New temperature and magnetic field sensors for cryogenic applications developed under a European Project*

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Progress is reviewed, in the development of various semiconductor sensors for measurement of temperature and magnetic field that are intended for use in cryogenic engineering and low-temperature physics, which have been developed in an international collaboration supported by the European Union. A range of resistance thermometers based on both bulk and film of Ge and SiC has been developed, to provide high sensitivity over complementary temperature ranges, within the overall range 0,03 to 500 K. New types of Si and GaAs diode temperature sensor have also been produced. A novel multisensor for concurrent measurements of temperature and magnetic fields has been designed, which consists of a Ge-film resistance thermometer and a InSb-film Hall generator.

INTRODUCTION

In July 2001 an EU project (European Commission INTAS Contract n° 2000-0476) was established to develop, characterize and establish production of, novel temperature and multifunctional sensors, for use in various cryogenic applications. This project connects seven groups of researchers from West- and East-European research centers, universities, institutes and industrial companies with complementary activities in the field of semiconductor technology, microsystems and sensors, low-temperature physics, cryogenic thermometry and metrology. The primary objective of this collaborative project was the development of new technological approaches to the solution of some urgent problems in cryogenic thermometry, namely, measurement in the presence of high magnetic fields and stability in the presence of ionizing radiation. The project aims to provide a number of types of new temperature and multifunctional sensors that cover the temperature range from 0,03 to 500 K. The first results for this international collaboration and development have been reported by N.S. Boltovets et. al. [1].

This paper presents a review of sensors that are produced and characterized due to European Project. They are: (i) resistance thermometers based on both film and bulk Ge and SiC; (ii) diode temperature sensor based on Si and GaAs; (iii) dual element resistance thermometers (DERTs), in which the overlapping T/R characteristics of two temperature sensitive elements are combined to provide a measurement range from 0,1 K to 400 K; and (iv) dual function sensors (DFS) for concurrent measurements of temperature (1,5 K to 400 K) and magnetic field.

* Work partially funded under European Commission INTAS Contract n° 2000-0476.

DESIGN OF SENSORS AND THEIR OPERATING CHARACTERISTICS

Ge-film resistance thermometers

The basis of the resistance thermometer is a Ge-film resistor deposited on a semi-insulating GaAs substrate. The principles of designing such sensors and the fabrication technology involved have been reported previously by V.F. Mitin et. al. [2] and the characteristics of fabricated thermometers have also been reported [3-5]. The fabrication technology of such Ge-film thermometers is now well developed and new types of thermometers and multisensors have been produced, using micro-electronic design and production methods, to meet the requirements of the modern cryogenic sensor market.

Ge-film resistance thermometers have been produced with cylindrical canister packages, made from gold plated copper. The dimensions of this package are 3 mm in diameter and 5 mm long. The thermometers have four copper or phosphor bronze contact leads. A micro-package has also been designed for temperature measurements with high spatial resolution and a fast thermal response time. These micro-thermometers measure 1.2 mm in diameter by 1,0 mm long. Typical dependencies of resistance and sensitivity $S=dR/dT$ on temperature for the different types of thermometer are shown in Figures 1.

Ge and SiC bulk resistance thermometers

The Ge thermometers are made from heavy doped and compensated bulk Ge. Doping is carried out using a set of impurities with various activation energies by both the metallurgical method and neutron transmutation method. These thermometers cover the temperature range for operation from 0,3 to 300 K. The temperature dependencies of resistance and sensitivity $S=dR/dT$ for the different types of the Ge-bulk thermometers are shown in Figures 2

A new high sensitive thermometer for the 50 to 400 K temperature range has also been developed and produced on the basis of bulk SiC. The typical resistance-temperature dependence for this thermometer is shown in Figure 1 (curve 7).

Si and GaAs diode temperature sensors

Shown in Figures 3 are the typical temperature dependencies of forward voltage, U, and sensitivity, $S=dU/dT$, for the Si and GaAs diodes. These diodes show quite different U-T dependencies at temperatures below 80 K. Their behaviours in magnetic fields are now under characterization.

Dual element thermometers

New, dual element thermometers (DERTs) have been designed and produced. These provide temperature measurements over wide range, from ultralow to high temperatures, with high sensitivity and resolution over the whole range. The DERT contains two Ge-film resistor elements which have high sensitivity over complimentary ranges within the extended temperature range. The elements are incorporated in the same parallelepiped package, made from gold plated copper. The dimensions of this 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. Using one element, for example, in the 0,1 K to 4 K range and the another for the 4 to 400 K range one can obtain high sensitivity and resolution both at ultralow and high temperatures. Typical dependencies of resistance and sensitivity $S=dR/dT$ on temperature for the elements of the dual element thermometer are shown in Figures 1.

Dual function sensors

The dual function sensors (DFSs) for temperature and magnetic field measurements consist of a Ge-film resistance thermometer and an InSb-film Hall-effect magnetic field sensor. The package for the DFS is the same as that for the DERT (3,5 mm wide, 2,2 mm high and 10,1 mm long). The dual function sensor also has eight copper contact leads:- four leads for the thermometer and four leads for the Hall "generator". At constant current the Hall generator provides an output voltage proportional to magnetic field induction. The main aim for development of the dual function sensor is to provide accurate temperature measurements in high magnetic fields. Typical thermometric characteristics for the DFS are included in Figures 1. Operating characteristics for magnetic field measurements are listed in Table 1.

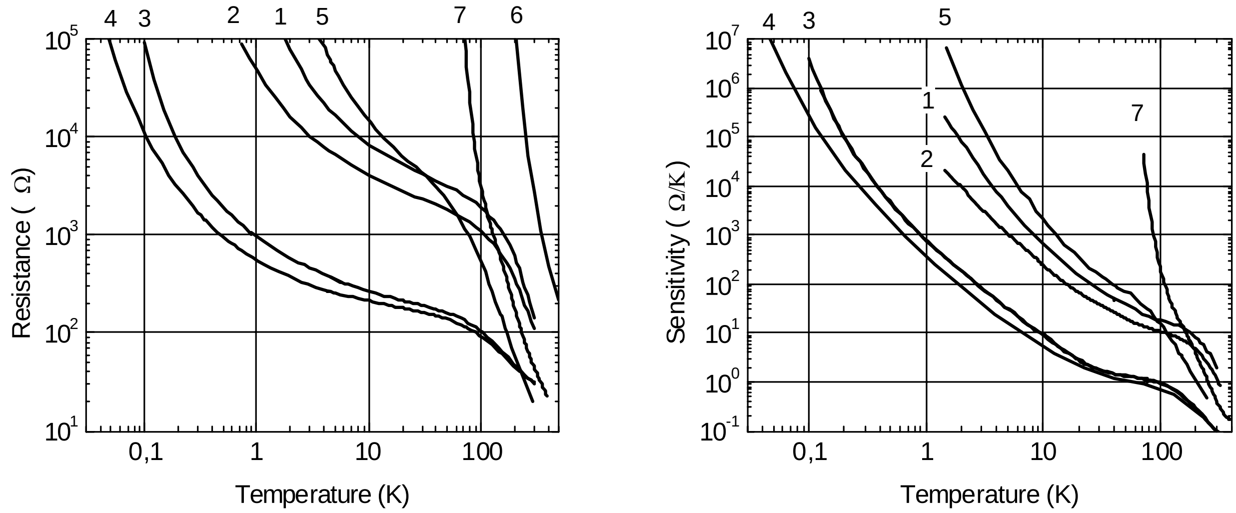

Figure 1 Resistance and sensitivity vs. temperature curves for DFS (1), DERT (1, 3), and Ge-film thermometers of different models: TTR-G (2), TTR-D (4), TTR-M (5), TTR-3 (6) and SiC-bulk sensor (7)

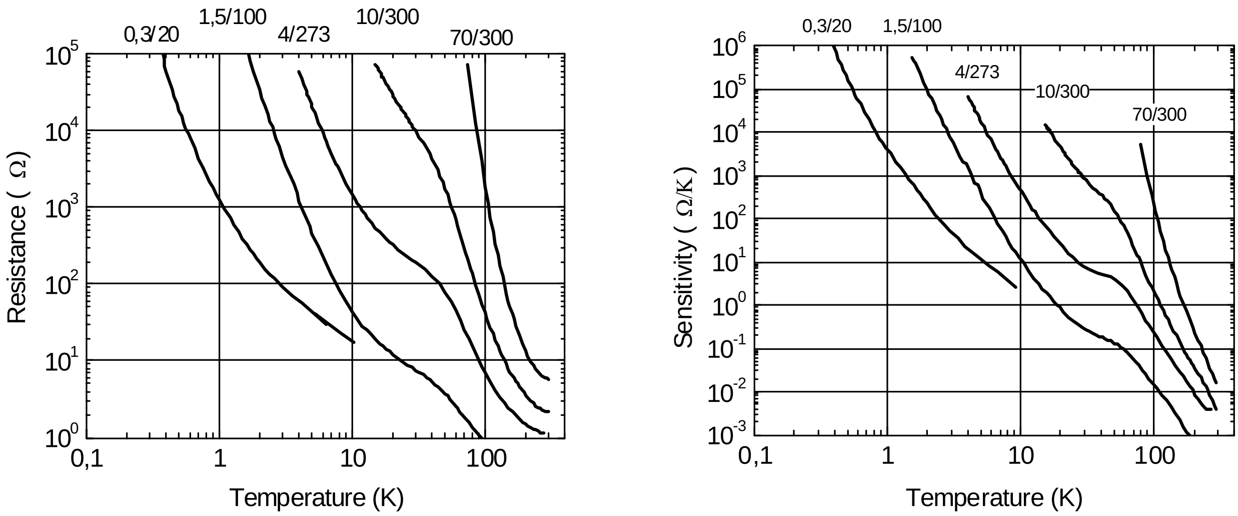

Figure 2: Resistance and sensitivity vs. temperature curves for Ge-bulk thermometers of different models

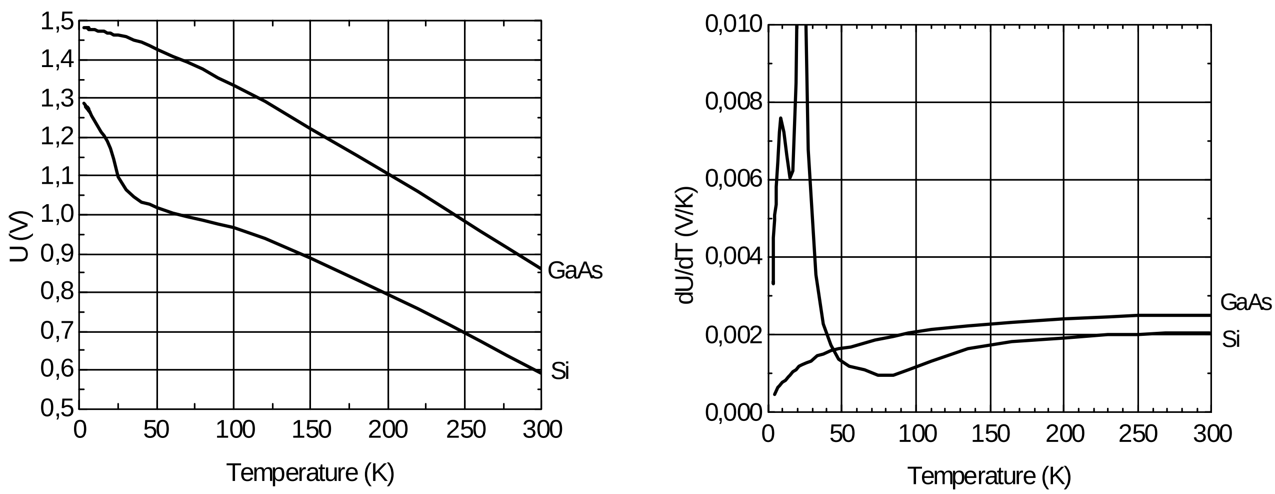

Figure 3: Forward voltage and sensitivity vs. temperature curves for the Si and GaAs diodes at dc. current of 10 µA

Table 1 Hall generator characteristics

Operating temperature range	1 to 400 K
Input resistance	20 to 70 Ω
Output resistance	50 to 150 Ω
Rated control current	0,5 mA
Magnetic sensitivity (at rated control current)	5 mV/Tesla
Zero field offset voltage (at rated control current)	0,2 mV (max.)
Temperature coefficient of magnetic sensitivity	0,03 %/K (max.)

EFFECT OF MAGNETIC FIELDS AND GAMMA IRRADIATION

The magnetic field effect varies for different models of Ge thermometers and depends on the nature of the conduction mechanisms in the sensor materials. It may be negative or positive and is dependent on temperature and magnetic field ranges. The behaviour of some models of Ge film thermometers in magnetic fields can be found in ref. [1, 3-5] and for Ge-bulk in ref [6]. New models of thermometers based on both bulk and film of Ge have been developed with low magneto-resistance for using in high magnetic fields. The temperature measurement error is not more than 1 % in magnetic fields up to 7 T at 4,2 K; 9 T at 3,0 K and 14 T at 2,0 K for the Ge-bulk thermometers, and for the Ge-film thermometers this error (1 %) is in the fields of 6 T at 4,2 K; 7 T at 1,0 K and 6 T at 0,3 K.

The gamma irradiation has very little effect on the Ge-film resistance thermometers up to a dose of 1.5×10^{8} rad. Their sensor resistance increases after a dose of 1.5×10^{8} rad and at the very large dose of 7.6×10^{8} rad, the error in the thermometer reading is ~2 %, i.e. 100 mK at 4.22 K and 2.0 K at 77.4 K.

CONCLUSIONS

A number of types of new temperature sensor have been developed, produced and characterized. They are: (i) resistance thermometers based on both film and bulk Ge and SiC; (ii) diode temperature sensor based on Si and GaAs; (iii) dual element resistance thermometers (DERTs), in which the overlapping T/R characteristics of two temperature sensitive elements are combined to provide a measurement range from 0,1 K to 400 K; and (iv) dual function sensors (DFS) for concurrent measurements of temperature (1,5 K to 400 K) and magnetic field. Further studies are planned for the comprehensive evaluation of these temperature sensors under various environmental conditions.

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