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CONDENSED MATTER

Effect of the Semiconductor Spacer on Positive Exchange Bias in the CoNi/Si/FeNi Three-Layer Structure

G. S. Patrin[a, b, *], **I. A. Turpanov**[a], **V. I. Yushkov**[a, b], **A. V. Kobyakov**[a, b],
K. G. Patrin[a], **G. Yu. Yurkin**[a], **and Ya. A. Zhivaya**[a]
[a] *Siberian Federal University, Krasnoyarsk, 660041 Russia*
[b] *Kirensky Institute of Physics, Federal Research Center KSC, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, 660036 Russia*
**e-mail: patrin@iph.krasn.ru*

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Films consisting of a hard magnetic ferromagnet CoNi and a soft magnetic ferromagnet FeNi interacting through a nonmagnetic Si semiconductor spacer are experimentally studied. The temperature and field dependences of the magnetic properties of film structures with different silicon thicknesses are examined. It is found that the multilayer structure has the properties inherent in magnetic springs and exhibits positive exchange bias as a function of the silicon thickness.

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INTRODUCTION

Nanomagnetic materials are of both fundamental and applied interest because of their unusual properties caused by their specific structure [1]. Layered structures with different nanoscale magnetic layers in various combinations are the most convenient objects for spintronics devices; in particular, these are film systems consisting of alternating layers of soft and hard magnetic materials. The interlayer interaction in such systems is responsible for the formation of a magnetic state. When the ferromagnetic and antiferromagnetic layers are conjugated, the exchange bias effect is usually implemented [2] and the entire observed magnetization process is associated with the behavior of the ferromagnetic layer. When ferromagnetic soft and hard magnetic layers are conjugated, a new “magnetic spring” state may arise. In this case, the magnetization process goes through certain stages, and the hysteresis loop has a characteristic step shape [1].

Initially, such systems were studied in connection with the study of multicomponent permanent magnets [3]. Then, the features of magnetization of layered inhomogeneous structures were studied as a function of the thicknesses of the soft and hard magnetic layers, the interlayer interaction, and the layer anisotropy [4–6] as applied to spintronics problems. Further, in order to improve the properties of film permanent magnets for increasing the energy density $(BM)_{\max}$, trilayer structures were manufactured by introducing a soft magnetic layer as an intermediate layer between two $Nd_2Fe_{14}B/Fe/Nd_2Fe_{14}B$ [7] and $SmCo_5/Fe/SmCo_5$ hard magnetic layers [8].

Magnetic spring structures were also studied as media for perpendicular magnetic recording both theoretically in ferromagnetic bilayer structures [9] and experimentally in $FePt/Fe_3Pt/FePt$ [10] and $DyCo_5/Ta/Fe_{76}Gd_{24}$ [11] ferrimagnetic trilayer structures. The effects of the magnetic field on the conductivity were studied in the SmCo/FeNi structures [12], where magnetoresistance was observed (~1.5%). Here, the main contribution to the effect is made by the anisotropic magnetoresistance in the soft magnetic layer. The effect of giant magnetoresistance ~32% was discovered in $[DyFe_2/YFe_2]_n$ superlattices [13], which already seems very promising in practice.

Exchange bias and the magnetic spring effect were observed simultaneously in a number of film structures. The $FeGd_{\text{ferri}}/FeSn_{\text{ferro}}$ or $FeGd_{\text{ferri}}/FeTb_{\text{ferri}}$ structure with ferrimagnetic layers [14] exhibits the magnetic spring effect and positive or negative exchange bias, respectively. In the Co/NiO structure, the state of an antiferromagnetic magnetic spring is implemented [15]. In $[(CoP)_{\text{soft}}/NiP/(CoP)_{\text{hard}}/NiP]_n$ (NiP is nonmagnetic) multilayer structures, the change in the shape of the magnetization loop and the oscillation of the saturation field depending on the number n of structural blocks were found [16].

To control the interlayer interaction as a determining parameter when fabricating structures such as a magnetic spring with specified characteristics, additional spacers were introduced between the magnetic layers in a few works. It was established that the interaction between the CoNi layers in the CoNi/Gd/CoNi structure [17] depends strongly on the gadolinium thickness. The long-range interaction in the $FM_{hard}/NM/\alpha\text{-}Fe/NM/FM_{hard}$ (FM_{hard} = $RE_{16}Fe_{71}B_{13}$, RE = Nd, Pr; NM = Mo, Cu, Cr) multilayer structure [18] is manifested, which is determined by the substantial dependence of the exchange length (L_{ex} [19]) on the thickness of the nonmagnetic metal layer.

The aim of this work is to study the possibility of controlling the properties of magnetic spring structures by changing the interlayer interaction between the hard and soft magnetic layers and the effect of anisotropy and external impacts.

EXPERIMENTAL TECHNIQUE

The CoNi/Si/FeNi films were synthesized for the first time by ion-plasma sputtering (basic vacuum was 10^{-8}–10^{-7} mmHg). The nickel contents in the CoNi and FeNi layers were 19.5 and 83 at %, respectively. The thickness of the CoNi layer, t_h = 53 nm, was chosen such that this layer behaves as a hard magnetic layer in the measurements in available magnetic fields. The thickness of the FeNi soft magnetic layer was t_s = 72 nm, and the magnetization can be twisted in this layer. For better adhesion with the substrate and the uniaxial anisotropy production, the CoNi layer was deposited at a substrate temperature of 450 K; then, the substrate was cooled to 373 K. The silicon and permalloy layers were deposited at this substrate temperature to prevent (minimize) the formation of silicides. The layer deposition rate was $v \approx 0.15$ nm/s.

The ratio of magnetic anisotropies of the hard and soft magnetic materials at room temperature is about 100 [20], which only increases with decreasing temperature. The thickness of the nonmagnetic semiconductor layer was varied in the range of t_{Si} = 0–15 nm. The thicknesses of the layers were determined by X-ray spectroscopy. The magnetization was measured on an MPMS-XL magnetometer in the temperature range from liquid helium to room temperature. Electron-microscopy studies of the cross section were carried out on a JEOL JEM-2100 electron microscope (when preparing the sample on a Gatan PIPS installation) and showed a clear interface between the silicon layer and two magnetic layers (Fig. 1). No trace of silicide phases was detected. It was also found that the CoNi film was polycrystalline and was in the hexagonal phase. To induce axial magnetic anisotropy, sputtering and subsequent cooling were carried out in a magnetic field of 200 Oe. Subsequently, all measurements were carried out for the direction of the external magnetic field along this induced easy axis. The measurement procedure was standard. After cooling in the "negative" magnetic field $-H_S$, the measurement was carried out according to the cycle $-H_S \to +H_S \to -H_S$. The exchange bias field is usually determined as $H_E = (H_{C2} + H_{C1})/2$ (see Fig. 2c), where H_{C1} and H_{C2} are the coercive fields of the remagnetized control layer (in the case of the ferromagnet/antiferromagnet (FM/AFM) structure, it will be a ferromagnetic layer).

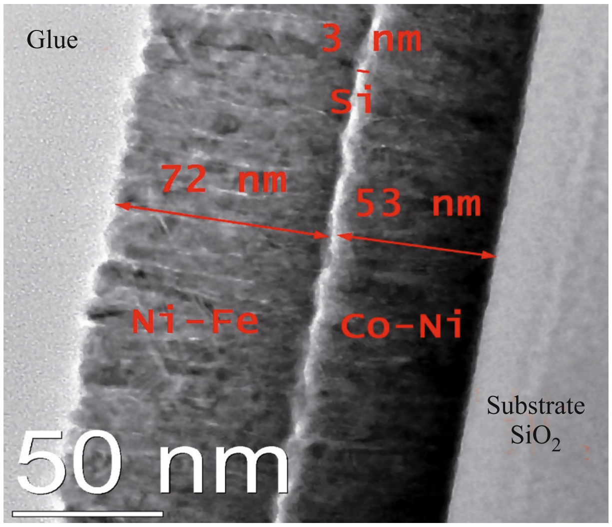

Fig. 1. (Color online) Transverse cut of the CoNi/Si/FeNi film.

RESULTS AND DISCUSSION

As a first step, the magnetization $M(H)$ of the initial reference CoNi and FeNi films were measured. Figure 2 shows the hysteresis loops of the soft (Fig. 2a) and hard magnetic (Fig. 2b) layers indicated above at different temperatures. It can be seen that the coercive forces of the films are very different, which indicates a noticeable difference in their magnetic anisotropies ($H_c = 2K/(M_S\gamma(\theta))$ [21]; $\gamma(\theta)$ is the parameter depending on the angle θ between the easy axis and the direction of the magnetic field; the remaining notation is conventional. In the formed CoNi/FeNi bilayer structure (Fig. 2c) with given layer thicknesses, the magnetization curve is symmetric and corresponds to a ferromagnetic behavior. Here, it can be seen that the mutual influence of the layers takes place, and the coercive force of the bilayer film is smaller than that of a single hard magnetic layer. This behavior is characteristic of strong ferromagnetic interlayer coupling [4] and, in the case of magnetization by rotating the magnetic moment of the soft magnetic layer, corresponds to the behavior of the magnetic spring [5].

When the hard and soft magnetic layers are conjugated through a nonmagnetic semiconductor silicon layer with the thickness t_{Si}, the shape of the magnetization loop depends on the Si layer thickness (see Fig. 3). In all films studied, a two-step hysteresis loop is observed.

Figure 3 shows the dependence of the magnetization along the easy axis on the magnetic field at differ-

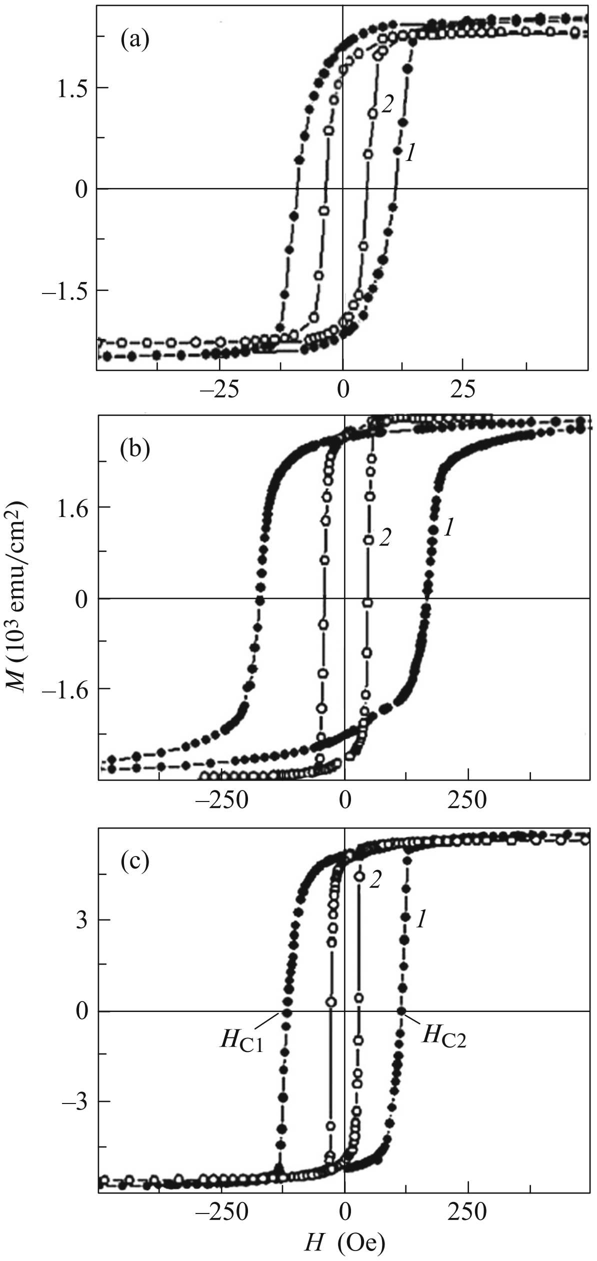

Fig. 2. Magnetic field dependences of the magnetic moment of the unit surface area of the (a) FeNi, (b) CoNi, (c) CoNi/FeNi films at the temperatures T = (*1*) 20 and (*2*) 250 K.

ent temperatures. It can be seen in this figure that, as the spacer thickness increases to t_{Si} = 5 nm, the coercive force of the exchange-coupled trilayer structure determined as $H_C = (H_{C2} - H_{C1})/2$ decreases and then increases again. For the films with a nonmagnetic spacer, the shape of $M(H)$ curves corresponds to the behavior of the magnetization characteristic of a magnetic spring with a moderate interlayer coupling. It is found that, for films with thicknesses t_{Si} = 2.75, 3.5, and 5.75 nm, a "positive displacement" of the loops is observed at low temperatures, while the loop for the thickness t_{Si} = 1.2 nm is symmetric with respect to the reflection of the origin of M–H coordinates; i.e., exchange bias is absent. As the temperature increases, the effect of loop displacement decreases, and it disappears completely at $T \geq 100$ K (Fig. 4).

For the ferromagnet/antiferromagnet systems, negative exchange bias ($H_E < 0$) is usually observed. However, for the $Tb_x(Fe_{80}Co_{20})_{100-x}$(200 nm)/$Tb_{16.2}(Fe_{80}Co_{20})_{83.8}$ (100 nm) structure (pinning layer) [22], which refers to the (FM/FM) case, either negative or positive exchange bias can occur depending on the rare-earth content x. In the case of the antiferromagnetic interaction between the subsystems, the effect here is determined by which 3*d*- or 4*f*-element subsystem in the layer is determinant. The effect of exchange bias was also observed in a system of two ferrimagnetic spinel dielectric layers [23]. Here, the existence of a strong interlayer interaction comparable with the intralayer interaction is important. This indicates a strong interface interaction.

As a rule [24], the effect of positive exchange bias ($H_E > 0$) is implemented in systems when cooling occurs in the negative magnetic field ($h_f < 0$) and the positive interlayer interaction ($J > 0$) under the condition ($J\ S_{AFM}$) < 0 (taking into account the direction of the spin $\mathbf{S}_{AFM}$ in the antiferromagnetic layer) or when $h_f > |J\ S_{AFM}|$, but the interlayer exchange is negative ($J < 0$).

In our case, where both layers are ferromagnetic, positive exchange bias, defined as the displacement of a part of the loop (which can be attributed to the soft magnetic layer) depends on the thickness of the nonmagnetic semiconductor layer. This means that the dependence of the sign of this interaction on the silicon layer thickness is observed along with the effect of the semiconductor layer on the interlayer interaction. Figure 4 demonstrates that the dependence of exchange bias on the thickness of the semiconductor layer is nonmonotonic. In this case, the two-step behavior characteristic of a magnetic spring with the moderate interlayer interaction is preserved for all spacer thicknesses. It should also be noted that positive exchange bias correlates with the width of the hard magnetic step. This behavior suggests that the interlayer interaction has a sign-alternating character and, where it is negative, a positive shift of the magnetization loop occurs. The analogous behavior was observed in the $(Pt/Co)_3/NiO/(Co/Pt)_3$ structure [25], where the oscillation period is two NiO monolayers. This is possible if the magnetic layer interacts ferromagnetically with the interface layer of the antiferromagnetic NiO spacer. For multilayer films with nonmagnetic semiconductor spacers, in particular, for the Fe/Si/Fe structure with the silicon spacer [26], the antiferromagnetic interlayer interaction occurs depending aperiodically on the spacer thickness.

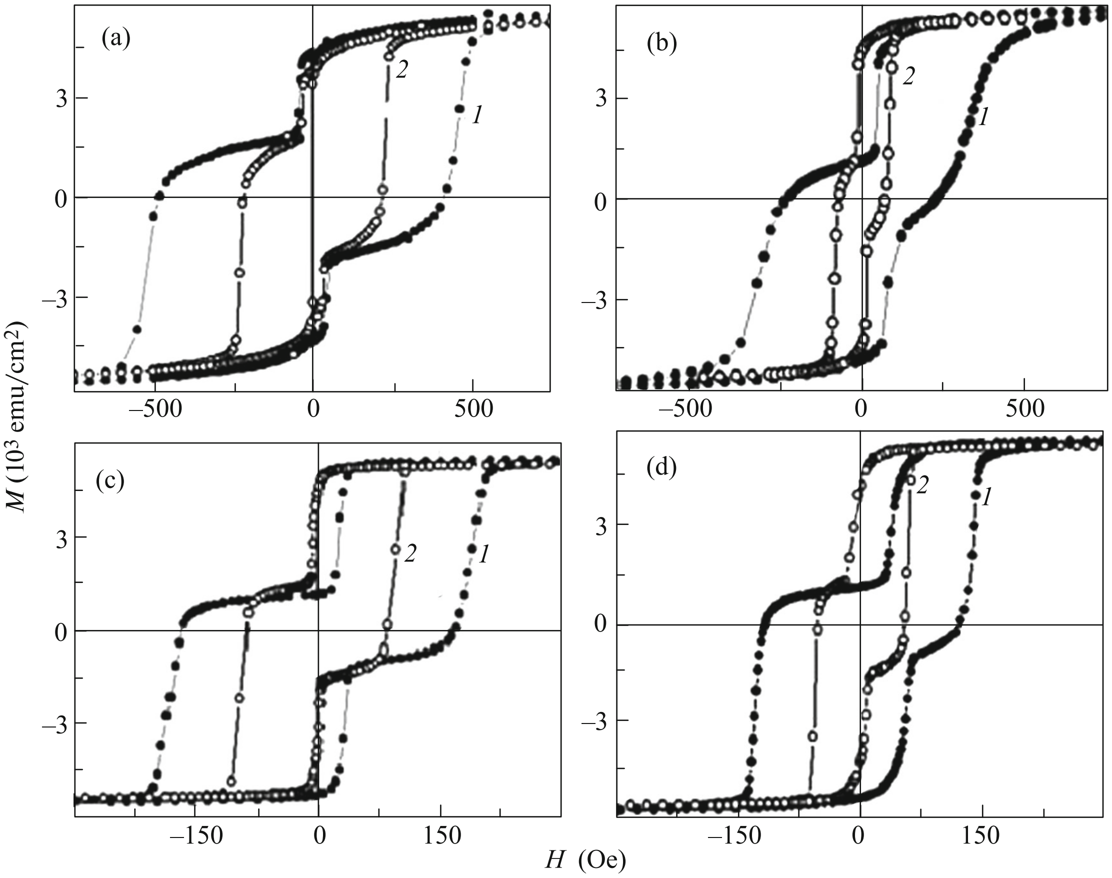

Fig. 3. Magnetic field dependences of the magnetic moment of the unit surface area of CoNi/Si/FeNi films with the Si thicknesses t_{Si} = (a) 1.25, (b) 2.75, (c) 3.5, and (d) 5.75 nm at the temperatures T = (*1*) 40 and (*2*) 250 K.

It was found (Fig. 4) that the temperature dependence of H_E has a maximum in the region of $T \approx$ 20 K. This indicates either the competitive nature of the mechanisms that determine the effect of exchange bias or the activation mechanism responsible for the formation of the magnetic state. Since we did not perform additional operations to prepare the effect of exchange bias, and the anisotropy was induced only during the deposition of films, an asymmetric two-minimum potential is apparently formed with respect to the rotation of the magnetization vector. The situation is somewhat similar to the superparamagnetism of an ensemble of uniaxial particles with the magnetic energy $E = -K\cos^2\theta - MH\cos\theta$ (the field along the easy anisotropy axis). Here, the main temperature-adjustable parameter is the anisotropy constant. In our case, the interlayer exchange interaction $-\lambda M_{\mathrm{hard}} M_{\mathrm{soft}} \cos(\theta_{\mathrm{hard}} - \theta_{\mathrm{soft}})$ through a silicon layer, where both magnetizations are functions of the external magnetic field, is added and plays an important role. The sign of the constant λ will determine the direction of bias of the magnetization curve.

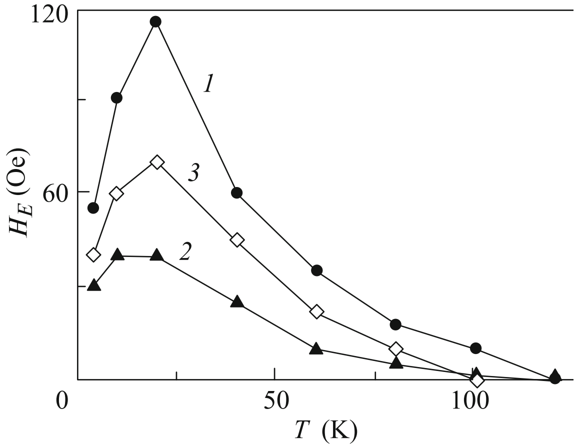

Fig. 4. Temperature dependences of the exchange bias field of CoNi/Si/FeNi films with the Si thicknesses t_{Si} = (*1*) 2.75, (*2*) 3.5, and (*3*) 5.75 nm.

The main results of this work are as follows.

(i) The structure with the controlled interlayer interaction is produced in the system consisting of hard magnetic and soft magnetic materials and a semiconductor spacer.

(ii) The interlayer interaction depends on the thickness of the semiconductor spacer.

(iii) The effect of positive exchange bias is detected.

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