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Magnetization reversal of ferromagnetic film with perpendicular crystallographic axis orientation [110] by pulses of an alternating magnetic field

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This work deals with the nonlinear magnetic dynamics in a thin ferromagnetic film under the influence of an alternating circular magnetic field. Two main precession modes were observed and the areas of their existence depending on the magnitude of the constant magnetic field, the frequency and amplitude of the alternating magnetic field and the magnitude of the magnetic anisotropy of the film material were outlined. Magnetization reversal diagrams, time dependencies and phase portraits of the magnetic dynamics of the film depending on the parameters of the external magnetic field were constructed.

Keywords: ferromagnets, magnetocrystalline anisotropy, magnetization switching, modes of magnetic oscillations and precession.

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1. Introduction

Currently the non-linear dynamic and orientation magnetic defects in planar structures command great interest for the development of nonlinear physics and in the context of possible practical applications for use in nonvolatile data storage and information processing [1,2]. This paper, using the method of micromagnet modeling, studies the switching of magnetic states of ferromagnetic films by short pulses of alternating magnetic field. Design of devices on such basis has certain benefits compared to the similar switching technology, but with laser exposure [1,3], since in this case fewer movable mechanical parts are necessary, or may even be absent [4]. This paper solves the objective of remagnetization of a thin ferromagnetic film with perpendicular orientation of a crystallographic axis [110] and permanent magnetic field to the plane of the film, which in general approaches is a continuation of paper [5] on the magnetic dynamics of ellipsoid single-domain nanoparticles in the permanent and alternating magnetic fields, and dynamic chaos phenomena arising at the same time in respect to the ferromagnetic films with cubic magnetic anisotropy from papers [3,6], but without acoustic effect.

2. Theory

Micromagnet calculations used an equation of magnetic dynamics with a relaxation member in the form of Landau–Lifshitz [1]:

$$\frac{d\mathbf{m}}{dt} = -\frac{\mu_0\gamma}{1+\alpha^2}\left(\left[\mathbf{m}\times\mathbf{H}_{\text{eff}}\right] + \alpha\left[\mathbf{m}\times\left[\mathbf{m}\times H_{\text{eff}}\right]\right]\right)$$

where α — magnetization vector precession dissipation coefficient, γ — gyromagnetic ratio of electron, $\mu_0 = 4\pi\cdot 10^{-7}$ H/m — magnetic constant, $\mathbf{m}$ — single vector of film magnetization, $\mathbf{H}_{\text{eff}}$ — effective magnetic field determined as functional derivative of magnetic energy density presented in this study as the sum of densities of cubic anisotropy energies F_{an}, energy of dipole-dipole interaction (demagnetizing field energy) F_{dem} and external field energy (Zeeman energy) F_z, accordingly [6]:

$$F = F_{\text{an}} + F_{\text{dem}} + F_z.$$

Let us consider the normally magnetized ferromagnetic film located in plane XY and having cubic magnetic anisotropy with orientation along axis [110]. Ferromagnetic film is magnetized with permanent magnetic field $\mathbf{H}_0$ along axis Oz, i.e. perpendicularly to film plane; alternating magnetic field $\mathbf{h}$ is set as a circularly polarized nanosecond radio impulse with duration τ, oriented in the film plane:

$$h_x = h_0\sin(2\pi f t), \quad h_y = -h_0\cos(2\pi f t),$$

here h_0 and f — amplitude and frequency of alternating magnetic field. At such orientation of the film the nonzero component of the demagnetizing field would only be the component

$$H^{(z)}_{\text{dem}} = -M_0 m_z,$$

where M_0 — saturation magnetization. Density of cubic anisotropy energies expressed via magnetization vector components of the film with crystallographic axis [110] directed along axis Oz, will be as follows

$$F_{\text{an}} = -\frac{K_1}{4}\left(m_y^4 + m_z^4 - 2m_y^2m_z^2 + 4m_x^2m_y^2 + 4m_x^2m_z^2\right),$$

where K_1 — the first constant of cubic anisotropy ($K_1 > 0$). In this case the axes of light magnetization will be the

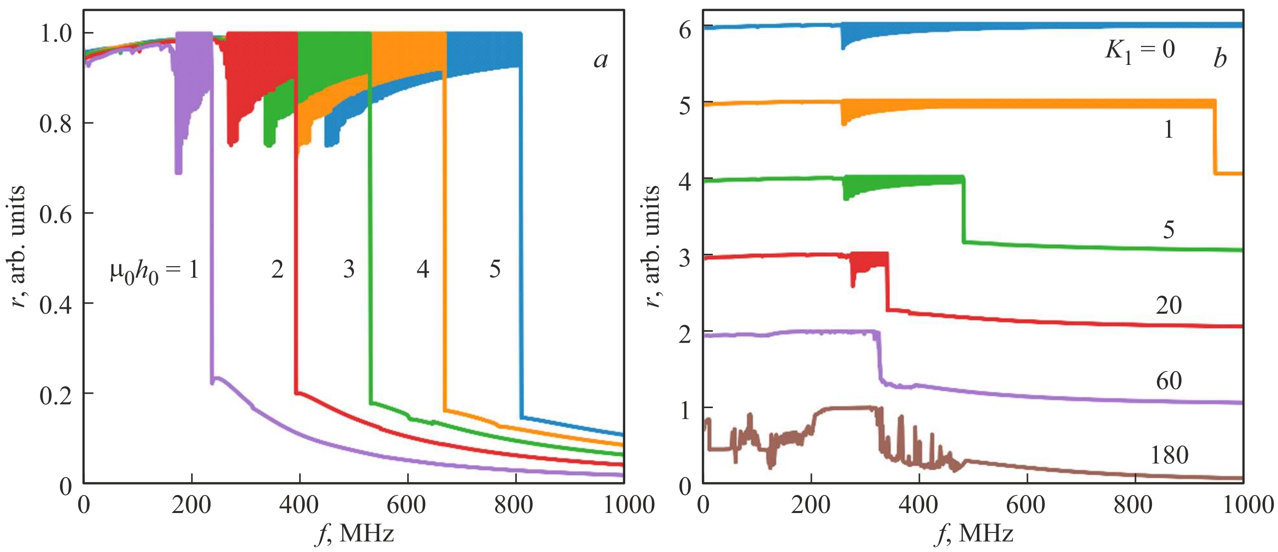

Figure 1. Frequency dependences of magnetization vector procession area radius r at a) different amplitudes of AC magnetic field h_0 (anisotropy constant $K_1 = 10\,\mathrm{J/m^3}$) and b) different values of the first anisotropy constant K_1 (field amplitude $\mu_0 h_0 = 2\,\mathrm{mT}$). Alternating magnetic field inductance values $\mu_0 h_0$ in mT and K_1 in J/m^3 match the numerical designation of the curves in the figures. Permanent magnetic field inductance $\mu_0 H_0 = 10\,\mathrm{mT}$.

directions along axis Oz and directions in the plane XY: $[110]$, $[1\bar{1}0]$, $[110]$ and $[\bar{1}10]$. Computer modeling of nonlinear modes of magnetic vibrations in the ferromagnetic film was carried out by Runge–Kutta method of 4th order of precision using formulas above, for the following internal parameters: coefficient of magnetic dissipation $\alpha = 0.15$, magnetization of film saturation $M_0 = 32\,\mathrm{mT}/\mu_0$ under permanent magnetic field $\mu_0 H_0 = 10$ and 50 mT. Other parameters varied within the following limits: $K_1 = 0{-}50\,\mathrm{J/m^3}$, amplitude of alternating magnetic field $\mu_0 h_0 = 0{-}5\,\mathrm{mT}$ with variable frequency of the field from the range of 1 MHz–1 GHz.

3. Results

Let us analyze the results of modeling the dynamics of nonlinear vibrations of the magnetization vector in the film. Figure 1 presents the frequency dependence of the film magnetization vector precession area radius at different amplitudes of alternating fields and values of anisotropy constants. From Figure 1 one can conclude that two main precession modes exist, with their boundaries, depending on the amplitude of alternating magnetic field and constant of the film magnetic anisotropy. Under permanent magnetic field in 10 mT the frequency of ferromagnetic resonance (FMR) in the absence of magnetic anisotropy ($K_1 = 0$), calculated using Kittel formula [6], is 600 MHz. The dependences presented in Figure 1, a, with small magnetic anisotropy $K_1 = 10\,\mathrm{J/m^3}$, one can see that low frequencies of the field show the mode of extended circular precession (Figure 2, a), when the precession amplitude is practically maximal, and its frequency is synchronized with the alternating field frequency f. With further increase of frequency f the extended circular precession fails to the equilibrium position precession mode [7,8], when the large precession ring is filled with small circular turns with condensations correlating to the energy density of magnetic anisotropy (Figure 2, b). In this transition mode the frequency of forced vibrations of the magnetization vector is synchronized with frequency f, and the full rotation of the magnetization vector occurs at frequency of around 20 MHz (for Figure 2, b this frequency is equal to 22 MHz), gradually decreasing with growth of f, and is an order lower than the FMR frequency. With further increase of frequency f, the transition occurs to the mode of small-amplitude precession around the nearest local minimum of magnetic anisotropy energy density. As alternating field amplitude h_0 increases, the transition mode shifts towards higher frequencies f with noticeable increase of its width (Figure 1, a). To assess the impact of anisotropy fields, a series of precession area radii dependences was built for various values of the first constant of anisotropy (Figure 1, b). As the constant of anisotropy K_1 increases, the transition mode first narrows, and then broadens gradually at $K_1 = 100{-}150\,\mathrm{J/m^3}$. With further growth of the constant $K_1 \approx 180\,\mathrm{J/m^3}$ the extended precession mode disappears, and the mode of precession occurs around the equilibrium position.

Diagrams were obtained for reorientation of the film magnetization vector depending on the amplitude of the alternating magnetic field with frequency $f = 300\,\mathrm{MHz}$ for various durations of alternating magnetic field exposure $\tau = 1{-}60\,\mathrm{ns}$ (Figure 3, a) and magnetic anisotropy constants $K_1 = 0{-}40\,\mathrm{J/m^3}$ (Figure 3, b) at permanent magnetic field value of $\mu_0 H_0 = 50\,\mathrm{mT}$. The obtained diagrams clearly show the serial alternation of the end positions of the magnetization vector in the directions along the crystallo-

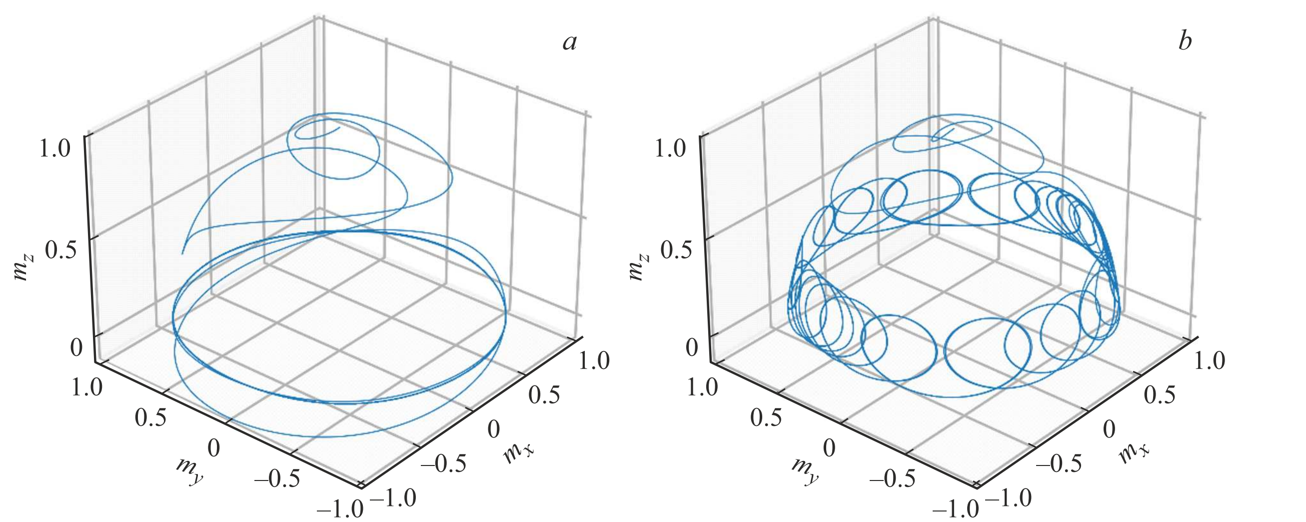

Figure 2. Trajectory of single film magnetization vector end motion at field frequency a) $f = 200$ MHz and b) 500 MHz. $K_1 = 10\,\mathrm{J/m^3}$, $\mu_0 H_0 = 10$ mT and $\mu_0 h_0 = 3$ mT.

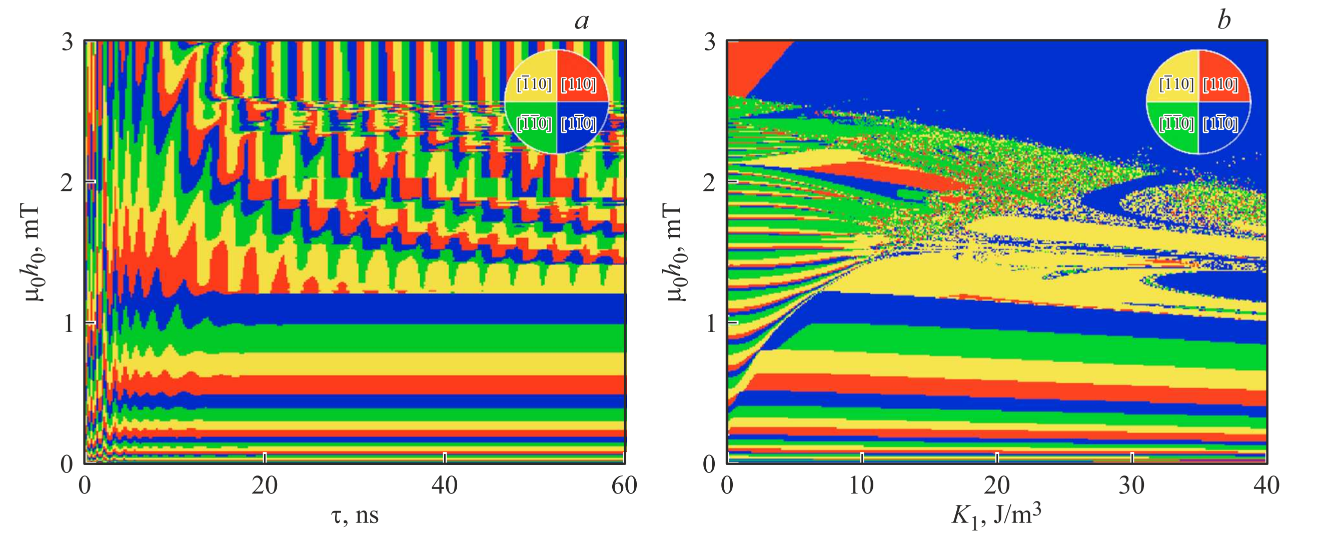

Figure 3. Diagrams of film magnetization vector reorientation at different alternating field amplitudes h_0 a) depending on duration of its effect τ at $K_1 = 10\,\mathrm{J/m^3}$ and b) depending on the value of the first constant of anisotropy K_1 at $\tau = 200$ ns. $\mu_0 H_0 = 10$ mT and $f = 300$ MHz.

graphic axes [110], [$\bar{1}$10], [$\bar{1}\bar{1}$0] and [1$\bar{1}$0], which matches the direction of the film magnetization vector end rotation (Figure 2). The diagrams of Figure 3 clearly shows the boundaries of the precession modes described above. As the alternating field amplitude h_0 increases, first the transition mode is observed, and then — mode of extended circular precession, where the moment of magnetization vector stop is determined mostly by the duration of impulse τ, and not its amplitude h_0. The area of the small-amplitude precession mode, as field amplitude h_0 grows in the entire considered interval of the constant values K_1, changes to the intermediate mode, the width of which gradually narrows with growth of K_1, and then changes to the area of the extended circular precession mode; the end position of the magnetization vector is defined mainly by duration of pulse (Figure 3, a). Since to build the diagram (Figure 3, b) the duration of pulse τ was fixed, only two large areas are observed with the end position of the magnetization vector, matching the directions [110] at low values K_1 and [1$\bar{1}$0] — at high ones K_1.

4. Conclusion

Computer modeling of nonlinear magnetic dynamics and magnetization vector precession for a thin ferromagnetic film was completed. The main modes of precession and their boundaries were identified depending on the permanent magnetic field value, frequency and amplitude of alternating magnetic field and value of the first constant of the magnetic anisotropy of the film. Reorientation of the magnetization vector was found from the position of the minimum observed at the density of energy of the magnetocrystalline anisotropy, to the other minima. Intervals of optimal amplitudes and pulse duration were determined for the film remagnetization, which is shown in the remagnetization diagrams. The completed calculations show that the alternating magnetic field pulse amplitudes by energy are rather small; therefore, the considered remagnetization of the magnetization vector is energetically more beneficial that in the cases considered previously for the terphenol films [3] and for nickel nanoparticles [6], which were remagnetized by elastic impulses. Based on the results of the current study, it is possible to develop memory and logical devices, including neuron systems [2], and sensors and nonlinear frequency converters of alternating magnetic fields.

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Conflict of interest

The authors declare that they have no conflict of interest.

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