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Ge-film resistance and Si-based diode temperature microsensors for cryogenic applications

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Abstract

New types of miniature (1.2 mm diameter × 1.0 mm long) temperature sensors based on germanium (Ge) films and silicon diodes have been developed and produced. The Ge-film microthermometers are intended for use at temperatures from 1 to 400 K, and silicon microdiodes cover operating temperature range from 2 to 600 K. The designs of sensitive elements and miniature package as well as sensor characteristics are presented. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The main trend in the progress of cryogenic temperature sensors is to make them miniature and low cost, to expand their operating temperature range, reduce the effect of magnetic field, and increase their radiation tolerance. These requirements are dictated by the emergence of new cryogenic technologies and modern low-temperature physics.

Novel sensors that meet the new requirements of the cryogenic sensor market can be realized by the production of new semiconductor film materials having the required properties and by the application of modern microelectronic and micromachining technologies to sensor manufacture.

To measure cryogenic temperatures, one may use sensors based on various physical effects and fabricated from different materials. The review of state of the art in cryogenic thermometry can be found in [1]. The most widely used cryogenic thermometers are resistance and diode ones.

This work deals with development of both the resistance and diode temperature microsensors. We reported on designing the several types of resistance thermometers based on germanium (Ge) films [2–5]. Here, we present some new models of Ge-film resistance microthermometers (TTR-1G model) and Si-based diode temperature microsensors (DS-1A model). As sensitive elements of diode temperature sensors, the p^+–n–n^+ planar Si-based diodes with improved radiation and thermal stability have been designed. Such diodes are intended for use in the 2–600 K temperature range. The Ge-film thermometers have been designed for use at temperatures from 1 to 400 K. The design of the sensitive elements and a miniature package, as well as the properties and operating characteristics of sensors in the 2–600 K temperature range and in the magnetic fields are presented. Furthermore, the conduction mechanisms for Ge-film thermometers at low temperatures have been analyzed.

2. Design of sensors

2.1. Ge film on GaAs substrate as sensitive material for resistance thermometer

Ge/GaAs heterostructure can serve as sensitive material to fabricate a number of various physical sensors, such as temperature, magnetic field, strain, pressure, and optical radiation sensors, as well as heat-resistant MESFETs [2–5].

The electrical properties of Ge films grown on semi-insulating GaAs substrates depend on details of their preparation. They are determined by the following two factors: diffusion of Ga and As atoms from the GaAs substrate during the film growth, and the degree of structural perfection of the film. The crystalline structure of the film depends

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primarily on the substrate temperature during the film deposition. As the crystalline perfection degree grows, some changes occur in the character of temperature dependencies of all the film characteristics, such as conductivity, charge carrier's concentration and mobility. Changing the conditions of film preparation and using various physico-chemical treatments of GaAs, one is able to obtain poly- and single-crystal Ge films of both p- and n-type with different levels of doping and compensation degrees [2]. Depending on the film-formation conditions, the free charge carrier concentration in Ge films at room temperature may vary from 10^{14} to 5×10^{20} cm^{-3}. By varying the conditions of germanium deposition, one can prepare films having the needed electrical and optical properties, and produce various physical sensors to measure temperature, strains, pressure, magnetic field, and optical radiation.

To obtain Ge films with electrical properties suitable for use as a temperature sensor, one must find the parameters of film deposition resulting in a spectrum of impurity states in the film that will yield the electrical parameters desired.

The thermosensitive films for thermometers were deposited using evaporation of Ge in a vacuum onto semi-insulating GaAs substrates. Fig. 1 shows the design of a sensitive element. To form electric contacts to Ge, we used sequential deposition of thin AuGe (eutectic) and Au layers. Their total thickness was about 0.3 μm. In some cases, a thin Mo interlayer was formed between the AuGe and Au layers. The metal films were deposited using magnetron sputtering in a vacuum. To provide a reliable microwelding, an additional Au layer (about 5 μm thick) was electrochemically deposited. Such a multilayer metal structure was to provide a good electric contact to Ge over a wide temperature range, from ultralow to room temperature, as well as high strength of microwelded connections. On the GaAs side, Ge–Au–Mo–Au layers were also formed (whose total thickness was about 3 μm) to provide the microwelded connections. The Ge/GaAs sensitive element of the thermometer measured 0.3 mm wide × 0.3 mm long × 0.2 mm high.

2.2. The p^+–n–n^+ planar Si diode as temperature sensor

The reason for the fact that the temperature dependence of forward voltage drop on diodes is widely used to measure temperature is as follows. First, the forward voltage drop at a constant current through a p–n junction is relatively linear in temperature over wide temperature range (the low-temperature region, $T < 50$ K, provides an exception). Second, the forward voltage change with temperature is easily measured for diodes. At present, several firms produce special diode temperature sensors based on silicon and gallium arsenide [1]. The principal objective of this work was to develop the Si-based diode temperature microsensors with improved radiation and thermal stability for local temperature measurement in a wide (from 2 to 600 K) temperature range.

The silicon element for temperature sensors is a p^+–n–n^+ planar diode. The diode structure was prepared in the following way. At first, silicon epitaxial n^+–n structures have been prepared. Resistivity of the epitaxial n-layer (1.5 μm thick) was 0.15 Ω cm. A SiO_2 layer (0.5 μm thick) was then formed on the epitaxial n-layer, and windows, 100 μm in diameter, were made in this layer. Through these windows, boron diffusion to the depth of 0.8 μm was performed to make a p^+-layer. The electric contacts to this p^+-layer were formed by sequential Ti, TiB_2, and Au deposition using magnetron sputtering followed by electrochemical deposition of gold. The electric contacts to the n^--layer were Pd_2Si–Ti–Au structure. The Ti–TiB_2–Au and Pd_2Si–Ti–Au multilayer metal structure was deposited to improve radiation and thermal stability of the devices. We have shown [6] that contact systems based on the silicides, borides, and nitrides of refractory metals are promising for production of diodes having an improved radiation tolerance and reliability when operating for a long time at elevated temperatures.

The size of the diode structure obtained was 0.35 mm × 0.35 mm. The design of a silicon element for diode temperature sensor is shown in Fig. 2.

2.3. Design of miniature package

It is known that some specific requirements are imposed upon the package design when producing a device that operates in a wide temperature range (especially at low

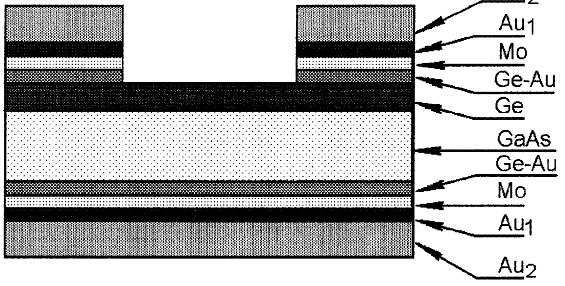

Fig. 1. Design of Ge-film sensitive element for resistance temperature sensor.

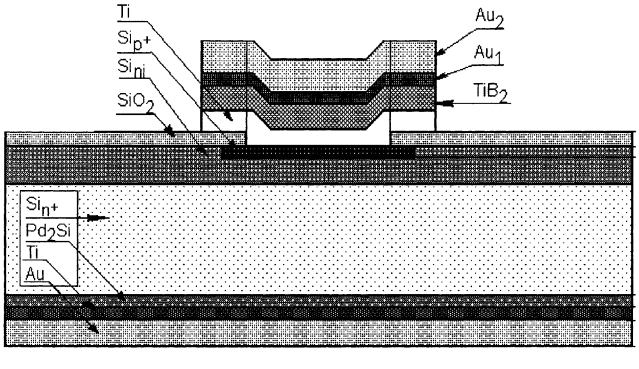

Fig. 2. Design of silicon element for diode temperature sensor.

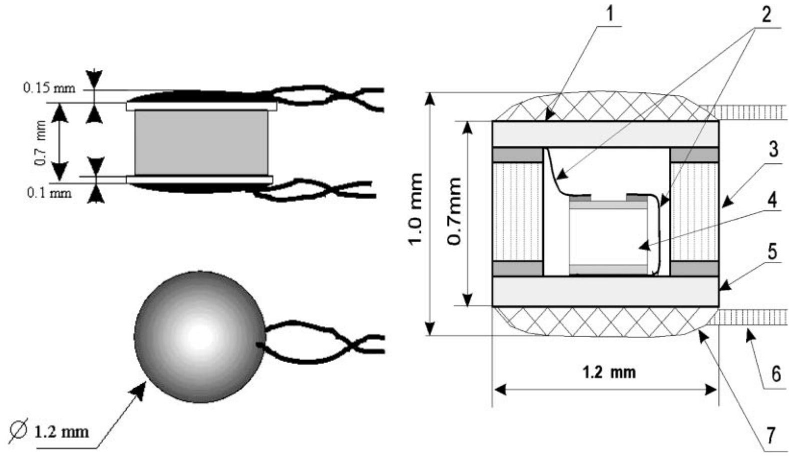

Fig. 3. Design and dimensions of thermometer — (1) and (5): copper discs; (2): gold strip; (3): corundum cylinder; (4): sensitive element; (6): copper wire; (7): tin.

and high temperatures). Such a design has to provide the required thermal properties, high reliability and stability of device characteristics during repeated cooling and heating cycles (in particular, at fast thermal shocks).

The sensor package design is shown in Fig. 3. The leads to Ge and Si structures were formed using thermal compression or pulse welding of a thin (6 μm) gold strip (about 150–200 μm wide) or a gold wire (30 μm in diameter). The package involved a corundum cylinder and two copper discs covered with a thin Au layer. Similar thin Au layers were deposited also onto the corundum cylinder ends. The discs were sealed to the corundum cylinder using thermodiffusion welding of Au layers. A sensitive element was placed at one of the copper discs using thermodiffusion welding. Copper wires (50 micrometer in diameter) were tin-soldered to the copper discs; they served as outer terminals. Taking into account the outer terminals and tin solder thickness values, one can see that the thermometer overall size was Ø 1.2 mm × 1.0 mm. This nonmagnetic miniature package protects a sensitive element from harmful external actions.

3. Characteristics of Ge-film thermometers

3.1. Thermometric characteristics

The industrial batch of temperature sensors has been produced by means of microelectronic technology, and about 100 sensors have been investigated. The application of bath techniques of microelectronics to sensor manufacturing allows to produce a great number of sensors with the close thermometric characteristics.

Shown in Fig. 4 are the experimental typical thermometer resistance, R, and sensitivity, $|S| = |dR/dT|$, as functions of temperature in the 2–400 K temperature range. The thermometer resistance depends smoothly on temperature over a wide temperature range and temperature sensitivity of thermometer is high.

The investigation of volt–ampere characteristic of thermometer shows that at the temperature 4.2 K, when the thermometer is placed in the liquid helium, its volt–ampere characteristic is symmetrical and linear with an accuracy better than 0.1% up to the dc current of about 2 μA. At higher currents, the essential reduction of the resistance is observed due to self-heating of the thermometer.

Preliminary investigation of stability of sensors at 4.2 K has been performed. Stability data was obtained by subjecting sensor to 30 thermal cycles from 300 to 4.2 K. The time of cooling and heating of sensors was about 20 min. Resistance shifts were measured for each cycle at 4.2 K only. Sensors were placed in liquid helium. Deviations of sensor resistance under thermal cycles corresponded to temperature error not more than ±10 mK. Obtained data was close to accuracy of measuring equipment and cryostat system. Therefore, the stability of sensors may be much better.

3.2. Mechanisms of low-temperature conduction

Consider low-temperature conduction mechanisms in Ge films that are responsible for the thermal sensitivity. Generally, the temperature dependence of resistivity, ρ, in semiconductors may be expressed as $\rho = \rho_0 T^m \exp(T_x/T)^x$. For $x = 1$, this expression corresponds to the activation-type conduction, the constant activation energy being $E = kT_x$. The case $x < 1$ corresponds to the variable-range hopping. The x may take different values, depending on the density of states $g(\varepsilon)$ near the Fermi level. For instance, in the Mott model [7] $x = 0.25$, while in the Shklovskii model [8] $x = 0.5$. From analysis of the temperature dependence of hopping conductivity for compensated and amorphous semiconductors, one can conclude that x may vary from 0.2 to 0.8 for different semiconductors [9].

Shown in Fig. 5 is the dependence of the resistance as a function of the square root of reciprocal temperature. From analysis of the temperature dependence of resistance, we can

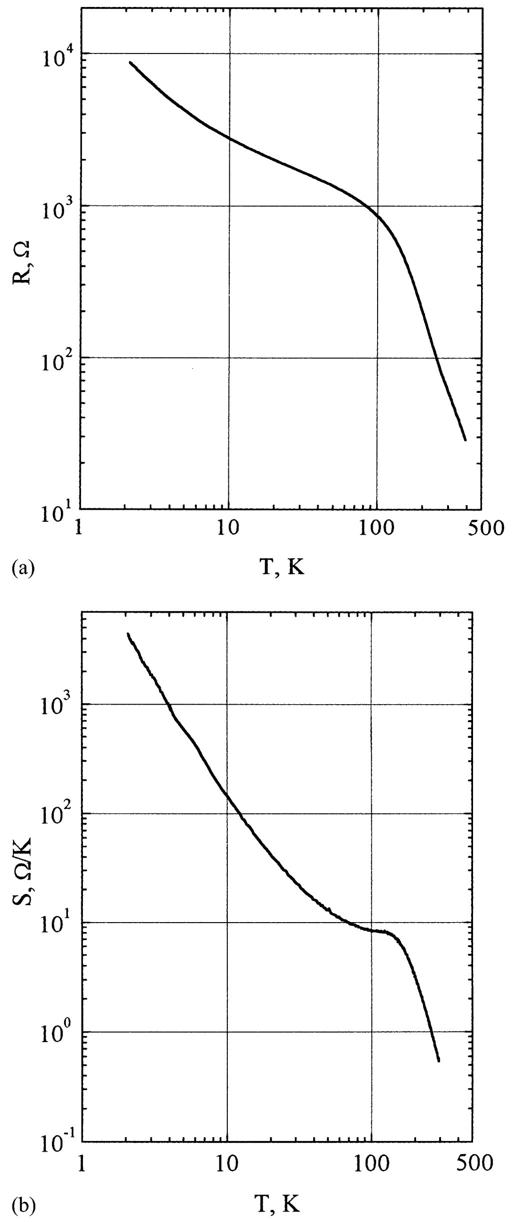

Fig. 4. Resistance R (a) and sensitivity S (b) vs. temperature curves for Ge-film thermometer.

conclude that the Ge-film conductivity does not obey an exponential law with constant activation energy at low temperatures. One can see that in the temperature range from 2 to 15 K, the dependence of conductivity on the temperature can be described by the variable-range hopping with $x = 0.5$ that corresponds the Shklovskii model [8]. This model assumes that a gap exists in density of states near the Fermi level.

3.3. *Effect of magnetic field on Ge-film thermometers*

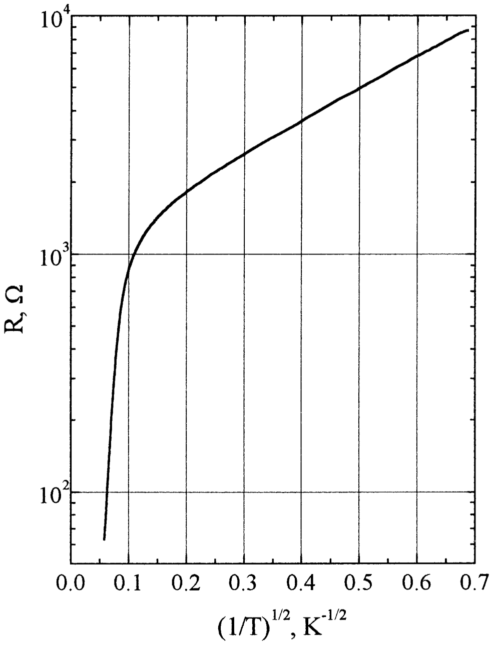

Fig. 5. Dependence of the resistance, R, as a function of the square root of reciprocal temperature.

In cryogenic engineering and low-temperature physics, there is a demand for measurements of temperature in high magnetic fields. Accurate temperature measurements in the presence of magnetic fields are a problem for cryogenic thermometry. Therefore, it is very important to develop special thermometers for operation in magnetic fields [10,11]. An inaccuracy in temperature measurements due to the presence of a magnetic field is an important characteristic of the cryogenic thermometers [10,11].

The behavior of the Ge-film microthermometers in high magnetic field has been studied. Any applied magnetic field changes the calibration of the sensor, which results in an error in the temperature measurement. Magnitude of these errors substantially depends on the properties of the material from which the thermosensitive element is made and on the transport mechanism responsible for the thermal sensitivity. Therefore, different temperature sensors exhibit different behaviors in magnetic field. The effect of magnetic field on some models of Ge-film thermometers has been described in [4,5].

In Fig. 6(a) is displayed the dependence of the sensor magneto-resistance on magnetic field at different temperatures for Ge-film thermometer of TTR-1G model. The orientation of magnetic field B is $\boldsymbol{j} \perp \boldsymbol{B} \| \boldsymbol{n}$, where $\boldsymbol{n}$ is the normal to the film surface and $\boldsymbol{B}$ and $\boldsymbol{j}$ the vectors of the magnetic induction and current, respectively. The magnetoresistance is positive and it increases when temperature decreases.

The error in the thermometer reading, induced by magnetic field, can be expressed by a ratio $\Delta T/T$, where $\Delta T = T(B) - T$, T is the temperature measured at magnetic field $B = 0$, and $T(B)$ the temperature measured by the

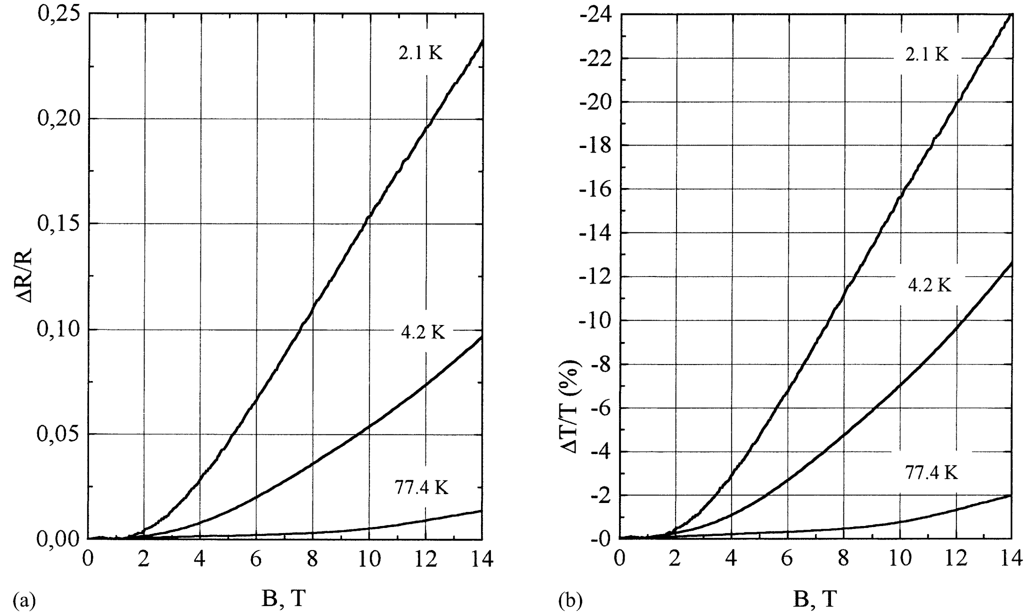

Fig. 6. Magneto-resistance $\Delta R/R$ (a) and temperature error $\Delta T/T$ (in %) (b) vs. magnetic field curves at different temperatures.

sensor at magnetic field B. The magnetic field-dependent temperature errors, $\Delta T/T$, for the Ge-film thermometer of TTR-1G model at various magnetic fields and temperatures are displayed in Fig. 6(b).

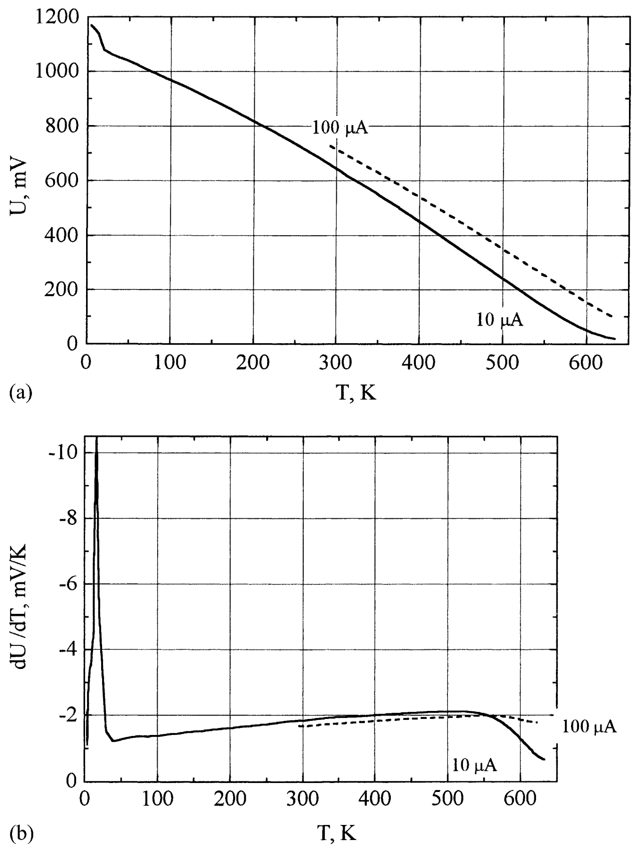

Fig. 7. Voltage U (a) and sensitivity dU/dT (b) vs. temperature curves at different currents.

4. Thermometric characteristics of Si-based diode temperature sensors

Shown in Fig. 7 are the experimental typical forward voltage, U, and sensitivity, S, versus temperature curves in the 2–600 K temperature range at different dc currents. One can see from Fig. 7 that such diode temperature sensors demonstrate high thermal sensitivity and relatively good linearity of their thermometric characteristics in the 30–600 K temperature range.

5. Conclusions

The temperature microsensors based on Ge films and Si diodes have been developed and manufactured. The nonmagnetic miniature package with size of 1.2 mm in diameter and 1.0 mm long has been designed. This micropackage protects the sensitive elements from harmful external actions and is intended for use in the temperature range from 1 to 600 K. The basic properties and thermometric characteristics of microsensors have been investigated. The Ge-film microthermometers can be used in the 1–400 K temperature range and Si-diode temperature microsensors are intended for use in the 2–600 K temperature range.

The effect of magnetic field on Ge-film microthermometers has been studied. The magneto-resistance of thermometers is positive over the whole range of temperatures and magnetic fields studied. The magnetic field effect is very sensitive to temperature, however the error in the thermometer reading, induced by magnetic field, is relatively small. It allows using them for temperature measurements in the presence of magnetic field.

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Biographies

N.S. Boltovets was born in 1945 in Ukraine. He graduated from Kiev Pedagogical Institute in 1965 and received his PhD degree in 1970. At present, he is a chief of the Department of Technology of Microwave Devices of the State Research Institute "Orion", Kiev. Presently, his main interests include the technology of microwave devices and sensors.

V.V. Kholevchuk was born in 1967 in Ukraine. He graduated from Ivano-Frankovsk University in 1991 and received his MSc degree in physics and mathematics. At present, he is a junior research fellow of the Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine, Kiev. His research and development interests are cryogenic thermometry and electrical properties of Ge films.

R.V. Konakova was born in 1941 in Russia. She graduated from Mordoviya University, Russia, in 1964 and received her MSc degree in electrical engineering. She received her PhD degree from the Research Institute of Physical Problems, Moscow, in 1970 and DSc degree from the Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine, Kiev, in 1987. Since 1992, she has been a professor at the Institute of Semiconductor Physics. Her scientific interests include the physics and technology of microwave devices.

V.F. Mitin was born in 1957 in Kiev, Ukraine. He graduated from Kiev Technical University "Politechnical Institute" in 1982 and received his MSc degree in electronics engineering. He received his PhD degree in semiconductor physics from the Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine in 1990. At present, he is a senior scientist of the Institute of Semiconductor Physics, Kiev. He is also a founder and director of the Research and Production Company MicroSensor Ltd. His scientific interests are in the field of semiconductor films technology, low-temperature physics, and sensors for measurement of temperature, magnetic field, strain, and pressure. In addition, his current interest is in development of temperature microsensors and multifunctional sensors for cryogenic application based on new semiconductor film materials and modern microelectronic and micromachining technologies.

E.F. Venger was born in 1947 in Ukraine. He graduated from Vinnitsa Pedagogical Institute in 1970. He received his PhD degree in semiconductor physics from the Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine in 1980 and his DSc degree in 1990. Since 1992, he has been a professor at this Institute and is also its deputy director.