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Electric polarization in bi-layered ferromagnetic film with combined magnetic anisotropy

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ABSTRACT

Magnetoelectric phenomena become one of the most attractive fields of magnetism. One of discussable items is inhomogeneous magnetoelectricity leading to appearance of electric polarization of magnetic domain walls, improper polarization of multiferroics etc. In our article we attract attention to the modulation of electric polarization by magnetic inhomogeneity in exchange coupled ferromagnetic film whose layers differ by magnetic anisotropy. Our goal is to explore the influence of combined magnetic anisotropy (especially its cubic component) on the behavior of electric polarization of bi-layered film placed in magnetic field. We perform theoretical analysis in a frame of phenomenological modeling of spins structures considering two geometries of magnetic field (magnetic field oriented perpendicular to a film plane and magnetic field oriented in a film plane along "hard magnetization" axis). Our results show that the presence of cubic magnetic anisotropy ($K_c < 0$) in the layers allocates the planes of magnetic inhomogeneities and correspondingly the directions of electric polarization. We demonstrate that magnetic field applied along the "hard magnetization" axis leads to the rotation of electric polarization in the 45° range and magnetic field applied along normal to a film influences the magnitude of electric polarization leading to the lowering of polarization after attaining the maximum value.

1. Introduction

Great current activity is devoted to investigation of magnetoelectric materials holding a great potential for science and application. Interplay between several order parameters (electric, magnetic and elastic) opens a variety of opportunities in the design of multifunctional devices for data storage, transducers, sensors, spintronics.

Though the materials exhibiting the coexistence of magnetic and electric properties are rare in nature, up-to-date technologies allow crafting multiferroics and magnetoelectric composites combining magnetic and electric ordering [1–5]. Nevertheless, the application of single phase multiferroics is so far limited since the most known of them does not display both reasonably large magnetic and electric properties at room temperature. This compels the scientists and technologists look for an alternative approach to construct composite materials, whose magnetoelectric properties are improved due to ferroelectric–antiferromagnetic–ferromagnetic coupling [5–7], magnetically modulated electric polarization [8–11], strain transferred from the phase boundaries etc. The mechanisms of underlying interactions, voltage control magnetism in a multiferroics/ferromagnetic heterostructures, electric polarizations arising close to magnetic inhomogeneities have been studied intensively [12–17]. However while non-uniform magnetoelectric effect bringing about to electric properties of magnetic domain walls has been fairly well studied [14–16] electrostatics of magnetic layered structures has been given insufficient attention.

In this article, we appeal to electric polarization induced by non-uniform distribution of magnetization in a vicinity of interface between magnetically ordered layers in ferromagnetic exchange coupled film. Our goal is to explore how magnetic anisotropy affects the magnetically modulated electric polarization in ferromagnetic bi-layers differing by uniaxial magnetic anisotropy in external magnetic field by taking ferrite garnet films as an example. We suppose that the studied film is placed in the magnetic field oriented in a film plane or along normal to a surface and explore polarization field (P–H) dependences at different relations between constants of magnetic anisotropy paying special attention to the role of cubic magnetic anisotropy.

2. General equations

Let's consider bi-layered exchange coupled ferromagnetic

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structure in external magnetic field $\boldsymbol{H}$. The Cartesian reference frame is chosen in the following way, the axis [100] (***OX***) is taken to be normal to the film, the axis [001] (***OZ***) is oriented along the interface (Fig. 1). The position of the local magnetization vector $\boldsymbol{M}$ ($M = M_0(\sin\theta\cos\Phi,\ \sin\theta\sin\Phi,\ \cos\theta)$) is determined by the polar Θ and the azimuthal Φ angles, where the angle Θ is measured from the positive direction of axis ***OZ*** and the angle Φ is measured from the positive direction of axis ***OX***, M_0 is the magnetization of saturation. We suppose that films have different thicknesses and are characterized by combined magnetic anisotropy including natural cubic anisotropy and induced magnetic anisotropy of the "easy axis" and the "easy plane" type.

The density of free energy of a system incorporating the exchange energy, the energies of cubic and induced magnetic anisotropies, the energy of interaction with external magnetic field, the energy of non-uniform magnetoelectric interaction, the electrostatic energy, the energy of interlayer exchange, and the electric field energy is taken in a form

$$E = \sum_{i=1}^{2}\left(A\left[\left(\frac{\partial M_{ix}}{\partial x}\right)^2 + \left(\frac{\partial M_{iy}}{\partial y}\right)^2 + \left(\frac{\partial M_{iz}}{\partial z}\right)^2\right] + K_c\left(M_{ix}^2M_{iy}^2 + M_{ix}^2M_{iz}^2 + M_{iy}^2M_{iz}^2\right) + + K_i(\boldsymbol{M}_i\boldsymbol{n})^2 - \boldsymbol{M}_i\boldsymbol{H} - J\boldsymbol{M}_1\boldsymbol{M}_2 + \gamma\tilde{\boldsymbol{P}}_i[(\boldsymbol{M}_i\nabla)\boldsymbol{M}_i - \boldsymbol{M}_i(\nabla\boldsymbol{M}_i)] + \frac{\tilde{P}_{ix}^2 + \tilde{P}_{iy}^2 + \tilde{P}_{iz}^2}{2\chi_e} - \tilde{\boldsymbol{P}}_i\boldsymbol{E}\right) \tag{1}$$

where A is the constant of non-uniform exchange interaction, K_1 is the constant of magnetic anisotropy of the "easy axis" type, K_2 is the constant of magnetic anisotropy of the "easy plane" type, K_c is the constant of cubic magnetic anisotropy ($K_c < 0$), J is the constant of interlayer exchange interaction, $\tilde{\boldsymbol{P}}$ is the polarization vector, χ_e is the dielectric susceptibility, γ is the coefficient of non-uniform magnetoelectric interaction, $\boldsymbol{H}$ is the applied magnetic field, $\boldsymbol{E}$ is the electric field.

The stable configurations of magnetization (Θ, Φ) and polarization ($\tilde{\boldsymbol{P}}$)

$$\tilde{P}_y = \chi_e\gamma\,\sin^2\theta\frac{d\Phi}{dx} \tag{2}$$

$$\tilde{P}_z = \chi_e\gamma\left(-\frac{d\theta}{dx}\cos\Phi + \sin\theta\cos\theta\sin\Phi\frac{d\Phi}{dx}\right) \tag{3}$$

determined by the minimum of the free energy have been found numerically by applying to the multidimensional minimization procedure [18].

In accordance to expressions (2) and (3) electric polarization is oriented perpendicular to the plane of magnetization rotation across magnetic inhomogeneity.

It should be noted that the cubic anisotropy allows arising of magnetic inhomogeneity close to one of trigonal axes (of < 111 > family). In the present research we investigate electric polarization attributed to rotation of magnetization in a vicinity of one of the trigonal crystal axes of [111] type. We consider the most important geometries of a magnetic field, namely the magnetic field applied along normal to a film ($\boldsymbol{H}$ ∥ [100]) and the magnetic field applied in a film plane in the direction of "hard magnetization" (in a case of $Kc < 0$, the "hard magnetization" direction corresponds to the axis [010]) ($\boldsymbol{H}$ ∥ [010]). As the model objects we take ferrite–garnet films, materials possessing with magnetoelectric properties [14,19–21], whose characteristic parameters vary in a wide range, we use $A = 10^7$ erg/cm^2, $M_0 = 70$ G, $K_{1,2,c} \sim (10^3\text{–}10^5)$ erg/cm^3, $\gamma = 10^{-6}$ (erg/cm)$^{1/2}$.

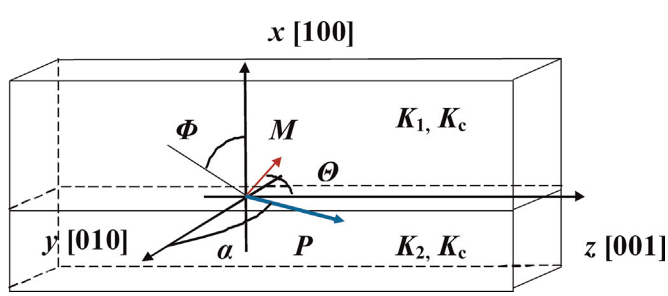

Fig. 1. Geometry of a problem.

3. Results and discussion

The profiles of P_y, P_z components in magnetic field applied along the "hard magnetization" axis ($\boldsymbol{H}$ ∥ [010]) are shown in Fig. 2 (a, b) ($\boldsymbol{P} = \frac{\tilde{\boldsymbol{P}}}{\chi_e\gamma}$). It is seen that electric polarization is distributed across entire film and attains maximum values close to interface. The polarization shrinks with magnetic field enhancement, and the components P_y and P_z change differently with varying of magnetic field. The last evidence indicates the rotation of polarization vector.

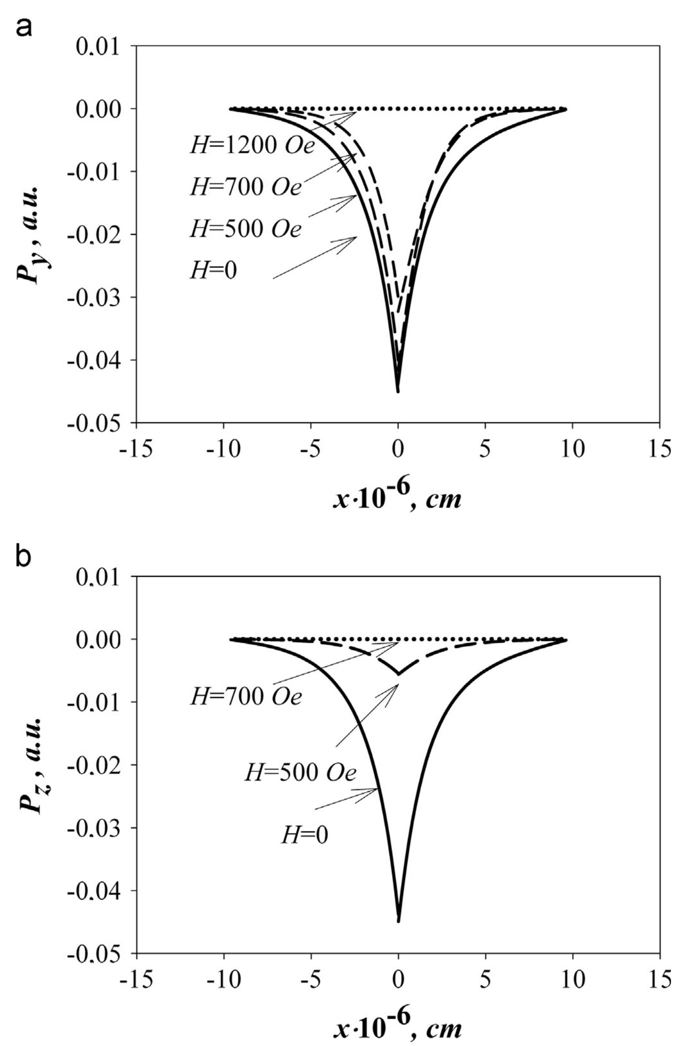

Fig. 2. Distribution of polarization components across the film, $\boldsymbol{H}$ ∥ [010]. (a) $P_y(x)$, (b) $P_z(x)$.