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MICROSYSTEMS

A Linear Temperature Probe with a Low Power Supply Voltage

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Abstract—A new principle of arranging temperature measurements in integrated temperature probes is suggested that makes it possible to attain a high linearity in a simple way. Circuitry implementation and techniques that allow one to reduce power supply voltage are considered. The experimental results obtained are given.

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1. INTRODUCTION

There is a wide class of problems connected with measuring and controlling (monitoring) temperature, in particular, there is an urgent problem of creating miniature temperature probes to be used in both thermometers and portable devices operating from one power supply element [1, 2]. It is possible to obtain a quasi-linear voltage dependence $U(T)$ on temperature if we use the circuit of a current source, which is in proportion to temperature and, e.g., is based on transistors in the weak inversion mode or on two diodes with different current density. [3]. Here, the error of measurements made by means of a built-in ADC will be mainly contributed by the temperature dependence of the reference voltage source $U_{\mathrm{re}}(T)$ relative to which the measurements are carried out. The numerical simulation shows that the error contributed by a classical source of reference voltage based on diodes attains several degrees per 100°C. To increase the accuracy, it is necessary to create a source of reference voltage on the basis of more complex circuits, in particular, with quadratic compensation that increases both power consumed by the circuit and the chip size.

2. OPERATION PRINCIPLE OF A TEMPARATURE PROBE. CODE LINEARIZATION

The construction of a linear temperature probe consists of separate linearization of not individual components $U(T)$ and $U_{\mathrm{re}}(T)$ but direct linearization of the relationship $U(T)/U_{\mathrm{re}}(T)$, which is the value under measurement. In order to increase the signal-to-nose ratio, the relation of differential signals $(U_{RT}(T) - U(T))/(U_{RT}(T) - U_{RB}(T))$, where $U_{RT}(T)$ and $U_{RB}(T)$ are the upper and lower boundaries of the voltage range $U(T)$, which are produced by the reference voltage. This relation changes from 0 to 1 in a selected temperature range.

To attain accuracy in a wide temperature range of measurements, it is necessary to create a sensor with

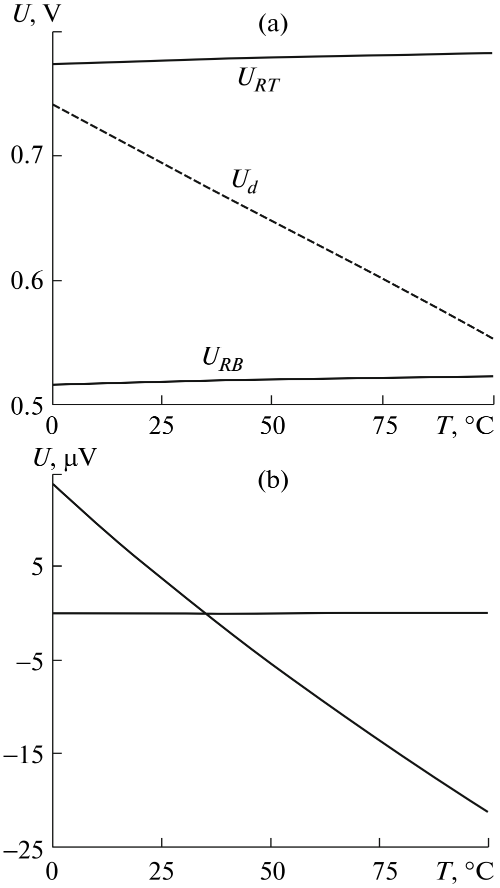

Fig. 1. Temperature dependence (a) and non-linearity of the measured value (b).

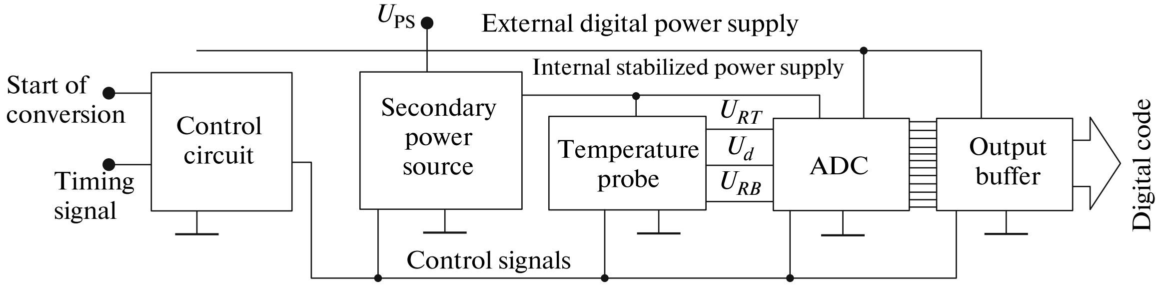

Fig. 2. Architecture of a temperature probe.

the maximal linear dependence of the output data on temperature. In the suggested measurement circuit there are both a sensor based on a diode with the output voltage directly depending on temperature $U_d(T)$ and a reference voltage source $U_{\mathrm{re}}(T)$ somewhat depending on temperature. Figure 1 shows the calculated curves of the temperature dependences and nonlinearity of the measured parameters. The nonlinearity was ±20 pm, i.e., the theoretical limit of the probe nonlinearity under correct adjustment attains $\pm 2 \times 10^{-3}$°C per 100°C. An important result of the theoretical calculations is the fact that the largest linearity of the measured parameter is not attained at the point of zero temperature drift of the source of the reference voltage (RVS) but is attained at a significantly lower temperature. In particular, if it is necessary to produce the maximum linearity of the output code at a temperature of 50°C, the point of full compensation of the temperature drift of RVS is needed to be selected at about 150°C, which was confirmed by practical results.

The developed architecture of a temperature probe that implements the above principle is shown in Fig. 2. It contains a temperature sensor unit, an ADC, a voltage regulator, a control circuit, and an output buffer.

In the temperature probe, a 12-bit double-integration ADC is used to convert a parameter under measurement into a digital code and directly yields the desired relation $(U_{RT}(T) - U_d(T))/(U_{RT}(T) - U_{RB}(T))$ at the digital output. This is achieved due to the fact that, during the first integration phase, the difference $U_{RT}(T) - U_d(T)$ is applied to it; and during the second integration phase, $U_{RT}(T) - U_{RB}(T)$.

To produce a high linearity of conversions, it is necessary to stabilize the supply voltage of the precise circuits of the temperature probe, namely, the sensor itself and the analog circuit of the ADC. For solving this problem, a secondary power source is used that stabilizes the power voltage of the analog circuit of the probe.

3. CIRCUITRY TECHNIQUES FOR REDUCING THE IC POWER SUPPLY

A feature of this IC is that it can operate the supply voltage reduced to as low as 1.1 V, which makes it possible to use it in portable systems with one power element. This requires application of the low-voltage option of RVS, a paraphase operational amplifier, and comparators.

Figure 3 shows the construction of a low-voltage RVS chosen as the basis. The operational amplifier (OA) consists of the input, intermediate, and output stages, The latter is combined with the resistor–capacitor part of the RVS *R*1–*R*2, *D*1, *D*2. The OA represents a three-stage structure which is chosen for yielding the required accuracy of the probe under all possible differences in transistor models. The embedded Miller's compensation was used to compensate the OA [3]. Differential pairs in the OA are made without current sources that provide unit operation under low power voltage. Resistors are used instead of the current sources to limit the dispersion of current consumed by the OA under variation of reference voltage.

The sensor output $U_d(T)$ is formed on a single diode *D*3. Here, it is important that the voltage level of the sensor diode is within the upper and lower levels of the reference voltage in the measured temperature range within the manufacturing tolerance (dispersion).

The signal from the sensor and reference outputs of the RVS comes to the inputs of the integrator made of a paraphase OA (POA).The POA performance at a power voltage as low as 1.1 V imposes a reasonable

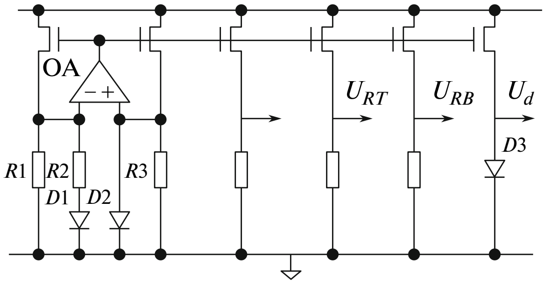

Fig. 3. Low-voltage reference source.

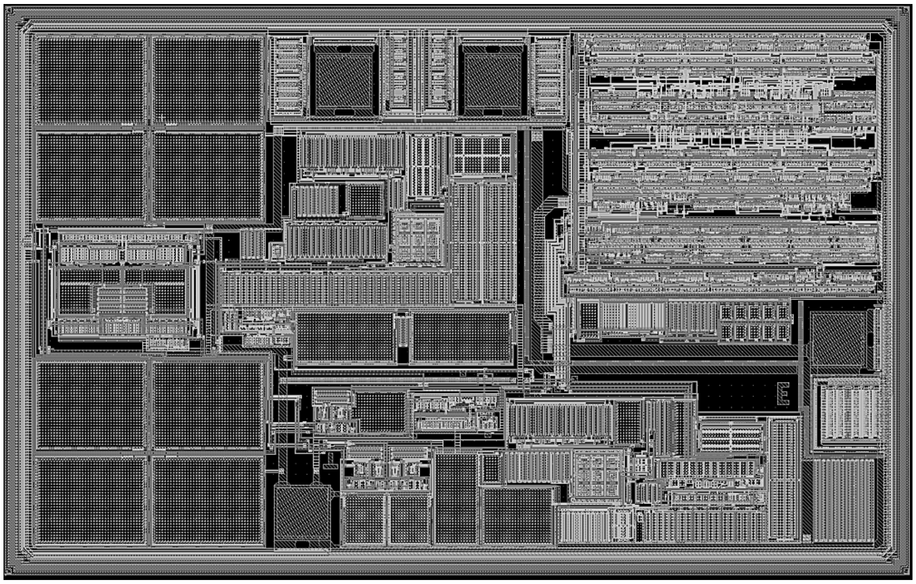

Fig. 4. Chip topology.

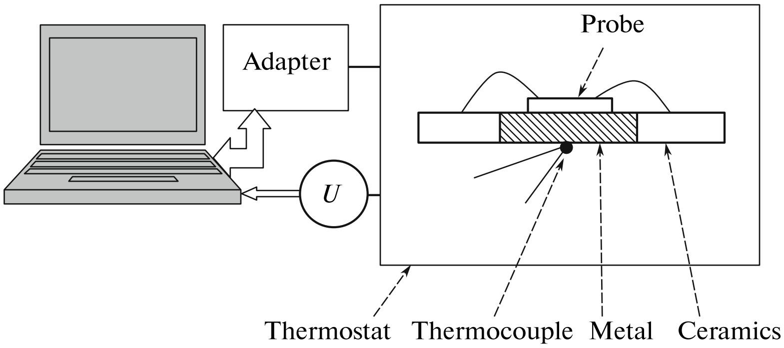

Fig. 5. Measuring facility.

limit to the swing of the input signal. The main reason for this is the value of the transistors' reference voltage that is equal to 0.5–0.7 V.

The simplest technique for reducing the dependence of the circuit functioning on the threshold voltage of transistors involved in the circuit is control by the substrate. The transistor's threshold voltage depends on the substrate–drain voltage by the law [3]

$$U_{th} = U_{th\,0} + \gamma(\sqrt{|2\phi_F - U_{BS}|} - \sqrt{|2\phi_F|}), \qquad (1)$$

where $U_{th\,0}$ is the nonbiased threshold voltage; γ is the bias coefficient of the threshold voltage, and ϕ_F is the Fermi potential.

For p-channel transistors, $2\phi_F \approx -0.7$ V, $\gamma \approx -0.5B^{1/2}$, $U_{th\,0} \approx -0.6$ V, and $U_{BS} > 0$.

Applying a negative bias substrate–drain voltage, we reduce the transistor's threshold voltage. However, while increasing the bias voltage, the current through a parasitic bipolar transistor increases and the amplifying properties of the MOS transistor decreases. This can be controlled if we set the bias current but not voltage in a substrate.

To implement the principle, we selected a simple two-stage OA with an *RC*-integrator and additional differential pairs fixing the common point. Due to control by the substrate, the minimal power voltage of the POA was 800–900 mV depending on the dispersion of the IC parameters. The frequency of unit gain is 300 kHz, the maximal gain is 70 dB, and the consumption current is 10 μA. Here, due to the presence of leakage currents, the amplitude–frequency characteristic of this amplifier is worse than that of such an amplifier without control by the substrate and for which the frequency of the unit gain is 400 kHz, the maximal gain is 80 dB. However, the minimal power voltage of the POA without control by the substrate is 1.3 V.

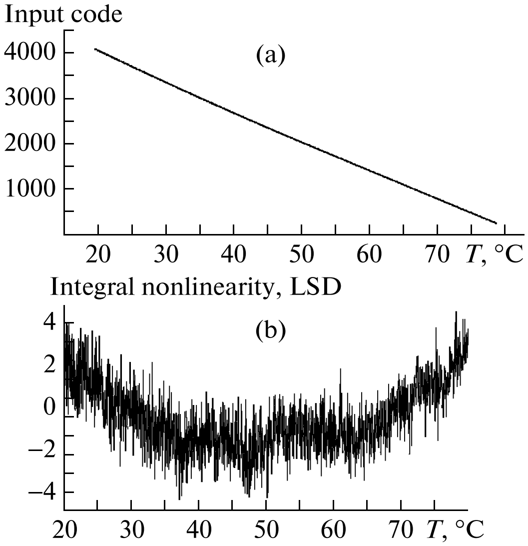

Fig. 6. Dependence of the input code on temperature (a) and integrated nonlinearity of conversion (b).

A comparator was designed with the minimal power voltage of 700 mV, the consumption current of 3 μA, and the switching time for typical process parameters was 1 μs.

4. RESULTS

The test samples of the temperature probe were manufactured using the 1-μm KMOS process at OAO Angstrem. The chip topology is shown in Fig. 4. The IC size was 1.1 × 1.6 mm.

Figure 5 shows the measuring facility whose feature is an automated algorithm of its operation.

The consumption current in the measurement mode was 130 μA at a power voltage of 1.5 V. The maximal integrated nonlinearity is ±5 LSD (Fig. 6) that corresponds to ±0.01°C per 10°C.

The suggested architecture and the circuitry solutions allow us to create a universal temperature probe with a wide measurement range, a high resolution, a small nonlinearity and a low power voltage that makes it possible to use it to solve a wide field of problems in developing digital measuring systems.

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