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ACCELEROMETER SENSING ELEMENT BASED ON NANOSTRUCTURED SILICON

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Abstract: In this work we consider sensing elements of an accelerometer which is made using the combined technologies of silicon-on-insulator (SOI) structures and silicon nanocrystals whiskers manufacturing. On their basis a quick-response, high sensitive to acceleration and displacement device with submicrometer and nanometer typological sizes has been designed. This enabled us to create, on its basis, both a discrete device and an element of integrated nanoelectromechanical element silicon-on-insulator structures, which provides control of displacement up to 200 nm.

Keywords: accelerometer, polysilicon, structure silicon-on-insulator, etching, nanoelectromechanical system.

1. Introduction

One of the promising areas of modern solid-state electronics is developing and using nanoelectromechanical systems (NEMS) emerged as a result of combining technologies and constructions of sensitive, actuator elements and plans of transforming information from them on one or few crystals with electrical, optical and radio communacations [1-4], the so-called devices – "More than Moore". The devices "More than Moore" are the complex of systems (devices) on a crystal with the following integrated elements: CMOS-logik, built-in RAM, analog interfaces, nonvolatile memory (NVM), processor (CPU) cores, MEMS, NEMS, sensors. This type of integrated systems opens new prospects for security systems (motion sensors, alarm systems) and communications (wireless communication systems, mobile systems), medical equipment, instrumentality for "smart houses" (intelligent control systems: climate control, control of lighting and electricity, infrastructure of the house) and energetics (alternative sources of energy), etc. In this case, progress of More than Moore direction seems to be important that is motivated by new technological possibilities and unlimited potential of practical experience focused on creating a large number of micro-and nanoelectronic systems. At the same time, development of microelectronics and prospects of nanoelectronics, significantly increased the possibilities of modern microprocessor technology and features of its using in highly informative (intelligent) systems, require implementation of new approaches to the creation of primary measuring transducers, which provide conversion of controlled values into an easily used signal. Nowadays layers of polycrystalline silicon on the surface of oxidized silicon wafer (SOI structure) are widely used in micro-and nanoelectronics. Such wafers are usually formed by chemical vapor deposition (CVD) [5]. Using the SOI structures opens great opportunities of creating highly senvitive devises of microelectronics, and in combination with methods and techniques of nanotechnology; it enables to create a new class of devices with enhanced functionalities, which, by their characteristics, exceed the existing analogues [6-9]. Appropriately, there are many methods for growing nanostructures, namely molecular beam epitaxy, catalytic growth using a laser, and growth from a supercritical phase of liquid solution, laser ablation or simple evaporation [10-13]. However, these methods are energy-consuming and expensive. That is why using cheap technologies to create Si nanostructures is one of the important problems in the development of nanotechnologies for their subsequent use in nanoelektromechanical devices. One of such technologies is the use of chemical etching and chemical vapor deposition, which has been compatible with technology manufacturing micro-and nanoelectronic devices for a long time [14–22].

The main purpose is to create a sensing element of an accelerometer, using modern resourse-saving methods in manufacturing silicon micro- and nanostructures.

2. Experimental procedure

Processes specific for the technology of integrated circuits (diffusion or ion doping, oxidation, photolithography, vacuum metallization, cleaning and heat treatment, etc.) make a foundation for the technological process of creating a sensing element of the accelerometer based on silicon nanostructures. However, there are also processes that are not typical in the semiconductor technology. First of all, anisotropic and isotropic chemical profiling, growth of silicon nanoobjects by the method of chemical transport reactions must refer to such processes.

Fig. 1 shows a schematic representation of the accelerometer based on silicon nanostructures.

The basic processes for the formation of an accelerometer sensor are as follows:

- forming silicon nanoobjects (sensing tip of stationary electrode, wich serves like emission electrode) by chemical vapor deposition;
- pyrolytic oxidation (stop-layer for anisotropic and isotropic etching cavities);
- forming original structure SOI by micro zone laser crystallization of polysilicon.
- ion implantation of boron in the polysilicon layer (for creating the required level of concentration of a polycrystalline movable electrode);
- forming an accelerometer cavity, and metallization of electrodes .

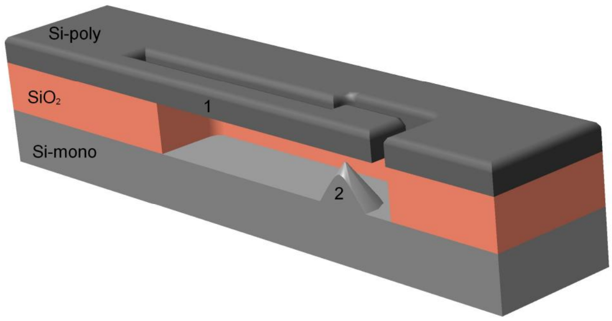


Fig. 1. Schematic representation of sensing accelerometer element based on silicon nanostructures: 1- movable electrode; 2- stationary electrode.

All these processes are important and, to a great extent, determine the metrological characteristics of fabricated devices. We will note the basic processes that were used in manufacturing the accelerometer sensor based on silicon nanostructures.

2.1. Forming a stationary electrode

To develope a real electrode, the processes of growth of silicon nano-objects on Si-substrate with (111) orientation have been studied. For this purpose, gold films of different thickness - from 4 to 10 nm were deposited. To obtain a uniform distribution of gold in crystals, 30 min's annealing of the samples was carried out at the temperature of 600 ^{o}C, followed by cooling at a rate of about 3 ° C / min.

The substrates having been treated thermally, coagulation of the gold in drops took place. The average diameter of the droplets Si-Au depends strongly on the thickness of the deposited film, and decreases from 100 to 40 nm with film thickness decreasing from 10 to 4 nm. After high-temperature annealing of the plate, and coagulation of the deposited layer in drops, we obtain a plate for further growth of edges of stationary electrodes by chemical vapor deposition. Si growing was performed on silicon substrates with different thickness of the gold film - 10 nm and 4 nm. The analysis of the growth experiments was carried out using the methods of electron and atomic-force microscopy. To ensure regularity of the formed nano-objects [17,18] using pattern there was formed gold cells (Fig. 2), with an array of pedestals (nuclear centers)obtained on each of them, which were subsequently used to form a fixed electrode tip Si.

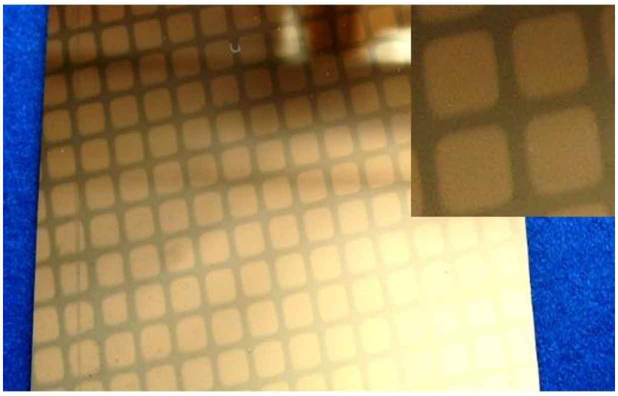


Fig. 2. Plate with deposited film and formed cells.

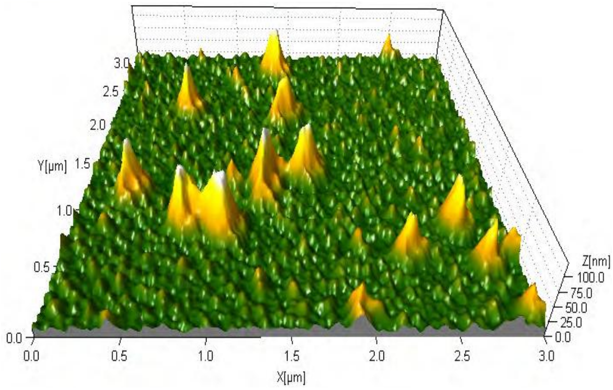


Fig.3. AFM image midsize of pedestals on Si substrate with a gold film thickness of 10 nm.

As a result of the experiments [19-22] an array of pedestals Si, the average size of which is shown in (Fig. 3) has been formed on the silicon wafer. Sizes of the emission electrodes according to which the calculation of autoemission was performed were ~ 1.8 m (Fig. 5).

2.2. Formation of cavities in an accelerometer.

To create a sealed cavity, movable consoles, electrodes, beams, etc., and given the trend of reducing elements to the nanometer sizes there has been conducted a pyrolytic oxidation of the formed nanostructures (silicon substrate with the grown silicon pedestal) to a thickness that provided the complete protection to the sensitive emission electrodes during subsequent technological processes and amounted to 2-3 microns.

2.3. Forming a movable electrode

The formation of a movable electrode of the accelerometer was based on laser polysilicon recrystallization as a method of obtaining advanced semiconductor layers in silicon-on-insulator structures, which was used to create a variety of sensors of physical quantities [23, 24]. For this purpose, an appropriate preconditioning of the initial samples was carried out. On the formed oxidized silicon wafers from the gas phase in the reduced-pressure reactor, polysilicon 0.5 micron layers were deposited at the temperature of 625oC. To control the processes of nucleation and growth of the grains during the micro-zone recrystallization at the formation stage of KNI-structures, we envisaged application of the method of selective heating of materials to create a given temperature profile in the heat-affected zone of emission [24].

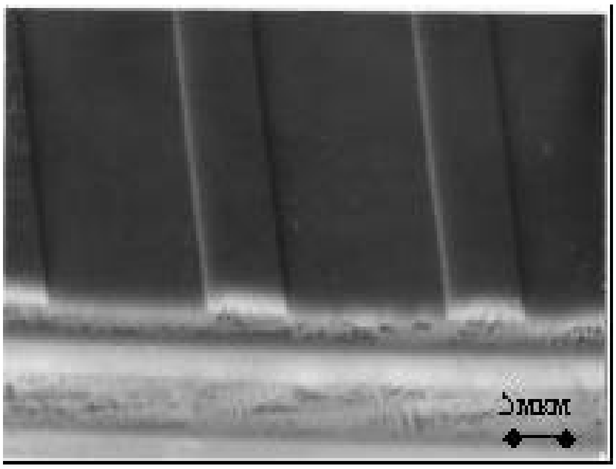


Fig. 4. Photo of section of SOI structure.

For this purpose, a SiO_2 0.75 microns film was additionally additionaly deposited onto the polysilicon layer. Besides, Si_3N_4 strips with a width of 5 microns and increments of 30 mm were created as shown in Pic.4. As a result of the laser recrystallization we have obtained monocrystal blocks with an average crystallite size of 20 × 500 microns which will be used in the future as moving parts of accelerometer.

The final stage of the formation of the accelerometer sensor is the creation of a topological figure on the surface of the SOI structure with the subsequent processes of microprofiling using anisotropic and isotropic etching, which can be described as:

- isotropic plasma - chemical etching of unmasked areas of a SOI structure at a depth of 1.5 microns;
- re-deposition of a Si_3N_4 layer with a thickness of 0.02 microns, deposition of SiO_2 layer with a thickness of 0.1 microns and the formation of plasma-chemical etching and photolithography masking areas on the horizontal surface of the SOI structure;
- anisotropic plasma-chemical etching of pyrolytic SiO_2 at the bottom of etched holes in the SOI structure;
- anisotropic plasma-chemical etching of SiO_2 to increase the height of etched holes in a silicon wafer by 0.5 microns;
- isotropic etching of silicon at a depth of 0.5 microns for creating three-dimensional depth cavities under the surface of SOI structures.

Thus, during the formation of a movable electrode of an accelerometer, the basic technological processes are used as those underlying the production of integrated circuits.

3. Experimental results

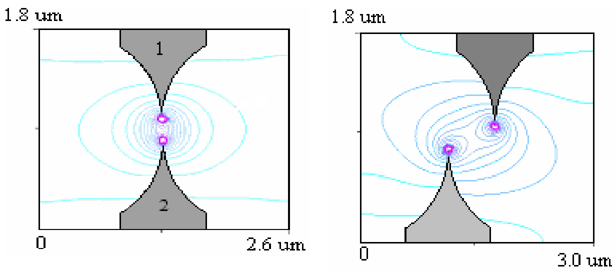
A sensing element of the accelerometer operates as follows. When a potential difference between movable and fixed electrodes, initial emission current is induced (Fig. 5a). With the moving mass of the electrode displacing (Fig.5b), the distance between the edges increases. This leads to reducing intensity of the electric field in the cavity, as well as emission current, which is registered with a gauge or fixing scheme.

Table 1 represents the values of the intensity of electric field and autoemission current calculated for a given displacement of a movable element when a potential difference between the electrods is 1000V; radius of curvature at the tip of electrode equals 5nm.

Table 1

Autoemission current with displacements of a movable electrode

Displacement, μm	*Electric field intensity, V/sm*	Autoemission current, *A*
0	$4{,}6x10^7$	$1{,}5x10^{-6}$
0,2	$4{,}2x10^7$	$3{,}2x10^{-7}$
0,4	$3{,}8x10^7$	$7{,}2x10^{-8}$



a) b)

Fig. 5. Principle of the accelerometer based on silicon nanostructures

Considering strong dependence of the autoemission current on the value of movement, as evidenced by the results shown in Table 1, and very little inertion of the movable electrode, the proposed elements can be the basis for creating supersensitive accelerometers with registration of changes of emission currents both in discrete performing and for the creation of accelerometer elements within nanoelectromechanical systems [25].

It should be noted that the constructive insulating layer of SiO_2 the autoemission sensing element of the accelerometer withstands the intensity of an electric field up to 1000 V/μm, so is appropriate for high-voltage application in devices and in integrated nanoelectro-mechanical systems.

4. Conclusion

As a result of the complex research we have designed a sensitive element of accelerometer based on silicon nanostructures and proposed a construction which improves sensitivity parameters, resistance to external influences of electromagnetic fields, provides its low inertness. The device is appropriate for creating both a discrete and nanoelectromechanical systems. Based on the experimental reserch it has been found that offset between the electrodes of accelerometer leads to two order change of the autoemission current. The sensitive element of the accelerometer can be used in both industry and scientific research, particularly for the creation and exploitation of devices intended to register acceleration under high vacuum, for example in aerospace applications.

References

[1] J.Wilson, *Sensor Technology Handbook.* Amsterdam, Netherlands: Elsevier, 2005.

[2] Y.Cui and C.Lieber, “Functional Nanoscale Electronic Devices Assembled Using Silicon Nanowire Building Blocks”, *Science*, vol. 291, 2001.

[3] E.Sicard and S.Delmas, *Advanced CMOS cell design.* NewYork, USA: McGraw-Hill, 2007.

[4] K. Bernstein and N. Rochler. *SOI circuit design.* USA, New York, USA: Kluwer Academic Press, 2002.

[5] V.Popov, I.Antonova, A. Francuzov, L.Safonov, G.Feofanov, O. Naumova, and D. Kilanov, “Properties structures and devices of silicon-on-insulator”, *Semiconductors,* vol.35, 2001.

[6] R.He and P.Yang, “Giant piezoresistance effect in silicon nanowires”, *Nature nanotechnology*, vol.1, 2006.

[7] O.Naumova, I.Antonova, V.Popov, Yu.Nastaushev, T.Gavrilova, I.Litvin, and A.Aseyev, “Modification of silicon-on-insulator structures under nano-scale Device fabrication”, *Microelectronic Engineering,* vol. 69, 2003.

[8] V.Turchanikov, A.Nazarov, V.Lysenko, J.Carreras, and B.Garrido, “Charge storage peculiarities in poly-Si-SiO2-Si memory devices with Si nanocrystals rich SiO_2”, *Microelectronics Reliability*, vol. 45, 2005.

[9] O. Naumova, V. Popov, A. Aseyev, Yu. Ivanov, and A. Archakov, ”Silicon-on-insulator nanowire transistor for medical biosensors, in *Proc. EuroSOI International conference,* pp.69-70, Goteborg, Sweden, 2009.

[10] C. Lee, T. Tseng, S. Li, and P. Lin, “Growth of zing oxide nanowires on silicon (100)”, *Tamkang Journal of Sience and Engineering*, vol. 6, 2003.

[11] Y. Zhang, Y. Tang, N. Wang, D.Yu, C. Lee, I. Bello, and S. Lee, “Silicon nanowires prepared by laser ablation at high temperature”, *Appl. Phys. Lett.*, vol. 72, 1998.

[12] Y.Wu, R.Fan, and P.Yang, “Block-by-block growth of single-crystalline Si/SiGe superlattice nanowires”, *Nano Letters*, vol. 2, 2002.

[13] C.Deng, W. Sigmon, G. Giust, and J.Wu, “Wybourne M.N. Novel scheme to fabricate SiGe nanowires using pulsed ultraviolet laser induced epitaxy”, *J. Vac. Sci. Technol.* vol.A 14(3), 1996.

[14] I.Zubel and M.Kramkowska, “The effect of iso-propyl alcohol on etching rate and roughness of (100) Si surface etched in KOH and TMAH solutions”, *Sensors & Actuatuators*, vol. A93, 2001.

[15] M.J.Hampden-Smith, “Chemical Vapour Deposition of Metals. Part 1. An Overview of CVD Processes”, *Journal Chemical Vapour Deposition*, vol.1, 1995.

[16] A. Druzhynin, I.Ostrovskyi, Yu.Khoverko, and S.Nichkalo, “Growth of Si wires array by CVD method”, in *Proc. 2009 Spring Meeting, Book of Abstracts (E-MRS). Symposium: I Advanced Silicon materials research for electronic and photovoltaic applications*, p.155, Strasbourg, France, 2009.

[17] A.Druzhynin, I.Ostrovskii, Yu.Khoverko, and S.Nichkalo, “Peculiarities of Si nanowires growth”, in *Proc. Materials of International Meeting “Clusters and nanostructured materials” (CNM-2)*, p. 58, Uzhgorod, Ukraine, 2009.

[18] A.Druzhynin, I.Ostrovskyi, Yu.Khoverko, and S.Nichkalo, ”Growing of silicon nano- and microwires by CVD and their possible sensor applications”, *Scientific and Technical. "Electronics and Communications"*, vol. 2-3, p. 56-60, 2009.

[19] A.Druzhynin, I.Ostrovskyi, Yu.Khoverko, and S.Nichkalo, “Growing of nanosized crystals of Si by gas-phase epitaxy”, *Elektronika*, pp. 11-16, vol.646, Lviv, Ukraine: Lviv Polytechnic National University, 2009. (Ukrainian)

[20] A.Druzhynin, I.Ostrovskyi, Yu.Khoverko, and S.Nichkalo, “Features of creation nanosized silicon crystals”, *Physics and Chemistry of Solids,* vol.10, no. 4, pp. 777-780, Ivano-Frankivsk, Ukraine: V. Stefanyk Precarpathian National University 2009.

[21] A.Druzhynin, I.Ostrovskyi, Yu.Khoverko, and S.Nichkalo, ”Receiving nanowires from Si and SiGe”, *Nanosystemy, nanomaterialy ta nanotekhnolohiyi*, vol. 9, pp. 925-931, Kyiv, Ukraine: Institute for Metal Physics, 2011.

[22] A. Druzhynin, I.Ostrovskyi, S. Nichkalo, and Yu. Khoverko, *A method of producing arrays of silicon nanocrystals,* Ukraine Patent № 63926, 2011. (Ukrainian)

[23] A Druzhynin, E.Lavitska, I.Maryamova, and Y.Khoverko, “Laser recrystallized SOI layers for sensor applications at cryogenic temperatures”. In F. Balestra et al., eds. *Progress in SOI structures and Devices Operating at Extreme Conditions*, pp. 233-237, Netherlands: Kluwer Acad. Publishers, 2002.

[24] A.Druzhynin, I.Maryamova, I.Kogut, and Yu.Khoverko, “Polysilicon on Insulator Structures for Sensor Application at Electron Irradiation & Magnetic Fields”, *Advanced Materials Research,* vol. 276, pp. 109–116, 2011.

[25] A.Druzhynin, I.Kogut, V.Golota, and Yu.Khoverko, *Autoemission sensitive element of acselerometer*, Ukraine Patent № 62951, 2011.

ЧУТЛИВИЙ ЕЛЕМЕНТ АКСЕЛЕРОМЕТРА НА ОСНОВІ НАНОСТРУКТУР КРЕМНІЮ

Анатолій Дружинін, Ігор Когут, Юрій Ховерко, Віктор Голота

У роботі розглянуто чутливий елемент акселерометра, виконаний з використанням суміщеної тех.-нології створення структур кремній-на-ізоляторі та ниткоподібних нанокристалів кремнію. На його основі розроблено малоінерційний, швидкодіючий, високочутливий до прискорення і переміщень пристрій із субмікрометровими та нанометрровими топологічними розмірами. Це дало можливість реалізувати як дискретний прилад, так і елемент зінтегрованих наноелектромеханічних систем зі структурою кремній-на-ізоляторі, який за безпечує контроль переміщення з точністю до 200 нм.

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Under his supervision three Doctor of Engineering and ten Ph.D. dissertations in engineering science have been defended.

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Prof. Kogut has authored over 350 scientific papers including more than 40 inventor's certificates and patents. Prof. Kogut leads a scientific work of postgraduate students and has supervised Ph.D. dissertation thesis.

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Research interests cover physics and technology of semiconductor devices, micro-and nanoelectronic structures and sensor electronics. Research findings have been published in more than 150 scientific papers, and 7 patents have been granted by Ukraine.

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The researcher has authored 55 publications, including 40 scientific publications and 15 patents for utility models. His research interests relate to thedevelopment of and research into promising micro-and nanoelectronic components for the creation of specialized computer systems, such as systems-on-chip, including sensory, using programmable logic integrated circuits.