14th Czech and Slovak Conference on Magnetism, Košice, Slovakia, July 6–9, 2010

Electronic Transport Properties and Growth Mechanisms of Ni–Fe/Au/Co/Au Multilayers from *In Situ* Conduction Measurements

M. Błaszyk[a,*], M. Kempiński[b], K. Buchta[a], P. Chomiuk[a] and T. Luciński[a]

[a]Institute of Molecular Physics, Polish Academy of Sciences, M. Smoluchowskiego 17, 60-179 Poznań, Poland

[b]Physics Department, A. Mickiewicz University, Umultowska 85, 61-614 Poznań, Poland

In the following we present the role of surface scattering at Au/Co and Au/Ni–Fe interfaces in Ni–Fe/Au/Co/Au multilayers deposited in different temperatures. Specularity parameter, which describes the electron scattering, is calculated from fitting *in situ* collected conductance data with the Fuchs–Namba–Tesanovic model. Application of the parallel resistors model enabled to depict changes between Au/Co and Au/Ni–Fe interfaces within multilayers for each repetition. The correlation between enhanced grain boundary scattering for higher deposition temperatures and surface roughness of Ni–Fe/Au/Co/Au multilayers is found.

PACS numbers: 73.50.−h, 73.61.−r, 75.70.Cn, 72.15.−v

1. Introduction

In the last decade a great interest is observed in ferromagnetic multilayers (Mls) with alternating in-plane and out-of-plane magnetizations of adjacent ferromagnetic layers, and exhibiting giant magnetoresistance (GMR) [1–6]. Such Mls attract much attention because of their facility in potential application in high density storage devices or in novel magnetic information storage methods via magnetic patterning [7]. In $(Py/Au/Co/Au)_N$ Mls (where Py stands for $Ni_{80}Fe_{20}$ alloy, and N denotes the number of repetitions) Py acts as a soft magnetic sublayer whose magnetization remains in the Mls plane, and Co thickness ranges from 0.6–1.2 nm to obtain perpendicular direction of sublayers magnetization [2]. Au spacer layers are thick enough to provide weak interlayer coupling.

Previously, the changes in magnetotransport properties of $[Py(2\ nm)/Au(2\ nm)/Co(0.8\ nm)/Au(2\ nm)]_{15}$ Mls induced by deposition temperatures variations were reported [8, 9]. It was found that application of deposition temperature $T_D > 25\,°C$ enhances the three-dimensional growth of Co at Au surfaces, which leads to the discontinuous character of Co sublayers deposited at $T_D = 150\,°C$. Co islands in $(Py/Au/Co/Au)_{15}$ systems were found to be superparamagnetic in nature [9]. In the following, we outline the interface scattering changes of conduction electrons in such Mls due to the application of theoretical models of electrical conductance.

2. Experimental

$[Py(2\ nm)/Au(2\ nm)/Co(0.8\ nm)/Au(2\ nm)]_{15}$ Mls were prepared with magnetron sputtering at different temperatures $25\,°C \le T_D \le 150\,°C$. The deposition rates were 0.053, 0.062, and 0.0475 nm/s for Py, Au, and Co, respectively. During each deposition process an *in situ* time-dependent conduction measurement was performed ($G(t)$). Additionally $G(t)$ during the deposition of 400 nm thick single Py, Co, and Au films was measured to fit the data with theoretical models of electrical conductance in thin metallic films [3–6]. The electronic transport parameters such as mean free path (λ_0) of conduction electrons, specularity parameter (p) and resistivity (ρ_0) was determined.

3. Models

The experimental $G(d)$ datasets (where d denotes thickness) collected during the deposition of pure Py, Co and Au were fitted with simple Fuchs–Sondheimer model [10, 11], two other originating from it: Fuchs–Namba [12] and Fuchs–Namba–Tesanovic [13] models; and a model with completely different approach to the electrical conductivity, the Mayadas–Schatzkes model [14]. The fitting procedure was performed using the Lavenberg–Marquardt algorithm in the *Mathematica 7* program.

In Table λ_0 and ρ_0 values, obtained by the fitting procedures, are presented with respect to the applied model. Unfortunately, none of the used theoretical models of electrical conductivity reflects ideally the real physical situation during the growth of the metallic thin films. The Fuchs–Sondheimer model assumes that metallic surfaces are perfectly flat, their roughness is not taken into account.

In polycrystalline films conduction electrons are mostly scattered at the grain boundaries, not at the films bottom and top surfaces. However, the Mayadas–Schatzkes

* corresponding author; e-mail: blaszyk@ifmpan.poznan.pl

model is constructed assuming such a situation, it does not reflect the changes in conductivity at the early-growth stage (before percolation). The two other models used for fitting $G(d)$ are based on the work of Namba [12, 13], where the rough surface of the film is modeled with the one-dimensional, sinusoidal wave. It seems oversimplified, especially at the early-growth stage, when the lateral dimensions of grains change. However, only the models based on the Namba model enable fitting experimental data for very small thicknesses. That is why only the fitting parameters for the Fuchs–Namba–Tesanovic model [13] were used in further calculation. Some other drawbacks of various theoretical models were presented by Sambles [15].

TABLE

λ_0 and ρ_0 obtained from fitting the data theoretical models.

Model	Mean free path λ_0 [nm]			Bulk resistivity ρ_0 [$\mu\Omega$ m]		
	Py	Au	Co	Py	Au	Co
Fuchs–Sondheimer	11	30.9	10.4	0.69	0.16	0.11
Namba–Fuchs	10.7	10.9	9.3	0.69	0.16	0.11
Fuchs–Namba–Tesanovic	9.3	18.8	13	0.69	0.17	0.12
Mayadas–Schatzkes	20.8	17.6	29.2	0.66	0.16	1

The parameters λ_0 and ρ_0 obtained from fitting with the Fuchs–Namba–Tesanovic model were used in further calculation of the changes of the specularity parameter Δp from the parallel resistors model developed by Reiss [16, 17]. Within this model each sublayer in a multilayer acts as a resistor with resistance R, which is in parallel connection with other resistors (other sublayers). Hence, the change in resistance due to the coverage of one sublayer by another can be expressed with a following equation [17]:

$$\Delta R = R_{\mathrm{covered}} - R_{\mathrm{uncovered}}\,, \quad (1)$$

where $R_{\mathrm{uncovered}}$ and R_{covered} denote the resistances of uncovered sublayer and resistance of the covered sublayer with a continuous layer of the material of the subsequent sublayer, respectively. Applying (1) to the Fuchs–Sondheimer electrical conduction theory one obtains [17]:

$$\Delta R = \frac{3}{8}\frac{l}{b}\frac{\lambda_0\rho_0}{d^2}\Delta p\,, \quad (2)$$

where l and b stand for the length and width of the sample and Δp is defined as [17]:

$$\Delta p = p_{\mathrm{uncovered}} - p_{\mathrm{covered}}\,. \quad (3)$$

The parameters $p_{\mathrm{uncovered}}$ and p_{covered} stand for the probability of the electrons to be specularly reflected from the uncovered surface of the layer and covered by the continuous layer of the material of the subsequent sublayer, respectively.

4. Results

The changes of Δp as a function of the inversed number of repetitions (N^{-1}) of Au/Co and Au/Py interfaces are presented in Fig. 1. According to the parallel resistors model, the changes of the slope of $\Delta p(N^{-1})$ reflect the differences between the interfaces [16, 17]. For Au/Co interfaces, $\Delta p(N^{-1})$ in Fig. 1a, corresponding to the deposition temperatures of 25 °C and 100 °C, are not linear for the first three Au/Co interfaces. Hence, for $N < 3$ the differences between subsequent Au/Co interfaces are large and may be connected with the structural changes at the interfaces. In the second region in $\Delta p(N^{-1})$ for $T_{\mathrm{D}} = 25$ °C and $T_{\mathrm{D}} = 100$ °C, $0.17 \le N^{-1} \le 0.33$ ($3 \le N \le 6$), the dependence $\Delta p(N^{-1})$ is linear. Thus, the Au/Co interfaces between 3rd and 6th repetition have the equal ability to scatter the conduction electrons. In consequence, they are structurally similar (in terms of roughness for example). Within the last region of $\Delta p(N^{-1})$, for $N^{-1} < 0.17$ ($N > 6$), the values of Δp are almost equal and zero. Hence, the scattering of the conduction electrons at the sublayer boundaries is almost unobservable and the scattering at the grain boundaries is dominant. So it is difficult to depict any changes between subsequent Au/Co interfaces for $6 < N < 15$. In case of the $\Delta p(N^{-1})$ dependence for Au/Co interfaces in Mls deposited at $T_{\mathrm{D}} = 150$ °C, the grain boundary scattering exceeds the sublayer boundary scattering in the entire range of N, causing almost zero values of Δp for each N. It correlates with enhanced Volmer–Weber growth mode of Co at Au surface [8, 9].

For the deposition temperatures of 25 °C and 100 °C for Au/Py interfaces similar three ranges of $\Delta p(N^{-1})$ may be distinguished. The first interface Au/Py is strongly distorted by the structural changes of the first repetition of the Py/Au/Co/Au sequence. The second range of $\Delta p(N^{-1})$, $0.14 \le N^{-1} \le 0.33$ (with an exception of $N^{-1} = 0.17$) suggests the similarity between Au/Py interfaces in the range $3 \le N \le 7$. Within the last linear range $N^{-1} \le 0.14$, as in the case of Au/Co interfaces, the scattering at the grain boundaries in the entire volume of the Ml dominates and the scattering at the sublayer

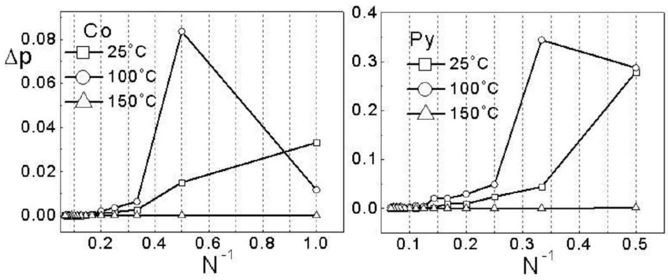

Fig. 1. The changes of Δp as a function of N^{-1} for the interfaces created by depositing Co or Py onto Au surface at different temperatures.

boundaries is not observed. Similarly, for Mls deposited at $T_{\mathrm{D}} = 150\,^{\circ}\mathrm{C}$, the Δp for each N is almost zero, as in the range of $N^{-1} \leq 0.14$ for Mls deposited at lower temperatures.

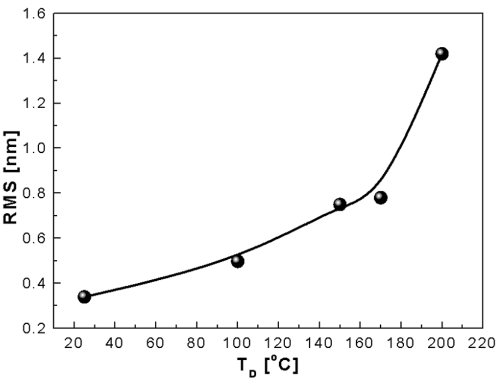

Fig. 2. Root mean square (RMS) roughness of Mls deposited at different temperatures.

Dominating grain boundary scattering for both Au/Co and Au/Py interfaces for $T_{\mathrm{D}} > 100\,^{\circ}\mathrm{C}$ correlates with the enhanced surface roughness of Mls deposited at $T_{\mathrm{D}} > 25\,^{\circ}\mathrm{C}$ (Fig. 2). Higher deposition temperatures intensify the island-like growth mode and both: surface roughness and scattering at the grain boundaries.

5. Conclusion

In summary, it was shown that application of the parallel resistors model enables to characterize the scattering of the conduction electrons at the interfaces, and the changes in such scattering, that give the information of the structural inequality of Au/Co and Au/Py interfaces in $(\mathrm{Py/Au/Co/Au})_{15}$ multilayers for each N. In addition, the diminishing role of scattering at the interfaces with the increase of the deposition temperature correlates with the increasing surface roughness measured with scanning tunneling microscopy (STM).

References

[1] F.B. Mancoff, J.H. Dunn, B.M. Clemens, R.L. White, *Appl. Phys. Lett.* **77**, 1879 (2000).

[2] F. Stobiecki, B. Szymański, T. Luciński, J. Dubowik, M. Urbaniak, K. Roell, *J. Magn. Magn. Mater.* **282**, 32 (2004).

[3] B. Szymański, F. Stobiecki, M. Urbaniak, P. Siffalovic, E. Majkova, *Acta Phys. Pol. A* **113**, 205 (2008).

[4] B. Szymański, F. Stobiecki, M. Urbaniak, *Phys. Status Solidi A* **243**, 235 (2006).

[5] M. Błaszyk, T. Luciński, *Acta Phys. Pol. A* **113**, 663 (2008).

[6] M. Urbaniak, F. Stobiecki, B. Szymański, A. Ehresmann, A. Maziewski, M. Tekielak, *J. Appl. Phys.* **101**, 013905 (2007).

[7] W. Glapka, P. Kuświk, I. Sveklo, M. Urbaniak, K. Jóźwiak, T. Weis, D. Engel, A. Ehresmann, M. Błaszyk, B. Szymański, A. Maziewski, F. Stobiecki, *Acta Phys. Pol. A* **115**, 348 (2009).

[8] M. Błaszyk, P. Chomiuk, K. Buchta, T. Luciński, *Acta Phys. Pol. A* **115**, 363 (2009).

[9] M. Błaszyk, M. Kempiński, B. Andrzejewski, T. Luciński, *J. Optoelectron. Adv. Mater.* **10**, 1038 (2009).

[10] J. Vancea, H. Hoffmann, *Thin Solid Films* **92**, 219 (1982).

[11] K. Fuchs, *Proc. Camb. Philos. Soc.* **34**, 100 (1938).

[12] Y. Namba, *Jpn. J. Appl. Phys.* **9**, 1326 (1970).

[13] Z. Tesanovic, M.V. Jaric, S. Maekawa, *Phys. Rev. Lett.* **57**, 2760 (1986).

[14] A.F. Mayadas, M. Schatzkes, *Phys. Rev. B* **1**, 1382 (1970).

[15] J.R. Sambles, *Thin Solid Films* **106**, 321 (1983).

[16] G. Reiss, *Electronic properties of metallic multilayers*, Universität Regensburg, 1989 (in German).

[17] T. Eckl, G. Reiss, H. Brückl, H. Hoffmann, *J. Appl. Phys.* **75**, 362 (1994).