Indonesian Journal of Electrical Engineering and Computer Science
Vol. 42, No. 1, April 2026, pp. 40~47
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v42.i1.pp40-47

A sub-threshold CMOS temperature sensor circuit core with 2.41 mV/°C sensitivity for ultra-low-power applications (-100°C to 100°C)

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Article Info

Article history:

Received Jul 27, 2025
Revised Feb 16, 2026
Accepted Mar 4, 2026

Keywords:

CMOS
Sub-threshold
Temperature sensor
Ultra-low-power
Wide-range

ABSTRACT

This paper presents a sub-threshold complementary metal-oxide-semiconductor (CMOS) temperature sensor core for ultra-low-power applications, with the key advantage of reliable operation over an exceptionally wide temperature range from –100 °C to 100 °C, which is rarely reported in existing CMOS-based designs. The proposed architecture operates entirely in the sub-threshold region and is evaluated using circuit-level simulations, with validation through comparison to a previously reported temperature sensor. Simulation results show excellent linearity across the full temperature range, achieving a coefficient of determination of R^2 = 0.99997 and a sensitivity of approximately 2.41 mV/°C. At a supply voltage of 1.4 V and 25°C, the sensor core consumes only 22 nW, highlighting its suitability for energy-constrained applications. These results demonstrate the potential of sub-threshold CMOS temperature sensing for wide-range, ultra-low-power sensing systems.

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1. INTRODUCTION

Temperature measurement plays a critical role across a wide range of fields, influencing physical, electronic, chemical, mechanical, and biological systems [1]–[3]. Accurate temperature monitoring is particularly essential for the storage and control of temperature-sensitive products, including food, vaccines, and medical substances like plasma, especially at low temperatures [4]–[6]. In many modern applications, especially in wearable health-monitoring devices and internet of things (IoT) systems, ultra-small, unobtrusive, and low-power sensors are required [7]–[9].

In industrial applications, various types of temperature sensors, such as thermocouples, resistance temperature detectors (RTDs), and thermistors, are routinely employed. Each type offers specific advantages and disadvantages in terms of accuracy, cost, sensitivity, and operating conditions [10]–[12].

Electronic temperature sensors can be implemented using various components such as resistors, bipolar junction transistors (BJTs), or metal-oxide-semiconductor field-effect transistors (MOSFETs). BJTs are widely used in industry due to their high resolution and broad temperature range; however, they typically require a relatively high supply voltage [3], [13]–[17]. In contrast, MOSFET-based sensors offer advantages in terms of reduced area and lower power consumption, making them suitable for compact, energy-efficient systems [18]. In addition, MOSFET transistors, when operated in the sub-threshold region, enable ultra-low-energy consumption, making them ideal for power-constrained applications. In this regime, the drain current exhibits an exponential dependence on the gate-source voltage, even when the transistor is technically 'off ' (i.e., $V_{GS} < V_{th}$). Importantly, the sub-threshold current is highly sensitive to temperature due to its reliance on thermally activated carrier diffusion. This temperature dependence is particularly advantageous in our design, as the MOSFETs are used as temperature sensors, sub-threshold CMOS operation has rarely been studied over a very wide temperature range, especially at extreme temperatures. The predictable and measurable variation in sub-threshold current with temperature allows for accurate thermal sensing without the need for additional power-hungry circuitry, aligning with the overall goal of low-power operation [19], [20].

Temperature sensor circuits often rely on voltage outputs that are either proportional to absolute temperature (V_{PTAT}) or complementary to absolute temperature (V_{CTAT}) [13], [14]. After temperature detection, the resulting signal must be converted into a form that can be processed by an electronic system. Common signal conversion methods include time-to-digital conversion (TDC), frequency-to-digital conversion (FDC), and analog-to-digital conversion (ADC). TDC measures the propagation delay of a signal and converts it into a digital output, while FDC relies on frequency variation. Both TDC and FDC methods are advantageous in low-power applications. Nevertheless, ADC-based temperature sensors remain popular due to their high resolution and accuracy. Recent advancements in ADC technology have also enabled low-power designs that do not significantly compromise on area or energy requirements [4], [21]–[23].

This work presents a low-power CMOS temperature sensor core based on MOSFET technology, designed for accurate and linear temperature sensing over a wide range from –100 °C to 100 °C. While most sub-threshold CMOS temperature sensors reported in the literature operate over limited temperature ranges, this work extends the operating range down to –100 °C, which is rarely reported. The proposed circuit operates entirely in the sub-threshold region and is powered by a low-voltage DC supply, enabling ultra-low power consumption with high linearity. Its performance is evaluated through simulations and compared with a previously reported experimental design using both BJT- and MOSFET-based sensing elements. Owing to its compact six-transistor architecture and low energy consumption, the proposed sensor is well suited for wireless sensor networks and other energy-constrained applications.

2. ANALYTICAL STUDY OF THE PROPOSED SENSOR CORE CIRCUIT

The circuit operates with a low DC power supply and utilizes six MOSFET transistors, all biased in the sub-threshold region to enable ultra-low power consumption. The sensor's core architecture generates two output voltages: V_{PTAT} (proportional to absolute temperature) and V_{CTAT} (Complementary To Absolute Temperature), both of which exhibit linear dependencies on temperature, as illustrated in Figure 1 [24]. To facilitate circuit analysis, we adopt an approximate expression for the drain current of a MOSFET operating in the sub-threshold region. This current can be expressed as,

$$i_D = I_{S,s-t}\, exp(\frac{v_{GS}-V_{th}}{\eta\varphi_t})(1 - exp\frac{-v_{DS}}{\varphi_t}) \quad (1)$$

Where: $I_{S,s-t}$ is the sub-threshold saturation current,
v_{GS} is the input gate-source voltage,
V_{th} is the threshold voltage,
η is sub-threshold swing parameter,
$v_{DS}$is the drain-source voltage.
The thermal voltage φ_t is defined as,

$$\varphi_t = \frac{kT}{Q} \quad (2)$$

where k is the Boltzmann constant, T is the temperature, q is the elementary charge. Given that $v_{DS} \gg \varphi_t$, the second exponential term in (1) becomes negligible. Therefore, the drain current expression simplifies to,

$$I_{sub} = k_n'(\frac{W}{L})\varphi_t{}^2\, exp(\frac{V_{gs}-V_{th}}{\eta\varphi_t}) \quad (3)$$

where $k_n' = \mu_n C_{OX}$ is the process conduction parameter, W is the channel width and L is the channel length. V_{PTAT} voltage is the voltage difference between the gate-source voltages of transistors M_2 and M_3, hence,

$$V_{PTAT} = V_{gs2} - V_{gs3} = \eta\varphi_t\, ln(\frac{k_{n3}'}{k_{n2}'}) + (V_{th2} - V_{th3}) \quad (4)$$

V_{CTAT} voltage is the complement to V_{DD} of the voltage difference between the gate-source voltages of transistors M_2 and M_1.

$$V_{CTAT} = V_{DD} + V_{gs1} - V_{gs2} = V_{DD} - \eta\varphi_t \, ln(\frac{k'_{n1}}{k'_{n2}}) + (V_{th1} - V_{th2}) \quad (5)$$

In this paper, we focus on evaluating the linearity and measurement range of the proposed sensor. We present the differential voltage V_{diff}, defined as the difference between V_{PTAT} and V_{CTAT}, which serves as the input to a voltage-to-time converter. Although the converter itself is not discussed in this work, V_{diff} is provided for completeness and future integration [24].

$$V_{diff} = V_{PTAT}(T) - V_{CTAT}(T) \quad (6)$$

The x-coordinate of the intersection point between $V_{PTAT}(T)$ and $V_{CTAT}(T)$ defines the reference temperature T_0. By reformulating (6) and incorporating (2), we obtain,

$$V_{diff} = a(T - T_0) \quad (7)$$

where a is the sensitivity or the slope of the voltage V_{diff} vs temperature curve.

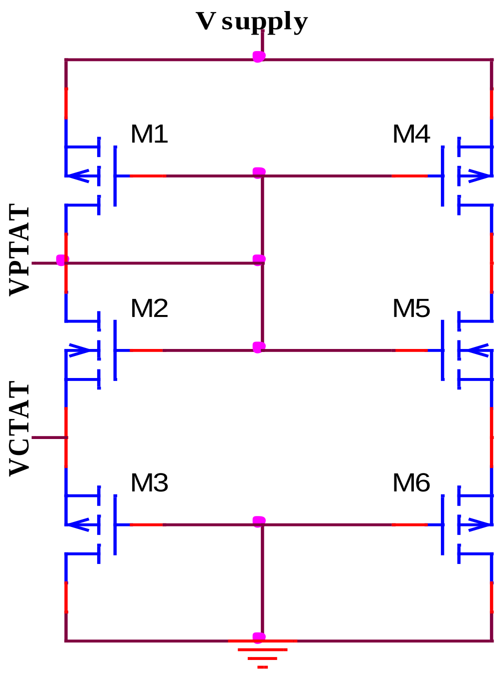


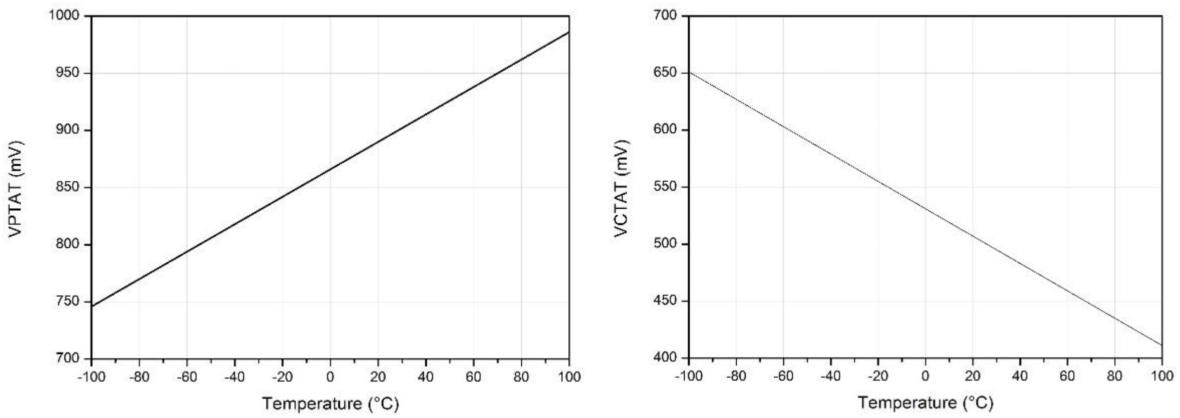
Figure 1. V_{PTAT} and V_{CTAT} generator

3. RESULTS AND DISCUSSION

3.1. Simulation results of proposed circuit

The primary objectives of this work are to design a temperature sensor core that offers high linearity, a wide temperature operating range, low supply voltage requirements, and minimal energy consumption. The proposed sensor core generates two key output signals: V_{PTAT} and V_{CTAT}, as illustrated in Figure 2. These signals are fundamental for accurate temperature measurement and control, and their precision and stability are critical to the overall performance of the sensor.

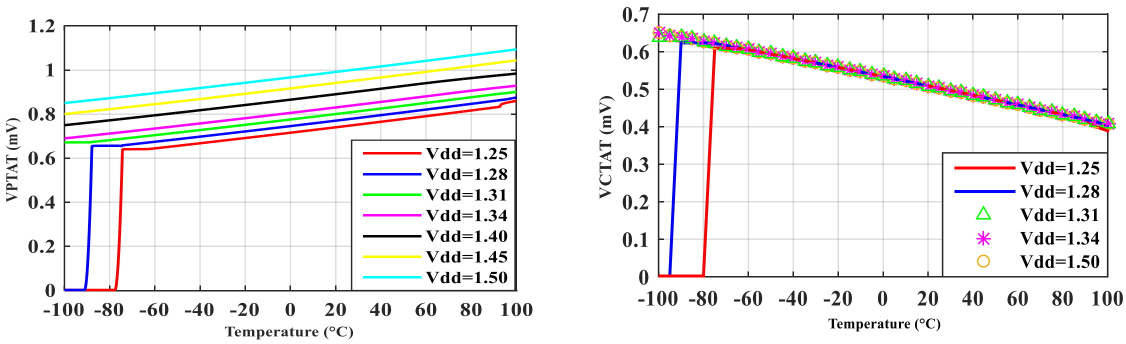
Across the temperature range of -100 °C to 100 °C, the sensor core demonstrates excellent linearity, with coefficients of determination R^2 = 0.9997 for V_{PTAT} and R^2 = 0.9994 for V_{CTAT}. While the slopes of these output signals slightly deviate from the theoretical values given by (7), this discrepancy is attributed to the temperature dependence of the threshold voltage and other transistor parameters. Figure 2 shows the variation of V_{PTAT} and V_{CTAT} as functions of temperature over the full range. Specifically, V_{PTAT} increases from 746 mV to 986 mV Figure 2(a), while V_{CTAT} decreases from 651 mV to 411 mV Figure 2(b). This corresponds to an approximate sensitivity of 1.2 mV/°C for both signals. These results highlight the feasibility and effectiveness of the proposed design in achieving high linearity over a wide temperature range with low power consumption.



(a) (b)

Figure 2. The simulation results of (a) V_{PTAT}, (b) V_{CTAT} for temperature range of -100 °C to +100 °C

In practical applications, battery voltage may degrade over time, which can affect the long-term stability of the sensor's linearity and operational range. To investigate this behavior, an experiment was conducted, with results shown in Figure 3. The test began with a supply voltage (V_{DD}) of 1.50 V, approximately three times the threshold voltage of the transistors used, placing the device at the edge of the sub-threshold operating region. As V_{DD} was gradually reduced, the system approached the cutoff region, resulting in a significant reduction in the linearity range of the sensor core. Both V_{PTAT} Figure 3(a) and V_{CTAT} Figure 3(b) were notably affected by this drop in supply voltage. These findings suggest that the proposed sensor core maintains good stability in terms of linearity and output range within a defined voltage window. Therefore, for reliable long-term operation, it is essential to optimize and monitor the supply voltage throughout the sensor's lifespan.



(a) (b)

Figure 3. The effect of supply power on (a) V_{PTAT} and (b) V_{CTAT}

3.2. Experimental results

To evaluate the performance of the proposed temperature sensor circuit, a series of experimental measurements were conducted and compared with those of an integrated CMOS temperature sensor reported in [13]. For validation, two reference sensors were used: a PT100 resistance thermometer and a thermocouple. The complete measurement setup was placed inside a temperature-controlled chamber to ensure accurate and consistent thermal conditions.

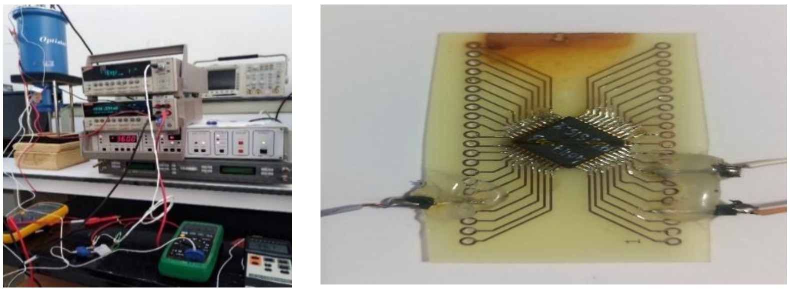


Figure 4. Overview of the integrated circuit and test setup

To record the output voltage as a function of temperature, a cryostat system equipped with an intelligent temperature controller (ITC-502s) was employed, working in conjunction with both the PT100 and a thermocouple. This configuration enabled precise thermal monitoring and reliable data acquisition. The experimental setup, including the integrated sensor and measurement instruments, is shown in Figure 4.

The experimental results exhibit a nearly linear variation of the output voltage (V_{out}) with temperature Figure 5, consistent with the behavior of a V_{PTAT} circuit. This linearity arises from the generation of a voltage proportional to absolute temperature (ΔV_{BE}), developed between two BJTs operating under different bias conditions. The resulting ΔV_{BE} signal is amplified by a MOSFET stage, yielding an output voltage that ranges from 0.55 V to 2.35 V across a temperature span of 20 °C to 100 °C. This corresponds to a sensitivity of approximately 22.5 mV/°C.

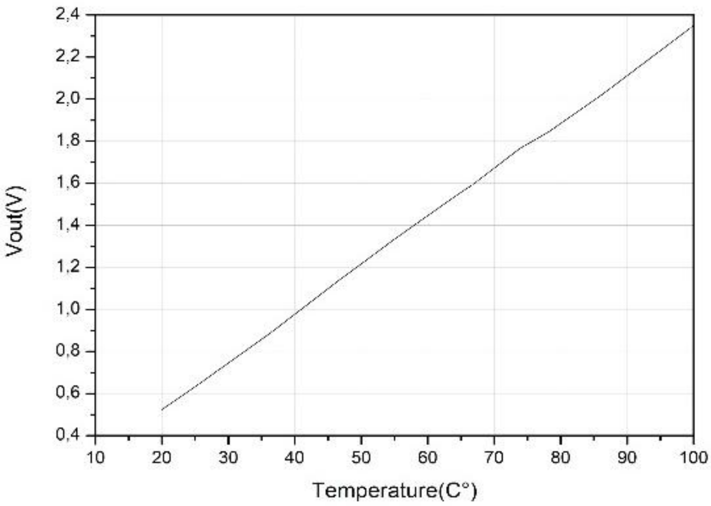


Figure 5. Variation of output voltage Vout with temperature in a V_{PTAT} circuit

3.3. Experimental and simulation comparison of the BJT-based integrated circuit and the proposed CMOS-based circuit

Figure 6 presents the experimental results of a temperature sensor integrated circuit utilizing BJT transistors associated to a differential amplifier, tested over a temperature range from room temperature to 100°C. For practical implementation, we employed a cryostat, ITC-502s, thermocouples, and PT100 sensors to measure the corresponding temperature-to-voltage output, as shown in Figures 4. The experimental data reveals an impressive linearity, with a correlation coefficient (R) of 0.997 Figure 6(b). The simulation results of the integrated sensor demonstrate that the curve exhibits excellent linearity with an R value of 0.9997 after reaching a temperature of 10°C Figure 6(a). However, the curve displays poor linearity below this temperature, as observed visually, as shown in Figure 6.

To evaluate the performance of the proposed MOSFET-based temperature sensor core, we compared its simulation results with those of an integrated BJT-based temperature sensor (Figure 6(c)). The simulation results reveal that the proposed sensor core exhibits superior linearity and a wider measurement range compared to the BJT-based reference. Notably, the circuit architecture demonstrates accurate temperature sensing across a broad range from –100 °C to 100 °C, with a high coefficient of determination R^2=0.99997 for the V_{diff} versus temperature relationship. This exceptional linearity indicates that the output voltage remains highly predictable across the entire temperature span. In addition to its wide range and accuracy, the sensor core operates with ultra-low power consumption, making it highly energy-efficient.

The combination of high linearity, wide temperature measurement range, and ultra-low power operation underscores the suitability of the proposed sensor core for a wide range of practical applications, particularly in power-constrained environments such as battery-operated, wearable, and implantable devices. To validate the effectiveness of the proposed design, a comparative analysis with state-of-the-art temperature sensors reported in the literature is presented in Table 1. This comparison considers key parameters including process technology, power consumption, supply voltage, sensitivity,terimakasih mas and operating temperature range.

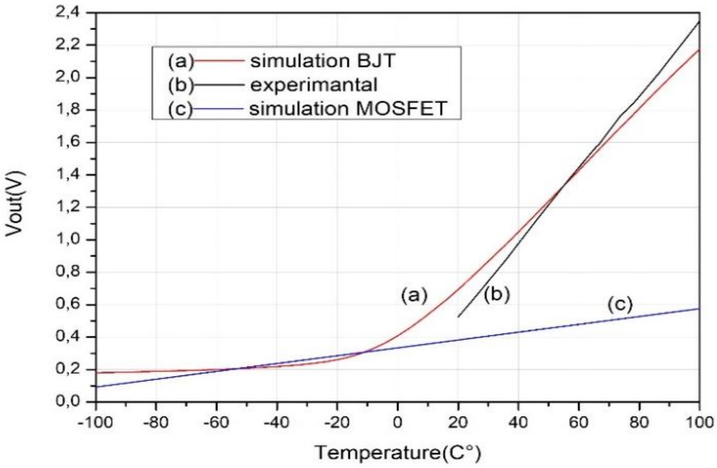


Figure 6. Experimental and simulation results of output voltage (Vout) versus temperature: (a) simulation BJT response, (b) experimental BJT response, and (c) our MOSFET-based simulation

Table 1. Sensor performance comparison with state-of-the-art

Ref	Process technology [nm]	Power consumption [µW]	Supply voltage [V]	Sensitivity [mV/˚C]	Temperature range [˚C]
[1]	130	558.2	1.2	-	0 / 80
[13]	350	495	3.3	19.1	20 / 90
[17]	180	3.8-5.7	1.5-2	150-440	-50 / 180
[19]	65	-	1.2	1.8	-20 / 120
[20]	130	18.9 - 23.6	1	-	-40 / 90
[25]	55	9.8	0.8	5.76	-40 / 125
[26]	55	0.86	0.8	5.8	-40 / 85
[27]	65	0.0064	0.8	2.8	-30 / 70
[28]	180	0.020	0.8-1.6	900	0 / 100
This work	180	0.022	1.4	2.41	-100 / 100

4. CONCLUSION

This paper provides a comprehensive analysis and the design topology of a low-power temperature sensor, created utilizing CMOS technology. The sensor's core is designed to operate over a broad temperature range, from -100 °C to 100 °C, catering to various applications. To gauge the performance of our architecture, we conducted both experimental and simulation studies, contrasting the results with those from a previously established circuit in existing literature.

The simulation results demonstrated exceptional linearity and accuracy, with all MOSFET transistors of the sensor core functioning optimally in the sub-threshold region. The collected data indicated that linearity is primarily influenced by the power supply voltage (Vdd) and the inherent characteristics of the transistor.Operating at 25 °C, the core sensor's power consumption registers a mere 22nW with a power supply of 1.4V. The sensor's sensitivity, a crucial metric in temperature sensing applications, stands at approximately 2.41 mV/°C. Although the proposed sensor achieves ultra-low power consumption, its sensitivity is lower than that of BJT-based designs, which may limit applications requiring high-resolution measurements.

Future research will focus on integrating the sensor with an analog-to-digital converter and embedding the design into a single chip for RFID and other ultra-low-power sensing applications, as well as performing experimental validation under process and temperature variations to ensure robustness and practical applicability.

ACKNOWLEDGMENT
The authors would like to sincerely thank Professor Francesco G. Della Corte, Dr. Massimo Merenda, and the Department of Information Engineering, Infrastructure and Sustainable Energy (DIIES), Reggio Calabria, Italy, for their valuable guidance and for providing their sensor to enable a comparison with ours.

FUNDING INFORMATION
The authors state no funding is involved.

AUTHOR CONTRIBUTIONS STATEMENT
This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Abdelhakim Megueddem	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓
Khaled Bekhouche	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT
The authors state no conflict of interest.

DATA AVAILABILITY
Derived data supporting the findings of this study are available from the corresponding author [AM] on request.

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