Germanium resistance thermometers with low magnetoresistance

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Received 9 May 1989; revised 20 November 1989

This paper presents details of the technology, construction and properties of semiconductor thermometers manufactured at the Institute of Semiconductors in Kiev, USSR. The thermometers are characterized by a monotonic function of R *versus* T in the temperature range 1.5–300 K, reproducibility at helium temperatures better than 1 mK and small magnetoresistance. The results of magnetoresistance measurements in the temperature range 2–15 K and in magnetic fields up to 14 T show that the error $\Delta T/T$ is less than 2% in fields of 6 T. This error increases to 12% in very high magnetic fields. Anisotropy effects are less than 1% in the temperature range 2–15 K and in magnetic fields of 14 T.

Keywords: thermometers; magnetoresistance; semiconductors; magnetic fields

Recently, a paper written by Besley *et al.*[1] appeared in **Cryogenics** where the authors, drawing on information available in the literature, desrcibed certain properties of germanium resistance thermometers manufactured at the Institute of Semiconductors, Academy of Sciences of Ukrainian SSR, in Kiev. In the authors' opinion, these thermometers, unlike other typical germanium thermometers, are characterized by small magnetoresistance in the low temperature range and they can, therefore, be very useful devices for temperature measurement in the low temperature range in the presence of high magnetic fields.

This article induced some criticism[2]. The observations dealt mainly with an uncertainty as to whether all the Kiev germanium thermometers described in cited work were the same or different types, and whether the number of measurements made with these thermometers was sufficient to substantiate the above conclusion.

The principal aim of this paper is to comment on certain doubts that have been expressed and to present more quantitative results of measurements on the germanium thermometers fabricated in Kiev, and thus be better qualified to make some generalizations and comparisons.

The first information about semiconductor thermometers fabricated at the Institute of Semiconductors in Kiev appeared in 1971[3]. Some 16 papers[3–18] have now been written on the subject, most of them in Russian. In these papers, some written by producers, others by users, chosen properties of the thermometers have been presented.

All the thermometers described in the mentioned literature were made from appropriately heavy doped and highly compensated germanium. Using multi-component doping technology it is possible to make a germanium thermometer that is able to measure temperature over a very wide range, from 1.5 to 300 K. The sensitivity as well as nominal resistance value of the thermometers in a chosen temperature range can be changed by appropriate selection of impurities. In *Table 1* various types of thermometers manufactured at the Institute of Semiconductors are presented, together with their working temperature range. The letters symbolizing the thermometers originate logically, from descriptions in Russian, for instance: letter K denotes komnatnaja, room temperature; A denote azotnaja, (liquid) nitrogen temperature; V denotes vodorodnaja, (liquid) hydrogen temperature; and G denotes gielevaja, (liquid) helium temperature; Therefore a KG type thermometer operates in the range from room to helium temperatures.

For several years the Institute of Semiconductors has been making a lot of the germanium thermometers which have been used in industry and scientific laboratories in the USSR and other countries of Eastern Europe. Even if

Table 1 Types of germanium resistance thermometers produced by the Institute of Semiconductors in Kiev

Type of thermometer	Temperature range (K)
VG	1.3–20
KG	4.2–300
KV	20–300
KA	77–300
KGG	1.3–300

0011-2275/90/060533-05

measurement results described in the cited literature have, in the main, been obtained from a small number of investigated thermometers, they can still be used in a generalized way because they were randomly selected. Usually, typical, commonly doped germanium resistance thermometers have been used, where the most common criterion of choice when acquiring the particular device was the required working temperature range, and the shape and quality of the thermometer capsule.

Thermometers

Materials

The technology and properties of materials used for constructing Kiev thermometers have been described in detail previously[3–5]. Here only the main principles of preparing the doped semiconductors for the purposes of cryothermometry are presented.

The temperature dependence of the carrier concentration, $N(T)$, in semiconductors is usually made use of in thermosensitive devices with high sensitivity. The temperature dependence of N in semiconductors doped with different donor and acceptor impurities may be written as follows

$$N = A_0 \exp\left[-\frac{E_0}{kT}\right] + A_1 \exp\left[-\frac{E_1}{kT}\right] + A_2 \exp\left[-\frac{E_2}{kT}\right] + A_3 \exp\left[-\frac{E_3}{kT}\right] \qquad (1)$$

The values of parameters A_i are determined by the material properties and by doping levels. A_i changes with temperature very slightly. The terms in Equation (1) are the carrier concentrations appearing as a result of:

1 ionization of the host (matrix) semiconductor atoms;
2 activation of the impurity atoms;
3 carrier transition between the same impurity atoms; and
4 hopping processes between donor–acceptor pairs.

The desired thermosensitivity of a semiconductor material having a definite forbidden bandwidth E_0 can be obtained by suitable doping. For example, the distance between the percolation and Fermi levels determines the thermosensitivity in the region E_1, in which the conductance is defined by the activation energy, E_1. The value E_1 in highly compensated semiconductors is described by the equation

$$E_1 = \frac{e^2}{\kappa}\left(\frac{4\frac{\pi}{3}n_D}{1-k}\right)^{1/3} \qquad (2)$$

where k is the grade of compensation, n_D is concentration of donors and κ is the permittivity of the seniconductor. The values of E_2 and E_3 depend on donor and acceptor concentrations and on their ratio. In most cases, Mott's law is satisfied to describe these values[20].

Precise doping is the most complicated operation in obtaining the desired thermosensitivity. As noted in a Lake Shore information leaflet, it is not only careful doping that is required to prepare good material, but a little 'black magic' is also involved. However, mastering the details of this technology allows the manufacture, in a reproducible way, of semiconducting material suitable for thermometrical purposes. Germanium is widely used for this purpose, as it is the most suitable material from the technological point of view.

Ordinary methods of doping based on dissolving dopants in a melted host material are not able to provide the necessary quantitative accuracy and homogeneity of admixture distribution. Therefore, from the end of the 1970s onwards, transmutation methods of doping were adopted, namely irradiation of the original semiconductor with thermal neutrons[21]. As a result of the nuclear reactions, impurity atoms of gallium, arsenic and selenium appear, if germanium is used as the basic material. The impurities are generated with extremely high homogeneity in the semiconductor volume due to the very small absorption coefficient of thermal neutrons. Owing to this, it is possible to prepare a great number of thermometers with similar characteristics. In some cases, using the purest germanium, one can even obtain interchangeable thermometers. For narrow temperature regions, semiconductors with dislocation bands may be utilized to increase sensitivity.

Construction of sensors

Two types of thermometrical sensor are currently made: two-lead thermometers intended for measurements in industry with low precision and four-lead sensors for precise measurements.

The two-lead sensors have a cuboid shape with dimensions of, typically, ≈ 1 mm^3 or a cylindrical shape with a base of 1 mm^2 and height of 1 mm. The cross-section of such a sensor is shown in the *Figure 1*. On opposite sides of the cylinder (1 in *Figure 1*) or cube, two holes are etched and filled with special contact alloy (2), ensuring low resistance between the semiconductor material and soldered electrical leads (4). The effective working part of the sensor is the thin layer of thickness 0.1–0.3 mm lying between the pieces of contact alloy. The total weight of the sensor does not exceed 10 mg. Such sensor construction enables the thermometers to have a low time constant and allows them to be applied to temperature measurements on small objects. This sensor can be used with no capsule but it is also possible to put it into a cylindrical metallic capsule with a diameter of ≈ 2 mm and length 3–5 mm.

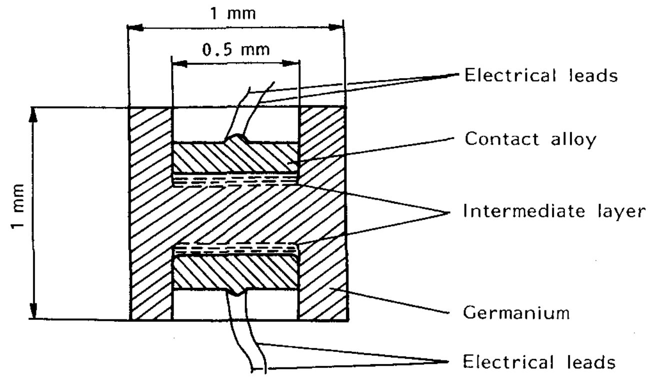

Figure 1 Cross-section of semiconductor thermometer

ney, Australia, and Office for Standardization, Metrology and Quality Control in Berlin, GDR).

Magnetoresistance

The first magnetoresistance investigations of heavy doped germanium thermometers manufactured at the Institute of Semiconductors in Kiev were carried out in the early 1970s. Typical values of temperature error, ΔT, against magnetic fields up to 5 T at 4.2 K were less than 6 mK, as presented in Reference 4. In 1977 the magnetoresistance of several KGG type thermometers was measured within the temperature range 2-12 K and in magnetic fields up to 12 T[14]. The following year the same measurements were carried out, this time for thermometers of the KG type. It was found that the behaviour of both the KGG and KG types of thermometer, in the presence of a magnetic field in the low temperature range, was identical. The magnetoresistance at 4.2 K and in a field of up to 6 T is less than 1%, but an increase in magnetic field or change in temperature causes an increase in magnetoresistance up to a few dozen per cent in the highest fields. A few users[16–18] of Kiev thermometers have obtained similar results following independent investigations of these thermometers in the presence of magnetic fields. The magnetoresistance of KV and KA type thermometers tested at higher temperatures (20.4 and 78 K, respectively) and magnetic fields up to 6 T are presented in Reference 12.

Recently, investigations on the influence of magnetic fields on the properties of the thermometers were repeated. Measurements were made on six typical, randomly chosen, four-lead thermometers. Typical values of relative magnetoresistance, $\Delta R/R_0$, *versus* magnetic induction, B, for eight different temperatures in the range 2-15 K and in magnetic fields up to 14 T are presented in *Figure* 4 for KGG type thermometers. These functions are monotonic and the maximum value of ratio $\Delta R/R_0$ did not exceed 40 % in 14 T. For this same thermometer the relative magnetoresistance, $\Delta R/R_0$, *versus* temperature for constant magnetic fields is presented in *Figure 5*. These curves show a maximum value of $\Delta R/R_0$ in the low temperature range. Because the sensitivity, dR/dT, of the semiconductor thermometers in the low temperature range is large, the temperature error, $\Delta T/T_0$, for KGG type thermometers is small, even in high magnetic fields.

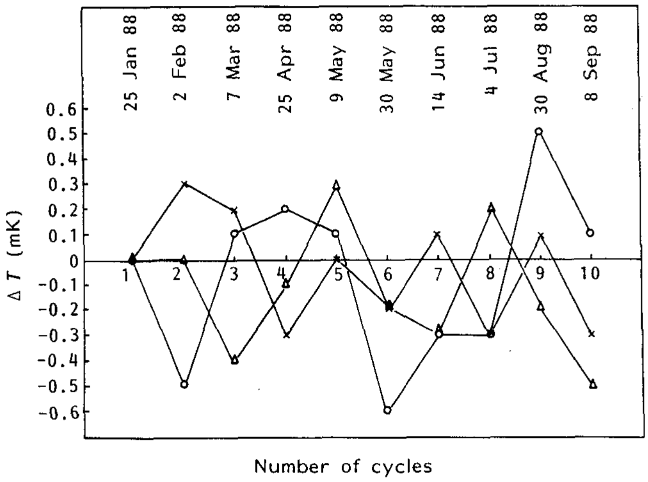

Figure 3 Reproducibility of thermometers at superconducting fixed point of indium, T = 3.414 K. ○, no. 20E-12; ×, no. 20E-18; △, no. 20E-21

The relative temperature error, $\Delta T/T_0$, *versus* magnetic induction for T = constant for KGG type thermometers is presented in *Figure 6*. It can be seen that the error for

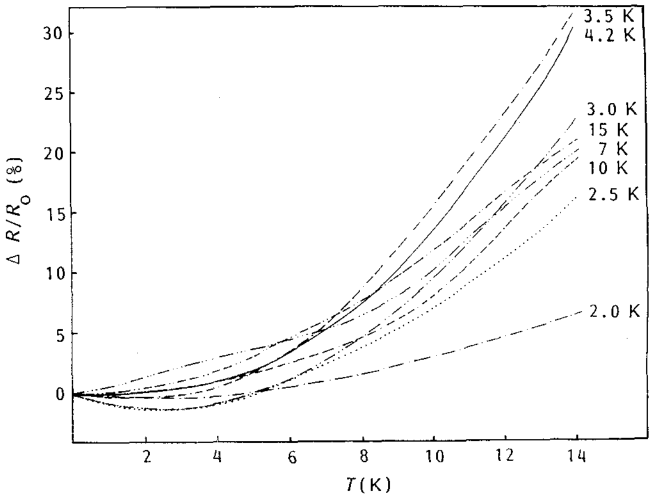

Figure 4 Magnetoresistance, $\Delta R/R_0$, *versus* magnetic induction B, for T = constant, for KGG type thermometers in the temperature range 2–15 K and in magnetic fields up to 14 T

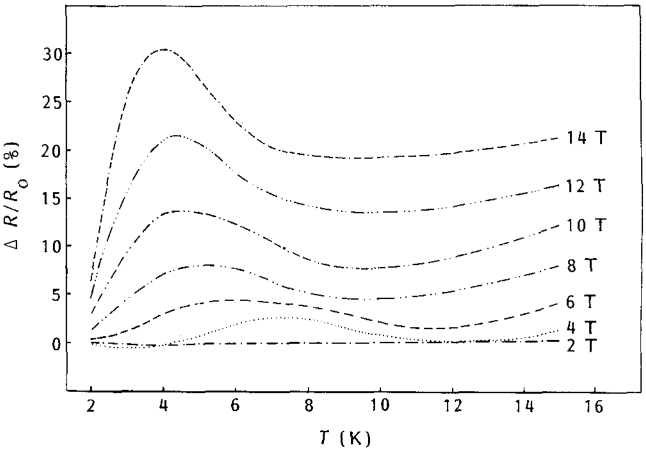

Figure 5 Magnetoresistance, $\Delta R/R_0$, *versus* temperature for B = constant, for KGG type thermometers in the temperature range 2–15 K and in magnetic fields up to 14 T

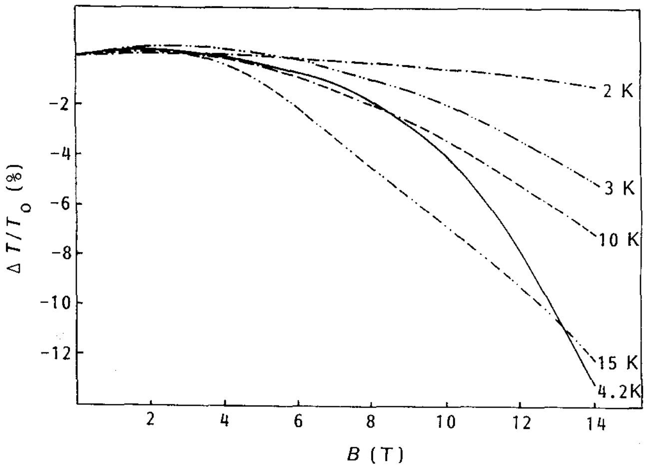

Figure 6 Relative temperature error, $\Delta T/T_0$, *versus* magnetic induction for T = constant, for KGG type thermometers

The four-lead thermometers are cut from a monocrystalline plate of semiconductor, as for typical germanium resistance thermometers, in the shape of a bridge with arms for two potential and two current leads. The sensor is hermetically encapsulated in a metallic tube. The wires are taken out through low temperature epoxy resin which seals the tube.

Thermometrical characteristics

Resistance-temperature relations for germanium Kiev thermometers have been presented in many publications[4,5,7,13–18]. In this paper the only results presented (see *Figure 2*) are those showing the typical dependence of resistance on temperature for thermometers of the KGG type, designed for temperature measurement over the range 1.5 – 100 K. Other types of these thermometers have similar monotonic characteristics in their working temperature range.

The relation R *versus* T of these thermometers in the temperature range 1.5-100 K can be described by the equation

$$\log R = \sum_{i=1}^{n} A_i (\log T)^i \qquad (3)$$

where $n = 5 - 8$.

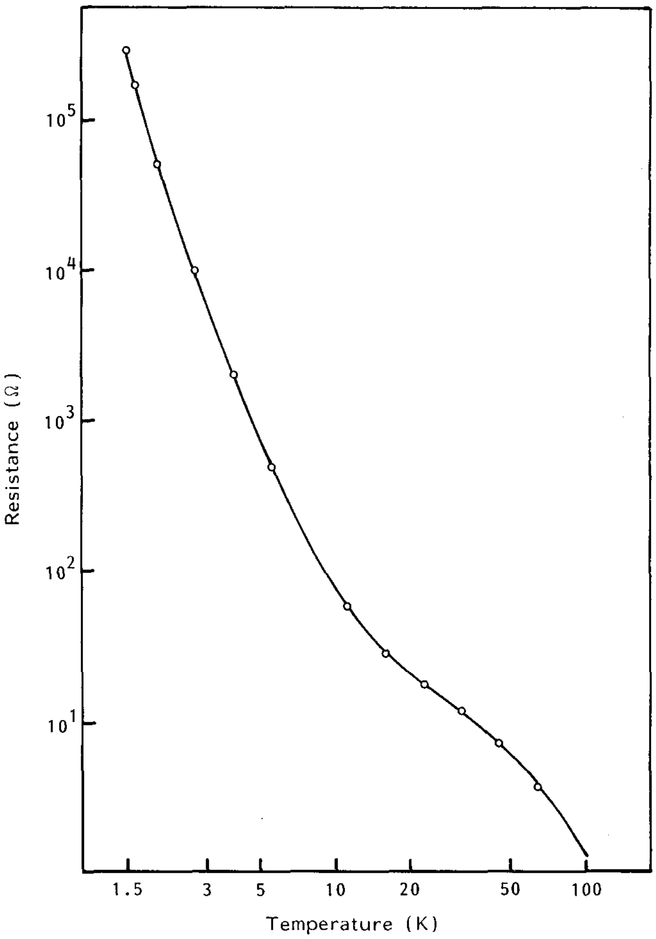

Figure 2 Typical dependence of resistance on temperature for KG thermometer in temperature range 4.2–100 K

Reproducibility

Systematic tests on long term reproducibility of Kiev thermometers have been carried out over a number of years at the Institute of Low Temperature and Structure Research in Wrocław, Poland. The reproducibility was measured at the superconductive fixed point of indium, $T = 3.414$ K. The obtained widths of the superconducting transition of indium, W, was less than 0.6 mK and the reproducibility of T_c was better than 0.2 mK. An a.c. resistance bridge with an accuracy of 0.003 %[22] was used to measure thermometer resistance.

Since, in many cases, the reproducibility of results from different types of thermometers is poor over the first thermal cycle and becomes more stable after several thermal cycles, before starting the thermometer reproducibility measurements each thermometer was thermally cycled 10-20 times between room and liquid helium temperatures.

The reproducibility of the thermometers at temperature T_0 was defined as the mean square error

$$\sigma = \left[\frac{1}{n-1} \sum_{i=1}^{n} (\bar{T} - T_i)^2 \right]^{1/2} \qquad (4)$$

where $\bar{T}$ is the mean value of temperature and is equal to

$$\bar{T} = \frac{\bar{R}}{\left(\frac{\mathrm{d}R}{\mathrm{d}T}\right)_{T = T_0}} \qquad (5)$$

where $\bar{R}$ is the mean value of thermometer resistance at temperature T_0 and T_i is the temperature value calculated for the ith thermal cycle using the formula

$$T_i = \frac{R_i}{\left(\frac{\mathrm{d}R}{\mathrm{d}T}\right)_{T = T_0}} \qquad (6)$$

where R is the value of thermometer resistance measured at temperature T_0 at the ith cycle of cooling of the thermometer to temperature T_0 and heating to room temperature.

Twenty two-lead thermometers taken from different manufacturing batches were tested at the fixed point of indium. It was found that the reproducibility of these thermometers was no better than 3 mK.

The four-lead thermometers are characterized by better reproducibility. In 40 four-lead thermometers tested in the Institute of Semiconductors in Kiev, where the precision of measurements was equivalent to 2 mK, the reproducibility in liquid helium appeared to be equal to the precision of measurement.

Most of these thermometers were also tested at the superconducting fixed point of indium. The results of measurements obtained over a half-year period show that the reproducibility of the four-lead thermometers in the low temperature range is better than 0.5 mK. In *Figure 3* results are presented for three typical four-lead germanium thermometers, bearing manufacturers numbers 20E-12, 20E-18 and 20E-21.

A selection of the four-lead thermometers was sent, for the purpose of further testing, to other metrological laboratories (Institute of Metrology 'G. Colonnetti' in Turin, Italy, National Measurement Laboratory in Syd-

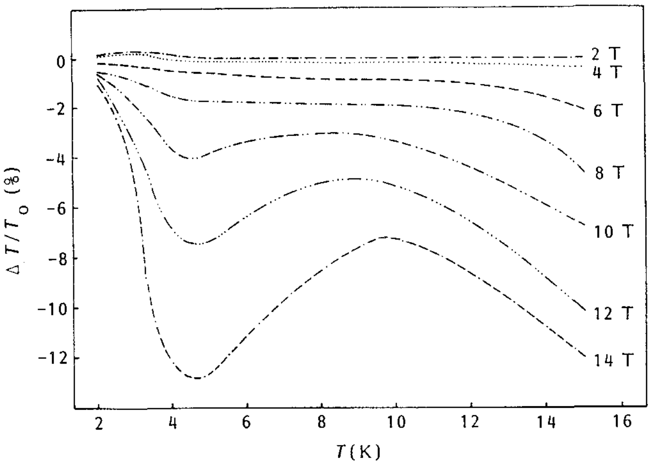

Figure 7 Relative temperature error, $\Delta T/T_0$, *versus* temperature for B = constant, for KGG type thermometers

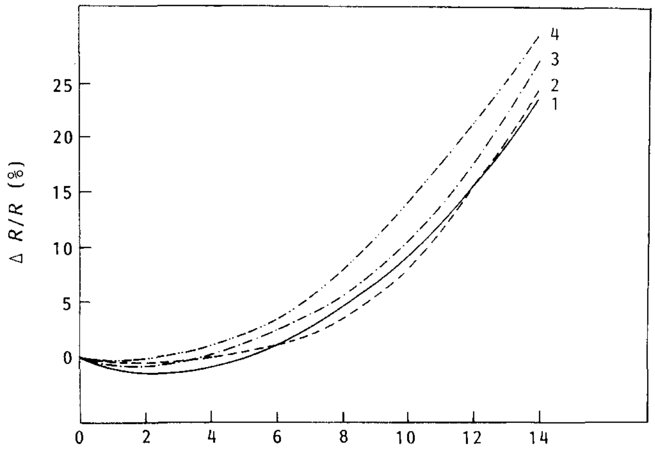

Figure 8 Comparison of $\Delta R/R_0$ dependences in magnetic fields up to 14 T at 4.2 K for four thermometers investigated over 10 years. 1, no. 9L-86 thermometer tested in 1977; 2, no. 16C-98 thermometer tested in 1979; 3, no. 90L 87 thermometer tested in 1987; 4, no. 41OL-08 thermometer tested in 1988

the temperature range 2–10 K and in magnetic fields up to 6 T is less than 1%. Values of the function of $\Delta T/T_0$ *versus* temperature for B = constant are presented in *Figure 7*.

Typical magnetoresistance curves, $\Delta R/R_0 = f(B)$, at 4.2 K obtained for four thermometers investigated over the last 10 years are shown in *Figure 8*.

Magnetoresistance anisotropy resulting from the different influence of transverse and longitudinal magnetic fields on the thermometer is presented in *Figure 9*. The anisotropy effect is negligible in fields up to 6 T and less than 1% in fields up to 14 T.

Conclusions

The results adduced and the long term experience of using a great number of Kiev thermometers in USSR and East European countries show promise for making good use of these thermometers in what is practically such an important region, 2 – 10 K, in the presence of magnetic fields. The magnetoresistance errors in fields up to 7 T are rather small and for higher fields the monotonic character of the magnetoresistance allows it to be taken into account to reduce the error. The latest data on reproducibility of these thermometers are also promising.

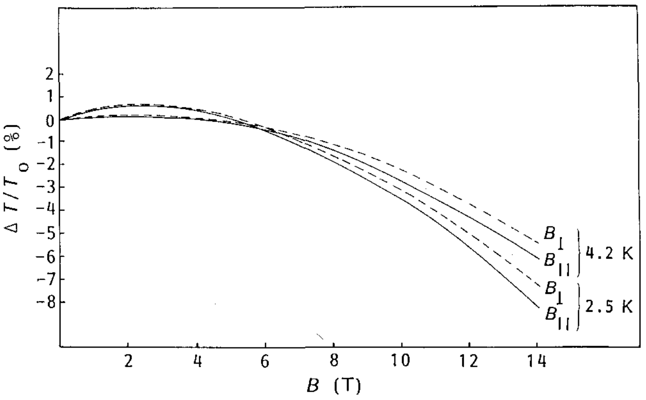

Figure 9 $\Delta T/T_0$ dependence on orientation of magnetic field at 4.2 and 2.5 K for thermometer no. 90L-87

Acknowledgements

The authors wish to express their thanks to B. Greń from the International Laboratory of High Magnetic Fields and Low Temperatures in Wrocław for making the measurements on thermometer characteristics in magnetic fields.

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