MINIATURE RESISTANCE THERMOMETERS BASED ON Ge FILMS ON GaAs

V.F. Mitin

Institute of Semiconductor Physics of the
National Academy of Sciences of Ukraine
Prospect Nauki 45, 252650 Kiev-28, Ukraine

ABSTRACT

Several types of miniature resistance thermometers based on Ge films have been developed and fabricated. They can operate in the 0.5 to 300, 77 to 400 and 200 to 500 K temperature ranges. The behavior of cryogenic thermometers has been investigated at low temperatures (1.7, 4.2 and 77.4 K) and in magnetic fields up to 14 T.

INTRODUCTION

The variety of cases where temperature measurements are needed, as well as the diversity of operational requirements, have motivated the development and availability of a wide range of devices for measuring temperature. The present microelectronic thin-film technology opens fresh opportunities for developing miniature temperature sensors whose characteristics can meet the nowadays requirements.

The works [1-3] were devoted to development of the basic principles of designing sensors (for measuring temperature, strain, magnetic field, optical radiation) based on Ge films on GaAs substrates. Here we discuss the problem of developing miniature resistance thermometers. Such thermometers are suited to operate in the 0.5 to 500 K temperature range. We present thermometric characteristics of thermometers and discuss the conduction mechanisms in Ge films which are responsible for thermal sensitivity. Also we report on the behavior of cryogenic thermometers at low temperatures and in high magnetic fields.

PRINCIPAL PREREQUISITES FOR DEVELOPING THE RESISTANCE THERMOMETERS BASED ON THE Ge-GaAs HETEROSTRUCTURE

The Ge-GaAs heterostructure seems to be promising for the temperature sensor development. The following reasons give grounds for such a statement. First, Ge and GaAs constitute an ideal heteropair. Their lattice misfit is extremely small (0.08 %). Their thermal

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expansion coefficients practically coincide over a wide temperature range. It is well known that absence of temperature stresses in a sensitive element is of great importance for devices operating in a wide temperature range. Second, during the process of epitaxial deposition of the Ge onto GaAs substrates, Ga and As atoms strongly diffuse from the substrate into the growing film and the solubility limits and diffusion coefficients of these impurities in the film turn out to be significantly (by 10^2-10^3 times) higher than those in the Ge bulk. This interdiffusion disobeys the classical diffusion laws, and so it may be called anomalous. Interpenetration of both materials essentially depends on the technological conditions of the heterostructure formation. Ga (As) atoms serve as acceptors (donors) in Ge. Related to them are shallow impurity states in the Ge gap whose energies (~ 0.01 eV) are close. Ge serves as an amphoteric impurity in gallium arsenide.

Thin Ge films on the GaAs substrate are characterized by a complex spectrum of impurity states in the gap. This spectrum substantially depends on the film growth conditions. There exist three main sources of charge carriers in a Ge film (in addition to the intrinsic charge carriers), namely, Ga and As impurities and structural defects. Both the structural perfectness degree and the structural defect concentration are mainly determined by the substrate temperature during Ge deposition. The film structure may vary over a wide range - from poly- to single-crystalline. A quantity of structural defects (predominantly acceptors) exists in Ge films along with point defects - acceptors (Ga) and donors (As). A relationship between their concentrations substantially depends on the film growth conditions. Presence of the above defects results in the fact that Ge films on GaAs are both doped and compensated. The diffusion processes at the Ge/GaAs interface and in the transition region are determined by the technological conditions of the heterostructure formation. Among such conditions are the substrate temperature, deposition rate and the GaAs surface condition before the Ge deposition. Autodoping makes it possible to obtain Ge films of *p*-, as well as *n*-, type, and also of different doping levels (from 10^{17} to 10^{21} cm^{-3}) and compensation degrees. Under certain conditions the compensation degree may be close to unity for Ge films. Depending on the film formation conditions, the free charge carrier concentration (resistivity) in Ge films at room temperature may vary from 10^{14} to 5×10^{20} cm^{-3} (140 to 10^{-3} Ω cm).[2]

A distinguishing feature of diffusion processes in the Ge - GaAs heterostructure is that the anomalously quick diffusion that occurs during the film deposition significantly differs from the diffusion that occurs during the heat treatment of the formed hetetrostructure. Anomalous values of the impurity diffusion coefficients are immediately related to the very process of the epitaxial film formation. Heat treatment of the formed heterosystem does not lead to the anomalously quick diffusion of impurities. So the devices based on the Ge/GaAs heterostructure may be considered to be heat - resistant.

A variety of electrical properties exist for Ge films on the GaAs substrates. This enables using the Ge - GaAs heterostructure as a versatile sensitive material when developing different physical sensors (of temperature, strain, pressure, magnetic field, optical radiation).[2] To produce a wide-range resistance thermometers, it is necessary to provide a high thermosensitivity in a wide temperature range. This is commonly achieved through multicomponent doping and compensation of a semiconductor. Thus in a semiconducting material there exist several different mechanisms of conductivity, and each of them provides thermosensitivity in a definite temperature range. By varying the doping level and the compensation degree of Ge films, one can obtain the resistance thermometers characterized by different thermal sensitivity in different temperature ranges.

In this work the films have been prepared by thermal evaporation of Ge in a vacuum (2×10^{-4} Pa) onto semiinsulating GaAs (100) substrates. To produce sensitive elements, we have used a conventional microelectronic technology. It included the following procedures: (i) ohmic contacts deposition by thermal evaporation of AuGe in a vacuum; (ii) photolithography to form the topology of the sensitive region and terminal areas; (iii)

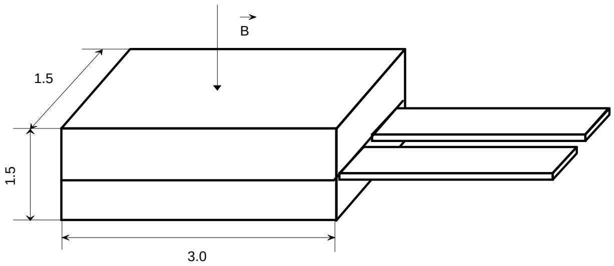

Figure1. The external view and dimensions (in mm) of the sensor.

wafer slicing; (iv) microassembly; (v) packaging. The sizes of sensitive elements were 0.5 × 0.5 × 0.2 and 1.0 × 1.0 × 0.2 mm for different types of sensors. The sensitive elements were placed into packs whose sizes were 3.0 × 1.5 × 1.5 and ∅1.6 × 4.0 mm.

RESISTANCE THERMOMETERS FOR THE 0.5 TO 300 K TEMPERATURE RANGE

We have fabricated cryogenic wide-range resistance thermometers of two types, designated as TTR-1A and TTR-1B. They can operate in temperature range from 0.5 to 300 K. The external view and dimensions of the sensor are shown in Figure 1.

Figure 2 shows the characteristics of thermometers. The TTR-1A thermometers are more sensitive in 50 to 300 K range, while the TTR-1B thermometers are more sensitive at low (< 10 K) temperatures. The sensitive elements of the thermometers have been made under various technological conditions and thus differ in their thermometric characteristics. The thermal sensitivity of a thermometer depends on the technological conditions of film preparation, since they determine both the doping level and the compensation degree of Ge films. The thermometer resistance is determined by the sensitive element topology formed by lithography. By varying the film preparation conditions and the thermosensitive area topology, one can fabricate resistance thermometers differing in both resistance value and thermal sensitivity.

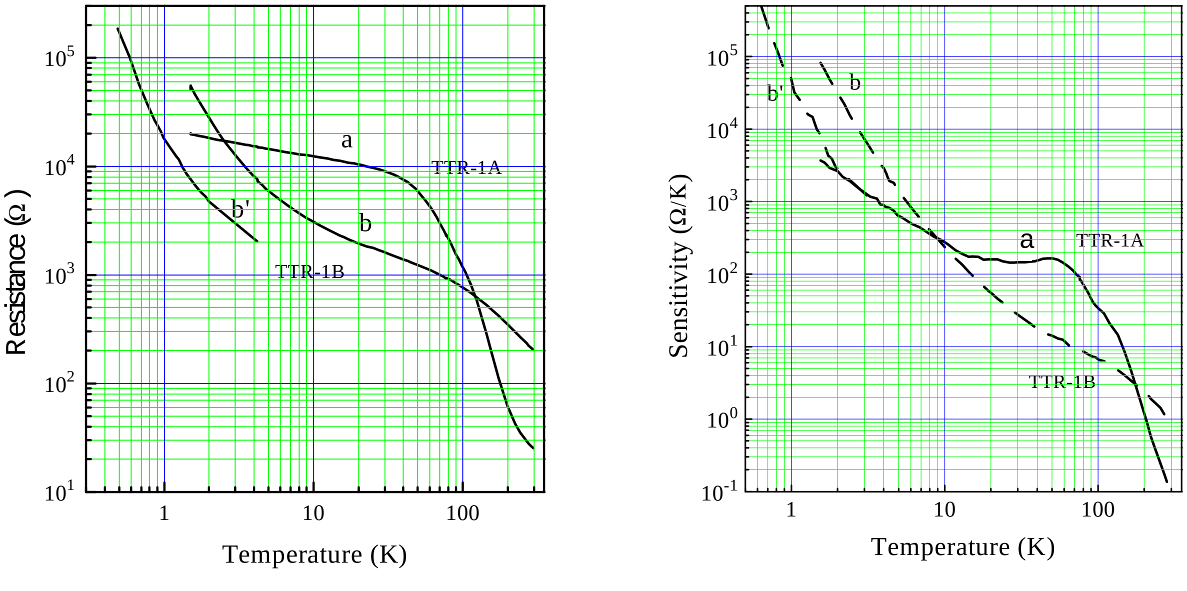

Figure 2. Thermometer resistance and sensitivity versus temperature curves: a - TTR-1A, b and b' - TTR-1B.

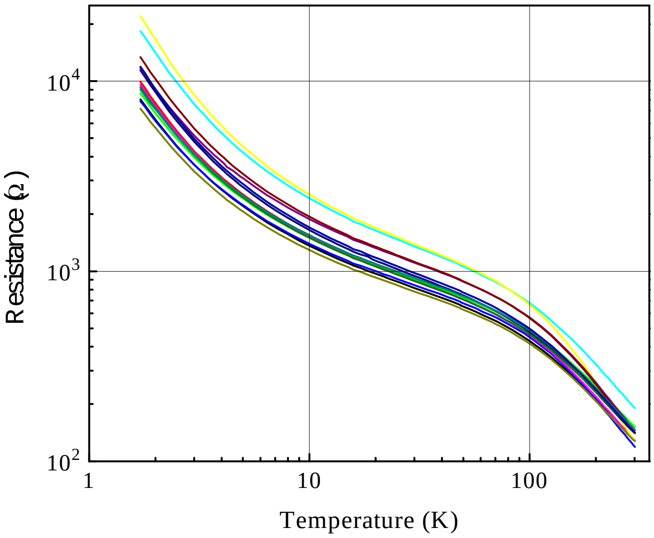

Figure 3. TTR-1B thermometer resistance versus temperature curves.

Figure 2b' shows the temperature dependence of the TTR-1B thermometer resistance in the 0.5 to 4.2 K temperature range. The resistance thermometers operating at low temperatures should not have high input resistance. Otherwise, even a small supply current will warm up the thermometer by Joule effect, which will result in a temperature measurement error. That is why we have chosen the TTR-1B thermometers with lower resistance for operating at the temperatures below 1.5 K. The TTR-1A thermometers also could be used at these temperatures, but their thermal sensitivity is lower than that of the TTR-1B ones.

Figure 3 illustrates difference of the characteristics of TTR-1B thermometers. Such thermometers have been produced from the same wafer of Ge/GaAs heterostructure. It is necessary to note, that about 10000 sensitive elements of thermometers may be produced from one wafer by means of microelectronic technology. In this sense a microelectronic technology is profitable and permits to manufacture cheap devices.

Figure 4 shows the dependencies of resistance on the supply current for two typical TTR-1B thermometers at 4.2 K. An essential change of resistance of thermometers has been observed at a current above 20 μA. Degree of constancy for resistance in the range of current up to 10 μA provides measurement of temperature with accuracy about 1 mK.

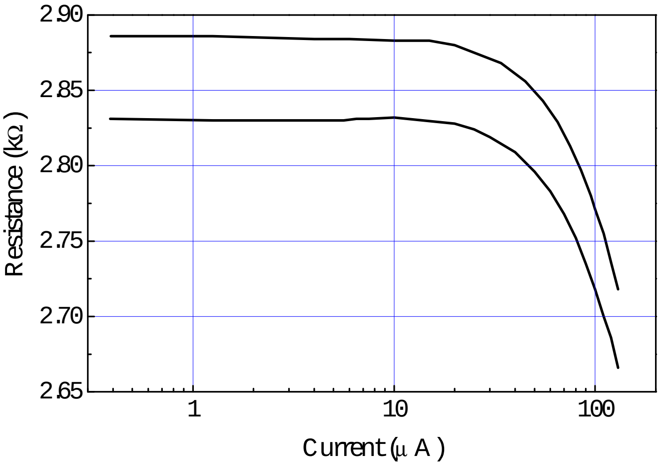

Figure 4. TTR-1B thermometer resistance versus current curves at 4.2 K.

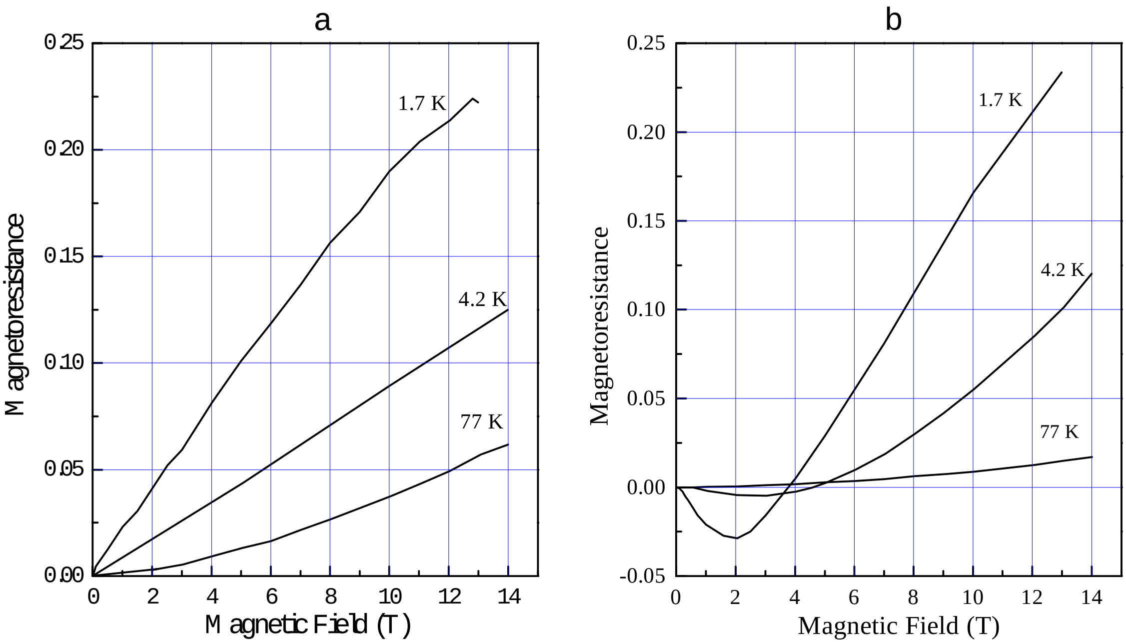

Figure 5. Dependence of the magnetoresistance (ΔR/R) on the magnetic field for two types of Ge film resistance thermometers: a - TTR-1A, b - TTR-1B.

EFFECT OF MAGNETIC FIELD ON Ge FILM THERMOMETERS

In cryogenic engineering and experimental physics there is a demand for miniature temperature sensors that can operate in a wide temperature range and in high magnetic fields. Such sensors must have high accuracy of temperature measurements in magnetic fields.

The behavior of the Ge film resistance thermometers has been studied in high magnetic fields up to 14 T. The orientation of the magnetic field with respect to the sensor is shown in Figure 1. In that configuration the transverse magnetoresistance has been observed in the thermosensitive Ge films ($\boldsymbol{j} \perp \boldsymbol{B} \| \boldsymbol{n}$, where $\boldsymbol{n}$ is the normal to the film surface, $\boldsymbol{B}$ and $\boldsymbol{j}$ are the vectors of the magnetic induction and current, respectively). The magnetic field dependencies of magnetoresistance (ΔR/R) for thermometers are given in Figure 5. The TTR-1A thermometer shows a positive magnetoresistance in the whole range of magnetic fields and temperatures. On the contrary, the TTR-1B thermometer shows a negative magnetoresistance below 4.2 K in magnetic fields up to 4 T. But at 77 K its magnetoresistance is positive.

The magnetoresistance causes an error in the thermometer reading. The error can be given as a ratio $\Delta T/T$ (%), where $\Delta T = T(B) - T$, T is the temperature measured at magnetic field $B = 0$, and $T(B)$ is the temperature measured at magnetic field B. The magnetic field dependent temperature errors, $\Delta T/T$ (%), for the Ge thin film thermometers at various magnetic fields and at 1.7, 4.2, and 77 K are displayed in Figure 6 and Table 1. At temperatures below 77 K the TTR-1B thermometer has the error in the temperature reading (caused by the magnetic field) much smaller than the TTR-1A thermometer has. At 77 K the temperature errors of both thermometers are close. The TTR-1B thermometer has small magnetic field-induced temperature errors, and can be used for temperature measurements at the presence of magnetic fields. The Ge film thermometers are better than typical bulk Ge thermometers if measurement in magnetic fields.^{4}

Table 1. Magnetic Field-Dependent Temperature Errors ΔT/T(%) at Magnetic Field

Sensor Type	T(K)	Magnetic field (T)			
		2.5	4	8	14
TTR-1A	1.7	-18.35	-28.72	-55.15	-
	4.2	-9.39	-14.82	-30.94	-54.77
	77.4	-0.13	-0.28	-0.85	-1.97
TTR-1B	1.7	1.04	-0.21	-4.62	-
	4.2	0.45	0.25	-2.61	-10.67
	77.4	-0.11	-0.23	-0.81	-2.25

RESISTANCE THERMOMETERS FOR THE 77 TO 400 AND 200 TO 500 K TEMPERATURE RANGES

We have fabricated thermometers intended for operating in the 77 to 400 and 200 to 500 K temperature ranges, designated as TTR-2 and TTR-3, respectively. A high compensation degree in the Ge film is required to reach higher thermal sensitivity at the temperatures above 77 K. Shown in Fig.7 are the characteristics of the TTR-2 and TTR-3 thermometers. Conduction in these thermometers is of activation type. The conductivity activation energy for TTR-2 thermometers is constant in the 77 to 400 K temperature range and may vary from 0.07 to 0.15 eV (depending on technological conditions of film preparation).

To fabricate the resistance thermometers for the 200 to 500 K temperature range, we have used the heavily doped and highly compensated (HDHC) Ge films[5, 6]. The resistivity versus temperature curve for a HDHC Ge film usually includes two exponential sections and may be described by the following expression:

$$\rho = \rho_1 \exp(E_1/kT) + \rho_2 \exp(E_2/kT).$$

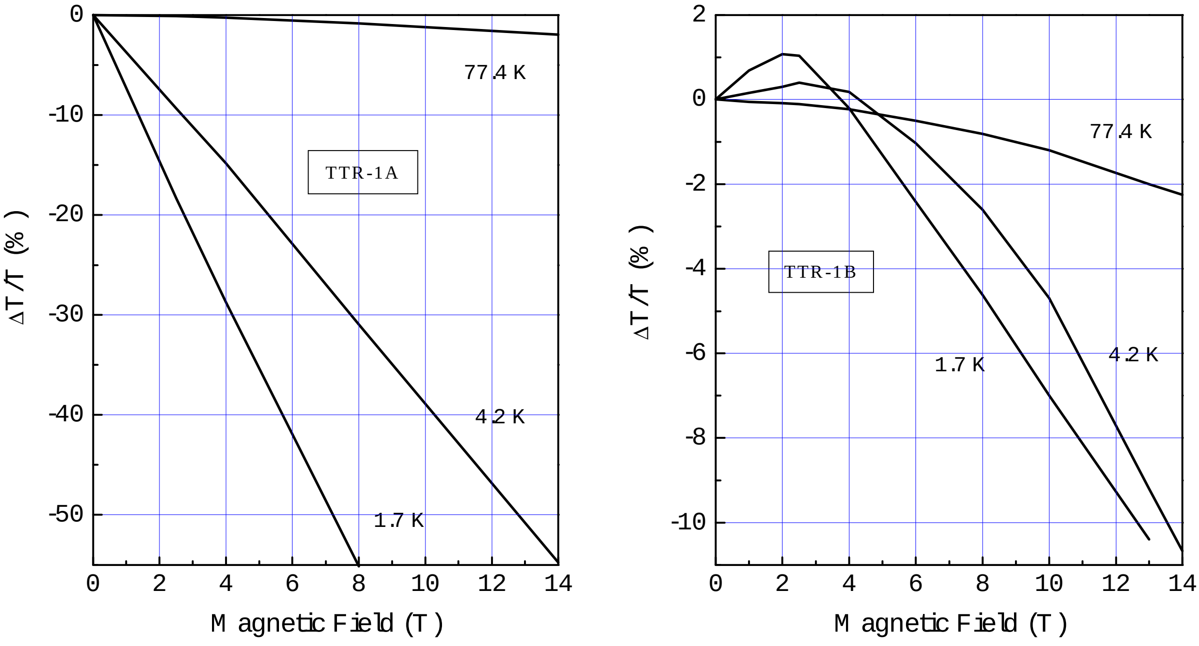

Figure 6. Temperature error in % versus magnetic field curves.

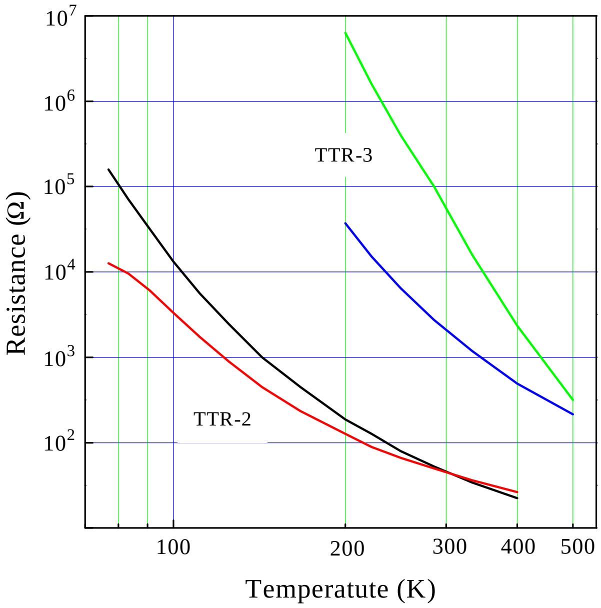

Figure 7. TTR-2 and TTR-3 thermometers resistance versus temperature curves.

A single-crystalline HDHC Ge film represents a complicated system of nonuniform composition. The properties of such a system are determined by the electrostatic potential fluctuations due to the nonuniform distribution of impurities.[5, 6]

At high temperatures the activation-type conduction in such films is determined by the thermionic emission of charge carriers from the Fermi level, ε_F, to the percolation level, ε_p. The activation energy is $E_1 = |\varepsilon_p - \varepsilon_F|$. Both ε_p and ε_F values depend on the compensation degree, dimensionality of the operating area and correlation in the impurity positions.[7] For the HDHC Ge films the activation energy of resistivity E_1 may reach half the band gap of Ge.[5, 6]

At low temperatures the conduction in HDHC Ge films is mostly realized through the localized states near the Fermi level and can be characterized by the activation energy $E_2 \neq E_1$. The temperature value at which a transition occurs from the conduction at the percolation level to that through the localized states depends on both the doping level and the compensation degree. It is determined by the two competing mechanisms, namely, thermionic emission and charge carriers tunneling in a potential relief. For the HDHC Ge films of the highest compensation degree the transition temperature is 250 - 290 K as a rule.[5, 6]

The resistance thermometers on the base of HDHC Ge films are characterized by a very high thermal sensitivity. Depending on the technological conditions of the Ge films preparation, this thermal sensitivity may be varied from 1.0 to 6.0 % K^{-1} (at $T = 300$ K).

CONCLUSIONS

Based on Ge films on GaAs substrates, several types of miniature resistance thermometers have been developed. Their operating temperature regions overlap the 0.5 to 500 K temperature range. A distinguishing feature in the fabrication technology of thermal sensitive elements is the possibility of obtaining the resistance thermometers of different both resistances and their temperature dependencies. Thermal sensitivities and resistances of such thermometers depend on the technological conditions of epitaxy. These conditions determine both the doping level and the compensation degree of Ge films. The thermometer resistance is also determined by the sensitive element topology. It is formed by photolithography and may be varied over wide limits. This enables one to fabricate thermometers which are intended for operating in different temperature ranges and whose operational characteristics can meet the user's demands.

The effect of magnetic field on some of there cryogenic thermometers has been studied. The Ge film thermometers designated as TTR-1B shows a small magnetic field induced temperature errors. Such thermometers can be used for temperature measurements under high magnetic fields.

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