http://www.moderntechno.de/index.php/meit/article/view/meit32-00-085
DOI: 10.30890/2567-5273.2024-32-00-085

UDC 621.316.825

SOME WAYS OF MEASURING TEMPERATURE AND MODERN SENSORS

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Abstract. *Several methods of measuring temperature and sensors for these purposes are considered. The main characteristics and designs of the technical means used are given. The main attention is paid to semiconductor temperature sensors based on the thermistor effect. The results of a study of thermistors based on dispersed germanium in the range from room to cryogenic temperatures are presented.*

Keywords*: sensors, temperature, thermistors, semiconductors, measurements.*

1. Introduction There are various methods, techniques and technical means of measuring temperature. Any properties of solid, liquid, gaseous substances that depend on temperature can be used to create a temperature sensor. For example, physical and chemical states, dimensions, electrical characteristics, etc. At the same time, sensors that utilize quite a small number of electrophysical properties of materials and measurement methods have found wide practical application. In [1-4] many methods and techniques of temperature measurement, designs and characteristics of various sensors are considered.

2. Main text

a. Thermodiodes and thermotransistors. Thermodiodes and thermotransistors are used in temperature sensors operating in the range from -80 to +150 °C. The upper limit of the temperature range is limited by thermal breakdown of the p-n junction and for some types of germanium sensors reaches 200 °C, and for silicon sensors up to 500 °C. The lower boundary of the temperature range of thermodiodes and thermotransistors is determined by the decrease in the concentration of the main carriers and can reach for germanium sensors -(240 - 260) °C, for silicon sensors -200 °C.

The main advantages of thermodiodes and thermotransistors are small dimensions, interchangeability and, most importantly, cheapness, allowing their use in sensors of single use.

b. Thermoelectric transducers (thermocouples). The principle of operation of a thermocouple is based on the thermoelectric effect [3], which consists in the fact that in a closed circuit consisting of two dissimilar conductors, a thermoelectric EMF (voltage) arises if the junction points of the conductors have different temperatures. If we take a closed circuit consisting of dissimilar conductors (thermoelectrodes), then on their junctions there will appear thermal EMF $\varepsilon(t)$ and $\varepsilon(t_0)$, which depend on the temperatures of these junctions t and t_0. Since the considered thermoelectrodes are included in a countermeasure, the resulting thermoelectric EMF acting in the circuit will be defined as ε(t) - ε(t_0).

In the case of equal temperature of both junctions the resulting thermoEMF will be equal to zero. In practice, one of the junction of the thermocouple is immersed in a thermostat (usually melting ice) and the temperature difference and temperature of the other junction are determined relative to it. The junction that is immersed in the controlled (investigated) medium is called the working end of the thermocouple, and the second junction (in the thermostat) is called the free end.

Thermocouples can be used to measure temperatures in the range from -270 to 2200 °C. To measure temperatures up to 1100 °C, thermocouples made of base metals are used, to measure temperatures between 1100 and 1600 °C, thermocouples made of noble metals and platinum group alloys are used. To measure even higher temperatures, thermocouples made of heat-resistant tungsten-based alloys are used.

Currently, platinum, platinum-rhodium, chromel, and alumel are most commonly used for thermocouples.

c. Thermometers based on the thermoresistive effect. The electrical resistance of most substances changes significantly with temperature. This dependence is used to create thermometers - thermoresistors [1, 4-7]. A thermistor is a device consisting of a current conductor whose electrical resistance depends on temperature and to which electrical leads are connected.

The temperature dependence of the electrical resistance of metals is due to the dependence of the mobility of current carriers (electrons), in semiconductors the main role is played by the temperature dependence of the concentration of current carriers.

The measuring range of thermometers is limited mainly by high temperatures, which affect the linearity of the sensor characteristic, as well as the mechanical properties of the material of the sensor sensing element and housing.

The temperature dependence of the resistance of metals can be expressed:

$$R = R_o(1+\gamma t) \qquad (1),$$

where R_o - resistance at 0 °C, γ - temperature coefficient of resistance, t - temperature in °C.

As materials for the sensitive element of the thermistor thermometer thermistor are used: platinum, nickel, copper, etc. Metal-based thermometer sensing elements are very thin wires wound on a frame or film deposited on an insulating substrate.

Typical dependences of resistance of some metals on temperature are shown in Figure 1. They indicate the possibility of obtaining a high degree of linearity of the relationship between resistance and temperature.

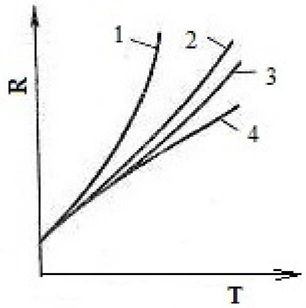

Figure 1. Characteristic dependences of resistance R of some metals on temperature T: ***1*** *- nickel,* ***2*** *- tungsten,* ***3*** *- copper,* ***4*** *– platinum.*

Source: built by the author based on [1].

d. Semiconductor resistance thermometers are temperature sensors (thermistors) that utilize the temperature dependence of the electrical resistance of a semiconductor [4-9]. This dependence can be expressed as:

$$R = R_o \cdot e^{B/T} \quad (2),$$

where R_o is the resistance at temperature T tending to infinity, B is the coefficient determining the sensitivity to temperature.

The exponential dependence shows a strong nonlinearity of the characteristic of such a thermometer and this is one of the main disadvantages of such a sensor. On the other hand such thermometers are the most sensitive to temperature change. At liquid helium temperatures their sensitivity can reach 100-200 %/K. In addition, the high resistance (up to 1 megohm) allows neglecting interference at the connection points of the wires of the electrical circuit. Semiconductors such as silicon, germanium, gallium arsenide, etc., as well as metal oxides [4] are used for manufacturing such thermometers.

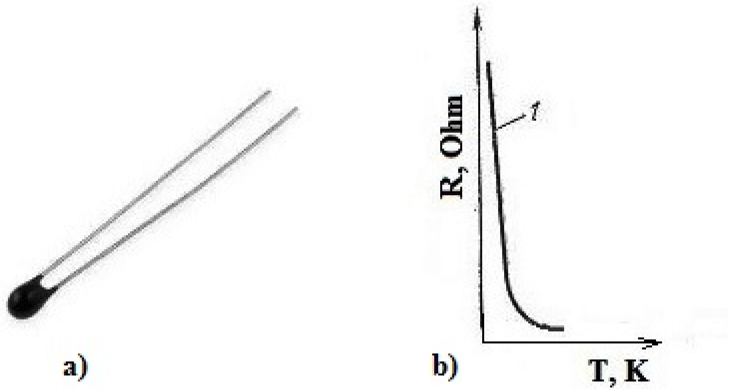

Figure 2. a) - sample of semiconductor miniature thermistor, b) - temperature dependence of resistance of a typical thermistor.

Source: built by the author.

Semiconductor thermometers can be of many different types. With the help of microelectronics technology, the sensing element of the thermistor can be made micro-miniature. Figure 2.a shows one of the designs of semiconductor thermometers.

The total size of thermistors can be less than 1 mm3, electrical resistance from several Ohm to 100 kOhm, supply currents, as a rule, 10 - 100 μA, sensitivity from 3 %/K in the area of room temperature to 100 %/K in the area of cryogenic temperatures, inertia can reach several tens of milliseconds and less.

In a wide temperature range, the temperature dependence of semiconductor resistance R(T) has a complex character and depends on the type of doping impurity and doping level. Therefore, it is impossible to express the dependence of R(T) by a simple formula that would allow to perform calibration with high accuracy. As a rule, the whole temperature range is divided into separate sections, where the dependence of R(T) is described by its own interpolation formula.

A group of semiconductor temperature-sensitive transducers used in thermometric devices are often referred to as thermistors. They have a non-linear characteristic but can be effectively used in systems for temperature measurement.

A typical characteristic of a thermistor is shown in Figure 2.b. Their temperature coefficient of resistance is significantly greater than that of metals. The resistance decreases with increasing temperature, i.e. their temperature coefficient of resistance is negative.

Thermistors are significantly smaller in size than metal resistive transducers and therefore respond more quickly to temperature changes. On the other hand, the small size of thermistors results in a small current required for self-heating. Therefore, it can be assumed that the current affects the accuracy of the measurement.

e. Low-temperature (cryogenic) resistance thermometers - thermistors. Temperature measurement in the cryogenic region. To measure temperature in the cryogenic region, semiconductor and metal sensors - resistance thermometers (thermistors), as well as thermocouples with suitable characteristics are used.

Among the known metallic resistance thermometers we can mention platinum thermistors, which are characterized by high metrological characteristics. However, for example, a magnetic field of B=2 Tesla at a temperature of 12 K causes a resistance rise equivalent to 5 K. It is considered possible to take into account the influence of the magnetic field only at temperatures above liquid nitrogen temperatures (77 K).

Rhodium-iron thermistors are less sensitive to magnetic fields. At a temperature of 4.2 K, a 3 Tesla field leads to a 3% increase in resistance (equivalent to about 0.5 K)

Among semiconductor thermistors, germanium thermistors are the most widely used [2,3,6-8]. They have good long-term stability, high sensitivity ($\cong$ 100 %/K at 4.2 K) and can provide accuracy of about 0.01 K. The germanium resistance thermometers are made of bulk germanium, dispersed germanium, germanium films on insulating substrates. There are known germanium thermistors, which due to low magnetoresistance value and in magnetic fields up to 6 Tesla provide accuracy at the level of 0,01 K.

In addition to germanium, other semiconductor materials, such as gallium arsenide, are also used for cryogenic thermistors. However, it is considered that metrological characteristics of such thermometers, as a rule, are worse than those of germanium thermometers.

There are also carbon sensors, resistance thermometers, which are often used in measuring temperatures in the cryogenic region in the presence of magnetic fields.

f. Cryogenic thermistors based on dispersed germanium. Pure germanium is not used in thermometry because at low temperatures it has a very high resistance, low sensitivity. Often measurements must be carried out under conditions of various external influences (presence of magnetic fields, etc.), which, affecting the resistance of pure germanium, can lead to significant errors. Currently, to obtain suitable electrophysical properties of bulk germanium, various rather expensive and labor-intensive doping methods are used. They also use germanium in film form. In some works cryogenic thermistors based on germanium films on semi-insulating gallium arsenide have been investigated. At 4.2 K they can have a sensitivity of about 20%/K, some are resistant to neutron irradiation at 77 K to doses of the order of 10^{15} cm^{-2}.

We have studied experimental samples of thermistors [5,7-9] based on bulk dispersed germanium obtained by mechanical pressing at different temperatures and pressures of finely dispersed powder of monocrystalline germanium. The aim of the study was to create thermistors for the temperature range of 4.2-300 K resistant to extraneous external influences. The temperature dependence of electrical resistance in the above temperature range, magnetoresistance at T=4.2 K and the effect of neutron irradiation on electrical resistance at room temperatures were studied [9].

Dispersed germanium was obtained from powder of monocrystalline germanium of *n*-type conductivity with a resistivity of 15 Ohm.cm,. Samples were produced by exposure to high pressures and temperatures. It was found that the pressure and temperature at which the powder was pressed determine the electrophysical properties of the obtained dispersed germanium. For creation of thermoresistors for cryogenic temperatures the most suitable samples were used. The obtained dispersed germanium had p-type conductivity, specific resistance at room temperature $\rho = (1\text{-}4)$ Ohm.cm. It can be assumed that the acceptor levels are due to the peculiarities of the crystal structure of the obtained material. The peculiarities of the structure of dispersed (powder) germanium can also explain the increased radiation resistance of such material.

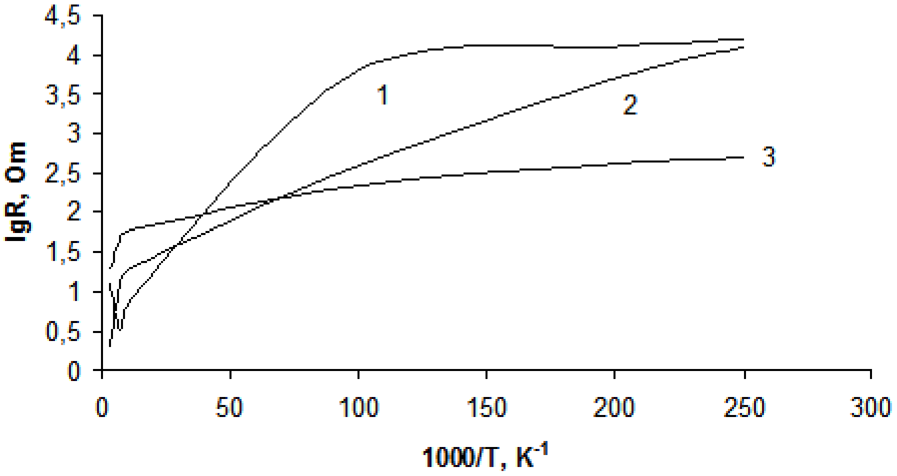

Figure 3. Temperature dependence of electrical resistance:
1 *- bulk initial monocrystalline germanium,* ***2*** *- thermistor based on dispersed germanium type A,* ***3*** *- thermistor based on dispersed germanium type B. Types A and B differ in temperature and pressure value when obtaining dispersed germanium - pressure 6 GPa and temperature 700 °C (type A) and 500 °C (type B).*

Source: built by the author.

The results of measurements of temperature dependence of electrical resistance are presented in Figure 3. It shows the temperature dependence of resistance of single-crystal bulk germanium of *n*-type conductivity (curve 1) and experimental thermistors from dispersed germanium (curves 2,3).

The temperature dependence of the electrical resistance of thermistors made of dispersed (powder) germanium type A (curve 2) at low temperatures is steeper than the dependence of monocrystalline original germanium and in the whole temperature range has a more monotonic character. The smooth character of the temperature dependence of the electrical resistance allows to approximate it with mathematical formulas quite simply and with good accuracy. For a sample of type A, for example, even for the temperature range 77-300 K using a polynomial of the form

$$\ln R = \sum_{i=0}^{n} A_i(\ln T) \qquad (3),$$

where Ai - constant coefficients determined by the least squares method, n - determined from the condition of the smallest approximation error) already for n =3 we obtain the dependence

lnR = 15.1077031+1.6552736*lnT - 1.7901811*(lnT)2 + 0.193233*(lnT)3

with correlation coefficient r2 = 0.9995 and an error of about 0.1 K in the 77K region.

The sensitivity of type A thermistors in the liquid helium temperature region (4.2 K) reaches values of more than 100 %/K. Sensitivity of thermistors made of type B material is about 20 %/K and at 4.2 K they have electrical resistance as a rule not exceeding 500 Ohm.

Figure 4 shows the dependence of the error ΔT of temperature measurement in the liquid helium region in the presence of magnetic fields on the magnitude of the magnetic field. The error of thermistors made of A-type material (curve 1) in the 8 Tesla field is approximately 0.02 K, and that of B-type thermistors in the 4 Tesla field reaches 0.15 K.

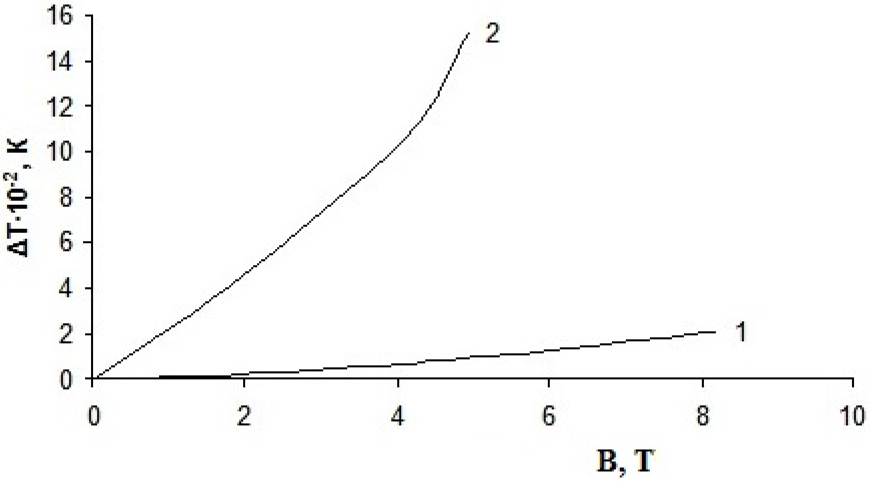

Figure 4. Dependence of the temperature measurement error ΔT in the region of 4.2 K on the magnetic field B for thermistors of type A (curve 1) and type B (curve 2).

Source: built by the author.

Conclusions

Some of the known methods and means of temperature measurement are considered. The main characteristics of applied sensors and measurement techniques are given. Advantages and disadvantages of certain methods of temperature measurement are analyzed. Special attention is paid to the possibilities of temperature measurement by semiconductor thermistors in a wide temperature range. High sensitivity of the developed thermistors based on dispersed germanium, their suitability for temperature measurement in the cryogenic range, high accuracy in the presence of magnetic fields are shown.

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