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Influence of the Deposition Temperature on Magnetotransport Properties of Ni–Fe/Au/Co/Au Multilayers

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A correlation between the growth process and electrical properties of $[Ni_{80}Fe_{20}(2\text{ nm})/Au(2\text{ nm})/Co(0.8\text{ nm})/Au(2\text{ nm})]_{15}$ multilayers is presented. A set of multilayers of identical composition was deposited in different temperatures. The changes in giant magnetoresistance amplitude were correlated with the changes in Co layers growth process that occur in different temperatures. The *in situ* conductance measurement leads to the growth mechanism identification in high temperatures as formation of Co islands. Intensified islandisation of Co was eventually confirmed by the temperature changes in shape of the Hall voltage loops, and the evolution of Co layers contribution.

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1. Introduction

The ferromagnetic multilayered systems (Mls) exhibiting giant magnetoresistance (GMR), in particular Mls with a strong perpendicular anisotropy, are intensively studied due to their potential applications in magnetic data storage devices [1]. In the $(Py/Au/Co/Au)_N$ systems (Py stands for $Ni_{80}Fe_{20}$ and N denotes the number of repetitions) Py layers are characterised by in-plane magnetisation, and Co layers have the magnetisation perpendicular to the samples plane if the Co thickness ranges from 0.4 nm to 1.2 nm [1]. For thicker Co layers the magnetisation remains in the layers plane. The GMR amplitude measured in magnetic field H perpendicular to the samples plane is sensitive to Co thickness [1], and the number of repetitions in a Ml [2]. Both parameters may have influence on the roughness of each interface. Consequently, if the possible structural or roughness variations are concerned, the electronic properties (GMR, Hall voltage) should depend on the preparation temperature. Although some temperature research has been already done [3], so far the results of depositing $(Py/Au/Co/Au)_N$ in different temperatures are not known. The reported annealing process proved the considered Mls are thermally stable in terms of GMR. It was supposed that the large difference of the anisotropies of Py and Co is the cause of such a behaviour. Some research reported previously [4] has demonstrated that the conductance G locally changes during deposition revealing a conductance minima while Co or Py deposition onto Au. The minima were correlated with the Volmer–Weber growth mode of two ferromagnetic materials rather than intermixing. The conduction electrons are stronger scattered when Py or Co layers are incomplete, thus G locally decreases, and after the percolation of Py or Co the electron scattering diminishes leading to G increase. Therefore, the time-dependent *in situ* conductance measurement, $G(t)$ is sensitive to growth mechanism changes. Altering the deposition temperature should modify the growth process resulting in $G(t)$ variation.

2. Experimental details

The Mls composed of $[Py(2\text{ nm})/Au(2\text{ nm})/Co(0.8\text{ nm})/Au(2\text{ nm})]_{15}$ were deposited onto oxidised Si(100) substrate with magnetron sputtering in different temperatures. The Mls were designed in order to obtain the perpendicular direction of magnetisation of the Co layers, and the in-plane direction of magnetisation of Py layers. During each deposition the *in situ* $G(t)$ measurements were performed. The deposition rates were 0.053 nm/s, 0.062 nm/s and 0.0475 nm/s for Py, Au and Co, respectively. In addition, with the same method a set of similar Mls but with altering Co thickness was sputtered. The GMR of all Mls was measured with the two-point probe in the current-in-plane geometry in the H range of ±2 T. The GMR(H) measurements were supported with the Hall voltage loops measurements, $U_H(H)$, performed with the van der Pauw method in order to eliminate the planar Hall effect.

3. Results and discussion

In the GMR(H) dependence of the $[Py(2\text{ nm})/Au(2\text{ nm})/Co(0.8\text{ nm})/Au(2\text{ nm})]_{15}$ Mls measured in H perpendicular to the Mls plane two main sections may be distinguished. The first one is in the low H range and reflects the influence of the Co layers stripe domain structure on the Py layers. In this H range the stripe domain

structure of Co layers nucleates in magnetic field H_N and annihilates in saturation field H_S [5]. Both values are defined in the GMR(H) plot in the inset of Fig. 1. The second section of GMR(H) is the high H range, where the influence of Py layers with in-plane magnetisation is observed.

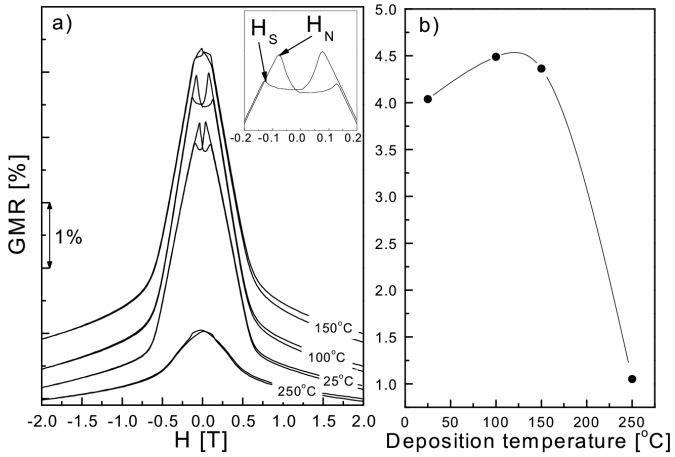

Fig. 1. (a) The GMR(H) dependences of [Py(2 nm)/Au(2 nm)/Co(0.8 nm)/Au(2 nm)]$_{15}$ Mls deposited in various temperatures. In the inset the H_N and H_S for Co are defined. (b) The influence of the deposition temperature on the GMR amplitude.

The GMR(H) dependence measured in H perpendicular to the Mls plane, for Mls deposited at different temperatures, are presented in Fig. 1a. The characteristic values H_N and H_S for Co layers are higher for the Ml deposited at 100°C than for the reference Ml deposited at room temperature (RT). Additionally, the characteristic features of the GMR(H) in the low H range are hardly visible for the deposition temperature of 150°C and are not observed for the deposition temperature of 250°C. Those changes are accompanied by the GMR amplitude variation, which is displayed in Fig. 1b.

The earlier research of Szymański et al. [3] shows that the increase in H_N and H_S for Co layers may be also obtained with annealing procedure, although the GMR amplitude variation was not observed. Hence, different mechanisms may be responsible for H_N and H_S changes during annealing than the H_N and H_S changes for Mls deposited in different temperatures. Therefore, the annealing cannot be directly compared with high temperature deposition process.

Interestingly, the GMR(H) shape for the Ml deposited in 250°C resembles the GMR(H) curve for Ml with very thin Co layers (Fig. 2). In the GMR(H) for Ml with the 0.25 nm thick Co layer in the low H range no H_N and H_S were observed, and, in the high H range, the GMR(H) slope suggests strong superparamagnetic contribution. Consequently, Co is suspected to form grains during the deposition rather than a continuous layer. Similar GMR(H) shape was observed as the Ml was deposited at 250°C (Fig. 1a), so it may be expected that during the deposition the islandisation of Co is intensified.

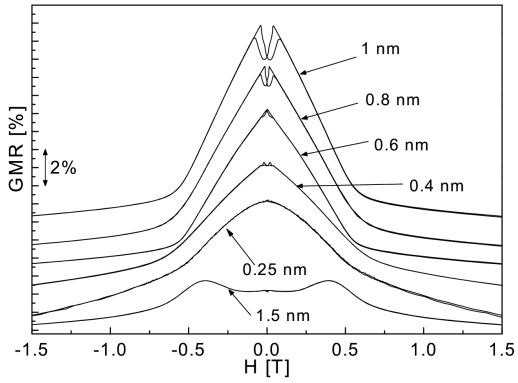

Fig. 2. The GMR(H) dependences for Mls with different Co layer thicknesses. Mls with Co thicknesses ranging from 0.4 nm to 1 nm have magnetisation perpendicular to Co layers plane.

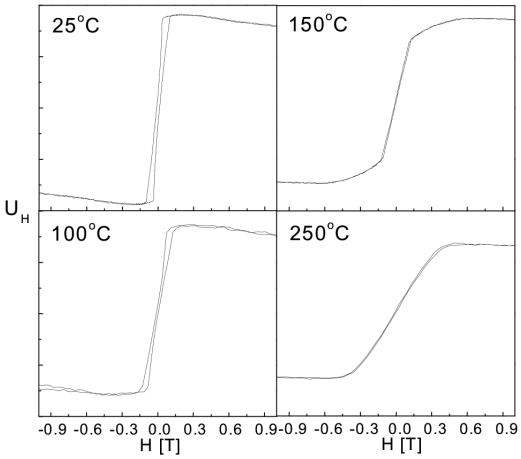

Fig. 3. Hall voltage loops $U_H(H)$ for Mls deposited at temperatures 100°C, 150°C, 250°C and the reference Ml deposited at room temperature.

The GMR(H) differences for Mls deposited at various temperatures are in agreement with the $U_H(H)$ changes (Fig. 3). The $U_H(H)$ dependence may be approximated by a sum of Py contribution, in high H, and a hysteresis loop in lower H, which is the Co contribution. The Ml deposited at RT is characterised by $U_H(H)$ shape that is dominated by the Co contribution in the low H range. However, when the Ml was deposited at higher than 100°C temperatures, the coercivity field H_C is decreased and Py contribution in higher H is more clearly visible, which suggests diminishing the Co contribution. For the Ml deposited in 250°C the $U_H(H)$ hysteretic character is lost, suggesting no contribution from continuous Co layers with perpendicular anisotropy. Only Py, which has its hard axis in the H direction (perpendicular to the Ml plane), contributes to the $U_H(H)$.

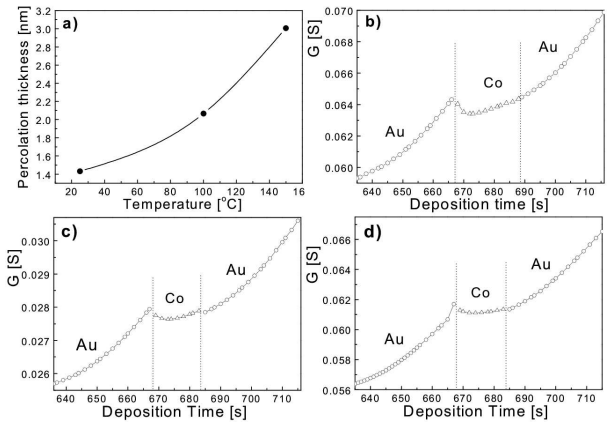

Fig. 4. The thickness for which percolation of Mls deposited at RT, 100°C, and 150°C occurs; and the $G(t)$ dependences for Co layer and adjacent Au layers for samples deposited at (b) RT, (c) 100°C, and (d) 150°C.

Additionally, if the grains formation dominates during Mls deposition, the percolation threshold will be delayed (Fig. 4a), and during Co onto Au deposition, the contribution of Co layer to the *in situ* $G(t)$ should be smaller during deposition at 100°C and 150°C. In consequence, the parts of the $G(t)$ plot reflecting the Co layers deposition are supposed to be flatter. Both $G(t)$ dependences, measured during the deposition at RT and at 100°C (Fig. 4b and c, respectively), exhibit a characteristic $G(t)$ minimum during Co layers deposition, which originates from the increased surface scattering of the conduction electrons as long as the Co layer is incomplete. After the percolation of the Co islands the scattering diminishes and $G(t)$ regains its growing tendency when complete Co layer is formed. If the Ml was deposited at 150°C (Fig. 4d) the Co layer hardly contributes to $G(t)$, which is represented as almost flat section of the plot. Such a behaviour confirms that during Co deposition at higher than 100°C temperatures the islandisation is enhanced and the subsequent Au layer fills the space between the Co islands increasing G.

4. Conclusions

A study on the deposition temperature influence on the Mls composed of [Py(2 nm)/ Au(2 nm)/Co(0.8 nm)/Au(2 nm)]$_{15}$ with perpendicular anisotropy of Co layers was presented. The deposition temperature has a strong influence on the GMR amplitude and shape suggesting the superparamagnetic Co in Mls deposited at 250°C. This fact supported by the $U_{\mathrm{H}}(H)$ changes for different deposition temperatures leads to a conclusion that at higher deposition temperatures Co tends to form grains on Au surface instead of a continuous layer. The mechanism of Mls formation was monitored with the *in situ* $G(t)$ measurement, which additionally confirms that the growth mechanism of Co is strongly temperature dependent by the intensification of islandisation. However, a further research, scanning tunnelling microscopy (STM) in particular, would be helpful in developing full model of high temperature Co growth.

Acknowledgments

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