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INFLUENCE OF *f-d* EXCHANGE INTERACTION ON THE PROPERTIES OF NANOSCALE STRUCTURES BASED ON Fe, Co, Ni METALS AND REM OXIDES. A REVIEW

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A review of the works of the authors published in the period 2009–2022 and devoted to the study of the properties of nanosized structures containing contacting layers of Fe, Co, Ni, Fe_2O_3 / REM (Rare Earth Metal) oxide is carried out. The technology for the creation and structural features of these nanostructures are also considered. Physicochemical phenomena in the interface of contacting layers are very multidisciplinary. This is a consequence of their dependence on various conditions, primarily on the modes of technologies for their production and the properties of the initial components. The problem becomes much more complicated when studying magnetic nanostructures. To study effectively the properties of layered nanostructures containing ferromagnetic films, we used magnetic research methods. Using the EPR method, it has been found that between atoms with unfilled f- and d-electron sub-shells, which are part of the contacting layers, an f-d exchange interaction occurs, which orders the magnetic structure of the ferromagnetic layers. Using the method of the anomalous Hall effect, it is shown that the ordering of the magnetic structure leads to an increase in their magnetization. The enhancement of the galvanomagnetic properties in the Fe_3O_4/REM oxide/Fe_3O_4 structures shows that the exchange interaction can have both f-d and d-d character. And this, in turn, leads to an increase in magnetization-dependent properties, such as galvanomagnetic, magneto-optical, and current-voltage properties. This can be used in nanotechnologies to enhance the above properties without energy consumption and the use of amplifying equipment.

Keywords*: f-d interaction, thin-films structures, EPR, anomalous Hall effect, magnetic properties*

INTRODUCTION

The exchange *f-d* interaction between atoms of transition elements with unfilled *f*- and *d*-electron sub-shells has long attracted the attention of researchers because it can significantly affect the properties of a substance [1]. Thus, in bulk samples of $RFeO_3$ orthoferrites and $R_3Fe_5O_{12}$ ferrite garnets (R-Rare-earth metal - REM), it leads to the emergence of unique magneto-optical properties that make it possible to use these materials to control laser radiation in switching devices [2, 3]. In thin-films structures based on contacting layers of *f*- and *d*-metals, the possibility of artificial formation of a magnetic structure, magnetic anisotropy and magneto-striction arises [4].

Recently, we found that in nanoscale structures consisting of contacting layers based on *d*-metals of the iron group Fe, Co, Ni and oxides of *f*-rare-earth metals, the *f-d* exchange interaction also occurs [5]. This interaction leads to the ordering of the magnetic structure of *d*-metals, an increase in their magnetization [6], and an increase in the properties of ferromagnetic layers that depend on it, such as galvanomagnetic [7], magneto-optical [8], and current-voltage [9]. Similar phenomena are observed both in Fe, Co, Ni/REM oxide structures containing layers of pure metals, and in Fe_3O_4/REM oxide structures based on layers of semimetal magnetite Fe_3O_4 [10–12]. In the world literature, information on the study of the properties of these nanosized structures is limited to only a few articles [13–16]. Therefore, the consequential set of results is undoubtedly of scientific and practical interest.

This article provides a review based on the results of studies conducted in the period 2009–2022, with nanosized structures of Fe, Co, Ni, Fe_3O_4 / REM oxide. The technology of their creation, structural features, the causes of the exchange *f-d* interaction between the contacting layers, its influence on the properties of these structures are considered.

CREATION TECHNOLOGY AND STRUCTURAL FEATURES

Nanoscale structures of Fe, Co, Ni, Fe_3O_4 / REM oxide were created by successive

deposition of metal or oxide layers on the substrate by electron beam evaporation in vacuum. Moreover, to create an oxide in the process of metal evaporation, oxygen was admitted into the working chamber. The metal layer deposition conditions were, on average, as follows: $p = 5 \cdot 10^{-3}$ Pa, $v = 10 \div 50$ nm/min, $t = 25$ and 250 °C; REM oxide layers $p_{O_2} = 2 \cdot 10^{-2}$ Pa, $v = 10 \div 50$ nm/min, $t = 25$ °C. The high temperature (250 °C) of deposition of the first metal layer ensured good adhesion of this layer and the entire structure to the substrate. The low temperature of Ni/Y_2O_3 layers deposition protected them from possible chemical interaction with each other. This makes it possible to create multilayer films from alternating Ni/Y_2O_3 layers. Fused quartz and glass were used as a transparent substrate. Sitall was used as the opaque substrate.

The thickness of deposited layers was controlled by the optical method.

In accordance with the results of X-ray diffraction and electron diffraction analysis, the structure of Fe, Co, Ni, and Fe_3O_4 metal films deposited at 250 and 25 °C was polycrystalline. The structure of the layers of REM oxides deposited at room temperature is amorphous, since, according to [17], the crystallization of most of these films begins at higher temperatures (80–250 °C).

According to [18], there is a mutual influence of the structure of two- and multilayer films of Fe, Co, Ni / REM oxide, caused by the difference in the parameters of their crystal lattices.

It was shown in [19] that, in Ni (4–150 nm) / Y_2O_3 (10–200 nm) films, the Ni layers have an island structure at a small thickness. The shape of Ni clusters is rounded. Some of the clusters touch each other forming chains of 2 and 3 particles (Fig. 1).

The distribution of Ni clusters is close to normal. Coalescence of Ni clusters begins at a Ni film thickness of (23–30 nm), which is accompanied by a sharp drop in the resistivity of Ni/Y_2O_3 films. With an increase in the number of layers in these films, the resistivity increases linearly dependent on their number.

The absence of nickel wetting of the Y_2O_3 surface, the interaction with Y_2O_3 with the formation of Ni oxides, and the dissolution of Ni in Y_2O_3 were noted.

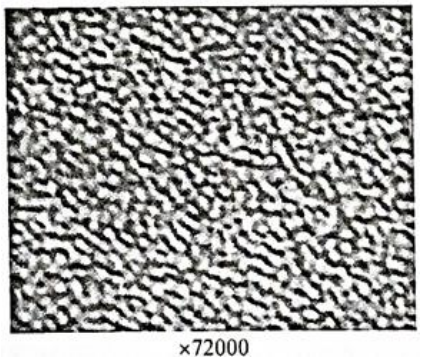


Fig. 1. Electron microscopic image of nickel island film 13 nm thick

In multilayer films, there is a decrease in the lattice period Ni from 0.355 to 0.345 nm with a decrease in their thickness from 25 to 4 nm. A similar decrease in the lattice period of the Y_2O_3 layers can be explained by Laplace compression.

It has been shown that the application of a magnetic field with an inductance of 30 mT to a growing Ni/Y_2O_3 film strongly affects its structure and morphology [20]:

— The temperature of crystallization of clusters Ni decreases by 100 K. At the same time, the Y_2O_3 layers remain amorphous.

— Compression voltages arise in the crystal lattice of Ni clusters, which increase with an increase in the number of layers in the Ni/Y_2O_3 films. These voltages lead to a decrease in the lattice constant and the size of the blocks of coherent scattering of clusters Ni.

— In Y_2O_3 layers, on the contrary, tension is observed. In this case, a corrugated surface is formed in the Ni/Y_2O_3 film freely suspended on the grid.

— Clusters Ni have an ellipsoidal shape. In the direction of the minor axis of the ellipse, the size distribution of clusters is close to the distribution of clusters Ni grown without a field. In the direction of the major axis, the distribution is strongly shifted to the region of large sizes, with a maximum close in value to the thickness of the layers Ni (5 nm).

— In the direction of the principal axis of the ellipse, the Ni clusters coalesce into chains with length longer than in Ni/Y_2O_3 films grown without a field. The presence of the prevailing direction of cluster growth Ni, however, does not lead to the formation of a texture.

The observed features of the Ni/Y_2O_3 films grown in a magnetic field are explained from the standpoint of the orientation of the magnetic

moments of Ni clusters by the field and the resulting mutual repulsion of these clusters and their merging in the direction of the field.

EXCHANGE *f-d* INTERACTION AND ITS INFLUENCE ON THE MAGNETIZATION OF FERROMAGNETIC LAYERS IN Fe, Co Ni / REM OXIDE NANOSCALE STRUCTURES

The *f-d* exchange interaction arises when atoms with unfilled *f*- and *d*-electron sub-shells approach to a sufficiently close distance of 1÷2 Å. In this case, the spin and orbital moments of electrons interact on these sub-shells. In the case of the presence of an oxygen atom between the *f*- and *d*- ions, the *f-d* exchange interaction can be carried out with its participation, as, for example, it occurs in $R_3Fe_5O_{12}$ ferrite garnets [2].

One of the methods sensitive to the state and interaction of electrons in a substance is electron paramagnetic resonance (EPR) [21]. Here, the intensity of the interelectronic interaction can be estimated from the value of the exchange interaction parameter *P* equal to

$$P = \mu_B W H_R , \quad (1)$$

where μ_B – Bohr magneton, W – EPR spectrum width, H_R – resonance magnetic field.

It was shown in [5] that the deposition of a Fe layer (112 nm) on a Gd_2O_3 layer (68 nm) with the formation of a Gd_2O_3 / Fe two-layer structure leads to a significant change in the EPR spectra of individual Gd_2O_3 and Fe layers (Fig. 2).

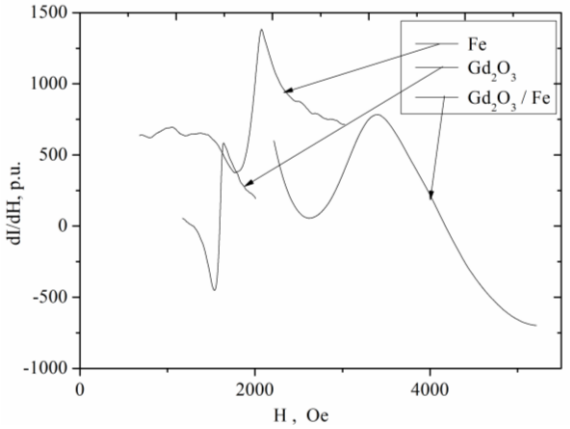


Fig. 2. EPR spectra of Fe, Gd_2O_3 and Gd_2O_3/Fe films

Changes in the parameters of the objects under study, determined from the EPR spectra, are presented in Table.

Table. Parameters of the objects under study determined from the EPR spectra

Parameter	Gd_2O_3	Fe	Structure Gd_2O_3/Fe
Resonance magnetic field H_R, Oe	1604	1986	2862
EPR line width W, Oe	296	496	1637
Exchange interaction parameter P, rel. units	474	985	4685
g-factor	4.4	3.5	2.4

The Lande multiplier or g factor determines the relative value of the magnetomechanical ratio and is equal to

$$g = \frac{h\nu}{\mu_B H_R} , \quad (2)$$

Where ν – resonator frequency, h – Planck's constant.

Significant changes in the g-factor and the exchange interaction parameter *P* for the Gd_2O_3 / Fe structure compared to individual Gd_2O_3 and Fe layers indicate the probability of a strong *f-d* exchange interaction between them.

The effect of *f-d* exchange interaction on the magnetization force of ferromagnetic layers in Fe, Co, Ni / REM oxide structures was demonstrated in [6] using the example of a two-layer structure Ni (70 nm) / Gd_2O_3 (40–160 nm). Here, using the anomalous Hall effect, which is sensitive to the magnetization of the layers, it was shown that when a Gd_2O_3 layer is deposited on a Ni film, with an increase in the thickness of this oxide layer in the range (40–160 nm), an increase in the Hall potential V is observed in the process of its dependence on the strength of the external magnetic fields H (Fig. 3).

The mathematical apparatus developed in [6] makes it possible to relate the observed change in the Hall potential with the magnitude of the magnetization $M_{f\text{-}d}$ of the Ni layer, which arises due to the exchange *f-d* interaction.

$$V_2 - V_1 = \pm \frac{R_S \cdot M_{f-d}}{d} I \ , \qquad (3)$$

where V_1 and V_2 – Hall potential of the Ni layer before and after the deposition of the Gd_2O_3 layer on it, R_S – the coefficient of the anomalous Hall effect, d – the thickness of the Ni layer, and I – the current flowing through the Ni film.

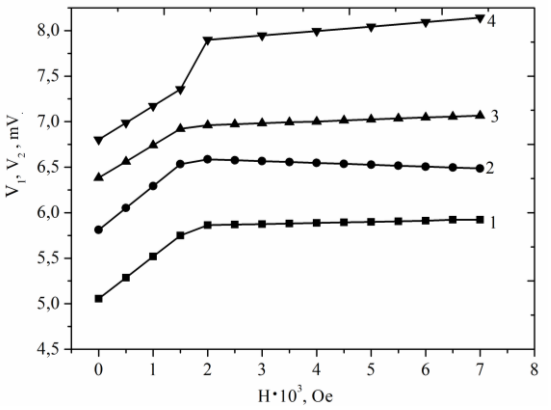


Fig. 3. Dependence of V_1 on the strength of the external magnetic field H in the Ni layer (70 nm) – *1*, and V_2 in Ni/Gd_2O_3 structures with a Gd_2O_3 layer thickness of 40 nm – *2*, 100 nm – *3*, 160 nm – *4*

It follows from Figure 3 that an increase in the thickness of the Gd_2O_3 layer from 40 to 160 nm leads to an increase in the Hall potential, and hence the magnetization M_{f-d}, by 15–35 %, respectively. That is, the value is due to the ratio of the thickness M_{f-d} of the Ni and Gd_2O_3 layers.

It was also shown in [6] that in the case of equal thicknesses of the Ni and Gd_2O_3 layers, when the number of atoms entering into the *f-d* exchange interaction in both layers is approximately the same, the external magnetic field is unable to influence the value of M_{f-d}. In the case when there are more *d*-atoms in the Ni layer than there are *f*-atoms in the Gd_2O_3 layer, then the *d*-atoms not involved in the *f-d* interaction can take part in the formation of the ferromagnetic structure of this layer, and the magnetic field, enhancing such formation, prevents the *f-d* interaction , decreasing M_{f-d}. In the case of the predominance of *f*-atoms in the Gd_2O_3 layer, the magnetic field, on the contrary, stimulates their involvement in the *f-d* interaction, causing an increase in M_{f-d}. Thus, the mechanism of the influence of the magnetic field on the value of M_{f-d} becomes clear.

It was also found that the vector $\overrightarrow{M}_{f-d}$ is directed from the Gd_2O_3 layer to the Ni layer.

INFLUENCE OF *f-d* EXCHANGE INTERACTION ON THE PROPERTIES OF Fe, Co, Ni/ REM OXIDE NANOSCALE STRUCTURES

The effect of the *f-d* exchange interaction on the galvanomagnetic properties of nanosized structures was demonstrated in [7]. It was shown that the formation of a two-layer structure Fe (80 nm) / Dy_2O_3 (140 nm) increases the magnetoresistance $\frac{\Delta\rho}{\rho_0}$ of a ferromagnetic metal by a factor of 1.6 (Fig. 4).

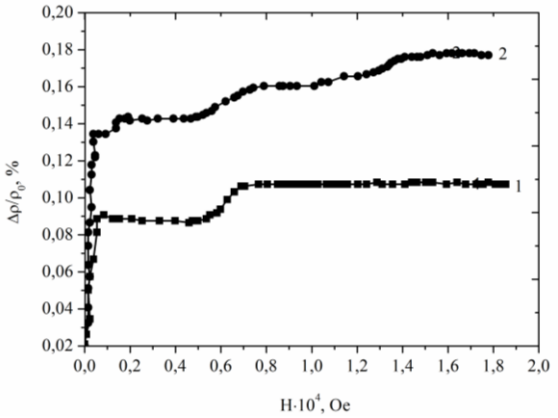


Fig. 4. Magnetoresistance of the Fe film (*1*) and the two-layer structure Fe/Dy_2O_3 (*2*) depending on the magnetic field strength H at $\vec{H} \| \vec{i}$

Taking into account the known relationship between the magnetoresistance $\frac{\Delta\rho}{\rho_0}$ and the magnetization M of a ferromagnet [1]

$$\frac{\Delta\rho}{\rho_0} = \alpha M^2 \ , \qquad (4)$$

where α – coefficient of proportionality, it can be stated that the formation of the Fe/Dy_2O_3 structure is accompanied by an increase in the magnetization and, therefore, in the magnetoresistance of the Fe layer.

It was also shown that with an increase in the effective magnetic moment μ of atoms, that is, according to the theory [2], with an increase $\frac{\Delta\rho}{\rho_0}$ in the *f-d* interaction energy, the structures of Fe/La_2O_3, Eu_2O_3, Tb_2O_3, Dy_2O_3 increase (Fig. 5)

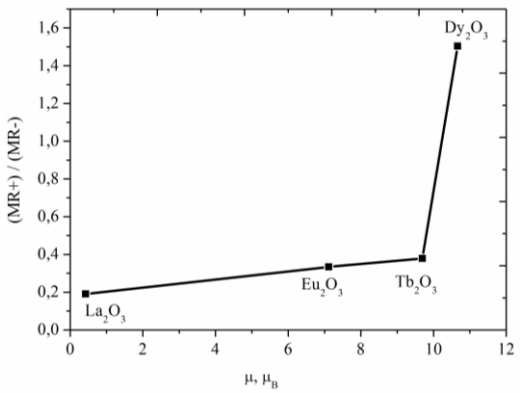


Fig. 5. Magnetoresistance of a Fe film with an oxide coating of REM (MR+) and without an oxide coating of REM (MR-) as dependent on the effective magnetic moment of these oxides; $H = 6 \cdot 10^3$ *Oe*

With growth μ, the magnetoresistance of Fe, Ni, Co / Dy_2O_3 structures also increases (Fig. 6).

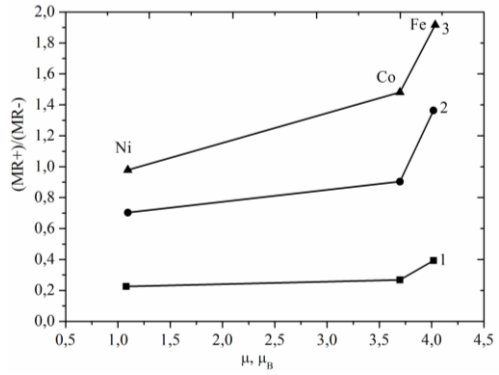


Fig. 6. Ratio (MR+)/(MR-) for Fe, Co and Ni films coated with Dy_2O_3 with a thickness of 30 (*1*), 100 (*2*) and 140 (*3*) nm dependent on the effective magnetic moment of these metals; $H = 6 \cdot 10^3$ *Oe*

Thus, Figs. 5 and 6 are direct evidence of the dependence of the magnitude of the magnetoresistance and the magnetization of the ferromagnet layers in the structures of Fe, Co, Ni / REM oxide on the energy of the exchange *f-d* interaction.

In the Fe/Tb_2O_3 thin-film structure, the *f-d* exchange interaction leads to an increase in the Faraday effect [8], which reaches a maximum at a Tb_2O_3 layer thickness of 40 nm (Fig. 7).

To find this dependence, a mathematical separation of the influence of interference and *f-d* interaction of layers on the Faraday effect was carried out. It has been found that the highest intensification obtained for the Tb_2O_3 / Fe structure is ~ 2 times, and the highest specific Faraday angle is $\varphi_F = 1.8 \cdot 10^6$ deg/cm. The enhancement increases with an increase in the thickness of the Fe layer from 40 to 120 nm and disappears at a thickness of 30 nm or less. The enhancement of the Faraday effect is ensured by both the action of only spontaneous and the combined influence of spontaneous and induced magnetizations of the Fe film.

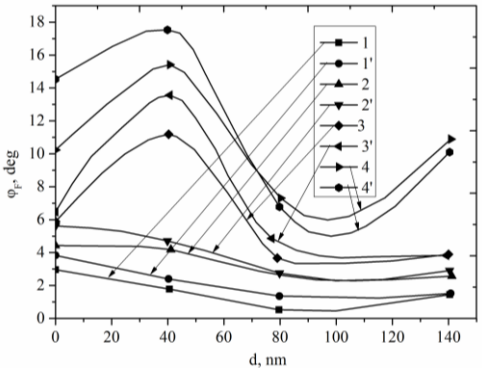


Fig. 7. Dependence of the Faraday angle on the thickness *d* of the Tb_2O_3 layer in the Tb_2O_3/Fe structures in the absence (*1*–*4*) and under the action (*1'*–*4'*) of an external magnetic field of 600 Oe for different thicknesses of the Fe film: (*1*, *1'*) 30 nm, (*2*, *2'*) 40 nm, (*3*, *3'*) 65 nm, (*4*, *4'*) 120 nm

The spectral dependence of the Faraday effect in Fe (30 and 120 nm) / Tb_2O_3 (140 nm) nanostructures was considered in [22]. The spectral dependence of the Faraday effect in the visible region (0.4–0.5 μm) has a parabolic character $\varphi_F \sim \lambda^2$ both at a small thickness of the Fe layer (30 nm), when the influence of light interference is significant, and at a greater thickness of the metal layer (120 nm) when this effect is weak (Fig. 8),

It was shown in [9] that the *f-d* exchange interaction leads to an increase in current-voltage characteristics (CVC) of metal-insulator-metal (MIM) structures. Using the example of thin-film structures of Fe, Co, Ni / Tb_2O_3 / Fe, Co, Ni, it was found that the exchange *f-d* interaction significantly reduces the height of the potential barrier for the transfer of charges between the electrodes and increases the current flowing through the MIM structure. Under the conditions of the over-barrier mechanism of Schottky charge transfer, the magnitude of the force F_{f-d} and energy ε_{f-d} of the *f-d* interaction on the motion of an electron in an MIM structure is determined.

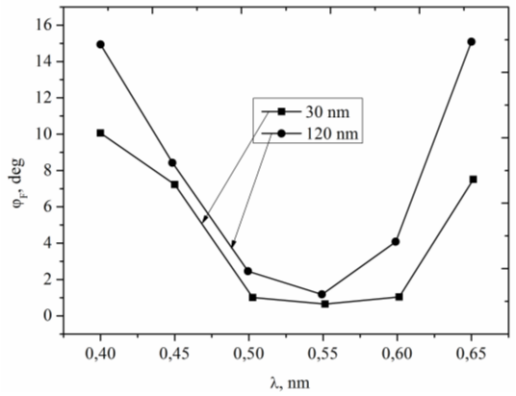


Fig. 8. Dependence of the Faraday angle φ_F of the Tb_2O_3/Fe structures on the light wavelength λ for Fe thicknesses of 30 and 120 nm. The strength of the external magnetic field is 700 Oe

An increase in temperature reduces the effect of the *f-d* interaction on the CVC of the MIM structures (Fig. 9).

At the same time, an external magnetic field enhances this effect (Fig. 10).

This may be due to the influence of these factors on the ordering of the arrangement of the magnetic moments of the atoms of the transition elements in the region of the *f-d* interaction.

The dependence of ε_{f-d} on temperature and magnetic field strength, calculated for the charge transfer through the boundary of Fe, Co, Ni / Tb_2O_3 structure at the distance of 3 Å from the ferromagnet, has the same character as for the transition through the MIM structure [23, 24].

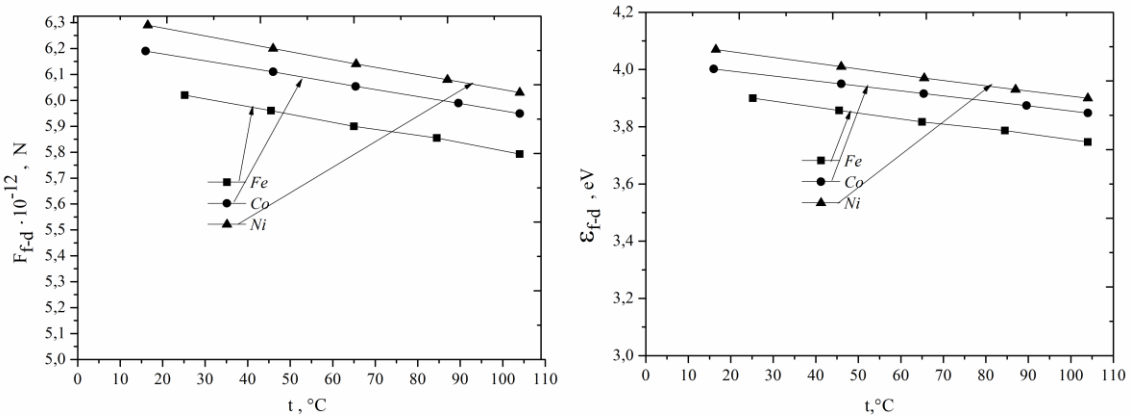


Fig. 9. Dependence F_{f-d} (*a*) and ε_{f-d} (*b*) on the temperature of MIM structures

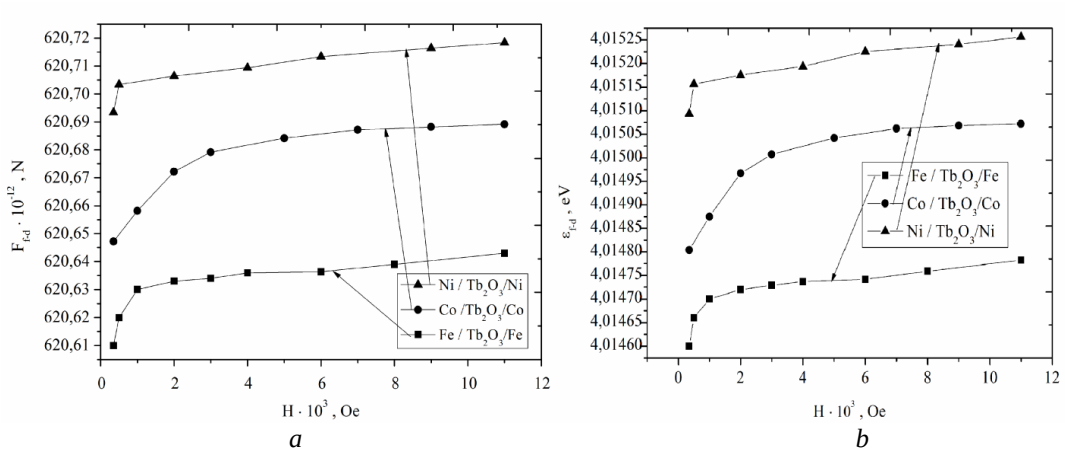


Fig. 10. Dependence F_{f-d} (*a*) and ε_{f-d} (*b*) on the strength of the external magnetic field *H*

The electrical and galvanomagnetic properties of Ni/Y_2O_3 multilayer structures were studied in [19]. The resistivity of multilayer structures increased linearly with an increase in the number of layers (Fig. 11).

The conduction mechanism of the structures corresponded to the hopping mechanism, as evidenced by the temperature dependence $\rho(T)$:

$$\log \rho = A \cdot T^{-\frac{1}{4}} . \quad (5)$$

The magnetoresistance increased with an increase in the number of layers, reaching 50% in the 30-layer Ni (5 nm) / Y_2O_3 (10 nm) structure (Fig. 12).

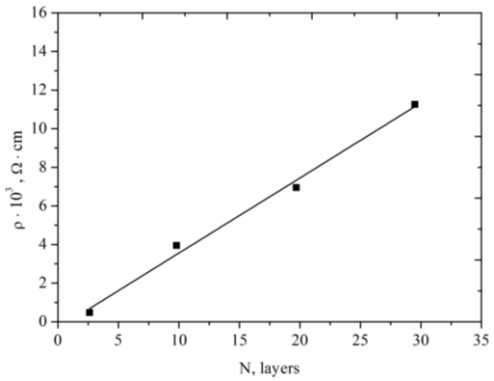


Fig. 11. The dependence of the resistivity of the multilayer system on the number of Y_2O_3-Ni layers at direct current

The frequency dependence of the resistivity $\rho(f)$ and $\varepsilon(f)$ permittivity of Ni/Y_2O_3 multilayer structures is close to that in two-layer structures (Fig. 13).

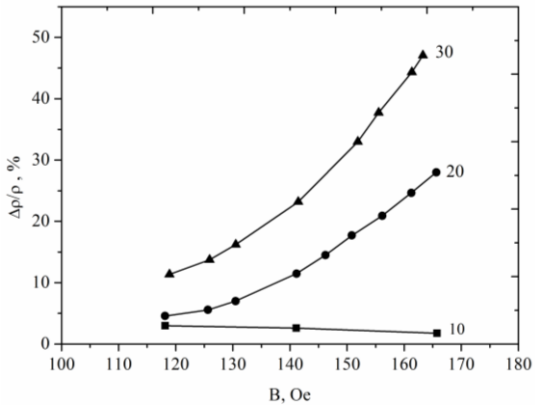
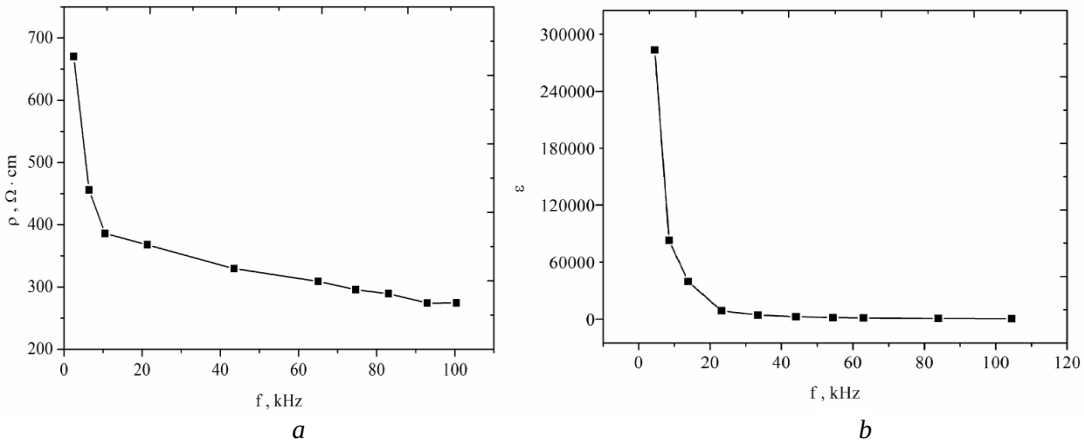


Fig. 12. Dependence of magnetoresistance on magnetic field for Y_2O_3-Ni multilayer films

It was shown that the possibility of influencing the properties of nanofilms, Fe, Co, Ni / REM oxide by reasons alternative to *f-d* interaction, such as the difference in structures [18], magnetic characteristics and conductivity of layers [6], surface magnetic vacancies [25, 26, 27], is much lower than the effect of the *f-d* interaction itself.



a *b*

Fig. 13. Frequency dependence of resistivity (*a*) and permittivity (*b*) of the Y_2O_3-Ni multilayer system

EFFECT OF *f-d* EXCHANGE INTERACTION ON THE PROPERTIES OF Fe_3O_4 / REM. OXIDE NANOSCALE STRUCTURES

Magnetite Fe_3O_4 has a number of remarkable features: it is a ferromagnet with a high Curie temperature of 858 K, belongs to semimetals with a theoretically achievable 100 % polarization of electron spins at the Fermi level. It is suitable for the manufacture of both bulk and nanosized products, due to the high manufacturability of processing.

Magnetite is especially attractive for applications in nanotechnology, for the manufacture of tunnel magnetoresistances (TMR) used for reading and writing heads, memory elements, and displacement sensors.

The TMR effect, discovered in 1975 [28], consists in the difference in resistance for electron transfer between two ferromagnet films separated by a thin layer of non-magnetic material for the cases of their parallel and antiparallel magnetization, since in the latter case energy is required to rotate the electron spin. The formula describing the value of TMR in this case has the form [29]:

$$TMR = \frac{R^{\uparrow\downarrow} - R^{\uparrow\uparrow}}{R^{\uparrow\downarrow}} = \frac{P_1 P_2}{1 - P_1 P_2}\ , \qquad (6)$$

where P_1 and P_2 are the values of the spin polarization in the first and second layers of the ferromagnet, $R^{\uparrow\uparrow}$ and $R^{\uparrow\downarrow}$ – resistance of the three-layer structure with parallel and antiparallel magnetization of the ferromagnetic layers. It can be seen from formula (6) that in the case when the polarization of electron spins is 100 %, as in Fe_3O_4, ($P_1 = P_2 = 1$) is the value of $TMR \to \infty$, which is attractive for nano-technologies, primarily for spintronics.

In practice, due to the presence of a large number of defects in Fe_3O_4 films, especially in the surface region, which violate the polarization $P = 100\%$ of electron spins, the value turns out to be unattainable. Therefore, the ordering of the magnetic structure of the surface of magnetite films due to the *f-d* interaction during their contact with REM oxide gives a chance to increase the value and achieve high values of TMR. In order to elucidate this possibility, a number of studies were undertaken to develop a technology for creating and studying the properties of films and structures based on Fe_3O_4 / REM oxide contacts.

The optimal technology for the deposition of thin Fe_3O_4 films was developed in [30]. For films of stoichiometric composition deposited by electron-beam evaporation of Fe in the presence of oxygen, such conditions are: film growth rate (5–50) nm/min, oxygen partial pressure ($5\cdot10^{-4} – 2\cdot10^{-3}$) Pa, substrate temperature (25–200) °C. The films were polycrystalline and had an $O_h^7 - Fd3m$ cubic structure with a lattice constant a = 0.843 nm. It was also shown that the structural, electrical, and optical properties of the obtained Fe_3O_4 films are close to those of bulk magnetite samples.

TMR in the Fe_3O_4 / REM oxide / Fe_3O_4 structures was studied according to the scheme shown in Fig. 14 [31].

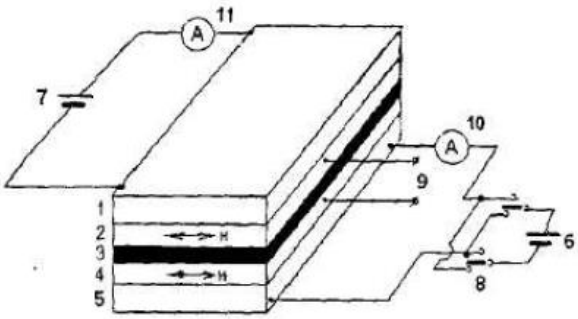


Fig. 14. Scheme for measuring the transverse resistance of the nanostructure Fe_3O_4 / REM oxide / Fe_3O_4: *1*, *5* – Cu-electrodes; *2*, *4* – Fe_3O_4 layers; *3* – interlayer Y_2O_3; *6*, *7* – DC voltage sources; *8* – switch; *9* - ohmmeter; *10*, *11* – ammeters

Here, the structure 2–4 is enclosed between two copper film electrodes 1, 5, through which a direct current passes, excited by constant voltage sources 6, 7. Switch 8 makes it possible to pass current through in the same or in opposite directions. The current passing through the Cu electrodes excites a transverse magnetic field in the Fe_3O_4 layers adjacent to them, respectively, with antiparallel and parallel directions of the strength vectors. Ohmmeter 9 measures the transverse resistance of the Fe_3O_4 / REM oxide / Fe_3O_4 structure with parallel $R^{\uparrow\uparrow}$ and antiparallel $R^{\uparrow\downarrow}$ spin polarization, which is set in the Fe_3O_4 layers by a magnetic field. The obtained values of $R^{\uparrow\uparrow}$ and $R^{\uparrow\downarrow}$ were used to determine by formula (6) the magnitude of the magnetoresistance and the spin polarization *P*.

The proof of the possibility of controlling the magnetization of the Fe_3O_4 layers using currents flowing through the adjacent Cu electrodes was carried out by the magneto-optical method. It was shown in [32] that Fe_3O_4 thin films have a strong Faraday effect, at which the specific angle of rotation of the light polarization plane reaches a significant value $1.8\cdot10^6$ deg/cm. Taking advantage of this fact it was found in [33] that the passage of a direct current through the transparent conductive SnO_2 layer adjacent to Fe_3O_4, which generates a magnetic field that affects magnetite, leads to the observation of the Faraday effect in it. Thus, it was confirmed that in the scheme in Fig. 14, the passage of current through Cu electrodes can be used to control the magnetization and polarization of electron spins in Fe_3O_4 layers.

When studying magnetoresistance using the circuit shown in Fig. 14 [31], it was found that

with an increase in the current in Cu electrodes, that is, with an increase in the strength of the magnetic field created by them, an increase occurs in both the polarization of electron spins in Fe_3O_4 layers and, respectively, the magnitude of the magnetoresistance of the structure Fe_3O_4 / REM oxide / Fe_3O_4 (Fig. 15 *a*).

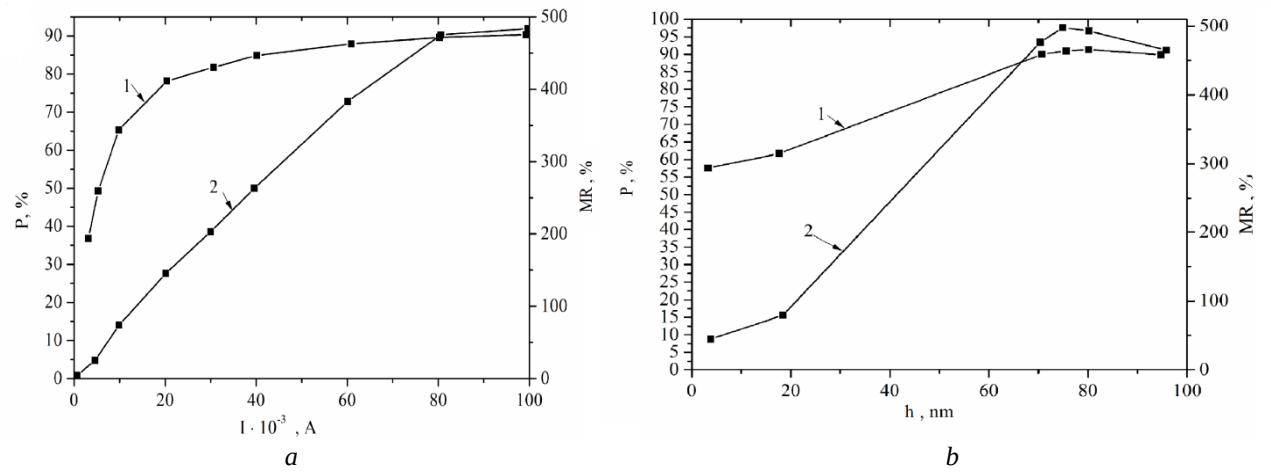


Fig. 15. Dependence of polarization *P* (*1*) of electron spins in Fe_3O_4 layers and magnetoresistance MR (*2*) of the Fe_3O_4 / REM oxide / Fe_3O_4 structure on the magnitude of the exciting current (*a*) and on the thickness of the REM oxide layer (*b*). I = 0.1 A

At the same time, with an increase in the thickness h of the REM (Y_2O_3) oxide layer from 3 nm, when the transfer of electrons between Fe_3O_4 layers is carried out by tunneling, and up to 100 nm, when the transfer occurs using other mechanisms (over-barrier Schottky transition; current limited by space charge), an increase in *P* and magnetoresistance is also observed (Fig. 15 *b*). The lower value of *P* and MR during tunneling is apparently due, firstly, to the fact that, in the case of a thin layer (3 nm) of REM oxide, the magnetic fields created by the current in the Cu electrodes and on the neighboring Fe_3O_4 layers are partially affected.

Fig. 16 shows the dependence of the polarization *P* of electron spins and the tunneling magnetoresistance of the TMR of Fe_3O_4 / REM oxide / Fe_3O_4 structures on the effective magnetic moment μ of REM ions [10], *i.e.*, according to [2], on the energy of the exchange interaction between iron ions in magnetite and REM ions.

As can be seen from this figure, with an increase μ in and the energy of the exchange interaction, which contributes to the ordering of the magnetic structure of Fe_3O_4, the value of *P*, and with it, TMR also increases. This is direct evidence of the connection between the exchange interaction between Fe_3O_4 layers and REM oxides and the properties of related nanostructures.

A similar dependence of *P* of electron spins and tunneling magnetoimpedance TMZ on μ of REM ions in the Fe_3O_4 / REM oxide / Fe_3O_4 structures during their operation on alternating current is shown in Fig. 17 [10].

This shows that the ordering of the magnetic structure of the Fe_3O_4 layers and the enhancement of *P* and TMZ due to the exchange interaction between the layers also manifests itself under an conditions. However, the frequency dependence of *P* and TMZ passes through a series of extremes caused by the inertia of the remagnetization of the Fe_3O_4 layers and the loss of synchronism with the current phase (Fig. 18).

The depth of penetration into the REM oxide layer of the region of magnetic interaction of the ions of these metals with iron ions can be estimated from the saturation of the *P*(*h*) and MR(*h*) plots, where *h* is the REM layer thickness. Such an assessment showed that the penetration depth increases from 36 nm for Y_2O_3 to 120 nm for Tb_2O_3, that is, it increases with an increase in the magnetic moment of REM ions or with an increase in the energy of the exchange interaction between REM and iron ions.

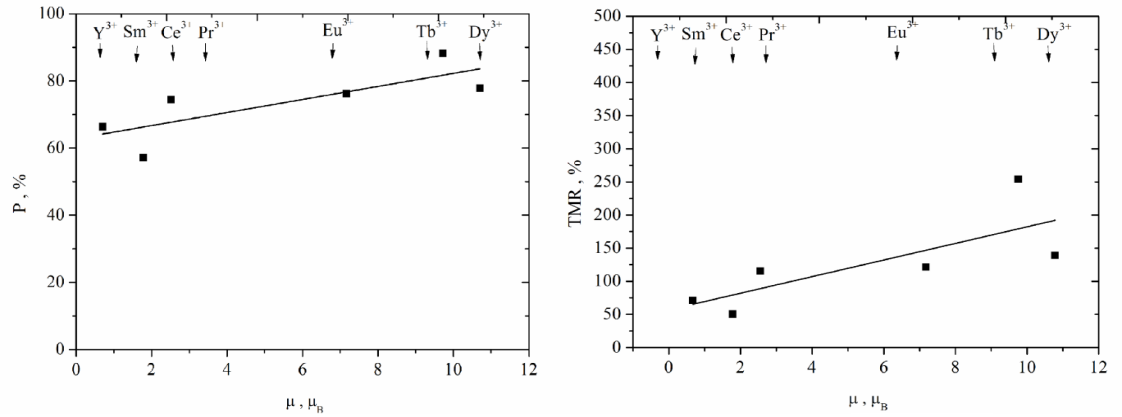


Fig. 16. Dependences of polarization P (*a*) of conduction electron spins in Fe_3O_4 and TMR (*b*) layers of Cu–Fe_3O_4–Me_2O_3–Fe_3O_4–Cu nanostructures on the value μ of the magnetic moment of REM ions in the composition of the oxide layer: $I^{\uparrow\uparrow} = I^{\uparrow\downarrow} = 50$ mA

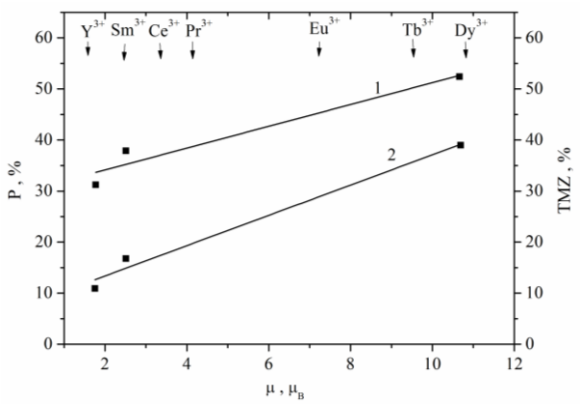


Fig. 17. Dependence of the polarization P (*1*) of the conduction electron spins in Fe_3O_4 and TMZ (*2*) layers of Cu–Fe_3O_4–Me_2O_3–Fe_3O_4–Cu nanostructures on the value of the magnetic moment μ of REM ions: $f = 5$ kHz, $I = 10$ mA

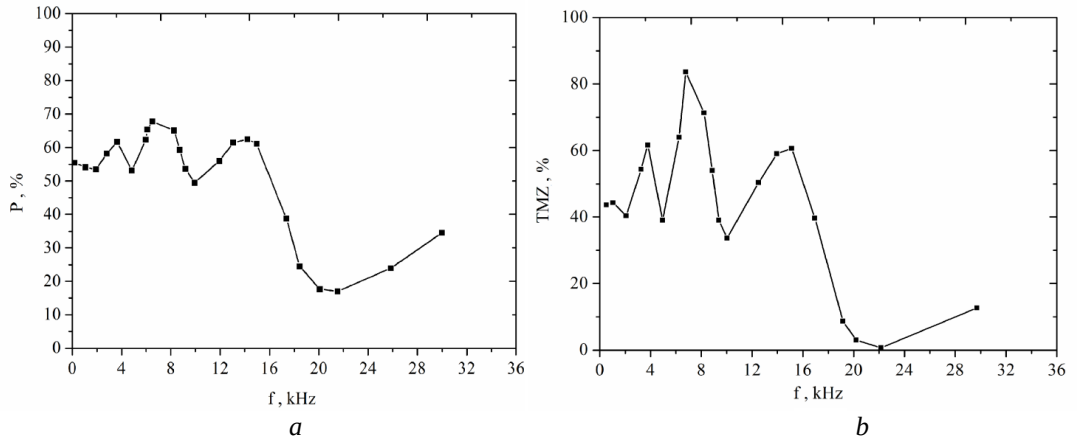


Fig. 18. Dependence of the polarization P (*a*) of the conduction electron spins in the Fe_3O_4 and TMZ layers (*b*) in the Cu–Fe_3O_4–Dy_2O_3–Fe_3O_4–Cu nanostructure on the frequency of magnetization currents f; $I^{\uparrow\uparrow} = I^{\uparrow\downarrow} = 10$ mA

As can be seen from [10–12, 31, 34, 35], enhancement of the galvanomagnetic properties in the Fe_3O_4 / REM oxide / Fe_3O_4 structures is observed both when rare-earth ions with an unfilled 4*f* electron sub-shell (lanthanides) are used, and when the yttrium ion is used, which has an empty 4*d* sub-shell. That is, the exchange interaction between the Fe_3O_4 and REM oxides layers, which orders the magnetic structure and increases the magnetization of the ferromagnet, can have both *f-d* and *d-d* nature.

CONCLUSIONS

A series studies of the properties in nanosized structures containing contacting layers of Fe, Co, Ni, Fe_2O_3 / REM oxides was carried out using various methods.

Structural. The observed features of the Ni/Y_2O_3 films grown in a magnetic field are explained from the standpoint of the orientation of the magnetic moments of Ni clusters by the field and the resulting mutual repulsion of these clusters and their merging in the direction of the field.

EPR. Significant changes in the g-factor and the exchange interaction parameter *P* for the Gd_2O_3 / Fe structure compared to individual Gd_2O_3 and Fe layers indicate the probability of a strong *f-d* exchange interaction between them.

Anomalous Hall effect. A mathematical connection is found of the potential of Hall contacts and additional magnetization stimulated by the exchange *f-d* interaction. Using this relationship, the mechanism of the effect of an external magnetic field on additional magnetization had revealed. It is shown that this magnetization depends on the ratio of the thicknesses of the Ni and Gd_2O_3 layers. It has been found that the vector of this magnetization is directed from the Gd_2O_3 layer to the Ni layer.

Galvanomagnetic. The enhancement of the galvanomagnetic properties in the Fe_3O_4/REM oxide/ Fe_3O_4 structures showed that the exchange interaction between Fe_3O_4 layers and REM oxides, which orders the magnetic structure and increases the magnetization of the ferromagnet, can have both *f-d* and *d-d* character.

Magneto-optical. The enhancement of the Faraday effect is ensured by both the action of only spontaneous and the combined influence of spontaneous and induced magnetizations of the Fe film.

Current-voltage characteristics. The exchange *f-d* interaction significantly reduces the height of the potential barrier for the transfer of charges between the electrodes and increases the current flowing through the Fe, Co, Ni / Tb_2O_3 / Fe, Co, Ni structures. Under the conditions of the over-barrier mechanism of Schottky charge transfer, the magnitude of the force F_{f-d} and energy ε_{f-d} of the *f-d* interaction on the electron motion in this structure is determined.

It is shown that between atoms with unfilled *f*- and *d*-electron sub-shells, which are part of the contacting layers, an *f-d* exchange interaction takes place, which orders the magnetic structure and increases the magnetization of the Fe, Co, Ni, Fe_2O_3 ferromagnetic layers and so enhances the properties. This can be used in nanotechnologies to enhance the above properties without energy consumption and the use of amplifying equipment.

Вплив обмінної f-d взаємодії на властивості нанорозмірних структур на основі металів Fe, Co, Ni та оксидів РЗМ. Огляд

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Проведено огляд робіт авторів, опублікованих у період 2009–2022 років, та присвячених дослідженню властивостей нанорозмірних структур, що містять шари, що контактують Fe, Co, Ni, Fe_3O_4 / оксид РЗМ (рідкісноземельного металу). Розглянуто також технологію створення та структурні особливості даних наноструктур. Фізико-хімічні явища в інтерфейсі контактуючих шарів дуже багатопрофільні. Це є

наслідком їхньої залежності від різних умов, насамперед, від режимів технологій їхнього отримання та властивостей вихідних компонентів. Завдання пізнання значно ускладнюється щодо магнітних наноструктур. Для ефективного дослідження властивостей шаруватих наноструктур, що містять феромагнітні плівки, нами використовувалися магнітні методи досліджень. Методом ЕПР встановлено, що між атомами з незаповненимиелектронними оболонками, що входять до складу контактуючих шарів, встановлюється обмінна f-d взаємодія, що впорядковує магнітну структуру феромагнітних шарів. Методом аномального ефекту Холла показано, що впорядкування магнітної структури призводить до зростання їхньої намагніченості. Посилення гальваномагнітних властивостей у структурах Fe_3O_4/REM оксид/Fe_3O_4 показало, що обмінна взаємодія може мати як f-d, так і d-d характер. А це, у свою чергу, призводить до посилення властивостей, що залежать від намагніченості, таких як гальваномагнітні, магнітооптичні, вольт-амперні. Це може бути використано в нанотехнологіях для підвищення вищевказаних властивостей без споживання енергії та використання підсилювального обладнання.

***Ключові слова**: f-d взаємодія, тонкоплівкові структури, ЕПР, аномальний ефект Холла, магнітні властивості*

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