The study of the Metglas/GaAs/Metglas magnetostrictive-piezo-semiconductive structure for practical application

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Abstract. The results of the samples study of the magnetostrictive-piezo-conductive structure based on Metglas/GaAs/Metglas with different geometric dimensions are presented in this article. The sizes of the studied samples were 10.2x5 2x0.63 mm; 15.2x5.1x0.63 mm; 20.1x5.2x0.63 mm - with epitaxial layers on a gallium arsenide (GaAs) plate and 15.2x5.1x0.62 mm - without epitaxial layers. The obtained results confirm the initial theoretical calculations of the observation of the maximum magnetoelectric effect in the plane of the GaAs (100) plate with the orientation of the long side of the sample along the crystallographic direction [011]. The maximum $\alpha_{\text{ME}}$ was observed in a sample with dimensions of 15.2x5.1x0.62 mm without epitaxial layers and was equal to $\alpha_{\text{ME}} = 54.19 \text{ V/(cm} \cdot \text{Oe)}$ at the resonance frequency $RF = 145.8 \text{ kHz}$. In conclusion, the prospects for practical application of a design based on the Metglas/GaAs/Metglas magnetostrictive-piezo-semiconductive structure as a magnetoelectric resistor, a magnetoelectric diode and a magnetoelectric transistor are given.

1. Introduction

Modern research and development in the field of magnetically sensitive electronic component base are focused on the search for new materials and structures that can significantly improve the parameters of electronic devices (sensitivity, speed, dynamic range, energy consumption, noise, resistance to external influences, etc.) and expand the scope of their application (sensors, biomedical equipment, automotive electronics, geological exploration, control systems, power electronics, etc.).

Against the background of the variety of magnetically sensitive components presented on the electronic market, magnetoelectric components are distinguished, the principle of operation of which is based on the magnetoelectric (ME) effect.

Due to the unique combination of properties, piezo-semiconductive materials (GaAs, SiC, GaN, AlN, etc.) have been widely used in recent years to create new electronic devices operating in a wide frequency range, gradually replacing silicon (Si) – traditionally the main material of semiconductor microelectronics.

Combining the unique properties of various magnetostrictive and piezo-semiconductive materials makes it possible to obtain new magnetostrictive-piezo-semiconductive structures.

The research of new magnetostrictive-piezo-semiconductive structures and the development of technologies for their manufacture conduces the implementation of ME devices based on them in a wide frequency range, which is currently a very urgent task.
The investigation in the field of the ME effect in various materials and the formation of promising composite ME structures for appliances and devices has been actively conducted in many world scientific centers in recent years, and the number of publications is growing from year to year. Currently, more and more scientific groups are already moving from the study of various materials to the development of physical principles for the creation, calculation and modeling of devices whose work is based on the ME effect. The analogues of ME devices are products of magnetically sensitive electronics, primarily discrete magnetic field converters (Hall elements, magnetodiodes, magnetotransistors, magnetotyristors, magnetoresistors) and integrated devices (magnetically sensitive and magnetically controlled integrated circuits) [1].

The ME effect consists in inducing electric polarization in the material in an external magnetic field or in the appearance of magnetization in an external electric field. The ME effect in single-crystal materials is observed at temperatures significantly lower than room temperature, and in the materials themselves, the values of the ME coefficients are insufficient for practical use. To a large extent, composite materials based on magnets and piezoelectrics are free from these disadvantages. Due to the possibility of varying materials with different physical properties, there are wide opportunities for composite materials to optimize the characteristics of devices based on them [2, 3].

Composite ME materials are bulk and layered structures based on magnetostrictive materials (magnetic metals and their alloys, ferrites) and piezoelectrics (ferroelectrics, piezo-semiconductors). Composite materials have not only the properties of the initial components, but also exhibit new properties, for example, the ME effect [4, 5], due to the mechanical interaction between the piezoelectric (piezo-semiconductive) and magnetic (magnetostrictive) phases of the composite material. In such materials, the ME effect is already manifested at room temperatures. In addition, it becomes possible to plan the ME properties of a composite material by changing the composition of the magnetic (ferrite) and piezoelectric (piezo-semiconductive) phases. From a macroscopic point of view, a composite ME material can be described as a homogeneous material with an ME effect that is absent in each phase of the composite material separately.

The purpose of this article is to study the effect of the epitaxial layer of the GaAs plate on the value of the ME effect in the Metglas/GaAs/Metglas magnetostrictive-piezoelectric-semiconductive structure. It is planned to further use this structure for the design of a ME resistor, a ME diode and a ME transistor with specified parameters.

2. Magnetoelectric effect in piezo-semiconductive structures

In recent years, there has been an increase in the number of works devoted to the study of the ME effect in magnetostrictive-piezoelectric structures based on piezoelectric conductors (semiconductor materials with a piezoelectric effect). Such materials include GaAs, SiC, GaN, AlN, etc.

In [6], the ME effect in the AlN/CoFe structure was studied, and a systematic study of structural, piezoelectric, magnetic and magnetoelectric properties was carried out. The two-layer thin film demonstrated good piezoelectric and magnetic (ferromagnetic) properties, as well as the ME effect. In [7], the ME effect in the field of electromechanical resonance (EMR) was experimentally studied for the first time in structures in the form of gallium arsenide substrates metallized on both sides with a thin film of nickel or cobalt and gold films (Ni-GaAs-Au and Co-GaAs-Au). The dependence of the ME effect on the magnetizing field in the Ni-GaAs-Au structure has an anomalous shape, which is unusual for known composite ME materials based on ceramic piezoelectrics. The maximum ME coefficient in the resonance is 81.2 V/A, which corresponds to a giant ME effect at room temperature. It is shown that this resonance is characterized by a high Q-factor which amounts up to 8000. In [8], the ME effect was found in the structure of gallium arsenide/amorphous ferromagnetic alloy. The authors investigated the ME effect in the gallium arsenide plane (100) within the EMR range of 200-240 kHz and obtained the maximum of \( \alpha_{ME} \) 120 V/A in the displacement field of 3.6 kA/m for a composite ME sample whose long side was oriented in the direction [011]. The paper also discusses the ME effect in the planes (110) and (111). The results can be used for designing new electronic devices based on magnetostriective-piezo-conductive materials. The paper [9] presents the results of
modeling and measuring the output currents and sensitivity of a gallium nitride magnetotransistor with high electron mobility (MagHEMT) with two sources. Conclusions are drawn about the prospects of GaN as a magnetotransistor material. In [10], the magnetic anisotropy of Fe films grown on GaAs substrates of orientation (001) using Ge buffer layers was studied by measuring the planar Hall effect. In addition to the phenomena arising from the dominant cubic symmetry of the Fe sample, the study of the angular dependence of the magnetization reversal revealed a violation of this symmetry in the form of systematic asymmetric shifts of magnetic hysteresis loops around the crystallographic directions [110]. In the article [11], the ME characteristics of multiferroic heterostructures with different thicknesses of a nanocrystalline soft magnetic alloy in the low frequency range are studied. The proposed heterostructures not only significantly improve the ME coupling, but also expand the operating range of the direct current (DC) magnetic displacement and overcome the limitations of a narrow displacement range. In [12], a giant ME effect is reported in a thin-film composite consisting of thin films of AlN and an amorphous ferromagnetic alloy obtained by magnetron sputtering on a silicon substrate. The $\alpha_{ME}$ was 737 V/cm·Oe at the EMR frequency amounted to 753 Hz. In [13], the ME effect was studied in a composite consisting of layers of lithium niobate with a bidomain structure and Metglas in the bending mode. The maximum measured sensitivity to the magnetic field of such a structure reached 200 fT. Thus, a large number of materials with the presence of the ME effect, suitable for practical use, have been studied at present. However, most of the proposed appliances and devices, the operation of which is based on the use of the ME effect, does not imply the use of semiconductor materials and structures to create active appliances and devices.

3. The design of the studied structures
In this paper, layered structures consisting of a semiconductor piezoelectric material – gallium arsenide (GaAs) with a crystallographic surface orientation (100) and an amorphous magnetic material Metglas were studied for the presence of the ME effect and further application of the Metglas/GaAs/Metglas magnetostrictive-piezoelectric-semiconductive structure in devices based on a new component base. The design of the studied Metglas/GaAs/Metglas magnetostrictive-piezoelectric-semiconductive structures is shown in Figure 1.

![Figure 1. The design of the studied Metglas/GaAs/Metglas magnetostrictive-piezoelectric-semiconductive structures.](image)

The Metglas/GaAs/Metglas structure consists of a gallium arsenide (GaAs) (100) plate with a thickness of 0.5 mm (500 microns) and three layers of amorphous soft magnetic Metglas AMAG492 alloy (JSC "MSTATOR", Russia) on each side of the plate with a total thickness of 0.06 mm (60 microns) (the thickness of the Metglas layer (plate) is 0.02 mm (20 microns)). The gallium arsenide (GaAs) (100) plate contains epitaxial layers: GaAs n+ with a thickness of 0.1 microns and a concentration of 5x10¹⁸ cm⁻³; GaAs n with a thickness of 0.3 microns and a concentration of 5x10¹⁶ cm⁻³; GaAs n- with a thickness of 1 microns and a concentration of 1x10¹⁴ cm⁻³. The Metglas plates
were connected to the GaAs plates by means of an adhesive layer. BF-2 GOST 12172-2016 was chosen as the glue. The thickness of the adhesive joint in all magnetostrictive-piezoelectric structures amounted to 0.01 mm (10 microns).

The sizes of the studied samples of magnetostrictive-piezoelectric structures equal to 10.2x5.2x0.63 mm; 15.2x5.1x0.63 mm; 20.1x5.2x0.63 mm - with epitaxial layers on the gallium arsenide (GaAs) plate, necessary according to the technology for the manufacture of semiconductor devices, and 15.2x5.1x0.62 mm - without epitaxial layers on the gallium arsenide (GaAs) plate.

4. Measuring stand for conducting research
The research was carried out on a measuring stand (Figure 2), which is a set of equipment consisting of an HMO722 oscilloscope (for displaying research results), a constant magnetic field source (a permanent magnet) and an alternating magnetic field source (an HMF2550 generator with a Helmholtz coil). The studied sample of the magnetostrictive-piezoelectric structure was affected by constant and alternating magnetic fields. The values of the magnetic field were measured by an intelligent digital gaussmeter / teslameter DX-180.

The measuring stand works as follows. An alternating signal from the generator is applied to the Helmholtz coil, providing an alternating magnetic field $H_\sim$ of 1 Oe. A permanent magnet creates a constant magnetic field $H_0$, which is 60 Oe. As a result of the influence of the magnetostrictive-piezoelectric structure of constant and alternating fields on the sample due to the transverse ME effect, an electric voltage arises between the upper and lower layers of the Metglas, which is recorded by an oscilloscope.

![Figure 2. Structural scheme of the measuring stand.](image)

5. Findings
The theoretical study of the ME interaction in layered structures of an amorphous ferromagnetic alloy and single-crystal gallium arsenide was profoundly considered in [8].

Experimental studies of the Metglas/GaAs/Metglas magnetostrictive-piezo-semiconductive structure samples with epitaxial layers on a GaAs gallium arsenide plate of different sizes and without epitaxial layers are shown in Figures 3, 4.
Figure 3. The correlation of the $\alpha_{ME}$ and frequency in the Metglas/GaAs/Metglas magnetostrictive-piezo-semiconductive structure of the studied samples with epitaxial layers on the GaAs gallium arsenide plate.

Figure 3 shows the results of the correlation of the $\alpha_{ME}$ and frequency in the Metglas/GaAs/Metglas magnetostrictive-piezo-semiconductive structure of the studied samples with epitaxial layers in a GaAs gallium arsenide plate of different sizes.

Theoretical calculations were carried out using formulas 1 and 2 for the longitudinal mode [3].

The main resonant frequency:

$$f_r = \frac{1}{2l} \sqrt{\frac{c_{11}}{\rho}}$$  \hspace{1cm} (1)

Resonant maximum of the $\alpha_{ME}$:

$$\alpha_{ME} = \frac{8Q^mP_0^m\eta q_{11d33}}{\pi^2c_{11}(\varepsilon\varepsilon_0^2\rho x_{11}-d_{33}^2)}$$  \hspace{1cm} (2)

The maximum values of the $\alpha_{ME}$ and resonant frequencies for the Metglas/GaAs/Metglas structure of various geometric dimensions are summarized in Table 1.
Table 1. Comparison of calculated and measured resonant frequencies.

| Sample dimensions, mm | Theoretical Findings | Experimental Findings |
|-----------------------|-----------------------|-----------------------|
|                       | Resonant frequency, kHz | $\alpha_{\text{ME}}, \text{V/(cm-Oe)}$ | Resonant frequency, kHz | $\alpha_{\text{ME}}, \text{V/(cm-Oe)}$ |
| 10.2x5.2x0.63         | 196.7                  | 12.274                | 207.2                  | 11.05                  |
| 15.2x5.1x0.63         | 131.2                  | 42.242                | 139.6                  | 41.91                  |
| 20.1x5.2x0.63         | 98.375                 | 49.096                | 106.8                  | 46.35                  |

Thus, the theoretical calculation is in satisfactory agreement with the experimental data. Small discrepancies between the theoretical and experimental resonant frequencies may be due to the fact that the glue connection is not taken into account in the theoretical calculation. Also, the conclusions soldered to the Metglas in order to remove the $\alpha_{\text{ME}}$ could somewhat violate the model of a completely free sample used in the theoretical calculation. The quantitative difference between the theoretical and experimental resonant values of the ME coefficient is due to the fact that the calculation used the value of the $q_{11}$ pseudo-piezomagnetic coefficient at the optimal magnetizing field, when it and, consequently, the magnetoelectric coefficient have the maximum value. In the experiment, the value of the $q_{11}$ coefficient did not reach its maximum value, which led to a slight quantitative discrepancy between the theoretical calculations and the experimental results.

It can be seen from Figure 3 and Table 1 that as the sample length increases, the $\alpha_{\text{ME}}$ increases and the resonance frequency decreases. The increase in the ME coefficient is due to an increase in the amplitude of mechanical vibrations of both the piezoelectric (piezo-semiconductive) and magnetostrictive phases of the composite material.

Two peaks corresponding to the resonances of interrelated oscillations in the magnetostrictive and piezoelectric phases are observed in a sample of the Metglas/GaAs/Metglas magnetostrictive-piezoelectric-semiconductive structure with dimensions of 20.1x5.2x0.63 mm. This is caused by an imperfect contact between the phases at the resonant frequency – a poor-quality connection of the GaAs gallium arsenide plate and the Metglas plates.

In the studied samples of magnetostrictive-piezoelectric structures on the GaAs gallium arsenide plate, there were epitaxial layers required according to the technology for the manufacture of semiconductor devices.

Further, studies of samples of magnetostrictive-piezoelectric structures on a GaAs gallium arsenide plate without epitaxial layers were carried out.

The GaAs gallium arsenide plate with epitaxial layers was etched in a buffer etcher: water – hydrogen peroxide – sulfuric acid in a ratio of 200:1:1 for 100 minutes (1 hour 40 minutes). The thickness of the etched epitaxial layers of the GaAs plate under consideration was 0.01 mm (10 microns). It follows that the thickness of the GaAs plate has decreased from 0.5 mm to 0.49 mm.

After etching the epitaxial layers on the GaAs plate, a sample of the Metglas/GaAs/Metglas structure with dimensions of 15.2x5.1x0.62 mm was obtained.

The results of measurements of the Metglas/GaAs/Metglas structure samples without epitaxial layers and with epitaxial layers are shown in Figure 4.
Figure 4 shows a comparison of the correlation between the $\alpha_{ME}$ and the frequency in Metglas/GaAs/Metglas structure samples with dimensions of 15.2x5.1x0.63 mm with epitaxial layers on a GaAs gallium arsenide plate and dimensions of 15.2x5.1x0.62 mm without epitaxial layers.

The maximum values of the $\alpha_{ME}$ and resonant frequencies for the Metglas/GaAs/Metglas structure of various sizes are summarized in Table 2.

| Sample dimensions, mm | Theoretical Findings | Experimental Findings |
|-----------------------|----------------------|-----------------------|
|                       | Resonant frequency, kHz | $\alpha_{ME}$, V/(cm·Oe) | Resonant frequency, kHz | $\alpha_{ME}$, V/(cm·Oe) |
| 15.2x5.1x0.63         | 131.2                 | 42.242                 | 139.6                 | 41.91                  |
| 15.2x5.1x0.62         | 131.6                 | 56.46                  | 145.8                 | 54.19                  |

The theoretical calculation is in satisfactory agreement with the experimental data. Small discrepancies between theory and experiment are explained by the same reasons.

It is known that with approximately the same mechanical compliance of the magnetostrictive and piezoelectric phases, the optimal composition of the layered composite corresponds to approximately equal thicknesses of both phases. The sample with the etched epitaxial layer has a slightly smaller thickness of the piezoelectric layer, so its phase composition is somewhat closer to the optimal one. Therefore, it is clear that its resonant value of the $\alpha_{ME}$ is greater than that of a sample with an epitaxial layer.
6. Conclusion

The results of the samples' study of the Metglas/GaAs/Metglas magnetostrictive-piezo-semiconductive structure with epitaxial layers on a GaAs gallium arsenide plate and without them are presented in this article.

An important result obtained in this study is the possibility of practical application of the ME structure design for the development of various ME devices.

Since the presence of epitaxial layers in GaAs does not significantly reduce the ME effect, this fact enables manufacturing ME resistors of various geometric sizes for a wide range of resistances, which expands the possibilities of their production (a large range of resistances, small size, low cost, etc.).

In addition, the use of epitaxial layers for the manufacture of ME active elements, such as a ME diode and a ME transistor, etc., makes it possible to change the doping profile in the manufactured structure in a much wider range. This property will significantly improve the characteristics of the ME of active elements and expand the possibilities of using the developed electronic devices.

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