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Magnetoimpedance modulation in a planar magnetoelectric ferromagnet – piezoelectric heterostructure

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Abstract. The effect of a giant change in the impedance of ferromagnetic materials under the action of an external magnetic field is widely used to elaborate highly sensitive magnetic field sensors. The *purpose* of this work was to demonstrate the possibilities of controlling the magnitude of the magnetoimpedance in a ferromagnet-piezoelectric structure using an electric field. *Method.* In the measurements, we used a planar heterostructure containing a strip of amorphous ferromagnet Metglas, 25 μm thick and 25 mm long, mechanically connected to a bimorph, 0.5 mm thick and 30 mm long, made of piezoceramic lead zirconate titanate. An alternating current with a frequency of 30 kHz...10 MHz was passed through the strip, the structure was placed in a longitudinal permanent magnetic field of 0...500 Oe, an alternating electric field up to 400 V/cm with a frequency of 60 Hz...50 kHz was applied to the piezobimorph, and the change in the impedance of the strip was recorded. *Results.* In the absence of electric field, a narrowing of the magnetoimpedance magnetic fields region with a decrease in the current frequency and saturation of the magnetoimpedance in magnetic fields above 334 Oe were observed. The maximum value of the magnetoimpedance reached 18% at a current frequency of 1 MHz. The application of electric field to the piezobimorph led to the appearance of side components in the frequency spectrum of the voltage on the ferromagnetic layer, which indicates the amplitude-phase modulation of the magnetoimpedance. The amplitude modulation coefficient reached a maximum value of $6 \cdot 10^{-3}$ for the electric field frequency of 11.2 kHz and decreased monotonically with an increase in the magnetic field. The modulation of the magnetoimpedance occurs due to the converse magnetoelectric effect in the heterostructure, which leads to the modulation of the magnetization of the ferromagnetic layer, and the subsequent change in the relative magnetic permeability and thickness of the skin layer in the ferromagnet. The results obtained can be used to create magnetic fields sensors controlled by an electric field.

Keywords: magnetoimpedance, composite heterostructure, ferromagnet, piezoelectric, magnetoelectric effect.

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Introduction

The effect of giant magnetoimpedance (GMI) in amorphous magnetic conducting materials has been intensively studied in recent decades in connection with the prospects of its use for the creation of highly sensitive magnetic field sensors [1]. The effect manifests itself in a change in the impedance of a sample with a high-frequency current flowing through it under the action of a constant magnetic field and occurs due to a change in the magnitude of the magnetic permeability and the skin layer of the magnetic conductor [2, 3]. In amorphous ferromagnets based on iron and cobalt, having a giant magnetic permeability ($\mu \sim 10^5$) in weak magnetic fields ($H \sim 100$ Oe), the impedance change caused by the magnetic field can reaches hundreds of percent and strongly depends on the composition and geometry of the samples (microfibers, films, multilayer structures), the technology of their manufacture, the frequency and amplitude of the current, various external influences [4]. It is shown, in particular, that the deformation of the sample (stress-impedance effect) [5] leads to a change in the impedance of amorphous materials with magnetostriction. In amorphous magnetic tapes of various compositions, an impedance change of up to 40% was observed under the action of tensile mechanical stresses of 200 MPa [6]. The impedance of such materials changes due to inverse magnetostriction (Villari effect), which causes a change in the magnetization of M, and, consequently, the magnetic permeability μ of the material, under the action of deformation.

Of particular interest is the study of GMI in composite heterostructures containing mechanically coupled ferromagnetic (FM) and piezoelectric (PE) layers. In such structures, magnetoelectric (ME) effects occur, leading to a change in the electric polarization of the structure P under the action of the magnetic field H (direct ME effect) or a change in the magnetization of the structure M under the action of the electric field E (converse ME effect) [7]. ME effects occur as a result of a combination of magnetostriction of the FM layer and piezoelectricity in the PE layer of structures. It is obvious that ME effects can be used to dynamically control the magnetic impedance of the FM layer using magnetic or electric fields.

To date, only a few papers have been published on the study of GMI in composite heterostructures. In a ring resonator with layers of lead zirconate-titanate (PZT) and Terfenol ceramics at an acoustic resonance frequency of 70 kHz, a change in the capacitive component of the impedance by 225% was observed under the action of a magnetic field of 800 mT [8]. In the layered structure of the amorphous ferromagnet Metglas – PZT of rectangular shape at a resonance frequency of about 60 kHz, a change in the inductive and capacitive components of the impedance up to 450% in a magnetic field of 100 Oe [9] was detected. The authors of [10] investigated GMR in Metglas – PZT and Terfenol – PZT structures and showed that the magnitude of the magnetoimpedance significantly depends on the magnetic and dielectric permittivity, magnetostriction and Young's modules of the layers of structures, at a resonance frequency of 130 kHz, a magnetic field-induced change in the impedance of the Metglas structure was registered – PZT by 600%, which is 8.6 times more than for the Terfenol structure – PZT.

In this paper, the effect of GMI in the planar heterostructure of Metglas – PZT in a wide frequency band of current flowing through a ferromagnetic layer is investigated. For the first time, the effect of modulation of magnetoimpedance under the action of a harmonic electric field applied to the PZT layer of the structure was discovered. The first part of the article describes the heterostructure and measurement methods. The second part presents the measurement results. Further, the results are discussed and the main conclusions of the work are formulated.

1. Sample and measurement methods

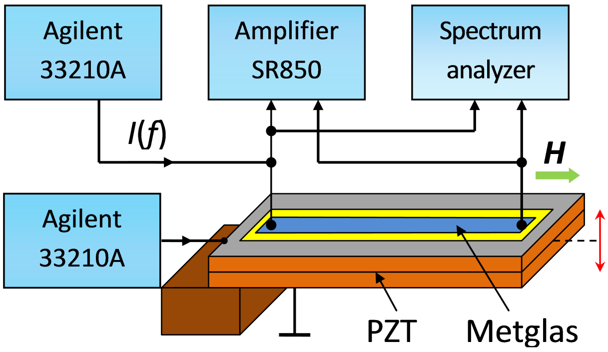

Fig. 1. Schematic representation of the Metglas – PZT bimorph structure and block diagram of the measuring setup

The investigated heterostructure and the block diagram of the measuring unit are schematically shown in Fig. 1. The structure contained an FM layer and a PE layer. The FM layer is made of FeBSiC amorphous ferromagnetic tape (Metglas 2605SA1, Metglas Inc., USA), had dimensions of 23 × 1.7 mm, thickness of 25 microns, saturation magnetization $M_S = 1.56$ T, maximum magnetic permeability $\mu \sim 1.2 \cdot 10^5$, saturation magnetostriction $\lambda_S = 25 \cdot 10^{-6}$ and resistivity $\rho \approx 120 \cdot 10^{-6}\ \Omega \cdot sec$ The PE layer was a bimorph made of two piezoceramic plates $PbZr_{0.52}Ti_{0.48}O_3$(PZT) (JSC "Research Institute Elpa", Moscow, Russia) with dimensions of 30 × 13 mm and a thickness of 0.25 mm each. Ag electrodes with a thickness of approximately 3 microns were deposited on the surface of the bimorph and the layers were polarized towards each other. The Metglas layer and the PZT-bimorph were connected using cyanoacrylate glue. The adhesive layer with a thickness of about 10 microns transmitted mechanical deformations across the interface and provided electrical insulation of the Metglas layer from the PZT-bimorph electrode. The structure was fixed on a massive base at one end, so that it could make bending vibrations. The choice of the PZT bimorph, which creates significantly larger deformations than a single PZT layer, allowed us to study the effects at low frequencies. The structure was placed between the poles of the electromagnet in a permanent magnetic field $H = 0...400$ Oe, applied along its long axis. Alternating current $I\cos(2\pi ft)$ was passed through the Metglas strip with an amplitude up to $I = 200$ mA and a frequency in the range of $f = 50$ Hz...10 MHz from the Agilent 33210A arbitrary waveform generator. An alternating voltage of U was applied to the PZT-bimorph electrodes from the second Agilent 33210A generator!$\cos(2\pi Ft)$ with a frequency of $F = 10$ Hz...100 kHz and an amplitude of up to 10 V, which created an alternating field in the piezoelectric with an amplitude of up to $E = 400$ V/cm. With the help of the lock-in amplifier SR850, the voltage drop $u\cos(2\pi ft + \varphi)$ was measured between the ends of the FM strip, where φ is the phase shift between voltage and current. From the measured values of voltage u and current I, the impedance of the Metglas strip $Z = u/I$ was determined, and then the magnitude of the magnetoimpedance MI at the field H was calculated by the formula

$$MI(H) = \frac{Z(H) - Z(H_S)}{Z(H_S)} 100\% \,, \tag{1}$$

where $Z(H)$ is the impedance of the FM strip at the field H, $Z(H_S)$ is the impedance in the saturation field H_S. The magnetic field was measured with a LakeShore model 421 gaussmeter with an accuracy of 0.1 Oe. Measurements were carried out first in the absence of an electric field, and then at different amplitudes and frequencies of the E field applied to the PZT bimorph. The frequency spectrum of the voltage on the Metglas strip was measured using a Siglent SSA3021X spectroanalyzer. All measurements were carried out at room temperature, which was maintained with accuracy 0.5° C.

2. Measurement results

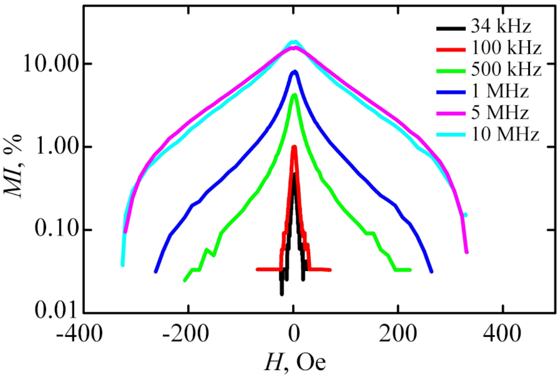

Fig. 2. Magnetoimpedance of the Metglas – PZT bimorph structure vs. dc magnetic field H for different current frequencies f (color online)

At the first stage, the characteristics of the magnetoimpedance in the described structure were investigated without applying voltage to the PZT bimorph. The current through the strip was set in the range $I = 20...200$ mA. In the absence of a field $H = 0$ at a current of 200 mA with a frequency of 1 MHz, the voltage drop on the strip was $u = 137$ mV and the impedance value was $Z(0) = 0.635$ Ω, and at a saturation field $H_S = 400$ Oe the impedance was equal to $Z(H_S) = 0.61$ Ω.

Figure 2 shows the dependences of the magnetoimpedance MI on the magnetic field H for different frequencies of the current f through the Metglas strip at a current amplitude $I = 200$ mA. For clarity, a logarithmic scale is selected along the vertical axis of the graph. It can be seen that with an increase in the current frequency from 34 kHz to 10 MHz, the magnitude of the magnetoimpedance increases and the field area where the magnetic field affects the impedance expands from about 20 to 334 Oe. The experimentally determined field $H_\mathrm{S} \approx 334$ Oe can be considered the saturation field of the magnetoimpedance (see formula (1)) in the strip Metglas.

The shape of the dependencies did not change when the direction of the magnetic field was inverted ($H \to -H$). Figure 3 shows the dependence of the magnetoimpedance MI on the frequency of the current f through the ferromagnetic layer of the structure in the absence of a magnetic field at $I = 200$ mA. It can be seen that with an increase in the frequency of the current, the magnetoimpedance monotonically increases and reaches a maximum value of 18 % at a frequency of about 10 MHz. Moreover, in the frequency range from 10 kHz to approximately 2 MHz in logarithmic coordinates, the dependence is linear. With an increase in the current frequency above 10 MHz, the magnetoimpedance decreased.

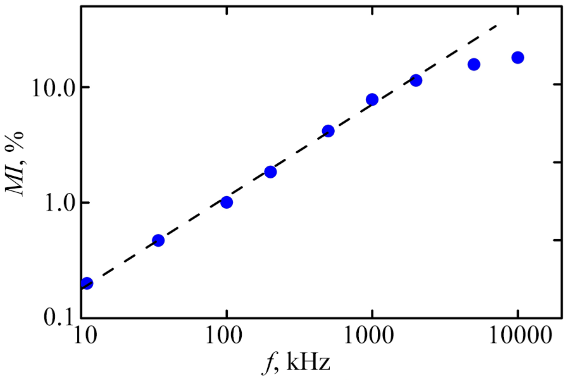

Fig. 3. Magnetoimpedance of the Metglas – PZT bimorph structure vs. current frequency f at $H = 0$

Then the effect of the electric field E applied to the PZT bimorph on the characteristics of the magnetoimpedance in the structure was investigated. Figure 4 shows an example of the MI voltage spectra measured for a current with an amplitude of 200 mA and a frequency of $f = 1$ MHz at $H = 0$ and different frequencies of the electric field F. It can be seen that the electric field leads to the modulation of the magnetoimpedance of the structure. In the absence of an alternating field ($E = 0$) and at all frequencies of the field, the amplitude of the central line of the spectrum was $u_0 \approx 10$ mV, and the width of the line at the base was 54 Hz. When an electric field was applied to the PZT-bimorph, two side lines appeared in the voltage spectrum on each side of the central component, spaced from it by a multiple of the pumping frequency. The appearance of side lines was observed at modulation frequencies from 60 Hz to 100 kHz. The amplitude of the lateral components of the spectrum nonmonotonically depended on the frequency of the electric field F. As can be seen from Fig. 4, the largest amplitude is $u_1 \approx 30$ m kV the first side component had at the frequency of the electric field $F = 11.2$ kHz.

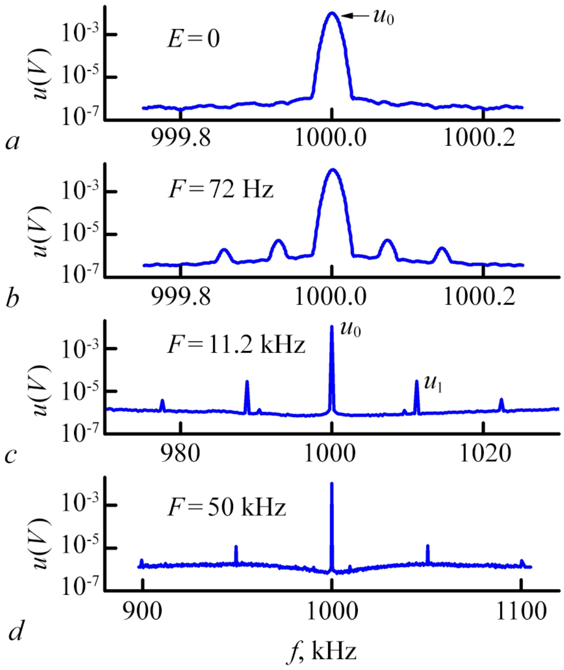

Fig. 4. Frequency spectrum of the MI voltage: a — without electric field, at the field $E = 400$ V/cm with frequency F: b — 72 Hz, c — 11.2 kHz, d — 50 kHz

Figure 5 shows as an example the dependence of the amplitude of the lateral component of the spectrum u_1 on the amplitude of the alternating electric field E at a current frequency

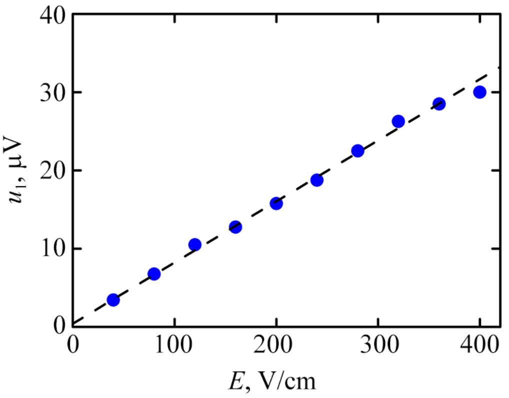

Fig. 5. Dependence of the spectrum side-line amplitude u_1 on the electric field E applied to the PZT bimorph at $f = 1$ MHz and $F = 11.2$ kHz

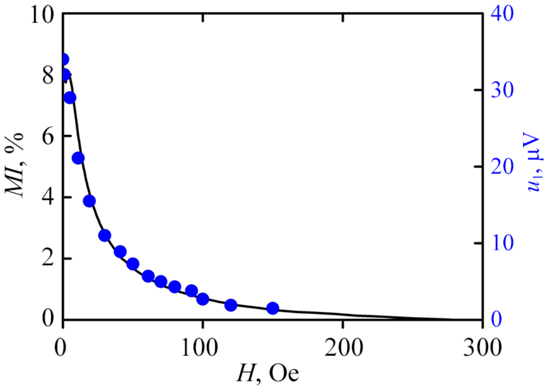

Fig. 6. Dependence of the spectrum side-line amplitude u_1 and magnetoimpedance MI on the dc magnetic field H at $f = 1$ MHz and $F = 11.2$ kHz

of 1 MHz, the frequency of the field $F = 11.2$ kHz and $H = 0$. It can be seen that in the studied range of field amplitudes, the dependence is linear. Figure 6 shows the dependence of the amplitude of the lateral component of the spectrum u_1 on the constant magnetic field H at the current frequency $f = 1$ MHz, the field frequency $F = 11.2$ kHz and the field amplitude $E = 400$ V/cm. For comparison, the same figure shows the field dependence of the magnetoimpedance $MI(H)$. It can be seen that the two field dependences practically overlap each other: the amplitude of the lateral component and the magnitude of the magnetoimpedance monotonically fall with the growth of the field. Dependences similar to those shown in Figs. 5 and 6 were observed at other frequencies of the current through the ferromagnet f and other frequencies of the electric field F.

3. Discussion

The magnetoimpedance effect in the ferromagnetic conductor layer occurs, as shown in [3], due to a decrease in the transverse magnetic permeability of the ferromagnet μ_T with an increase in the constant field H. Reducing μ_T causes an increase in the thickness of the skin layer

$$\delta = c/\sqrt{4\pi^2 f \sigma \mu_T}, \tag{2}$$

where c is the speed of light, $\sigma = 1/\rho$ is the material conductivity, f is the frequency. On the other hand, as follows from (2), the thickness of the skin layer δ decreases with an increase in the frequency of the current f. The competition of the two mechanisms leads to a change in both the real and imaginary parts of the impedance. The impedance of the strip ceases to change when the thickness of the skin layer becomes equal to about half the thickness of the ferromagnetic layer. This explains, in particular, the narrowing of the magnetic fields of the magnetoimpedance with a decrease in frequency (see Fig. 2). The shape of the $MI(H)$ and $MI(f)$ dependences shown in Fig. 2 and Fig. 3 and the maximum measured value of the magnetoimpedance in the Metglas strip are consistent with the data of other studies of magnetoimpedance in layers of amorphous ferromagnets at frequencies up to 10 MHz [1, 11].

The influence of the electric field E on the magnetoimpedance occurs due to the reverse ME effect in the composite structure [12]. The field applied to the PZT-bimorph causes bending deformation due to the inverse piezoelectric effect, this deformation is transmitted to the Metglas layer and reverse magnetostriction (the Villari effect) changes its magnetization M. As a result, the magnetic permeability μ changes, and hence the magnetoimpedance of the layer. When bending a PZT-bimorph, the deformation along its length is distributed inhomogeneously, which makes it difficult to establish a quantitative relationship between the impedance and the field strength E. In the dynamic mode, the ME effect leads to the modulation of the magnetoimpedance. The frequency spectrum shown in Fig. 4 has the form typical for a signal with amplitude modulation [13]

$$u(t) = u_0[(1 + m\cos(2\pi Ft)] \cdot \cos(2\pi ft). \tag{3}$$

Here m is the modulation coefficient, which is related to the amplitude of the main and side components of the spectrum as $m = 2u_1/u_0$. Substituting the data in Fig. 4, *c*, we get $m \approx 6\cdot10^{-3}$. The presence of a second side component in the spectra of Fig. 4 indicates the presence of a weak phase modulation of the magnetoimpedance voltage. The same type of field dependences of the magnetoimpedance $MI(H)$ and the amplitude of the side harmonic of the frequency spectrum MI voltage in Fig. 6 confirms the proposed explanation of the effect.

The measurements described above were also carried out on a structure where an amorphous ferromagnet without magnetostriction was used as a magnetic layer. Magnetoimpedance was observed in such a structure, but there was no modulation of the magnetoimpedance by an electric field, which confirms the role of the magnetoelectric effect.

Conclusion

Thus, the effect of magnetoimpedance in the planar composite heterostructure of Metglas–PZT in the frequency range from 10 kHz to 10 MHz is experimentally investigated. The maximum magnitude of the magnetoimpedance in the non-resonant mode reached 18.5%, which is consistent with the literature data. The narrowing of the magnetic fields of the magnetoimpedance with decreasing frequency is shown and explained. The effect of amplitude modulation of magnetoimpedance by an alternating electric field with a frequency of 60 Hz has been discovered and investigated...50 kHz applied to the piezo layer. The modulation occurs as a result of the converse magnetoelectric effect in the structure, which leads to a change in the magnetization of the ferromagnetic layer. The results can be used to create magnetic field sensors controlled by electric voltage.

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