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Annealing Effects on Py/Cu GMR Multilayer Films with Limited Number of Sublayers

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The influence of annealing on giant magnetoresistance (GMR) effect and magnetization reversal processes has been investigated in Py/Cu (Py = $Ni_{83}Fe_{17}$) sputter-deposited multilayers (MLs) with a limited number of magnetic sublayers ($N \leq 6$) and equal sublayer thicknesses both for Py and Cu (t_{Cu} = 2 nm, t_{Py} = 2 nm). Based on the magnetization and magnetoresistance measurements it has been shown that the magnetic behavior of such MLs is strongly influenced by annealing driven disruption of magnetic layers (lateral decoupling) and nonmagnetic layers (magnetic bridging between Py layers). A comparison of experimental hysteresis curves with model dependences indicates that annealing causes a change of the magnetization reversal from a local to an absolute energy minimum mode leading to quasi-two-state magnetoresistance characteristics.

1. Introduction

Multilayered structures made from ferromagnetic layers separated by non-ferromagnetic, conducting spacer layers of a certain thickness display relatively large electrical resistance changes upon the application of a small external magnetic field. This is the so called giant magnetoresistance (GMR) effect [1–3]. It has been shown [4–6] that multilayers and spin-valve structures with permalloy (Py) used as magnetic layer are especially interesting since they display moderately high resistance changes which take place in small magnetic fields. This leads to relatively high, promising from an application point of view, values of GMR field sensitivity [7]. In a previous paper [8] three of us have shown that it is possible to obtain (Py/Cu) multilayers from a second AF-coupling range, with a limited number of repetitions of the basic bilayer (N = 6), exhibiting a sensitivity of the GMR effect reaching 5×10^{-3}%/A/m (0.4%/Oe). These MLs were shown to display a low hysteretic behavior of the GMR(H) dependence and a relatively high sheet resistivity (15 Ω/□). In this paper, we present an analysis of the magnetoresistance (MR) and magnetization reversal processes in $Ni_{83}Fe_{17}$/Cu multilayers with a limited number of Py sublayers (N = 2–6 and 31) obtained by a double face-to-face sputtering [9]. The influence of low temperature annealings ($T_a \leq 200$ °C) on the magnetoresistance and magnetization reversal processes is also discussed.

2. Experimental

Glass/Py-2 nm/[Cu-2 nm/Py-2 nm] × (N−1) (where N = 2–6 and 31 and Py = $Ni_{83}Fe_{17}$) multilayers have been obtained at room temperature (RT) by the double face-to-face sputtering [9]. The base pressure was about 1×10^{-4} Pa and Ar pressure during deposi-

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tion was about 0.05 Pa. The deposition rates were 0.05 nm/s for Py and 0.1 nm/s for Cu sublayers. The Cu sublayer thickness was chosen so as to obtain the samples from the second AF-coupling range [10, 11] and the Py sublayer thickness used maximizes the GMR value in the Py/Cu MLs [3, 11]. High-angle X-ray diffraction measurements showed that a reference sample with $N = 31$ was polycrystalline with a weak (111) texture. A well-defined periodic structure as evidenced by the low-angle diffraction was also observed. For samples with $N \leq 6$ a structure determination was not possible in our diffractometer. The magnetization reversal processes were examined at room temperature with a vibrating sample magnetometer (VSM) and by a longitudinal magneto-optical Kerr effect (MOKE). The RT magnetoresistance measurements were performed with the conventional four-point method. We define the field dependence of the GMR as

$$\mathrm{GMR}(H) = 100 \times \frac{R(H) - R(3183\ \mathrm{A/m})}{R(3183\ \mathrm{A/m})}\,, \tag{1}$$

where a reference field of 3183 A/m (40 Oe) was chosen to focus the attention on the small field range. In this paper, a maximum resistance, not its zero-field value, determines the GMR amplitude. The anisotropic magnetoresistance (AMR) value in the investigated samples was small ($(R-R_\perp)/R_\perp \approx 0.1\%$) and so the GMR value was approximated by the total MR value. Unless otherwise stated the external magnetic field in all the measurements reported was applied in plane and parallel to an easy axis (EA) direction. The annealing was performed in vacuum at several temperatures (twice at 125 °C and once at 150, 175 and 200 °C). All annealings lasted 1 h except the first one, which lasted 2 h.

3. Results and Discussion

Figure 1 collects the easy axis VSM hysteresis loops obtained at three stages of thermal treatment for the multilayers with $N = 4$, 5 and 6. Figure 2 shows the VSM and magnetoresistance hysteresis loops for $N = 3$ in an as-deposited state and after the first annealing at 125 °C.

3.1 As-deposited multilayers

For $N = 2$ neither the GMR effect nor any traces of AF-coupling on the hystersis curve were observed. This agrees well with our previous results of in-situ resistance measurements obtained for similar multilayers [8]. In thin film systems there is a good correlation between the initial mesoscopic roughness found by scanning tunneling microscopy and the onset of Ohmic conductivity [12]. This correlation allowed us to estimate the initial roughness of Py deposited on glass at about 1.2 nm. This value, about six times higher than the bulk Py lattice spacing, suggests an island growth mode at the initial deposition stage. It strongly suggests that the first Py layer can have an overwhelming small grain or superparamagnetic fraction (permalloy rich areas isolated from the Py layers), which is not visible in the GMR effect, at least at small fields. Additionally, the large initial roughness can lead to an extensive bridging between the first two Py sublayers, which results in a ferromagnetic coupling and no GMR even with a buffer Py layer having some ferromagnetic fraction. Correlated roughness, i.e., in-phase waviness

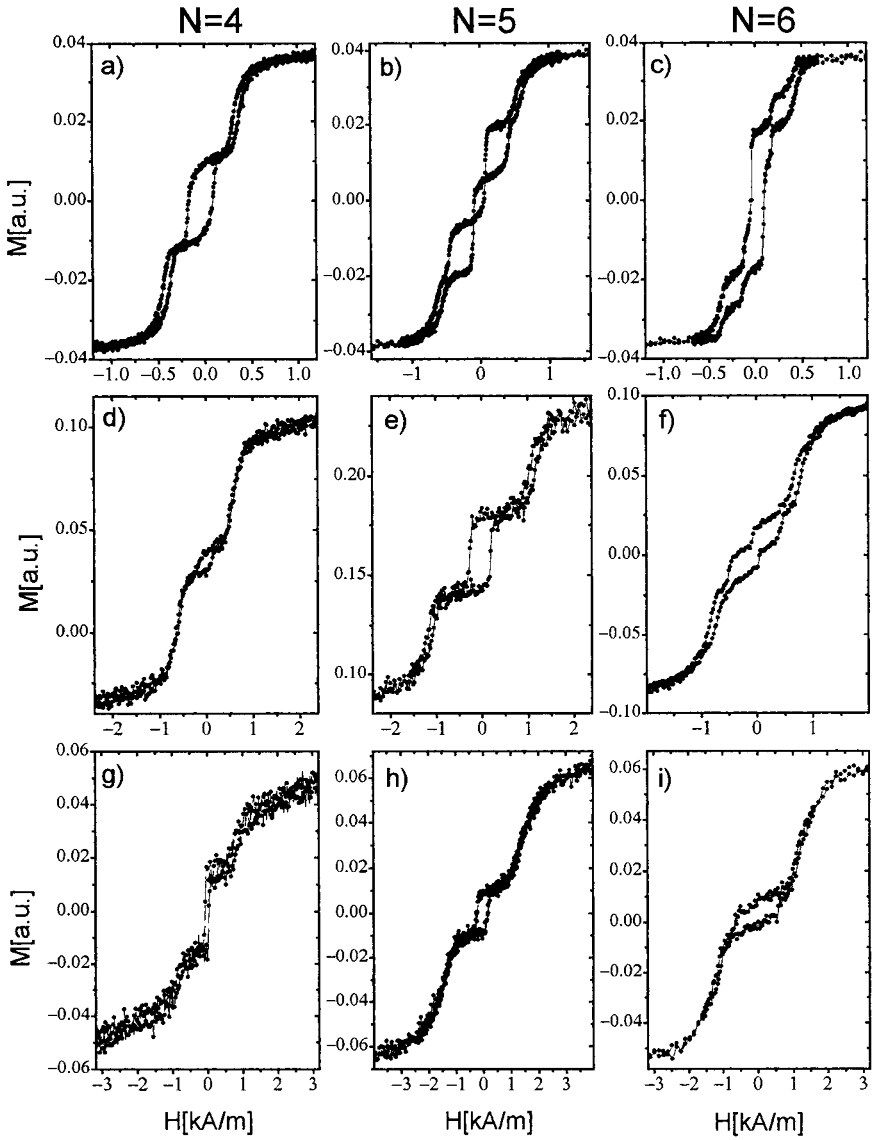

Fig. 1. Exemplary $M(H)$ curves for the Py(2 nm)/Cu(2 nm) MLs with nominally N = 4, 5 and 6 Py sublayers. Columns 1, 2 and 3 (from left to right) show curves for N = 4, 5 and 6, respectively. Rows 1, 2 and 3 show curves obtained in the as-deposited state, after a consecutive 1 h annealing at 150 °C (preceded by a 3 h annealing at 125 °C) and after 1 h annealing at 200 °C, respectively. Additionally, in the latter case, the intermediate 1 h anneal at 175 °C preceded

of neighboring Py/Cu interfaces, can also lead to a magnetostatic, so called "orange peel" ferromagnetic coupling [13].

The absence of antiferromagnetic coupling between the buffer and the second Py layer is consistent with the results obtained for N = 3 (Fig. 2). The $M(H)$ curve is similar to those characteristic of bilinearly exchange coupled bilayers [14, 15] with an

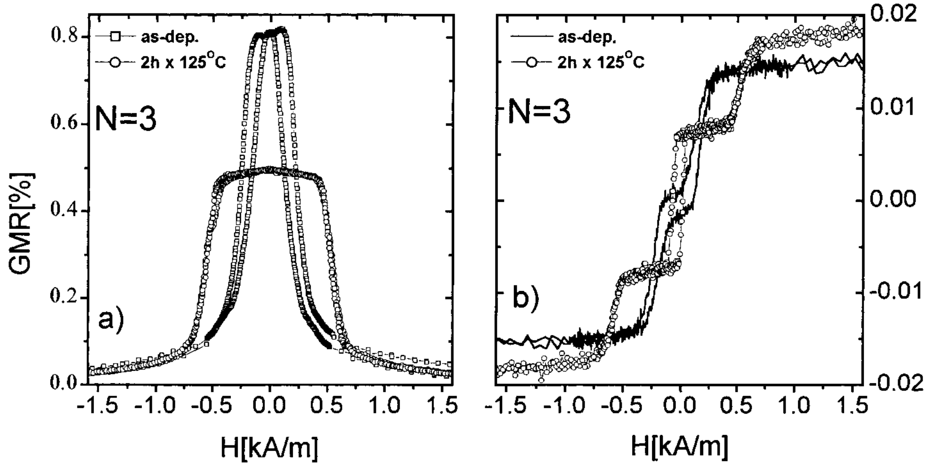

Fig. 2. a) GMR(H) and b) $M(H)$ dependences obtained for the Py(2 nm)/Cu(2 nm) ML with nominally three Py sublayers in the as-deposited state and after a 2 h annealing at 125 °C. The near-zero feature, i.e., the different from zero remanence value, is not predicted in the model of Dieny [14]

additional feature, a remanence value different from zero. For higher N, the $M(H)$ dependences are similar in shape to those predicted by a phenomenological Stoner-like model of Dieny [14, 15] (see Fig. 3). In the presented model it was assumed that the magnetization is uniform in each layer and that the system relaxes through Stoner coherent rotation to the local energy minimum. It should be thus emphasized that, as in the case of $N = 3$, in order to obtain at least a qualitative similarity it must be assumed in the modeling (John Oti's freeware program SimulMag was used [16]) that in the as-deposited state the actual number of ferromagnetic layers is less by one than the nominal number. This discrepancy between the nominal and the actual number of Py layers agrees with the previously mentioned in-situ resistance measurements [8].

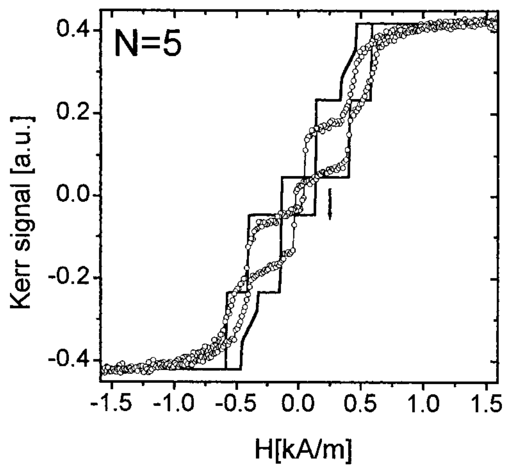

Fig. 3. Exemplary comparison of the experimental MOKE curve (circles) obtained in the as-deposited state for Py(2 nm)/Cu(2 nm) MLs with nominally five Py sublayers with a model curve (full line) for a ML with four magnetic sublayers. The model curve was obtained with the SimulMag program (see text). It was assumed that all Py sublayers were 2 nm thick (except the outer layer for which the thickness was taken to be 3 nm) and that their magnetization was equal to 800 kA/m. The coupling field was set to be equal in magnitude to the uniaxial anisotropy field (232 A/m). To avoid dipole interactions influencing the calculation the distance between 1×1 mm^2 layers was set at 5 mm. A switching order on decreasing the field from the saturation was as follows: (substrate/)↑↑↑↑, ↑↓↑↑, ↑↓↑↓, ↓↓↑↓, ↓↓↓↓. No attempt was made to fit the switching fields of both curves

In most of the measured $M(H)$ dependences (Figs. 1 to 3) there are traces of the reversal of the individual layers. However, a quantitative analysis of the $M(H)$ curves is very difficult. The shapes of these dependences, with a relatively abrupt saturation through spin flop and not a linear increase, indicate that the coupling constant is of the order of a uniaxial anisotropy energy ($j_{AF} \approx K_U t_{Py}$, where K_U is a uniaxial anisotropy constant [14]). It seems interesting to note that for MLs with $N = 5$ (Fig. 1b, 3) the change of sign of the net magnetic moment (relative to the field direction) takes place in the positive field region. This can be seen both in the VSM and MOKE curves and is consistent with the phenomenological model (Fig. 3) [14]. The observed discrepancy between the measured and the model curve comes from structural imperfections. Py layers situated closer to the substrate can have more rough interfaces than those more distant and this influences not only their effective magnetic moment but can also lead to changes of the effective interlayer coupling [17].

The dependence of surface density of the magnetic moment of the investigated MLs on the number of Py layers (Fig. 4) clearly indicates that the magnetization of the first Py sublayers is smaller than that of the sublayers more distant from the substrate. This is most probably due to intermixing processes leading to the appearance of (Ni–Fe)–Cu alloy at the interfaces [11, 18] and may indicate that the thickness of the alloy region is higher at the Py/Cu interfaces which lie close to the substrate than in the rest of the ML. In the near substrate regions a higher density of grain boundaries (Fig. 5) promotes a mass transport through grain boundary diffusion. This may lead to a more intensive intermixing in these areas and the grain boundaries become a preferable path for the diffusion driven bridging. This process is quickened by the presence of the high mesoscopic roughness, which locally can diminish the distance between the Py layers (Fig. 5a). The dependence shown in Fig. 4 indicates therefore that the amount of structural defects in the investigated MLs diminishes with increasing the distance from the substrate. Consequently, in the MLs with small N structural changes caused by diffusion should be more pronounced than in the MLs with higher N. It has already been shown [19, 20] that the bridges can result in an effective 90° coupling (so called biquadratic coupling) which favors a perpendicular orientation of the magnetic moments of the neighboring magnetic layers. Such a coupling influences the shape of the hysteresis curve [20] and should manifest itself in a convex shape of the hard axis $M(H)$ depen-

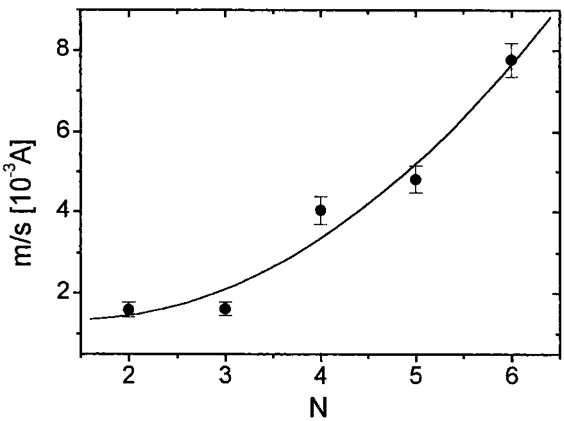

Fig. 4. Surface density m/s of the saturation magnetic moment m of the Py(2 nm)/Cu(2 nm) MLs in the as-deposited state (solid dots) for different numbers of Py sublayers, N. The solid line is a guide to the eye. Bulk magnetization of Py, measured on a 250 nm thick film, is 8.7×10^5 A/m

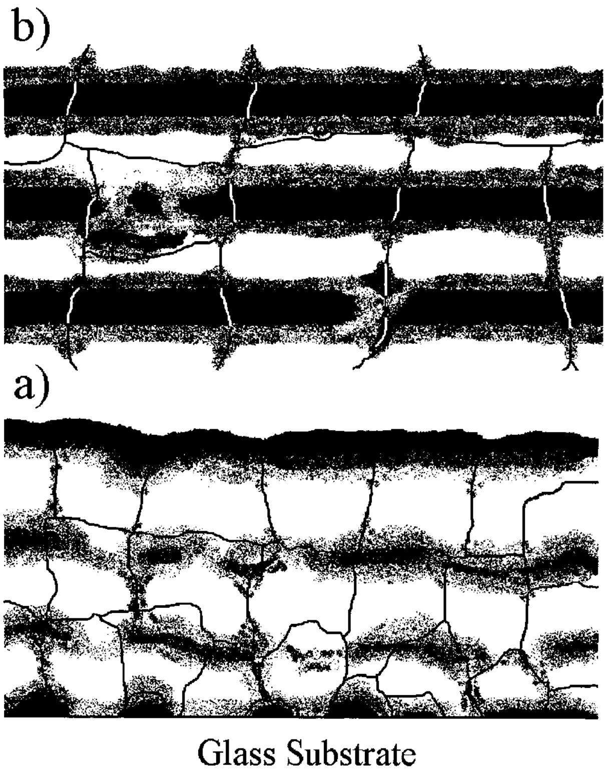

Fig. 5. a) Schematic picture of the Py/Cu multilayer after the deposition of four Py layers and b) the structure of the regions more distant from the substrate. The Ni–Fe fraction is drawn black. In b) the grain boundaries crossing compact Py layers are drawn white

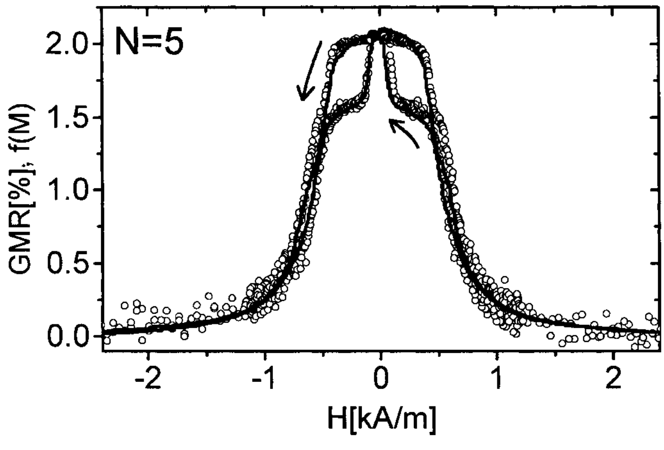

Fig. 6. Comparison of the GMR(H) dependence (thick line) for the Py(2 nm)/Cu(2 nm) MLs with nominally five Py sublayers with the corresponding transformed $M(H)$ dependence obtained from the VSM (circles) (Fig. 1b), see text. The $M(H)$ dependence was transformed according to equations $f(M) := -1309M^2 + 2.07$ and $H := H + 21.5$ (A/m) to get the GMR(H) dependence

dences which was not observed in our samples. Therefore, we assumed that the biquadratic coupling term does not significantly influence the behavior of the MLs investigated in this work.

In most cases we observed a very good correspondence between the GMR and VSM curves (see Fig. 6) as evidenced by a comparison of the GMR(H) dependence with the scaled $M^2(H)$ value. Here it is assumed that in the course of the magnetization reversal the angle between the magnetic moments and EA (and the applied field direction) is the same for all sublayers (except for some transient states which are not visible in the quasi-static measurements, flip or flop transitions [14]). It follows then from the cosines dependence of the GMR change on the angle between projections of the neighboring sublayers' magnetic moments on their common interface plane [3] ($\Delta R_{\mathrm{GMR}} \propto \cos(\theta)$) that the squared magnetization along the field direction is proportional to ΔR_{GMR}, i.e., $M^2 = (M_\mathrm{s} \cos(\theta/2))^2 \propto \cos(\theta) \propto \Delta R_{\mathrm{GMR}}$.

3.2 Annealed multilayers

The $M(H)$ dependences similar to those observed in our MLs were previously reported [21] for (Co/Pd)/Ru MLs with strong AF-coupling and high perpendicular magnetic anisotropy. We show here that such dependences can also be observed in very small magnetic fields for MLs with a limited number of Py layers. This is essential from the application point of view. However, it is also required that they should be thermally stable. As mentioned before (see the discussion concerning Fig. 4) the density of structural defects is higher in the vicinity of the substrate than in the rest of the sample. Since the defects lead to an increase of the diffusion processes and this may be deficient for the thermal stability, we have investigated the effect of low temperature annealings on the magnetoresistance and magnetization reversal processes for MLs with $N \geq 3$.

For $N = 3$ the GMR(H) dependence after annealing (2 h at 125 °C) (Fig. 2a) is almost non-hysteretic. The observed non-hysteretic behavior may result from non-coherent magnetization reversal processes, i.e., the presence of independently reversing Py grains and/or domain walls, which always allow the system to relax to the absolute energy minimum [15]. The transformation of the $M(H)$ dependence caused by annealing (Fig. 2b) is very pronounced and allows a somewhat easier interpretation. Most probably the annealing results in a creation of ferromagnetic bridges (pinholes [19, 20]), which couple ferromagnetically some areas of neighboring Py sublayers and lead to a decrease of the GMR amplitude [8] (F-coupled areas do not contribute to the GMR effect since the mutual orientation of their magnetic moments does not change in the course of the magnetization processes). It is further corroborated by the fact that the GMR amplitude change after the annealing at 125 °C ($\approx -40\%$) roughly corresponds to the change of an antiferromagnetically coupled fraction of the sample $-\Delta F_{\mathrm{AF}} \approx -30\%$ ($F_{\mathrm{AF}} = 1 - M_\mathrm{R}/M_\mathrm{S}$, where M_S and M_R are the saturation and remanence magnetization, respectively [11]) provided that the near-zero feature comes from the F-coupled fraction of the bilayer. The existence of F-coupled areas in the AF-coupled bilayer is confirmed by the lack of any traces of magnetization reorientation in the magnetoresistance curve taking place at about -80 A/m (see Figs. 2a and b). It should be noted that after a 3 h annealing at 125 °C, due to the strong increase of the surface density of the pinholes, the same sample shows no AF-coupling and no GMR and behaves similarly as a single ferromagnetic layer ($H_\mathrm{C} \approx 24$ A/m).

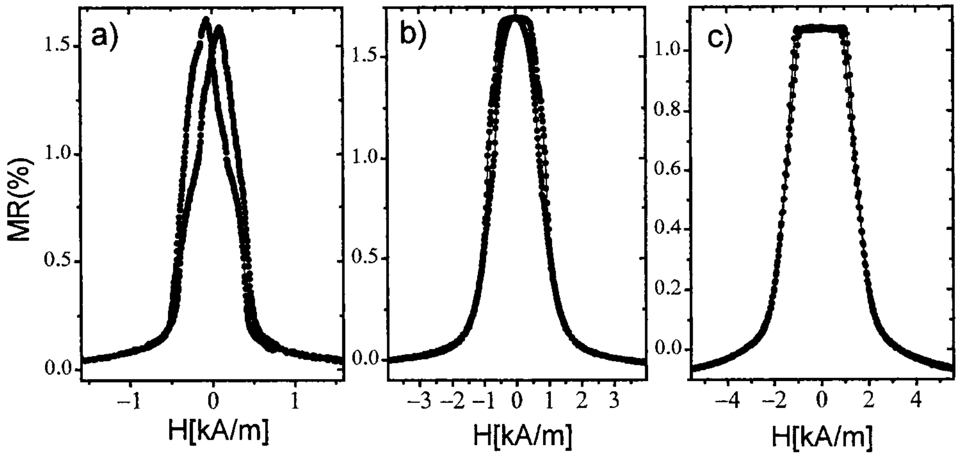

Fig. 7. GMR(H) dependence of the Py(2 nm)/Cu(2 nm) multilayer with $N = 6$ in the as-deposited state and after annealings at 150 and 200 °C. Panels a, b and c correspond to panels c, f and i of Fig. 1, respectively

In contrast to the ML with $N = 3$, in the MLs with $N = 4$, 5 and 6 interlayer exchange coupling and GMR are still present even after the 200 °C anneal (see Figs. 1 and 7). In all samples annealing caused a gradual disappearance of the traces of a single layer reversal in the $M(H)$ curve. For $N = 4$, the 200 °C annealing leads to a similar effect as for the sample with $N = 3$ at 125 °C, i.e., to an abrupt appearance of the ferromagnetically coupled (by pinholes) volume in the multilayer (Fig. 1g). In general it is difficult to state unambiguously whether the pinholes caused the two given sublayers to behave as one magnetic entity and changed the $M(H)$ dependence or whether the pinholes penetrate through several layers and give in result the F-coupled fraction without changing the effective N [22].

In spite of the pronounced differences in the magnetization reversal after the consecutive annealings between all samples investigated, the GMR(H) dependences of all

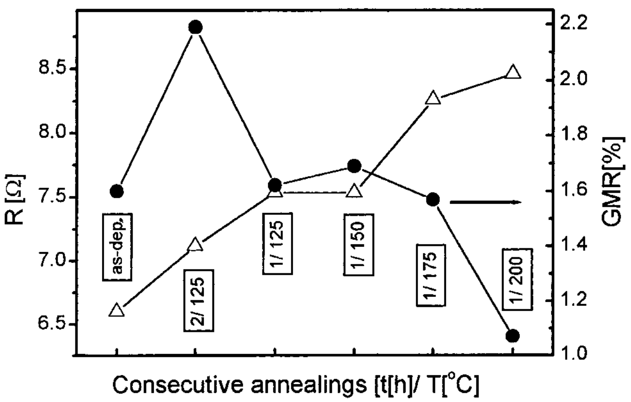

Fig. 8. Zero field resistance and magnetoresistance of the Py(2 nm)/Cu(2 nm) multilayer with nominally six Py sublayers after the consecutive stages of thermal treatment

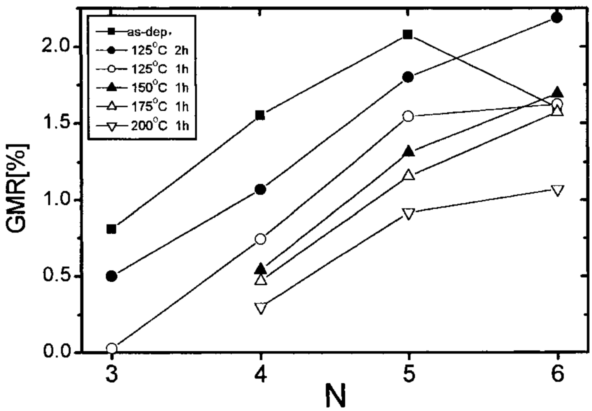

Fig. 9. GMR effect for all investigated MLs as a function of the number of sublayers N after the consecutive stages of thermal treatment

films change with the thermal treatment in a very consistent way. Figures 2 and 7 show representative examples. The results shown in Fig. 8 lead us to believe that changes of the GMR value in the course of thermal treatment are mainly caused by changes in F_{AF} value and/or small Py grain formation (see the discussion of Fig. 10) and only in a little degree by resistance (R) changes. For $N = 6$ for instance the change of the GMR value correlates with that of the resistance only after annealing at 175 °C. For $N = 3$, the increase of R affects the GMR value only slightly ($\Delta R \approx 7\%$). The GMR amplitude increases after the first annealing only for $N = 6$ where it is evidently caused by the increase of F_{AF} (Figs. 1c, f). In the remaining cases the GMR values decrease after each consecutive annealing (Fig. 9). Similarly to the case of $N = 6$ the GMR amplitude

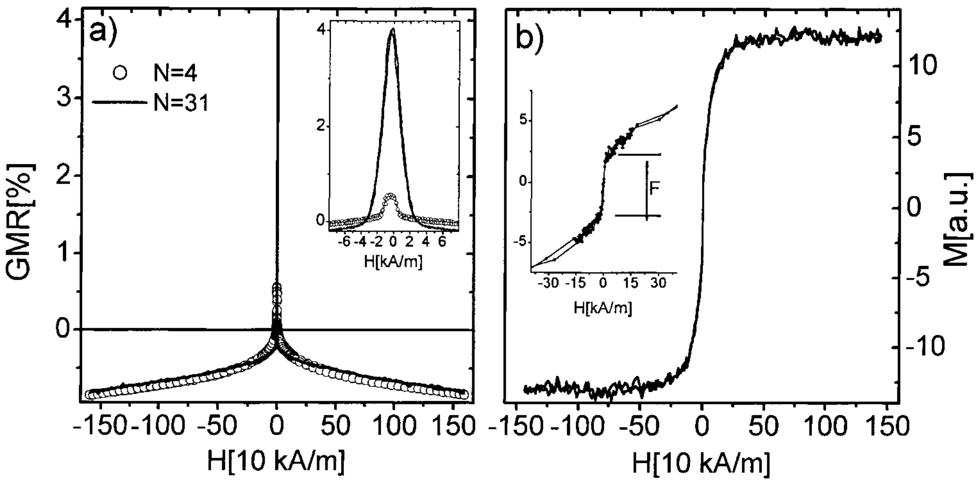

Fig. 10. a) Comparison of the GMR(H) dependences for the Py(2 nm)/Cu(2 nm) MLs with nominally 4 (circles) and 31 (full line) Py sublayers after the annealing at 175 °C. The insert shows the small field range changes. b) $M(H)$ dependence for the Py(2 nm)/Cu(2 nm) multilayer with $N = 4$ after annealing at 175 °C. The insert explains the definition of the low field fraction of the $M(H)$ curve. Note that F corresponds to the small field saturation (see for example Fig. 1a) and not to the remanence

increases in multilayers with $N = 31$ after 1 h annealing at 175 °C from 3.6% to 4.1% and decreases after subsequent 200 °C anneal to 3.6%. It was shown earlier [23] that for $N = 101$ under the same annealing conditions our samples are thermally stable and the 2 h annealing at 200 °C (preceded by an anneal at 175 °C) increases their GMR value from 4 to 4.7%. In the most thermally stable MLs investigated in this contribution (i.e., with $N = 5, 6$) the small field GMR value (i.e., the maximum GMR value, see Eq. (1)) is reduced by a factor two in the course of the whole thermal treatment. Since accompanying changes of a high field magnetoresistance, i.e., GMR(1.581×10^6 A/m), are much smaller, the annealing results in the GMR(H) dependences in which a considerable part of the resistance change takes place in the high field range. As expected, in thinner, more defected samples ($N = 4, 5$) high field changes dominate (Fig. 10a). Previously it was shown [11, 24] that temperature dependences of the magnetization (ZFC, FC curves) unambiguously indicate the existence of a superparamagnetic fraction in Py/Cu MLs. The ZFC(T) curve shows a broad maximum at approximately −200 °C which corresponds to disrupted parts of the Py layers but there are also grains switching at much lower temperatures, i.e., much smaller than 3 nm in diameter, too. It should be noted that the high field tails of the $M(H)$ and GMR(H) dependences themselves do not necessarily indicate that the Py grains are superparamagnetic. They could originate from a broad distribution in the magnitude of the local demagnetizing field caused by shape and size distributions of the Py grains and/or from intergrain magnetostatic interactions [25]. The appearance of loose, i.e., not exchange coupled to the others, Py grains is probably caused by the initial roughness [8] in the thin samples and by the intermixing at Py/Cu interfaces [25] in the thicker ones. In the latter case the interdiffusion at the interfaces, strengthened by the presence of grain boundaries, leads to the formation of discontinuities in the magnetic layers. The cut-off part of the Py layer is decoupled from the rest of the layer by Cu diffusion to a boundary region (Fig. 5b). For comparison, it is worth noting that after the second annealing (2 h + 1 h at 125 °C) the ratio of the low field fraction (see

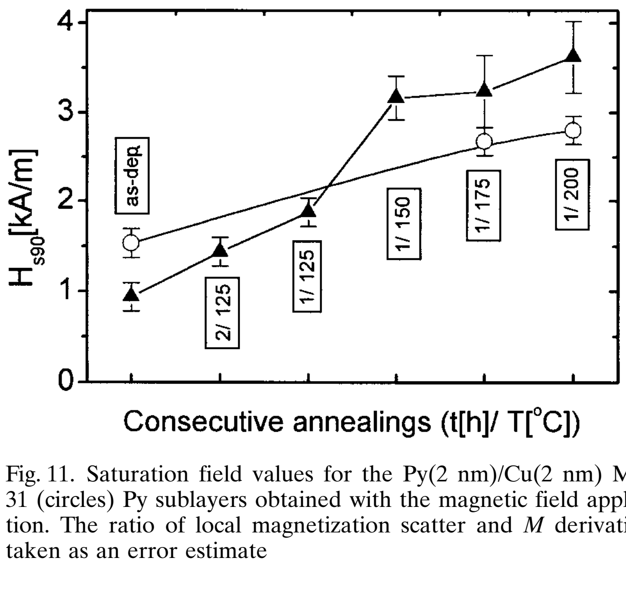

Fig. 11. Saturation field values for the Py(2 nm)/Cu(2 nm) MLs with nominally 6 (triangles) and 31 (circles) Py sublayers obtained with the magnetic field applied perpendicularly to the EA direction. The ratio of local magnetization scatter and M derivative over the applied field value was taken as an error estimate

Fig. 10b) of the $M(H)$ curve to the saturation magnetization is equal to about 0.8 for $N = 31$, 0.5 for $N = 6$ and 0.2 for $N = 3$ indicating that in thin Py/Cu multilayers the concentration of the loose Py grains is highest close to the substrate.

Both in the $M(H)$ and GMR(H) dependences there is a steady increase in saturation field value, H_s, on consecutive annealings (see Figs. 1, 2, 7 and 11). H_s is defined here as the magnetic field at which saturation of only low field fraction occurs (see Fig. 10b) since the total magnetization saturates at much higher fields. The data presented in Fig. 11 originate from the measurements taken with the magnetic field applied perpendicularly to the EA direction. In such a configuration N dependent changes of the $M(H)$ curve shape [14, 21] are the least probable to cause an erroneous determination of H_s. It can be seen that annealing leads to an almost fourfold increase in H_s for $N = 6$ (see also Fig. 7) leading to a decrease of the GMR field sensitivity. Similar changes occurred for $N = 3$ (Fig. 2), although H_s increases here much less; most probably because this sample had many defects already in the as-deposited state (see the following discussion on a lateral decoupling).

After a series of annealings all the samples display a quasi-two-state GMR(H) characteristics (Figs. 2a and 7c) with a relatively small switching field between those states and a plateau near zero (Fig. 7c). Comparing the GMR(H) dependences from Figs. 2a and 7c one can see that H_s, which is roughly proportional to the coupling energy j [14], for $N = 6$ takes four times the value observed for $N = 3$. It agrees well with the fact already pointed out that due to the initial roughness the AF-coupling between the first layers is weaker [8, 17, 21] than in the rest of the multilayer. All the GMR(H) and $M(H)$ curves (although here the F-coupled fraction makes it less obvious), evolve into hysteresis-free ones in the course of thermal treatment. According to the absolute energy minimum model of Dieny [15] it means that Py sublayers do not switch coherently, as would appear in the as-deposited state, and that the annealing creates magnetic regions which reverse independently. These regions are most probably Py grains created by the thermal disruption of Py layers.

In summary, it can be stated that diffusion processes play a decisive role in determining the behavior of the investigated MLs in the course of thermal treatment. These processes take place primarily in the most defected regions, i.e. in the intergrain areas and on the interfaces. Consequently, the thinnest, relatively poor in quality, multilayers are mostly affected. The diffusion leads to a break-up of the continuous Py sublayers into discontinuous ones. Some of the Py grains are connected by pinholes with the grains of neighboring layers (Fig. 5b) what decreases the AF-coupled fraction while the others are effectively more strongly antiferromagnetically coupled since they are not magnetically connected with the F-coupled fraction of the layer [26]. It is the so called lateral decoupling [27], which leads to the increase of H_s. The occurrence of the high field tails in both the $M(H)$ and $R(H)$ dependences can be due to the above-mentioned small Py grains located at or near the Py/Cu interfaces. Alternatively, it can be argued that annealing causes a smoothing of the interfaces and leads to an increase of the effective interlayer exchange coupling. Since in the second antiferromagnetic region a maximum strength of the coupling is observed for the Cu sublayer thickness t_{Cu} close to 2 nm [11] smoothing of the Py/Cu interfaces for nominal t_{Cu} = 2 nm can lead to an increase of the coupling strength and consequently H_s. The second of the mechanisms sketched seems to us less probable because it requires a perfect structure of the layers. As a consequence of the structural changes the hysteretic character of the $M(H)$ dependences after the annealing at 200 °C originates from the ferromagnetically coupled (by pinholes), part of the multilayer. On the other hand, the GMR(H) dependences, in which the F-coupled fraction is not visible, are non-hysteretic.

4. Conclusions

The influence of annealing on the magnetization reversal processes and the magnetoresistance of the Py (2 nm)/Cu(2 nm) multilayers with a limited number of repetitions was investigated. We conclude that the annealing driven diffusion leads to:

– the increase of the surface density of pinholes which results in the appearance of ferromagnetically coupled areas in the multilayer and the decrease of the GMR value; a small amount of pinholes is detectable already in the as-deposited state;

– the disruption of the Py layers resulting in a magnetic uncoupling within the ferromagnetic layers; this leads to an increase of the saturation field values in isolated ferromagnetic areas with AF-coupling;

– the formation of small, less than 3 nm in diameter, Py grains causing an increase of the high field resistance changes.

In the course of the thermal treatment the above-mentioned processes take place independently but the presented sequence reflects the fact that they dominate at different temperatures and were consequently observed in the same sequence. In MLs with small N, in which the sublayers with relatively more defects occupy a higher volume fraction, these processes begin visibly to influence the magnetic behavior at temperatures lower than in MLs with higher N.

The structural changes described above lead to a change of the magnetization reversal from the local energy minimum mode in the as-deposited state to the absolute energy minimum mode in the annealed samples.

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