New Generation of Resistance Thermometers Based on Ge Films on GaAs Substrates*

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Abstract. Recent results in the development of resistance thermometers based on germanium films on gallium arsenide are summarized. Preliminary results in the development of a new generation of radiation-resistant thermometers and multifunction sensors intended for use in the range 0.03 to 500 K in the presence of high magnetic fields are discussed. These sensors have been produced in an international collaboration recently funded through the EU INTAS program.

INTRODUCTION

Resistance thermometers are widely used for measurements at low temperatures; however such measurements are commonly made against a background in which temperature is not the only physical variable. Thus there are several problems in cryogenic thermometry.

Firstly, there is a problem of measurement in high magnetic fields. The sensitivity of a resistance thermometer to magnetic fields depends not only on the materials of construction of the sensor but also its design and manufacturing technology. Thermometers capable of accurate measurement in high magnetic fields would have important applications, including for example, use in the diagnostics of superconducting magnet systems, and there is a continuing effort to produce resistance thermometers with low magnetic field sensitivity [1-5].

The radiation tolerance of sensors is an important factor when sensors operate in atomic and nuclear power plants, as well as in accelerators (such as CERN's), which produce high-energy particles, and in space vehicles. In these applications the sensors are exposed to intense ionizing radiation (neutrons and gamma-rays) and for these applications it is necessary to study the radiation tolerance of both the sensor materials and design.

In addition, there is a need in experimental physics to make measurements of temperature with high spatial resolution. This requires the development of specific microsensors having very small dimensions and fast thermal response times.

Moreover, often in cryogenic engineering and experimental physics there is a requirement to provide simultaneously measurements of temperature, magnetic field and strain, for example, when testing large superconducting magnet systems for magnetic resonance imaging or high energy physics applications. Thus, there is a need for multifunctional sensors for the concurrent measurement of a number of parameters.

To measure cryogenic temperatures, one may use sensors based on various physical effects and fabricated from different materials. Resistive and diode sensors are most often used. A review of the state of

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the art in cryogenic thermometry can be found in [6, 7].

At present, commercially available cryogenic resistance thermometers are made of germanium (for use from 0.05 K to 100 K), carbon-glass (from 1.4 K to 325 K), metal-oxide (from 0.05 K to 420 K), rhodium-iron (from 1.4 K to 325 K) and platinum (from 14 K to 800 K) fabricated both as bulk materials, as well as films.

Resistance thermometers for measurement of temperatures over the range 0.03 K to 500 K are also fabricated using germanium films on gallium arsenide substrates [8-11].

This paper summarizes the latest achievements in the development and fabrication of resistance thermometers based on a Ge/GaAs hetero-structure and presents novel sensors that are being developed in the framework of an international collaboration recently funded by the European Union (EU) through its INTAS program.

RESISTANCE THERMOMETERS BASED ON GERMANIUM FILMS

Development of resistance thermometers based on Ge films on GaAs began more than ten years ago.

In the first stage of development, basic efforts were directed to study the process of the Ge/GaAs hetero-system formation, electrical properties, and low-temperature transport mechanisms in Ge films. Based on these studies the general principles for fabrication of low temperature sensors on the basis of Ge films on GaAs have been developed. The principles of designing such sensors and the fabrication technology have been previously reported [12, 13].

One main advantage of this fabrication technology is the ability to adapt thermometer operation for different temperature and magnetic field ranges, tailored to meet specific user demands. This is achieved by careful control of the technical conditions of Ge film preparation and by employing modern microelectronic and micro-machining technologies. During a second stage of development, a range of thermometer types have been designed and constructed [9-11].

In the third stage; under the INTAS project, the following tasks will be carried out: (i) optimization of fabrication technology; (ii) design and development of a new type of sensors and multisensors (especially for the 1 K to 400 K temperature range and use in magnetic fields); and (iii) setting-up of large-scale production.

Design of the Thermometers

The thermometers are based on Ge-film resistors deposited on semi-insulating GaAs substrates using vacuum technology [12, 13].

The sensitive thermometric chips (0.3×0.3×0.2) mm were fabricated using microtechniques and mounted in non-magnetic micropackages [11]. The present sensor design is shown in Fig. 1. The thermometer, including its micropackage, measures 1.2 mm in diameter by 1.0 mm long. These micro-thermometers can be used when there is a need to make measurement of temperature with high spatial resolution and a fast thermal response time. They may also be incorporated in other packages, when high spatial resolution or fast response times are not required. Figure 2 shows a package that was designed for high accuracy four-terminal measurements.

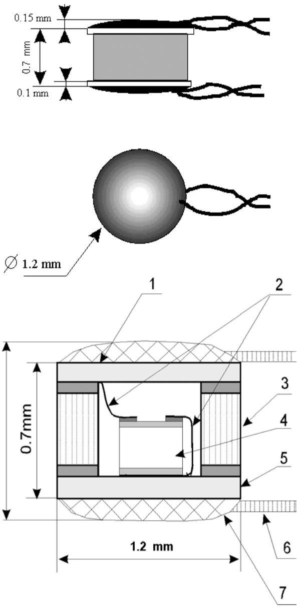

FIGURE 1. Overall and detailed views of the current microthermometer design. The temperature sensitive element (4) is contained within an alumina tube (3) which has copper end caps (1, 5). The element is bonded to the lower end cap (5) and electrical contact made to both caps through 30 µm gold wires (2). Finally, copper wires (6) are soldered (7) to the end caps to facilitate four- terminal measurement.

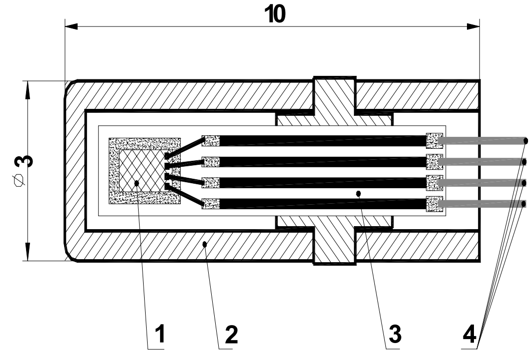

FIGURE 2. New four-wire design of the thermometers (dimensions in millimeters): (1) Ge/GaAs sensitive element; (2) copper can; (3) plate; (4) copper or phosphor bronze wires.

Thermometric Characteristics

Figures 3 and 4 show typical curves of the temperature dependence of resistance and sensitivity, for different types of thermometer constructed using Ge films on GaAs.

Figure 5 presents temperature dependencies of resistance for a batch of sensors produced from the same Ge/GaAs structure. The variation in thermometric characteristics for different sensors in a batch is related to nonuniformity of the Ge films. Nonuniformity of the electrical properties of films is due to many technical factors. From a great 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. Usually, from a single Ge/GaAs wafer (30 to 35 mm in diameter), up to 1500 temperature sensors can be produced with characteristics that meet a desired specification.

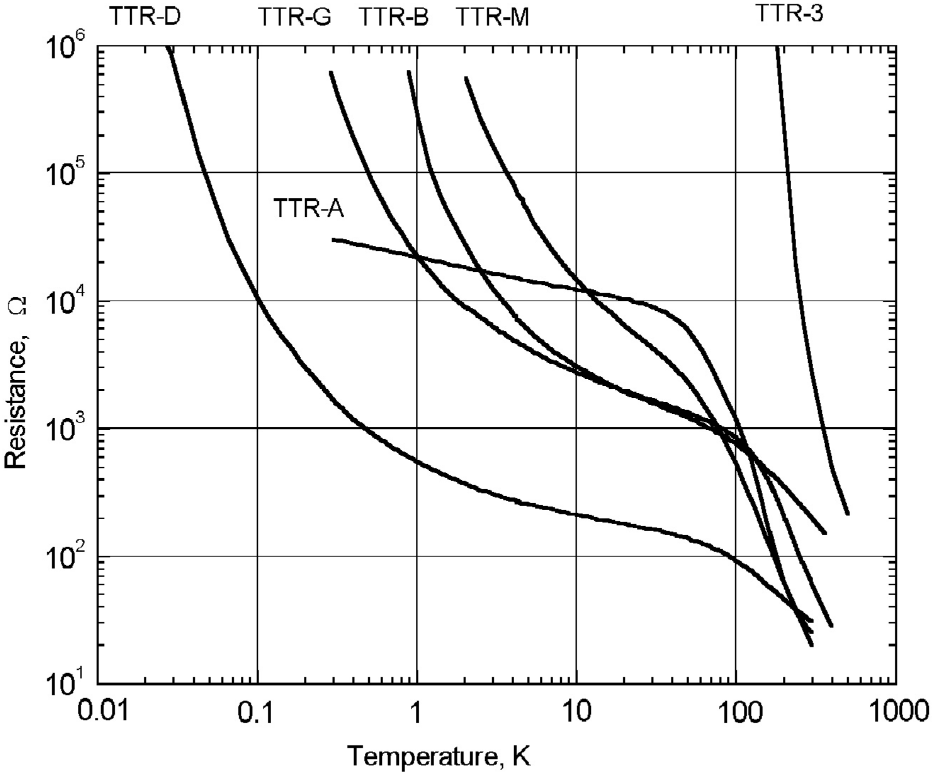

FIGURE 3. Resistance vs. temperature characteristics for several Ge-film thermometer models.

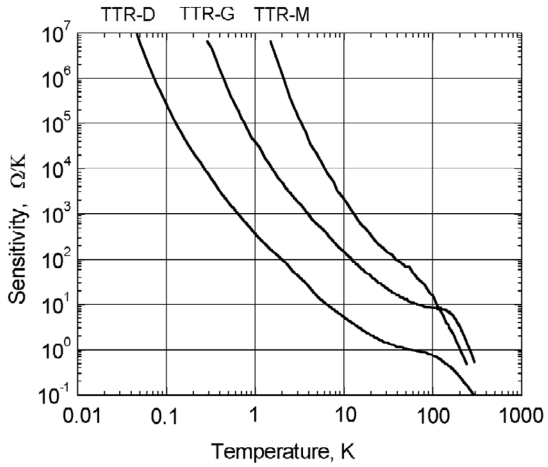

FIGURE 4. Sensitivity vs. temperature for two Ge-film thermometer models.

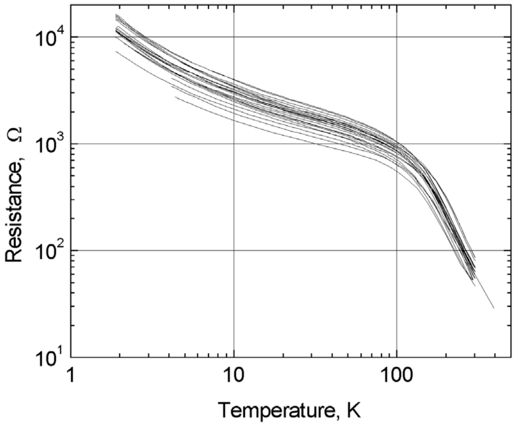

FIGURE 5. Uniformity of the resistance vs. temperature characteristics of elements from a single wafer of thermometer model TTR-G.

Behavior of Thermometers in Magnetic Fields

Discussion of the behavior in magnetic fields of the Ge-film thermometers can be found in [8-11].

The effect of magnetic fields on the thermometric characteristics of Ge-film sensors depends on the technical conditions of the film preparation. By careful control of the fabrication procedures, it is possible to make a Ge film with low magneto-resistance.

The error in the thermometer reading due the presence of a static magnetic field can be given as the ratio $\Delta T/T_0$, where $\Delta T = T(B) - T_0$, T_0 is the temperature measured at magnetic induction $B = 0$, and $T(B)$ is the temperature measured at the magnetic induction B. The magnetic-field-dependent relative temperature errors, $\Delta T/T_0$, for the present Ge-film thermometer types at various magnetic fields and temperatures, are shown in Table 1. Work is continuing in this area.

Effect of Gamma Irradiation

For high energy physics and space applications the effect of irradiation (gamma-ray and neutron) on the TTR-A, TTR-B and TTR-D models of Ge-film thermometers has been investigated and discussed in [9, 10, 14].

The radiation tolerance of thermometers depends on their design and the properties of the sensor materials. Work has already been carried out to improve the radiation-resistance of sensors by optimization of the sensor design. Preliminary investigations of the effect of gamma irradiation on TTR-G model thermometers were carried out at room temperature using ^{60}Co (E = 1.25 MeV) as the source of gamma rays. The temperature in the irradiation zone was about 300 to 315 K. Figure 6 shows the sensor resistance as a function of the gamma-ray dose measured at 4.22 K and 77.4 K respectively.

Ge-film microsensors #1 to #8 were exposed to gamma radiation. Sensor #9 was not irradiated, but cooled down with the other samples as a control. At T = 4.22 K (77.4 K) a change of sensor resistance of 1.0 Ω corresponds to a change in temperature of about 1.0 mK (100 mK). The main results of irradiation are: (i) the gamma irradiation has very little effect on sensor characteristics up to a dose of 1.5×10^8 rad; (ii) the sensor resistance increases after a dose of 1.5×10^8 rad; and (iii) at the very large dose of 7.6×10^8 rad, the error in the thermometer reading is ~2 %, i.e., 80 to 100 mK at 4.22 K and 1.5 to 2.0 K at 77.4 K. Extension of this work is planned within the frame of the INTAS project.

TABLE 1. Temperature Errors, $\Delta T/T_0$, (in percents) as a Function of Magnetic Field and Temperature

Model	Temperature (K)	Magnetic field induction (T)				
		2.5	4	6	8	14
TTR-A	1.7	−18.3	−28.7	−41.9	−55.15	-
	4.2	−9.39	−14.8	−22.8	−30.9	−54.77
	77.4	−0.13	−0.28	−0.54	−0.85	−1.97
TTR-B	1.7	1.04	−0.21	−2.43	−4.62	-
	4.2	0.45	0.25	−1.04	−2.61	−10.67
	77.4	−0.11	−0.23	−0.48	−0.81	−2.25
TTR-G	0.5	0.43	−1.74	−3.65	−6.2	-
	1.0	0.0	−0.3	−0.8	−15.0	-
	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	-	-

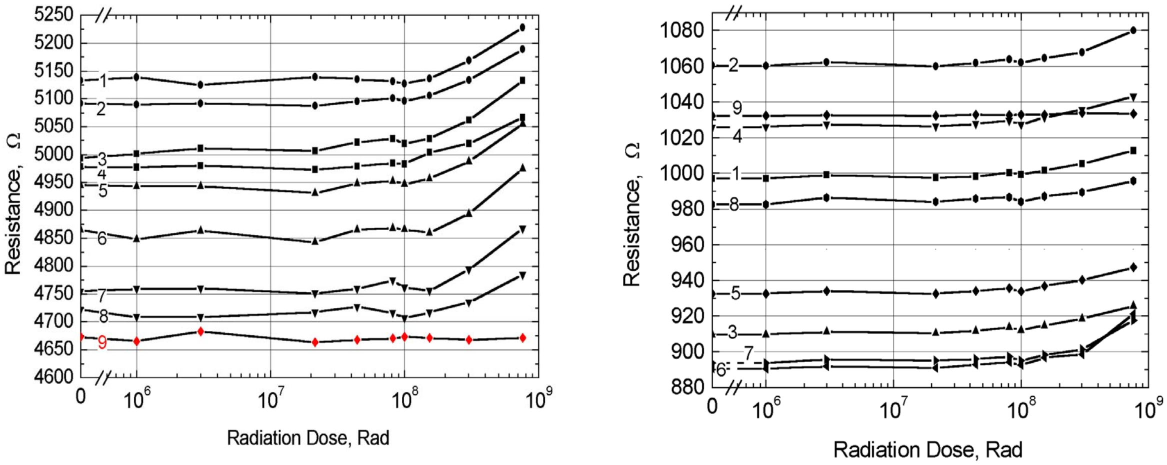

FIGURE 6. Sensor resistance vs. gamma radiation dose for model TTR-G at 4.22 K (left graph) and at 77.4 K (right graph).

MODELING

A theoretical approach has been developed [12, 15] and is being improved, to enable modeling of the main characteristics of the Ge-film thermometers, such as the temperature dependence of resistance and the sensitivity to temperature and magnetic fields. The basis of this approach is related to the variable-range hopping mechanism of conductivity below the mobility edge in the presence of strong Coulomb interactions (Efros-Shklovskii mechanism) and also to a negative magneto-resistance due to suppression of the quantum interference of hopping trajectories in a magnetic field. For the calculation of magneto-resistance a scaling theory of localization is used, which has proved to be valid in the close vicinity of the mobility edge. The main reason of this choice is that one must model conductivity and magneto-conductivity in a heavily doped and strongly compensated semiconductor. For the calculation of the mobility edge position, weak localization theory is used, which allows us to take into account rigorously the band parameters of the Ge semiconductor and the spin-orbit interaction. The spin-orbit interaction is related to the impurity scattering with relativistic corrections and to the spin-orbit coupling in the Hamiltonian of the valence band of Ge. The variation of the mobility edge with magnetic field is considered in a scaling form. This does not allow one to perform the modeling using only the known and wellestablished material parameters, because there are several constants which are not exactly determined by the existing theories. The modeling shows that the magneto-resistance of the thermometers can be significantly decreased for magnetic fields below 6 T.

CONCLUSIONS

Ge films on GaAs substrates can provide sensitive base elements for the fabrication of high-performance temperature sensors that cover the temperature range from 0.03 K to 500 K. Based on these elements several different types of resistance thermometer have been developed, produced and investigated in magnetic fields and under gamma irradiation. This work will continue in the frame of a new European Commission Project.

The sensors based on Ge-GaAs and their manufacturing technology have great potential. This technology is compatible with the integrated technology of semiconductor device fabrication. Employment of the batch approach commonly used in microelectronics to fabricate sensors makes it possible to produce them with close characteristics, to reduce their dimensions and cost, and to expand the application range. The modern micromachining technology, developed for Ge and GaAs materials, allows fabrication of microthermometers for various purposes, in particular for microcalorimetry.

The Ge-GaAs thermometers can be competitors to zirconium oxy-nitride (CernoxTM) and RuO ones. The main advantages of the Ge-GaAs thermometers may be: (i) a wide temperature range of operation; (ii) high thermosensitivity not only at low temperatures, but at high temperatures (above 10 K) also; (iii) small effect of magnetic fields; and (iv) high radiation-resistance. Several models of the Ge-GaAs thermometers are now commercially available [16].

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