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REGULAR ARTICLE

Magnetoresistive Properties of Discontinuous Thin-film Systems Based on $Ni_{80}Fe_{20}$ and SiO_x ($x \cong 1$)

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The paper presents the results of experimental studies of the structure and magnetoresistive properties of discontinuous multilayers $[Ni_{80}Fe_{20}(d)/SiO_x(5)]_5$/Substrate, $x \cong 1$. The method of layer-by-layer electron-beam evaporation was used for the deposition of samples. The thickness of the magnetic layers (d) varied from 4 to 8 nm. To investigate the annealing temperature effect on magnetoresistive properties, samples were annealed at step-increasing temperatures within the T_{ann} = 300 – 700 K range. It was demonstrated that an anisotropic character of magnetoresistance (positive longitudinal and negative transverse magnetoresistance) is observed for all as-deposited and annealed at 400 K samples, which are typical for single-layer structurally continuous films of the $Ni_{80}Fe_{20}$ alloy. Familiar to all field dependences $(\Delta R/R_0)(B)$ with an anisotropic character is a sharp change in magnetoresistance in the field range of – 10 – + 10 mT and a tendency to saturate in more vital fields. It was found that annealing the samples at a temperature of 500 K with d = 4 – 5 nm leads to the transition to isotropic magnetoresistance. This is due to an increase in the size of permalloy granules to 10 nm and the formation of insulator channels with a width of 1 – 2 nm between them. The maximum values of isotropic magnetoresistance at room temperature are about 0.1 %. After annealing at a temperature of 600 K, the reappearance of anisotropic magnetoresistance in structures with d = 4 nm is observed. The reason for this transition is the destruction of the structural continuity of the insulator layers and, as a result, the formation of a metal cluster throughout the structure. It is shown that an increase in the annealing temperature to 700 K does not cause a change in the nature of the magnetoresistance but only leads to a rise in its value.

Keywords: Discontinuous thin-film systems, Permalloy, Magnetoresistance, Annealing.

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1. INTRODUCTION

Scientific and technological progress is impossible today without the widespread use of micro- and nanoelectronics, spintronics, computing, robotics, etc. The successful development of these areas requires a modern element base, provided mainly by magnetically inhomogeneous materials [1-3]. Using such materials can dramatically improve the reliability of devices and significantly reduce their size, weight, power consumption, and cost [3-6]. Such materials, in particular, include granular metal-insulator structures and layered structures based on ferromagnetic alloys and insulator layers. Despite many experimental and theoretical studies of granular structures [7-10], some questions remain open. For example, the influence of the size and shape of magnetic granules on such materials' magnetic and magnetoresistive properties and the nature of their distribution in the insulator matrix volume are not fully understood. At the same time, much less attention has been paid to the study of layered structures based on ferromagnetic metals and insulator layers obtained by layer-by-layer condensation [11-15]. However, recent research shows that such structures have advantages over granular films. In particular, layered structures can be considered composite materials with an amorphous insulator matrix without ferromagnetic metal atoms, almost the same magnetic granules size, and a change in these sizes if necessary [15-18].

Given the above, this work aimed to experimentally study the magnetoresistive properties of layered structures $[Ni_{80}Fe_{20}(d)/SiO_x(5)]_5$/S (S-substrate, $x \cong 1$) as possible thermostable sensitive elements of instrument structures.

2. EXPERIMENTAL DETAIL

The $[Ni_{80}Fe_{20}(d)/SiO_x(5)]_5$/S ($x \cong 1$) discontinuous multilayers, where n = 5 is the number of FM/I bilayers, were prepared at RT in an HV chamber with a base pressure of 10^{-4} Pa. The method of layer-by-layer electron-

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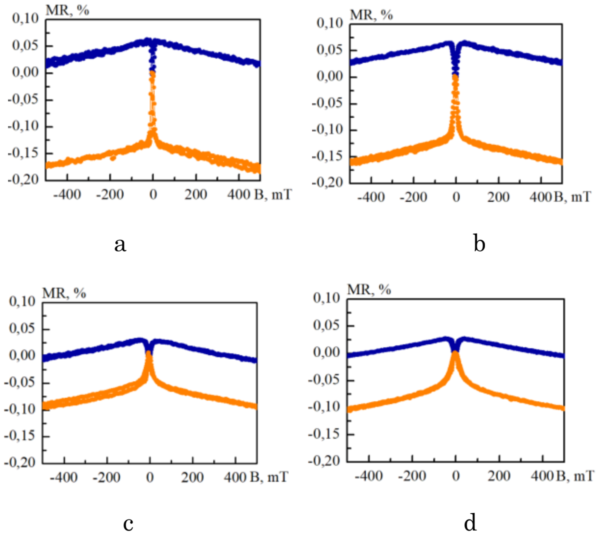
beam evaporation was used for the deposition of samples. The thickness of the magnetic layers (d) varied from 4 to 8 nm. The thickness of the layers was controlled by two independent *in situ* quartz resonators with an accuracy of 10%.

The magnetoresistive properties were measured using a software-hardware complex with current-in-plane geometries in an external magnetic field from 0 to 600 mT. All measurements were performed at room temperature. The measuring current was $I = 1$ mA. The value of longitudinal (magnetic field in the sample plane and parallel to current) and transverse (magnetic field in the sample plane and perpendicular to current) magnetoresistance 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.

To investigate the annealing temperature effect on magnetoresistive properties, samples were annealed in step-increasing temperatures within the T_{ann} = 300-700 K range, staying at each temperature for 20 min. The annealing was performed in a vacuum chamber with a 10^{-3} Pa pressure.

3. RESULT AND DISCUSSION

Fig. 1 illustrates the field dependences of the magnetoresistance for non-annealed structures with different thicknesses of permalloy layers.



a b

c d

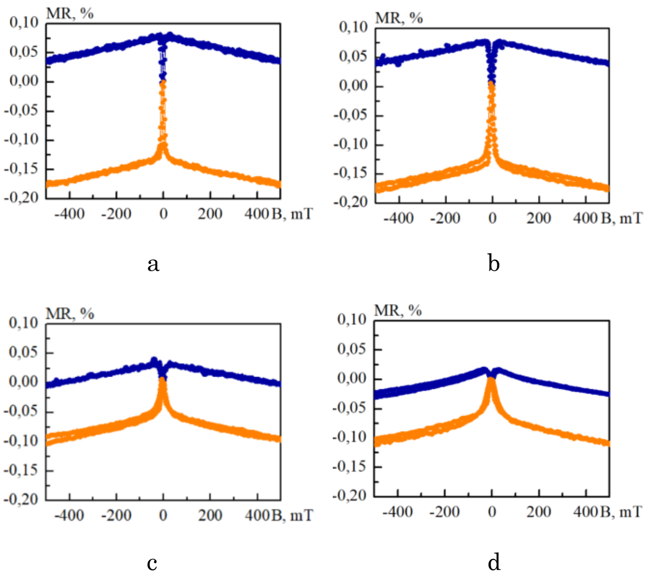
Fig. 1 – Field dependencies of the magnetoresistance for the layered system $[Ni_{80}Fe_{20}(d)/SiO_x(5)]_5/S$ ($x \cong 1$) at d = 8 nm (a), 6 nm (b), 5 nm (c), and 4 nm (d) after condensation

As can be seen from the figure, for all as-deposited samples, an anisotropic character of magnetoresistance (positive longitudinal and negative transverse magnetoresistance) is observed, which is typical for single-layer structurally continuous films of the $Ni_{80}Fe_{20}$ alloy. Common to all field dependences $(\Delta R/R_0)(B)$ with an anisotropic character is a sharp change in magnetoresistance in the field range of – 10 – + 10 mT and a tendency to saturate in more vital fields.

Obviously, in the process of condensation in such structures, even at a layer thickness of d = 4 nm, "infinite" ferromagnetic clusters are formed, and, as a result, the structures are electrically continuous. The formation of extended ferromagnetic clusters determines the realization of anisotropic magnetoresistance due to the interaction of conduction electrons with external electrons, whose spin moments cause spontaneous magnetization.

The value of the AMR at room temperature for such samples is 0.05 – 0.15%, depending on the thickness of the permalloy layers. The relatively low AMR values can be explained by a decrease in the saturation magnetization due to the large defectiveness of as-deposited permalloy layers and their structural inconsistency.

The effect of the annealing temperature on the nature of the field dependencies and the magnitude of the magnetoresistance of the studied structures illustrates Figs. 2-5. It is worth noting that annealing at 400 K does not change the nature of the field dependencies of the magnetoresistance and its value (Fig. 2).



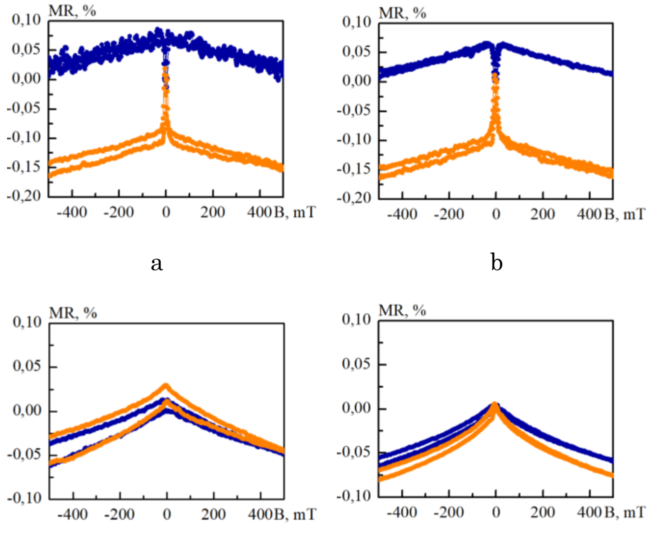
a b

c d

Fig. 2 – Field dependencies of the magnetoresistance for the layered system $[Ni_{80}Fe_{20}(d)/SiO_x(5)]_5/S$ ($x \cong 1$) at d = 8 nm (a), 6 nm (b), 5 nm (c), and 4 nm (d) after annealing to 400 K

As can be seen from Fig. 3c, d, the field dependences of the magnetoresistance are isotropic in the longitudinal and transverse geometries of measurement (the resistance of the samples decreases in the magnetic field). At the same time, in most cases, the field dependences obtained in different geometries coincided with the experimental error, and no magnetoresistive hysteresis was recorded on the field dependences of magnetoresistance. This fact indicates that the influence of magnetoresistance anisotropy is not significant.

The maximum values of isotropic magnetoresistance at room temperature are about 0.1 %. Structural features can explain such peculiarities of magnetoresistance behavior.



a b c d

Fig. 3 – Field dependencies of the magnetoresistance for the layered system $[Ni_{80}Fe_{20}(d)/SiO_x(5)]_5$/S ($x \cong 1$) at d = 8 nm (a), 6 nm (b), 5 nm (c), and 4 nm (d) after annealing to 500 K

According to electron microscopic studies, crystallite size increases after annealing the samples at a temperature of 500 K. The increase in the size of crystallites in structures with a permalloy layer thickness of 4 – 5 nm leads to the formation of islands with insulator channels between them with a width of 1 – 2 nm. In such films, the insulator layers prevent direct ferromagnetic exchange between neighboring islands within the same layer but allow interisland tunneling [19-21]. Also, the structural continuity of the insulator layer is likely to be preserved, which excludes direct ferromagnetic exchange between magnetic islands of adjacent layers.

Thus, a structure is formed in which an insulator barrier separates the magnetic granules, so the transfer of an electron from one granule to another will be carried out only by the tunneling effect. In such a metal-insulator-metal system, an electron with a particular spin state can tunnel through the barrier only to the same spin state. The probability of tunneling an electron to a state with an opposite spin is zero [22]. It is maximal when the magnetic moments of neighboring islands are oriented in parallel and minimal in the case of antiparallel orientation. Macroscopically, this relationship can be represented by the Eq. (1):

$$\Delta R = -P^2 \cdot \frac{M}{M_s} \tag{1}$$

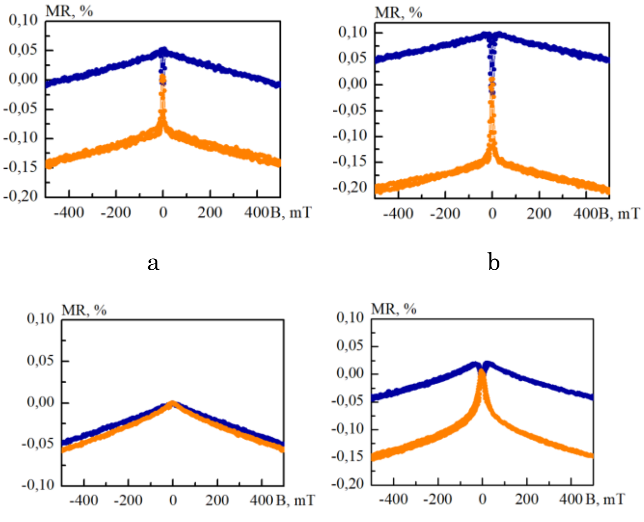
where ΔR is the change in the film resistance, P is the electron polarization coefficient, M is the film magnetization in an external field, and M_s is the saturation magnetization.

Note that such a correlation is characteristic only of negative isotropic magnetoresistance. Thus, for the layered structures of $[Ni_{80}Fe_{20}(d)/SiO_x(5)]_5$/S ($x \cong 1$) at d = 4 – 5 nm, tunneling magnetoresistance is realized.

Considering that the films are island-like at effective permalloy layer thicknesses of 4 – 5 nm, according to Eq. (1), they can be in a superparamagnetic state. This is confirmed by the absence of hysteresis on the isotropic field dependences and their nonlinearity, which is a consequence of the lack of magnetic hysteresis and the nonlinear dependence of the magnetic moment on the magnetic field Eq. (1).

For structures with d = 6 – 10 nm, in which an infinite ferromagnetic cluster is formed in the initial state, annealing at 500 K does not lead to its fragmentation (formation of an island structure). As a result, the character of the magnetoresistance remains anisotropic Fig. 3 a, b.

The peculiarities of the magnetoresistive properties of the layered structures after annealing at 600 K are presented in Fig. 4. As in the cases discussed above, no change like the field dependences was observed for structures with d = 6 – 10 nm (Fig. 4 a, b).



a b c d

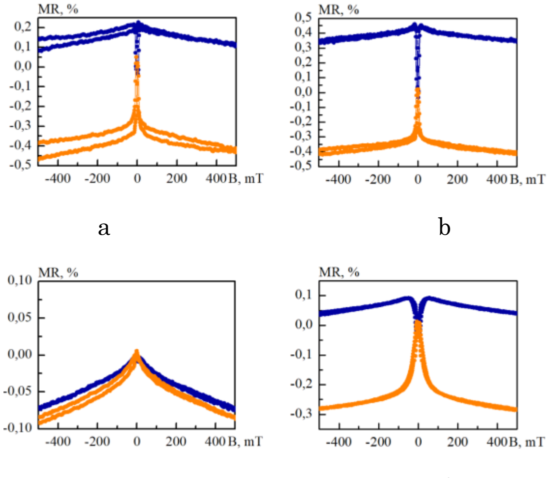
Fig. 4 – Field dependencies of the magnetoresistance for the layered system $[Ni_{80}Fe_{20}(d)/SiO_x(5)]_5$/S at d = 8 nm (a), 6 nm (b), 5 nm (c), and 4 nm (d) after annealing to 600 K

Only a slight increase in the transverse and longitudinal magnetoresistance values can be noted due to increased metal granule size and reduced crystal structure defects.

The magnetoresistance behavior after annealing at 600 K of a layered structure with d = 4 nm is particularly interesting. As shown in Fig. 4d, a transition to an anisotropic character of the magnetoresistance is observed after annealing. This magnetoresistance behavior can be explained by violating the structural continuity of the dielectric layers. As a result, a direct ferromagnetic exchange between the magnetic islands of neighboring layers appears.

This leads to forming a ferromagnetic cluster in the entire structure volume and, as a result, the realization of anisotropic magnetoresistance.

A further increase in the annealing temperature to 700 K, regardless of the thickness of the layers of the structures, does not lead to a change in the nature of the



a b

c d

Fig. 5 – Field dependencies of the magnetoresistance for the layered system $[\mathrm{Ni_{80}Fe_{20}}(d)/\mathrm{SiO}_x(5)]_5/\mathrm{S}$ at d = 8 nm (a), 6 nm (b), 5 nm (c), and 4 nm (d) after annealing to 700 K

magnetoresistance (Fig. 5). Only a 2-fold increase (up to 0.1%) in the value of isotropic magnetoresistance and a 2-3-fold increase (up to 0.3 – 0.5%) in the anisotropic magnetoresistance are recorded. This increase in magnetoresistance is due to a significant increase in the size of the granules (up to 10 – 20 nm), which is confirmed by the results of electron microscopic studies.

4. CONCLUSION

For all non-annealed and annealed at 400 K layered structures $[\mathrm{Ni_{80}Fe_{20}}(d)/\mathrm{SiO}_x(5)]_5/\mathrm{S}$ ($x \cong 1$) with effective permalloy layer thicknesses $d = 4 - 10$ nm and $d_{\mathrm{SiO}x} = 5$ nm, an anisotropic character of magnetoresistance is observed. After annealing at a temperature of 500 K, the structures with d = 4 – 5 nm show a transition to isotropic magnetoresistance, which is due to an increase in the size of permalloy granules to 10 nm and the formation of insulator channels with a width of 1 – 2 nm between them. A further increase in the annealing temperature to 600 and 700 K leads to the appearance of anisotropic magnetoresistance in structures with $d = 4$ nm. The reason for this transition is the destruction of the structural continuity of the insulator layers and, as a result, the formation of a metal cluster throughout the structure.

The anisotropic and isotropic magnetoresistance values increase with the heat treatment temperature due to the increase in the size of the magnetic granules and the improvement of their crystal structure.

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Магніторезистивні властивості розривних тонкоплівкових систем на основі $Ni_{80}Fe_{20}$ та SiO_x ($x \cong 1$)

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У роботі наведено результати експериментальних досліджень структури та магніторезистивних властивостей розривних мультишарів $[Ni_{80}Fe_{20}(d)/SiO_x(5)]5$/Підкладка, $x \cong 1$. Використовувався метод пошарового електронно-променевого напарювання. для депонування зразків. Товщина магнітних шарів (d) змінювалася від 4 до 8 нм. Щоб дослідити вплив температури відпалу на магніторезистивні властивості, зразки відпалювали при ступінчастому зростанні температур у діапазоні $T_{\text{від.}}$ = 300–700 К. Показано, що для всіх наплавлених і відпалених при 400 К зразків спостерігається анізотропний характер магнітоопору (позитивний поздовжній і негативний поперечний) зразків, характерний для одношарових структурно-неперервних плівок сплаву $Ni_{80}Fe_{20}$. Знайомі всім польові залежності $(\Delta R/R_0)(B)$ анізотропного характеру – це різка зміна магнітоопору в діапазоні полів – 10 – + 10 мТл і тенденція до насичення в більш важливих полях. Встановлено, що відпал зразків при температурі 500 К з d = 4 – 5 нм призводить до переходу до ізотропного магнітоопору. Це пов’язано зі збільшенням розміру гранул пермалою до 10 нм і утворенням між ними каналів ізолятора шириною 1 – 2 нм. Максимальні значення ізотропного магнітоопору при кімнатній температурі становлять близько 0,1 %. Після відпалу при температурі 600 К спостерігається повторна поява анізотропного магнітоопору в структурах з d = 4 нм. Причиною такого переходу є руйнування структурної безперервності шарів ізолятора і, як наслідок, утворення металевого кластера по всій структурі. Показано, що підвищення температури відпалу до 700 К не викликає зміни характеру магнітоопору, а призводить лише до зростання його величини.

Ключові слова: Розривні тонкоплівкові системи, Пермалой, Магнітоопір, Відпал.