Conceptual basis for creating new-generation high-stable high-temperature microelectromechanical sensors based on a silicon-on-isolator heterostructure with a monolithic integral tensoframe for intelligent transducers

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Abstract
The conceptual basis for creating new-generation microelectromechanical transducers based on a silicon-on-isolator heterostructure with a monolithic integral tensoframe has been proposed from the analysis of physical and technological problems, which restrain the rise of technical level of semiconductor pressure transducers for information measurement and control systems.

Keywords: High-stable, high-temperature, microelectromechanical, sensors, silicon-on-isolator heterostructure

1. Introduction
The up-to-date and particularly advanced aerospace, shipbuilding, automobile and other automated technologies impose high requirements to technical and operational performance of sensors, which often significantly exceed the technical level of known semiconductor transducers [1, 2].

Most aircraft systems use tens to hundreds of sensing elements to measure physical and mechanical parameters, and pressure transducers are a considerable part among them.

As compared with non-integral electromechanical transducers, which feature high labour input due to an individual manufacturing technology, semiconductor microelectromechanical sensors (SMEMS) have advantages in the capabilities of integrating with microprocessor-based signal processing techniques (system on chip) and manufacturing these sensors in groups on the basis of microelectronics and micromechanics technologies. These main advantages determine growing demands in SMEMS for up-to-date and advanced automated technologies [3].

However, even though some experience in developing silicon microelectromechanical transducer sensors has been accumulated, the time instability of a conversion characteristic and the narrow range of operating temperatures are the primary causes that hold back the extensive application of conventional silicon force, pressure, acceleration sensors and other sensors in information measurement, control and diagnostics systems [4-6].

Due to the instability of the conversion characteristic the capabilities of microprocessor-based error correction for conversion characteristic linearization, temperature compensation and other parameters are essentially complicated.

The main problems, which restrain the implementation of conventional silicon sensors, can be solved by creating semiconductor microelectromechanical transducers (SMEMT) based on silicon-on-isolator (SOI) structures and SOI technologies as a principal alternative to a traditional silicon technology [5].

The SOI technology has been selected by a number of the leading manufacturers in the world, such as IBM, Motorola, AMD, as a strategic line of development of silicon microelectronics, including sensors, and superhigh-speed and superlarge-scale ICs [7]. The results of investigations in this field have not been found in known publications and literature.
2. Goal and general concepts

The goal is to lay a foundation to develop design guidelines for high-stable high-temperature strain transducers with a SOI heterostructure and to create intelligent pressure transducers, which feature high precision and reliability and operate under severe operational conditions specifically for aircraft, rocket and spacecraft equipment.

It is necessary to eliminate p-n junctions in a transducer design as a source of instability to achieve the goal. Moreover, the production technology should not be complicated and be based, if applicable, on the planar technology of microelectronics. Sensors based on SOI SMEMTs must be competitive in both basic performance and low manufacturing costs.

The p-n junctions in the transducer design can be eliminated by forming an integral measuring bridge circuit of mono- or polycrystalline silicon on a dielectric substrate with the thermal expansion coefficient, which at most coincides with this coefficient for silicon within a wide temperature range. In these conditions, as known from the semiconductors physics, the maximum operating temperature for silicon devices will be determined by the silicon limit temperature, T_{lim}=300...400°C.

Mono-crystalline silicon has an advantage of the higher strain conversion coefficient over polycrystalline silicon, but unfavourably compares in terms of the temperature resistance coefficient [8].

The absence of diffusion or implantation operations in forming resistance strain gauges in a substrate and isolating the resistance strain gauges from the substrate with a reverse-biased p-n junction also eliminates the formation of local elastic strains and therefore relaxation processes, that minimizes the long-term drift of the transducer transfer characteristic.

The arrangement of a tensoframe on a thin dielectric layer, which has infinite electrical resistance and finite thermal resistance, allows leakage currents to be excluded, as well as resistance strain gauge overheat due to the temperature of environment being measured to be minimized.

Glass, which meets the above electrophysical requirements for dielectrics, is also an ideal stop-layer in the process of two-way silicon anisotropic etching, and that results in providing membrane thickness precision and integral tensoframe height.

A new impetus is given to the evolution of this concept after the novelty of ideas stated in the concept has been certified by Patent of Russian Federation for the invention of a microelectromechanical transducer [9].

3. First results of concept implementation

The analysis of physical and technological problems and current technical level of conventional semiconductor sensors enabled a patent for the structure of a principally new microelectromechanical transducer based on a silicon-on-isolator heterostructure with a monolithic integral tensoframe, which is shown on Fig. 1.

At the same time priority technical requirements, such as a long-term instability of no more than 0.1% per year within the operating temperature range from −60 to +250 °C, as well as existing and new [10] capabilities of microelectronics and volume micromechanics technologies in precision microprofiling of a three-dimensional silicon frame on a device layer of the SOI plate with a correct geometry and a deep narrow slot were taken into account.

The wide base of monolithic tensoframe 1 with a trapezoidal section, which forms a measuring bridge circuit, is permanently connected to h thick membrane 3 through thin glass layer 2. Simultaneously, the symmetry axes of the membrane and the frame are precisely aligned, and the long sides of the frame in the transverse direction have maximum proximity to the longitudinal symmetry axis, which coincides with the crystallographic direction [110], i.e., the direction of the maximum strain sensitivity of silicon.
The transducer feature is a practically ideal isolation between the measuring bridge circuit and the low-resistance membrane silicon through the glass layer, as well as no p-n junctions.

The precision alignment of membrane and tensoframe axes of coordinates provides the linearity of the conversion characteristic for high strain sensitivity, since the resistance strain gauges of the bridge circuit are precisely positioned in required areas on the membrane surface, namely in the areas of equal strain sensitivity [11].

Fig. 1. a) Cross section of a microelectromechanical sensor based on a Silicon-On-Isolator heterostructure: 1 – monolithic integral tensoframe; 2 – thin glass layer; 3 – membrane; b) Arrangement of crystallographic planes on a tensoframe after anisotropic etching of silicon in plane (100).

The maximum proximity of the long sides of the tensoframe to the longitudinal axis of the transducer allows the sensitivity to be increased, because the sensitivity of resistance strain gauges working in tension is maximum close to the membrane jamming loop and the sensitivity of resistance strain gauges working in compression is maximum close to the longitudinal axis of the frame symmetry, in the intersection area of the longitudinal and lateral axes of frame symmetry. If the frame length is equal to or exceeds the linear dimension of the side of square membrane $2a$, frame stiffness increases and sensitivity decreases.

$\gamma$ is the angle formed by crystal planes \{100\} and \{111\} after anisotropic etching of monolithic silicon to a depth of $H - h$, where $H$ is the height of a microprofiled reference element in the transducer (see Fig. 1,a).

Varying the frame height from 10 to 150 $\mu$m and the frame length from 1000 to 4000 $\mu$m to provide the required rated resistance of the tensoframe, as well as varying the frame dimensions, which correspond to the frame length and specified rated pressure, makes it possible to create a unified series of microelectromechanical transducers and pressure sensors based on these transducers for measurements within the wide limits of absolute, excessive and differential pressure.
The transducer operation is based on the resistance change of four resistance strain gauges in the monolithic silicon tensoframe, which forms a measuring bridge circuit, as a function of external mechanical effects on the membrane, which result in elastic strains in the membrane. These strains are different in both extent and sign (tension or compression) in various areas of the membrane.

4. Conclusion
For the first time the conceptual basis has been developed for creating new generation competitive high-stable high-temperature microelectromechanical transducers for intelligent sensors, information measurement and control systems, which operate under severe operational conditions specifically for aircraft, rocket and spacecraft equipment.

The innovative transducers based on a silicon-on-isolator heterostructure with an integral monolithic tensoframe enhance essentially the capabilities of microprocessor-based signal processing for high precision of measurements, which can not be implemented with the use of currently known microelectromechanical transducers.

An actual scientific and technical problem, which results from low long-term stability of the conversion characteristic and the narrow range of operating temperatures of conventional silicon sensors, has been established and stated for creating high-stable high-temperature microelectromechanical transducers (SOI MEMT).

It has been found that the problem of time instability of conventional semiconductor pressure sensors limits the capabilities of microprocessor-based signal processing and is a key to required reliability and high precision.

It has been shown that the development of integral microelectromechanical transducers with a silicon-on-isolator structure enables the above problem to be solved and agrees with the present concept of avionics evolution.

Prototypes of microelectromechanical sensors have been developed in accordance with the proposed concept for experimental research.

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References
11. L. Sokolov. *SENSOR TECHNO International Conference (Sensor Systems and Components)*. St.-Petersburg. 1993, pp. 53-57.