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Magnetic Resonance in $[(CoP)_{soft}/NiP/(CoP)_{hard}/NiP]_n$ Multilayer Magnetic Springs

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The magnetic resonance properties of $[(CoP)_{soft}/NiP/(CoP)_{hard}/NiP]_n$ multilayer films with the properties of magnetic springs have been experimentally studied. It has been found that the deposition of a NiP non-magnetic amorphous layer on a $(CoP)_{soft}$ magnetic layer induces the appearance of perpendicular interface anisotropy. The increase in the number of blocks n in the multilayer structure leads to the appearance of the third absorption peak, which is explained by the formation of a noncollinear three-sublattice magnetic structure.

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The film systems consisting of alternating layers of soft and hard magnetic materials are suitable objects for solving a number of spintronics problems. The interlayer interaction in such systems is responsible for the formation of a magnetic state. When ferromagnetic and antiferromagnetic layers are conjugated, the effect of exchange bias is usually implemented and the entire observed magnetization process is related to the behavior of the ferromagnetic layer [1, 2]. When soft and hard ferromagnetic layers are coupled, a new state of the "magnetic spring" type arises [3]. Such structures were first studied for improving the properties of permanent magnets [4] and for using them as a medium for perpendicular magnetic memory [5]. An additional intermediate magnetic layer was introduced to give the structure the necessary characteristics [6]. When the interlayer interaction is adjustable, for example, when a nonmagnetic layer is introduced, new manifestations can be expected. Such an attempt was made in the $FM_{hard}/NM/\alpha\text{-}Fe/NM/FM_{hard}$ multilayer structure ($FM_{hard} = RE_{16}Fe_{71}B_{13}$, RE = Nd, Pr; NM = Mo, Cu, Cr) [7]. Magnetization processes in multilayer magnetic springs were also experimentally studied in order to analyze the change in interlayer interactions at the formation of a multilayer structure [8, 9].

We previously showed [10] that an increase in the number of blocks (n) in the structure of soft and hard ferromagnetic layers in the $[(CoP)_{soft}/(CoP)_{hard}]_n$ structure enhances the effect of the soft magnetic layer on the magnetization process in the film structure. The introduction of a nonmagnetic interlayer leads to the unusual process of magnetization of the film with oscillations in the coercive force. Here, the nonmagnetic interlayer affects the interlayer interaction between the ferromagnetic layers. It was found that the behavior of the magnetic spring type is observed under magnetization and the effect is more pronounced as the number of structural blocks increases. This work is devoted to the study of the change in the magnetic state in multilayer film structures with alternating soft and hard magnetic layers separated by a nonmagnetic interlayer with the increase in the number of blocks in the structure.

A detailed procedure for obtaining films is described in [10]. The $[(CoP)_{soft}/NiP/(CoP)_{hard}/NiP]_n$ films were obtained by chemical deposition. The phosphorus content in all layers was 8 at %. The hard magnetic layer CoP_{hard} was in a hexagonal polycrystalline state, whereas the soft magnetic layer CoP_{soft} was in an amorphous state. The ratio of magnetic anisotropies of hexagonal and amorphous cobalt exceeds two orders of magnitude. The intermediate NiP layer was in an amorphous state and was nonmagnetic [11, Table 8.1, p. 208]. The CoP_{soft} and $(CoP)_{soft}/NiP$ films and multilayer structures with the number of blocks $n = 1$, 5, and 10 were synthesized. Both magnetic layers had the thickness $t = 5$ nm and the nonmagnetic layer had the thickness $t_{NiP} = 2$ nm. The ferromagnetic resonance method was chosen as a method sensitive to changes in the internal fields of various natures. The electron magnetic resonance spectra were measured on a Bruker E 500 CW EPR spectro-

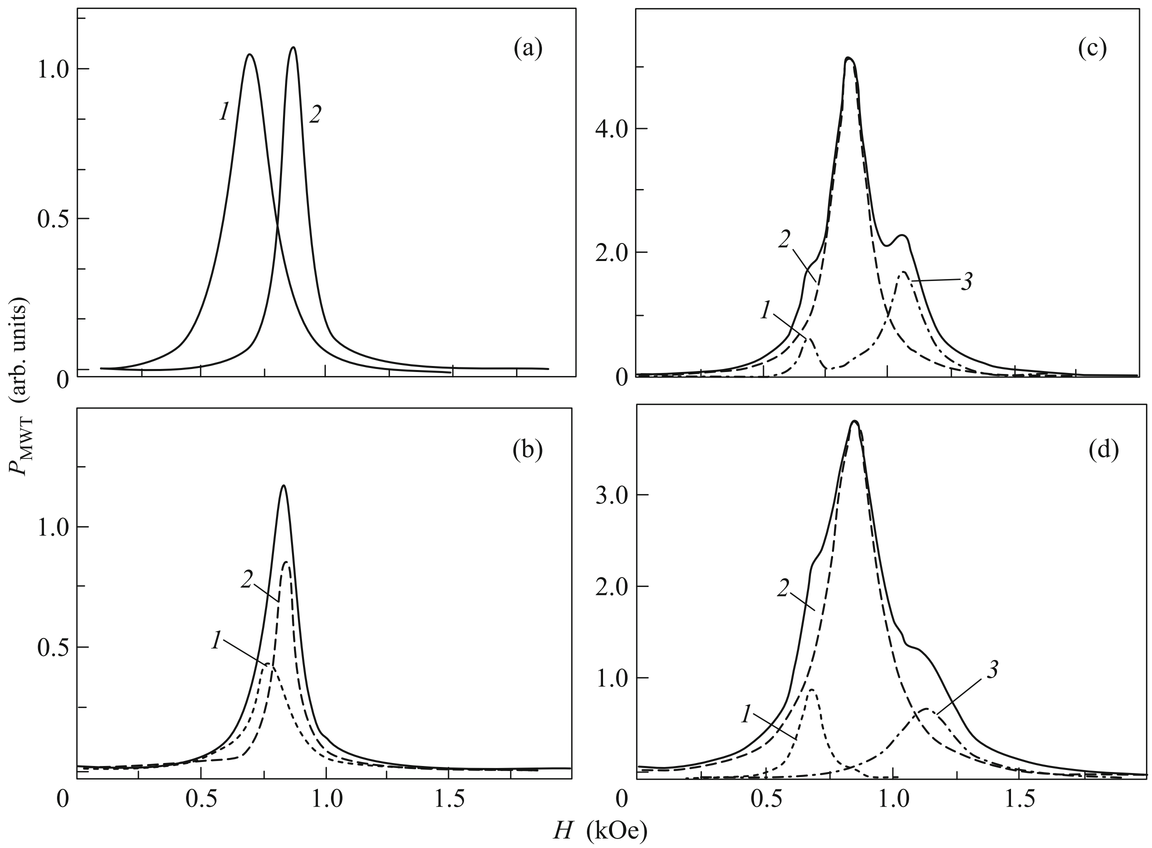

Fig. 1. Microwave absorption spectrum in $[(CoP)_{soft}/NiP/(CoP)_{hard}/NiP]_n$ films for (a) (*1*) CoP_{soft} and (*2*) $(CoP)_{soft}/NiP$, n = (b) 1, (c) 5, and (d) 10.

meter operating at the frequency ω_{MWF} = 9.4 GHz. In the experiment, a static magnetic field was in the plane of the film. The spectra were processed by fitting the experimental integral absorption curve to the Lorentzian components.

The observation of ferromagnetic resonance in the Sm–Co/Fe two-layer magnetic spring was reported in [12]. The authors observed three absorption peaks, where one peak was attributed to the bulk mode, and the other two were attributed to the surface modes of the iron layer.

It follows from the magnetostatic data [10] that the saturation magnetization field for all the films studied satisfies the condition $H_s \le 500$ Oe. It can be seen from the figures below that all the films under magnetic resonance conditions are in the saturated state. Figure 1a shows the microwave absorption (P_{MWF}) for the CoP_{soft} single layer (curve *1*) and for the $(CoP)_{soft}/NiP$ two-layer film (curve *2*). It can be seen that the deposition of the nonmagnetic NiP layer leads to the displacement of the resonance curve toward higher magnetic fields. In the case of the anisotropic magnetic film, the resonance frequency squared is given in the conventional notation by the formula [13, p. 54]

$$(\omega/\gamma)^2 = H(H + H_A + H_M), \tag{1}$$

where

$$H_M = 4\pi M, \quad H_A = 2K/(t_{FM}M). \tag{2}$$

Using the magnetization value $M \approx 1400$ G for the single soft magnetic layer from [10], which roughly coincides with the magnetization value for the cubic phase at the cobalt layer thickness $t_{Co} \approx 5$ nm [14], under the condition $H_A = 0$, we obtain good agreement between the experimental resonance field value (Fig. 2a, curve *1*) and that calculated by Eq. (1) (H_r = 664 Oe at T = 120 K). It follows from Eq. (1) that the effect of the amorphous nickel layer can be related either to the decrease in the magnetization caused by the appearance of a "dead layer" at the magnetic–nonmagnetic layer interface or to the appearance of perpendicular anisotropy. In the latter case, the estimate from Eq. (1) for the same magnetization values gives the interface anisotropy field H_A = –4350 Oe. It is known [15] that the magnetic anisotropy changes at the nickel–germanium interface and this change increases with a decrease in the nickel

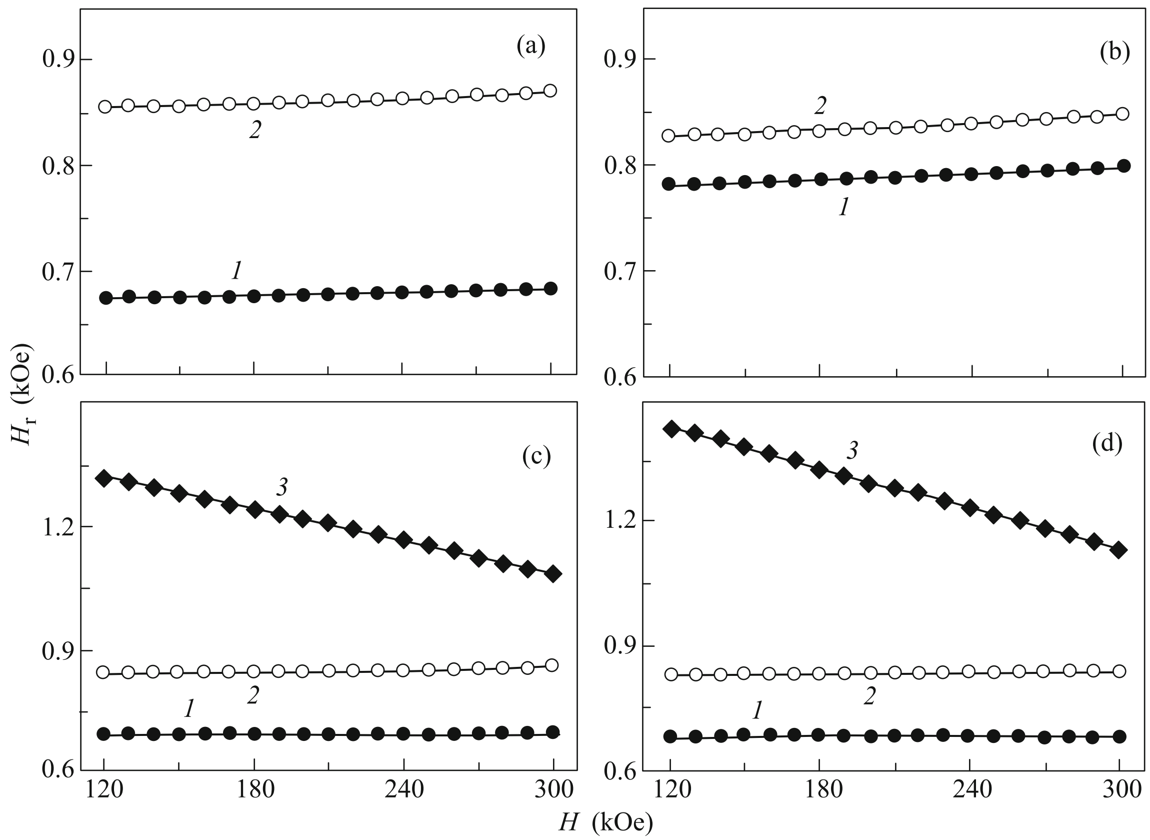

Fig. 2. Temperature dependences of resonance fields of $[(CoP)_{soft}/NiP/(CoP)_{hard}/NiP]_n$ films for (a) (*1*) CoP_{soft} and (*2*) $(CoP)_{soft}/NiP$, n = (b) 1, (c) 5, and (d) 10.

layer thickness, and the perpendicular anisotropy arises in the Co/Ni structure with thin layers [16].

The study of the isolated nonmagnetic NiP layer showed the absence of any microwave signal.

In the three-layer film structure with $n = 1$, the spectrum consists of two microwave absorption lines (see Fig. 1b), but both lines are in the interval of magnetic fields between the values corresponding to the resonance fields of the soft magnetic layer (CoP_{soft}) and the bilayer film (CoP_{soft}/NiP). This means that the modes of magnetic oscillations are coupled. When the number of blocks n increases, the third microwave absorption peak arises. The structure of the spectrum is such that the low-field lines (lines *1* and *2*) have close resonance field values and are in the range of the resonance fields inherent in the film with $n = 1$ (see Fig. 1). It is established that the shape of the resonance spectrum changes together with a noticeable change in the resonance field value of the high-field peak (line *3*) with an increase in the number of blocks n.

The temperature dependences of the resonance field (H_r) are obtained for all films (Fig. 2). For the films with n = 5 and 10, the resonance field values of low-field peaks increase with the temperature, and H_r of the high-field peak decreases under the same conditions. (The numbering of curves in Figs. 2 and 3 corresponds to the absorption peaks in Fig. 1.)

In the case of film structures with a large number of blocks, the appearance of the third absorption peak does not fit into the simple scheme of the two-sublattice model. Naturally, the question arises, which subsystem is divided into two?

Figures 1b–1d show that peak 2 having the greatest intensity in the microwave absorption spectrum for all multilayer films is located approximately in the fields corresponding to the resonance field value for the (CoP_{soft}/NiP) film (cf. Fig. 2). This suggests that this peak in multilayer structures refers to the resonance absorption in the subsystem formed by soft magnetic layers.

The consideration of the magnetization loops [10] shows that the relative contribution to the total magnetization from the subsystem of hard magnetic layers in comparison with the contribution of the soft magnetic subsystem decreases with increasing n. This behavior is attributed to the strong effect of the soft magnetic layer on the magnetization process of the hard magnetic layer. In this case, the features of the magnetization can be explained by the existence of the

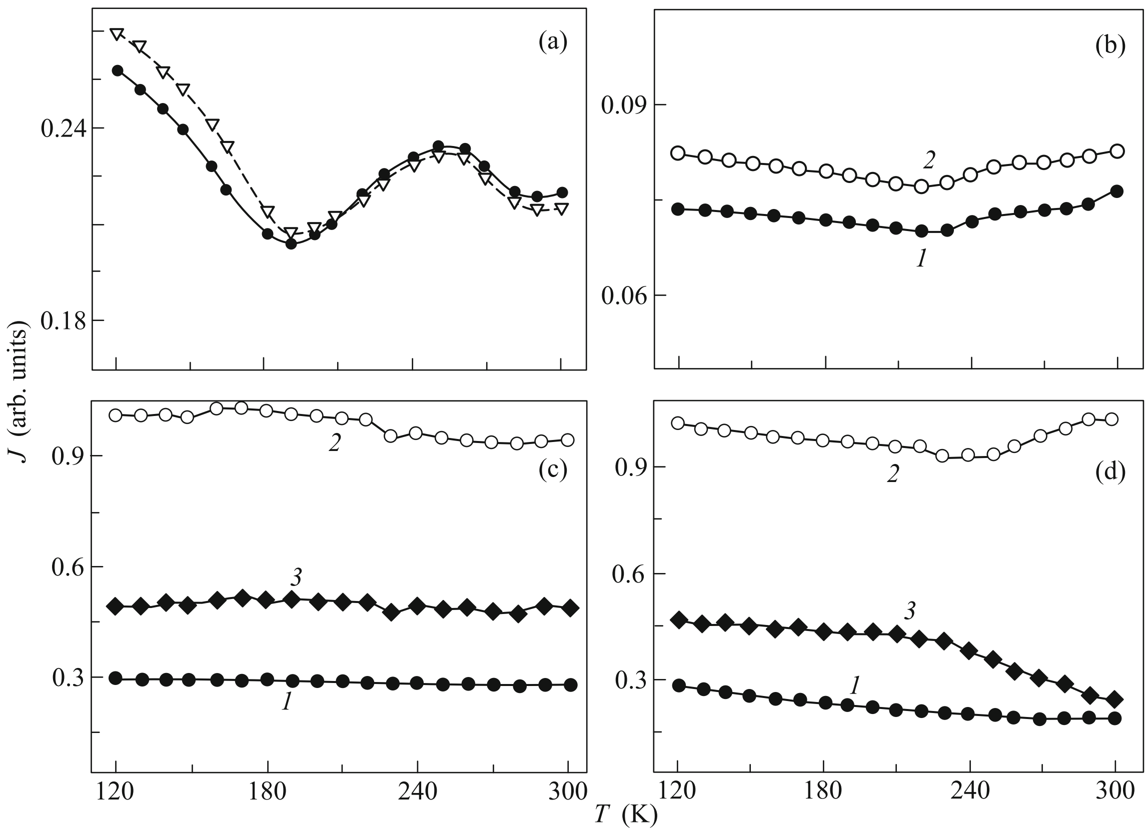

Fig. 3. Temperature dependences of the intensities of the resonance absorption lines of $[(CoP)_{soft}/NiP/(CoP)_{hard}/NiP]_n$ films for (a) (*1*) CoP_{soft} and (*2*) $(CoP)_{soft}/NiP$, n = (b) 1, (c) 5, and (d) 10.

long-range interlayer interaction, i.e., more distant than the interaction between the nearest neighboring layers. The negative biquadratic interlayer interaction can be responsible for a skewed structure, but the system still remains two-sublattice. The formation of the noncollinear structure was observed earlier in $[Gd/Si/Co]_n$ multilayer films [17], where a behavior similar to the spin-glass one occurs, with the negative exchange interaction between the total magnetic moments of the rare earth and cobalt layers. In this case, the rare-earth subsystem formed a conical structure. The noncollinear magnetic state was also studied in $[Fe/Cr]_n$ multilayer films [18], but noncollinearity in these structures is determined by a spin density wave in chromium and depends on the thickness of its layer, rather than on the number of blocks in the structure.

If one subsystem is divided into two, a situation similar to the Yafet–Kittel ordering [19, Rus. p. 266] for ferrites can occur, when a skewed magnetic structure is formed; i.e., the antiferromagnetic interaction between the layers following the nearest magnetic layer is necessary. Consequently, there is the ferromagnetic interaction between the soft and hard magnetic layers, and the antiferromagnetic interaction exists between the nearest layers of one of the subsystems. Since the effect of the soft magnetic subsystem increases with n when the multilayer structure is magnetized [10], the subsystem of hard magnetic layers is apparently divided into two skewed sublattices. Indirectly, this is favored by the behavior of the intensities J of absorption lines in Fig. 3 (defined as areas under the corresponding curves in Fig. 1). It can be seen (Fig. 3a) that the deposition of the nonmagnetic nickel layer hardly changes the absorption intensity of the single cobalt layer and its temperature behavior. For a film with $n = 1$, the line intensities are comparable in magnitude (Fig. 3b). The ratio of intensities for films with $n = 5$ is $J_3/J_1 \approx 3/2$, and this ratio for $n = 10$ tends to 1. The observed difference in intensities can be due to the difference in the excitation conditions of these modes. Such intensity ratios are consistent with the ratio of the number of layers in each of the skewed subsystems.

To summarize, magnetic resonance has been observed for the first time in a multilayer magnetic spring and it has been established that the interlayer interaction depends on the number of layers in the structure. The mechanisms leading to long-range interactions in a multilayer structure are still unclear, and this is the task of the next studies. The origin of the small anomaly in the temperature dependence of the intensity near $T \approx 220$ K is also still unknown, while this is not manifested in the dependence of the resonance fields.

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