Research for promising materials and constructive-technological solutions for temperature-sensitive elements of micromechanical accelerometers

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Abstract. The paper analyzes the advantages and disadvantages of piezoelectric micromechanical accelerometers. The designs, materials and methods for obtaining the sensitive elements of these micromechanical accelerometers are considered. It is shown that the choice of new design solutions, materials and structures allows you to create a modern domestic competitive element base with improved output characteristics.

1. Introduction
Micromechanical accelerometers are the most common devices made by MEMS technologies. Micromechanical accelerometers, made on the ground of basic MEMS technologies, got widespread due to the miniature crystal size of sensitive elements (SE), low mass, low power consumption and cost and high reliability. Silicon micromechanical accelerometers are divided on the operating principle into two classes - capacitive and piezoresistor accelerometers [1].

The use of monocrystalline silicon as a structural material in the manufacturing of physical quantity sensors - elements of primary information converters — allowed to bring the technical characteristics of devices that have received the general name MEMS sensors to an absolutely new level [2]. The advantages of monocrystalline silicon are unique mechanical and electrical properties, such as the absence of long-term fatigue and hysteresis, the ability to create layers with different electrophysical properties in the crystal volume, wherein silicon is common, its technology is well developed [3].

The advantage of piezoresistive micromechanical accelerometers is the ability of measuring linear accelerations, including shock acceleration, in a fairly wide frequency range. This group of micromechanical devices is based on MEMS technologies, which are characterized by group production with uniform temperature characteristics, as well as high mechanical strength, the possibility of a technical scheme against temperature drift, no hysteresis, a high level of stability, and ability to withstand technical cyclic loads without mechanical degradation processes. Silicon crystal facilitates the formation of high-quality protective layers during the creation of sensitive elements and allows the implementation of controlled anisotropic and plasma-chemical etching.

However, the disadvantages of silicon piezoelectric micromechanical accelerometers include the limited temperature range of measurement (up to +85 °C).
In reality, there is a practical need to measure linear accelerations in a wider range of temperatures (up to 100 - 120 °C). For this purpose a creation of microaccelerometers capable of carrying out measurements under shock loads and vibrations is required [4]. This class of microaccelerometers is able to work in these conditions, providing good metrological characteristics at temperatures of about 120 °C.

Natural quartz crystals are one of the best materials for piezoelectric sensor elements. Quartz has the ability to work at high temperatures, uniform sensitivity in the temperature range, high strength, linear effect, the absence of hysteresis under the effects of various kinds, high output resistance.

Among other materials suitable for creating piezoelectric elements, piezoelectric polymer films are distinguished. Known polymer film piezoelectric acceleration sensors based on them. Devices of this type are inexpensive, but their commercialization is limited by serious shortcomings — low accuracy, significant variation in characteristics, and high sensitivity to temperature and pressure changes.

Domestic developers pay attention to the fact that the search for the use of new materials and structures of sensitive elements of micromechanical accelerometers, can lead to a significant expansion of the temperature range of measurements. Silicon carbide and silicon-dielectric-silicon (SDS) can be effectively used.

When using SDS structures, devices with improved characteristics are obtained, in particular, such as radiation and temperature stability. This is the result of the presence of reliable isolation of the working volume of the piezoresistor from the silicon substrate. However, this advantage has a number of disadvantages inherent to these structures. In particular, a different approach to etching from the planar and non-planar sides is required, which reduces manufacturability [5]. Unfortunately, in the domestic market there is no high quality SDS plate, and this fact hinders the development of the Russian market of high-temperature devices in general. The creation of these structures requires expensive equipment and the need for long-term development of the technological process.

More promising is using silicon carbide SiC with a band gap of 2.3–3.4 eV. This material allows the operability of sensors at elevated temperature, radiation, and mechanical stresses, as well as conditions in strong electric fields. The temperature range of these structures can withstand loads of up to 1000 C, however, the range of interest is + 120 °C + 600 °C, at which the parasitic leakage currents are eliminated. However, this material has certain disadvantages: the lower measuring range of sensors on silicon carbide is 3 times higher than that of monolithic silicon. The difficulty lies in the process of doping of silicon carbide, as well as thermal oxidation of the surface of silicon carbide. The absence of such structures of good quality on the Russian market and the absence of developed technical process are limiting factors.

A potential option of a sensitive element of a micromechanical accelerometer is a constructive-technological solution presented on Figure 1. It is a sensitive element of a micromechanical accelerometer of piezoresistive type.

![Figure 1](image_url)

**Figure 1.** The crystal of the sensitive element of the micromechanical accelerometer based on polysilicon piezoresistors: 1 – silicon crystal; 2 – elastic bridge; 3 – a through hole between the inertial
mass and the frame of the crystal; 4 – areas for electrostatic connection of a crystal with glass parts; 5 – polysilicon piezoresistor; 6 – a layer of thermally grown silicon oxide on the surface of a silicon wafer; 7 – a protective layer of silicon oxide on the surface of piezoresistors; 8 – metallization.

Piezoresistor accelerometers consist of a sensing element with an inertial mass, fixed by elastic suspensions with a crystal frame. Piezoresistors are arranged on an elastic suspension forming the simplest secondary transducer - the Wheatstone bridge circuit. When exposed to acceleration the deformation of the elastic suspension leads to a change in the resistance of the piezoresistors, the imbalance of the bridge and the appearance of the output signal. Silicon micromechanical accelerometers can be made using technologies of surface or bulk micromechanics. The technology of surface micromechanics, which focuses on basic silicon microtechnology, is currently one of the main MEMS technologies. Surface micromachining is based on the deposition of thin layers on the surface of a silicon substrate and etching one or more layers [6]. The release of moving parts (structural layers) of sensitive elements (removal of the sacrificial layers) is carried out at the last stage of the manufacturing process. The following materials can be used as sacrificial layers: SiO₂, Si₃N₄, GaAs, AlGaAs, Al, phosphorosilicate glass (FSS, PSG), borosilicate glass (BSS, BSG), AlN, etc.

Surface micromachining is characterized by the construction of a microstructure on the silicon surface by deposition of thin protective and structural layers. The main part of the substrate in this process is not affected. This method was originally used only to create devices with a thickness of less than 2 microns, since only thin films can be applied to the substrate. This class of technological processes is more promising and common for the creation of mass accelerometers [7]. Currently, the thickness of the formed structures in the surface micro-processing does not exceed 30 microns.

The advantages of the surface microprocessing technology include a possibility of creating a large number of sensitive MEMS elements in one technological manufacturing cycle, as well as a compatibility with the technology of integrated circuits. The disadvantages of the surface microprocessing technology include the sticking of thin suspended parts of MEMS elements to the substrate, which occurs in the process of washing the etching products of the sacrificial layers and during the operation of the element; limited measurement range associated with a small mass of structural layers. In bulk micro-processing, structures are formed by etching the initial monocrystalline silicon substrate. Two types of silicon etching are distinguished: anisotropic and isotropic. Each type of etching differs in its selectivity with respect to the materials used, the etching rate, etching patterns, etc.

However, although manufacturing processes for elements of integrated circuits and MEMS are similar, there are differences between them related to the requirements for the geometric dimensions of the formed elements. The use of various combinations of technological operations of the technologies of volumetric and surface micromechanics allows the formation of sensitive elements of MEMS accelerometers of capacitive and piezoresistive types.

The structure of a piezoresistive MEMS accelerometer crystal comprises a miniature inertial (seismic) mass, which is suspended by elastic bridges, on which piezoresistive elements are located in the zones of maximum deformation.
Figure 2. The sensitive element of the piezoresistive accelerometer.

Silicon crystal with inertial mass is located between two plates (Fig. 2), which can be made of glass or of monocrystalline silicon. Indentations are formed in the plates, wherein these indentations on the one hand allow the inertial mass to move freely, and on the other hand limit the movement of the inertial mass during overloads experienced by the accelerometer. Inertial mass and elastic bridges are formed by the methods of anisotropic etching of silicon, piezoresistors are made by diffusion or ion doping of impurities into open windows on the surface of silicon wafers in a layer of thermally grown silicon oxide. The assembly of the sensing element into a monolithic structure is carried out by electrostatic coupling methods. A distinguishing feature between piezoresistive sensitive elements and capacitive ones is a more complex technological process, due to the need of forming piezoresistors on the surface of elastic bridges. The advantages of piezoresistive accelerometers are high mechanical strength, good signal-to-noise ratio, small size, which allows to use them for structural failure tests, measurement of impact processes and high-frequency vibrations.

2. Findings
Thus, the considered features of the technologies of surface and bulk micromechanics are associated with a different approach in the manufacture of crystals of MEMS accelerometers — the formation of structures on the surface or in the bulk of the substrate material. The advantages and disadvantages of the considered technologies are shown: surface micromachining allows forming multiple sensitive elements for creating mass production accelerometers, and technologies for volumetric micromachining are less productive, but they provide sensitive elements of accelerometers with high output parameters. Consequently, the technological features of manufacturing silicon crystals of MEMS accelerometers define the output parameters of MEMS devices.

As a result of a number of compromising solutions and searching for new materials and structures, it is possible to talk about expanding the range of temperature measurements and creating sensors with improved output parameters.

3. References

[1] Raspopov V Y 2007 Micromechanical devices (Moscow: Mechanical Engineering) p 400
[2] Kalinkina M E, Kozlov A S, Labkovskaia R Y, Pirozhnikova O I and Tkalic V L 2018 14th Conference on Actual Problems of Electronic Instrument Engineering, APEIE-2018 Vol 1(6) p 272-276
[3] Okopny Yu A, Radin V P, Khromatov V E, Chirkov V P 2004 Mechanics of materials and structures. Collection of tasks (Moscow: Mashinostroenie) p 416
[4] Kalinkina M E, Kozlov A S, Labkovskaia R Ia, Pirozhnikova O I, Romanova A 2018 Development of mathematical model of accelerometer errors (Electronic
http://kmu.ifmo.ru/collections_article/7178/razrabotka_matematicheskoy_modeli_pogreshnostey_akselerometra.html

[5] Trambitckii K, Anding K, Polte G, Garten D, Musalimov V, Kuritcyn P 2016 The application of texture features to quality control of metal surfaces *Acta IMEKO IET–2016* Vol 5(4) p 19-23

[6] Korobeynikov A G, Pirozhnikova O I 2014 Software systems and computational methods 2(7) pp 160–165

[7] Bibikov S V, Kalinichenko S V, Obukhov A V 2017 *Technical science* 2(12) p 380-391

[8] Velichko E, Grishentsev A, Korikov C, Korobeynikov A 2015 On Interoperability in Distributed Geoinformational Systems *Internet of Things, Smart Spaces, and Next Generation Networks and Systems* (Berlin: Springer-Verlag Berlin) Vol 9247