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Theory of the Low Frequency Magnetoelectric Effect in Three Layered Asymmetric Structures

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Abstract The theory of the low-frequency magnetoelectric effect in three-layer structures of a magnet - piezoelectric - magnet with opposite signs of magnetostriction is presented. The relationship between the layer thicknesses for the maximum effect was obtained. It is shown that the efficiency of magnetoelectric conversion of an asymmetric three-layer structure is much higher than the conversion efficiency of a bilayer structure. The results of calculations for asymmetric structures are presented.

INTRODUCTION

Composite multiferroics attract more and more attention due to the presence in them of the interconnection of electrical and magnetic characteristics, which opens the possibility of creating fundamentally new electronic devices on their basis, both in the low-frequency region and in the microwave [1-5]. They are of particular interest for straintronics, a new direction in electronics that has been actively developing in recent years [6]. The magnetoelectric (ME) effect consists in a change in the polarization of a substance under the action of a magnetic field (direct ME effect) and, conversely, in a change in magnetization under the action of an electric field (inverse or conversion ME effect). In composite multiferroics, it arises because of the mechanical interaction of the magnetostrictive and piezoelectric subsystems of the composite. In a magnetic field, mechanical deformations arise in the magnetostrictive component, which are by mechanical interaction transferred to the piezoelectric phase, because of which a change in polarization occurs, which leads to the appearance of a voltage between the plates of the sample. Due to the presence of the ME effect, it is possible to create devices with double control, i.e., devices in which control is carried out simultaneously by both electric and magnetic fields [7-10]. At present, the most widespread are bulk composite multiferroics made by ceramic technology and layered multiferroics obtained by gluing, spraying, or galvanic deposition. Layered multiferroics, as a rule, demonstrate a better efficiency of ME conversion compared to bulk composites. Until now, bilayer structures with sequential [11] and parallel [12-17] arrangement of layers of various geometric shapes and compositions have been widely studied to obtain the maximum magnitude of the ME interaction. The ME effect in layered structures is associated with the propagation of planar vibrations, bending vibrations, and thickness vibrations. The resonant frequency of the effect is determined by the geometric characteristics of the structure, Young's moduli, and the density of the material of the layers, and the methods of fixing the structure. For thickness vibrations, the resonant frequency is the highest, and for bending modes, the resonant frequency is the lowest. It should be noted that for three-layer symmetric structures, bending modes are absent, and only planar and thickness vibrations are realized. During bending vibrations in two-layer structures, the magnitude of the ME effect depends on the physical parameters and the ratio of the thicknesses of the magnetostrictive and piezoelectric layers [18]. To enhance the magnitude of the ME interaction in [19], a bimorph structure was used, consisting of two magnetostrictive layers with different signs of magnetostriction and two layers of piezoelectric with opposite polarization directions located between them. The magnitude of the ME coefficient in such structures exceeded the magnitude of the ME coefficient in two-layer structures with similar parameters. The disadvantage of such structures was the need to polarize the piezoelectric layers in opposite directions, which complicates the process of fabricating the structures. In addition, to achieve the most efficient ME conversion between the layer thicknesses, a certain ratio must be fulfilled. In this work, we consider a three-layer asymmetric structure consisting of a piezoelectric and two layers of a magnet with opposite signs of magnetostriction. The relationship between the layer thicknesses is obtained, at which the structure has the maximum ME conversion efficiency. The dependence of the magnitude of the effect on the parameters of the piezoelectric and magnetostrictive layers is analyzed.

MODEL and BASIC EQUATIONS

Asymmetric three-layer structures are of great interest for research since they make it possible to achieve a higher, in comparison with bilayer structures, efficiency of conversion of a magnetic field into an electric field. The use of materials with positive and negative magnetostriction increases the bending moment, which leads to an increase in deformations in the piezoelectric layer and, consequently, enhancement of the ME conversion.

From the bending theory [20], the following statements can be obtained:

1) mechanical stresses on opposite sides of the neutral line have different signs, therefore, structures in which the neutral line coincides with the interface of the magnetostrictive layer and of the piezoelectric layer will have the maximum efficiency;

2) the position of the neutral line is determined by the thickness of the structure layers. A change in the thickness of one of the layers leads to a shift in the neutral line and, consequently, can lead to a change in the sign of deformations in the piezoelectric layer.

As a model, we will consider a three-layer structure of magnetic 1 / piezoelectric/magnetic 2 with opposite signs of magnetostriction. A schematic representation of such a structure is shown in Fig. 1. The origin of the coordinate system is compatible with the center of the sample, and the $X\,(1)$ axis is compatible with the interface between the piezoelectric layer and the lower magnetic layer with negative magnetostriction.

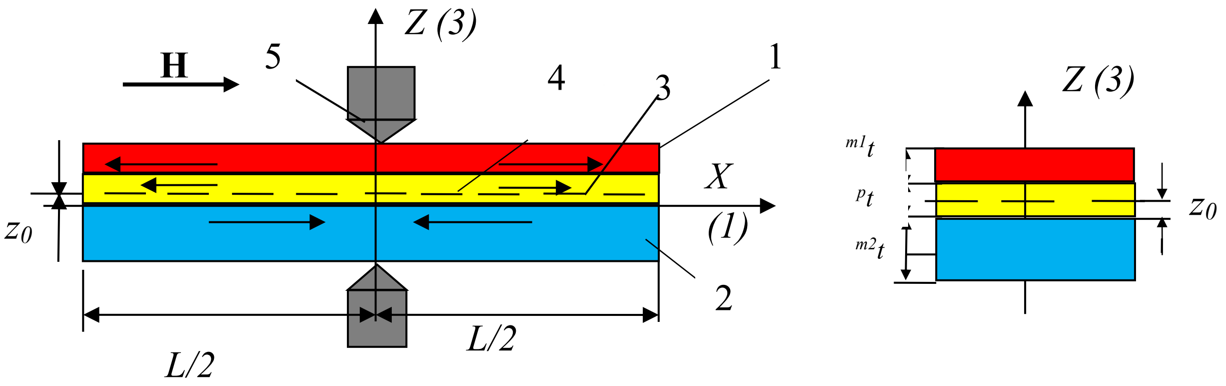

Fig. 1 Schematic drawing of the structure. 1 - magnetic layer 1 (positive), 2 - magnetic layer 2 (negative), 3 - piezoelectric layer, 4 - neutral line, 5 - electrodes.

Follows this, we will assume that the length of the sample is much greater than its width and thickness. In this approximation, the constitutive equations for the piezoelectric and magnetostrictive phases will have the following form:

$$ {}^{P}S_1 = \frac{1}{{}^{P}Y}\,{}^{P}T_1 + {}^{P}d_{31}E_3\,, \tag{1} $$

$$ {}^{m1}S_1 = \frac{1}{{}^{m1}Y}\,{}^{m1}T_1 + {}^{m1}q_{11}H_1\,, \tag{2} $$

$$ {}^{m2}S_1 = \frac{1}{{}^{m2}Y}\,{}^{m2}T_1 + {}^{m2}q_{11}H_1 \tag{3} $$

$$ {}^{P}D_3 = {}^{P}\varepsilon_{33} {}^{P}E_3 + {}^{P}d_{31} {}^{P}T_1 \quad (4) $$

where ${}^{P}S_1$, ${}^{m1}S_1$, ${}^{m2}S_1$ are the components of the strain tensor of the piezoelectric, first and second magnetostrictive layers, ${}^{P}Y$, ${}^{m1}Y$, ${}^{m2}Y$ are Young's modules, ${}^{P}T_1$, ${}^{m1}T_1$, ${}^{m2}T_1$ are the components of the stress tensor of the piezoelectric and magnetostrictive phases, ${}^{P}d_{31}$, ${}^{m1}q_{11}$, ${}^{m2}q_{11}$ are the piezoelectric and piezomagnetic coefficients, ${}^{P}\varepsilon_{33}$ is the permittivity of the piezoelectric.

METOD of the CALCULATION

Using Bernoulli's hypothesis, and the condition of equality to zero of the X - projection of the resulting force, for the coordinate of the neutral line z_0 we obtain the following expression:

$$ z_0 = \frac{1}{2} \frac{{}^{p}Y\,{}^{p}t^2 + 2\,{}^{m1}Y\,{}^{p}t\,{}^{m1}t + {}^{m1}Y\,{}^{m1}t^2 - {}^{m2}Y\,{}^{m2}t^2}{\bar{Y}t}, \quad (5) $$

where ${}^{p}t$, ${}^{m1}t$, ${}^{m2}t$ are the thickness of the layers, $t = {}^{m1}t + {}^{m2}t + {}^{p}t$ is the total thickness of the sample, $\bar{Y} = ({}^{p}Y\,{}^{p}t + {}^{m1}Y\,{}^{m1}t + {}^{m2}Y\,{}^{m2}t)/t$ is the average value of Young's modulus.

The z_0 parameter can be either positive or negative. The structure will be optimal if its value is equal to either $z_0 = 0$ or $z_0 = {}^{p}t$. In this case, the piezoelectric will experience only one type of deformation - either tension ($z_0 = 0$) or compression ($z_0 = {}^{p}t$). The electric field will have one direction over the entire thickness of the piezoelectric. In the case when the neutral line lies inside the piezoelectric, part of the layers of the piezoelectric is tensioned, the other part is compressed. The electric field in different parts has different directions, because of which the total electric field decreases.

Using Eq. (5), we obtain the ratio between the layer thicknesses for the optimal asymmetric structure in the form:

for the case $z_0=0$ we get expression

$$ {}^{m2}Y\,{}^{m2}t^2 = {}^{p}Y\,{}^{p}t^2 + {}^{m1}Y\,{}^{m1}t^2 + 2\,{}^{m1}Y\,{}^{m1}t\,{}^{p}t \ ; \quad (6) $$

for the case $z_0 = {}^{p}t$ we have following equation

$$ {}^{m2}Y\,{}^{m2}t^2 = {}^{p}Y\,{}^{p}t^2 + {}^{m1}Y\,{}^{m1}t^2 + 2\,{}^{m1}Y\,{}^{m1}t\,{}^{p}t - 2\bar{Y}t\,{}^{p}t \quad (7) $$

Equations (6) and (7) make it possible, knowing the thickness of two layers, to easily determine the thickness of the third layer at which the structure will have the maximum efficiency of ME conversion.

When the structure is placed in a magnetic field of strength H_1 due to magnetostriction, a bending moment occurs, for which we can write the expression in the form:

$$ M_y = ({}^{m1}q\,{}^{m1}Y\,{}^{m1}t({}^{p}t + {}^{m1}t/2 - z_0) - {}^{m2}q\,{}^{m2}Y\,{}^{m2}t({}^{m2}t/2 + z_0))WH_1 \quad (8) $$

Under the action of this bending moment, the structure bends, and deformations arise in it. Since the layers are thin, we can assume that the deformations in each layer are the same, i. e. ${}^{p}S_1 = {}^{m1}S_1 = {}^{m2}S_1 = S_1$. According to the theory of bending [20], the deformations are determined by the expression:

$$S_1 = (z - z_0)/\rho\,, \tag{9}$$

where ρ is the radius of curvature of the neutral line which is related to the bending moment by the following relation

$$\frac{1}{\rho} = \frac{M_y}{D}\,. \tag{10}$$

Here D is cylindrical stiffness, which for a given structure is determined by the expression:

$$D = {}^{m1}Y\,{}^{m1}J_{y0} + {}^{p}Y\,{}^{p}J_{y0} + {}^{m2}Y\,{}^{m2}J_{y0}\,. \tag{11}$$

The axial moments of inertia relative to the neutral axis ${}^{m1}J_{y0}, {}^{p}J_{y0}, {}^{m2}J_{y0}$ are determined by the following expressions:

$${}^{p}J_{y_0} = W\left(\frac{1}{12}\,{}^{p}t^3 + {}^{p}t\,({}^{p}t/2 - z_0)^2\right), \tag{12}$$

$${}^{m1}J_{y_0} = W\left(\frac{1}{12}\,{}^{m1}t^3 + {}^{m1}t\,({}^{m1}t/2 + {}^{p}t - z_0)^2\right), \tag{13}$$

$${}^{m2}J_{y_0} = W\left(\frac{1}{12}\,{}^{m2}t^3 + {}^{m2}t\,({}^{m2}t/2) + z_0)^2\right) \tag{14}$$

The magnitude of the induced electric field we determine from the open circuit condition $I = 0$, as a result, which of we obtain:

$${}^{P}E_3(z) = {}^{P}Y\frac{{}^{P}d_{31}}{{}^{P}\varepsilon_{33}}S_1 = {}^{P}Y\frac{{}^{P}d_{31}}{{}^{P}\varepsilon_{33}}\frac{M_y}{D}(z - z_0) \tag{15}$$

The magnetoelectric voltage coefficient (MEVC) α_E is found from the relationship:

$$\alpha_E = \langle E_3 \rangle / H_1\,, \tag{16}$$

where $\langle E_3 \rangle$ is the average value induced electric field, which for given structure is determinate by follow expression:

$$\langle E_3 \rangle = \frac{1}{{}^{P}t}\int_0^{{}^{P}t} E_3\,dz\;\;. \tag{17}$$

Substituting Exp. (15) into Eq. (17) and performing integration, we obtain

$$\langle E_3 \rangle = {}^{P}Y\frac{{}^{P}d_{31}}{{}^{P}\varepsilon_{33}}\frac{M_y}{D}({}^{p}t/2 - z_0)\;\;. \tag{18}$$

Finally, for MEVC we get the expression in the following form:

$$\alpha_E = {}^{P}Y\frac{{}^{P}d_{31}}{{}^{P}\varepsilon_{33}}\frac{{}^{m1}q\,{}^{m1}Y\,{}^{m1}t({}^{p}t + {}^{m1}t/2 - z_0) - {}^{m2}q\,{}^{m2}Y\,{}^{m2}t({}^{m2}t/2 + z_0)}{(D/W)}({}^{p}t/2 - z_0)\,. \tag{19}$$

In Eq. (19), the value (D/W) in the denominator does not depend on the sample width *W*; therefore, the MEVC value is determined by the physical parameters of the magnets and piezoelectric and the thicknesses of their layers. Fig. 2 is showed the dependence of MEVC calculated by the formula (19) on the thickness of the permendur (Pe) layer for the structures Ni - PZT - Pe at a fixed thickness of the nickel layer ${}^{Ni}t$=1.0 mm and the piezoelectric thickness ${}^{P}t$=0.2 mm. At the calculations, the parameters presented in Table 1 were used.

Table 1 Parameters of the materials

Material	Young's modulus, GPa	Density ρ, 10^3 kg/m^3	Piezomodules, d, pC/N; q ppm/Oe	Permitivity ${}^{P}\varepsilon_{33}$
PZT	66.7	8.2	-175	$1750 \cdot \varepsilon_0$
Ni	215	8.9	-0.06	-
Pe	207	8.1	0.1	-

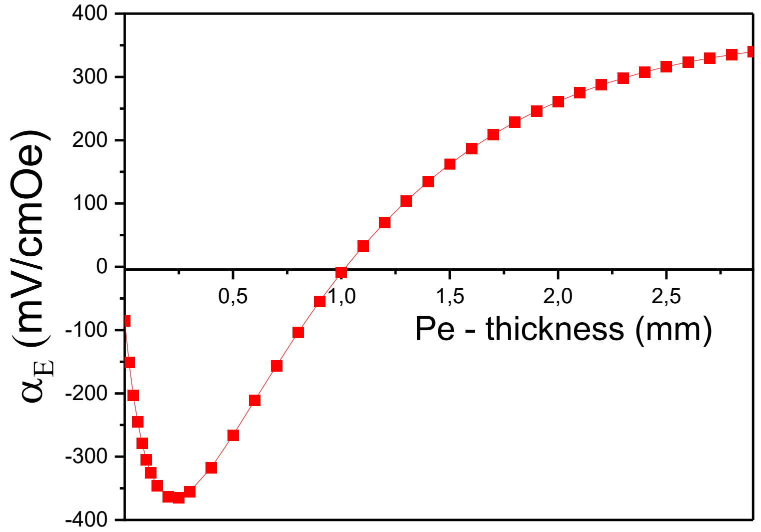

Figure: 2 Dependence of the low-frequency MEVC on the Pe thickness of the for a fixed thickness of the Ni layer ${}^{Ni}t$=1.0 mm and the thickness of the piezoelectric PZT layer ${}^{P}t$= 0.2 mm.

RESULTS and DISCUSSION

As can see from Fig.2, with the initial increase in the thickness of the layer with positive magnetostriction (Pe), MEVC begins to increase. This is due to two reasons: firstly, there is an increase in the bending moment due to the layer with positive magnetostriction, and secondly, this is the displacement of the neutral line located at the beginning in the nickel layer to the interface Ni-PZT. With a further increase in the thickness of the second magnetic layer, as soon as the neutral line coincides with the Ni - PZT interface, the maximum MEVC is observed. With a further increase in the thickness of the second layer, even though the bending moment increases, a decrease in MEVC is observed. This is since the neutral line is shifted into the piezoelectric, while part of the piezoelectric is tensile, and the other part is compressed, because of which electric fields of the opposite direction arise, which leads to a decrease in MEVC, and when the neutral line coincides with the middle of the piezoelectric, MEVC becomes equal to zero, after which it changes sign and begins to grow. With a further increase in the thickness of the second layer, a maximum of MEVC is again observed, after which a decline is observed again, although it is slower than with an initial increase in the thickness of the second layer. This is since with a large thickness of the second, the structure becomes more rigid and less sensitive to changes in parameters.

It should be noted that at the maximum the MEVC value for the three-layer asymmetric Ni-PZT-Pe structure is 3.5 times higher than for the bilayer Ni-PZT structure. Thus, asymmetric three-layer structures have a more efficient ME conversion compared to bilayer structures.

CONCLUSION

Three-layer asymmetric structures, consisting of a piezoelectric and two magnets with opposite signs of magnetostriction, demonstrate a much better efficiency of ME conversion compared to bilayer structures. To achieve the maximum efficiency of ME conversion, it is necessary that a certain ratio be fulfilled between the layer thicknesses. The MEVC value of asymmetric three-layer structures with such a ratio is several times higher than its value for bilayer structures. This makes it possible, by varying the geometric parameters of the layers, to create structures with high efficiency of ME conversion.

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