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## 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.

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  $(5-6) \times 10^{-3}$  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  $p = (5-7) \cdot 10^{-5}$  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].

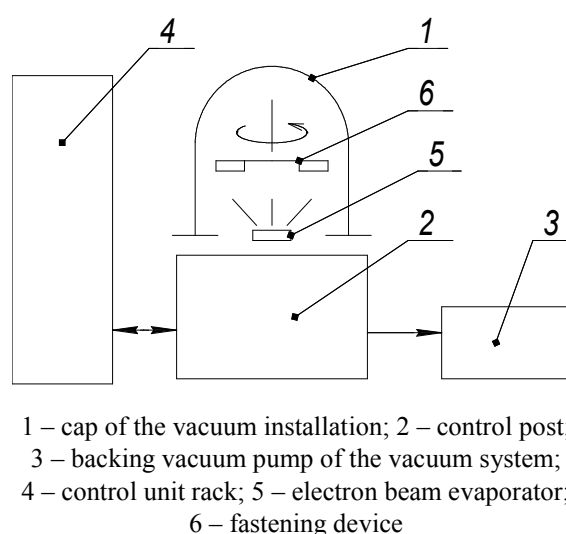
The technology for obtaining modified electrodes on piezoceramic elements is based on a combined process of thermal vacuum deposi-

tion of a thin (80 ... 120  $\mu\text{m}$  thick) silver coating on the piezoelectric ceramics of the PZT grade.

An industrial vacuum installation YBH-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.

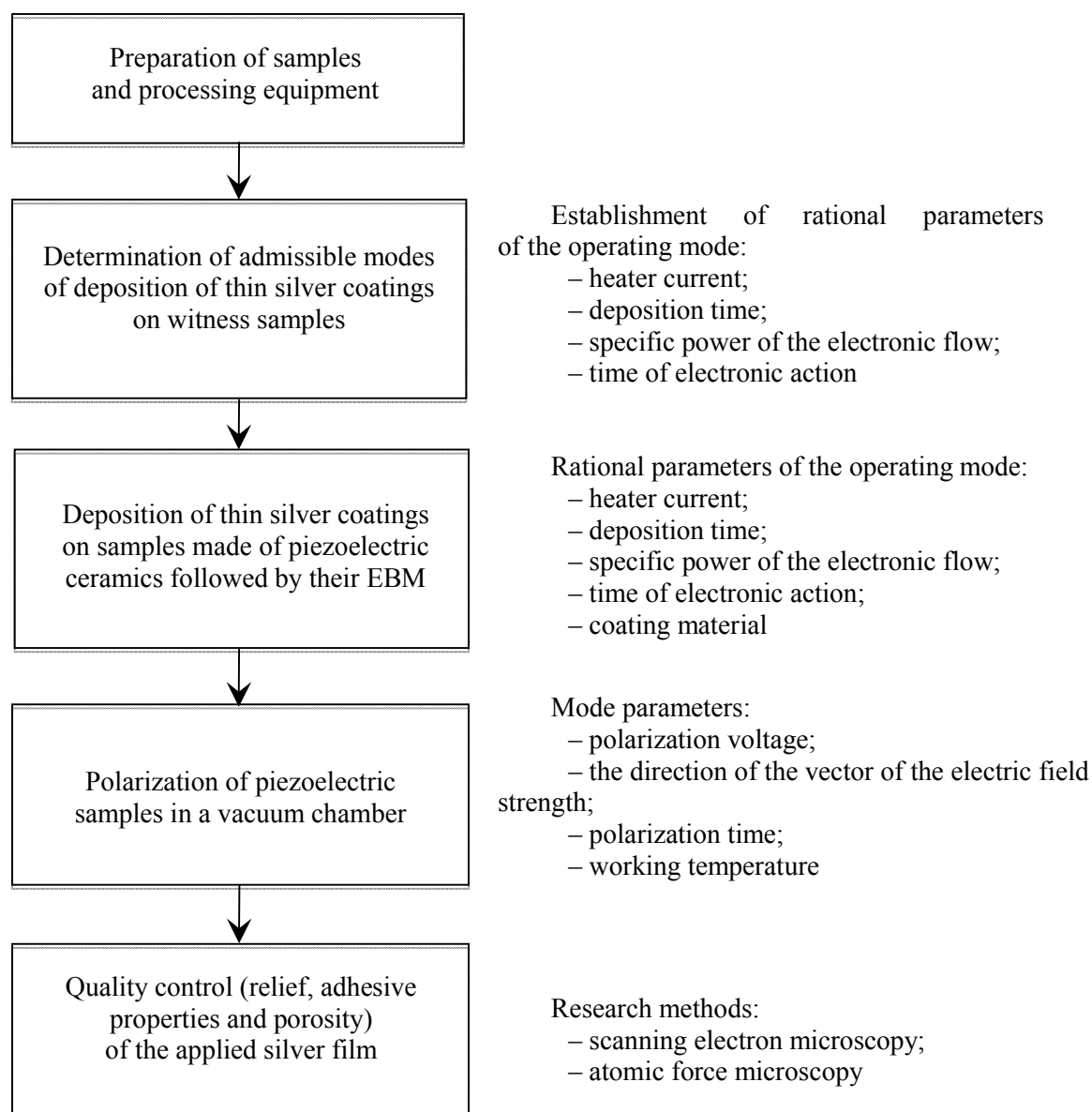
General view and diagram of the EBI are shown in Fig. 1.



**Figure 1 – Structural diagram of a vacuum installation YBH-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].



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

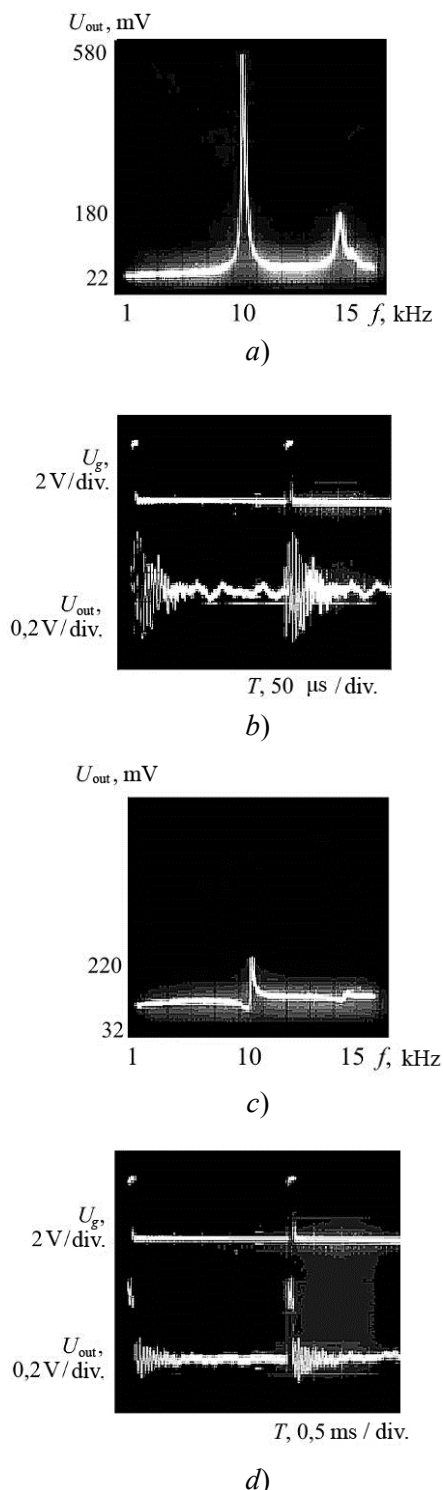
Compared to traditional (industrial) methods of manufacturing such elements, the combined EPM method has 1.5-2.3 times higher adhesive strength, 1.2-1.8 times higher wear resistance, 3.5-4.2 times less surface microroughness and less than 1.3-1.5 times porosity. This leads to an increase in the time 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].

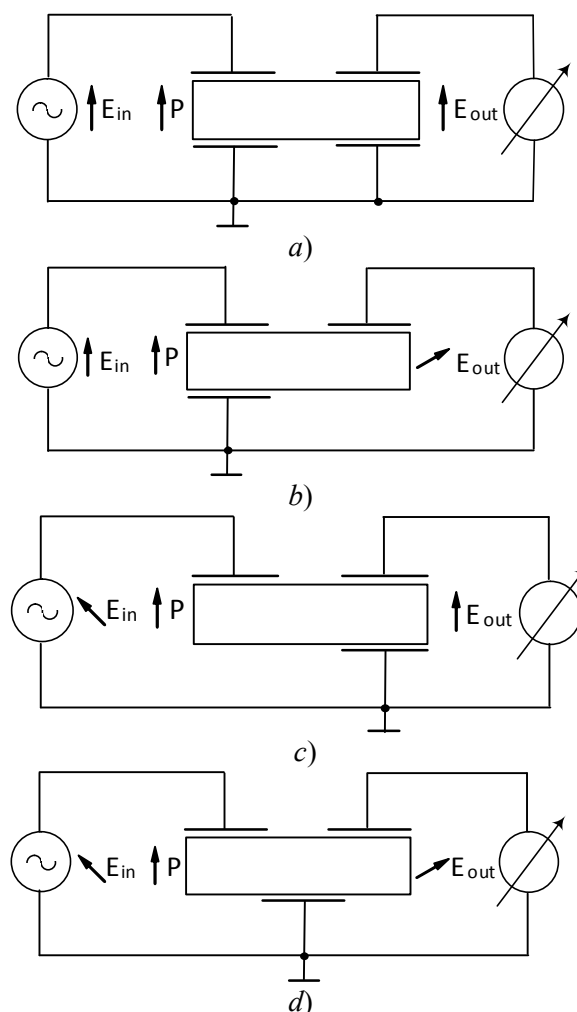
The main advantage of using transducers from piezoceramic materials with separated electrodes in computer systems (a method for modifying the formation of conductive electrodes) is due to their special structure. This makes it possible to implement fundamentally different cir-

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  $\alpha$  between the polarization vector  $P$  and the electric field vector of the excitation voltage  $E_{in}$  (generator voltage) is equal to zero. Similarly, the angle  $\beta$  between the polarization vector  $P$  and the vector of the electric field of the output voltage  $E_{out}$  is equal to zero.

2. The input section of the piezoelectric transformer is built according to the traditional scheme ( $\alpha = 0$ ), and for the output section the angle  $\beta \leq 90^\circ$ .

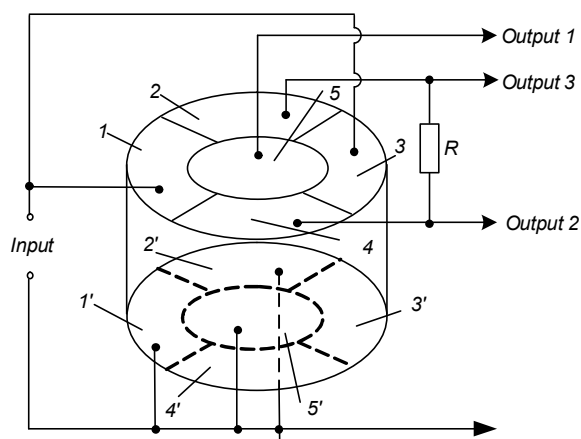
3. The input section of the piezoelectric transformer is constructed in such a way that  $0 < \alpha \leq 90^\circ$ , and the output section is built according to the traditional scheme  $\beta = 0$ .

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

**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].

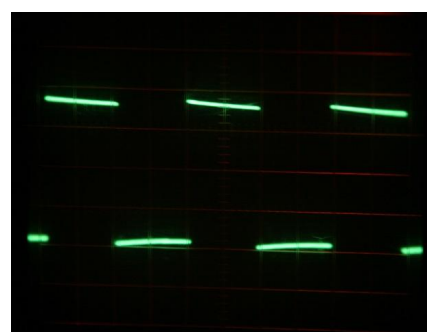
For a piezoceramic transducer, one should take into account not only the location of the electric field vector of the output signal, but also the electric field vector of the input signal (generator) [14, 15].

In this case, if piezoelectric elements of small thickness are used, the angle between the vectors of the electric field  $\mathbf{E}$  and polarization  $\mathbf{P}$  can be close to  $90^\circ$ . 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**

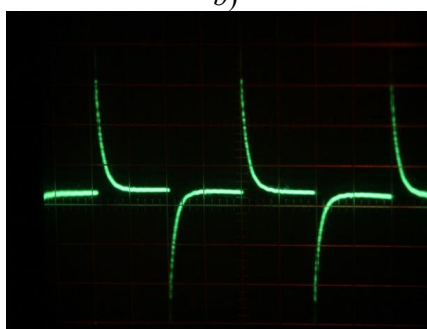
As seen from Fig. 6, depending on the connection diagram of the electrodes (that is, on the relative position of the vectors  $\mathbf{F}$ ,  $\mathbf{E}_{in}$  and  $\mathbf{E}_{out}$ ), it is possible to obtain a signal corresponding to the oscillatory (Fig. 6, *b*), differentiating (Fig. 6, *c*) and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



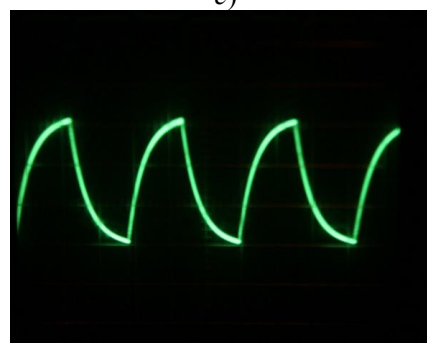
*a)*



*b)*



*c)*



*d)*

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

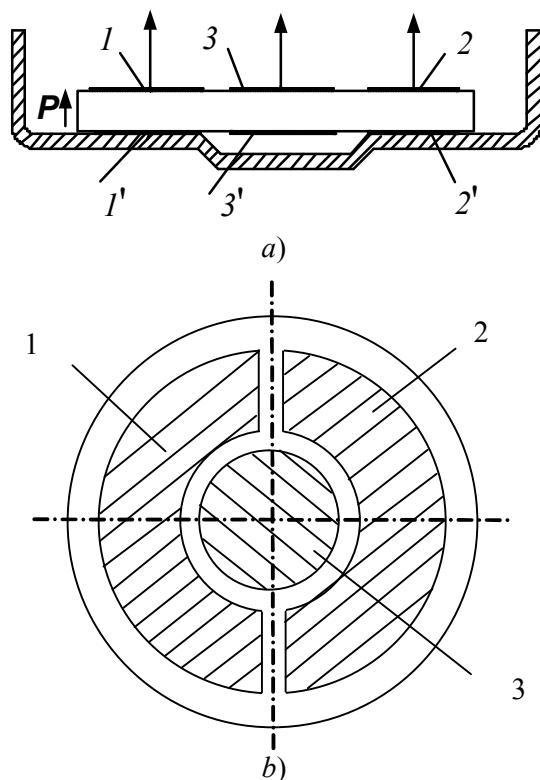
**Figure 6 – Oscillograms of signals from a piezoelectric transducer**

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

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.



**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  $90^\circ$ . 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.

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.

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## МОДИФІКАЦІЯ ТА ПРАКТИЧНЕ ЗАСТОСУВАННЯ П'ЄЗОЕЛЕКТРИЧНИХ ПЕРЕТВОРЮВАЧІВ З РОЗДІЛЕНИМИ ЕЛЕКТРОДАМИ

В роботі наводяться результати удосконалення технології формування струмопроводних 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 термовакuumного напилення при отриманні покриттів електродів на виробках з п'єзоелектричної кераміки сорту ЦТС. Особливістю такого комбінованого методу є здійснення його в одному технологічному циклі «термовакuumне осадження – електронно-

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.