Mechanism of domain wall interaction with electric field in iron garnet films

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Abstract. Domain walls in ferrimagnetic iron garnet films move under the influence of the applied static electric field and thus show the magnetoelectric behavior. We study theoretically two mechanisms proposed to describe this phenomenon. First one is based upon the inhomogeneous magnetoelectric interaction and the second one relies on the change of magnetic anisotropy parameters caused by electric field. We show that neither mechanism can be excluded by the general qualitative arguments.

1. Introduction

Physical quantities of electric and magnetic nature behave differently under space inversion and time reversal operations. Electric field (polarization) can be associated with charge displacements, so it changes sign under space inversion and remains intact under time reversal. Magnetic field (magnetization), which is classically related to the circular motion of point charge shows the opposite behavior.

Maxwell equations relate quantities of different symmetry by means of spatial and temporal derivatives. At first sight it seems that the static coupling between electricity and magnetism is impossible. While this is true in vacuum, solid state systems provide numerous counter examples. These are known as magnetoelectric (ME) materials.

The simplest kind of ME effect is called linear and homogeneous. If the crystal cell breaks both inversion symmetry (by the crystal structure) and time-reversal symmetries (due to magnetic order), it is possible to have ME term \( f_{ME} \) in the free energy expansion given by

\[
\begin{align*}
\frac{f_{ME}}{\alpha_{ij}} = \alpha_{ij} E_i \mathbf{H}_j.
\end{align*}
\]

A well-known example of the material with ME coupling of this type is \( \text{Cr}_2\text{O}_3 \), which has been being studied since 1960s. Interestingly, some of the microscopic details of the ME interaction in this compound still remain unclear [1].

Another way to obtain ME coupling in theory is to use the term that includes magnetic parameter twice together with the electric one and the spatial derivative. Indeed, such a combination is invariant under both the inversion and time-reversal symmetries, and thus can be present as a part of the free energy. For instance, one can arrange these quantities in the following manner:

\[
\begin{align*}
\frac{f_{ME}^t}{\gamma_{ijkl}} = \gamma_{ijkl} P_i M_j \partial_k M_l.
\end{align*}
\]

This combination corresponds to the case of inhomogeneous ME effect [2] . Electric polarization may appear as a consequence of the presence of the spatial spin structure that breaks inversion symmetry.
One can also consider the term with the spatial derivative acting on the electric parameter (external electric field in this case)[3]:

\[ f_{ME}^{a} = \beta_{ijkl} M_{i} M_{j} \partial_{k} E_{l} \] (2)

which can be thought as the change of magnetic anisotropy parameters under the influence of the spatially inhomogeneous electric field.

Experimentally it was found that domain walls in ferrimagnetic iron garnet films bend and shift out of the equilibrium position when electric field created by sharp non-magnetic electrode is applied [4]. This situation includes non-uniform magnetization distribution and highly inhomogeneous electric field as well, so in principle both \( f_{ME}^{a} \) and \( f_{ME}^{n} \) contributions can play a certain role [3].

The aim of the present work is to determine which mechanism underlies the magnetolectric interaction in the iron garnet films. We begin with brief review of experimental results in Section 2 and then analyze proposed mechanisms in Section 3.

2. Magnetoelectric behavior of domain walls in iron garnet films

Equilibrium, room temperature state of magnetization vector distribution in the iron garnet films studied in [4] is stripe domain structure, characterized by domain width of approximately 20\( \mu m \). Static electric field created by sharp (tip radius is about 5\( \mu m \)) non-magnetic electrode acts on the nearby domain wall differently depending on the sign of the applied voltage. Domain walls attract to the electrode if the voltage is positive and repel otherwise. Total amount of the wall displacement near the electrode is approximately 1\( \mu m \) at the voltage value of 500V.

In the modified setting, additional in-plane magnetic field is applied which deforms domain wall micromagnetic structure but doesn’t destroy domains. Magnetic field is directed perpendicular to the domain walls [5]. This changes domain wall behavior significantly. First, the displacement increases up to tens of micrometers and involves several domain walls. Secondly, the direction of displacement depends on the direction of magnetic field. Thirdly, the direction of the shift changes from one wall to another.

One should also note that the presence of the magnetoelectric properties of the domain walls relies heavily on the crystallographic orientation of the film. These effects were only observed in the films with “low-symmetry” substrate orientation such as (210) or (110), and never in (111) films. Details of the experiment can be found elsewhere [6].

3. Possible mechanisms of ME interaction

3.1. Inhomogeneous ME effect

For the crystal of cubic symmetry the coupling of the type (1) takes the following form [7]:

\[ \vec{P} = \gamma \chi_{e}[[\vec{M} \cdot \nabla)\vec{M} - \vec{M}(\nabla \cdot \vec{M})] \] (3)

where \( \chi_{e} \) is the dielectric susceptibility.

It follows that the domain wall can possess the bulk electric polarization and associated surface electric charges, depending on its magnetization vector distribution. For instance, domain wall of the Bloch type in which magnetization vector rotates in the plane of the wall does not break inversion symmetry and thus makes the appearance of polarization impossible (Eq. (3) gives \( \vec{P} = 0 \) in this case).

In order to calculate the force of the electric field acting on the domain wall we take the derivative of the energy of the interaction \( w(\vec{M}, \vec{E}) = -\vec{P}(\vec{M}) \cdot \vec{E} \) with respect to the position \( x_{0} \) of the domain wall:

\[ F_{x} = -\frac{\partial}{\partial x_{0}} \left( \int_{a}^{b} w(\vec{M}, \vec{E}) \, dx \right) \] (4)
Figure 1. Typical magnetization vector distributions for two neighboring domain walls in the absence (upper panel) and in the presence of the medium (middle panel) and strong (lower panel) magnetic field. Trajectories of the magnetization vector in the ($x, z$) plane for both domain walls are shown on the right.

where $x$ axis is directed perpendicular to the wall’s plane and $a, b$ stand for the coordinates of the middle points of the neighboring domains. Here we assume that displacement of the domain wall occurs without change of its micromagnetic structure. Our model is one-dimensional which is justified by the fact that effective field of magnetic anisotropy in the films under consideration is stronger then magnetostatic stray fields and suppresses spatial variation of magnetization in the plane of the domain wall ($y, z$). In three dimensions, the force $F_x$ is to be thought of as the pressure on the domain wall’s surface.

We suppose that variation of the electric field on scale of the domain wall’s width is negligibly small. Then the last expression takes the form:

$$F_x = \left( \int_{DW} \gamma \chi e(\vec{M} \nabla) \vec{M} - \vec{M}(\nabla \vec{M}) dx \right) \left( \frac{\partial \vec{E}}{\partial x} \right)_{x=x_0},$$   \hspace{1cm} (5)

where $DW$ means region containing domain wall.

Linear density of the bound electric charge, or the $z$-component of the vector appearing as a result of the integration here has a simple visual interpretation. It can be shown that this quantity equals the area swept out by the magnetization vector in the ($x, z$) plane (Fig. 1, right). For the domain wall of Bloch type this area equals zero. Magnetic anisotropy of the films determines complex form of the magnetization vector distribution. We are interested, however, only in the area, which is a topological property in a sense that it does not depend on the details of the geometry of $\vec{M}(x)$.

Thus the force depends on the electric field direction and on the micromagnetic structure of the domain wall. Once the latter is deformed by the external magnetic field, the response of the domain wall to the electric field changes together with its electric polarization.

One can assume that initially all the domain walls have uniform sense of rotation. It is reasonable because the inversion symmetry of the sample is broken by the substrate and by the
very process of the epitaxial growth. Thus it can lead to the presence of the “built-in” uniform background polarization along the film normal which forces all the walls to have the same sense of rotation.

With this assumption the plausible picture of the magnetization vector path deformation gives the correct behavior of the domain wall in the presence of the magnetic filed. As shown in Fig. 1, applying of the magnetic field leads eventually to the relatively large electric charges of opposite sign at the neighboring walls (lower panel). During the process, charge of the one of the domain walls will pass through zero value (middle panel) — the fact that is observed experimentally as the vanishing of the displacement of the wall at some value of the magnetic field $H$.

3.2. Change of the anisotropy parameters

Now we consider the energy of the form given by the Eq. (2) as a cause of the force acting on the domain wall. As in the previous case, we differentiate the interaction energy with respect to the position of the domain wall:

$$F_{kl}^{xz} = -\frac{\partial}{\partial x_0} \left( \int_a^b \beta_{kl}(\vec{M}(x)) \frac{\partial E_l}{\partial x_k} \, dx \right)$$

where we denote $\beta_{kl}(\vec{M}) \equiv \beta_{ijkl} M_i M_j$.

If one takes into account only those $kl$ components that lead to a reasonable force direction (the force does not depend on the side the electrode approaches the wall from etc.), we are left with two components, $F_{zz}^{zz}$ and $F_{xz}^{zz}$.

Physically, change of the anisotropy constants creates potential landscape for any magnetic texture which contains magnetization vector that does not lie in the easy plane or the easy axis (see Fig. 2). Since in the present case this change can be caused by the inhomogeneous electric field, one can expect that any magnetic texture will be attracted to, or repelled from the electrode without any reference to the magnetization vector distribution. This explains the behavior of the domain walls in the absence of the external magnetic field and can be described by the following equation:

$$F_{zz}^{xz} = -\left[ \int_{DW} \beta_{zz}(\vec{M}(x)) \, dx \right] \frac{\partial}{\partial x} \left( \frac{\partial E_z}{\partial z} \right)_{x=x_0}.$$ 

Since the expression is quadratic in $M_i$, domains do not contribute to the force, because one has $\vec{M}_1 = -\vec{M}_2$ for the magnetization of the nearby domains.

However, in the presence of the external magnetic field, magnetization direction in domains is tilted and the last equality does not hold. Instead, one has $\vec{M}_1^+ = -\vec{M}_2^- = -\vec{M}_1^-$, which can be deduced from the fact that anisotropy energy is quadratic in magnetization vector.
components (for the notation $\vec{M}^\pm$, see figures). Thus domain wall displacement can lower the energy of the system because of the change of the volumes of the domains divided by this wall.

In the case of $\vec{H} = \vec{H}^+$ we have:

$$F_{xx}^z = (\beta_{xz}(\vec{M}_2^+ - \vec{M}_1^+)) \left( \frac{\partial E_z}{\partial x} \right)_{x=x_0} \tag{8}$$

One can see that the last expression changes sign both on the reversal of the direction of $\vec{H}$ (i.e. $\vec{M}^+ \leftrightarrow \vec{M}^-$) and for neighboring domain walls ($\vec{M}_1 \leftrightarrow \vec{M}_2$). It follows that the hypothesis of the electric-field-induced change of the anisotropy constants allows one to explain, at least in principle, all the experimental results.

4. Conclusion

Domain walls in the iron garnet films show the rich variety of magnetoelectric phenomena, but it is not clear which mechanism underlies this behavior, even at the phenomenological level. We have considered two possible mechanisms, inhomogeneous magnetoelectric interaction and changing of the magnetic anisotropy constants under the influence of the electric field. It is shown that both mechanisms can, in principle, lead to the observed behavior of the domain walls.

The first mechanism based on the inhomogeneous ME interaction is sensitive to the domain wall internal micromagnetic structure and requires that all the walls have the same chirality in the state with no magnetic field applied. The second one works without any assumptions apart from that the values of $\beta_{zz}(\vec{M})$ and $\beta_{xz}(\vec{M})$ are significantly large.

To outline directions of the further study, one may note that our setting was very general. For instance, it did not include important information about crystallographic orientation of the film. This may put some restrictions on the particular components of the material tensors describing both mechanisms.

Acknowledgments

Author thanks A. P. Pyatakov, T. B. Kosykh and E. P. Nikolaeva for fruitful discussions. Support of RFBR grant No. 16-32-00840 mol is gratefully acknowledged.

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