Paper

On possibility to extend the operation temperature range of SOI sensors with polysilicon piezoresistors

Anatoly Druzhinin, Elena Lavitska, Inna Maryamova, Igor Kogut, and Yuri Khoverko

Abstract — The aim of this work was to study the possibilities of developing mechanical sensors with poly-Si piezoresistors on insulating substrate for operation in different temperature ranges (low, elevated and high temperatures). Laser recrystallization is used as a technological tool to adjust the electrical and piezoresistive parameters of the polysilicon layer. For this purpose a set of studies including numerical simulation and experimental work has been carried out. The main three directions of the studies are considered: problems of thermal stabilization of the pressure sensor performance at elevated and high temperatures; problem of sensor operation at cryogenic temperatures; development of a multifunctional pressure-temperature sensor.

Keywords — SOI, mechanical sensors, poly-Si piezoresistor, ZMR.

1. Introduction

Zone-melting recrystallization (ZMR) technique in its application to polysilicon-on-insulator structures represents a method of fabrication of relatively large areas of monocrystalline silicon [1]. The electrical properties of a laser-recrystallized SOI film on a slice surface may be controlled to a certain extent by a change of the parameters of laser treatment, the selection and corresponding preparation of the initial SOI structures, the choice of the scan direction for the laser beam; seeds, covering strips to control defect location in recrystallized poly-Si, etc. In order to improve performance of IC's and sensors fabricated on laser-recrystallized SOI structures the film layout should correspond to the layout of device active elements. This goal may be achieved using the lateral epitaxy; a method providing separate islands of recrystallized silicon film [2]. Since one can succeed in placing the active elements in the perfect material, this way is believed to be highly promising.

Investigations presented here were aimed to solve the following practical problems: development of high-temperature pressure sensors, study of possibilities to develop pressure sensors for operation at cryogenic temperatures and development of a two-functional pressure-temperature sensor.

Since laser recrystallization influences all the electrical and piezoresistive parameters of SOI layers prediction of the laser treatment results requires careful analysis of many factors and needs both theoretical simulation and experimental verification.

2. On the temperature invariance of piezoresistance in the climatic range and at elevated temperatures

Using the model [3] of boron-doped p-type polycrystalline silicon software has been developed to calculate electrical and piezoresistive properties of polysilicon layers numerically with the average grain size as a parameter. The main transport mechanism in polycrystalline poly-Si was suggested to be thermionic emission over the barriers at the grain boundaries combined with diffusion through the grain boundaries and the traditional carrier transport through the crystallites [4].

Figures 1 and 2 present the calculated temperature dependencies of resistivities of boron-doped poly-Si layers with grain size L as a parameter. Figure 3 shows the measured $\Delta R/R_{20C}$ dependencies for the samples before and after laser recrystallization with two different initial carrier concentrations. Theoretical considerations show that laser recrystallization of poly-Si layers increases carrier concentration due to the enlargement of the average grain size, which results in the reduction of the total surface of grain boundaries, and due to trap passivation. Therefore, it changes the contributions of thermionic emission and diffusion in the carrier transport. On the other hand, the contribution of the grain boundaries themselves in the total resistivity of polycrystalline silicon strongly depends on the average

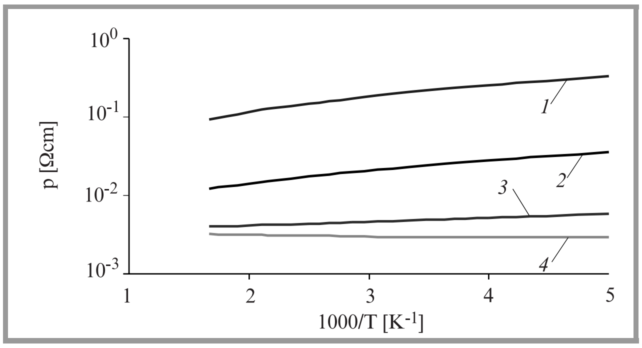

Fig. 1. Calculated p-type poly-Si resistivity versus temperature for carrier concentration $N = 1.3 \cdot 10^{20}$ cm^{-3} and the following values of the average grain size: *1* – 100 nm; *2* – 1 μm; *3* – 10 μm; *4* – 100 μm.

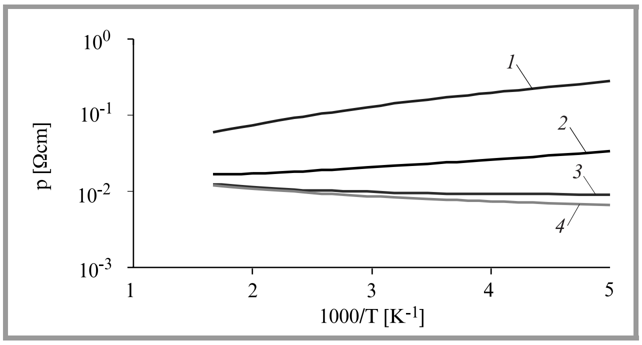

Fig. 2. Calculated p-type poly-Si resistivity versus temperature for carrier concentration $N = 3.2 \cdot 10^{19}$ cm^{-3} and the following values of the average grain size: *1* – 100 nm; *2* – 1 μm; *3* – 10 μm; *4* – 100 μm.

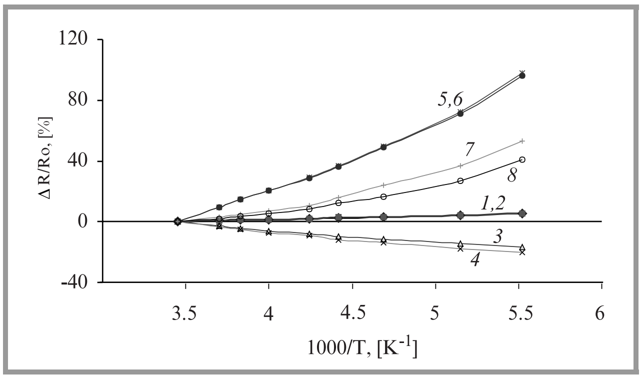

Fig. 3. Measured resistance versus temperature for the samples before *(1, 2, 5, 6)* and after laser recrystallization with two different initial carrier concentrations: *1, 2* – $3.9 \cdot 10^{19}$ cm^{-3}; *5, 6* – $2.4 \cdot 10^{19}$ cm^{-3}. The samples were parallel *(4, 8)* and perpendicular *(3, 7)* to the scan direction of the laser beam.

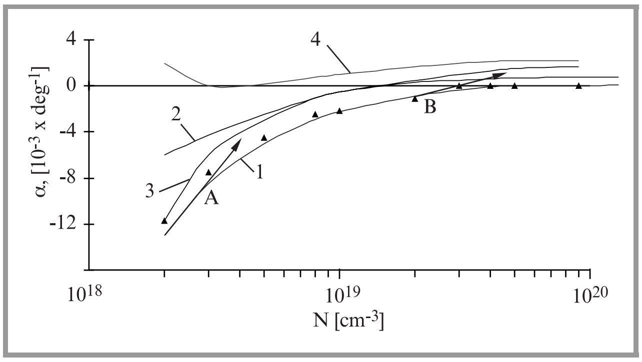

Fig. 4. Calculated TCR of poly-Si resistors near 20°C for *1* – L = 120 nm and *2* – $L = 1\,\mu$m, compared with *3* – simulation and experimental data from [5] (triangles). Curve *4* corresponds to the data for bulk silicon.

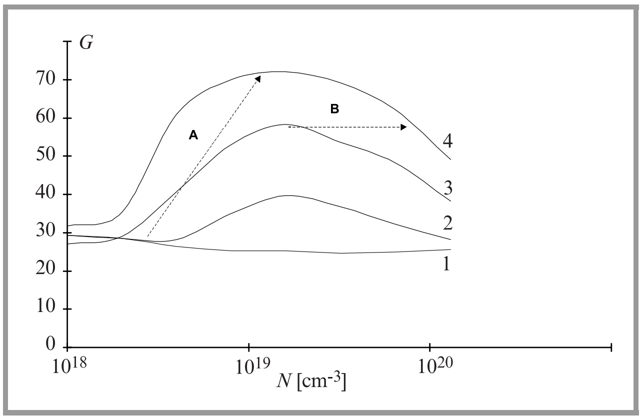

Fig. 5. Calculated longitudinal gauge factor in boron-doped polysilicon piezoresistors for the following values of average grain size: *1* – $L = 20$ nm; *2* – $L = 1\mu$m; *3* – $L = 10$ μm; *4* – $L = 100$ μm.

grain size L. After laser recrystallization the volume of the grains dominates in the electrical conductivity of polycrystalline material.

Figures 4 and 5 present calculated concentration dependencies of the temperature coefficient of resistance and longitudinal gauge factor for poly-Si piezoresistors with the average grain size L as a parameter. The investigations demonstrate that the initial doping (boron) concentration in poly-Si piezoresistors to be used in mechanical sensors should be less than $1 \cdot 10^{19}$ cm^{-3}. In this case laser recrystallization leads to a rise of the longitudinal gauge factor and reduces the temperature coefficient of resistance (TCR) of poly-Si piezoresistors [1]. Arrows **A** and **B** in Figs. 4 and 5 show the two possible consequences of laser ZMR action on poly-Si piezoresistors: arrow **A** shows the most desirable result when after recrystallization the gauge factor increases and TCR decreases, while arrow **B** corresponds to the situation where neither sensitivity nor thermal stability is improved.

There are two important coefficients which define the temperature dependence of the piezoresistor output signal: temperature coefficient of the gauge factor (TCGF) α_G and temperature coefficient of resistance (TCR) α_R. These coefficients are defined by the following formulae:

$$\alpha_G(T) = \frac{1}{G(T)} \frac{\partial G(T)}{\partial T}\,, \tag{1}$$

$$\alpha_R(T) = \frac{1}{R(T)} \frac{\partial R(T)}{\partial T}\,. \tag{2}$$

If the condition $\alpha_G + \alpha_R \approx 0$ is satisfied over a certain temperature range in the sensor measuring bridge supplied by the current source, then it is possible to achieve self-compensation of the temperature dependence of the sensor output. In this case the decrease of the sensor output due to the gauge factor reduction with temperature is compensated by the output rise due to the increase of the piezoresistor's resistance. The conditions required to achieve such a situation are explained by Figs. 4 and 5 where calculated temperature coefficient of resistance and gauge factor of boron-doped poly-Si piezoresistors are plotted as functions of carrier concentration and average grain size.

Some theoretical predictions concerning the temperature-dependence of the characteristics were made. On the basis of the studies two regions of the doping concentration were recommended where the temperature invariance of piezoresistance is achievable:

- Non-recrystallized poly-Si layers with $N \approx$ $\approx (5 \div 8) \cdot 10^{19}$ cm^{-3}; for these layers TCGF is small and negative whilst TCR is small and positive.
- Moderately doped poly-Si layers with impurity concentration in the initial samples $N \approx$ $\approx (2 \div 3) \cdot 10^{18}$ cm^{-3}; appropriate choice of the recrystallization regime provides positive TCR in the layers with enlarged grain size and similar values of TCGF but with the opposite sign. Both coefficients are higher than in the previous case. Besides temperature stability laser recrystallization provides increases the gauge factor of the samples. That is why this concentration region combined with the laser treatment is recommended for the development of the mechanical sensors with improved sensitivity.

3. Low-temperature region

At cryogenic temperatures, when a significant freezing of the carriers is expected, one should consider an alternative carrier transport mechanism: quantum transport by the states at grain boundaries (GB). The difference in the barrier heights at GBs results in a random potential relief due to the energy band bending near the GBs. That is why this system may be considered as a heavily doped and strongly compensated semiconductor where the boundary states play a role of compensating impurities [6].

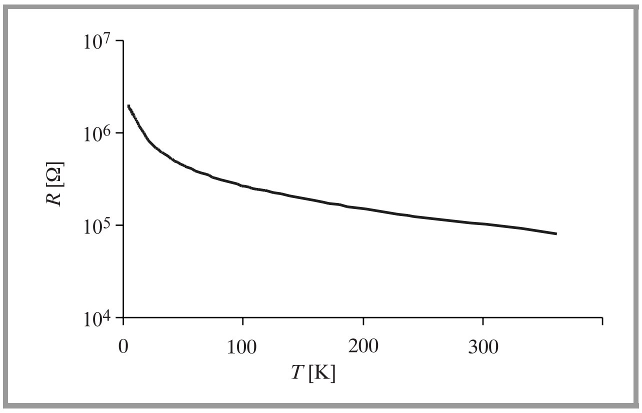

Fig. 6. Low-temperature resistance of non-recrystallized poly-Si resistor with $N = 2.4 \cdot 10^{18}$ cm^{-3}.

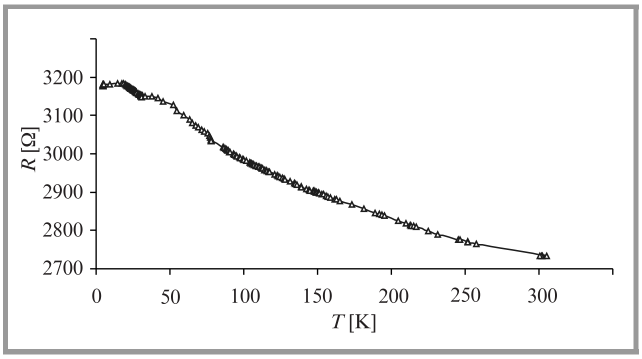

Fig. 7. Low-temperature resistance of non-recrystallized poly-Si resistor with $N = 3.9 \cdot 10^{19}$ cm^{-3}.

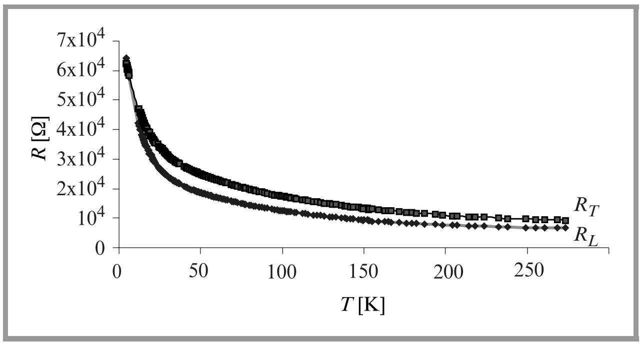

Fig. 8. Low-temperature resistance of recrystallized poly-Si resistors with $N = 4.8 \cdot 10^{18}$ cm^{-3}. R_T and R_L represent transversal and longitudinal resistance as related to the laser scan direction.

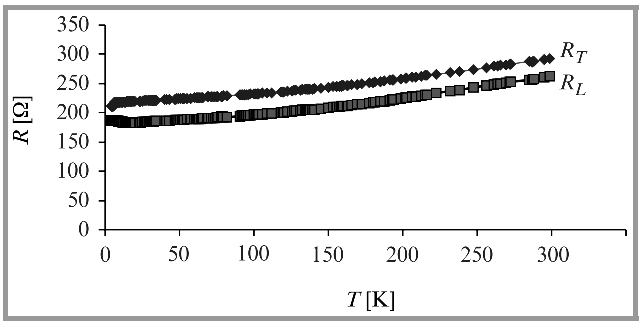

Fig. 9. Low-temperature resistance of recrystallized poly-Si resistors with $N = 1.7 \cdot 10^{20}$ cm^{-3}. R_T and R_L represent transversal and longitudinal resistance as related to the laser scan direction.

In order to study the feasibility of using poly-Si resistors at cryogenic temperatures with ZMR as a method to improve their parameters the resistance of poly-Si samples presented in Fig. 3 was measured as a function of temperature in the range of $4.2 \div 300$ K. Figures 6 and 7 show resistance-versus-temperature dependencies in non-recrystallized samples, while Figs. 8 and 9 present these dependencies for laser-recrystallized samples. The analysis of the experimental results proves that for moderately doped samples (Figs. 6 and 7) at relatively high temperatures $200 \div 300$ K there is a traditional carrier drift through the crystallite volume combined with thermionic emission at the grain boundaries while at cryogenic temperatures the electrical conductivity is due to the carrier transport along the grain boundaries that could be described in terms of percolation theory [6]. Moderately doped non-recrystallized poly-Si has a strong temperature coefficient of resistance (Fig. 6) and could be recommended to be used as a thermoresistor in a wide temperature range. Other samples (Figs. $7 \div 9$) show a reasonable change of the resistance in the range $4.2 \div 300$ K. This result combined with theoretical assessment of their piezoresistive properties [1] let us expect that it is possible to use them as piezoresistive elements at cryogenic temperatures.

4. Development of a microelectronic pressure-temperature sensor

The problem of the development of multifunctional sensors simultaneous measurement of several parameters, mechanical and thermal in particular, is a task for different branches of science and engineering. The IC fabrication process on SOI substrates seems particularly prospective for manufacturing these sensors.

The investigation indicates that in the case of the most thermally stable poly-Si layers with the initial boron density $\approx (2 \div 5) \cdot 10^{18}$ cm^{-3} laser recrystallization using the technique developed for such SOI-structures results in the change of resistance within the limits of 1% (Fig. 10) in the range of $+20 \ldots 140$°C. The studies of the temperature characteristics of poly-Si-on-insulator layers show that the strongest temperature dependence of resistivity for non-recrystallized, i.e. fine-grained, poly-Si layers is found for the doping density of $\approx 2.4 \cdot 10^{18}$ cm^{-3} (Fig. 10).

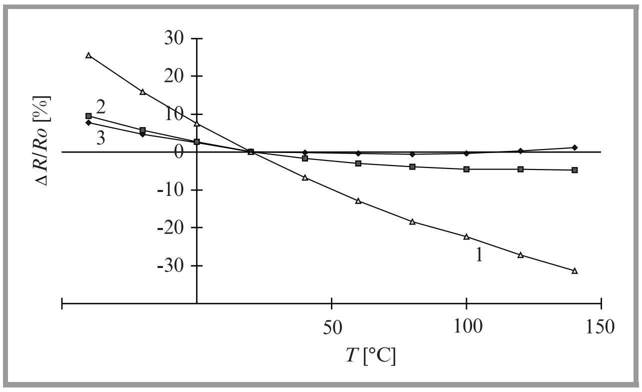

Fig. 10. Relative change of resistance versus temperature for the sample with $N = 2.4 \cdot 10^{18}$ cm^{-3} before *(1)* and after *(2, 3)* laser recrystallization in longitudinal *(2)* and transversal *(3)* direction as related to the scan direction.

The experimental data enabled a concept of the multifunction microelectronic sensor for the pressure-temperature measurement to be developed. It is proposed that non-recrystallized poly-Si layers with boron concentration $\approx 2.4 \cdot 10^{18}$ cm^{-3} be used as thermoresistors for temperature measurements. As far as pressure measurements are concerned it is proposed that piezoresistors based on laser-recrystallized poly-Si layers with initial boron concentration $\approx 2 \cdot 10^{18}$ cm^{-3} ($4.8 \cdot 10^{18}$ cm^{-3} after the laser recrystallization) be used. These piezoresistors have sufficiently high gauge factor and show reasonable thermal stability over a wide temperature range.

A layout of such microelectronic pressure-temperature sensors has been developed. According to this layout (Fig. 11) SOI-based piezoresistors $R_1 \div R_4$ connected to form a bridge circuit were placed on a micromachined membrane while the thermoresistor R_5 was fabricated of appropriately doped poly-Si. The thermoresistor is on the same chip but not on the membrane. Thus it is insensitive to the mechanical stress in the membrane under external pressure.

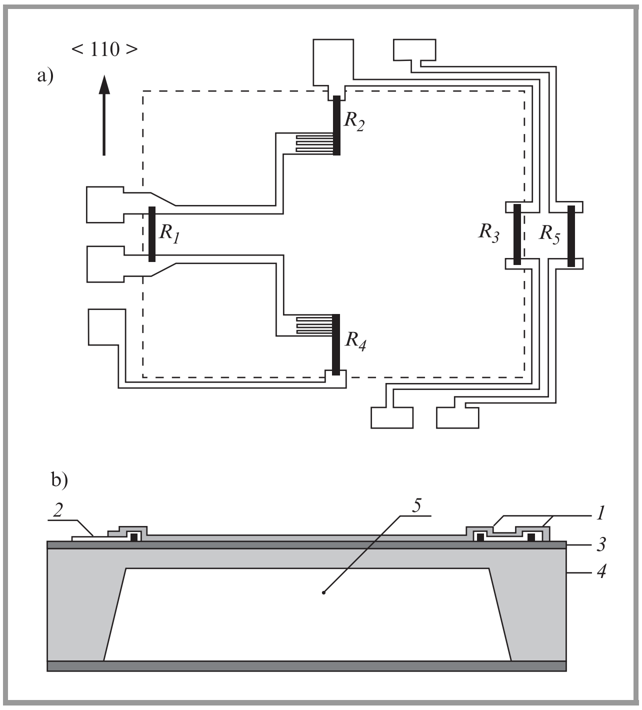

Fig. 11. Layout (a) and design (b) of SOI pressure-temperature sensor: $R_1 \div R_4$ – poly-Si piezoresistors; R_5 – poly-Si thermoresistor; *1* – poly-Si resistors; *2* – Al contacts; *3* – SiO_2 layer; *4* – Si wafer; *5* – Si membrane.

The fabrication process of the microelectronic pressure-temperature sensor was based on the fabrication process of microelectronic pressure sensors with laser-recrystallized polysilicon piezoresistors [7]. Because the polysilicon piezoresistors and thermoresistor in the multifunctional sensor have the same initial boron concentration ($\approx 2.4 \cdot 10^{18}$ cm^{-3}), doping of these resistors does not require any additional technological operation. Doping of poly-Si layers was carried out by the ion implantation method. During laser recrystallization of poly-Si piezoresistors the poly-Si thermoresistor was protected by Si_3N_4/SiO_2 film with the thickness sufficient to provide absorption of laser irradiation.

Using the developed technology the experimental sensors have been fabricated for different pressure and temperature ranges:

1. pressure $0 \div 2.4 \cdot 10^5$ Pa ($0 \div 2.5$ bar), temperature $20 \div +150$°C;

2. pressure $0 \div 1.6 \cdot 10^5$ Pa ($0 \div 1.6$ bar), temperature $-40 \div +60$°C.

The performance of the multifunction sensors is presented in Figs. 12 and 13. Temperature coefficient of resistance of the developed temperature sensor is $-0.386\% \cdot \mathrm{deg}^{-1}$.

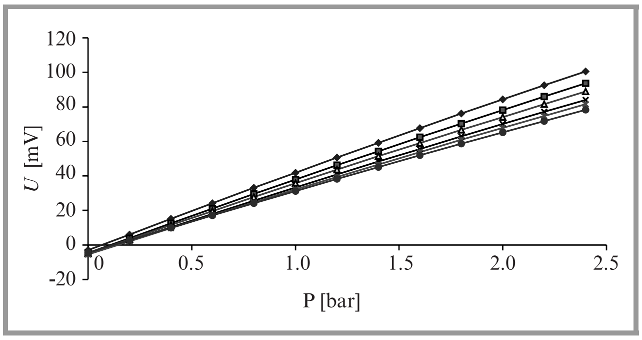

Fig. 12. Pressure-dependent output signal of the multifunctional sensor at several temperature points.

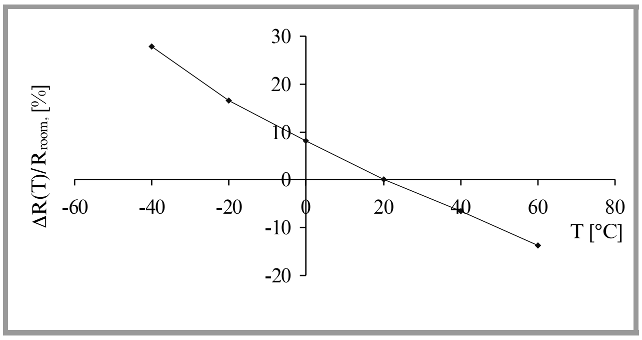

Fig. 13. Output performance of the thermoresistor of multifunctional sensor.

The chips size is 5 mm × 5 mm, while membrane size is 2 mm × 2 mm. For certain applications, especially in medicine, the size of the chip could be significantly reduced.

The advantages of pressure-temperature sensors based on poly-Si resistors are a simple and reproducible fabrication process and adjustability of the temperature coefficient by appropriate choice of doping concentration and laser recrystallization regime. The developed multifunctional sensors may be applied in different branches of industry, science and medicine.

5. Conclusions

Our studies reveal that:

- poly-Si piezoresistors exhibit regions of thermal stability at climatic and elevated temperatures;
- these piezoresistors may be used at cryogenic temperatures.

In both cases laser recrystallization represents a method to tailor the parameters of poly-Si piezoresistors to the desired temperature range.

Multifunction pressure-temperature sensors have been developed as an application of the results of the studies performed.

References

[1] A. A. Druzhinin, I. I. Maryamova, E. N. Lavitska, Y. M. Pankov, and I. T. Kogut, „Laser recrystallized polysilicon layers for sensor application: electrical and piezoresistive characterization” in *Perspectives, Science and Technologies for Novel Silicon on Insulator Devices*, P. L. F. Hemment *et al.*, Eds. Kluwer, 2000, pp. 127–135.

[2] A. A. Druzhinin, V. G. Kostur, I. T. Kogut, I. M. Pankevich, and Y. L. Deschinsky, „Microzone laser recrystallized polysilicon layers on insulator” in *Physical and Technical Problems of SOI Structures and Devices*, J. P. Collinge *et al.*, Eds. Kluwer, 1995, pp. 101–106.

[3] A. O. Druzhinin, O. M. Lavitska, and I. I. Maryamova, „Simulation of piezoresistance of the potential barrier at the grain boundary in polysilicon”, *Ukr. Phys. J.*, vol. 40, pp. 572–575, 1995.

[4] J. Seto, „The electrical properties of polycrystalline silicon films”, *J. Appl. Phys.*, vol. 46, pp. 5247–5254, 1975.

[5] J. Suski, V. Mosser, J. Goss, and E. Obermeier, „Polysilicon SOI pressure sensor”, *Sens. Actuat.*, vol. A17, pp. 405–414, 1989.

[6] B. I. Shklovskii and A. L. Efros, *Electron Properties of Doped Semiconductors*. Moskow: Nauka, 1979.

[7] V. A. Voronin, I. I. Maryamova, A. A. Druzhinin, E. N. Lavitska, and Y. M. Pankov, „SOI pressure sensors based on laser recrystallized polysilicon” in *Physical and Technical Problems of SOI Structures and Devices*, J. P. Collinge *et al.*, Eds. Kluwer, 1995, pp. 281–286.

Anatoly Druzhinin was born in Ukraine in 1946. He received his Ph.D. degree in 1977, and D.Sc.(Tech.) in 1993. Since 1980 he works in Lviv Polytechnical University. Professor, head of the Laboratory of Sensor Electronics and Laser Technology. His field of interests is physics and technology of semiconductor materials and devices.
e-mail: druzh@polynet.lviv.ua
Lviv Polytechnical University
Kotlarevsky st 1
Lviv 79013 Ukraine

Elena Lavitska was born in Ukraine in 1955. She graduated from the Lviv Polytechnical University in 1977 and works there till today; in 1986 she received the Ph.D. degree. Field of her interests: strain-induced effects in semiconductors, sensors on their basis and technology of microelectronic sensors.
e-mail: Lavits@polynet.lviv.ua
Lviv Polytechnical University
Kotlarevsky st 1
Lviv 79013 Ukraine

Inna Maryamova graduated from the Lviv Ivan Franko University in 1961 and works as a leading researcher in the Department of Semiconductor Electronics of the Lviv Polytechnical University; in 1972 she received her Ph.D. Her field of activity concerns piezoresistive mechanical sensors.
Lviv Polytechnical University
Kotlarevsky st 1
Lviv 79013 Ukraine

Igor Kogut was born in Ukraine in 1953. He graduated from the Lviv Polytechnical University in 1975 and works in the industrial firm „Rodon", Ivano-Frankivsk, till today. In 1993 he received the Ph.D. degree. Field of his interests: development of semiconductor devices on the basis of silicon-on-insulator structures.
Lviv Polytechnical University
Kotlarevsky st 1
Lviv 79013 Ukraine

Yuri Khoverko was born in Ukraine in 1968. He graduated from the Lviv Polytechnical University in 1992 and works there till today. Field of his interests: technology of microelectronic sensors on the basis of silicon-on-insulator structures.
Lviv Polytechnical University
Kotlarevsky st 1
Lviv 79013 Ukraine