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Micromagnetic Structures near a Second Order Phase Transition in Monocrystalline Ferrite Garnet Plates

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The main parameters of micromagnetic structure formation in a vicinity of a second order phase transition were determined experimentally and theoretically. The theoretical study was performed using micromagnetic approach. External magnetic field H_c of appearance of micromagnetic structure and micromagnetic structure period L_c were determined for (001)-oriented plate with uniaxial K_u and cubic K_1 magnetic anisotropy. The plate was saturated by the field applied in its plane. In the model we assumed that magnetization vector undergoes small deviations from equilibrium if magnetic field is slightly reduced. These deviations are periodic in nature: micromagnetic structure has a form of a plane wave. Dependences of H_c and L_c on an azimuthal angle of external magnetic field and on anisotropy constants K_u and K_1 were derived analytically in this work. Experimental studies of micromagnetic structure near the second order phase transition were conducted on $(EuEr)_3(FeGa)_5O_{12}$ (001)-oriented 50 μm thick ferrite-garnet plate with $K_u = 5700$ erg/cm^3 and $K_1 = -3700$ erg/cm^3. Micromagnetic structure was revealed by means of magnetooptic Faraday effect. The in-plane field was increased up to 2000 Oe. Experimentally determined values of H_c and L_c were compared with theoretical estimates.

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1. Introduction

The nucleation of new magnetic phases is a fundamental problem in studies of magnetization reversal processes. This nucleation begins with appearance of magnetic inhomogeneities. Their further reorganization results in domain structure formation. In crystals with the complex nature of magnetic anisotropy the emergence of the broad range of magnetic states is possible. The nucleation problem for such crystals is of particular interest. The magnetization reversal process in static field was described in terms of thermodynamics in [1]. The nucleation of new domain patterns in quasi-uniaxial films was observed experimentally in [2]. Domain structure of (111)-oriented iron garnet crystals at the second-order spontaneous spin-reorientation phase transition on temperature was experimentally studied in [3].

This article is concerned with studies of the second-order phase transition on magnetic field in ferromagnetic (001)-oriented plates with induced uniaxial and cubic magnetic anisotropies. Theoretical solution was obtained within the framework of micromagnetic approach.

2. Theoretical analysis

In this paper a (001)-oriented ferromagnetic plate with uniaxial (specified by reduced constant β_0; the easy axis is perpendicular to the sample plane) and cubic (specified by constant β_1) magnetic anisotropies is considered. Let d be the plate's thickness and M_s be the saturation magnetization. The plate is saturated by magnetic field $\boldsymbol{H}$, that lays in the plane of the sample. Figure 1 shows the geometry of the problem.

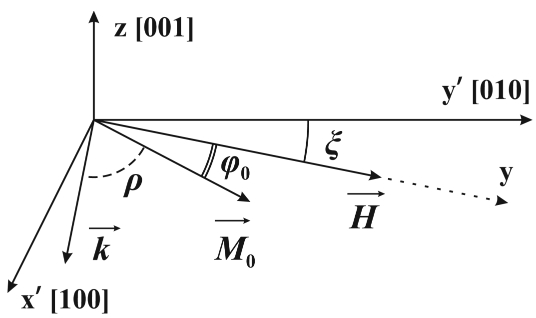

Fig. 1. The geometry of the problem.

The magnetic field $\boldsymbol{H}$ is oriented at angle ξ to the [010] crystallographic axis. If the magnetic field is reduced, so that its value corresponds to the second-order phase transition, a magnetic phase stratification starts. Magnetization vector undergoes small deviations from equilibrium (in the equilibrium state there is an angle φ_0 between average magnetization vector $\boldsymbol{M}_0$ and external field $\boldsymbol{H}$). These deviations are periodic in nature. Micromagnetic structure (MMS) has a form of a plane wave. Within the framework of micromagnetic approach we show that such MMS forms at the in-plane field H_c and has period L_c.

Possible magnetization distribution in MMS is shown in Fig. 2. Long arrows represent the magnetization vector, short arrows — small deviations of the magnetization vector from the equilibrium state. If one observes the described above structure using the Faraday effect, a low-contrast pattern of alternating light and dark bands with transition gray areas between them corresponds to the MMS (Fig. 2, upper part).

For MMS description it is convenient to introduce the magnetization vector $\boldsymbol{M}(\boldsymbol{r}, t)$ as follows:

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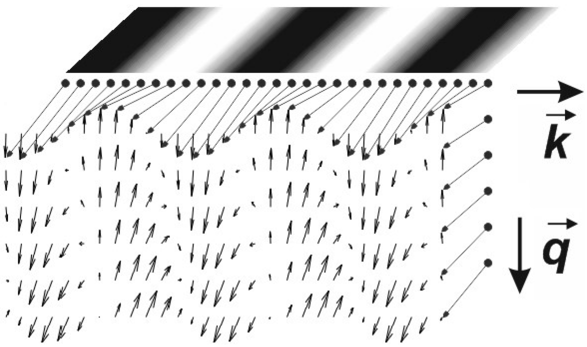

Fig. 2. Magnetization distribution in a plane wave (bottom) and the corresponding magnetooptical picture of the magnetic structure in the geometry of the Faraday effect (top). Here q is the vertical component of a wave vector; k is its in-plane component.

$$\boldsymbol{M}(\boldsymbol{r},t)=\boldsymbol{M}_0+\boldsymbol{\delta M}(\boldsymbol{r},t), \tag{1}$$

where $\boldsymbol{\delta M}(\boldsymbol{r},t)$ denotes small deviations of magnetization vector from the equilibrium state $\boldsymbol{M}_0$.

The free energy of ferromagnetic crystal E consists of five terms: uniaxial E^{u} and cubic E^1 anisotropy energies, exchange energy E^J, external field energy E^{ex} and stray-field energy E^m. The effective field $\boldsymbol{H}^{\mathrm{eff}}$, that determines the dynamics of the magnetization vector, is given by

$$\boldsymbol{H}^{\mathrm{eff}}=-\frac{\partial E}{\partial \boldsymbol{M}}+\sum_{i=1}^{3}\frac{\partial}{\partial x_i}\left[\frac{\partial E}{\partial(\partial \boldsymbol{M}/\partial x_i)}\right]. \tag{2}$$

In the assumption that the magnetization deviations from the equilibrium state are small, $\boldsymbol{H}^{\mathrm{eff}}$ was represented as a sum of two parts: the uniform part $\boldsymbol{H}_0^{\mathrm{eff}}$ and the time- and space-dependent part $\boldsymbol{\delta H}^{\mathrm{eff}}(\boldsymbol{r},t)$:

$$\boldsymbol{H}^{\mathrm{eff}}(\boldsymbol{r},t)=\boldsymbol{H}_0^{\mathrm{eff}}+\boldsymbol{\delta H}^{\mathrm{eff}}(\boldsymbol{r},t). \tag{3}$$

Expression (3) was substituted into the Landau–Lifshitz equation. By virtue of $\boldsymbol{\delta M}(\boldsymbol{r},t)$ and $\boldsymbol{\delta H}^{\mathrm{eff}}(\boldsymbol{r},t)$ smallness, the linearized equation of magnetization motion in effective field was obtained

$$-\frac{1}{\gamma}\frac{\partial \boldsymbol{M}(\boldsymbol{r},t)}{\partial t}=\boldsymbol{M}_0\times\boldsymbol{\delta H}^{\mathrm{eff}}(\boldsymbol{r},t)+\boldsymbol{\delta M}(\boldsymbol{r},t)\times\boldsymbol{H}_0^{\mathrm{eff}}. \tag{4}$$

The tensor of magnetic permeability $\boldsymbol{\mu}$ was derived from Eq. (4). After that two Maxwell's equations for the stray field $\boldsymbol{H}^m$:

$$\mathrm{rot}(\boldsymbol{H}^m)=0, \tag{5}$$

$$\mathrm{div}(\widehat{\boldsymbol{\mu}}\boldsymbol{H}^m)=0, \tag{6}$$

were solved with boundary conditions on plate's surfaces. The expressions for H_{c} and L_{c} were found using the existence condition for solution in a form of a stationary plane wave that models MMS:

$$H_{\mathrm{c}}(q)=\frac{M_{\mathrm{s}}}{\cos\varphi_0}\left(\beta_0-\beta_1\left(1-\frac{1}{2}\sin^2(2\varphi_0+2\xi)\right)-\alpha q^2\right), \tag{7}$$

$$L_{\mathrm{c}}=2\pi/\left[\left(\frac{4\pi}{\alpha\eta}\right)^{1/4}q^{1/2}\right]. \tag{8}$$

Here a dimensionless value $\eta\approx 1$. It was demonstrated that the vertical component of the wave vector $q\approx\pi/d$ for thick plates.

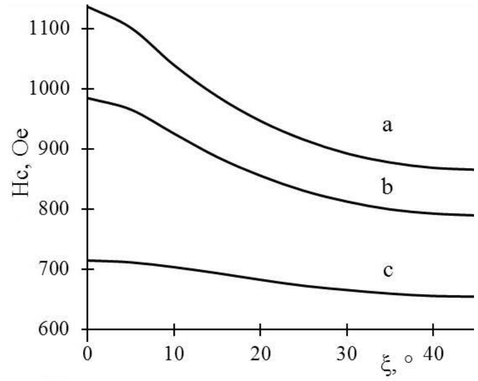

Fig. 3. Dependences of the MMS formation field $\mathrm{H_c}$ on the angle ξ of external magnetic field orientation for different anisotropy constants ratios: β_0/β_1 is equal to (*a*) 1.1, (*b*) 1.5, (*c*) 5.

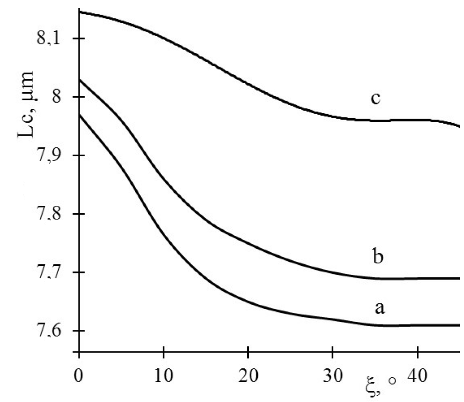

Fig. 4. Dependences of the MMS period L_{c} on the angle ξ of external magnetic field orientation for different anisotropy constants ratios: β_0/β_1 is equal to (*a*) 1.1, (*b*) 1.5, (*c*) 5.

Dependences of H_{c} and L_{c} on the azimuthal angle ξ of external magnetic field for the different ratios of anisotropy constants β_0/β_1 are presented in Fig. 3 and Fig. 4.

3. Experimental results

The emergence of MMS and its evolution in the in-plane magnetic field were observed using magnetooptical Faraday effect. For our experiments we used the (001)-oriented $(\mathrm{EuEr})_3(\mathrm{FeGa})_5\mathrm{O}_{12}$ iron garnet plate 50 μm thick with saturation magnetization $M_{\mathrm{s}}=19$ Gs, $K_u=5700$ erg/cm^3, $K_1=-3700$ erg/cm^3.

Field $\boldsymbol{H}$ was applied in the sample plane along crystallographic axes. Figure 5 shows magnetic structures, observed during magnetization reversal process in the field $\boldsymbol{H}$ that was oriented along the hard magnetization axis [010].

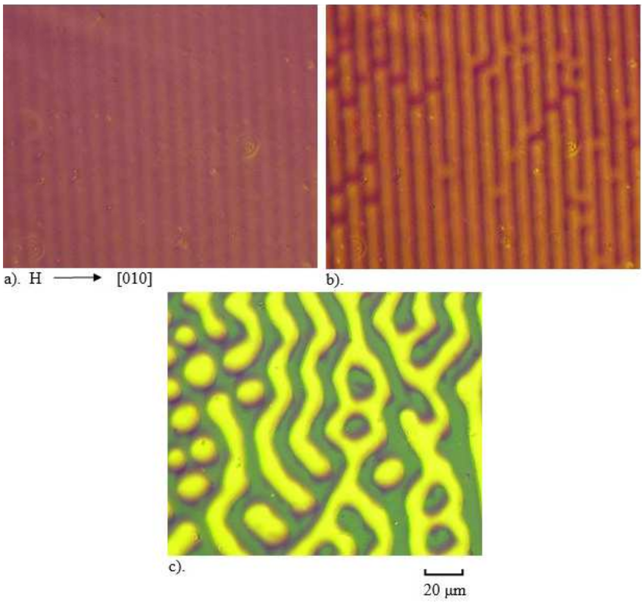

Fig. 5. MMS (a) and domain structure (c), visualized using magnetooptic Faraday effect in the magnetic field $\boldsymbol{H}$, oriented along [010] axis ($\xi = 0$). $\boldsymbol{H}$ is equal to: (*a*) 650, (*b*) 505; (*c*) 0 Oe.

With decrease of $\boldsymbol{H}$ from saturation ($H_s = 750$ Oe), in the field $H = 730$ Oe the stratification of the sample into magnetic phases was observed. Low contrast light and dark 4.5 μm wide bands appear, which we interpret as MMS. The observations show that contrast increases with decrease of the field H (Fig. 5a). At $H = 630$ Oe the modulation of bands with respect to their width appears and the relative contrast increases simultaneously. With further decrease of H, the bands, modulated with respect to their width, break apart (Fig. 5b) and bubble domains form. After the removal of the field (Fig. 5c) the sample comes to a mixed polarity state with yellow and green domains.

4. Discussion

Our expressions for H_c (7) and L_c (8) transform into well-known formulae [4] if β_1 tends to zero (the case of a uniaxial crystal).

For all anisotropy constants ratios the dependences shown in Fig. 3 and Fig. 4 have a common property. The magnetic field of MMS formation H_c decreases with ξ. The smallest value of H_c corresponds to $\xi = 45°$. In this case the orientation of external magnetic field is aligned with [110] axis, which is the projection of easy magnetization axis [111] on a plate's plane. The dependence of H_c and L_c on ξ weakens with β_0/β_1 increase. For example, if $\beta_0/\beta_1 = 5$, the values of H_c and L_c depend weakly on the orientation of the external magnetic field.

The field value that corresponds to the MMS formation was obtained experimentally and is equal to 730 ± 50 Oe. Formula (7) gives theoretical value of $H_c = 1000$ Oe. The value of MMS period obtained experimentally was equal to 9 ± 0.5 μm, which is slightly higher than the theoretical value of $L_c = 8$ μm, that was calculated using formula (8).

Some differences between experimental data and theoretical estimates can be explained by low contrast of the MMS stripes that makes their visual observation difficult.

Acknowledgments

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