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Ge-on-GaAs film resistance thermometers for cryogenic applications

V.F. Mitin [a,b], P.C. McDonald [c,*], F. Pavese [d], N.S. Boltovets [e], V.V. Kholevchuk [a,b], I.Yu. Nemish [a], V.V. Basanets [e], V.K. Dugaev [f], P.V. Sorokin [g], R.V. Konakova [a], E.F. Venger [a], E.V. Mitin [a,b]

[a] V. Lashkarev Institute of Semiconductor Physics, National Academy of Sciences, Kyiv, Ukraine
[b] Research and Production Company "MicroSensor", Kyiv, Ukraine
[c] Institute of Cryogenics, University of Southampton, Southampton, UK
[d] CNR – Istituto di Metrologia "G.Colonnetti", Torino, Italy
[e] State Research Institute "Orion", Kyiv, Ukraine
[f] Institute of Materials Science Problems, Ukrainian Academy of Sciences, Chernovtsy, Ukraine
[g] National Science Centre, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

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Abstract

Our paper discusses and reviews the properties of a range of semiconductor sensors, which have been developed for thermometry in cryogenic applications. The range of sensors developed includes a family of single and dual element resistance thermometers based on Ge-on-GaAs films. The thin film devices were produced using standard semiconductor processing techniques and provide high device sensitivity within the range 0.03–500 K. The construction and characteristics of the sensors are presented together with a discussion of their sensitivities to magnetic fields and ionising radiation.

Keywords: A. Semiconductors; A. Thin films; D. Cryoelectronics; D. Instrumentation; D. Magnetic measurements

1. Introduction

Many cryogenic applications require temperature measurement, with high accuracy in difficult environmental conditions; such as high magnetic fields and ionizing radiations and there are a number of devices for performing these measurements; each with their own limitations. Most adapted and commercially available devices for applications in high magnetic fields and under radiation are made of carbon, carbon–glass and carbon ceramic (1.4–325 K), fabricated from bulk materials, and films based on ruthenium oxide (0.05–40 K), and zirconium oxy-nitride (0.3–420 K). A review of the state of the art in cryogenic thermometry can be found, for example, in Ref. [1,2].

The objective of the work reported and reviewed here, has been the development of a number of new types of temperature sensor covering the temperature range 0.03–500 K, by the application of semiconductor-film and micromachining fabrication techniques to their "industrial" production. This work has been particularly concerned with the development of sensors capable of answering current problems in cryogenic thermometry, namely, the measurement of temperature in the presence of high magnetic fields, thermometer stability in the presence of ionizing radiation and the measurement of temperature with high spatial resolution and fast thermal response time.

Our paper contains two parts: (i) a short review of previous results on Ge–GaAs sensor designs (partly published in Refs. [3–7]), which formed the basis for the present developments, and (ii) original results, obtained under an

* Corresponding author. Tel.: +44 23 8059 3348; fax: +44 23 8059 3938. *E-mail address:* pcm@soton.ac.uk (P.C. McDonald).

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international collaborative research project funded by the European Union (INTAS 2001-04 Project), which was established for the development of new cryogenic temperature sensors. The first results for this EU project collaboration have previously been reported in conference proceedings [8–12].

In this paper, we discuss resistance thermometers based on films of Ge and dual element resistance thermometers (DERTs), in which two temperature sensitive elements with overlapping T/R characteristics, are combined to provide a thermometer with good sensitivity over the measurement range from 0.1 to 400 K.

The different constructions of the developed devices are briefly discussed, together with their sensing characteristics. This is followed by a discussion of continuing work being carried out on the magnetic field sensitivity and the radiation tolerance of the Ge-on-GaAs film resistance thermometers.

2. Ge-on-GaAs film resistance thermometers

2.1. Preparation principles, design of sensor elements and packages

The method of production of the Ge-film resistance thermometers was based on the deposition of a Ge film on to a semi-insulating GaAs substrate, by the evaporation of Ge in a vacuum. The basic principles of designing such sensors and the fabrication technology involved have been reported previously by Mitin et al. [4,13]. The salient features of Ge-on-GaAs films and their fabrication technology are the following.

The electrical properties of the Ge film in the Ge–GaAs "heterostructure" essentially depend on the film preparation conditions and are determined by two main factors. These are the diffusion into the Ge film, of the Ga and As atoms from the GaAs substrate, during film growth and the degree of physical imperfection of the film.

The concentration of structural defects in the Ge films is primarily determined by the temperature of the GaAs substrate during film deposition and depending on substrate temperature, one can obtain amorphous, poly- and single-crystal Ge films [4]. The interdiffusion processes of Ga and As in the Ge–GaAs heterostructure are more complicated and are dependent on a number of factors in the conditions of film preparation. Among these factors are the substrate temperature, deposition rate and the state of the GaAs surface before Ge deposition. The structure of the GaAs surface can be transformed by means of various chemical and physical treatments, including ion-beam milling. All these physico-chemical factors affect the diffusion processes at the film-substrate interface and determine the electrical properties of the Ge films.

Structure defects and Ga atoms act as acceptors in Ge films, but As atoms act as donors, so that the Ge on GaAs films are both doped and compensated. The electrical resistivity of the Ge film and its temperature dependence are determined by doping level and compensation degree so that by varying these i.e. by careful control of the conditions of film growth, it is possible to fabricate films with controlled resistance–temperature characteristics, which may be used as the sensing elements of thermometers having specific sensitivities in different regions of the cryogenic temperature range.

An additional feature of the Ge–GaAs heterostructures is that the components have well matched lattice constants resulting in thermal expansion coefficients that are close, so that no significant residual stresses are generated upon cooling to low temperature. This is an important factor for the production of thermometers operating over a wide temperature range, which must retain their calibration.

After the fabrication of Ge films with the required electrical properties, the following microelectronic procedures were used to produce sensing elements: (i) preparation of metal films for electrical contacts by magnetron sputtering and electrochemical deposition; (ii) photolithography to form the topology of the sensitive elements and metal contacts; (iii) micromachining to produce the resistive elements; typically 0.3 mm square by 0.15 mm thick. The prepared Ge–GaAs sensing elements were then employed in different packages as discussed below.

A micropackage for the sensor elements was developed Ref. [14] to provide a micro-thermometer with dimensions of 1.2 mm diameter by 1.0 mm thick as shown in Fig. 1a. The micro-packaged thermometer can also be bonded to a sapphire plate (2 mm square by 0.15 mm thick) for ease of mounting on a surface (Fig. 1b). These micro-thermometers enable temperature measurements to be made with high spatial resolution and their low mass; <5 mg, results in fast thermal response time, so that they are suitable for use in applications such as transient response thermometry and microcalorimetry.

The micro-thermometer may also be repackaged for general thermometry and we have produced Ge-film resistance thermometers in a cylindrical canister package, made from gold plated copper. The dimensions of this package are 3 mm in diameter by 5 mm long and four-terminal connection to the sensing element is made using copper or phosphor bronze contact leads.

2.2. Operating characteristics

As described above, by careful control of the conditions of the Ge film growth we have been able to produce a range of thermometer "models", having different sensitivity characteristics over the cryogenic temperature range and these we have identified and differentiated in the following discussions by the labels TTR-x. The first models of Ge-on-GaAs film temperature sensors have partly been reported together with their characteristics in Refs. [3,5–7]. These models were TTR-A and TTR-B; designed for operation in the 1.5–400 K range, TTR-2 for 77–400 K, and TTR-3 for 200–500 K [5,6].

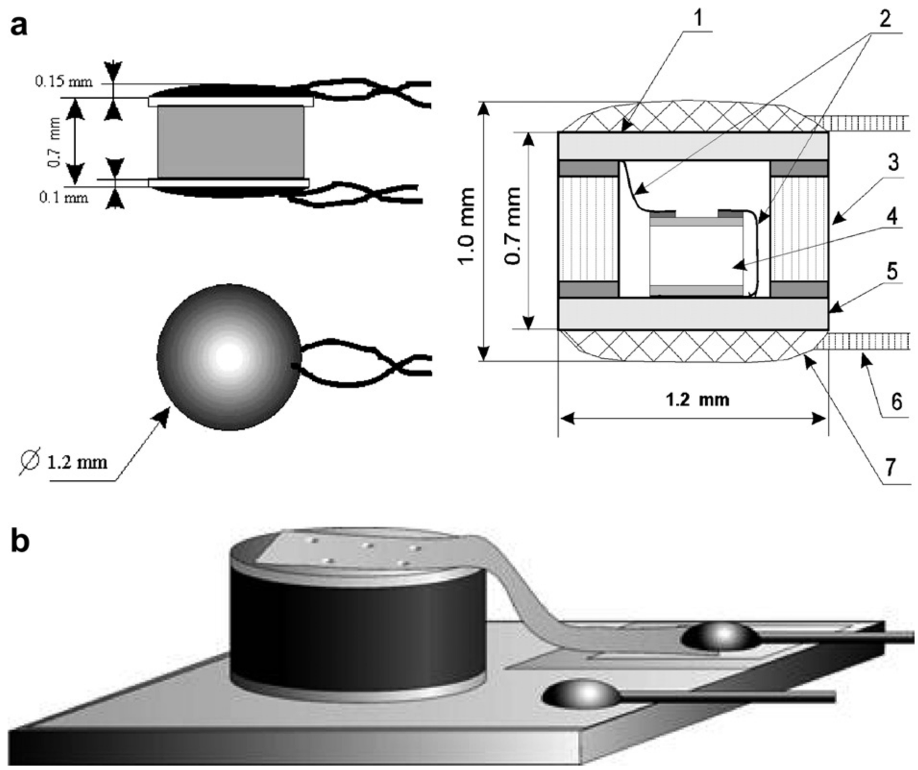

Fig. 1. Overall and detailed views of the micro-thermometer design: (a) the temperature sensitive element (4) is contained within an alumina tube (3) which has copper end caps (1, 5). The element is bonded to the lower end cap (5) and electrical contact made to both caps through 30–50 μm gold wires (2). Finally, copper wires (6) are soldered (7) to the end caps to facilitate four-terminal measurements; (b) the micro-packaged thermometer mounted on a sappire plate for improved thermal contact in measurement.

Below we present data on new models of the Ge-on-GaAs film thermometers labelled TTR-D (0.03–300 K), TTR-G (0.3–300 K), and TTR-M (4.2–400 K). Due to optimization of the sensor design and packaging technology these models show improved characteristics; in comparison with the TTR-A and TTR-B models, of short and long term stability, behaviour in magnetic fields and radiation tolerance.

The resistance vs temperature characteristics of the new Ge-on-GaAs devices, are discussed below, together with their sensitivity to magnetic fields and ionising radiation.

2.2.1. Temperature dependence of resistance

Figs. 2 and 3 show typical resistance–temperature characteristics and sensitivity, $S = dR/dT$, over the temperature range 0.03–500 K for different "models" of thermometer; i.e. for sensors incorporating Ge-on-GaAs film elements which have been produced under different specific conditions of film preparation. It may be seen from Figs. 2 and 3 that it is possible to produced thermometers with high sensitivity in different ranges of the overall range 0.03–500 K.

Fig. 4 illustrates the spread in characteristics obtained for two particular models: TTR-G and TTR-D. The variation in thermometric characteristics between different sensors in a batch, results from nonuniformity of the Ge films. However, from the large number of sensors produced using a single Ge–GaAs wafer, it is possible to select groups of sensors with matched thermometric characteristics, which may be used interchangeably and from a single Ge–GaAs wafer, up to ∼1500 temperature sensors can be produced, with characteristics that meet desired specifications.

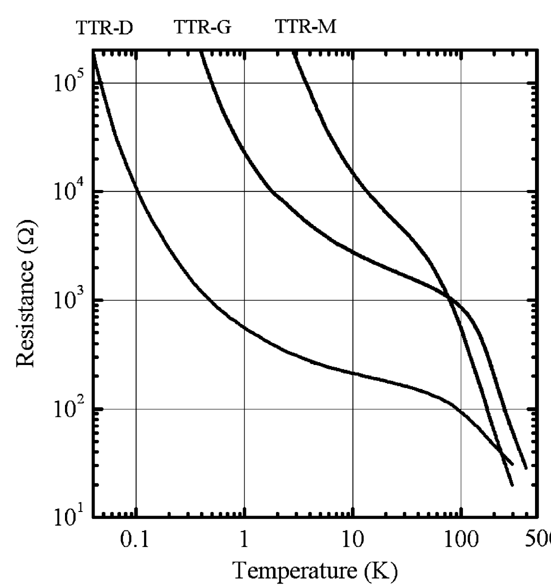

Fig. 2. Resistance versus temperature curves for different models of Ge-film thermometer.

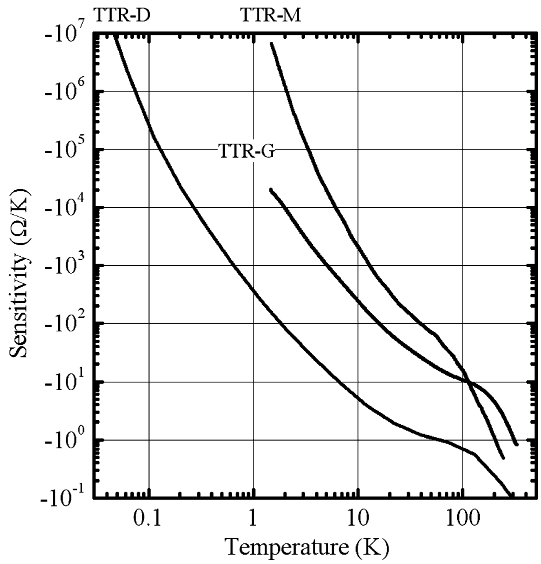

Fig. 3. Sensitivity versus temperature curves for different models of Ge-film thermometers.

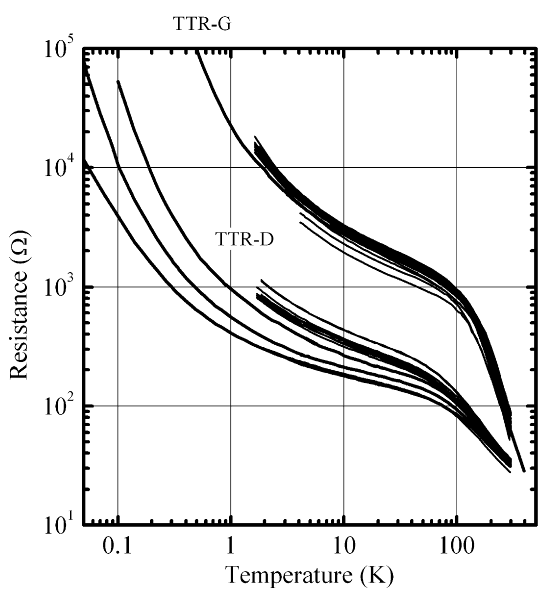

Fig. 4. Resistance versus temperature for single wafer batches of thermometers – models TTR-G and TTR-D.

Fig. 5 shows measurements made on the stability with time of TTR-G thermometers measured over a period of 2.6 years. Six TTR-G sensors have been recalibrated (2.0–300 K) over a period of 943 days. The sensors have also been subjected to mounting and demounting in a cryostat with rapid thermal cycling from 4.2 to 300 K between recalibrations. This plot is of 4.4 K data. The best sensor has $\Delta T = +33$ mK, and the worst sensor has $\Delta T = +70$ mK for the 2.6 years period. The calibration accuracy is estimated to be ±5 mK, but the overall precision of the measurements may also include non-reproducible variations associated with mounting the thermometers into the cryostat. These studies are continuing.

Generally the temperature dependence of conductance, σ, in semiconductors may be expressed as follows:

$$\sigma(T) = \sigma_0 \exp[(T_x/T)^x], \tag{1}$$

where T is temperature and σ_0 and T_x are material parameters. For $x = 1$ this expression corresponds to "activation"-type conduction, the constant activation energy being $E = kT_x$. The case $x < 1$ corresponds to variable-range hopping [15,16]. It has been shown experimentally that x may take different values, depending on the density of states $g(\varepsilon)$ near the Fermi level. From analysis of the experimental temperature dependence of "hopping" conductivity for various compensated and amorphous semiconductors one can conclude that x may vary from 0.2 to 0.8 (see for example [17]).

From analysis of the resistance dependencies for different types of Ge-on-GaAs film thermometers, we can conclude that the experimental temperature dependence of resistance fits well to the law (1) with x close to 0.5 for the TTR-D model in the 0.03–1 K, for the TTR-G model in the 0.3–10 K, and for the TTR-M model in the 4.2–20 K temperature ranges. The dependence (1) with $x = 0.5$ corresponds a form predicted by Efros and Shklovskii [16] and assumes that a gap exists in density of states near the Fermi level due to Coulomb interaction. In this case, the parameter $T_x = T_{1/2}$ can be related to the radius of electron localized states. These parameters in the dependence (1) are very sensitive to the doping (hole density), compensation level (ratio between acceptor and donor impurity density), and also magnetic field.

For practical thermometry, an approximation method for description of the thermometric characteristics (functions $R = R(T)$ and $T = T(R)$) of Ge-film thermometers using orthonormal polynomials, has been proposed by Bogdanova et al. in Ref. [18].

2.2.2. The effects of magnetic fields on Ge-film thermometers

All conducting materials are sensitive to magnetic fields and show magnetoresistance. In a resistive thermometer this causes an error in the sensor reading. The effect of magnetic field on the Ge–GaAs film thermometers varies between the different models and depends on the nature of the conduction mechanisms in the Ge films. These are affected by the degree of film structure imperfection, impurity composition, doping level and compensation degree and the magnetoresistance of the different models of Ge-film thermometer may be negative or positive and is dependent on temperature and magnetic fields. The behaviour of the first models; (TTR-A and TTR-B) is discussed in Refs. [3,5–7,19].

The error in a thermometer reading caused by a magnetic field can be represented as the ratio $\Delta T/T$, where $\Delta T = T(B) - T_0$, T_0 is the temperature measured at magnetic field $B = 0$, and $T(B)$ is the temperature indicated at magnetic field B. Table 1 shows magnetoresistance data as, the field induced, percentage temperature error $\Delta T/T_0$ for the new TTR-D, TTR-G, and TTR-M type

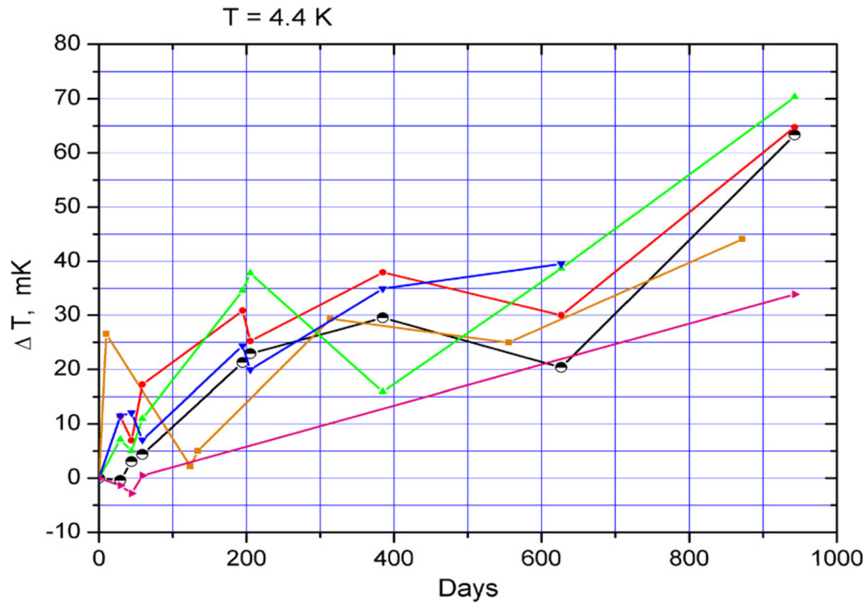

Fig. 5. Stability of TTR-G thermometers measured over a period of 2.6 years.

Table 1
Temperature errors, $\Delta T/T_0$, (%) as a function of magnetic field and temperature

Model	Temperature (K)	Magnetic field induction (T)				
		2.5	4	6	8	14
TTR-G	0.5	0.43	−1.74	−3.65	−6.2	–
	1.0	0.0	−0.3	−0.8	–	–
	2.1	−0.82	−2.8	−6.8	−11.1	−24.1
	4.2	−0.4	−1.0	−2.7	−4.7	−12.5
	77.4	−0.13	−0.21	−0.3	−0.45	−2.0
TTR-D	0.1	63.9	66.7	69.5	–	–
	0.3	0.5	−0.55	−1.0	–	–
	4.2	−5.0	−8.1	−12.0	–	–
TTR-M	4.2	0.5	0.37	−0.44	−2.0	–

thermometers. It may be seen that in the TTR-G types, the magneto-resistance is positive (apparent reduction in temperature) over the whole operating temperature range $T > 1$ K. The behaviour of the TTR-G in magnetic fields in comparison with the zirconium oxynitride (Cernox™) film thermometers can also be found in Ref. [20]. For the TTR-M models at $T < 5$ K the magneto-resistance is negative with maximum at 2–3 T. As the field increases the negative magnetoresistance reduces, becoming positive at fields around 5–6 T. For ultra-low-temperature thermometers of the type TTR-D, it has been shown [21,22] that the magnetoresistance is negative at temperatures below 0.5 K, and increases as the temperature decreases. The magnetic-field dependence for such magnetoresistance also shows interesting behaviour. The negative magnetoresistance increases between zero and 1.5 T and becomes constant for higher fields. At temperatures between 0.5 K and 4.2 K the magnetoresistance is positive and small.

The physics of the behaviours of Ge–GaAs film thermometers in magnetic fields may be explained using hopping theory of conductivity with localization corrections. It is well known [23] that the transport properties of heavily doped and strongly compensated semiconductors at low temperatures are mostly determined by localization effects. These effects are responsible for the temperature dependence of resistance and magnetoresistance in the close vicinity of metal–insulator (Anderson) transitions in semiconductors. To explain the experimentally observed magnetic field dependences, we have combined several theoretical models of the physical properties of disordered semiconductors at low temperatures. The main elements of our model include the variable-range hopping mechanism of conductivity at the insulator side of the metal–insulator transition, combined with a localization radius of carriers (electrons and holes in n and p-type, respectively) which strongly depends on the difference between the chemical potential and the mobility edge. We have also used weak localization theory to describe the location of the mobility edge and its dependence on the temperature, external magnetic field, spin–orbit interaction, and the density of magnetic impurities; which can be small and poorly controllable.

The results of our theoretical calculations are in good agreement with the experimental data obtained on the Ge-film thermometers and it has been possible to explain the features of the observed magnetoresistance, such as the "zero-magnetoresistance" effect [24] as well as indicating the possibility of a giant magnetoresistance effect [22]. We have found that in addition to the expected influence of doping and compensation, the weak spin–orbit interaction can be of principal importance, strongly affecting the magnitude of the magnetoresistance effect and leading to the change of sign from negative to positive magnetoresistance.

2.2.3. The effects of irradiation on Ge-film thermometers

For high-energy physics and space applications, the effects of irradiation on different types of Ge-on-GaAs film thermometers have been investigated under various conditions (neutrons, gamma-rays, electrons and bremsstrahlung photons) at different experimental facilities.

The results on behaviour of the first models of TTR-A and TTR-B thermometers under fast neutrons plus accompanying gamma irradiations can be found in Refs. [19,25]. We will briefly summarize these results in order to have a basis for consideration of the future developments.

Radiation at room temperatures [19]: The TTR-B thermometerswere irradiated at 290 K and measured at four temperatures: 1.87 K, 4.24 K, 77.4 K, and 287.5 K. No changes were observed in characteristics up to neutron and gamma doses of 1.5×10^{13} n/cm^2 and 0.22 kGy, correspondingly. After a dose of 2×10^{14} n/cm^2 plus 3 kGy, the temperature measurement error, ΔT, for these thermometers was -10 mK at 1.87 K and 4.24 K, -20 mK at 77.4 K, and -530 mK at 287.5 K.

Radiation in liquid nitrogen [19,25]: Irradiation of the TTR-A thermometers was performed in liquid nitrogen. This model of Ge-film thermometer showed errors in temperature readings at 77.4 K of less than 100 mK up to the dose of 1.5×10^{15} n/cm^2 plus 33 kGy. In TTR-B sensors the temperature shift ΔT reached the value of 1.1 K at 2.4×10^{14} n/cm^2. After warming up to 290 K and cooling down to 77.4 K, additional shifts were revealed.

We believe that the observed behaviour under radiation was not a property of the sensor material but was due to details in the construction of the sensor packages of these early models, which resulted in low resistance to the thermal cycling. The TTR-D thermometers, intended for ultralow temperature operation, were also irradiated in liquid nitrogen [25]. They showed errors of less than 100 mK up to doses 10^{14} n/cm^2 plus 10 kGy. Further irradiation up to doses of 4×10^{14} n/cm^2 led to an error of about 4 K. However, when the sensors were warmed up to 290 K, they fully recovered their characteristics.

Radiation in superfluid helium [25]: The TTR-B sensors were also investigated under neutron radiation at 1.8 K. The temperature shift observed was $\sim$0.3 K at a total dose of 4×10^{14} n/cm^2. After warming up to 300 K annealing was very effective and the sensors recovered their characteristics to within 98%.

The above results summarize the behaviour of these early sensor models under neutron irradiation (more information can be found in Refs. [19,25,26]). The subject of more recent work has been the development of Ge-on-GaAs film resistance thermometers having improved radiation tolerance and reliability when operating for extended periods under ionizing radiation and at elevated temperatures.

It is well known that the radiation tolerance of semiconductor-film devices strongly depends on their design and the material properties, and especially on the radiation resistances of the electrical contacts made to the semiconductor element. The preparation of reliable ohmic metal contacts to semiconductors, working at high temperature or in radiation, presents a difficult materials problem. During the course of operation in a high radiation environment, the main mechanism of contact degradation is due to the mass transfer of the metal layer into the semiconductor element structure. The process of the contact degradation may change the resistance and thermosensitivity of sensors. Usually, structure defects, which are also generated by radiation in the heavily doped Ge films, have less affect on the thermal sensor properties and can strongly affect sensor properties only after very high dose. We have therefore sought to improve the radiation-resistance of sensors by optimization of the sensor design and improvement of the radiation tolerance of the electrical contacts to the Ge film sensitive element. This has been achieved by the development of multilayer metal contact structure, with a buffer layer preventing mass transfer in the Ge-film.

Below we present some results on irradiation of new TTR-G sensors (intended for operation in the 1–400 K range) using gamma-rays up to integral doses of 7.6 MGy, bremsstrahlung photons up to integral doses of 1 MGy and electrons up to integral doses of 38 MGy.

2.2.3.1. ^{60}Co gamma rays source. Gamma irradiation of the TTR-G sensors was carried out using a ^{60}Co ($E =$ 1.25 MeV) source (at the Institute of Physics of the National Academy of Sciences, Kiev) with the dose rate of 2.52 kGy/h up to very high integral doses of 7.6 MGy. The temperature in the irradiation zone was approximately 300–315 K. Nine gamma-ray expositions and sensor measurements were performed during five months period of experiment. Eight sensors were exposed to gamma radiation for statistics. After each gamma-ray exposition measurements of the sensor resistance were made at 4.22 K and 77.4 K using storage dewars of liquid helium and liquid nitrogen, respectively. One sensor was not irradiated, but cooled down with the other samples as a control. The sensors were subjected to the procedure of mounting and demounting in and from the cryostat to perform the irradiation and measurements of over ten cycles. The overall uncertainty of these measurements, including the deviation of liquid helium and nitrogen temperatures during five months period of experiment, combined with the uncertainty of the reference thermometer and the data acquisition system, was estimated to be $\sim\pm 10$ mK at liquid helium and $\sim\pm 25$ mK at liquid nitrogen temperatures. The results obtained are presented in Figs. 6 and 7 and show the temperature shifts, ΔT, due to gamma irradiation as a function of the gamma-ray dose measured at 4.22 K and 77.4 K, respectively.

At 4.22 K practically all sensors had fluctuations in sensor resistance approximately equivalent to a temperature shift, ΔT, within ± 10 mK around zero up to the dose about 1.5 MGy. After gamma-ray dose of 1.5 MGy, one can see that the sensor resistance increased substantially

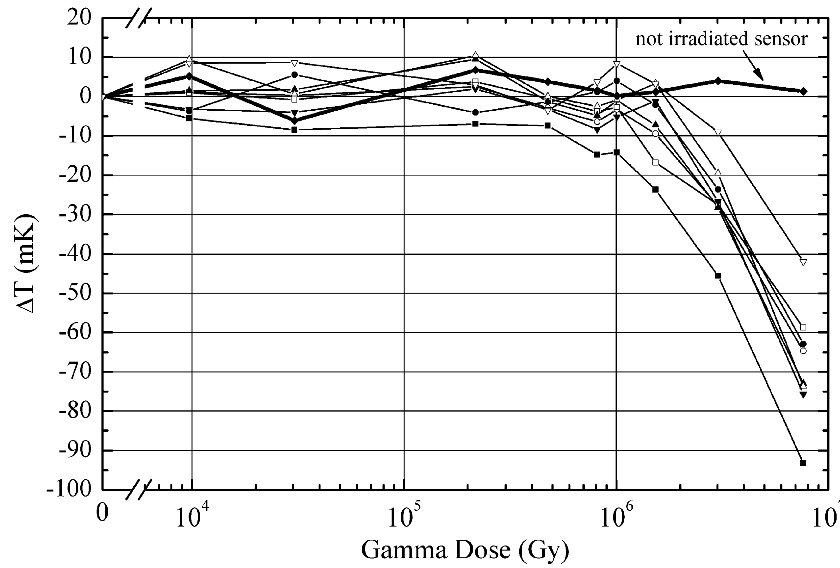

Fig. 6. The temperature shifts, ΔT, due to gamma irradiation as a function of the gamma-ray dose measured at 4.22 K.

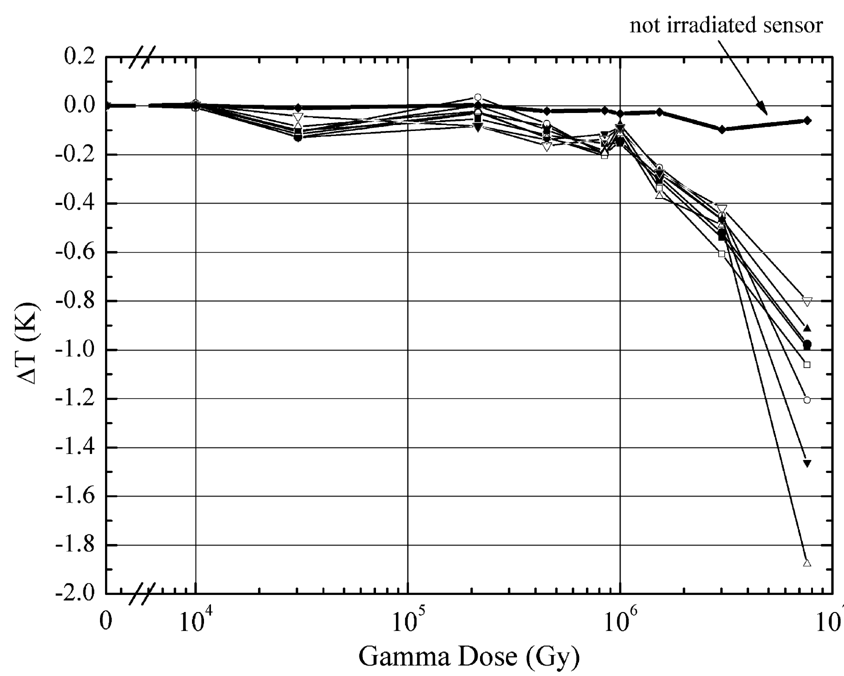

Fig. 7. The temperature shifts, ΔT, due to gamma irradiation as a function of the gamma-ray dose measured at 77.4 K.

and the equivalent temperature shifts ΔT, vary over the range 42–93 mK (for different sensors) at the dose of 7.6 MGy.

At 77.4 K the temperature shifts, ΔT, are less than -0.2 K up to the dose of $\sim$1 MGy and then increase substantially to over the range 0.8–1.9 K (for different sensors) at the dose of 7.6 MGy.

2.2.3.2. Van-de Graf electron accelerator. Gamma irradiation: The TTR-G sensors were also irradiated by bremsstrahlung photons from a Van-de Graff 3 MeV electron accelerator at the National Science Centre, Kharkov Institute of Physics and Technology, Kharkov, Ukraine. In these experiments the dose rates of irradiation depended on the distance between the electron–photon converter and the irradiated sensors and could reach 1 MGy/h, with uniformity less then 10%, in an area of (1.2×1.2) cm^2 at 5 mm from the gamma converter. Our experiments were performed at a dose rate of 0.133 MGy/h (40 mm from the electron-to-photon converter) up to doses of 1 MGy. The total dose of 1 MGy was accumulated in portions of 0.1 MGy with intervals of 1.5 h.

Measurements of sensor resistance were made during the irradiation at a temperature of approximately 294 K, after irradiation at 77.4 K in liquid nitrogen, and then again at 290.3 K. Irradiation resulted in direct heating of the sensors with an increase of temperature of 3–4°. At 290.3 K, up to doses of 1 MGy, the sensors had fluctuations in their resistances with average values less than ±0.5%, which corresponds to equivalent temperature fluctuations of less then ±0.5 K and this was close to the temperature stability during the measurements, so that one can say that these variations of resistance were related to fluctuations of temperature rather than the result of irradiation damage. At 77.3 K the resistance of the sensors increased steadily with $\Delta R = 5\Omega$ at integral dose of 1 MGy. This corresponds to equivalent temperature shifts of $\Delta T = -0.38$ K. A comparison of these results to those obtained using the ^{60}Co source ($\Delta T = -0.1$ to -0.2 K at 1 MGy, Fig. 5), which produces 52 times lower dose rates than the Van-de Graff electron accelerator, would indicate some dependence on dose rate as well integral dose.

Electron irradiation: The radiation-resistance of the TTR-G model was investigated under irradiation by electrons at a dose rate of 36 MGy/h up to integral doses of 38 MGy. The electron beam was produced by a Van de Graf accelerator with energy of 3 MeV and a current of 5.1 $\mu A/cm^2$. The irradiation of the sensors was carried out in a two-contour cryostat of liquid nitrogen. An area of (10×10) mm^2, where the sensor was placed, was created by scanning the electronic beam with a diameter of about 5 mm.

The irradiation dose of the samples was calculated by the Monte Carlo method taking into account the material and thickness of the entrance windows, the wall of the liquid nitrogen cryostat and the size of the sensor materials. The dose rate at the conditions mentioned above was 36 MGy/h (within 10%).

The accuracy of the sensor resistance measurements in liquid nitrogen was estimated to be 0.01%. The sensors were fixed on a bar which held the sensors in the zone of the irradiation and (upon obtaining the set dose) enabled them to be quickly moved into the zone of measurement.

In the irradiation zone the temperature was maintained with an accuracy of 1 K which resulted in a significant spread in the results of the measurements. In the measurement zone a temperature of 91.9 K was stabilized with an accuracy of ±0.1 K which resulted in one order less variability of the data. In view of this circumstance the procedure of measurements of sensor resistance has been chosen as follows. The sensors were located in the zone of irradiation, the resistance was measured before irradiation and then every 10 s. during the course of irradiation. After the set dose was collected, the accelerator was switched off, the sensors were transferred to the measurement zone and in 25 min after the termination of irradiation the resistance of the sensors was measured. There were six stages of the consecutive sets of the dose up to 1 MGy, 1.75 MGy, 4.15 MGy, 9 MGy, 18 MGy, and 38 MGy. Thus the dose rate of 36 MGy/h was maintained constantly with an accuracy of 2–3%.

Obtained results have shown that the sensors are not sensitive with accuracy of $\Delta T = \pm 100$ mK to irradiation up to integral dose of approximately 10 MGy. At doses of more than 10 MGy, a growth in resistance was observed to be linearly dependent on the dose. At integral dose of 38 MGy the resistance of the sensor grew by 1.75% that corresponds to the temperature shift $\Delta T = -1.4$ K. After annealing at room temperature the sensor resistances returned to the values observed before irradiation.

It should also be stressed that for the described here models of Ge-on-GaAs film thermometers no further studies were performed on the effect of neutron irradiation.

3. Dual element thermometers

Dual element thermometers (DERTs) have been designed and produced. The main aims of the development of a DERT have been to provide temperature measurements over a wide range, from ultralow to high temperatures, with high sensitivity and resolution over the whole range. This is achieved by using two Ge-film resistor elements which have high sensitivity over complementary ranges within the extended temperature range. The elements are incorporated in a single parallelepiped package, made from gold plated copper. The construction of the DERT is shown in Fig. 8. The dimensions of the package are 3.5 mm wide, 2.2 mm high, and 10.1 mm long. The dual element thermometer has eight copper contact leads: four leads for each element. For the temperature sensing elements of the DERT we have used TTR-D and TTR-M type elements (Fig. 2). By using one element, for example, in the 0.1–4 K range (TTR-D model) and the another for the 4–400 K range (TTR-M model) it is possible to obtain high sensitivity and resolution at both ultra-low and high temperatures.

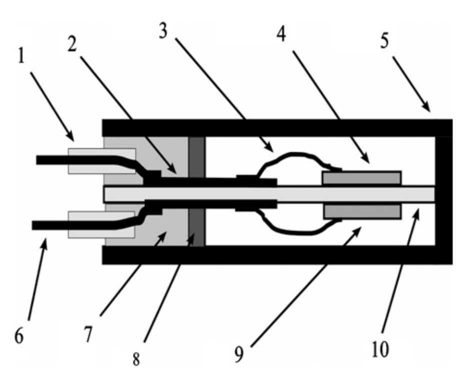

Fig. 8. Schematic drawing of DERT package: 1 – protective polymer tube, serving as mark to distinguish between leads; 2 – current tracks; 3 – gold leads to chip; 4 and 9 - sensitive elements (resistance thermometers); 5 – gold plated copper package; 6 – leads; 7 – epoxy sealing; 8 – protective wall; 10 – dielectric plate.

4. Conclusion

New Ge-on-GaAs film resistance thermometers developed on the basis of thin film semiconductor fabrication techniques have been designed, produced and characterised. They cover the temperature range for operation from 0.03 to 400 K. Magnetic field effect studies show the possibility of their use in high field environments. Gamma-ray radiation resistance studies show high radiation tolerance up to integral doses of 1 MGy. It should also be stressed that the radiation resistance result applies to gamma and electron fluxes only, no studies were performed on the effect of neutron irradiation for the described here models of Ge-on-GaAs film thermometers.

Dual element resistance thermometers (DERT) have been designed. These enable measurement of temperature over a wide range, with high sensitivity and resolution over the whole range. This is achieved by incorporating two Ge-on-GaAs film sensor elements in a single package. The two sensor elements have high sensitivities but over different; overlapping, temperature ranges, so that by selection of the appropriate element the DERT thermometer provides high sensitivity from ultralow to high temperatures. By using this dual element thermometer one can increase the resolution and accuracy of temperature measurements over a wide range from ultralow to high temperatures.

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