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The Influence of the Magnetic Field on Electrically Induced Domain Wall Motion

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Abstract. Domain walls in iron garnet films demonstrate magnetoelectric properties that manifest themselves as a displacement induced by inhomogeneous electric field. In this paper the results of the study of electric field induced domain wall dynamics and its dependence on external magnetic field are presented. The measured velocity of the electrically induced domain wall motion increased by an order with the magnetic field applied perpendicular to the domain wall plane. The numerical simulation shows that the observed behaviour of the domain wall can be explained by magnetic field induced modification of its internal micromagnetic structure and enhancement of the electric polarization associated with the wall.

Introduction

The contribution of the inhomogenous magnetoelectric effect to the free energy density of the cubic crystal of iron garnets can be presented as follows [1, 2]:

$$F_{ME} = \gamma \mathbf{E}(\mathbf{M}(\nabla\mathbf{M}) - (\mathbf{M}\nabla)\mathbf{M}) \quad (1)$$

where **M** is magnetization vector, ∇ is differential operator vector, **E** is electric field, γ is inhomogeneous magnetoelectric interaction constant. The electric polarization of the spatially modulated structure can be written as:

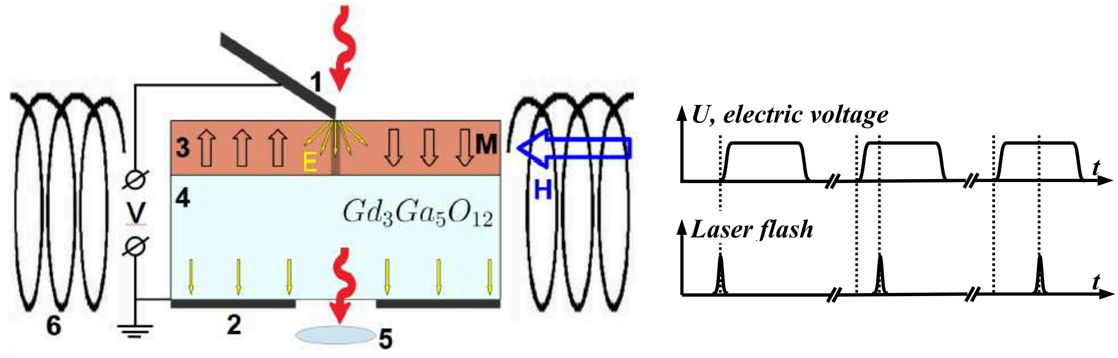
$$\mathbf{P} = -\frac{\partial F_{ME}}{\partial \mathbf{E}} \quad (2)$$

Thus, the inhomogenous distribution of the magnetization may lead to the appearance of the electric polarization and the surface electric charge. An example of a magnetic structure possessing electric polarization is a Neel-type domain wall [3]. It was experimentally confirmed by observation of the domain wall displacement in the field of tip electrode [4, 5]. Application of a permanent magnetic field can modify the domain wall internal structure and, in turn, its electric polarization. As it was shown earlier, domain wall displacement caused by electric field depends on the strength and the direction of the magnetic field applied [6, 7].

In this paper the results of experimental study of the domain walls motion induced by electric field are presented. It was shown that the wall velocity can be increased at least by an order by the external magnetic field changing the domain wall structure. Computer simulation results based on the solution of Landau-Lifshitz-Gilbert equation show qualitative agreement with experimental results.

Experiment

We used iron garnet films $(BiLu)_3(FeGa)_5O_{12}$ grown on (210) and (110) gadolinium gallium garnet substrates by liquid-phase epitaxy. In this paper the results are presented for the sample with the parameters: substrate orientation (210), iron garnet film thickness h = 9.9 μm, $4\pi M_s = 62$ Gs, M_s – saturation magnetization; period of domain structure p = 28 μm [8]. Measurements were performed at room temperature. The electric field was applied with the tip electrode touching the surface of the film near the domain wall location. The absence of the leakage currents was controlled with the microampermeter. To observe domain walls and their displacement caused by the electric field, we used magneto-optical Faraday microscopy with laser pulses illumination (Fig. 1a). For dynamic measurements the high speed photography technique [5] was used: the pulses of electric voltage at the tip (voltage amplitude U=1.5 kV, pulse width ~ 0.6 μs, the rise time ~ 100 ns) were followed by pulses of laser illumination (duration ~ 10 ns) to get an instant photograph of the domain wall. Varying the time delay between field and laser pulses enabled us to observe the consecutive position of domain wall and thus investigate its dynamics (see Fig. 1 (b)). Magnetic field was applied in the plane of the film perpendicularly to the domain walls. Photographs shown in Fig. 2 demonstrate instant images of the domain wall moving under the influence of the voltage applied to the tip.



a b

Fig.1. (a) Schematic representation of the geometry of the experiment and the configurations of the electric field and magnetization. The electric field is formed in the dielectric medium of the sample between the tip (1) and the cooper foil (2), which plays the role of the grounding electrode. The maximum field strength is reached in the iron garnet film (3) near the tip; it decreases rapidly in the bulk of $Gd_3Ga_5O_{12}$ substrate (4). The absence of the leakage currents is controlled with the milliampermeter (mA). Coils (6) create a permanent magnetic field in the film plane. The incident light (denoted with wavy arrows) is along the normal to the surface. The objective lens (5) is placed behind the pinhole in the foil (2). In the magnetic film (3) the domains and domain wall are schematically shown.
(b) Time diagrams of the electric field pulses and laser flashes.

In the absence of the magnetic field, the direction of the domain wall motion is determined only by the sign of the tip voltage. With the positive voltage the wall is attracting to the tip, with the negative one – repulsing. This behavior is related to the domain wall chirality and was discussed in our previous communications [7, 9]. External magnetic field dramatically changes the observed effect. In particular, with the increase of the magnetic field amplitude the domain wall velocity is raising, while the displacement direction start to vary from wall to wall.

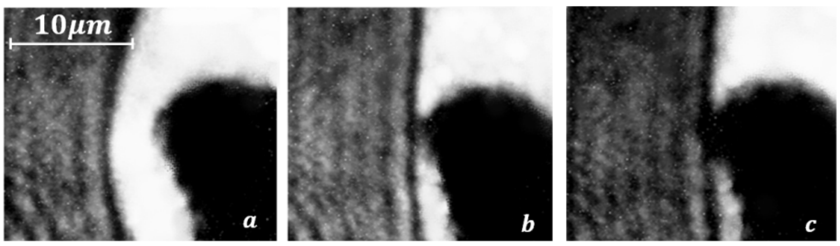


Fig.2. The motion of the domain walls caused by positive potential on the tip. Time delay from the electric field pulse start: 0.1 μs (a), 0.3 μs (b), 0.5 μs (c). In-plane magnetic field 120 Oe. Electric voltage at the tip is 1.5 kV.

Series of photographs with different delay time of the laser pulse were used to calculate average domain wall speed for given external magnetic field, the results are shown in Fig. 3. All dynamic measurements were carried out with positive voltage at the tip (1 on Fig.1); red and blue points correspond to the domain wall with opposite chiralities (domain wall 1 and domain wall 2). One can see that without the external magnetic field (H = 0) walls of both types are attracted to the tip. As the magnetic field grows in one or other direction, the domain wall velocity is steadily increasing or decreasing. For each domain wall there is a critical value of the magnetic field when the wall does not react on the electric field pulse. For the sample used in this paper the critical magnetic field value H_{cr} = 25 ± 5 Oe was determined by previous static experiments, described in [6].

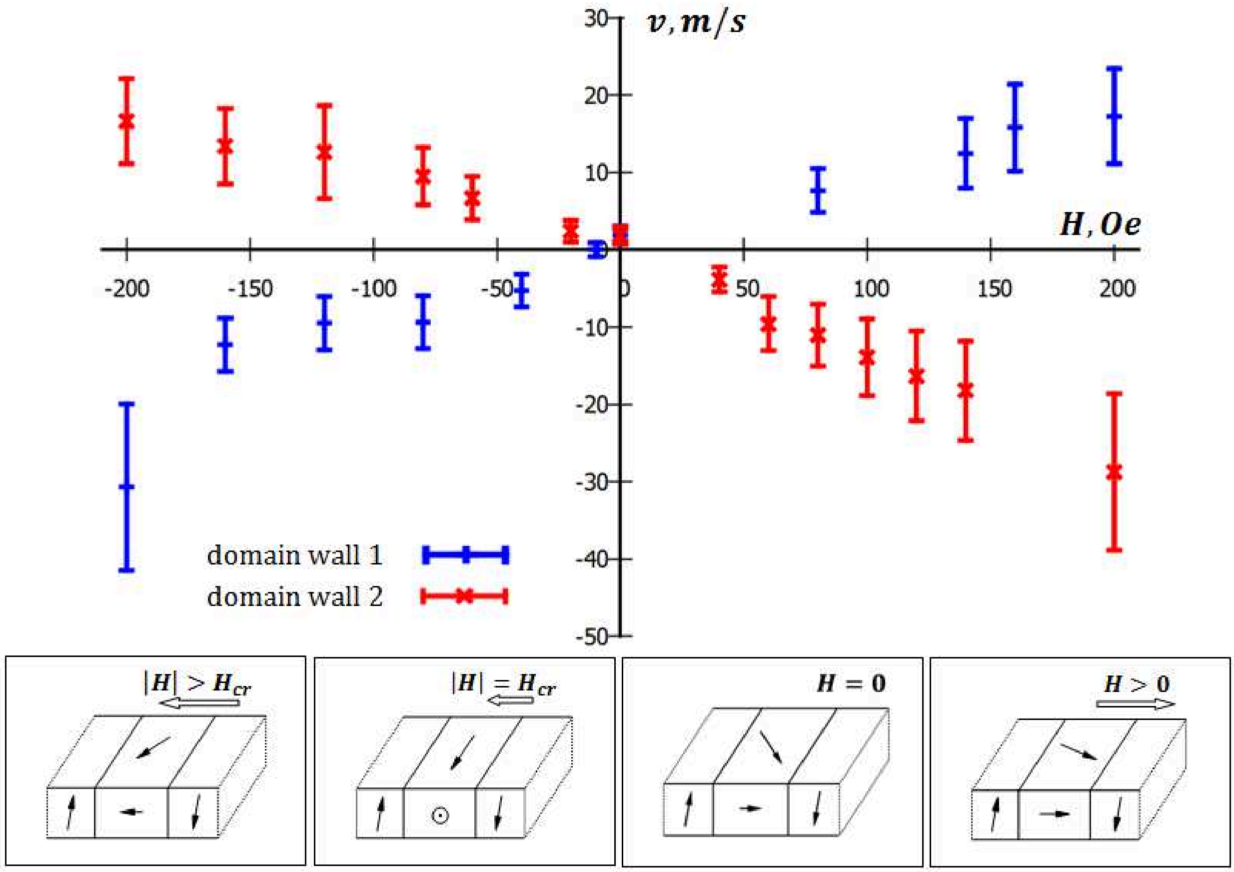


Fig. 3. Magnetic field dependence of the velocity of electrical field induced domain wall motion. The voltage at the tip was 1.5 kV. The magnetization distribution in the domain wall at different values of the magnetic field is schematically shown at the bottom

Computer simulation

We also performed micromagnetic simulations of the electric field induced domain wall motion in a strip of the magnetic material with the parameters of the sample used in the dynamic measurements. All simulations were carried out via the Nmag solver [10], equipped with the magnetoelectric module [11].

The strip had the following dimensions: 10 μm x 1 μm x 1 μm (with the long side perpendicular to the domain wall plane). At the beginning of the simulation (t = 0) magnetization inside the strip was split into the three homogenous parts - two domains and a wall between them (the picture with $|H| = H_{cr}$ at the bottom of the Fig. 3 can be used as reference, with the wall region being much narrower). If the external magnetic field is applied, domain wall starts to slide towards one of the ends of the strip. So to calculate wall's internal structure with |H| > 0, domain regions were initially "frozen" (dm/dt = 0); magnetization direction inside the domains was calculated for each given H value to set proper border conditions for the wall. Once the wall region relaxed to the smooth enough magnetization distribution, domain regions were freed so one can observe domain wall movement. The simulations shows that the wall structure doesn't change while the wall is moving and what is more important that for $|H| > H_{cr}$ walls of two different types have opposite chiralities (see Fig. 4).

Same simulation then was carried out again with a point electric charge representing the copper tip in our experiments. It is revealed that the structure of a domain wall doesn't change in the course of its movement. Electric field leads to change of speed of a wall, but the structure of a wall doesn't change. The difference of wall speed with and without the charge can be attributed to electric field induced movement. This difference grows with the external magnetic field value and is in qualitative agreement with the experimental results.

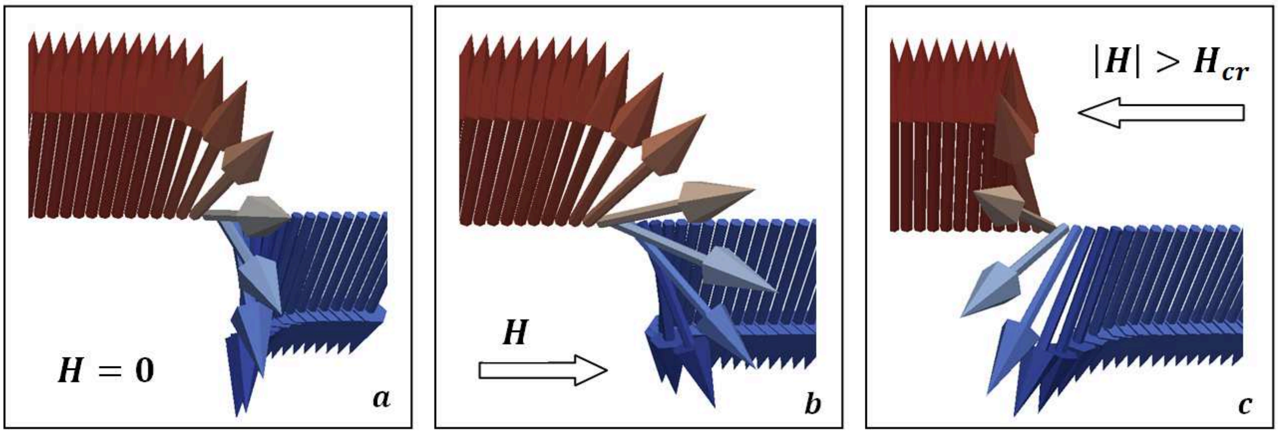


Fig. 4. Computer simulation of the magnetization distribution in a domain wall. (a) H=0, (b) H=120 Oe, (c) H=100 Oe.

Conclusions

It was experimentally demonstrated that one can change the velocity of the electrically induced domain wall motion by magnetic field. Depending on the direction and the strength of the magnetic field the character of the wall motion varies: the wall can stop reacting on the electric field, it can change direction of the motion to the opposite one or the wall velocity may increase at least by an order. We explain the observed features of the domain wall motion by the domain wall transformation to the Neel-type structure caused by the in-plane magnetic field. This, in turn, leads to the changes of the electric polarization of the wall. Comparison of the results of numerical simulation with the experimental data revealed that the wall velocity directly depends on the Neel component, i.e. the projection of magnetization vector on the normal to the domain wall plane.

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