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Dual function sensors for concurrent measurement of temperature and magnetic field in cryogenic applications

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ABSTRACT

Dual function sensors (DFSs) for concurrent measurement of temperature and magnetic field in cryogenic applications have been developed and characterized. The DFS consists of a Ge-on-GaAs film resistance thermometer and an InSb-on-GaAs film Hall-effect magnetic field sensor combined in a single package with dimensions: 3.5 mm wide, 2.2 mm thick and 10.1 mm long. The construction and characteristics of two models of the DFSs; which are intended to provide measurements of temperature in the 1.5–400 K and 0.1–400 K ranges, and magnetic fields up to 30 T, are presented.

1. Introduction

Concurrent measurement of temperature and magnetic field is required for many experiments in low-temperature physics, as well as in the diagnostics of large superconducting magnet systems for magnetic resonance imaging or high energy physics applications. The effect of magnetic field on temperature sensing devices in most cases causes an error in the temperature determination.

Resistive and diode sensors are often used to measure low temperatures. As a rule, diode temperature sensors are not used for temperature measurement in a magnetic field because the field causes a large error in the diode thermometer reading. A number of resistive sensors are available for performing temperature measurements in high magnetic fields each with their own limitations. Most adapted and commercially available resistive sensors for these applications are made of: carbon, carbon-glass, carbon ceramic (1.4–425 K) [1–3] some germanium [1,4,5] fabricated on bulk materials, and films based on ruthenium oxide (0.05–40 K) [1,6,7], zirconium oxy-nitride (0.3–420 K) [1,3,8] and germanium [9-12].

All conducting materials are sensitive to magnetic fields and show magnetoresistance to different degrees, and it is not possible to develop a resistive sensor that has effectively zero magnetoresistance except in a narrow, selected temperature range.

The main objective of this work has been to develop a novel approach to cryogenic thermometry and magnetometry through the development of multi-functional devices, capable of providing accurate and simultaneous measurements of temperature and magnetic field. The developed "dual function sensors" (DFSs) address the following two problems: (i) simultaneous measurements of temperature and magnetic field, and (ii) more accurate measurements of temperature in high magnetic fields by using a correction method based on the direct measurement of the local field value, to compensate for the magnetic field sensitivity of the thermometer. The DFS approach and the computational correction of the field effects on the thermometer will be capable of providing more accurate temperature measurements in high magnetic field environments.

This paper presents the construction of these multi-functional devices together with their sensing characteristics. The first results for the development of the T&B multi-functional devices have previously been reported in conference proceedings [13–15].

2. Design of dual function sensors

The DFS consists of a Ge-on-GaAs film resistance thermometer and an InSb-on-GaAs film Hall-effect magnetic field sensor, which

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at constant current, provides an output voltage proportional to magnetic field induction. These sensors are incorporated in a parallelepiped-shaped package, made from gold plated copper, sealed with epoxy. The dimensions of this package are 3.5 mm wide, 2.2 mm thick and 10.1 mm long. The DFS has eight copper contact leads: four leads for the resistance thermometer and four leads for the Hall-effect magnetic field sensor. Fig. 1 shows a photograph of the DFS. The internal construction and schematic drawing of the DFS are presented in Fig. 2.

The resistance temperature sensors were produced by vapour deposition of *p*-Ge films onto semi-insulating GaAs substrates under vacuum. The basic principles of designing such Ge-on-GaAs film sensors and the fabrication technology involved have been reported previously and can be found, for example, in [16]. The Ge-on-GaAs film approach makes it possible to produce a range of resistive sensors covering the temperature range for operation, from 0.03 K to 500 K. The characteristics of various models of Ge-on-GaAs film thermometers can be found, for example, in [6,9–12].

The Hall-effect magnetic field sensors were produced by the deposition of *n*-InSb films onto semi-insulating GaAs substrates under vacuum. Choice of materials for the Hall sensor was made so as to fulfill as far as possible, the requirements of maximum magnetic sensitivity, with minimum temperature coefficients of, the magnetic sensitivity and resistivity, over the temperature range. The most suitable characteristics were observed for Hall sensors based on *n*-InSb films 1–2 μm thick with carrier concentrations of (3–6) × 10^{17} cm^{-3}. These films provide good magnetic sensitivity, with low sensitivity to temperature.

After the fabrication of Ge and InSb films with the required electrical properties for thermometry and magnetometry, standard microelectronic procedures were followed to produce sensing elements (see for example [12]). The Ge-on-GaAs resistive elements were 2.0 mm long, 1.3 mm wide and 0.15 mm thick and the InSb-on-GaAs Hall elements were 1.0 mm square by 0.15 mm thick.

3. Operating characteristics

Two models of the DFS have been developed and produced. Figs. 3 and 4 show typical temperature dependence of resistance, *R*, and sensitivity, $S = |dR/dT|$, for these two models of the DFS, which are intended for use in the 1.5–400 K (DFS-1 model) and 0.1–400 K (DFS-2 model) temperature ranges. The properties of Ge-on-GaAs film resistance thermometers used for the DFSs can also be found in Ref. [9]. Their behaviour in various environmental conditions is also listed in Table 1.

The magnetic field measurement parameters of the DFS are shown in Fig. 5 and are also given in Table 2. The developed

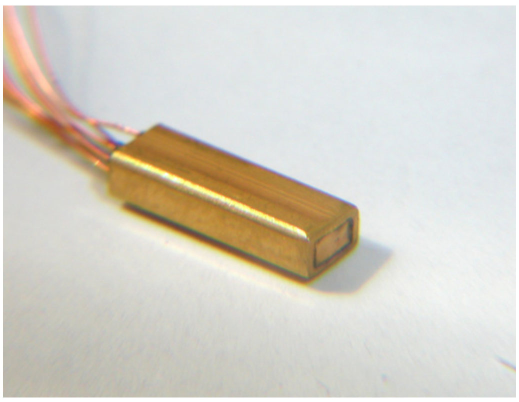

Fig. 1. Photograph of the DFS.

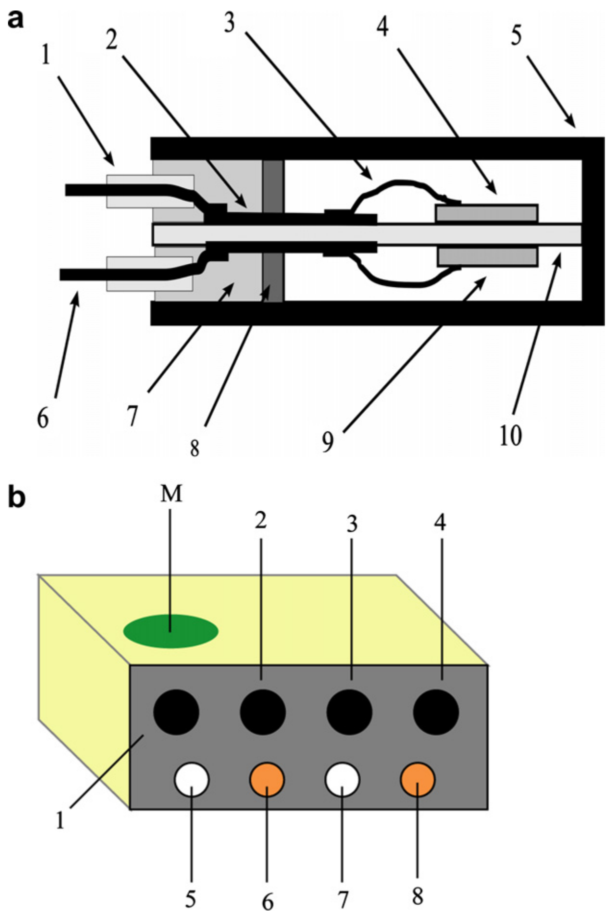

Fig. 2. Schematic drawing of DFS package: (a) 1 – protective polymer tube, serving as mark to distinguish between leads; 2 – current tracks; 3 – gold leads to chip; 4 and 9 – sensitive elements, resistance thermometer and Hall sensor; 5 – gold plated copper package; 6 – leads; 7 – epoxy sealing; 8 – protective wall; 10 – dielectric plate and (b) Leads configuration: Coloured mark on the package surface – M; numbers from 1 to 4 and from 5 to 8: 1 and 3 (black tube) – thermometer current (I_{RT}); 2 and 4 (black tube) – thermometer voltage (U_{RT}); 5 and 7 (white tube) – Hall sensor current (I_{HS}); 6 and 8 (bare varnished lead) – Hall sensor voltage (U_{HS}).

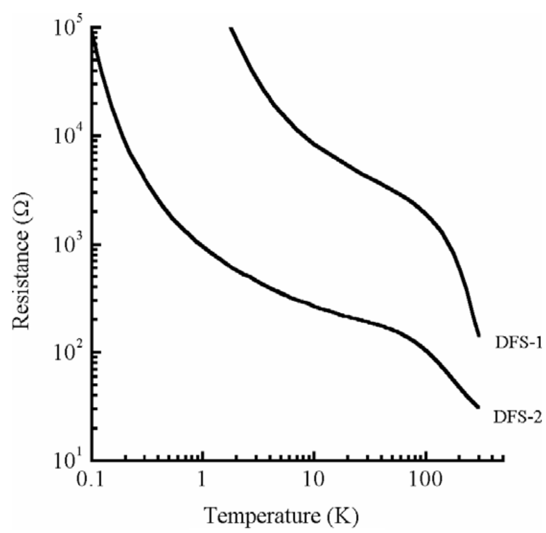

Fig. 3. Resistance versus temperature curves for different models of Ge-film thermometer used in the DFS.

InSb-on-GaAs film Hall-effect magnetic field sensor provides good sensitivity, which is independent of temperature at the level

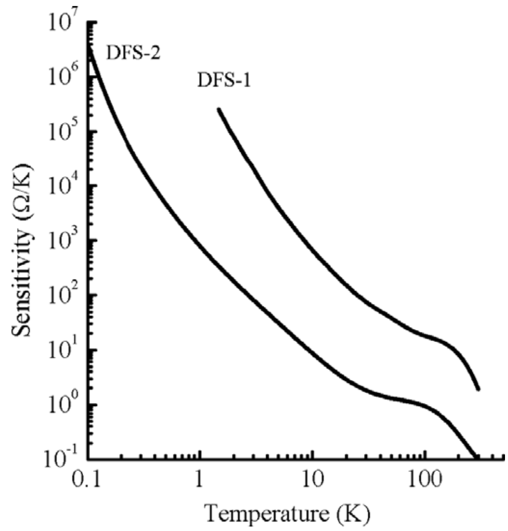

Fig. 4. Sensitivity versus temperature curves for different models of Ge-film thermometers used in the DFS.

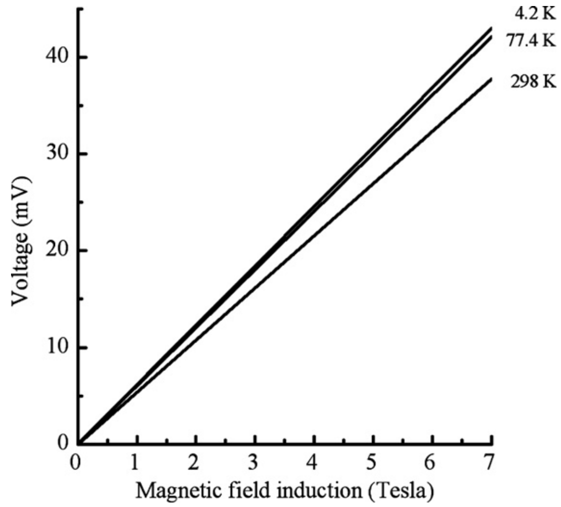

Fig. 5. Voltage versus magnetic field curves for DFS Hall-effect magnetic field sensor at control current of 0.5 mA and temperatures 4.2 K, 77.4 K and 298 K.

Table 1
Typical operating characteristics of DFS resistance thermometers types DFS-1 and DFS2

Operating temperature range	
DFS-1	1.5–400 K
DFS-2	0.1–400 K
Typical resistance of DFS-1 thermometer at 1.5 K (approximately)	100 kΩ
Typical resistance of DFS-1 thermometer at 400 K (approximately)	30 Ω
Typical resistance of DFS-2 thermometer at 0.1 K (approximately)	100 kΩ
Typical resistance of DFS-2 thermometer at 400 K (approximately)	30 Ω
Typical magnetic field-induced temperature errors of DFS-1 thermometer without correction, $\Delta T/T$ (%), at 4.2 K in magnetic fields	
(T)	$\Delta T/T$ (%)
2.5	0.5–0.6
4	0.4–0.5
6	−0.2 to −0.5
8	−1.2 to −2.0
Typical error in the thermometer reading, ΔT and $\Delta T/T$ (%), at 4.22 K after gamma radiation at 310 K up to doses	
1.0 MGy	±10 mK; ±0.24%
7.6 MGy	−40 to −100 mK; −0.95% to −2.4%

Table 2
InSb-on-GaAs film Hall-effect magnetic field sensor characteristics

Operating temperature range (K)	1–400
Input resistance (Ω)	10–20
Output resistance (Ω)	15–30
Rated control current at $T \geqslant 4$ K (mA)	0.5
Magnetic sensitivity at rated control current (mV T^{-1})	5–6
Zero field offset voltage at rated control current (mV)	0.05 (max.)
Temperature coefficient of magnetic sensitivity (%K^{-1})	0.03 (max.)

<0.03% K^{-1} so that the effect of temperature on the magnetic field measurements is very small.

Since the magnetic field sensitivity of a Hall sensor is proportional to control current, in order to obtain high sensitivity it is necessary to supply the sensor with as high a current as is possible. However a large current can cause self-heating and affect the thermal environment of the sensor. Thus the choice of the Hall sensor current is very important for correct temperature measurements when using the DFS. Our studies have shown that for the present design of DFS a constant Hall sensor current of 0.5 mA provides a level of self-heating that does not effect (less than 5 mK) temperature measurements above 4 K. At this current the magnetic field sensitivity of the sensor is approximately 5–6 mV T^{-1}.

Mounting of the DFS should follow common good practice for thermal anchoring. Due to the shape of the package, gluing into a slot on a flat surface is to be preferred to insertion into a circular well.

The Hall-effect magnetic field sensing element in the DFS measures only one field component, this corresponds to the component for which the (anisotropic) sensitivity of the temperature sensor is the maximum, and for correct measurement of magnetic field, the orientation of the surface of the Hall-effect sensing element must be perpendicular to the vector of magnetic field induction. The surface of the Hall sensor is parallel to the DFS surface and aligned along the major axis of the package.

Calibration of the DFS includes the generation of data on the magnetoresistance of the thermometer, which enables corrections during the measurements of temperature in a magnetic field. Optimisation of the calibration technique and the best approach to computational correction is under development.

4. Conclusion

Dual function sensors (DFSs) for concurrent and coincident measurements of temperature (0.1–400 K or 1.5–K) and magnetic field (up to 30 T) have been produced. The DFS approach can be applied to the problem in cryogenic thermometry of temperature measurements in high magnetic fields, since, by simultaneous, direct measurements of temperature and local magnetic field, and knowledge of the field sensitivity of the thermometer it is possible to compute a correction for the field effects on the thermometer, and to provide in a compact way both temperature and magnetic field information.

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