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TRANSISTOR-BASED TEMPERATURE MEASURING DEVICE

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Abstract. *The schematic diagrams of the temperature measuring device based on transistor structures are presented in the paper. The temperature dependence of collector current without and with linearization of the conversion function is analysed. The linearization method based on compensation current formation is proposed. This allowed to reduce the temperature measurement error up to ± 0.006°C over the temperature ranges 40… 60°C and 60… 80°C and up to 0.08°C over the temperature range 10… 90°C.*

Keywords: temperature measurement, transistor structures, linearization

TRANZYSTOROWY UKŁAD DO POMIARU TEMPERATURY

Streszczenie. *W artykule zostały przedstawione schematy miernika temperatury opartego na strukturach tranzystorowych. Została przeanalizowana zależność prądu kolektora od temperatury bez i przy zastosowaniu linearyzacji funkcji przetwarzania. Zaproponowano metodę linearyzacji opartą na formowaniu prądu kompensacyjnego, która pozwoliła zmniejszyć błąd pomiaru temperatury do ± 0,006°C w zakresach temperatury 40… 60°C i 60… 80°C oraz do ±0,08°C w zakresie 10… 90°C.*

Słowa kluczowe: pomiar temperatury, struktury tranzystorowe, linearyzacja

Introduction

The increasingly widespread implementation of cyber-physical systems (CFS), Internet of Things devices and scattered measurement systems requires the improvement of sensor devices that collect and transmit environmental and physiological information to base stations [2, 6, 13]. High-precision temperature measurements are important in many applications [7]. Temperature measurements provide valuable information when conducting medical research [1]. Continuous 24-h body core and skin temperature monitoring allows you to track circadian rhythms that carry information about the functioning of the central nervous and immune systems. Body temperature is one of the key parameters for monitoring the health of preterm infants in the neonatal intensive care unit [4]. In addition, accurate temperature monitoring can facilitate early detection of diseases, including cancer. In the case of controlled hyperthermia in cancer, it is necessary to control the temperature with an accuracy better than 0.05°C in the range of 30–50°C [8].

Temperature measurement is also important for agriculture [14, 17], construction industry [16]. However, in order to optimize the use of resources in precision agriculture, it is necessary to measure the temperature with an accuracy of no less than 0.05ºC.

Ecological, marine, and oceanographic researches, with the aim of studying physical and biological processes based on forecasting systems and sensor networks, require accuracy levels of up to 0.01°C. [12, 18]

Different types of sensors are used for temperature measurement [18]. Thermocouples and Resistance Temperature Detectors (RTDs) are the most commonly used temperature sensors in the industry. Thermocouples provide measurements over a wide temperature range from -270 to 2300°C [7], but the measurement accuracy is within the range from 0.5 to 2°C, and could be increased up to 0.1°C in the narrower range [15]. Thermocouples also require the compensation of cold-junction temperatures [10, 11]. RTDs are used over the temperature range from -260 to 850°C [9], providing a high accuracy of 0.03…1°C [7], but they are characterized by high cost. The infrared sensors operate in a wide temperature range from -40 to 3000°C, but they are characterized by low accuracy of ±2°C which is dependent on object radiation and background noise [5, 7].

Particular progress has been made in modern thermometry through the use of primary temperature transducers based on p-n junctions of transistor structures [3, 19].

The main advantage of primary temperature transducers based on transistor structures compared with thermocouples and RTDs is the high sensitivity. However, their disadvantage is the lack of linearity of the conversion function.

The informative parameters of transistor-based primary transducers are the dependence of the voltage drop across the forward bias p-n junctions and the dependence of the collector or emitter currents on the temperature change. The use of the temperature dependence of collector currents provides the highest sensitivity.

The aim of the work is to develop the high-accuracy temperature measuring device based on transistor transducer for in-situ measurements in biomedicine, pharmacy and agriculture.

1. Design of high-precision temperature measuring device

The schematic diagram of the designed temperature measuring device is shown in Fig. 1. The temperature measuring device consists of the primary temperature transducer and the secondary transducer of the primary transducer measuring current to voltage. The secondary transducer comprises the current to voltage converter (CVC), the compensator of initial output current of the primary transducer (CCPT), the former of base current of the primary transducer, the output voltage bias generator (OVBG) and the devices for output voltage linearization.

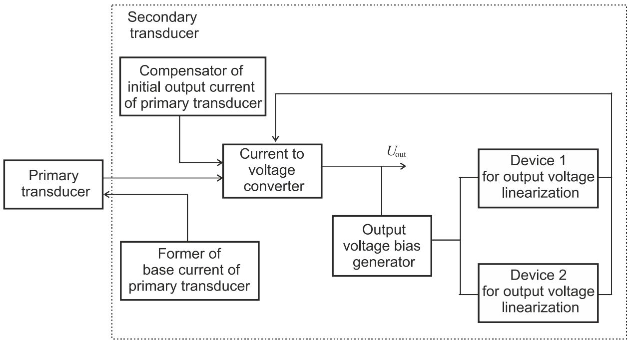

Fig. 1. Schematic diagram of the temperature measuring device

The temperature-dependent output current of the primary transducer is described by the following expression:

$$I = I_{t0} + \Delta I_t t, \tag{1}$$

where I_{t0} is the initial output current of the primary transducer at $t = 0$°C, ΔI_t is the change of output current with temperature change by 1°C, t is the measuring temperature in °C.

The compensator CCPT compensates the initial component of the output current I_{t0} and the following voltage is generated at the CVC output:

$$U_{out} = \Delta I_t t k_1, \tag{2}$$

where k_1 is the conversion factor of CVC.

By choosing the coefficient k_1, the output voltage is formed, the value of which is equal to the value of the measured temperature.

The CVC output voltage through OVBG is fed to the inputs of the linearization devices. The output bias voltage generator forms the following voltage:

$$U_b = \Delta I_t t_{av} k_1 \,, \tag{3}$$

where t_{av} is the temperature value equal to the average temperature value of the measurement range.

The bias voltage of the OVBG is equal to the value of the output voltage of the PSN at the average temperature value of the measuring range. At $U_{out} > U_b$ the positive polarity voltage is applied to the inputs PL1 and PL2, and at $U_{out} < U_b$, the negative ones.

The output current of linearization devices is determined from the following expression:

$$I_l = \left(U_{out} - U_b\right) k_2 \,, \tag{4}$$

where k_2 is the conversion factor of linearization devices.

The currents of the linearization devices flow to the CVC converter and at the output the following compensating voltage is formed:

$$\Delta U_{out} = \left(U_{out} - U_b\right) k_1 k_2 \,. \tag{5}$$

After the corresponding substitution we get the following:

$$\Delta U_{out} = \Delta I_t k_1{}^2 k_2 \left(t - t_{av}\right). \tag{6}$$

As a result of linearization, the output voltage of the PSN is described as follows:

$$U_{out} = \Delta I_t k_1 \left(t + k_1 k_2 (t - t_{av})\right). \tag{7}$$

As can be seen, the linearization accuracy depends on the value of the coefficient k_2 and the temperature measurement range.

Schematic diagram of the designed dual-band temperature measuring device is shown in Fig. 2.

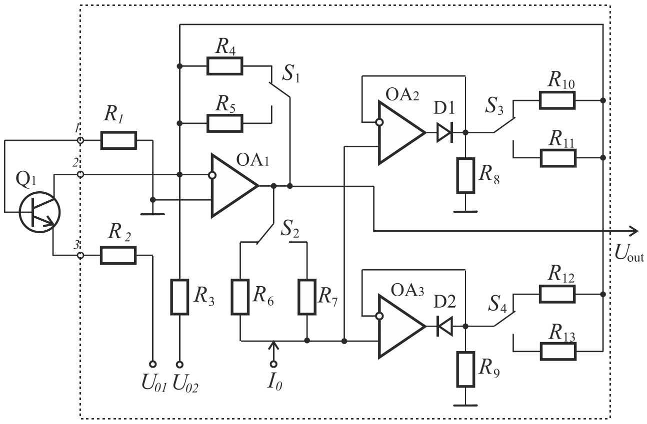

Fig. 2. Schematic diagram of the temperature measuring device

The Q_1 transistor-based primary transducer is connected to the inputs 1, 2, 3 of the secondary transducer by three lead wires. The base current of the transistor is formed by the reference voltage U_{01} and by the resistors R_1, R_2, and can be expressed as follows:

$$I_b = \frac{U_{01} - U_{R2} - U_{be}}{R_1} \,, \tag{8}$$

where U_{R2} is the voltage drop on resistor R_2, U_{be} is the voltage at the base-emitter junction of the transistor Q_1.

The voltage drop across resistor R_2 equals:

$$U_{R2} = \left(I_c + I_b\right) R_2 \,, \tag{9}$$

where I_c, I_b are collector and base currents of the transistor, respectively.

After the corresponding substitution we get:

$$I_b = \frac{U_{01} - U_{be}}{R_1(1+k)} \,, \tag{10}$$

where $k = \frac{(\beta+1)R_2}{R_1}$, β is the gain factor of transistor.

At the temperature change the base-emitter voltage changes. The base current is determined from the following expression:

$$I_b = \frac{U_{01} - U_{be0}}{R_1(1+k)} + \frac{\Delta U_{be} t}{R_1(1+k)} \tag{11}$$

where U_{be0} is the voltage at the base-emitter junction at $t = 0$°C, ΔU_{be} is the voltage change at the base-emitter junction when the temperature changes by 1°C.

The collector current of transistor is equal:

$$I_c = \frac{U_{01} - U_{be0}}{R_1(1+k)} \beta + \frac{\Delta U_{be} t}{R_1(1+k)} \beta \,. \tag{12}$$

The analysis of the expression shows that the collector current contains a constant and variable component.

In order to compensate the constant component, the compensation current is used, the value of which is set by the resistor R_3, connected to the positive polarity reference voltage U_{02}. The resistance value of the resistor R_3 equals:

$$R_3 = \frac{U_{02} R_1 (1+k)}{\left(U_{01} - U_{be0}\right)\beta} \,. \tag{13}$$

After compensation of the constant component of the collector current, the inverting input of the operational amplifier OA_1 receives the variable component of the collector current and the following voltage is formed at the OA_1 output:

$$U_{OA1} = \frac{\Delta U_{be} t}{R_1 \left(1+k\right)} \beta R_4 \,. \tag{14}$$

By choosing the resistance value of the resistor R_4, we obtain the required value of the output voltage, proportional to the numerical value of the measured temperature.

In order to ensure the linearity of the conversion function within the temperature range $t_{min} \ldots t_{av}$, the linearization circuit based on the operational amplifier OA_3 is used, which generates the compensation current expressed by:

$$I_{com1} = \frac{U_{OA1} - U_{tav}}{R_{12}} \,, \tag{15}$$

where U_{tav} is the value of the voltage in the middle of the measurement range.

In order to ensure the linearity of the conversion function within the temperature range $t_{min} \ldots t_{av}$, the linearization circuit based on the operational amplifier OA_2 is used, which generates a compensation current according to the expression:

$$I_{com2} = \frac{U_{OA1} - U_{tav}}{R_{10}} \,. \tag{16}$$

In order to generate a voltage equal to the voltage in the middle of the measurement range U_{tav} it is used the bias on the resistor R_6, through which the reference current I_0 passes. Then the voltage U_{tav} equals:

$$U_{tav} = I_0 R_6. \tag{17}$$

The resistor R_6 is connected in series to the output of the operational amplifier OA_1, and the following voltage is fed to the inputs of the operational amplifiers OA_2, OA_3:

$$U_{in} = U_{OA1} - I_0 R_6 \,. \tag{18}$$

If the following condition is met: $U_{in} < 0$, then at the output of the operational amplifier OA_3 a negative polarity voltage is generated, which is passed through the resistor R_{12} to the inverting input of the operational amplifier OA_1.

If the following condition is met: $U_{in} < 0$, then at the output of the operational amplifier OA_2 a positive polarity voltage is formed, which is passed through the resistor R_{10} to the inverting input operational amplifier OA_1.

In order to determine the required polarity of the output voltage in the output circuits of operational amplifiers OA_2, OA_3

the diodes D_1, D_2 are used. In order to reduce the influence of the diodes reverse currents on the accuracy of the formation of linearization compensation currents the resistors R_8, R_9 are used. The resistances of the resistors R_8, R_9 are much smaller than the ones of the resistors R_{10}, R_{12}.

The measurement ranges are chosen by changing the feedback resistors of the operational amplifier OA_1 (R_4, R_5), the resistors at the outputs of the operational amplifiers OA_2 and OA_3 (R_{10}, R_{11} and R_{12}, R_{13}), and the resistors at the input of the compensation circuits (R_6, R_7).

2. Investigation of the designed temperature measuring device

The investigation of the designed temperature measuring device was carried out in the Electronic Workbench, in accordance with the model shown in Fig. 3.

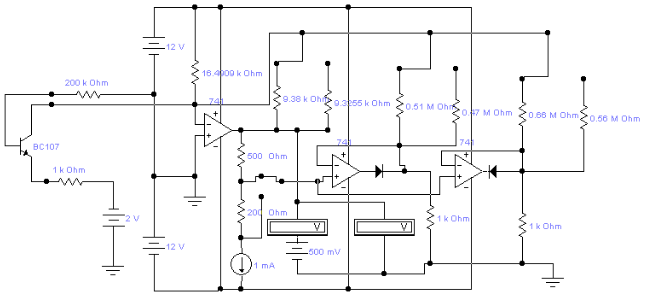

Fig. 3. Model for investigation of the designed temperature measuring device

BC107 transistor was used for investigations. The formation of collector current of the measuring temperature-dependent transistor is carried out by the reference voltage of 2 V, the base resistor of 200 kΩ and the emitter resistor of 1 kΩ. The initial collector current is compensated by a resistor connected to a positive +12 V supply voltage and to the inverting input of the input operational amplifier. The output voltage of the input operational amplifier is regulated by the resistor in the feedback. The reference DC source of 1 mA and the resistors in series (200 Ω, 500 Ω) connected to the input of the input amplifier are used to choose the required linearization range. A millivoltmeter was used to measure the output voltage of the input amplifier. A microvoltmeter and a reference voltage source were used to determine the voltage, which is equal to the nominal value of the output voltage.

The compensation of the constant component of transistor's collector current was carried out at 0°C. The calibration of the temperature measuring device was carried out at the temperature equal to the average value t_{av} of the measurement range. In this case the resistance of the resistor in the feedback of the first operational amplifier was set equal to 9.38 kΩ for the temperature range 40… 60°C and equal to 9.325 for the range 60… 80°C.

Graph dependencies of nonlinearity errors of temperature measurement for different temperature ranges are depicted in Figs. 4 and 5.

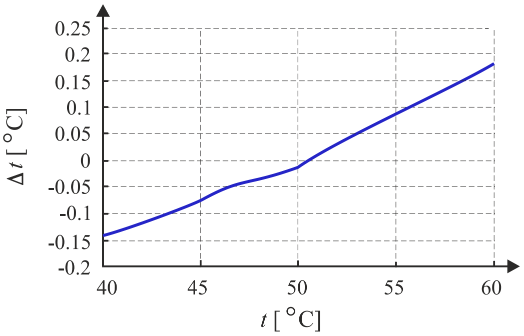

Fig. 4. Relationships between the errors of nonlinearity of temperature measurement and the temperature without linearization over the temperature range 40…60°C

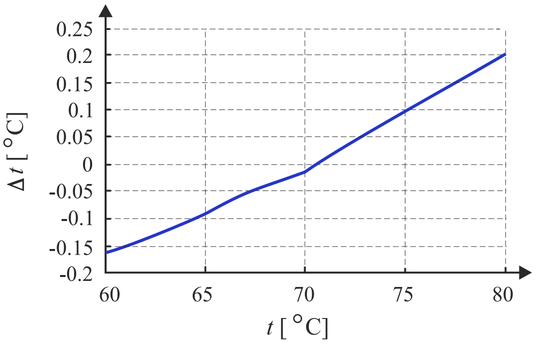

Fig. 5. Relationships between the errors of nonlinearity of temperature measurement and the temperature without linearization over the temperature range 60…80°C

The conducted analysis shows that the designed scheme of the temperature measuring device based on the transistor structure when using the temperature dependence of collector currents without linearization ensures the absolute measurement error not exceeding 0.2°C over the temperature ranges 40…60°C and 60…80°C.

The errors of nonlinearity of temperature measurement versus temperature with linearization for different ranges are depicted in Figs. 6 and 7.

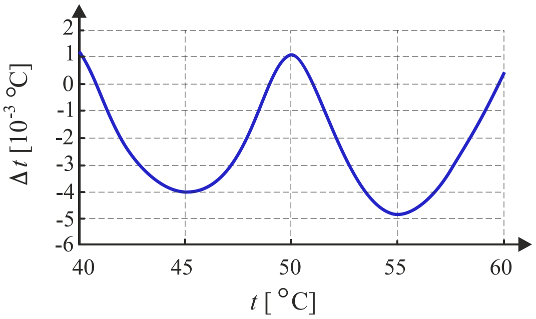

Fig. 6. Relationships between the errors of nonlinearity of temperature measurement and the temperature with linearization over the temperature range 40…60°C

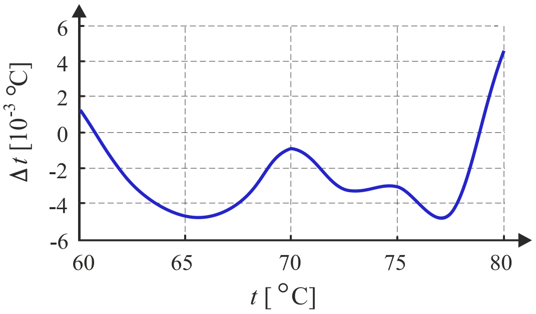

Fig. 7. Relationships between the errors of nonlinearity of temperature measurement and the temperature with linearization over the temperature range 60…80°C

As can be seen from the plots, the absolute measurement error does not exceed ±0.006°C over the temperature ranges 40… 60°C and 60… 80°C when performing linearization.

Improving of the accuracy of temperature measurements over a wider range is possible by introducing additional temperature ranges, which are chosen by additional resistors in the feedback loop of the input operational amplifier and by the output resistors of the linearization devices connected to the inverted input of the first operational amplifier.

Improving of the measurement accuracy over a wider range is also possible when compensating for nonlinearity errors at the temperature points higher than t_{av}+10°C and lower than t_{av}-10°C.

Relationships between the errors of nonlinearity of temperature measurement and the temperature during compensation at the points of 40°C and 60°C (curve 1), 30°C and 70°C (curve 2), 20°C and 80°C (curve 3) are plotted in Fig. 8.

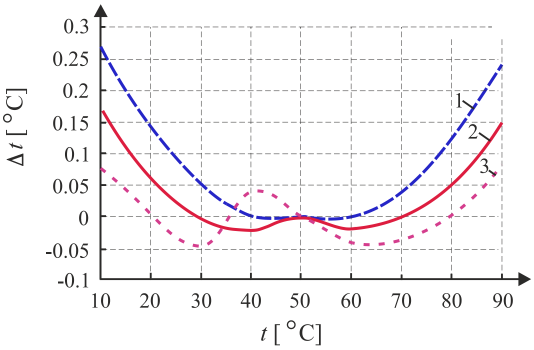

Fig. 8. Relationships between the errors of nonlinearity of temperature measurement and the temperature with linearization over the temperature range 10…90°C

As it can be seen from the graphical dependencies presented in Fig. 8 the absolute measurement error over the range 10… 90°C does not exceed 0.27°C for compensation at the points of 40°C and 60°C, does not exceed 0.17°C for compensation at the points of 30°C and 70°C, does not exceed 0.08°C for compensation at the points of 20°C and 80°C.

In order to improve the accuracy of temperature measurement, it is advisable to use additional compensation circuits over different measurement ranges.

3. Conclusions

The temperature measuring device based on transistor structures was developed using the temperature dependence of collector current as an informative signal, which provides the high sensitivity of temperature measurement.

In order to improve a measurement accuracy the method for nonlinearity compensation is proposed. The method is based on formation of a compensation current functionally dependent on the difference between the measured temperature value and the temperature value in the middle of the measurement range. This ensures the high measurement accuracy of ±0.006°C over the temperature ranges 40…60°C and 60… 80°C. Increasing of the temperature measurement accuracy over a wider range is possible by optimal choosing of compensation points in the middle of the measurement range. In the case of compensation at the points 20°C and 80°C, the measurement error does not exceed 0.08°C over the range 10… 90°C.

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