Proceedings of the European Conference "Physics of Magnetism" (PM'08), Poznań 2008

Anisotropy Distribution in NiFe/Au/Co/Au Multilayers

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We present results of FMR investigations of anisotropy distribution in uncoupled $[\mathrm{NiFe/Au/Co/Au}]_N$ structures with alternating in-plane (NiFe) and out-of-plane anisotropies (Co). It is concluded that for NiFe layers anisotropy distribution is negligible and can be increased by "dusting" of NiFe with ultrathin Co layers. The perpendicular anisotropy K_{U}^2 of Co layers depends on Co thickness in a standard way $\propto 1/d_{\mathrm{Co}}$, and is distributed in a range of $\approx$ 10–20% of K_{U}^2 (i.e., $\approx 1.5 \times 10^6$ erg/cm^3).

PACS numbers: 73.21.Ac, 75.30.Gw, 76.50.+g

1. Introduction

Ultrathin Co layers in contact with Au possess relatively strong effective perpendicular anisotropy [1] and ultrathin NiFe layers, just a quite opposite, exhibit "in-plane" anisotropy. In $[\mathrm{NiFe/Au/Co/Au}]_N$ (N is the number of repetitions) multilayers the successive magnetic layers do not couple in a simple ferro- or antiferromagnetic way, but in a non-collinear arrangement; every second ultrathin magnetic layer (Co) has a magnetization direction pointing "out-of-plane", as opposed to the "in-plane" intermediate layers (NiFe = $\mathrm{Ni_{80}Fe_{20}}$) [2, 3]. The interlayer coupling is very small and may be neglected [4]. The aim of our contribution is to investigate a distribution of anisotropy in the multilayers assuming that the magnetization of Co is practically independent of its thickness. The anisotropy is expected to be somehow distributed across a whole stack of layers. In case of negligibly small interlayer coupling, ferromagnetic resonance (FMR) is a good method for such investigations, since the total FMR response may be treated in the first approximation as a sum of independent responses (acoustic modes) of individual layers. Since additionally in the structures with perpendicularly oriented easy axes the effective magnetic fields differ substantially [5], we are able to "see" FMR responses of these layers separately in most cases.

2. Experimental and results

$[\mathrm{NiFe\text{-}2/Au\text{-}2/Co\text{-}}x\mathrm{/Au\text{-}2}]_{10}$ multilayers (where the numbers denote thickness in nm and x = 0.0, 0.4, 0.6, 0.8, and 1.2 nm) were deposited in Ar atmosphere using high vacuum magnetron sputtering on Si(100) substrates with native oxide. Since in all structures the thickness of Co was varied, the samples will be referred to as Co-x, where x = 0.0, 0.4–1.2 (see Table). Details concerning preparation and characterization of the same films using giant magnetoresistance effect, vibrating sample magnetometer (VSM), low- and high-angle X-ray diffraction, Mössbauer spectroscopy, and element specific soft X-ray resonant magnetic scattering are reported in Refs. [2–4]. Additionally, three other samples with slightly modified geometry were deposited: +Co-0:$[$NiFe-3.2/Au-2/Co-0.8/Au-2$]_{11}$, +Co-0.6:NiFe-3.2/Au-2/Co-0.8/Au-2+$[$Co-0.6/NiFe-2.6/Au-2/Co-0.8/Au-2$]_{10}$, and +0.6-Co:NiFe-3.2/Au-2/Co-0.8/Au-2+$[$NiFe-2.6/Co-0.6/Au-2/Co-0.8/Au-2$]_{10}$. The sample +Co-0 serves as the reference sample for this series and +Co-0.6 and +0.6-Co differ from each other in such a way that ultrathin Co-0.6 nm layers were deposited either on the "bottom" and the "top" side of the NiFe-2.6 nm layers. FMR measurements were performed at 9.08 and 33.5 GHz at room temperature.

TABLE

The effective magnetization and ratio of magnetic moments values (calc. — calculated, VSM, FMR — measured with VSM and FMR, respectively) for different $[NiFe/Au/Co/Au]_N$ structures.

Film	Structure	$4\pi M_{\rm eff}^{\rm Co}$ [kG]	$4\pi M_{\rm eff}^{\rm NiFe}$ [kG]	$\frac{m^{\rm NiFe}}{m^{\rm Co}}$ calc.	$\frac{m^{\rm NiFe}}{m^{\rm Co}}$ VSM	$\frac{m^{\rm NiFe}}{m^{\rm Co}}$ FMR
Co-1.2	$[NiFe/Au/Co\text{-}1.2/Au]_{10}$	−1.0	6.2	0.6	0.7	0.6
Co-0.8	$[NiFe/Au/Co\text{-}0.8/Au]_{10}$	−4.0	6.2	0.85	0.8	0.9
Co-0.6	$[NiFe/Au/Co\text{-}0.6/Au]_{10}$	−6.9	6.1	1.1	1.2	4–5
Co-0.4	$[NiFe/Au/Co\text{-}0.4/Au]_{10}$	−6.4	6.2	1.65	4	> 10
Co-0.0	$[NiFe\text{-}2/Au\text{-}4]_{10}$	0	6.0	–	–	–
+Co-0	$[NiFe\text{-}3.2/Au/Co/Au]_{11}$*	−4.1	6.8	1.54	–	2
+Co-0.6	$[Co\text{-}0.6/\ NiFe\text{-}2.6/Au/Co/Au]_{10}$*	−4.3	4.4	1.9	–	–
+0.6-Co	$[NiFe\text{-}2.6/\ Co\text{-}0.6/Au/Co/Au]_{10}$*	−4.0	6.3	1.9	–	–

*The thickness of Co of 0.8 nm and Au of 2 nm was kept the same for this series. The +Co-0.6 and +0.6-Co structures were deposited on a [NiFe-3.2/Au-2/Co-0.8/Au-2] buffer. The parameters for this series were evaluated from X-band data.

Figure 1a shows FMR spectra of Co-0.8 sample. The spectra were taken with the magnetic field applied nearly perpendicular to the film plane (due to limited field in our electromagnet, only a portion of the high field mode is visible at $\Theta_H = 0°$) and with the magnetic field applied in-plane ($\Theta_H = 90°$). Since both the Co and NiFe signals are visible over almost full angular range, it is possible to plot corresponding polar angular dependence of all modes (Fig. 1b). The spectra shown in Fig. 1a are typical of $[NiFe\text{-}2/Au\text{-}2/Co\text{-}x/Au\text{-}2]_{10}$ series. Two $NiFe^0$ and $NiFe^1$ modes, which we ascribe to NiFe layers show the expected in-plane easy axis, whereas Co mode shows the behavior typical of a film with perpendicular anisotropy. The nature of the less intensive $NiFe^1$ mode remains unexplained. It may be tentatively related to the first NiFe layer(s) next to the Si substrate. Otherwise, it might be one of the first spin-wave modes excited in the stack of NiFe layers. We checked that its position and intensity hardly depend on the presence of Co layers of different thickness (but is visibly smaller for Co-0.0 sample). Moreover, for Co-0.0 sample (with no Co layers) we found higher-order spin-wave modes. Although we regard the multilayers as consisting of independent magnetic layers, we conclude that $NiFe^1$ mode might originate from a sort of collective spin-wave excitations with $k \neq 0$ in the NiFe layers. Similar observation has been reported for Co/Pt multilayers [6].

Effective fields acting on magnetic layers in $[NiFe/Au/Co/Au]_N$ are fitted (see Fig. 1b, continuous lines) using standard method (see Ref. [5]). Angular dependence of the resonance field $H_{\rm res}$ can be obtained by solving the Smith–Beljers equation for the anisotropic part of the free energy density, which includes uniaxial anisotropy $K_{\rm U}^2$:

$$E = -MH\cos(\Theta_H - \Theta) + (2\pi M^2 - K_{\rm U}^2)\cos^2\Theta. \quad (1)$$

Θ_H and Θ are the polar angles between film normal and the magnetic field H and magnetization M, respectively. We introduce the effective magnetization $4\pi M_{\rm eff} = 4\pi M - 2K_{\rm U}^2/M$, where $2K_{\rm U}^2/M = H_{\rm U}^2$ is the perpendicular anisotropy field. The results of the respective calculations of the FMR data are listed in Table. It is seen that for the series Co-x (x = 0–1.2), the effective magnetization of 2 nm thick NiFe layers is of 6 kG in accordance with the earlier results [2–4]. The effective magnetization of Co layers depends on Co thickness $\propto 1/d_{\rm Co}$ (except for Co-0.4 sample with the thinnest Co of 0.4 nm, similarly to Ref. [1]) with a substantial surface contribution arising from a uniaxial surface anisotropy at the Au/Co/Au interfaces with the value of $K_{\rm S}$ of 0.4 erg/cm^2, close to that reported earlier [7]. The values of $K_{\rm U}^2$ of Co layers are in the 12×10^6–17×10^6 erg/cm^3 range, depending on $d_{\rm Co}$. In our calculations we assumed the magnetization of Co (M = 1400 G) independent of Co thickness since the Curie temperature of Co is 1400 K, but we are aware that for the thinnest Co it is a rough assumption.

For the initial characterization of the multilayers, a comparison of the ratios of NiFe and Co magnetic moments can be useful: (i) calculated from geometry of the structures — $m^{\rm NiFe}/m^{\rm Co} \propto (M^{\rm NiFe}\ d_{\rm NiFe})/(M^{\rm Co}\ d_{\rm Co})$ ($M^{\rm NiFe}$ = 480 G, $M^{\rm Co}$ = 1400 G); (ii) evaluated from VSM measurements; (iii) evaluated from intensity of FMR absorption at the in-plane configuration [8]. It appears that if the calculated ratio $m^{\rm NiFe}/m^{\rm Co} \leq 1$ both methods give approximately the same values as calculated ones. This again validates our model of the uncoupled layers. However, if the calculated ratio is greater than 1 and $d_{\rm Co} \leq 0.6$ nm, FMR method gives substantially higher $m^{\rm NiFe}/m^{\rm Co}$ values. We argue that some fraction of nominally flat Co layers (0.4 and 0.6 nm thick) form actually islands of superparamagnetic Co or even paramagnetic centers. Figure 2 shows absorption spec-

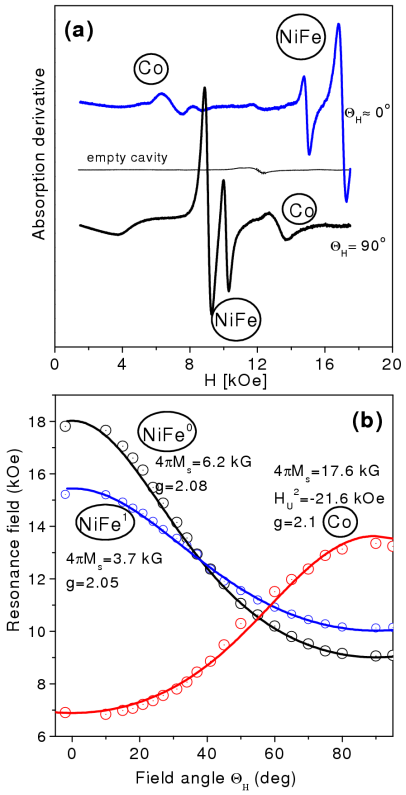

Fig. 1. (a) Exemplary FMR spectra at $\Theta_H \approx 0^\circ$ and 90° for Co-0.8 structure. (b) Angular dependences of the resonance field with respect to the polar angle Θ_H for Co-0.8 structure. g-factor of 2.05 to 2.1 was taken to obtain the best fits. The spectra were taken at 33.5 GHz.

tra (symbols) of Co layers in Co-1.2, Co-0.8, and Co-0.6 samples — integrals of the "Co" portion of FMR spectra (see Fig. 1a) — taken at the perpendicular configuration at 33.5 GHz. Since for such a configuration the resonance field $H_\mathrm{r} = \omega/\gamma + 4\pi M_\mathrm{eff}$, shape of absorption spectra results from distribution of the anisotropy (and hence $4\pi M_\mathrm{eff}$) in the entire stack of the uncoupled Co layers. Deconvolution of such spectra is frequently somewhat arbitrary but they can be confidently fitted with 2–4 components centered at the characteristic fields with the main components denoted with arrows. The distribution of the anisotropy field is quite large for Co-1.2 sample ($8 \le H_\mathrm{r} \le 12$ kOe). An unexpected result is that the distribution for Co-0.8 ($7 \le H_\mathrm{r} \le 12$ kOe) is much higher than that for Co-0.6, for which there are only two peaks centered at 4 and 12 kOe, respectively. This may result both from a strong $K_\mathrm{U}^2 \propto 1/d_\mathrm{Co}$ dependence of the perpendicular anisotropy and from transformation of a substantial fraction of Co into superparamagnetic islands in Co-0.6 sample. Indeed, there are some experimental evidences that nominally 0.3 nm thick Co layers in our structures are already superparamagnetic. The integrated intensities of the fitted components (numbers in the component absorptions in Fig. 2) show that a fraction of 0.5–0.6 of Co has relatively uniform distribution of H_U^2 of about 1–2 kOe, i.e., to $\approx 10\%$ of H_U^2. However, the overall distribution in H_U^2 is greater (4–5 kOe) with a fraction of 0.2 of Co centered at $H \approx 12$ kOe. For Co-0.8 it becomes bimodal with a fraction of 0.4 centered at $H \approx 12$ kOe, which may be ascribed to superparamagnetic islands.

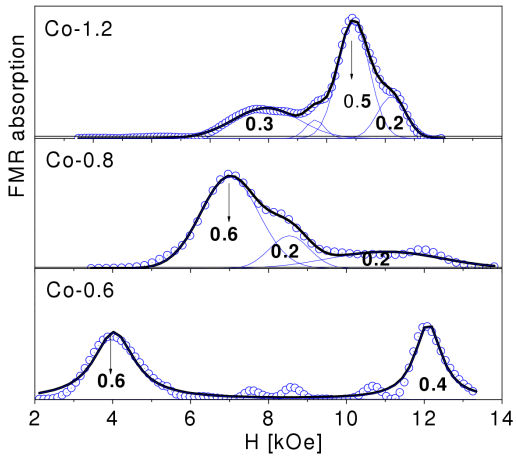

Fig. 2. FMR absorption spectra (symbols) of the Co layers in the different $[\mathrm{NiFe/Au/Co/Au}]_{10}$ structures with $d_\mathrm{Co} = 1.2, 0.8$, and 0.6 nm, respectively. The absorption intensity can be fitted (thick lines) with 2–4 components (thin lines). Numbers inside absorption components show approximate values (normalized to 1) of area under absorption. The absorption spectra (symbols) represent the results of integration of "Co" portions FMR spectra measured at the perpendicular configuration at 33.5 GHz.

Keeping in mind our discussion of spin-wave modes in NiFe layers, there is actually no distribution in the effective fields acting in NiFe layers (if there is any, it is of the order of the line width of 300–500 Oe). However, if NiFe layers are "dusted" with ultrathin Co-0.6 layers, their "subtle" structure can be revealed. It is seen from Table that the Co-0.6 layers coupled to NiFe-2.6 layers on the "bottom" side (. . . Au/Co-0.6/NiFe-2.6/Au. . .) results in a 2.4 kG decrease in $4\pi M_\mathrm{eff}$ due to a contribution of perpendicular anisotropy originating from the Au/Co interfaces. If however, Co-0.6 layers are "dusted" on the "top" side of NiFe (. . . Au/NiFe-2.6/Co-0.6/Au . . .), the contribution from surface anisotropy practically vanishes but due to the presence of thickness fluctuations in Co-0.6 the FMR spectrum of these coupled NiFe/Co layers consists of several (7–8) sharp lines characteristic of the local modes of the individual layers.

Acknowledgments

This work was in part supported by the Polish National Scientific Network ARTMAG: "Magnetic nanostructures for spintronics".

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