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Magnetoresistive Properties of Thin Film Systems Based on Fe(Co)/Gd/Fe(Co)

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The paper is devoted to the general laws of the influence of the layer thickness based on Gd and thickness of the ferromagnetic layer on the value of magnetoresistance and coercivity in layered Fe/a-Gd/Fe and Co/a-Gd/Co films at different measurement geometries and orientation angles of the samples in an external magnetic field. It is found that the greatest value of magnetoresistance is observed in the perpendicular measurement geometry. It is shown that with the change in the thickness of a-Gd layer and upper layers of ferromagnets, the values of magnetoresistance and coercivity have oscillatory behavior.

Keywords: Structural-phase state, Magnetoresistance, Coercivity, Multilayer film systems.

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1. INTRODUCTION

Last years a great attention of scientists has been devoted to the study of the properties of composite-non-uniform films based on rare-earth (R) and 3-d transition (T) metals (see, for example, [1, 2]). This is connected with two circumstances. Firstly, progress in the technique of vacuum deposition allows to generate structures with the specified characteristics [3-5]. Secondly, investigation technique of the structural-phase state, magnetic, magnetoresistive, optical, and other properties is updated.

The aforesaid circumstances are very important from the point of view of further use of such systems as the structural components for modern microelectronic devices and sensors. Since from the point of view of practical use, for example, magnetic-field sensor based on R and T metals, it is necessary to know how the dimensional effects (dependence of the properties on the thickness of separate layers) and orientation of the samples in an external magnetic field influence the value of magnetoresistive and electrophysical properties. Also, stability of the properties of multicomponent systems significantly depends on the diffusion processing occurring there and their structural-phase state [6].

In connection with the aforesaid, the aim of our work was the complex investigation of the structural-phase state of three-layer films based on Fe and Gd and Co and Gd and dimensional effects in magnetoresistive properties in different measurement geometries.

2. EXPERIMENTAL TECHNIQUE

Three-layer Fe/a-Gd/Fe/S and Co/a-Gd/Co/S (S is the substrate) films were obtained in vacuum $P \sim 10^{-4}$ Pa by the layer-by-layer condensation of metal layers by the electron-beam method on glass-ceramic substrates (for the determination of magnetoresistive properties) and films-substrates of amorphous carbon (structural investigations). The substrate temperature was equal to $T_s \cong 460$ K, the mean condensation rate of Gd was 0,05-0,15 nm/s, and of Fe and Co – 0,1-0,3 nm/s. Thickness of film samples was controlled using quartz resonator method. Quartz plate and substrates were placed on different holders but on the same distance from evaporator. Such placement allowed to realize a local heating of the substrate, and temperature of quartz plate was constant ($T = 320$ K).

Investigations of the crystalline structure and phase composition of the film samples were carried out using the transmission electron microscope PEM-125 K in the bright-field and microdiffraction operating modes (without introduced selection diaphragm).

Magnetoresistive properties of three-layer film samples based on Fe and Co and Gd were studied using hardware-software complex by the four-point scheme in three measurement geometries (transverse, perpendicular, and longitudinal) at room temperatures by the technique described in the work [7].

3. STRUCTURAL-PHASE STATE

Structural-phase state of the films is an important from the point of view of the formation of many physical properties of the films including magnetoresistive ones [6, 8-10]. Therefore, for three-layer film systems it is necessary to know not only phase composition of separate layers but of the system in whole [8, 11], since phase-formation in the diffusion zone on the bedding interface influences the quality of interfaces, scattering conditions of charge carriers, and, as a result, the electrophysical and magnetoresistive properties.

Results of investigation of the phase composition of single-layer films based on Fe at the effective thicknesses of 1-1,5 nm have shown that they are in a quasi-amorphous state while Co films are nanocrystalline ones. At the increase in the effective thickness of Fe and Co films from 2 to 10 nm, lines on the electron diffraction patterns become clearer that indicates the coarsening of crystals and transition from quasi-amorphous phase (Fe films) to crystalline. Fe films are single-phase and have the bcc-lattice. In contrast to them, Co films have two-phase state. Two lines (111) and (200) for the fcc-Co phase are fixed on the electron diffraction patterns along with the lines which correspond to the hcp-Co. Reflections, which correspond to the fcc-Co, belong to packing defects of the hcp-Co, since, according to [12], crystallographic correspondence (111) fcc || (100) hcp exists between two Co phases. Single-layer Gd films of the effective thickness from 1 to 10 nm are found to be in amorphous state that agrees with the data of many authors (see, for example, [8, 9, 13]).

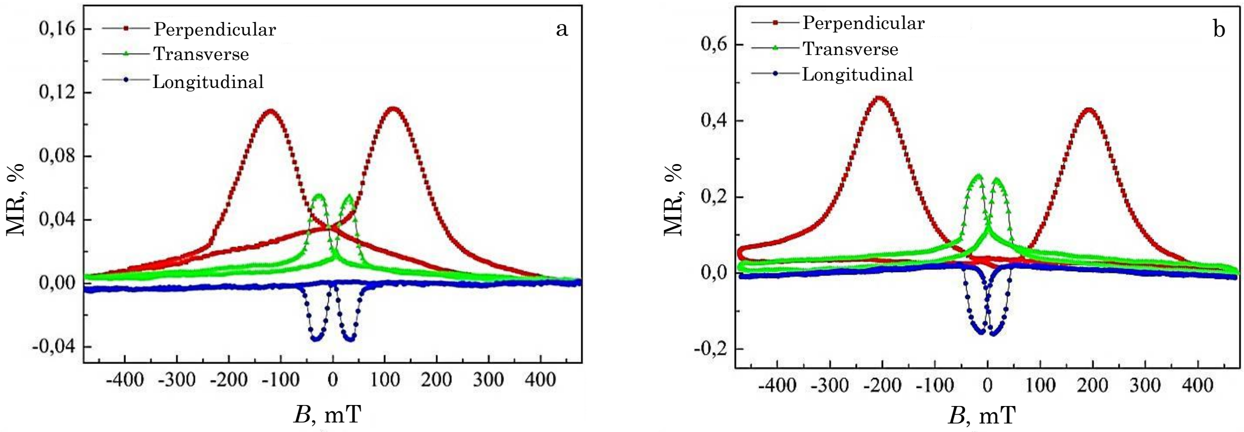

Fig. 1 – Dependence of the MR value on the applied external magnetic field at three measurement geometries for the following film systems: a – Fe(2)/a-Gd(2)/Fe(6)/S; b – Co(10)/a-Gd(1)/Co(10)/S. Thickness in nm is given in brackets

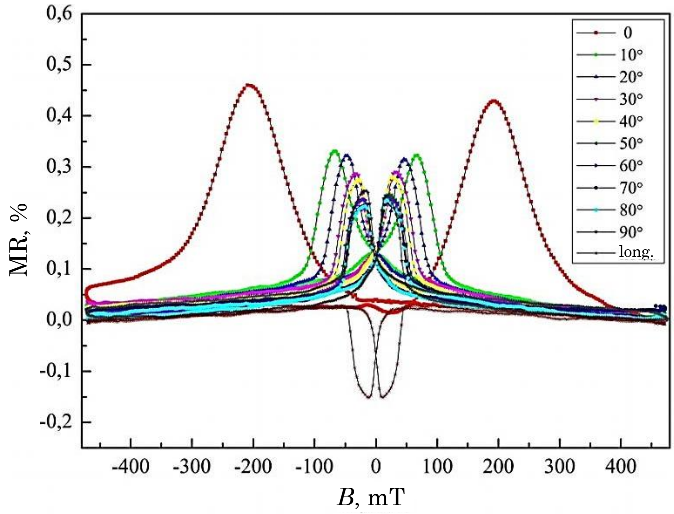

Fig. 2 – Dependence of the MR value on the applied external magnetic field at the transition from the perpendicular to the transverse measurement geometry with the step of 10° and at the longitudinal geometry for Co(10)/a-Gd(1)/Co(10)/S film system

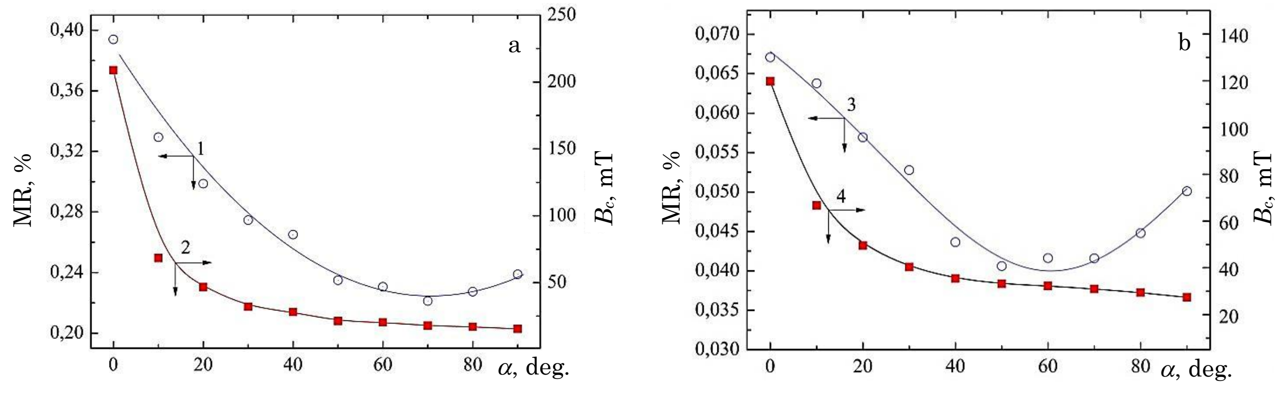

Fig. 3 – Dependences of the MR value (curves 1, 3) and coercivity (curves 2, 4) on the orientation angle of the sample relative to the applied external magnetic field for the following film systems: a – Co(10)/a-Gd(1)/Co(10)/S; b – Fe(2)/a-Gd(2)/Fe(6)/S

Diffraction investigations of three-layer film systems based on Fe(x)/a-Gd(y)/Fe(x)/S and Co(z)/a-Gd(y)/Co(z)/S, where x, y, z are the effective thicknesses of separate layers which do not exceed 10 nm, have shown that they have bcc-Fe + a-Gd and hcp-Co + fcc-Co + a-Gd phase compositions, respectively (a is amorphous).

4. MAGNETORESISTIVE PROPERTIES

Magnetoresistive properties of film systems depend not only on the structural-phase composition, but also on the thicknesses of magnetic layers and sublayers of R metals and measurement geometry.

In Fig. 1 we illustrate the typical family of the field dependences of magnetoresistance (MR) on the example of Fe(2)/a-Gd(2)/Fe(6)/S and Co(10)/a-Gd(1)/Co(10)/S three-layer films. Having analyzed these results, we note the following. Firstly, anisotropic MR is exhibited in the systems irrespective of the thickness of each layer. Secondly, for all samples in the transverse and perpendicular measurement geometries the MR value initially increases with the increase in the value of the external magnetic field induction (B), achieves the maximum at B_c (B_c is the coercivity), and then sharply decreases and becomes saturated (we should note that the value of B_c was determined by the position of the maximum on the field dependences). An inverse tendency is observed at the longitudinal measurement geometry. Thirdly, the maximum value of MR of 0,1% and 0,45%, respectively, for Fe/a-Gd/Fe and Co/a-Gd/Co systems is observed in the perpendicular measurement geometry. At the transition from the perpendicular to the transverse measurement geometry, the value of MR decreases in both cases (Fig. 1) and is equal to 0,045% for a system based on Fe and Gd (Fig. 1a) and 0,25% for a system based on Co and Gd (Fig. 1b).

Such abrupt change in the MR value up to 2 times in the perpendicular geometry relative to the transverse one can be explained by "exclusion" of electric current to ferromagnetic layers because of high resistivity of a-Gd sublayer. Therefore, MR of R/T films, mainly, represents MR of ferromagnetic layers. Taking into account this feature, it is necessary to choose for further investigations and practical application that measurement geometry, in which electrical current through the sample passes perpendicular to the film surfaces, and magnetization is realized in the film planes (perpendicular geometry), since in the case of the transverse and longitudinal measurement geometries there is a possibility to obtain the MR values not of the whole system but only of ferromagnetic layers.

Taking into consideration these circumstances, we have performed the investigation of the influence of the sample orientation change with respect to the external magnetic field on the values of MR and coercivity. This is important from the point of view of the use of the mentioned systems as one of the structural components of microelectronic sensors.

In Fig. 2 we show the dependence of the MR value on the applied external magnetic field at the transition from the perpendicular to the transverse measurement geometry with the step of 10° and at the longitudinal geometry on the example of Co(10)/a-Gd(1)/Co(10)/S film. Based on the obtained results one can note that change in the values of MR and coercivity occurs at the transition from the perpendicular to the transverse measurement geometry. The data represented in Fig. 3 gives the information about typical behavior of the dependences of the MR and coercivity on the sample orientation angle in an external magnetic field.

As seen from this data, dependence of the MR on the angle has two characteristic regions. The value of MR for Co(10)/a-Gd(1)/Co(10)/S film decreases from 0° to 70°, and from 70° to 90° its slight increase is observed. Such tendency of the MR dependence on d is also typical for Fe(2)/a-Gd(2)/Fe(6)/S film, but minimum is more pronounced. In the angle range from 0° to 50° the value of MR decreases 1,5 times and then increases with the increase in the angle up to 90°.

As for the coercivity, its value decreases on the total range of angles at the transition from the perpendicular to the transverse orientation in the case of both systems. Such behavior of the dependences is connected with the transition from the hard to the easy magnetization axis [14, 15]. Thus, the maximum values of both the MR and coercivity are observed at the perpendicular measurement geometry.

Since thickness of non-magnetic sublayers influences the values of MR and coercivity of film systems [16], we have studied the field dependences of the resistance with the change in the thickness of R metal sublayer from 1 to 10 nm at the fixed values of the ferromagnetic layer thicknesses (10 nm). The aforesaid dependences are illustrated in Fig. 4. In Table 1 we present the numerical values of MR and coercivity on the example of Fe/a-Gd/Fe system. As it follows from this data, the values of MR and B_c depending on the thickness of a-Gd layer have oscillating behavior. Such dependence takes place for all measurement geometries. Oscillating dependence on the non-magnetic sublayer thickness similar to the given in Table 1 was firstly observed in the investigation of the giant MR in the work [17]. The authors of [17] explain such behavior of the dependence of the MR by an oscillating dependence of the exchange interaction between magnetic layers through conduction electrons.

Thickness of ferromagnetic layer also has an important influence on the values of MR and B_c. Therefore, we have studied the influence of the thickness of the ferromagnetic upper layer on the values of MR and coercivity in Co(x)/a-Gd(3)/Co(5)/S and Fe(x)/a-Gd(3)/Fe(3)/S systems, where x is the effective thickness varied from 1 to 5 nm with the step of 1 nm. Results of the stated investigations are represented in Fig. 5.

Analysis of these dependences shows that the values of MR (Fig. 5, curves 1, 3) and coercivity (Fig. 5, curves 2, 4) have damped oscillatory behavior at the increase in the effective thickness of the ferromagnetic upper layer. Comparing the data for film systems based on Fe and Gd and Co and Gd, one can indicate that in whole the values of minimums and maximums are observed at different values of Fe and Co layer thickness. We note the fact that in Fe/a-Gd/Fe system in the latter case the value of MR is larger than for Co/a-Gd/Co system, though above we have shown (see Fig. 3 and Fig. 4) that the reverse tendency takes place. Such result can be connected with the oxidation processes mainly in the upper Fe layer of the effective thickness not less than 5 nm. Though the presence of the oxide phase is not always fixed by the electron-diffraction method, its presence can induce the MR increase. Both our data and the data of other authors (see, for example, the works [18, 19]) imply this fact. Obviously that concentration of the oxide phase in the films of less thickness is larger. One cannot exclude the fact that structural state of Fe layers, namely, the presence of amorphous phase, also influences the MR value in the given case.

Higher value of resistivity is typical for amorphous phase than for crystalline one [20]. Therefore, resistivity of the whole system increases. In this case, shunting does not occur when electrical current passes through the sample, as a result, a larger value of MR is observed.

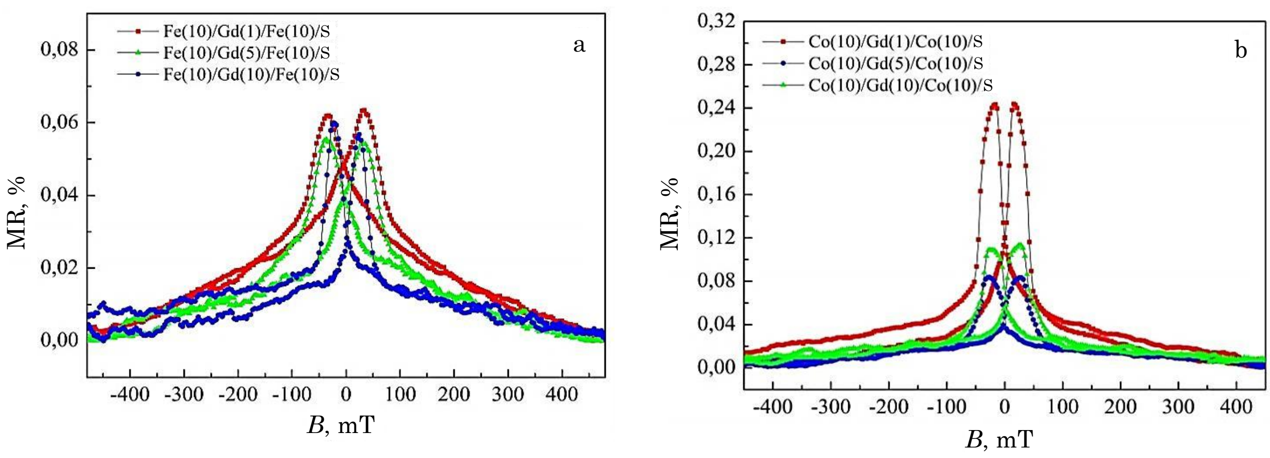

Fig. 4 – Dependence of the MR value on the a-Gd sublayer for systems: a – Fe(10)/a-Gd(n)/Fe(10)/S, b – Co(10)/a-Gd(n)/Co(10)/S

Table 1 – Dependence of the MR value and coercivity on the a-Gd sublayer for Fe(10)/a-Gd(n)/Fe(10)/S system

d_{Gd}, nm	1,2	2,2	3	3,5	4	5	6	7	8,3	9	10
MR, %	0,061	0,076	0,069	0,049	0,053	0,056	0,045	0,062	0,063	0,048	0,058
B_c, mT	25,988	32,44	32,77	18,04	26,09	35,73	25,37	25,86	29,51	21,20	32,04

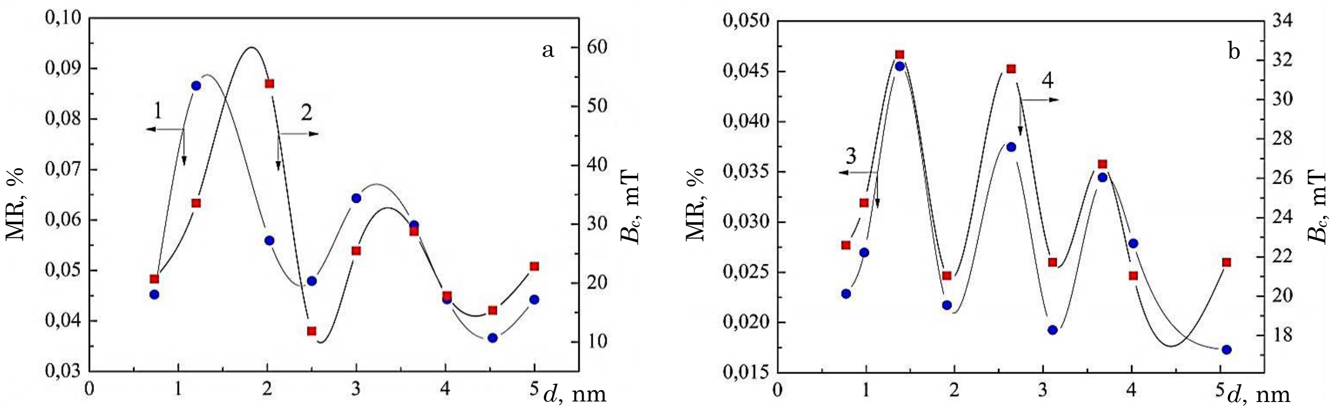

Fig. 5 – Dependences of the MR value (curves 1, 3) and coercivity (curves 2, 4) on the thickness of the upper Fe and Co layer for Fe(n)/a-Gd(3)/Fe(5)/S and Co(n)/a-Gd(3)/Co(5)/S (where n is the effective thickness of Fe and Co) systems, respectively

5. CONCLUSIONS

Thus, on the ground of the results of this work we can conclude the following.

1. Three-layer systems based on Fe and Gd and Co and Gd obtained at $T_s \cong 460$ K have the bcc-Fe + a-Gd and hcp-Co + fcc-Co + a-Gd phase compositions.

2. The maximum value of MR is observed in the perpendicular measurement geometry and is equal to 0,1% for Fe/a-Gd/Fe/S and 0,5% for Co/a-Gd/Co/S films. At the transition from the perpendicular to the transverse orientation of the sample in an external magnetic field the MR value decreases in the range from 0° to 50°-70° (depending on the system type and effective layer thicknesses) and then increases, while the coercivity value in these systems decreases at the transition from the perpendicular to the transverse measurement geometry.

3. The values of MR and coercivity have oscillatory behavior at the change in the effective thickness of R metal sublayer and upper ferromagnetic layer.

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