The formation of multi-axis micromechanical gyroscopes and accelerometers using surface micromachining

E Yu Gusev¹, J Y Jityaeva², Al V Bykov³
Southern Federal University, Institute of Nanotechnology, Electronics and Electronic Equipment Engineering, Taganrog 347922, Russia

¹eyugusev@sfedu.ru, ²julia.yityaeva@gmail.com, ³alvbykov@nt.ru

Abstract. The process flow of unified integral multi-axis micromechanical gyroscopes and accelerometers fabrication by surface micromachining was developed. The process flow for typical n-type silicon wafer Si (100) contains over 20 primary operations, including 5 lithography steps using 5 masks with minimum features size of 1 µm. Special operations were discussed. Experimental results of sacrificial SiO₂ etching for poly-Si-on-SiO₂ structures using buffered solution of hydrofluoric acid and ammonium fluoride (1:4) were obtained. The undercut etching rate was approximately of about 20 nm/sec and the minimum time required for sacrificial SiO₂ removing under beams of 0.5-2.5 width was in in the range of 11 to 62.5 seconds. Finally two and three-axis micromechanical gyroscopes and accelerometers were fabricated.

1. Introduction
The integration of micromechanical components with microelectronics has led to the emergence of a new technology - technology microelectromechanical systems (MEMS) and microtechnology. Using typical processes if the IC technology a series of mechanical elements were fabricated, like membranes, motors, pumps and valves [1-4]. Design and development of bulk and surface micromachining, high aspect ratio technology of nanotructures (nanomechanics) allowed to get micro- and nanomechanical sensors (gyroscopes and accelerometers), as well as to expand their applications from household appliances to high-tech aerospace applications [3-7]. One of the most commonly used transducers are inertial sensors like accelerometers and gyroscopes. The current requirements for these devices are – multi-axis sensitivity, small size, light weight and low power consumption.

Well-known micromechanical sensors allow to measure the characteristics of, e.g. a linear acceleration along one or two axes of sensitivity. The requirement of the multi-axis sensitivity makes it necessary to microassembly, followed by precision alignment, or an increase in the overall dimensions when several sensors with different sensitive axis directions placed on a substrate or chip. Moreover they are not always made by industrial technologies. Locality of these methods (e.g., focused ion beam and scanning probe nanolithography [8-12]) limited their usage on the level of laboratory research.

Decision of the designated problem was the development of integrated multi-axis sensors and their manufacturing technologies by surface micromachining [13,14]. Thus the basic material is polysilicon due to its structural and electrical properties and easy handling [2-4].
Previously the design two-axis micromechanical gyroscope and three-axis micromechanical accelerometer based on two layers of polycrystalline silicon with capacitive registration system) was performed [14]. The goal of this research is to develop and realize a process flow of multi-axis MEMS gyroscopes and accelerometers manufacturing based on polycrystalline silicon by surface micromachining.

2. Experimental details
The unified process flow was proposed [14] for developed designs the MEMS gyroscope and accelerometer [10]. Method of experimental fabrication for micromechanical structures is given in [10]. The photolithography was conducted using five masking coatings: aluminum, chrome, photoresists FP-051KI, MICROPOSIT SP25-10 and Ultra i-0.8 by two modes – soft and hard contact.

In order to determine the optimal modes of removing the sacrificial layer (time and composition of the etching solution) have been designed and manufactured test elements based on the structure of poly-Si/SiO\textsubscript{2}/Si. The topologic pattern of test elements was fabricated by focused ion beam (FIB) lithography (Nova NanoLab 600). The current ion beam and accelerating voltage were 3 nA and 30 keV, respectively. The removal of the silicon dioxide sacrificial layer was carried out under continuous stirring and room temperature in buffered solution of hydrofluoric acid and ammonium fluoride (40\%HF:40\%NH\textsubscript{4}F=1:4) in the range time from 10 to 60 seconds. The etch depth was monitored by scanning electron microscopy. Finally, party of experimental sample multi-axis MEMS gyroscopes and accelerometers were fabricated.

3. Results and discussion
The results of the primary science research of materials and technologies allowed to choose required modes. It allow to achieve the desired values of thickness layers, of lateral dimensions of the structural elements at lithography and to provide high quality of deposition and removal photoresist and In particular, the polycrystalline silicon layer was produced by plasma deposition and doping using diffusion of phosphorus. Values of concentration, mobility of charge carriers and surface resistivity amounted to \(\sim 2 \cdot 10^{20} \text{cm}^{-3}\), \(\sim 30 \text{cm}^2/(\text{V} \cdot \text{sec})\) and \(2-9 \Omega/\text{sq}\), at that the microhardness and Young module of doped films were 13.7–23.6 GPa and 224.3–380.4 GPa, respectively [15-17].

Test structures were fabricated for preliminary studies of photolithography and removing the sacrificial layer.

High-quality photolithography is achieved by improving the adhesion of the photoresist, changing the time of exposure and emergence as well as gap the photomask-substrate. Photoresists that specially designed for reactive ion etching of (FP-051KI, MICROPOSIT SP25-10) were used as masks. It has been established that components of photoresist are evaporating in the resulted of etching poly-Si of 2\(\mu\)m and SiO\textsubscript{2} of 1.5 \(\mu\)m. The mask of aluminum and chromium thickness of 50-100 nm was formed for the etching such layers. There is a problem to remove the plasma-processed photoresist, even for oxygen plasma plasma it was difficult. Mask less exposure to dose to clear allowed to remove photoresist residues. For this reason, for structural layer etching the mask of chromium or aluminum was used.

Experimental investigation of etching of test elements in hydrofluoric acid solution allowed to determine the characteristics necessary for removing the sacrificial layer and for releasing the inertial mass. The calculated average value of etch rate SiO\textsubscript{2} was 20 nm/sec at room temperature. Analysis of the received SEM images (Fig. 1a, b) gave the opportunity to determine the undercut of the sacrificial layer in the horizontal direction (Fig. 1c). The dependence is linear. The presence of open windows at the structural layer significantly reduces the amount of time required to remove the sacrificial layer, and prevents sticking.

Analysis of the experimental results allowed to specify design and technological solution of multiaxial microgyroscopes and accelerometer [14], and to develop a photomasks and the manufacturing flow with a minimum element size of 1 mm (Figure 2).
Figure 1(a-c). SEM images of the poly-Si/SiO$_2$ structure at 10 (a) and 40 (b) seconds of sacrificial etching; undercut vs etching time curve (c)

(a) Cleaning of silicon wafer (RCA)
(b) Deposition of Si$_3$N$_4$ layer of 0.6 μm (ICP CVD): insulation layer
(c) Deposition and doping of Polysilicon film 0.3 μm (PECVD): bottom conductive layer
(d) 1$^{st}$ Lithography (PR, RIE ICP etching): bottom polysilicon patterning
(e) Deposition of SiO$_2$ layer of 1.5-2.0 μm (ICP CVD): sacrificial layer
(f) 2$^{nd}$ Lithography (PR, RIE ICP etching): oxide patterning
(g) Deposition and doping of Polysilicon film of 2.0 μm (PECVD): top conductive layer
(h) 3$^{rd}$ Lithography (PR, RIE ICP etching): structural layer patterning
(i) 4$^{th}$ Lithography (PR, RIE ICP): oxide patterning
(j) 5$^{th}$ Lithography (PR,PR, Metal deposition, lift-off): metal layer patterning
(k) Rapid thermal annealing of metal layer
(l) Wet etching of sacrificial layer: release inertial mass
(m) Scribing and packaging

Figure 2. Process flow of the micromechanical gyroscope and accelerometer fabrication

The following it should be noted. The mask #3 contains a matrix of transparent square fields, which transfer to a photoresist layer and finally to underlying layer – square windows or openings (h), to facilitate the release of the structural layer on the sacrificial etching step (l). To decrease release stiction effect during removing sacrificial layer step the guarding areas were used (f-g). The lift-off lithography is easier to handle for low conformity coating (electron beam evaporation than sputtering).

Series of multi-axis MEMS gyroscopes and accelerometers was fabricated in accordance with the developed route (Fig. 3) and sent to the testing.
Figure 3(a-c). Optical image of the processed wafer (a), microgyroscope (b) and microaccelerometer (c) chip on the package.

It is important to emphasize that the workability of the proposed route allows to fabricate multiple types of devices (multi-axis accelerometers and gyroscopes) in a single technological cycle. Nanomechanical tunneling accelerometers can be created by the inclusion of additional operation local modification of the structure using methods of the focused ion beams [11].

4. Conclusion
The process flow of integral multiaxis micromechanical gyroscopes and accelerometers was developed applied to equipment of research and educational center “Nanotechnologies” and center of collective use of equipment of Southern Federal University. The process flow contains over 20 primary operations (substrate cleaning, plasma deposition of silicon nitride, polycrystalline silicon and silicon oxide, its plasma etching, wet etching of silicon oxide, polysilicon doping, deposition of contacts and its thermal annealing, as well as photolithography), including 5 lithography steps using 5 masks with minimum features size of 1 micron. Sacrificial etching for releasing inertial masses was discussed as well as other specific operations. Questions of inertial structures design, masks development and packaging are not affected. According to the developed flow a series of two and three-axis polysilicon micromechanical gyroscopes and accelerometers was fabricated by surface micromachining and sent for testing. The results of the work can be used for process flow developments of micromechanical gyroscopes and accelerometers and MEMS&NEMS devices.

Acknowledgment
The equipment of the Centre of Collective Use of Equipment "Nanotechnologies" of Southern Federal University was used. The study was supported by The Ministry of Education and Science of Russian Federation within the contract/project 14.575.21.0045 (unique identifier RFMEFI57514X0045).

References
[1] Sniegowski J J, Boer M P 2000 Annual Review of Materials Research 30 299-333
[2] Maboudian R 1998 Surface Science Reports 30 207-269
[3] Berman D, Krim J 2013 Progress in Surface Science 88 171-211
[4] French P J 2002 Sensors and actuators A Physical 99 3
[5] Yun W 2012 Microsystems and Nanotechnology (Springer-Verlag Berlin Heidelberg) 653
[6] Yasaitis J, Judy M, Brosnihan T, Garone P, Pokrovskiy N, Sniderman D, Limb S, Howe R, Boser B, Palaniapan M, Jiang X, Bhave S 2003 Proceedings of SPIE - The International Society for Optical Engineering 4979 145

[7] Core T A, Tsang W K, Sherman S J 1993 Solid State Technology 36 39

[8] Ageev O A, Smirnov V A, Solodovnik M S, Rukomoikin A V, Avilov V I 2012 Semiconductors 46 (13) 1616

[9] Avilov V I, Ageev O A, Kolomiitsev A S, Konoplev B G, Smirnov V A, Tsukanova O G 2014 Semiconductors 48 (13) 1757

[10] Ageev O A, Balakirev S V, Bykov Al V, Gusev E Yu, Fedotov A A, Jityaeva J Y, Il’in O I, Il’ina M V, Kolomiytsev A S, Konoplev B G, Krasnoborodko S U, Polyakov V V, Smirnov V A, Solodovnik M S, Zambur E G 2016 Springer Proceedings in Physics (New York: Springer International Publishing) 175 563

[11] Ageev O A, Gusev E Yu, Kolomiytsev A S, Lisitsyn S A, Bykov Al V 2016 Journal of Physics: Conference Series 741 012177

[12] Vopilkin E A, Klimov A Yu, Rogov V V, Ryakhin D A, Gusev S A, Skorohodov E V, Shuleshova I Y, Shashkin V I 2014 IEEE Sensors Journal 14 (6) 1831

[13] Senturia S D 2002 Microsystem design (Kluwer academic publishers: New York: Boston: Dordrecht: London: Moscow)

[14] Konoplev B G, Ryndin E A, Lysenko I E, Denisenko M A, Isaeva A S 2016 Proceeding of the International Conference “Micro- and Nanoelectronics – 2016” (ICMNE-2016, Moscow-Zvenigorod, Russia) 158

[15] Gusev E Yu, Jityaeva J Y, Bykov Al V, Bespoludin V V 2015 Izvestiya SFedU. Engineering Sciences 9 126

[16] Ageev O A, Gusev E Yu, Jityaeva J Y, Kolomiytsev A S, Bykov Al V 2016 CRC Press/Balkema (London: Taylor & Francis Group) 13

[17] Ageev O A, Gusev E Yu, Jityaeva J Y, Ilina M V, Bykov Al V 2016 Journal of Physics: Conference Series 741 012001