Analysis of Technical Characteristics of Temperature Sensors for the Design of Medical Thermometers

Serhii Moroz
Department of Electronics and Telecommunications Lutsk National Technical University
Lutsk, Ukraine
s.moroz@lntu.edu.ua

Anatolii Tkachuk
Department of Electronics and Telecommunications Lutsk National Technical University
Lutsk, Ukraine
a.tkachuk@lntu.edu.ua

Valentyn Zablotskyi
Department of Electronics and Telecommunications Lutsk National Technical University
Lutsk, Ukraine
v.zablotsky@lntu.edu.ua

Stanislav Prystupa
Department of Electronics and Telecommunications Lutsk National Technical University
Lutsk, Ukraine
s.prystupa@lntu.edu.ua

Valentyn Talakh
Department of Finance, Banking and Insurance Lutsk National Technical University
Lutsk, Ukraine
talaxvi@gmail.com

***Abstract*—The paper analyzes the technical features that must be taken into account during the construction of medical thermometers. An analysis of thermometers was carried out from the point of view of their suitability for monitoring temperature fluctuations on the surface of a biological object. The dependence of the resolution of the thermometer for different temperature ranges is considered. Expanding the range of measured temperatures leads to a decrease in the transmission coefficient, and vice versa, a decrease in the range leads to an increase in the steepness by the same number of times. A comparative analysis of various types of temperature sensors was carried out, in particular, a temperature-voltage converter (TC1047) from Microchip in a SOT23 case, a thermosensor (SMT16030) from Smartec in a TO18 case, a thermistor (203JG1F) from NTC in a DO35 case, (LM19) from National Semiconductor in a TO92 case, and (TSIC306) by Hygrosens in the SO8 case. The informativeness coefficients of the conversion of thermal sensors, and the dependence of the thermal time constant on the mass of the sensor in different types of housing are considered. It has been established that thermometers with sensors based on semiconductor diodes have a high perspective since sensors of this type provide high speed, short response time, operation in the mode of microcurrents, which maximally reduce self-heating of the sensor, high sensitivity, good linearity in a given temperature range (25...40°C), stability of electrical parameters. Along with high operational characteristics, sensors based on a semiconductor diode have a low cost.**

Keywords—Medical Thermometer, Thermosensitive Element, Semiconductor Diode, Thermal Resistance.

I. INTRODUCTION

The human body in a healthy state is able to regulate the temperature of the central nervous system, internal organs, and large vessels with a deviation within 0.1°C. Human body temperature is the balance between heat generation in the body and heat loss through the body surface, especially the skin (up to 90...95%). Heat is mainly released through the skin and by respiration and evaporation of moisture from the skin's surface. Heat transfer occurs according to the laws of physics: heat conduction, convection, and radiation [1, 2].

When measuring temperature, an objective assessment of the quality of measuring devices is carried out according to the following main indicators: sensitivity, range, accuracy, ease of calibration, stability, frequency range, absence of noise and unwanted signals, and ease of use [3].

There are 2 types of electronic medical thermometers that use different electronic temperature transmitters with a heat-sensitive element, 1 - contact, 2 - non-contact. Non-contact thermometers use pyrometers as heat-sensitive elements. Pyrometers are usually used to measure high temperatures, but with the development of the electronic base of radioelements, practical designs for low temperatures have been developed. Common types of electronic thermometers are contact thermometers, there are 3 subclasses of contact electronic sensors (resistance thermometers, semiconductor thermometers, and thermometers based on thermocouples) (Fig. 1) [4].

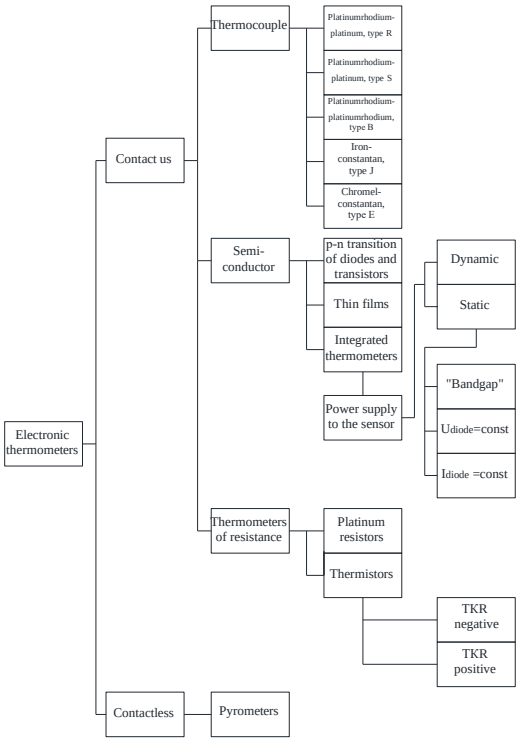


Fig. 1. Types of electronic thermometers that use different temperature sensors. Source: compiled by the author based on: [3, 4]

XXX-X-XXXX-XXXX-X/XX/$XX.00 ©20XX IEEE

All these 3 classes have subclasses depending on different properties, sensor material (thermocouples), methods of connecting the sensor to the thermometer circuit (semiconductor temperature sensors), the method of changing electrical quantities (voltage, current, resistance) due to changes in physical quantities (temperature) [5].

II. Literature Review

The effect of temperature on the electro-physical parameters of semiconductors is manifested in a change in the concentration of charge carriers, which leads to a corresponding change in electrical conductivity [6]. Semiconductor thermistors work on this principle. Diodes and transistors are also used as semiconductor temperature sensors, where a change in the concentration of charge carriers leads to a change in the current flowing through the semiconductor device [7]. Table 1 lists common temperature sensors and their features.

TABLE I. Types and features of common temperature sensors

Thermocouple	RTD	Thermistor	Semiconductor sensor
Range: -184...+2300°C	Range: -200...+850°C	Range: 0...+100°C	Range: -55...+150°C
High accuracy and reproducibility	Qualitative linearity	Strong nonlinearity	Linearity: 1°C
Requires voltage compensation on cold (support) junction	Requires current excitation	Requires current excitation	Requires current excitation
Low voltage output	Low cost	High sensitivity	Typical output signal - 10 mV/°C, 20 mV/°C or 1 μA/°C

Despite the improvement of electronic thermometers and the gradual replacement of mercury thermometers with electronic ones, the problem of increasing their speed remained unsolved for a long time. It should be noted that since the temperature of the environment is lower than the temperature of the human body (normal measurement conditions are meant), the touch of the thermometer to the surface of the skin causes cold irritation, as a result of which the vessels of the superficial plexus, as a rule, narrow, and the deep ones, on the contrary, are expanding [8]. This leads to a decrease in the temperature of the outer layers of the skin, and therefore to a decrease in heat transfer. At the same time, the temperature of the deep layers of the skin increases, which protects them from cooling, so the heating of the sensitive element and part of the body of the thermometer comes from the surface layer of the skin. This means that at the moment of thermal contact, the heat transfer from the human body to the sensitive element of the thermometer decreases sharply (blood is the main carrier of heat). This increases the temperature measurement time [9, 10].

The measurement time will be shorter, the closer the initial temperature of the sensitive element of the thermometer is to the temperature being measured. So, one of the ways to increase the speed of thermometers is to pre-heat them to a temperature close to the measured value. It is not only a matter of reducing the transient component at the initial moment of measurement (it is equal to the difference between the set and initial temperature values of the sensitive element). Here, it is advisable to apply compensatory measurement, when the sensitive element of the thermometer is heated not by the object of measurement, but beforehand [11]. The touch of a heated thermometer causes thermal irritation, which is accompanied by the expansion of blood vessels of the skin of both plexuses (superficial and deep), but this leads to an increase in heat transfer from the human body to the sensitive element of the thermometer, that is, a decrease in the time of temperature measurement. So, if you apply preliminary heating of the thermometer (technically it is not difficult to implement), then the option when the initial temperature of the thermometer exceeds the measured value will be appropriate [12, 13].

III. Research Methodology

The purpose of the article is to analyze the quality indicators and characteristics of temperature sensors based on semiconductor diodes and transistors and formulate conclusions and recommendations for practical use in the manufacture of electronic thermometers.

To achieve the goal, the following tasks must be solved:

1. Analysis of thermometers from the point of view of their suitability for monitoring temperature fluctuations on the surface of a biological object.

2. Investigate the dependence of the resolution of the thermometer for different temperature ranges.

3. Determination of the dependence of the speed of the thermometer on the mass of the sensor.

4. Study of the thermal resistance of the transducer as an important factor characterizing the effect on its internal self-healing.

Let's consider existing serial thermometers from the point of view of their suitability for monitoring temperature fluctuations on the surface of a biological object. We will analyze their technical parameters and characteristics, such as speed and resolution. The most important qualitative indicators of various thermal sensors, taking into account their use in a narrow temperature range, are listed in the Table 2. The symbol '+ + +' indicates a high level of suitability for this parameter, '+ +' and '+' respectively mean and low.

TABLE II. Quality indicators of temperature sensors

Sensor view	Parameters of thermometers in the narrow temperature range (20…40°C)					
	Speed action	Expansion	Precision	Sensitivity	Linearity	Stability
Thermistor	+ + +	+	+	+ + +	+	+ + +
Pyrometer	+ + +	+ + +	+	+ +	+ +	+ +
Thermometer resistance	+ +	+ +	+	+ +	+ + +	+ + +
Thermocouple	+ + +	+	+	+ +	+ +	+ + +
Diode (c)	+ +	+ + +	+ +	+ +	+ + +	+ +
Diodes (b/c)	+ + +	+ + +	+ +	+ + +	+ + +	+ +

From the comparison of the given parameters of the transducers, it can be concluded that the most suitable for the mentioned purposes are semiconductor diode transducers in caseless design, which have a higher speed. It should be noted that pyrometers also have high speed, but their disadvantages include low sensitivity and high cost. The resolution of the thermometer (slope) is related to its transmission coefficient V/°C, since the output voltage of the

operational amplifier is limited to the range of 3…10 V, and is a constant value. Expanding the range of measured temperatures leads to a decrease in the transmission coefficient, and vice versa, a decrease in the range leads to an increase in the slope by the same number of times. It is important to note that with a limited maximum output voltage of the thermometer, there is a constancy of reproducing the range of controlled temperatures ΔT by the temperature-to-voltage conversion factor U/°C. The specified dependence of the steepness of the characteristic for different temperature ranges is shown in Fig. 2. at $U_{out\ max}$ = 10 V.

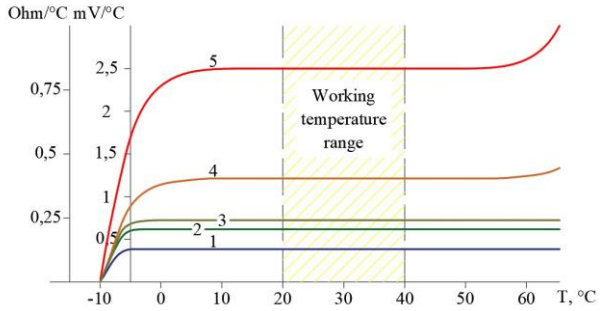


Fig. 2. Coil characteristic for different temperature ranges at Uout max = 10 V; 1 - thermocouple (K); 2 - thermocouple (J); 3 - thermocouple (E); 4 - thermistor (pt100); 5 - semiconductor diode

The output signals of thermal sensors differ in their conversion function, so a thermocouple converts temperature into voltage, and thermosensitive sensors change their resistance when the temperature changes. There are two types of thermistors with positive and negative temperature coefficients of resistance. Semiconductor diode sensors are characterized by a decrease in direct voltage when the temperature increases. An evaluation of the coefficient of informativeness of temperature conversion of contact thermal sensors is proposed in Table 3.

TABLE III. THE COEFFICIENT OF INFORMATIVENESS OF THE TRANSFORMATION OF TEMPERATURE SENSORS ACCORDING TO FIG. 2

Sensor type	Temperature coefficient transformation	Informativeness of the output parameter in the temperature range 20…40°C, %
Thermocouple (K)	41 μV/°C	0.0082
Thermocouple (J)	55.2 μV/°C	0.011
Thermocouple (E)	68 μV/°C	0.0136
Thermistor (pt100)	0.38 Ω/°C	0.076
Semiconductor diode	2.5 mV/°C	0.50

From the conducted evaluation, it follows that the informativeness of the transformation of a physical quantity (temperature) into an electrical parameter is greater in semiconductor diodes, which leads to an increase in the resolution of the sensor.

IV. RESULTS

It was established that the speed of the thermometer is deter-mined by the mass of the sensor since it is set by the value of the thermal time constant. Areas illustrating this relationship (Fig. 3) for some types of sensors in different types of cases (Fig. 4), for example, a temperature-voltage converter (TC1047) by Microchip in a SOT23 case, a thermal sensor (SMT16030) by Smartec in a TO18 case, thermistor (203JG1F) of the NTC company in the DO35 case, (LM19) of the National Semiconductor company in the TO92 case, and (TSIC306) of the Hygrosens company in the SO8 case. Thermal time constants term in still air for the housings of semiconductor sensors, depending on their mass, are shown in Fig. 3.

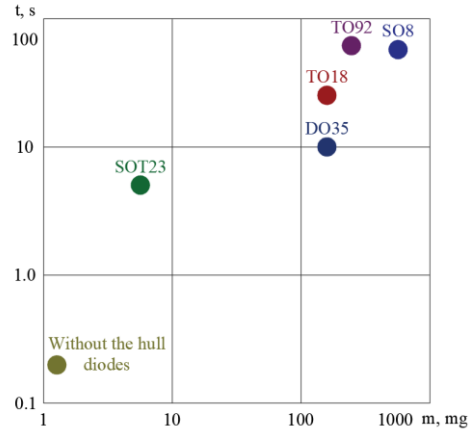


Fig. 3. Dependence of the thermal constant time on the mass of the sensor in different types of cases

For high-speed biothermometry, it is necessary to use sensors with a minimum mass, in particular, caseless semiconductor diodes and transistors. The second important factor of the sensor, which characterizes the effect on its internal self-heating, is thermal resistance.

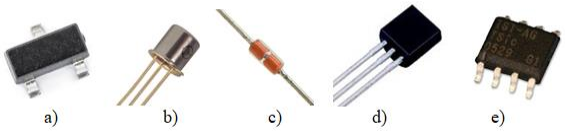


Fig. 4. Types of thermal sensors: a) TC1047; b) SMT16030; c) 203JG1F; d) LM19; e) TSIC306

The thermal resistance R_{th} of the housings of semiconductor sensors is found by dividing the difference between the transition temperatures T_j and the ambient temperature T_a,

$$R_{th} = \frac{T_j - T_a}{P} \quad (1)$$

where R_{th} is the thermal resistance in the area of the thermal circuit, °C/W; T_j - transition temperature, °C; T_a - ambient temperature, °C; P is the power dissipated at the junction, W.

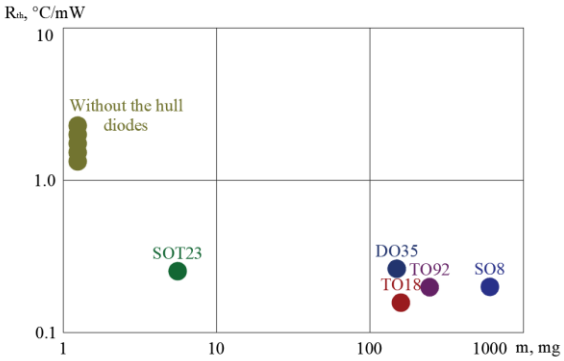


Fig. 5. Dependence of the thermal resistance of temperature sensors on their mass in different case designs

Figure 5 shows data on the relationship between mass and thermal resistance of several common types of integrated circuit housings.

V. CONCLUSIONS

From the analysis of Fig. 4, it follows that for monitoring temperature oscillations of the body surface, the most effective are caseless semiconductor diode and transistor (in diode connection) temperature sensors with a thermal time constant in the range of hundredths of a second and a thermal resistance of 2…5 °C/mW.

As a sensitive element, it is recommended to choose a caseless diode or transistor, the dimensions of which do not exceed 1 mm with a mass of up to 0.5 g. As the mass of the sensor decreases, the mass of the thermometer itself decreases, which has a positive effect on the thermal time constant (it decreases) and therefore increases the speed work the device.

To ensure high sensitivity in the temperature range of 20...40°C, a diode sensor should be used in the mode of operation with a constant voltage Upr, with an output temperature-dependent parameter of the diode current. The specified mode of power supply of the diode ensures the temperature sensitivity of the sensor is five times higher than when powering the diode with direct current and the output parameter in the form of direct voltage.

So, sensors based on a semiconductor diode provide high speed, short response time, and operation in the mode of microcurrents, which would maximally reduce the self-heating of the sensors, high sensitivity, good linearity in a given temperature range (25...40°C), stability of electrical parameters.

REFERENCES

[1] Y. -S. Chen, Y. -R. Chuang, H. -H. Chiang and Y. -L. Chen, "The Design of an Automatic Body Temperature Regulator," 2019 IEEE International Conference on Consumer Electronics - Taiwan (ICCE-TW), Yilan, Taiwan, 2019, pp. 1-2, doi: 10.1109/ICCE-TW46550.2019.8991786.

[2] R. J. Crosbie, J. D. Hardy and E. Fessenden, "Electrical Analog Simulation of Temperature Regulation in Man," in IRE Transactions on Bio-Medical Electronics, vol. 8, no. 4, pp. 245-252, Oct. 1961, doi: 10.1109/TBMEL.1961.4322924.

[3] H. -F. Tang and K. Hung, "Design of a non-contact body temperature measurement system for smart campus," 2016 IEEE International Conference on Consumer Electronics-China (ICCE-China), Guangzhou, China, 2016, pp. 1-4, doi: 10.1109/ICCE-China.2016.7849773.

[4] F. Ghassemi, M. S. Hoseinzadeh and A. Ekhlasi, "Design and Implementation of Wireless Body Temperature Monitor with warning system via SMS," 2020 6th Iranian Conference on Signal Processing and Intelligent Systems (ICSPIS), Mashhad, Iran, 2020, pp. 1-5, doi: 10.1109/ICSPIS51611.2020.9349541.

[5] H. Fajrin, M. Ilahi, B. Handoko та I. Sari, «Моніторинг температури тіла на основі телемедицини», Journal of Physics: Conference Series , vol. 1381, № 1, стор. 012014, 2019.

[6] Z.-j. Fu and X.-y. Hou, "Implementation of non-contact hunman-body thermometer based on TS118-1", Journal of Jiangsu teachers university of technology, vol. 13, pp. 6-10, 2007.

[7] Moroz, S.A., Khvyshchun, M.V., Tkachuk, A.A., Lyshuk V.V., Prystupa, S.O.: Investigation of Features of Functioning of the Pyroelectric Sensors in Electronic Security Devices. IEEE 12th International Conference on Electronics and Information Technologies (ELIT), pp. 27-32, (2021) https://doi.org/10.1109/ELIT53502.2021.9501138

[8] Lavia C, Bonnin S, Maule M, Erginay A, Tadayoni R, Gaudric A. VESSEL DENSITY OF SUPERFICIAL, INTERMEDIATE, AND DEEP CAPILLARY PLEXUSES USING OPTICAL COHERENCE TOMOGRAPHY ANGIOGRAPHY. Retina. 2019 Feb; 39(2):247-258. doi: 10.1097/IAE.0000000000002413. PMID: 30550527; PMCID: PMC6358199.

[9] I. Opriş, "Predicting temperature in thermometers with high response time," 2017 10th International Symposium on Advanced Topics in Electrical Engineering (ATEE), Bucharest, Romania, 2017, pp. 892-897, doi: 10.1109/ATEE.2017.7905023.

[10] C. A. Boano, M. Lasagni, K. Römer and T. Lange, "Accurate Temperature Measurements for Medical Research Using Body Sensor Networks," 2011 14th IEEE International Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing Workshops, Newport Beach, CA, USA, 2011, pp. 189-198, doi: 10.1109/ISORCW.2011.28.

[11] M. Herrejón-Escutia et al., "Compensation of the Temperature Measurement Signal in an Experimental Dilatometer by Joule Heating and Controlled Atmosphere," 2018 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC), Ixtapa, Mexico, 2018, pp. 1-5, doi: 10.1109/ROPEC.2018.8661443.

[12] M. Morega, A. M. Morega and A. Săndoiu, "Sensitivity to parameters variation in numerical simulation of microwave thermotherapy," 2015 9th International Symposium on Advanced Topics in Electrical Engineering (ATEE), Bucharest, Romania, 2015, pp. 313-316, doi: 10.1109/ATEE.2015.7133821.

[13] H. -D. Nguyen, T. -H. Huynh, T. -T. Dai and T. -N. Tran, "Measuring the Distance Body Temperature in Real-Time based on the Recursive Least Square Estimation," 2022 6th International Conference On Computing, Communication, Control And Automation (ICCUBEA, Pune, India, 2022, pp. 1-6, doi: 10.1109/ICCUBEA54992.2022.10010841.