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RESEARCH ARTICLE

# Magnetoelectric effects in stripe- and periodic heterostructures based on nickel–lead zirconate titanate bilayers

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**Abstract**
**Objectives.** A topical task in the design of magnetoelectric (ME) devices based on composite ferromagnetic–piezoelectric heterostructures involves reducing their dimensions to increase their operating frequencies and optimize their integration in modern electronics. The study set out to investigate the influence of in-plane dimensions on the characteristics of ME effects in stripe and periodic nickel–lead zirconate titanate heterostructures manufactured via electrolytic deposition.
**Methods.** Lead zirconate titanate disks with Ag-electrodes were used for manufacturing the ME heterostructures; Ni was deposited on one Ag-electrode only.
**Results.** While a reduction in stripe size leads to an increase in the frequency of the resonant ME effect, it is followed by a decrease in ME conversion efficiency. The ME coefficient for the periodic heterostructures is about ~1 V/(Oe·cm). By increasing the angle between the magnetic field $H$ and the Ni-stripe axis from 0° to 90°, a 2.5-fold increase in the optimal field $H_m$ and a 4-fold drop in the maximum amplitude of ME voltage $u_{max}(H_m)$ was achieved.
**Conclusions.** In periodic heterostructures, the frequency of the resonant ME effect is determined by the substrate's size, while ME conversion efficiency depends on the width of the Ni stripes and the distance between them. The observed anisotropy of the ME effects in the investigated heterostructures is explained in terms of demagnetization effects. In the future, the anisotropic ME effect in the periodic heterostructures could be used to develop magnetic field sensors that are sensitive to field orientation.

**Keywords:** magnetoelectric effect, magnetostriction, piezoelectric effect, anisotropy, magnetic field sensor

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НАУЧНАЯ СТАТЬЯ

# Магнитоэлектрический эффект в двухслойных полосковых и периодических гетероструктурах никель – цирконат-титанат свинца

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**Резюме**
**Цели.** Актуальной задачей при создании магнитоэлектрических (МЭ) устройств на основе композитных гетероструктур ферромагнетик-пьезоэлектрик является уменьшение их размеров, что позволит повысить рабочие частоты устройств и интегрировать их в современную электронику. Цель работы – исследование влияния размеров на характеристики МЭ эффектов в полосковых и периодических гетероструктурах никель – цирконат-титанат свинца, изготовленных методом электролитического осаждения.
**Методы.** Для изготовления образцов использовали диски цирконата-титаната свинца с Ag-электродами. На одну поверхность диска электролитически наносили слой Ni. Исследовали резонансную частоту МЭ эффекта, коэффициент МЭ преобразования на этой частоте и величину оптимального магнитного поля смещения для полученных образцов.
**Результаты.** Показано, что уменьшение размера в плоскости полосковых структур до ~1 мм приводит к росту частоты резонансного МЭ эффекта до ~1 МГц и одновременно к снижению эффективности МЭ преобразования. МЭ коэффициент для периодических гетероструктур с шириной Ni-полосок ~100 мкм и расстоянием между ними 20–100 мкм составляет ~1 В/(Э · см). Показано, что при увеличении угла φ между направлением постоянного поля $H$ и осью Ni-полосок от 0° до 90° величина оптимального поля $H_m$ возрастает в ~2.5 раза, а максимальная амплитуда напряжения $u_{max}(H_m)$ падает в 4 раза.
**Выводы.** В периодических структурах частота резонансного МЭ эффекта определяется размером подложки и может составлять единицы кГц, а эффективность преобразования полей зависит от ширины Ni-полосок и расстояния между ними. Обнаружена и объяснена анизотропия характеристик МЭ эффектов в исследованных гетероструктурах, возникающая из-за эффектов размагничивания. Анизотропия МЭ эффекта в периодических гетероструктурах может быть использована для создания датчиков постоянных магнитных полей, чувствительных к ориентации поля.

**Ключевые слова:** магнитоэлектрический эффект, магнитострикция, пьезоэлектрический эффект, анизотропия, датчик магнитного поля

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## INTRODUCTION

In recent years, much research attention has been attracted to the study of magnetoelectric (ME) effects in composite heterostructures containing ferromagnetic (FM) and piezoelectric (PE) layers due to the possibility of developing valuable devices based on these structures. Prototypes of highly sensitive ME sensors for determining constant and variable magnetic fields can be used in electrically controlled devices for processing radio signals, as well as in autonomous electrical energy sources [1–3]. It has been shown that ME effects arising in FM–PE structures due to mechanical coupling between the FM (magnetostriction) and PE (layers piezoelectricity) [4] are manifested in the generation of an alternating electrical voltage $u$ by the structure under the action of an alternating magnetic field $h$ (direct effect) or a change in the magnetization of the structure $m$ under the action of an alternating electric field $e$ (reverse effect). It has been shown that the efficiency of the ME field conversion increases by ~2 orders of magnitude when the frequency of the exciting field coincides with the acoustic resonance frequency of the structure [5]. At present, the main challenge lies in miniaturizing the ME elements to increase the operating frequencies of devices and integrate them into modern electronics and microsystems technologies. In addition, it is necessary to study the interaction of ME elements as part of spatially distributed structures for measuring magnetic fields in biology and medicine [6]. It has been experimentally shown that a decrease in the size of FM–PE heterostructures in the plane to ~0.5–1.0 cm leads to an increase in the acoustic resonance frequency of the structure $f_0$ and a decrease in the amplitude of the generated ME voltage $u(f_0)$ at this frequency [7].

In addition, the increased optimal bias magnetic field $H_m$ arising due to demagnetization effects must be applied to the structure [8]. When using heterostructures having the form of long stripes, shape anisotropy becomes strong [9], which can be used to develop sensors for determining constant magnetic fields taking field direction into account [10]. To the best of the present authors' knowledge, no studies of the characteristics of ME effects in periodic structures containing a set of ME elements have been carried out to date.

The purpose of this work was to study the characteristics of ME effects in stripe and periodic heterostructures with an FM layer of nickel (Ni) and a PE layer of piezoceramic lead zirconate titanate (PZT) of millimeter and submillimeter dimensions in the plane. The choice of materials stems from the possibility of using electrodeposition technology to deposit thick layers of Ni to provide a sufficiently high magnetostriction in low magnetic fields. The first part of the work describes a method for fabricating Ni–PZT heterostructures in the form of separate stripes and a method for fabricating periodic structures in the form of a grating of Ni stripes on the surface of a PZT substrate, as well as measurement techniques. The second part presents the results of experimental studies of the ME characteristics of individual Ni–PZT stripes with linear dimensions of ~1–15 mm. In the third part of the work, the ME characteristics of Ni–PZT heterostructures with Ni-gratings with periods of 0.12–0.20 mm are described, including frequency, field, and amplitude dependences. According to the developed theory, the occurrence of a strong anisotropy is explained in terms of the ME effect in periodic structures taking into account the magnetic interaction between individual grating stripes. On the basis of the main conclusions, recommendations for future research are formulated.

## MATERIALS AND METHODS

In order to experimentally study the influence of the linear dimensions of the ME structure on the characteristics of the direct resonant ME effect, structures of two types were fabricated. The first type consisted of two-layer composite heterostructures with layers of piezoelectric ceramics of lead zirconate titanate $PbZr_{0.52}Ti_{0.48}O_3$ (PZT) and Ni, whose schematic view and photographs are shown in Figs. 1a and 1b, respectively. Piezoceramic PZT was selected due to being a widely-available, isotropic and easily machined material. The ceramic piezoelectric modulus was $d_{31} \approx 175$ pC/m, and the permittivity $\varepsilon \approx 1700$. Ferromagnetic Ni layers have a high magnetostriction $\lambda_S = -30 \cdot 10^{-6}$ and saturate in low magnetic fields $H_S \approx 1$ kOe. The samples were fabricated using commercially available PZT disks of 25 mm in diameter and $a_p = 200$ µm thick with Ag electrodes of ~2-µm thick (Elpa Research Institute, Moscow, Russia). A layer of Ni with a thickness of $a_m \approx 10$ µm was deposited on one surface of the disk by electrolytic deposition from an aqueous solution of $NiCl_2$ and $NiSO_4$ salts [11]. At a current density of 1 A/cm$^2$, the Ni deposition rate was 1 µm/min. Stripes 1 mm wide were cut from the central part of the disk. Then structures with lengths $L$ = 1.2, 2, 4, 6, 8, 10, 15, and 23 mm were fabricated from the stripes. By using the electrolytic deposition method, it was possible to fabricate monolithic structures with in-plane isotropic properties and good mechanical bonding between the layers.

ME structures of the second type comprised gratings of parallel Ni stripes deposited on the surface of a PZT substrate. The same disks of 25 mm in diameter and $a_p = 200$ µm thick with 2-µm thick Ag electrodes on the surfaces were used as the PZT substrate. A grating of Ni stripes was fabricated by the following method. First, both electrodes of the PZT disk were coated with

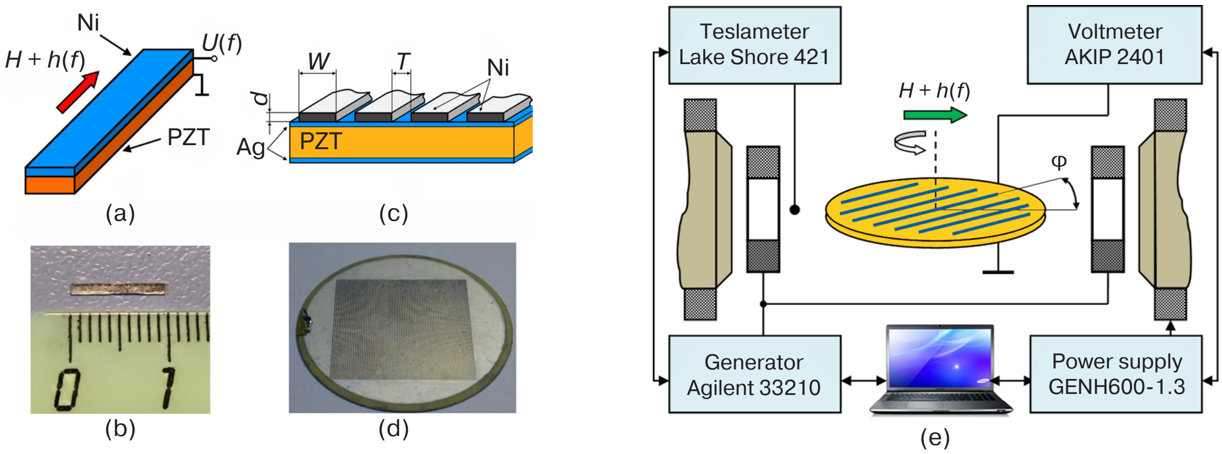



**Fig. 1.** View and schematics of researched composite Ni–PZT heterostructures (a)–(d) and block-diagram of the setup for measurements (e)

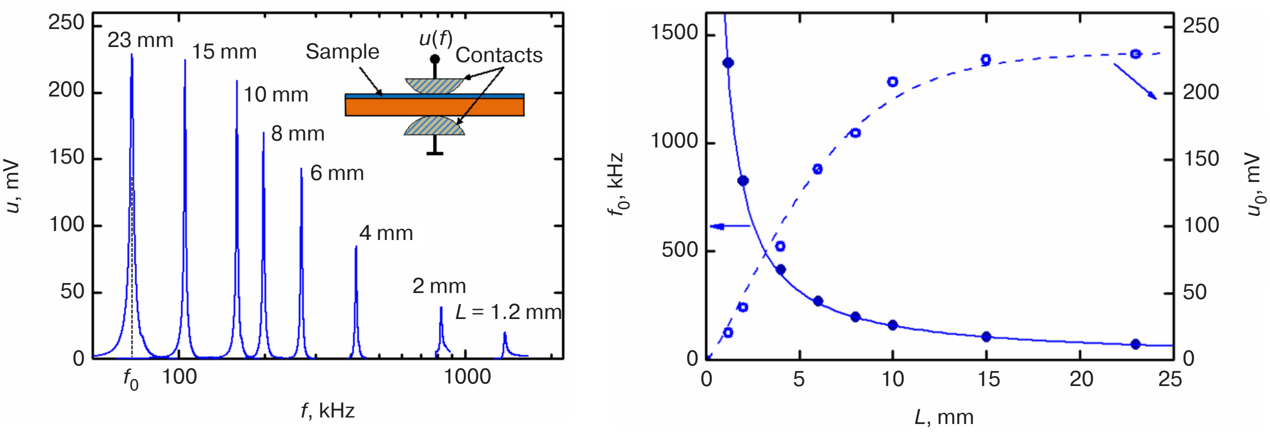
a layer of positive photoresist CRC Kontakt Chemie Positiv 20/200 (Belgium) having a thickness of ~2 μm. One of the surfaces was exposed through a 16 × 16 mm photomask in the form of parallel stripes to ultraviolet radiation for 60 s. Then, the exposed areas of the photoresist were removed with an aqueous solution of sodium hydroxide having a concentration of 6 g/L. After that, a Ni layer with a thickness of $a_m \approx 10$ μm was electrolytically deposited on the free sections of the Ag electrode. The cross section of the fabricated samples is shown schematically in Fig. 1c, while in Fig. 1d the visual appearance of one of the samples is depicted. This method was used to fabricate several structures with a grating of Ni stripes $w = 100$ μm wide and having a distance between stripes $T$ = 20, 50, and 100 μm, respectively. For comparison, one of the surfaces of a sample was covered with a continuous layer ($T = 0$) of Ni having a thickness of $a_m \approx 10$ μm. The saturation magnetization of Ni measured on this sample was $M_S$ = 5900 G; the saturation magnetostriction reached $\lambda_S = -30 \cdot 10^{-6}$ in the saturation field $H_S \approx 1$ kOe.

The block diagram of the setup for studying ME effects is shown in Fig. 1e. The samples were placed between Helmholtz coils with a radius of 15 cm connected to an Agilent 33210A generator (Agilent Technologies, USA). The coils generated an alternating exciting magnetic field $h\cos(2\pi ft)$ with a frequency $f$ from 1 kHz to 2 MHz and an amplitude up to $h$ = 4 Oe. A constant magnetic field $H$ = 0–2 kOe was created using an electromagnet having a pole diameter of 50 mm connected to a TDK GENH600-1.3 power supply unit (TDK-Lambda Corporation, Germany). The $H$ field was measured with a Lake Shore 421 Teslameter (Lake Shore Cryotronics, Westville, Ohio, USA). The fields $h$ and $H$ were applied in the plane of the structure and parallel to each other. In studying the anisotropy of the ME effect, the heterostructure with the Ni grating was rotated around the vertical axis by changing the angle φ between the fields and the axis of the Ni stripes. The voltage $u$, generated due to the ME effect between the electrodes of the PZT disk, was measured using an AKIP 2401 voltmeter having an input impedance of 10 MΩ. The dependences of the ME voltage on the excitation field frequency $f$ and the bias field strength $H$ were recorded for different orientations of the structure (angle φ). The setup was operated in automatic mode under the control of a specialized program in the *LabVIEW* environment[1]. The magnetostriction of the FM layer of the structure was measured using a strain gauge glued to the surface of the Ni film; the magnetization curves of the Ni film were measured using a Lake Shore 7407 vibrating magnetometer (Lake Shore Cryotronics, Westville, Ohio, USA).

## MAGNETOELECTRIC EFFECT IN Ni–PZT STRIPES

At the first stage, the linear ME effect was studied in two-layer Ni–PZT heterostructures taking the form of stripes of different lengths $L$. Figure 2 shows the measured dependences of the ME voltage amplitude $u$ on the frequency $f$ of the exciting magnetic field with an amplitude $h$ = 1.3 Oe for structures of different $L$. For each sample, the measurements were carried out in the optimal constant field $H_m$ directed along the stripe axis at which the ME conversion is most efficient. As $L$ decreases from 23 to 1.2 mm, the resonant frequency $f_0$ increases from 68.7 to 1380 kHz, while the signal amplitude at the resonant frequency drops by ~12 times. The quality factor of the resonances $Q = f_0/\Delta f$ (where $\Delta f$ is the bandwidth at a level of 0.7) was $Q \approx 100$ for structures with $L$ = 4–23 mm and then dropped to $Q \approx 67$ and $Q \approx 150$ as $L$ decreased to 2.0 and 1.2 mm, respectively. Figure 2b shows the dependence

[1] The environment for creating applications for the collection, processing, and visualization of information received from instruments, laboratory facilities, process control and devices, was developed by National Instruments, USA. https://www.ni.com. Accessed November 22, 2021.




(a) (b)

**Fig. 2.** (a) Dependences of the ME voltage amplitude $u$ on the frequency $f$ of the exciting magnetic field at a field amplitude $h$ = 1.3 Oe for Ni–PZT stripes of different lengths $L$. The inset schematically shows the method of fixing the specimens; (b) Dependences of the resonant frequency $f_0$ and voltage $u_0$ generated at the frequency $f_0$ on the length of the Ni–PZT stripe $L$. The points are the experimental data, the solid line is the calculation by formula (1), the dashed line is the approximation

of the resonant frequency $f_0$ and the ME voltage at a given frequency $u_0$ on the length of the structure $L$. For a sample with a length $L$ = 1.2 mm, the resonant frequency $f_0$ = 1380 kHz is almost 5 times higher than for a structure with a length of 5 mm described in [12]. The amplitude of the ME voltage, which remained constant at $u_0 \approx 230$ mV for structures with a length $L$ = 25–10 mm, then dropped approximately linearly to $u_0 \approx 19$ mV as $L$ decreased to 1.2 mm.

Figure 3 shows the dependences of the ME voltage $u_0$ on the constant magnetic field $H$ for Ni–PZT stripes of different lengths $L$. The shape of the dependences is typical for the linear ME effect: initially, $u_0$ increases linearly with increasing $H$, subsequently reaching a maximum at $H_m$, which is different for each sample, then smoothly dropping to zero when the FM layer becomes saturated. As the stripe length decreases, the field $H_m$ shifts to higher fields, while the voltage amplitude $u_0$ drops by a factor of ~12 at $H_m$.

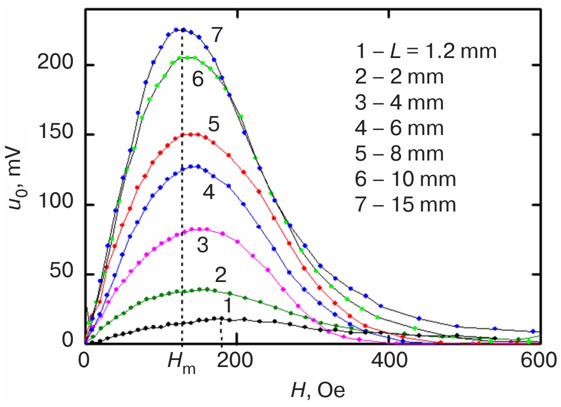



**Fig. 3.** Dependences of the ME voltage $u_0$ on the constant magnetic field $H$ at $h$ = 1.3 Oe for structures of various lengths $L$. The field $H_m$ is only shown for a 15 mm long stripe

The most important characteristics of the ME effect in heterostructures are the resonant frequency $f_0$, the ME conversion coefficient at this frequency $\alpha_E = u(f_0)/(a_p h)$, and the magnitude of the optimal bias magnetic field $H_m$. The resonance frequency for the structures under study can be estimated from the formula for the frequency of the fundamental mode of acoustic oscillations of a free rod $f_0 = (1/2L)\sqrt{Y/\rho}$ [13]. The effective values of Young's modulus $Y$ and density $\rho$ for a Ni–PZT structure with two Ag-electrodes are obtained as $Y = \sum Y_k a_k / \sum a_k$ and $\rho = \sum \rho_k a_k / \sum a_k$, where $Y_k$, $\rho_k$, and $a_k$ are Young's modulus, density, and thickness of the corresponding structure layer, respectively. Substituting the values of the layer parameters into the formula ($Y_m = 21.5 \cdot 10^{10}$ N/m$^2$, $Y_p = 7 \cdot 10^{10}$ N/m$^2$, $Y_{Ag} = 7.9 \cdot 10^{10}$ N/m$^2$; $\rho_m = 8.9 \cdot 10^3$ kg/m$^3$, $\rho_p = 7.7 \cdot 10^3$ kg/m$^3$, $\rho_{Ag}$ = 10.5 · 10$^3$ kg/m$^3$; $a_m$ = 10 μm, $a_p$ = 200 μm, $a_{Ag}$ = 2 μm), we obtain the dependence of the resonance frequency on the sample length $f_0 = 1570/L$ kHz, where $L$ is given in millimeters. The calculated dependence shown in Fig. 2b by a solid line satisfactorily describes the measurement data. We note that the frequency $f_0$ changed slightly (<1%) when the magnetic field $H$ was tuned due to a change in the Young's modulus of the FM layer of the structure [14]. The maximum value of the ME coefficient for Ni–PZT stripes 15 mm long was $\alpha_E \approx 8.8$ V/(Oe·cm). The observed increase in the optimal field $H_m$ from ~120 to ~180 Oe along with a decrease in the length of the heterostructure from 15 to 1.2 mm is explained by the demagnetization effect [2]. The drop in the amplitude of the ME voltage with decreasing length $L$ (and increasing frequency $f_0$) of the structure is mainly due to an increase in losses in the PZT layer caused by an increase in the resonance frequency. A decrease in the acoustic quality factor $Q$ and the piezoelectric modulus $d_{31}$ of the PZT layer with an increase in the resonance frequency can also lead to a voltage drop.

## MAGNETOELECTRIC EFFECT IN PERIODIC Ni–PZT HETEROSTRUCTURES

At the second stage, the characteristics of the ME effect in periodic heterostructures with Ni-gratings were studied. As an example, Fig. 4 shows the dependences of the ME voltage $u$ on the frequency $f$ of the exciting field for structures in which the distance between the Ni stripes $T = 20$ μm and $T = 100$ μm for a field $h = 1$ Oe and a constant field $H = 90$ Oe is directed along the Ni stripes. The resonance peak near the frequency $f_0 \approx 2.74$ kHz with a quality factor $Q \approx 150$ at a level of 0.7 corresponds, as shown below, to the excitation of the lowest bending vibration modes of the structure. It can be seen that the amplitude of the peak $u_0$ decreases by several times, while the frequency $f_0$ increases slightly with greater distance between the Ni stripes. The value of the ME coefficient for a periodic structure with $T = 20$ μm at the resonance frequency was $\alpha_E \approx 1.0$ V/(Oe·cm), i.e., was of the same order as in structures with a continuous Ni layer [11].

Figure 5 demonstrates the transformation of the dependence $u_0(H)$ upon rotation of the direction of the field $H$ in the plane of the structure for a structure with $T = 100$ μm. As the angle φ between the field $H$ and the axis of the Ni stripes increases from zero to 90°, the value of $H_m$ can be seen to increase from ~70 to ~230 Oe, while the maximum voltage amplitude $u_{max}(H_m)$ decreases monotonically from ~8 to ~ 2 mV.

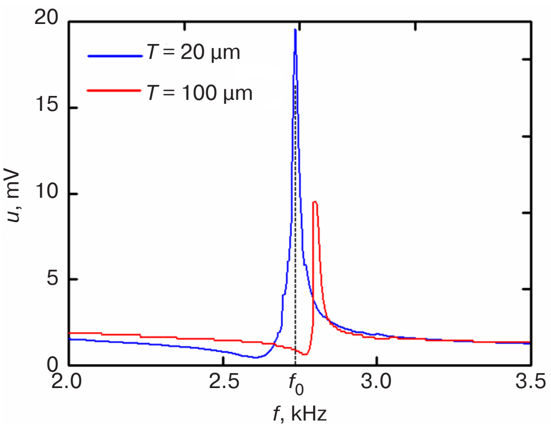



**Fig. 4.** Dependence of the ME voltage $u$ on the frequency $f$ of the exciting field for periodic Ni–PZT heterostructures with a distance between Ni stripes of 20 and 100 μm at a field $H = 90$ Oe directed along the Ni stripes

The angular dependences of the ME voltage $u$ for the structure with $T = 100$ μm shown in Fig. 6 are constructed using data similar to those shown in Fig. 5. The curve demonstrates a strong anisotropy of the linear ME effect in the structure. Here the ME voltage can be seen to reach a maximum when the structure is magnetized along the Ni stripes (at φ = 0°) and drop by a factor of ~4 when magnetized across the stripes (at φ = 90°).

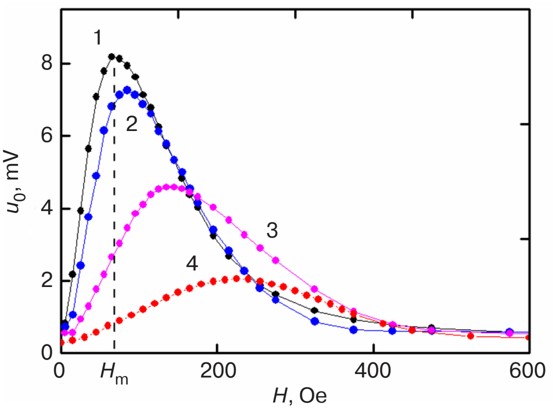



**Fig. 5.** Dependence of the voltage $u_0$ on the field $H$ for a periodic Ni–PZT structure with $T = 100$ μm for different orientations of the field $H$:
1: φ = 0°, 2: φ = 30°, 3: φ = 60°, 4: φ = 90°

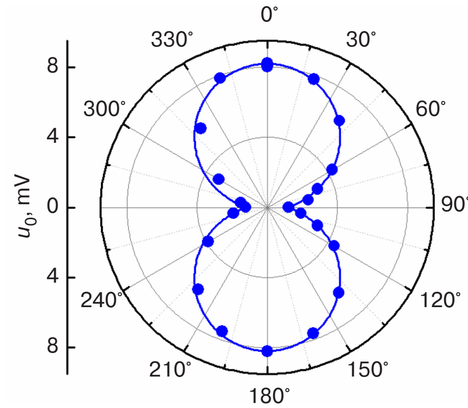
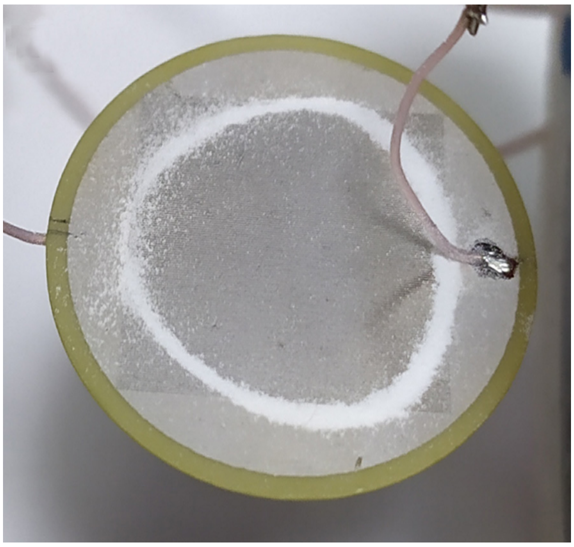


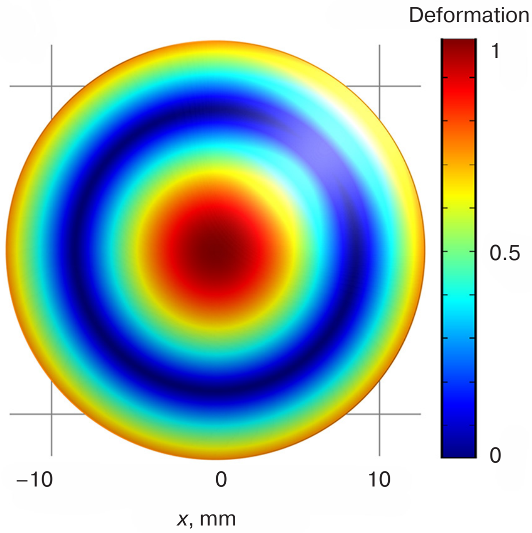

**Fig. 6.** Dependence of the voltage $u_0$ for a periodic Ni–PZT structure with $T = 100$ μm on the orientation angle φ of the field $H$ in the plane. Points—experiment, solid line—calculation

In order to clarify the nature of the resonance peak shown in Fig. 4, the spatial structure of the Ni–PZT vibrational mode of the disk was visualized using the Chladni method. For this purpose, a thin layer of $TiO_2$ powder with a particle size of ~2–3 μm was poured onto the surface of a Ni–PZT disk excited at a resonance frequency $f_0 \approx 2.74$ kHz. The powder collected near the line of zero vertical displacement has the shape of a distorted circle as seen in Fig. 7a. The distribution of deformations of the disk flexural mode was also calculated using the *COMSOL Multiphysics*[2] software (COMSOL Group, Sweden). Figure 7b shows that the main oscillation mode has one nodal circle. The calculated frequency of this mode, $f_{cal} = 2.24$ kHz, agrees satisfactorily with the measured frequency of 2.74 kHz. The difference between the calculated and measured frequencies and the difference between the shape of the nodal diameter and the circle can be associated with the influence of the disk mounting location.

[2] The software for modeling constructions, devices, and processes in engineering, production, and scientific applications.



(a)




(b)

**Fig. 7.** (a) Chladni figure for the Ni–PZT oscillation mode of the disk at the resonance frequency; (b) Ni–PZT disk flexural mode deformation distribution calculated in *COMSOL Multiphysics*

## DISCUSSION OF RESULTS

To explain the characteristics of ME effects in stripes and periodic Ni–PZT heterostructures, we use the theory of the low-frequency linear ME effect in planar FM–PE structures [15]. The magnitude of the ME voltage generated by the structure at the resonance frequency is described by the simplified formula

$$u(H) \approx AQ\frac{d_{31}\lambda^{(1)}}{\varepsilon}h, \tag{1}$$

where $A$ is a constant coefficient depending only on the dimensions and mechanical parameters of the layers; $Q$ is the quality factor of acoustic resonance; $d_{31}$ and $\varepsilon$ are the piezoelectric modulus and permittivity of the PE layer; $\lambda^{(1)}(H) = \partial\lambda / \partial H|_H$ is the piezomagnetic coefficient; $\lambda(H)$ is the field dependence of the magnetostriction of the FM layer; $h$ is the amplitude of the exciting magnetic field. At the resonance frequency, the voltage amplitude increases by a factor of $Q$. It was observed in the experiment. The shape of the dependence $u_0(H)$ for the linear ME effect (see Fig. 3 and Fig. 5) is explained by the field dependence of the piezomagnetic coefficient $\lambda^{(1)}(H)$. The voltage reaches a maximum at the optimal field $H_m$ corresponding to the maximum $\lambda^{(1)}$, and then drops due to a decrease in the piezomagnetic coefficient as the FM layer is saturated. The amplitude of the generated voltage $u_0$ increases linearly with the field $h$.

The anisotropy of the characteristics of the linear ME effect in the described structures arises due to demagnetization effects. Let us first consider the effect of demagnetization on the ME effect in one Ni stripe. It is known that in an FM sample of an ellipsoidal shape, the magnetic field inside the ferromagnetic $H_{in}$ is related to the external field $H$ by the relation [16]

$$H_{in} = H - NM(H_{in}), \tag{2}$$

where $N$ is the demagnetizing factor along the main axis of the ellipsoid; $M$ is the magnetization of the ferromagnet.

For Ni, the relation $M = \chi H_{in} \approx \mu H_{in}$ is valid since the magnetic permeability $\mu = \chi + 1$ and the magnetic susceptibility $\chi$ are much greater than unity.

Then from (2) we obtain the relation

$$H_{in} \approx \frac{H}{1 + N\mu}, \tag{3}$$

that is, due to demagnetization, the field $H_{in}$ inside the ferromagnet decreases by a factor of $1 + N\mu$.

For a rectangular Ni stripe of ~20-mm long, 100-μm wide, and 10-μm thick, the calculation [17] gives demagnetizing factors $N_1 \approx 0.000002$ and $N_2 \approx 0.67$ when the field $H$ is oriented in the plane along and across the stripe axis, respectively. Let us decompose the field $H$ into two components $H_1 = H\cos\varphi$, parallel to the stripe axis, and $H_2 = H\sin\varphi$, perpendicular to the stripe axis. Relation (3) is applicable for each component separately.

The total field inside the stripe $H_{in} = \sqrt{H_{in1}^2 + H_{in2}^2}$. In this case, when the FM stripe is tangentially magnetized at an angle $\varphi$ to its axis, the field inside the stripe can be found as

$$H_{in}(H,\varphi) = H\sqrt{\frac{\cos^2\varphi}{(1+N_1\mu)^2} + \frac{\sin^2\varphi}{(1+N_2\mu)^2}}. \tag{4}$$

Differentiating (4) with respect to the magnetic field, we find the dependence of the piezomagnetic coefficient $\lambda^{(1)}(H, \varphi)$ on the magnitude of the field $H$ and the angle $\varphi$ specifying the orientation of the field with respect to the axis of the Ni stripes of the structure. It should also be taken into account that the value of the excitation field $h_{in}$ inside the FM layer is similarly affected by demagnetization. Calculations have shown that with an increase in the angle $\varphi$, the optimal bias magnetic field $H_m$ increases, while the magnitude of the ME voltage generated in this case $u_0(H_m)$ decreases; this is in agreement with the measurement data shown in Fig. 5. The angular dependence of the ME voltage amplitude $u_0(\varphi)$ calculated by the described method using expressions (1) and (4), the values of the parameters corresponding to the experiment, as well as the fitting coefficient $A_1 = 4.8 \cdot 10^{15}$ V$^2$/m, are shown by the solid line in Fig. 6. It can be seen that the proposed theory describes the results of the experiment well. Thus, by comparing the experimental data with the results of calculations taking into account the demagnetization in a single Ni stripe we conclude that the anisotropy of the linear ME effect can be qualitatively described in a periodic Ni–PZT heterostructure. Moreover, the magnitude of the anisotropy of the ME effect in structures with a grating-like Ni layer also depends on the distance between adjacent stripes. It was shown in [18–20] that the dipole–dipole interaction between neighboring FM stripes leads to a weakening of the demagnetization followed by an increase in the internal field in a ferromagnetic material.

To illustrate this point, a finite element simulation was carried out in the *COMSOL Multiphysics* software. The calculations were performed for a grating with dimensions in a plane of 16 × 16 mm, consisting of Ni stripes with a width $W$ = 100 μm, a length $L$ = 16 mm, and a thickness $a_m$ = 10 μm. The distance between the stripes was changed from $T$ = 0.5 μm to $T$ = 100 μm. The magnitude of the external magnetic field and the relative magnetic permeability Ni were taken to be $H$ = 90 Oe and $\mu$ = 350, respectively. The internal magnetic field $H_{in}$ was calculated in the middle of the central Ni stripe of the grating. Figure 8 shows the calculated dependence of the field $H_{in}$ on the distance $T$ between the stripes when the grating is magnetized perpendicular to the stripe axis (curve 1).

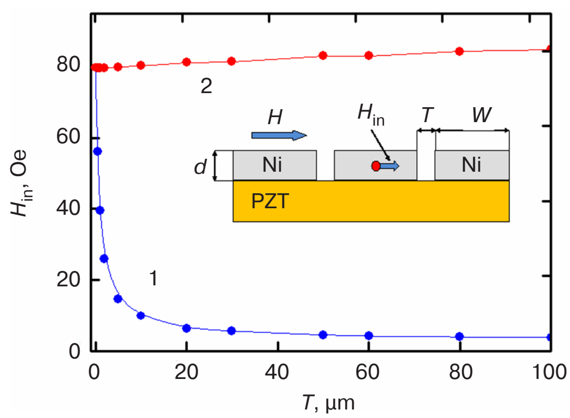



**Fig. 8.** Dependence of the internal field $H_{in}$ in the middle of the central Ni stripe on the distance between the stripes of a grating magnetized in a field $H$ = 90 Oe across (1) and along (2) the axis of the Ni stripes. The inset schematically shows the cross section of a Ni grating on a PZT substrate

At large distances $T >> a_m$, when each Ni stripe can be considered as isolated from the others, the field inside the central stripe is $H_{in} \approx H/(1 + \mu N_2) \approx 0.4$ Oe, i.e., the external field is weakened due to demagnetization. Figure 8 shows that the dipole–dipole interaction begins to manifest itself at $T \sim a_m$ = 10 μm. As $T$ decreases to zero (i.e., upon transition to a continuous Ni layer), the internal field becomes equal to $H_{in} \approx H/(1 + \mu N_3) \approx$ ≈ 79 Oe, where $N_3 \approx 0.0004$ is the demagnetizing factor for a continuous Ni layer with in-plane dimensions of 16 × 16 mm and a thickness of 10 μm [17]. When the structure is magnetized along the Ni stripes (curve 2 in Fig. 8), the internal field decreases insignificantly, from $H_{in} \approx H/(1 + \mu N_1) \approx 89.6$ Oe (isolated Ni stripe) to $H_{in} \approx H/(1 + \mu N_3) \approx 79$ Oe (solid Ni layer). Since the amplitude of the ME voltage depends on the internal field in the FM layer, a decrease in the distance between the Ni stripes leads to a decrease in the anisotropy of the linear ME effect. Thus, by changing the distance between the FM stripes in the grating, it is possible to control the magnitude of the internal field in the stripes, and, consequently, the anisotropy of the ME effect in periodic heterostructures. The described anisotropic ME effect in periodic heterostructures containing an FM layer in the form of a grating can be used to create magnetometers sensitive to the magnetic field orientation [21, 22].

## CONCLUSIONS

It has been shown that the frequency of the resonant ME effect and the ME conversion coefficient in stripes based on Ni–PZT heterostructures are determined by the dimensions of the stripe in the plane. As the stripe length decreases from 23 to ~1 mm, the resonance frequency increases to ~1.4 MHz, while the ME conversion coefficient drops from $\alpha_E \approx 8.8$ V/(Oe·cm) to almost zero. In periodic heterostructures taking the form of a grating of Ni stripes on the surface of a PZT substrate, the frequency of the resonant ME effect is determined by the dimensions of the substrate in the plane, while the ME conversion coefficient depends on the width of the Ni stripes and the distance between the stripes. The ME coefficient for periodic heterostructures with a Ni stripe width of ~100 μm and a distance between them of 20–100 μm is ~1 V/(Oe·cm). Thus, in order to explain the anisotropy of the ME effect, it is necessary to change the theory to take into account the effects of demagnetization when the orientation of the constant bias field relative to the stripe axis. The anisotropy of the ME effect in periodic heterostructures can be used to create sensors for constant magnetic fields that are sensitive to field orientation.

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**F.A. Fedulov**—conducting measurements, manufacturing samples.

**D.V. Saveliev**—conducting measurements.

**D.V. Chashin**—research methodology design.

**V.I. Shishkin**—processing of results.

**Y.K. Fetisov**—research concept development.

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