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High sensitivity GMR with small hysteresis in Ni–Fe/Cu multilayers

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Abstract

Giant magnetoresistance (GMR) effect and magnetisation reversal processes have been investigated in Py/Cu(Py = $Ni_{83}Fe_{17}$, permalloy) multilayers (Mls) obtained by face-to-face sputtering method. The investigated films had constant sublayer thicknesses both for Py and Cu ($d_{Cu} = 2$ nm, $d_{Py} = 2$ nm) and various numbers of ferromagnetic sublayers. It has been shown that for such Mls a high field sensitivity of GMR effect ($S \approx 0.4\%/\mathrm{Oe}$) and negligible hysteresis can be obtained for a low number of Py layers. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Exchange coupling; GMR sensitivity; Magnetoresistance; Multilayer; Permalloy

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1. Introduction

Multilayered structures consisting of ferromagnetic layers separated by a nonmagnetic, conducting spacer are the subject of a very intensive study. One of the reasons is a phenomenon of a giant magnetoresistance (GMR), i.e., a considerable change of resistance upon the application of magnetic field [1]. The occurrence of GMR effect in multilayer systems is often the result of the existence of an antiferromagnetic interlayer exchange coupling [2]. It turns out that multilayers with Py as magnetic layer display moderately high GMR amplitudes and low saturation fields [3–7]. The above leads to very promising, from the application point of view, values of GMR field sensitivity which in our samples attain 0.6%/Oe [7]. In this paper we present an analysis of the influence of the number of magnetic layers, N, in a stack on the GMR effect field sensitivity of $Ni_{83}Fe_{17}$/Cu multilayers obtained by double face-to-face sputtering [8]. It is shown that the GMR saturation field decreases with decreasing N much more than predicted theoretically for ideal multilayer. We show that due to a low uniaxial anisotropy of Py sublayers and a relatively weak interlayer exchange coupling in Py/Cu multilayers a negligible hysteresis in $R(H)$ behaviour can be accompanied by GMR field sensitivity close to 0.4%/Oe.

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2. Experimental

The glass/Py$-d_{\mathrm{Py}}$/[Cu$-$2 nm/Py$-d_{\mathrm{Py}}$]$\times(N-1)$ (where $N = 2, 6, 11, 21, 51, 101$ and d_{Py} denotes Py = $\mathrm{Ni_{83}Fe_{17}}$ thickness, $d_{\mathrm{Py}} = 2$ and 2.3 nm. Cu sublayer thickness is denoted by d_{Cu}) multilayers have been obtained at room temperature (RT) by double face-to-face sputtering [8]. In this sputtering geometry the substrate is placed outside the plasma discharge. It has two advantages: the substrate temperature is lower than for other sputtering methods and the in situ resistance measurements are possible. The Cu and Py sublayer thicknesses were determined by X-ray fluorescence method (XRF) [9]. For samples with a greater number of repetitions a well-defined periodic structure was confirmed by low and high angle X-ray diffraction which allowed us to determine the concentration modulation wavelength ($\lambda = d_{\mathrm{Py}} + d_{\mathrm{Cu}}$). The X-ray measurements revealed that our polycrystalline samples show a dominant (1 0 0) texture. The magnetisation reversal processes were examined with a vibrating sample magnetometer (VSM) and by a longitudinal magneto-optical Kerr effect (MOKE). The DC magnetoresistance measurements were performed at RT with the conventional four-point method while in situ resistance characteristics were measured with the two-point method. We define the field dependence of the GMR as:

$$\mathrm{GMR}(H) = 100 \times \frac{R(H) - R(H_{\max})}{R(H_{\max})},$$

where $H_{\max} \approx 700$ Oe denotes the maximum magnetic field applied in our experiment. In this paper the maximum resistance, not its zero-field value, determines the GMR amplitude. The external magnetic field in all measurements was applied in-plane, while the sensing current was always perpendicular to the magnetic easy axis (EA) direction.

3. Multilayers growth

Fig. 1 gives a representative example of the in situ conductance (G) of the Py(2.3 nm)/Cu(2 nm)

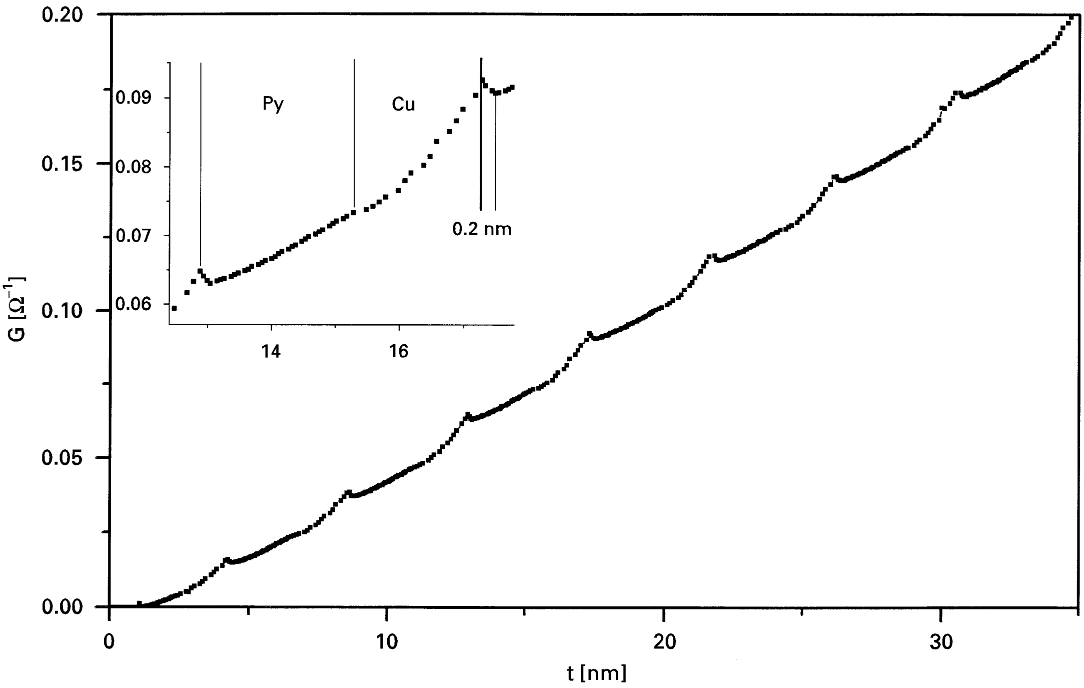

Fig. 1. Conductance of Py(2.3 nm)/Cu(2 nm) multilayer as a function of the total thickness.

multilayer as a function of the thickness. The onset of conductivity was observed to occur at the nominal Py thickness of about 1.2 nm. It suggests an island growth mode and implies that the initial mesoscopic roughness exceeds 1.2 nm [10]. The minimum of $G(d_{\mathrm{Py}})$ during Py growth on Cu surface which indicates the completion of the first homogeneous Py layer [11,12], appears at a thickness of about 0.2 nm (about 1 ML) suggesting a layer-by-layer growth (see insert in Fig. 1). The decrease of conductance is due to an increase of diffuse scattering of Cu conduction electrons at the sample surface [13]. Conductance varies almost linearly with the number of deposited Py/Cu bilayers which indicates that irrespective of the position in the stack the transport properties are similar (perfectly linear variation corresponding to parallel resistors would mean no giant magnetoresistance). Our in situ resistance measurements do not allow us to estimate the quality of Py/Cu interface, i.e. for Cu deposited on Py, since in this case no minimum in $G(d_{\mathrm{Cu}})$ dependence is seen. It could be argued that there is no evidence for an island growth since in a 3D growth mode a plateau in $G(d_{\mathrm{Cu}})$ should be observed [12].

4. Interlayer exchange coupling

Fig. 2a presents a typical Kerr rotation $\Theta_{\mathrm{K}}(H)$ dependence together with a model curve obtained for Py(2 nm)/Cu(2 nm) multilayer with 101 magnetic sublayers. The fitting procedure was performed within the two-layer model proposed by Dieny et al. [14]. It was assumed that a total energy of a system consists of exchange coupling energy, Zeeman energy and anisotropy energy (it was shown previously that in our multilayers a distinctive uniaxial in-plane anisotropy is present [7]). Thus, the energy of bilayer per surface unit has a form (with magnetic field applied parallel to EA direction)

$$E = -BM_{\mathrm{S}}t(\cos\Theta_1 + \cos\Theta_2) - J\cos(\Theta_1 - \Theta_2) - K_{\mathrm{U}}t(\cos^2\Theta_1 + \cos^2\Theta_2),$$

where M_{S} and t are saturation magnetisation and thickness of magnetic layers, respectively; K_{U} is a uniaxial anisotropy constant, Θ_1 and Θ_2 are angles between magnetisations and magnetic field direction and J is a bilinear coupling constant. In the calculation a steepest descent method with the basic step equal to 0.0005 rad was used to find the local energy minimum. Dieny et al. [14] have shown that a calculation performed for a bilayer (only two magnetic sublayers) could be used to describe the behaviour of a multilayer with large, odd number of magnetic layers provided that the coupling constant is multiplied by 2.

Magnetisation and thickness values used in our calculations were determined experimentally from VSM and XRF measurements, respectively. The

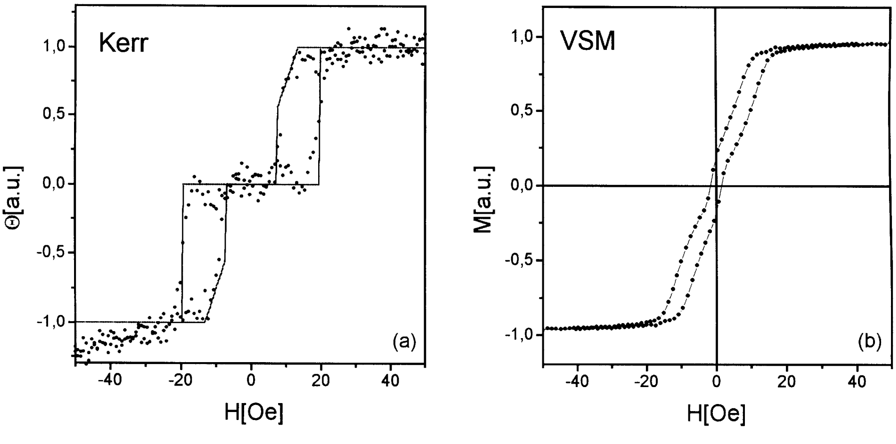

Fig. 2. The field dependence of (a) the Kerr rotation $\Theta_{\mathrm{K}}(H)$ (line shows a fit according to the model of Dieny (see text)) and (b) magnetisation $M(H)$ of Py(2 nm)/Cu(2 nm) multilayer with 101 magnetic sublayers.

obtained antiferromagnetic exchange coupling constant values are small, about 0.5–0.8 × 10^{-6} J m^{-2}, which as shown later allowed us to obtain $R(H)$ characteristics with small saturation fields. The relatively high hysteresis present in $\Theta_K(H)$ dependence is not observed in $M(H)$ curves obtained with VSM (see Fig. 2b) and in $R(H)$ measurements. It reflects the fact that in contrast to the resistance and VSM measurements a MOKE signal is collected from a thin (~20 nm) surface layer and thus it is much less affected by thickness inhomogeneities inevitably present in our Mls. The loss of the modulation periodicity (different Cu spacer thicknesses) causes the coupling energy between different pairs of neighbouring Py layers to vary. As a result, different layers rotate at different field values and the GMR effect field sensitivity is diminished.

5. The influence of number of repetitions on $R(H)$ behaviour

Exemplary GMR(H) curves obtained for multilayers with different number, N, of magnetic sublayers are displayed in Fig. 3. Decreasing of GMR amplitude with N (Fig. 4a) is partly caused by an increased contribution of outer boundary scattering to conducting processes and a lower number of magnetic–nonmagnetic interfaces within electron mean free path [1]. The $N = 2$ stack shows no GMR effect. In this case we observe only a small magnetoresistive signal coming from the scattering of the conduction electrons by paramagnetic and/or superparamagnetic fluctuations localised near Py/Cu interfaces, as discussed by Lucinski et al. [6]. We conclude that coupling between first two sublayers is absent or favours parallel alignment of their magnetic moments [15]. The absence of antiferromagnetic interlayer coupling can be explained by initial roughness (island growth) (see Fig. 1) which can change the effective spacer thickness. In our samples even very small, less than 0.3 nm, departure from a nominal Cu thickness can reduce GMR amplitude to zero [6].

Complementary magnetisation reversal measurements performed with VSM (Fig. 2b) seem to confirm that antiferromagnetic interlayer exchange coupling is stronger for layers more distant from the substrate. As can be seen from Fig. 4a, AF-coupled fraction of the sample F_{AF} (where $F_{AF} = 1 - M_R/M_S$, M_R denotes remanence magnetisation) increases with increasing N, i.e., as the relative contribution of first layers to the total magnetic moment of the sample decreases.

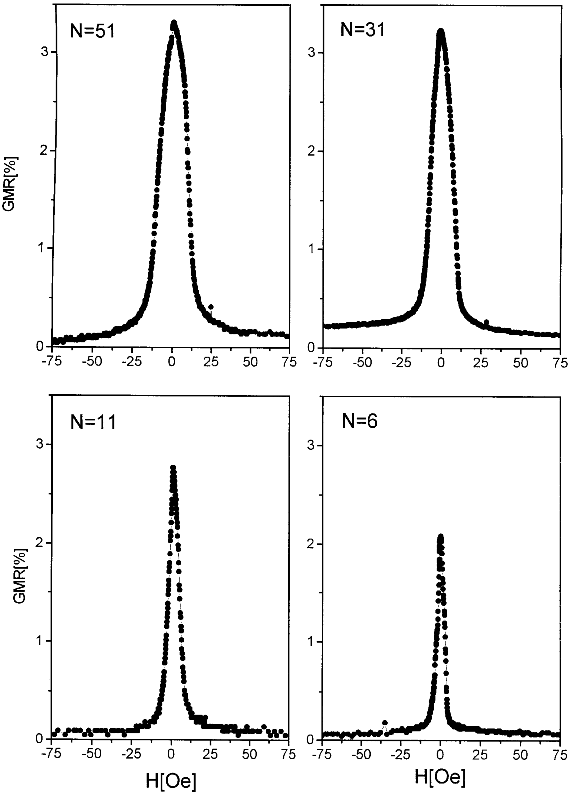

Fig. 3. Exemplary GMR(H) curves for Py(2 nm)/Cu(2 nm) multilayers with different number of magnetic sublayers.

We have observed a decrease of the saturation field, H_S, with lowering N (Fig. 4b). This effect was theoretically explained by Dieny [14]. Note that H_S changes much more than by a factor of 2, as predicted by Dieny et al. for an ideal stack, on decreasing N. It suggests, similarly to the GMR amplitude dependence on N, that the coupling is stronger for layers at larger distances from the substrate [15]. Comparing Fig. 4a and Fig. 4b one can see that there is a range of N in which GMR amplitude is almost constant while H_S decreases

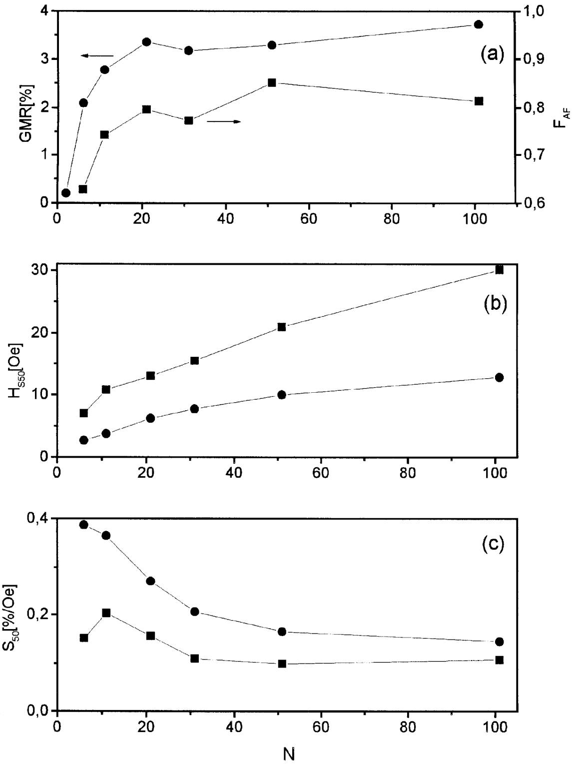

Fig. 4. (a) The GMR effect amplitude and F_{AF} dependence on the number N, of magnetic layers in Py(2 nm)/Cu(2 nm) multilayers for field applied parallel to EA direction. (b) The GMR effect 50% saturation field, H_{S50}, dependence on the number N, of magnetic layers in Py(2 nm)/Cu(2 nm) multilayers. Dots show H_{S50} for field applied parallel, while squares for field perpendicular to EA direction. (c) The GMR effect field sensitivity dependence on the number N, of magnetic layers in Py(2 nm)/Cu(2 nm) multilayers. Dots show S_{50} for field applied parallel, while squares for field perpendicular to EA direction.

considerably. We define the GMR field sensitivity, S_{50}, in a usual way: $S_{50} = \mathrm{GMR}/(2H_{S50})$ (where H_{S50} is the field change necessary to reduce the GMR value from maximum to 50% of its amplitude). Fig. 4c shows that when N is decreased from 101 to 6, S increases about two times and nearly reaches the value of 0.4%/Oe. Sensitivity can be further increased by increasing magnetic layer thickness, but unfortunately the GMR amplitude decreases simultaneously and hysteretic effects become more pronounced (due to the domination of anisotropy over exchange coupling) [7]. As can be seen in Fig. 5, we have obtained high sensitivity GMR(H) characteristic with small hysteresis. Nevertheless, it must be noted that the GMR(H) curve is no longer smooth when N is small as opposed to Mls with high number of magnetic sublayers. It may result from the N dependence of the shape of $M(H)$ curves, which is the case even for a structure with identical layers [1], and on the other hand, from the fact that in our samples antiferromagnetic exchange coupling is weaker in the first layers of the stack. From the application point of view it is also advantageous that our samples are thin and have thus high resistance values (for $N = 6$ sheet resistivity is about 15 $\Omega/\square$).

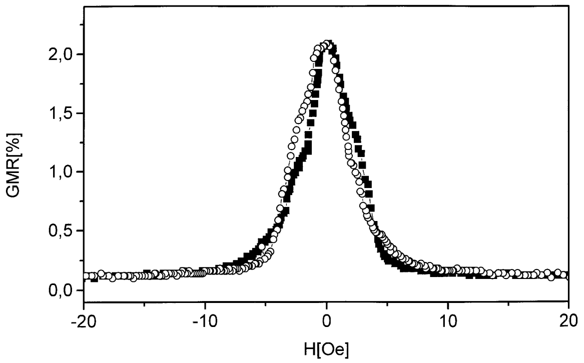

Fig. 5. GMR(H) dependence for Py(2 nm)/Cu(2 nm) multilayer with six magnetic layers. The magnetic field was applied parallel to the EA direction.

6. Conclusions

The results of magnetic, in situ resistance and magnetoresistance measurements performed at RT on Py(2 nm)/Cu(2 nm) multilayers presented above allow us to determine the influence of the number of magnetic layers on their magnetoresistive properties. We conclude that:

1. small values of interlayer exchange coupling constant, equal to about $0.8 \times 10^{-6}\ \mathrm{J\,m^{-2}}$ in topmost sublayers, were observed for Cu spacer thickness of 2 nm;
2. strong dependence of GMR saturation field on the number of magnetic layers in the stack allowed us to obtain Mls with high sensitivity and relatively small hysteresis;

3. due to the island growth mode we do not observe GMR effect in a bilayer consisting of two magnetic Py sublayers.

The sensitivity in our samples is much lower than in exchange-biased spin valves [16] but the host of unresolved technological aspects (read noise, electromigration, thermal stability) [17] still makes them potentially attractive from the application point of view [18].

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