Micro- and nanoelectronics. Condensed matter physics

Микро- и наноэлектроника. Физика конденсированного состояния

UDC 531.8; 681.518.3
https://doi.org/10.32362/2500-316X-2025-13-3-103-121
EDN KBLENU

REVIEW ARTICLE

Microelectromechanical systems for improved gyroscope design

Pavel S. Kuznetsov @

State Scientific Research Institute of Instrument Engineering, Moscow, 129226 Russa
@ *Corresponding author, e-mail: ps_kuznetsov@mail.ru*

• **Submitted:** 31.10.2024 • **Revised:** 13.02.2025 • **Accepted:** 21.03.2025

Abstract
Objectives. Microsystem engineering is currently receiving a great deal of research attention due to the very wide scope of application of its various elements. The present study of the development and creation of modern gyroscopes based on microelectromechanical systems (MEMS gyroscopes) analyzes the risks associated with the technological aspects of their production and identifies promising areas for further development both of MEMS gyroscopes themselves and the technologies used to manufacture them.
Methods. A detailed analysis of existing scientific publications, analytical reviews, and other available sources on MEMS gyroscopes and current trends in the field of microoptoelectromechanical technologies and ferroelectric films was carried out.
Results. A brief description of the design solutions of modern MEMS gyroscopes and their integration into mechatronic systems is presented. The production technologies of MEMS gyroscopes and specifics of the technological equipment used are considered. A separate section discusses the configuration and calibration aspects of these devices. Promising directions for the development of MEMS gyroscopes with an emphasis on the use of microoptoelectromechanical converters and ferroelectric films are highlighted.
Conclusions. Based on the analysis, the prospects for the development of MEMS gyroscopes are shown, despite the existing technological challenges. It is noted that new physical principles and unique technologies can contribute to the emergence of new types of MEMS gyroscopes using micro-optoelectromechanical converters and ferroelectric films. This, in turn, opens up new horizons for future developments in this area. The necessity of developing new production technologies and specialized equipment to improve the quality of MEMS gyroscopes is demonstrated.

Keywords: MEMS gyroscope, microsystem technology, creation technology, production equipment, microoptoelectromechanical converter, optical tunneling effect, photonics, ferroelectricity

For citation: Kuznetsov P.S. Microelectromechanical systems for improved gyroscope design. *Russian Technological Journal.* 2025;13(3):103–121. https://doi.org/10.32362/2500-316X-2025-13-3-103-121, https://www.elibrary.ru/KBLENU

Financial disclosure: The author has no financial or proprietary interest in any material or method mentioned.

The author declares no conflicts of interest.

ОБЗОРНАЯ СТАТЬЯ

Микроэлектромеханические системы: путь к совершенствованию гироскопов

П.С. Кузнецов @

АО «Государственный научно-исследовательский институт приборостроения», Москва, 129226 Россия
@ Автор для переписки, e-mail: ps_kuznetsov@mail.ru

• **Поступила:** 31.10.2024 • **Доработана:** 13.02.2025 • **Принята к опубликованию:** 21.03.2025

Резюме

Цели. Микросистемная техника является одним из наиболее популярных и перспективных направлений, которые активно развиваются в настоящее время. Область применения элементов микросистемной техники весьма широка. Настоящая работа направлена на всестороннее изучение процессов разработки и создания современных гироскопов на основе микроэлектромеханических систем (МЭМС-гироскопов). Целью исследования является анализ рисков, связанных с технологическими аспектами их производства, а также определение перспективных направлений для дальнейшего развития как самих МЭМС-гироскопов, так и технологий их изготовления.

Методы. В ходе работы осуществлен детализированный анализ существующих научных публикаций, аналитических обзоров и других доступных источников, посвященных МЭМС-гироскопам и актуальным трендам в области микрооптоэлектромеханических технологий и сегнетоэлектрических пленок.

Результаты. Представлено краткое описание конструктивных решений современных МЭМС-гироскопов, а также их интеграция в мехатронные системы. Рассматриваются технологии производства МЭМС-гироскопов и специфика используемого технологического оборудования. В отдельном разделе обсуждаются аспекты настройки и калибровки этих устройств. Выделены перспективные направления развития МЭМС-гироскопов с акцентом на применение микрооптоэлектромеханических преобразователей и сегнетоэлектрических пленок.

Выводы. На основе проведенного анализа показана перспективность развития МЭМС-гироскопов, несмотря на имеющиеся технологические вызовы. Отмечено, что новые физические принципы и уникальные технологии могут способствовать появлению новых видов МЭМС-гироскопов, использующих микрооптоэлектромеханические преобразователи и сегнетоэлектрические пленки. Это, в свою очередь, открывает новые горизонты для будущих разработок в данной области. Показана необходимость разработки новых технологий производства и специализированного оборудования для повышения качества МЭМС-гироскопов.

Ключевые слова: МЭМС-гироскоп, микросистемная техника, технология создания, оборудование производства, микрооптоэлектромеханический преобразователь, оптический туннельный эффект, фотоника, сегнетоэлектричество

Для цитирования: Кузнецов П.С. Микроэлектромеханические системы: путь к совершенствованию гироскопов. *Russian Technological Journal*. 2025;13(3):103–121. https://doi.org/10.32362/2500-316X-2025-13-3-103-121, https://www.elibrary.ru/KBLENU

Прозрачность финансовой деятельности: Автор не имеет финансовой заинтересованности в представленных материалах или методах.

Автор заявляет об отсутствии конфликта интересов.

INTRODUCTION

Microsystem technology (MST) is a popular and promising area of research due to the wide field of application of its components. These include primary information sensors of electrical and non-electrical quantities, micromotors and various elements of avionics, as well as medical microinstruments.

Microelectromechanical systems (MEMS) and MEMS gyroscopes in particular are among the most demanded areas in microsystems technology [1]. The main purpose of a MEMS gyroscope is to determine the motion parameters of systems and devices in which they are installed. Their small overall dimensions and low power consumption make them attractive for use in many industries such as automotive technology, robotics, cell phones, and many others. In particular, their use in special-purpose systems (unmanned aerial vehicles, guided projectiles, inertial navigation systems, etc.) determines the increased requirements pertaining to the characteristics and technology of MEMS gyroscopes [2–6].

The purpose of the present work is to study the process of creating MEMS gyroscopes, to analyze its features, as well as to identify promising directions for the development of MEMS gyroscopes and methods of their manufacture.

SPECIFIC FEATURES OF MODERN MEMS DESIGN

Microsystems technology comprises a set of scientific, technical and technological methods that ensure the creation of an ordered composition of micron and submicron regions of materials with a given composition, structure and geometry in the volume and (or) on the surface of a solid body. This characteristic enables the realization of the functions of perception, transformation, storage, processing, translation of information, energy, motion and generation of control actions in the required modes and operating conditions [7].

A microelectromechanical system is a system that combines microelectronic and micromechanical elements (Fig. 1). These devices with the help of mechanical elements convert the external impact into an electrical signal (gyroscopes, accelerometers, pressure sensors, etc.) or under the influence of electrical forces they themselves make movements [8].

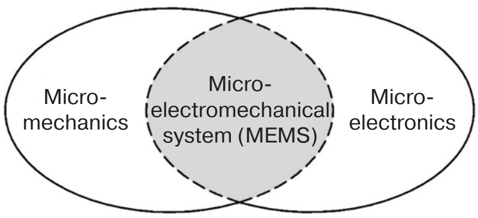

Fig. 1. MEMS diagram [8]

A MEMS gyroscope is a microminiature electromechanical system in which the energy of primary (forced) oscillations of inertial mass under the influence of external angular velocity is converted into the energy of secondary oscillations on which basis information about the measured impact may be obtained [9–11].

Thus, the simplest MEMS-based gyroscope consists of two main functional elements: an angular velocity sensor (AVS) and service electronics that perceive, amplify and processes the signal from the capacitive output of the sensor, as well as controlling the operation of the micromechanical structure. Let us consider the structural characteristics of these two elements, as well as how they are arranged in the assembly.

Most MEMS gyroscopes belong to the gyroscopes of the oscillation type. Depending on the type of inertial mass, all designs of micromechanical sensors (MMS) used in gyroscopes can be divided into several main types as presented in Fig. 2 [12, 13].

The first type is beam inertial masses. The principle of their operation can be described as follows: piezo elements provide an oscillatory motion to the cantilever beam in the direction of the *X* axis (Fig. 3). Rotation about the *Z* axis, which is parallel to the longitudinal axis of the beam, causes oscillations along the *Y* axis according to the Coriolis force, which are registered by other piezo elements [14].

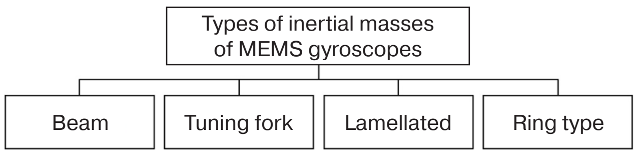

Fig. 2. Types of inertial masses of MEMS gyroscopes

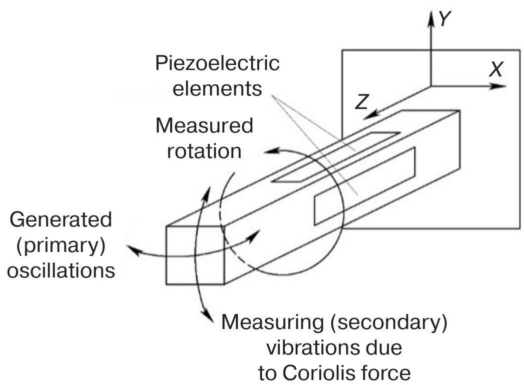

Fig. 3. Principle of operation of the beam gyroscope

The second type of inertial masses are tuning fork gyroscopes, named according to the design of the resonator. Gyroscopes built on this principle work quite simply (Fig. 4): rotation around a vertical axis causes the masses oscillating in counter-phase in one plane to oscillate in a plane perpendicular to the primary oscillations. Secondary oscillations detected using capacitive sensors provide information about the angular velocity [14].

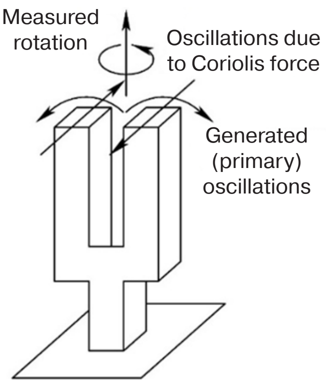

Fig. 4. Principle of operation of the tuning fork gyroscope

Due to the presence of vertical oscillations, these gyroscopes cannot be fabricated using planar technology, which prevents their mass production.

Another type of gyroscopes utilizes plate inertial masses [9–11, 15]. Depending on the type of motion of primary and secondary oscillations of inertial masses, gyroscopes are L-L-type (linear-linear), R-R-type (rotate-rotate), and R-L-type (rotate-linear), and R-L and L-R combinations are possible (Fig. 5) [15, 16]. Significant progress in the field of L-L-type gyroscopes was achieved by Analog Devices (USA), which created the integrated MEMS technology [5]. The MEMS gyroscope of this type (Fig. 6) works as follows. Inertial masses *1*, suspended through two-dimensional springs *2*, sway in opposite directions (antiphase), causing primary oscillations to arise. The springs *2* ensure the movement of the inertial masses in two directions by means of an electrostatic force sensor. When angular velocity occurs, Coriolis forces are generated, which cause the inertial masses to move in a direction perpendicular to the direction of primary oscillation, also counter-phase. The inertial masses cause the movement of the removal combs connected with them through two-dimensional springs *2* and hung on one-dimensional springs *4*, which enable the removal brushes to move only in one direction. The take-off combs are connected with each other according to the differential scheme, which allows us to obtain at the output a signal equivalent to the acting angular velocity.

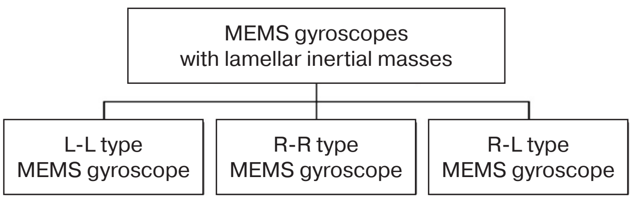

Fig. 5. Types of MEMS gyroscopes based on inertial masses

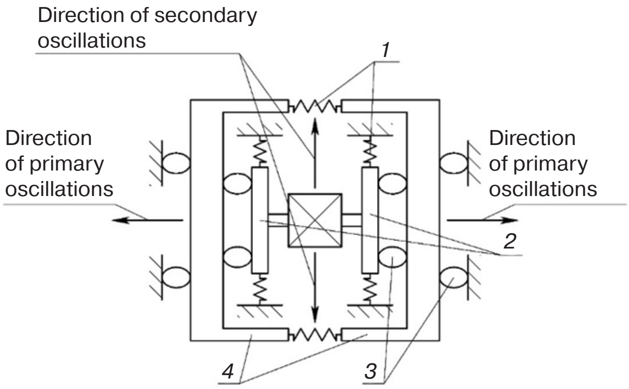

Fig. 6. Operating principle of L-L-type gyroscope: (*1*) one-dimensional springs; (*2*) removal strip contacts; (*3*) two-dimensional springs; (*4*) inertial masses

A schematic diagram of the R-R-type gyroscope, another type of MEMS gyroscope, is shown in Fig. 7. The inertial mass (rotor) relative to the anchors installed on the substrate (base) has a suspension mechanism including elastic and intermediate elements. The electrostatic actuator causes primary oscillatory motion of the rotor around the *Z*-axis. When the transfer angular velocity Ω_x of the base appears, the variable gyroscopic torque causes secondary oscillations of the rotor around the *Y* axis, which can be detected by capacitive displacement meters [9–11, 17, 18].

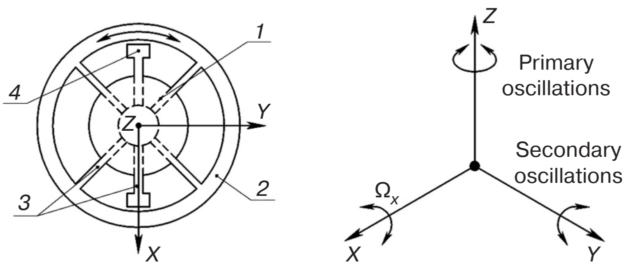

Fig. 7. Operating principle of R-R-type gyroscope: (*1*) intermediate (kinematic) suspension element; (*2*) rotor; (*3*) elastic suspension elements; (*4*) anchor

The last type of MEMS gyroscopes is the R-L-type gyroscope. According to the design (Fig. 8), it is a tuning gyroscope realized as two inertial masses fixed by elastic elements on the outer frame. The frame itself is connected to the base through elastic elements that provide it with rotational motion around the axis. The electrostatic motor, which is presented in the form of a crested structure, excites antiphase progressive oscillations of the masses. In the presence of angular velocity Ω, whose vector coincides with the measuring axis of the frame rotation, Coriolis forces arise to create a variable torque that leads to angular oscillations of the frame around the axis having a frequency equal to that of the motor. The amplitude of the frame oscillation is

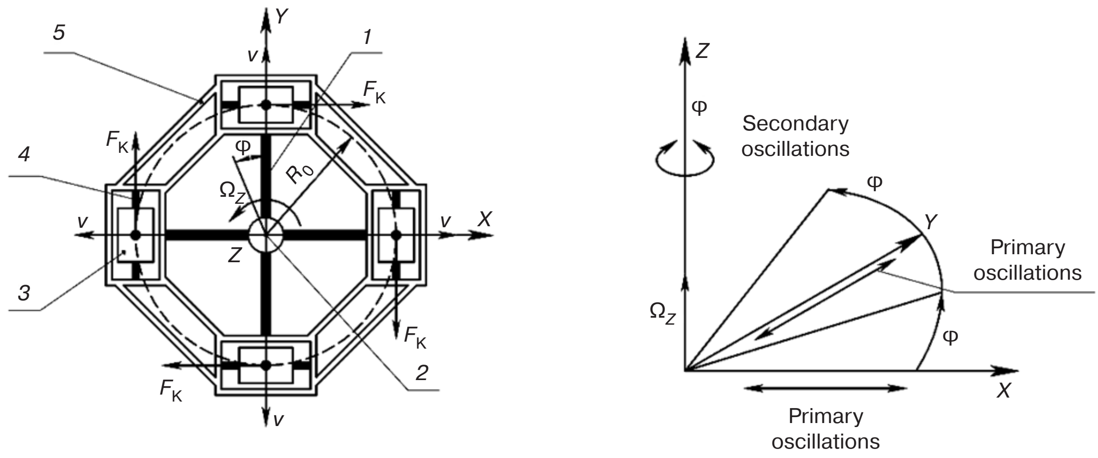

Fig. 8. Operating principle of R-L-type gyroscope:
(*1*) elastic suspension elements of secondary oscillations; (*2*) anchors; (*3*) inertial mass;
(*4*) elastic suspension elements of primary oscillations; (*5*) rigid suspension elements.
F_K is a Coriolis force vector; *v* is a velocity vector; φ is a rotation angle of the sensitive element (SE)

a measure of the angular velocity being measured. The frame oscillations are measured by means of a capacitive sensor, the electrodes of which are located on the base under the inertial masses.

The ring MEMS gyroscope is a special case of an AVS with distributed parameters. The ring resonator oscillates in the direction corresponding to the main vibrational mode. Under the influence of angular velocity (rotation of the ring), the orientation of the vibrational mode relative to the ring itself changes. This is due to the impetus to maintain its orientation under the action of the inertia force caused by Coriolis acceleration [11]. As such, the ring MEMS gyroscope can be considered as a type of wave solid-state gyroscope.

Among many existing technologies of MMS fabrication included in MEMS gyroscopes [5, 10, 11, 15, 16], let us consider in detail the silicon-on-glass technology. The micromechanical sensors manufactured by this technology comprise a vacuum-dense capsule in which the leads from the silicon structure elements are led hermetically through metallized holes in the glass to the surface where they are connected with contact pads. The micromechanical silicon structure in vacuum inside the capsule is a vibrating microgyroscope. The design of MMS in capsule version is presented in Fig. 9.

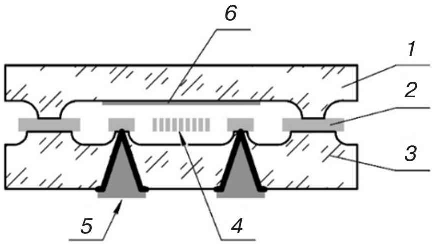

Fig. 9. MMS design in capsule version:
(*1*) cover; (*2*) base frame (Si); (*3*) base;
(*4*) silicon structure; (*5*) contacts (Al); (*6*) getter (Ti)

Several approaches are taken to the manufacture of MMS and service electronics. The smallest and the most technologically labor-intensive is the variant in which the sensor and the chip are located on one crystal and sealed in one housing. An alternative variant has similar design with the difference that the elements are executed on two different crystals. In this case, the resulting MEMS gyroscope is used as an independent element. A third design variant assumes separate encapsulation of the sensor and chip, after which they are located on the switching board together with other elements of the system. The fourth option, which is the most convenient from the point of view of its subsequent use, features a design in which the encapsulated sensor and integrated circuit are mounted on the switching board and placed in one sealed enclosure as separate elements.

Among the possible variants of MMS design, silicon-on-glass technology has the following positive features:

1) closest technology to silicon microelectronics technology and consequently well mastered;
2) technology has the possibility of group production;
3) silicon and glass wafers used in production are produced by industry;
4) specialized equipment produced for this technology is constantly upgraded and improved;
5) technology enables the production of various types of MMSs;
6) finished encapsulated element is an independent assembly element, which makes it possible to separately control its parameters, thereby reducing the yield of defective MEMS gyroscopes.

We now turn to the design of the entire MEMS gyroscope in the final design, which involves the integration of an encapsulated MMS and an integrated circuit of service electronics.

There are several variants of mutual arrangement of the capsule and chip. The first variant is a classical planar arrangement, i.e., the micromechanical converter and the service electronics circuit are located next to each other. The second variant is a two-tier arrangement, i.e., in a special case with the chip located at the bottom and the encapsulated element at the top. This arrangement has an advantage over the first embodiment because of the reduced size of the final product with a slight increase in height. However, it also requires the design of a special case, which complicates production.

The third option involves mounting the micromechanical transducer directly on the integrated circuit. The disadvantage of this design consists in the risk of damage to the chip when the capsule is mounted on it. Other design options are impossible due to the need to place the chip on the bottom for heat dissipation [19].

Let us consider in detail the second variant from the point of view of possibility of manufacturing of prototype and serial samples of MEMS gyroscopes. The finalized version (Fig. 10) with the addition of an intermediate ceramic board for mounting the micromechanical converter and its electrical switching with the microcircuit has the following advantages:

1) possibility to control all components of the MEMS gyroscope before final assembly;
2) possibility to install micromechanical transducers of various designs and sizes on the switching board;
3) sensor capsule replaceability;
4) sealing of the enclosure, providing protection from external influencing factors of the microcircuit in the enclosureless version and the micromechanical converter [20, 21].

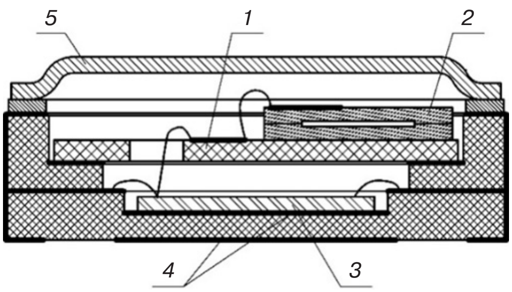

Fig. 10. MEMS gyroscope design:
(*1*) switching board; (*2*) encapsulated MMS;
(*3*) integrated circuit; (*4*) metallization; (*5*) cover [8]

MEMS GYROSCOPES—A CLASS OF MECHATRONIC SYSTEMS

Mechatronics is a field of science and technology based on the synergetic combination of mechanics, electronics, and a controlling computer system for the design and creation of fundamentally new systems and modules having intelligent control of their functional motion [8, 22–25]. Figure 11 depicts a schematic representation of this definition. In essence, MEMS is a mechatronic node that lacks a control system.

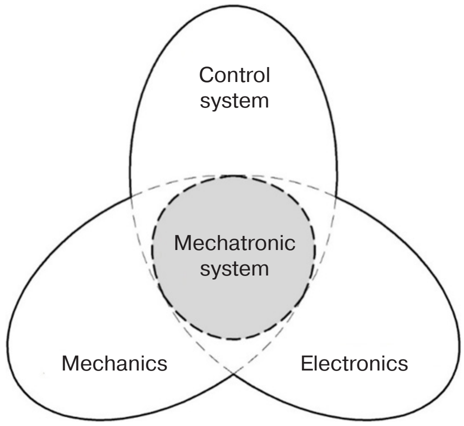

Fig. 11. Schematic diagram of the mechatronic system [8]

A more detailed study of the MEMS gyroscope design, which includes service electronics, demonstrates that it has the character of a mechatronic system. Let us analyze the products developed by GIROOPTIKA[1] (Russia) presented in Fig. 12 [14, 26–31]. Figure 13 shows the structural diagram of the micromechanical angular velocity transducer. As can be seen, in addition to the main MMD of angular velocity, the presented sensor also includes an additional MMD of linear acceleration (accelerometer), and the service electronics is represented by ASIC chip, produced by GIROOPTIKA.

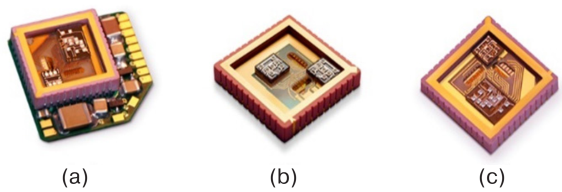

Fig. 12. Micromechanical transducers produced by GIROOPTIKA: (a) angular velocity; (b) linear acceleration; (c) complex transducer

The function of the accelerometer in the presented MEMS gyroscope is to measure linear acceleration and subsequent MMS compensation of angular velocity to accelerations.

The purpose of an ASIC chip is to provide amplification and direct digital conversion of the signal from the MMS outputs of angular velocity and linear acceleration, as well as digital formation of MEMS gyroscope output signals and control signals for MMS. In addition, the chip has a built-in processor unit with a permanent memory device (ROM), which provides the possibility

[1] http://gyro.ru/. Accessed March 22, 2025.

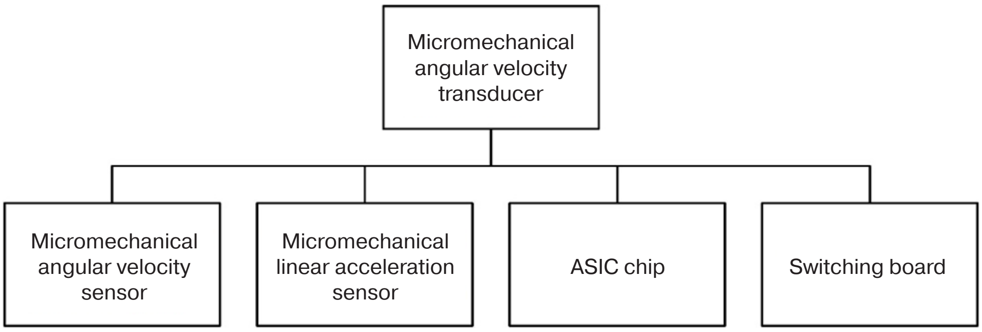

Fig. 13. Structural diagram of a micromechanical angular velocity transducer

of individual adjustment and calibration of each AVS, taking the technological variation of parameters and their temperature dependence into account. The processor unit is used to adjust the MMS (adjusting the frequency of natural oscillations of the MMS along the measuring axis relative to the frequency of forced oscillations), to correct the nonlinearity of the scale factor and zero offset. Compensation of technological variation of parameters and their temperature dependence and sensitivity to overload along the output axis of the angular velocity MMS is calculated in accordance with the data recorded in ROM, taking into account the signal of the on-chip built-in temperature sensor with its own analog-to-digital converter and linear acceleration MMS.

Although the complex micromechanical transducer (Fig. 12c) is similar in structure to the angular velocity transducer, the information on linear acceleration is not only used for internal correction, but is also output to an external consumer.

Thus, it is a ready-made mechatronic system capable of performing certain tasks. Further development of microsystem technology using the principles of mechatronics can lead to the creation of highly intelligent micromechatronic systems: an integrated circuit will control the entire system, micromechanical devices will, on the one hand, control and recognize the processes occurring around them, and, on the other hand, will become microminiature actuators. The first samples of micromechatronic robots already exist [8, 25, 32, 33].

BASICS OF MEMS GYROSCOPE PRODUCTION TECHNOLOGY

MEMS gyroscope manufacturing can be divided into 4 main processes:

1) MMS production in capsule version;
2) manufacturing of an integrated circuit that performs signal processing and control of the MMS;
3) switch board manufacturing;
4) finished product assembly.

The most complex processes in the creation of MEMS gyroscopes, which involve the fabrication of the MMS and the control integrated circuit, require special equipment. However, the largely typical ASIC fabrication process has already been technologically perfected. Let us dwell in more detail on the production of encapsulated MMS [34], whose manufacturing technology is based on the bulk micromechanics group technology. The deep plasma-chemical etching of silicon and anodic joining of silicon and glass wafers is necessary due to the design requiring a hermetic connection between them. In this technology, the starting materials are double-sided polished silicon wafers and glass wafers of the same diameter.

The glass plate is pre-treated, as a result of which through-holes for contacts in the lower plate are created by micro-abrasive processing, and recesses with a depth of about 50 µm are formed in the upper plate. After that, the upper plate is sprayed with a getter to maintain vacuum in the inner volume of the MMS.

The silicon wafers, which are also pre-treated, have a required silicon between 50 and 70 µm. Great care is required when handling these wafers, which are not industrially produced due to their non-standard size. Therefore, it is common to use either standard silicon wafers (100–500 µm thickness for 100 mm diameter) or silicon-on-insulator wafers with a 70 µm thick working layer and 500-µm thick silicon backing layer. This enables the use of standard equipment when processing silicon.

At the first stage of the production process cycle, photolithography and deep plasma chemical etching of silicon are performed on silicon wafers to form bilateral alignment marks on the wafer. The next step involves plasma chemical etching of cavities in the silicon. In this process, silicon oxide is used as a mask, on which photolithography is followed by etching. Next, plasma chemical etching of silicon to a depth of 20 µm is performed. Although the linear dimensions in this working layer are not critical, it is important to obtain good uniformity in depth during the etching process. After removing the silicon oxide from the formed structure, the surface is cleaned prior to carrying out the anodic bonding operation. The last process brings together the glass plate with the holes and silicon wafer. At this stage, it is important to control the gas pressure in the cavity since both low vacuum and high overpressure can lead to the destruction of the silicon layer during the subsequent thinning operation.

The essence of the silicon thinning process consist in the formation of a silicon layer having a total thickness of 70 µm from the initial silicon wafer. The silicon thinning process is followed by a projection photolithography operation. In this step, a pattern is formed with the structure in the silicon layer.

The deep plasma chemical etching operation following the projection photolithography forms the majority of the MMS structure. At an etching depth is 50 µm and minimum gap is 2 µm, the maximum aspect ratio is defined as 1 : 25. The quality of MMS functioning is affected by nonuniformity of etching and deviation of geometrical dimensions to one side or the other, as well as inclination and roughness of walls: large deviations from the set values can lead to significant deterioration of its characteristics up to rejects.

During the etching process, all the main structures of the MMS, including moving parts and elastic elements, are formed. From this point on, any operations that may damage the structure, including photoresist application and liquid plate processing, should be excluded from the technological process.

The next step in the process flow is the anodic bonding of the top glass wafer to the silicon base. At this stage, the structure is sealed at the level of the wafer. At the same time, it is necessary to maintain a given vacuum level in the MMS volume, which is achieved by thermal activation of the thin-film getter sprayed on the glass. In the process of sealing the product by anodic bonding, two opposite processes occur: the release of oxygen from the glass and its absorption by the getter at elevated temperature.

The final operations of the technological process, which are carried out at the level of the wafer, involve the creation of external metallization. At this stage, a thick layer of aluminum is sprayed, which covers the silicon contact pads at the bottom of the through holes in the glass, as well as the side walls of these holes with the metallization output to the glass surface.

The next step is the cutting of wafers into crystals, which is performed using a disk wafer cutting unit in two passes. After that, the wafer is transferred to the functional test. Those chips that successfully pass the function test are transferred to the following stages for installation into the housing and further assembly of the transducer.

When considering such technology, it is important to note that the processes of anode bonding with preliminary alignment of the wafers to be bonded (double-sided alignment) and the process of dry or deep plasma chemical etching of silicon are processes that cannot be performed on standard equipment for producing integrated circuits and/or semiconductor devices. Other processes can in principle be carried out on standard equipment with appropriate changes in the modes and materials used. This applies to chemical processing, photolithographic processes, vacuum coating processes, wafer-to-crystal separation, etc. Such a requirement may be facilitated by the use of glass and silicon wafers with standard dimensions (thickness and diameter) for the manufacture of the micromechanical elements.

Manufactured encapsulated MMSs after separation into separate crystals are checked for resonance frequencies and goodness of fit in addition to visual inspection. Here, not only the difference between the output and input frequencies will be checked, but also the presence of the necessary vacuum inside the encapsulated element. Such control permit a considerable reduction in the labor intensity and increased percentage of yield of good products at the operations of assembly and tuning of MEMS gyroscopes. However, it is impossible to completely exclude poorly working angular velocity MMSs at the early stages of manufacturing, since for this purpose it would first be necessary to connect the MMS to the processing electronics and its tuning, including mechanical effects in the form of rotations and turns.

The MEMS gyroscope is assembled by 3D-integration of an encapsulated integrated circuit and encapsulated MMS using a ceramic switching board into a special ceramic-metal housing. Integration is performed by sequential mounting of the elements into the housing followed by their mutual connection with microwires using the ball-and-wedge method.

The ASIC crystal, switch board, and encapsulated element are assembled using a conductive adhesive used in microelectronics. Sealing of the case is carried out by soldering the ceramic cover to the base of the case. A tightness check is carried out with the help of helium leak detector according to the methods and criteria used for microcircuits in ceramic-metal cases. In order to ensure that the product operates with the specified technical characteristics, transducer adjustment and calibration operations are additionally performed.

MEMS GYROSCOPE MANUFACTURING EQUIPMENT

The choice in favor of silicon-on-glass or silicon-on-insulator technologies made in the previous sections was based, among other things, on the possibility of using industrial equipment in gyroscope manufacturing technology. The selected technologies can be divided into two parts: technologies transferred from microelectronics and technologies that are inherent only in the manufacture of micromechanical devices. Thus, the equipment providing the corresponding technological processes is also divided into two groups. The equipment of the first group was initially produced by the USSR industrial sector and later by the CIS countries. However, today this market is dominated by foreign manufacturers from various countries and regions.

There is a wide range of options for selecting manual, semi-automatic or automatic equipment for standard microelectronics processes such as vacuum deposition, photolithography operations, chemical treatments, thermal oxidation, etc. Special attention should be paid to equipment designed for special processes within the selected technology of volume micromechanics and silicon-on-glass technologies. Such processes should include:

- deep plasma chemical etching of silicon and glass;
- double-sided connection of silicon and glass wafers;
- anode bonding of silicon and glass wafers without loss of alignment accuracy;
- silicon thinning on glass.

A few features of MEMS equipment should be noted here:

- specialized equipment for micromechanics operations is high-precision and very expensive and is produced by manufacturers only to order and for specific technology and customer requirements;
- the same basic equipment, as a rule, is manufactured in two modifications. The first is a variant of manual or semi-automatic equipment designed for research and development, small batch production or pilot production. The second modification is an automatic equipment with loading through cassettes, designed for manufacturing;
- the equipment is also available in cluster version to combine with units performing related operations, i.e., to create a cluster that automatically performs a whole cycle of operations;
- most manufacturers have recently started to offer the technology together with the equipment, and all manufacturers include commissioning and training in the price [35].

Regardless of the specific features of the technological process, the main requirement for equipment for the production of elements and devices of microelectronics and micromechanics consist in the possibility to maintain production with the lowest percentage of defects.

Requirements for the level of introduced contaminants and the composition of the residual gas environment inside the working chamber play an important role both in microelectronics manufacturing (neighboring tracks shorting out (Fig. 14a)) and in micromechanics manufacturing (microparticle blocking motion (Fig. 14b)). Figure 15 shows the structure of high technology equipment, where the pumping means and motion input elements in the vacuum allow us to create and maintain an ultra-clean vacuum environment. In addition, they have the ability to protect the process volume from particles and contaminants created by other elements of the vacuum system. This is primarily due to the fact that cryogenic pumping elements have no moving elements at all, while devices with contactless magnetic interaction have no rubbing elements. Their main features and basic properties are presented in numerous specialized literature [36–41].

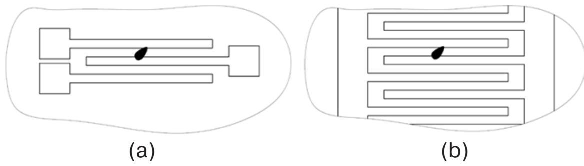

Fig. 14. Trapped microparticles on the product surface: (a) shorting of neighboring chip tracks; (b) blocking the movement of micromechanics crests

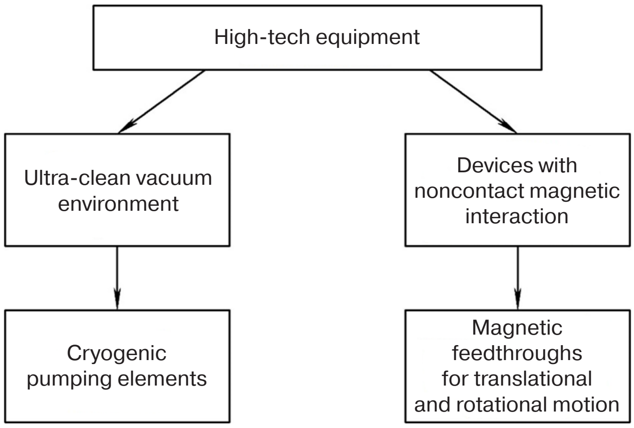

Fig. 15. Structure of environmentally friendly high-tech equipment

DETERMINATION OF PARAMETERS IN THE MANUFACTURING OF MEMS GYROSCOPES

The functional purpose of MEMS angular velocity detection (MEMS gyroscopes) is to convert non-electrical physical quantities (angular velocity) into an electrical measuring signal containing quantitative information about the influencing angular velocity.

The main parameters determining the functional purpose and application area are as follows:

- angular velocity measuring range;
- resolving power;
- scaling factor nonlinearity.

The main technical characteristic of the MEMS gyroscope is the output (conversion) characteristic, i.e., the dependence of the output signal on the values of the determined angular velocities within the measurement range. The output characteristic used in the transducer channel of the MEMS gyroscope is an information channel that provides the generation of information about the angular velocity projections on the sensitivity axes of the AVS and transmission of this information to the consumer in accordance with the information exchange protocol.

Therefore, it is necessary to take into account the errors in the output characteristics of MEMS gyroscopes that may occur during their manufacture. The errors are divided into two categories: basic errors and additional errors. Basic errors are determined under normal conditions, i.e., in the absence of external influencing factors. These include nonlinearity and instability of output characteristics. The instability of the output characteristic includes the zero offset instability and the instability of the scale factor of the MEMS gyroscope.

Additional errors occur under the influence of external factors such as ambient temperature, mechanical effects, etc. Since MEMS gyroscope MMSs are a complex three-layer structure and have temperature dependence of their parameters, the temperature error of the output characteristic has the greatest influence. This is primarily due to the fact that the measuring gaps in silicon capacitors have values of 2–3 μm, while the recorded minimum displacements have values less than a nanometer. At such small values and micromechanical structural complexity, even the use of differential measurement methods cannot exclude the influence of temperature [42, 43].

In general, it is not only the micromechanical element that is temperature dependent, but also the electronics processing the signal from capacitive sensors and controlling the gyroscope operation. Therefore, it is necessary to adjust and calibrate the MEMS gyroscope.

MEMS gyroscope tuning, which is necessary for obtaining stable output parameters, consists in setting and stabilization operations within the temperature range of the bandwidth and scaling factor of the MEMS gyroscope. In addition, the temperature drift of the zero offset must be determined and compensated.

The setting operations are carried out in a climate chamber on a rotary stand. The climate chamber is used to set the temperature according to the requirements, while the stand automatically works out the specified set of angular velocities to determine the scaling factors. A temperature sensor built into the MEMS gyroscope is used to measure the temperature.

The result of tuning consists in the dependencies of coefficients responsible for bandwidth and scaling factor on the readings of the built-in temperature sensor. These dependencies, which are presented in tabular (matrix) form, are used by the control program in the piecewise linear approximation algorithm, which calculates the coefficient values for any reading of the built-in temperature sensor.

After the temperature dependence of the coefficients is added to the control program, the temperature drift of the zero offset is determined.

MEMS gyroscope tuning, which invariably precedes calibration, is intended to ensure its operability in the range of operating temperatures and angular velocities. As a result, the MEMS gyroscope can be guaranteed to have technical parameters close to the required ones. Final adjustment of parameters is carried out during calibration.

MEMS gyroscope calibration is performed to determine the output characteristics of the angular velocity transducer channels under normal conditions (basic errors) and under the influence of external factors (additional errors). Accurate calibration over the entire temperature range is typically performed during the final setup and calibration of the inertial measurement unit (IMU) into which the MEMS gyroscopes are installed. Since the IMU controller is usually much more powerful than the integrated circuit of the sensor’s control electronics, it algorithmically compensates for all errors of the MEMS gyroscopes and the IMU.

ALGORITHMIC COMPENSATION OF THE MEMS GYROSCOPE ERRORS

Compensation of sensor errors for normal conditions and for each of the operating range temperatures at which the calibration is performed is performed in the IMU controller using a special control program that uses the error compensation algorithms determined during the calibration. These algorithms are based on the use of temperature dependencies of MEMS gyroscope characteristics, which are formalized in the form of tables obtained during the calibration process.

The final version of the sensor characteristics table is obtained by simulation and control of these characteristics in a special program while checking the IMU output characteristics. Modeling is performed using the files recorded during calibration and additional measurements performed following calibration. On the basis of the obtained physical values from the unit output data and their errors during modeling, a conclusion is drawn about fulfillment or non-fulfillment of the requirements to the final IMU parameters.

Compensation of nonlinearity, instability, and asymmetry of the output characteristics of the AVS is carried out using the calibration characteristics determined during calibration in the climatic chamber in the range of operating temperatures of the IMU and across the whole range of angular velocity measurement from ±0.01°/s to the maximum value according to the documentation.

The output characteristics of the AVS after calibration in the climatic chamber are presented as a piecewise linear approximation of the real dependence of the output signal on the set value of the angular velocity for the formed temperature range set in the climatic chamber.

As a result of implementation of the above algorithms, nonlinearity, instability, and asymmetry are removed from the output signal of the AVS. Thus, the scaling factor and zero offset are made identical at all temperatures and at all angular velocities in the operating range [44–48].

Now let us consider the compensation of errors of MEMS gyroscopes caused by vibration. When the MMS is mounted on a vibrating base, inertial forces caused by vibration acceleration act on the moving masses.

MMS has increased output signal noise due to the sensitivity of gyroscopes to linear overload due to finite suspension stiffness in the in-phase direction of motion of the moving masses and technological asymmetry of the suspension. In case of asymmetric sensitivity of gyroscopes to linear acceleration in case of vibration, parasitic offset of their zero signal can be formed. Nonlinearity of sensitivity to linear acceleration under the action of constant acceleration (measured or free fall acceleration) leads to the appearance of asymmetry of sensitivity to superimposed variable acceleration and, accordingly, to the constant zero offset of gyroscopes.

Additional compensation of residual errors is performed algorithmically. The influence of MMS sensitivity to linear acceleration is reduced by calibrating them taking into account the effective gravitational acceleration 1g and introducing correction factors with reference to external accelerometers.

PROMISING DIRECTIONS OF THE MEMS GYROSCOPE DEVELOPMENT

In addition to the positive qualities of MEMS gyroscopes, such as their low cost and small overall dimensions, there are also negative aspects. This type of transducer is characterized by the high instability of parameters from start to start. Zero offset of MEMS gyroscope can reach values of about 70°/h. These features, which are inherent both to Russian and foreign samples, require periodic testing and recalibration, including the possibility of self-calibration of channels during operation. All this limits the possibility of using MEMS gyroscopes in special-purpose equipment requiring high accuracy. Moreover, their use in the equipment of other classes can lead to complications and increased final costs.

The accuracy and stability of MEMS gyroscope parameters depend on how the detection of MMS micro-movements is performed. Capacitive data acquisition is most often used, i.e., the capacitance between fixed and moving parts (electrodes) of the MMS designed for this purpose changes during movement. In this case, there is a mutual influence of control and detection circuits of the useful signal of the sensor.

The accuracy of MEMS gyroscope output parameters is also significantly affected by the signal-to-noise ratio. Attempts to eliminate this problem by improving the MMS design lead to contradictions. To increase the noise immunity of the MMS, it is necessary to increase the initial capacitance. This leads to an increase in the area of the electrodes and a decrease in the gap between them, which results in increased damping of the moving parts. In order to compensate for this, it is necessary to perforate the silicon structure of the MMS, which in turn leads to a decrease in the area of the electrodes and consequent decrease in the initial capacitance.

Improved MMS parameters can be achieved with the use of optical technologies to detect micro-movements. The combined use of MEMS and microoptics can lead to synergistic effects that can solve many problems. For example, a microoptoelectromechanical (MOEM) transducer is a miniaturized device that performs measurement and subsequent processing of an optical signal when inertial mass movements occur.

Recently, the optical tunneling effect has been increasingly used in measuring devices for data acquisition. This effect is based on the process according to which light penetrates from an optically denser medium into an optically less dense medium under the condition of complete internal reflection from the interface. In this case, the electromagnetic field appearing in the optically less dense medium exponentially decays along the normal to the interface at a distance equal to the wavelength of the radiation source. Devices based on the optical tunnel effect have high resolution, low temperature error, and high noise immunity [49–53].

The principle of operation of the primary transducer made of fused quartz is based on the dependence of the light reflection coefficient of the medium-gap-medium structure on the gap size [54]. The angle of incidence of light on the boundary between the first medium and the gap (air) is chosen such that there is a complete internal reflection at a large gap value. If the gap value is comparable to the wavelength of radiation, its part passes (tunnels) through the gap into the second medium to decrease the reflection coefficient of the medium-gap-medium structure. Thus, the power of optical radiation reflected from the medium-gap-medium structure carries information about the size of the gap and, accordingly, about the nature of the object motion.

Figure 16 shows the schematic diagram of the MOEM displacement detector. The main PE of this device is a thin plate of quartz glass on which a kind of beam is cut with the help of a laser. A laser beam is directed to the end of this plate, which spreads along the plate and transfers part of its energy to photodetectors installed at some small distance from the top and bottom of the plate. Under the action of external forces, the beam bends and some difference appears between the values of energy transmitted to the photodetectors as the distance to the sensors begins to differ (Fig. 17). This difference is what is used to determine the displacement of the beam [55].

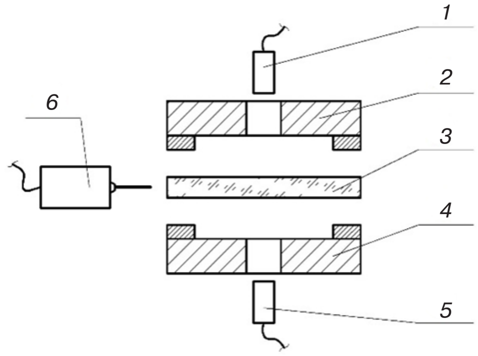

Fig. 16. Basic circuit of the MOEM detector: (*1*) photodetector F_1; (*2*) housing cover; (*3*) quartz plate (CE); (*4*) enclosure base; (*5*) photodetector F_2; (*6*) laser source [55]

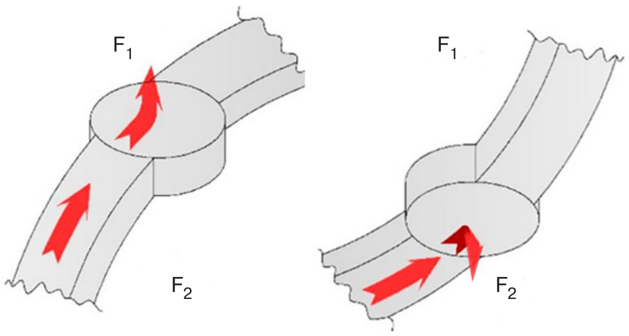

Fig. 17. Readings from the CE of the detector [55]

Technologies currently being developed involving optical processors include those aimed at optical or photonic computers, hypothetical computing devices in which calculations are performed by photons emitted by lasers or light-emitting diodes. Most current research is aimed at replacing traditional (electronic) computer components with their optical equivalents. Importantly, the frequency of a light wave is several orders of magnitude higher than the frequency of electrical signals and waves used in silicon technology. Due to the small wavelength of the light wave, it is possible to process information at increased speeds.

In most works on optical computing [56–61], the translation of information into an optical signal is required to start processing. In the design of the MOEM detector presented above (Fig. 16), there are two photodetectors for information acquisition and conversion into an electrical signal. If the laser radiation is directly sent to the optical signal receiver of the photonic calculator, the information about the CE oscillations before the processing is not transformed in any way, thus obviating the risk of distortions, which is important for special-purpose equipment.

The use of segmentoelectrics and segmentoelectric films is becoming increasingly popular in microelectronics devices, sensors, actuators, etc. Much attention is paid to the application of segmentoelectric structures in MEMS [62–66].

A segnetoelectric device is a crystalline dielectric having two or more stable (or unstable) states with different non-zero electric polarization at zero external influence (electric field, temperature, etc.), which is termed spontaneous polarization [67].

The use of segnetoelectric films in MEMS gyroscopes for motion detection has a number of advantages over classical strain-resistive and capacitive methods in terms of qualitatively expanding the capabilities of sensors. The threshold sensitivity of dynamic strain sensors based on segmentoelectric films decreases to $(\Delta l/l) \approx 10^{-9}$. The use of such devices promises to increase the sensitivity of sensors by up to two orders of magnitude as compared to existing analogs. Such generator-type sensors offer long-term stability and do not require a source of stabilized voltage.

The creation of such sensors is associated with the solution of certain technological problems. The first one consists in a combination of the technology used to create segmentoelectric films with that used for creating silicon mechanical structures. To solve the second problem, it is necessary to develop methods for creating a stable polarized state in the film [63, 68].

CONCLUSIONS

The ever-increasing demand for the production of MEMS gyroscopes and other MMSs contributes to the rapid development of microsystems technology. The entire process of creating a particular product requires constant management, not only in terms of design development, where all input elements must be precisely calculated, but also in when it comes to tuning and calibration.

An important factor in the production of such devices is the competent organization of the technological process of CE creation, which includes the operations themselves, as well as the selection and operation of special vacuum equipment.

In spite of all the discussed difficulties, novel types of MEMS gyroscopes operating on new principles are constantly appearing. This requires the development of progressive technologies for their production, as well as new specialized equipment and methods for their adjustment.

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About the Author

Pavel S. Kuznetsov, Cand. Sci. (Eng.), Deputy Head of the Experimental Complex of Microelectronics and Micromechanical Systems, State Scientific Research Institute of Instrument Engineering (GosNIIP) (125, Mira pr., Moscow, 129226 Russia). E-mail: ps_kuznetsov@mail.ru. RSCI SPIN-code 6564-9540, https://orcid.org/0000-0001-5459-7883

Об авторе

Кузнецов Павел Сергеевич, к.т.н., заместитель начальника экспериментального комплекса микроэлектроники и микромеханических систем, Акционерное общество «Государственный научно-исследовательский институт приборостроения» (АО «ГосНИИП») (129226, Россия, Москва, пр-т Мира, д. 125). E-mail: ps_kuznetsov@mail.ru. SPIN-код РИНЦ 6564-9540, https://orcid.org/0000-0001-5459-7883

Translated from Russian into English by L. Bychkova
Edited for English language and spelling by Thomas A. Beavitt