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Studying the Mechanism of Exchange Coupling in Ferro/Ferrimagnet NiFe/DyCo Film Structures

G. I. Frolov, V. A. Seredkin, and V. Yu. Yakovchuk

Kirensky Institute of Physics, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, Russia
Siberian State Aerospace University, Krasnoyarsk, Russia
e-mail: sava@iph.krasn.ru

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Abstract—Dependence of the magnetic and magnetooptical properties of an exchange-coupled NiFe/DyCo bilayer system on the thickness (t_{DyCo}) of a magnetically hard layer has been studied. It is established that the unidirectional anisotropy vanishes at t_{DyCo} ~ 400 Å, while the coercive field in the magnetically soft layer becomes comparable to the exchange-induced field shift. In this case, the DyCo layer magnetization is almost parallel to the film plane, whereas a reference DyCo film exhibits a perpendicular anisotropy. A model of the magnetic state of layers in the ferro/ferrimagnetic layer structure under consideration is proposed, which assumes that a 180° domain wall is formed at the interface upon magnetization reversal in the magnetically soft layer.

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The exchange coupling between magnetically soft (MS) and magnetically hard (MH) layers in thin-film structures leads to the appearance of unidirectional anisotropy in the magnetically soft layer. Although this phenomenon was discovered more than half a century ago [1], the mechanism responsible for the formation of this anisotropy is still not completely clear. At the beginning of the 1980s, a model was proposed [2] that assumed the formation of a magnetic transition region at the interface with a thickness (t_{in}) equal to that of the domain wall in the MH layer. However, the results of experiments with ferro/antiferromagnetic layer structures showed that this condition was not obeyed and the interfacial region thickness was smaller by an order of magnitude than the domain wall thickness [3, 4]. In order to explain this discrepancy, data on the magnetic structure of the interface are necessary. However, obtaining this information in ferro/antiferromagnetic film structures is hindered by small thickness of the interfacial transition region (t_{in} < 50 Å).

We have studied the mechanism of unidirectional anisotropy formation in a NiFe/DyCo bilayer film system, in which an amorphous alloy of rare-earth and transition metals is used as the MH layer. Distinctive features of the exchange-coupled ferro/ferrimagnetic film structures are (i) the mutually perpendicular orientation of effective magnetic moments in the two layers (in-plane orientation in the ferromagnetic NiFe layer versus normal orientation in the DyCo layer) and (ii) a much greater value of the unidirectional anisotropy field (and the exchange-induced shift H_E) in these systems as compared to that in ferro/antiferromagnetic film structures [5]. This work was aimed at evaluating the interfacial region thickness in NiFe/DyCo bilayer film structures, studying the influence of the DyCo layer thickness on the magnetic and magnetooptical properties of exchange-coupled NiFe/DyCo film structures, and determining the magnetic structure of the interface. This task was solved using the magnetic induction and magnetooptical techniques.

The experiments were performed with samples comprising a single-layer (reference) DyCo film and a NiFe/DyCo bilayer structure (Fig. 1a) deposited on the same substrate. The thickness of the DyCo layer was about 700 Å and that of the NiFe layer was about 1000 Å. Figure 1b shows the typical hysteresis loop observed for the NiFe layer (with $H_E \approx 22$ Oe and the coercive field $H_C \approx 2$Oe).

Figure 2 presents the wavelength dependences of the polar magnetooptical Kerr effect (MOKE) in the reference DyCo film and the MH layer of the NiFe/DyCo structure. The measurements were performed in a magnetic field of H = 14 kOe (applied along the normal to the film plane) in a 400–800-nm wavelength range. As can be seen, the MOKE magnitude in the two cases coincide at λ = 400 nm. The difference observed for λ > 400 nm is related to the fact that the permalloy layer in the NiFe/DyCo bilayer structure at H > 5 kOe is magnetized along the normal to the film plane. This leads to a change in the magnetic state of an interfacial region of the DyCo layer. As the wavelength of the incident light is decreased, a difference in the MOKE magnitudes in the reference film and the MH layer of the NiFe/DyCo bilayer structure decreases and eventually vanishes (at

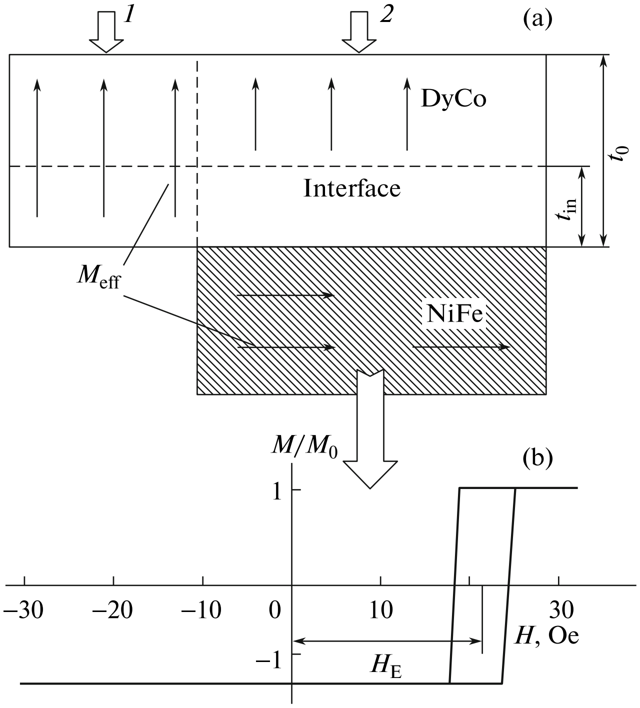

Fig. 1. (a) Schematic diagram of the sample with (*1*) a reference DyCo film and (*2*) a NiFe/DyCo bilayer structure and (b) the typical hysteresis of magnetization in the NiFe layer.

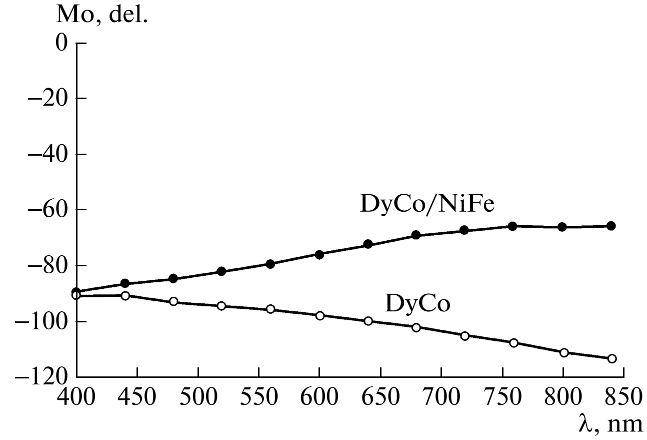

Fig. 2. Wavelength dependences of the polar MOKE in the reference DyCo film and the MH layer of the NiFe/DyCo structure.

$\lambda > 400$ nm). Assuming that, in the latter case, the response signal is related to a part of the MH layer not affected by the permalloy film and evaluating the depth δ of light penetration in the DyCo layer at $\lambda =$ 400 nm, we can estimate the interfacial layer thickness to be $t_{in} = t_0 - \delta$ (Fig. 1a). Estimated in this way, the interfacial layer thickness in the samples studied is $t_{in} \approx$ 400 Å, which is about half of the domain wall thickness in DyCo films.

In order to check for the value of the interfacial layer thickness calculated as described above, we have prepared and studied a series of NiFe/DyCo bilayer structures with the same thickness of the MS (permalloy) layer and the MH (DyCo) layer thickness varied in the range $t_{DyCo} \geq t_{in}$. Figure 3 shows the magnetization hysteresis loops observed for samples with $t_{DyCo} =$ 700 (sample 1) and 400 Å (sample 2), both with $t_{NiFe} =$ 300 Å. In the former case, the hysteresis is indicative of a unidirectional anisotropy (with $H_E = 80$ Oe), while in the latter case the loop is not shifted and the coercive field is equal to the exchange-induced shift for sample 1 ($H_C = H_E$). As is known [4], this behavior corresponds to a situation where the MH layer thickness is equal to that of the interfacial layer. Therefore, the bilayer films under consideration have $t_{in} \approx 400$ Å, in agreement with the data obtained from our magnetooptical measurements.

In order to elucidate the mechanism of formation of the unidirectional anisotropy in the bilayer films under consideration, it is necessary to obtain information on the magnetic structure of the interfacial region. For this purpose, we have studied the dependence of the magnetic state of the MH layer on its thickness by measuring the magnetooptical hysteresis loops (polar MOKE) at $\lambda = 400$ nm for samples 1 and 2 (Fig. 3) in the lateral and normal magnetic fields. It was established that the magnetic moment of the DyCo layer in sample 2 occurs almost in plane of the film, while that in sample 1 is directed along the normal to the plane.

Thus, the influence of the MS layer on the DyCo layer in the NiFe/DyCo bilayer structure leads to a change in the magnetic state of the MH material within a depth comparable with t_{in}. The magnetic moment of the MH material in this transition region is oriented in plane of the sample. In view of these data, we propose the following model of a magnetic state of layers in exchange-coupled films of NiFe and a rare earth–transition metal alloy (Fig. 4). If the permalloy layer occurs in a magnetized state, the MH layer separates into two regions. The upper part of the DyCo layer acquires magnetization perpendicular to that of the NiFe layer, while the magnetization of the lower part of the DuCo layer is rotated by 90° (Fig. 4a). During the magnetization reversal in a longitudinal field $H > H_E$, the magnetization in the NiFe film rotates by 180° and a 180° domain wall is formed in the interfacial region of the DyCo layer (Fig. 4b). An analogous pattern of magnetization in the interfacial region was previously proposed by Cain and Kruder [6] for NiFe/TbCo structures, but these samples exhibited some features that were difficult to explain: (i) the unidirectional anisotropy was only observed for a nonmagnetized MH layer and disappeared when this layer was magnetized; (ii) the coercive field in the NiFe

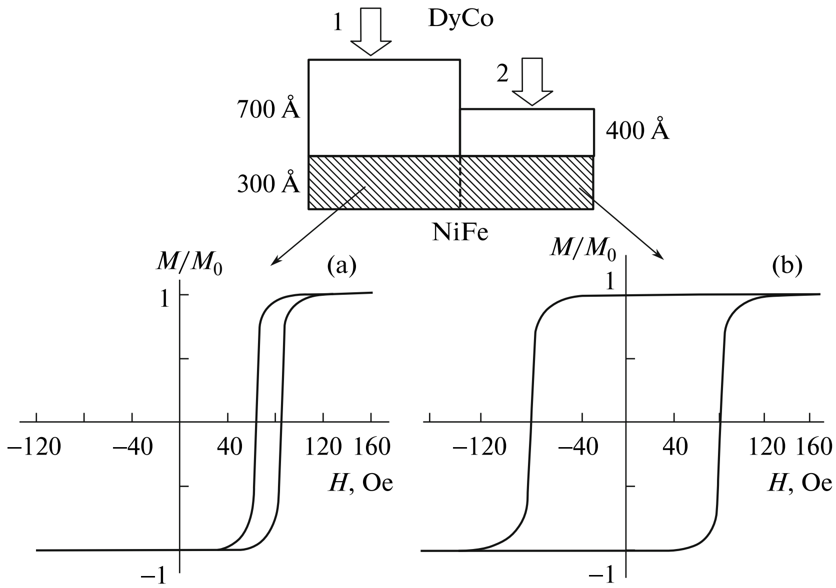

Fig. 3. Magnetization hysteresis loops observed for NiFe/DyCo bilayer structures with different MH layer thicknesses: (a) t_{DyCo} = 700 (sample 1); (b) t_{DyCo} = 400 Å (sample 2).

layer was an order of magnitude greater than that of usual permalloy films. These results are at variance with the data reported in [5, 7].

For deeper insight into the mechanism of unidirectional anisotropy formation in exchange-coupled ferro/ferrimagnetic layer structures, it would be of interest to study the dependence of the exchange interaction between layers on the MH layer thickness in the range $t < t_{in}$ and on the MS layer thickness in a range where the relation $H_E \sim 1/t_{NiFe}$ is violated.

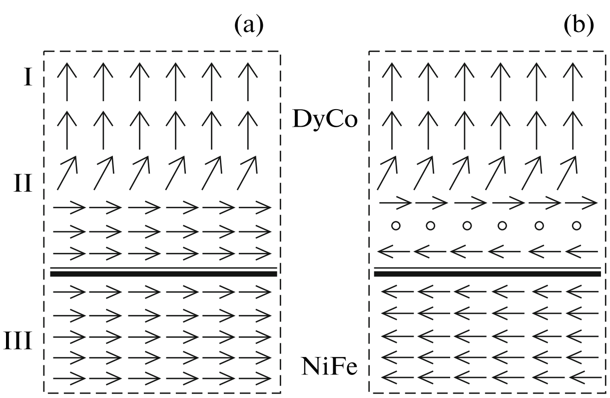

Fig. 4. Model of the magnetic state in exchange-coupled films of NiFe and a rare earth–transition metal alloy (a) in the initial state and (b) upon magnetization reversal.

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