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Theory of quasi-static magnetoelectric interaction in three-layer asymmetric piezomagnetostrictive structures

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The work is devoted to the theoretical investigation of the quasi-static magnetoelectric interaction in three-layer structures consisting of a piezoelectric and two magnetic layers with positive and negative magnetostriction. Using the system of elasto- and electrostatics equations for the piezoelectric and magnetostrictive phases, expressions for the electrical response of the structure in a magnetic field are obtained. The contributions from longitudinal and bending deformations are taken into account in value of ME interactions. It is shown that the use of an asymmetric three-layer asymmetric structure leads to an increase in the magnitude of the ME interaction by almost an order of magnitude compared to a two-layer structure. The dependences of the effect magnitude on the thickness of the third layer for the nickel/lead zirconate titanate/metglas structure are presented.

Keywords: piezomagnetostrictive composites, magnetostriction, piezoelectricity, magnetoelectric effect, gyrator, harvester.

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Introduction

In piezomagnetostrictive composites due to the mechanical interaction between the magnetostrictive and piezoelectric phases a relationship is formed between the electrical and magnetic properties of materials. When the structure is placed in a magnetic field, an electric voltage arises between the plates of the sample (direct magnetoelectric (ME) effect), or, conversely, the magnetization of the sample changes when it is placed in an electric field (converse ME effect).

The use of piezomagnetostrictive composite materials turned out to be very promising for the creation of current-to-voltage converters (ME gyrators) [1–3], energy harvesters [4], highly sensitive magnetic field sensors [5–11], electrically retuned inductors [12]. To obtain the maximum effect the question of increasing the efficiency of the ME conversion remains fundamental, especially in the low-frequency region, where the value of the ME coupling is practically independent of frequency. The magnitude of the ME effect in the region of electromechanical resonance is much higher than its low-frequency value, however, since the width of the electromechanical resonance line is rather narrow, it is impractical to create energy harvesters operating only at this frequency due to the small fraction of energy attributable to the resonant region.

In contrast to single crystals, where the ME interaction mechanism is a change in the spin-orbit interaction of an electron when an external electric field is applied [13], in piezomagnetostrictive composites the mechanism of the ME response occurrence of the system is the mechanical interaction of the piezoelectric and magnetostrictive subsystems [14]. When a magnetic field is applied in ferromagnet, due to magnetostriction the mechanical deformations occur, which, due to the mechanical bond presence at the ferromagnet-piezoelectric interface, are transferred to the piezoelectric by means of occurring voltages, resulting in change in polarization, and a potentials difference arises between the plates. The most common materials for creating piezomagnetostrictive structures as ferromagnets are permendur, nickel, D-terfenol, an amorphous metglas alloy, and piezoceramics PZT, single crystals of quartz, gallium arsenide are usually used as piezoelectrics. When they are placed in magnetic field in the plane of the sample, longitudinal deformations of the tension-compression type occur. These deformations also lead to the appearance of tension-compression deformations in the layered structure, and bending deformations in the asymmetric structure.

When studying ME coupling in the region of bending deformations, two-layer piezoelectric-ferromagnet structures are usually used [15]. Along with them, in order to increase the efficiency of ME conversion, three- and four-layer asymmetric structures began to be used. This makes it possible, by varying the composition and physical properties of the layers, to better control the structure parameters and to increase the efficiency of the ME interaction. In the paper [16] a bimorph asymmetric structure was studied, consisting of two layers of PZT piezoceramic with opposite polarization directions, located between two layers of ferromagnets, as such ferromagnet the amorphous metglas alloy of the composition $Fe_{90.3}Ni_{1.5}Si_{5.2}B_3$ with positive longitudinal magnetostriction and nickel layer with negative magnetostriction was used. The magnitude of the ME interaction in such a structure turned out to be by an

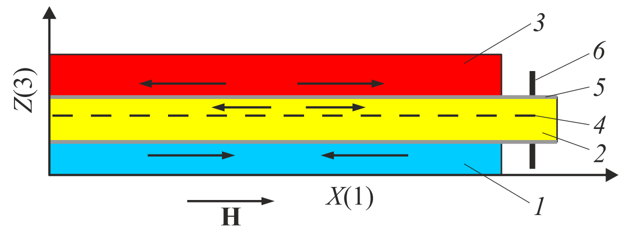

Figure 1. Schematic representation of the structure: *1* — first layer — magnet t^{m1} thick (negative magnetostriction); *2* — second layer — piezoelectric t^p thick; *3* — third layer — magnet t^{m2} thick (positive magnetostriction); *4* — neutral layer; *5* — thin layer Ag; *6* — electrodes.

order of magnitude higher than in the Ni/PZT two-layer structure with similar parameters and comparable sizes. In [17,18] experimental studies of ME coupling in the Terfenol–D/PZT/Ni structure at various nickel thicknesses are given. In these papers it was experimentally shown that the efficiency of ME conversion in the region of the bending mode of oscillations significantly exceeds the ME interaction in two-layer structures. However, during the experiment the ratio between the thicknesses of the piezoelectric and ferromagnet layers was not calculated in order to obtain the maximum value of the ME interaction, as a result of which the structure was not optimal. The theory of the ME effect caused by bending deformations in a non-standard asymmetric three-layer structure, in which the piezoelectric layer was located not inside, but outside of two magnetostrictive layers, is presented in [19]. In this work, the contribution to the magnitude of the ME interaction from bending vibrations was taken into account only. However, as shown in the paper [20], in two-layer structure the contributions to the effect from longitudinal and bending oscillations have different signs, and as a result depending on the ratio of thicknesses between layers they make different contributions to the value of the resulting ME effect. In this paper, we consider a typical three-layer asymmetric structure in which the piezoelectric layer is located between two layers of ferromagnets with positive and negative magnetostriction. When considering the effect, the contribution to the effect from planar and bending vibrations is simultaneously taken into account. The purpose of this paper was to determine the third layer influence on the magnitude of ME interaction and to determine the ratios between the layer thicknesses at which the magnitude of ME coupling has a maximum value.

1. Model. Main equatiuons

As a model, let us consider a three-layer asymmetric structure consisting of a piezoelectric material located between layers of ferromagnets with positive and negative magnetostriction. A schematic representation of the structure is shown in Fig. 1.

Further we will assume that the sample length 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:

$$S_i^p = \frac{1}{Y^p}(T_i^p - \nu T_j^p) + d_{31}^p E_3, \tag{1}$$

$$S_i^{m1} = \frac{1}{Y^{m1}}(T_i^{m1} - \nu T_j^{m1}) + q_{1i}^{m1} H_1, \tag{2}$$

$$S_i^{m2} = \frac{1}{Y^{m2}}(T_i^{m2} - \nu T_j^{m2}) + q_{1i}^{m2} H_1, \tag{3}$$

$$D_3^p = \varepsilon_{33}^p E_3^p + d_{31}^p (T_1^p + T_2^p), \tag{4}$$

where the indices i and j take the values 1 and 2, with $i \neq j$. Here $S_i^p, S_i^{m1}, S_i^{m2}$ are components of the deformation tensor of the piezoelectric, first and second magnetostrictive layers, Y^p, Y^{m1}, Y^{m2} are their Young's moduli, ν is Poisson's ratio, E_3^p, D_3^p are components of the vector of electric field strength and electric induction, $T_i^p, T_i^{m1}, T_i^{m2}$ are stress tensor components of the piezoelectric and magnetostrictive phases, d_{31}^p, q_{1i}^{m1}, q_{1i}^{m2} are piezoelectric and piezomagnetic coefficients, ε_{33}^p is component of the piezoelectric permittivity tensor.

When a sample is placed in magnetic field, in a layer with negative magnetostriction (nickel, ferrite nickel spinel) a compressive strains occurs, and tensile strains occurs in the layer with positive magnetostriction (permendur, D-terfenol, amorphous metglas alloy). By means of a mechanical connection through the interface these deformations are transferred to the piezoelectric material, as a result of which longitudinal tensile or compressive deformations occur in it. Besides, since the mechanical stresses resulting from the deformations are not axial, a bending moment is generated, which leads to the bending deformations occurrence. As a result, when the sample is placed in the magnetic field, two types of deformations occur simultaneously in the piezoelectric — longitudinal deformations and bending deformations. Both types of these deformations contribute to the magnitude of the ME interaction.

2. Longitudinal deformations

When considering the ME interaction, we restrict ourselves to the quasi-static case, i.e. the case when the length and width of the sample are much less than the length is of acoustic waves propagating in the plane of the sample. For typical sample sizes of about 10^{-2} m this is true up to frequencies of about several kHz. In this case, one can neglect the change in deformations and stresses along the length and width of the sample. Besides, we will assume that the layers of ferromagnets and piezoelectric are thin; therefore, we can assume that the deformations of the layers are the similar, i.e. at longitudinal deformations the following equality takes place:

$$S_i^p = S_i^{m1} = S_i^{m2} = S_i. \tag{5}$$

The equilibrium condition, namely the equality to zero of X and Y force projections, gives the following equation connecting the stresses in the piezoelectric and magnetostrictive layers:

$$t^pT_i^p + t^{m1}T_i^{m1} + t^{m2}T_i^{m2} = 0. \quad (6)$$

Expressing from equations (1)–(3) the components of the stress tensor in terms of the components of the deformation tensor, and then substituting the resulting expressions into equation (6), we obtain the following equation, which connects the deformation with the applied magnetic and induced electric fields

$$(S_i + S_j) = \frac{1}{Yt}\left\{2Y^pt^pd_{31}^pE_{3,long} + \begin{bmatrix} Y^{m1}t^{m1}(q_{1i}^{m1} + q_{1j}^{m1})+ \\ Y^{m2}t^{m2}(q_{1i}^{m2} + q_{1j}^{m2} \end{bmatrix} H_1\right\}. \quad (7)$$

Here, $\bar{Y} = (Y^pt^p + Y^{m1}t^{m1} + Y^{m2}t^{m2})/t$ denotes the mean value of the Young's modulus of the structure, and $t = t^p + t^{m1} + t^{m2}$ denotes the total thickness of the structure.

Using the open circuit condition, which for the quasistatic case will be written in the form $D_3 = 0$, and substituting the resulting equation (7) into the expression for the stress tensor, and then into equation (4), we obtain, for the electric field induced by longitudinal deformations $E_{3,long}$ the following expression:

$$E_{3,long} = \frac{Y^pd_{31}^p}{\varepsilon_{33}Yt} \times \frac{\left[Y^{m1}t^{m1}(q_{11}^{m1} + q_{12}^{m1}) + Y^{m2}t^{m2}(q_{11}^{m2} + q_{12}^{m2})\right]}{[1 - \nu - 2k_p^2(1 - Y^pt^p/Yt)]} H_1. \quad (8)$$

Here $k_p^2 = Y^p(d_{31}^p)^2/\varepsilon_{33}$ denotes the square of the coefficient of electromechanical coupling.

The parameter characterizing the efficiency of the ME conversion is the ME voltage coefficient (MEVC) α_E, defined as $\alpha_E = E_3/H_1$. Using this definition, for the MEVC, dependent on longitudinal oscillations, we obtain the expression in the form

$$\alpha_{E,long} = \frac{Y^pd_{31}^p}{\varepsilon_{33}Yt} \times \frac{\left[Y^{m1}t^{m1}(q_{11}^{m1} + q_{12}^{m1}) + Y^{m2}t^{m2}(q_{11}^{m2} + q_{12}^{m2})\right]}{[1 - \nu - 2k_p^2(1 - Y^pt^p/Yt)]}. \quad (9)$$

Along with MEVC, which characterizes the efficiency of magnetic field conversion into electric one, another coefficient can be used to characterize the ME coupling. In practice, as a rule, the electric voltage on the sample is removed when it is placed in an ac magnetic field, therefore, for the efficiency of the ME conversion, one can use a coefficient equal to the ratio of the induced electric voltage U to the intensity of the ac magnetic field that caused it, i.e. $\beta_U = U/H_1$. This coefficient, which, according to [20], was named as „magnetoelectric sensitivity coefficient" (MESC), for longitudinal vibrations will be determined by the expression:

$$\beta_{U,long} = \frac{Y^pt^pd_{31}^p}{\varepsilon_{33}Yt} \times \frac{[Y^{m1}t^{m1}(q_{11}^{m1} + q_{12}^{m1}) + Y^{m2}t^{m2}(q_{11}^{m2} + q_{12}^{m2})]}{[1 - \nu - 2k_p^2(1 - Y^pt^p/Yt)]}. \quad (10)$$

Expressions (9) and (10) include a small parameter $k_p^2 \ll 1$, so these expressions can be simplified and written in an approximate form more convenient for analysis

$$\alpha_{E,long} = \frac{Y^pd_{31}^p[Y^{m1}t^{m1}(q_{11}^{m1} + q_{12}^{m1}) + Y^{m2}t^{m2}(q_{11}^{m2} + q_{12}^{m2})]}{\varepsilon_{33}Yt}, \quad (11)$$

$$\beta_{U,long} = \frac{Y^pt^pd_{31}^p[Y^{m1}t^{m1}(q_{11}^{m1} + q_{12}^{m1}) + Y^{m2}t^{m2}(q_{11}^{m2} + q_{12}^{m2})]}{\varepsilon_{33}Yt}. \quad (12)$$

Equations (11) and (12) make it possible to analyze the contribution of longitudinal deformations to the magnitude of the ME interaction depending on the physical parameters of the piezoelectric and ferromagnets that make up the composite, and the geometric dimensions of the structure.

3. Bending deformations

When considering bending oscillations, we will assume that the hypothesis of Bernoulli's planar sections [21] is valid, and the coupling between the layers is ideal. In this case, the deformations occurring during bending in the layer with coordinate z are determined by the expression

$$S_1 = \frac{(z - z_0)}{\rho}, \quad (13)$$

where ρ — radius of curvature of the neutral layer, z_0 — its coordinate. For the structure shown in Fig. 1 the position of the neutral layer is given by

$$z_0 = 0.5\Big[Y^{m1}(t^{m1})^2 + Y^p(t^p)^2 + Y^{m2}(t^{m1})^2 + 2Y^pt^{m1}t^p + 2Y^{m2}(t^{m1} + t^p)t^{m2}\Big]/\bar{Y}t. \quad (14)$$

According to the theory of bending [21], the radius of curvature ρ is related to the bending moment M_y by the relation

$$1/\rho = M_y/D, \quad (15)$$

where the notation $D = Y^{m1}J_{z_0}^{m1} + Y^pJ_{z_0}^p + Y^{m2}J_{z_0}^{m2}$ are cylindrical rigidity of the structure is introduced. Here $J_{z_0}^{m1}$, $J_{z_0}^p$, $J_{z_0}^{m2}$ are the moments of inertia of the layers sections relative the z_0 axis, which, according to the Steiner theorem, are defined by the following expressions:

$$J_{z_0}^{m1} = \frac{1}{12}W(t^{m1})^3 + Wt^{m1}(0.5t^{m1} - z_0)^2, \quad (16)$$

$$J_{z_0}^{p} = \frac{1}{12} W(t^{p})^{3} + Wt^{p}(t^{m1} + 0.5t^{p} - z_0)^{2}, \quad (17)$$

$$J_{z_0}^{m2} = \frac{1}{12} W(t^{m2})^{3} + Wt^{m2}(t^{m1} + t^{p} + 0.5t^{m2} - z_0)^{2}, \quad (18)$$

where W is sample width.

The bending moment arising in the structure as a result of magnetostriction in the external magnetic field is found from the relation

$$M_y = W\left[q_{11}^{m1}Y^{m1}t^{m1}\left(\frac{t^{m1}}{2} - z_0\right) + q_{11}^{m2}Y^{m2}t^{m2}\left(t^{m1} + t^{p} + \frac{t^{m2}}{2} - z_0\right)\right]H_1. \quad (19)$$

Under the bending moment action the structure bends, and due to the resulting deformations the electric field is induced in the piezoelectric layer. Using equations (13) and (15), as well as the open circuit condition, for the electric field resulting from bending deformations we obtain the following expression:

$$E_{3,bend}^{p} = Y^{p}\frac{d_{31M_y}^{p}}{\varepsilon_{33}^{p}D}(z - z_0). \quad (20)$$

In contrast to planar oscillations, in which the occurring electric field is homogeneous through the thickness of the sample, during bending oscillations the induced electric field is heterogeneous through the thickness of the piezoelectric, so the magnitude of MEVC $\alpha_{E,bend}$ associated with bending oscillations is determined as follows:

$$\alpha_{E,bend} = \langle E_{3,bend}\rangle / H_1, \quad (21)$$

where $\langle E_{3,bend}\rangle$ is the average value of the induced electric field, which for a given structure is determined as follows:

$$\langle E_{3,bend}\rangle = \frac{1}{t^{p}}\int_{t^{m1}}^{t^{m1}+t^{p}} E_{3,bend}\,dz. \quad (22)$$

Substituting expression (20) into equation (22) and integrating, we obtain the expression for $\langle E_{3,bend}\rangle$. Then, substituting the resulting expression into the definition of MEVC given by relation (21) using expressions (16)−(19) finally, for the magnitude of the coefficients MEVC and MESC determined by bending, we obtain the following expressions:

$$\alpha_{E,bend} = Y^{p}\frac{d_{31}^{p}\left[q_{11}^{m1}Y^{m1}t^{m1}\left(\frac{t^{m1}}{2} - z_0\right) + q_{11}^{m2}Y^{m2}t^{m2}\left(t^{m1} + t^{p} + \frac{t^{m2}}{2} - z_0\right)\right]}{\varepsilon_{33}^{p}(Y^{m1}J_{z_0}^{m1} + Y^{p}J_{z_0}^{p} + Y^{m2}J_{z_0}^{m2})/W} \times \left(\left(t^{m1} + \frac{t^{p}}{2}\right) - z_0\right), \quad (23)$$

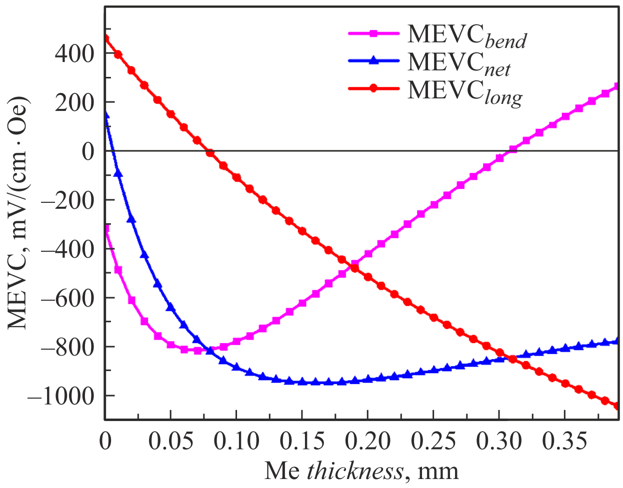

Figure 2. Quasistatic MEVC vs. thickness of the Metglas layer t^{m2} for the Ni/PZT/Metglas structure at fixed nickel thickness $t^{m1} = 0.2$ mm and a piezoelectric $t^{p} = 0.2$ mm thick.

$$\beta_{E,bend} = Y^{p}\frac{d_{31}^{p}t^{p}\left[q_{11}^{m1}Y^{m1}t^{m1}\left(\frac{t^{m1}}{2} - z_0\right) + q_{11}^{m2}Y^{m2}t^{m2}\left(t^{m1} + t^{p} + \frac{t^{m2}}{2} - z_0\right)\right]}{\varepsilon_{33}^{p}(Y^{m1}J_{z_0}^{m1} + Y^{p}J_{z_0}^{p} + Y^{m2}J_{z_0}^{m2})/W} \times \left(\left(t^{m1} + \frac{t^{p}}{2}\right) - z_0\right). \quad (24)$$

The second area moments $J_{z_0}^{m1}$, $J_{z_0}^{p}$ and $J_{z_0}^{m2}$ are proportional to the sample width W, so the denominators in expressions (23) and (24) do not depend on the width of the sample, and the efficiency of ME conversion is determined only by the physical parameters of the piezoelectric, two ferromagnets and the thicknesses of their layers.

4. Results and discussion

The magnitude of the resulting MEVC $\alpha_{E,net}$ and MESC $\beta_{U,net}$ will be determined by the sum of the contributions from the longitudinal and bending deformations. Fig. 2 shows the dependences of the contributions to MEVC$_{net}$ from the longitudinal MEVC$_{long}$ and bending MEVC$_{bend}$ deformations for the Ni/PZT/Metglas structure on the thickness of the layer of the second ferromagnet, (metglas is Me) at a fixed layer thickness of the first ferromagnet (Ni) and a fixed thickness of the piezoelectric (PZT). The physical parameters of the materials presented in the Table were used in the calculations. The data for the piezomagnetic coefficients q_{11} and q_{12} were obtained by differentiating the magnetostriction curves presented in the papers [22,23] for a bias field $H_{bias} \approx 50$ Oe.

The choice of nickel and metglas as magnetostrictive materials is due to the fact that they have opposite signs of magnetostriction and the maximum magnitude of the piezomagnetic coefficient q at approximately same values of

Matwerial parameters

Material	Young's modulus, GPa	Density ρ, 10^3 kg/m^3	Piezo modulus d_{31}, pC/N, q_{11}, q_{12} ppm/Oe	Dielectric permeability, ${}^{P}\varepsilon_{33}$
PZT	66.7	8.2	-175	$1750\varepsilon_0$
Ni	215	8.9	$q_{11} = -0.06$, $q_{12} = +0.02$	–
Metglas	110	8.2	$q_{11} = +0.3$, $q_{12} = -0.03$	–

the bias field of about 50 Oe. When the structure is placed in the magnetic field, the nickel layer experiences compression, and the metglas layer experiences tension. As a result, depending on the thickness of the nickel and metglas layers, the piezoelectric layer can experience compression or tension, or, depending on the neutral layer position, one part can experience tension and the other one compression. At small thicknesses of the Me layer the compression force is greater than the tensile force, as a result of which the contribution from longitudinal oscillations to the magnitude of the effect is positive and decreases with Me thickness increasing until, as follows from equation (11), the following equality occurs:

$$Y^{m1}t^{m1}(q_{11}^{m1} + q_{12}^{m1}) + Y^{m2}t^{m2}(q_{11}^{m2} + q_{12}^{m2}) = 0. \qquad (25)$$

At the thickness of the third layer, at which equality (25) is satisfied, the contribution to MEVC from longitudinal oscillations is equal to zero. With a further thickness increasing of the metglas layer, the value of MEVC$_{long}$ changes sign to the opposite and begins to grow, and at thicknesses $t^{m2} \gg t^{m1}, t^p$ tends to the limiting value equal to

$$\lim_{t^{m2}\to\infty}(\alpha_{E,long}) = Y^p d_{31}^p (q_{11}^{m2} + q_{12}^{m2})/\varepsilon_{33}. \qquad (26)$$

The contribution to the magnitude of ME interaction from bending deformations MEVC$_{bend}$ at small thicknesses of the third layer has the sign opposite to sign of MEVC$_{long}$. As the thickness of the Me layer increases, it begins to grow and reaches a maximum when the neutral layer lies at the interface between the layers with negative and positive magnetostriction, i.e. when the relation is satisfied

$$t^{m1} = 0.5\Big[Y^{m1}(t^{m1})^2 + Y^p(t^p)^2 + Y^{m2}(t^{m1})^2 + 2Y^p t^{m1} t^p + 2Y^{m2}(t^{m1} + t^p)t^{m2}\Big]/\bar{Y}t. \qquad (27)$$

With a further thickness increasing of the Me layer, the magnitude of the coefficient begins to decrease due to the fact that the neutral layer moves into the piezoelectric, as a result of which part of the piezoelectric experiences tension and part compression, which leads to the magnitude decreasing of the ME interaction. In the case when the neutral layer lies in the middle of the piezoelectric layer, i.e. for a given structure, when the relation $z_0 = t^{m1} + t^p/2$ is satisfied, then in this case, according to equation (23), the contribution from bending oscillations to the magnitude of the ME interaction will be equal to zero. With further thickness increasing of the Me layer, the value of MEVC$_{bend}$ begins to increase, but the analysis of the contribution with further thickness increasing of the third layer is of no interest, since such structures are not realized in practice.

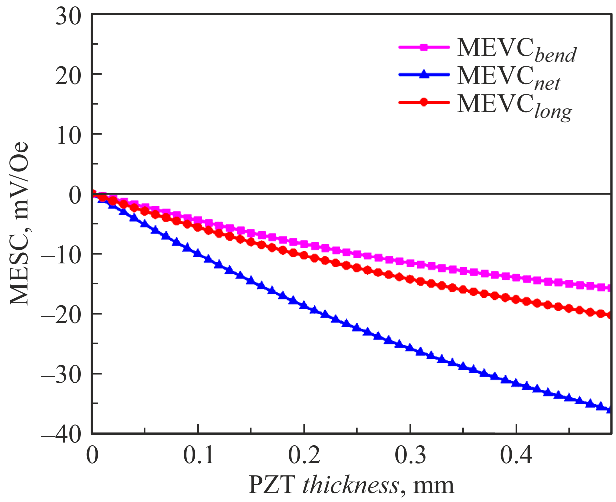

Figure 3. Quasi-static MESC vs. piezoelectric layer thickness t^p for the Ni/PZT/Metglas structure at a fixed nickel thickness $t^{m1} = 0.2$ mm and metglas $t^{m2} = 0.15$ mm thick.

Measured in practice MEVC$_{net}$ will be determined by the sum of the coefficients MEVC$_{long}$ and MEVC$_{bend}$. As follows from the graph in Fig. 2, it has a sloping maximum in the region located behind the region where MEVC$_{long}$ changes sign, and MEVC$_{bend}$ has a maximum, while for this structure the MEVC value is by seven times greater than for the two layer Ni/PZT structure. With further thickness increasing of the second layer, MEVC$_{net}$ decreases due to MEVC$_{bend}$ decreasing caused by the rigidity increasing of the structure.

Fig. 3 shows the dependences of the coefficients of sensitivity of the structure to magnetic field on the thickness of the piezoelectric at fixed thickness of the ferromagnet layers. The thickness of the ferromagnet layers is chosen such that the MEVC has a maximum value. At small piezoelectric thicknesses compared to the thicknesses of ferromagnetic layers, the value of the coefficient increases linearly with thickness increasing of the piezoelectric layer and tends to saturation at thickness $t^p \gg t^{m1}, t^{m2}$, the value of which is equal to

$$\lim_{t^p \to \infty} (\beta_{U,net}) = d_{31}^p \left[Y^{m1} t^{m1} (q_{11}^{m1} + q_{12}^{m1}) + Y^{m2} t^{m2} (q_{11}^{m2} + q_{12}^{m2}) \right] / \varepsilon_{33}. \qquad (28)$$

This value of the coefficient in practice can be achieved for structures obtained by magnetostrictive layers deposition on a piezoelectric substrate.

Conclusion

The magnitude of the ME interaction in three-layer asymmetric structures strongly depends on the ratio of the thickness of the layer with positive magnetostriction to the thickness of the layer with negative magnetostriction, which makes it possible to control the magnitude of the ME response at the stage of structure fabrication. By changing the thickness of the second magnetostrictive layer, it is possible to obtain a structure in which the contribution to the ME response from longitudinal deformations will be zero, and the magnitude of the ME response will be determined only by bending deformations. At the same time, the presence of the second magnetostrictive layer instead of strengthening the ME interaction, can lead to its weakening, and at a certain ratio between the thicknesses of the magnetostrictive layers, the ME response will be equal to zero. At the same time, the use of a three-layer asymmetric structure at a certain ratio between the thickness of the layer with positive and negative magnetostriction leads to an increase in the ME response by almost an order of magnitude compared to the two-layer structure.

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Conflict of interest

The authors declare that they have no conflict of interest.

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