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The Effect of Pinholes on Magnetic Behaviour of Antiferromagnetically Coupled Ni-Fe/Cu Mulitlayers

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The magnetisation behaviour of polycrystalline permalloy/copper multilayers with mixed antiferromagnetic/ferromagnetic coupling was investigated as function of temperature. The results are discussed in a framework of a realistic model of anitferromagnetically coupled layers connected by ferromagnetic pinholes. A microstructure of pinholes (their density and dimensions) was varied either by a proper annealing treatment or by choosing samples with various Cu spacer thicknesses. It was demonstrated that the temperature changes of the net magnetic moment measured in a magnetic field smaller than the saturation field was strongly affected by the composition of the pinholes, their density, cross-sectional area and their lengths.

1. Introduction

Magnetic multilayers (Mls) with antiferromagnetic (AF) coupling and spin valves are interesting for giant magnetoresistance (GMR) applications. Copper and permalloy (Py) are the most extensively used constituents of such structures. Thus, the extensive investigations of magnetic and transport properties of sputtered Py/Cu Mls are necessary. In our previous paper [1] we described the magnetisation reversal processes and GMR effect in sputtered Py/Cu Mls with various thicknesses of permalloy (t_{Py}) and copper (t_{Cu}) sublayers. In this paper, we report the magnetisation behaviour as a function of temperature for as-deposited and annealed samples with various t_{Cu} thickness. The results of our studies allowed us to demonstrate the influence of magnetic pinholes on the behaviour of hysteresis loops of Py/Cu Mls.

2. Experimental

The Si(100)/Cu-20 nm/(Py-t_{Py}/Cu-t_{Cu})$\times 100$ (where Py= $Ni_{83}Fe_{17}$) Mls were deposited in Ar by double face-to-face sputtering. Low and high angle X-ray diffraction (LAXRD and HAXRD) analysis confirmed the existence of well defined periodic structures of the samples and allowed us to determine their modulation wave-lengths ($\lambda = t_{Cu} + t_{Py}$). Separately t_{Cu} and t_{Py} were determined by X-ray fluorescence (XRF) method. A good agreement between λ values obtained from XRF and XRD measurements was found. The HAXRD (Fig. 1) revealed the polycrystalline structure of Mls with the domination of the (100) over the (111) texture independently of t_{Cu} and t_{Py}. The satellite peaks (reflecting the superlattice structure) were observed both for crystallites with (100) as well as with (111) texture. Thus, we may assume that the dimension of the crystallites in the direction perpendicular to the sample surface is larger than λ.

The dependencies of the net magnetic moment (M) at field (H) were examined in the temperature range $150 \leq T \leq 400$ K by a vibrating sample magnetometer (VSM) in N_2 atmosphere or by a SQUID magnetometer ($100 \leq T \leq 300$ K). Successive isothermal annealing treatments were performed at T_a=423, 448, 473, 498 K in a VSM for 2 hours at each temperature. For all measurements the magnetic field was applied in plane of the sample parallel to the easy axis direction. The presence of the uniaxial anisotropy characterized by anisotropy field $H_k \approx 10$ Oe resulted, presumably, from an oblique deposition in face-to-face geometry.

3. Results and Discussion

Field dependencies of the net magnetic moment of Py/Cu Mls (in as-deposited state) with $t_{Cu} \approx 1$ nm, i.e., for the first AF coupling region, are presented in Fig. 2a. The remanent magnetisation M_r increases significantly with decreasing temperature. Due to a pronounced curvature of the $M(H)$ dependencies it was difficult to determine the saturation field H_s with a high accuracy. Therefor saturation field was determined as a threshold separating the

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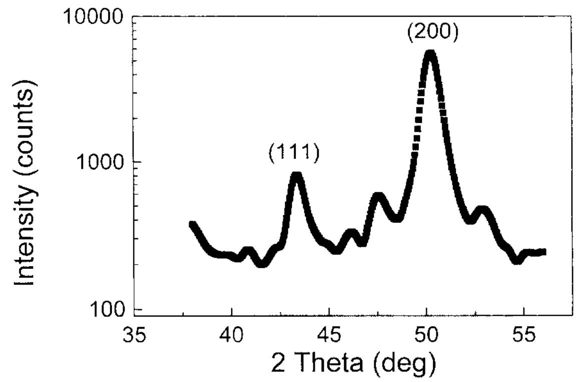

Fig. 1. Examples of high angle X-ray diffraction pattern for Si (100)/Cu-20 nm/(Py-1.5 nm/Cu-2.1 nm)× 100 multilayers (the diffraction peaks of the Ni-Fe and Cu layers cannot be distinguished because they have identical crystal structures and almost the same lattice parameters).

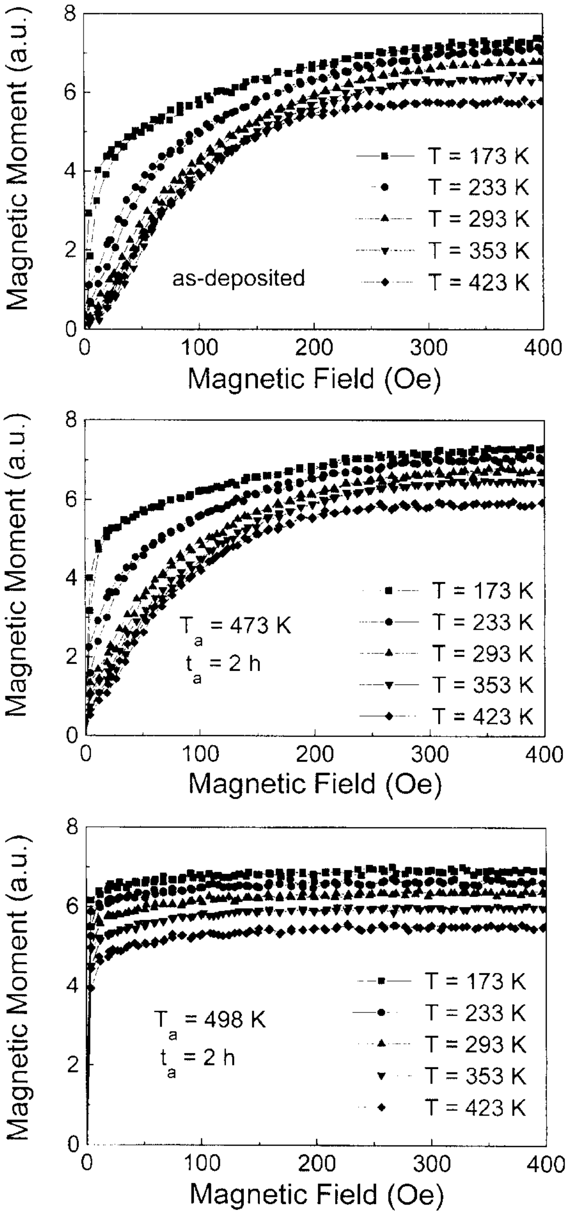

Fig. 2. First quadrant of hysteresis loops for a Si(100)/Cu-20 nm/ (Py-2.6 nm/Cu-1 nm)× 100 multilayer measured at various temperatures. The measurements were performed in as-deposited state (a) and after annealing at Ta=473 K (b) and 498 K (c).

initial nonlinear magnetisation behaviour from the linear region. The linear part of $M(H)$ dependence is presumably caused by the presence of the superpara- and /or paramagnetic entities located at the Py/Cu interfaces. Defined in this way Hs, strongly increases with decreasing temperature. This effect can be more clearly seen in magnetoresistance measurements [2]. The temperature changes in the magnetic interface profiles in our Py/Cu Mls [3] seem to be responsible for the variation in Hs vs. T. This is in agreement with arguments presented by Persat and Dinia [4] for Co/Cu/Co sandwiches. Similar changes of $M(H)$ dependencies with temperature were observed by Rodmacq *et al.* [5] for Py/Ag Mls and were interpreted as due to strongly temperature dependent biquadratic contributions to the coupling energy. An alternative interpretation for such behaviour of Co/Cu Mls was proposed by Bobo *et al.* [6]. Their model takes into account the presence of magnetic pinholes which are able to create the ferromagnetically coupled regions in Mls with AF coupling. It was demonstrated that this realistic model can also explain a convex shape of $M(H)$ curves and an apparent remanence M_r. Such an interpretation seems to be confirmed by the specific changes in magnetisation behaviour in our Py/Cu Mls due to a low-temperature annealing. The annealing, similarly as the reduction of Cu sublayer thicknesses in Co/Cu Mls [6, 7], leads to a higher pinholes density, and thus, to a more pronounced curvature of $M(H)$ curves as well as to an increase in the M_r values (Fig. 2b). Concerning the diffusion process in polycrystalline Py/Cu Mls, it is known [8, 9] that at low annealing temperatures ($Ta \leq 500$K) the grain boundary diffusion is mainly responsible for rearrangements of atoms (the volume diffusion in this temperature range is negligible). Moreover, it should be noted that grain boundary diffusion coefficient for Ni atoms in polycrystalline Cu is about 10 times higher than that for Cu atoms in Ni [8]. Thus, the grain boundaries of Py/Cu Mls are likely to be already filled with Ni-Fe-Cu alloy during the sputtering process or Ni-Fe-Cu alloy is formed at the grain boundaries after low-temperature annealing. The concentration of Ni-Fe-Cu alloy along the grain boundaries depends on layers thicknesses and diffusion coefficients. For small t_{Cu} (comparing to t_{Py}), Ni concentration at grain boundaries may be higher than 50 at.% producing a ferromagnetic alloy. Therefor, creation of magnetic bridges (pinholes) across Cu layers can lead to a strong, but localized in the vicinity of pinholes, ferromagnetic coupling between alternating Py layers. The antiferromagnetic coupling in Mls with a high pinholes density, i.e. those annealed at higher temperatures (T_a>500 K) can be totally destroyed. In such cases the observed $M(H)$ dependencies are characteristic of a ferromagnetic coupling (Fig. 2c).

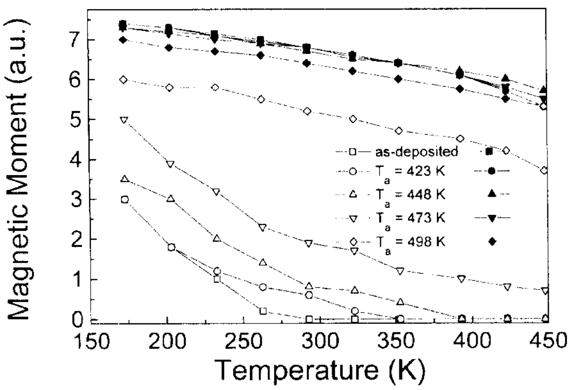

Fig. 3. Temperature dependence of the net magnetic moment *M* of a Si(100)/Cu-20 nm/(Py-2.6 nm/Cu-1 nm)× 100 multilayer in as-deposited state. The magnetic moment was determined from hysteresis measurements at magnetic field H=0 (open symbols) and $H>H_s$ (full symbols).

For as-deposited and annealed at low temperatures Mls the cross-sectional area and/or the concentration of ferromagnetic elements in pinholes is relatively small. In this case the influence of pinholes on magnetic properties of Py/Cu Mls with AF coupling can be eliminated due to the thermal fluctuation of spins (by increasing temperature) and/or due to the concentration dependence of Curie temperature inside pinholes. The detailed discussion concerning the magnetic behaviour of antiferromagnetically coupled layers connected by ferromagnetic pinholes was given by Fulghum and Camley [10]. Temperature dependencies of the net magnetic moment of our Py/Cu Mls with AF coupling are in a qualitative agreement with their conclusions. Fig. 3 shows some $M(T)$ dependencies for as-deposited and annealed samples taken for magnetic field H=0 and for $H>H_s$.

For $H>H_s$, $M(T)$ dependencies for Mls with $t_{Py}\geq 2$ nm are almost independent of t_{Py} and t_{Cu} (see also [3]) and of pinholes density or cross-sectional area. For H=0, the magnetic remanence moment (M_r) is attributed to the ferromagnetically coupled regions (for)$<H<H_S$ $M(T)$ should be nearly independent on T [10]). Taking into account that the existence of such regions results from pinholes, we can conclude that $M_r(T)$ describes the magnetic properties of pinholes. According to the prediction by Fulghum and Camley [10], with increasing density and cross-sectional area of pinholes both the remanence magnetic moment measured at low temperature and the temperature at which ferromagnetic coupling can be eliminated, increase. In our experiment, the increase in density and cross-sectional area of pinholes were achieved by annealing, which results in enhanced grain boundary diffusion of ferromagnetic elements. Similar changes in $M_r(T)$ dependencies, as demonstrated in Fig. 3 for as-deposited and annealed samples, are observed in Fig. 4 for as-deposited Mls with various t_{Cu}. This effect could be explained as resulting from a high density of pinholes due to discontinuous structure of Cu layers with small nominal thickness (see also [7]).

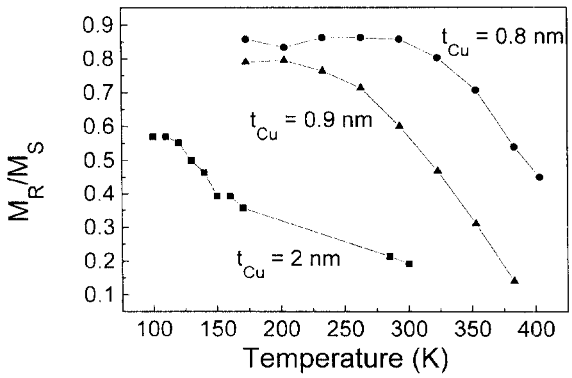

Fig. 4. Remanence to saturation magnetisation ratio vs. temperature for three permalloy/copper multilayers with different t_{Cu}.

4. Conclusions

The results of the temperature measurements of magnetic properties of permalloy/copper multilayers with AF coupling show:

- the decrease of the remanence magnetic moment (M_r) with increasing temperature,
- the strong temperature dependence of the net magnetic moment of permalloy/Cu Mls, measured at magnetic field essentially lower than the saturation field,
- the strong influence of pinholes density and sizes (varied by grain boundary diffusion or thicknesses of Cu layers) on the temperature dependence of M_r.

We have demonstrated that the temperature changes of the net magnetic moment of permalloy/copper multilayered samples with antiferromagnetic coupling are mainly determined by the density and sizes of ferromagnetic pinholes bridging neighbouring permalloy layers.

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