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Electrophysical Properties of Multilayer Film Systems Based on Permalloy and Silver

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Comprehensive investigation of the phase state and the electrophysical properties (resistivity and temperature coefficient of resistance (TCR)) of $[Py/Ag]_n/S$ multilayer film systems with a constant total thickness of 54 nm in a range of bilayer repeats from 1 to 16 was presented. Thin films based on permalloy $Ni_{80}Fe_{20}$ (Py) and Ag were prepared by the electron-beam layer-by-layer evaporation method in a vacuum 10^{-4} Pa at room temperature. Their phase state was studied using electron diffraction methods. Samples after deposition show phase state corresponding to the combination of face-centered cubic (fcc) Ni_3Fe and fcc-Ag lattices. The film phase state remained unchanged within the entire range of Py/Ag bilayer repeats. It was demonstrated that the process of the heat treatment also did not affect their structure. The samples after deposition were annealed in a vacuum during two cycle "heating ↔ cooling" up to the temperature of healing defects. The heat treatment of the samples was done in the automated mode that allowed to control the speed of heating, experimental data (resistance and temperature) recording and processing. Results of the study of electrophysical properties demonstrate that metallic behavior of resistivity temperature dependences is observed for all films. The values of resistivity and TCR have an order of $\rho \sim 10^{-7}$ Ohm·m and $\beta \sim 10^{-3}$ K^{-1}, respectively, that are typical for components of investigated samples. At the same time, the increase of the number of the bilayer repeats from 1 to 16 leads to the increase of resistivity value from $0.78\cdot10^{-7}$ to $2.40\cdot10^{-7}$ Ohm·m, and to the decrease of the TCR value from $4.70\cdot10^{-3}$ to $2.23\cdot10^{-3}$ K^{-1}. The mean reasons of such change of ρ and β values can be associated with the growth of probability of electron interface scattering and the breaking of individual layer continuous at the increase of Py/Ag bilayer numbers at the constant total thickness.

Keywords: Multilayer film systems, Layer-by-layer condensation, Resistivity, Temperature coefficient of resistance, Interface scattering.

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1. INTRODUCTION

Permalloy $Ni_{80}Fe_{20}$ (Py) is a soft magnetic material which is characterized by high saturation magnetization, high susceptibility and low coercive force, and can be used in read heads, magnetic memory and spin devices [1, 2]. Practical application of the Py thin films has been widely expanded by addition of the third constituent element [3, 4]. Permalloy based thin films can be applied in magnetic sensors based on anisotropic, giant or tunneling magnetoresistive effects. As a result, the broad practical application of the Py based thin films stimulates intensive investigation of their magnetic and magnetoresistive properties [5, 6]. One of the priority areas of research is improving temperature stability of magnetic parameters. Formation of the functional elements of various purposes with improved thermal stability of magnetic performance characteristics allow to produce highly efficient devices [7].

The measurements of thermoresistive (resistivity (ρ) and temperature coefficient of resistance (TCR, β)) or strain (integral and differential strain coefficients) properties of permalloy and permalloy based thin films have been conducted rather occasionally (see, for example Ref. [8, 9]). Though, such parameter as resistivity is one of the base characteristic which affects the electronic, strain, magnetic, etc. properties of thin film materials. An analysis of the literature devoted to the study of thin film structures reveals that their electrophysical properties strongly depend on preparation conditions, thickness, and concentration of crystal structure defects. A composition of two or more thin metal film phases can improve the thermoresistive and strain properties [10-12]. This fact stimulates investigations of temperature, concentration and size dependences of resistivity and TCR of thin film structures prepared by co-evaporation or layer-by-layer methods.

In our previous work [13] we investigated electrophysical properties of thin film systems based on permalloy and silver prepared by co-evaporation methods. It was shown that the change of concentration of non-magnetic atoms in the range from 20 to 85 at.% leads to appear minimum or maximum respectively on the dependences of ρ and β at the concentration of Ag atoms of 48 at.%. This peculiarity is connected with changes in crystal structure of the samples.

In this paper, the experimental investigation focuses on electrophysical properties of multilayer film systems based on permalloy and silver. The basic framework was two-layer thin film Py(16)/Ag(38)/S (S is substrate, the thickness in the brackets is in nanometers). The selection of layer thickness was made based on the results for structures prepared by co-evaporation method and corresponded to the composition of Ag atoms of 48 at.%.

It is also known that electrophysical properties strongly depend on number of interfaces in multilayer system [14]. Thus, at the formation of subsequent samples $[Py/Ag]_n/S$, the number of bilayers Py/Ag (n) increases from 1 to 16. The total thickness and concentration of components remained unchanged

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2. EXPERIMENT TECHNIQUE

The sample preparation was carried out by electron-beam sputter deposition onto substrate at the temperature 300 K in HV chamber with a base pressure of 10^{-4} Pa. Amorphous glass-ceramic plates (for investigation of electrophysical properties) and copper grids with predeposited layer of carbon (for investigation crystal structure of samples) were used as substrates. Firstly, the sample with nominal composition Py(16)/Ag(38)/S were obtained. All samples were prepared at the same vacuum condition with the use of a cylindrical substrate holder. The sputtering rate was 0.1 nm/s. The thickness of each layer (accuracy of up to 10%) was monitored by the method of the quartz resonator.

Secondly, the samples with nominal composition $[Py/Ag]_n/S$ were prepared. The number of bilayer Py/Ag was increased from 2 to 16. The total thickness remained unchanged. As a result the following samples were obtained: $[Py(8)/Ag(19)]_2/S$; $[Py(4)/Ag(9.5)]_4/S$, $[Py(2)/Ag(5)]_8/S$, and $[Py(1)/Ag(2.5)]_{16}/S$. The schematic diagram of the multilayer thin film structures $[Py/Ag]_n/S$ is presented in Fig. 1.

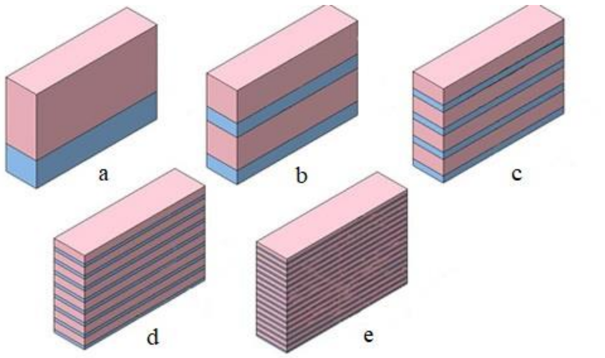

Fig. 1 – The schematic diagram of the multilayer thin film structures $[Py/Ag]_n/S$ with the total thickness d = 54 nm = const and different numbers of repeats of bilayer n: 1 (a), 2 (b), 4 (c), 8 (d), and 16 (e). The basic structure is [Py(16)/Ag(38)]/S

The samples after deposition were annealed during two cycle "heating ↔ cooling" up to the temperature of healing defects. The annealing was performed in a vacuum chamber at 10^{-4} Pa. Note, that the heat treatment of the samples was done in the automated mode. It allowed to control the speed of heating, experimental data (resistance and temperature) recording and processing. The value of temperature coefficient of resistance has been calculated on the base of temperature dependences of resistivity by the equation: $\beta = (1/\rho_{in}) \cdot (\Delta\rho/\Delta T)$, where ρ_{in} is the initial value of resistivity, ΔT = 5 K.

3. EXPERIMENTAL RESULTS

3.1 Phase State

In order to study the effect of diffusion processes during condensation and annealing on electrophysical properties of multilayer systems based on Py and Ag, it is necessary to have a good understanding of their phase state in as-deposited and heat treatment conditions. So, at the first stage of this work, the investigation of the phase state of thin film structures $[Py/Ag]_n/S$ was done.

Fig. 2 shows electron diffraction patterns for $[Py(8)/Ag(16)]_2/S$ thin film systems after deposition and heat treatment to 550 K. It is clear that diffraction rings of the as-deposited sample (Fig. 2a) correspond to fcc-Ni_3Fe and fcc-Ag reflections. Ni_3Fe (111) reflection overlaps with Ag (200) reflection, but all others are well-defined that confirm their crystalline nature. No other reflections corresponding to the solid solutions, intermetallic structures or impurities like oxides or hydrides are not observed. Thus, obtained samples have a two-phase state with relatively high purity. At the annealing up to 550 K, the diffraction rings become sharper, and the phase state of the total system does not change (Fig. 2b). It corresponds to the fcc-Ni_3Fe + fcc-Ag. After the heat treatment at 550 K, lattice constants increase from 0.3552 nm for fcc-Ni_3Fe and 0.4080 nm for fcc-Ag to 0.3562 nm and 0.4084 nm, respectively.

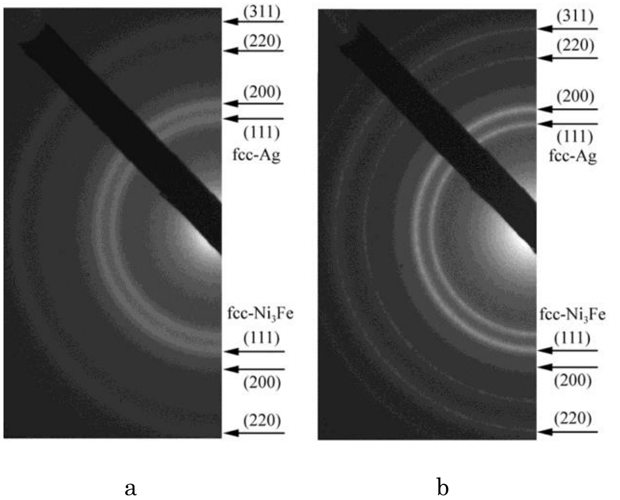

Fig. 2 – Diffractions patterns of the two-layer thin films Py(16)/Ag(38)/S after deposition (a) and heat treatment at 550 K (b)

It should be noted that a two-phase state of as-deposited and annealed thin film systems remains the same for all investigated samples.

3.2 Electrophysical Properties

Consider the results of electrophysical properties investigations for multilayer thin film structures $[Py/Ag]_n/S$. Fig. 3 illustrates temperature dependences of resistivity $\rho(T)$ and TCR $\beta(T)$ for thin film systems at n = 1, 2, 8, 16. Their character is conditional on processes that occur in the volume of the samples, such as: (i) an irreversible decrease of the resistivity value at the first cycles of heating. This is closely associated with the processes of recrystallization and the healing of defects. These processes lead to an increase of the electron mobility along with film samples and decrease the probability of the electron scattering at the grain boundaries and impurities. (ii) The following process of cooling gives rise to the appearance of typical for the

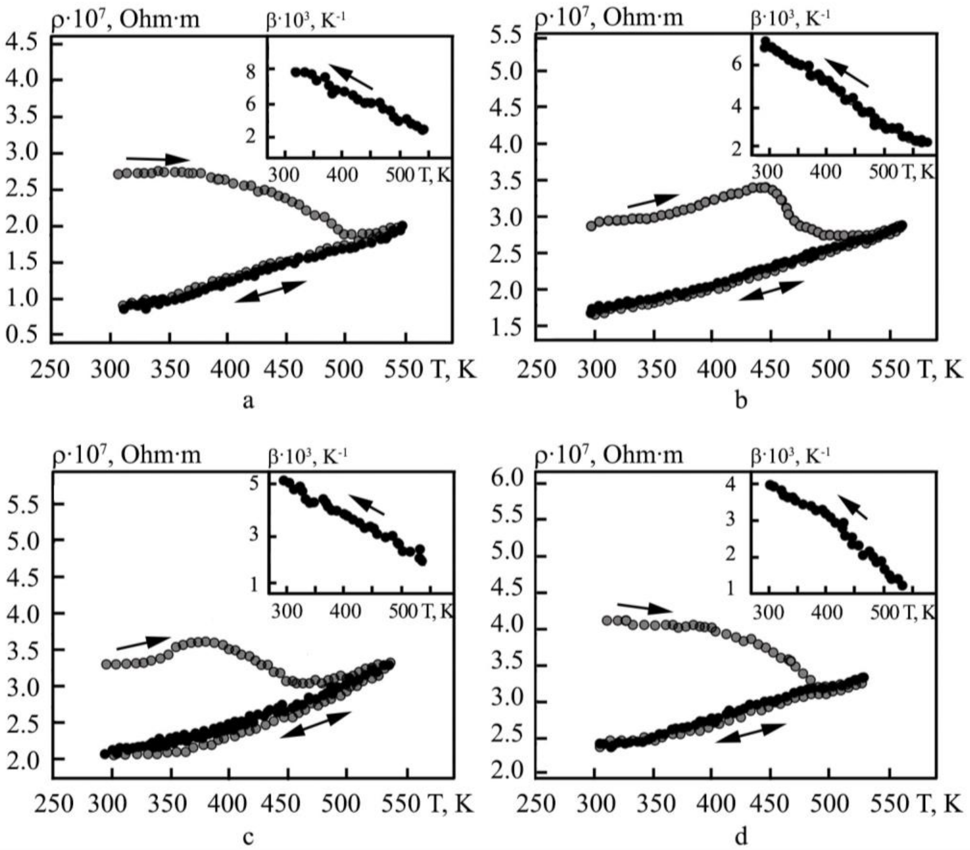

Fig. 3 – Temperature dependences of resistivity and TCR (in the insert) of the multilayer thin film structures $[Py/Ag]_n/S$ with the total thickness d = 54 nm = const and different numbers of repeats of bilayer n: 1 (a), 2 (b), 8 (c), and 16 (d). The basic structure is [Py(16)/Ag(38)]/S

metals temperature dependence of resistance. The ρ value decreases with a linear low at the samples cooling to the room temperature. The temperature that corresponds to the minimum of resistivity at the dependence $\rho(T)$ at the first cycles of annealing we define as temperature of the healing of defects. The processes of healing of defects, recrystallization processes, and, especially, the condensation speed have an influence on the values of datum temperature. Note, the dependence of resistivity vs. temperature remains linear at second cycles of cooling too. This is evidence of thermostabilization processes completion in the system. At the graph $\beta(T)$ the value of TCR gradual decreases with the temperature grows, that is $\beta \sim 1/T$ (the inserts at the Fig. 3). The change of a number of bilayer repeats does not change in the general the nature of $\rho(T)$ curves.

It was found that values of resistivity and TCR have an order of $\rho \sim 10^{-7}$ Ohm·m and $\beta \sim 10^{-3}$ K^{-1}, respectively, regardless of n. This is associated with the high defectiveness of the samples. Resulting evaluation of resistivity and TCR at the increase of a number of bilayer repeats for thin film structures $[Py/Ag]_n/S$ presented at Fig. 4. It should be noted that resistivity of the sample $[Py/Ag]_n/S$ grows from $0.78 \cdot 10^{-7}$ to $2.40 \cdot 10^{-7}$ Ohm·m with an increase of n from 1 to 16. At the same time, the value of TCR decreases from $4.70 \cdot 10^{-3}$ to $2.23 \cdot 10^{-3}$ K^{-1}. In the case, when the total thickness is constant, such change of ρ and β associated with the rise of the probability of electron scattering at the interfaces with an increasing number of fragments of the system.

Comparing the value of ρ and β for $[Py(1)/Ag(2.5)]_{16}/S$ system ($\rho = 2.40 \cdot 10^{-7}$ Ohm·m, $\beta = 2.23^{-3}$ K^{-1}) and for the thin film based on Py and Ag at the c_{Ag} = 60 at.% with thickness 55 nm prepared by co-evaporation method [13] ($\rho = 2.50 \cdot 10^{-7}$ Ohm·m, $\beta = 2.01^{-3}$ K^{-1}) allows concluding that they are very similar. It is necessary to take into account the fact that in the $[Py(1)/Ag(2.5)]_{16}/S$ system the effective thickness of the layers does not exceed 5 nm. Each

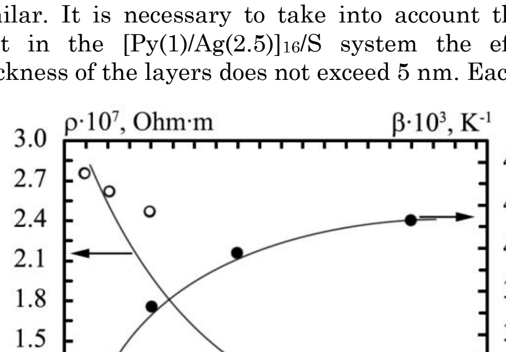

Fig. 4 – Resistivity and TCR values as a function of the number of Py/Ag bilayer repeats

layer in the system became discontinuous at the stage of condensation yet. Hence, the structure of the multilayer system become close to the structure of the thin films prepared by co-evaporation technique.

4. CONCLUSION

The two-phase state is fixed in multilayer thin film systems [Py/Ag]$_n$/S prepared by the layer-by-layer condensation method at n = 1-16. This phase state corresponds to the combination of fcc-Ni_3Fe + fcc-Ag and does not change after the heat treatment up to 550 K.

The comparative analysis of the experimental dependences $\rho(T)$ and $\beta(T)$ of film systems based on Py and Ag with the same total thickness of 54 nm was shown that the increase of the number of the bilayer repeats from 1 to 16 leads to the increase of resistivity value from $0.78\cdot10^{-7}$ to $2.40\cdot10^{-7}$ Ohm·m, and to the decrease of the TCR value from $4.70\cdot10^{-3}$ to $2.23\cdot10^{-3}$ K^{-1}. The mean reason for such change of ρ and β values can be associated with the growth of probability of electron interface scattering at the increase of Py/Ag bilayer numbers at the constant total thickness. Another reason is the breaking of individual layer continuous at the decrease of their effective thickness.

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Електрофізичні властивості багатошарових плівкових систем на основі пермалою та срібла

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Представлені результати комплексного дослідження фазового стану та електрофізичних властивостей (питомий опір та термічний коефіцієнт опору (ТКО)) багатошарових плівкових систем [Py/Ag]$_n$/П. Плівкові зразки на основі пермалоєвого сплаву (Py) та срібла були отримані методом електронно-променевого пошарового осадження у вакуумі 10^{-4} Па за кімнатної температури. Загальна товщина зразків залишається незмінною і становить 54 нм, а кількість повторів бішару Py/Ag зростає з 1 до 16. Дослідження фазового стану плівок проводилося методом електронної дифракції. Фазовий стан плівок після конденсації відповідає комбінації двох ГЦК граток (ГЦК-Ni_3Fe та ГЦК-Ag) та залишається незмінним при збільшення кількості повторів бішару у системі. Також було показано, що процес термообробки зразків не впливає їх фазовий склад. Термообробка зразків після конденсації проводилася у вакуумній камері протягом двох циклів «нагрівання ↔ охолодження» до температури заліковування дефектів у автоматичному режимі, що дозволило контролювати швидкість нагрівання, проводити запис експериментальних даних (опір та температура) та їх обробку. Результати досліджень електрофізичних властивостей показали, що для всіх зразків спостерігається металевий характер залежності питомого опору від температури. Величина питомого опору і ТКО мають порядок 10^{-7} Ом·м та 10^{-3} К$^{-1}$ відповідно, що є типовим для складових компонент досліджуваних систем. У той же час збільшення кількості повторів бішару Py/Ag з 1 до 16 приводить до зростання величини питомого опору з $0{,}78\cdot10^{-7}$ до $2{,}40\cdot10^{-7}$ Ом·м та до зменшення величини ТКО з $4{,}70\cdot10^{-3}$ до $2{,}23\cdot10^{-3}$ К$^{-1}$. Основними причинами зміни величини ρ та β може бути збільшення ймовірності інтерфейсного розсіювання електронів на межі поділу шарів, а також порушення суцільності окремих шарів при збільшенні кількості повторів бішару Py/Ag при незмінній загальній товщині шарів.

Ключові слова: Багатошарова система, Пошарова конденсація, Питомий опір, Термічний коефіцієнт опору, Інтерфейсне розсіювання.