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Magnetoresistive Properties of Multilayer Film Systems Based on Permalloy and Silver

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In this paper, the experimental investigation focuses on the magnetoresistive properties of nanosized film systems. Their structure changes from layered to granular due to transition from bilayer FM/NM (FM is a ferromagnetic material, NM is a nonmagnetic material) to $[FM/NM]_n$ multilayer film at a constant total thickness of samples. As ferromagnetic and nonmagnetic materials were chosen permalloy $Ni_{80}Fe_{20}$ (Py) and Ag, respectively. It was demonstrated that the shape of the field dependences of magnetoresistance depends on the number of bilayer Py/Ag. For as-deposited $[Py/Ag]_n/S$ at $n = 8$, 16, the transition from the antiferromagnetic ordering of magnetic moments to ferromagnetic one occurs under an external magnetic field. As a result, the resistivity of the samples reduced, and the giant magnetoresistive effect was realized. The increase of the number of bilayers repeats from 2 to 16 at the unchanged total thickness of the system leads to the growth of the magnetoresistance from 0.10 to 0.35 %. During annealing up to 600 K, the magnetoresistive effect is reduced, but it does not disappear completely.

Keywords: multilayer film systems, layer-by-layer condensation, magnetoresistive properties, thermal annealing

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Introduction

Among different modern preparation methods of thin-film structures, the alternate and co-deposition of ferromagnetic and nonmagnetic materials can be distinguished. At this, various methods like thermal evaporation, electron beam or magnetron deposition, laser lithography can be used [1-4]. Regardless of the chosen method, the physical properties of nanostructures will depend on technological conditions: a base pressure in a vacuum chamber, the composition of the residual atmosphere, type and temperature of a substrate, deposition rate, and so on. Hence, the choice of preparation method will be significantly affected on the samples crystal structure, determine the features of the diffusion processes, magnetic anisotropy, as well as the mechanisms of spin-dependent electron scattering.

Using the methods of alternate condensation can be formed as multilayer structures of general and periodic types. The co-deposition method is more used for the formation of composite materials. The structures of the general type include three-layer $FM_2/NM/FM_1$ [5, 6], multilayer $[FM/NM]_n$ [7, 8], and spin-valve $AFM/FM_2/NM/FM_1$ [9] systems (FM, NM, and AFM are the ferromagnetic, nonmagnetic and antiferromagnetic materials respectively). Among the ferromagnetic materials that have found practical application, we can distinguish $Ni_{80}Fe_{20}$ and $Ni_{50}Fe_{50}$ alloys.

At the formation of nanostructures by the co-deposition method, usually used the combination of magnetic and nonmagnetic components with low mutual solubility. It is alloyed realize structures that consist of magnetic nanoparticles randomly distributed in metal [10, 11] or insulator matrix [12, 13].

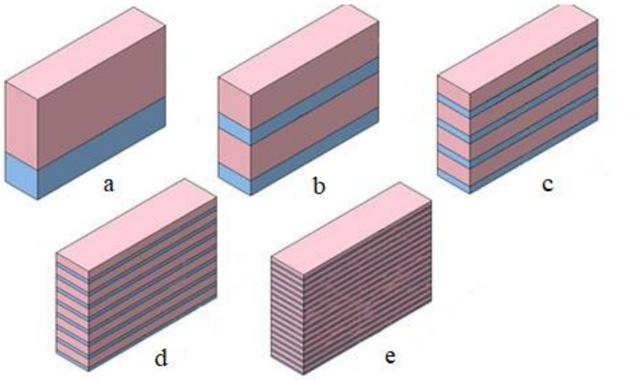

Fig. 1. The schematic diagram of the [Py/Ag]$_n$/S multilayer film structures with the total thickness d = 54 nm = const and different numbers of repeats of bilayer n: 1 (a), 2 (b), 4 (c), 8 (d), and 16 (e). The basic structure is [Py(16)/Ag(38)]/S.

In this paper, the experimental investigation focuses on the magnetoresistive properties of nanosized film systems. Their structure changes from layered to granular due to transition from the bilayer FM/NM to [FM/NM]$_n$ multilayer film at the constant total thickness of samples. Permalloy $Ni_{80}Fe_{20}$ (Py) and Ag were chosen as ferromagnetic and nonmagnetic materials, respectively. The heat treatment effect on the nature and magnitude of magnetoresistance of such structures will also be done.

I. Experimental Procedure

The sample preparation was carried out by electron-beam sputter deposition onto a substrate at the temperature of 300 K in a HV chamber with a base pressure of 10^{-4} Pa. Amorphous glass-ceramic plates were used as substrates. Firstly, the sample with nominal composition Py(16)/Ag(38)/S was 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 [Py/Ag]$_n$/S multilayer thin-film structures is presented in Fig. 1.

The magnetoresistive properties were measured using a software-hardware complex with current-in-plane geometries in an external magnetic field from 0 to 500 mT at room temperature. The measuring current was I = 1 mA. The value of longitudinal and transverse magnetoresistance (MR) have been calculated by equation $MR = (R(B) - R(B_0))/R(B_0)$, where $R(B)$ is the current value of resistance in the magnetic field B; $R(B_0)$ is the resistance of the sample in the field of the B_0.

For an investigation of the annealing effect on magnetoresistive properties, samples were isothermally annealed at T_{ann} = 400, 500, and 600 K for 20 min.

II. Results and discussion

Fig. 2 shows field dependences of the longitudinal and transverse magnetoresistance for Py(16)/Ag(32)/S, [Py(8)/Ag(19)]$_2$/S, [Py(2)/Ag(5)]$_8$/S, and [Py(1)/Ag(2.5)]$_{16}$/S systems in the as-deposited state. As expected, the as-deposited Py(16)/Ag(32)/S system is characterized by the anisotropic character of field dependences of magnetoresistance (Fig. 2a). Such behavior is typical for structurally integrated permalloy thin films [14]. The MR value in both longitudinal and transverse geometries does not exceed 0.1%. In this case, the Ag layer performs a function of protecting layer, and due to relatively high thickness shunts the signal from ferromagnetic one. For [Py(8)/Ag(19)]$_2$/S system, the change of the MR(B) curve shape is observed. Such behavior is typical for isotropic magnetoresistance with the presence of hysteresis and saturation in the relatively weak magnetic fields (B_s < 100 mT) (Fig. 2b). The reason for magnetoresistive hysteresis appearing is displacement delay of domain walls (irreversible displacement), irreversible rotation of spontaneous magnetization, and delayed formation and growth of remagnetization centers. This system can be presented as three-layer FM/NM/FM with an additional protective layer. This result is close to those presented in Ref. [15] for a similar system $Fe_{0.2}Co_{0.8}$/Cu/$Fe_{0.2}Co_{0.8}$.

For the as-deposited [Py/Ag]$_n$/S system at n = 8, 16 (Fig. 2c, d), a completely different type of MR(B) dependence was observed. For those samples under an external magnetic field, the transition from the antiferromagnetic ordering of magnetic moments to the ferromagnetic one occurs. As a result, the resistivity of the samples is reduced and the giant magnetoresistive effect is realized [16]. Besides, the saturation in the magnetic field up to 500 mT is not observed. The decrease of effective thickness of magnetic and nonmagnetic thickness to value less than 5 nm leads to the breaking of individual layer continuous. As a result, the structure of the multilayer system becomes close to the structure of the thin films prepared by the co-evaporation technique. The structure

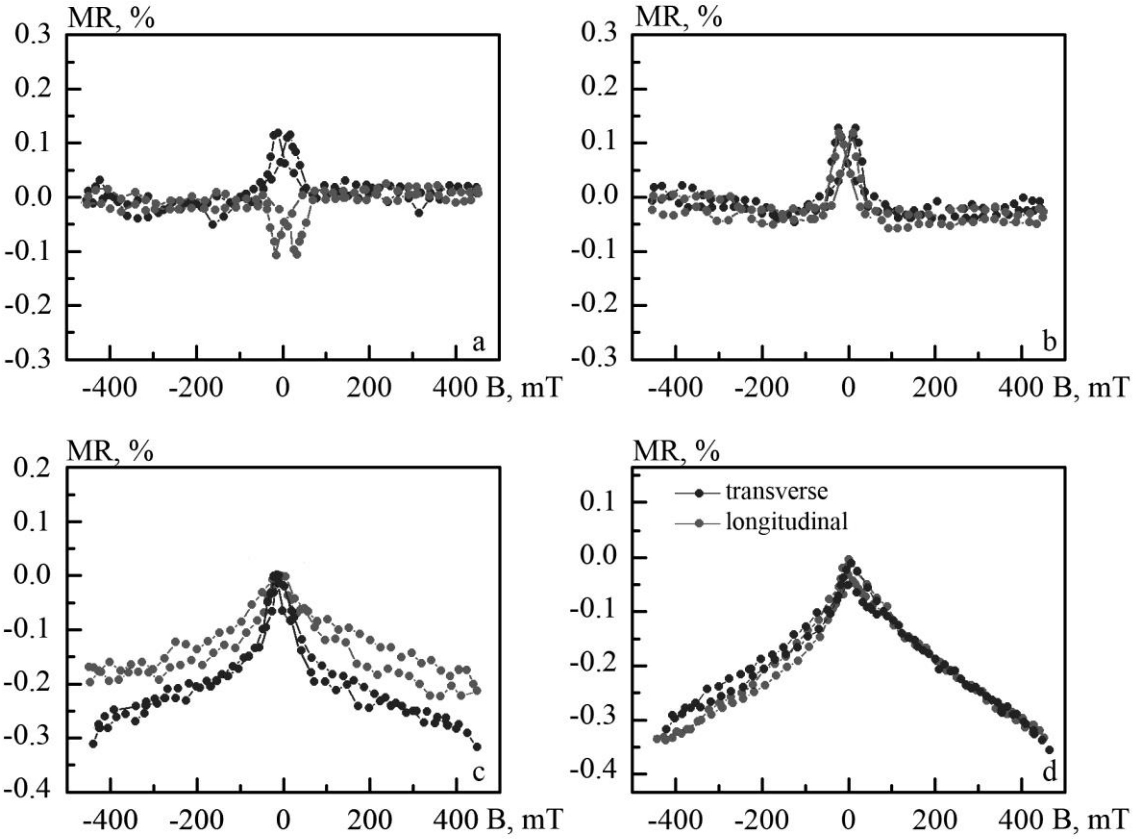

Fig. 2. The field dependences of magnetoresistance for $[Ni_{80}Fe_{20}(16)/Ag(38)]/S$ (a); $[Ni_{80}Fe_{20}(8)/Ag(19)]_2/S$ (b), $[Ni_{80}Fe_{20}(2)/Ag(5)]_8/S$ (c), and $[Ni_{80}Fe_{20}(1)/Ag(2,5)]_{16}/\Pi$ (d) film systems in as-deposited state.

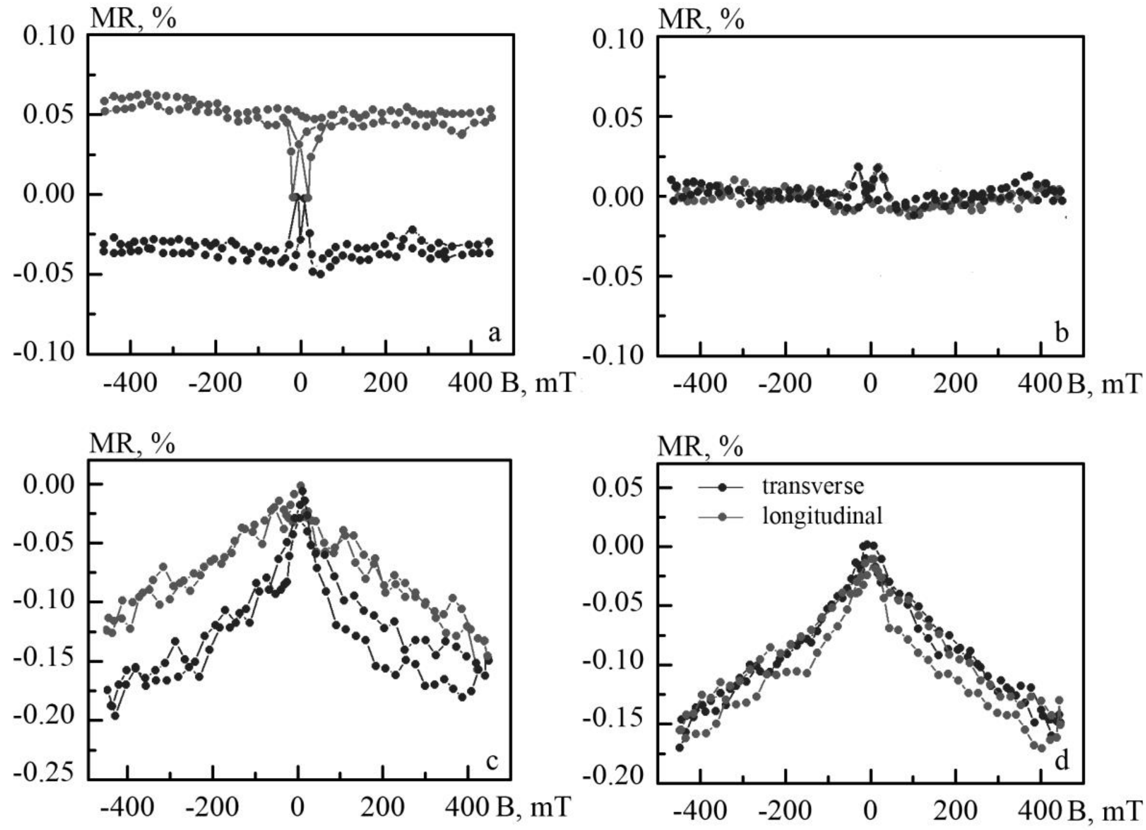

Fig. 3. The field dependences of magnetoresistance for $[Ni_{80}Fe_{20}(16)/Ag(38)]/S$ (a); $[Ni_{80}Fe_{20}(8)/Ag(19)]_2/S$ (b), $[Ni_{80}Fe_{20}(2)/Ag(5)]_8/S$ (c), and $[Ni_{80}Fe_{20}(1)/Ag(2.5)]_{16}/\Pi$ (d) film systems after annealing up to 500 K.

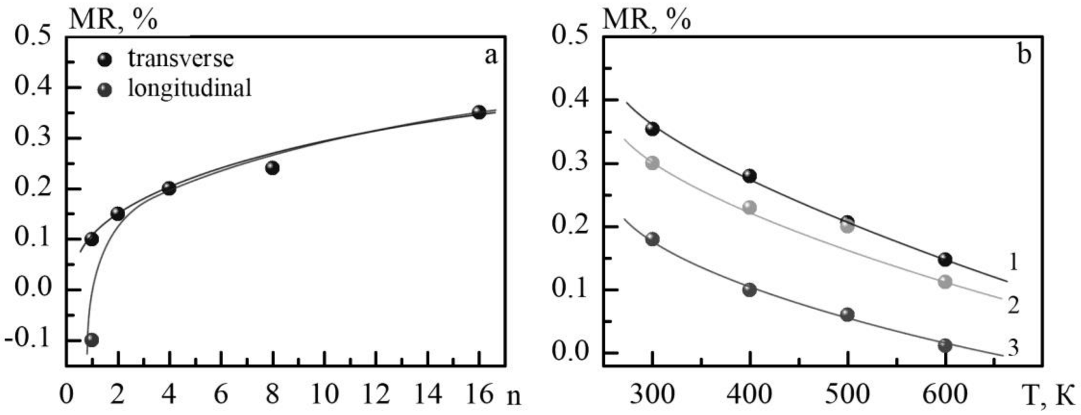

Fig. 4. The magnetoresistance as a function of the number of repeats n in $[Py/Ag]_n/S$ multilayer film system (a) and the temperature dependence of magnetoresistanse for $[Ni_{80}Fe_{20}(1)/Ag(2.5)]_{16}/S$ (1), $[Ni_{80}Fe_{20}(2)/Ag(5)]_8/S$ (2) $[Ni_{80}Fe_{20}(4)/Ag(9.5)]_4/S$ (1) film systems (b).

of the $[Py/Ag]_n/S$ multilayer films at $n = 8$, 16 consists of separated permalloy ferromagnetic particles embedded into a nonmagnetic Ag matrix [17]. The MR magnitude remains small with a maximum of 0.35 % for $[Py/Ag]_{16}/S$ multilayer systems. This result correlates with data obtained in Ref. [18] devoted to magnetotransport properties of $[Ni_{81}Fe_{19}(2)/Ag(4)]_{20}/S$ multilayers. Though, this value is lower compared to that of the earlier reported for the similar systems prepared by the co-evaporation technique [17, 19]. The peculiarities of $[Py/Ag]_8/S$ multilayer system is noncoincidence of field dependences of longitudinal and transverse magnetoresistance (Fig. 2c). Besides, the value of transverse MR is higher than the value of longitudinal MR. This is caused by the influence of multi-domain particles of even clusters in the magnetic layers on the GMR magnitude [20].

Consider, how the annealing process affects the magnetoresistive properties of $[Py/Ag]_n/S$ multilayer systems (Fig. 3). The annealing process up to 500 K does not change the MR(B) curves behavior for all investigated samples. The insignificant displacement of the extreme at the field dependences of magnetoresistance is observed. For samples with $n < 4$, the reduction of MR magnitude is associated with the coalescence of ferromagnetic grains, reorientation of Ag crystallites, and, as a result, blurring of interfaces magnetic grain/nonmagnetic matrix [11]. This leads to the weakening of electron spin-dependent scattering role and more effective emerging of electron-phonon scattering. The rise of the probability of electron-phonon scattering processes prevents electron transition from one ferromagnetic grain to another [21].

The resulting dependences of magnetoresistance as a function of the number of repeats n in the $[Py/Ag]_n/S$ multilayer system and the MR temperature dependence presented in Fig. 4. The analysis of data presented in Fig. 4 allows concluding that the increase of the number of bilayer repeats from 2 to 16 at the unchanged total thickness of the system leads to the MR value grow from 0.1 % to 0.35 %. The transition from anisotropic to isotropic behavior of magnetoresistive effect occurs at the $n = 2$. During annealing, the effect is reduced, but according to Fig. 3b, it does not disappear completely.

Conclusion

We have studied the heat treatment effect on the nature and magnitude of magnetoresistance of nanosized film systems, whose structure changes from layered to granular due to transition from bilayer Py/Ag to $[Py/Ag]_n$ multilayer film at a constant total thickness of samples. The shape of the field dependences of magnetoresistance depends on the number of bilayers Py/Ag. The transition from anisotropic to isotropic MR behavior occurs at the n =2. The increase of the number of bilayers repeats from 2 to 16 at the unchanged total thickness of the system leads to the MR value grows from 0.1 % to 0.35 %. During annealing up to 600 K, the effect is reduced, but it does not disappear completely.

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Магніторезистивні властивості багатошарових плівкових систем на основі пермалою та срібла

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У даній роботі експериментальні дослідження зосереджено на магніторезистивних властивостях нанорозмірних плівкових систем. Їх структура змінюється з пошарової до гранульованої за рахунок переходу від двошарової FM/NM (FM – феромагнітний матеріал, NM – немагнітний матеріал) до $[FM/NM]_n$ багатошарової плівкової системи за незмінної загальної товщини зразків. Як магнітний і немагнітний матеріали були обрані пермалоєвий сплав $Ni_{80}Fe_{20}$ (Py) та Ag, відповідно. Показано, що форма польових залежностей магнітоопору залежить від кількості повторів бішару Py/Ag. Для свіжосконденсованих систем $[Py/Ag]_n$/П при $n = 8$, 16 відбувається перехід від антиферомагнітного до феромагнітного упорядкування магнітних моментів при прикладанні зовнішнього магнітного поля, що призводить до зменшення опору зразків і, як наслідок, до прояву ефекту гігантського магнітоопору. Збільшення кількості повторів бішару з 2 до 16 за незмінної загальної товщини системи призводить до зростання величини магнітоопору з 0,10 до 0,35 %. У процесі відпалювання до 600 K магніторезистивний ефект послаблюється, але не зникає повністю.

Ключові слова: багатошарова плівкова система, пошарова конденсація, магніторезистивні властивості, відпалювання.