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Analysis and Research of Methods of Linearization of the Transfer Function of Precision Semiconductor Temperature Sensors

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The analysis of nonlinearity of the transfer function of primary temperature transducers based on transistor structures has been performed. It's shown that the quadratic component of the transfer function creates a significant nonlinearity error up to 0.2 - 0.6°C. We have developed methods of linearization based on both the formation of compensatory measuring current and change of the conversion factor of the output scaling amplifier at certain ranges of temperature measurement, which ensure their use in precision temperature measuring devices. The investigation of the developed schematic diagram has shown that in the case of usage the linearisation method based on the formation of compensating base current, the measurement accuracy of $\pm 0.01^\circ\text{C}$ is provided. At the application of the method with a variable conversion factor of output scaling amplifier, the accuracy of $\pm 0.005^\circ\text{C}$ is provided in the range 30 - 100°C.

Keywords: transistor, temperanure sensor, linearisation.

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Introduction

Temperature sensors are widely used in measuring and control systems for laboratory, industrial and home applications. High accuracy, linearity, sensitivity, low power consumption are the main requirements for such sensors [1-3]. To conduct biomedical research, it is important to create precision temperature sensors in the range 30 - 100°C.

A significant number of modern temperature sensors in the measurement range from 0°C to +120°C use semiconductor transistor structures as primary transducers [2]. Modern transistors are characterized by extremely small size (from millimeters to micrometers), and temperature sensors based on them, provide significantly higher temperature sensitivity compared with resistance temperature detectors (RTDs) or thermocouples [2]. In addition, the use of transistors opens up the possibility of expanding functionality, in particular, providing both temperature measurement and controlled heating [4, 5].

Primary temperature transducers based on transistor structures provide high sensitivity. In particular when the

temperature dependence of the base-emitter voltage is used as an informative value, the sensitivity equals 2 mV/°C [6]. The main disadvantages of transistor structures are the significant variation of temperature-dependent characteristics ($\pm 10^\circ\text{C}$) and the nonlinearity of the transfer function. To reduce the impact of the scatter of the characteristics in the operating conditions, additional calibration of the characteristics of the transistor structures is performed. Compensation of the nonlinearity of the temperature dependence of the base-emitter voltage can be performed by digital and analogue methods. In digital methods, special linearization algorithms are used. Additional linearization schemes are used in analogue methods. The advantage of analogue methods is their ability to be implemented for different types of the secondary measuring devices.

I. Analysis of temperature-dependent characteristics of transistor structures

The dependence of the transistor base-emitter

voltage on the temperature change is described by the equation:

$$U_{bet} = U_{bet0} - \Delta U_A t - \Delta U_B t^2$$

where U_{bet0} is the value of the base-emitter voltage at $t = 0^\circ\text{C}$; ΔU_A is the linear coefficient of change of base-emitter voltage from temperature; ΔU_B is the quadratic coefficient of change of base-emitter voltage from temperature; t is the value of the measured temperature.

The linear coefficient is mainly determined at the temperature of 0°C or at the temperature of the initial value of the measuring range with a corresponding change in temperature by 1°C .

The quadratic coefficient of the base-emitter voltage change equals:

$$\Delta U_B = \frac{U_{bet0} - U_{betm} - \Delta U_A t_m}{t_m^2},$$

where U_{betm} is the value of the base-emitter voltage at the maximum value of the temperature measurement range t_m .

The change in base-emitter voltage from temperature is described as follows:

$$\Delta U_{bet} = -\Delta U_A t - \Delta U_B t^2.$$

To obtain the value of the output voltage numerically equal to the value of the measured temperature, it is necessary to calibrate the output voltage at the end of the temperature range according to the expression.

$$t_m \cdot 10\text{mV}/^\circ\text{C} = (\Delta U_A t + \Delta U_B t^2)k,$$

where k is the gain factor of the output scale amplifier.

The effect of the quadratic component is fully compensated and the equivalent value of the linear coefficient is equal to:

$$\Delta U_A = \frac{10\text{mB}/^\circ\text{C}}{k}.$$

The nonlinearity error is described as follows:

$$\Delta_t = (\Delta U_A t + \Delta U_B t^2)k - t \cdot 10\text{mV}/^\circ\text{C}.$$

The optimal value of the nonlinearity error can be ensured by the optimal choice of calibration points on individual measurement ranges.

Graphical dependences of nonlinearity errors for different calibration points for $\Delta U_A = 1.882 \text{ mV}/^\circ\text{C}$ and $\Delta U_B = 0.41 \mu\text{V}/^\circ\text{C}^2$ are depicted in Fig. 1.

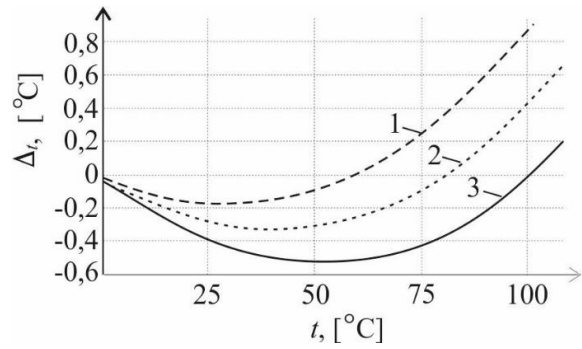


Fig. 1. Dependences of nonlinearity errors during calibration at points: 1 - 60°C , 2 - 80°C , 3 - 100°C .

As can be seen from the plots, the reduction of the nonlinearity error is achieved by reducing the measurement range. It does not exceed 0.53°C over the range $0 \dots 100^\circ\text{C}$, 0.32°C over the range $0 \dots 80^\circ\text{C}$, and 0.19°C over the range $0 \dots 60^\circ\text{C}$.

II. The method of linearization based on the change of the measuring current of the transistor primary transducer

The linearization of the PTT transfer function can be performed by forming an additional compensation current through the PTT in the linearization range.

The structural scheme of the temperature sensor with the formation of the base compensating current is shown in Fig. 2.

The transistor PTT is connected to a secondary temperature transducer (STT), which contains an inverting input amplifier (IIA), a former of the measurement current (FMC), an output scale summing amplifier (OSSA), a former of the compensating voltage (FCV), a linearization device (LD) and a bias voltage generator (BVG).

When the reference measuring current passes through the PTT at the output of the IIA the voltage is formed:

$$U_1 = U_{bet0} - \Delta U_A t - \Delta U_B t^2.$$

The former of the compensating voltage FCV is used

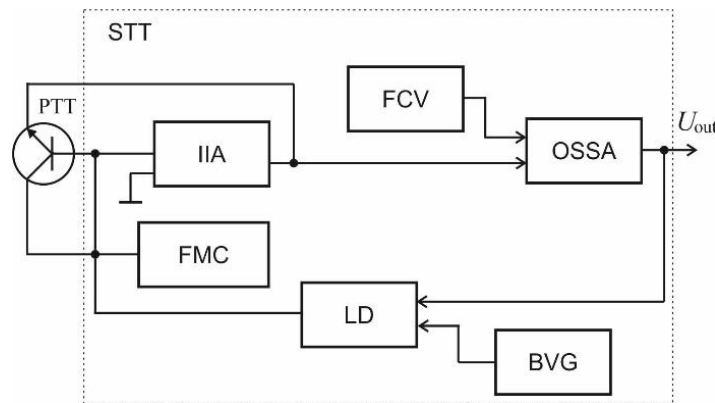


Fig. 2. Structural scheme of the temperature sensor with the formation of the base compensating current.

for compensation of U_{be0} . In this case, a voltage at the output of the OSSA is described by the following expression:

$$U_{out} = (-\Delta U_A t - \Delta U_B t^2)k,$$

where k is the conversion factor of the OSSA.

The value of the coefficient k is chosen from the condition of ensuring the numerical equality of the output voltage to the value of the measured temperature at the calibration point.

In the linearization range, the LD generates compensation current:

$$I_c = (U_{out} - U_z)k_l,$$

where U_z is the bias voltage, the value of which is equal to U_{out} at the temperature equal to the temperature value at the beginning of the linearization range, the beginning of the first linearization range is equal to the calibration temperature.

When the compensating current passes through the PTT at the output of the IIA the voltage is formed:

$$U_1 = U_{be0} - \Delta U_A t - \Delta U_B t^2 + I_c r_{in},$$

where r_{in} is the internal resistance of the base-emitter junction.

At equality $\Delta U_B t^2 = I_c k_{in}$ the quadratic component of change of base-emitter voltage from temperature at the end of the range of linearization t_{max} is completely compensated.

III. The method of linearization of the transfer function based on the change of the conversion factor of the secondary transducer

For analogue linearization, we propose to use the method of changing the conversion factor of the output scale amplifier of the secondary transducer (SST) on separate ranges of temperature measurement. The structural scheme of a semiconductor temperature sensor with linearization of the transfer function is shown in Fig. 3.

The transistor primary temperature transducer (PTT) is connected to the device for determining the base-emitter voltage change (DDVC). In this case, a voltage,

the value of which is equal to the value of the change in the base-emitter voltage from the temperature changes, is formed at the output of the DDVC.

$$\Delta U_t = \Delta U_A t + \Delta U_B t^2.$$

The signal from the DDVC is fed to the input of the output scale summing amplifier OSSA, at the output of which the voltage is equal to:

$$U_{out} = (\Delta U_A t + \Delta U_B t^2)k,$$

where k is the gain factor of the OSSA.

The calibration at certain points of the measurement range is performed to compensate the quadratic component of the PTT transfer function. The value of the gain factor k is selected from the condition of ensuring numerical equality of the value of the output voltage to the measured temperature at the appropriate point.

In order to compensate the quadratic component in the entire measurement range, a linearization device (LD) is used. It generates the voltage:

$$U_c = [(\Delta U_A t + \Delta U_B t^2)k - U_z]k_l,$$

where U_z is the bias voltage, the value of which is numerically equal to the value of the temperature at the calibration point; k_l is the conversion factor of the LD.

Accordingly, the output voltage of the OSSA in the range of linearization is described by the expression:

$$U_{out} = (\Delta U_A t + \Delta U_B t^2)k(1 - k_l) + U_z k_l.$$

The choice of nonlinearity coefficient k_l ensures the fulfilment of the condition $\Delta U_B t^2 = U_c$ at the end of the range of linearization. The nonlinearity error is fully compensated at this point.

IV. Investigation of the schematic diagrams of temperature sensors with linearization of the transfer function

In accordance with the proposed structural schemes, the schematic diagrams of temperature sensors based on transistor transducers with linearization of the transfer function are developed. The model of investigation the schematic diagram of the temperature sensor with formation of compensating base current is shown in Fig. 4.

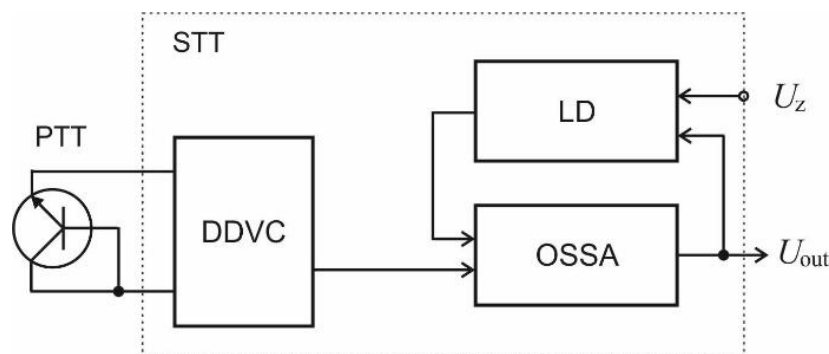


Fig. 3. Structural scheme of a semiconductor temperature sensor with linearization of the transfer function based on the change of the conversion factor of the secondary transducer.

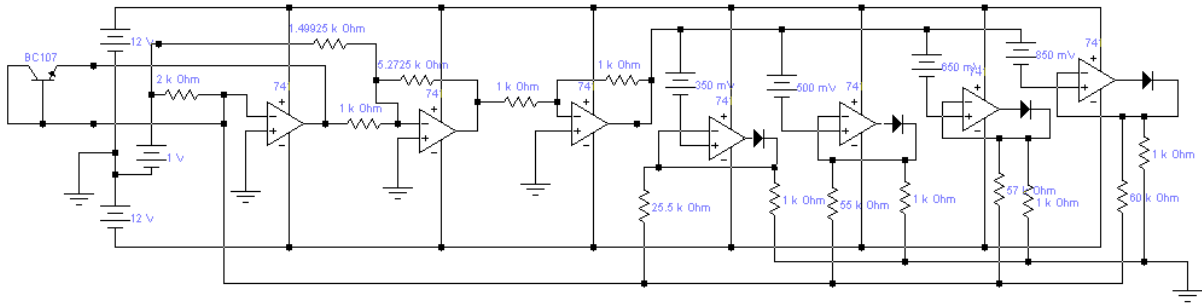


Fig. 4. Model of investigation the schematic diagram of the temperature sensor with formation of compensating base current.

The transistor primary transducer is connected into the feedback of the input operational amplifier, the inverting input of which is connected through a resistor to a source of sample voltage $U_0 = 1$ V.

Accordingly, the reference measuring current passing through the base-emitter junction is equal to:

$$I_0 = \frac{U_0}{R_0}.$$

The voltage of the input operational amplifier is determined from the expression:

$$U_1 = -U_{be0} + \Delta U_A t + \Delta U_B t^2.$$

The voltage of the first operational amplifier is fed to the first input of the scaling summing amplifier on the second operational amplifier. In order to compensate the initial base-emitter voltage, the reference voltage U_0 is connected to the second input of the OSSA.

In order to compensate U_{be0} it is necessary that:

$$\frac{U_{be0}}{R_1} = \frac{U_0}{R_2},$$

where R_1, R_2 is the input summing resistors of the scale inverting amplifier, which are respectively equal to 1 kOhm and 1.4992 kOhm.

Accordingly, the output voltage of the OSSA is equal to:

$$U_{out} = -(\Delta U_A t + \Delta U_B t^2)k,$$

where $k = \frac{R_1}{R_3}$ is the conversion factor of the OSSA, R_3 is the resistance of the feedback resistor.

A voltage, generated at the output of the third operational amplifier, is equal to:

$$U_3 = (\Delta U_A t + \Delta U_B t^2)k \frac{R_{in3}}{R_{z3}},$$

where R_{in3}, R_{z3} are the input and the feedback resistors of the third operational amplifier, respectively.

If $R_{in} = R_z$ then

$$U_3 = (\Delta U_A t + \Delta U_B t^2)k.$$

In order to linearize the transfer function on individual measurement ranges, the appropriate circuit of compensation current formation are used. The output voltage of the temperature sensor is equal to:

$$U_3 = (\Delta U_A t + \Delta U_B t^2 - I_c r_{be})k$$

where r_{be} is the base-emitter transient resistance of the PTT, which is equal to the ratio of the voltage change at the base-emitter junction to the change in the base

$$\text{current } r_{be} = \frac{\Delta U_{be}}{\Delta I_b}.$$

The linearization device generates a compensation current according to the expression:

$$I_c = \frac{U_3 - U_z}{R_{c1}},$$

where R_{c1} is the resistance value of the output resistor of the linearization device, which is connected to the base-emitter junction of the PTT; U_z is the bias voltage at the input of the linearization device, which is equal to the output voltage at the beginning of the linearization range.

In order to fully compensate the quadratic component at the end of the linearization range, it is necessary to perform the equality:

$$\Delta U_B t_{c1}^2 = I_c r_{be} = \frac{U_{3c1} - U_{z1}}{R_{c1}} r_{be}.$$

After linearization, the output voltage is equal to

$$U_3 = (\Delta U_A t + \Delta U_B t^2)k(1 - k_{l1}) + U_{z1}k_{l1},$$

where U_{z1}, k_{l1} are the bias voltage and linearization factor in the first range, respectively. In this case $k_{l1} = \frac{r_{be}}{R_{c1}}$.

In the second linearization range, the output voltage is described by the expression:

$$U_3 = [(\Delta U_A t + \Delta U_B t^2)k(1 - k_{l1}) + U_{z1}k_{l1}](1 - k_{l2}) + U_{z2}k_{l2},$$

where U_{z1}, k_{l1} are the bias voltage and linearization factor in the second range, respectively.

The results of the investigation are shown in Fig. 5.

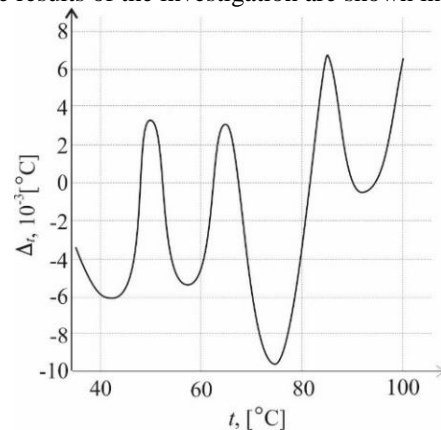


Fig. 5. Relationships between the errors of nonlinearity and the temperature.

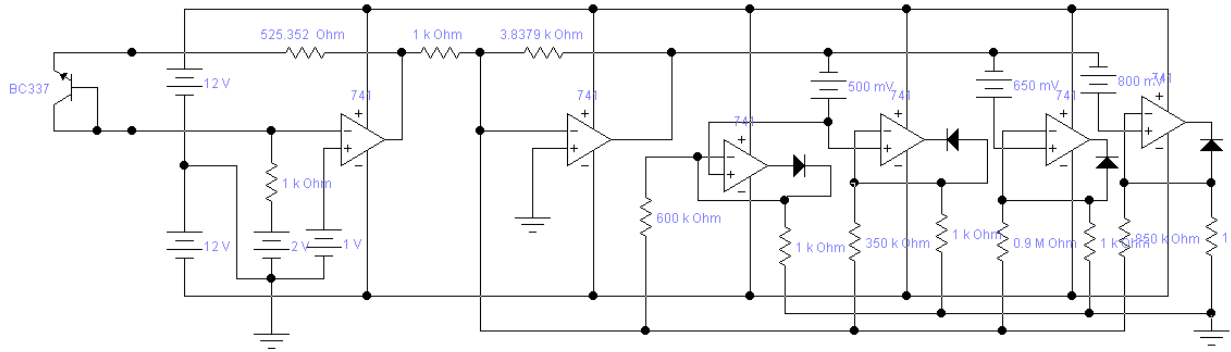


Fig. 6. Schematic diagram of a temperature sensor with a variable conversion factor of the output scaling amplifier of STT.

From the analysis of the conducted researches it can be seen that the developed schematic diagram of the temperature sensor with formation of compensating base current provides a nonlinearity error that does not exceed 0,01 °C.

The model of investigation the schematic diagram of the temperature sensor with a variable conversion factor of the output scale amplifier is shown in Fig. 6.

In the schematic diagram of a temperature sensor with a variable conversion factor of the output scaling amplifier, the transistor primary transducer is connected in series with a compensation resistor connected into the feedback circuit of the input operational amplifier. In this case, the inverting input of the operational amplifier is connected through a resistor $R = 1 \text{ k}\Omega$ to the reference voltage source $U_{01} = 2 \text{ V}$. In order to compensate the influence of the initial voltage of PTT at 0°C, the non-inverting input is connected to the reference voltage source $U_{02} = 1 \text{ V}$. Accordingly, the output voltage is determined from the expression:

$$U_1 = U_{02} - U_{be0} - I_0 R_{ad} + U_A t + \Delta U_B t^2,$$

where $I_0 = \frac{U_{01} - U_{02}}{R}$ is the value of the measuring current.

If $U_{be0} + I_0 R_{ad} = U_{02}$, then $U_1 = \Delta U_A t + \Delta U_B t^2$.

The output voltage of the first operational amplifier is fed to the input of the inverting scale amplifier whose output voltage is equal to:

$$U_2 = -(\Delta U_A t + \Delta U_B t^2)k,$$

where k is the conversion factor of the inverting scale amplifier.

The coefficient k is chosen from the condition of equality of the output voltage value to the numerical value of the temperature at the calibration point $t_c = 50 \text{ }^\circ\text{C}$. After calibration, the nonlinearity of the transfer function of PTT in the range $t < t_c$ creates a negative error component $\Delta t < 0$, and in the range $t > t_c$ - a positive component $\Delta t > 0$.

In order to compensate the nonlinearity error, the compensating voltages of different polarities are formed by the linearization devices.

In order to compensate the nonlinearity in the range

$t < t_c$, an operational amplifier is used, the non-inverting input of which is connected to the output of the output amplifier through the bias voltage source $U = 500 \text{ mV}$. At a temperature $t < t_c$, the output voltage of the output amplifier is $|U_{out}| < |U_z|$, and at the output of the operational amplifier of the linearization device, a positive voltage is formed, which through the diode in the direct connection and the output resistor is fed to the input of the output amplifier. The output voltage of the output amplifier is determined from the expressions:

$$U_{out} = -(\Delta U_A t + \Delta U_B t^2)k(1 + k_{l1}) - U_{z1}k_{l1}, \quad t < t_c,$$

$$U_{out} = -(\Delta U_A t + \Delta U_B t^2)k(1 - k_{l2}) + U_{z2}k_{l2}, \quad t > t_c,$$

where U_{z1} is bias voltage; k_{l1} , k_{l2} are linearization coefficients.

The linearization coefficients are determined by the values of the resistance of the output resistors of the LD operational amplifier and the value of the resistance of the feedback resistors of the output scale amplifier.

The results of investigation are shown in Fig. 7.

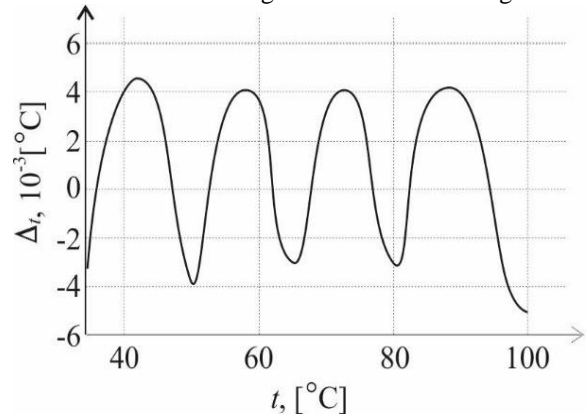


Fig. 7. Relationships between the errors of nonlinearity and the temperature.

From the analysis of the conducted researches it can be seen that the developed schematic diagram of a temperature sensor with a variable conversion factor of the output scaling amplifier of STT provides a nonlinearity error that does not exceed 0.005 °C.

Increasing the accuracy is possible by reducing the measurement range or by increasing the number of

linearization ranges.

Conclusions

The methods of linearization of the transfer function of semiconductor temperature sensors based on the formation of compensatory base measuring current and with formation of an additional conversion factor of the output amplifier are proposed. In this case the quadratic component of the transfer function of the transistor primary transfer at different temperature ranges is compensated at individual temperature ranges of measurement. The investigation of the developed

schematic diagram has shown that in the case of usage the linearisation method based on the formation of compensating base current, the measurement accuracy of ± 0.01 °C is provided. At the application of the method with a variable conversion factor of output scaling amplifier, the accuracy of ± 0.005 °C is provided in the range 30 – 100 °C.

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Аналіз і дослідження методів лінеаризації функції перетворення прецизійних напівпровідникових сенсорів температури

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Проведено аналіз нелінійності функції перетворення первинних перетворювачів температури на основі транзисторних структур, який показав, що квадратична складова функції перетворення створює значну похибку нелінійності 0,2 - 0,6°C. Нами розроблено методи лінеаризації на основі формування компенсаційного вимірювального струму та на основі зміни коефіцієнта перетворення вихідного масштабуючого підсилювача на окремих температурних діапазонах вимірювання, які забезпечують їх використання в прецизійних пристроях вимірювання температури. При цьому похибка вимірювання не перевищує 0,01 °C в діапазоні 30 - 100°C.

Ключові слова: транзистор, сенсор температури, лінеаризація.