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PHYSICS OF MAGNETIC PHENOMENA

MICROMAGNETIC ANALYSIS OF EDGE EFFECTS IN A THIN MAGNETIC FILM DURING LOCAL EXCITATION OF MAGNETIZATION OSCILLATIONS

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The method of numerical micromagnetic simulation was used to study the magnetization dynamics of a thin film with uniaxial magnetic anisotropy during ferromagnetic resonance (FMR) excitation in it on the local sites by a linearly polarized high-frequency magnetic field emitted from the 1 mm opening in the metallic screen of the transmission line. It was established that non-uniformities of demagnetizing fields emerging near the film edges lead not only to the change in the FMR field, but also to the change in the value and direction of the uniaxial anisotropy field. The distribution of non-uniformities of the magnetic anisotropy characteristics over the area of 60 nm thick permalloy film that was measured on the scanning FMR spectrometer agrees well with the micromagnetic simulation results. Demagnetizing fields were proved to be the main cause for the edge effects in magnetic films.

Keywords: micromagnetic simulation, thin magnetic film, edge effects, ferromagnetic resonance, magnetic anisotropy.

INTRODUCTION

It is well known that thin-film magnetic structures have a number of unique physical properties that distinguish them from bulk magnetic materials. For instance, thanks to their microstructure, thin nanocrystalline magnetic films demonstrate high magnetic susceptibility and low losses at microwave frequencies [1], which makes them promising media to be used in high-frequency sensors of weak magnetic fields and signal processing devices [2, 3]. Obviously, characteristics of any devices based on magnetic films depend on the uniformity of magnetic parameter distribution over the sample surface, but devices where magnetic films are under condition of uniform ferromagnetic resonance (FMR) [4] are especially susceptible to non-uniformity. As far as film samples in devices have finite dimensions, even when they are magnetized by a uniform magnetic field in the plane the demagnetizing field created by 'magnetic charges' on the sample edges [5] will be non-uniform. As a rule, in thin magnetic films, spatial non-uniformity of the demagnetizing field on the edges is taken into account only when sample dimensions become comparable with their thickness. In such samples, magnetostatic oscillation modes with a finite wavelength [6, 7] may be excited under the impact of the uniform high-frequency field, and interesting features associated with oscillation localization near their edges are also observed [8, 9].

Nevertheless, as will be shown in this paper, huge values of demagnetizing fields existing on the edges of permalloy films have considerable impact on the integral magnetic characteristics even in those samples the dimensions

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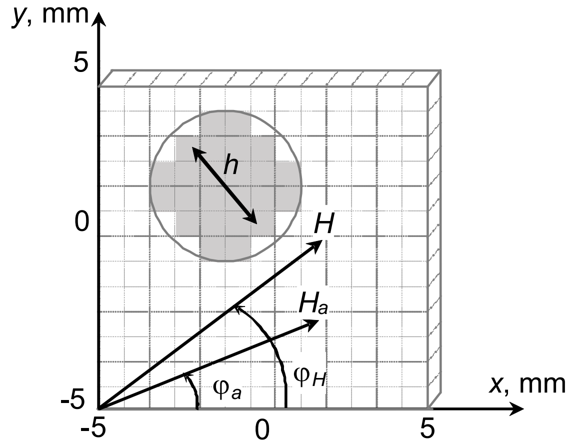

Fig. 1. Model of thin magnetic field with uniaxial magnetic anisotropy. Grey color indicates the local site on the film surface that is affected by the exciting microwave field *h*.

of which exceed their thickness by several orders of magnitude. The paper presents the micromagnetic calculation of the locally excited magnetization oscillations of a thin permalloy film with uniaxial magnetic anisotropy. Numerical analysis allowed not only estimating the impact of edge effects on high-frequency film properties, but also making a comparison with previous experimental research on non-uniformities of magnetic parameter distribution over the film surface [10, 11] using a scanning spectrometer of ferromagnetic resonance [12].

1. MICROMAGNETIC SIMULATION

Numerical analysis of magnetization dynamics of the examined thin magnetic film with uniaxial magnetic anisotropy was performed by means of the micromagnetic calculation of its 3D model. The examined object was split into identical discrete elements (cells) shaped as parallelepipeds with square bases. Each cell was considered uniformly magnetized and characterized by some averaged magnetic moment vector. In calculations between discrete elements, we took into account the energy of magnetostatic and exchange interactions, as well as the energy of interaction of each element with external constant magnetic field H and magnetic anisotropy field H_a. From the condition of free energy density minimum of the film, we determined the ground (equilibrium) magnetization state [13]. Based on the produced equilibrium distribution of magnetic moments and then by means of solving the system of equations describing the magnetization motion (linearized Landau–Lifshitz equations) we calculated the high-frequency properties of the thin magnetic film.

At present, two approaches are usually used when solving the Landau–Lifshitz equation system in problems dealing with magnetization dynamics: the method based on solution expansion in oscillation eigenmodes [6, 14] and the method of undetermined coefficients [15, 16]. The former method requires considerably higher computational power, but allows determining the contribution of each eigenmode into the spectrum of resonance frequencies that are excited by the external high-frequency field, which is a crucial advantage of this method. The latter method does not require high computational power, but as was shown in [16], high-frequency magnetic susceptibilities of films calculated by the two methods concur. That is why, if one does not need information on the contribution of each eigenmode into the spectrum, but rather needs to perform a large number of calculations of the frequency or field dependence of magnetic susceptibility, then the method of undetermined coefficients is obviously preferable.

The present research examined a single-layer thin film model with dimensions of 10×10 mm and thickness of 60 nm that was split into 256×256×1 discrete elements (Fig. 1). In order to compare the calculation results with the experiment, magnetic parameters of the model were chosen as corresponding to the examined $Ni_{75}Fe_{25}$ permalloy film:

saturation magnetization M_s = 1070 G, exchange constant $A = 1\cdot10^{-6}$ erg/cm, uniaxial anisotropy field H_a = 6 Oe, damping coefficient of magnetization precession α = 0.005. External constant magnetic field H was applied in the film plane at an angle φ_H in relation to axis x, and the planar variable linearly polarized field h was always directed orthogonally to H (Fig. 1). Magnetization dynamics was calculated at fixed variable field frequency equal to 2.3 GHz.

A crucial distinguishing feature of this research is that we attempted to fully reproduce a real experiment from the research on magnetic parameter distribution over thin magnetic film area using a scanning spectrometer of ferromagnetic resonance [10, 11]. That is why in our model we considered the case when variable high-frequency field h affected not the entire film, but only its local site, the boundaries of which were determined by a circle on the film surface with diameter d = 1 mm, as is shown in Fig. 1. Therefore, field h directly excited the magnetization oscillations in 523 discrete elements (out of 65536), which in their turn, due to the exchange and magnetostatic coupling, propagated from the locally excited site further on over the film area. Let us note that the use of the undetermined coefficients method when solving the Landau–Lifshitz equations allowed calculating a huge number of spectra of the microwave power absorption by a thin magnetic film without large machine time expenditure.

2. RESEARCH RESULTS

Micromagnetic calculation of magnetization dynamics during excitation of the local film site was done for the case when the easy magnetization axis (EMA) is directed along axis y (φ_a = 90°) and the constant magnetic field H is oriented in the same direction (φ_H = 90°). Fig. 2 presents, for three local sites on the film, the amplitude distributions of variable magnetization m_a produced when oscillations are excited in the sample center (*a*), near the center of the edge parallel to axis x (*b*), and near the center of the edge parallel to axis y (*c*).

Calculation of these sites was performed for four constant magnetic field values: in the ferromagnetic resonance field H = 43.9 Oe; in the fields near the resonance on the left and on the right from it, respectively H = 30 and 50 Oe, as well as in the ‘weak’ magnetic field far from the resonance H = 10 Oe. Non-uniform magnetization oscillations are excited in the film, because the high-frequency field affects it locally. One can see that in the fields below the FMR field, magnetization oscillations propagate in the form of waves to the right and to the left from the local excitation region perpendicularly to the magnetic moment orientation. It is important to note that in this field region, the real component of high-frequency magnetic permeability assumes negative values, and this is the existence condition for bulk magnetostatic waves [6]. Magnetization waves quickly attenuate due to relatively large microwave power losses in the film that correspond to the imaginary component of magnetic permeability. As one knows, the maximum of microwave power absorption is observed in the FMR field; that is why the magnetization oscillation waves disappear. They are also absent in the fields above the ferromagnetic resonance field, as far as high-frequency magnetic permeability in this region assumes positives values. One can see in Fig. 2 that the characters of wave processes generated by the local impact of the microwave field on the film not only depend on the constant magnetic field value, but also differ considerably in the cases of the central sample area excitation and excitation in the regions near its edges. The most significant differences are observed for oscillations excited near the film edge parallel to axis y, which is obviously associated with the wave reflections from the film edge. One should mention that there is a notable difference between the FMR fields measured from the sites in the sample center and on its edges in the cases of two magnetic scanning field orientations: along EMA and orthogonally to EMA, i.e. along the hard magnetization axis (HMA). This fact can be explained by the presence of demagnetizing fields on the film edges [17].

Indeed, the demagnetizing field on the very edge of the film $H_d \sim -4\pi M_S\cos(\varphi_M)$, where φ_M is the angle of equilibrium magnetization direction. When the equilibrium magnetization is oriented perpendicularly to the film edge, the demagnetizing field can reach huge absolute values ~13 kOe. However, as numerical calculation of the micromagnetic model shows, module of the field H_d very quickly decreases with the distance from the film edge. Fig. 3 presents the dependence $H_d(y)$ built with the increase in distance from the center of the film edge parallel to axis x, when the external field H = 44 Oe is directed along EMA (φ_H = 90°). One can see that when approaching the film edge, the absolute value of the demagnetizing field grows exponentially. At the distance of 20 μm from the film edge H_d = –4 Oe, at the distance of 1 μm H_d = –91 Oe, and on the very edge of the film H_d is close to the maximum (in terms of absolute value) value $4\pi M_S$, because the micromagnetic calculation showed that magnetization vectors of discrete

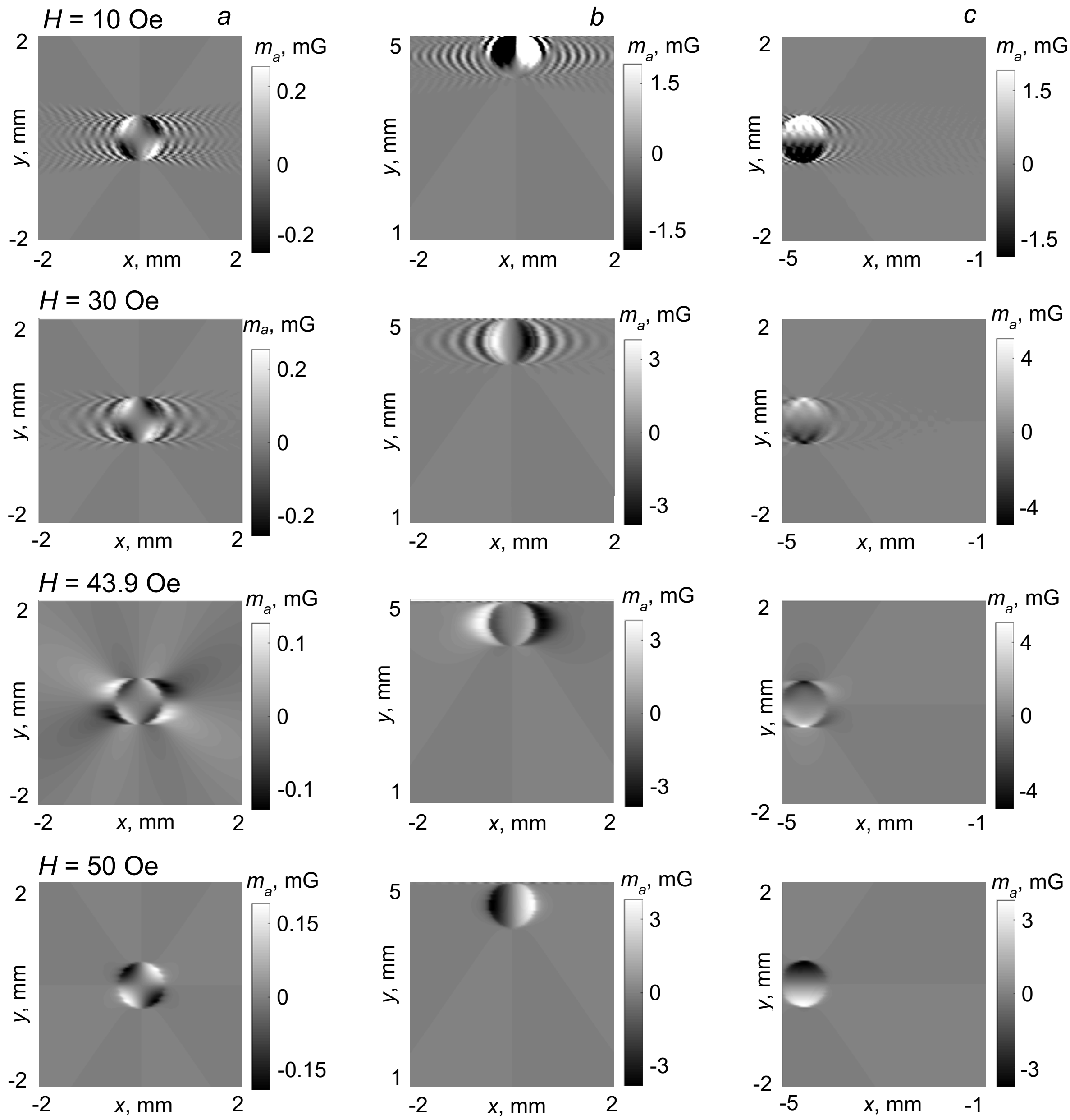

Fig. 2. Amplitude distribution of variable magnetization m_a for four external field values H during excitation of oscillations in the film center – a (x = 0 mm, y = 0 mm), near the edge parallel to horizontal axis – b (x = 0 mm, y = 4.5 mm), and near the edge parallel to vertical eaxis – c (x = −4.5 mm, y = 0 mm).

elements that fall into the film excitation area only insignificantly deviate from the external field direction. On average, the angle of equilibrium orientation of magnetization φ_M in discrete elements on the film edge is ~88°. At the same time, in the film center at the distance of 5 mm from the edges, the value of demagnetizing field is only –0.03 Oe. That is why the impact of demagnetizing fields on the film properties can manifest itself only in the immediate proximity to its edges.

In order to study the impact of demagnetizing fields emerging near the film edges on the effective magnetic anisotropy parameters, we calculated the FMR spectra for when the direction of constant scanning magnetic field φ_H

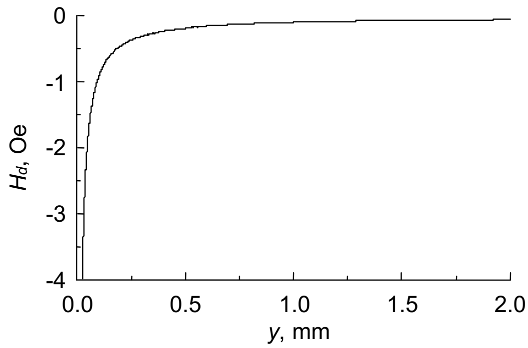

Fig. 3. Dependence of the demagnetization field of a thin film with increase in the distance from its edge.

changes in the range of 0–360° in 5° increments on each local site over the entire film surface with a 1 mm step. Parameters of the effective uniaxial magnetic anisotropy on each local site, just as in experiment [10, 11], were determined based on the angle dependences of the resonance field in accordance with the methodology described in [18, 19]. One should note that in this paper we de facto simulated the experimental studies of thin magnetic films that had been previously carried out using the scanning FMR spectrometer [10, 11]. Fig. 4*a* presents the calculation results of distribution over the film surface of the field and anisotropy direction angle, respectively H_a and φ_a. One can see that near the film edges, field H_a deviates from the field value in the center by 0.5 Oe, and the deviations of H_a from the field value in the center have opposite signs near adjacent edges. With the increase in distance from the edge, this effect quickly goes down. One can also see that the anisotropy field direction deviates on the film edges from the set direction in its center, and this deviation is ±0.7°. The observed behavioral features of the value of uniaxial anisotropy angles over the film surface are easily explained, if one takes into account the deviations of directions of the demagnetizing fields H_d from the direction of the magnetizing fields that are observed only near the film corners.

One can also easily explain the behavior of the anisotropy field value on the film edges. In discrete elements that are far from the sample corners, magnetic moments are oriented strictly along the magnetizing field H, if it is directed parallel to EMA or parallel to HMA. Let the external scanning field H be directed along axis y (along EMA), then the demagnetizing fields near the film edges parallel to axis y are close to zero, as far as magnetic moments in the corresponding discrete elements are parallel to these edges and do not create magnetic charges. Meanwhile, the resonance fields estimated for the local sites near these edges will be close to the FMR fields in the central part of the film. However, H_d near the adjacent film edges parallel to axis x, in the case of such orientation of the magnetizing field H, obviously reaches the maximum values. This field H_d needs to be compensated, that is why the resonance field on these sites will be larger than the FMR field in the film center.

On the contrary, when the scanning field is oriented along axis x (along HMA), the demagnetizing fields near the film edges that are parallel to axis y will reach maximum values, and near the film edges that are parallel to axis x, they will be close to zero. As a result, when the sample is magnetized along HMA and along EMA, the difference between the resonance fields will increase for the edges parallel to axis y and decrease for the adjacent edges parallel to axis x. That is why the anisotropy field increases on the edges parallel to axis y and decreases on the edges parallel to axis x, in relation to the anisotropy value in the central part of the sample.

These results produced using micromagnetic simulation agree well with the earlier experimental research on the edge effects in thin permalloy films [10, 11]. Fig. 4*b* presents the distributions of magnetic uniaxial anisotropy parameters obtained using a scanning FMR spectrometer for $Ni_{75}Fe_{25}$ film with thickness of 60 nm and dimensions of 10×10 mm. The details of this experiment are described in [11]. Measurements showed that the effective saturation magnetization of the film is 1065 G, and the field of uniaxial magnetic anisotropy in its center is 5.8 Oe. All parameters of the experimental sample are close to those parameters that were used in the micromagnetic calculation. Good

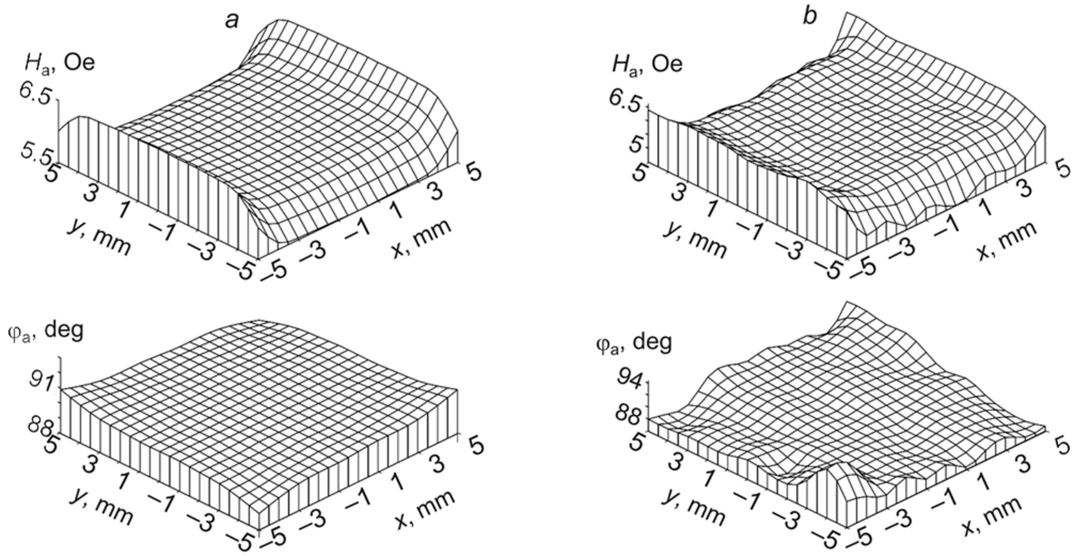

Fig. 4. Distribution over the film surface of field H_a and orientation angles φ_a of uniaxial magnetic anisotropy: *a* – micromagnetic simulation, *b* – experiment.

agreement of the measured distributions of value and angle of uniaxial magnetic anisotropy over the film surface with the estimated characteristics proves that demagnetization fields are the main reasons for the formation of edge effects.

CONCLUSIONS

Therefore, the method of numerical analysis of micromagnetic model of a thin magnetic film was used to study the magnetization dynamics of $Ni_{75}Fe_{25}$ permalloy film during excitation of magnetization oscillations by external high-frequency field on the local sites of the sample. This research showed that magnetization oscillations excited near the film edges are different in terms of character and amplitude from oscillations in its center. It also showed that local impact of the high-frequency field on the film excites non-uniform magnetization oscillations in it. In fields below the ferromagnetic resonance field, magnetization oscillations propagate perpendicularly to the magnetic moment orientation in the form of waves to the right and to the left from the local region. However, in the FMR field and in the large fields, waves of magnetization oscillations disappear.

This research explains the nature of the earlier experimentally observed effects of increase and decrease in uniaxial anisotropy fields on the adjacent film edges, as well as the change in directions of these fields near the film edges. Good agreement of the calculation with the experiment proves that the observed effects are associated with the non-uniform demagnetizing fields emerging on the edge of finite size samples and reaching maximum values at orthogonal orientation of magnetic moments to the edge.

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