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Effect of "Refraction" of Magnetic Domain Boundaries at Electrical Inhomogeneities

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A magnetoelectric effect, which manifests itself as a "refraction" of domain walls at the location of an electrode deposited on the surface of an iron garnet film, is studied. The "refractive index" depends on the electric voltage applied to the electrode and varies from 0.6 to 1.2. An electrically induced change in the surface energy of a domain wall due to an inhomogeneous magnetoelectric coupling is suggested as the mechanism of this effect.

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1. INTRODUCTION

The concept of the surface tension as a force that tends to reduce the interface area between phases is one of the universal ideas widely used in various models of condensed matter physics and beyond. In particular, the mechanisms for formation of boundaries between biological tissues [1] and geographical dialects [2] are also interpreted involving the same concept of an additional energy associated with interfaces or boundary lines.

Magnetic domain boundaries with a characteristic width much smaller than the size of domains themselves are treated in the classical models of micromagnetism as infinitely thin walls with a surface energy determined only by the magnetic parameters of the sample and independent of the location, orientation, and curvature of the boundary [3]. Such a simplification, in particular, makes it possible to explain the formation and stability of bubble domains in magnetic films and plates made of ferro- and ferrimagnetic materials [4].

In [5], the effect of "refraction" of a domain wall by topographic inhomogeneities of a sample was recently demonstrated: the domain wall in the Cr_2O_3 magnetoelectric material changed direction when passing under a stepwise ridge (a "mesa") at the crystal surface, and after passing the mesa, it returned to its original direction. In this case, the ratio of the angles of "incidence" and refraction corresponds to Snell's law. Similarity with refraction stems from Fermat's principle in optics: light travels between two points along the path corresponding to the minimum of the optical path length functional, whereas the domain wall surface energy density, which depends on the topographic features of the crystal, serves as of the refractive index in the case of a domain wall, and the configuration of the domain wall minimizes its total energy.

As shown in [6–9], the surface energy of domain walls in magnetoelectric materials and in thin magnetic films depends on the electric field; therefore, it is of interest to study the refraction of domain walls by strip electrodes deposited on the surface of an iron garnet film. In this case, the "refractive index" can be controlled by varying the magnitude and polarity of the voltage applied to the electrode.

2. SURFACE ENERGY OF A DOMAIN BOUNDARY

The orientation of domain walls in the sample plane is determined by minimizing the energy of the domain wall

$$W = \int_a^b \sigma(l) h dl, \tag{1}$$

where σ is the surface energy density of a domain wall, h is the film thickness, and l is the length of the domain wall fragment.

The surface energy density of the domain wall depends on the component of the electric field E normal to the film plane [6, 7]

$$\sigma = 4\sqrt{AK} - \gamma\pi E. \tag{2}$$

Here, A is the exchange stiffness, K is the magnetic anisotropy (due to a small value of the saturation magnetization, about 5 G, we neglect the magnetostatic contribution to the domain wall energy coming from the Néel magnetization component), and γ is the inhomogeneous magnetoelectric coupling constant [10], which is determined by the following contribution to the free energy [11]:

$$F_{\mathrm{ME}} = \gamma \mathbf{E} \cdot \{\mathbf{m}(\nabla \cdot \mathbf{m}) + [\mathbf{m} \times [\nabla \times \mathbf{m}]]\}, \qquad (3)$$

where $\mathbf{E}$ is the electric field strength and $\mathbf{m}$ is the unit magnetization vector. This contribution is also referred to as the flexomagnetoelectric one by analogy with the flexoelectric effect in liquid crystals [11, 12], and it is considered as a kind of the Dzyaloshinskii–Moriya interaction depending on the electric field [8].

By analogy with Fermat's principle in optics, the domain wall is oriented in such a way that the ratio of sines of the angles of incidence and refraction is the same as the ratio of the surface energy of the domain wall in the presence of an inhomogeneity in the energy distribution and the surface energy of the unperturbed domain wall

$$\frac{\sin\theta_1}{\sin\theta_2} = 1 - \frac{\gamma\pi E}{4\sqrt{AK}} + C = n, \qquad (4)$$

where θ_1 is the angle of incidence, θ_2 is the angle of refraction, n is the refractive index, and $C = \mathrm{const}$. The constant C appears because the electrode deposited on the iron garnet film creates an inhomogeneity in the energy distribution over the sample surface, being not only a topographic feature, but also forming a contact region between the metal and insulator; therefore, the domain wall, passing across it, is slightly refracted even in the absence of any voltage applied to the wall.

3. DESCRIPTION OF THE EXPERIMENT

In this work, we study the refraction of domain walls near charged strip electrodes. An array of palladium strip electrodes is deposited on the surface of a $(BiLu)_3(FeGa)_5O_{12}$ iron garnet film sample grown by liquid-phase epitaxy on a (210) gadolinium gallium garnet substrate. A voltage is applied to one of such electrodes. The domain structure of the film is observed using the magneto-optical effect in the Faraday geometry. The orientation of the stripe domain structure with respect to the electrode could be changed by applying a magnetic field pulse in the film plane. If the domain walls far from the strip electrode are inclined by a certain angle θ_1 to its normal (the angle of incidence), then the domain walls near it change their orientation, making an angle θ_2 (the angle of refraction), different from θ_1. The scheme of the experiment and a typical magneto-optical image observed when the voltage is applied between the electrode and the substrate are shown in Figs. 1a and 1b, respectively. The phenomenon of refraction is reproduced regardless of the chosen electrode and of its location on the sample surface. We should emphasize that the refraction is observed even at a certain distance from the electrode due to a nonzero electric field there.

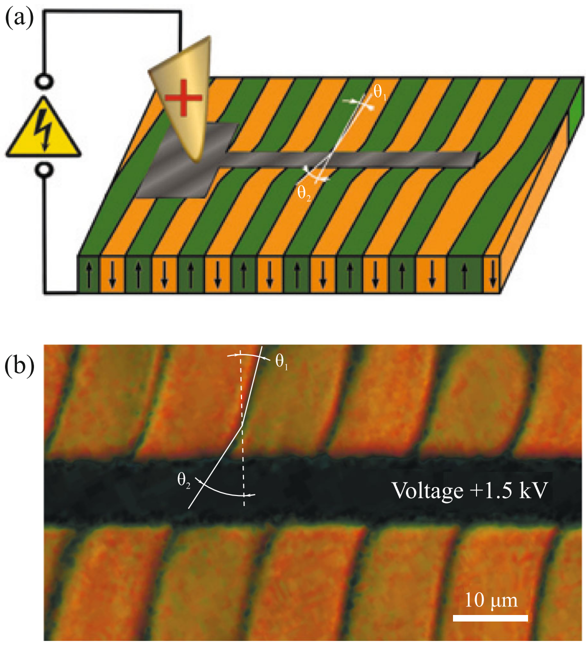

Fig. 1. (Color online) (a) Sketch of the experiment. The arrows indicate the direction of magnetization in the domains. (b) Magneto-optical image of the stripe domain structure and the electrode when a positive voltage is applied to the electrode relative to the substrate.

4. RESULTS AND DISCUSSION

Dependences of the sine of the angle of incidence θ_1 on the sine of the angle of refraction θ_2 for various voltages applied to the electrode (in total, more than twenty such plots were obtained) are shown in Fig. 2. In agreement with the assumption corresponding to the minimization of the energy of the domain wall, these dependences are linear, similar to Snell's law in geometrical optics: the slope of the straight lines in Figs. 2 corresponds to the effective refractive index n at a given voltage. Note that since the surface energy of the domain wall in an electric field can, depending on the electric polarity, not only increase but sometimes decrease, the refractive index can be both larger and smaller than unity.

This occurs because in the spontaneous state, domain walls already have a certain direction of magnetization rotation (chirality), the change in which, as follows from experiments reported in [13, 14], requires an applied magnetic field of about 50 Oe. The microscopic analysis of antisymmetric exchange in an iron garnet crystal [15] showed that the mechanical strain

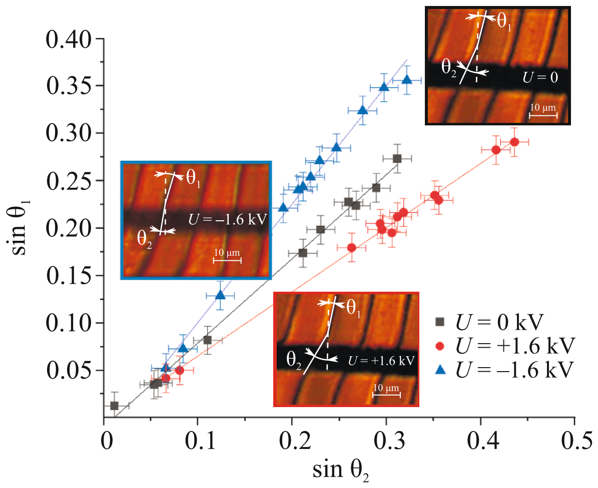

Fig. 2. (Color online) Sine of the angle of incidence θ_1 versus the sine of the angle of refraction θ_2 for various voltages applied to the electrode. The insets show the magneto-optical images (from bottom to top) at a positive voltage applied to the electrode, at a negative voltage, and at zero voltage.

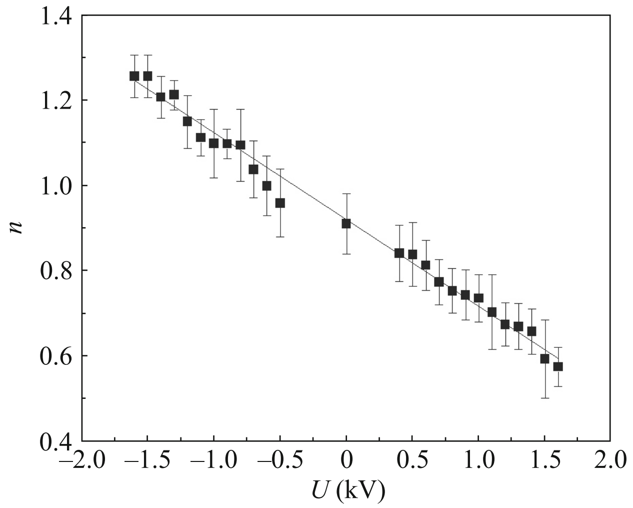

Fig. 3. Refractive index versus the voltage applied to the electrode.

gradient due to epitaxial stresses in films causes the inversion symmetry breaking in the crystal, the formation of domain boundaries of a certain chirality, and a nonzero contribution to the energy from the Dzyaloshinskii–Moriya interaction. This contribution, estimated from the mismatch between the lattice constants of the iron garnet film and the substrate, is consistent with the characteristic energy of the magnetoelectric interaction [15].

In Fig. 3, we present the experimental dependence of the refractive index on the voltage between the electrode and the substrate.

The linear fit to the plot in Fig. 3 by Eq. (4) with the characteristic parameters of the sample under study (the surface energy density of the domain wall $\sqrt{AK} \cong 0.01$ erg/cm^2 and the electrode width $w = 10^{-3}$ cm) allows us to determine both the constant $C = -0.078$ and the magnetoelectric coefficient corresponding to the slope of the plot

$$\gamma = (0.85 \pm 0.05) \times 10^{-6} \sqrt{\frac{\text{erg}}{\text{cm}}}.$$

To illustrate the magnitude of the magnetoelectric effect, we estimate its contribution to the domain wall surface energy (the second term in Eq. (2)) at the maximum applied electric voltage used in our experiments ($U = 1.6$ kV)

$$\sigma(U = 1.6\ \text{kV}) = (1.4 \pm 0.1) \times 10^{-2}\ \frac{\text{erg}}{\text{cm}^2}.$$

Thus, the magnetoelectric contribution to the free energy at maximum voltages is about one third of the surface energy density of the domain wall far from the electrode. With an increase in the electric field (due to an increase in the voltage or a decrease in the size of the electrode), the surface energy of the domain wall can completely vanish according to Eq. (2). This is indeed possible, which is confirmed by the observation of the electric field-induced nucleation of new domains, a phenomenon previously discovered in [16].

5. CONCLUSIONS

To summarize, a magnetoelectric effect studied in this work that is the refraction of a stripe domain structure at a strip electrode can be explained with the model of the surface energy of domain walls modulated by the electric field. The estimates of the magnetoelectric constant obtained from the experiment are consistent with the values determined in experiments on electrically induced nucleation of magnetic domains [6, 16] and on the electric field-induced motion of domain walls [17].

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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