Magnetic domain wall motion triggered by electric field

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Abstract. We propose the new approach to the problem of electrically controlled magnetic state: the electric field driven domain wall motion. The effect is demonstrated in iron garnet films in ambient conditions. The theoretical model based on inhomogenous magnetoelectric interaction provides with the necessary criteria of the effect and the way to maximize it.

1. Introduction

The conventional means of magnetic data writing put the limit for increasing storage density. The inductive coils and conducting lines that are used to generate magnetic field suffer from energy losses, which cause the progressive damage of the metal conductors [1]. The alternative approach to magnetic writing such as spin-current induced domain wall motion was proposed in [2]. However the spin transfer also requires large current densities of $10^6-10^7$ A/cm$^2$.

In [3, 4] we proposed the new approach to the problem of electrically controlled magnetic state: the electric field driven domain wall motion. It was implemented in epitaxially grown single crystal iron garnet films at room temperature. The characteristic features of the effect evidenced for its magnetoelectric nature [3]. This paper is focused on the experimental search for means to maximize this effect and theoretical analysis of it.

2. Experiment

In our experiments we used iron garnet films grown by liquid-phase epitaxy on (111), (110), and (210) Gd$_3$Ga$_5$O$_{12}$ substrate. The parameters of the samples are listed in Table 1. In contrast to the (111) films in which both the cubic anisotropy and growth induced anisotropy assign the easy axis along the normal to the surface of the film the characteristic feature of (110) and (210) samples was the considerable deviation of easy axis from the normal due to the misalignment of the growth direction and [111] cubic easy axis.

The electric field of high strength was produced by a tip electrode (curvature radius $R_{tip}=5\mu m$) touching the surface of dielectric sample. The magnetooptical technique in Faraday geometry was used to observe the micromagnetic structure (the experimental details are described elsewhere [4]). We registered the magnetization distribution in initial state and the position of domain wall with static

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electric field applied. The direction of the displacement was opposite at the reversal of electric polarity of the tip (fig. 1) and did not depend on the magnetic polarity of the domain over which the tip was located. As soon as the dc voltage was switched off the domain walls came back to the equilibrium position. This effect of electric field controlled domain wall positioning was observed in iron garnets films with (210) and (110) substrate orientation and was not observed in (111) films (see Table 1, note that to illustrate the idea the Table 1 lists the most representative examples while much more samples were tested to verify the dependence on substrate orientation).

**Table 1.** Parameters of the (BiLu)$_3$(FeGa)$_5$O$_{12}$ samples under study. Symbol $h$ stands for thickness of the iron garnet film, $M_S$ is saturation magnetization, $p$ is a period of domain structure, $\alpha$ is a tilt angle of magnetization in domain $M_0$ with respect to the normal of the film. The films in which the effect is observed are highlighted in bold.

| Substrate orientation | $h$, $\mu$m | $4\pi M_S$, G | $p$, $\mu$m | $\alpha$, deg. |
|----------------------|-------------|--------------|-------------|---------------|
| 1 (111)              | 8.5         | 63           | 77          | 0             |
| 2 (111)              | 19          | 78           | 39          | 0             |
| 3 (110)              | 4           | 162          | 9           | 10            |
| 4 (110)              | 6           | 76           | 14          | 10            |
| 5 (210)              | 10          | 53           | 34          | 40            |
| 6 (210)              | 7.4         | 77           | 44          | 46            |
| 7 (210)              | 11          | 43           | 36          | 46            |

The most prominent changes were observed in (210) films at stripe domain heads (Fig. 1). The reversible domain wall displacements up to $5 \mu$m were detected. At higher values of displacement the modification of the micromagnetic structure had irreversible character.

### 3. Theoretical analysis and discussion

The influence of electric field on micromagnetic structure was predicted theoretically in the series of works [5-9]. These theoretical models took into account the so-called *inhomogeneous magnetoelectric interaction* that gives rise to electric polarization associated with magnetic inhomogeneities.
The inhomogeneous magnetoelectric contribution into thermodynamic potential for the bulk crystal of ferrite garnets with cubic symmetry takes the following highly symmetric form [6, 8]:

\[ \gamma_{ME} = \gamma \cdot E \cdot (M \cdot (\nabla \cdot M) - (M \cdot \nabla)M) \]  

(1)

where \( M \) is magnetization vector, \( \nabla \) is differential operator vector, \( E \) is electric field, \( \gamma \) is inhomogeneous magnetoelectric interaction constant. One can learn immediately from Eq. (1) that the effect is odd with respect to electric field \( E \) and does not change the sign with magnetization \( M \) reversal, which agrees with experiment.

The electric polarization induced by magnetic inhomogeneity can be found in the following way:

\[ P_{ME} = -\frac{\partial F}{\partial E} = \gamma \cdot (M \cdot (\nabla \cdot M) - (M \cdot \nabla)M) \]  

(2)

To account for the enhancement of the effect observed at stripe domain heads in magnetic film let us consider the special features of the boundary between domains with tilted magnetization (fig. 2).

This magnetization lies in \( yz \) plane and is directed at angle \( \alpha \) with respect to the \( z \)-axis normal to the surface (fig 2 a). However the plane of magnetization rotation is not the same for different point of domain heads. The intersection of the rotation plane and film surface changes its direction from point to point (see tangent to the domain boundary marked with dotted line and symbol “x’” in figure 2 b). So it is more convenient to use the coordinate system \( (x',y') \) rotated at angle \( \beta \) with respect to the \( (x,y) \), where \( x' \)-axis is directed along the intersection line and \( y' \)-axis along the direction of spin modulation.

In this case the rotation of the magnetization in domain wall is expressed by the dependence \( \theta(y') \) where \( \theta \) is the angle with respect to the direction of magnetization in the domain \( M_0 \) (fig.2c). The orientation of \( M_0 \) in the plane of magnetization rotation is determined by angle \( \theta_0 \) (fig.2 c), that can be found from the relation between the coordinate systems (see fig. 2 a,b,c):

\[ \sin \theta_0 = \sin \alpha \cos \beta \]  

(3)

The magnetization components in terms of angles \( \alpha, \beta, \) and \( \theta_0 \) can be written in the following way:

\[ M_y = -M_0 \sin(\theta_0 + \theta(y')) \]  

(4)
\[ M_y = M_0 \cos(\theta_0 + \theta(y')) \sin \alpha \sin \beta(\cos \theta_0)^{-1} \]
\[ M_z = M_0 \cos(\theta_0 + \theta(y')) \cos \alpha(\cos \theta_0)^{-1} \]

Assuming for \( \theta(y') \) the conventional law [10]:
\[ \theta = 2 \arctan \left( \frac{y'}{\Delta} \right) \]

where \( \Delta \) is the width of the domain wall one can obtain from (2) and (4):
\[ P_y = M_0^2 \sin \alpha \sin \beta(\cos \theta_0)^{-1} f(y') ; P_y = 0 ; P_z = 0 \]

where \( f(y') = \frac{2}{\Delta} \left( 1 + \exp\left( \frac{2y}{\Delta} \right) \right)^{-1} \exp\left( \frac{y'}{\Delta} \right) \).

One can readily seen from (6) that the film polarization is zero at \( \alpha=0 \), that explains the absence of the effect in (111) films. Nonvanishing effect should be observed in the case of (210) and (110), and it should be more pronounced in the films with larger angles \( \alpha \), i.e. (210) films (see Table 1). Furthermore, effect is maximum at those domain wall segments where \( (\beta=90^\circ, \theta_0=0) \) i.e. at the domain head, while at the segments of the wall parallel to the projection of magnetization on film surface \( (\beta=0^\circ, \theta_0=\alpha) \) the polarization should be zero.

4. Conclusion
Summarizing, the theoretical model of the electric field induced magnetic domain wall motion based on inhomogeneous magnetoelectric mechanism explains the basic features of the effect (the dependence on the electric polarity of the tip electrode and independence on the magnetic polarity of the domains). It also predicts the maximum value of the effect for stripe domain heads in (210) films that corresponds to the results of experimental study.

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