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Parameters of the Transition Layer in the Exchange-Biased NiFe/DyCo Film Structure

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Abstract—The parameters of the transition layer in exchange-biased film structures are necessary agents to understand the mechanism of formation of unidirectional anisotropy. The layer thickness in NiFe/DyCo films has been determined by comparison of signals of the polar magneto-optical Kerr effect from a reference DyCo film and a hard magnetic layer of the exchange-biased structure. The layer thickness obtained is one order of magnitude larger than that characteristic of ferromagnet–antiferromagnet bilayer films. The mechanism of magnetization reversal of the structure under study has been explained within the model suggesting the formation of 180° boundaries in the interface.

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1. INTRODUCTION

The exchange biasing between hard magnetic and soft magnetic layers in the film structure creates a unidirectional anisotropy in the soft magnetic layer, which leads to a shift of the hysteresis loop along the axis of the magnetization reversal field by the value of H_E [1]. To explain the magnitude of the bias field observed experimentally and the dependence $H_E = f(1/t_{FM})$ (t_{FM} is the thickness of the soft magnetic layer), the model of formation of unidirectional anisotropy was proposed, which suggest the formation of a transition region (interface) in the hard magnetic layer [2]. In the interface, a magnetic structure different from the structures of the soft magnetic and hard magnetic layers is formed. The balance of the magnetostatic energy and the energy of unidirectional anisotropy leads to the phenomenological expression for the hysteresis loop shift

$$H_E = \Delta\sigma / M_{FM} t_{FM}, \qquad (1)$$

where M_{FM} is the magnetization of the soft magnetic layer and $\Delta\sigma$ is the change in the exchange energy during magnetization reversal of the ferromagnetic layer.

In this approach, the quantity $\Delta\sigma$ is equivalent to the energy of a domain wall in the hard magnetic layer, and the transition layer thickness corresponds to the domain wall width. However, the experiments performed on ferromagnet/antiferromagnet (FM/AF) structures show that the latter condition is violated [3]. The interface thickness is one order of magnitude smaller than the domain wall width. To explain these differences, another model in which the formation of the Bloch wall in the interface is suggested was proposed in [4]. Despite the great interest in this problem, we have no clear concept of the magnetic structure of the interface in ferromagnet/antiferromagnet film structures. Some researchers use the model with the Néel wall [5], other of them, the model of Bloch wall with elements of the cylindrical domains [6].

In this work, we study the influence of the thickness of the hard magnetic layer on the magnetic properties of two-layer exchange-biased ferromagnet/ferrimagnet film structures. In these structures, the role of the hard magnetic layer is played by amorphous alloys of rare-earth (terbium group) and transition metals (RE–TM). The difference between the ferromagnet/ferrimagnet structure and the better known ferromagnet/antiferromagnet structure is that the magnetization of the RE–TM layer has the component normal to the sample plane [7, 8]. At the same time, the value of H_E in NiFe/(RE–TM) films exceeds the value of the unidirectional anisotropy in structures with an antiferromagnetic layer [9, 10]. Since, in NiFe/(RE–TM) films, as in the NiFe/AF films, $H_E = f(1/t_{FM})$ [11], it can be suggested that the model related to the formation of the interface in a hard magnetic layer is suitable also for given samples. Because of this, to interpret specific features of the exchange interaction between ferromagnetic and ferromagnetic layers, we need information on the interface parameters and, first of all, the data on its thickness.

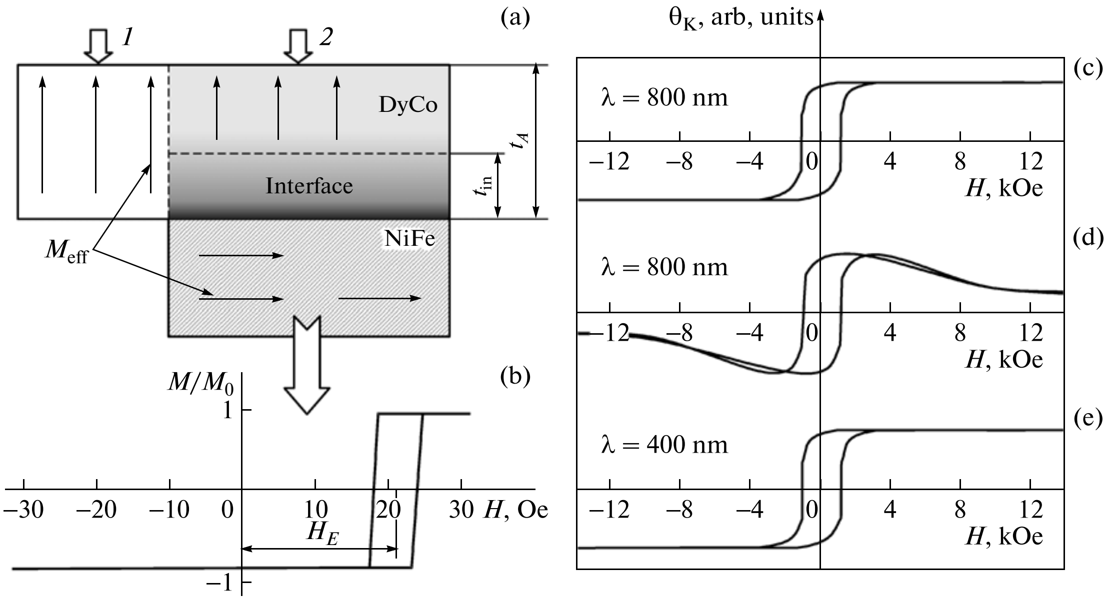

Fig. 1. (a) Cross section, (b) induction hysteresis loop, and (c–e) magneto-optical hysteresis loop of the films under study.

2. DETERMINATION OF THE INTERFACE THICKNESS

It was shown in [12] that there is a critical thickness of a hard magnetic layer (t_{in}) at which the unidirectional anisotropy disappears. In this case, the hard magnetic layer is unreversibly remagnetized together with the soft magnetic layer, which brings about an increase in the coercive force of the NiFe film. It occurs when the condition is fulfilled as follows:

$$t_A \le t_{in} = \Delta\sigma / K_A, \qquad (2)$$

where t_A is the thickness, and K_A is the constant of anisotropy of the hard magnetic layer.

The simplest method of determining t_{in} is seemingly to obtain a set of the samples, in which t_{FM} = const and t_A is varied. However, such an approach is thought to be incorrect, since the process of their preparing can be accompanied by a change in the chemical composition of the hard magnetic layer, which leads to changes in its properties.

To determine t_{in} in the NiFe/(RE–TM) film structure, we used the fact that RE–TM alloys have good magneto-optical effects, and the interface thickness can be found from the spectral dependence of these effects. These studies were performed on NiFe/DyCo two-layer films with the exchange unidirectional anisotropy. For this purpose, we prepared the samples that were (*1*) single-layer DyCo (reference) and (*2*) two-layer NiFe/DyCo films combined on the same substrate (Fig. 1a). The DyCo layer thickness was 700 Å, and the NiFe layer thickness was 1000 Å; the hard magnetic layer composition was: 22 at % Dy and 78 at % Co. Figure 1b depicts the induction hysteresis loop from the NiFe layer ($H_E \sim 22$ Oe, $H_C \sim 2$ Oe). The hysteresis loops measured using the polar magneto-optical Kerr effect (θ_K) and the spectral dependences of θ_K obtained from the reference DyCo film and from the hard magnetic layer of the exchange-biased NiFe/DyCo film in the magnetic field H = 14 kOe normal to the film plane in the wave length range 400–850 nm are depicted in Figs. 1c–1e and 2, respectively. Figure 1c shows the hysteresis magneto-optical loop from the reference DyCo film at λ = 800 nm. The loop shape demonstrates that the effective magnetization is directed along a normal to the film plane, and $H_C \sim$ 1 kOe. Figures 1d and 1e show the hysteresis loops for DyCo layer measured at λ = 800 and 400 nm. It is seen that the hysteresis loop shape measured at the wave length λ = 800 nm in magnetic fields ~5–14 kOe is different from the magnetization reversal curve of the reference film by the existence of a kink at $H > 5$ kOe. This result is related to the fact that, in noted fields, the NiFe layer magnetization is directed along a normal to

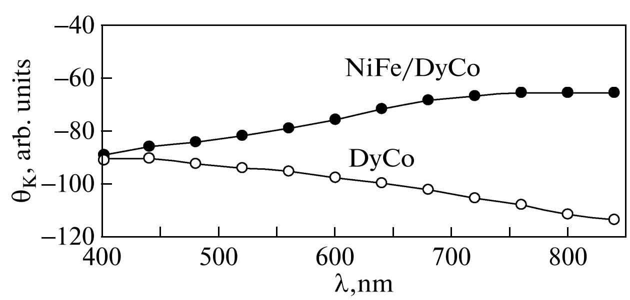

Fig. 2. Spectral dependence of the polar magneto-optical Kerr effect (θ_K) in the DyCo film and NiFe/DyCo film structure.

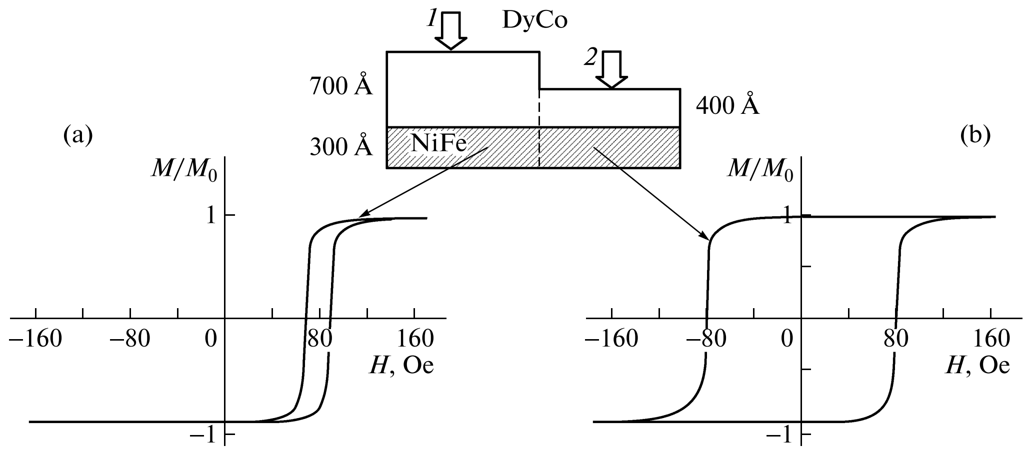

Fig. 3. Induction hysteresis loops for the NiFe/DyCo films with different thicknesses of the hard magnetic layer t_{DyCo} = (*1*) 700 and (*2*) 400 Å at t_{NiFe} = 300 Å.

the film plane. In this case, the magnetic state in the DyCo layers bordering NiFe is changed. The magnitude of the kink decreases with the wave length of the incident light, and the loop shapes from the DyCo layer and from the reference film coincide at λ = 400 nm (Fig. 1e). Figure 2 depicts as well that the values of the magneto-optical effects of these films coincide at $\lambda \sim 400$ nm. If to assume that the signal is measured from a part of the hard magnetic layer that does not undergoes the influence of the NiFe layer, we can determine also the interface thickness $t_{in} = t_A - \delta$ by estimation of the light penetration depth δ at λ = 400 nm (Fig. 1a).

To calculate δ, we use the study [13] which presents the calculations of the optical properties of metallic films (dependence of the coefficients of damping, transmission, and absorption on the wave length of the incident light and sample thickness). These dependences were calculated for the strongly reflecting and moderate reflecting films. Based on our data on the spectral dependence of the transmission coefficient of the DyCo film, we can consider them moderate reflecting films. As a result, we obtain $\delta \sim 300$ Å for our samples at λ = 400 nm. Then, the interface thickness of our films is $t_{in} = t_A - \delta = 400$ Å.

To verify the obtained values of the interface thickness, we synthesized a series of NiFe/DyCo films in which the thickness of the soft magnetic layer was retained constant, and the DyCo layer thickness was varied in the range $t_A \geq t_{in}$. Figures 3a and 3b show the induction hysteresis loops for film *1* (t_{DyCo} = 700 Å) and film *2* (t_{DyCo} = 400 Å) (t_{NiFe} = 300 Å). The chemical composition of hard magnetic layer was: 24 at % Dy and 76 at % Co. As seen from Fig. 3b, there is no unidirectional anisotropy in film *2*, and its coercive force is equal to the bias field in film *1* ($H_C = H_E$). According to Eq. (2), this coincidence takes place as the hard magnetic layer thickness is equal to the interface thickness, i.e., the films have t_{in} = 400 Å, which coincides with the result of magneto-optical measurements.

In connection with that the interface thickness is one order larger than that in NiFe/FeMn films, it is of interest to compare it with the domain wall width in the RE–TM films. The exchange parameter of the RE–TM amorphous films is $A \sim 3 \times 10^{-7}$ erg/cm [14]. Since the magnetic anisotropy constant in the interface (K_A) can be different from the anisotropy of the DyCo layer because of violation of the surface topology of the NiFe layer, we determined this constant using the approach as follows. It follows from Eqs. (1) and (2) that

$$K_A = H_E M_{FM} t_{FM}/t_{in}. \quad (3)$$

Substituting the parameters of the NiFe/DyCo film structure, whose hysteresis loops are shown in Fig. 1 (t_{NiFe} = 1000 Å, t_{in} = 400 Å, M_{FM} = 800 emu/cm^3, and H_E = 22 Oe) into Eq. (3) gives $K_A \sim 4 \times 10^4$ erg/cm^3. Then, the domain wall thickness $d_W = \pi(A/K_A)^{1/2} \sim$ 800 Å, this is, the interface thickness for this structure is $t_{in} \sim d_w/2$.

3. MAGNETIC STRUCTURE OF THE INTERFACE

Because when building a more correct model of the mechanism of formation of the unidirectional anisotropy in exchange-biased magnetic films, an important problem is the direct observation of the interface domain structure, the ferromagnet/ferrimagnet film structure opens wide possibilities of solving this problem owing to good magneto-optical effects in the RE–TM alloy and a large thickness of the transition layer. In this connection, it is of interest to study the influence of the hard magnetic layer thickness on its magnetic properties. For this purpose, we measured the

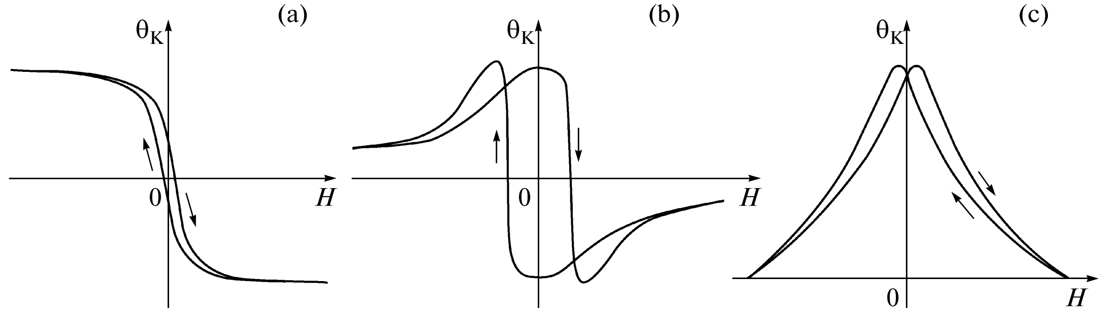

Fig. 4. Magneto-optical hysteresis loops (polar Kerr effect) for the NiFe/DyCo films with (a) $t_{DyCo} < t_{in}$ and (b, c) $t_{DyCo} > t_{in}$. The field **H** is (a, b) perpendicular to the sample plane and (c) parallel to this plane.

magneto-optical hysteresis loops (polar Kerr effect) of the DyCo layer in films *1* and *2* (Fig. 3) in magnetic fields parallel and perpendicular to the film plane. The data are depicted in Fig. 4. As seen from Fig. 4a, for the loop with $t_{DyCo} < t_{in}$, the magnetic moment of the DyCo layer is practically in the film plane (the signal in the longitudinal field is one order of magnitude weaker than that in $H_\perp$, and it is not shown in the figure). The hysteresis loops for the film with $t_{DyCo} > t_{in}$ indicate that the magnetization of the DyCo layer is directed along a normal to the film plane (Figs. 4b and 4c). The magneto-optical loops measured from the reference films show that the magnetizations in both the samples are directed along a normal to the film plane.

Thus, we can state that the influence of the soft magnetic layer on the DyCo layer in such a structure leads to a change in its magnetic state at the thicknesses comparable with t_{in}. The magnetic moment of this layer practically lies in the sample plane. This result contradicts to the data from [8, 9] in which it was suggested that the unidirectional anisotropy is due to the existence of a plane component of the magnetization in the initial structure of the RE–TM films, and the effects of the exchange interaction with the soft magnetic layer do not cause its transformation.

Based on our data, the model of the layer magnetic state in exchange-biased NiFe/(RE–TM) films can be proposed as follows (Fig. 5). If the permalloy layer is in a magnetized state, the hard magnetic layer is separated into two portions: the upper DyCo layer portion has the magnetization perpendicular to the magnetization of the NiFe layer; and the magnetization in the lower DyCo layer portion changes its direction by 90° (Fig. 5). In some theoretical studies, the idea on a possibility of appearance of the interface in the soft magnetic layer has been suggested [15, 16]. However, the experimental data do not support this assumption. In [17], the magnetization profile in the NiFe/FeMn ($t_{NiFe} = t_{FeMn} = 400$ Å) film structure was studied by the diffraction of polarized neutron and no deviations of the magnetic moment in the NiFe layer thickness were detected. As the samples were remagnetized in a field $H > H_E$, the experiment did not show formation of domain wall in the soft magnetic layer. The reason may be the fact that, in these structures, the domain wall energy in the soft magnetic layer is higher then the domain wall energy of the hard magnetic layer [10]. This condition is also fulfilled in our films.

Because of this, as the films are remagnetized in a longitudinal field $H > H_E$, the magnetization of the NiFe layer is rotated by 180°, and the 180° domain boundary is formed in the DyCo transition layer (Fig. 5b). Similar pattern of the interface magnetic state in the NiFe/TbFe films was proposed in [18]. However, these samples exhibit a number of entirely unexplained specific features: first, the unidirectional anisotropy exists only as the hard magnetic layer is demagnetized, and it disappears as this layer is magnetized; second, the coercivity of the NiFe layer exceeds that of usual permalloy films by an order of magnitude. These data contradict to both our results and the data presented in [8].

Summing all of the preceding, we can conclude the following.

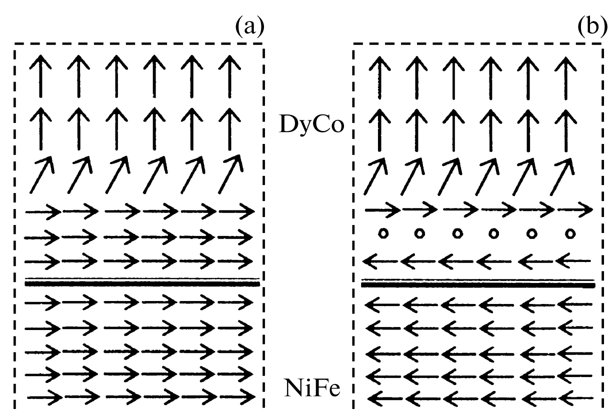

Fig. 5. Magnetic state of layers in the exchange-biased NiFe/(RE–TM) film: (a) the structure is in the initial state of the structure, and (b) the soft magnetic layer is remagnetized in a longitudinal field $H > H_E$.

(1) In the exchange-biased ferromagnet/ferrimagnet film structure, the transition layer whose magnetic properties are different comparing the properties of main layers is formed. The interface thickness is one order of magnitude larger than that in the ferromagnet/ferrimagnet structures, and this fact opens wide possibilities for studying in more detail of the mechanism of formation of the unidirectional anisotropy.

(2) In the interface, the magnetic structure is formed, which reflect the transition from the direction of the magnetization of the soft magnetic layer to that of the hard magnetic layer; i.e., the exchange interaction between the layer brings about a change in the magnetic structure of a part of the hard magnetic layer contacting with the soft magnetic layer. This effect is similar to the spin-flop transition in the FM/AF structures with the orthogonal (in the film plane) arrangement of the magnetizations in the layers [19].

(3) To further study the nature of the unidirectional anisotropy in exchange-biased ferro–/ferromagnetic film structures, it is of interest to study the influence of the thicknesses of the hard and soft magnetic layers in the range $t_{\mathrm{RE-TM}}$, $t_{\mathrm{NiFe}} \ll t_{\mathrm{in}}$.

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