Temperature effects in composite structures of resonant frequency pressure sensor

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Abstract. The influence of temperature on the metrological parameters of measuring instruments is one of the primary challenges in their design. Temperature effects can introduce significant errors in measurements and also cause a reduction in sensitivity thresholds during operation. This article aims to investigate the response of a microelectromechanical pressure sensor with a resonant-frequency type transducer to temperature influence. This paper presents the results of studies on the impact of temperature fields on structural deformations and natural frequencies of composite resonators in a resonant-frequency microelectromechanical pressure sensor. The structure and functional features of the sensor under development are described, along with the phenomena occurring in the composite structure of resonators when exposed to a temperature field. Based on the research results, various resonator configurations were examined, designed as layered composite structures based on titanium and aluminum oxide. An analysis of their frequency characteristics was conducted, and options for reducing thermal stress effects in the composite layers were proposed.

1 Introduction

Pressure sensors are in high demand and widely used as measurement devices in production and operational spheres of the global economy, including chemical manufacturing, hydrocarbon extraction, food production, transportation and processing of various raw materials, as well as in many other industrial sectors. Currently, high-tech pressure measurement equipment is entering the global market, specifically pressure gauges manufactured using microelectromechanical systems (MEMS) technologies. MEMS sensors have found their niche primarily where miniaturization and high integration with other measurement systems are required, as well as in applications necessitating mass production of sensors [1-3].

Despite the apparent advantages of MEMS devices and the use of advanced technological solutions in their production, such measurement systems are subject to the influence of negative factors during both manufacturing and operation. The main factors destabilizing the metrological indicators and quality parameters of MEMS pressure sensors are not only errors in the manufacture of the MEMS crystal but also certain features of technological processes, such as growth, etching, and film deposition in an atmosphere of heated gases. Under high-

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temperature conditions, the thermal stress state of the structural elements of the MEMS crystal changes, leading to a shift in the qualitative indicators of the pressure sensor, for example, altering the elastic properties of the sensitive membrane. Similar problems arise during sensor operation. MEMS pressure sensors can operate in a fairly wide temperature range, which necessitates the inevitable use of automated control for the correctness of sensor readings and their correction. In this regard, special attention should be paid to assessing the influence of temperature on the behavior of MEMS sensors when designing their sensitive elements.

2 Functional features of the research object

There are several physical conversion methods upon which MEMS pressure sensors can be based: capacitive, strain-resistive, piezoresistive, frequency-resonant, and others. Capacitive and piezoresistive transducers have gained the most widespread use. Their relatively simple designs provide advantages such as good resistance to aggressive environments, high sensitivity, and excellent technological reproducibility in serial and mass production [4]. Among the drawbacks of such transducers are the non-linearity of the output signal as a consequence of temperature hysteresis effects, high influence of parasitic electrical capacitances in capacitive transducers [5], and low zero stability in the case of piezoelectric transducers [6].

The resonance-frequency conversion method is based on measuring the natural frequency of a resonating oscillator, which typically depends on the longitudinal tensile or compressive loads in the oscillator. The resonance-frequency measurement method using mechanical resonators has found wide application in sensors of many modern devices and systems [7]. The advantages of such sensors include the absence of hysteresis, no need for digitization of the output signal, and high measurement stability in the absence of temperature influence. Functionally, this method can be used in primary force or temperature transducers [8]. Typically, the nodes of such transducers in MEMS implementation are made in the form of a cantilever-fixed or double-fixed beam of arbitrary cross-section, which represents a mechanical resonator.

A competitive analog of the investigated prototype is a resonance-frequency type sensor from Yokogawa, whose sensing element is made of monocrystalline silicon and contains a membrane with two resonators located on it. The sensitivity of such a sensor is estimated at 0.001 - 0.005 Hz/Pa in the range from 0.01 to 10 MPa [9]. Another analog is a model from Siemens, whose relative error is estimated at 0.03%. Both analogs operate in the temperature range from minus 40 to plus 120 °C.

In the developed sample of the MEMS pressure sensor sensing element, a resonance-frequency type transducer is used, which is a membrane with two resonators formed on it. The operating principle of the pressure sensor is based on measuring the natural frequency of the resonators, which experience longitudinal deformations from the membrane when exposed to the measured pressure. The resonators are positioned so that their deformations, and consequently their natural frequencies, differ in sign when a pressure difference is applied to the membrane (Fig. 1). The frequency difference of the resonators in a steady state when a pressure difference is applied to the membrane is directly proportional to the applied pressure.

In the forced oscillation mode of resonators at the resonance frequency of their fundamental tone, they perform oscillations in a plane perpendicular to the membrane plane. The forced oscillation mode is provided by an electromagnetic excitation system, where the main element is a permanent magnet.

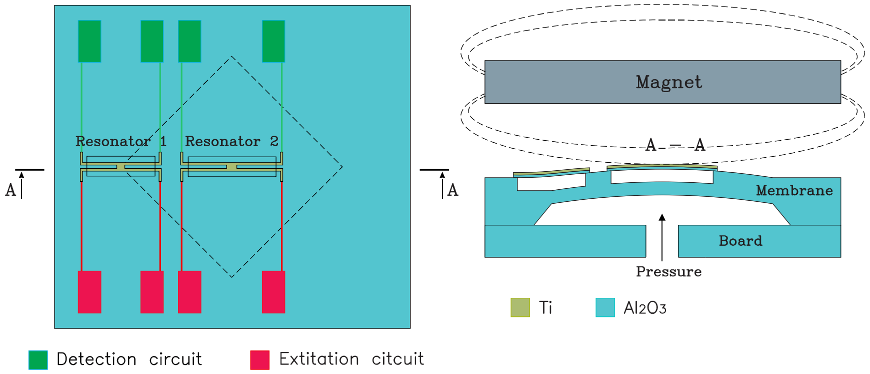

Fig. 1. Design of the pressure sensor sensitive element.

When an alternating current flows in the oscillation excitation circuit inside the resonators located in the field of a permanent magnet, alternating electromagnetic forces arise with the frequency of the flowing current, which ensure the forced oscillation mode. The resonance of the sensor's oscillatory system is achieved when the frequency of the electric current in the excitation circuit equals the natural frequency of the resonators.

3 Results and discussion

In the prototype under development, one of the primary objectives is to enhance sensitivity to the measured pressure. As the sensitivity threshold is directly related to the steepness of the curve representing the relationship between the resonators' natural frequency and the measured pressure, a study [9] proposed the use of a two-layer composite structure consisting of titanium (Ti) and aluminum oxide (Al_2O_3) for the resonators, which allowed for a certain degree of improvement in the pressure sensor's sensitivity. The mechanical properties of composites, specifically their elastic properties, enable the selection of required strength and frequency characteristics for the resonators by utilizing a layered structure in the form of thin films made from various materials and with different geometric configurations.

Composite materials can be highly susceptible to temperature effects due to their heterogeneity. As a result of exposure to temperature fields, layered composites are capable of accumulating mechanical stresses, particularly at the interfaces between dissimilar layers, which may negatively impact the frequency characteristics of oscillatory systems constructed from such materials.

The frequency characteristics of the oscillatory system in the sensor being designed can be evaluated using an equation that characterizes the natural frequencies of the first mode of oscillation for each resonator individually, taking into account internal structural stresses [10]:

$$f = f_0 \left(1 \pm \frac{\sigma S l^2}{\pi^2 EI}\right)^{1/2} \tag{1}$$

where, f_0 is the natural frequency of the unloaded resonator, S is the cross-sectional area of the resonator, l is the length of the resonator, EI is the total stiffness of the resonator's cross-section.

The stresses σ in equation (1) characterize the stress state of each resonator and can be a consequence of both thermal stresses and the impact on them from the membrane deforming under the action of the measured pressure. Considering the thermally stressed state of the resonators from the perspective of solid deformable body mechanics, their behavior can be described as a change in geometric dimensions due to the accumulation of thermal stresses proportional to the body temperature:

$$\sigma = \varepsilon E \tag{2}$$

$$\varepsilon = \alpha(T_1 - T_0) \tag{3}$$

where, ε represents deformations, α is the thermal expansion coefficient (TEC), T_1 - T_0 denotes the temperature difference leading to thermal deformations, and E is Young's modulus.

In the case of contact between dissimilar materials with different TECs, asymmetric deformation will be observed in the cross-section. This behavior of materials occurs in resonators, as the TECs of titanium and aluminum oxide layers differ. The thermal influence can be clearly observed during the fabrication of resonators using electron beam deposition methods, which is conducted at a temperature of 250 °C followed by cooling to room temperature. As a result of the temperature differential, non-uniform compression of the composite layers occurs, accumulating internal stresses, which are the cause of the drift in the natural frequencies of the resonators.

During the study, an assessment of the dependence of natural frequencies on temperature was conducted for one of the resonators. The evaluation of temperature influence was carried out for several resonator configurations, namely for a solid two-layer resonator, a resonator with longitudinal perforation of the titanium layer, a three-layer resonator, and a configuration of a fully silicon solid resonator chosen as a comparative sample.

The designed geometry of the resonators has the form of a two-rod beam with a crosspiece, with the composite layers assumed to be equal in thickness. The initial condition was set as the deposition temperature of the titanium film on the aluminum oxide layer, equal to 250 ºC. The boundary conditions were set as a steady-state temperature of minus 50 ºC, as well as the absence of resonator fixations.

The results of the temperature stress analysis for unfixed resonators are presented in Figure 2.

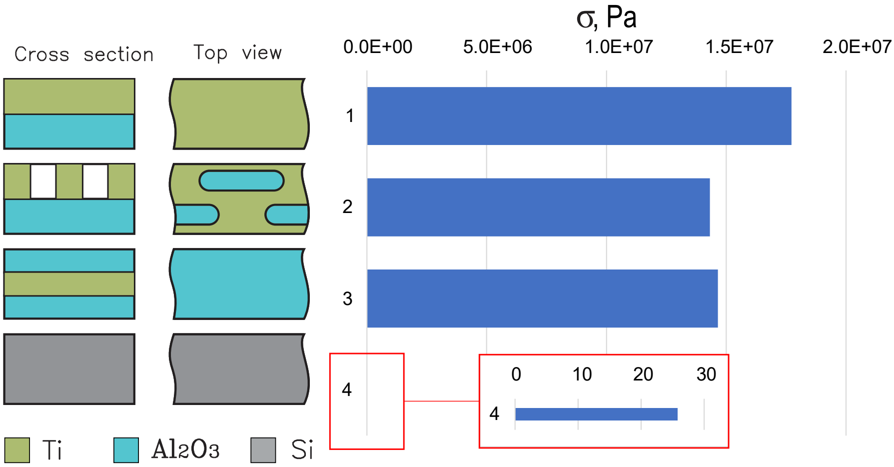

Fig. 2. Averaged voltages in resonators with different cross-section configurations.

In accordance with equation (3), under steady-state thermal conditions, the deformations of the titanium layer will be greater in absolute magnitude than the deformations of the Al2O3 layer due to the fact that the thermal expansion coefficient of titanium exceeds that of Al_2O_3, which will result in bending deformations and stress concentration in the contact zone between the layers (Fig. 3).

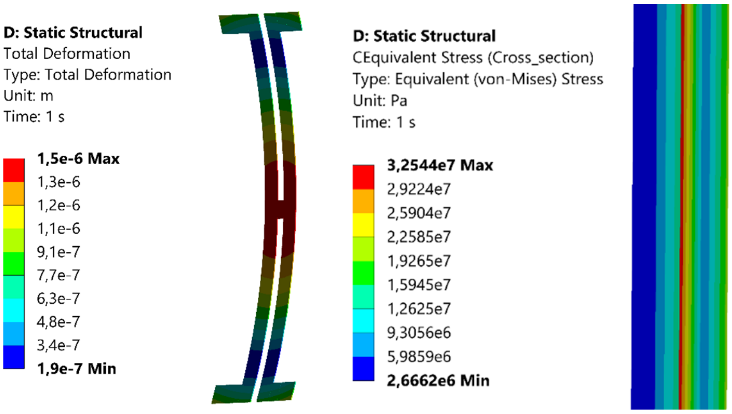

Fig. 3. Temperature deformations (left) and stresses in the cross-section (right) of a solid composite resonator.

The membrane on which the resonator is mounted contributes significantly to the thermal stress state of the resonator, specifically through its thermophysical properties. In cases where there is a difference in the thermal expansion coefficients of the contacting materials of the membrane and the resonator, harmful deformations will occur in the resonator structure, leading to stress accumulation. A study evaluating temperature resistance revealed that two types of layered configurations can be considered most suitable: longitudinally perforated (configuration 2 Fig. 2) and three-layer structures (configuration 3 Fig. 2). Both configurations significantly surpass the two-layer structure with a solid cross-section (configuration 1 Fig. 2) in terms of stability.

To analyze the degree of membrane influence on the resonator, it was sufficient to investigate the membrane area surrounding the resonator. Stress calculations for a solid composite resonator mounted on a membrane, subjected to a temperature range from plus 250 ºC to minus 50 ºC, yielded the results shown in Fig. 4.

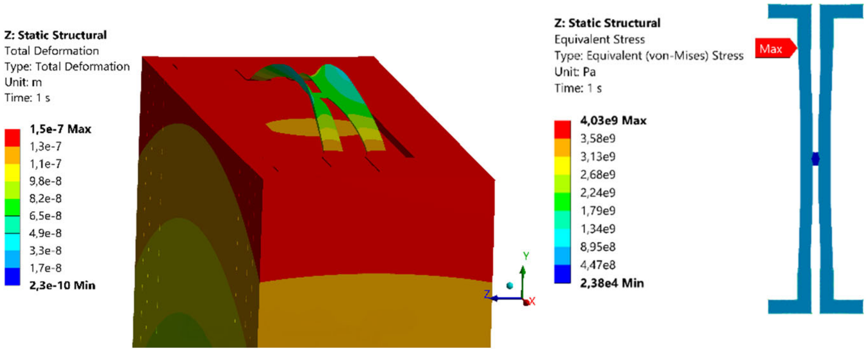

Fig. 4. Solid composite resonator on a silicon membrane. Resonator deformations (left), stresses in the resonator (right).

In the case of two-layer resonator configurations, torsional deformations are present (Fig. 4 left), which is due to the higher coefficient of thermal expansion (CTE) of the titanium layer of the resonator. Significant stresses are also present in the contact area between the resonator and the membrane at the transition point from the membrane plane to the technological recess under the resonator (Fig. 4 right).

The stresses introduced due to the contact of heterogeneous materials significantly affect the natural frequencies of resonators, therefore it is extremely important to reduce their influence. The diagram below illustrates the temperature effect on the natural frequency of the resonator together with the membrane in the temperature range from minus 50 to plus 85 °C.

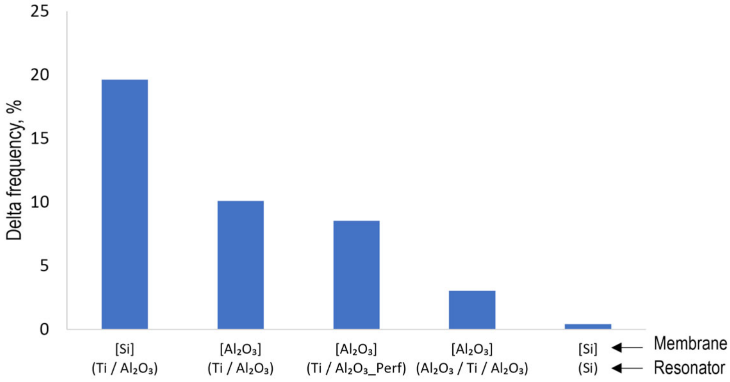

Fig. 5. Relative frequency shift in the operating temperature range.

In the expected temperature range of the resonator's operation, the drift of the natural frequency of the three-layer resonator in combination with the Al_2O_3 membrane was approximately 3%, which, compared to the fully silicon structure of the membrane and resonator, where the drift of the natural frequency is about 0.4%, provides a negligible increase in maximum deviation.

4 Conclusion

The analysis of the obtained data leads to the conclusion that the most suitable configuration for the sensitive element is a three-layer configuration with an intermediate conductive titanium layer and a membrane made of Al_2O_3. Thus, by utilizing a three-layer composite as the resonator material and ensuring the thermal expansion coefficient compatibility of the resonator's boundary layer and the membrane, it was possible to achieve a reduction in temperature-induced deformations in the resonator to values approaching those of a fully silicon-based sensitive element structure.

The results were obtained within the state assignment of the Ministry of Science and Higher Education of the Russian Federation (theme no. FEWM -2024-0008).

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