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Temperature dependences of the interlayer exchange constant of three-layer FeNi/Dy/FeNi films studied by the resonance method

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Three-layer FeNi/Dy/FeNi films were studied by ferromagnetic resonance method in the temperature range from 4 to 300 K. The acoustic and optical peaks recorded in microwave spectra demonstrate the presence of exchange coupling between the ferromagnetic FeNi layers of the planar system and allow us to establish the sign and value of the constant of the interlayer exchange interaction. Temperature dependences of the interlayer exchange interaction constant for three-layer films with intermediate layer thicknesses Dy 5 and 10 nm show a number of features (change in sign and extremum point), which reflect transformations of the magnetic structure Dy.

Keywords: interlayer exchange coupling, helical magnetic structure, ferromagnetic resonance, three-layer films.

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The discovery of the exchange interaction through the intermediate layer between two ferromagnetic layers [1] initiated the studies of such structures, which continue to this day, and their results find practical applications [2]. Let us note the possibility to control the parameters of these systems by fairly simple technological methods: changing the layer material or its thickness.

The main magnetic characteristic of these planar systems is the interlayer magnetic exchange interaction J_{12}, whose magnitude and sign determine the qualitative and quantitative assessment of the entire planar system. Verification J_{12} was performed using the ferromagnetic resonance method, which belongs to the dynamic methods and has such advantages as simplicity in execution and in interpretation of experimental results [3].

Most of the works are devoted to the study of the exchange-coupled films in which the transition metal (Cr, Ru, Cu, V, Au) [3–6] was chosen as the intermediate layer material. One of the main results is the dependence of the exchange interaction type (sign J_{12}) on the intermediate layer thickness. We consider it challenging to identify other parameters that determine ferromagnetic or antiferromagnetic exchange coupling. $Fe_{20}Ni_{80}$/Dy/$Fe_{20}Ni_{80}$ films were chosen as an object of research to solve this problem. Dy single crystal has three magnetic states depending on temperature. It is paramagnetic at zero magnetic field above the Neel temperature ($T_N \approx 180$ K), between ~ 90 and ~ 180 K a helicoidal antiferromagnetic structure is observed for it, below Curie temperature ($T_C \approx 90$ K) the magnetic order is ferromagnetic [7]. Let us note the change in the values of T_N and T_C for nanostructured Dy films depending on their thickness [8]. The influence on the interface magnetic characteristics from the magnetic subsystem of the CoDy alloy established in [9] was also taken into account when selecting Dy for the intermediate layer.

Thus, the purpose of this work is to study the effect of the magnetic state of the intermediate layer of the three-layer system on the exchange coupling parameters.

The three-layer films were obtained by thermal evaporation in vacuum (10^{-6} mm Hg) by successive spraying of $Fe_{20}Ni_{80}$ and Dy layers from independent evaporators with a ring cathode onto glass substrates. The thickness of each ferromagnetic layer was 70 nm and the thickness of the Dy layer (t_{Dy}) — 5 and 10 nm (SEM image of $t_{\mathrm{Dy}} \approx 10$ nm film is presented (in the supplementary materials).

Microwave spectra were measured on an ELEXSYS E580 spectrometer (Bruker, Germany) in the range of 4 to 300 K with transverse pumping of the microwave resonator field at $f = 9.2$ GHz. The sample was placed in the variable magnetic field region $h_\sim$ of the cavity resonator, and the constant magnetic field was applied in the film plane. The microwave absorption curves were decomposed into components using a differentiated Lorentz function, the choice of which took into account the absence of the contribution of the electric component (due to the resonator design and the sample size).

The exchange coupling between ferromagnetic layers separated by a nonmagnetic layer and having a difference in magnetic parameters creates conditions for excitation in the microwave spectrum of both acoustic and optical modes, intense enough for its registration regardless of the orientation of the constant and high-frequency field [3]. The mutual position of the peaks makes it possible to determine the type of magnetization vectors alignment in neighboring

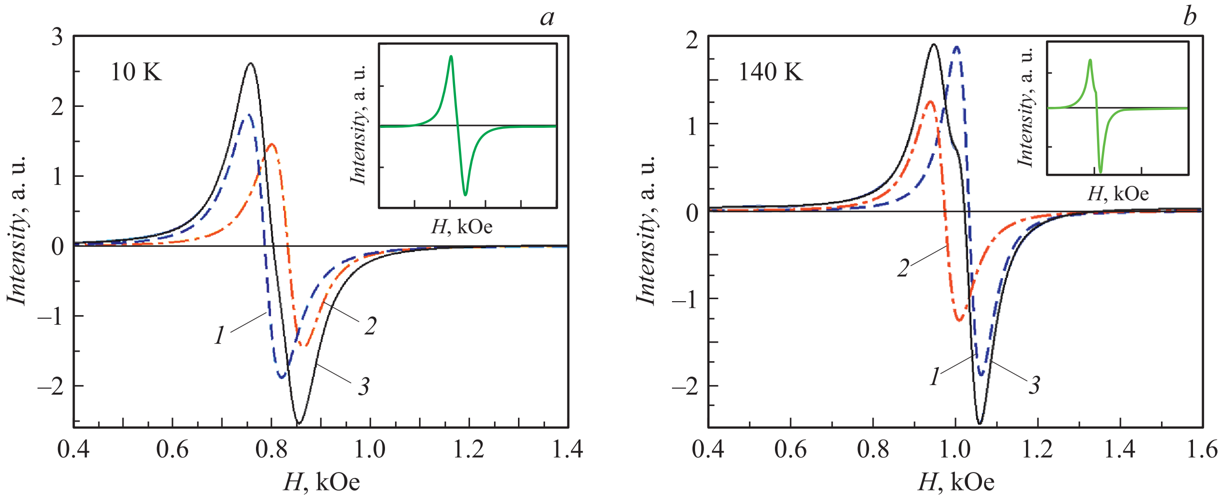

Figure 1. The adjusting curve (line *3*) of experimental microwave spectra for film with thickness Dy $t_{\mathrm{Dy}} = 5$ nm, measured at 10 (*a*) and 140 K (*b*). *1* and *2* — acoustic and optical modes, respectively. The insets show experimental curves.

layers: ferromagnetic or antiferromagnetic [4,10–14]. In the first case, the value of $J_{12} > 0$, and the optical mode is observed in lower fields than the acoustic mode (Fig. 1, *b*). In the second case, at $J_{12} < 0$, the optical mode is observed at higher fields than the acoustic mode (Fig. 1, *a*).

The magnitude of the interlayer exchange interaction can be estimated using the expression [3]:

$$J_{12} = \frac{1}{2} M_S L |H_E|, \qquad (1)$$

where M_S — saturation magnetization, L — thickness of the ferromagnetic layer, H_E — shift of the resonant fields of acoustic and optical peaks.

Temperature dependences of the resonant field and line width ΔH of the acoustic and optical modes (are presented in additional materials. The line width of a single peak is less than the difference between their resonant fields: $\Delta H_{ac(op)} \leqslant |H^{ac}_{res} - H^{op}_{res}|$, indicating that the decomposition of the experimental spectrum into two separate peaks is valid. The realization of exchange-coupled oscillations in the form of acoustic and optical modes is also confirmed by the angular dependence of their resonance fields.

The main contributions determining the temperature dependences of the interlayer exchange interaction constant $J_{12}(T)$ take into account the parameters of the extreme ferromagnetic layers (thickness, magnetic order) and the intermediate layer, as well as the influence of interfaces. A common feature of most works is that the type of exchange interaction is independent of temperature, and $J_{12}(T) \sim 1 - xT^y$ (convex function) [6,15–18].

Dy, which has two phase magnetic transitions in the temperature range from 80 to 200 K, strong antiferromagnetic interaction at the interface with transition metal as rare-earth material [19], potential to realize Dzyaloshinskii–Moriya interface interaction was chosen as intermediate layer material in this work. The temperature dependences $J_{12}(T)$ of $Fe_{20}Ni_{80}/Dy/Fe_{20}Ni_{80}$ films with Dy thicknesses $t_{\mathrm{Dy}} = 5$ and 10 nm are shown in Fig. 2.

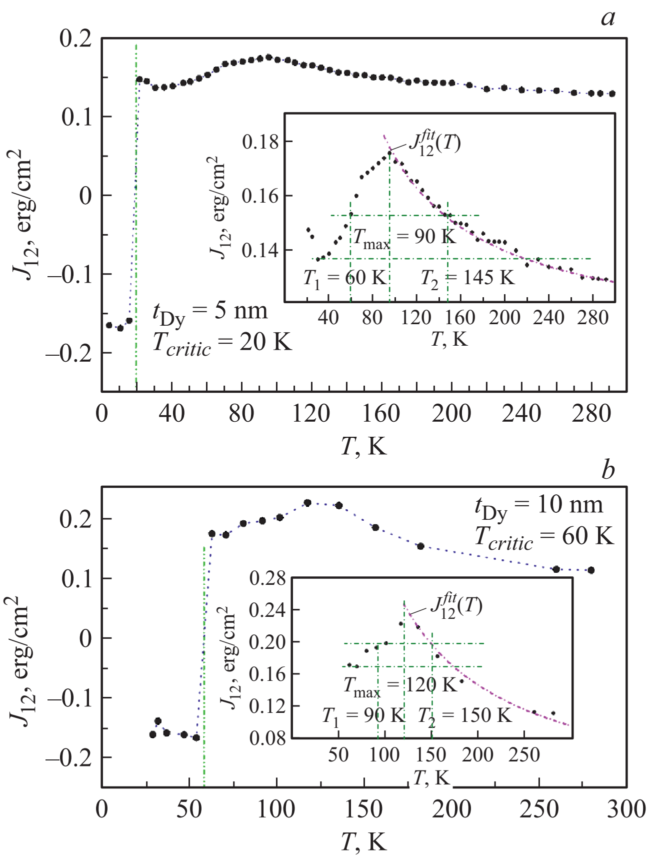

Figure 2. J_{12}(T) of film $Fe_{20}Ni_{80}/Dy/Fe_{20}Ni_{80}$ with $t_{\mathrm{Dy}} = 5$ (*a*) and 10 nm (*b*). The inset shows the adjusting curve $J^{fit}_{12}(T)$ in the temperature range from $T_{\max}$ to 300 K.

We assume that the recorded features of $J_{12}(T)$ are due to the two magnetic transformations of Dy (at T_{critic},

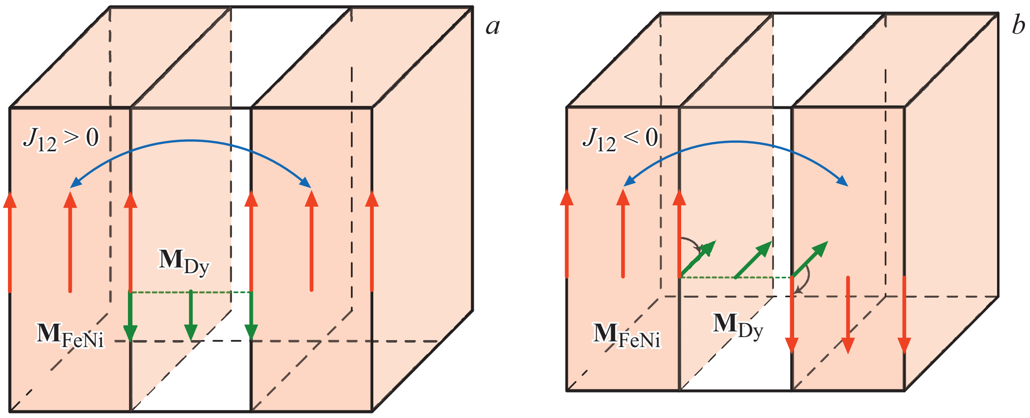

Figure 3. Model of magnetization vectors distribution in Dy and FeNi layers in the range from 4 K to T_{critic}.

the ferromagnetic order is changed to antiferromagnetic, and at $T_{\max}$ — antiferromagnetic to paramagnetic), and the boundary conditions at the interfaces FeNi/Dy. The contribution of the interfaces (in the range from 4 K to T_{critic}) manifests itself in the orientation of the magnetization vectors in the adjacent layers of permalloy $\mathbf{M}_{\mathrm{FeNi}}$ and dysprosium $\mathbf{M}_{\mathrm{Dy}}$ and, consequently, in the type (sign) of the effective interlayer exchange interaction. If we assume that the direction of vectors $\mathbf{M}_{\mathrm{FeNi}}$ and $\mathbf{M}_{\mathrm{Dy}}$ is determined only by antiferromagnetic interaction, they should be oriented opposite to each other at the interfaces, and as a consequence, the value J_{12}^{eff} should be greater than zero (Fig. 3, *a*). The recorded antiferromagnetic interlayer exchange interaction ($J_{12} < 0$) at ferromagnetic alignment of Dy can be explained within the framework of the realization of Dzyaloshinskii–Moriya interaction [20,21] at FeNi/Dy and Dy/FeNi interfaces, which promotes the formation of orthogonally oriented exchange-coupled systems (Fig. 3, *b*). Obviously, in the range from 4 K to T_{critic} the Dzyaloshinskii–Moriya interaction prevails over the antiferromagnetic interaction of Dy and FeNi. The Dzyaloshinskii–Moriya interaction in Dy–ferromagnetic metal layers is considered in [22].

The experimental values of $J_{12}(T)$ at the paramagnetic state Dy ($T_{\max} < T < 300\,\mathrm{K}$) were compared with the fitting curve $J_{12}^{fit}(T) = J_0 + C/T$, where J_0 and C are constant coefficients. As can be seen from Fig. 2, the adjusting curves have very little deviation from the experimental values (the determination coefficient for each curve was more than 0.95, and the relative error for J_0 and C is no more than 5%).

Analysis of the ferromagnetic resonance spectra in the range from 4 to 300 K of the three-layer films allowed to reveal the presence of exchange coupling between the ferromagnetic layers FeNi through the intermediate layer Dy. We assume that the features of the temperature dependence of the interlayer exchange interaction constant $J_{12}(T)$ — a sign change J_{12} at T_{critic} (20 and 60 K for $t_{Dy} = 5$ and 10 nm, respectively), and the extremum point at $T_{\max}$ (90 and 120 K for $t_{\mathrm{Dy}} = 5$ and 10 nm, respectively) — reflect transformations of the Dy magnetic structure: change from ferromagnetic to antiferromagnetic state at T_{critic} and from antiferromagnetic to paramagnetic state at $T_{\max}$. The realization of antiferromagnetic interlayer exchange interaction ($J_{12} < 0$) at ferromagnetic order Dy in the temperature range from 4 K to T_{critic} is explained by the presence of Dzyaloshinskii–Moriya interaction at FeNi/Dy and Dy/FeNi interfaces, promoting the formation of orthogonally oriented exchange-coupled systems. The proposed functional dependence $J_{12}^{fit}(T)$ quite accurately describes the experimental data in the temperature range from $T_{\max}$ to 300 K.

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Conflict of interest

The authors declare that they have no conflict of interest.

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