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The magnetic Kerr effect and magnetoresistance in multilayer Nb|FeNi systems deposited in the geometry of the Stern−Gerlach effect

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The magnetic properties of multilayer Nb|FeNi structures were studied. Magnetic anisotropy was found in these systems, the orientation of which coincides with the orientation of unidirectional optical anisotropy. While studying the resistivity of structures ρ, we found that they have a negative value of the thermal resistance coefficient α, i. e. the structures belong to the class of metal structures with negative α (Mooij rule). A magnetoresistance of no more than 1 % was found in the percolation transition region for FeNi films. Magnetoresistance anisotropy was observed, which depended on both the orientation of the external magnetic field and the surface orientation of the current when measuring magnetoresistance.

Keywords: thin film, island film, non-reciprocity, anisotropy, magnetism.

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1. Introduction

Many both theoretical and experimental papers are dedicated to the studies of multilayer systems „superconductor — non-superconducting material“ [1,2]. Such interest is caused by the possibility of using such systems as the elements of neuronetwork and quantum computations. Besides, you can expect the increase of temperature of transition to the superconducting state in these systems at certain parameters, which is confirmed by some theoretical and experimental studies [3,4]. We believe that one of such systems may be structures of superconductor–magnetic type. We suggested multilayer structures Nb|FeNi [5], grown in the Stern–Gerlach geometry to one of the potential systems of such type [6].

Previously we studied the dielectric permittivity and effect of optical nonreciprocity in multilayer structures Nb|FeNi, grown in the heterogeneous magnetic field (Stern–Gerlach effect geometry) [5]. Nonlinear dependence was detected between the dielectric permittivity ($\mathrm{Re}\,\varepsilon$) and the distance between the magnetic layers FeNi, which was related to the features of exchange interaction between the FeNi layers. It was found that for all studied structures $\mathrm{Re}\,\varepsilon < 0$, which means a metal nature of their optical response. The important feature of the obtained dependences was the absence of lateral anisotropy $\mathrm{Re}\,\varepsilon$, i. e. upon rotation of samples around their axis the value of $\mathrm{Re}\,\varepsilon$ did not change. Besides, in these structures the effect of optical nonreciprocity was also found, the value of which depended on both the thickness of FeNi magnetic layers and the distance between them. The effect of optical nonreciprocity occurred because of the features in the method where Nb|FeNi structures are produced (high frequency sputtering in the Stern–Gerlach geometry). We will provide the results of the studies of magnetic properties of these structures.

2. Samples

All structures studied in this paper were grown by high frequency sputtering method. The growth technology is described in more detail, for example, in [5,7–9]. Two series of samples Nb(d_1)-FeNi-Nb(d_2)-FeNi-Nb(d_1) were grown on the polished ceramic polycrystalline glass substrates (rutile phase TiO_2 [9]). The first series grew structures with alternating thickness Nb(d_2) and constant effective thickness of FeNi layer (1 nm), i. e. in this series the distance d_2 changed between magnetic layers of FeNi. Thickness d_2 varied from 0.5 to 4.0 nm with step of 0.5 nm. In the structures of this series the total thickness of Nb layers was constant and equal to 15 nm. This means that when the distance changes between layers FeNi (i. e. Nb layer with thickness of d_2) thicknesses of the two remaining Nb(d_1) layers also changed to maintain the total thickness of Nb $d = 2d_1 + d_2 = 15$ nm. In the second series the thickness of FeNi layers varied (from 0.8 to 2.2 nm with step of 0.2 nm) at the constant distance between them (Nb layer with thickness of $d_2 \approx 1$ nm). The thickness of other Nb layers was $d_1 = 7$ nm. Thickness of all layers in the structures was effective. The effective thickness of layers was determined by the time of sputtering at the known speeds of film deposition.

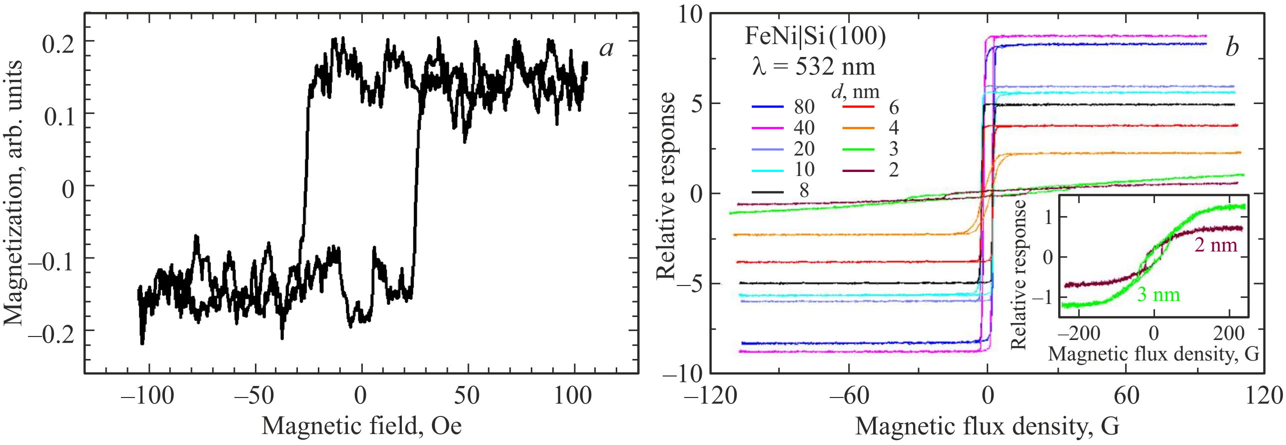

Figure 1. *a*) Hysteresis loop of the first series structure with $d_2 = 0.5$ nm with sample orientation in $\varphi = 110^\circ$ direction. *b*) Hysteresis loops for FeNi films of various thickness obtained previously [11].

3. Research results

Magnetic properties of Nb|FeNi|Nb|FeNi|Nb structures were studied using meridional magneto-optic Kerr effect (MOKE), when the magnetic field is oriented in the plane of light incidence and along the sample surface. In this case p-polarized radiation ($\lambda = 0.633\,\mu$m) came down on the sample at the angle of 70°. The magnetic field was developed by two Helmholtz coils. To study the anisotropy of the magnetic properties, the structures turned around their axis with a step of $\varphi = 30^\circ$, as it happened when the effect of optical nonreciprocity was studied for these structures [5], and Kerr effect was measured for every angle φ. The initial orientation (position) for all samples was the same and matched the direction of the axis of light magnetization for the FeNi volume layer. It is important to note that according to the results of the optical nonreciprocity effect study [5,10] the unidirectional axis of optical anisotropy for the FeNi layers is oriented in the direction of $\varphi \approx 100^\circ$ vs. the initial position of the sample ($\varphi = 0^\circ$).

For the first series of structures (with alternating distance between the FeNi layers) the noticeable Kerr effect was observed only for one structure with the least distance between the FeNi layers — 0.5 nm (Figure 1, *a*). Absence of magnetization for the remaining structures of the first series is probably related to the weakening of the exchange interaction between the FeNi layers and their small thickness (1 nm). Observation of the Kerr effect for the structure with $d_2 \approx 0.5$ nm is due to the strong exchange interaction between the FeNi layers. Note that previously [11] the noticeable Kerr effect was observed for the FeNi films, starting from the thickness of 2 nm (Figure 1, *b*).

Note that the maximum value of magnetization (height of the hysteresis loop) was observed for the sample orientation in the direction of the unidirectional optical anisotropy (Figure 1, *a* — $\varphi = 100^\circ$). In this case the unidirectional magnetic anisotropy is minor, i.e. only the uniaxial magnetic anisotropy is available. Nevertheless, uniaxial magnetic anisotropy and optical unidirectional anisotropy in this sample had the same orientation. At certain orientations of the sample relative to the magnetic field orientation (direction 0 and 150°) there was practically no magnetization in this structure.

For the samples from the 2nd series, when the thickness of FeNi layers varied with the stable thicknesses of Nb layers, the Kerr effect was observed for all structures with the thickness of FeNi layers equal to $d > 1.2$ nm. Figure 2 shows as the example the dependences of the Kerr effect for the sample No. 1 ($d \approx 1.2$ nm).

Figure 3, *a* presents the dependence of the height of the hysteresis loop (magnetization value) on the thickness of the FeNi layers. You can see that the magnetization of the structures increases as the thickness of the FeNi layers increases. Figure 3, *b* shows as the example the typical dependence of magnetization of the structure with the thickness of FeNi layers of $d \approx 1.8$ nm from the angle of the sample rotation to the initial position $\varphi = 0^\circ$. You can see the presence of the uniaxial magnetic anisotropy in sample orientation $\varphi \approx 100^\circ$. Similar behavior of the magnetization dependence on the rotation angle is observed for other structures as well with the different thicknesses of FeNi layers. I.e. the unidirectional magnetic anisotropy is weak for all structures with various FeNi-layer thicknesses. However, the uniaxial magnetic anisotropy for these structures manifests itself strongly.

To study the magnetoresistance of these structures, first their specific resistance ρ was studied, including dependence ρ on temperature (range 77−300 K). It was found that the specific resistance of all structures was of the same order ($\rho \approx 100{-}200\,\mu\Omega\cdot$cm) and did not depend on the direction of current flow, i.e. no anisotropy was found ρ. As the temperature reduces, the resistance of all structures increased monotonously (dielectric nature of conductivity), i.e. the thermal resistance coefficient α

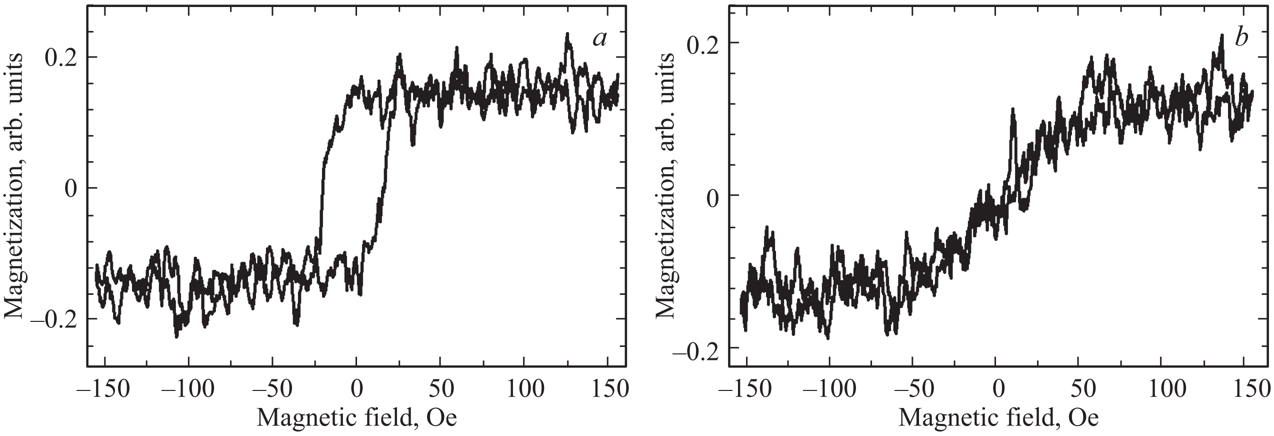

Figure 2. Hysteresis loops of the second series structure with $d = 1.2$ nm in two perpendicular directions with magnetic field orientation *a*) along and *b*) perpendicularly to the axis of optical anisotropy.

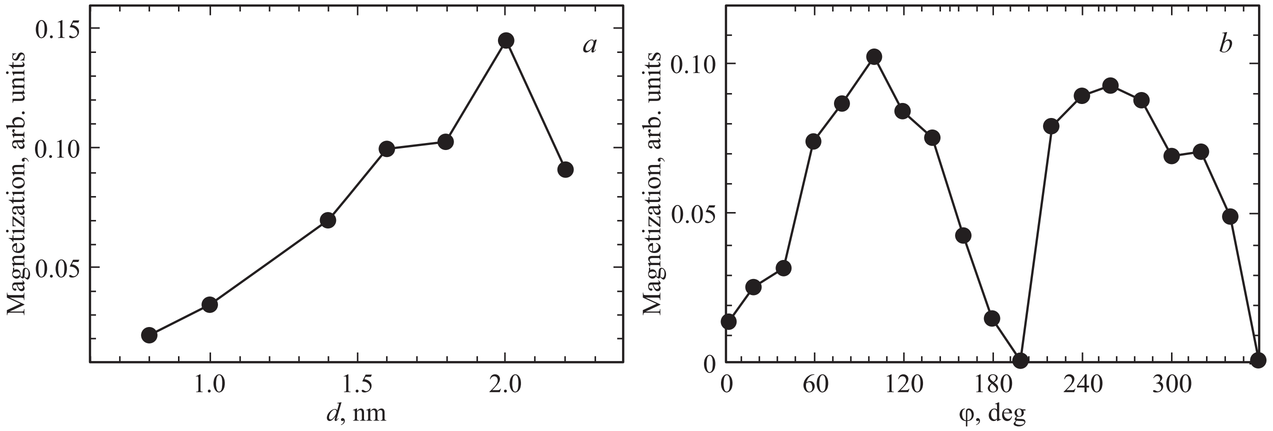

Figure 3. *a*) Dependence of the value of maximum magnetization of the second series samples on the thickness of the FeNi layers. *b*) Dependence of the magnetization value of the second series No. 6 sample on the direction of the magnetic field.

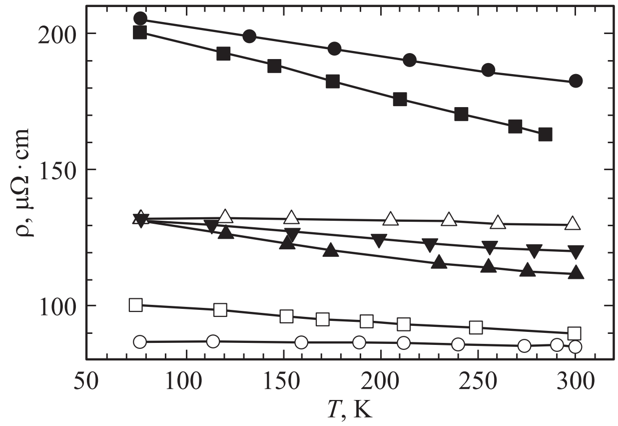

Figure 4. Specific resistance of the first series samples.

had a negative sign in equation $\rho(T) = \rho_0 \cdot [(1 + \alpha(T - T_0)]$ (Figure 4). Note that previously [5] it was shown that for these structures $\mathrm{Re}\,\varepsilon < 0$, which indicates the metal nature of conductivity. However, for the metal structures with such value ρ there is the Mooij [8] rule, which says that there is certain specific resistance $\rho \geq 150\,\mu\Omega \cdot \mathrm{cm}$, which shares positive and negative α values. Therefore, all the structures studied in the paper are related to the class of metal structures with negative heat resistance α. The reasons for the occurrence of the negative α may differ (see, for example, [12,13]), and additional trials are necessary to study these reasons. Note that we also previously observed such behavior of temperature dependence ρ with the negative value α for Ta [9] thin films and Ta|FeNi multilayer structures [14].

The study of $R_H = 100\,\% \cdot (R(H) - R(H=0))/R(H=0)$ magnetoresistance was only conducted for the second series of the samples, where the thickness of FeNi layers was measured at the constant thickness of the Nb separation layer. The samples of the first series weakly respond to the magnetic field as specified above, therefore it was decided not to study magnetoresistance in them.

To measure R_H magnetoresistance of the structures, ohmic contacts were developed on the top layer of Nb|FeNi multi-layer systems by application of indium layer on the

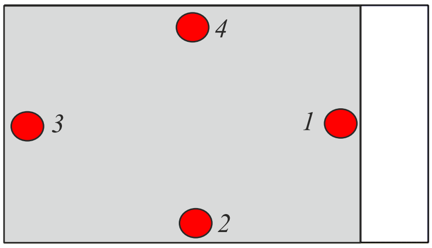

Figure 5. Schematic image of the sample with contact pads.

surface. Two pairs of contacts were formed that were oriented perpendicularly to each other (Figure 5). The magnetic field was applied both perpendicularly to the surface of ($H_\perp$) structures and in the plane of the structures, being oriented in two perpendicular directions along contacts *1* and *3* ($H_{1,3}$) and *2* and *4* ($H_{2,4}$). Note that contacts *1* and *3* were arranged in parallel to the axis of magnetic anisotropy of the structure, and contacts *2* and *4* — perpendicularly to this axis. Magnetoresistance was measured at room temperature 300 K in constant magnetic field $H \approx 2.5$ kOe. Besides, a pair of contacts, for example, *1* and *3*, were exposed to constant voltage $U \approx 1$ V, and magnetoresistance R_H was measured for three different orientations of the magnetic field ($H_\perp$, $H_{1,3}$ and $H_{2,4}$). The important was the fact the initially magnetoresistance in all structures was negligibly low. However, magnetoresistance R_H increased after weak thermal annealing of the structures without the magnetic field for 5 min at $T \approx 280\,^\circ$C. Note that as it was shown previously [6], such weak annealing does not result in anisotropy disappearance or change of nonreciprocity effect. Moreover, such annealing improves magnetic properties of multi-layer magnetic structures [7]. However, magnetoresistance was found only in the structures, where the thickness of FeNi layers was in the field of percolation transition for FeNi — $d \approx 1.8$ nm, namely, in the range of 1.6–2.2 nm.

The dependence of magnetoresistance R_H on the magnetic field orientation was found relative to the studied structures. Besides, substantial differences R_H were found in the case of measurement of resistance along contacts *1* and *3* (along the anisotropy axis) and *2* and *4* (perpendicularly to the anisotropy axis) for various orientations of the magnetic field $H_\perp$, $H_{1,3}$ or $H_{2,4}$ (Figure 6).

In the case when magnetoresistance was measured along the axis of magnetic anisotropy (contacts *1* and *3*), magnetoresistance R_H arises in the orientation of the magnetic field in direction $H_{1,3}$ and is practically absent in the orientation of the magnetic field in direction $H_{2,4}$. Such behavior is specific for anisotropic magnetic effect ($R_H \propto \cos^2\varphi$, where φ is the angle between the directions of current flow and orientation of the sample magnetization). When R_H is measured perpendicularly to the axis of magnetic anisotropy (contacts *2* and *4*), then, on the contrary, R_H is maximum at orientation of the magnetic field perpendicularly to the flowing current ($H_{1,3}$) and is minimum when the magnetic field is parallel to current ($H_{2,4}$), i.e. $R_H \propto \sin\varphi$, besides, magnetoresistance has a negative sign. Therefore, anisotropy of magnetoresistance was found in the studied structures. Note that the magnetoresistance value in the structures was below 1 %. Maximum magnetoresistance for any orientation of measuring contacts (*1* and *3* and *2* and *4*) is observed when the magnetic field $H_\perp$ is directed perpendicularly to the sample surface and is caused by Lorentz force.

4. Conclusion

Uniaxial magnetic anisotropy was found in Nb-FeNi multi-layer structures, orientation of which matched the orientation of the unidirectional optical anisotropy. Besides, the unidirectional magnetic anisotropy was hardly pronounced. Only the structures with alternating thickness of FeNi layers had magnetic properties. When the specific resistance ρ was studied, it was found that all structures have negative value

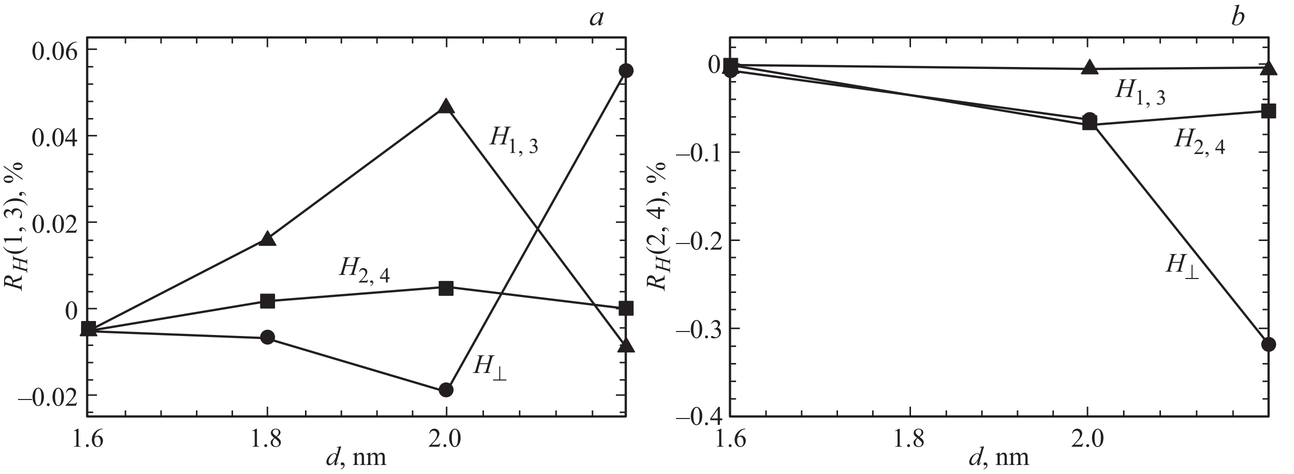

Figure 6. Dependence of the second series sample magnetoresistance value on FeNi layer thickness for various directions of current flow and various directions of the magnetic field.

of heat resistance coefficient α (dielectric nature of temperature dependence of conductivity), even though for the same structures $\mathrm{Re}\,\varepsilon < 0$, which indicates „metal" nature of optical response. Therefore, all the structures studied in the paper are related to the class of metal structures with negative heat resistance α and is subject to Mooji rule. Besides, no anisotropy ρ was found. In Nb|FeNi structures with thickness of FeNi layers in the field of percolation transition (for FeNi films), magnetoresistance R_H was recorded with the value not exceeding 1 %. This magnetoresistance had noticeable anisotropy that depended both on the orientation of the external magnetic field and on the orientation of contacts in process of magnetoresistance measurement.

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Conflict of interest

The authors declare that they have no conflict of interest.

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