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THE USE OF TECHNOLOGIES FOR STABILIZING THE ELECTROPHYSICAL CHARACTERISTICS OF SENSOR STRUCTURES USED IN THE DEVELOPMENT AND MANUFACTURE OF MEASURING TRANSDUCERS

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The object of the study is the design, manufacturing technology and methods of stabilizing the electrophysical characteristics of measuring transducers. The problem solved in the research is the creation of methods and design and technological solutions to ensure stability used in the development and manufacture of measuring transducers. As a result of the conducted research, designs and technologies for manufacturing and stabilizing the electrophysical characteristics of measuring transducers were developed. The features of the developed designs of measuring transducers are increased in comparison with the known time stability with a basic error of no more than 0.1 %/year. Technologies for stabilizing the parameters of measuring transducers, in contrast to the known ones, differ in their versatility, since most elastic elements that perceive mechanical magnitude are membranes and beams, on which thermocompensating films are easily applied. The stabilization of the parameters of the entire measuring transducer, unlike the known ones, is carried out after the removal of internal mechanical stresses of each element and part of the measuring transducer through the integrated use of current and vibration dynamic loads. Thus, the use of complex compensation due to the application of a new method of compensation of internal mechanical stresses in the structure, based on the use of multilayer film compositions formed on sensitive elements, followed by thermal and vibration stabilization of measuring transducers. In addition, reducing the measurement error and increasing the time and parametric stability of the measuring transducers is achieved through the use of specialized heat treatment modes, training resonant vibration and current loads. When developing structures and stabilization methods, previously developed engineering mathematical models were used, including constructive, informational, dimensional, technological and circuit engineering. At the same time, depending on the adopted design and the technology used, engineering models were modified by including known coefficients and dependencies. This method has significantly reduced the cost and complexity of development

Keywords: physical model, stabilization method, thermal training, polyfilm compensation, shock cycles, temporary stability

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1. Introduction

The creation of new products and systems for special and hazardous applications in science and technology or the modernization of existing measuring systems for new applications requires an individual approach to their design processes. In particular, it is very difficult or even impossible to use existing measuring systems designed for shallow water to study the bottom relief or the dynamics of changes in processes in the seas and oceans at great depths. At the same time, pressure sensors (PS) must be replaced with new ones or have protective enclosures and multipliers that protect previously used PS and normalize their measuring signals. Accelerometers are also used, which are equipped with vibration compensators or resonators that normalize the vibration measured by the accelerometer: decrease in the first case or increase in the second. In certain cases of PS application, so-called engineering methods and PS design models are often used. At the same time, engineering design, as a rule, includes extensive experience of previously conducted research and development in the field of materials management, new designs and technological solutions. The basis of analytical and computational mathematical models, as a rule, are formulas and calculations of well-known mathematicians, materials scientists and technologists who previously offered both generalized formulas and conclusions from their fundamental works.

Examples of the use of the proposed models and methods are the developed and repeatedly tested analytical models of sensitive elements (SE) in statics and dynamics, which allows for effective calculations of the functioning of the SE under the influence of external influencing factors [1–3].

It should be noted that most complex and expensive modeling programs (Matlab (Simulink), ANSYS, COMSOL) are based on the use of grid computing methods. At the same time, initially well-known equations and models of resistance of materials, electrodynamics, electrostatics, microelectronics, etc. are used. The use of engineering techniques and models will significantly reduce the cost of modeling a real PS and not spend significant funds on new software packages and their extensions. So, according to information from the Internet, the cost of the COMSOL Multiphysics software product is 2,650,000 rubles [4, 5].

In practice, there are many engineering models in science and technology that are actively and widely used, having absorbed the previous constructive and technological experience in the production of various devices and mechanisms. At the same time, the use of engineering models often brings significant advantages, which consist in the fact that there is no need to purchase additional programs, as well as train operators to use them in practice. In addition, when using engineering models and methods, there is no need to buy expensive libraries for advanced calculation of structures, etc.

Currently, methods for improving the stability of devices have not been developed. The proposed stabilization methods are due to the use of metal and dielectric films applied to SE sensors, which reduce internal mechanical stresses. In addition, shock modes of thermal and vibration cyclic loads are used for temporary stabilization.

Therefore, an urgent problem is the development of SE stabilization methods that will ensure the rapid development and achievement of temporal and parametric stability of sensors.

The creation of new products and systems for special fields of science and technology, as well as the modernization of existing measuring systems (MS) for new applications, requires an individual approach to their design processes. In particular, it is very difficult or even impossible to use existing MS designed for shallow water to study the bottom relief or the dynamics of changes in processes in the seas and oceans at great depths. At the same time, PS must be replaced with new ones or have protective enclosures and multipliers that protect previously used PS and normalize their measuring signals. Accelerometers are also used, which are equipped with vibration compensators or resonators that normalize the vibration measured by the accelerometer: decrease in the first case or increase in the second. In certain cases of PS application, so-called engineering methods and PS design models are often used. At the same time, engineering design, as a rule, includes extensive experience of previously conducted research and development in the field of materials management, new designs and technological solutions. The basis of analytical and computational mathematical models, as a rule, are formulas and calculations of well-known mathematicians, materials scientists and technologists who previously offered both generalized formulas and conclusions from their fundamental works.

Examples of the use of the proposed models and methods are developed and repeatedly tested analytical models of SE in statics and dynamics, which allows for effective calculations of the functioning of the SE under the influence of external influencing factors [1–3].

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In practice, there are many engineering models in science and technology that are actively and widely used, having absorbed the previous constructive and technological experience in the production of various devices and mechanisms.

Currently, methods for improving the stability of devices are insufficiently developed. The proposed stabilization methods are due to the use of metal and dielectric coatings applied to SE sensors, which reduce internal mechanical stresses. In addition, shock modes of thermal and vibration cyclic loads are used for temporary stabilization.

Therefore, an urgent problem is the development and implementation of SE stabilization methods that will ensure the rapid development and achievement of temporal and parametric stability of measuring transducers.

2. Literature review and problem statement

The article [1] provides information on the construction of a composite membrane element consisting of several separate membranes connected along the periphery. This construction is functionally unstable, and it is difficult to calculate, since constructive assumptions are used.

In the article [4] elastic elements with piezoelectric films formed on their surface are considered, as studies have shown, piezo films have a significant spread in electrophysical characteristics (EPC) and cannot measure static loads. In addition, the article does not specify methods for stabilizing EPC.

The sources [6, 7] describe a method and analytical models for designing micromechanical accelerometers and sensors, taking into account the influence of interference on them. It is noted that when developing mathematical models of accelerometers, a very important point is the creation of their digital analogue. And in order to take into account and analyze the influence of influencing quantities and interference on the operation of sensors, it is proposed to divide them into static and dynamic in time of action and amplitude and compensate for them using the MathWorks program. The described methods and models are not suitable due to the lack of specificity in the designs and methods. In addition, the article does not provide methods of temporal and parametric stabilization.

The article [8] describes a method for modeling a microelectromechanical (MEMS) acceleration sensor. At the same time, in the Simulink environment of the MatLab software package, a behavioral model of a linear acceleration sensor with two sensitivity axes is synthesized based on a mathematical model of this device in the form of differential equations. The results of modeling the dynamics of the synthesized model of sensor behavior in the form of transients and spectral analysis when the system reacts to external influences are presented. The article is difficult to apply to the proposed structures due to weak structural disclosure, and there is also no data on the stabilization of the acceleration sensor, since the main obstacle in them is accumulated instability.

The publication [9] describes a photovoltaic system in which a software simulation model was developed to help analyze the performance of photovoltaic modules, as well as a general circuit model that can be used to test any commercial photovoltaic module. This article presents a simulation of a mathematical model of a photovoltaic module that increases the power of a DC-to-AC converter, and also simulates the operating modes of a solar generating system with different load characteristics. This proposal may be useful for a measuring system, but it is inefficient for individual sensors and cannot be applied to the developed models and methods.

The article [10] describes the development of design models of multifunctional sensors, the interaction of measuring channels is considered, but there are no materials to ensure the stability of measurements and design and technological solutions are not given, which makes it difficult to use them in the developed PS.

The article [11] describes methods for monitoring and stabilizing the main parameters of various designs and manufacturing technologies of microsensors, including circuitry and design solutions; for various applications. Their studies have shown that they are complex and require unique technological equipment for the implementation and subsequent stabilization of parameters.

The article [12, 13] presents the designs and manufacturing technologies of micromechanical sensors designed for various fields – from medicine to industrial technologies. In addition, mathematical models describing sensitive elements are given. The presented materials and technological equipment are difficult to use, in addition, the article lacks information on ways to stabilize their characteristics, which differ from their application, so it is very difficult to implement them in the proposed designs and technologies.

The article [14] presents sensors made on the basis of the sensor structure and its mathematical models based on the COMSOL Multiphysics program. The main disadvantage is the high cost of the program and the inadequacy of its solutions, which must be checked during metrological tests.

In the article [15], studies of pressure/deformation sensors of a significant area and a matrix based on nanomaterials printed were carried out. These designs and technologies cannot be applied to serial sensors, in addition, there is no information about their stability in the materials.

The article [16] provides data on the design features of microelectronic sensors for aviation and space technology, while there is no information on the stabilization of their effectiveness.

The article [17] describes the technology of forming electrostatic stops for pendulum accelerometers, which ensure the stability of the separation of the central beam of the accelerometer, there is no data on the stability of this structural and technological solution, while the separation problem is solved by profiling the SE.

The article [18] highlights the issues of control of the electrophysical properties of materials and structures of microelectronic sensors through the use of constructive measures, but there are no indications of stabilization of their parameters.

The article [19] discusses multifunctional fiber-optic sensors for space infrastructure and there is no information about operations to stabilize their EFP.

The article [20] describes the technological processes of forming nanofilms for sensors, but there is no indication of optimizing their parameters.

A review of the sources showed that they do not investigate methods for stabilizing the structures of the MS, since the introduction of parameter stabilization technologies requires development and experience in this direction. Thus, the use of design solutions and methods of manufacturing and stabilization of MS will improve their quality and temporary stability. This problem is not an easy problem, because it requires significant production experience, proven stability and reproducibility, as well as high professionalism to solve it.

3. Th aim and objectives of the study

The aim of the study is to develop, manufacture and test MS of various physical quantities, as well as technologies for their manufacture and stabilization of EPC, using the created engineering models and techniques.

To achieve this aim, it is necessary to perform the following objectives:

– development and research of design and technological solutions used to compensate for internal stresses in elements and assemblies of measuring transducers;

– selection and research of methods of constructive and technological stabilization of elements and components of an information system (IS);

– analysis and selection of engineering models and methods of MS development with a view to their possible modification and refinement.

4. Materials and methods

In the course of a literary search, approaches were investigated and design and technological solutions were identified, the use of which led to compensation of internal stresses in the elements and nodes of measuring transducers, but the discovered sources suggest the use of complex technologies, in particular, the use of ion doping with significant doses of ions that neutralize internal mechanical stresses. This approach is due to significant material costs for technological equipment.

Literary research has also been carried out in the field of choosing methods of constructive and technological stabilization of IC elements and structures in order to ensure the temporal and parametric stability of measuring transducers. The described methods consist in heat treatment with a laser beam of individual sensory structures or the entire SE. But, as practice has shown, the internal stresses in the measuring converter itself remain, while quite significant, which are caused by the interaction of parts and assemblies when they are connected.

A significant number of publications are devoted to modeling using complex, expensive software packages (Simulink, MatLab, COMSOL Multiphysics program, etc.). Although, as experiments have shown, there is a satisfactory coincidence between complex software models and well-known analytical models that are modified and refined for the object under study (design, technological process, etc.). Therefore, the use of engineering methods and models is economically advantageous when designing an object.

The object of the research is designs, technologies, engineering models and methods of increasing the temporal and parametric stability of the measuring transducer (MT). At the same time, the research is based on patent and literature reviews and new design and technological solutions proposed based on the results of the research, which allow increasing the stability of measuring transducers.

The main hypothesis of the study is the possibility of controlling the EPC of the MT using targeted thermophysical effects.

The simplifications adopted in the work include engineering models and methods that use constructive and technological constants, which can be obtained and be different for different components of MT parts, as well as for existing technological equipment.

The research did not use methods that involve the use of radiation and ion treatments, as well as exposure to aggressive gases, since this is associated with the danger and use of complex technological equipment that requires decontamination of waste.

5. Results of design and development of manufacturing technology for MC used in extreme operating conditions

5. 1. Development and research of design and technological solutions used to compensate for internal stresses in elements and assemblies of measuring transducers

It should be noted that the greatest influence on the characteristics of the entire MC is exerted by SE containing an elastic element (EE) and SE formed on its surface or in volume [14]. Therefore, it is necessary to stabilize its characteristics, since in case of insufficient stability, other methods will not ensure its operation when exposed to external interference.

For modeling, the sensitive areas of the SE crystal can be represented as thin plates fixed at the ends, therefore, a thin rectangular silicon plate coated with a metal or dielectric film should be considered as a computational model of the compensator (Fig. 1, *a*). A physical and mathematical model of the films thermal compensator can be obtained based on a diagram of the thermal expansion of the plate with the film coating shown in Fig. 1, *b*.

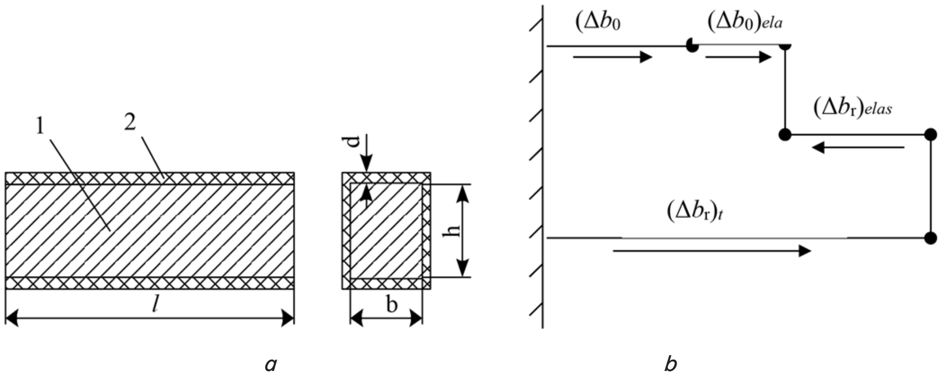

Fig. 1. Diagram of the film compensator: *a* – geometric model; *b* – design model; 1 – plate; 2 – coating

From the calculation model (diagrams in Fig. 1, *b*) it follows:

$$\Delta b_0 = \left(\Delta b_0\right)_t \pm \left(\Delta b_0\right)_{elas} = b\alpha_0 \cdot \Delta t \pm C_0 \cdot N, \tag{1}$$

$$\Delta b_{tap} = \left(\Delta b_{tap}\right)_t \pm \left(\Delta b_P\right)_{elas} = b\alpha_{tap} \cdot \Delta t \pm C_P \cdot N, \tag{2}$$

where Δb_t, Δb_{0elas} – the components of the total elongation (Δb_0) from the action of temperature and elastic forces; C – malleability; N – the force of interaction between the plate and the coating; α – the temperature coefficient of linear expansion (TCLE); Δt – the temperature increment; the indices “0” and “P” refer to plate and coating, respectively [15].

From the continuity condition of the system, the plate coating follows:

$$\Delta b_0 = \Delta b_P = \Delta b_{FP}, \tag{3}$$

$$\Delta b_0 = b \cdot \alpha_{FP} \cdot \Delta t, \tag{4}$$

where

$$\alpha_{FP} = \Delta b_{FP} / b \cdot \Delta t. \tag{5}$$

From expressions (1) and (3) it is possible to define N and Δb_0:

$$N = \frac{b\alpha_P \cdot \Delta t - \Delta b_P}{C_P}, \tag{6}$$

$$\Delta b_{FP} = \frac{l\left(\alpha_F C_{FP} + \alpha_P C_F\right)\Delta t}{C_P + C_F}. \tag{7}$$

Substituting (7) into (5), let’s obtain:

$$\alpha_{FP}=\frac{\alpha_F C_P+\alpha_P C_F}{C_P+C_F}. \tag{8}$$

The ratios are valid for EE:

$$C_P=\frac{b}{E_P F_P}, \tag{9}$$

$$C_F=\frac{b}{E_F F_F}. \tag{10}$$

Substituting them into (8), let's obtain:

$$\alpha_{FP}=\frac{\alpha_P E_P F_P+\alpha_F E_F F_F}{E_P F_P+E_F F_F}=\frac{\alpha_P+\alpha_F\frac{E_F F_F}{E_P F_P}}{1+\frac{E_F F_F}{E_P F_P}}=$$

$$=\frac{\alpha_P+k\alpha_F}{1+k}=\alpha_0\frac{1+k\frac{\alpha_F}{\alpha_P}}{1+k}=\alpha_P\frac{1+kL}{1+k}, \tag{11}$$

where k, L are constructive coefficients.

By entering a notation $\alpha_{FP}/\alpha_P=D$, expression (11) can be represented as:

$$D=\frac{1+kL}{1+k}. \tag{12}$$

(11) and (12) represent a mathematical model of the system – many films compensator. The analysis of model (12) can be performed by constructing a series of curves $D=F(L)$ in coordinates D and L for different values of k (Fig. 2) [16].

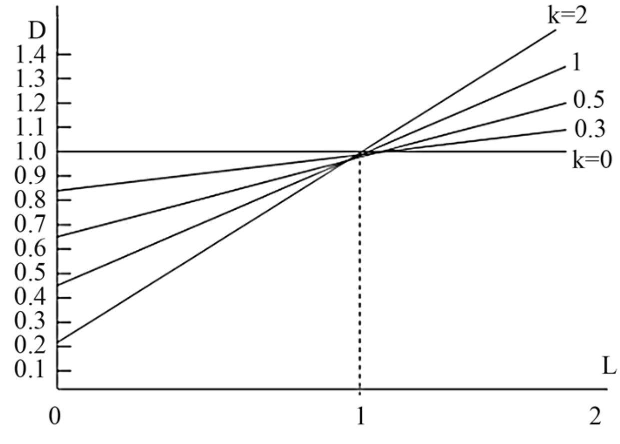

Fig. 2. Dependence of the linear expansion of the film-coated plate on the ratio of the physical and mechanical properties of the plate and the coating materials

To construct a numerical model for variables, the following values are taken:

– plate material: mono-Si (α_P=3.5·10^{-6}1/°C, E$_P$=1.6·10^5 MPa);

– plate dimensions: a×b=50 mm×5 mkm;

– coating – aluminum film with a thickness of 2 microns ((α_F=24·10^{-6}1/°C, E$_F$=71 kN/mm^2, F_F=10^{-8} mm^2).

Substituting these values in expression (10) let's obtain α_{PF}=2.4·10^{-9} 1/°C, that is, the TCLE of the considered plate after coating (aluminum) decreases from 3,5·10^{-6} 1/°C before 2.4·10^{-6} 1/°C.

Similarly to Nickel with a thickness of 2 µm, (α_F=12.5·10^{-6} 1/°C, E$_F$=2·10^4 kH/mm^2) and the same TCLE sizes, get α_{PF}=3.5·10^{-10} 1/°C [18].

Thus, in the semiconductor-film composite structure, after applying compensating film coatings, a decrease in temperature stresses is achieved by at least an order of magnitude.

Thus, the use of a poly-film coating consisting of several layers of metallic and dielectric films, the total TCLE of which is equal to the TCLE of the elastic element, but opposite in sign, reduces temperature interference to practically zero in a wide temperature range [16].

5. 2. Selection and research of methods of constructive and technological stabilization of elements and components of an information system (IS)

Internal mechanical stresses are almost always present in sensor nodes, so it is necessary to develop technologies to minimize them by applying specialized technological operations to which the node, unit or sensor as a whole is subjected (heat stroke, vibrations, etc.).

Sensors are an essential part of control and measuring, control and regulatory systems in various industries, defense and life support, automated process control systems.

In addition, sensors used at strategic facilities such as nuclear and hydroelectric power plants, aircraft turbines, etc., must have a very significant resource and high stability of characteristics. This is due to significant difficulties in replacing sensors in the event of their failure at the measurement and control facility.

Without sensor equipment measuring and controlling various physical quantities (PQ), it is impossible to launch, diagnose and operate various products and systems of aviation equipment. Insufficient equipment with modern sensor of physical quantities (SPQ) makes it difficult to manage technically complex systems and complexes in aviation, technological systems, etc.

As diagnostic objects, it is advisable to consider not only the SPQ and the systems in which they function, performing the tasks of monitoring, diagnostics and management, but also the structural elements of the SPQ: SE and measuring module (MM), as well as the technological processes of the formation of the latter.

This is due to the fact that due to the development of SPQ production by various firms, including small ones, specialization and division of labor are taking place, while instrument-making firms have begun to produce structurally and functionally completed measuring modules. In its manufacture, high technologies (micromechanical, thin-film, hybrid) and carefully designed designs are used, which belong to leading instrument-making firms [17–19, 21].

At the same time, it should be borne in mind that the diagnostic methods used and the instrumentation of diagnostic systems depend on many factors, the main of which are:

– the physical principle of transformation;

– ranges of change of controlled parameters;

– a product or system that uses sensors;

– the type and level of external quantities affecting the sensor (interference);

– information and energy compatibility of the diagnosed parameters in various sensors.

Let's look at these factors in more detail. The vast majority of static-dynamic pressure sensors used in industry use three types of physical conversion principles: piezoresistive, piezoelectric and, to a lesser extent, capacitive [19–25].

The next factor influencing the choice of diagnostic methods is the measurement range, which determines the magnitude and shape of the current diagnostic signal. Thus, thermodiagnostics based on controlled thermal deformations of SE are used only for thin Si membranes, since thermodiagnostics are difficult to apply for thick Si membranes.

The choice of methods and means of functional diagnostics is significantly influenced by those products of the system in which static-dynamic pressure sensors is used and where removing the sensor from the object is either impossible at all, or is associated with high labor costs and the possibility of reducing reliability. Such situations are especially typical for products and industrial facilities, in particular, thermal power plants and dams. Also, diagnostic methods depend on the specific products and devices in which sensors are used, since the method of installation, fastening, protection and inclusion in a single information system also determines the possibilities and varieties of test actions and checks carried out.

Let's see what can be suitable for the diagnosis of strain-resistant pressure sensors. In monitoring and diagnostic systems, SPQ calibrators are used to simulate (simulate) the output of a natural value, for example, pressure, which connect precise resistors of a certain value in parallel to one of the arms of the sensor bridge circuit. This connection causes the appearance of an electrical signal (imbalance) at the output of the sensor, by the magnitude of which the metrological serviceability of the SPQ is judged. The influence of temperature is also modeled, at which the temperature change is modeled by a change in the resistance of a thermoresistive element (Fig. 3).

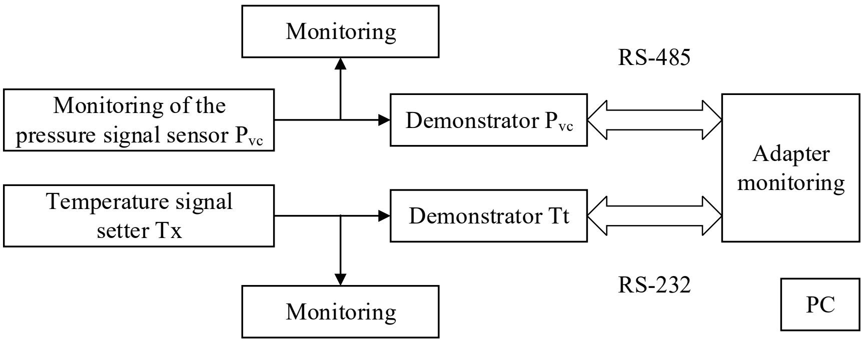

Fig. 3. Simulation diagram of virtual pressure and temperature effects on an integrated test bench of an aircraft engine

Briefly consider the requirements and types of diagnostic actions that are performed during testing.

During the production of sensors, at all stages of the technological process, the sensor is subjected to diagnostic and control operations (Fig. 4).

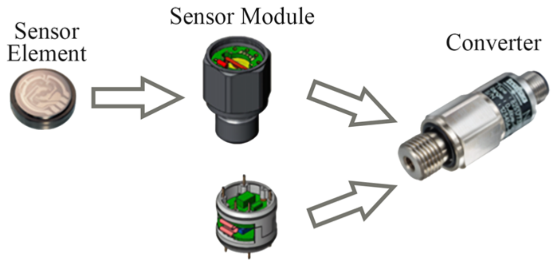

Fig. 4. Step-by-step testing of sensors during the production process

The testing algorithm consists of the following stages:
- temperature coefficient T_c;
- zero Z_p;
- S_p range;
- stability [μV].

Step-by-step testing:
- measurement of the temperature coefficient T_c;
- measurement of zero Z_p;
- accelerated aging 180g at 120 °C;
- zero Z_p measurement;
- measurement of the temperature coefficient T_c.
- heating up to 80 °C;
- measurement of zero and range at 80 °C;
- cooling to 20 °C;
- measurement of zero and range at 200 °C;
- calculation of the temperature coefficient;
- the result is good/not good?

Pressure.

Accelerated tests:
- accelerated aging tests;
- sensor operation at high temperatures;
- exposure to high temperatures at different pressure ranges;
- accelerated load tests;
- high pressures, pressure shocks>4000 bar for sensor at 400–600 bar;
- temperature jumps, cycles of at least 100–200 cycles (–40/+125 °C, 30 min);
- vibrations (20–40 g RMS ~with overloads of 40–80 g with a harmonic frequency of 20...2000 Hz).

Permissible distortions, or the difference between the projected and operational limits that determine how reliable the products are

Additional tests
- preparation for temperature cycles;
- temperature changes from –80 °C to 160 °C;
- step-by-step vibrations from 5 g to 50 g;
- step-by-step vibrations from 5 g to 50 g at –80 °C;
- step-by-step vibrations from 5 g to 50 g at 160 °C.

Combined conditions: constant vibrations of 50 g, temperature cycles of –80 °C and 160 °C, at constant pressure.
- preparation for temperature cycles;
- temperature changes from –80 °C to 160 °C;
- step-by-step vibrations from 5 g to 50 g;
- step-by-step vibrations from 5 g to 50 g at –80 °C;
- step-by-step vibrations from 5 g to 50 g at 160 °C.

Combined conditions: constant vibrations of 50 g, temperature cycles of –80 °C and 160 °C, at constant pressure.

According to the accepted methodology for stabilizing the structures of the developed measuring transducers, each of the elements and blocks of the IS should be stabilized (Fig. 5).

The cyclogram of loads during accelerated sensor tests is shown in Fig. 6. The use of accelerated testing significantly reduces the overall duration of sensor manufacturing. Accelerated tests are carried out with an increase in the main external factors: temperature, thermal cycles of pressure, vibration, while all impacts are carried out cyclically, so the total test time is significantly reduced.

Fig. 5. Block diagram of the sensor

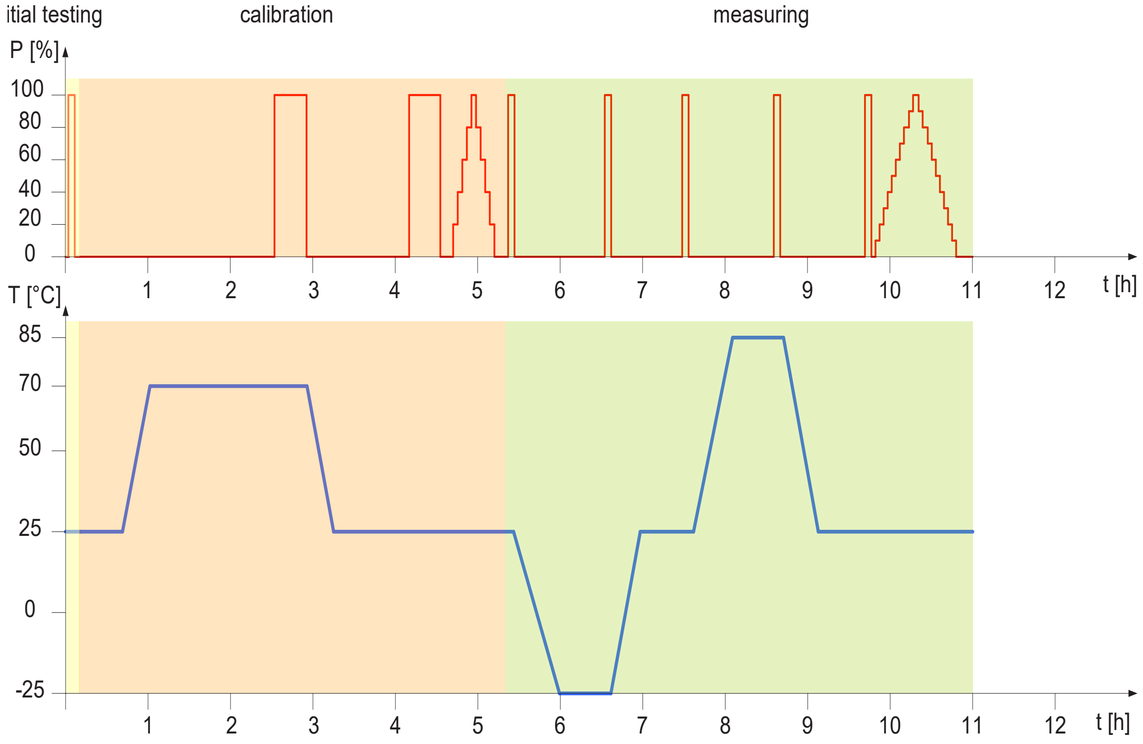

Fig. 6. Cyclogram of accelerated load tests of the sensor

The measured pressure P_x acting on the membrane is transformed into deformation ε_x. Strain ε_x is transformed by strain gages into a relative change in their resistance ΔR_x. The relative change in the resistance ε_{Rx} of the bridge circuit is converted into an output signal, the value of which U_x is proportional ΔR_x to quently, the input value – the pressure P_x. Fig. 7 shows the curve of sensor failures during their life cycle.

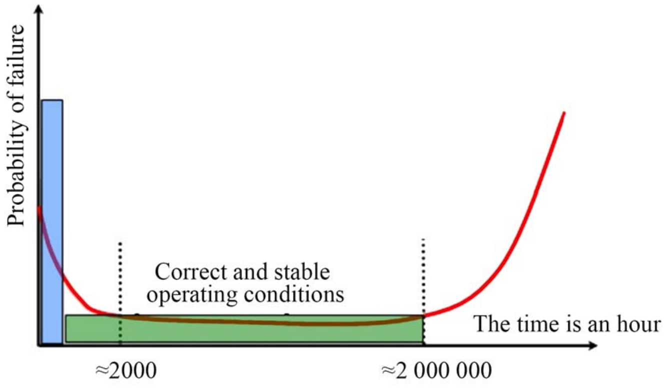

Fig. 7. Diagram of reliability during operation of manufactured sensors

The main node of the sensor being developed is a sensing element (Fig. 7), which is a membrane with a rigid center, on which a bridge measuring circuit using thin-film technology is applied. Using the methods of engineering calculations, let's give an example of determining its basic dimensions, which determine its sensitivity.

The design models of the sensors given in the article, as well as effective methods for stabilizing their parameters by accelerated testing and thermal cycling, have made it possible to increase their temporal and parametric stability.

5. 3. Analysis and selection of engineering models and methods of MS development with a view to their possible modification and refinement

In order to ensure the specialization of engineering models that are used in the modeling of structures and in the technology of manufacturing sensors, they require refinement and modification. Let's look at these procedures in more detail.

The following layers are present in the structure of the SE under consideration: a membrane layer, a strain gauge layer, unalloyed polycrystalline silicon and passivating (protective) silicon oxide, an insulating layer of silicon oxide, which affect the rigidity of the SE. Let's investigate the effect of these nanolayers on the rigidity of the SE during bending.

The strain gauge layer, due to its small area (the total area occupied by strain gauges on the membrane is 0.06 %), as well as the SiO_2 insulating layer located under it, can be neglected.

Let’s analyze the structure of the remaining layers (since they occupy the entire diagnostic area), presented in Fig. 8 in the form of an elementary ray.

In this case, let’s associate the *XYZ* coordinate system with the beam, the 0*y*, 0*x* and 0*z* axes relative to the main axes of the beam section, the 0 point is located in the center of gravity of the beam section (Fig. 8).

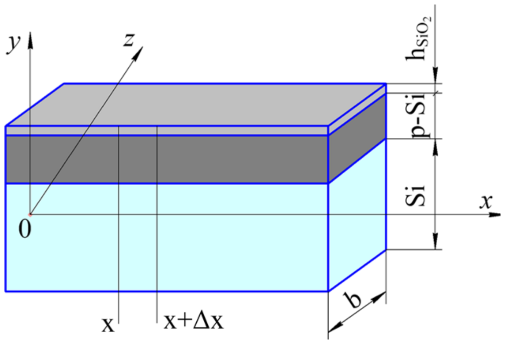

Fig. 8. Geometric model (tank) of the original Semiconductor sensing element structure

In deriving the dependence determining the bending stiffness of the beam, let’s base the Bernoulli hypothesis on flat layers [18] and assume that the middle layer of the beam is inextensible.

To determine the bending stiffness of the beam in the direction of the Oy axis, let’s look at the deformable [*x*; *x*+Δ*x*] (Fig. 9).

The expression for determining the stress arising in the section dξ:

$$\sigma = E(y)\xi\phi, \tag{13}$$

where *E* – the elastic modulus of the first kind; ξ – the distance from the midline to the section dξ; ϕ – the angle of rotation of the section relative to section *x* (Fig. 9).

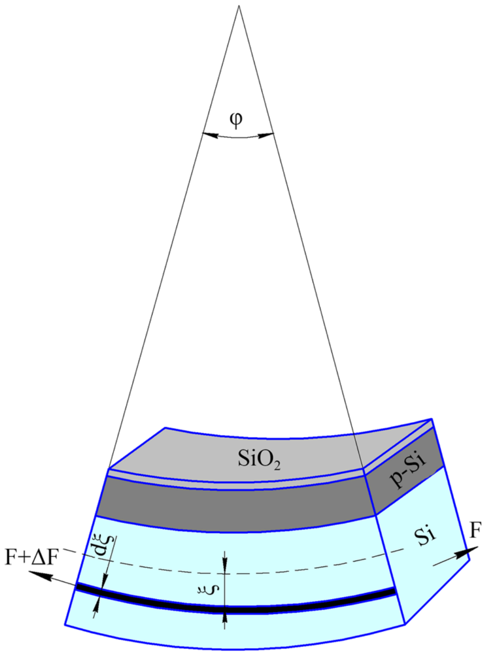

Fig. 9. The loaded sector (beam) of the multilayer Semiconductor sensing element

The dependence for the angle is obvious:

$$\phi = \left.\frac{dw}{dx}\right|_{x} - \left.\frac{dw}{dx}\right|_{x+\Delta x} = \frac{\partial^2 w}{\partial x^2}. \tag{14}$$

Thus, the stress in the cross section is determined by the dependence:

$$\sigma = E(y)\xi\frac{\partial^2 w}{\partial x^2}, \tag{15}$$

where *w* – the linear displacement of the beam section in the direction of the axis 0y.

Multiplying the expression (15) by the cross-sectional area, let’s proceed to the expression defining the force in the cross-section arising from the strain of stretching (compression) of this section:

$$dF = E(y)\xi\frac{\partial^2 w}{\partial x^2}bd\xi. \tag{16}$$

Therefore, the moment of force arising in the beam section will be determined by the dependence:

$$M = \int_{-H/2}^{H/2}\Delta E(y)\frac{\partial^2 w}{\partial x^2}b\xi^2 d\xi, \tag{17}$$

H – the thickness of the elastic element, $H=h_{Si}+h_{p\text{-}Si}$, where h_{Si} – the thickness of the silicon layer; $h_{p\text{-}Si}$ – the thickness of the layer of non-metallic polycrystalline silicon p-Si.

Thus, the bending stiffness of the beam in the direction of the 0y axis will be determined by the dependence:

$$B = \int_{-H/2}^{H/2}\Delta E(y)\frac{\partial^2 w}{\partial x^2}b\xi^2 d\xi. \tag{18}$$

Let’s suppose that all the beams we are considering are homogeneous, therefore, the Young’s modulus *E*(*y*) can take two values depending on the *y* coordinates: Young’s modulus, at and Young’s modulus.

Taking into account the above, let’s rewrite the expression (18) for the bending stiffness of the beam:

$$B = E_{Si}b\int_{-h_{Si}/2}^{h_{Si}/2}\Delta\xi^2 bd\xi + {}$$

$$+E_{SiO_2}b\int_{-h_{Si}/2-h_{SiO_2}}^{-h_{Si}/2}\Delta\xi^2 d\xi + E_{SiO_2}b\int_{h_{Si}/2}^{h_{Si}/2+h_{SiO_2}}\Delta\xi^2 d\xi. \tag{19}$$

Finally, the expression for bending stiffness has the form:

$$B = E_{Si}\frac{bh_{Si}^3}{12} + E_{SiO_2}b\left(\frac{1}{2}h_{Si}^2 h_{SiO_2} + h_{Si}h_{SiO_2}^2 + \frac{2}{3}h_{SiO_2}^3\right). \tag{20}$$

The first term in the expression (20) determines the bending stiffness of the silicon part of the beam and coincides with the well-known elementary formula for the resistance rate of materials, the second part of the expression (20) determines the influence introduced by the layers on the bending stiffness of the beam.

If the layers are located along the entire perimeter of the beam, as shown in Fig. 9, then a term is added to the expression for bending stiffness in the direction of the 0_y axis (20):

$$2E_{SiO_2} b \int\limits_{-h_{Si}/2-h_{SiO_2}}^{-h_{Si}/2} \Delta\xi^2 d\xi + \int\limits_{-H/2}^{H/2} \Delta\xi^2 d\xi db = E_{SiO_2} \frac{H^3 b_{SiO_2}}{6}, \quad (21)$$

which determines the bending stiffness of two sections of layers parallel to the 0_y axis.

Thus, the bending stiffness of a rectangular beam covered with layers around the perimeter will be determined by the following dependence:

$$B = E_{Si} \frac{b h_{Si}^3}{12} + E_{SiO_2} \left(b\left(\frac{1}{2} h_{Si}^2 h_{SiO_2} + h_{Si} h_{SiO_2}^2 + \frac{2}{3} h_{SiO_2}^3 \right) + \frac{\left(h_{Si} + 2h_{SiO_2}\right)^3 b_{SiO_2}}{6} \right). \quad (22)$$

Let's consider the contribution of layers with different elastic modules of the first kind to the stiffness of the suspension during bending.

The Young's modulus of silicon nitride (Si_3N_4) thin films used in the production of semiconductors is 380 GPa. For a 0.5 microns thick silicon nitride film grown by plasma chemical deposition from the gas phase, Young's modulus is 210 GPa. Thin films of silicon oxide used in microelectronics have a Young's modulus equal to 75 GPa. The value of the Young's modulus for aluminum oxide in the monocrystalline state is 530 GPa, and for aluminum oxide ceramics – 344.83...408.99 GPa [17].

From the above results, it can be seen that if the geometric dimensions of the sections of the silicon part of the beam and the layers differ several times, then the layers have a very significant effect on the bending stiffness of the beam as a whole.

Even if this difference is more than two orders of magnitude, the surface layers will also have an effect (up to several percent) on the bending stiffness of the beam.

It should be noted that the flexural stiffness of the suspension of any micromechanical device is the determining factor on which both the dynamic and static characteristics of this device depend. From the above results, it follows that when designing micromechanical devices, it is necessary to take into account the influence exerted by layers on the mechanical characteristics of structures.

As a result, analytical models of multilayer SE were investigated, and then, using numerical models, the actual values of the deformation of the SE were determined: bending moments, bending, deformation of layers, etc.

The results obtained during the study of models can be used in the development of sensors, elastic elements. The conditions of application of the obtained results can be used in the manufacture of models of sensors of physical quantities, for example, pressure and temperature, force and deformation.

In addition, the models developed in the course of research can be applied in the educational process and in the registration of patents for inventions.

As a result of the conducted research and the introduction of new design and technological solutions, experimental samples of sensitive elements, measuring modules and sensors were developed.

Let's briefly consider the main designs and features of SE and MM (Fig. 10–13), produced by various firms and organizations [17].

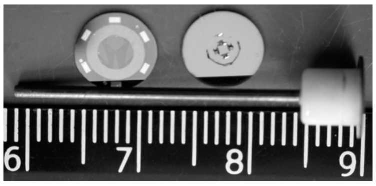

Fig. 10. Measuring module and sensor element of a semiconductor pressure sensor

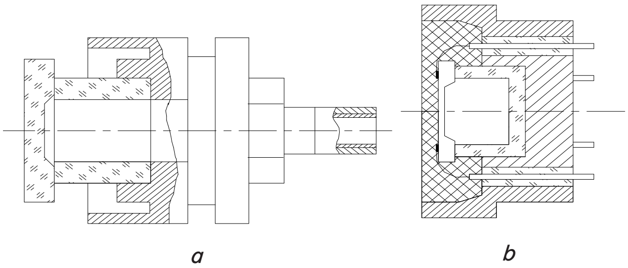

Fig. 11. Designs of sensor sensing elements: *a* – for overpressure; *b* – absolute pressure

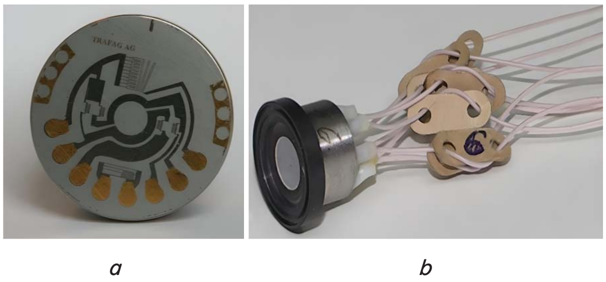

Fig. 12. Measuring modules 100 % ready: *a* – thin-film 4 measuring module Trafag; *b* – measuring module of a semiconductor sensor

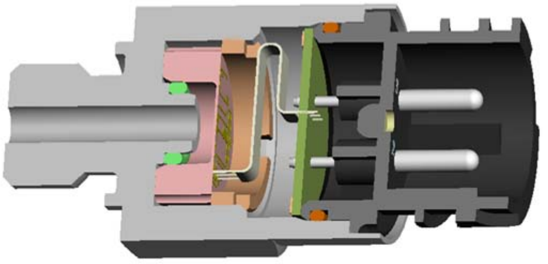

Fig. 13. High temperature ceramic pressure converter for motors

As search studies have shown, there are currently several types of functionally and structurally complete MM available on the sensor market with 100 % availability at fairly reasonable prices. They are delivered tested and subjected to sufficiently severe friction, including heat shock, vibration and hydraulic loads of sufficiently long duration. During the accelerated tests, hidden defects and imperfections in the sensitive elements of the MM are revealed, which makes it possible to reject potentially unreliable MM.

By installing standardized SE and MM in a physical quantity sensor of various configurations, it is possible to obtain a range of absolute, differential, relative and overpressure sensors.

As practice has shown, the use of purchased sensors can significantly reduce the cost and complexity of manufacturing sensors in general, as well as to manufacture SPQ in the conditions of medium and small enterprises.

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By installing standardized MS and MM in SPQ of various configurations, it is possible to obtain a number of absolute, differential, relative and overpressure sensors.

As practice has shown, the use of purchased sensors can significantly reduce the cost and complexity of manufacturing sensors in general, as well as produce SPQ in the conditions of medium and small enterprises.

6. Discussion of the results of the development, manufacture and testing of the design of converters of various physical quantities, as well as technologies for their manufacture and stabilization

The following scientific results were obtained during the study:

1. The use of multilayer compensator films deposited on the CE surface and having different temperature coefficients of linear expansion significantly minimizes thermal stresses in SE nodes and parts, which ultimately reduces the multiplicative error of the entire sensor, increasing the temporal and parametric stability of the sensors (Fig. 10–13).
2. The proposed cyclic dynamic stabilization modes, including vibrations, temperature, pressure, vibrations, can significantly reduce residual mechanical stresses (Fig. 6, 7).
3. The use of advanced engineering methods and models modified for real designs and technologies make it possible to quickly and economically simulate sensor elements and assemblies and reduce development costs [5, 6].

The conducted studies have shown that:

1. Reduction of errors from the effects of thermal stresses can be achieved using multilayer films and compositions.
2. Reduction of residual mechanical stresses can be achieved by using training.
3. When applying rigid modes of acceptance testing of sensor elements and structures, the temporal and parametric stability increases.
4. Modification of engineering models and techniques significantly reduce the cost of sensor development.

This study is limited for measuring transducers by the operating temperature range (from −50 °C to +120 °C), the influence of external factors: vibration of no more than 10 g in the range of 50–1000 Hz, the absence of radiation for semiconductor devices. If these limitations are met, the results of engineering modeling and experimental data will be adequate.

In order to reduce errors in the future, it is necessary to conduct additional studies in the extended ranges of the effects of destabilizing factors.

In order to expand the scope of application of the developed methods and models to other areas, it is necessary to obtain information about the long-term stability of the IC at various amplitudes and frequencies of stabilizing factors, which is complicated by a long period of stabilization and further testing.

7. Conclusions

1. The developed mathematical models and methods of using film coatings to reduce the level of internal mechanical stresses allowed to reduce errors by 1.5–1.8 times.
2. Developed and tested stabilization methods based on shock vibration and sudden thermal effects lead to a decrease in temporal and parametric instability by 20–30 % (established during accelerated tests).
3. Analysis and selection of modified engineering models and MS development methods showed that the complexity of product development is reduced by about 10–15 % with the coincidence of practical results, while the cost of creating an SPQ is reduced by 2–3 times, depending on the SPQ model.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

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