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Effect of electrically induced deformations on ferromagnetic resonance in multiferroic-based heterostructures

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Abstract. The paper considers the change in the spectrum of ferromagnetic resonance in ferrite-piezoelectric layered structures in an external electric field. The induced magnetic anisotropy through the magnetoelastic interaction is generally non-uniform in thickness due to the presence of bending deformations. As a result, the applied electric field leads to a shift and broadening of the magnetic resonance line, which are determined by the composition and geometric dimensions of the structure layers. The paper presents a theoretical modeling of the magnetic resonance line broadening when additional buffer layers are inserted between the ferrite and piezoelectric layers to reduce the effect of a high-permittivity piezoelectric on the microwave field structure in the ferrite. The simulation results are considered on the example of layered structures of the composition of iron-yttrium garnet - lead titanate-zirconate. It is shown that at certain thicknesses of the magnetic and piezoelectric layers, the broadening of the magnetic resonance line as a function of the thickness of the buffer layer has a maximum. The results can be used in frequency-selective microwave devices with electrically tunable range.

1. Introduction

It is known that the magnetoelectric (ME) effect is the polarization of the material in an external magnetic field and, conversely, in magnetization in an external electric field. In a magnetostriction-piezoelectric layered structure, this effect is associated with mechanical deformations [1]. A significant enhancement of the ME effect is observed in the area of electromechanical resonance. In the area of magnetic resonance, this effect manifests itself in the form of a change in the spectrum of ferromagnetic resonance (FMR) in an external electric field [2–6]. The application of a constant electric field to the piezoelectric layer leads to the appearance of mechanical stresses in the ferrite component, and, consequently, to the induction of magnetic anisotropy and a shift of the resonant magnetic field. In a two-layer ferrite-piezoelectric structure due to bending deformations of the sample, electrically induced mechanical stresses of non-uniform thickness are observed, which in turn lead to a shift of the resonant magnetic field and inhomogeneous broadening of the FMR lines [7]. The use of a magnetic phase in the form of a ferrite film on a dielectric substrate makes it possible to reduce the influence of the piezoelectric layer with a high dielectric constant on the microwave field in the ferrite. In this case, the ME effect weakens due to the effect of clamping the ferrite from the substrate [8]. In the three-layer structure of the piezoelectric - ferrite - piezoelectric with opposite polarization directions of the piezoelectric layers, it is possible to obtain a pure bending of the sample and, therefore, the broadening of the FMR line in the absence of a line shift [9]. The objective of this article is to theoretically simulate the broadening of the magnetic resonance line when introducing the additional buffer layers between the ferrite and piezoelectric layers to reduce the effect of the piezoelectric with high dielectric constant on the microwave field structure in the ferrite.

2. Theoretical modeling of the magnetic line broadening in a piezoelectric - ferrite - piezoelectric layered structure

Consider a three-layer structure of a piezoelectric - ferrite - piezoelectric with opposite polarizations of the piezoelectric layers. It is assumed that the magnetizing and constant electric fields are directed along the axis [001] perpendicular to the sample plane. We assume that the magnetizing field H_0 applied to the ferrite



component has a value sufficient to obtain a single-domain structure. An alternating magnetic field H , which is necessary for observing magnetic resonance, is also applied to the ferrite layer. We assume that the magnetic field H_0 is parallel to the Oz axis, and the alternating field H is parallel to the xOy plane.

For a theoretical simulation of the change in the magnetic resonance spectrum induced with an external electric field, one should obtain a solution to the equation of motion of the magnetization.

$$\frac{\partial M}{\partial t} = -\gamma[M, H_{eff}] \quad (1)$$

In equation (1), the effective field H_{eff} is defined as the derivative of the free energy density by the magnetization M :

$$H_{eff} = -\frac{\partial^m W}{\partial M}. \quad (2)$$

By ${}^m W$ is meant the free energy density of the ferrite. For a ferrite single crystal, this value includes the energy of magnetic anisotropy of shape, the energy of crystallographic anisotropy, and also magnetoelastic energy.

We assume that in the expression for the Zeeman energy $W_H = -M \cdot H_i$ the internal magnetic field H_i includes the demagnetization field. It is known that the energy of the cubic crystal anisotropy W_{an} with the constant cubic anisotropy K_1 and the saturation magnetization M_0 is determined by the expression

$$W_{an} = \frac{K_1}{M_0^4} (M_1^2 M_2^2 + M_2^2 M_3^2 + M_3^2 M_1^2) \quad (3)$$

It is also known that, taking into account the magnetoelastic constants B_1 and B_2 , the magnetoelastic energy W_{ma} is written in the form:

$$W_{ma} = \frac{B_1}{M_0^2 (M_1^{2m} S_1 + M_2^{2m} S_2 + M_3^{2m} S_3)} + \frac{B_1}{M_0^2 (M_1 M_2^m S_6 + M_2 M_3^m S_4 + M_1 M_3^m S_5)} \quad (4)$$

where S_i is the deformation components. In addition, the elastic energy can be represented as:

$$W_{ac} = \frac{{}^m c_{11} ({}^m S_1^2 + {}^m S_2^2 + {}^m S_3^2)}{2} + \frac{{}^m c_{44} ({}^m S_4^2 + {}^m S_5^2 + {}^m S_6^2)}{2} + {}^m S_{12} ({}^m S_1^m S_2 + {}^m S_2^m S_3 + {}^m S_1^m S_3) \quad (5)$$

where ${}^m c_{ij}$ are the elastic moduli of the ferrite phase.

The linearized equation of motion can be obtained under the assumption that the variable components of the alternating magnetic field and magnetization are negligible compared to the constants. For free oscillations of the sample, this equation takes the form:

$$i\omega m + \gamma m \times H_{eff} + \gamma M_0 \times h_{ef} + i\alpha \omega [m \times M_0]/M_0 = 0 \quad (6)$$

Based on the effective demagnetizing factor method, an expression for the magnetic susceptibility of the sample can be obtained:

$$\chi^M = \begin{bmatrix} \chi_1 & \chi_s + i\chi_a & 0 \\ \chi_s - i\chi_a & \chi_2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (7)$$

The following symbols are used here: ω , γ and $N_{k'n}^i$ - circular frequency, magnetomechanical ratio and effective demagnetizing factors corresponding to the above types of magnetic anisotropy. $(1', 2', 3')$ is the coordinate system in which the axis $3'$ is directed along the direction of the equilibrium magnetization. To calculate the broadening and shift of the FMR line using formula (7), it is necessary to calculate the components of the tensor of mechanical stresses generated in the ferrite layer when an external electric field is applied. For this purpose, we will use the generalized Hooke law relating the components of stress, strain, and electrical induction for the PZT layer, the component of stress, strain, and magnetic induction for the ferrite layer, as well as the component of stress and strain for the buffer layers. It is also necessary to use the material equations [1].

In expression (7) the following notation is used:

$$\begin{aligned}
\chi_1 &= D^{-1}\gamma^2 M_0 [H_{03'} + M_0 \sum_i (N_{2'2'}^i - N_{3'3'}^i)]; \\
\chi_2 &= D^{-1}\gamma^2 M_0 [H_{03'} + M_0 \sum_i (N_{1'1'}^i - N_{3'3'}^i)]; \\
\chi_s &= -D^{-1}\gamma^2 M_0^2 \sum_i N_{1'2'}^i; \\
\chi_a &= D^{-1}\gamma M_0 \omega; \\
D &= \omega_0^2 - \omega^2; \\
\omega_0^2 &= \gamma^2 [H_{03'} + \sum_i (N_{1'1'}^i - N_{3'3'}^i) M_0] [H_{03'} + \\
&+ \sum_i (N_{2'2'}^i - N_{3'3'}^i) M_0] - (\sum_i N_{1'2'}^i M_0)^2
\end{aligned}$$

For the sake of simplicity, we will assume that the layers of the structure under consideration have perfect mechanical contact. We take into account that the shear stresses in each layer lead to the appearance of torques, since the efforts are directed asymmetrically relative to the median planes of each layer. In order to take into account the contribution of bending deformations to axial deformations of layers, the latter should be represented as a function of the vertical coordinate z_j and the radius of curvature R .

$${}^j S_i = {}^j S_{i0} + \frac{z_j}{R}, \quad (8)$$

where ${}^j S_{i0}$ is the axial deformation of the layer j along the length of the sample (x axis) without bending, z_j is measured from the mid-plane of the j -th layer.

$${}^m S_{j0} - {}^p S_{j0} = \frac{h_p}{R_j} \quad (9)$$

$${}^g S_{j0} - {}^m S_{j0} = \frac{h_g}{R_j} \quad (10)$$

From geometric considerations it can be assumed that $h_p = ({}^m t + {}^p t)/2$, $h_g = ({}^m t + {}^p t)/2$, where ${}^m t$, ${}^p t$ are the thickness of the ferrite and piezoelectric layers, respectively.

The radius of curvature and deformation, corresponding to the median planes, can be determined on the basis of the equilibrium conditions of the structure, which consist in equating to zero the sum of the axial forces acting in each layer, as well as the sum of the torques.

3. Calculation results for structures based on yttrium iron garnet and PZT

Let us apply the theoretical model discussed above to simulate a change in the parameters of the FMR line of the three-layer structure PZT-YIG- PZT. The PZT layers have the same dimensions and opposite polarization directions. In this structure, purely bending deformations are observed, which lead to the broadening of the resonance line. The average shift of the resonant magnetic field is zero. To reduce the effect of the piezoelectric on the microwave field in the ferrite, 2 identical buffer layers are used between the layers of YIG and PZT. The paper assumes that the buffer layers consist of gallium-gadolinium garnet. It is assumed that the magnetizing and constant electric fields are directed along the axis [001] perpendicular to the sample plane. The calculated broadening of the FMR line as a function of the ratio of the thicknesses of the layers of ferrite and piezoelectric is shown in figure 1.

The simulation results given in Figure1 show that the maximum broadening of the FMR 7.2 Oe line is observed in the absence of buffer layers with a ratio of the thicknesses of the YIG and PZT layers equal to 1.3. An increase in the thickness of the buffer layer leads to a decrease in the maximum broadening of the FMR line, while the ratio of the thickness of the layers of YIG and PZT, corresponding to the maximum broadening of the FMR line, decreases. This is due to the effect of clamping the ferrite layer from the buffer layer, as well as the redistribution of mechanical stresses in the sample.

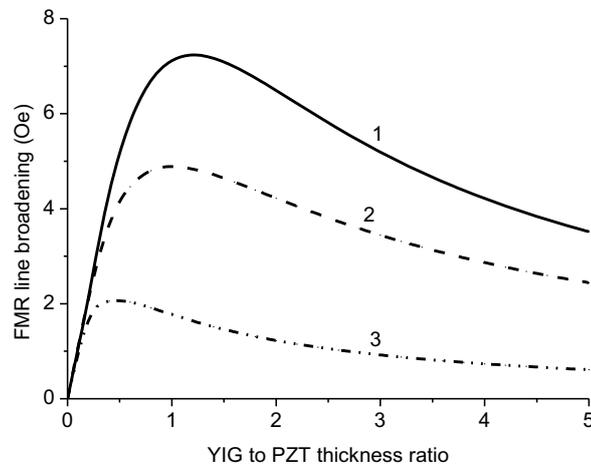


Figure 1. Dependence of the broadening of the FMR line on the ratio of the thickness of the layers of YIG and PZT at $E = 6 \text{ kV / cm}$ for the ratio of the thicknesses of the buffer layer and YIG equal to zero (curve 1), 0.5 (curve 2) and 2 (curve 3).

In figure 2 the dependence of the broadening of the FMR line on the ratio of the thickness of the buffer layer and ferrite is shown.

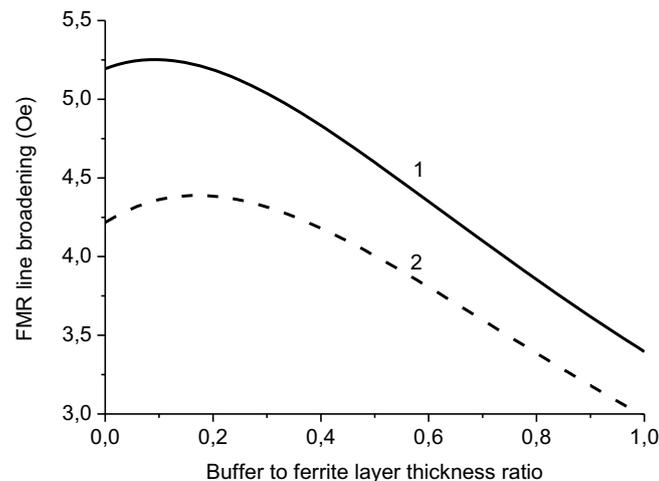


Figure 2. Dependence of the broadening of the FMR line on the ratio of the thicknesses of the buffer layer and YIG at $E = 6 \text{ kV / cm}$ for the ratio of the thicknesses of the layers of YIG and PZT equal to 3 (curve 1) and 4 (curve 2).

Figure 2 shows that the plot of FMR line broadening versus buffer to ferrite layer thickness ratio shows a maximum for certain ferrite to piezoelectric thickness ratios. This fact allows us to optimize the choice of the geometric parameters of the structure layers.

4. Conclusion

This article presents a theoretical simulation of the magnetic resonance line broadening in a layered ferrite-piezoelectric structure with the introduction of additional buffer layers between the ferrite and piezoelectric layers to reduce the effect of a piezoelectric with high dielectric constant on the structure of the microwave field in the ferrite. The simulation results are considered on the example of layered structures of lead titanate-zirconate composition - yttrium iron-garnet-lead titanate-zirconate using additional buffer layers. It is shown that the dependence of the FMR line broadening on the YIG to PZT thickness ratio has a maximum. It is shown that at certain thicknesses of the magnetic and piezoelectric layers, the broadening

of the magnetic resonance line as a function of the thickness of the buffer layer also has a maximum. The results can be used in frequency-selective microwave devices with electrically tunable operating range.

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