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# FUNCTIONALLY INTEGRATED DEVICE FOR TEMPERATURE MEASUREMENT

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***Abstract.*** *The article presents a method of implementing a functionally integrated device for temperature measurement, which allows for controlled heating of the primary temperature transducer, measurement of the heating temperature as well as the temperature and differential temperature of the investigated and reference samples. The heating speed is regulated by the selection of the frequency and duration of the control impulses. To measure the temperature and temperature difference, it is proposed to use measuring currents of different polarity, which make it possible to simplify the device design. The methods of linearisation of the conversion function of primary temperature transducer based on the formation of compensating currents in given measurement ranges have been investigated. The conducted studies showed that the temperature measurement error does not exceed 0.11°C and 0.005°C in the control heating mode and in the temperature measurement mode, respectively. The temperature measurement error of the investigated and reference samples and the differential temperature measurement error does not exceed ±0.003°C and 0.001°C, respectively.*

**Keywords**: temperature measurement, transistor, linearisation

## FUNKCJONALNIE ZINTEGROWANY PRZYRZĄD DO POMIARU TEMPERATURY

***Streszczenie.*** *W artykule przedstawiono sposób realizacji funkcjonalnie zintegrowanego przyrządu do pomiaru temperatury, który pozwala na kontrolowane nagrzewanie pierwotnego przetwornika temperatury, pomiar temperatury nagrzewania, a także pomiar temperatury i różnicy temperatur próbki badanej i referencyjnej. Prędkość nagrzewania jest regulowana poprzez wybór częstotliwości i czasu trwania impulsów sterujących. Do pomiaru temperatury i różnicy temperatur proponuje się stosowanie prądów pomiarowych o różnej polaryzacji, co pozwoliło uprościć ogólną konstrukcję urządzenia. Badano metody linearyzacji funkcji przetwarzania pierwotnego przetwornika temperatury bazującego na tworzeniu prądów kompensacyjnych w określonych zakresach pomiarowych. Przeprowadzone badania wykazały, że błąd pomiaru temperatury nie przekracza odpowiednio 0,11°C i 0,005°C w trybie kontrolowanego nagrzewania i w trybie pomiaru temperatury. Błąd pomiaru temperatury próbki badanej i referencyjnej oraz błąd pomiaru różnicy temperatur nie przekracza odpowiednio ±0,003°C i 0,001°C.*

**Słowa kluczowe**: pomiar temperatury, przetworniki tranzystorowe, linearyzacja

## Introduction

Control and monitoring of temperature and heat fluxes are important in many fields, especially in power engineering, environmental protection and medicine [1, 2, 11, 12, 33]. One type of heat flux field measurements is microcalorimetry, in which the differential temperature measurements of the investigated and reference samples are used. Microcalorimetry is used in fundamental and applied research, for example in chemistry [9, 32]. Recently, it has increasingly been used in biological and medical research [10, 14]. Microcalorimetry allows studying the metabolism and growth of human cell cultures. It can be an excellent tool for rapid detection of infection or microbial contamination of clinical products or samples [10], drug susceptibility testing and drug screening in microbiology [15]. Differential scanning calorimetry is used to determine the denaturation temperature of collagen proteins [21, 26]. In this case collagens were denatured in the temperature range from 20 to 120°C. Also, differential scanning calorimetry is used for the qualitative and quantitative thermal analyses of crystalline and amorphous d(−)-fructose. The equilibrium melting temperatures are close to 97°C [25]. The double-needle method can be used to measure the thermal properties of biological tissues as the temperature changes [4, 22]. These methods make it possible to analyse and detect changes in the temperature of a sample of small volume in the range from nanoliters (nl) to picoliters (pl) [20, 23].

In order to measure the temperature of the investigated and reference samples, as well as the temperature difference during heating, different sensors can be used [34]. The most common are thin film temperature sensors, such as RTDs, thermocouples or transistors [7, 16–19, 27, 29, 31].

A new trend in the development of modern sensors is the improvement of functional integration, which involves combining multiple complementary measurement methods into a single sensor device [3, 5, 6]. This integration allows for greater versatility in sensor applications. Functional integration enables the sensor to perform tasks such as controlled heating of the sample under investigation, following a predefined heat flow modulation algorithm. Additionally, it allows for precise measurement of the sample's temperature or the temperature change between the investigated sample and a reference sample, significantly enhancing the sensor's diagnostic capabilities.

Transistor structures can be used to conduct controlled heating of investigated samples as well as to measure heat flow. They provide high sensitivity of temperature measurement in biochemical and medical investigations in the range of -10 +100°C [8, 13, 26, 28].

The voltage drop at the forward-biased p-n junctions is mainly used as an informative parameter of primary temperature transducers based on transistor structures. The main problem that arises in this case is a significant dispersion of the characteristics of different transistors, which causes problems when replacing them in operational conditions. Accordingly, when designing temperature transducers on transistor structures, it is necessary to ensure that temperature-dependent parameters are brought to nominal (normalised) values. Nominal values of temperature-dependent parameters change in the temperature range of measurements. Therefore, in order to increase the accuracy of measurement in a wide range of temperatures, it is necessary to ensure the linearisation of the transformation function [24, 30].

The purpose of the work is the development of a functionally integrated device based on semiconductor transistor structures for biochemical and medical research.

## 1. Functionally integrated device with controlled heating

The design of a functionally integrated device is shown in Fig. 1. It includes: 1 – passive thermostat, 2 – places for investigated and reference samples, 3 – primary temperature transducers, 4 – heat equalising element, 5 – dual-function temperature transducer. The dual-function temperature transducer provides the necessary heat flow, which is evenly transmitted to the places (2) through the heat equalising element (4) and, accordingly, to the investigated and reference samples. The temperature difference between the samples is measured by transistor primary temperature transducers (3). A passive thermostat is used to reduce heat dissipation (1). Primary temperature transducers (3) are connected to the differential temperature transducer, which measure the temperature and temperature difference of the investigated and reference samples.

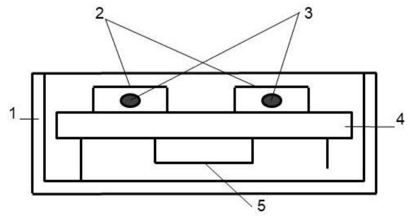


*Fig. 1. The design of the functionally integrated device*

The designed structural diagram of the dual-function temperature transducer, which provides controlled heating of the primary temperature transducer and measurement of the heating temperature, is shown in Fig. 2.

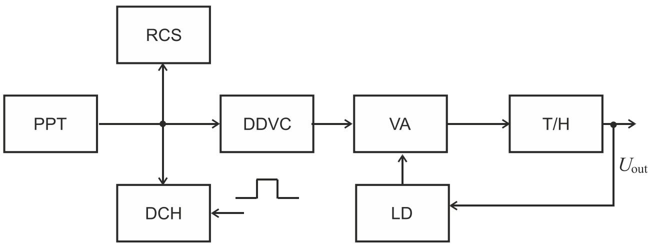


*Fig. 2. Structural diagram of a dual-function temperature transducer*

The proposed structural diagram of the dual-function temperature transducer includes a primary temperature transducer based on transistor PTT, a reference current source RCS, a device for controlling the heating of the primary transducer DCH, a device for determining the primary transducer voltage change with temperature DDVC, a voltage amplifier VA, track and hold circuit T/H and a device for linearisation of the conversion function of the primary transducer LD.

The proposed dual-function temperature transducer operates in two modes: controlled heating and temperature measurement modes. It enables temperature regulation during the heating process and precise temperature measurement.

To ensure two different modes of operation, it is proposed to generate currents of different values passing through the collector of the transistor. The choice of controlled heating and measurement modes is suggested to be carried out sequentially or periodically with impulses of the selected frequency. Control of the thermal process is carried out by changing the duration of the heating impulses. In the absence of impulse, the process of measuring the temperature of the transistor structure takes place. To ensure the required speed of the heat flow of heating the investigated sample and the reference sample, the temperature of the controlled heating is measured.

In the temperature measurement mode, the measuring current from the RCS is supplied to the PTT, and accordingly, at the output of PTT, we obtain:

$$U_t = U_{be0} - \Delta U_{bet} t \tag{1}$$

where $U_{be0}$ is the value of the initial output voltage of the PTT at 0°C, $\Delta U_{bet}$ is the value of the PTT voltage change due to the temperature change of 1°C, and $t$ is the value of the measured temperature.

The PTT voltage enters the DDVC input, which fully compensates for the constant component of the PTT output voltage, and accordingly, the DDVC output voltage is described by the expression:

$$U_1 = \Delta U_{bet} t k_1 \tag{2}$$

where $k_1$ is the DDVC conversion coefficient.

The output voltage of the DDVC enters the input of the VA, the voltage at the output of which is equal to

$$U_2 = \Delta U_{bet} t k_1 k_2 \tag{3}$$

where $k_2$ is the conversion coefficient of VA in the corresponding measurement range.

By analysing the expression it can be seen that to ensure the equality of the output voltage to the numerical value of the measured temperature the following condition should be ensured:

$$\Delta U_{bet} k_1 k_2 = 10mV/°C \tag{4}$$

Accordingly, we will obtain the value of the measured temperature:

$$t = \frac{U_2 mV}{10mV/°C} \tag{5}$$

The output voltage of the VA enters the input of the T/H circuit, the output voltage of which is equal to:

$$U_2 = \Delta U_{bet} k_1 k_2 t \tag{6}$$

The output voltage of the T/H circuit is the output voltage of the dual function temperature transducer and it enters the input of the LD linearisation device. From the LD the voltage enters the VA input, and at the output of the temperature transducer one can obtain:

$$U_{out} = \Delta U_{bet} k_1 k_2 [t - (t - t_0) k_l] \tag{7}$$

where $k_l$ is the LD conversion coefficient in the corresponding measurement range, and $t_0$ is the temperature value at the beginning of the corresponding measurement range.

In the controlled heating mode, control impulses are put to the input of the DCH device. Accordingly, the DCH switches the PTT to the controlled heating mode. With this choice of voltage and current for heating the PTT, a heat flow for heating the investigated and reference samples is formed.

Control of the heat flow is carried out by choosing the frequency and duration of the control impulses. After the end of the control impulse, a reference measuring current passes through the PTT and a voltage proportional to the heating temperature of the PTT is applied to the T/H input. At the same time, the VA output voltage is saved by the T/H device and is stored during the next heating impulse. The heat flow of the PTT through the heat-conducting element is transmitted to the investigated sample and the reference one.

The structural diagram of the designed differential temperature transducer is shown in Fig. 3.

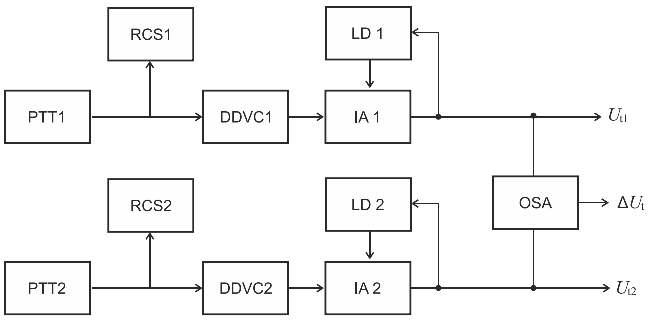


*Fig. 3. Schematic diagram of the transistor based differential temperature transducer*

It contains primary temperature transducers based on transistors PTT1, PTT2, reference current sources RCS1, RCS2, devices for determining voltage changes of the primary transducers DDVC1, DDVC2 with temperature, inverting amplifiers IA1, IA2, devices for linearising the conversion function LD1, LD2 and the output summing amplifier OSA.

The reference current source RCS1 forms a measuring current of negative polarity and at the output of PTT1 we obtain a voltage described by the expression:

$$U_{t1} = -U_{t10} + \Delta U_{t1} t_1 \tag{8}$$

where $U_{t10}$ is the voltage value of the PTT1 at t = 0 °C, $\Delta U_{t1}$ is the PTT1 voltage change value due to the temperature change of 1°C, and $t_1$ is the measured temperature.

The RCS2 source forms a measuring current of positive polarity and the PTT2 voltage is determined by the following expression:

$$U_{t2} = U_{t20} - \Delta U_{t21} t_2 \tag{9}$$

The output voltages of the PTT1 and PTT2 are fed to the inputs of DDVC1 and DDVC2, at the outputs of which voltages are formed:

$$U_1 = -\Delta U_{t1} k_{U1} \quad U_2 = \Delta U_{t2} k_{U2} \tag{10}$$

where $k_{U1}$, $k_{U2}$ are the conversion coefficients of the DDVC1 and DDVC2, respectively.

As a result, the DDVC1 and DDVC2 devices fully compensate for the constant voltage component of $U_{t10}$ and $U_{t20}$ of the PTT1 and PTT2 devices.

A voltage is formed at the IA1 and IA2 outputs:

$$U_{out1} = \Delta U_{t1} k_{U1} k_{m1} [t_1 - (t_1 - t_0) k_{l1}] \tag{11}$$

$$U_{out2} = -\Delta U_{t2} k_{U2} k_{m2} [t_2 - (t_2 - t_0) k_{l2}] \tag{12}$$

where $k_{m1}$, $k_{m2}$ are respectively the conversion coefficients of the IA1 and IA2, and $k_{l1}$, $k_{l2}$ are correspondingly the conversion coefficients of the LD1, LD2.

By choosing the values of the coefficients $k_{m1}$, $k_{m2}$ the numerical equality of the output voltages of the IA1, IA2 and the values of the measured temperatures $t_1$, $t_2$ is ensured. Accordingly, the deviation of the parameters of the transistor is compensated.

The output voltages of the IA1 and IA2 are applied to the input of the output summing amplifier, the output voltage of which is determined by the following expression:

$$\Delta U_{out} = \Delta U_n (t_1 - t_2) \tag{13}$$

where $\Delta U_n = \Delta U_{t1} k_{U1} k_{m1} = \Delta U_{t2} k_{U2} k_{m2}$ is the normalised conversion coefficient.

When changing the values of the base-emitter voltage by 1°C within the range of 1.8-2.2 mV/°C, it is appropriate to choose the value of the normalised temperature coefficient equal to $\Delta U_n$ = 10mV/°C.

## 2. Investigation of the main metrological characteristics of the functionally integrated device

The designed dual-function temperature transducer was investigated in the Electronic Workbench, in accordance with the circuit shown in Fig. 4.

Primary temperature transducer is connected by three-wires to the reference voltage source on the operational amplifier, to the non-inverting input of which a reference voltage source of +1 V is connected. The collector and base of the transistor converter are connected to the output of the first operational amplifier through diodes, which ensures independent control of the collector. The diodes are placed in the operational amplifiers feedback loops and do not affect the measurement accuracy. High-voltage diodes are chosen to reduce reverse currents. The value of the reference measuring current is determined by the resistance of the resistor connected to the inverting input of the first operational amplifier. The heating control device is based on two switches, which are controlled by an additional control device. In the model, the switches are controlled by a generator of rectangular impulses with frequencies of 5 and 10 Hz. During the heating of the transistor, its collector is connected to the +12V power source through the switch, and the emitter of the transistor is connected to the common power bus through the second switch through a 3 Ohm resistor.

The switches are closed when a positive impulse is put at their control inputs and, accordingly, a heating current passes through the transistor. After the impulse end a measuring current passes through the transistor. Regulation of the thermal process is carried out by changing the duration of the positive impulse and frequency.

The base-emitter voltage is applied to the input of the device for determining the temperature change in voltage, which is based on the second operational amplifier, the non-inverting input of which is connected to the reference voltage source of 1 V.

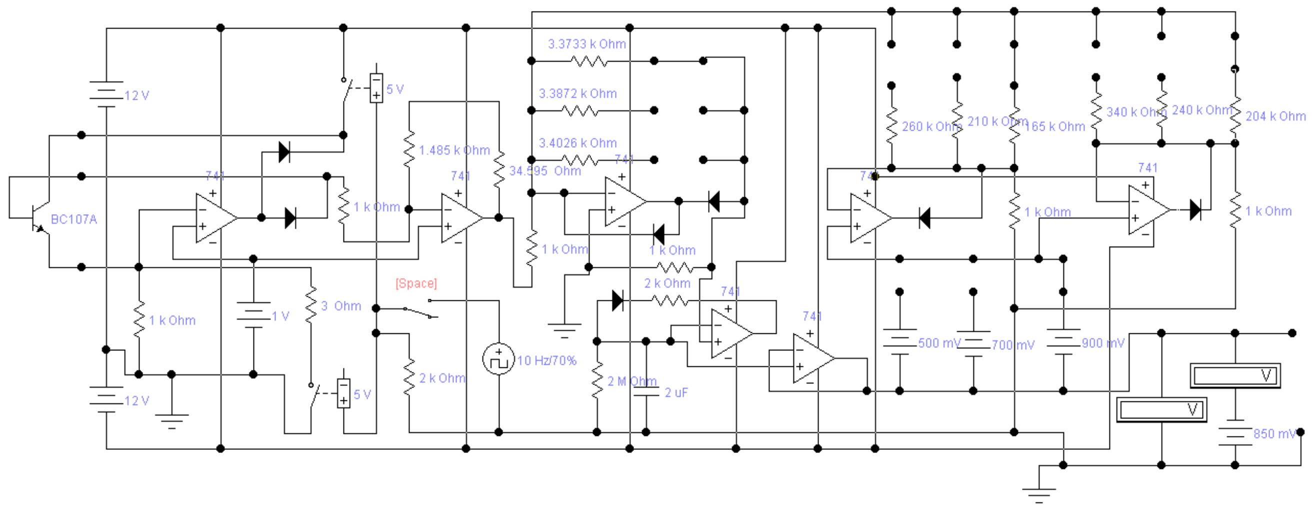


*Fig. 4. Circuit for the investigation of the designed dual function temperature transducer*

The output voltage of the second OA is determined by the expression:

$$U_{out1} = U_0 - \frac{U_{be0} R}{R_{in}} + \frac{\Delta U_{bet} t R}{R_{in}} \tag{14}$$

where $R_{in}$ is the resistance of the input resistor of the second operational amplifier, and $R$ is the resistance of the feedback resistor of the second operational amplifier.

Under the conditions of $U_0 = \frac{U_{be0} R}{R_{in}}$ and $k_1 = \frac{R}{R_{in}}$ we will obtain:

$$U_{out1} = \Delta U_{bet} t k_1$$

Voltage $U_{out1}$ is put on the input of the scaling inverting amplifier based on the third operational amplifier, the non-inverting input of which is connected to the common bus. In order to reduce the effect of transient processes during the operation of the devices in pulse repetition mode, the forward bias diode is connected to the operational amplifier feedback. The output voltage of the operational amplifier of the IA is determined by the expression:

$$U_{out2} = \Delta U_{bet} t k_1 k_{2i} \tag{15}$$

where $k_{2i}$ is the conversion coefficient of the IA in separate measurement ranges.

To store the output voltage of the IA in the pulse repetition mode a T/H was used. It is constructed on the fourth operational amplifier, in the feedback of which a diode and a resistor are connected in series. At the same time, the storage capacitor and resistor are connected in parallel to the non-inverting input of the operational amplifier and the common supply bus.

During the transistor heating a voltage of zero value is supplied to the T/H input. During passing of the sample measuring current through the PTT the base-emitter voltage of the PTT transistor is supplied. As a result, the temperature change of the base-emitter voltage is stored in the capacitor. To reduce the discharge of the capacitor during heating an additional operational amplifier is used in the pulse repetition mode.

To linearise the function of converting temperature into voltage in the ranges $t_{min}…t_{av}$ and $t_{av}…t_{max}$, linearisation devices based on two operational amplifiers were used. The non-inverting inputs of these operational amplifiers are connected to the IA output through bias voltage sources. The compensating current for linearisation is formed by resistors, which connect the outputs of the LDs operational amplifiers with the inverting input of the IA operational amplifier. The temperature measurement ranges are selected by changing the resistance of the resistors in the IA operational amplifier feedback and at the LD operational amplifier outputs and by changing the bias voltage at the LD operational amplifier inputs.

In order to measure the output voltage in the model a millivoltmeter was used. To assess the absolute voltage measurement error, a microvoltmeter and a reference voltage source were utilized. The value of reference voltage source was chosen to be equal to the nominal value of the output voltage of the dual function temperature transducer. In this case, the output voltage of the aforementioned transducer was equal to the numerical value of the measured temperature.

Research was conducted in two modes: measurement mode and controlled heating mode. The rectangular impulse generator with frequencies of 5 and 10 Hz was used in the heating-measurement mode.

The results of the investigations are shown in Figs. 5–6.

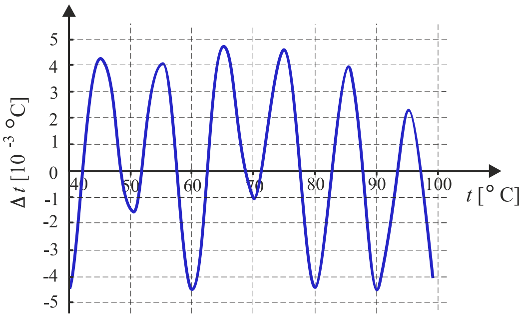


*Fig. 5. The relationship between the absolute temperature measurement error and temperature in measurement mode*

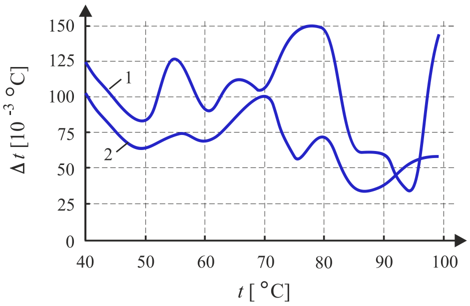


*Fig. 6. The relationship between the absolute temperature measurement error and temperature in heating-measurement mode for frequencies of 5 Hz (1) and 10 Hz (2)*

As can be seen, in the controlled heating mode, the temperature measurement error does not exceed 0.15°C, and in the measurement mode the error does not exceed 0.005°C.

Reducing the error can be achieved by choosing the frequency and the duration of the heating impulse. To increase the accuracy at every instant of time, it is necessary to switch the converter to the measurement mode. The selection of modes can be carried out automatically or by an operator.

A circuit for the investigation of the differential temperature transducer is shown in Fig. 7.

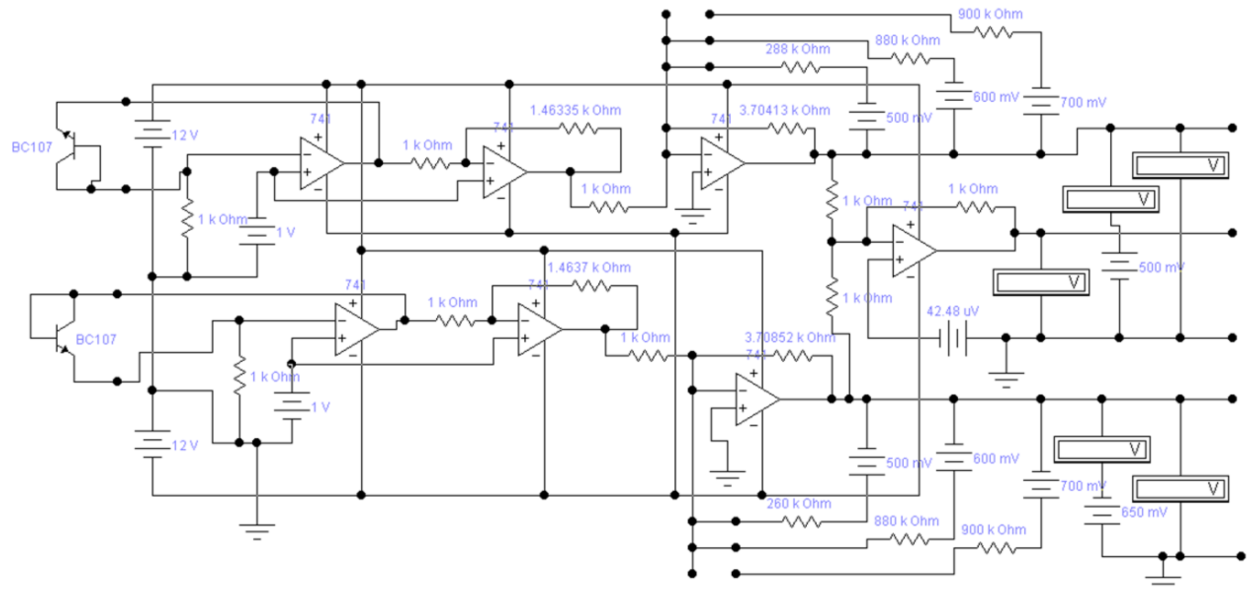


*Fig. 7. Circuit for the investigation of the differential temperature transducer*

The first primary temperature transducer is connected to the reference current source of negative polarity. It is constructed on the first operational amplifier, the non-inverting input of which is connected to the reference voltage source of negative polarity of -1 V.

The second temperature transducer is connected to the source of the reference current of positive polarity based on the second operational amplifier, the non-inverting input of which is connected to the reference voltage source of positive polarity of +1 V.

To ensure the necessary temperature measurement accuracy the reference voltage sources are chosen to be highly stable.

The base-emitter voltages of the transistors enters the inputs of the DDVC1 and DDVC2. They are built using the operational amplifiers in the inverting mode. Non-inverting inputs of operational amplifiers are connected to sources of reference voltages of -1 V and +1 V.

The output voltages of DDVC operational amplifiers are determined by the following expressions:

$$U_1 = -1 + \frac{U_{t10} - \Delta U_{t1} t_1}{R_{in1}} R_{f1} \tag{16}$$

$$U_2 = 1 - \frac{U_{t20} - \Delta U_{t2} t_2}{R_{in2}} R_{f2} \tag{17}$$

where $R_{in}$, $R_f$ are input and feedback resistors of DDVC operational amplifiers, respectively.

If the following conditions are ensured:

$$\frac{U_{t10}}{R_{in1}} R_{f1} = 1; \frac{U_{t20}}{R_{in2}} R_{f2} = 1 \tag{18}$$

then the output voltages are equal to:

$$U_1 = -\frac{\Delta U_{t1} t_1}{R_{in1}} R_{f1} \tag{19}$$

$$U_2 = \frac{\Delta U_{t2} t_2}{R_{in2}} R_{f2} \tag{20}$$

From the analysis of the expression it can be seen that the DDVCs determine the temperature dependent base-emitter voltage change with the amplification factor $k = R_f/R_{in}$.

At the same time, for full compensation of the initial value of the base-emitter voltage at $t = 0$°C, the following condition should be ensured:

$$k_1 = \frac{1}{U_{t10}}; k_2 = \frac{1}{U_{t20}} \tag{21}$$

The output voltages of DDVCs are put to the inputs of the IAs. The non-inverting inputs of the IAs operational amplifiers are connected to a common power bus.

The output voltages of the IAs operational amplifiers are determined as:

$$U_{t1} = \Delta U_{t1} k_1 t_1 \frac{R_{f1}}{R_{in1}} \tag{22}$$

$$U_{t2} = -\Delta U_{t2} k_2 t_2 \frac{R_{f2}}{R_{in2}} \tag{23}$$

where $R_{in}$, $R_f$ is the resistance of the input resistors and feedback resistors of the IAs operational amplifiers, respectively.

By choosing the values of the resistance of the feedback resistors of the IAs operational amplifiers, the equality of the output voltages $U_{t1}$ $U_{t2}$ and the numerical values of the measured temperatures $t_1$, $t_2$ is ensured.

Accordingly, if the following condition is fulfilled:

$$\Delta U_{t1} k_1 t_1 \frac{R_{f1}}{R_{in1}} = \Delta U_{t2} k_2 t_2 \frac{R_{f2}}{R_{in2}} = 10 \frac{mV}{°C} \tag{24}$$

the output voltages of the IAs operational amplifiers are equal to:

$$U_{t1} = 10 \frac{mV}{°C} t_1 \tag{25}$$

$$U_{t2} = -10 \frac{mV}{°C} t_2 \tag{26}$$

In order to linearise the conversion function of primary temperature transducer, LD linearisation devices are used. LDs are based on the bias sources with series-connected resistors in the IAs feedbacks. At the same time, the bias voltage is equal to the output voltage of the IA at the beginning of the linearisation ranges. The resistance of the linearisation resistor is selected by calibration at the end point of the linearisation range.

Accordingly, the compensating components of the IAs output voltage are described by the following expressions:

$$\Delta U_{c1} = \frac{U_{t1} - U_{b1}}{R_{l1}} R_{f1} \tag{27}$$

$$\Delta U_{c2} = \frac{-U_{t2} + U_{b2}}{R_{l2}} R_{f2} \tag{28}$$

where $U_b$ is the bias voltage on the corresponding linearisation range, $R_l$ is the resistance of the linearisation resistor, and $R_f$ is the resistance of the IA feedback resistor.

In each subsequent linearisation range one additional resistor is connected.

The output voltages of the IAs are put to the input of the output summing amplifier based on operational amplifiers with summing resistors. At the same time, the resistance of the feedback resistor is equal to the resistance of the input resistors. Accordingly, the output voltage of the OSA operational amplifier is determined by the expression:

$$\Delta U_{out} = U_{t1} - U_{t2} = 10 \frac{mV}{°C} (t_1 - t_2) \tag{29}$$

A voltage source connected to the non-inverting input of the operational amplifier is used to compensate the offset voltage of the operational amplifier.

The results of the investigations are shown in Fig. 8.

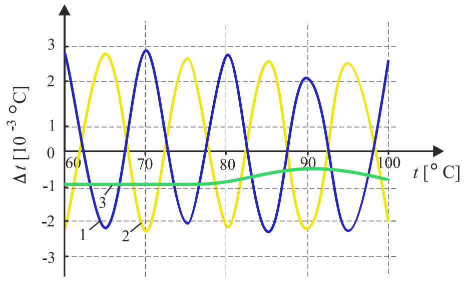


*Fig. 8. Temperature dependencies of the absolute temperature measurement error of the investigated (1) and reference (2) samples, differential temperature measurement error (3)*

As can be seen, the temperature measurement error of the investigated and reference samples does not exceed ±0.003°C. The differential temperature measurement error does not exceed 0.001°C.

## 3. Conclusions

A functionally integrated device for temperature measurement has been developed. It allows for controlled heating of the primary temperature transducer and measurement of the heating temperature, as well as measurement of temperature and temperature difference of the investigated and reference samples.

The proposed design of the sensor includes a heating device that allows for the formation of a heat flow that is transmitted through the heat-conducting element to the investigated and reference samples. At the same time, the same transistor is used both for heating and for measuring the temperature of the heat flow, which is ensured by the selection of different currents passing through the transistor. The heating speed is regulated by the selection of the frequency and duration of the control impulses.

The differential temperature transducer is designed for measuring temperature and differential temperature of samples. The measuring currents of different polarities are used to form temperature-dependent quantities, allowing to simplify the device design. To linearise the conversion function of primary transducers, linearisation devices are used. They form linearisation currents in the feedback circuit of the output inverting amplifier. The linearisation accuracy depends on the linearisation range.

The investigation of the developed device showed that the temperature measurement error does not exceed 0.11°C and 0.005°C in the controlled heating and in the measurement modes, respectively. The temperature measurement error of the investigated and reference samples and the differential temperature measurement error does not exceed ±0.003°C, 0.001°C, respectively. Such temperature measurement errors and the differential temperature measurement errors are acceptable and the developed device can be used for biomedical investigation.

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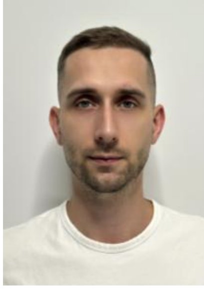

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