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Influence of the deposition temperature on Co structure in Ni-Fe/Au/Co/Au multilayers

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In this paper we present a correlation between the deposition conditions of the ferromagnetic multilayers Ni-Fe/Au/Co/Au with perpendicular anisotropy, with their magnetotransport properties such as giant magnetoresistance (GMR) and Hall voltage loop. A series of such multilayers was deposited with magnetron sputtering at different temperatures. The surface roughness and the *in-situ* conductiance measurements evidenced the structural differences in the growth mode of the Co layers depending on the deposition temperature. The magnetic moment measurements revealed for certain deposition temperatures the existence of superparamagnetic Co entities.

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1. Introduction

The ferromagnetic multilayers (Mls) exhibiting giant magnetoresistance (GMR), with a strong perpendicular anisotropy are in the scope of a research due to the possible high data storage density and the facility of being commercially applied [1]. In particular much effort is devoted to Py/Au/Co/Au Mls (Py stands for permalloy, $Ni_{80}Fe_{20}$), where the Py layers magnetisation remains in the layers planes while Co layers have the magnetisation direction perpendicular to the layers planes [2-6]. The direction of the Co layers magnetisation has been proved to be sensitive to the Co layer thickness [2]. If the Co thickness ranges from 0.4 nm to 1.2 nm, the magnetisation direction is evidenced to be perpendicular to the Mls plane. Above 1.2 nm the spin reorientation transition takes place, so for Mls with thicker Co layers all ferromagnetic layers in a Ml have in-plane magnetisation direction.

Since the electron transport properties such as GMR and Hall voltage U_H depend on the roughness and surface structure changes (see for instance [7] and the references therein), what is closely connected to the deposition conditions. The deposition temperature seems to be the crucial parameter, which has not been so far discussed in detail. Only in [4] information on the post-deposition temperature treatment over the $(Py/Au/Co/Au)_N$ Mls is given. However, the performed annealing of deposited at room temperature Mls cannot be directly compared with the deposition at various temperatures.

The deposition process is easy to observe with the *in-situ* conductance measurement, what was presented in the previous work, where the deposition of $(Py/Au/Co/Au)_{15}$ at room temperature was monitored with the time-dependent *in-situ* conductance measurement G(t) [5]. It was demonstrated that the conductance G locally changes during the deposition process, depending on the deposited material and the material of the underlying layer. The G(t) dependence contained a series of local minima while Py or Co deposition onto Au, what was interpreted as a result of the enhanced scattering of the conduction electrons at the beginning of the deposition of two ferromagnetic materials. Only when a complete layer of one of those materials is formed, G regains its growing tendency. Therefore, the changes in the deposition process caused by the altering the temperature are expected to be visible in G(t) dependence.

2. Experimental details

A series of multilayers of identical $[Py(2nm)/Au(2nm)/Co(0.8nm)/Au(2nm)]_{15}$ composition was deposited onto naturally oxidised Si(100) substrate at different temperatures with magnetron sputtering. The thickness of Co sublayers was chosen to obtain perpendicular to the Mls plane direction of magnetization, while Py magnetization direction remains in-plane. The deposition rates were 0.053 nm/s, 0.062 nm/s, and 0.0475 nm/s for Py, Au, and Co, respectively. During each deposition process an *in-situ* G(t) measurement was performed.

After the deposition the GMR(H) of all Mls was measured with the four-point probe in the current-in-plane geometry in the H range of ±2T. The GMR(H) measurements were suplemented with the Hall voltage loops measurements, $U_H(H)$, performed with the van der Pauw method.

The root mean square (RMS) roughness of deposited Mls was estimated from the STM images obtained with the use of RHK UHV750 STM.

To examine the magnetic properties the zero-field-cooled (ZFC) and field-cooled (FC) data in the temperature ranging from liquid He to 300 K were collected. ZFC and FC (at H=100 Oe) measurements were performed with Quantum Design VSM.

3. Results and discussion

The GMR(H) measurements of $[Py/Au/Co/Au]_{15}$ Mls sputtered onto Si (111) substrate being at different temperatures, and plotted in Fig. 1a, revealed correlation between the deposition temperatures and the magnetic properties of such Mls. The characteristic points at the GMR(H) dependence, such as the value of H in which the magnetic stripe domains are nucleated (H_N) and the value of H in which they annihilate (H_S), the saturation field, change [6,8].

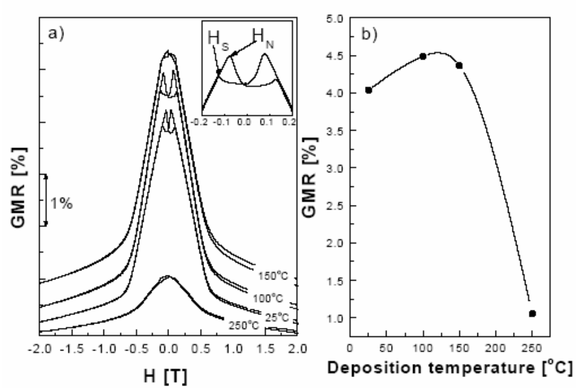
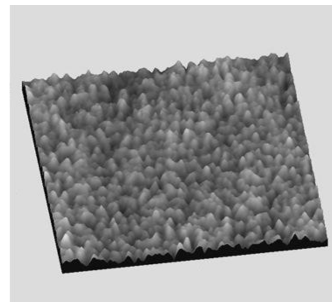


Fig. 1. (a) The GMR(H) for Mls of the composition $[Py(2nm)/Au(2nm)/Co(0.8nm)/Au(2nm)]_{15}$ deposited at room temperature, at 100°C, 150°C and 250°C. The nucleation field H_N and the annihilation field H_S are defined in the inset at an exemplary curve. (b) The GMR dependence on the deposition temperature.

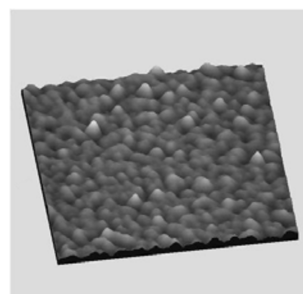
At the GMR(H) dependences measured for Mls deposited above 150°C H_N and H_S are not observed. In the same time the change of the GMR(H) slope with deposition temperature in the higher field range (above ±1T) was observed what might suggest the enhanced superparamagnetic contribution of Co into GMR(H). Additionally, the GMR(H) of deposited at higher than room temperatures was initially observed to grow slightly and then to drop above 150°C (Fig. 1b).

The changes in the magnetic properties of Au/Ni-Fe/Au/Co Mls such as GMR may be connected with the fact, that setting higher temperature of the substrate during the deposition results in the roughness increase. In the Fig. 2a and 2b are presented the STM images of Mls deposited at 100°C and 200°C, respectively. The measured RMS with STM tends to increase with temperature (Fig. 3), what correlates with the GMR(H) reduction with temperature.

In general, the low field range in performed magneto-transport measurements (GMR, Hall voltage) reflects the changes of the magnetic properties of the Co layers in the Py/Au/Co/Au Mls with perpendicular anisotropy of the Co layers. Here, the perpendicular to the Mls plane direction of the magnetic field H equals the direction of the easy axis of Co sublayers, and the direction of the hard axis of Py sublayers. In the H range exceeding ±1T only the Py contribution is observed (the Py layers anisotropy remains in the Mls plane). Comparing GMR(H) results to the Hall loop measurements $U_H(H)$ (displayed in Fig. 4) it is clear, that the contribution of the Co layers with perpendicular anisotropy diminishes with the deposition temperature. The Hall loops become narrower and start to resemble the $U_H(H)$ obtained for Py only with the in-plane anisotropy. The reduction of the Co contribution in the high field range provokes a question of the origin of such changes.



(a)



(b)

Fig. 2. The STM images ($1\mu m^2$) of the multilayers $[Py(2nm)/Au(2nm)/Co(0.8nm)/Au(2nm)]_{15}$ deposited at 100°C (a) and 200°C (b) with the RMS of 0.27nm and 0.43nm, respectively.

The enhanced roughness evidenced with STM suggest intensified islandisation of Co during growth, what is supported with the vanishing Co contribution to $U_H(H)$. Some evidence of this hypothesis may be set by the *in-situ* conductance G(t) measurements that were performed during growth of each Ml. In Fig. 5a, b, and c the insight into the G(t) dependence is presented for Mls deposited at room temperature, 100°C, and 150°C, respectively. The flattening of the G(t) at Co part is easily observable and suggests the decrease of the Co contribution into overall conductance of the Mls. This fact may be caused by the change in the growth mode of Co onto Au with the deposition temperature variation. When the deposition of Co onto Au layer takes place in 100°C or more, Co tends to form independent from each other islands rather than a continuous layer. Those separate islands of Co do not contribute to conductance, what is observed as an almost flat part of the G(t). Additionally, the in-situ G(t) measurement showed the increase of the initial thickness for which Mls percolate (Fig. 5d), what supports the STM evidence of the enhanced roughness.

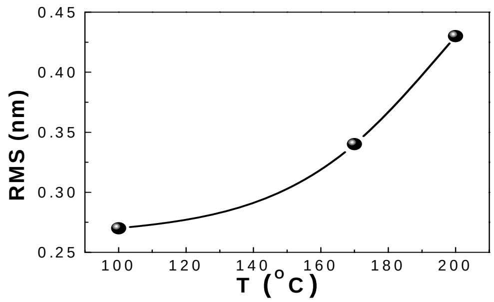


Fig. 3. The RMS values for Mls deposited in different temperatures, measured with the STM .

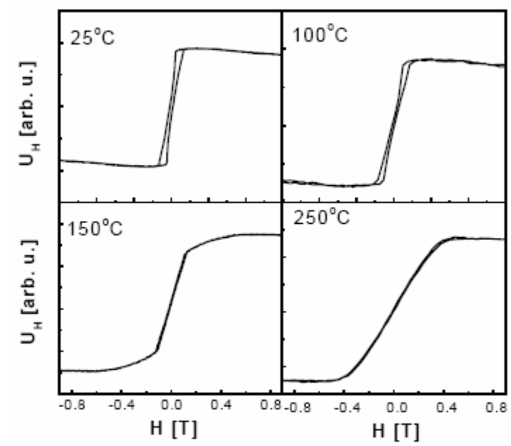


Fig. 4. Hall voltage loops $U_H(H)$ for Mls deposited at temperatures 100°C, 150°C and 250°C. The $U_H(H)$ for Ml deposited at room temperature is set as a reference.

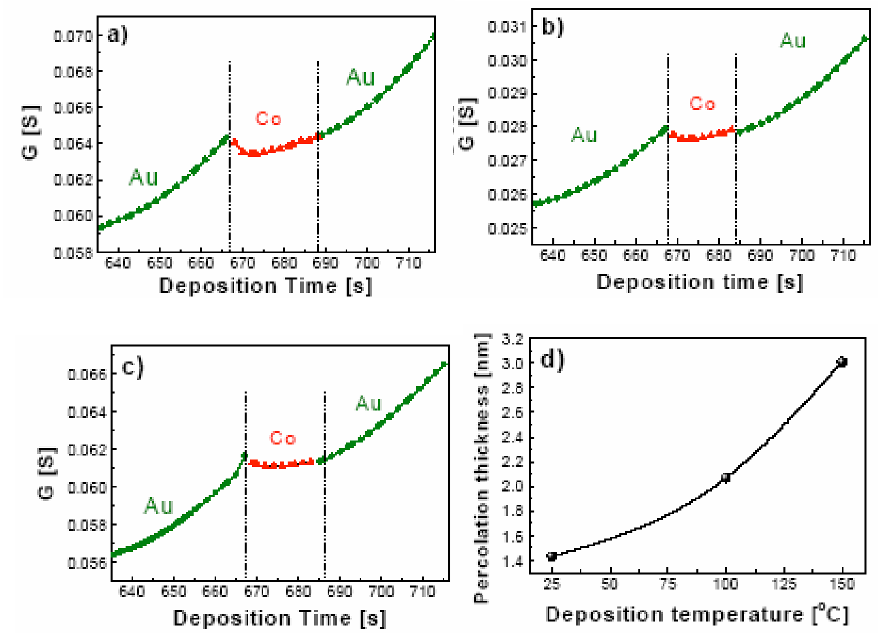


Fig. 5. The G(t) dependences for Co layer and adjacent Au layers for Mls deposited at a) RT, b) 100°C, and c) 150°C. d) the percolation threshold for Mls deposited at different temperatures.

However, the key argument for the enhanced islandisation of the Co with deposition temperature are changes of the magnetic moment with temperature known as the field cooling (FC) and zero-field cooling (ZFC) curves. In Fig. 6 three FC-ZFC curves are presented for Mls deposited at room temperature, 100°C and at 200°C. According to [9], the last two curves reflect the superparamagnetic behaviour of discontinuous Co layers. For Mls deposited at higher temperatures a larger thermal hysterisis is observed between FC(T) and ZFC(T).

These results indicate enhanced superparamagnetic contribution with deposition temperature. Above dataset interpretation stays in the agreement with the observed slope enhancement at the GMR(H) dependence in the high field range (H>±1 T) in Fig 1b. At registered ZFC curves for higher than room temperatures of the deposition process it is not easy to define the blocking temperature T_B, which is characteristic for FC-ZFC measurements. Hence, it is concluded, that the islands of Co formed at Au surfaces during the deposition vary strongly in size between each other.

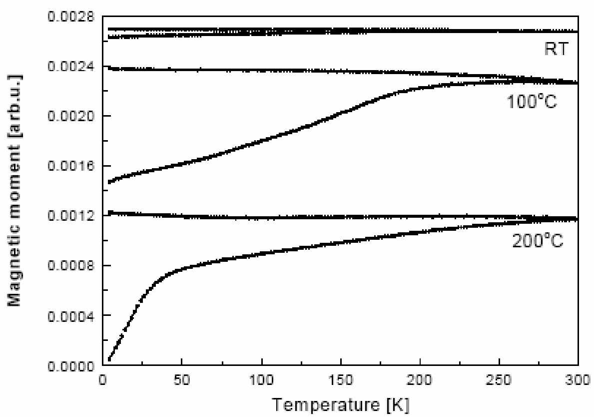


Fig. 6. The normalized FC-ZFC for Mls deposited in different temperatures. Only for the Ml deposited at room temperature the superparamagnetic contribution is not observed. Second two exemplary FC-ZFC curves evidence the presence of the superparamagnetic phase in Mls deposited at 100°C and 200°C.

4. Conclusions

It was presented that the magnetotransport properties of $[Py/Au/Co/Au]_{15}$ Mls are strongly correlated with the deposition conditions such as the deposition temperature. Higher deposition temperatures were proven to increase the surface roughness, enhancing in the same time the island-like growth mode of the Co sublayers. Rougher Au surfaces are difficult to wet by Co leading to the Co granules formation. Created Co granules at Au surface are found to be superparamagnetic in nature.

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