Eq. (4). For clarity only one sweep direction, with descending field value, is shown

Nevertheless we think that the analysis presented above gives the reasonable estimate of the magnetostatic interactions in our Py/Au/Co/Au multilayers.

4. CONCLUSIONS

The correlation between magnetization and magnetoresistance of $Ni_{83}Fe_{17}$/Au/Co/Au multilayers was discussed. The important influence of the stray fields from domains of perpendicularly magnetized Co layers on magnetization distribution in permalloy layers and in consequence on magnetoresistance is documented. The values of stray fields, acting on permalloy layers, determined from magnetoresistance measurements, are in the range of 10^2 kA/m.

Acknowledgements

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References

[1] F. Stobiecki, B. Szymański, T. Luciński, J. Dubowik, and K. Röll, J. Magn. Magn. Mater. **239**, 276 (2002).
[2] M. R. McCartney, R. E. Dunin-Borkowski, Michael R. Scheinfein, D. J. Smith, S. Gider, and S. S. P. Parkin, Science **286**, 1337 (1999).
[3] Luc Thomas, Mahesh G. Samant, and S. S. P. Parkin, Phys. Rev. Lett. **84**, 1816 (2000).
[4] W. S. Lew, S. P. Li, L. Lopez-Diaz, D. C. Hatton, and J. A. C. Bland, Phys. Rev. Lett. **90**, 217201 (2003).
[5] W. Kuch, L. I. Chelaru, K. Fukumoko, F. Porrati, F. Offi, M. Kotsugi, and J. Kirchner, Phys. Rev. **B67**, 214403 (2003).
[6] C. Chappert and P. Bruno, J. Appl. Phys. **64**, 5736 (1988).
[7] J. Dubowik, F. Stobiecki, and T. Luciński, Phys. Rev. **B57**, 5955 (1998).
[8] F. Stobiecki, B. Szymański, T. Luciński, J. Dubowik, M. Urbaniak, M. Schmidt, and K. Röll, J. Magn. Magn. Mater. **272-276**, e751 (2004).
[9] B. H. Miller, E. Yojun Chen, and E. Dan Dahlberg, J. Appl. Phys. **73**, 6384 (1993).
[10] W. Allen, J. F. Gregg, K. Ounadjela, M. Viret, M. Hehn, S. M. Thompson, and J. M. D. Coey, J. Magn. Magn. Mater. **165**, 121 (2002).