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Mössbauer and giant magnetoresistance effect study of magnetic structure in NiFe/Au/Co/Au multilayers with perpendicular anisotropy of the Co layers

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Abstract

The influence of magnetostatic coupling on the magnetic structure in sputter-deposited $[\mathrm{Ni_{80}Fe_{20}/Au/Co/Au}]_N$ multilayers was studied by magnetoresistance and Mössbauer spectroscopy. The remanent magnetization configuration revealed by Mössbauer measurements correlates well with the results obtained from the magnetic field dependence of resistance. This correlation is observed for samples with Co layers having strong perpendicular anisotropy. Micromagnetic simulations qualitatively explain the observed behavior.

1. Introduction

Magnetic films with perpendicular magnetic anisotropy (PMA) have been investigated intensively because of their potential applications for data storage [1]. In the area of spintronics, where the spin of the electron is influenced by the magnetic configuration of the nanostructure [2], the magnetoresistance of PMA materials is interesting from both the scientific [3] and technological [4, 5] points of view. In our previous paper [6] we investigated the giant magnetoresistance (GMR) of $[\mathrm{NiFe/Au/Co/Au}]_N$ multilayers (MLs), in which Co layers display PMA, and concluded that the coupling between the NiFe and Co layers originates mainly from the magnetostatic fields of the Co layers. In this paper we show that the Mössbauer-probe technique used by Hamada *et al* to investigate the magnetic configuration in Co/Au MLs [7] allowed us to confirm the picture previously postulated on the basis of resistance and magnetization measurements.

2. Experimental details

In our investigation, we used MLs in which the effect of magnetostatic coupling is varied. This is done either by changing the thickness of the Co layers, i.e. the strength of the magnetostatic fields of stripe domains, or by changing the effective easy-plane anisotropy through adding Co at the NiFe/Au interfaces. Six MLs used in this study have been deposited by magnetron sputtering on Si(100) substrates (for details, see [6]). We used two kinds of structures. The first one consisted of four layers in each repetition period: $[\mathrm{Ni_{80}Fe_{20}(2\ nm)/Au(2.4\ nm)/Co}(t_{\mathrm{Co}})\mathrm{/Au(2.4\ nm)}]_{10}$ with $t_{\mathrm{Co}} = 0.4$, 0.8 and 1.2 nm. The thickness of the Co layers ensured the existence of PMA. The second kind of ML was deposited on Si substrates covered by $\mathrm{Ni_{80}Fe_{20}}$ (3.2 nm)/Au(2.4 nm)/Co(0.8 nm)/Au(2.4 nm) buffer. The MLs consisted of several layers in each repetition period: $[X\mathrm{/Au(2.4\ nm)/Co(0.8\ nm)/Au(2.4\ nm)}]_{10}$, with X denoting $\mathrm{Ni_{80}Fe_{20}}$ (3.2 nm), $\mathrm{Ni_{80}Fe_{20}}$ (2.6 nm)/Co(0.6 nm) and Co(0.6 nm)/$\mathrm{Ni_{80}Fe_{20}}$ (2.6 nm), respectively, for three consecutive MLs. The presence of Co in the X layers allowed us to lower the effective in-plane anisotropy of these hybrid bilayers [8] and thus to make them more susceptible to stray fields.

Conversion electron Mössbauer spectroscopy (CEMS) was used to determine the magnetization direction of the $\mathrm{Ni_{80}Fe_{20}}$ layers. These layers were sputtered from a mosaic

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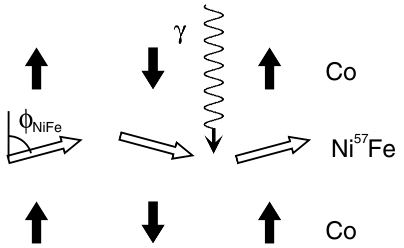

Figure 1. Schematic of the structures investigated. The magnetic field originating from the Co layers deflects the magnetic moments of the NiFe layers out of the plane. (The real structure consists of several magnetic layers.) The symbol ϕ_{NiFe} denotes the angle between the local magnetic moment of the NiFe layer and the normal direction, which is simultaneously the incidence direction of γ-rays used in Mössbauer measurements.

target consisting of a $Ni_{80}Fe_{20}$ plate decorated with ^{57}Fe (95.3 at.%) and Ni foils. Magnetoresistance was measured with a magnetic field applied perpendicularly to the sample plane using a four-point method in the current-in-plane configuration. All reported measurements were performed at room temperature.

3. Results and discussion

In the usual techniques utilized in the investigation of magnetic films, the information obtained is not element sensitive. Our previous studies [6] making use of magnetometry provided information on the combined magnetization of NiFe and Co layers only. The interpretation of data is especially difficult in the case of magnetization changes occurring in magnetic fields corresponding to the simultaneous reversal of Co and NiFe layers. In that range, the interlayer coupling makes it impossible to determine the field dependence of magnetization ($M(H)$) of constituent layers without the detailed theory, which is not available yet. The Mössbauer-probe technique enables independent determination of the magnetic moment orientation of the NiFe layers at remanence. The total thickness of the investigated MLs ranges between 72 and 97 nm, which is less than the 100 nm characteristic range of the ^{57}Fe CEMS investigations [9]. It is thus reasonable to assume that CEMS probes the whole sample.

Figure 1 shows a schematic of the structures investigated. The magnetic layers, separated by an Au spacer, interact primarily via magnetostatic coupling. Direct coupling through magnetic bridges is negligible for $t_{\mathrm{Au}} > 1$ nm [10]. The RKKY (Ruderman–Kittel–Kasuya–Yosida)-like coupling that was observed in well-textured Co/Au(111)/Co samples [11] is insignificant in our MLs and in Co/Au MLs [10, 12]. We have previously shown that interaction between Co and NiFe layers through Au spacer can be approximated well without an oscillatory contribution (see figure 4 of [6]). In the limiting case of infinite separation, the NiFe layers exhibit easy-plane shape anisotropy and the $M(H)$ dependence in perpendicular field is linear up to saturation ($H_{\mathrm{S}} = M_{\mathrm{S}}^{\mathrm{NiFe}} \approx 480$ kA m^{-1}). The Co layers in our MLs display stripe domains which are characteristic of the structures having PMA [6, 13, 14]. In MLs with thin Au spacers the magnetic moments of the NiFe layers are deflected under the influence of domains in the Co layers, and this leads to the changes in resistance related to the GMR effect [6]. Simulations show that the period of NiFe magnetization undulation corresponds to the stripe domain period [6], which is 180–400 nm in the MLs described here.

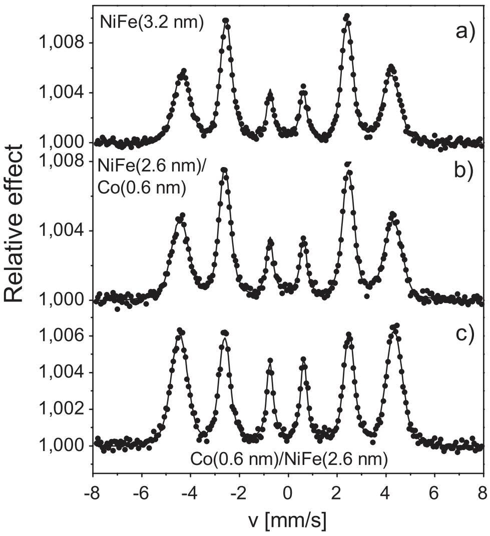

Figure 2. CEMS spectra, obtained at remanence, of $[X(3.2\ \mathrm{nm})/\mathrm{Au}(2.4\ \mathrm{nm})/\mathrm{Co}(0.8\ \mathrm{nm})/\mathrm{Au}(2.4\ \mathrm{nm})]_{10}$ MLs with different X [$Ni_{80}Fe_{20}$ (3.2 nm), $Ni_{80}Fe_{20}$ (2.6 nm)/Co(0.6 nm) and Co(0.6 nm)/$Ni_{80}Fe_{20}$ (2.6 nm) in (a)–(c)].

The CEMS spectra presented in figure 2 allow the determination of the average cosine squared of the relative angle between the magnetic moments of ^{57}Fe atoms and the incidence direction of gamma rays (ϕ_{NiFe}) from the intensity ratios of absorption lines: $D_{23} = 4\sin^2(\phi_{\mathrm{NiFe}})/(1 + \cos^2(\phi_{\mathrm{NiFe}}))$ [15]. Here, D_{23} denotes the parameter describing the ratio of the intensities of the second and third lines in the Mössbauer sextet. This technique is frequently used in the investigation of magnetic anisotropy in thin films [16, 17]. It is assumed here that, due to direct exchange coupling between Ni and ^{57}Fe atoms, ϕ_{NiFe} is a good measure of the orientation of the NiFe layer's magnetic moment. The CEMS spectra were fitted using the hyperfine field distribution method (the NORMOS program was used). The hyperfine field distributions were extracted from the experimental spectra using a constrained Hesse–Rubartsch method [18, 19]. The ratios of the line intensities of the Zeeman sextets, used in the fit, were assumed to be $3{:}D_{23}{:}1{:}1{:}D_{23}{:}3$, and D_{23} was a fitting parameter. It is to be noted that the D_{23} ratios are considerably different for the spectra of figures 2(b) and (c), although corresponding MLs differ from each other only in the sequence of the layers in a hybrid X layer. We have shown previously that a Au/Co/$Ni_{80}Fe_{20}$/Au structure saturates in a lower perpendicular field than Au/$Ni_{80}Fe_{20}$/Co/Au (see figure 3 of [8]). The difference is due to sequence-dependent growth. As a result, both layers react differently to magnetostatic fields of neighboring layers—see the discussion of figure 4.

The GMR effect allows an estimation of the average cosine of the angle between magnetic moments of the

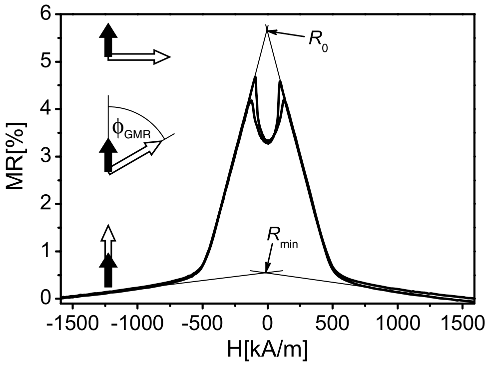

Figure 3. Exemplary *MR*(*H*) dependence measured for [$Ni_{80}Fe_{20}$(2 nm)/Au(2.4 nm)/Co(1.2 nm))/Au(2.4 nm)]$_{10}$ ML. AMR is less than 0.1%. The meanings of R_{min} and R_0 are explained in the text. The drawing presents the dependence of resistance R on the angle ϕ_{GMR}: R is minimal when ϕ_{GMR} is zero.

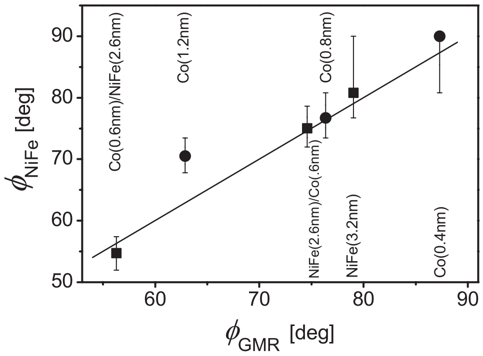

Figure 4. The ϕ_{NiFe} versus ϕ_{GMR} dependence comparing data obtained from Mössbauer spectroscopy and GMR measurements. The dots represent [$Ni_{80}Fe_{20}$/Au/Co/Au]$_{10}$ MLs and the squares the MLs with $Ni_{80}Fe_{20}$-Co bilayers. The solid line is a $\phi_{\mathrm{GMR}} = \phi_{\mathrm{NiFe}}$ dependence.

neighboring regions of Co and NiFe layers from the field dependence of resistance [20]: $R(H) = R_0 - (R_0 - R_{\mathrm{min}})\cos(\phi_{\mathrm{GMR}})$. Here R_{min} denotes the resistance in saturation, i.e. when all magnetic moments of the sample point in the external field direction. R_0 corresponds to the configuration in which moments of neighboring layers are perpendicular and ϕ_{GMR} denotes the angle between neighboring magnetic moments of Co and NiFe layers (see figure 3). It should be pointed out that R_{min} does not correspond to the lowest resistance shown in figure 3. This is due to the fact that the superparamagnetic precipitates, present at interfaces, contribute to resistance changes up to much higher fields [21] determined by the Langevin function. This effect was taken into account by determining R_{min} from the linear extrapolation of high-field resistance changes (figure 3). The anisotropic magnetoresistance (AMR), which in our samples never exceeds 0.5% and is less than or equal to 10% of the total resistance change, is neglected in our analysis [6]. The hysteresis visible in figure 3 in ±150 kA m^{-1} range originates from the stripe domain structure of the $M(H)$ dependence of Co layers that are magnetized in their easy direction [6]. It should be emphasized that the determination of the average ϕ_{GMR} from GMR is an approximation, since the resistance of the system is not necessarily the sum of the resistances of its components, determined by the local angle ϕ_{GMR}.

Figure 4 illustrates the main finding of the present study. It shows the dependence of the average angle between magnetic moments of NiFe layers and the sample normal, ϕ_{NiFe} (obtained from $\cos^2(\phi_{\mathrm{NiFe}})$), on the average angle between neighboring moments of NiFe and Co layers (ϕ_{GMR}). The values obtained from CEMS and GMR measurements are approximately equal ($\phi_{\mathrm{GMR}} \approx \phi_{\mathrm{NiFe}}$). Four-point resistance measurements, like CEMS (see the discussion of figure 2), probes virtually homogeneously the whole depth of our MLs. This is because the thickness of the MLs is four orders of magnitude smaller than the resistance probe spacing (≈2.5 mm) [22]. We can therefore directly compare information from both measurements. The largest discrepancy between these angles occurs for multilayers with $t_{\mathrm{Co}} = 1.2$ nm, which corresponds to weak PMA (for thicker Co layers, shape anisotropy dominates over perpendicular surface anisotropy of Co sandwiched between the Au layers [6]). In all other MLs the Co layers possess a perpendicular anisotropy which favors parallel alignment of the Co layers' magnetic moment with the normal (this is not the case within domain walls [6, 14]). The angle that the magnetic moments of the NiFe layers makes with the normal (ϕ_{NiFe}) should then be close to those relative to the local Co moment direction (ϕ_{GMR}). This behavior is seen clearly in figure 4.

As expected [6], the angle ϕ_{NiFe} depends markedly on t_{Co}, because the stray fields are stronger in structures with thicker Co layers (dots in figure 4). The perpendicular components of stray fields $H_\perp$ are of the order of 100 kA m^{-1}. We explained the $\phi_{\mathrm{NiFe}}(t_{\mathrm{Co}})$ dependence previously [6]. The basic idea is that NiFe films are magnetized in a hard direction defined by the shape anisotropy and, consequently, $\cos(\phi_{\mathrm{NiFe}}) = H_\perp/H_{\mathrm{A\ eff}}^{\mathrm{NiFe}}$, i.e. the $M(H_\perp)$ dependence is linear ($H_{\mathrm{A\ eff}}^{\mathrm{NiFe}}$ denotes the effective easy-plane anisotropy of the NiFe layers). As a result, ϕ_{NiFe} decreases with increasing t_{Co}. In case of MLs with hybrid X bilayers, Co and NiFe, due to strong exchange coupling between them, behave like a single magnetic layer [23]. The effective anisotropy of a bilayer ($H_{\mathrm{A\ eff}}^{\mathrm{NiFe}}$) is thus smaller due to the influence of the perpendicular anisotropy of the Co layer. As mentioned in the discussion of figure 2, $H_{\mathrm{A\ eff}}^{\mathrm{NiFe}}$ depends on the sequence of the layers, and therefore ϕ_{NiFe} is higher for NiFe/Co bilayers than for Co/NiFe (the squares in figure 4).

The attempts were made to use micromagnetic simulations in order to explain the results obtained. We have used the free-domain OOMMF software package [24]. The software allowed us to obtain the magnetization configuration by numerically integrating the Landau–Lifshitz equation and taking into account the self-magnetostatic field. In the calculation we assumed an exchange constant of 13×10^{-12} J m^{-1} for NiFe layers, 30×10^{-12} J m^{-1} for Co layers, and a damping constant of 0.5. The simulation cell size was $5 \times 0.4 \times 200$ nm^3 and the in-plane area was about 1×1 $\mu\mathrm{m}^2$; t_{Co}-dependent perpendicular anisotropy was calculated using constants from [6]. Five to 11 stripe domains (their widths, d, were measured using magnetic force microscopy, MFM)

Table 1. Comparison of data obtained from CEMS and GMR measurements with results from micromagnetic simulations. All angle values are expressed in degrees of arc.

t_{Co} (nm)	d (nm)	ϕ_{NiFe} [a]	ϕ_{NiFe} [b]	ϕ_{GMR} [a]	ϕ_{GMR} [b]
0.4	200	90	88.5	87.3	84.6
0.8	200	76.7	82.6	76.4	78.7
1.2	90	70.5	77.7	62.9	78.8

[a] From measurement.

[b] From simulation with OOMMF package.

in each Co layer and a single domain state in the NiFe layers were assumed as the starting configuration (for details, see [6]). Reasonable qualitative agreement between the measured values and simulation is observed for $t_{Co} < 1.2$ nm only (table 1). For $t_{Co} = 1.2$ nm, the PMA is too weak to support normal orientation of magnetic moments of the Co layers, and hence the simulation becomes unreliable. In agreement with the measurements, the simulations show that the deflection angle, ϕ_{NiFe}, is a strong function of t_{Co}.

4. Conclusions

In summary, we have shown that Mössbauer effect measurements confirm that the magnetic moments of NiFe layers in $[NiFe/Au/Co/Au]_{10}$ MLs are deflected out of the easy-plane by magnetostatic fields of stripe domains of Co layers. This result is consistent with our prior hypothesis based on GMR and magnetic measurements.

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