

Synaptic behavior of a composite multiferroic heterostructure FeBSiC – PZT at resonant excitation

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Received 27 March 2024 ♦ Accepted 19 April 2024 ♦ Published 4 July 2024

Citation: Fedulov FA, Savelev DV, Fetisov YuK (2024) Synaptic behavior of a composite multiferroic heterostructure FeBSiC – PZT at resonant excitation. *Modern Electronic Materials* 10(2): 91–101. <https://doi.org/10.3897/j.moem.10.2.124089>

Abstract

Nowadays, one of the promising ways for the development of computing systems with high performance and low energy consumption is the creation of artificial synaptic devices that imitate the functions of biological synapses. Such devices have a significant potential for effectively solving problems of pattern recognition, classification, control, and the treatment of diseases of the nervous system. The work demonstrates the imitation of synaptic behavior in a composite multiferroic heterostructure based on the piezoceramics of lead zirconate titanate (PZT) and the amorphous magnetic alloy Metglas. The characteristics of the heterostructure were measured by resonant excitation of the magnetoelectric (ME) effect and applying electric field pulses of various amplitudes and polarities. The ME coefficient α_E was considered as a synaptic weight, and the output electrical voltage of the heterostructure as a postsynaptic potential. The study demonstrates the possibility of simulating long-term potentiation (LTP) and depression (LTD) in the ME heterostructure, as well as spike-timing-dependent plasticity (STDP). This work shows promise for creating neuromorphic computing systems based on multiferroic composite heterostructures.

Keywords

magnetoelectric effect, multiferroic heterostructure, synaptic device, magnetostriction, piezoelectricity, STDP

1. Introduction

The rapid development of information technology stimulates research in the field of computing systems with high efficiency and low power consumption. One of the promising ways is the creation of neuromorphic computing systems that go beyond the traditional von Neumann architecture [1–5]. The basis of such systems is artificial synaptic devices that can imitate the functions of biological synapses. The most important property of such devices is their ability to simulate synaptic plasticity and learning by implementing multi-step transitions between different stable states with very low power consumption [6].

In the last decade, the main attention has been paid to the study of synaptic devices based on various memristive structures, where imitation of synaptic behavior is realized by changing the resistance of the active layer of the structure when applying electrical voltage pulses [7–11]. The resistance value of memristor is interpreted as synaptic weight, characterizing the strength of the connection between two neighboring neurons [8, 12–15]. Synaptic behavior has been demonstrated in memristors using various physical mechanisms [16], such as phase-change materials [12, 17], properties of ferroelectric domains [13, 18], magnetoresistance in composite materials [8, 19,] and resistive switching based on the redox potential [11, 20].

In addition to memristors, the search for new potential candidates for the role of artificial synaptic devices that use other physical effects continues. One of the promising directions is the creation of devices based on magnetoelectric (ME) effects in composite ferromagnetic-piezoelectric (FM-PE) multiferroic heterostructures. ME effects in layered FM-PE heterostructures manifest themselves in the generation of an electric field E when a magnetic field H is applied to the heterostructure (direct effect) or a change in the magnetization of the heterostructure M when an electric field E is applied (inverse effect). ME effects arise due to a combination of magnetostriction in the FM layer and piezoelectricity in the PE layer [21]. Intensive research on ME effects in such heterostructures based on various FM and PE materials has already led to the creation of various devices [22], including highly sensitive magnetic field sensors and spectrum analyzers [23–25], tunable inductors [26, 27], frequency doublers [28], compact antennas [29, 30] etc.

The efficiency of field conversion at the direct ME effect is characterized by the coefficient $\alpha_E = e/h$, where e is the amplitude of the electric field generated by the structure by applying a magnetic field h . The magnitude and sign of the α_E can be smoothly changed from positive to negative with a large number of nonvolatile levels by applying electric field pulses of different amplitudes and polarities to the PE layer. Thus, the α_E can be considered as a synaptic weight and the corresponding output electrical voltage of the heterostructure is either an excitatory postsynaptic potential (EPSP) or an inhibitory postsynaptic potential (IPSP) [6].

Previously, synaptic behavior, including long-term potentiation (LTP), long-term depression (LTD) and simulated spike-timing-dependent plasticity (STDP) was observed in planar ME structures with layers of lead magnesium niobate/lead titanate piezoceramics (PMN-PT) and ferromagnetic layers of Ni and FeGa. The heterostructures were excited by an alternating magnetic field with a frequency of 10 kHz and an amplitude up to 2 Oe [31, 32]. When electric field pulses of different polarities were applied to the PE layer, a change in the generated ME voltage was observed in the range of ± 20 μ V. The value of the ME coefficient, which acts as a synaptic weight, increased by 2 orders of magnitude when using a Metglas amorphous alloy as the FM layer. The estimated energy required to switch the ME structure between two stable nonvolatile states is ~ 7.7 mJ/cm³ per pulse, which is comparable to the energy consumption of a biological synapse [6].

Attempts have been made to create ME synaptic devices based on organic PE materials such as polyvinylidene fluoride (PVDF) and its copolymers, such as poly(vinylidene fluoride-trifluoroethylene) P(VDF-TrFE). LTP and LTD were observed in a Cu/P(VDF-TrFE)/Ni heterostructure excited by an alternating magnetic field with an amplitude of 2.2 Oe and frequency of 1 kHz. The change in the ME coefficient α_E is caused by the application of electric field pulses with an amplitude up to 70 MV/m

of different polarities. As well as the generation of EPSP and IPSP potentials corresponding to an increase or decrease in the output ME voltage of the structure has been experimentally demonstrated [33].

Thus, the conducted studies demonstrate the promise of further research on synaptic behavior in ME structures to create artificial synaptic devices with low power consumption for neuromorphic computing systems.

However, in the described heterostructures, the amplitude of the generated ME voltage was about of microvolts – tens of millivolts, which makes it difficult to measure and use it for practical purposes. In addition, the PMN-PT material has a low Curie temperature ($T_c \sim 150^\circ\text{C}$), and PVDF-based piezopolymers melt at $T \sim 170\text{--}180^\circ\text{C}$. It is also worth noting the poor availability, the manufacturing complexity, and the high cost of the listed PE materials.

This work is devoted to the study of synaptic behavior in an ME heterostructure based on piezoceramics of lead zirconate titanate (PZT) and amorphous magnetic alloy Metglas in the resonant mode, which significantly increases the value of the ME coefficient and the amplitude of the generated ME voltage. A larger range of ME coefficient values allows increasing the range of nonvolatile stable states of the ME heterostructure.

2. Methods and materials

In the measurements, we used a heterostructure containing a layer of piezoceramic lead zirconate titanate of composition $\text{PbZr}_{0.52}\text{Ti}_{0.48}\text{O}_3$ (PZT-19) with a thickness of $a_p = 250$ μm with Ag electrodes (Elpa Research Institute, Russia) [34] and a layer of amorphous magnetic alloy FeBSiC (Metglas 2605SA1, Metglas Inc., USA) [35] with a thickness $a_m = 25$ μm . The layers were mechanically bonded together using cyanoacrylate glue. The in-plane dimensions of the heterostructure were 19×8 mm². The piezoelectric modulus and relative permittivity of the PZT were $d_{31} = -160$ pC/N and $\epsilon_{33} = 1750$, respectively. The saturation magnetostriction and initial magnetic permeability of the Metglas alloy were $\lambda_s \approx 22 \cdot 10^{-6}$ in a saturation field $H_s \sim 50$ Oe and $\mu \approx 10^4$, respectively. A schematic representation and an appearance of the heterostructure are shown in Fig. 1.

During the measurements, the heterostructure was placed in an alternating excitation magnetic field $h \cos(2\pi ft)$ with amplitude $h = 0\text{--}4.8$ Oe and frequency $f = 40\text{--}120$ kHz and a constant magnetic field $H = 0\text{--}100$ Oe. The fields were directed along the sample. The alternating field was created using a solenoid with a diameter of 45 mm, a length of 63 mm, with the number of turns $N = 97$, inductance $L = 245$ μH and resistance $R = 1.28$ Ω , which was powered by an Agilent 33210A function generator. A constant field was created using Helmholtz coils with a diameter of 23 cm, which were fed by a TDK-Lambda GENH-600-1.3 power supply. The voltage $u \cos(2\pi ft)$ generated by the ME heterostructure

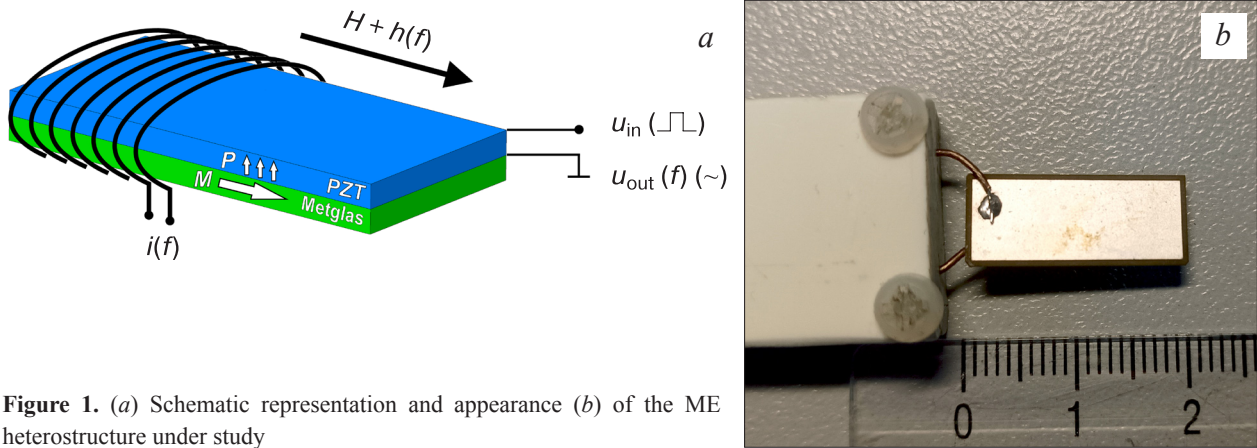


Figure 1. (a) Schematic representation and appearance (b) of the ME heterostructure under study

was measured with an AKIP-2401 digital voltmeter with an input impedance of 10 MΩ. The voltmeter was connected through a Stanford Research SR560 band-pass filter to suppress industrial network noise with a frequency of 50 Hz.

To study the influence of electric field pulses on the value of the ME coefficient α_E , rectangular voltage pulses of different polarities were applied to the PZT layer of the heterostructure. The pulse amplitude and duration were $U = 0\text{--}400\text{ V}$ and $\tau = 5\text{ s}$, respectively. The applied voltage pulses created in the PZT layer electric field pulses with an amplitude of $E = 0\text{--}16\text{ kV/cm}$. A voltage pulse was created by applying a single pulse from an Agilent 33210A function generator to the analog input of the Stanford Research PS350 voltage source. In this case, the voltage source acted as a voltage amplifier with a gain $k = 500$. During the study, the amplitude of the ME voltage was recorded when changing the constant field H , the frequency f and amplitude h of the excitation magnetic field, the amplitude E and the polarity of the electric field pulses.

3. Results and discussion

3.1 Characteristics of direct ME effect

At the first stage, the characteristics of the direct ME effect in the described heterostructure were measured using the method of harmonic magnetic field modulation [36]. Figure 2a shows the dependence of the ME voltage on the frequency of the excitation field $u(f)$ at $h = 4.8\text{ Oe}$ and $H = 12.8\text{ Oe}$. It can be seen a peak near the frequency $f_0 \approx 78\text{ kHz}$ with the amplitude $u_m \approx 600\text{ mV}$ and a quality factor $Q = f_0/\Delta f \approx 29$, where Δf is a resonance width at the level of $0.707u_m$. The peak corresponds to the excitation of the fundamental longitudinal acoustic oscillations in the heterostructure, when the magnitude of deformations and the amplitude of ME voltage increase sharply. Figure 2b shows the dependence of the resonance peak height on a constant field $u_m(H)$, measured at $h = 4.8\text{ Oe}$. The maximum peak voltage is ob-

served at the field $H_m \approx 12.8\text{ Oe}$, at which the maximum linear piezomagnetic coefficient of the FM layer is achieved $q = \lambda^{(1)}(H) = \partial\lambda/\partial H|_H$, where $\lambda(H)$ is the dependence of the magnetostriction of the FM layer on the magnetic field H .

The ME interaction in the heterostructure under study is explained by the theory of the low-frequency linear ME effect in planar FM-PE heterostructures [37]. The magnitude of the ME voltage generated by the heterostructure at its own resonance frequency is determined by the simplified formula

$$u(H) \approx AQ \frac{d_{31}q}{\epsilon} h,$$

where A is a coefficient that depends only on the geometric dimensions and mechanical characteristics of the FM and PE layers; Q is the quality factor; d_{31} and ϵ are the piezoelectric modulus and dielectric constant of the PE layer, respectively; q is piezomagnetic coefficient; h is the amplitude of the excitation magnetic field.

Figure 2c shows the dependence of the ME voltage at the resonance frequency f_0 on the excitation field $u_m(h)$, measured at the field H_m . In the amplitude range $h < 1.4\text{ Oe}$, the dependence is linear; however, as the field increases, the voltage u_m tends to saturation, which is associated with the increase in contribution of nonlinear harmonic generation at large amplitudes of the excitation field [38].

Let us estimate the frequency of the longitudinal acoustic resonance of the heterostructure using the formula for the fundamental oscillations of a free rod

$$f_{\text{cal}} = \frac{1}{2L} \sqrt{\frac{Y}{\rho}},$$

where L is the length of the structure $Y = (Y_m a_m + Y_p a_p)/(a_m + a_p)$ and $\rho = (\rho_m a_m + \rho_p a_p)/(a_m + a_p)$ are the effective Young's modulus and the effective density of the heterostructure, respectively [39]. The indices "m" and "p" correspond to the FM and PE layers. Substituting the material parameters into the formula: $Y_p = 5.9 \cdot 10^{10}\text{ N/m}^2$, $Y_m = 18.6 \cdot 10^{10}\text{ N/m}^2$, $\rho_p = 7.4 \cdot 10^3\text{ kg/m}^3$, $\rho_m = 8.2 \cdot 10^3\text{ kg/m}^3$, $a_p = 250\text{ }\mu\text{m}$, $a_m = 25\text{ }\mu\text{m}$ we obtain a resonant frequency $f_{\text{cal}} \approx 81\text{ kHz}$, which agrees well with the measured one.

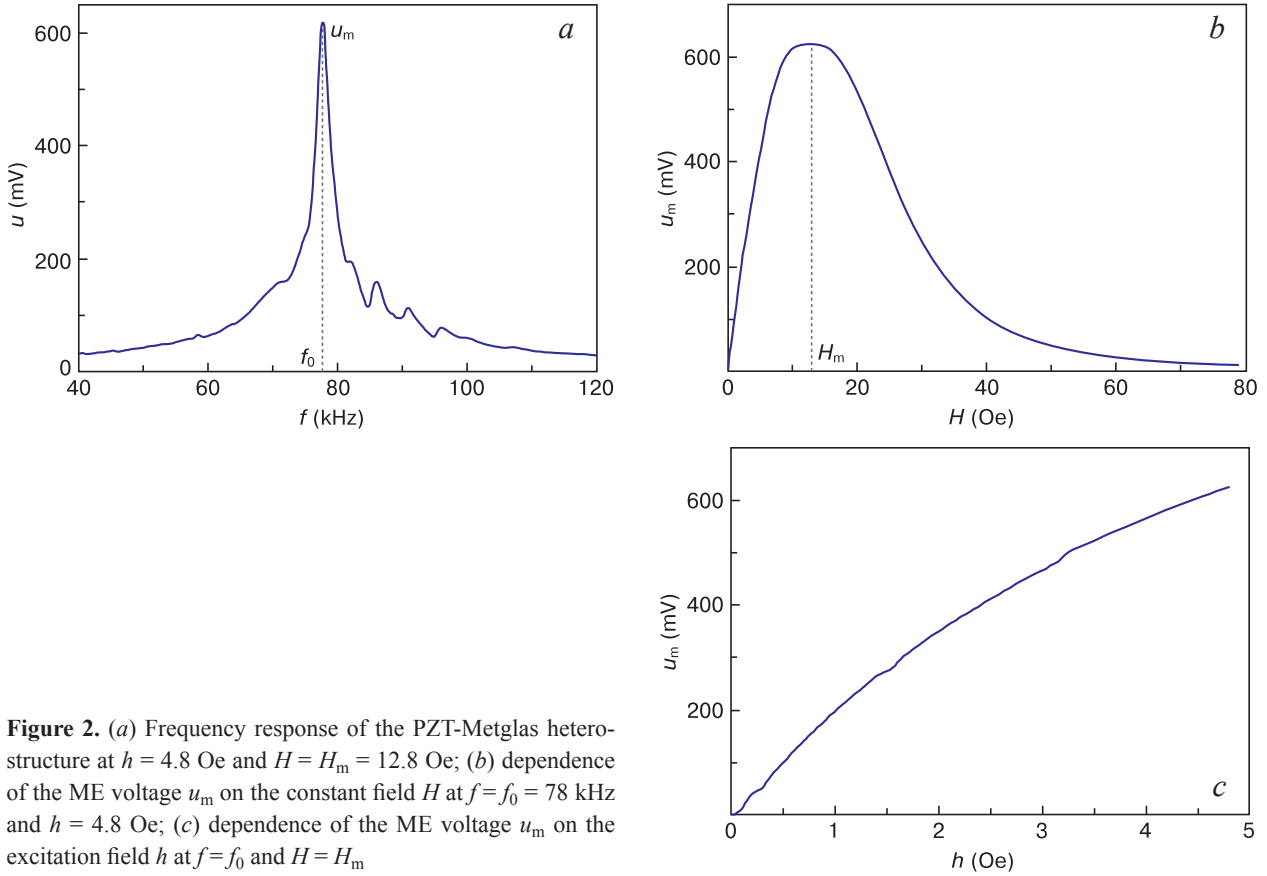


Figure 2. (a) Frequency response of the PZT-Metglas heterostructure at $h = 4.8$ Oe and $H = H_m = 12.8$ Oe; (b) dependence of the ME voltage u_m on the constant field H at $f = f_0 = 78$ kHz and $h = 4.8$ Oe; (c) dependence of the ME voltage u_m on the excitation field h at $f = f_0$ and $H = H_m$

Using the data in Fig. 2, we can find the value of the ME coefficient at the resonance frequency $\alpha_E = u_m / (a_p \cdot h) \approx 5.2$ V/(Oe·cm). The resulting resonant ME coefficient is typical for heterostructures with layers of PZT and Metglas and is ~ 2 orders of magnitude higher than the ME coefficient in the non-resonant mode [38]. The value of the ME coefficient outside the resonance can be estimated using the formula $\alpha_E / Q = 5.2 / 29 \approx 0.18$ V/(Oe·cm), where Q is the resonance quality factor.

3.2 The influence of the electric field on the ME effect

At the next stage, the influence of single electric field pulses on the characteristics of the ME effect was studied. To do this, single electric field pulses of different polarity with amplitude $E = 16$ kV/cm and duration $\tau = 5$ s were applied to the heterostructure. Then the output ME voltage was measured at the resonance frequency f_0 at a constant field $H_m = 12.8$ Oe and $h = 4.8$ Oe. The choice of field strength $E = 16$ kV/cm was justified by a compromise between the maximum possible value of residual polarization P_r and the dielectric strength of the PZT, since electrical breakdown was observed at $E \geq 20$ kV/cm.

Figure 3a shows the time dependences of the ME voltage u_m and ME coefficient α_E after applying electric field pulses.

The graph shows a clear switching of the ME voltage amplitude and the ME coefficient value between 2 nonvolatile stable states with $u_m = \pm 624$ mV and $\alpha_E = \pm 5.2$ V/(Oe·cm). The states have mutually opposite directions of the polarization P and correspond to a phase shift of ME voltage u_m of π (Fig. 3b). After applying each electric field pulse, the measurement of u_m was carried out for $t = 70$ s to demonstrate the stability of the switched state over time.

The dynamic range α_E is determined by the remnant polarization P_r of the piezoceramics, both positive and negative. Within this range, it is possible to create lot of nonvolatile stable states with different P_r values, which determines the number of possible values of α_E and, thus, the weight bit-width of a synaptic device based on an ME heterostructure [40]. The mechanism for controlling the value of the α_E due to changes in the remnant polarization P_r is shown in Fig. 4, which shows the dependence of the polarization P of a ferroelectric material on the applied electric field E . The application of electric field pulses E changes the value of P_r due to movement along the major and minor hysteresis loops. Electric field pulses of the same polarity and growing amplitude increase the value of P_r . The maximum value of P_r is determined by the saturation field E_s and movement along the major hysteresis loop. A decrease in P_r and a change in its sign occur due to applying electric field pulses of opposite polarity with growing amplitude. After applying the electric field pulse and returning to the state $E = 0$,

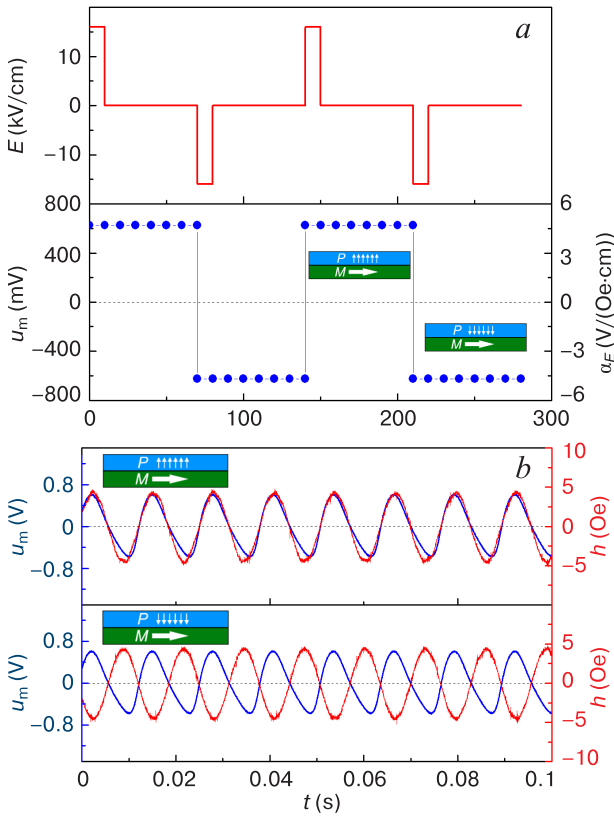


Figure 3. Switching between 2 nonvolatile stable states after applying electric field pulses of different polarities and a fixed amplitude $E = 16$ kV/cm to the ME heterostructure (a) and time dependences of the ME voltage u_m and the excitation magnetic field h , demonstrating a phase shift by π at opposite directions of the polarization P of piezoceramics (b)

the piezoelectric modulus of piezoceramics changes as $d = \partial S / \partial E|_{E=0}$, where S is the strain. Minor hysteresis loops have different slopes at $E = 0$ and, consequently, different values of the piezoelectric modulus d , which directly affect the ME voltage u_m .

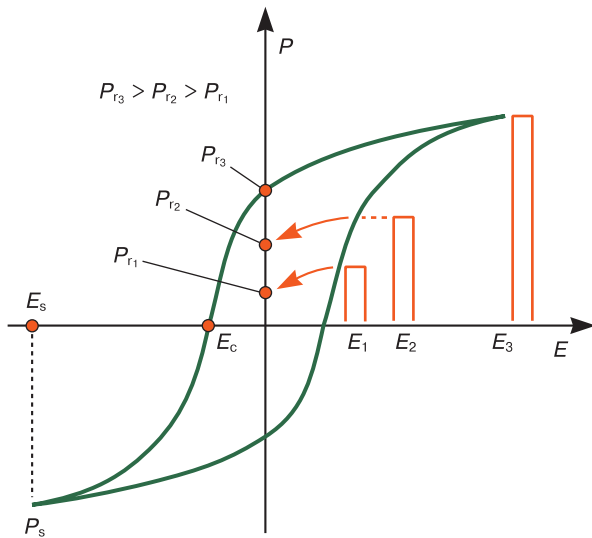


Figure 4. Dependence of polarization P of a ferroelectric material on the applied electric field E

3.3 Neuromorphic behavior of a heterostructure

In biology, the main characteristic of a synapse is a synaptic weight – a parameter that determines the effectiveness of the action potential of a presynaptic neuron (pre-neuron) on changing the membrane potential and the probability of generating its own action potential by a post-synaptic neuron (post-neuron). The action potential of a neuron (spike) is considered to be a sharp, abrupt surge in the membrane potential of the cell when the threshold value of about -10 mV is exceeded. The process of spike transmission between neurons is schematically presented in Fig. 5a. The synaptic weight is determined by the amount of neurotransmitter molecules released into the synaptic cleft by the pre-neuron and captured by the receptors of the post-neuron upon the generation of one pre-spike [41]. Depending on the type of neurotransmitter, the membrane potential of the post-neuron may increase or decrease. In the first case, it is dealing with excitation of the post-neuron and an increase in the membrane potential by the value of the excitatory postsynaptic potential (EPSP). In the other case, it is inhibition by the value of the inhibitory postsynaptic potential (IPSP). The EPSP potential increases the probability of a neuron generating a spike, while the IPSP reduces this probability (Fig. 5b).

In the case of excitation, the greater the synaptic weight, the more neurotransmitter is released into the synaptic cleft and the greater the number of post-neuron receptors that receive it. This increases the membrane potential of the post-neuron by a larger EPSP value, so that the probability of generating a spike increases. When the post-neuron is inhibited, a larger synaptic weight leads to a decrease in the membrane potential of the post-neuron by a larger IPSP value, which reduces the probability of spike generation. The new value of the post-neuron membrane potential remains for a long time, thereby exhibiting long-term potentiation (LTP) or long-term depression (LTD). The membrane potential of the post-neuron is “reset” to the resting value of -70 mV only after generating its own spike.

For a ME heterostructure, from the point of view of neuromorphic behavior, the incoming electric field pulse can be considered as the action potential. The ME coefficient α_E is an analogue of the synaptic weight, and the ME voltage u_m generated by the ME heterostructure plays the role of a postsynaptic potential – excitatory (EPSP) or inhibitory (IPSP). Maintaining a stable value of α_E after applying electric field pulses resulting in an increase or decrease in the output voltage u_m , represents LTP and LTD, respectively.

To simulate the neuromorphic behavior in the PZT-Metglas heterostructure, electric field pulses of different polarity and gradually increasing amplitude were applied to the PE layer, followed by measuring the ME characteristics of the heterostructure. Fig. 6 shows how the first positive electric field pulse E with an amplitude of 16 kV/cm polarizes the PE layer so that the heterostructure generates a voltage with an amplitude $u_m \approx 620$ mV.

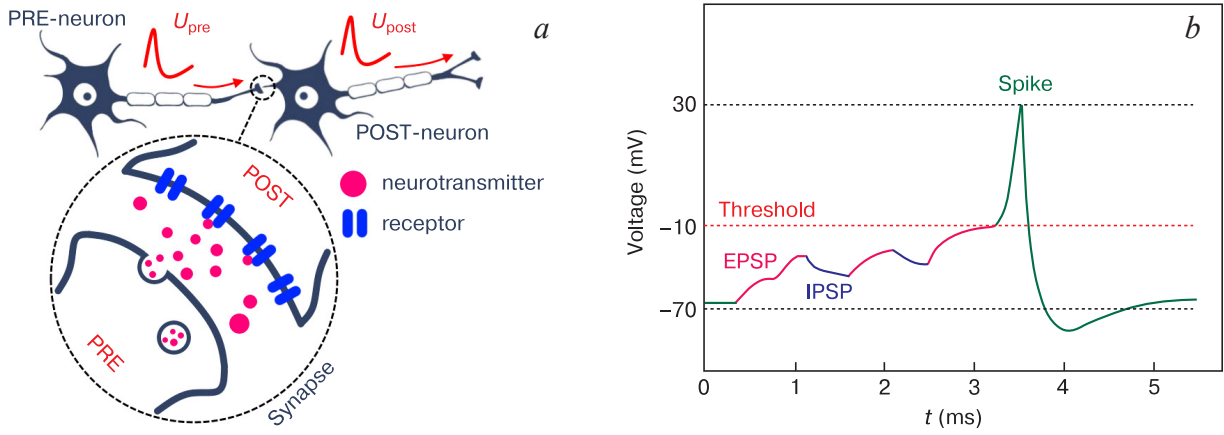


Figure 5. Schematic view of the spike transmission between neurons (a) and diagram of changing the neuron membrane potential (b)

Subsequent negative electric field pulses with increasing amplitude from 6 kV/cm to 16 kV/cm lead to a decrease in the amplitude of the generated ME voltage and then to a change in the phase of the voltage by π . After applying the 7th pulse to the structure at a time of ~ 500 s, u_m reaches an amplitude of 620 mV and stops growing until the application of a pulse with a field strength of 16 kV/cm. This moment indicates saturation of the PE layer. Subsequent application of positive electric pulses with an amplitude from 6 kV/cm to 16 kV/cm leads to a decrease in the u_m to zero, a phase change by π , a subsequent increase in amplitude to 620 mV and saturation of the PE layer. Similarly, applying electric field pulses to the PE layer leads to a change in the magnitude and sign of the ME coefficient α_E . When the field E increased from 8 to 16 kV/cm, no change in α_E was observed, which indicates that the remnant polarization of the PE layer P_r was close to saturation. Due to the slight increase in α_E , pulses within the range $E = 8\text{--}16$ kV/cm are not shown in the graph.

From Fig. 6 it follows that the application of positive pulses leads to an increase in α_E and u_m , while negative pulses reduce these values. Thus, an increase in u_m is equivalent to the appearance of the EPSP, and a decrease in u_m represents the IPSP.

Figure 7 shows the change in the ME coefficient α_E depending on the polarity of the applied electric field pulses. Taking the value $\alpha_E = 1$ V/(Oe·cm) as the initial stable state, we can increase it to $\alpha_E = 3.6$ V/(Oe·cm) when applying a positive pulse, demonstrating EPSP, or reduce it to $\alpha_E = -1.6$ V/(Oe·cm) due to a negative pulse, showing IPSP. New stable states remain for a long time, which is equivalent to the simulation of LTP and LTD.

Figure 8 shows the dependence of the ME coefficient α_E on the electric field strength E of applied pulses of different polarity at a fixed pulse duration $\tau = 5$ s. The dependence has the form of a hysteresis loop with clearly distinguishable thresholds $E_{th1} - E_{th4}$. When applying field pulses with an amplitude of $E_{th1} < E < E_{th2}$ or $E_{th3} < E < E_{th4}$, the change in α_E is maximum, while outside the indicated areas α_E changes slightly. Within these

thresholds, the change in the ME coefficient was $\Delta\alpha_E \approx 9$ V/(Oe·cm). Outside the thresholds, at $E < -7.2$ kV/cm and $E > 7.2$ kV/cm, the α_E varied only about $\Delta\alpha_E \approx 0.5$ V/(Oe·cm).

Applying the pulse with amplitude $E = E_c \sim 6.5$ kV/cm, corresponding to the coercive field of the piezoceramics, the values of u_m and α_E are close to zero. Further increase in the field amplitude changes the sign of u_m and α_E , which indicates a change in the direction of the

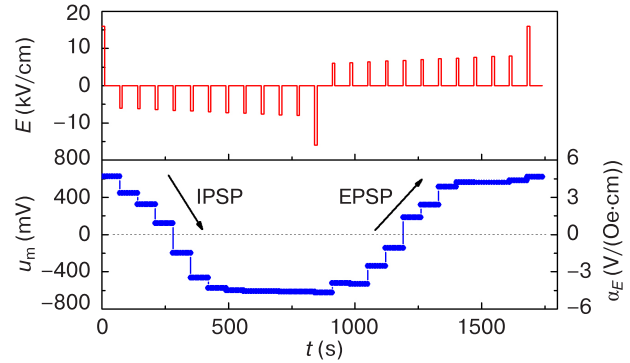


Figure 6. Time dependences of the generated voltage u_m and ME coefficient α_E when applying electric field pulses E of different amplitudes and polarities. The change in the sign of u_m and α_E corresponds to a change in the phase of the u_m by π

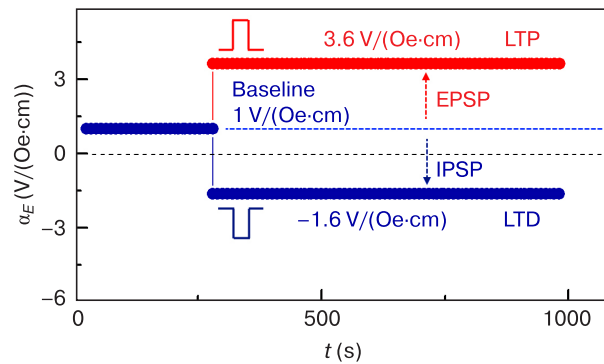


Figure 7. Change in the initial state of the ME coefficient α_E when applying electric field pulses of different polarities, demonstrating LTP and LTD

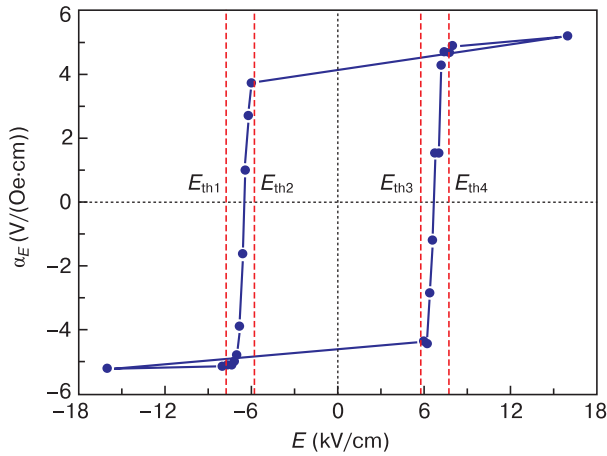


Figure 8. Dependence of the ME coefficient α_E on the amplitude of electric field pulses in the range $E = \pm 16$ kV/cm. Red dotted lines are the range of fields where the change in α_E is maximum

polarization P to the opposite and a change in the phase of the u_m by π . This behavior of α_E is directly related to the ferroelectric hysteresis loop of the PE material (see Fig. 4).

3.4 Synaptic plasticity in the ME heterostructure

In the nervous system, neurons transmit electrical and chemical signals to other neurons through synapses. One of the most important qualities of a synapse is synaptic plasticity, which is the ability to change the synaptic weight in response to external impact. Among the types of synaptic plasticity, it is worth highlighting spike-timing-dependent plasticity (STDP), which is believed to play a key role in brain learning and memory processes [42].

STDP plasticity in the nervous system can be represented in the form of strengthening or weakening of synaptic connections (increasing or decreasing the weight of individual synapses). This phenomenon manifests, in particular, in a change in the number of receptors that capture neurotransmitter molecules in the post-synapse [43, 44], due to the difference in the time between the generation of pre- and post-spikes in the corresponding neurons. The arrival of a pre-spike to the synapse before the generation of a post-spike (time delay $\Delta t > 0$) leads to excitation - an increase in synaptic weight and a greater contribution to the increase in the membrane potential of the post-neuron. Thereby, this condition increases the probability of post-spike generation (LTP). In this case, a cause-and-effect relationship between spikes can be observed. Otherwise, when the pre-spike arrives later than the post-spike (time delay $\Delta t < 0$), the synaptic connection is weakened, which leads to depression. In this case, the membrane potential does not grow, and the probability of generating a post-spike diminishes (LTD) because the post-spike cannot occur on its own [45].

In the case of the PZT-Metglas heterostructure under study, the presence of clear thresholds associated with a coercive field E_c in the PZT layer allows for the simulation of STDP plasticity [41, 46].

In an artificial synaptic device based on an ME heterostructure, the ME coefficient α_E , acting as the synaptic weight, can be adjusted by superposition of voltage pulses corresponding to pre- and post-spikes applied to both ends of an artificial synapse (Fig. 9) [6, 31–33].

Thus, the change in the weight will be determined by the voltage drop $U_{pre} - U_{post}$ on the ME structure and the corresponding field strength difference $E_{pre} - E_{post}$. The weight change reaches its maximum when a maximum overlap of pre- and post-spike pulses occurs. It is also

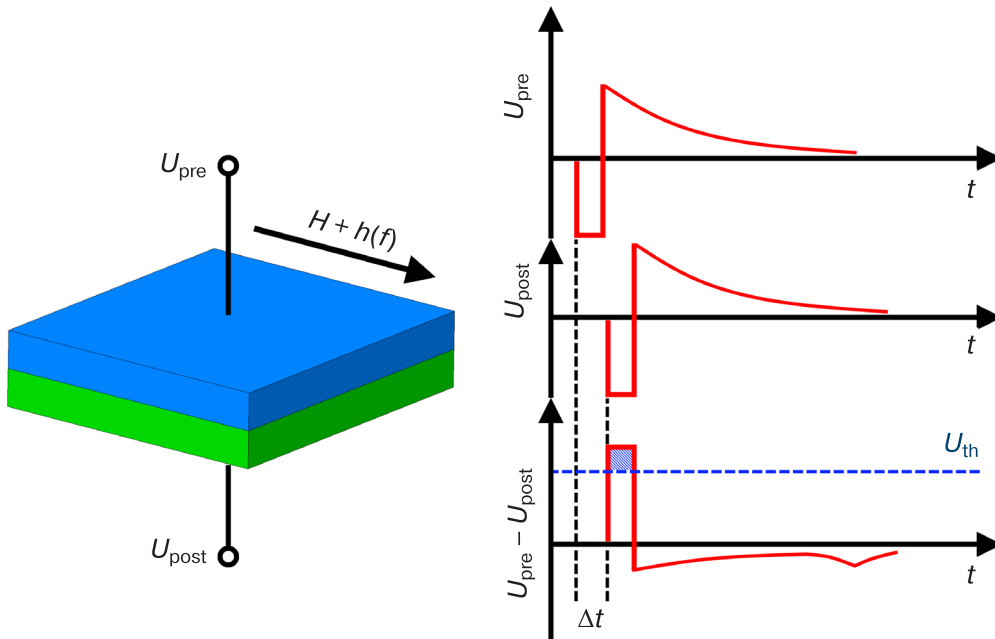


Figure 9. The mechanism for changing the ME coefficient α_E due to the superposition of voltage pulses $U_{pre} - U_{post}$, corresponding to pre- and post-spikes

important to select the amplitude and polarity of the pulses for the effective implementation of the STDP rule. A spike, corresponding to the waveforms generated by pre- and post-neurons, can be described as a sequence of electric field pulses of different polarities. In this work, STDP was examined using the above mentioned thresholds of electric field strength ($E_{th1} - E_{th4}$).

In the absence of time correlation between spikes, the polarization of the ME structure remains almost unchanged, since a single spike cannot exceed the threshold values of the E_{th} . In this regard, the remnant polarization P_r , and thereby α_E and u_m , should change significantly only when the pre- and post-spikes overlap. For this reason, the change in polarization caused by a single spike should be minimized. On the other hand, the change caused by the overlap of pre- and post-spikes should be maximum and take place within the $E_{th1}-E_{th2}$ and $E_{th3}-E_{th4}$ thresholds. In this work, the maximum amplitude of a single spike was reduced so that only the resulting pulse with the amplitude $E_{pre} - E_{post}$ could exceed thresholds.

Time dependences of pulse sequences corresponding to the pre-spike E_{pre} , the post-spike E_{post} and the resulting sequence $E_{pre} - E_{post}$ applied to the ME heterostructure for the case of LTD (post-spike precedes pre-spike) and LTP (pre-spike precedes post-spike) are presented in Fig. 10a and Fig. 10b, respectively.

The graphs show that individually, the maximum amplitudes of E_{pre} and E_{post} are significantly lower than the threshold values $E_{th1} = -7.2$ kV/cm, $E_{th2} = -6$ kV/cm, $E_{th3} = 6$ kV/cm, $E_{th4} = 7.2$ kV/cm. However, the amplitude of the resulting pulse $E_{pre} - E_{post}$ is within the thresholds $E_{th1} < E < E_{th2}$ and $E_{th3} < E < E_{th4}$, which results in LTD and LTP, respectively. An important parameter is the time window Δt , which determines the relative arrival time of pre- and post-spikes. In our case, the smaller Δt , the greater the amplitude of the resulting pulse. Figure 10a and Figure 10b show the cases for $\Delta t = -6$ s and $\Delta t = 6$ s, respectively. To effectively change α_E , before applying the resulting pulse $E_{pre} - E_{post}$ for each Δt , the piezoceramics was polarized by a single electric field pulse with an amplitude of $E = 16$ kV/cm (for LTD observation) and $E = -16$ kV/cm (for LTP observation), respectively.

Figure 11 shows the dependences of the absolute $\Delta\alpha_E$ and relative $\Delta\alpha_E/\alpha_{Ei}$ changes in the ME coefficient α_E according to the STDP rule on the time window Δt . The data was obtained by applying the resulting pulses $E_{pre} - E_{post}$ to the ME heterostructure. The pulses shifted relative to each other by $\Delta t = -54 - 54$ s with a step of 6 s. The calculation of the absolute change in α_E was carried out using the formula $\Delta\alpha_E = \alpha_{Ef} - \alpha_{Ei}$, where α_{Ei} and α_{Ef} are the values of the ME coefficient before and after applying the resulting pulse.

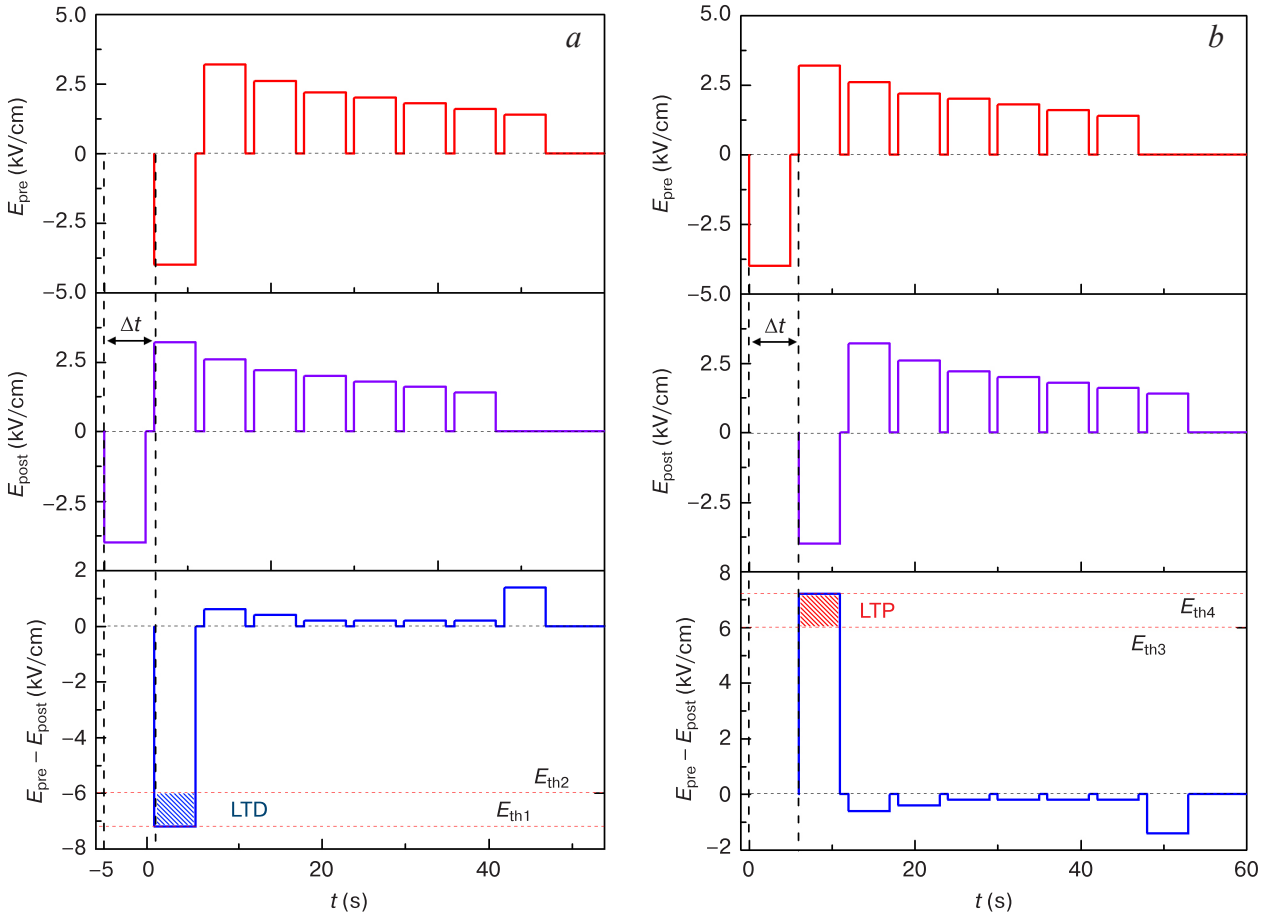


Figure 10. Time dependences of the pre-spike E_{pre} , the post-spike E_{post} and the resulting pulse $E_{pre} - E_{post}$ at $\Delta t = -6$ s for LTD case (a) and $\Delta t = 6$ s for LTP case (b)

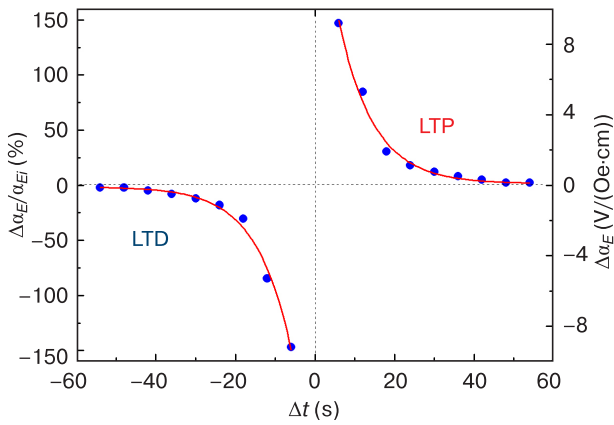


Figure 11. Dependences of the absolute $\Delta\alpha_E$ and relative $\Delta\alpha_E/\alpha_{Ei}$ changes in the ME coefficient α_E according to the STDP rule on the time window Δt (solid line – exponential approximation by the STDP learning function)

As seen from the graphs, the highest value of $\Delta\alpha_E$ was observed at $\Delta t = 6$ s due to the largest amplitude of the $E_{pre} - E_{post}$. However, with a further increase in Δt , the value of $\Delta\alpha_E$ decreases exponentially. The decrease in $\Delta\alpha_E$ is explained by less overlap of the E_{pre} and the E_{post} pulses and, accordingly, a smaller resulting amplitude of the $E_{pre} - E_{post}$.

With a further increase in Δt , the value $\Delta\alpha_E \sim 0$, which indicates that the E_{pre} and the E_{post} pulses do not overlap and so that α_E does not change significantly. The STDP behavior shown in Fig. 11 can be approximated by the STDP rule learning function described in [47]

$$\frac{\Delta\alpha_E}{\alpha_{Ei}}(\Delta t) = \begin{cases} k^+ e^{-\frac{\Delta t}{\tau^+}}, & \Delta t > 0, \\ k^- e^{\frac{\Delta t}{\tau^-}}, & \Delta t < 0. \end{cases}$$

In our case, the $k^+ = 294$, $k^- = -294$, $\tau^+ = 9$, $\tau^- = -9$.

It follows from the graphs that the magnitude of the change in the ME coefficient $\Delta\alpha_E$ depends on the arrival time of pre- and post-spikes.

Thus, it is shown that ME heterostructures have the potential for the development of artificial synaptic devices for the creation of neuromorphic computing systems. It is also worth noting the possibilities for improving the characteristics of the described ME heterostructure and further development prospects. The reproducibility of characteristics of ME heterostructures can be improved by more technologically advanced fabrication methods, such as vacuum and electrolytic deposition of FM layers on a PE substrate. The amplitude of the output

ME voltage can be increased by optimizing the sample mounting during the measurement. The number of non-volatile stable states corresponding to different values of α_E can be controlled with higher precision by applying electric field pulses with smaller steps. The shape of the STDP dependences $\Delta\alpha_E(\Delta t)$ can be controlled in an arbitrary manner by applying pulses of different shapes, amplitudes and polarities, corresponding to pre- and post-spikes. To increase performance, reduce energy consumption, and reliably simulate synaptic behavior, the duration of the applied electric field pulses must be comparable to the duration of the spike in biological systems (a few to tens of milliseconds). The size of the heterostructures themselves requires miniaturization. Moreover, the addition of FM layers with coercive field $H_c \sim 10\text{--}100$ Oe, such as Ni, will make it possible to observe the ME interaction without a bias constant magnetic field H .

4. Conclusion

The work experimentally demonstrates the imitation of synaptic plasticity STDP, as well as such synaptic properties as LTD, LTP, EPSP, and IPSP in the ME composite heterostructure PZT-Metglas under resonant excitation. The change in the ME coefficient α_E is caused by applying electric field pulses of different amplitudes and polarities, acting as neural spikes. Resonant excitation of the ME heterostructure significantly increases the value of the ME coefficient up to $\alpha_E = 5.2$ V/Oe·cm, and the magnitude of the generated ME voltage up to $u_m = 620$ mV, compared to non-resonant excitation described in previous studies by other authors. When modeling STDP plasticity, the absolute change in the ME coefficient was $\Delta\alpha_E \approx 8.1$ V/Oe·cm, and the relative change reached $\Delta\alpha_E/\alpha_{Ei} \approx 150\%$. The conducted research demonstrates the potential for creating neuromorphic computing systems based on piezoelectric-ferromagnetic multiferroic composite heterostructures.

Acknowledgements

The research was supported by the Russian Science Foundation, project No. 23-72-01053 (<https://rscf.ru/project/23-72-01053/>). A part of the measurements was performed on the equipment of the Joint Center of Collective Usage of RTU MIREA.

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