# Specific Features of Unidirectional Anisotropy in Exchange-Coupled DyCo/NiFe Film Structures

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**Abstract**—The dependence of the unidirectional anisotropy in a DyCo/NiFe bilayer system on the thickness of the magnetically soft layer has been studied using dynamic and static techniques. The magnitude of the exchange interaction between layers evaluated using the ferromagnetic resonance method is two times that determined from an analysis of the hysteresis loops. It is established that this difference is related to features of the magnetic microstructure of the DyCo layer.

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Exchange-coupled bilayer structures consisting of magnetically soft and magnetically hard layers constitute basic elements for an important direction in applied magnetism. There are two classes of phenomena used in these applications: (i) the "exchange spring" effect manifested by the collinear orientation of magnetizations in the magnetically soft and magnetically hard layers, which is caused by the direct exchange interaction of the Heisenberg type [1] and (ii) the "exchange shift" effect, which is manifested in ferromagnet–antiferromagnet (FM–AFM) systems by a shift of the hysteresis loop from the symmetric position [2]. Numerous reviews (see, e.g., [3]) and monographs (such as [4]) describe such effects and consider their possible applications in permanent magnets [1], magnetic sensors, spintronics, and magnetic memory [5].

The phenomenon of unidirectional anisotropy in TbFe/NiFe and DyCo/NiFe magnetic bilayer structures was originally reported in [6, 7]. Although the mechanism of unidirectional anisotropy in these systems was unclear, the bilayer structures were successfully used for the development of new magnetic sensors [8], which were free of some of the disadvantages inherent in FM–AFM film structures. This is related to the fact that amorphous TbFe and DyCo films represent FMs with a high perpendicular uniaxial anisotropy and large coercivity in the region of concentrations close to the compensation ($x_c$). In contrast, NiFe films are magnetically soft and possess a low induced uniaxial planar anisotropy. For this reason, the magnetic structure in (TbFe, DyCo)/NiFe bilayer systems is determined by orthogonally oriented effective magnetizations of the two layers. In the general case, the symmetry of interactions responsible for the unidirectional anisotropy in this magnetic system is unknown.

Hellman et al. [9] confirmed the existence of unidirectional anisotropy in the TbFe/NiFe system, but both the effect as such and its magnitude were related to a technological defect: deviation of the easy axis of the FM film by a small angle $\alpha$ from the normal to the film plane. In this case, the transition region of magnetization in the vicinity of the interface represents a 90° domain wall with different values of the surface tension at $90° - \alpha$ and at $90° + \alpha$, which account for the exchange shift proportional to $\sin\alpha$. More recent investigations (described in much detail in [10]) showed that the unidirectional anisotropy also exists in (TbFe, DyCo)/NiFe bilayer systems with strictly perpendicular easy axis of the FM layer.

Previously [11, 12], we attributed the unidirectional anisotropy to natural nanoscale fluctuations in the chemical composition of the amorphous magnetic alloy. Indeed, a macroscopically single-phase solid solution in the vicinity of the compensation composition ($x_c$) acquires macroscopically heterophase magnetic structure. The concepts of a magnetic matrix phase and magnetic impurity phase have been formulated. It was shown that, by assuming a direct exchange between the magnetization of the magnetically soft layer and the local magnetization of the $3d$ sublattice of the magnetic impurity phase in the magnetically hard layer, it is possible to explain the phenomenon of unidirectional anisotropy in the magnetically soft layer.

The present study was aimed at measuring the exchange shift in the DyCo/NiFe bilayer system using both dynamic and static techniques, determining the
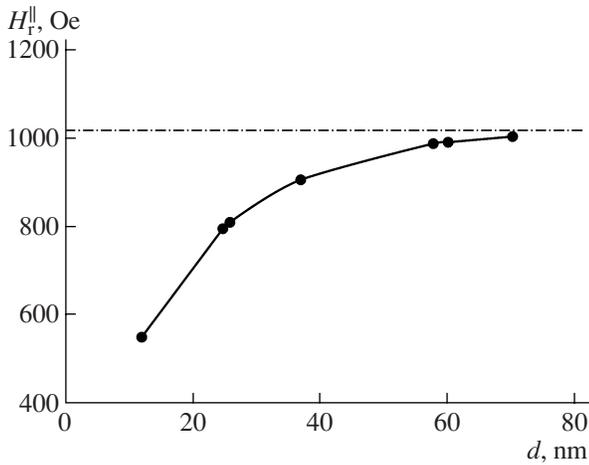
**Fig. 1.** A plot of the resonance field $H_{\mathrm{r}}^{\parallel}$ versus NiFe layer thickness $d$ in the exchange-coupled DyCo/NiFe bilayer measured in the parallel geometry. The dashed line shows the value of $H_{\mathrm{r}}$ for single-layer NiFe films.
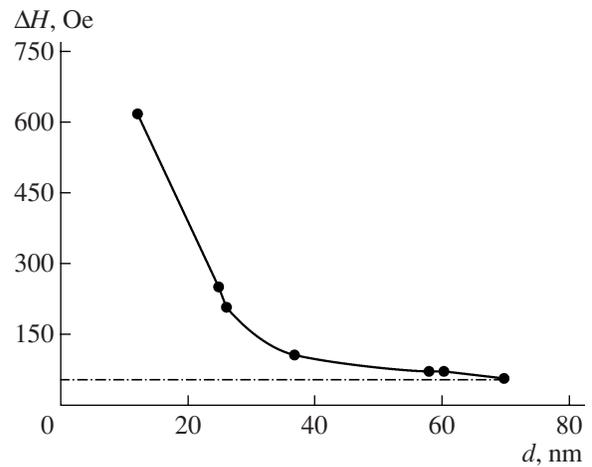


**Fig. 2.** A plot of the resonance absorption linewidth $\Delta H$ versus NiFe layer thickness $d$ in the exchange-coupled DyCo/NiFe bilayer measured in the parallel geometry. The dashed line shows the value of $\Delta H$ for single-layer NiFe films.

dependence of the magnitude of this shift on the thickness of the magnetically soft layer, and elucidating the mechanism of this effect.

The samples of DyCo/NiFe bilayers and the reference single-layer NiFe films were prepared by thermal deposition in vacuum at a residual pressure of $3 \times 10^{-6}$ Torr. The layers of NiFe and DyCo (Dy, 23–25 at. %; Co, 77–75 at. %) were deposited onto microscope cover glasses from independent evaporators with ring cathodes. The layers of amorphous DyCo alloy are characterized by a perpendicular magnetic anisotropy. The ferromagnetic NiFe films (in both single-layer and bilayer samples) were deposited in the presence of a magnetic field $H_0 = 50$ Oe oriented in the sample plane. The thickness and composition of a deposit were determined by X-ray spectroscopy. The magnetic properties were studied using magnetooptical Kerr effect (in a field of up to 15 kOe), hysteresis measurements (in a field of up to 250 Oe applied in the film plane) at a frequency of $f = 50$ Hz; and ferromagnetic resonance (FMR) measurements at a frequency of 9.2, 3.0, and 1.5 GHz.

The FMR at 9.2 GHz was measured at room temperature in two experimental arrangements, with the magnetic filed perpendicular or parallel to the film plane. In the perpendicular geometry, the values of resonance fields $H_{\mathrm{r}}^{\perp}$ for a DyCo($d = 70$ nm)/NiFe($d = X$ nm) structure (where $d$ is the film thickness) coincided with the analogous values for single-layer reference NiFe films ($d = X$ nm). The thickness $X$ of the permalloy layer was varied from 12 to 100 nm. In the parallel geometry, the resonance fields $H_{\mathrm{r}}^{\parallel}$ for the DyCo/NiFe bilayers and single-layer NiFe films coincided only in the interval of 70 nm $< X <$ 100 nm. For permalloy layer thicknesses

within 10 nm $< X <$ 100 nm, the values of $H_{\mathrm{r}}^{\parallel}$ for the bilayers and reference films were different and obeyed the relation $H_{\mathrm{r}}^{\parallel}$(DyCo/HiFe) $< H_{\mathrm{r}}^{\parallel}$(NiFe).

For single-layer NiFe films, the values of $H_{\mathrm{r}}^{\parallel}$ and $\Delta H$ (resonance absorption linewidth) were virtually independent of the film thickness in the entire range studied. Figure 1 shows plots of the experimental values of the resonance field $H_{\mathrm{r}}^{\parallel}$ versus FM (NiFe) layer thickness in the DyCo/NiFe bilayer structures, while the reference value for NiFe (independent of the layer thickness) is indicated by the dash–dot line. Figure 2 presents the FMR linewidth as a function of the magnetically soft layer thickness, also in comparison to $\Delta H$ for the magnetically soft (NiFe) reference film (dashed line). As can be seen, the resonance characteristics ($H_{\mathrm{r}}^{\parallel}$ and $\Delta H$) in the bilayer system exhibit significant variations depending on the FM layer thickness. We believe that such behavior is determined by the exchange interaction and will prove this statement below.

The results of measurements of the hysteresis loops showed that the directions of uniaxial and unidirectional anisotropy coincided to within a good accuracy. We have determined the coercive field in the magnetically soft layer ($H_c \approx 2$–4 Oe), the field of induced uniaxial anisotropy ($H_k \approx 6$–7 Oe), and the exchange shift field ($H_E$). The dependence of $H_E$ on the NiFe layer thickness $d$ was well described by a hyperbolic curve (Fig. 3). Using the expression

$$H_E = \frac{J_E}{Md}, \tag{1}$$

where $M$ is the saturation magnetization, we evaluated the energy of the exchange interaction between layers in the DyCo/NiFe system as $J_E^{(M(H))} \approx 0.2$ erg/cm$^2$.

The value of $H_E$ (and, hence, $J_E$) can also be evaluated using FMR measurements. For this purpose, the standard formula describing the FMR in the single-layer NiFe,

$$\left(\frac{\omega}{\gamma}\right)^2 = H(H + 4\pi M), \qquad (2)$$

should be replaced by the following expression:

$$\left(\frac{\omega}{\gamma}\right)^2 = (H + H_E)(H + H_E + 4\pi M), \qquad (3)$$

where $\omega = 2\pi f$ and $\gamma$ is the magnetomechanical ratio. This substitution has been justified in [13, 14]. Then, a comparison of the resonance fields in the bilayer system and the reference NiFe film (Fig. 1) allows the $H_E$ value to be calculated using Eqs. (2) and (3). The results of such calculations are presented in Fig. 3. As can be seen, the $H_E$ values determined using this approach obey the hyperbolic law ($H_E \sim 1/d$) in agreement with Eq. (1). However, the magnitude of the energy of exchange interaction between layers calculated for this $H_E$ value amounts to $J_E^{\mathrm{FMR}} = 0.4$ erg/cm$^2$, which is twice as much as the estimate obtained from the results of static measurements.

Now we will demonstrate that the experimental results described above (including the discrepancies between $J_E$ values determined using different experimental methods) are consistent with the model [11, 12] of a magnetically heterophase compensation composition for DyCo and TbFe films. Indeed, the effective magnetization of the magnetic matrix phase in our films is determined by the Dy sublattice and is oriented along the axis of perpendicular anisotropy. The effective magnetization of the magnetic impurity phase is determined by the Co sublattice and (owing to a strong exchange interaction with the Co sublattice of the magnetic matrix phase) is oriented in the plane of the magnetically hard layer. Expression (3), as well as formula (2), describes the isotropic FMR in the film plane. This implied that the internal resonance field $H_r \approx 1$ kOe saturates both the magnetization of the NiFe layer and the effective magnetization of the magnetic impurity phase in the magnetically hard layer. Then, the energy of exchange interaction between the two layers is determined by the standard expression of the Heisenberg formula type, $J_E = J\mathbf{M}_1\mathbf{M}_2$, where $\mathbf{M}_1$ and $\mathbf{M}_2$ are the magnetizations of the NiFe layer and the magnetic impurity phase in the DyCo layer. As the internal field decreases, the effective magnetization of the magnetic impurity phase also drops (as a result of scattering of the local magnetization directions) and, according to the well-known Stoner–Wholfarth model [15] reaches a value of $M_{2r} = (1/2)M_{2s}$, where $M_{2r}$ is the residual
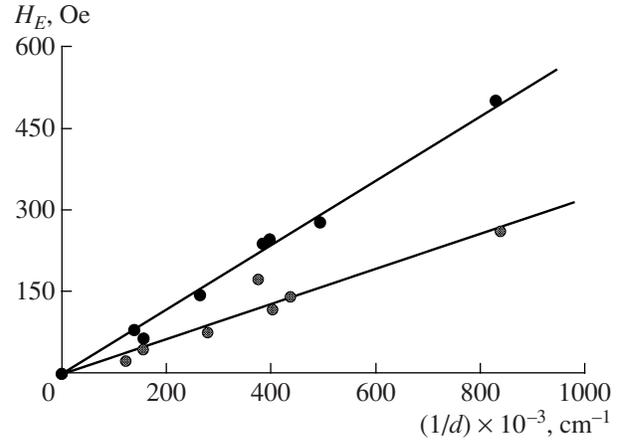


**Fig. 3.** Plots of the exchange field $H_r$ versus inverse thickness $1/d$ of the NiFe layer in DyCo/NiFe bilayer structures: (black circles) FMR measurements (gray circles) static $M(H)$ measurements.

magnetization and $M_{2s}$ is the saturation magnetization of the magnetic impurity phase. The standard expression of $J_E = J\mathbf{M}_1\mathbf{M}_{2r}$ should be modified accordingly. Therefore, the static experiments involving small values of internal fields reflect the influence of the residual magnetization of the magnetic impurity phase, whereas the dynamic measurements involving large internal fields deal with the saturation magnetization of this phase. This statement is confirmed by the results of FMR measurements at low frequencies, where a decrease in $\omega/\gamma$ leads to a decrease in the internal field $H_r$ in accordance with Eqs. (2) and (3). At a frequency of 3 GHz, the resonance field is still satisfactorily described by expressions (2) and (3). However, at 1.5 GHz, the anisotropy of $H_r(\varphi)$ (where $\varphi$ is the angle between the axis of unidirectional anisotropy and the external magnetic field) is manifested both by the field of uniaxial anisotropy $H_k$ and by the field of unidirectional anisotropy $H_E$, which can be evaluated from the finite difference $H_r(0) - H_r(\pi)$.

Thus, the two-fold difference between the measured values of $J_E^{\mathrm{FMR}}$ and $J_E^{M(H)}$ is related to features of the magnetic microstructure of ferromagnetic alloys, whereby the exchange shift in the DyCo/NiFe system is determined by the average magnetization of the magnetic impurity phase in the magnetically heterophase DyCo system.

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