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Unidirectional Anisotropy in Ferromagnetic–Ferrimagnetic Film Structures

G. I. Frolov[1], V. Yu. Yakovchuk[1], V. A. Seredkin[1], R. S. Iskhakov[1], S. V. Stolyar[1,2], and V. V. Polyakov[1]

[1]*Kirenskiĭ Institute of Physics, Siberian Division, Russian Academy of Sciences, Akademgorodok, Krasnoyarsk, 660036 Russia*

e-mail: sva@iph.krasn.ru

[2]*Krasnoyarsk State University, Krasnoyarsk, 660041 Russia*

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Abstract—A mechanism of unidirectional anisotropy formation in an exchange-coupled ferromagnetic–ferrimagnetic film structure with orthogonal effective magnetizations in the layers is investigated. The reason for unidirectional anisotropy is the magnetic heterogeneity of the ferrimagnetic layer in the compensation range. Magnetization reversal in the magnetically soft layer of an (REE–transition metal)/NiFe film structure is discussed based on a model of uniform rotation of magnetization. It is found that unidirectional anisotropy sharply decreases the magnetic noise level in the magnetically soft layer. The field of application of these materials is outlined. © *2005 Pleiades Publishing, Inc.*

Exchange interaction between magnetically soft and magnetically hard layers imparts intriguing properties to related structures, which are of great fundamental and applied interest. One of these properties is unidirectional exchange anisotropy in the magnetically soft layer, which shifts hysteresis loop ΔH along the magnetic field axis. Although this effect was discovered 50 years ago [1], it has not been yet completely understood. Therefore, to gain a deeper insight into the nature of unidirectional anisotropy remains a topical problem. Hot interest in these materials as candidates, e.g., for magnetic memory devices [2], spintronics devices [3], and magnetic sensors [4] is giving an additional impetus to research in this field.

Unidirectional exchange anisotropy has been studied mostly in ferromagnetic–antiferromagnetic (FM/AFM) film structures [5]. However, a number of disadvantages limit the application of these materials [6]. These are a poor temperature stability of ΔH, an increased coercive force of the magnetically soft layer compared with that of a one-layer FM film, and the evolution of the hysteresis loop with the number of a magnetization reversal cycle.

At the beginning of the 1980s, unidirectional anisotropy was discovered [7] in a TbFe/NiFe ferromagnetic–ferrimagnetic (FoM/FiM) film structure. These structures attracted attention, since they, on the one hand, lack the disadvantages typical of their FM/AFM counterparts and, on the other hand, unidirectional anisotropy here appears in layers with orthogonal effective magnetizations. A large body of data concerning investigation and application of FoM/FiM structures has been gained in recent years [8–15]. In our opinion, it is an appropriate time to analyze the state of the art in this field. In this work, we consider the nature of unidirectional anisotropy, its effect on the magnetic performance of the FM layer, and applications of FoM/FiM strictures.

MECHANISMS OF UNIDIRECTIONAL ANISOTROPY FORMATION

The phenomenological description of the effect of unidirectional exchange anisotropy is straightforward. It is based on the assumption that the magnetic moments at the interface are collinear,

$$j\mathbf{M}_1 \cdot \mathbf{M}_2 = JM_1M_2\cos(\hat{M_1M_2}). \quad (1)$$

In [7], where the existence of unidirectional anisotropy in a Tb_xFe_{1-x}/NiFe exchange-coupled film structure with orthogonal effective magnetizations of the layers was reported for the first time, we applied some considerations to the origin of this effect. It was conjectured that an amorphous ferrimagnetic layer may have the in-plane magnetization component resulting, for example, from a chemical inhomogeneity across the amorphous alloy film. This inhomogeneity, in turn, produces a compensation plane, in which the magnetization reverses.

Further investigations into the chemical composition of REE–transition metal (REE–TM) amorphous alloy films obtained by thermal evaporation have shown, however, that a concentration gradient normal to the plane is absent in such films. Therefore, other mechanisms come to the fore. For example, the in-plane magnetization component in amorphous REE–

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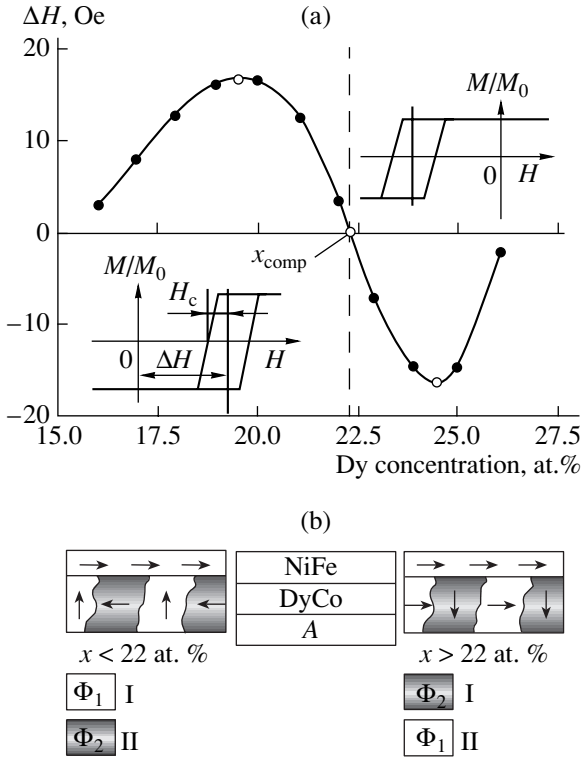

Fig. 1. (a) Hysteresis loop and concentration dependence of bias field $\Delta H(x)$ and (b) the orientation scheme for the magnetizations of 3*d* metals in exchange-coupled DyCo/NiFe film structures. *A*, substrate; I, matrix; and II, impurity.

TM films, which are characterized by perpendicular anisotropy, may be due to a local dispersion of the magnetic anisotropy axis. As a result, the general direction of the easy magnetic axis deviated from the normal to the film surface. If such a mechanism works and the composition of the REE–TM film is off-compensation, the amount of unidirectional anisotropy in exchange-coupled (REE–TM)/NiFe film structures is bound to grow, being minimal in those where the easy magnetic axis of the amorphous REE–TM layer lies in the plane of the film. However, our investigations [14], as well as those carried out by other authors [9, 11], show that the reverse is true. In (REE–TM)/NiFe structures, unidirectional anisotropy exists only in that concentration range of the amorphous alloy where perpendicular anisotropy in the REE–TM layer is observed.

The existence of unidirectional anisotropy in Tb_xFe_{1-x}/NiFe and Dy_xCo_{1-x}/NiFe film structures, which was first discovered in [7], indicates a specific magnetic microstructure of REE–TM layers. Namely, Dy_xCo_{1-x} and Tb_xFe_{1-x} alloys show nanoareas where the magnetization vector of the 3*d* metal sublattice has the in-plane component, and it is this component that takes part in exchange interaction with the FM layer of NiFe alloy.

To establish factors causing the in-plane component of the 3*d* metal sublattice in REE–TM alloy with layers that have near-compensation compositions and feature a high degree of integral perpendicular anisotropy is a challenge. This is because the amorphous ferrimagnetic REE–TM alloy has a low saturation magnetization ($M_s \longrightarrow 0$) and a high magnetic hardness (for example, the coercive field in the (REE–TM)/DyCo alloy may be as high as > 10 kOe). In light of this, we suggested that the physical properties of such magnetically hard materials be studied on NiFe/Dy_xCo_{1-x}/NiFe multilayer exchange-coupled film structures where the Dy_xCo_{1-x} layer is much thinner than NiFe, $d_{DyCo} \ll d_{NiFe}$. Exchange interaction between the Co sublattice of the ferrimagnetic alloy and the NiFe layer substantially modifies the magnetic performance of such a well-studied alloy as NiFe.

Based on the measurements of the dynamic and static magnetic characteristics of NiFe/Dy_xCo_{1-x}/NiFe composites, we developed a microheterogeneous model of the DyCo amorphous layer [15, 16]. The DyCo specific microstructure in the compensation range that follows from this model has allowed us to explain experimental data for FM resonance (FMR) and spin-wave resonance (SWR). To find specific features of DyCo, we (i) prepared NiFe/DyCo/NiFe three-layer structures with unidirectional exchange anisotropy and orthogonal effective magnetizations of the layers, (ii) studied the FMR and SWR spectra of these structures, and (iii) found that the spin system of the amorphous DyCo alloy in the concentration range of magnetic compensation can be represented in the form of two subsystems with the TM magnetization prevailing in one of them (nanophase Φ_1) and the REE magnetization in the other (nanophase Φ_2). This model embodies the basic structural feature of amorphous alloys: natural fluctuation (topological and composition) inhomogeneity. In the concentration ranges $x_i \pm \Delta x \ll x_{comp}$ (matrix Φ_1) and $x_i \pm \Delta x \gg x_{comp}$ (matrix Φ_2), the magnetic microstructures of amorphous ferrimagnets will differ substantially from the magnetic microstructure in the range $x_i - \Delta x < x_{comp} < x + \Delta x$. In this case, magnetic compensation point x_{comp} is defined by the condition $\langle M \rangle = pM_{eff}^{(\Phi_1)} + qM_{eff}^{(\Phi_2)} = 0$, where p and q are the volume fractions of nanophases Φ_1 and Φ_2 and $M_{eff}^{(\Phi_1)}$ and $M_{eff}^{(\Phi_2)}$ are the effective magnetizations of these phases at $x_i - \Delta x$ and $x_i + \Delta x$, respectively.

Figure 1 shows the experimental dependences of shift $\Delta H(x)$ of the hysteresis loop on the REE concentration in a planar DyCo/NiFe structure and the distributions of nanophases Φ_1 and Φ_2 in the DyCo layer. It is seen that the curve $\Delta H(x)$ for the Dy_xCo_{1-x}/NiFe structure is described by the asymmetric function $\Delta H(x - x_{comp})$ and has singular points: the coordinate of the zero (minimal value of ΔH) and extreme points. Also, it is seen that $\Delta H(x)$ in this planar structure reaches a maximum at $x \approx 19$ at.% for undercompensa-

tion compositions of DyCo and $x \approx 24$ at.% for overcompensation compositions.

The above results are readily explained in terms of the suggested model of amorphous DyCo alloy structure in the magnetic compensation range. Indeed, in the REE–TM concentration range $x \leq 16$ at.% ($x \geq 27$ at.%), the magnetic structure of amorphous DyCo is completely specified by magnetic nanophase Φ_1 (Φ_2). Hence, the magnetic moments of the Co and Dy sublattices are collinear with the perpendicular anisotropy axis in the DyCo layer and, as a consequence, the effective magnetizations of the DyCo and NiFe layers are mutually orthogonal (exchange coupling is absent). Such a situation takes place in the concentration range $x_i - \Delta x < x_{comp} < x + \Delta x$. Here, the magnetic structure of DyCo is formed by randomly mixed nanophases Φ_1 and Φ_2. If phase Φ_1 is a matrix, phase Φ_2 is an impurity and vice versa. The only exception is compensation point x_{comp}, where the volume fractions of the phases are roughly the same.

At any concentration x_i from the above range, the effective magnetization of matrix phase Φ_i in the DyCo layer is aligned with the perpendicular anisotropy field (M_{Co} and M_{Dy} are collinear with this field (as indicated by the polar Kerr effect). In this case, the magnetization of the Co sublattice, M_{Co}, in impurity nanophase Φ_j must have the in-plane component because of exchange interaction between the transition elements in the impurity and matrix and the effective magnetization of nanophase Φ_j has a chance to align with an external magnetic field. We believe that exchange interaction between magnetization M_{Co} of impurity phase Φ_j in the DyCo layer and the magnetization of the NiFe layer results in exchange unidirectional anisotropy in NiFe.

The form of the experimental dependence in Fig. 1 (asymmetry about x_{comp}) can also be treated in terms of our model. In this planar system, a Dy_xCo_{1-x} layer forms where the magnetization of the matrix phase is aligned with the perpendicular anisotropy axis, while the effective magnetization of the impurity phase lies in the plane of the payer. When a NiFe overlayer is grown, a permanent magnetic field is switched on to specify the easy direction and the effective magnetization of the impurity phase in the Dy_xCo_{1-x} layer is aligned with this field and, hence, with the unidirectional anisotropy axis in NiFe. In the range $x < x_{comp}$, the impurity phase meets the inequality $M_{Co} < M_{Dy}$, while at $x > x_{comp}$, the inverse inequality is valid. This means that, at $x < x_{comp}$, the magnetization vectors of the Co sublattice and NiFe layer are anticollinear, whereas, at $x > x_{comp}$, they are codirected (see Fig. 1b). That is why the sign of ΔH changes in going through concentration x_{comp} (Fig. 1a).

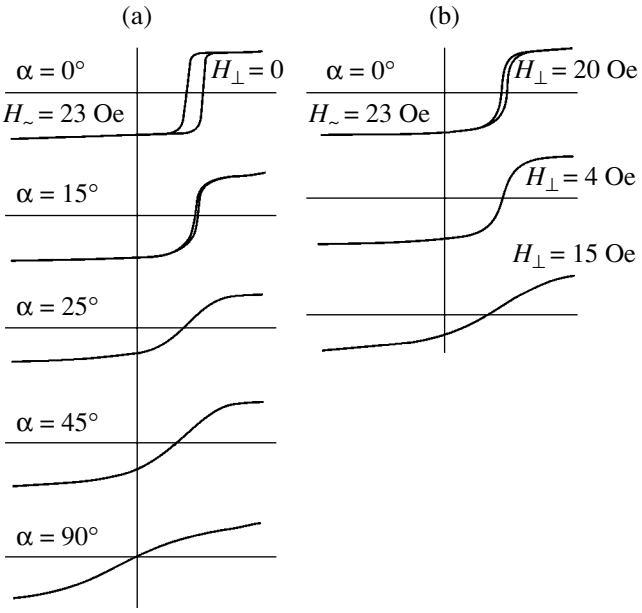

Fig. 2. (a) Angular dependence of ΔH and (b) dependence of the hysteresis loop on $H_\perp$ in the exchange-coupled DyCo/NiFe film structure.

QUASI-STATIC MAGNETIZATION REVERSAL IN FERROMAGNETIC–FERRIMAGNETIC FILM STRUCTURES

In exchange-coupled structures, the state of one layer may substantially affect the state of another. For example, direct exchange interaction between ferromagnetic layers (positive coupling) with different degrees of anisotropy may lead to the situation where both layers experiencing magnetization reversal will behave as a whole with a coercive force intermediate between the coercive forces of the layers [6]. In FM/AFM film structures, unidirectional anisotropy shifts the hysteresis loop, results in only one easy axis, stabilizes the domain structure of the ferromagnetic layer, etc. [17, 18].

In FoM/FiM structures, the magnetization reversal process somewhat differs from that in FM/AFM films. Figure 2a shows the angular dependence of the hysteresis loop for a DyCo/NiFe film (the layer thicknesses are, respectively, 70 and 210 nm; the easy axis coincides with the unidirectional anisotropy axis). In the easy axis direction ($\alpha = 0$), the hysteresis loop is the widest ($H_c = 2$ Oe) and is shifted along the field axis by $\Delta H = 10.5$ Oe. As angle α increases, the loop gets thinner and collapses at $\alpha = 25°$ (in the range 25°–90°, the process of magnetization reversal is hysteresis-free). The shift also decreases, and, at $\alpha = 90°$, the "loop" becomes symmetric (the anisotropy field determined from this curve is $H_a = 15$ Oe).

Figure 2b demonstrates the variation of the hysteresis loop for the same film when permanent magnetic field $H_\perp$ is applied along the hard axis. At $H_\perp = 4$ Oe,

the loop collapses and takes the form of the magnetization reversal curve for $\alpha = 25°$. At $H_\perp = H_a = 15$ Oe, the loop is still asymmetric.

Such an observation (collapsed hysteresis loop) differs from experimental data obtained on NiFe/FeMn films [17]. Magnetization reversal curves taken of two-layer exchange-coupled structures are usually treated in terms of the model assuming that the magnetization vector of one layer is fixed, while the magnetization vector of the other spirals under the action of an external magnetic field [19, 20]. The analytical solution presented in [20] gives the following results. If magnetization reversal takes place along the easy axis ($\alpha = 0$) in films with $d_{FM} < d_{cr}$, the hysteresis loop collapses and shifts along the field axis. In films with $d_{FM} > d_{cr}$, the loop "opens up" and expands with d_{FM}. (Here, $d_{cr} = 2A/M_s H_a d_{FM}^2 > 12/\pi^2$, where A is the exchange interaction constant and M_s, H_a, and d_{FM} are, respectively, the saturation magnetization, anisotropy field, and thickness of the magnetically soft layer.)

However, in none of the numerous experiments where magnetization reversal took place along the easy axis in FM/AFM and FoM/FiM structures did the hysteresis loop collapse even for $\Delta H \gg H_C$. The reason for the discrepancy between the analytical and experimental data seems to be an inadequate estimate of d_{cr}. For an exchange-coupled structure with parameters $M_s = 800$ G and $H_a = 3$ Oe for the magnetically soft material and exchange constant $A = 10^{-6}$ erg/cm^3, the critical thickness was estimated as $d_{cr} = 260$ nm [20]. At the same time, experiments with NiFe/FeMn films showed that the exchange constant is two orders of magnitude smaller [21]; that is, $d_{cr} = 3$ nm. However, the hysteresis loop did not collapse even when magnetization reversal along the easy axis took place in structures with d_{FM} (d_{NiFe}) < 3 nm [21].

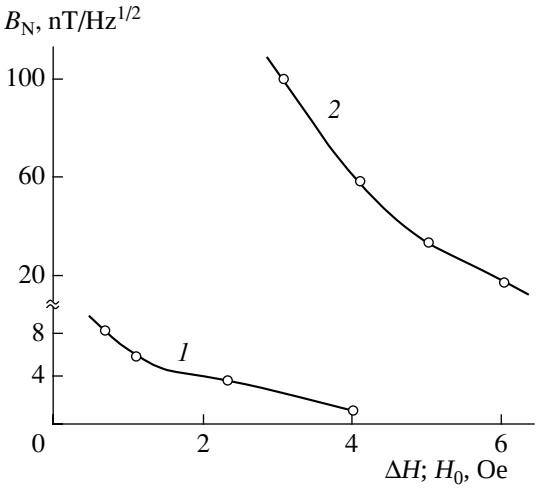

Fig. 3. Magnetic noise intensity (*1*) in the exchange-coupled DyCo/NiFe film structure vs. the amount of unidirectional anisotropy ΔH and (*2*) in the reference NiFe film vs. applied permanent magnetic field H_0.

Another model of quasi-static magnetization reversal in exchange-coupled structures that assumes coherent rotation of the magnetization in a magnetically soft layer was suggested in [17]. Here, the interaction between the layers is described in terms of specific surface energy E_s. In this case, we deal with thickness-averaged unidirectional anisotropy, the amount of which is inversely proportional to the thickness of the magnetically soft layer. Such a dependence of ΔH on the thickness of the magnetically soft layer is confirmed experimentally [9, 11]. When external magnetic field H is applied to the plane of the film at angle α to the easy axis, magnetization M of the magnetically soft layer rotates through angle β relative to the easy axis. Then, the energy of the FM layer can be written in the form

$$E = -HM\cos\varphi + E_k \sin^2\beta - \frac{E_s}{d_{FM}}\cos\beta, \qquad (2)$$

where $\varphi = \alpha - \beta$ and E_a is the unidirectional anisotropy constant.

Using the standard computational method, we derived an expression for the hysteresis loop for any α (except $\alpha = 0$ and π). It was found that the loop collapses at certain $\alpha > \alpha_{cr}$, α_{cr} depending on ratio $\Delta H/H_a$, where $\Delta H = E_s/Md_{FM}$. This model leads us to conclude that, first, magnetization reversal at an angle to the easy axis of an FM layer may proceed by rotation of vector M and, second, unidirectional anisotropy can be simulated by permanent magnetic field $H = \Delta H$. Both conclusions were corroborated in experiments, which means that the model adequately describes quasi-static magnetization reversal in exchange-coupled structures.

MAGNETIC NOISE IN FERROMAGNETIC–FERRIMAGNETIC FILM STRUCTURES

It is known that the magnetic noise in thin-film magnetic devices can be depressed, e.g., by applying a magnetic field, which makes the process of magnetization reversal more uniform. The same results can be obtained using structures with unidirectional anisotropy.

We performed special experiments to see how the external magnetic field and unidirectional anisotropy influence the magnetic noise in Permalloy films [22, 23]. The object of interest was fluctuations of the transverse emf in the presence of a constant bias (H_0, ΔH) applied along the easy magnetic axis or a high-frequency field ($H_{hf} < H_a$, H_0) applied along the hard magnetic axis.

Figure 3 shows the variation of magnetic noise B_N in the NiFe film incorporated into an exchange-coupled DyCo/NiFe structure 500 nm thick with bias field ΔH (curve *1*) and in a reference NiFe film magnetized by magnetic field H_0 (curve *2*).

As follows from Fig. 3, the magnetic noise in the exchange-coupled film structure is much lower than in the reference film. Presumably, unidirectional anisotropy is not totally equivalent (is superior) to the applied field in efficiency and exchange interaction in the structure makes the process of magnetization reversal in the magnetic layer more uniform.

APPLICATION OF EXCHANGE-COUPLED STRUCTURES

Film magnetic materials have found wide application in various fields of technology [2–4]. Here, we will concentrate on using (REE–TM)/NiFe FoM/FiM structures with unidirectional anisotropy as magnetooptic memory devices and weak-field magnetic sensors.

Memory devices. It is believed that, in this field, the film structures under consideration may decrease the power consumption and raise the speed of data writing and erasing.

Magnetooptic data writing on films with a magnetization normal to the film surface is in common use in disk storages of PCs. Data writing and erasing is accomplished by the thermomagnetic method in writing magnetic field H_3 = 400–500 Oe applied normally to the film (Fig. 4).

As materials for magnetooptic data carriers, REE–TM alloys are usually employed. Their basic disadvantages are (i) the need to apply high writing/erasing magnetic fields, which influence the electrodynamic suspension of the focusing lens holder and (ii) a large time delay between writing and erasing, which depends on the inductance of the magnetic field source winding [24].

We suggest another approach [16] to writing magnetooptic information on REE–TM/NiFe FoM/FiM structures with exchange anisotropy (see Fig. 5).Writing magnetic field $H_{wr} > H_C + \Delta H$ (10–15 Oe) is applied to a FoM/FiM structure (Fig. 5a) antiparallel to the initial magnetization in layer *3* (Fig. 5b). The magnetization of layer *3* reverses, while that of layer *2* does not. After layer *2* has been locally heated by a thermal pulse to a temperature close to Curie temperature T_C, the heated area turns into the paramagnetic state (Fig. 5c) and the magnetic state of layer *3* remains unchanged, since T_C of NiFe is much higher than T_C of DyCo. Due to exchange interaction between layers *2* and *3* (during cooling), the magnetization of the heated area of layer *2* reverses in accordance with the magnetization direction in the NiFe layer (Fig. 5d). After the thermal pulse is terminated and the writing field is switched off, the inverted state of the magnetic moment of the heated area in layer *2* persists (which corresponds to writing a bit of information), while the magnetization of the local area in layer *3* takes on a nonequilibrium (helical) structure (Fig. 5d), representing a compressed "spin spring." Data readout is accomplished using the polar Kerr effect.

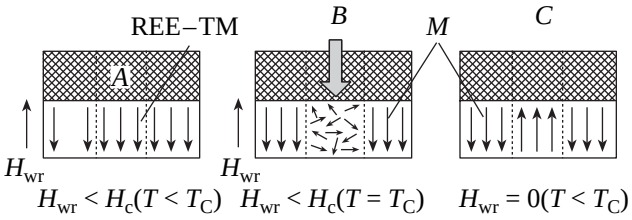

Fig. 4. Thermomagnetic data writing on REE–TM films with perpendicular magnetic anisotropy. *A*, substrate; *B*, radiation; and *C*, domain.

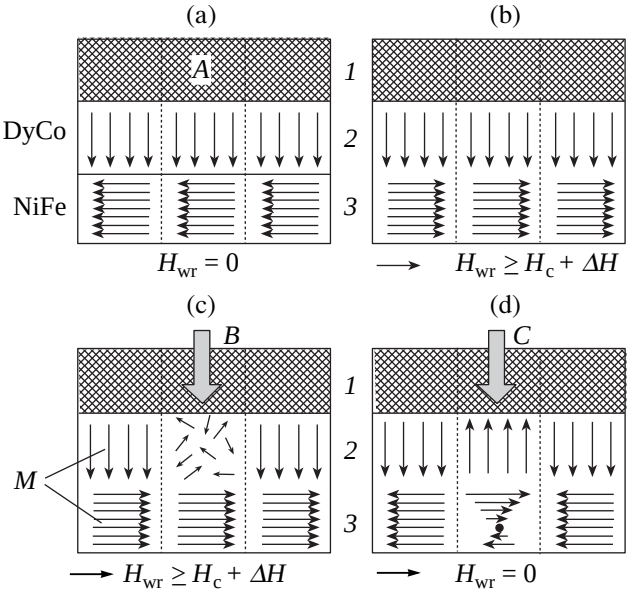

Fig. 5. Thermomagnetic data writing on exchange-coupled (REE–TM)/NiFe film structures. *A*–*C*, the same as in Fig. 4.

To erase information, it suffices to heat the same local area of layer *2* to the Curie temperature. Exchange interaction between this area and layer *3* then disappears, and the magnetization of the local area in layer *3* becomes aligned with the magnetization of the entire layer ("the helix untwists"). After the pulse is terminated and the local area of layer *2* cools, the magnetization of this area changes sense because of exchange interaction with layer *3* and the information is erased.

Thus, in our approach, writing magnetic field $H_{wr} \geq H_C + \Delta H$ is much lower than the writing field in the case of standard REE–TM films. Moreover, data erasing does not require a magnetic field at all. Accordingly, the magnetic field energy spent on data writing/erasing substantially decreases. At the same time, a low writing magnetic field, which makes it possible to generate H_3 pulses as short as several nanoseconds, and no need for switching the magnetic field at writing and/or erasing provide a higher speed of the processes. It should be emphasized that all the related advantages of REE–TM layers are retained.

Film magnetometers. FoM/FiM structures with unidirectional anisotropy were used to design a weak-field magnetic detector and study the dependence of the magnetic noise of this device on the static characteristics of the film magnetic structure and on excitation modes [22, 23]. The operating principle of this magnetometer is akin to that of a bubble magnetometer [25]. However, an exchange-coupled film structure used as a sensitive element made it possible to considerably suppress the low-frequency noise, which was found to be $\approx 2 \times 10^{-11}$ T/Hz$^{1/2}$ at a frequency of 1 Hz. The device was put to field tests, which shows that it can be applied in geophysics, specifically, in geoelectrical prospecting of shallow ore-bearing rocks and in shallow oil-and-gas prospecting [12].

CONCLUSIONS

We touched upon three issues concerning exchange-coupled FoM/FiM film structures consisting of a magnetically hard material (amorphous films of REE–TM alloys) and a magnetically soft Permalloy film. These are the mechanism of formation of exchange coupling between the layers, the magnetic properties of the structures, and application of the structures. In spite of extensive investigation, the problems considered here still need greater insight. However, wide application of these composites stimulates further effort in this field.

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