Journal of Magnetics 4(1), 17-21 (1999)

GMR and Magnetization Study of Sputtered Permalloy/Cu Multilayer: The Influence of Temperature, Thickness and Number of Magnetic Layer

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(Received 18 August 1998)

The GMR (d_{Cu}) oscillatory behaviour as well as the widths of first and the second antiferromagnetically coupled ranges of the Permalloy (Py=$Ni_{83}Fe_{17}$)/Cu multilayers have been found to be strongly affected not only by the presence of the superparamagnetic/paramagnetic entitles located at the Py/Cu interfaces but mainly by the existence of the magnetic bridges between Py layers. The effectiveness of the magnetic bridges has been found to be temperature dependent, leading to the temperature dependence of the remnant to saturation magnetization ratio (M_R/M_S). We have found that for Py/Cu multilayers with equal Py and Cu layer thicknesses a high field sensitivity of the GMR effect (0.4 %/Oe) and negligible hysteresis can be achieved when the number of Py layers decreases from 100 to 6. Sensitivity can be further improved by increasing the Py layers thickness, but the hysterstic effect becomes more pronounced then.

1. Introduction

Multilayered structures consisting of alternating nonmagnetic spacer layers and soft ferromagnetic layers have been extensively studied. The reason for this is their high giant magnetoresistance (GMR) sensitivity, *i.e.*, a moderately high GMR amplitude accompanied by a fairly low saturation field [1-3]. Moreover, the GMR effect as well as the magnetic properties of the Py/Cu multilayers (Mls) have been found to be strongly dependent on deposition techniques and the type of buffer layer [4]. In this paper, we present results of GMR and magnetization study of the Py/Cu multilayers with Cu sublayer thickness d_{Cu} ranging from 0.8 to 2.3 covering the first and the second antiferromagnetic (AF) coupling ranges. The influence of temperature and the number of Py layers on the amplitude of the GMR effect, interlayer exchange coupling, saturation field and on the AF-coupled fraction of the samples has been examined and discussed. Since, the Py/Cu multilayers revealed a higher GMR field sensitivity for the second antiferromagnetic coupling maxima (d_{Cu}~2 nm) [1] thus the influence of number of Py layers on GMR has been examined for multilayers with $d_{Py} = d_{Cu} = 2$ nm. An analysis of the influence of the number of magnetic layers, N, in a stack on the GMR field sensitivity is presented.

2. Experimental

The Si (100)/Cu-20 nm/[Py-d_{py}/Cu-d_{Cu})]*100 multilayers (where d_{Py} and d_{Cu} denote Py = $Ni_{83}Fe_{17}$ and Cu thicknesses, respectively and Cu-20 nm is the buffer layer) have been obtained at room temperature (R.T.) by the double face-to-face sputtering method [5]. The Cu and Py sublayer thicknesses were determined by the X-ray fluorescence method (XRF) [1]. Room temperature (R.T.) magnetization measurements were performed with the vibrating sample magnetometer (VSM) while the superconducting quantum interference device (SQUID) magnetometer was used for zero-filed-cooled (ZFC) and field-cooled (FC) magnetization measurements and the magnetic field of 20 Oe was sufficient to induce a magnetization in our Py/Cu Mls. The magnetization reversal processes were examined with a VSM and by a longitudinal magneto-optical Kerr effect (MOKE). The d.c. magnetoresistance measurements have been performed with the conventional four point method at room temperature as well as at 4.2 K. We define the amplitude of the GMR effect as GMR=$\triangle R/Rs$, where $\triangle$R=R (H=0)-R(H=H_s), R(H=H_s)=R_s and H_s denotes the saturation field. The external magnetic field was applied in th film plane and parallel to the easy axis direction.

3. Results and Discussion

3.1 The Influence of Temperature and Sublayer Thickness on GMR Effect

Figure 1 displays the GMR amplitude as a function of d_{Cu} at R.T. and at 4.2 K for the multilayers with $D_{py} \simeq$ 2 nm. It can be easily seen that the GMR effect in the Py/Cu multilayers is very sensitive to temperature. The maximum GMR amplitude at R. T. has been found to occur for d_{Cu} $\simeq$ 1 nm

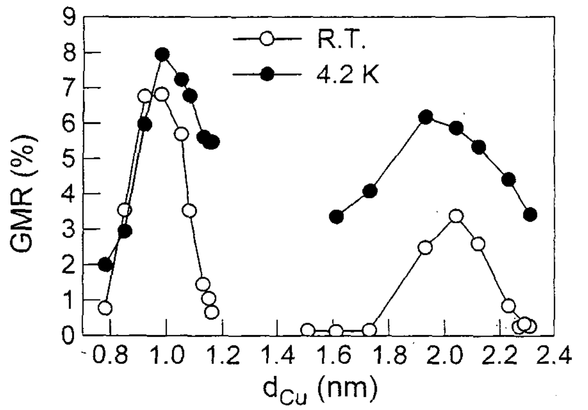

Fig. 1. The GMR amplitude as a function of d_{Cu} at R.T. and at 4.2 K for the Py/Cu multilayers with $d_{\mathrm{Py}} \simeq 2$ nm.

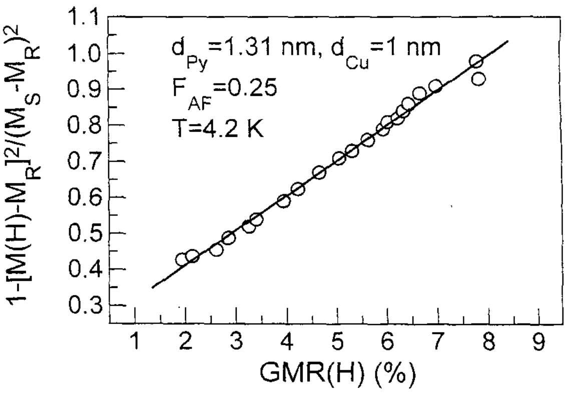

Fig. 3. Dependence of $1\text{-}[M(H)\text{-}M_R]^2/(M_S\text{-}M_R)^2$ ratio on the GMR(H) for Py/Cu multilayer with d_{Py}=1.31 nm, d_{Cu}=1 nm and F_{AF}=0.25 at 4.2 K.

and 2 nm. At 4.2 K the position of the first and the second maxima remain almost unchanged. However the most interesting feature of Fig. 1 is the influence of temperature on the value of the GMR amplitude. In case of the first maximum in can be noticed that the GMR amplitude increases very little for $d_{\mathrm{Cu}} \geq 1$ nm while for $d_{\mathrm{Cu}} < 1$ nm it is suppressed. However for second maximum the GMR amplitude clearly increases even for the Mls revealing GMR=0 at R.T., *i.e.*, for $d_{\mathrm{Cu}} < 1.8$ nm. The amplitude of the GMR effect in Py/Cu Mls depends on the AF coupled fraction (F_{AF}) of the sample since the ferromagnetically coupled fraction which can exist in real Mls does not participate in GMR effect. The fraction of the samples which is AF coupled can be directly extracted from magnetization vs field characteristics and $F_{\mathrm{AF}} = 1\text{-}M_R/M_S$; where M_R, M_S denote the remnant and saturation magnetization, respectively (under an assumption that other effects which can affect the M_R value like the presence of biquadratic coupling and/or twisted domain structure can be excluded). Thus, F_{AF}=1 for perfectly AF aligned Mls while F_{AF}=0 for ferromagnetically arranged Mls. Fiqure 2 displays some examples of the temperature dependence of the F_{AF} for the samples from the first and the second GMR (d_{Cu}) maximum. It can be seen that our Py/Cu Mls reveal almost perfect AF alignment only at R.T. while at 4.2 K F_{AF}~0.3. Taking the above into account we can write that $\mathrm{GMR(T)} \propto \mathrm{GMR_0(T)}*F_{\mathrm{AF}}(\mathrm{T})$; where $\mathrm{GMR_0(T)}$ denotes the temperature dependence of the GMR effect for F_{AF}=1. It means that the temperature dependence of the GMR amplitude can be influenced not only by the temperature changes of the mean free path (MFP) of the conduction electron affecting $\mathrm{GMR_0(T)}$ but also by the F_{AF}(T) dependence. We relate the decrease of the F_{AF}(T) parameter at 4.2 K to the activation of the magnetic bridges (inactive at R.T.) spanning across a few double layers which can lead to the direct ferromagnetic coupling between Py sublayers. Thus, at 4.2 K our Mls can be regarded as inhomogeneous on the macroscopic scale so that the ferromagnetically arranged areas (represented by M_R) have a size larger than MFP, and do not participate in the GMR effect. In such a case, the field dependence of the GMR should take a form $\mathrm{GMR(H)} \propto 1\text{-}[(M(H)\text{-}M_R)/(M_S\text{-}M_R)]^2$ for $H<H_S$ and $F_{\mathrm{AF}}<1$. Figure 3 shows an example (for d_{Cu}=1 nm, d_{Py}=1.3 nm and F_{AF}=0.25 at 4.2 K) that such a dependence is very well fulfilled. The enhancement of the GMR values at 4.2 K observed for the second maximum can be attributed to the increase of the MFP of the conduction electrons. Magnetically inactive at R.T. areas can exist not only at the grain boundaries (due to diffusion occurring during deposition processes) as the magnetic bridges/ pinholes between alternating Py layers but also at Py/Cu interfaces (due to the intermixing processes). The ZFC and FC magnetization measurements (Fig. 4) confirmed the presence of the paramagnetic/superparamagnetic areas in our samples for the Py sublayer thickness up to 2.11 nm. The FC(T) magnetization dependencies can be roughly ascribed as proportional to M_R(T). It can be seen from Fig. 4 that at 4.2 K the difference between ZFC and FC traces vanishes gradually with increasing Py thickness. If we assume that the magnetically inactive areas are located only at Py/Cu interfaces, one can expect that the lowering temperature will have the effect of decreasing the width of the nonmagnetic interfacial region resulting with a shift in position of

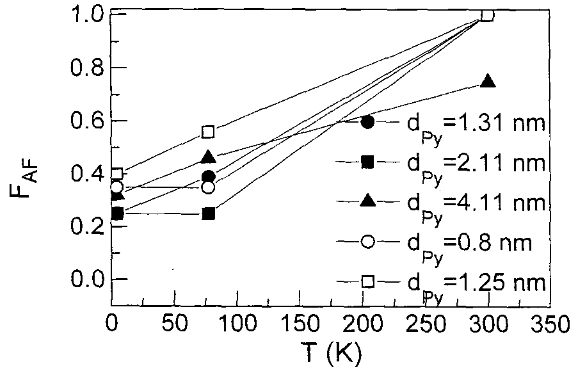

Fig. 2. Some examples of the temperature dependencies of the F_{AF} parameter for the samples with d_{Cu}=1 nm (filled symbols) and with d_{Cu}=2 nm (open symbols) and different Py sublayer thickness.

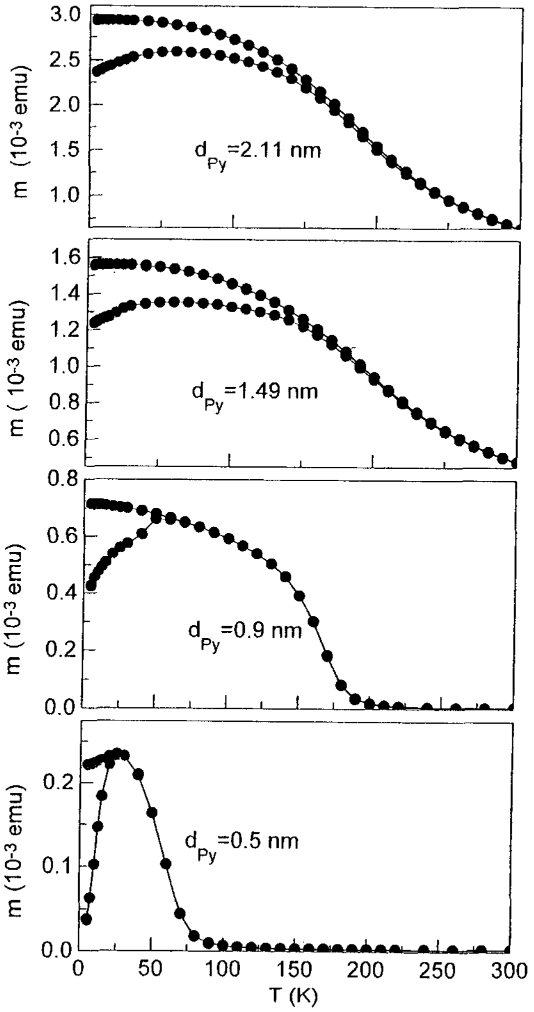

Fig. 4. The exemplary ZFC and FC magnetization curves of Py/Cu Mls with different Py sublayer thicknesses.

the maxima corresponding to AF coupling. Figure 5 representing the influence of temperature on saturation fields H_s shows that the position of the first AF maximum remains unchanged. However, the second one is largely broadened on decreasing temperature from R.T. to 4.2 K. Since, H_s is proportional to the interlayer coupling strength, such a behaviour suggests that the $F_{AF}(T)$ dependence arise mainly from magnetic bridges spanning across a few double layers. As the temperature decreases, these inactive at R.T. magnetic bridges become magnetically active and destroy the multilayered structure of our Py/Cu Mls. In our earlier studies the diffuse paramagnetic at R.T. interfacial areas was found to be present in Py/Cu Mls[1.6]. The existence of such interfacial paramagnetic (at R.T.) areas can modify the MFP of the condition electrons and in this way can affect $GMR_0(T)$. The enlargement of the H_s values observed at 4.2 K in comparison with those at R.T. points out that interlayer coupling strength increases with decreasing temperature.

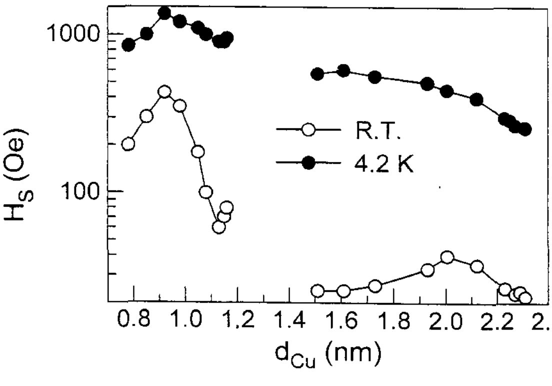

Fig. 5. Saturation field H_S of Py/Cu Mls with $d_{Py} \simeq 2$ nm as a function of Cu sublayer thickness measured at R.T. and at 4.2 K.

3.2 The Interlayer Exchange Coupling

Figure 6a presents a typical Kerr rotation $\Theta_K(H)$ 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.* [7]. 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 anisotropy is present [8]). Thus the energy of bilayer per surface unit has a form (with magnetic field applied parallel to EA direction):

$$E=-BM_S d_{Py}(\cos\Theta_1+\cos\Theta_2)-J\cos(\Theta_1-\Theta_2)-K_U d_{Py}(\cos^2\Theta_1+\cos^2\Theta_2)$$

where M_s and d_{Py} are saturation magnetization and thickness of magnetic layers respectively; K_U is a uniaxial anisotropy constant, Θ_1 and Θ_2 are angles between magnetizations and EA 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.* [7] 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.

Magnetization and thickness values used in our calculations were determined experimentally from VSM and XRF

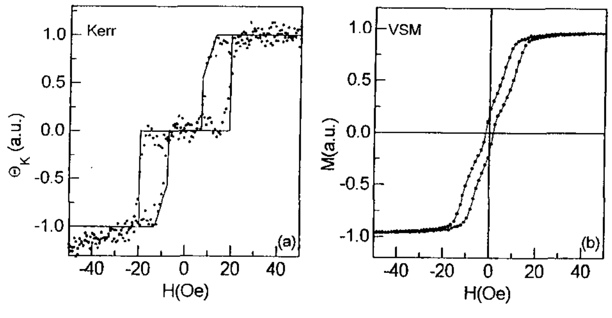

Fig. 6. The field dependence of (a) the Kerr rotation $\Theta_K(H)$ (line shows a fit according to the model of Dieny (see text) and (b) magnetization M(H) of Py(2 nm)/Cu(2 nm) multilayer with 101 magnetic sublayers.

measurements, respectively. The obtained antiferromagnetic exchange coupling constant values are small, about 0.5-0.8×10^{-6} jm^{-2}, which as shown later allowed us to obtain R(H) characteristics with small saturation fields. The relatively high hysteresis present in Θ_K(H) dependence is not observed in M(H) curves obtained with VSM (see Fig. 6b) and in R(H) measurements. It reflects the face 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.

3.3 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. 7. Decreasing of GMR amplitude with N (Fig. 8a) 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 [9]. 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 localized near Py/Cu interfaces. We conclude that coupling between first two sublayers is absent or favours parallel alignment of their magnetic moments [10] most probably due to rough growth mode 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 [1].

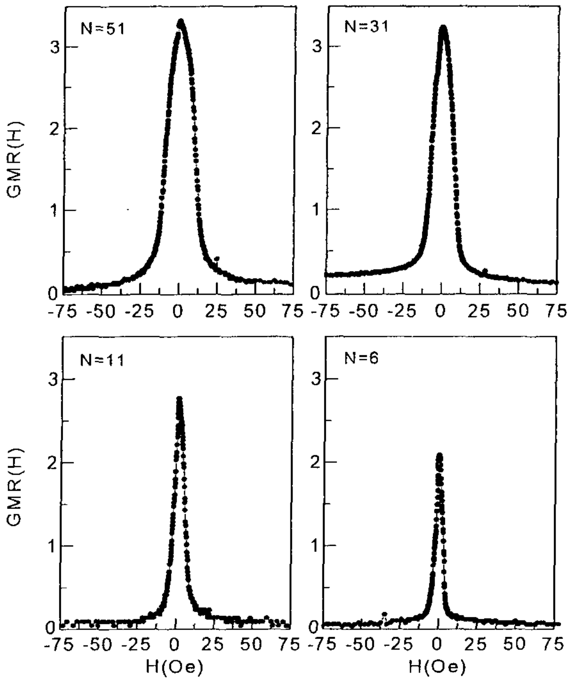

Fig. 7. Exemplary GMR(H) curves for Py(2 nm)/Cu(2 nm) multilayers with different number of magnetic sublayers.

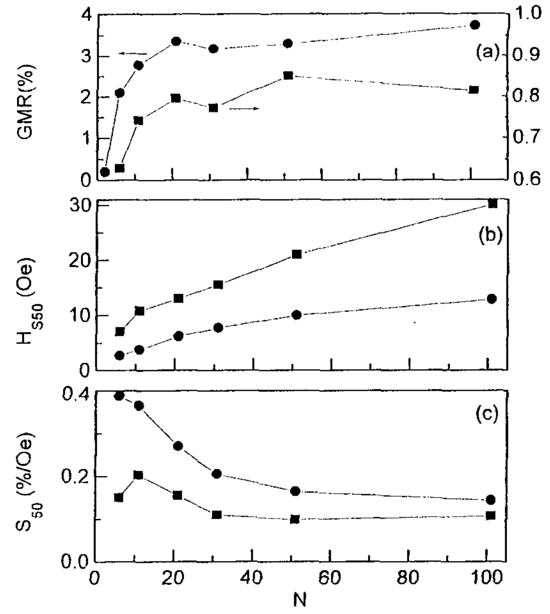

Fig. 8. The GMR effect amplitude and F_{AF} dependence on the number N, of magnetic layers in Py(2 nm)/Cu(2 nm) multilayers for field applied parallel to EA direction (a). The GMR effect 50% saturation field, H_{S50}, dependence on the number N, of magnetic layers in Py(2 nm)/Cu(2 nm) multilayers (b). Dots show H_{S50} for field parallel, while square for field perpendicular to EA direction. The GMR effect field sensitivity dependence on the number N, of magnetic layers in Py(2 nm)/Cu(2 nm) multilayers (c). Dots show S_{50} for field applied parallel, while squares for field perpendicular to EA direction.

Complementary magnetization reversal measurements performed with VSM (Fig. 6b) seem to confirm that antiferromagnetic interlayer exchange coupling is stronger for layers more distant from the substrate. As can be seen from Fig. 8a, AF-coupled fraction of the sample F_{AF} increases with increasing N, *i.e.*, as the relative contribution of first layers to the total magnetic moment of the sample decreases.

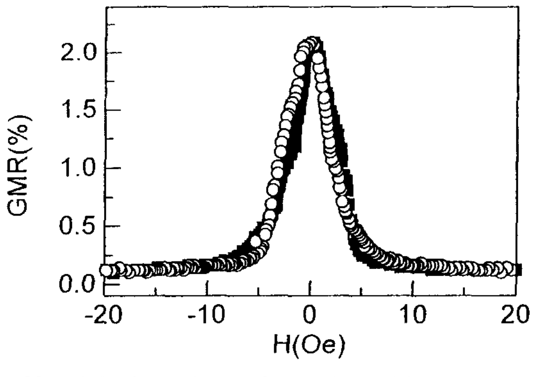

Fig. 9. GMR(H) dependence for Py(2 nm)/Cu(2 nm) multilayer with 6 magnetic layers. The magnetic field was applied parallel to the EA direction.

We have observed a decrease of the saturation field, H_s with lowering N (Fig. 8b). This effect was theoretically explained by Dieny [7]. 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 [10]. Comparing Fig. 8a and 8b one can see that there is a range of N in which GMR amplitude is almost constant while H_s decreases considerably. We define the GMR field sensitivity, S, in an usual way: $S=GMR/(2H_{s50})$ (where H_{s50} is the field change necessary to reduce the GMR value from maximum to 50% of its amplitude). Fig. 8c 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 hysteresis effects become more pronounced (due to the domination of anisotropy over exchange coupling) [8]. As can be seen in Fig. 9, 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 [7], 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 15Ω/□.

4. Conclusions

The temperature dependence of the GMR effect observed in Py/Cu Mls obtained by face-to-face sputtering method was found to be affected by the presence of inactive at R.T. magnetic bridges spanning across a few double Py/Cu layers as well as the paramagnetic Py-Cu interface and therefore can be ascribed as $GMR(T) \propto GMR_0(T)*F_{AF}(T)$. It has been shown that the paramagnetic at R.T. magnetic bridges/pinholes affect mainly the $F_{AF}(T)$ parameter whereas the interfacial paramagnetic layer modifying the MFP of the conducting electrons can influence the $GMR_0(T)$ behaviour. At 4.2 K, suppression of the GMR amplitude due to degradation of the F_{AF} parameter caused by magnetic pinholes (ferromagnetic at 4.2 K) is more efficient than enlargement of the MFP (in comparison to its R.T value) for thinner Cu layer, *i.e.*, for the Mls with $d_{Cu} < 1.2$ nm. For Mls with thicker Cu layers *i.e.*, for $d_{Cu} > 1.2$ nm in spite of the reduction of the F_{AF} parameter (at 4.2 K) the effect of enlargement of the MFP resulting the increase of the GMR amplitude seems to be more effective.

The results of magnetic and magnetoresistance measurements performed at R.T. on Py(2 nm)/Cu(2 nm) multilayers allow us to determine the influence of the number of magnetic layers on their magnetoresistive properties. We conclude that:

(i) small values of interlayer exchange coupling constant, equal to about $0.5\text{-}0.8\times10^{-6}$ Jm^{-2}, were observed for Cu spacer thickness of 2 nm,

(ii) 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.

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