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Optical properties of multi-layer Nb–FeNi systems

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Optical properties of five-layer structure Nb–FeNi–Nb–FeNi–Nb were studied with different thicknesses of FeNi and Nb layers grown in geometry of Stern–Gerlach effect. A non-linear dependence was found between dielectric permittivity and Nb thickness, which may be related to the behavior of exchange interaction between FeNi layers. Besides, in these structures there is also an effect of optical nonreciprocity found, the value of which strongly depended on both the thickness of FeNi magnetic layers and the distance between FeNi layers. It was detected that in the studied systems Nb–FeNi two orientations of a unidirectional axis of anisotropy may exist: one for the FeNi layers and the other one for Nb. The most promising parameters were determined for the periodical structures Nb–FeNi to study the optical properties.

Keywords: thin film, island film, Stern–Gerlach effect, dielectric permittivity, nonreciprocity, anisotropy.

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1. Introduction

Currently the superconductor–ferromagnetic systems are being studied intensively [1,2]. Many papers are dedicated to the study of the magnetic field effect on the origination of superconductivity. Such interest is related, in particular, to the possibility of using such systems as the key element of neuronetwork and quantum computations. Besides, multi-layer systems consisting of periodically alternating fine layers of superconducting (S) and non-superconducting (N) material — (S–N) are of great interest. Such interest is related to the ability to increase the temperature of superconducting junction T_C of regular (low-temperature) superconductors. Already in the 80s of the last century a small increase of T_C was found in thin films of low-temperature superconductors depending on the thickness of half-metal layers (protective coating of superconducting film), applied on top of the superconducting layers [3,4]. Such behavior T_C was explained by oscillation of boundary conditions at the superconductor–coating boundary [5]. Besides, it was when the increase of T_C was found in micron crystalline Sn particles containing twins [6]. The theoretical paper [7] showed that in multi-layer superconducting structures, where superconducting layers and fine layers of non-superconducting materials playing the role of twins alternate, T_C of the superconductor may change. It also showed the equivalence of the fine layer of the non-superconducting material (named „flat defect“) and twin. Besides, the thickness of such „flat defects“ and the distance between them must be determined experimentally. Previously, the substantial effect of structural parameters (S–N) at the behavior of T_C was found in systems S–N with Nb layers and hyperfine layers of Si or SiO_2 (around 1 nm): oscillations T_C were observed (with amplitude of around 1 K) depending on the thickness of the non-superconducting layers [8]. We believe that the studies of such multi-layer systems where „flat defects“ are thin ferromagnetic or diamagnetic metal layers are interesting. Since neither thickness, nor the material of the layers simulating flat defects, nor the distance between them are known in advance, the first steps in this paper are suggested as the study of the optical properties of multi-layer Nb–FeNi systems, where both the FeNi layer thickness and the distance between them vary. It is proposed to use both nano-island and fine solid layers of FeNi. Note that the nano-island layers of FeNi may stay in superparamagnetic, superferromagnetic and ferromagnetic states depending on the dimensions of nano-islands and distance between them. Therefore, you may expect differences in the behavior of optical properties depending on the magnetic state of nano-island layers, i. e. on the effective thickness of island layers. Besides, since all studied structures will be grown by method of RF-sputtering in the presence of heterogeneous magnetic field (i. e. the conditions are met to observe the Stern–Gerlach effect), the obtained multi-layer structures may have optical and magnetic unidirectional anisotropy [9], which may also impact the properties of superconducting systems. This paper will present the results of the study of optical properties in five-layer systems Nb(d_1)–FeNi–Nb(d_2)–FeNi–Nb(d_1) where thicknesses of both Nb (d_1 and d_2) layers and FeNi layers will change. In these structures it is proposed to study dielectric permittivity ε ($\mathrm{Re}\,\varepsilon$) and effect of optical nonreciprocity $\Delta\omega$, which defines the optical anisotropy of structures. Besides, in the future it is planned to study the features of magnetic properties and lateral conductivity in these systems. As a result of the studies of optical properties of Nb–FeNi systems, structures will be selected with „features“ of optical parameters. Then, in the future the superconducting properties of these structures will be studied, and a relationship will be established between the features of optical and superconducting properties. It is also planned to find out, which exactly optical and magnetic properties of structures cause features of superconducting properties of multi-layer Nb–FeNi systems.

2. Studied structures

The structures studied in this paper were grown by RF-sputtering method. The growth technology is described in more detail, for example, in [9–11]. Two series of specimens were grown on the polished ceramic substrates of sitall (rutile phase TiO_2 [12]). 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 pitch 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. of Nb d_2 layer thickness) thickness of the two remaining Nb (d_1) layers also changed to maintain the total thickness of Nb: $d = 2d_1 + d_2 = 15$ nm. Note that we have already found a percolation threshold for FeNi films grown by this method ($d^* \approx 1.8$ nm [13]), i. e. FeNi layers in this series were island. In the second series the thickness of FeNi layers varied (from 0.8 to 2.2 nm with pitch of 0.2 nm) at the constant distance between them (Nb layer with thickness of $d_2 \approx 1$ nm). Thickness d_1 of Nb layers was 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. The study of the cross sections and X-ray studies show that such sputtering method indeed helps to grow multi-layer structures in a controlled manner with the specified thicknesses [14]. For example, Figure 1 shows a typical image of the island FeNi layer produced using an electronic microscope [10].

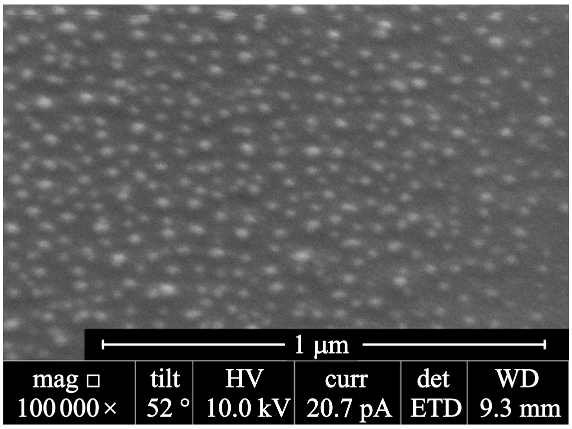

Figure 1. Typical view of island FeNi film on sitall substrate [10].

3. Research methods

To research the dielectric permittivity of the structures, the method of laser ellipsometry was used (with wavelength of 650 nm). In this method for each structure they measure ellipsometric parameters $\Delta(\lambda)$ and $\Psi(\lambda)$, which depend on the parameters of the structure, wavelength of the incident light λ and complex refractive index N [15]. Using the found values $\Delta(\lambda)$ and $\Psi(\lambda)$, the real part of dielectric permittivity $\mathrm{Re}\,\varepsilon$ was calculated. The calculation used the effective medium model, i. e. the multi-layer structure was replaced with a single layer of thickness equal to total thickness of the entire structure with the effective $\mathrm{Re}\,\varepsilon$ value. This model adequately describes the reaction of the structure in general to the external optical excitation. This model automatically accounts for all interactions between the layers. As a result the dependences of $\mathrm{Re}\,\varepsilon$ were found on distance d_2 between the magnetic FeNi layers and on thickness d of FeNi layers.

Besides, this paper also studied the effect of optical nonreciprocity, since this effect arises in metal structures obtained by the method of RF-sputtering in a setup with the built-in structurally heterogeneous magnetic field. In general, the effect of optical nonreciprocity is observed in the systems, where there is no symmetry in respect to the time inversion. It manifests itself, for example, when researching the reflection of polarized light from the specimen, i. e. it is observed, when the coefficient of reflectance of light R from the structure differs from R of the same structure, if the source and the receiver of radiation swap places. Sometimes it is simpler to rotate the specimen by 180° instead of swapping the places of the source and the receiver of radiation. For more precision studies of the nonreciprocity effect, instead of the study of optical reflectance coefficient R change they study the change of the rotation angle of the polarized light polarization plane $\Delta\omega$ when the specimen is rotated by 180°. In this paper, as in [16], we study the change in the rotation angle of polarization plane when p-polarized light is reflected from the structure as the specimen is rotated around its axis — thus the dependence of the polarization plane rotation angle ω on the specimen rotation angle ϕ is produced. For measurements the specimen was fixed in a certain position that was the same for all structures in a special goniometer, with the help of which the structure could be rotated around its axis by 360°. P-polarized light was incident on the structure at angle 70°, and the polarization plane rotation angle $\omega_1(\phi)$ of p-polarized light reflected from the specimen was measured. If $\Delta\omega = \omega_1(\phi) - \omega_2(\phi + 180°) \neq 0$, there is the effect of optical nonreciprocity. The initial position of the specimen in the goniometer was selected the same for all series of the structures.

4. Study results

Figure 2 provides the dependences of effective dielectric permittivity $\mathrm{Re}\,\varepsilon$ on thickness of Nb d_2 layer. You can see that there is nonlinear dependence $\mathrm{Re}\,\varepsilon$ on thickness d_2 of the separating Nb layer. You can notice that the studied structures are similar to the structures with giant magnetoresistance (GMR). In fact we have, as in the case of structures with GMR, two magnetic layers (there are FeNi layers), separated by non-magnetic Nb layer. It is known that [17] in the structures with GMR there is nonlinear (oscillatory) dependence of resistance on thickness of non-magnetic metal layer observed. Thus, in structures Co−Cu−Co the oscillatory dependence is observed between the exchange interaction (resistance) on the thickness of Cu layer with the period of around 1 nm. On the other hand, previously, for thin Nb layers it was found [18] that the nature of the behavior of dependence between DC-resistance and optical conductivity is defined as $\sigma = \nu\ \mathrm{Im}\,\varepsilon/4\pi$, where ν — light frequency) on the film thickness repeats dependence $\varepsilon(d)$. Therefore, the found dependence $\mathrm{Re}\,\varepsilon$ on Nb thickness may be related to behavior of exchange interaction between FeNi layers. You can see that for all specimens of this series of $\mathrm{Re}\,\varepsilon < 0$ structures, which indicates the metal nature of their conductivity.

Figure 3 presents the dependence of effective dielectric permittivity $\mathrm{Re}\,\varepsilon$ on thickness of FeNi layers at constant thicknesses of Nb $d_1 = 7$ nm and $d_2 = 1.0$ nm layers. Here $\mathrm{Re}\,\varepsilon$ was also calculated using the effective medium model. You can see that $\mathrm{Re}\,\varepsilon$ weakly depends on the thickness of FeNi layer (flat defect). Note that in this case as well $\mathrm{Re}\,\varepsilon < 0$ for all structures that indicates the metal nature of optical response of the studied structures. The important feature of the obtained dependences for $\mathrm{Re}\,\varepsilon$ was the absence of lateral anisotropy, i. e. upon rotation of specimens around their axis by any angle, the value of $\mathrm{Re}\,\varepsilon$ did not change.

Figure 4 provides dependences $\Delta\omega(\phi)$ for various values of distance between the magnetic FeNi layers (thicknesses of Nb d_2 layers). You can see that in all these structures the nonreciprocity effect is observed. However, its value was insignificant and did not exceed 0.2°, if the distance between the FeNi layers was in the range of 1.5−3.0 nm. At the same time at $d_2 \geq 4$ nm or $d_2 = 1.0$ nm the effect of optical nonreciprocity increases substantially to $\Delta\omega > 0.7°$. Note that usually for film structures the value of the optical nonreciprocity effect is low and amounts to units of angular minutes (for example, for arrays of magnetic nanoparticles [19]). The availability of nonreciprocity effect indicates the availability of unidirectional optical anisotropy in the structures. Therefore, for the studied series of structures the effect is maximum in the direction corresponding to the specimen rotation by angle $\phi \approx 70-80°$. Similar dependence of the optical nonreciprocity effect was observed for multi-layer structures FeNi−Al_2O_3 as well, where they measured dependence $\Delta\omega$ on thickness of Al_2O_3 layers at invariable thickness of FeNi $d \approx 1.2$ nm layers [20]. At the same time for Al_2O_3 layers the effect of nonreciprocity was absent. You may note that the obtained dependence $\Delta\omega(\phi)$ is approximated well by sinusoid, however, it shows a certain structure: there are two weak maxima in the field of $\phi \approx 70°$ and $\phi \approx 120°$. Note that for the structure without FeNi layers (Nb layer with thickness of 15 nm) the effect of nonreciprocity is maximum ($\Delta\omega = 1.2°$) and is observed in the direction of $\phi \approx 70°$, and the maximum at $\phi \approx 100-120°$ is not observed. At the same time the maximum $\Delta\omega$ in the area of $\phi \approx 100-120°$ is observed at the same angle of specimen rotation as for the structures with FeNi layers in multi-layer FeNi−Al_2O_3 [20] systems.

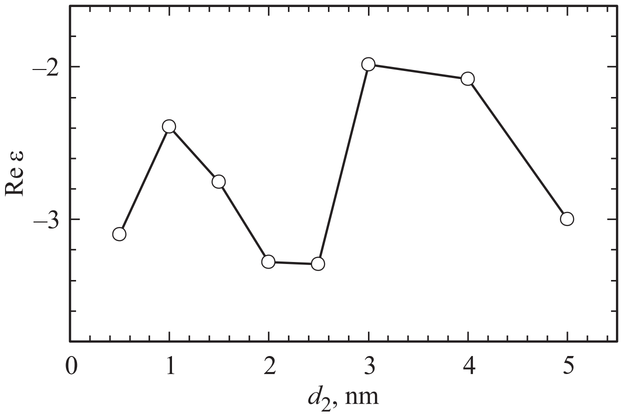

Figure 2. Dependence of effective dielectric permittivity of the studied structures on thickness of Nb d_2 layer.

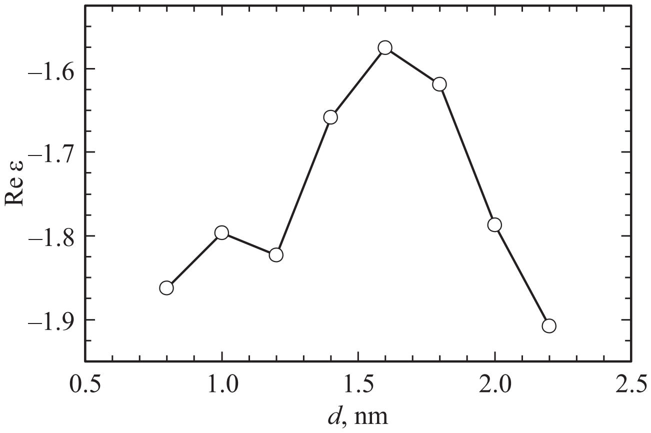

Figure 3. Dependence of effective dielectric permittivity of the studied structures on thickness of FeNi layers.

As it was specified previously [9], the responsible for occurrence of unidirectional anisotropy (effect of optical nonreciprocity) is the method to grow structures, namely the RF-sputtering in the heterogeneous magnetic field. In this case the orientation and value of the arising unidirectional anisotropy (effect of nonreciprocity) is determined by spin structure of sputtered atoms. Besides, previously in multi-layer Ag−Al_2O_3, Bi−Al_2O_3 systems

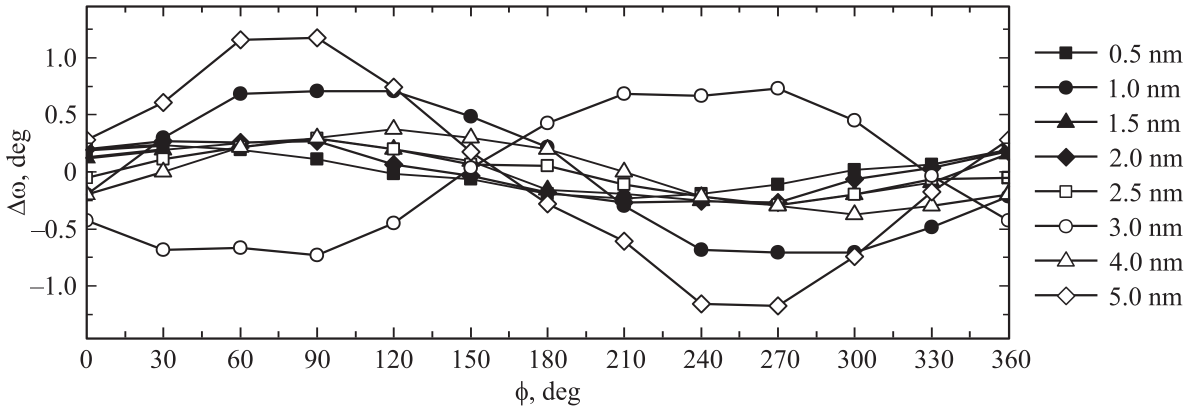

Figure 4. Dependence of nonreciprocity of $\Delta\omega$ structures on the angle of rotation for different values of Nb d_2 layer thickness.

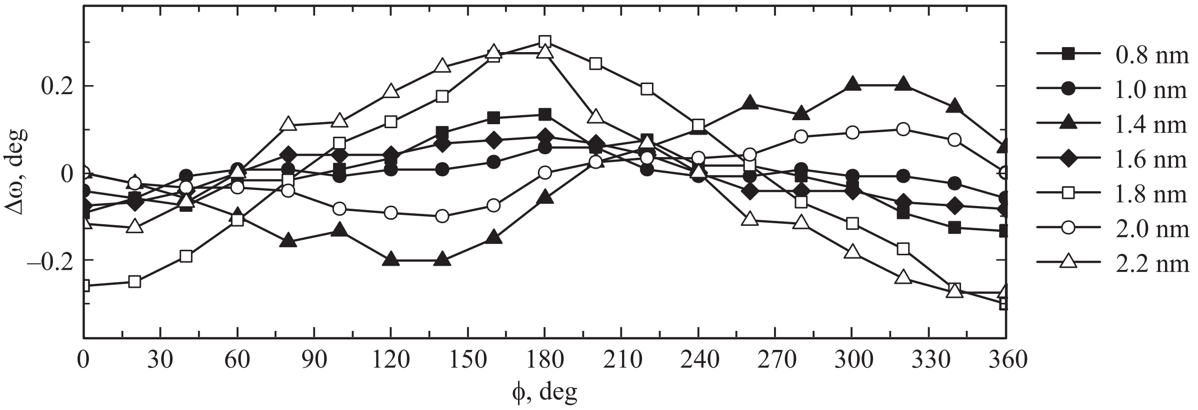

Figure 5. Dependence of nonreciprocity of $\Delta\omega$ structures on the angle of rotation for different values of FeNi layers.

and others it was found that orientation of unidirectional axis of anisotropy and the value of the nonreciprocity effect substantially depend on the thickness of metal layers and the distance between them (for example, Ag and Bi layers [9,21]). As it was found above, for the case of multi-layer Nb–FeNi structures (Figure 4), the value of effect of nonreciprocity depends strongly on the distance between FeNi (d_2) layers, whereas the orientation of axis of anisotropy ($\phi \approx 70^\circ$) hardly depends on thickness d_2. You can also see (Figure 4) that when d_2 reaches 3 nm, the unidirectional axis of anisotropy is directed to the opposite side relative to the orientation of this axis for all other structures. The occurrence of such feature for the FeNi layers was often observed in other papers (for example, in FeNi–Al_2O_3 structures [10]). The reasons for such abnormality are not clear yet. Therefore, you can assume that the studied Nb–FeNi systems contain two orientations of the unidirectional axis of anisotropy: one for FeNi ($\phi \approx 100–120^\circ$) and the other one for Nb ($\phi \approx 70^\circ$).

For the second series of the structures, where the thickness of FeNi layers (flat defects) varied with the invariable distance between them (1 nm), the effect of optical nonreciprocity is also available, but its value does not exceed $\Delta\omega = 0.3^\circ$ (Figure 5). Maximum value $\Delta\omega = 0.3^\circ$ is achieved for thickness of FeNi layers $d \approx 1.8$ nm, which coincides with a percolation threshold for FeNi [13], as in paper [20]. You can note a significant effect of the FeNi layers thickness at orientation and value of the unidirectional optical anisotropy, which was also detected previously for FeNi layers in FeNi–Al_2O_3 structures [9,10]. Besides, features were found in all structures in the dependence of the unidirectional axis in the area 180°, which may be related to Nb layers.

Therefore, the studies of the optical nonreciprocity effect in multi-layer Nb–FeNi structures showed that two unidirectional axes of optical anisotropy co-exist in these structures, one being related to Nb layers, and the second one — to FeNi layers. Besides, the value and orientation of the unidirectional axis for FeNi layers depended on their thickness.

As it was already noted above, the objective of this paper was to find the thickness of FeNi layers and the distance between them, when these layers could most closely imitate the flat defects (twin boundaries) in superconducting Nb. It was assumed that the closest to such systems will be the structures that have any optical features. From the data obtained on dielectric permittivity of Nb–FeNi systems you can identify the structures having maximum

$\mathrm{Re}\,\varepsilon \approx -3.3$ (high „metallicity") at the distance between FeNi layers at $d_2 \approx 2.0-2.5$ nm. Note that the exchange interaction between FeNi layers at such distance weakens. Besides, structures are also identified with the thickness of FeNi layers near the percolation threshold ($d^* \approx 1.8$ nm), since instead of being more „metallic" (with maximum module $\mathrm{Re}\,\varepsilon$) as the total thickness of metal (Nb and FeNi) increases, these structures become less „metallic" (module $\mathrm{Re}\,\varepsilon$ decreases).

The study of the optical nonreciprocity effect showed that it is maximum at the distance between FeNi layers at $d_2 \approx 0.8-1.0$ nm. Besides, at $d_2 \approx 3$ nm the orientation of the unidirectional axis of anisotropy is opposite to its direction in other structures. Note that the structures with features of dielectric permittivity (at $d_2 \approx 2.0-2.5$ nm) have the lowest value of nonreciprocity effect. At the same time it is possible to identify the structures with the thickness of FeNi layer $d \approx 1.8$ nm (percolation threshold for FeNi), where the nonreciprocity effect is maximum by value, and the structures with thickness of FeNi $d \approx 1.0$ nm, where this effect is minimum. Therefore, based on the optical properties of Nb−FeNi structures, the most promising would be the structures, whose thickness of FeNi layers is $d \approx 1.0$ nm or 1.8 nm, and the distance between these layers is $d_2 \approx 2.0-2.5$ nm.

5. Conclusions

Therefore, nonlinear dependence was found in Nb−FeNi structures between the dielectric permittivity and the thickness of Nb d_2 layer (distances between the magnetic FeNi layers), which may be related to the behaviour of exchange interaction between FeNi layers. Besides, in multilayer Nb−FeNi structures there is also an effect of optical nonreciprocity found, the value of which strongly depends on both the thickness of FeNi magnetic layers (flat defects) and the distance between FeNi layers. Besides, the value of the effect was insignificant for the structures, where the distance between FeNi layers d_2 was in the area of 1.5−3.0 nm. At the same time at $d_2 \geq 4$ nm or $d_2 = 1.0$ nm the effect of optical nonreciprocity increases substantially to $\Delta\omega > 0.7^\circ$. It was detected that in the studied systems Nb−FeNi two orientations of a unidirectional axis of anisotropy may exist: one for FeNi ($\phi \approx 100-120^\circ$) and the other one for Nb ($\phi \approx 70^\circ$). It was presumed that based on the optical properties of Nb−FeNi structures, the most promising for further studies are the structures, where the thickness of FeNi layers is $d \approx 1.0$ nm or 1.8 nm, and the distance between these layers is $d_2 \approx 2.0-2.5$ nm.

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Conflict of interest

The authors declare no conflict of interest.

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