Journal of Superconductivity and Novel Magnetism (2021) 34:2969–2975
https://doi.org/10.1007/s10948-021-06001-x

ORIGINAL PAPER

Study of Surface Anisotropy of the Interface of Two-layer DyCo/FeNi Films by the Spin-wave Resonance Method

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Received: 8 July 2021 / Accepted: 2 August 2021 / Published online: 2 September 2021

Abstract
Two-layer DyCo/FeNi films were studied by the spin-wave resonance method. The experimental microwave frequency absorption spectra of the two-layer DyCo/FeNi films demonstrate the bulk and surface peaks of the exchange spin modes. The dependence of the surface condition type formed at the interface on the composition of the hard-magnetic layer (before and after the compensation point) was found. The values of the surface anisotropy constant and the type of magnetization pinning at each surface of the FeNi layer were estimated.

Keywords Surface anisotropy constant · Spin-wave resonance · Thin magnetic films · Exchange-bias effect

1 Introduction

The unique physical properties of the two-layer films composed of a high-permeability layer and a hard-magnetic one have been of great interest since the last century. The unidirectional magnetic anisotropy [1] observed in such systems is a remarkable phenomenon caused by an exchange interaction between the layers. The anisotropy of this type was first observed in the ferromagnetic-antiferromagnetic system; but the structures with a ferrimagnetic film composed of an alloy of rare-earth and transition metals (RE-TM) used as a hard-magnetic layer [2–6] appear to be the most prospective from the viewpoint of practical application. One of the unique phenomena observed in the RE-TM structures is a normal position of the effective magnetization of their individual layers [2]. It should be noted that the magnetic properties of planar systems such as Tb_xFe_{1-x}/NiFe and Dy_xCo_{1-x}/NiFe are described not only by an unidirectional magnetic anisotropy studied in such structures [2] but also by the rare earth metal concentration in the composition of the hard-magnetic layer [7]. The influence of the hard-magnetic layer composition (before and after the compensation point) on the configuration of magnetization vectors in the ferri- and ferromagnetic layers as well as on the thickness of the effective magnetic layer d_{eff} was described in [5, 8] at the example of the two-layer DyCo/FeNi films.

A number of various methods (magneto-optical-Kerr-effect, SQUID magnetometry, and polarized-neutron-reflectivity) allowed the authors [9] to find new mechanisms of the exchange-bias effect due to the effects occurring at the interface between the DyCo and FeNi layers as well as due to the REM concentration in the ferrimagnetic layer. As is known, the sign and value of the surface anisotropy constant K_S can be used to estimate the interface conditions both qualitatively and quantitatively. Direct measurements of this parameter can be carried out by the spin-wave resonance method [10].

The aim of this study is to measure the surface anisotropy constant at the interface between the DyCo and FeNi layers of the two-layer exchange coupled films and to determine the type of dependence of magnetization pinning at the surface on the composition of the hard-magnetic layer.

2 Materials and Methods

Two-layer exchange-coupled DyCo/FeNi films were prepared by the thermal evaporation method (the high vacuum pressure was $3 \cdot 10^{-6}$ Torr) on a cover glass. The layers were

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sputtered from three independent evaporation sources with a ring-shaped cathode. When the permalloy layer ($Fe_{0.2}Ni_{0.8}$) was sputtered, the constant magnetic field (~20 Oe) was applied in the plane of the sample. The prepared samples had different compositions of the DyCo alloy—$Dy_{0.2}Co_{0.8}$ and $Dy_{0.3}Co_{0.7}$. The concentrations chosen by us were located on either side of the compensation point ($Dy_{0.22}Co_{0.78}$) on the composition axis; however, these alloys had similar values of the basic magnetic parameters (saturation magnetization $M_S = 8mT$, coercive field strength H_C~4 kOe and perpendicular magnetic anisotropy value ($K = 3 \cdot 10^4 J/m^3$) [11]. The magneto-optical-Kerr-effect (the field value up to 15 kOe) was used as an indirect method to control the hard-magnetic layer composition before and after the compensation point [8]. The thickness of the hard-magnetic layer was ~70 nm. The thickness of the $Fe_{0.2}Ni_{0.8}$ layer was ~150 nm for the film with the composition of the DyCo layer before the compensation and it was equal to ~300 nm for the film with the composition of the DyCo layer after the compensation. The technological methods (low temperature $\leq 50°C$ of the substrate during sputtering; high magnetic layer had amorphous structure) were used in order to obtain a sufficiently sharp edge between the ferro- and ferrimagnetic layers.

The thickness and chemical composition of the layers for all the prepared samples were tested by the X-ray analysis. The structure type was determined using a diffractometer DRON-4, the wavelength being $\lambda = 1.54056$ Å (Cu K_α).

The absorption spectra of the films were measured by a standard spectrometer (X-ray) at room temperature at a pumping frequency of the cavity ~9.2 GHz, and the wave vectors of the standing exchange spin waves ranged from 10^5 to $2 \cdot 10^6 cm^{-1}$. The films were placed in an antinode of a variable magnetic field of the transmission type cavity and magnetized normal to the surface $\theta_H = 0$ (Fig. 1).

Microwave spectra of the two-layer films were analyzed taking into account the magnetic parameters obtained from the resonance curves of two reference single-layer $Fe_{0.2}Ni_{0.8}$ films. The control of the cooling rate of the sample after sputtering and the use of the GeO film for protecting the surface from oxidation allowed creating the necessary boundary conditions at the outer surface [12]. A certain type of pinning at the interface "substrate-FeNi" was performed by controlling both the sputtering rate and substrate temperature. In a particular case, in order to estimate the value of the surface anisotropy constant K_S a film with the boundary conditions of the "easy plane" type at each surface was prepared (Fig. 2a). The microwave spectrum of the second sample of the $Fe_{0.2}Ni_{0.8}$ film (Fig. 2b), with the boundary conditions of the "easy axis" type being formed at each surface (thus, the surface contribution to the magnetic field was minimized), was used to detect the spin-wave (exchange) stiffness η. The experimental microwave spectra of the two-layer DyCo/FeNi films are presented in Fig. 2c, d. During the analysis of the recorded spectra, the individual modes were decomposed into components using the differentiated Lorenz function (Fig. 2). The choice of the Lorenz function was made taking into account the absence of the electric component contribution (due to the cavity design and film size).

3 Experimental Results and Discussion

Taking into account the equilibrium conditions [13, 14], the induced heterogeneous oscillations of magnetization m appearing as a result of the applied homogeneous variable magnetic field h (h⊥H) with the frequency ω are described by the dispersion relation

$$\left(\frac{\omega_0}{\gamma}\right)^2 = \left(Hcos(\varphi - \theta_H) - H_{eff}cos2\varphi + \frac{2A}{M_S}k^2\right) \times \left(Hcos(\varphi - \theta_H) - H_{eff}cos^2\varphi + \frac{2A}{M_S}k^2\right) \quad (1)$$

where A is the exchange interaction constant; k is the wave vector whose values are defined by the boundary conditions at the film surface; φ is the angle between the normal perpendicular to the film surface and the magnetization direction M; θ_H is the angle between the film normal and the

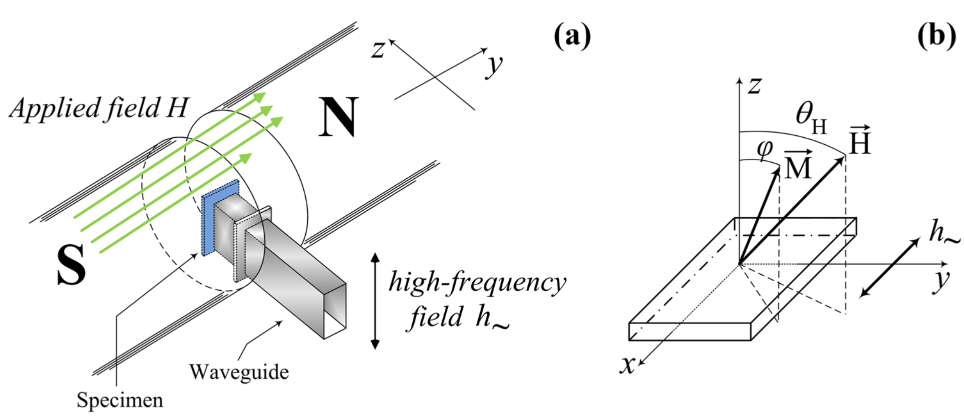

Fig. 1 The orientation of the film inside the cavity (**a**) and direction of the applied magnetic field relative to the film (**b**)

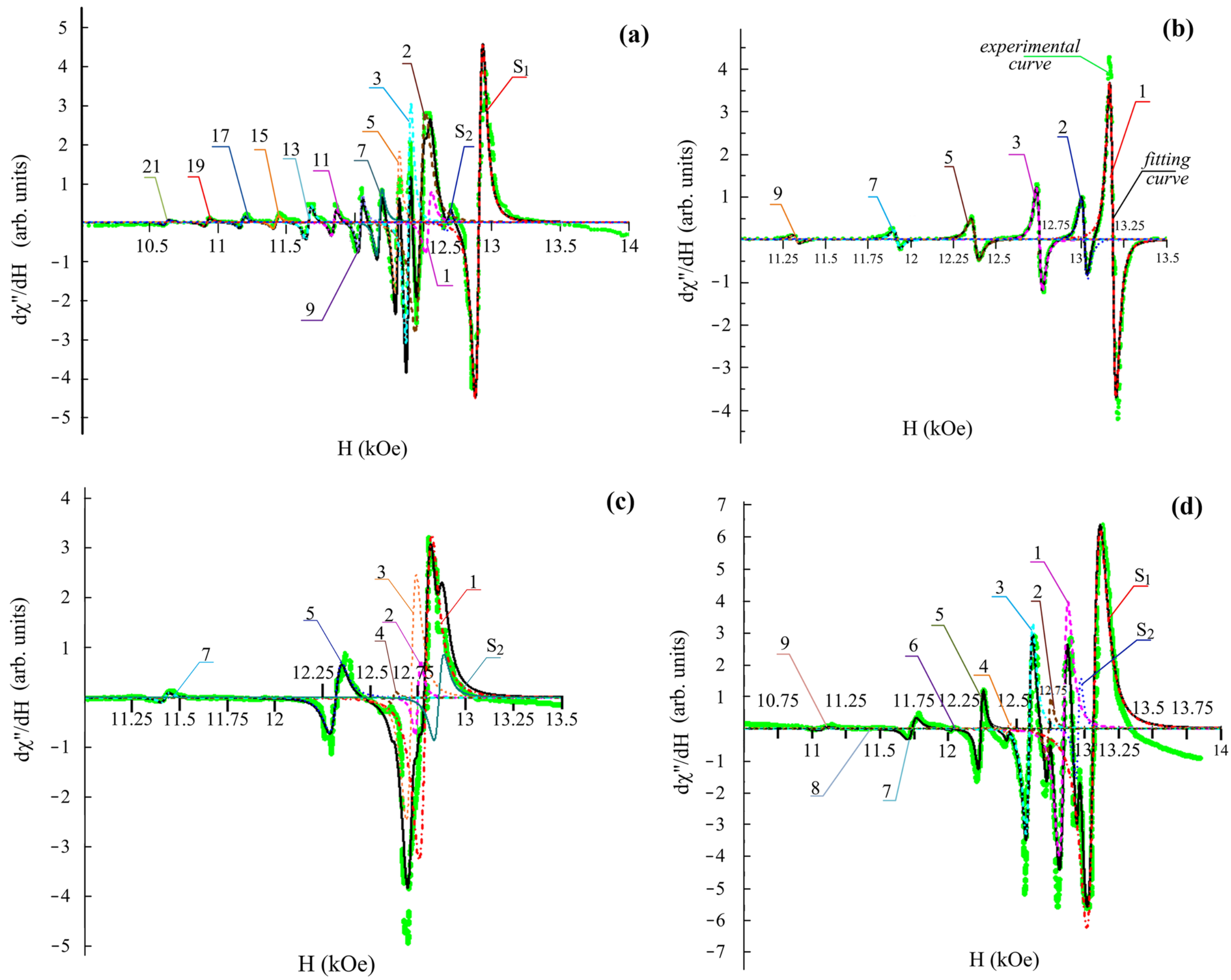

Fig. 2 The experimental microwave spectra of the single-layer $Fe_{0.2}Ni_{0.8}$ films (**a** and **b**) and two-layer films with the REM concentration in the DyCo film before (**c**) and after (**d**) the compensation point

applied field direction H; H_{eff} the effective field which takes into account the anisotropy impact from different sources.

Assuming that in the general case the surface spins on the opposite sides of the film are pinned differently, the exchange boundary conditions can be described using the expressions [15–17]

$$\left(\frac{\partial m}{\partial z}+\beta_1^S m\right)_{z=d/2}=0, \qquad \left(\frac{\partial m}{\partial z}+\beta_2^S m\right)_{z=d/2}=0, \quad (2)$$

where β_1^S and β_2^S are the pinning parameters of the surface spins on the opposite film sides related to the surface anisotropy constant K_S by $\beta^S = \frac{K_S}{A}$; and d is the film thickness.

Assuming that the solution of Eq. (2) is a plane wave, given the random pinning parameters at the upper and lower surface of the film, possible values of the wave vector k can be defined by equation [18]

$$tg(kd) = \frac{k\left(\frac{K_{S1}}{A}+\frac{K_{S2}}{A}\right)}{k^2-\left(\frac{K_{S1}}{A}\cdot\frac{K_{S2}}{A}\right)} \quad (3)$$

where K_{S1} and K_{S2} are the values of the surface anisotropy constant at the opposite surfaces of the film.

The recorded microwave spectra have a complex form which is characterized by many modes (2), the rules to recognize individual modes being reported in [15–17, 19–21].

Here, we note only the rules to recognize the modes which are the most significant for this study. An important condition to excite standing spin waves is the boundary conditions depending on the average value of the magnetic moment at the surface as well as the magnetization distribution through the film thickness [22]. The surface anisotropy constant K_S taking both positive and negative values is a quantitative and qualitative parameter which describes the implementation of one or another type of the boundary conditions. If $K_S > 0$, i.e., the easy axis of the surface anisotropy is normal to the film surface, there are only harmonic modes with the real values of k_n (Fig. 2b). When $K_S < 0$, i.e., the hard axis of the surface anisotropy is normal to the film surface along with the harmonic modes one can observe a hyperbolic evanescent exchange spin wave (surface wave) with the imaginary wave vector k_S (Fig. 2a). If $K_S = 0$, the homogeneous variable magnetic field excites only the heterogeneous magnetization fluctuation $m_0 \perp M$ (ferromagnetic resonance) since all other possible fluctuations $m(z)$ have a zero dipole moment.

According to [23], when there are symmetric boundary conditions (the value of the surface anisotropy constant at both surfaces is equal) with $K_S = \infty$, the value $k_n = \pi n/d$ where n is the number of the trigonometric mode taking the values 1,3,5,7.

The recognition of the modes in the microwave spectrum with the antisymmetric boundary conditions (there is pinning of the "easy axis" type at one of the surfaces and that of the "easy plane" type at the other) depends on the value $K_{S1} + K_{S2}$. In the first situation if $|K_{S1} = K_{S2}|$, the experimental spectrum has one surface mode in the resonance field which is stronger than the resonance field of the basic trigonometric mode, with the even modes being absent [10]. In the second case, when the values $|K_{S1}|$ and $|K_{S2}|$ vary greatly, then there are both even and odd modes in the microwave spectrum (Fig. 2c). And in the third case, when the value $K_{S1} + K_{S2}$ is slightly different from zero, resulting in the absence of the even mode with $n = 2$ in the spectrum. There is also a case where there are two surface modes in the microwave spectrum according to the terms of $K_{S1} < 0$ and $K_{S2} < 0$ [10] (Fig. 2a, d). The values of the wave vector are found for the bulk standing spin modes $k_n = \pi n/d$ as previously but for the surface mode $ik_S = K_S/A$ [17].

The important condition to interpret the spectrum is the intensity of the excited modes. The intensity of heterogeneous spin modes depends on the sample thickness as well as on the value and sign of the surface anisotropy constant [24]. The dependence of the relation between the intensity of the first bulk mode I_1 and the intensity of the surface mode I_S on the film thickness was studied [16].

The experimental spectra were interpreted using the described rules. The microwave curve of the reference single layer $Fe_{0.2}Ni_{0.8}$ film (Fig. 2a) demonstrates two surface modes ($S_1$and S_2) located in the fields larger than the field of the first bulk spin-wave mode, indicating the "easy plane" type pinning on each film surface. The preparation conditions of the second single-layer $Fe_{0.2}Ni_{0.8}$ film ensure the realization of the boundary conditions of the "easy axis" type and as a result, the microwave spectrum of this reference sample (Fig. 2b) contains only harmonic even and odd modes. The dependence of the resonance field positions H_{res} of the bulk standing spin modes on the square of the mode number n is described by Eq. (1) for each permalloy film with high accuracy (Fig. 3). The deviation of the first modes from the square dependence, in our opinion, is associated with more considerable heterogeneity of the magnetic parameters of the system near the surface, than in the film bulk due to the influence of the surface anisotropy [25, 26].

The theoretical [27, 28] and experimental [8] studies show that a node of the standing spin-wave pinning can be formed at the inner (effective) surfaces which do not coincide with the external geometric boundaries of the film. The difference between the directions of the magnetization vector M_{Co} of the Co sublattice in the ferrimagnetic layer and magnetization vector M_{FeNi} of the permalloy film before and after the

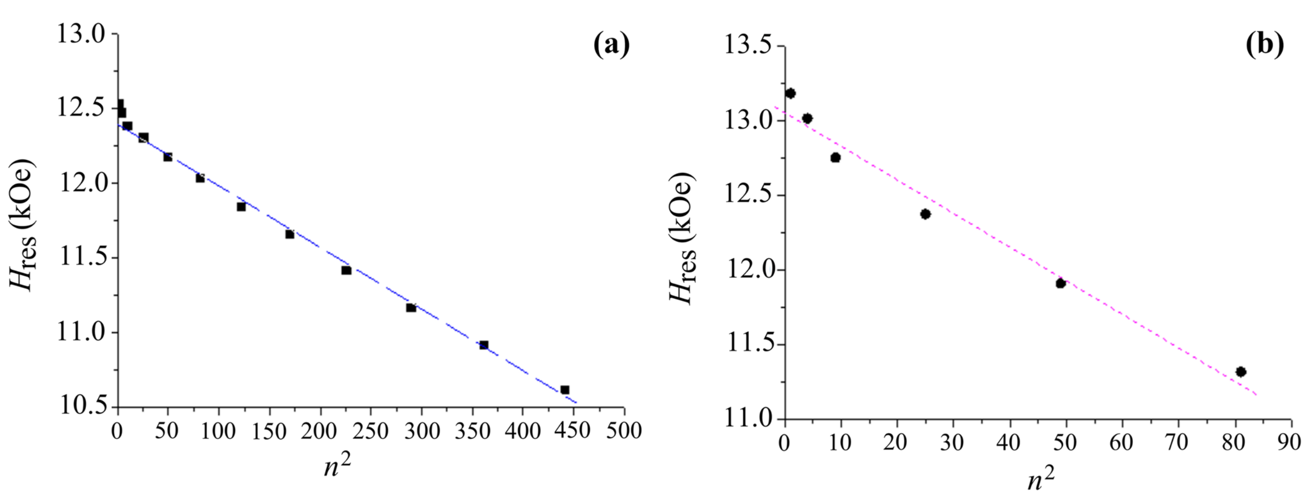

Fig. 3 The dependence of the resonance field H_{res} on the square of the mode number n for the $Fe_{0.2}Ni_{0.8}$ films with the magnetization pinning of the "easy plane" (**a**) and "easy axis" types (**b**) on each surface

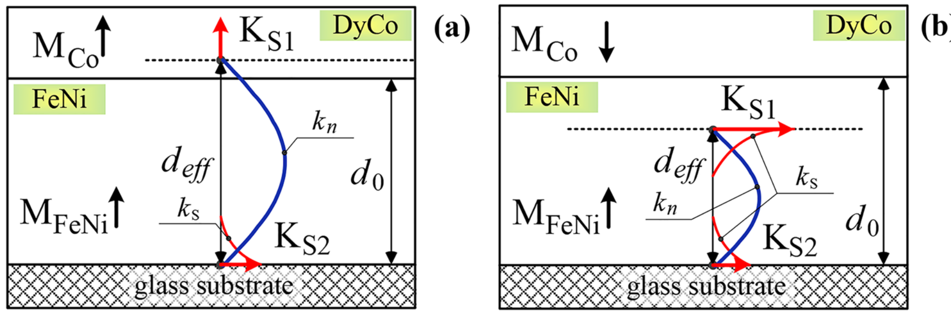

Fig. 4 The configuration of the magnetization vectors and surface anisotropy for the two-layer FeNi/DyCo films with the composition of the hard magnetic layer before (**a**) and after (**b**) the compensation

compensation point [8] (Fig. 4) determines the position of the effective surface where the standing spin wave is pinned at the DyCo-FeNi interface as well as the type of the formed boundary conditions on this plane, as is shown by our results. The unidirectional position of the vectors M_{Co} and M_{FeNi} in the case of the composition of the hard magnetic layer before the compensation and the exchange interaction of the local magnetic moment result not only in shifting the effective surface in the DyCo layer but also in the alignment of the surface anisotropy in this direction (Fig. 4a); i.e., the anisotropy of the "easy axis" type is observed.

The counter-directed vectors M_{Co} and M_{FeNi} form a transient layer between FeNi and DyCo, where there is a smooth turn of 3d metal spins by π. It results in a bias of the effective surface into the FeNi layer and pinning of the "easy plane" type in the interface area. This pinning type is more beneficial in terms of energy minimization.

The described assumptions concerning the influence of the hard magnetic layer composition on the type of pinning to the DyCo-FeNi interface area are confirmed by the experimental absorption microwave spectra (Fig. 2c and d). The spectrum of the film having the composition of $Dy_{0.2}Co_{0.8}$ before the compensation demonstrates a single surface mode S_2 (Fig. 2c) excited at the interface "substrate-FeNi"; i.e., the pinning type at this surface is "easy plane" ($K_{S2} < 0$). The absence of the second surface mode in the fields which are larger than the first trigonometric peak means that pinning of the "easy axis" type is observed at the DyCo-FeNi interface. The spectrum of the film having the composition of $Dy_{0.3}Co_{0.7}$ after the compensation (Fig. 2d) has two surface modes S_1 and S_2. It proves that there is "easy plane" type pinning on each boundary of the spatial region ($K_{S2} < 0$ and $K_{S1} < 0$), but the surface anisotropy constant has a different value on each boundary (Fig. 4b).

The present surface modes for the spectra ($K_S < 0$) allow us to find out the value of the surface anisotropy constant

$$|K_S| = \left[\frac{M_{eff}A}{2} \cdot \left[\left(H_S - H_1\right) - \frac{2A}{M_{eff}}\left(\frac{\pi}{d}\right)^2\right]\right]^{1/2} \quad (4)$$

where H_S and H_1 are the resonance fields of the surface and the first bulk standing spin wave, respectively.

The resonance field positions also allow us to estimate the exchange interaction constant A (Table 1)

$$A = \frac{M_{eff}}{2}\left(\frac{d}{\pi}\right)^2 \frac{H_n - H_{n+1}}{(n+1)^2 - n^2} \quad (5)$$

and the exchange stiffness η

$$\eta = \left(\frac{d}{\pi}\right)^2 \frac{H_{n-1} - H_{n+1}}{(n+1)^2 - (n-1)^2} \quad (6)$$

The bias of the effective plane either into the DyCo layer (composition before the compensation) or into the FeNi layer (composition after the compensation) results in a difference between the thickness d_0 of the FeNi layer and the thickness of the effective magnetic layer d_{eff} within which the standing spin waves are excited (Fig. 4). Using the value of the exchange interaction constant obtained for the monolayer permalloy film with the boundary conditions of the "easy axis" type and Eq. (5), we estimate the value d_{eff} for the two-layer films (Table 1). The obtained value d_{eff} allows us to determine the effective values of the exchange interaction constant and surface anisotropy constant for the films $Dy_xCo_{1-x}/Fe_{0.2}Ni_{0.8}$ (Table 1).

For the considered systems, the second spatial parameter can be found to be the penetration depth d_S of the surface spin wave which is inversely proportional to the wave vector k_S.

The values presented in Table 1 lead to several conclusions. First, the approximately equal values of the exchange interaction constant prove the equivalence of the magnetic parameters of the ferromagnetic layer of all the samples, which is one of the distinctive features of the high-quality preparation method. Second, comparing the difference between d_0 and d_{eff} for the two-layer films, it can be assumed that the hard magnetic layer influences not only the type of surface pinning but also the thickness of the effective magnetic layer. The size of the spatial area where the spin waves are excited for the film with the composition before the compensation is larger by 16% than the thickness of the permalloy layer. Meanwhile, the difference between d_0 and

Table 1 The estimated value d_{eff} for the two-layer films using the value of the exchange interaction constant obtained for the monolayer permalloy film with the boundary conditions of the "easy axis" type and Eq. (5)

		The reference films $Fe_{0.2}Ni_{0.8}$ with the boundary conditions		The two-layer films $Dy_xCo_{1-x}/Fe_{0.2}Ni_{0.8}$	
		"Easy axis"	"Easy plane"	Before the compensation ($Dy_{0.2}Co_{0.8}$)	After the compensation ($Dy_{0.3}Co_{0.7}$)
M_{eff}, mT		~78.9	~76.1	~77.7	~79.4
$A_{eff}\,10^{-11}$, J/m		~0.46	~0.59	~0.29	~0.30
$k_S, mJ/m^2$	S_1	-	~0.172	-	~0.152
	S_2	-	~0.129	~0.074	~0.100
$k_S 10^5, 1/cm$	S_1	-	~2.91	-	~5.06
	S_2	-	~2.18	~2.55	~3.33
d_S, nm	S_1		~34		~20
	S_2		~46	~40	~30
The thickness of the layer (film) $Fe_{0.2}Ni_{0.8}$ d_0, nm		~220	~280	~150	~300
d_{eff}, nm		-	-	~175	~185

d_{eff} for the film with the composition after the compensation is about 38%.

4 Conclusion

The study of the two-layer FeNi/DyCo films carried out by the spin-wave resonance method demonstrates the dependence of the surface anisotropy type at the interface between the FeNi and DyCo layers on the rare earth metal concentration in the hard magnetic layer. It is found that there is the surface anisotropy of the "easy axis" type at the interface, with the hard magnetic layer having the composition before the compensation point ($Dy_{0.2}Co_{0.8}$). The ferrimagnetic layer composition after the compensation point ($Dy_{0.3}Co_{0.7}$) leads to the surface anisotropy of the "easy plane" type at the interface between the FeNi and DyCo layers. It is also important to note that there is an influence of the hard magnetic layer on the spatial parameters of the distribution area of the spin exchange standing wave whose width d_{eff} does not coincide with the permalloy layer thickness d_0. Thus, $d_{eff} > d_0$ for the composition DyCo before the compensation and $d_{eff} < d_0$ for the composition of the hard magnetic layer after the compensation point in the two-layer film.

Note that the obtained influence of the hard magnetic layer composition in the two-layer DyCo/FeNi films on the surface anisotropy type is important not only from the viewpoint of fundamental research of the mechanisms creating magnetic anisotropy but also in view of the application of these structures in the novel area of magnetic electronics [29].

Funding The research was funded by RFBR, Krasnoyarsk Territory, and Krasnoyarsk Regional Fund of Science, project number 20–42-240010.

Declarations

Competing Interest The authors declare no competing interests.

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