УДК 537.9 DOI: https://doi.org/10.34680/2076-8052.2021.2(123).39-42

EXPLORATORY DEVELOPMENT OF THE LONGITUDINAL AND THICKNESS MODES OF THE MAGNETOELECTRIC EFFECT IN A MAGNETOSTRICTIVE-PIEZOELECTRIC TWO-LAYER STRUCTURE METGLAS/SILICON CARBIDE

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ИССЛЕДОВАНИЕ ПРОДОЛЬНОЙ И ТОЛЩИННОЙ МОД МАГНИТОЭЛЕКТРИЧЕСКОГО ЭФФЕКТА В МАГНИТОСТРИКЦИОННО-ПЬЕЗОЭЛЕКТРИЧЕСКОЙ ДВУХСЛОЙНОЙ СТРУКТУРЕ МЕТГЛАС/КАРБИД КРЕМНИЯ

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This article presents the results of a study of the longitudinal and thickness modes in the field of electromechanical resonance in a magnetoelectric composite structure. Magnetoelectric structures of the composition Metglas/4H-SiC and Metglas/6H-SiC were theoretically explored. When obtaining theoretical results, the material parameters of the constituent phases of the composite structures were used. The calculated characteristics are compared for two different polytypes of silicon carbide 4H-SiC and 6H-SiC. It was found that the value of the resonance magnetoelectric coefficient in the Metglas/6H-SiC structure is higher than in the Metglas/4H-SiC structure for both the longitudinal and the thickness modes. The results obtained can be used in the future in the design of active semiconductor devices based on the ME effect.

Keywords: magnetoelectric effect, magnetoelectric structure, silicon carbide

For citation: Sokolov O.V., Ivanov S.N., Petrov D.A., Bichurin M.I. Exploratory development of the longitudinal and thickness modes of the magnetoelectric effect in a magnetostrictive-piezoelectric two-layer structure Metglas/silicon carbide // Vestnik NovSU. Issue: Engineering Sciences. 2021. №2(123). P.39-42. DOI: https://doi.org/10.34680/2076-8052.2021.2(123).39-42

Представлены результаты исследования продольной и толщинной мод в области электромеханического резонанса в магнитоэлектрической композитной структуре. Были теоретически исследованы магнитоэлектрические структуры состава Метглас / 4H-SiC и Метглас / 6H-SiC. При получении теоретических результатов были использованы материальные параметры составляющих фаз композитных структур. Проведено сравнение расчетных характеристик для двух различных политипов карбида кремния 4H-SiC и 6H-SiC. Выяснено, что величина резонансного магнитоэлектрического коэффициента в структуре Метглас / 6H-SiC больше, чем в структуре Метглас / 4H-SiC как для продольной, так и для толщинной моды. Полученные результаты можно использовать в дальнейшем при проектировании активных полупроводниковых устройств, основанных на МЭ эффекте.

Ключевые слова: магнитоэлектрический эффект, магнитоэлектрическая структура, карбид кремния

Для цитирования: Соколов О.В., Иванов С.Н., Петров Д.А., Бичурин М.И. Исследование продольной и толщинной мод магнитоэлектрического эффекта в магнитострикционно-пьезоэлектрической двухслойной структуре Метглас/карбид кремния // Вестник НовГУ. Сер.: Технические науки. 2021. №2(123). С.39-42. DOI: https://doi.org/10.34680/2076-8052.2021.2(123).39-42

Introduction

The magnetoelectric (ME) effect manifests itself as the induction of electric polarization in a material in a magnetic field or magnetization in an electric field. In magnetostrictive-piezoelectric layered structures, the ME effect is due to the mechanical interaction of the magnetic and electrical subsystems; therefore, in the region of electromechanical resonance (EMR), for example, longitudinal or thickness, a significant increase in the ME coefficient is observed.

Quantitatively, the ME effect is characterized by the ME voltage coefficient α_E, which is equal to the ratio of the intensity of the induced alternating electric field to the intensity of the applied magnetic alternating field under conditions of an open electric circuit. The value of the coefficient is determined by the dimensions of the structure, magnetic, dielectric, piezoelectric and mechanical parameters of its constituent components. In contrast to single-phase materials, the ME interaction between the piezoelectric and magnetostrictive phases of the composite material leads to large values of the ME coefficients [1-3]. It was found that the values of the ME susceptibility at room temperature are several orders of magnitude higher than in the known single-phase ME materials. This allows the use of magnetostrictive-piezoelectric composite materials in multifunctional devices such as ME transducers, sensors, microwave devices, etc. [4.5]. The purpose of this article is a detailed theoretical study of the longitudinal and thickness modes of the magnetoelectric effect in the EMR region in the magnetostrictive-piezoelectric two-layer structures Metglas/4H-SiC and Metglas/6H-SiC.

Piezoelectric Coefficients and Compliance Coefficients of Silicon Carbide

4H-SiC and 6H-SiC belong to the C^4_{6v}-$P6_3mc$ symmetry group (hexagonal system). Therefore, the required components of the compliance tensor are expressed in terms of the known reference data on the stiffness coefficients [6] as follows

$$
\begin{aligned}
{}^{p}s_{11} &= \frac{{}^{p}c_{11}\,{}^{p}c_{33} - {}^{p}c_{13}^{2}}{\left({}^{p}c_{11} - {}^{p}c_{12}\right)\left({}^{p}c_{11}\,{}^{p}c_{33} + {}^{p}c_{12}\,{}^{p}c_{33} - 2\,{}^{p}c_{13}^{2}\right)},\\
{}^{p}s_{12} &= \frac{{}^{p}c_{13}^{2} - {}^{p}c_{12}\,{}^{p}c_{33}}{\left({}^{p}c_{11} - {}^{p}c_{12}\right)\left({}^{p}c_{11}\,{}^{p}c_{33} + {}^{p}c_{12}\,{}^{p}c_{33} - 2\,{}^{p}c_{13}^{2}\right)},\\
{}^{p}s_{13} &= \frac{-{}^{p}c_{13}}{{}^{p}c_{11}\,{}^{p}c_{33} + {}^{p}c_{12}\,{}^{p}c_{33} - 2\,{}^{p}c_{13}^{2}},\\
{}^{p}s_{33} &= \frac{{}^{p}c_{11} + {}^{p}c_{12}}{{}^{p}c_{11}\,{}^{p}c_{33} + {}^{p}c_{12}\,{}^{p}c_{33} - 2\,{}^{p}c_{13}^{2}}.
\end{aligned}
\tag{1}
$$

The necessary components of the piezoelectric tensor at constant mechanical stress are expressed through the known reference data on the piezoelectric coefficients at constant strain [7] as follows

$$
\begin{aligned}
d_{31} = d_{32} &= \left({}^{p}s_{11} + {}^{p}s_{12}\right)e_{31} + {}^{p}s_{13}e_{33},\\
d_{33} &= 2\,{}^{p}s_{13}e_{31} + {}^{p}s_{33}e_{33}.
\end{aligned}
\tag{2}
$$

Magnetoelectric effect in the region of the longitudinal mode

Let us consider longitudinal vibrations in a two-layer magnetostrictive-piezoelectric structure Metglas/silicon carbide. We will assume that the sample has the shape of a thin bar, whose thickness and width are much less than the length. In this case, we can consider only one component of the stress and strain tensor. The piezoelectric phase in the form of silicon carbide is cut from a plate lying in the (0001) plane, the long side is directed along the <2-1-10> crystallographic direction.

Total composite thickness:

$$t = {}^{p}t + {}^{m}t. \tag{3}$$

Volume fractions of piezoelectric and magnetostrictive phases:

$$
\begin{aligned}
{}^{p}v &= \frac{{}^{p}t}{t},\\
{}^{m}v &= \frac{{}^{m}t}{t}.
\end{aligned}
\tag{4}
$$

Effective composite density:

$$\rho = {}^{p}v\,{}^{p}\rho + {}^{m}v\,{}^{m}\rho. \tag{5}$$

The axis X is drawn along the interface between the magnetostrictive and piezoelectric phases:

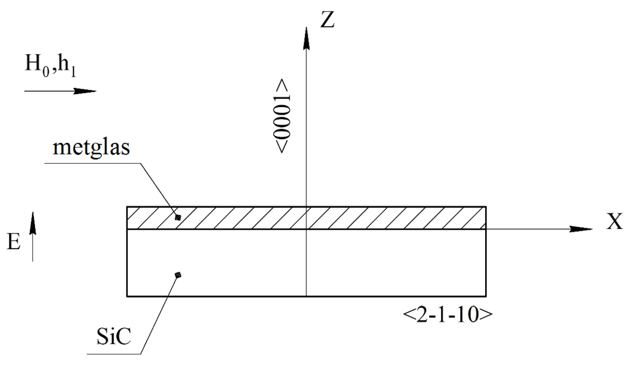

Figure 1. Direction of the applied magnetic fields to the ME composite in the case of the longitudinal ME effect

A detailed derivation of the formula for the ME voltage coefficient is given in [6]. Therefore, here we give only the final expression

$$\alpha_{E} = -\frac{2\,{}^{m}v\,{}^{p}t h_{31}\bar{q}_{11}\beta_{33}^{S}\tan(\eta)}{ktl\beta_{33}^{S}\langle c_{11}\rangle + 2h_{31}^{2}\,{}^{p}t\tan(\eta)}. \tag{6}$$

Figure 2 shows the calculated theoretical dependences of the ME voltage coefficient on the frequency of the alternating magnetic field. For the calculation, the following geometric dimensions were used ${}^{p}t = 0{,}5$ mm, ${}^{m}t = 29$ mkm, l = 1 cm, resonance quality factor Q = 130; material parameters 4H-SiC ${}^{p}s_{11}^{E} = 2{,}08{\cdot}10^{-12}$ m^2/N, $d_{31} = -3{,}96{\cdot}10^{-13}$ m/V; 6H-SiC ${}^{p}s_{11}^{E} = 2{,}09{\cdot}10^{-12}$ m^2/N, $d_{31} = -4{,}06{\cdot}10^{-13}$ m/V.

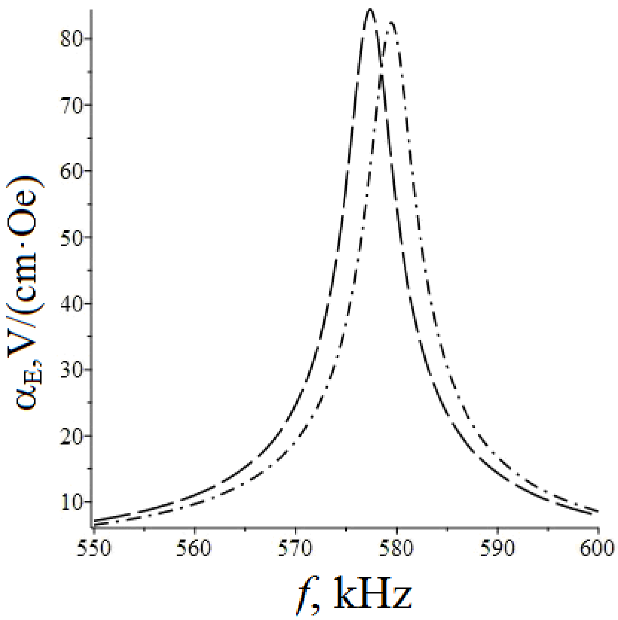

Figure 2. Frequency dependence of the ME voltage coefficient for the longitudinal mode. The dash-dotted line is 4H-SiC, the long-dashed line is 6H-SiC

As can be seen from Fig. 2, the resonance frequency for the 6H-SiC polytype is slightly lower than for 4H-SiC, and the magnitude of the resonant ME voltage coefficient, on the contrary, is somewhat higher.

Magnetoelectric effect in the region of the thickness mode

To excite the thickness mode, the dc and ac magnetic fields must be directed along the thickness of the ME structure:

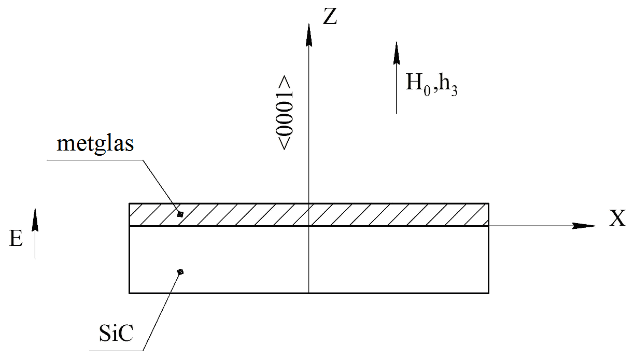

Figure 3. Direction of the applied magnetic fields to the ME composite in the case of the thickness ME effect.

Third components of strain tensors for magnetostrictive and piezoelectric phases:

$$
\begin{aligned}
{}^{m}S_3 &= \frac{\partial^{m} u_3}{\partial z},\\
{}^{p}S_3 &= \frac{\partial^{p} u_3}{\partial z}.
\end{aligned}
\tag{7}
$$

The third components of the stress tensor and the electric voltage vector of the piezoelectric:

$$ {}^{p}T_3 = \bar{c}_{33}^{D}\,{}^{p}S_3 - \bar{h}_{33} D_3, \tag{8} $$

$$ E_3 = -\bar{h}_{33}\,{}^{p}S_3 + \bar{\beta}_{33}^{S} D_3, \tag{9} $$

where

$$
\begin{aligned}
\bar{c}_{33}^{D} &= \left({}^{p}s_{33}^{E} - \frac{d_{33}^{2}}{\varepsilon_{33}^{T}\varepsilon_0} \right)^{-1},\\
\bar{h}_{33} &= \frac{\bar{c}_{33}^{D} d_{33}}{\varepsilon_{33}^{T}\varepsilon_0},\\
\bar{\beta}_{33}^{S} &= \frac{1 + \bar{h}_{33} d_{33}}{\varepsilon_{33}^{T}\varepsilon_0}.
\end{aligned}
\tag{10}
$$

The third component of the stress tensor of the magnetostrictive phase:

$$ {}^{m}T_3 = {}^{m}Y\,{}^{m}S_3 - \bar{q}_{33} h_3, \tag{11} $$

where $\bar{q}_{33} = {}^{m}Y q_{33}$.

Equations of thickness vibrations for magnetostrictive and piezoelectric phases:

$$
\begin{aligned}
{}^{m}\rho \frac{\partial^2\, {}^{m}u_3}{\partial \tau^2} &= \frac{\partial\, {}^{m}T_3}{\partial z},\\
{}^{p}\rho \frac{\partial^2\, {}^{p}u_3}{\partial \tau^2} &= \frac{\partial\, {}^{p}T_3}{\partial z}.
\end{aligned}
\tag{12}
$$

Let us also substitute (8) and (11) in the equations of thickness vibrations (12):

$$
\begin{aligned}
\frac{\partial^2\, {}^{m}u_3}{\partial z^2} + {}^{m}k^2\, {}^{m}u_3 &= 0,\\
\frac{\partial^2\, {}^{p}u_3}{\partial z^2} + {}^{p}k^2\, {}^{p}u_3 &= 0,
\end{aligned}
\tag{13}
$$

where

$$
\begin{aligned}
{}^{m}k &= \omega\sqrt{\frac{{}^{m}\rho}{{}^{m}Y}},\\
{}^{p}k &= \omega\sqrt{\frac{{}^{p}\rho}{\bar{c}_{33}^{D}}}.
\end{aligned}
\tag{14}
$$

General solutions of equations of motion (13):

$$
\begin{aligned}
{}^{p}u_3 &= A\cos({}^{p}kz) + B\sin({}^{p}kz),\\
{}^{m}u_3 &= C\cos({}^{m}kz) + D\sin({}^{m}kz).
\end{aligned}
\tag{15}
$$

Open circuit condition:

$$ D_3 = 0. \tag{16} $$

Boundary conditions for free fixing of the upper and lower edges of the magnetoelectric composite

$$
\begin{aligned}
{}^{m}T_3\big|_{z={}^{m}t} &= 0,\\
{}^{m}u_3\big|_{z=0} &= {}^{m}u_3\big|_{z=0},\\
{}^{m}T_3\big|_{z=0} &= {}^{p}T_3\big|_{z=0},\\
{}^{p}T_3\big|_{z=-{}^{p}t} &= 0.
\end{aligned}
\tag{17}
$$

From (17) we obtain a linear system of four inhomogeneous algebraic equations with respect to four unknowns A, B, C, D. Solving this system, we find

$$
\begin{aligned}
A &= \frac{\bar{q}_{33} r_3 (r_1 - 1) h_3}{\bar{c}_{33}^{D}\,{}^{p}k r_1 r_4 + {}^{m}Y\,{}^{m}k r_2 r_3},\\
B &= -\frac{\bar{q}_{33} r_4 (r_1 - 1) h_3}{\bar{c}_{33}^{D}\,{}^{p}k r_1 r_4 + {}^{m}Y\,{}^{m}k r_2 r_3},
\end{aligned}
\tag{18}
$$

where

$$
\begin{aligned}
r_1 &= \cos({}^{m}k\,{}^{m}t),\\
r_2 &= \sin({}^{m}k\,{}^{m}t),\\
r_3 &= \cos({}^{p}k\,{}^{p}t),\\
r_4 &= \sin({}^{p}k\,{}^{p}t).
\end{aligned}
\tag{19}
$$

Let's find the electric voltage across the piezoelectric:

$$ U = \int_{-{}^{p}t}^{0} E_3 dz = -\bar{h}_{33}\left[A(1 - r_3) + B r_4\right]. \tag{20} $$

Substituting (18) in (20) we find the ME voltage coefficient:

$$ \alpha_E = \frac{\bar{E}_3}{h_3} = -\frac{\bar{q}_{33}\bar{h}_{33}(1 - r_1)(1 - r_3)}{t\left(\bar{c}_{33}^{D}\,{}^{p}k r_1 r_4 + {}^{m}Y\,{}^{m}k r_2 r_3\right)}. \tag{21} $$

Below in Fig. 4 shows the dependence of the ME voltage coefficient on the frequency of the alternating magnetic field. For the calculation, the same geometrical dimensions and figure of merit were used as for the longitudinal mode; material parameters 4H-SiC ${}^{p}s_{33}^{E} = 1{,}75 \cdot 10^{-12}$ m^2/N, $d_{33} = 7{,}06 \cdot 10^{-13}$ m/V; 6H-SiC ${}^{p}s_{33}^{E} = 1{,}79 \cdot 10^{-12}$ m^2/N, $d_{33} = 8{,}08 \cdot 10^{-13}$ m/V.

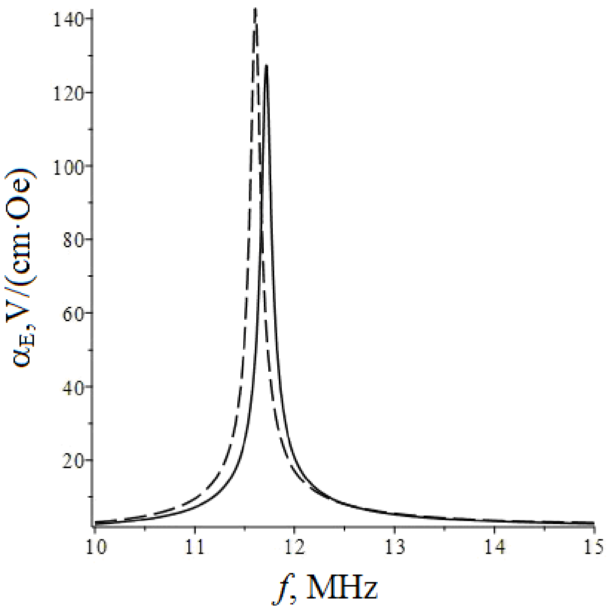

Figure 4. Frequency dependence of the ME voltage coefficient for the thickness mode. The solid line is 4H-SiC, the dashed line is 6H-SiC

Fig. 4 shows that the resonant frequency for the 6H-SiC polytype is somewhat lower than for 4H-SiC, and the magnitude of the resonant ME voltage coefficient, on the contrary, is somewhat higher.

Conclusion

The article discusses a theoretical model of the magnetoelectric effect for longitudinal and thickness modes in the EMR region. Two-layer samples consisting of a magnetostrictive Metglas material and piezoelectric semiconductor materials 4H-SiC and 6H-SiC were studied as structures under study.

In the theoretical calculation of the composite structures under study, the resonance value of the ME coefficient for the 6H-SiC polytype turned out to be somewhat higher than for the 4H-SiC polytype, both for the longitudinal mode and for the thickness mode.

Semiconductors 4H-SiC and 6H-SiC are promising for use as piezoelectrics in ME composites. Although they have slightly lower piezoelectric moduli than traditional piezoelectric materials, they have a lower relative permittivity, which contributes to an increase in the ME coefficients. It is also promising to use the active semiconductor properties of the considered materials in devices based on the ME effect.

The study was carried out with the financial support of the RFBR grant No. 19-07-00391 A.

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