Journal of Magnetism and Magnetic Materials 471 (2019) 304–309

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Research articles

Electric polarization in two-layer bounded ferromagnetic film

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ARTICLE INFO

Keywords:
Electrical polarization
Two-layer film
Magnetic vortices

ABSTRACT

A numerical study of the ground state of a two-layer ferromagnetic bounded film is carried out. The film layers have uniaxial anisotropy easy-plane and easy-axis. All calculations were carried out for films with parameters of ferrites-garnets – Materials that admit a magnetoelectric effect. The ground state was calculated using a three-dimensional micromagnet modeling package OOMMF for rectangular films of different sizes. It was shown that in a film, along with a homogeneous ground state, the vortex distribution of the magnetization is realized. For the vortex distribution, the electric polarization is calculated. It was found that the component of the electric polarization vector of the film perpendicular to the film plane is nonzero. This is due to the presence of the vortex core. The change in the electric polarization due to magnetic reversal of the film by an external magnetic field is studied. It is shown that as the field increases, the polarization modulus also increases to certain field values, and then decreases to zero. As the transverse dimensions of the film decrease, the magnitude of the maximum of the electric polarization increases.

1. Introduction

The magnetoelectric effect attracts the possibility of achieving an effective control of the magnetization in a multiferroic by an external magnetic field and electric polarization by an external magnetic field. At present, the increased interest in this phenomenon is due to the miniaturization of microelectronic elements. The use of a magnetoelectric effect to manipulate magnetic properties can significantly reduce energy dissipation in comparison with, for example, widely used technology, such as current-induced magnetization switching [1]. In addition, replacing the control of the magnetic field by electric one, it is possible to solve the problem of parasitic magnetic fields [2].

The magnetoelectric effect can be detected in multiferroics – Materials in which simultaneously at least two of the three types of ferro ordering coexist: magnetic, electric and mechanical [3–6]. It is the existence of the strong interaction between two ferroic orders can produce magnetoelectric effect. Another mechanism for the onset of electrical polarization is an inhomogeneous magnetoelectric effect. It was predicted by Bar'yakhtar et al. [7] and then widely studied [8,9]. The magnetoelectric effect can be realized in structures with an inhomogeneous distribution of magnetization: domain boundaries [10,11], skyrmions [12], near the interface of magnetic media [13–15] and in magnetic vortices. The possibility of using magnetic vortices generated at defects by magnetic anisotropy in devices with magnetic memory controlled by an electric field was discussed [16]. The conditions for the appearance of polarization on the magnetic inhomogeneity near the interlayer boundary of a two-layer ferromagnetic film were investigated under the assumption that its transverse dimensions are much larger than the thickness, and the magnetization in the film plane is uniformly distributed [13–15].

In this article we will consider the features of the electrical polarization of a bounded nanoscale two-layer ferromagnetic rectangular film whose magnetization distribution has a vortex character. The layers of the film have, respectively, uniaxial anisotropy "easy plane" and "easy axis". We will study the contribution to the polarization of different slices of the film and also investigate the effect of an external magnetic field and the transverse dimensions of the film.

2. Model

Let us consider a two-layer film whose layers possess uniaxial anisotropy of different signs. The film is of finite dimensions, rectangular in shape (see Fig. 1). The coordinate axis z coincides with the axis of anisotropy. The external magnetic field is directed parallel to the z axis. The density of free energy of the system includes the energy of uniaxial magnetic anisotropy of the easy-plane and easy-axis types, the demagnetization energy, the Zeeman energy, the energy of exchange interaction inside the layers and the energy of interlayer exchange interaction as follows:

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https://doi.org/10.1016/j.jmmm.2018.09.076
Received 9 April 2018; Received in revised form 31 July 2018; Accepted 21 September 2018
Available online 22 September 2018

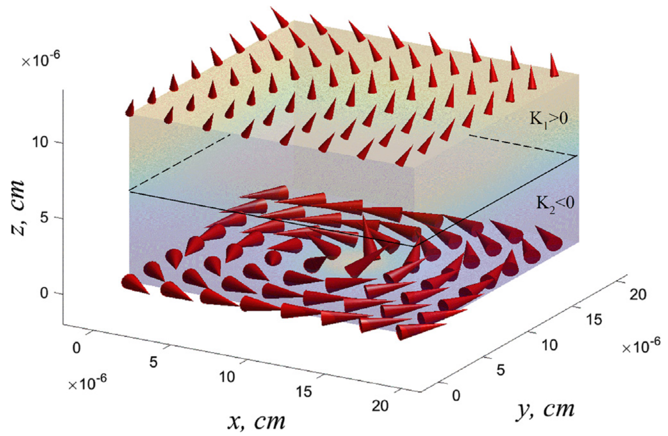

Fig. 1. The vortex ground state. Distribution of magnetization at the upper and lower boundaries of the film.

$$E = \sum_{i=1}^{2}\left(\frac{K_i}{M_i^2}\boldsymbol{M}_{z,i}^2 - \frac{1}{2}\boldsymbol{M}_i\boldsymbol{H}^{(m)} - \boldsymbol{M}_i\boldsymbol{H} + \frac{A_i}{M_i^2}\left[\left(\frac{\partial M_{ix}}{\partial x}\right)^2 + \left(\frac{\partial M_{iy}}{\partial y}\right)^2 + \left(\frac{\partial M_{iz}}{\partial z}\right)^2\right]\right) - \frac{J}{M_1M_2}\boldsymbol{M}_1\boldsymbol{M}_2 \quad (1)$$

where M_i are the saturation magnetizations of layers, K_i are the constants of magnetic anisotropy, $\boldsymbol{H}^{(m)}$ is the demagnetizing field, A_i are the constants of exchange interaction; and J is the constant of interlayer exchange interaction. On the surface of the film, boundary conditions are fulfilled, corresponding to the unpinned magnetization: $\frac{\partial \boldsymbol{M}}{\partial x} = \frac{\partial \boldsymbol{M}}{\partial y} = \frac{\partial \boldsymbol{M}}{\partial z} = 0$.

The problem of finding the equilibrium state of such a system was solved numerically. The calculations were performed using the OOMMF three-dimensional modeling software package [17] with a discretization on a rectangular grid with a step of 5 nm along the x and y coordinates and 3 nm along z coordinate. The calculation was carried out for the parameters of a two-layer film characteristic of an iron-garnet film: $M_1 \approx 30$ G, $M_2 \approx 70$ G, $A_i \approx 10^7$ erg/cm, $J \approx 1\ \text{cm}^{-1}$ and the anisotropy parameters $K_1 \approx 2 \times 10^4\ \text{erg/cm}^3$, $K_2 \approx -7 \times 10^4\ \text{erg/cm}^3$. The thicknesses of the layers are assumed to be equal. The samples were a square in cross section, its transverse dimensions ranged from 200 to 500 nm, thicknesses of the layers are 60 nm.

The initial distribution of the magnetization in the absence of the field was assumed to be homogeneous, the magnetization was oriented along the easy-axis. Then the equilibrium distribution of the magnetization is calculated. After that the external field is turned on. The equilibrium distribution is again calculated, after which the field is changed. The equilibrium distribution found in the previous stage is selected each time as a new initial distribution of the magnetization.

For the obtained magnetization distribution, the magnitude of the electric polarization vector **P** was calculated from the formula [8]:

$$\boldsymbol{P} = \gamma\chi_e\left[(\boldsymbol{M}\nabla)\boldsymbol{M} - \boldsymbol{M}(\nabla\boldsymbol{M})\right] \quad (1)$$

where χ_e is the dielectric susceptibility, γ is the coefficient of nonuniform magnetoelectric interaction. Hereinafter we will calculate the polarization vector in arbitrary units: $\boldsymbol{P} \to \boldsymbol{P}/\gamma\chi_e M_i^2$. The average polarization is calculated by formula [8]:

$$\langle \boldsymbol{P} \rangle = \frac{1}{V}\int_V \boldsymbol{P}(x, y, z)dxdydz \quad (2)$$

Averaging can be carried out both by the entire volume of the sample, in this case we denote the average polarization by $\langle \boldsymbol{P} \rangle_V$ and by the volume of a plane cell whose thickness is equal to the discretization step along the z axis, and the transverse dimensions coincide with the transverse dimensions of the film. In the latter case, we denote the average polarization by $\langle \boldsymbol{P} \rangle_S$.

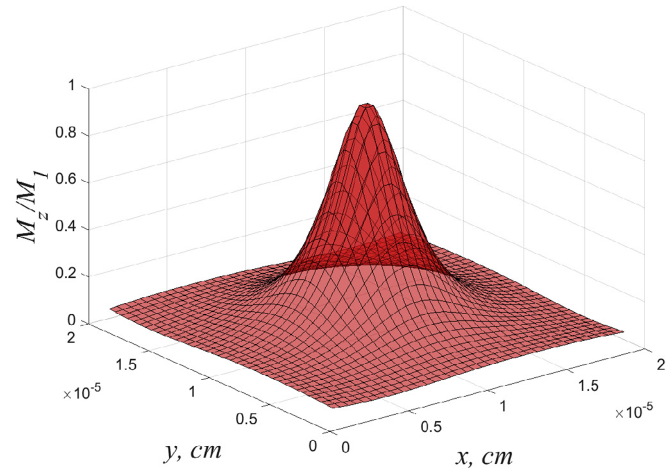

Fig. 2. Dependence of the reduced magnetization component M_z/M_1 on the x and y coordinates at the lower boundary of the film of transverse dimensions 200 × 200 nm. Henceforth, the red color of the plot corresponds to a positive value, the blue one to a negative one. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results and discussion

As shown by our calculations, two types of magnetization distribution can be realized in the ground state. In the case when the magnetization is homogeneous in the plane of the film layers in the ground state, the inhomogeneity of the magnetization along the film thickness arises at the interface of the layers. This inhomogeneity is the source of the magnetoelectric effect, which was investigated in the article [13].

The second type of magnetization distribution – Vortex, is investigated in this article. Fig. 1 shows the vortex distribution of the magnetization at the upper and lower boundaries of the film in the absence of an external magnetic field.

At the lower boundary, the magnetization everywhere on the periphery lies almost in the plane of the film. In the central region, called the vortex core, the magnetization comes out of the film plane (see Fig. 2). The distribution of the magnetization along the thickness of the film is also inhomogeneous. The smaller the transverse dimensions of the film, the greater the change in the magnetization along the thickness of the film.

If we take into account only the region spaced from the center of the vortex core by a distance greater than the radius of the vortex when calculating, the average polarization of the sample will be zero, since such a distribution of the magnetization generates a radial distribution of the polarization. However, due to the presence of the vortex core, a z component of polarization appears. Figs. 3 and 4 show the distributions in the (x, y) plane of the polarization components P_x and P_z at the lower boundary of the film. It can be seen that although the maximum values of the polarization component P_x are almost an order of magnitude higher than the maximum values of the component P_z, since the polarization component P_x takes opposite values in different parts of the distribution, the component of the average polarization $\langle P_x \rangle_V$ turn out to be zero within the calculation accuracy. This is also true for the component $\langle P_y \rangle_V$. When moving from the interlayer to the upper boundary of the film, P_z in the center of the sample decreases, but increases on the periphery.

Fig. 4a shows the distribution of P_z at the upper boundary of the film. For a sample with small transverse dimensions, a layer with an easy-axis anisotropy contributes to an average polarization less than the layer with an anisotropy easy-plane However, as the transverse dimensions of the film increase, the contribution of the layer with an easy-axis anisotropy increases.