УДК 621.315.592

DOI: 10.15222/TKEA2017.6.03

Dr. Sc. A. A. DRUZHININ, Dr. Sc. Yu. M. KHOVERKO, Dr. A. P. KUTRAKOV, Dr. N. S. LIAKH-KAGUY, S. Yu. YATSUKHNENKO

Ukraine, Lviv Polytechnic National University
E-mail: druzh@polynet.lviv.ua

SENSITIVE ELEMENT OF MULTIFUNCTIONAL SENSOR FOR MEASURING TEMPERATURE, STRAIN AND MAGNETIC FIELD INDUCTION

Sensitive element of multifunctional sensor for measuring temperature, strain and magnetic field induction has been developed based on the studies of electrical conductivity and magnetoresistance of silicon and germanium microcrystals in the temperature range 4.2—70 K, strain ±$1.5 \cdot 10^{-3}$ rel.un. and magnetic fields of 0—14 T. The feature of the sensitive element is the using of the p- and n-type conductivity germanium microcrystals as mechanical and magnetic field sensors, respectively, and the p-type silicon microcrystal — as temperature sensor. That allows providing the compensation of temperature influence on piezoresistance and on sensitivity to the magnetic field.

Keywords: sensitive element of multifunctional sensor, silicon and germanium microcrystals, magnetoresistance, cryogenic temperatures.

High-sensitivity, high-speed devices and solid-state electronics components operating under hard conditions of exploitation are widely used in modern technology, in particular in aerospace engineering, cryoelectronics, etc. [1—4]. However, deep cooling is necessary for the operation of such devices, and that significantly limits their using. In addition, a number of requirements are advanced to modern devices such as multi-functionality, miniature size, high precision of conversion, stability that can be achieved due to new structural and circuit design solutions [1—5].

Known multifunction sensors for simultaneous measurements of several parameters, such as temperature, strain, pressure, magnetic field, etc. need high-value special equipments and materials due to the use of the complex microelectronic technologies [6—8].

The authors of the paper [9] describe the construction of a multi-functional sensor for measuring strain, magnetic field and temperature, in which a thermistor based on a silicon whisker was used as a measuring element. The sensor was based on the single whisker that leads to a significant impact of the measured parameters on each other, and as a result, that has led to the reduction of measurement accuracy. However, this design does not allow providing the compensation of temperature influence on the sensor piezoresistance and the temperature dependence of the sensitivity to the magnetic field.

This work was devoted to the creation of the multifunctional sensor for measuring temperature in the range of 4.2—70 K, under strain of ±$1.5 \cdot 10^{-3}$ rel. un. and magnetic fields up to 14 T. The sensor was made using a simple technology that meets the current requirements for the primary converters.

Experimental procedure

The silicon and germanium whiskers grown by the method of chemical transport reactions in a closed bromide system were selected to create the sensitive elements of the multifunctional sensor [10]. The corresponding source material, silicon or germanium, was loaded into a quartz tube. The gold impurity was used as the initiator of the whisker growth. Silicon whiskers were doped with boron, and germanium whiskers — with gallium during their growth, to obtain the *p*-type conductivity. The germanium whiskers were also doped with antimony to obtain the *n*-type conductivity. Silicon whiskers have the doping concentration of $5 \cdot 10^{18}$ cm^{-3}, and germanium whiskers — $5 \cdot 10^{17}$ cm^{-3}. The temperature of the crystallization zone was 700—800°C, and the temperature of the evaporation zone was 1000°C. The silicon and germanium whiskers with a diameter of 3—9 μm and the length 2—4 mm were selected for the studying.

The original and easy-to-implement technique proposed by the authors of [11] was used to provide uniaxial compressive and tensile strain for the studied whiskers at cryogenic temperatures. Thus, the uniaxial strain of the silicon and germanium whiskers is created by the changing of the temperature due to the difference in coefficients of thermal expansion of the crystal and the substrate material. The whiskers were mounted on the substrates with different materials by using a glue of VL-931 with the polymerization temperature of +180°C.

The *p*- and *n*-type conductivity the silicon and germanium whiskers were placed on a special beam and installed in a helium cryostat where they were cooled to a temperature of liquid helium for the studying of the magnetoresistance and strain characteristics.

The influence of the magnetic field on the whisker properties were studied on a Bitter magnet with an induction up to 14 T and with the scan time in the field of 1.75 T/min in the temperature range 4.2—70 K.

The stabilized electric current through the whisker has determined by the current source Keithley 224 within range 1—100 μA depending on the resistance for investigated whiskers. The temperature has measured with using Cu-CuFe thermocouple.

The electric voltage at the whisker contacts, the output signal of the thermocouple and the magnetic field sensor were measured by digital voltmeters Keithley 199 and Keithley 2000 with an accuracy up to $1 \cdot 10^{-6}$ V. The simultaneous automatic registration of indicators on devices was carried out due to the parallel port of the personal computer and further their visualization on the monitor screen.

The studies in the temperature range 4.2—70 K and magnetic fields up to 14 T were carried out in the International Laboratory of High Magnetic Fields and Low Temperatures (Wroclaw, Poland).

Experimental results and discussion

The results of the investigations of the temperature dependence of the resistance R in the *p*-type conductivity Si whiskers are presented in **Fig. 1**. The dependences of relative change of the resistance vs applied uniaxial strain ($\Delta R_\varepsilon/R_0$) and the magnetic field induction ($\Delta R_B/R_0$) at different temperatures in the range 4.2—70 K for both types of conductivity Ge whiskers were shown in **Fig. 2** and **Fig. 3**.

The obtained data show that:

— the resistance sensitivity to the temperature change in the studied range is 0.42 Ohm/K for the *p*-type conductivity Si whiskers (Fig. 1);

— the resistance sensitivity to the maximum strain change ($1.5 \cdot 10^{-3}$ rel. un.) at liquid helium

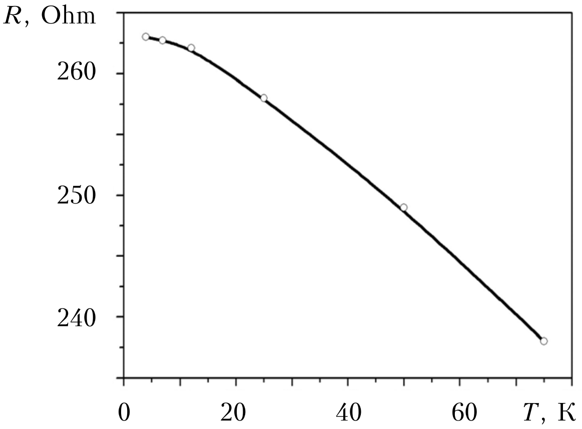

Fig. 1. The temperature dependence of the resistance in the *p*-type conductivity Si whiskers

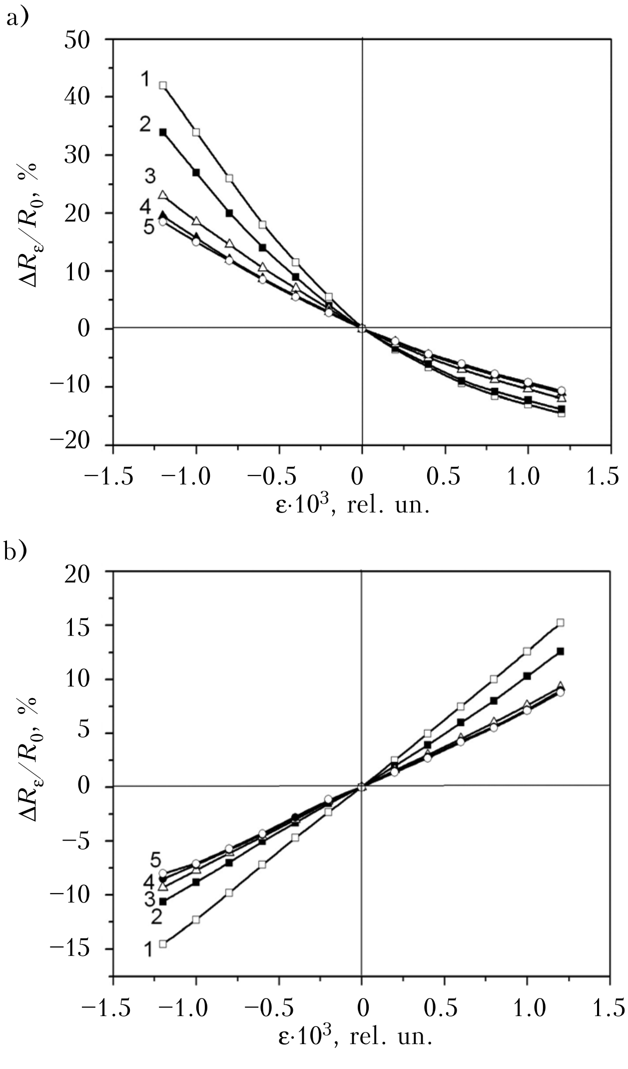

Fig. 2. The dependences of relative change of the resistance vs applied uniaxial strain for the *n*- (*a*) and *p*-type conductivity (*b*) Ge whiskers at different temperature:

1 — 4.2 K; *2* — 14 K; *3* — 24 K; *4* — 42 K; *5* — 70 K

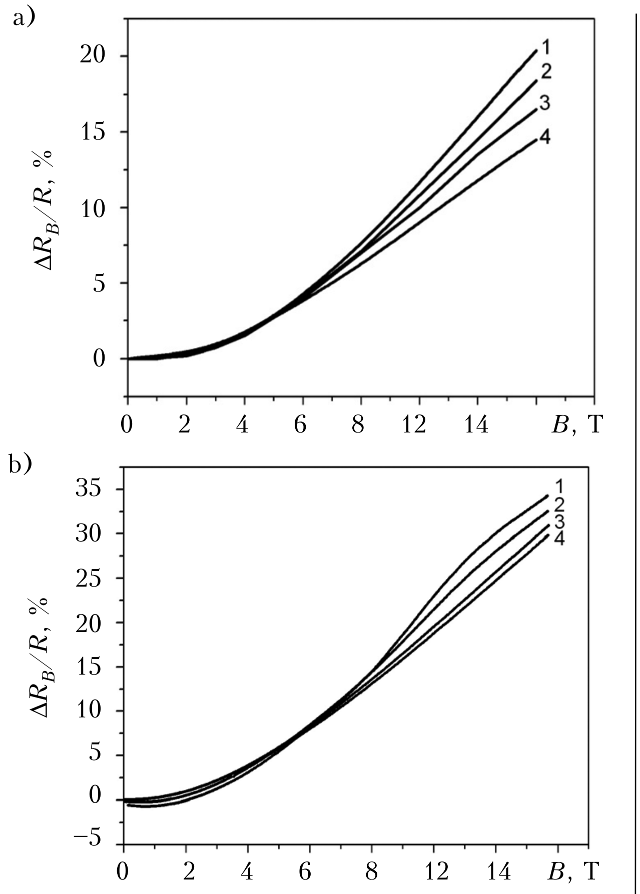

Fig. 3. The dependences of relative change of the resistance vs the magnetic field induction for the n- (*a*) and p-type conductivity of (*b*) Ge whiskers at different temperature:

1 — 4.2 K; *2* — 14 K; *3* — 24 K; *4* — 42 K; *5* — 70 K

temperature is more than 40% for the n-type conductivity Ge whiskers and it's about 15% for the p-type Ge whiskers (Fig. 2);

— the resistance sensitivity to the change in magnetic field induction from 0 to 14 T at temperature 14 K is about 20% for the n-type conductivity Ge whiskers and it's about 35% for the p-type Ge whiskers (Fig. 3).

Therefore, the obtained data indicate that the p-type conductivity silicon whiskers could be used as the temperature sensors in the range of 4.2—70 K, and the p- and n-type germanium whiskers — as the mechanical and magnetic field sensors, respectively.

Sensitive element of multifunctional sensor

The conducted studies allowed designing the sensitive element of the multifunctional sensor for measuring strain, magnetic field induction and temperature (**Fig. 4**).

The developed sensitive element of the multifunctional sensor was operated due to the simul-

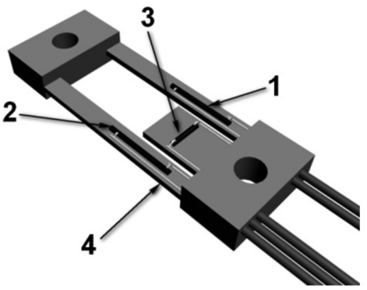

Fig. 4. Schematic image of the sensitive element of the multifunctional sensor:

1, 2, 3 — mechanical, magnetic field induction and temperature sensors, respectively; *4* — elastic element

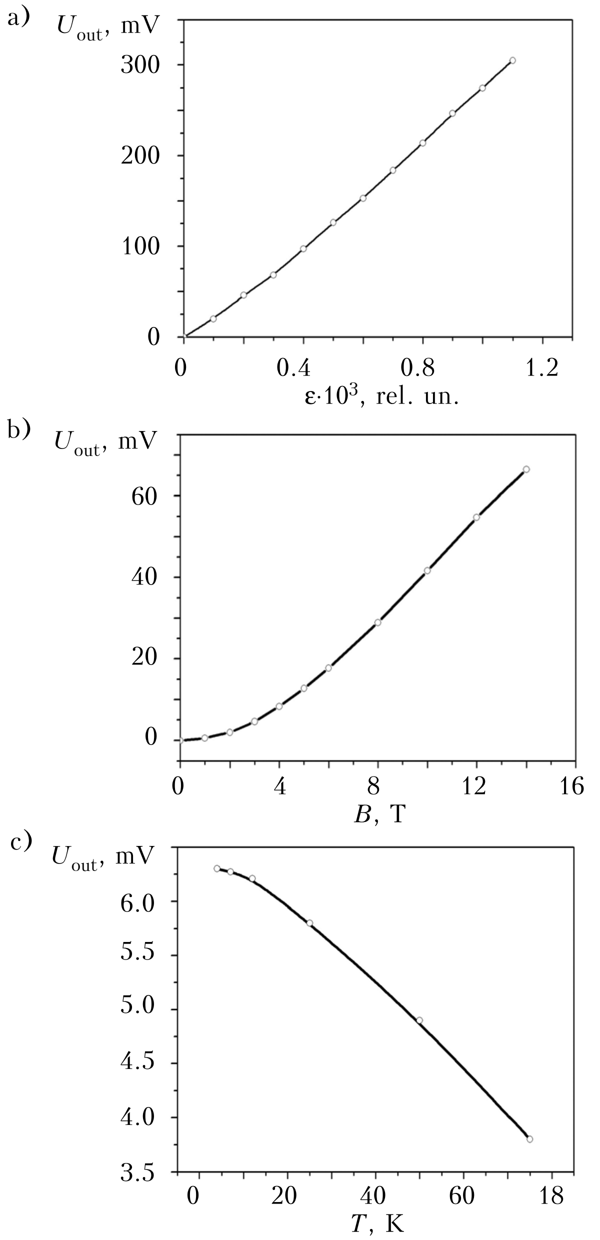

Fig. 5. The output signal of the multifunctional sensor for measuring strain (*a*), magnetic field induction (*b*) and temperature (*c*)

taneous using of three sensors with different types of conductivity: the temperature sensor — based on the *p*-type conductivity silicon whisker, the mechanical, magnetic field induction sensors — on the basis of the *n*- and *p*-type conductivities germanium whiskers, respectively. All three primary converters have mounted on the elastic element as shown in Fig. 4.

The sensitive elements of the multifunctional sensor for the measuring strain and magnetic field induction have switched in the adjacent shoulders of the bridge measuring circuit. As a result, the output signal of the circuit caused by the influence of deformation is determined by the difference in signals, while the signal caused by the effect of the magnetic field is determined by the sum of the signals.

The temperature sensor based on the *p*-type conductivity silicon whiskers, which are weakly sensitive to the influence of the magnetic field, was used to provide the compensation of temperature influence on the sensor piezoresistance [12]. Therefore, the compensation of temperature influence on piezoresistance and on sensitivity to the magnetic field in the multifunctional sensor were carried out by the electronic processing unit taking into account the output signal from the temperature sensor [13].

Output signals from three sensors of the multifunction sensor are shown in **Fig. 5**.

The output signal of the mechanical sensor reaches up to 300 mV at temperature 70 K, which corresponds to the strain level of $1{,}2 \cdot 10^3$ rel. un. (Fig. 5, *a*). And the output signal of the magnetic field sensor is about 65 mV at induction 14 T (Fig. 5, *b*).

Conclusions

Consequently, the sensitive elements of the multifunctional sensor for the measuring temperature, strain and magnetic field induction designed as the result of carried out studies that allows increaseing the accuracy of the measured parameters and extend the range of the magnetic field measurements up to 14 T in comparison with the existing analogues. The sensitivity of the temperature sensor is 0.42 Ohm/K in the temperature range of 4.2—70 K, the sensitivity of the mechanical sensor at liquid helium temperature reaches up to 40% and the sensitivity of the magnetic field sensor at induction 14 T is about 35%.

REFERENCES

1. A. A. Barlian, S. J. Park, V. Mukundan, B. L. Pruitt, Design and characterization of microfabricated piezoresistive floating element-based shear stress sensors. *Sensors and Actuators*, A., 2007, vol. 134, pp. 77-87. https://doi.org/10.1016/j.sna.2006.04.035

2. Baranskii P., Fedosov A., Gaidar G. *Fizichni vlastivosti kristaliv kremniyu ta germaniyu v polyakh efektivnogo zovnishn`ogo vplivu* [Physical properties of Si and Ge crystals in the fields of effective external influence], Lutsk, Nadstyrja, 2000, 280 p. (Ukr)

3. Egorov A. A. System, operating principles and applications of sensors. *Journal radioelectronics*, 2009, no 3, pp. 1-22. (Rus)

4. Voitovich I. D., Korsuns`kii V. M. *Intelektualni sensori* [Intelligent Sensors]. Kiev, Institute of Cybernetics of NASU, 2007, 514 p. (Ukr)

5. Druzhinin A. A., Ostrovskii I. P., Khoverko Yu. M., Liakh-Kaguj N. S., Kogut Iu. R. Strain effect on magnetoresistance of SiGe solid solution whiskers at low temperatures, *Materials Science in Semiconductor Processing*, 2011, vol. 14, no 1, pp.18-22. https://doi.org/10.1016/j.mssp.2010.12.012

6. Druzhinin A.A., Khoverko Yu.M., Kutrakov A.P., Koretskii R.M., Yatsukhnenko S.Yu. [Two-functional sensor of magnetic field and deformation based on microcrystals Si <B,Ni>]. *Tekhnologiya i Konstruirovanie v Elektronnoi Apparature*, 2017, no 3, pp. 24-29. (Ukr). http://dx.doi.org/10.15222/TKEA2017.3.24

7. Druzhinin A., Ostrovskii I., Khoverko Y., Koretskii R. Strain-induced effects in p-type Si whiskers at low temperatures, *Materials Science in Semiconductor Processing*, vol. 40, 2015, pp.766-771. https://doi.org/10.1016/j.mssp.2015.07.015

8. Alejnikov A. F., Capenko M.P. Multifunction Sensors, Handbook: Measurement, control, automation, vol. 2(74), 1990, pp. 50-57 (Rus)

9. Patent of Ukraine N28394, [*Multifunction sensor*]. R. I. Bajcar, S. S. Varshava, A. V. Prohorovich, E. F. Venger Bul. no 5, 2000. (Ukr)

10. Druzhinin A. A., Ostrovskii I. P. Investigation of Si-Ge whiskers growth by CVD, *Physica Status Solidi (C)*, 2004, vol.1(2), pp. 333-336. https://doi.org/10.1002/pssc.200303948

11. Druzhinin A., Lavitska E., Maryamova I., Oszwaldowski M., Berus T., Kunert H. Studies of piezoresistance and piezomagnetoresistance in Si whiskers at cryogenic temperatures", *Crystal Research and Technology*, 2002, vol. 37(2-3), pp. 243-257. http://dx.doi.org/10.1002/1521-4079(200202)37:2/3<243::AID-CRAT243>3.0.CO;2-L

12. Patent of Ukraine N95398, [Method of the compensation of temperature influence on piezoresistance]. A. Druzhinin, A.Kutrakov, N. Liakh-Kaguj, Lviv Polytechnic National University, Bul. no 4. (Ukr)

13. Patent of Ukraine N106175, [Multifunction sensor]. A. A. Druzhinin, O.P. Kutrakov, N. S. Liakh-Kaguj. Lviv Polytechnic National University, Bul. no 8. (Ukr)

Received 02.11 2017.

DOI: 10.15222/TKEA2017.6.03
УДК 621.315.592

Д. т. н. А. А. ДРУЖИНІН, д. т. н. Ю. Н. ХОВЕРКО,
к. т. н. А. П. КУТРАКОВ, к. т. н. Н. С. ЛЯХ-КАГУЙ,
С. Ю. ЯЦУХНЕНКО

Україна, Національний університет «Львівська політехніка»

E-mail: druzh@polynet.lviv.ua

ЧУТЛИВИЙ ЕЛЕМЕНТ БАГАТОФУНКЦІЙНОГО ДАТЧИКА ДЛЯ ВИМІРЮВАННЯ ТЕМПЕРАТУРИ, ДЕФОРМАЦІЇ ТА МАГНІТНОГО ПОЛЯ

На основі результатів дослідження залежності опору мікрокристалів кремнію і германію від температури, деформації та магнітного поля розроблено чутливий елемент багатофункційного датчика для вимірювання температури в інтервалі 4,2—70 К, деформації ±0,0015 відн. од. та індукції магнітного поля до 14 Тл. Особливістю чутливого елемента є використання мікрокристалів кремнію p-типу провідності як сенсора температури, а мікрокристалів германію p- і n-типу як сенсорів деформації і магнітного поля відповідно, що дозволило забезпечити компенсацію впливу температури на тензочутливість і чутливість до магнітного поля.

Ключові слова: чутливий елемент багатофункційного датчика, мікрокристали кремнію і германію, магнітоопір, кріогенні температури.

Д. т. н. А. А. ДРУЖИНИН, д. т. н. Ю. Н. ХОВЕРКО,
к. т. н. А. П. КУТРАКОВ, к. т. н. Н. С. ЛЯХ-КАГУЙ,
С. Ю. ЯЦУХНЕНКО

Украина, Национальный университет «Львовская политехника»
E-mail: druzh@polynet.lviv.ua

ЧУВСТВИТЕЛЬНЫЙ ЭЛЕМЕНТ МНОГОФУНКЦИОНАЛЬНОГО ДАТЧИКА ДЛЯ ИЗМЕРЕНИЯ ТЕМПЕРАТУРЫ, ДЕФОРМАЦИИ И МАГНИТНОГО ПОЛЯ

На основе результатов исследования зависимости сопротивления микрокристаллов кремния и германия от температуры, деформации и магнитного поля разработан чувствительный элемент многофункционального датчика для измерения температуры в интервале 4,2—70 К, деформации ±0,0015 отн. ед. и индукции магнитного поля до 14 Тл. Особенностью чувствительного элемента является использование микрокристаллов кремния p-типа проводимости в качестве сенсора температуры, а микрокристаллов германия p- и n-типа в качестве сенсоров деформации и магнитного поля соответственно, что позволило обеспечить компенсацию влияния температуры на тензочувствительность и чувствительность к магнитному полю.

Ключевые слова: чувствительный элемент многофункционального датчика, микрокристаллы кремния и германия, магнитосопротивление, криогенные температуры.