ISSN 1063-7834, Physics of the Solid State, 2007, Vol. 49, No. 9, pp. 1731–1739. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © B.A. Belyaev, A.V. Izotov, 2007, published in Fizika Tverdogo Tela, 2007, Vol. 49, No. 9, pp. 1651–1659.

MAGNETISM AND FERROELECTRICITY

Ferromagnetic Resonance Study of the Effect of Elastic Stresses on the Anisotropy of Magnetic Films

B. A. Belyaev and A. V. Izotov

Kirensky Institute of Physics, Siberian Branch, Russian Academy of Sciences, Akademgorodok, Krasnoyarsk, 660036 Russia
e-mail: belyaev@iph.krasn.ru

Received December 21, 2006; in final form, February 3, 2007

Abstract—The distribution of the magnitude and direction of the uniaxial magnetic anisotropy field over the area of permalloy films obtained by thermal evaporation in vacuum was studied using a scanning ferromagnetic resonance spectrometer. The films were deposited on glass substrates subjected to bending stress in the presence of an in-plane static magnetic field. Depending on the character of the elastic-stress distribution over a local spot of a film, the uniaxial anisotropy induced by a magnetic field is either enhanced or completely compensated, which is accompanied by a significant change in the direction of the easy axis of magnetization. The observed effects are in good agreement with phenomenological calculations.

PACS numbers: 75.70.-i, 75.90.+w

DOI: 10.1134/S106378340709020X

1. INTRODUCTION

The development of the physical basis and techniques for synthesizing thin magnetic films (TMFs) with a high microwave (mw) magnetic permeability is one of the most important problems in the modern physics of magnetic phenomena. Such films of magnetically soft materials find wide application, e.g., in sensors of weak magnetic fields, high-speed recording/reading heads, and various sensors and controlled mw devices. It is well known that the attainable parameters and reliable operation of many devices based on magnetic films are determined to a large extent by the degree of inhomogeneity of the magnetic characteristics of the material used and by the character of the distribution of such inhomogeneities over the film area. The dispersions in the magnitude and direction of the anisotropy field, the saturation magnetization, ferromagnetic resonance (FMR) linewidth, and the other parameters on which the magnetic susceptibility depends are determined by the specific technology of film fabrication and, as a rule, increase as the film thickness decreases [1, 2]. These relations are associated not only with the material (its roughness, degree of purity, the presence or absence of a buffer layer) but also with inhomogeneous stresses that arise in the interface between the film and substrate during preparation of the film, as well as with stress gradients that exist at the film surface in the presence of a covering layer. In other words, in contrast to a bulk magnetic material, a film cannot be considered while ignoring the substrate. The elastic stresses and their gradients caused by a substrate have a strong effect on almost all magnetic characteristics of films. In particular, stresses can cause magnetic anisotropy [3] and influence the magnitude and the degree of inhomogeneity of the anisotropy field, the coercive force, and the effective saturation magnetization [4].

As a rule, the mw magnetic permeability of films reaches a maximum near the frequencies of uniform FMR and resonances of various magnetostatic and spin-wave oscillations. However, magnetic inhomogeneities broaden resonance lines and can significantly decrease the magnetic permeability of TMFs. Moreover, even small inhomogeneities of the magnitude and direction of the uniaxial magnetic anisotropy field almost completely suppress the nonresonant magnetic susceptibility of films in the mw range [5] and the mw susceptibility associated with the metastability of the magnetic moment in TMFs [6].

Therefore, studying the nature of magnetic inhomogeneities in thin films is important. The results obtained in such studies can be useful in developing methods for optimizing the technological conditions under which films with very high characteristics can be produced. In this work, we theoretically and experimentally study the effect of intentionally created inhomogeneous elastic stresses in permalloy films on the character and magnitude of inhomogeneities of the uniaxial magnetic anisotropy.

2. SAMPLES AND CALCULATIONS OF ELASTIC STRESSES IN A FILM

The experimental study of the effect of elastic stresses on the magnetic properties of TMFs were performed on a series of three test samples [7]. The samples were 500-Å-thick films obtained by sputtering of permalloy $Ni_{75}Fe_{25}$ in vacuum onto polished glass sub-

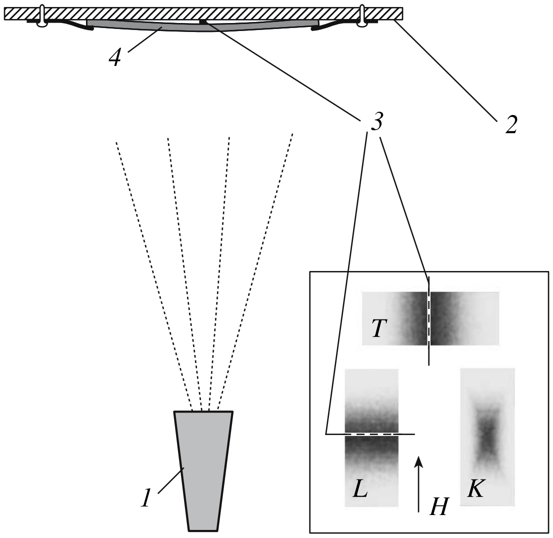

Fig. 1. Arrangement of substrates on the substrate holder during sputtering of samples *T*, *L*, and *K* (schematic): (*1*) crucible, (*2*) substrate holder, (*3*) copper wires to bend the substrates, and (*4*) substrate.

strates 10 × 24 × 0.5 mm in size heated to 250°C to increase adhesion. Sputtering was performed simultaneously onto three substrates placed in one plane in an orienting in-plane magnetic field **H**, which was directed along the long axes of two substrates (samples *L* and *K*) and was transverse to the long axis of the third substrate (sample *T*) (Fig. 1). During sputtering, the ends of the substrates were affixed to a metallic holder with special clamps. Substrates *L* and *T* were subjected to a small bending strain, which was caused by a copper wire 50 μm in diameter located between the holder and a substrate along the short axis. In this case, the wire and the clamps (covering the entire width of the substrate) bend the substrate into a nearly circular arc. In other words, the substrate takes the form of a segment of a cylindrical shell, which causes both longitudinal and transverse stresses to arise near its surface. After films were sputtered and substrates *L* and *T* were unclamped, the substrates straightened out, thereby causing a transverse and longitudinal inhomogeneous compression of the films. Since the substrates are much thicker than the films, the strain of the films is completely determined by that of the substrates.

In order to calculate the elastic stresses in a magnetic film deposited on a strained substrate, we introduce the following Cartesian coordinate system: the origin is located at the center of the substrate, the *xy* plane is parallel to the film plane, and the *x* axis is along the long axis of the substrate. The boundary conditions at the interface between the film and the substrate have the form [8]

$$U_i^s = U_i^f, \quad \sigma_{iz}^s = \sigma_{iz}^f, \qquad (1)$$

where U_i^s and U_i^f are the displacement vector components in the substrate and the film and σ_{iz}^s and σ_{iz}^f are the stress tensor components normal to the interface in the substrate and the film, respectively. These conditions ensure the continuity of the strain tensor components u_{xx}, u_{xy}, and u_{yy} and the stress tensor components σ_{xz}, σ_{yz}, and σ_{zz} of the bilayer system under study.

Since the thicknesses of the substrates and especially of the films are small in comparison with the lateral dimensions, the components σ_{xz}, σ_{yz}, and σ_{zz} can be neglected [9]. Since the ratio between the film and substrate thicknesses is of the order of 10^{-4}, we can also assume that the strain tensor components in the film u_{xx}^f, u_{xy}^f, and u_{yy}^f are uniform over the film thickness and are equal to the respective strain tensor components at the substrate surface u_{xx}^e, u_{xy}^e, and u_{yy}^e under the conditions of the mechanical equilibrium of the isolated bent substrate. In this case, the components of the external stress tensor of the film can be found to be [9]

$$\begin{aligned} \sigma_{xx}^e &= \frac{E}{1+\nu}\left[u_{xx}^e + \frac{\nu}{1-\nu}(u_{xx}^e + u_{yy}^e)\right], \\ \sigma_{yy}^e &= \frac{E}{1+\nu}\left[u_{yy}^e + \frac{\nu}{1-\nu}(u_{xx}^e + u_{yy}^e)\right], \qquad (2) \\ \sigma_{xy}^e &= \frac{E}{1+\nu}u_{xy}^e, \end{aligned}$$

where *E* is the Young's modulus and ν is the Poisson ratio of the material of the film.

It should be noted that the film is subjected not only to the strains caused by the bending of the substrate but also to the strains due to the difference between the coefficients of thermal expansion of the substrate and the film. However, thermal expansion of both the substrate and the film is isotropic. Therefore, the contribution from thermal expansion (uniform over the entire film surface) to the external stress tensor is likewise isotropic and will be ignored in what follows.

We calculated the strain tensor components u_{xx}^e, u_{xy}^e, and u_{yy}^e by the finite-element method using the Femlab program package. The distributions of the components of the external stress tensor of the film are calculated from Eq. (2) (Fig. 2). In the calculations, we used Poisson ratios ν = 0.17 for glass and ν = 0.3 for a permalloy film and Young's modulus *E* = 200 GPa for the film [10].

From analyzing these distributions, it follows that, in going to the center of the sample, the longitudinal compressive stress σ_{xx}^e increases linearly in magnitude and that isolines of this stress are nearly straight lines parallel to the *y* axis. The transverse stress σ_{yy}^e likewise

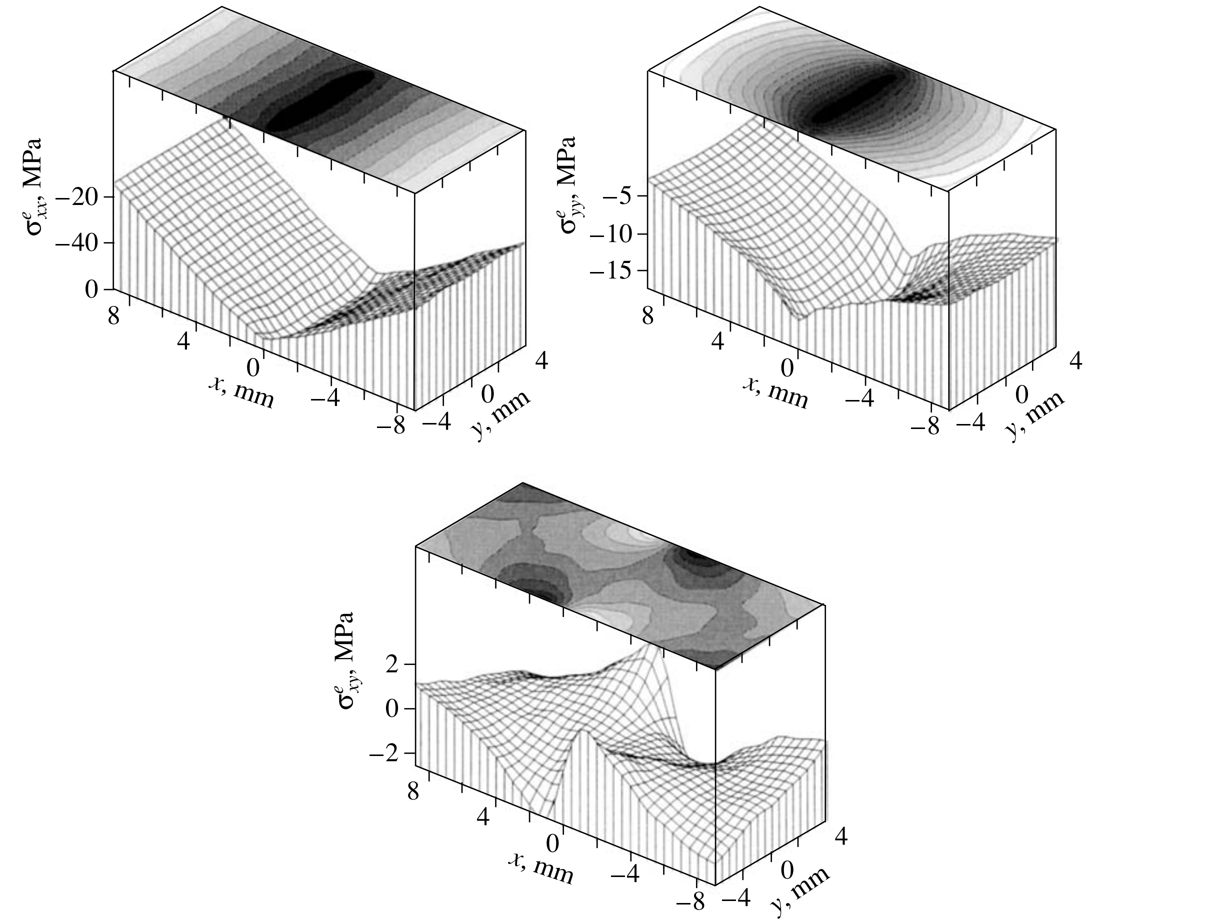

Fig. 2. Calculated distributions of the components of the external stress tensor over the area of a permalloy film on a substrate subjected to axial bending strains.

reaches a maximum at the center of the sample but is almost threefold less that the longitudinal stress, and its isolines are curved and resemble concentric ellipses. In addition to longitudinal and transverse stresses, a bent substrate is subjected to small shear stresses σ^e_{xy}, which vary from –2.5 to 2.5 MPa.

3. EXPERIMENTAL TECHNIQUE AND RESULTS

The magnetic parameters of local spots of the samples under study were measured using an automated scanning FMR spectrometer [11], with a sensor being a microstrip resonator (MSR) fabricated on a substrate with a high permittivity. Near an antinode of a mw magnetic field, the resonator ground plane has a small hole for making local measurements. Resonance mw power absorption of a spot of the film sample in the FMR spectrometer is detected in the usual fashion (using the modulation technique [1]) by measuring the Q factor of the MSR over the course of scanning of a static magnetic field applied in the film plane. The resonator is a driving circuit in a transistor mw generator located, together with a detector, within the sensor case. The measuring hole in the MSR is used simultaneously as a localized source of a mw magnetic field and as a coupling channel between the film under study and the resonator.

The main advantage of the scanning spectrometer is its high sensitivity owing to the fact that the sample occupies most of the sensor volume due to the smallness of the MSR. An advantage is also that the spectrometer is equipped with a set of mw sensors covering a fairly wide frequency range (0.1–6.0 GHz), which is important in studying magnetic inhomogeneities of thin films. Indeed, it is well known that certain TMF characteristics, such as magnetostriction and bulk and surface magnetic anisotropies, are dependent on the magnitude of a static magnetic field H applied to the sample. Inhomogeneities of the distributions of these quantities over the film plane, as a rule, become less pronounced as H increases. Since the FMR field increases almost linearly with the pump frequency f, one should significantly decrease the frequency f in order to measure the profile of magnetic inhomogeneities of films in weak fields. However, in standard spectrometers having cavity resonators with pump frequencies of the order of

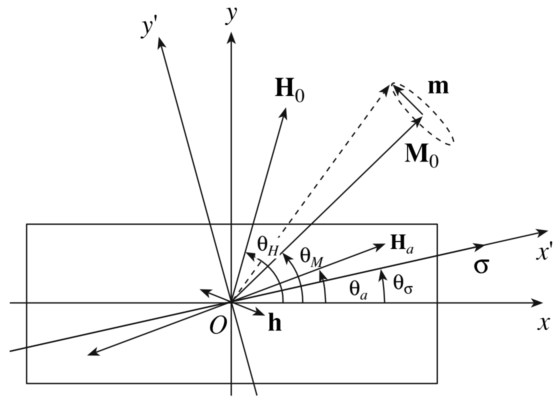

Fig. 3. Model of a magnetic film with in-plane uniaxial anisotropy.

10 GHz, the resonance magnetic fields are very high even in the case when the field is applied in the film plane and, hence, the demagnetization factors are close to zero. For permalloy films, e.g., the resonance fields are ~10^3 Oe.

In this work, we employed a scanning spectrometer with a mw sensor operating at a pump frequency f = 2.274 GHz and the resonance fields did not exceed 75 Oe for the samples under study. The diameter of the measuring hole of the sensor was ~1 mm; therefore, local measurements were performed for a spot area of ~0.8 mm^2. The angular dependences of the resonance field H_R were measured for each local spot of the film surface in steps of 1 mm. From these dependences, the main magnetic characteristics of the films were determined automatically with a computer program based on a phenomenological calculation [12]. In contrast to [12], the calculation in this work does not include the unidirectional anisotropy, which is usually small in comparison with the uniaxial anisotropy in permalloy films.

Let a TMF is positioned in the xy plane (Fig. 3). An external static field $\mathbf{H}_0$ and a mw magnetic field h (varying with time according to a sinusoidal law at a circular frequency ω) are applied in the film plane at angles θ_H and $\theta_H + \pi/2$ to the x axis, respectively. The direction of the uniaxial magnetic anisotropy field $\mathbf{H}_a$ along the easy magnetization axis (EA), which also lies in the film plane, is defined by angle θ_a.

The free energy density F of the film is the sum of the densities of the Zeeman energy (F_H), the uniaxial anisotropy energy (F_a), and the energy of magnetic charges arising on the film surfaces due to magnetization precession (F_M):

$$F = F_H + F_a + F_M = -(\mathbf{MH}) - \frac{H_a}{2M_0}(\mathbf{Mn})^2 + \frac{1}{2}(\mathbf{MNM}). \quad (3)$$

Here, $\mathbf{H} = \mathbf{H}_0 + \mathbf{h}$; $\mathbf{M} = \mathbf{M}_0 + \mathbf{m}$, where $\mathbf{M}_0$ and $\mathbf{m}$ are the static and dynamic components of the magnetic moment $\mathbf{M}$, respectively; $\mathbf{n}$ is a unit vector along the EA; and $\mathbf{N}$ is the demagnetization factor tensor, which has only one nonzero component $N_{zz} = 4\pi$ for a film sample.

The motion of the magnetic moment $\mathbf{M}$ under a magnetic field is described by the Landau–Lifshitz equation

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma[\mathbf{M} \times \mathbf{H}_{\text{eff}}], \quad (4)$$

where γ is the gyromagnetic ratio and $\mathbf{H}_{\text{eff}} = -\partial F/\partial \mathbf{M}$.

Solving Eq. (4) in a linear approximation under the assumption that $m \ll M_0$ and $h \ll H_0$, it is easy to obtain the following relation between the resonance magnetic field H_R and the magnetic characteristics of the sample at a fixed pump frequency ω:

$$\left(\frac{\omega}{\gamma}\right)^2 = [H_R\cos(\theta_H - \theta_M) + H_a\cos 2(\theta_a - \theta_M)] \times [4\pi M_0 + H_R\cos(\theta_H - \theta_M) + H_a\cos^2(\theta_a - \theta_M)], \quad (5)$$

where the angle θ_M defines the equilibrium direction of the saturation magnetization $\mathbf{M}_0$ of the film and can be found from the relation

$$H_0\sin(\theta_H - \theta_M) + \frac{1}{2}H_a\sin 2(\theta_a - \theta_M) = 0, \quad (6)$$

which can be derived by minimizing the free energy density F in Eq. (3).

Given the pump frequency ω, Eqs. (5) and (6) make it possible to determine the magnetic characteristics of any local spot of the film from the angular dependences of the resonance field $H_R(\theta_H)$ [12].

Figure 4 shows the resonance field H_R (points) measured for various values of the angle θ_H of the magnetic field in steps of 2° for a spot of a stressed permalloy film. In order to exclude ambiguities associated with hysteretic phenomena in the film, the angular dependences were measured in the regime of reverse magnetic-field sweeping [13]. In addition, prior to recording a new spectrum after each change in the angle θ_H, the sample was preliminarily magnetized in a field of 300 Oe [14]. The solid curve in Fig. 4 is the least-squares fit of the theoretical angular dependence of H_R to the experimental points for the following parameter values of the film spot: M_0 = 1187 G, H_a = 18.68 Oe, and θ_a = 94.5°. As already mentioned, these characteristics were determined automatically from the measured $H_R(\theta_H)$ values. In essence, in order to determine the magnetic parameters, a coordinate frame was reduced to the center of symmetry of the experimental $H_R(\theta_H)$ curve [12].

The accuracy with which the magnetic TMF characteristics are determined is dependent, above all, on the accuracy in determining the resonance fields, which, in turn, depends on the intensity and width of the FMR line of a specific sample. For the films under study, the field H_R was measured to within ±0.02 Oe. However, since the angular dependences obtained are based on the large number of experimental points, the accuracy in determining the magnetic characteristics of the samples is significantly better due to averaging over these points. In this case, obviously, the measurements require a long time. However, it was established experimentally in [14] that, for the TMF characteristics to be determined with the required accuracy, it is sufficient to perform measurements of the angular dependences of the resonance field at five or six points in steps of 5°–10° near each extremum.

Figure 5 shows the distributions of the magnitude and angle of the uniaxial magnetic anisotropy field over the area of stressed samples *T* and *L*. In sample *T*, in going along the long axis from an end of the TMF to its center, the increase in the elastic compression is seen to be accompanied by an almost linear increase in H_a by a factor of about 2 (roughly from 5.5 to 11.0 Oe). In this case, the distribution of H_a exhibits almost perfect mirror symmetry. It is of interest to trace the behavior of the angle θ_a between the EA and the external orienting magnetic field **H** that was applied along the short axis of sample *T* during sputtering of the film (Fig. 1). First, two hills and two valleys are clearly seen in the distribution of this angle in the middle of the film. These features are arranged in a checkerboard pattern and occupy approximately half of the film area. Second, the distribution of the angle θ_a exhibits almost perfect twofold axial symmetry and the angle varies from –2° to +8°. There is a close correlation between the distribution of the EA angle over the film area and the analogous distribution of the calculated shear stress tensor component σ^e_{xy} (Fig. 2).

For sample *L*, the distributions of the measured film characteristics over the film area are more complicated. In particular, in going along the long axis from an end to the center of the magnetic film, the field H_a first decreases linearly from ~2.5 Oe to almost zero and then increases linearly to ~3 Oe. The angle θ_a between the EA and the long axis of the substrate is close to zero at the ends of the magnetic film but changes sharply to approximately –90° in the transient region where H_a becomes zero. Moreover, the deviation of the angle θ_a from –90° has a checkerboard pattern roughly over half of the film area in the middle of the film, as is the case in sample *T*.

As expected, reference sample *K*, deposited on an unstrained substrate, exhibits substantially smaller changes in these characteristics over the film area. However, the distribution of the uniaxial magnetic anisotropy field over this sample likewise reflects the substrate shape. This field reaches a maximum ($H_a \approx$ 3.8 Oe) in the center of the film area and decreases monotonically to ~0.4 Oe in going along the long axis

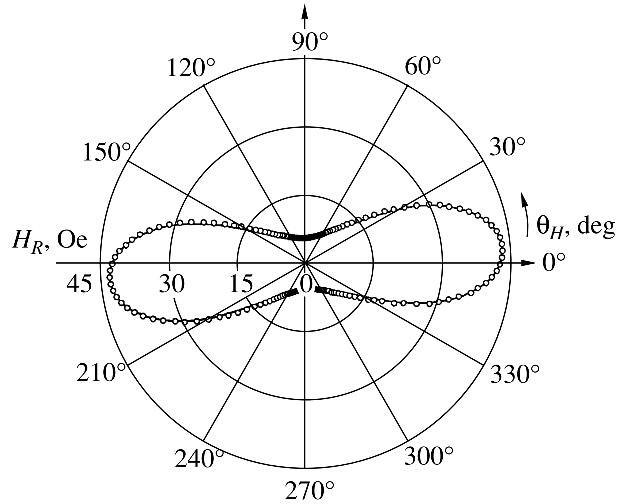

Fig. 4. Experimental (points) and theoretical (curve) dependences of the FMR field on the direction of the scanning magnetic field.

to the ends of the film. Obviously, this behavior is related to the inhomogeneous tension of the film along all directions from the edges to the center of the film caused by the significant difference between the coefficients of thermal expansion of the substrate and the permalloy film. We note that, in sample *K*, the EA angle likewise varies insignificantly over the film area, roughly from 2° to 5°.

4. ANALYSIS OF THE RESULTS

In order to explain the complicated experimental distributions of the field H_a and the angle θ_a in stressed samples, we phenomenologically calculated the effective values of the uniaxial magnetic anisotropy field and the EA angle. As is known [15], in an elastically isotropic medium with isotropic magnetostriction, the magnetic anisotropy caused by a uniaxial uniform stress σ can be determined from the magnetoelastic energy density

$$F_{\rm me} = -\frac{3}{2}\lambda_s\sigma\cos^2(\boldsymbol{\theta}_M - \boldsymbol{\theta}_\sigma), \quad (7)$$

where λ_s is the magnetostriction constant (which can be both positive and negative) and $(\boldsymbol{\theta}_M - \boldsymbol{\theta}_\sigma)$ is the angle between the magnetization vector and the direction of the uniform stress. In actual magnetic films, however, the stresses produced by a substrate are generally biaxial, as are the stresses induced by bending of substrates (Fig. 2). Therefore, the assumption (used frequently by researchers) that the stresses in films are uniform is not correct, which is manifested particularly clearly in local measurements. For this reason, we derive the magnetoelastic energy for the case where the external stress tensor σ^e_{ik} is biaxial.

The free energy density of an elastically isotropic magnet F_σ associated with its elastic properties is the sum of the densities of the magnetoelastic energy (F_{me}), the energy of elastic stresses in the material (F_{el}), and the energy of external stresses (F_{el}^e) [15]:

$$F_{me} = -3\lambda_s\mu\left[\left(\alpha_x^2 - \frac{1}{3}\right)u_{xx} + \left(\alpha_y^2 - \frac{1}{3}\right)u_{yy} + \left(\alpha_z^2 - \frac{1}{3}\right)u_{zz}\right] - 6\lambda_s\mu[\alpha_x\alpha_y u_{xy} + \alpha_y\alpha_z u_{yz} + \alpha_x\alpha_z u_{xz}],$$

$$\begin{aligned} F_{el} &= \frac{1}{2}(\lambda + 2\mu)(u_{xx}^2 + u_{yy}^2 + u_{zz}^2) \\ &+ \lambda(u_{xx}u_{yy} + u_{yy}u_{zz} + u_{zz}u_{xx}) \\ &+ 2\mu(u_{xy}^2 + u_{yz}^2 + u_{xz}^2), \\ F_{el}^e &= (u_{xx}\sigma_{xx}^e + u_{yy}\sigma_{yy}^e + u_{zz}\sigma_{zz}^e \\ &+ 2u_{xy}\sigma_{xy}^e + 2u_{yz}\sigma_{yz}^e + 2u_{xz}\sigma_{xz}^e). \end{aligned} \quad (8)$$

Here, λ and μ are the Lamé constants; α_x, α_y, and α_z are the direction cosines of the magnetic moment; u_{ik} are the elastic strain tensor components due to magnetostriction and the external stress; and σ_{ik}^e are the external stress tensor components.

The equilibrium magnetostriction strain components can be found from the condition that the free energy density be minimum, $\partial F_\sigma/\partial u_{ik} = 0$. Substituting these equilibrium components u_{ik} into the free energy density F_σ and keeping only the terms dependent on the direction of the magnetic moment, we obtain

$$\begin{aligned} F_\sigma &= -\frac{3}{2}\lambda_s(\sigma_{xx}^e\alpha_x^2 + \sigma_{yy}^e\alpha_y^2 + \sigma_{zz}^e\alpha_z^2 \\ &+ 2\sigma_{xy}^e\alpha_x\alpha_y + 2\sigma_{yz}^e\alpha_y\alpha_z + 2\sigma_{xz}^e\alpha_x\alpha_z). \end{aligned} \quad (9)$$

As already mentioned, we can assume that $\sigma_{iz}^e = 0$ for a TMF lying in the xy plane [9].

For convenience, we introduce a new ($x'y'z$) coordinate frame rotated about the z axis through an angle θ_σ (Fig. 3) such that its coordinate axes coincide with the principal axes of the external stress tensor σ_{ik}^e. In this case, the principal values σ_x^e and σ_y^e of the tensor σ_{ik}^e are [16]

$$\begin{aligned} \sigma_x^e &= \frac{1}{2}(\sigma_{xx}^e + \sigma_{yy}^e) \mp r, \quad \sigma_y^e = \frac{1}{2}(\sigma_{xx}^e + \sigma_{yy}^e) \pm r, \\ r &= \sqrt{\frac{1}{4}(\sigma_{xx}^e - \sigma_{yy}^e)^2 + \sigma_{xy}^{e2}}, \end{aligned} \quad (10)$$

where the upper (plus or minus) sign corresponds to the case $\sigma_{xx}^e \le \sigma_{yy}^e$ and the lower sign corresponds to the opposite case. The angle θ_σ is given by

$$\tan 2\theta_\sigma = \frac{2\sigma_{xy}^e}{\sigma_{xx}^e - \sigma_{yy}^e}. \quad (11)$$

Expressing Eq. (9) in terms of the principal values of the tensor σ_{ik}^e and keeping only the terms dependent on the direction of the magnetic moment, we obtain

$$\begin{aligned} F_\sigma &= -\frac{3}{2}\lambda_s(\sigma_x^e - \sigma_y^e)(\alpha_x\cos\theta_\sigma + \alpha_y\sin\theta_\sigma)^2 \\ &+ \frac{3}{2}\lambda_s\sigma_y^e\alpha_z^2. \end{aligned} \quad (12)$$

For a film with an in-plane magnetic moment, Eq. (12) simplifies to

$$F_\sigma = -\frac{3}{2}\lambda_s\sigma_{eff}^e\cos^2(\theta_M - \theta_\sigma). \quad (13)$$

Here, θ_σ is the angle between the principal axis x' of the external stress tensor and the x axis, which can be found from Eq. (11), and σ_{eff}^e is the effective uniform stress given by

$$\sigma_{eff} = \mp\sqrt{(\sigma_{xx}^e - \sigma_{yy}^e)^2 + 4\sigma_{xy}^{e2}}, \quad (14)$$

where the upper sign corresponds to the case $\sigma_{xx}^e \le \sigma_{yy}^e$.

The uniaxial magnetic anisotropy field induced by the elastic stresses in the film is

$$H_\sigma = \frac{3\lambda_s}{M}\sigma_{eff}^e. \quad (15)$$

It is important that, for the magnetic $Ni_{75}Fe_{25}$ films under study, the magnetostriction constant is positive ($\lambda_s \approx 5 \times 10^{-6}$) and the effective uniform stress σ_{eff}^e in these films as calculated from Eq. (14) is negative. Therefore, in the case where the shear components of the elastic stress tensor are zero ($\sigma_{xy}^e = 0$), we have $\theta_\sigma = 0°$ and the long axis of the TMF (axis x) is a hard magnetization axis. In other words, due to the magnetic anisotropy induced by the elastic stresses in the films deposited on strained substrates, the EA is oriented along the y axis. Calculations show that, due to the nonzero shear component of the elastic stress tensor calculated for the samples under study (Fig. 2), the EA deviates from the y axis through angles of up to ±6°, depending on the value and sign of σ_{xy}^e.

Let H_h be the uniaxial magnetic anisotropy field induced by the external static magnetic field that was applied during sputtering of the films (Fig. 1) and caused the EA to be directed along the long axis of the substrate

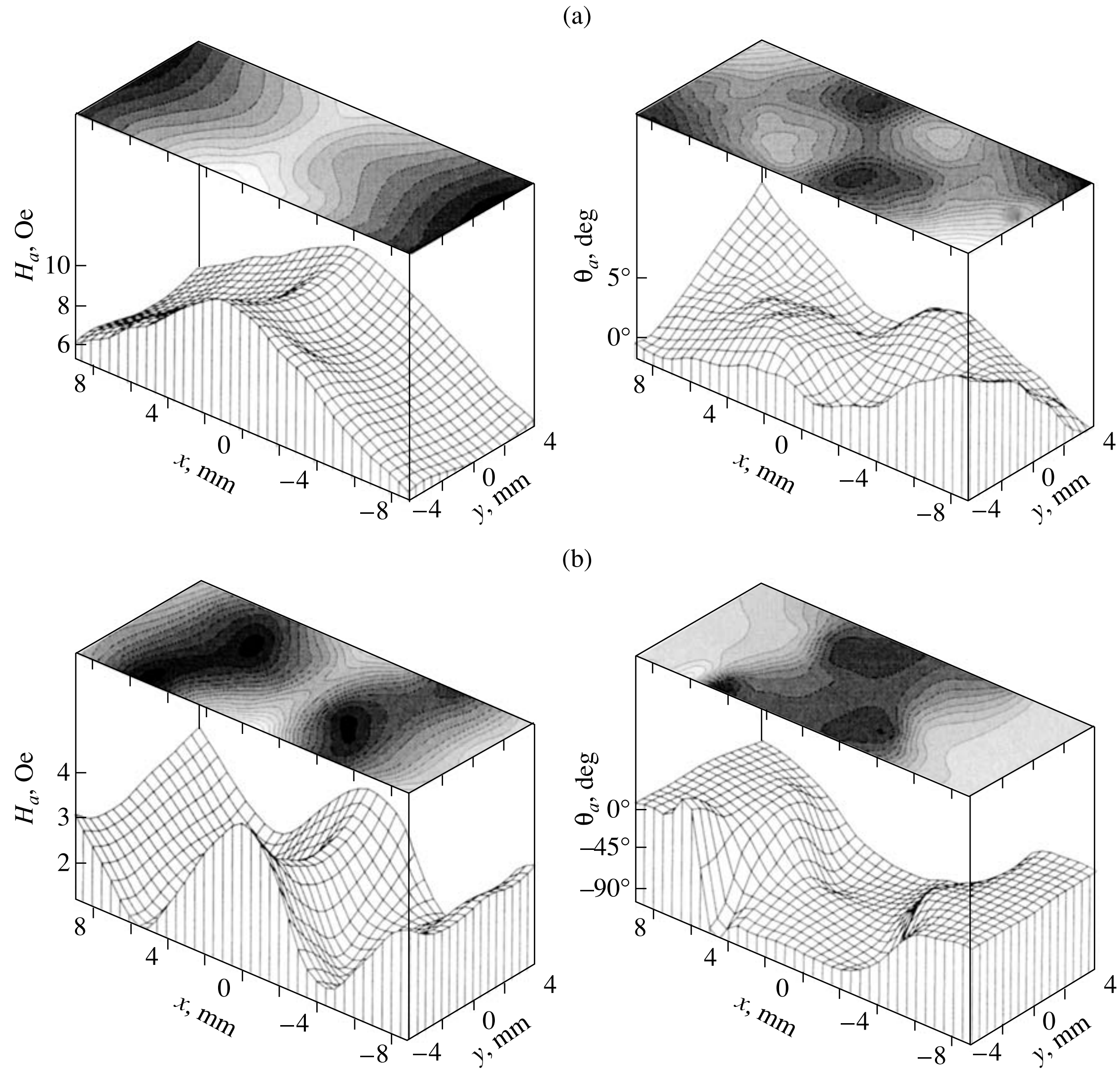

Fig. 5. Experimental distributions of the magnitude and angle of the uniaxial magnetic anisotropy field over the area of stressed films: (a) sample T and (b) sample L.

in samples K and L ($\theta_h = 0$) and along the short axis in sample $T(\theta_h = 90°)$. The experimentally observed uniaxial anisotropy energy $F_a = -\frac{H_a M}{2}\cos^2(\theta_M - \theta_a)$ is the sum of the magnetoelastic anisotropy energy $F_\sigma = -\frac{H_\sigma M}{2}\cos^2(\theta_M - \theta_\sigma)$ and the anisotropy energy induced by the magnetic field $F_h = -\frac{H_h M}{2}\cos^2(\theta_M - \theta_h)$. Using these expressions, it is easy to derive the set of equations

$$\begin{cases} H_a\cos 2(\theta_M - \theta_a) \\ = H_h\cos 2(\theta_M - \theta_h) + H_\sigma\cos 2(\theta_M - \theta_\sigma) \\ H_a\sin 2(\theta_M - \theta_a) \\ = H_h\sin 2(\theta_M - \theta_h) + H_\sigma\sin 2(\theta_M - \theta_\sigma) \end{cases} \quad (16)$$

from which the actual anisotropy field and its angle are determined to be

$$H_a = \sqrt{H_h^2 + H_\sigma^2 + 2H_h H_\sigma\cos 2(\theta_h - \theta_\sigma)},$$
$$\theta_a = \frac{1}{2}\left[\theta_h + \theta_\sigma + \arctan\left(\frac{H_h - H_\sigma}{H_h + H_\sigma}\tan(\theta_h - \theta_\sigma)\right)\right]. \quad (17)$$

Figure 6 shows the distributions of H_a and θ_a over the area of stressed permalloy films (samples T and L) calculated from Eqs. (17). In the calculations, the following parameter values are used: magnetostriction constant $\lambda_s = 5 \times 10^{-6}$; saturation magnetization $M_s = 960$ G; uniaxial anisotropy field induced by the orienting magnetic field $H_h = 4$ Oe; and EA angle $\theta_h = 0°$ and $\theta_h = 90°$ for samples L and T, respectively.

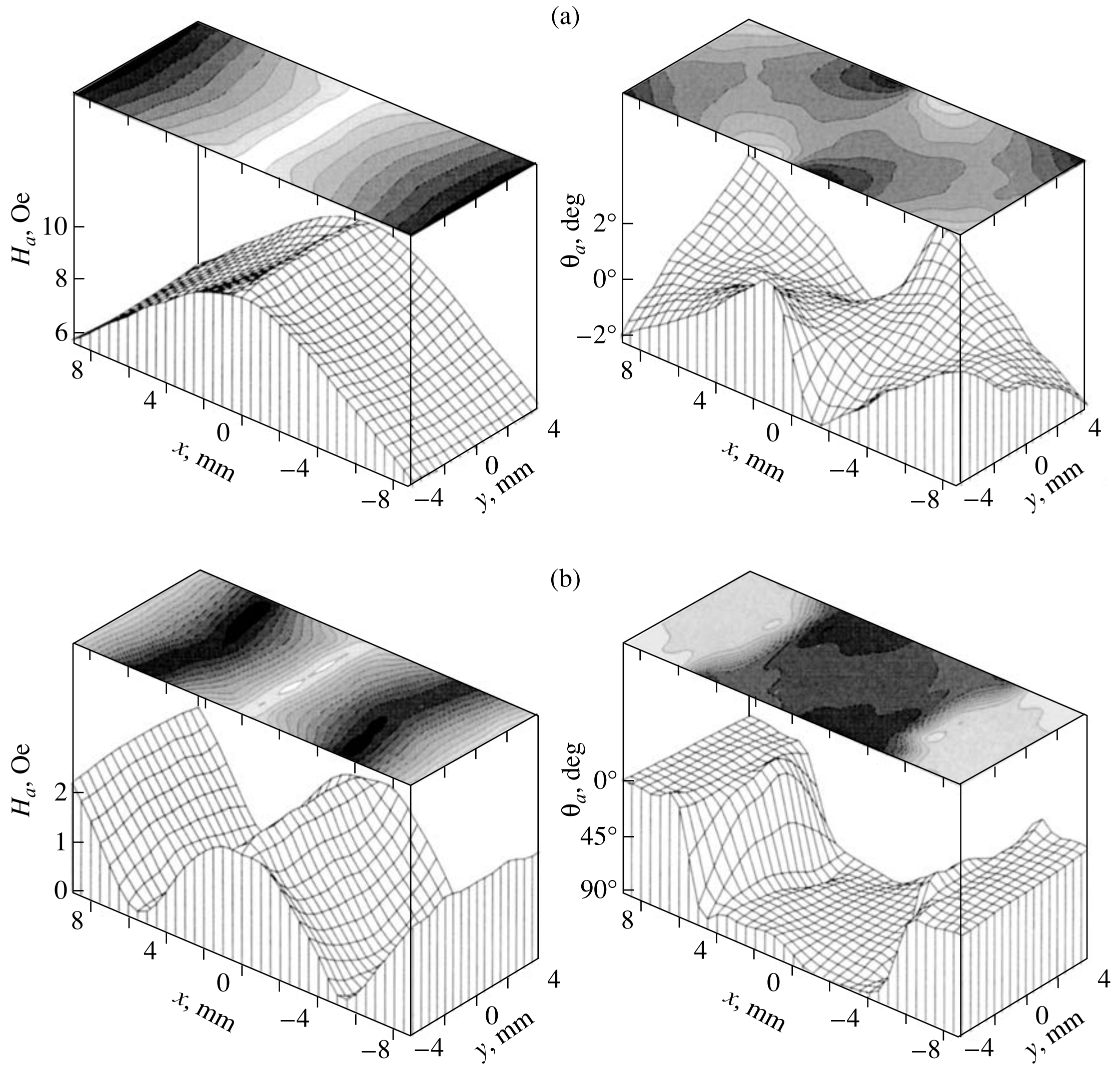

Fig. 6. Theoretical distributions of the magnitude and angle of the uniaxial magnetic anisotropy field over the area of stressed films: (a) sample *T* and (b) sample *L*.

The calculated distributions are in good qualitative and quantitative agreement with the experimental data (Fig. 5). The observed behavior of H_a and θ_a can be qualitatively explained as follows. In sample *L*, the EA of magnetic anisotropy H_h and the EA of magnetic anisotropy H_σ are almost perpendicular to each other. Therefore, as H_σ increases linearly in going along the long axis from an end of the film to its center, the effective anisotropy field $H_a \approx H_h - H_\sigma$ decreases linearly. The effective EA angle θ_a coincides with θ_h, and both are equal to zero. When H_a becomes zero, the angle θ_a changes sharply to 90° and coincides with the EA angle of the magnetoelastic anisotropy H_σ. As H_σ increases further in going to the center of the film, the effective anisotropy field $H_a \approx H_\sigma - H_h$ increases linearly.

In sample *T*, the EA of the magnetic anisotropy H_h almost coincides in direction with that of the magnetoelastic anisotropy H_σ. Therefore, as H_σ increases linearly in going along the long axis from an end of the film to its center, the effective anisotropy field $H_a \approx H_h + H_\sigma$ likewise increases linearly. In both samples, the checkerboard pattern of the deviation of the angle θ_a from its average value is due to small deviations of the EA of the magnetoelastic anisotropy H_σ caused by the nonzero shear component of the elastic stress tensor of the film.

5. CONCLUSIONS

Thus, performing local measurements with a scanning FMR spectrometer, we have detected and studied the complicated distributions of the magnitude and direction of the uniaxial magnetic anisotropy field over the area of inhomogeneously stressed permalloy films. The study has been performed on samples with different orientations of uniaxial anisotropy (which was induced by an external static magnetic field during deposition of the films in vacuum) with respect to the direction of the quasi-inhomogeneous elastic stress produced by bending the substrate along its long axis. We have calculated and constructed the distributions of the diagonal and shear components of elastic stresses over the area of the magnetic films under study. It was shown that the shear components are only one order of magnitude smaller than the diagonal components and, hence, can have a significant effect on the formation of magnetic anisotropy.

We have performed a phenomenological calculation of the distribution of the magnitude and direction of the effective uniaxial magnetic anisotropy over the film area. The calculation is in good agreement with the experimental data and explains the nature of the observed effects. In particular, the distribution of anisotropy angles over the film area having two hills and two valleys arranged in a checkerboard pattern and occupying approximately half of the film area in the middle of the film has been shown to be due to the shear components of the elastic stresses. It is the shear components that are responsible for the almost perfect twofold axial symmetry of the distribution of the easy axis (EA) angles, the deviation of which from the average value can be as large as several degrees.

For a film with transverse in-plane magnetic anisotropy induced by an external magnetic field, it has been shown that the effective anisotropy increases due to the increase in the magnetoelastic anisotropy. As a result, as the stress increases linearly in going along the long axis from an end of the film to its center, the anisotropy field increases almost linearly by a factor of approximately 2. The EA direction varies over a range of 10°. In a film in which the uniaxial magnetic anisotropy induced by the external field is oriented along the long axis, the magnetoelastic anisotropy is directed along the short axis. As the stress increases linearly in going along the long axis from an end of the film to its center, the effective anisotropy field first decreases linearly to zero and then increases, reaching a maximum at the center of the sample. In this sample, the EA almost coincides with the direction of the dominant anisotropy. For this reason, the anisotropy angle changes abruptly by 90° when the anisotropies compensate each other.

ACKNOWLEDGMENTS

This work was supported by the Council on Grants of the President of the Russian Federation for the Support of Leading Scientific Schools of the Russian Federation (project NSh-6612.2006.3).

REFERENCES

1. R. F. Soohoo, *Magnetic Thin Films* (Harper and Row, New York, 1965; Mir, Moscow, 1967).
2. N. M. Salanskiĭ and M. Sh. Erukhimov, *Physical Properties and Applications of Magnetic Films* (Nauka, Novosibirsk, 1975) [in Russian].
3. V. A. Ignatchenko, Zh. Éksp. Teor. Fiz. **40**, 1228 (1961) [Sov. Phys. JETP **13**, 863 (1961)].
4. B. A. Belyaev, A. V. Izotov, and A. A. Leksikov, Zavod. Lab., Diagn. Mater. **67**, 24 (2001).
5. B. A. Belyaev, A. V. Izotov, and S. Ya. Kiparisov, Pis'ma Zh. Éksp. Teor. Fiz. **74** (4), 248 (2001) [JETP Lett. **74** (4), 226 (2001)].
6. B. A. Belyaev and A. V. Izotov, Pis'ma Zh. Éksp. Teor. Fiz. **76** (3), 209 (2002) [JETP Lett. **76** (3), 175 (2001)].
7. B. A. Belyaev, A. G. Vladimirov, and V. V. Polyakov, in *Proceedings of the 16th All-Russian Workshop–School "New Magnetic Materials for Microelectronics," Moscow, Russia, 1998* (Moscow, 1998), Part I, p. 243 [in Russian].
8. E. Du Trimolet de Lacheisserie and J. C. Peuzin, J. Magn. Magn. Mater. **136**, 189 (1994).
9. L. D. Landau and E. M. Lifshitz, *Course of Theoretical Physics*, Vol. 7: *Theory of Elasticity* (Butterworth–Heinemann, Oxford, 1986; Nauka, Moscow, 1987).
10. Y. Shiroishi, K. Shiiki, I. Yuitoo, H. Tanabe, H. Fujiwara, and M. Kudo, IEEE Trans. Magn. **20**, 485 (1984).
11. B. A. Belyaev, A. A. Leksikov, I. Ya. Makievskii, and V. V. Tyurnev, Prib. Tekh. Éksp., No. 3, 106 (1997) [Instrum. Exp. Tech. **40** (3), 390 (1997)].
12. B. A. Belyaev, A. V. Izotov, and A. A. Leksikov, IEEE Sens. J. **5**, 260 (2005).
13. S. D. Bader, J. Magn. Magn. Mater. **100**, 440 (1991).
14. B. A. Belyaev, A. A. Ivanenko, A. A. Leksikov, I. Ya. Makievskiĭ, A. Z. Pashkevich, and V. V. Tyurnev, Preprint No. 761F (Institute of Physics, Siberian Division Russian Academy of Sciences, Krasnoyarsk, 1995) [in Russian].
15. C. V. Vonsovskii, *Magnetism* (Nauka, Moscow, 1971; Wiley, New York, 1974).
16. J. F. Nye, *Physical Properties of Crystals: Their Representation by Tensors and Matrices* (Oxford University Press, Oxford, 1957; Inostrannaya Literatura, Moscow, 1967).

Translated by Yu. Epifanov