A Nanoporous Anodic Aluminum Oxide as Basis on Creation of High-Performance Microsensors (Mechanical, Physical, Chemical, Bio-, MEMS and Actuators)

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ABSTRACT

Anodic alumina oxide (AAO) technology enables to modify material properties depending on the needs of concrete conditions of exploitation. It gives the possibility of quick creation of the necessary device prototype and customization of its characteristics. On the basis of an AAO template a prototype of the various sensors has been created and developed, including physical, gas, chemical and biological sensing, as well as multi-sensor systems with local nanodimensional elements. It is also proposed to create multiple constructions of high-efficient microsensors, such as humidity, vibration, acceleration, position, micro gyroscopic, static electricity, micro electromechanical optical switches, optical micro scanner, optical-electrostatic micro relay, electro-current micro relay, microchips for ecology monitoring of environment, and micro lab-on-chip. In comparison with other technologies and based on self-organization, aluminum oxide is the perspective for the formation of nanocapillary system matrices in relation to the demands of high quality magnetic, magneto resistive and magneto-optical materials and sensors based on them.

INTRODUCTION

At the modern stage of society development further scientific-technical progress is based on the wide implementation of automatic systems of managing and information systems into all spheres of life [1]. Nowadays large attention is paid to the development of a wide nomenclature of sensors based on anodic alumina oxide (AAO) template, obtained by anodic treatment of aluminum in acid electrolytes [2].

AAO with regular periodical structure of nanopores is one of perspective composition materials, applied for the creation of devices and technical systems. Such a material, obtained by the electrochemical oxidation of aluminum in acid electrolytes, possesses wide potential capabilities. The diversity of forms of units made of AAO stipulates the opportunity for the creation of various microsensors with the wide functionality. AAO technology enables to modify material properties depending on the needs of concrete conditions of exploitation.

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Porous AAO is used for creating the photonic [3] and optoelectronic structures [4], micromechanical systems [5] and sensors for various applications [6]. The regular periodic structure of membrane pores of AAO allows one to use it as a mask at manufacturing nanomaterials and nanostructures [7].

AAO films have a nanoporous structure perpendicular to the substrate surface. At the same time the diameter of pores and the distance between them can be regulated in wide ranges (from 10 nm up to hundreds of nm) by selection of the technological process. AAO has high electromechanical parameters. The units and various components, made of this material, have the high precision, planar and volumetric configurations with blind and through holes, slots and cavities. The diversity of units made of AAO stipulates the opportunity for the creation of various microsensors with the wide functionality.

In this paper a new types of physical, gas, chemical and mechanical sensors, as well as mutilsensor systems based on universal AAO template is described. The sensor design, fabrication and characterization are also studied.

UNIVERSAL TEMPLATE FOR CONSTRUCTION OF GAS MICROSENSORS (HYDROGEN, OZONE)

Basic preconditions for construction of effective gas microsensors are the following: i) thin film gas sensors work at heating of semiconducting sensitive layers up to 300-500 ºC; ii) sensitive layers are made of films of metal oxides and should preserve high adhesion to substrate; iii) substrates should have high isolation and thermal-conducting characteristics at working temperatures; iv) parasitic losses of electrical-energy for heating should be minimal.

As an example of efficiency of application of AAO technology on the basis of universal platform, several prototypes of gas microsensors can be developed as hydrogen sensor (Fig.1) and sensor of ozone concentration in environment (Fig.2).

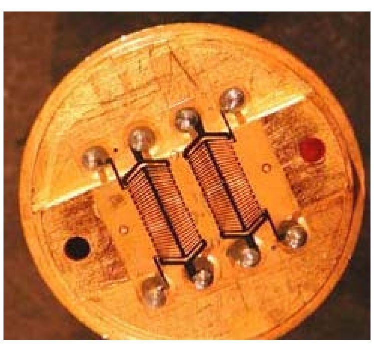


Figure 1. High stability selective microsensor of hydrogen concentration in wide range.

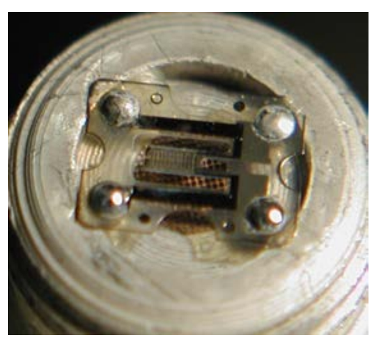


Figure 2. Microsensor of ozone concentration on the basis of thin semi-conducting film NiO.

High stability selective microsensor of hydrogen concentration in a wide range on thermoelectrical transformation (Fig.1) contains 2 autonomic sensitive elements: thermocatalyst (follows up the change of concentration within the range of 0.05-2% vol. H_2), thermoconductometric (follows up the change of concentration within the range of 2-100% vol. H_2). Some non- extreme characteristics of the prototype of hydrogen sensor are presented in the Table I. On the basis of thermoelectric transformation it is possible to create other sensors, such as sensors of ethyl spirit vapors, ammonia, monoxide of carbon and others. Their advantages are extremely high selectivity and stability.

Table I. Basic characteristics of the prototype of hydrogen sensor.

Range of the measured concentrations	0,05 – 100 % vol.
Sensitivity (thermocatalyst)	6 – 7 mvolt/% hydrogen
Sensitivity (thermoconductometric)	1,3 mvolt/% hydrogen
Response time	<30 s
Time of recovery	<30 s
Consumed power	<300 mWatt
Output parameter	thermoEMF
Substrate size	10×10 mm^2
Mass	3,2 – 5 g (depending on the body)
Time of transient period of working regime	<1 min.

There are no analogues to the developed prototype of hydrogen microsensor. At the corresponding improvement it is possible to create threshold prototype of hydrogen microsensor based on the concentration up to highly explosive and to widen of the working temperature range up to +300°C. The prototype of microsensor of the concentration of ozone (Fig.2) differs by high stability and reproducibility of parameters.

PHYSICAL SENSORS (HUMIDITY, PRESSURE, TEMPERATURE, POSITIONS, MICROGYROSCOPE)

On the basis of the use of MEMS and MOEMS various microsensors of pressure, shift, acceleration, angular speeds, specific weight, magnetic field and so on have been created. Their microsizes allow one to use at preparation new high-efficiency microtechnologies, and also to realize the possibility of their combination with chips of electron processing of measuring signals.

Unlike the known constructions, the proposed volumetric-planar constructive variant of humidity microsensor with the use of nanoporous AAO (Fig. 3) has improved characteristics. To increase the absorption ability thermal processing is made of substrates at temperatures providing maximal specific surface of the sensor. According to the test results high sensitivity, relatively high accuracy and repetition of characteristics of sensor within the range of values of relative humidity of 10-95% including at the change of environment temperature from 20 till 60^{0}C are shown. The developed variant can serve the prototype for construction of humidity sensors with electron scheme of transformation of capacity-voltage on the basis of large-scale integration [8].

The advantages of the proposed constructive variant of threshold temperature sensor (Fig. 4) are: i) high accuracies of response and sensitivity within a wide interval of temperatures of -70 °C…+500 °C, ii) small thermal and mechanical inertness in static conditions as well as in conditions of essential vibration and shocks.

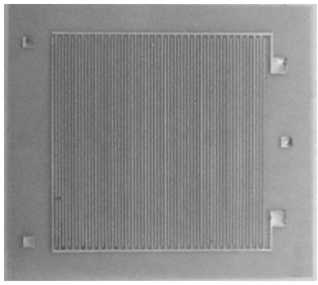


Figure 3. Image of planar-volumetric interdigital structure of humidity sensor on the basis of nanoporous AAO.

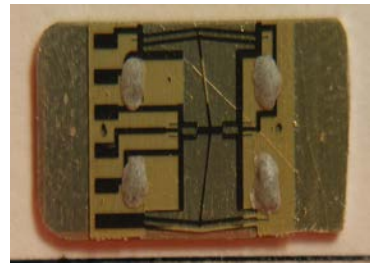


Figure 4. Photo of the prototype of the constructive variant of threshold sensors of temperature of planar construction (Patent No. 4536 BY) (increase in 40 times).

The temperature sensor is suitable for the work in extreme conditions of environment. It is perspective for application in systems of automation of industrial processes and control of temperature parameters of technological operations.

MECHANICAL SENSORS (FORCE, ACCELERATION, VIBRATION, KNOCK)

Mechanical microsensors are sensitive elements, reacting on the change of external influences (force, acceleration, vibration, knock and so on). They are used in systems of control and regulation of force parameters in technological processes and regimes of exploitation of energetic set-ups for measurements of micromovements. Proposed by us the constructional structure variant of electromechanical microsensor of force (Fig.5) differs by the essential values of deformations, larger sensitivity and increased accuracy of measurements, especially at small values of loads. It can be used in conditions of stretching and compression forces and pressures, and also for measurement of microshifts.

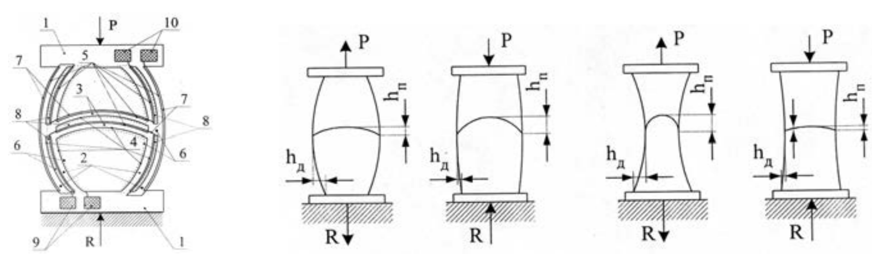
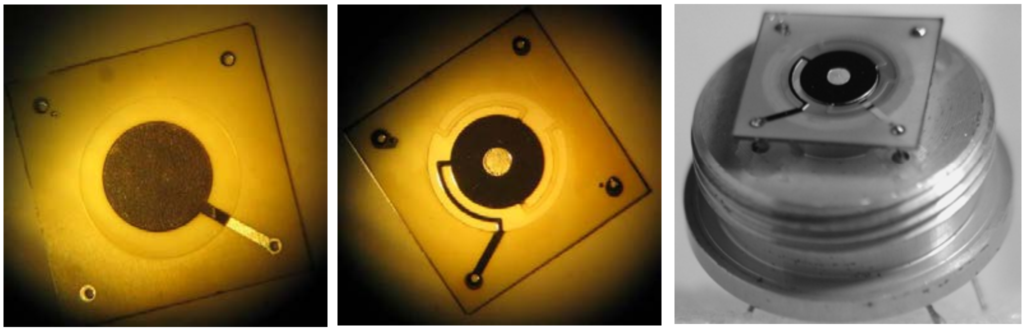


Figure5. Schematic image of planar constructive variant of electro-mechanical microsensor of force (Patent of the Republic of Belarus No.5534).

A distinctive feature of the prototype of vibration sensor (acceleration, knock) of volumetric constructive fulfillment (Fig.6) is high sensitivity and possibility of its regulation within a wide limits by changing the ratio of elastic properties of movable element and its mass. Planar plane-parallel variant of such a sensor is less sensitive but has the advantages of simpler technology, i.e. at its creation the assembling operation is excluded.

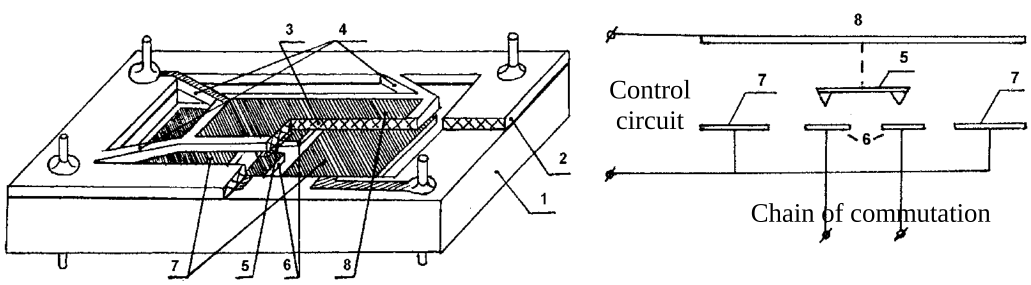


(a) (b) (c)

Figure 6. Elements and market sample of the sensor of vibrations: a) – plate with motionless electrode, b) – plate with movable element on the basis of elastic holder and movable electrode, c) – market sample of assembled plate on the base with outlet.

MICRO-ELECTROMECHANICAL SYSTEMS (MEMS)

Microswitches and microrelays built on the AAO substrates are based on the formation of precision movable elements, using special constructions of thin elastic keeper, providing plane-parallel shift of movable electrode relatively unmovable one, and also creation of microrelief in a volume of substrate. They need the conducting of calculations of the constructions with the set parameters of exploitation on universal formula dividing constant constructive characteristics and variable characteristics connected with the position of movable electrode relatively unmovable ones in each moment of working cycle [9]. In combination this allows one to achieve the manipulation of the position of movable electrode at moving within the whole working interelectrode interval. The developed demonstration variant of the prototype of electro-static microrelay of volumetric construction (Fig.7) proved its high but not ultimate characteristics: 1) electrical voltage of breakdown - >1 kV, 2) resistance of isolation between managing electrodes – 10^{12} Ohm, 3) resistance of isolation between commutating contacts – 10^{9} Ohm, 4) maximal voltage on the dead contacts - >1 kV, 5) nominal commutating current I_{nom} – 5 mA (contact areas – thin films Ni), 6) working frequency of response - >10^{3} Hz, 7) capacity of managing chain – 1,5 pF, 8) total dimensions of market sample – 5,2x4,0x0,2 mm^{3}, 9) weight – 0,01 g.



a) b)

Figure 7. Some perspective constructions of MEMS: a) prototype of microrelay of volumetric construction based on the electro-static principle of operation; b) equivalent circuit of electrostatic microrelay.

We have also proposed and developed a number of original variants of microrelays of volumetric and planar construction for various conditions of applications on the principles of electrostatic, electro-charging, and also electro-current interactions [10-13]. They have higher characteristics in comparison with the best analogies.

As an example in Fig.8 the schematic illustration is presented of electro-static microcommutator with normal dead contact and closed contact. It is characterized by widened functional possibilities, increased stability of parameters at vibration and impact loads due to fixation of movable element in both positions. MEMS on the basis of AAO give the possibility for creation of wide range of precise control-executive microdevices of multi-purposeful functional application. It allows making the reduction of work voltage for further miniaturization of electronic techniques. Also microdevices are perspective for the use in managing, regulating, commutating systems. One more example of the combined planar electro-static microrelay is shown in Fig. 9.

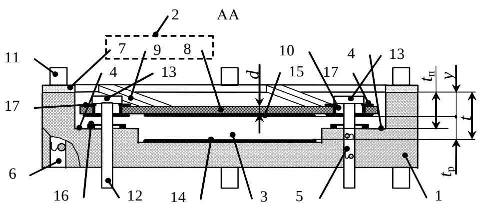


Figure 8. Schematic image of volumetric constructional variant of electro-static microcommutator (Patent of the Republic of Belarus No.8453).

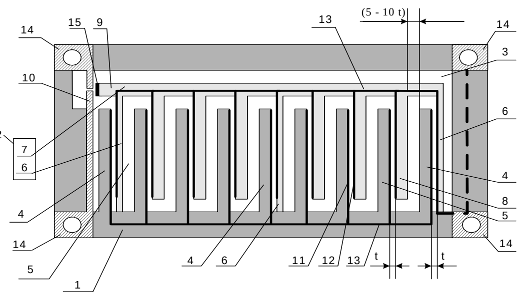
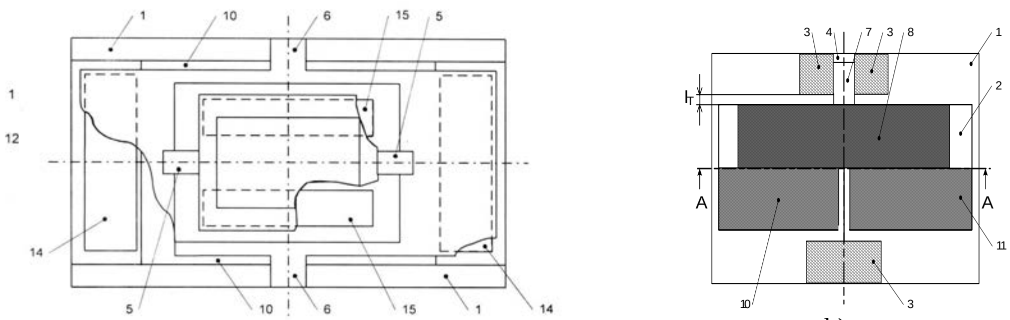


Figure 9. Combined planar electro-static microrelay (Patent of the Republic of Belarus No. 9717).

MICRO-OPTO-ELECTROMECHANICAL SYSTEMS (MOEMS)

The advantages of MOEMS are the increased accuracy of spatial positioning of the reflected optical beams within the wide angular range due to the reduction of inaccuracies in ratio value of electrical voltage – angle of anchor turn. Two examples of such devices are depicted in Fig. 10.



a) b)

Figure 10. Schematic image of micro-mechanical optical switcher (Patent of the Republic of Belarus No.7462) (a) and optical microscanner (Patent of RB No. 7959) (b).

The proposed micro-opto-electromechanical switcher and scanner are perspective for application in systems of commutation, television, informatics, computer and control engineering, for example, in devices of line scan and frame scan, spatial positioning of optical rays.

ACTUATORS

For the last time some models have been created of microsensors on the basis of MEMS, which have been probed in industry: to them relate the microsensors of pressure and acceleration, magnetic microsensors, vibration microhyroscopes and so on. Characteristics of microsensors can be improved due to the use of new more qualitative materials and technologies of production. One of examples of such a type of microsensors can served the proposed by us variant of electrostatic microactuator [14]. It exhibits the better output parameters and widening of functional possibilities due to the increase of accuracy of fulfillment of interelectrode distances. Such a microactuator can be used in systems of connection, automation, control and regulation technique.

It is very important to provide the possibility of optimal integration of microsensors into information systems. It is necessary also to pay attention on wider use of the notion of intellectuality at creation of microsensors and measuring systems. Modern sensor systems usually realize the functions of amplification and processing of signal and also functions of storage. In hybrid sensor microsystems on the basis of electronic chip the possibility of combination with chips of electronic processing of signal should be foreseen. Such a variant can be the developed by us sensor on the basis of chip where the sensitive element of two coordinate-sensor of acceleration can be fulfilled on the basis of AAO substrate with precision microrelief and thin-film electrodes, and the system of information processing of sensor is realized in a form of large-scale integration of transformator of electrical capacity – electrical voltage (Fig. 11).

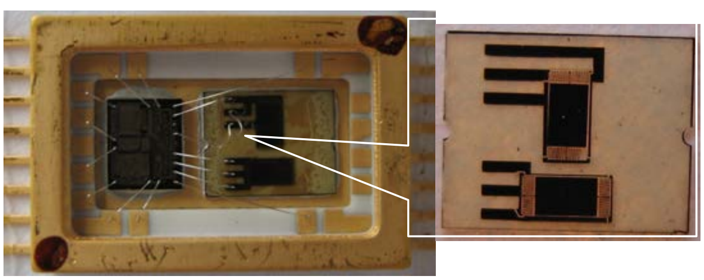


Figure 11. Photography of 2D accelerations sensor based on AAO sensitive elements and large-scale integration of transducer capacitor-voltage.

CONCLUSIONS

A wide range types of physical, gas, chemical and mechanical sensors, as well as multisensor systems with local nanodimensional elements based on porous AAO is described.

The developed multisensor systems are promising for application in a variety of techniques related to diagnostics and prognostics. The mentioned sensors are sensitive to the variations of optical, magnetic, electrostatic and other fields and assigned for the automatic control of operation of complex systems. An important advantage is the opportunity of their exploitation in active zones with the extreme environmental conditions, for example, in the operating zone of the nuclear reactor.

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