UDC 534.133

[0000-0002-1571-401X] **C. V. Bazilo,** *Dr.Sc. (Eng.), associate professor,*
[0000-0001-9806-3453] **V. V. Khlivnyi,**
[0000-0002-5179-8329] **Yu. Yu. Bondarenko,** *Ph.D. (Eng.), associate professor*
Cherkasy State Technological University
Shevchenko blvd, 460, Cherkasy, 18006, Ukraine

MODIFICATION AND PRACTICAL APPLICATION OF PIEZOELECTRIC TRANSDUCERS WITH SEPARATED ELECTRODES

The paper presents the results of improving the technology of forming current-conducting electrodes of piezoelectric elements and the development of devices from piezoelectric ceramics with separated electrodes by a method based on the technology of combined electron-beam modification. The prospect of using the method of thermal vacuum deposition for obtaining electrode coatings on products made of piezoelectric ceramics of the PZT grade is shown. It has been found that silver coatings formed by the proposed technology on piezoelectric elements are more uniform and homogeneous in comparison with the coatings obtained by the traditional (industrial) method. As a practical result of the implementation of the technology proposed in the article, designs of piezoelectronic devices based on elements made of piezoelectric ceramics with separated electrodes formed on their surface, in particular, a multisectional piezoelectric transducer, have been developed. Changing the size of the electrodes, their relative position allows to influence the parameters of the output signals and opens wide opportunities for the design of piezoelectric transducers of computer systems for critical applications. The main advantage of using transducers made from piezoceramic materials in computer systems is due to their special structure, which allows to implement fundamentally different schemes in one such element.

Keywords: *piezoelectric transducer, piezoelectric ceramics, conductive electrode, separated electrodes, combined electron-beam modification technology.*

Introduction. Currently, the leading manufacturers of radio-electronic components serially produce a fairly large list of elements that include various microelectromechanical structures. The main advantage of using elements made of piezoceramic materials in measuring devices is due to their special structure, which makes it possible to implement fundamentally different schemes in one such element, for example, for simultaneous measurement of temperature, pressure and humidity. The main indicators of the quality of a piezoelectric product that affect the smooth operation and reliability of their operation is the observance of the required level of microroughness of the surfaces of piezoelectric elements and the absence of microdefects on them [1].

For elements made of piezoelectric ceramics of the PZT grade, there are also questions of increasing the mechanical strength of silver (less often – nickel) electrodes, which, according to traditional technology, are chemically applied to the ceramic surface and have insignificant wear resistance and adhesive strength (no more than 8 MPa) [2].

Technological features of the manufacture of piezoceramics are described in sufficient detail in the monograph [3]. It should be noted that the technology for the manufacture of piezoelectric ceramics is quite complex and can be applied only at enterprises that have specialized equipment for the production and processing of piezoelectric ceramics (today, according to the review, there are no such enterprises in Ukraine). However, the technology of forming conductive electrodes and further polarization of the samples is subject to improvement in this work.

Promising and relevant in this direction of research is the improvement of the technology of forming current conductive electrodes of elements from piezoelectric ceramics, which will increase their wear resistance and adhesive strength without reducing the value of surface microroughness and the period of reliable operation of samples of these ceramics.

DOI: 10.24025/2306-4412.4.2020.216483

Therefore, ***the purpose of this work*** is to improve the technology of forming current conductive electrodes of piezoelectric elements and to develop devices with piezoelectric ceramics with separated electrodes.

Methods and materials. In [2], [4] it was shown that thermal deposition in vacuum can produce high-quality uniform coatings on the surfaces of piezoceramic elements.

With the participation of the authors, a combined method of deposition of metal coatings on the surface of dielectric materials with its subsequent low-energy electron-beam modification has been developed. The essence of this method is thermal (resistive or electron-beam) deposition of the coating material (for example, Ag) in vacuum $(5\text{-}6)\times10^{-3}$ Pa on a specially prepared piezoceramic surface [5] and subsequent action by electron flow of fixed power onto the surface of a piezoelectric material in one technological cycle. This action leads to heating and compaction of the coating material with a simultaneous increase in the depth of its diffusion penetration into the material of the piezoelectric element [6].

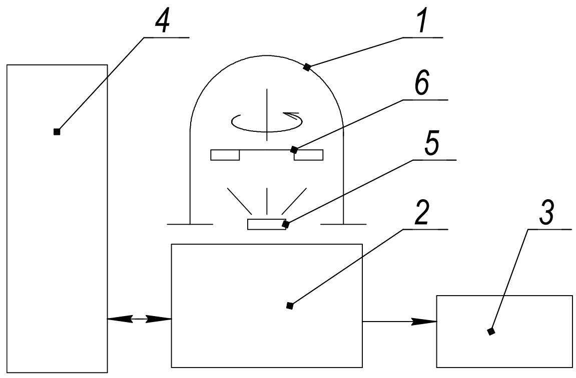
A feature of this combined method is its implementation in one technological cycle "thermal vacuum deposition – electron-beam modification of the coating" under constant conditions of the working environment (vacuum $p = (5\text{-}7)\cdot10^{-5}$ Pa), which excludes the formation of chemical compounds of the deposited coating with elements of the environment at the intermediate stage of the formation of the nanostructure [7].

The procedure for conducting a technological experiment is performed in the following sequence [7]:
– cleaning the glass surface from possible organic and inorganic contamination;
– preparation of the electron beam equipment for operation;
– resistive deposition of an electrode material on a sample surface in a vacuum;
– electron beam modification (EBM) of the obtained coating;
– finishing operations [8].

The technology for obtaining modified electrodes on piezoceramic elements is based on a combined process of thermal vacuum deposition of a thin (80 ... 120 μm thick) silver coating on the piezoelectric ceramics of the PZT grade.

An industrial vacuum installation УВН-71П3 was used as the base for the experimental electron-beam installation (EBI), which was expanded with additional equipment, namely:
– under-cap technological equipment;
– Pierce electron gun with a wire tungsten cathode;
– thermal furnace for preheating material in vacuum;
– mechanism for fastening and moving products to the processing area.

General view and diagram of the EBI are shown in Fig. 1.



1 – cap of the vacuum installation; 2 – control post;
3 – backing vacuum pump of the vacuum system;
4 – control unit rack; 5 – electron beam evaporator;
6 – fastening device

Figure 1 – Structural diagram of a vacuum installation УВН-71П3

The production of silver coatings for the electrodes of the elements of piezoelectric ceramics by the method of combined EBM in one technological cycle with the polarization of these elements (Fig. 2) made it possible to propose a qualitatively new technology for the manufacture of elements from piezoelectric ceramics.

It should also be taken into account that long-term operation of such piezoelements, which had a high number of microdefects before electron-beam recovery, simultaneously leads to a sharp decrease in the resonance peak from 580 mV to 220 mV (2.6 times) in the amplitude-frequency characteristics of these elements (Fig. 3) [9].

DOI: 10.24025/2306-4412.4.2020.216483

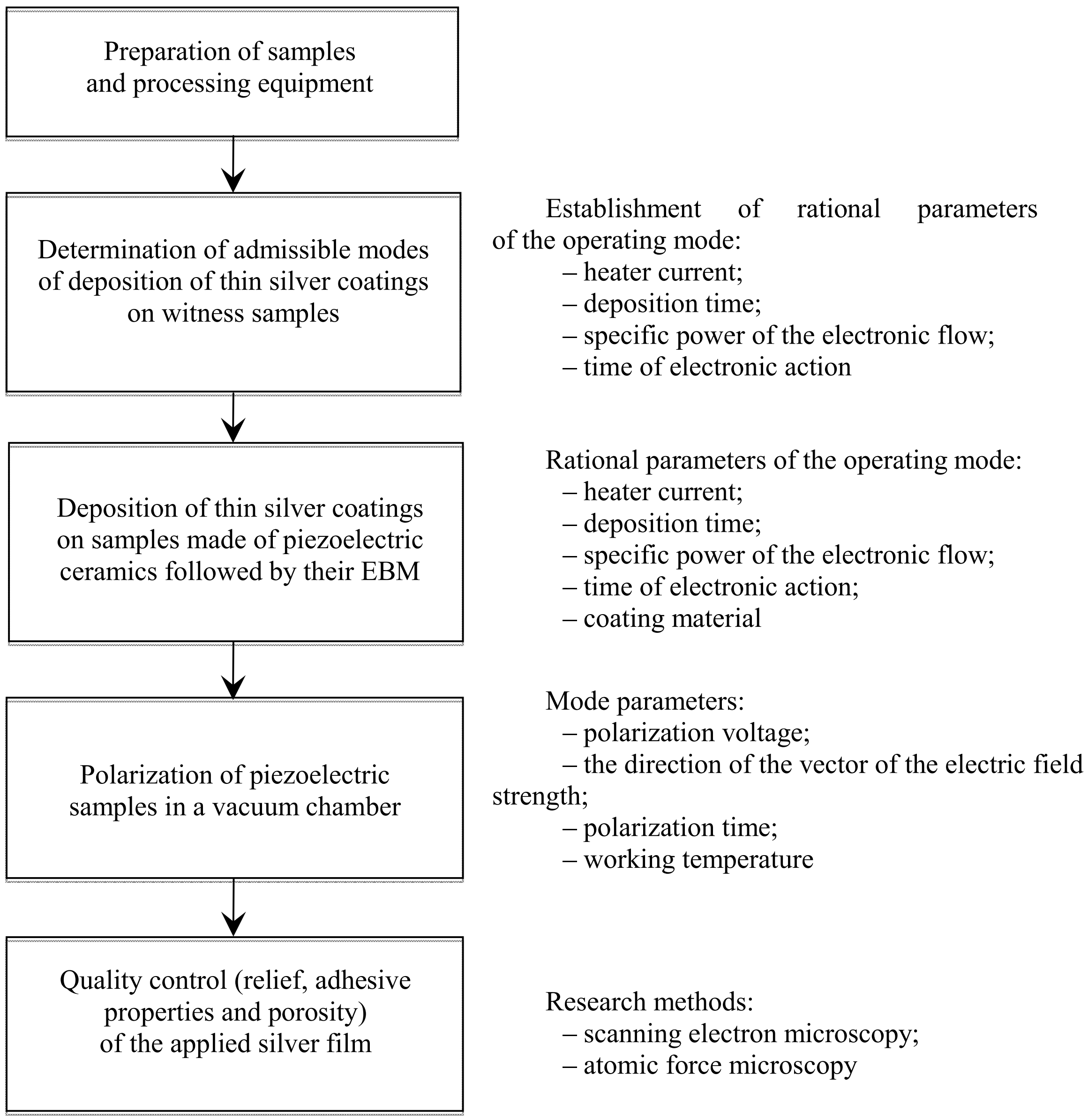


Figure 2 – The sequence of obtaining a silver coating by a combined electron-beam method on piezoelectric ceramics of PZT in one technological cycle

Compared to traditional (industrial) methods of manufacturing such elements, the combined EPM method has 1.5-2.3 times higher adhesive strength, 1.2-1.8 times higher wear resistance, 3.5-4.2 times less surface microroughness and less than 1.3-1.5 times porosity. This leads to an increase in the time of reliable operation of these elements by 1.6-2.0 times, the quality factor – by 3.5-5 times, the electromechanical coefficient – by 2.2-2.6 times [6].

Until recently, the scientific and technical basis for the design and improvement of piezoceramic transducers was mainly limited only by changing the shape, size and material of the piezoelectric element, as well as the type of excited vibrations. Existing approaches to increasing the efficiency of piezoelectric transducers, in particular, expanding the operating range, increasing the sensitivity and level of the output signal of piezoelectric transducers, require an inevitable compromise with the requirements for miniaturization of these transducers, the provision of which is especially important for critical applications [9, 10].

The main advantage of using transducers from piezoceramic materials with separated electrodes in computer systems (a method for modifying the formation of conductive electrodes) is due to their special structure. This makes it possible to implement fundamentally different cir-

DOI: 10.24025/2306-4412.4.2020.216483

cuits in one such element, while the degree of integration is determined by the number of functional elements combined in one unit [11].

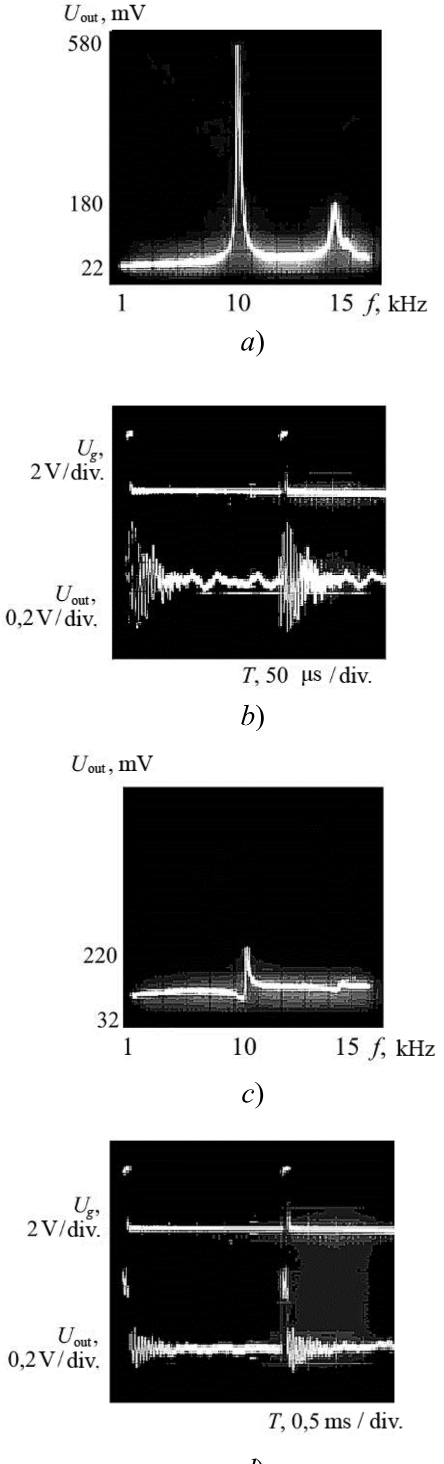


Figure 3 – Amplitude-frequency (*a*, *c*), pulse (*b*, *d*) characteristics of piezoelectric transducer (PZT, diameter 10 mm, thickness 0.3 mm) at the beginning and after 12 years of operation, respectively

The analysis of a significant number of possible connection schemes for disk piezoelectric transformers shows that they can all be reduced to four main types (Fig. 4) [12].

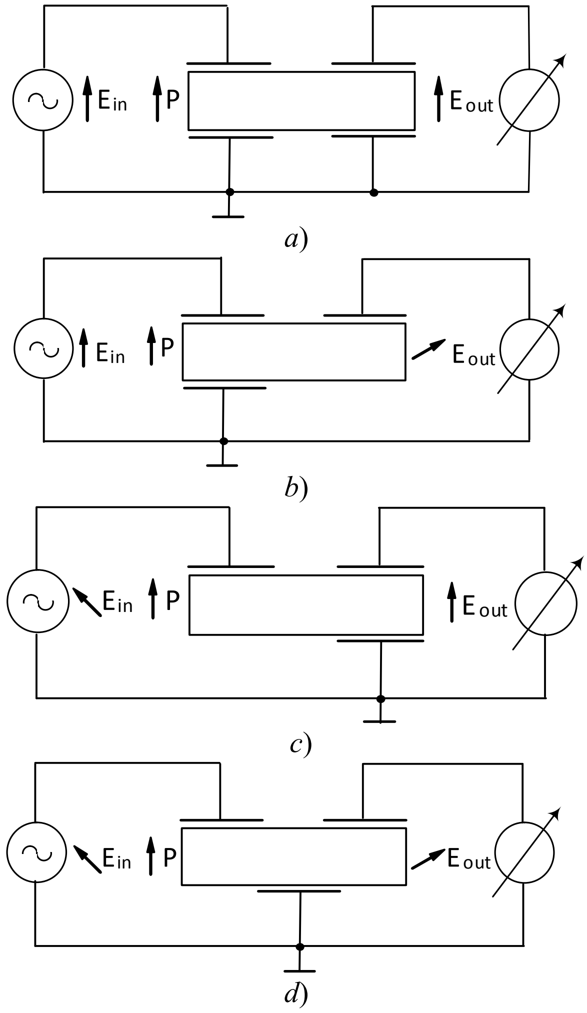


Figure 4 – Piezoelectric transformer designs

1. Traditional connection diagram. In this case, the angle α between the polarization vector **P** and the electric field vector of the excitation voltage $\mathbf{E_{in}}$ (generator voltage) is equal to zero. Similarly, the angle β between the polarization vector **P** and the vector of the electric field of the output voltage $\mathbf{E_{out}}$ is equal to zero.

2. The input section of the piezoelectric transformer is built according to the traditional scheme (α = 0), and for the output section the angle β ≤ 90 °.

3. The input section of the piezoelectric transformer is constructed in such a way that 0 < α ≤ 90°, and the output section is built according to the traditional scheme β = 0.

DOI: 10.24025/2306-4412.4.2020.216483

4. Connection diagram at which the angles between the polarization vector and the electric field vectors are $0 < \alpha \leq 90°$ and $0 < \beta \leq 90°$.

Experiments. Let's consider further a multisectional piezoelectric transducer [12]. As is known, a piezoelectric transformer is a converter of electrical voltage of one level into electrical voltage of another level. The piezoelectric transducer is made of PZT-4 piezoceramics with a diameter of 30 and a thickness of 0.8 mm. The transducer has five electrodes located on the end surfaces of the piezoelectric element, and the top electrodes are projections of the bottom ones [13].

For a piezoceramic transducer, one should take into account not only the location of the electric field vector of the output signal, but also the electric field vector of the input signal (generator) [14, 15].

In this case, if piezoelectric elements of small thickness are used, the angle between the vectors of the electric field **E** and polarization **P** can be close to 90°. The piezoelectric transducer switching circuit is shown in Fig. 5, and oscillograms of signals at the inputs and outputs of the transducer are shown in Fig. 6.

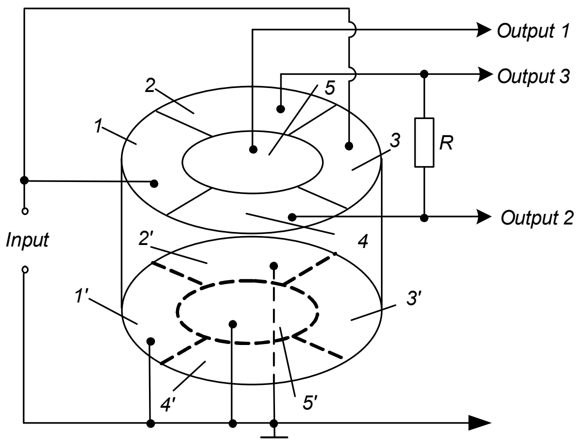
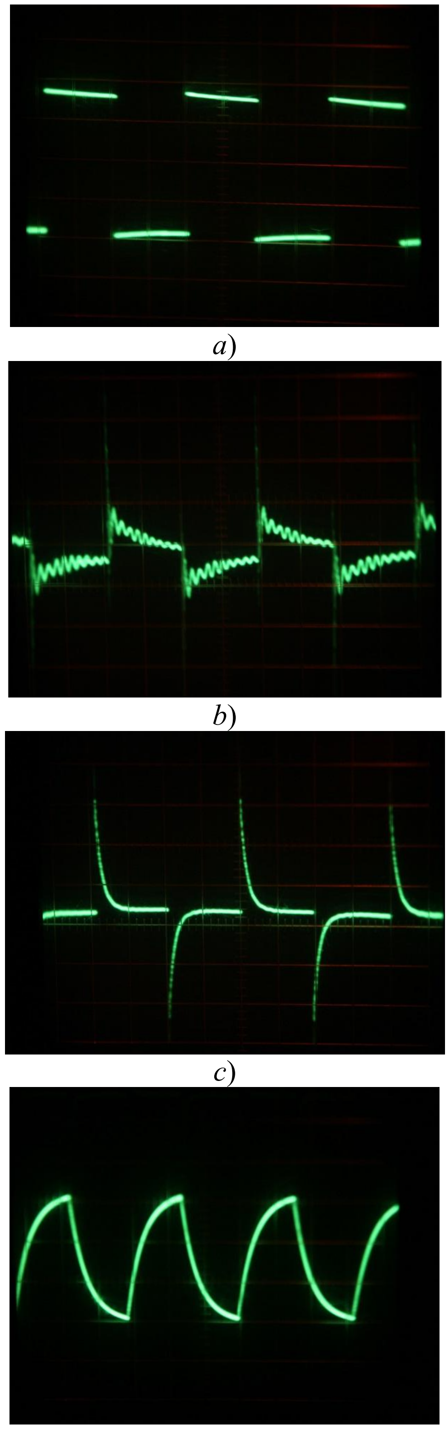


Figure 5 – Wiring diagram for electrodes of a multisectional transducer

As seen from Fig. 6, depending on the connection diagram of the electrodes (that is, on the relative position of the vectors **F**, $\mathbf{E}_{in}$ and $\mathbf{E}_{out}$), it is possible to obtain a signal corresponding to the oscillatory (Fig. 6, *b*), differentiating (Fig. 6, *c*) and integrating chains (Fig. 6, *d*).



a)

b)

c)

d)

a) input signal (square wave);
b) output 1; *c*) output 2; *d*) output 3

Figure 6 – Oscillograms of signals from a piezoelectric transducer

However, the most interesting in this case is that a piezoelectric element – an elastic monolithic solid – can have these properties simultaneously [13] due to the technological capabilities of the thermal vacuum deposition. This allows to

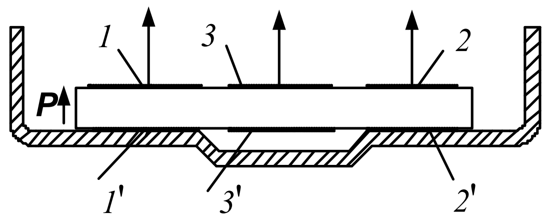
DOI: 10.24025/2306-4412.4.2020.216483

ISSN 2306-4412 (Print), ISSN 2306-4455 (CD-ROM), ISSN 2708-6070 (Online)

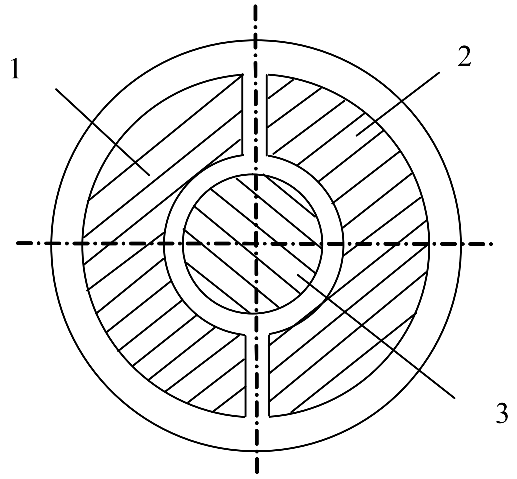
create multifunctional piezoelectric transducers on a single basis with a high degree of integration (3-4 times more than the base element).

Results and discussions. The described version of the piezoelectric transducer, which allows processing the input signal, is, of course, not the only one. Changing the size of the electrodes, their relative position allows to influence the parameters of the output signals and opens up wide opportunities for the design of piezoelectric transducers for computer systems of critical application.

For example, based on bimorph piezoelectric elements with separated electrodes, sound pressure sensors can be built [12]. One of the possible sensor designs is shown in Fig. 7.



a)



b)

Figure 7 – Pressure sensor design

The sensor consists of a piezoelectric element 30 mm in diameter and 0.8 mm thick. The piezoelectric element is glued to a metal plate (brass) 0.3 mm thick. The sensor has 3 electrode systems – 1-1', 2-2' and 3-3'. Electrodes 1' and 2' are connected to each other through a metal plate.

The sensor was installed in a vibroacoustic chamber (Fig. 8), where it was exposed to a sound pressure of 10 Pa (114 dB) at a frequency of 200 Hz.

Figure 8 – Experimental stand with vibroacoustic chamber

The results of measuring the output voltage of a pressure sensor based on a piezoelectric element with separated electrodes are given in Table 1.

Table 1 – **The value of the output voltage of the pressure sensor based on a piezoelectric element with separated electrodes**

Electrodes	1-1'	2-2'	3-3'	3-1'	1-3'	2-3'
Voltage sensitivity, mV / Pa	2,6	2,7	2,0	1,3	4,0	4,2
Capacitance between electrodes, nF	4,08	3,93	1,36	0,34	0,31	0,32

As can be seen from Table 1, depending on the connection scheme of the electrodes to the measuring instrument, the sensitivity of the sensor can vary almost three times. Moreover, an increase in sensitivity is achieved for the case when the angle between the electric field vector of the output signal and the polarization vector is close to 90^0. At the same time, in this case, the capacitance between these electrodes decreases [12].

Conclusions. The prospect of using the method of thermal vacuum deposition in obtaining electrode coatings on products made of piezoelectric ceramics of the PZT grade is shown.

It has been established that the silver coatings formed on piezoelectric elements by the proposed technology are more uniform and homogeneous in comparison with the coatings obtained by the traditional industrial method.

DOI: 10.24025/2306-4412.4.2020.216483

On the basis of a piezoelectric element – an elastic monolithic solid – it is simultaneously possible to create multifunctional piezoelectric transducers with a high degree of integration due to the technological capabilities of the thermal vacuum deposition method.

Designs of piezoelectronic devices based on piezoelectric elements with separated electrodes have been developed. In particular, the use of a structure with separated electrodes made it possible to increase the sensitivity of the pressure sensor by 1.5-2 times.

References

[1] "DIN ISO 2859-1-2014. Sampling procedures for inspection by attributes – Part 1: Sampling schemes indexed by acceptance quality limit (AQL) for lot-by-lot inspection (ISO 2859-1:1999 + Cor. 1:2001 + Amd.1:2011); Text in German and English; 01.08.2014".

[2] V. M. Sharapov, A. M. Gurzhii, M. O. Bondarenko, and Yu. Yu. Bondarenko, "Study of the characteristics of current conductive piezoceramic elements", *Visnyk Cherkaskogo derzhavnogo tehnologichnogo universitetu*, pp. 255-257, 2007 [in Russian].

[3] R. G. Dzhagupov, and A. A. Erofeev, *Piezoelectronic devices for computing technology, monitoring and control systems*. St. Petersburg, Politekhnika, 1994 [in Russian].

[4] M. A. Bondarenko, et. al., "Formation of ordered nanostructures on piezoelectric ceramics of the PZT system by thermal deposition in vacuum", in *Effektivnost' realizatsii nauchnogo, resursnogo i promyshlennogo potentsiala v sovremennyh usloviiah*, Slavske of Lviv Region, 2010, pp. 159-160 [in Russian].

[5] M. O. Bondarenko, "Investigation of the influence of low-energy electron beam on the microgeometry of the surfaces of piezoceramic elements", *Trudy Odesskogo politehnicheskogo universiteta*, no. 2 (32), pp. 149-153, 2009 [in Ukrainian].

[6] V. V. Medianyk, Yu. Yu. Bondarenko, C. V. Bazilo, and M. O. Bondarenko, "Research of current-conducting electrodes of elements from piezoelectric ceramics modified by the low-energy ribbon-shaped electron stream", *Journal of Nano- and Electronic Physics*, vol. 10, no. 6, pp. 06012-1-06012-6, 2018.

[7] V. S. Antoniuk, G. S. Tymchyk, Yu. Yu. Bondarenko, Yu. I. Kovalenko, M. O. Bondarenko, and R. P. Gaidash, *Coatings in instrumentation*. Kyiv, NTUU "KPI", 2016 [in Ukrainian].

[8] V. A. Vashchenko, M. O. Bondarenko, G. V. Kanashevich, et. al., "Technological foundations of obtaining ordered nanostructures on the surfaces of probes for atomic force microscopy", Cherkasy, research report, 2012 [in Ukrainian].

[9] V. Sharapov, *Piezoceramic Sensors*. Springer, 2011.

[10] V. Sharapov, Z. Sotula, and L. Kunickaya, *Piezo-Electric Electro-Acoustic Transducers*. Springer, 2014.

[11] V. D. Vavilov, S. P. Timoshenkov, and A. S. Timoshenkov, *Microsystem sensors of physical quantities*. Moscow, Tekhnosfera, 2018 [in Russian].

[12] V. M. Sharapov, I. G. Minaev, Zh. V. Sotula, K. V. Bazilo, and L. G. Kunitskaya, *Piezoceramic transformers and sensors*. Cherkasy, Vertikal', 2010 [in Russian].

[13] V. Sharapov, A. Vladišauskas, K. Bazilo, L. Kunitskaya, and Zh. Sotula, "Methods of synthesis of piezoceramic transducers: spatial energy force structure of piezoelement", *Ultrasound,* Kaunas, Lithuania, no. 4, pp. 44-50, 2009.

[14] V. M. Sharapov, O. N. Petrishchev, K. V. Bazilo, Zh. V. Sotula, and A. I. Mashtapa, "Classification of piezoelectric transformers", *Visnyk Cherkaskogo derzhavnogo tehnologichnogo universitetu,* no. 2, pp. 58-61, 2014 [in Russian].

[15] K. V. Bazilo, "Piezoelectric transformer", *Ukr. patent for a utility model, no. 92334*, Aug. 11, 2014 [in Ukrainian].

Список використаних джерел

[1] "DIN ISO 2859-1-2014. Sampling procedures for inspection by attributes – Part 1: Sampling schemes indexed by acceptance quality limit (AQL) for lot-by-lot inspection (ISO 2859-1:1999 + Cor. 1:2001 + Amd.1:2011); Text in German and English; 01.08.2014."

[2] В. М. Шарапов, А. М. Гуржій, М. О. Бондаренко, и Ю. Ю. Бондаренко, "Исследование характеристик токопроводящих

DOI: 10.24025/2306-4412.4.2020.216483

электропроводных пьезокерамических элементов", *Вісник Черкаського державного технологічного університету, спецвипуск*, с. 255-257, 2007.

[3] Р. Г. Джагупов и А. А. Ерофеев, *Пьезоэлектронные устройства вычислительной техники, систем контроля и управления: справочник*. Санкт-Петербург: Политехника, 1994.

[4] М. А. Бондаренко и др., "Формирование упорядоченных наноструктур на пьезоэлектрической керамике системы ЦТС термическим осаждением в вакууме", в *Эффективность реализации научного, ресурсного и промышленного потенциала в современных условиях*, с. Славское Львовской обл., 2010, с. 159-160.

[5] М. О. Бондаренко, "Дослідження впливу низькоенергетичного електронного потоку на мікрогеометрію поверхонь п'єзокерамічних елементів", *Труды Одесского политехнического университета: науч. и произв.-практ. сб. по техн. и естест. наукам*, № 2 (32), с. 149-153, 2009.

[6] V. V. Medianyk, Yu. Yu. Bondarenko, C. V. Bazilo, and M. O. Bondarenko, "Research of current-conducting electrodes of elements from piezoelectric ceramics modified by the low-energy ribbon-shaped electron stream", *Journal of Nano- and Electronic Physics*, vol. 10, no. 6, pp. 06012-1-06012-6, 2018.

[7] В. С. Антонюк, Г. С. Тимчик, Ю. Ю. Бондаренко, Ю. І. Коваленко, М. О. Бондаренко, і Р. П. Гайдаш, *Покриття у приладобудуванні*. Київ: НТТУ "КПІ", 2016.

[8] В. А. Ващенко, М. О. Бондаренко, Г. В. Канашевич, та ін., "Технологічні основи отримання впорядкованих наноструктур на поверхнях зондів для атомно-силової мікроскопії", Черкаси, звіт про науково-дослідну роботу, 2012.

[9] V. Sharapov, *Piezoceramic Sensors*. Springer, 2011.

[10] V. Sharapov, Z. Sotula, and L. Kunickaya, *Piezo-Electric Electro-Acoustic Transducers*. Springer, 2014.

[11] В. Д. Вавилов, С. П. Тимошенков, и А. С. Тимошенков, *Микросистемные датчики физических величин:* монография в двух частях. Москва: Техносфера, 2018.

[12] В. М. Шарапов, И. Г. Минаев, Ж. В. Сотула, К. В. Базило, и Л. Г. Куницкая, *Пьезокерамические трансформаторы и датчики*. Черкассы: Вертикаль, 2010.

[13] V. Sharapov, A. Vladišauskas, K. Bazilo, L. Kunitskaya, and Zh. Sotula, "Methods of synthesis of piezoceramic transducers: spatial energy force structure of piezoelement", *Ultrasound,* Kaunas, Lithuania, no. 4, pp. 44-50, 2009.

[14] В. М. Шарапов, О. Н. Петрищев, К. В. Базило, Ж. В. Сотула, и А. И. Маштапа, "Классификация пьезоэлектрических трансформаторов", *Вісник Черкаського державного технологічного університету,* № 2, с. 58-61, 2014.

[15] К. В. Базіло, "П'єзоелектричний трансформатор", *Патент України на корисну модель № 92334*, Серп. 11, 2014.

К. В. Базіло, *д.т.н., доцент*,
В. В. Хлівний,
Ю. Ю. Бондаренко, *к.т.н., доцент*
Черкаський державний технологічний університет
б-р Шевченка, 460, Черкаси, 18006, Україна

МОДИФІКАЦІЯ ТА ПРАКТИЧНЕ ЗАСТОСУВАННЯ П'ЄЗОЕЛЕКТРИЧНИХ ПЕРЕТВОРЮВАЧІВ З РОЗДІЛЕНИМИ ЕЛЕКТРОДАМИ

В роботі наводяться результати удосконалення технології формування струмопровідних електродів п'єзоелектричних елементів та розробка пристроїв з п'єзоелектричної кераміки з розділеними електродами методом, що базується на технології комбінованої електронно-променевої модифікації. Показано перспективу використання методу термовакуумного напилення при отриманні покриттів електродів на виробах з п'єзоелектричної кераміки сорту ЦТС. Особливістю такого комбінованого методу є здійснення його в одному технологічному циклі «термовакуумне осадження – електронно-

DOI: 10.24025/2306-4412.4.2020.216483

променева модифікація покриття» за незмінних умов робочого середовища, що виключає утворення хімічних сполук в осаджуваному покритті на проміжному етапі формування наноструктурних утворень. Встановлено, що утворені за запропонованою технологією срібні покриття на п'єзоелектричних елементах є більш рівномірними та однорідними порівняно з покриттями, отриманими у традиційний (промисловий) спосіб. Як практичний результат реалізації запропонованої в статті технології розроблено конструкції пристроїв п'єзоелектроніки на основі елементів із п'єзоелектричної кераміки зі сформованими на їх поверхні розділеними електродами, зокрема багатосекційного п'єзоелектричного перетворювача. Найбільш цікавим у цьому випадку є те, що п'єзоелемент (пружне монолітне тверде тіло) може одночасно мати різні властивості внаслідок технологічних можливостей методу термовакуумного напилення. Зміна розмірів електродів, їх взаємне розташування дають змогу впливати на параметри вихідних сигналів і відкривають широкі можливості для створення п'єзоелектричних перетворювачів для комп'ютерних систем критичного застосування. Основна перевага використання перетворювачів з п'єзокерамічних матеріалів у комп'ютерних системах пов'язана з їх особливою конструкцією, що дає можливість реалізувати принципово різні схеми в одному такому елементі.

Ключові слова: *п'єзоелектричний перетворювач, п'єзоелектрична кераміка, струмопровідний електрод, розділені електроди, технологія комбінованої електронно-променевої модифікації.*

Стаття надійшла 17.11.2020
Прийнято 14.12.2020

DOI: 10.24025/2306-4412.4.2020.216483