

Article

A High-Reliability, Flexible, Hybrid-Integrated Temperature Sensor

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Abstract

Accurate, real-time temperature monitoring of traction motors, battery packs, and power electronic modules is a critical requirement for the safety, efficiency, and long-term reliability of electric vehicles (EVs), particularly on the curved, space-constrained, and vibration-prone surfaces found on motor end-windings, battery-module casings, and busbar assemblies. To meet the needs of such automotive curved-surface applications, as well as wearable devices and flexible electronic skin, this paper presents complementary metal-oxide-semiconductor (CMOS) temperature sensor. Its core includes a CMOS sensor chip with an integrated bandgap reference circuit and dual-path electrostatic discharge (ESD) protection, combined with flexible printed circuit board (FPCB/FPC) for conformal mounting on curved surfaces. Circuit-level simulation predicts a typical reference-voltage temperature coefficient of 20 ppm/°C over −40 to 125 °C, while experimental temperature characterization yields a temperature output (TEMP) sensitivity of approximately 5.0 mV/°C over the reported temperature range. Absolute temperature error and linearity are not claimed as independently verified performance metrics in the present revision because the currently available experimental documentation does not preserve the reference-temperature calibration traceability, repeated-measurement information, measurement-uncertainty analysis, or calculation definitions required to substantiate the previously reported ± 1 °C and 0.99% values. After flexible integration and 100 bending cycles at a 10 mm radius, the reference-voltage variation remains below 0.1%, while the reported temperature-equivalent TEMP-output shift remains within ± 0.5 °C under the tested laboratory conditions. These results demonstrate short-term laboratory bending stability and temperature-sensing performance under the tested conditions rather than long-term fatigue or automotive vibration qualification. The proposed sensor therefore demonstrates potential for curved and space-constrained thermal-monitoring applications, including permanent magnet synchronous motor (PMSM) stator windings and battery-module surfaces, while validation on actual EV components and formal automotive qualification remain necessary for production deployment.

Keywords: flexible temperature sensor; CMOS sensing die; bandgap reference circuit; flexible electronic skin; electric vehicle thermal management



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1. Introduction

The rapid electrification of the global transportation sector has placed increasingly stringent demands on the thermal management and safety monitoring of electric vehicle (EV) powertrains [1–3]. Traction motors, particularly permanent magnet synchronous motors (PMSMs), generate substantial heat within stator windings and end-turns during high-torque acceleration and regenerative braking, while lithium-ion battery packs must be continuously monitored to prevent thermal runaway and preserve cycle life [4]. In addition, power electronic modules such as insulated-gate bipolar transistors (IGBTs) and silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs) within traction inverters experience rapid junction-temperature variations that must be monitored for control and protection purposes [5,6]. Unlike temperature sensing on flat and rigid electronic assemblies, many EV components have curved, irregular, or space-constrained surfaces, including motor end-windings, cylindrical or pouch-type battery cells, and busbar assemblies, where conventional rigid thermocouples or thermistor packages can be difficult to mount conformally and may introduce contact-interface errors [7–9]. These characteristics motivate the development of flexible temperature sensors that combine conformability with adequate sensing accuracy, stability, and electrical robustness for practical thermal-monitoring applications [10,11].

Flexible temperature sensing has also attracted considerable attention in robotic sensing, electronic skin, wearable health monitoring, and, increasingly, EV thermal-management applications [12–15]. As flexible and distributed sensing systems develop, temperature sensors are expected to operate reliably on curved or mechanically deformable surfaces while maintaining stable electrical characteristics [16]. In motor-driven systems, temperature information can support the monitoring of permanent-magnet machines, windings, bearings, and other thermally sensitive components [17,18]. In EVs, similar measurements are relevant to battery-pack thermal management, traction-motor temperature monitoring, and power-electronics thermal protection [19]. Accordingly, flexible temperature sensors intended for such applications should be evaluated in terms of sensing accuracy, operating temperature range, repeatability, mechanical conformability, and environmental robustness. For eventual automotive deployment, additional validation under vibration, thermal cycling, humidity, electromagnetic interference, and other application-specific conditions is also required [10].

Among existing flexible temperature-sensing approaches, metal thin films such as Pt and Ni fabricated on flexible substrates can provide relatively stable resistance–temperature characteristics, repeatability, and sensing accuracy [20,21]. However, their performance under repeated deformation can be influenced by film cracking, interfacial delamination, resistance drift, and fabrication-process variations. Carbon-based and organic flexible temperature-sensing materials provide high mechanical compliance, although their linearity, repeatability, and wide-temperature-range stability can depend strongly on material composition, device structure, and fabrication conditions [22]. Printed and solution-processed temperature sensors offer advantages such as low cost, lightweight construction, and compatibility with large-area fabrication, but their output characteristics can be affected by ink uniformity, curing conditions, contact resistance, material aging, and process variation [23]. Therefore, material-based flexible sensors generally provide attractive mechanical adaptability, whereas achieving simultaneously high electrical consistency, wide-temperature operation, and reproducible calibration remains an important design consideration. These issues are particularly relevant in EV thermal monitoring, where temperature-measurement errors may influence thermal-protection and control decisions.

Hybrid integration using flexible printed circuit boards (FPCs) provides an alternative route in which mature silicon sensing circuits can be combined with mechanically com-

pliant interconnects [24]. Compared with purely material-based flexible sensors, CMOS temperature sensors can provide compact size, low power consumption, good repeatability, high integration density, and compatibility with wafer-level fabrication. CMOS-compatible temperature-sensing circuits are therefore attractive where compact analog temperature monitoring and subsequent electronic interfacing are required [25]. Integrated temperature sensors commonly exploit the temperature dependence of semiconductor junction characteristics. In bipolar-device-based temperature-sensing structures fabricated within CMOS processes, the base-emitter voltage exhibits a complementary-to-absolute-temperature characteristic, while differences between appropriately biased junction voltages can generate proportional-to-absolute-temperature quantities [26–28]. These temperature-dependent components can be combined in a bandgap-reference architecture to obtain a comparatively stable reference voltage and a temperature-dependent sensing output. The achievable performance depends not only on circuit topology but also on device matching, layout, process variation, mechanical stress, packaging, and electrostatic-discharge protection. When a rigid CMOS die is integrated onto a flexible substrate, bending-induced strain, die-attach stress, encapsulation stress, and wire-bond deformation can affect the stability of the electrical output. The external pads and interconnections must also tolerate electrostatic-discharge events during fabrication, assembly, handling, and operation. In automotive environments, additional mechanical and environmental stresses may arise from vibration, thermal-expansion mismatch, repeated temperature cycling, humidity, and electromagnetic interference [29–31]. Consequently, flexible hybrid integration requires coordinated consideration of sensing-circuit performance, package-level mechanical behavior, interconnection integrity, and component-level electrical protection. Laboratory bending or electrostatic discharge (ESD) tests can provide useful design validation, but they should not be interpreted as substitutes for long-term fatigue testing or formal automotive qualification.

A remaining challenge is therefore to combine the electrical advantages of CMOS temperature sensing with the mechanical adaptability of a flexible substrate while maintaining stable operation under controlled bending and thermal conditions. Existing material-based flexible sensors provide excellent conformability but may involve trade-offs among accuracy, linearity, repeatability, fabrication consistency, and wide-temperature-range operation. Conversely, conventional CMOS temperature-sensing dies provide well-controlled electrical characteristics but are inherently rigid and require an appropriate flexible packaging and interconnection strategy for curved-surface mounting. For EV-related applications, such a sensor architecture may be particularly relevant to space-constrained or curved surfaces, although actual deployment requires component-level validation and automotive qualification beyond laboratory testing.

To investigate this approach, this work develops a flexible hybrid-integrated temperature sensor based on a customized 180 nm CMOS sensing die and FPC-based bare-die integration. The CMOS die incorporates a bandgap-reference circuit, proportional-to-absolute-temperature (PTAT), buffer circuits, and a dual-path ESD protection network. The die is thinned and assembled onto an FPC substrate using conductive epoxy mounting, gold-wire bonding, and PDMS encapsulation. This architecture is intended to retain the electrical precision and integration advantages of CMOS sensing while improving conformability for curved-surface temperature measurement.

The main contributions of this work are summarized as follows. First, a customized CMOS temperature-sensing die based on a bandgap-reference and PTAT-output architecture is designed, and its reference-voltage temperature behavior, startup characteristics, loop stability, and process-related variation are evaluated through circuit-level simulation. Second, a dual-path ESD protection structure is incorporated at the I/O and power pins and subsequently evaluated through component-level ESD testing. Third, an FPC-based hybrid

integration process combining die thinning, conductive attachment, gold-wire bonding, and PDMS encapsulation is implemented to enable controlled bending of the packaged sensor. Fourth, circuit-level simulation predicts a typical reference-voltage temperature coefficient of 20 ppm/°C over -40 to 125 °C, while experiments evaluate the TEMP-output characteristics and stability under the specified thermal and 100-cycle bending conditions. The experimental bending results are treated as short-term laboratory validation rather than evidence of long-term fatigue or automotive vibration qualification. Finally, the resulting flexible architecture is discussed in relation to curved and space-constrained thermal-monitoring applications, including potential EV motor and battery applications; however, validation on actual EV components and formal automotive qualification remain outside the scope of the present study.

2. Materials and Methods

This section presents the design architecture, circuit implementation, layout realization, and flexible packaging process of the proposed temperature sensor, with emphasis on the electrical design, component-level ESD protection, and mechanical characteristics relevant to flexible curved-surface temperature sensing. The design is considered in the context of potential EV motor and battery thermal-monitoring applications, while formal automotive qualification is outside the scope of this study. Figure 1 first provides an overview of the overall circuit architecture of the sensing die before the individual sub-blocks are described in detail.

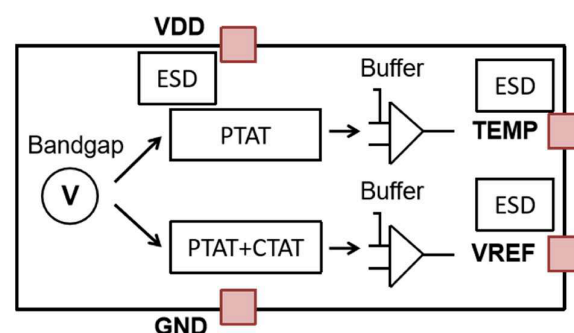


Figure 1. Circuit architecture of the CMOS temperature-sensing die. CMOS, complementary metal-oxide-semiconductor; ESD, electrostatic discharge; PTAT, proportional to absolute temperature; CTAT, complementary to absolute temperature; TEMP, temperature output; VREF, reference voltage; VDD, power supply; GND, ground.

As shown in Figure 1, the die generates a low-temperature-drift reference voltage with a bandgap reference circuit as the core. Internally, a bipolar transistor's ΔV_{BE} drives the PTAT circuit to produce a positive-temperature-coefficient current, which is then proportionally combined with a complementary-to-absolute-temperature (CTAT) in the zero-temperature-drift synthesis circuit to output a nearly zero-temperature-drift reference-voltage signal. This signal is buffered through a buffer circuit and reference voltage (VREF) pin, ensuring strong load interference immunity. The PTAT circuit of the bandgap reference is directly buffered and temperature output (TEMP) pin, providing the temperature-dependent analog sensing signal. A dual-path ESD protection network covers all pins; a clamp structure is used between VDD and GND, and a secondary discharge path is added at the TEMP and V_{REF} pins, providing dedicated electrostatic-discharge paths for the supply and signal terminals. The four pins have clear functions, VDD for power supply (5.5 V), GND for ground, TEMP for the temperature-dependent voltage output, and V_{REF} for the reference voltage, forming a compact four-pin interface that can be connected to an external analog acquisition circuit.

Building on the architecture summarized in Figure 1, Figure 2 details the transistor-level circuit implementation, separating the reference/temperature signal-generation path from the two electrostatic-discharge (ESD) protection paths that safeguard the input/output (I/O) and power pins. These protection structures are intended to improve component-level robustness against electrostatic transients; the applied ESD stress levels and observed test outcomes are reported separately in Section 3.

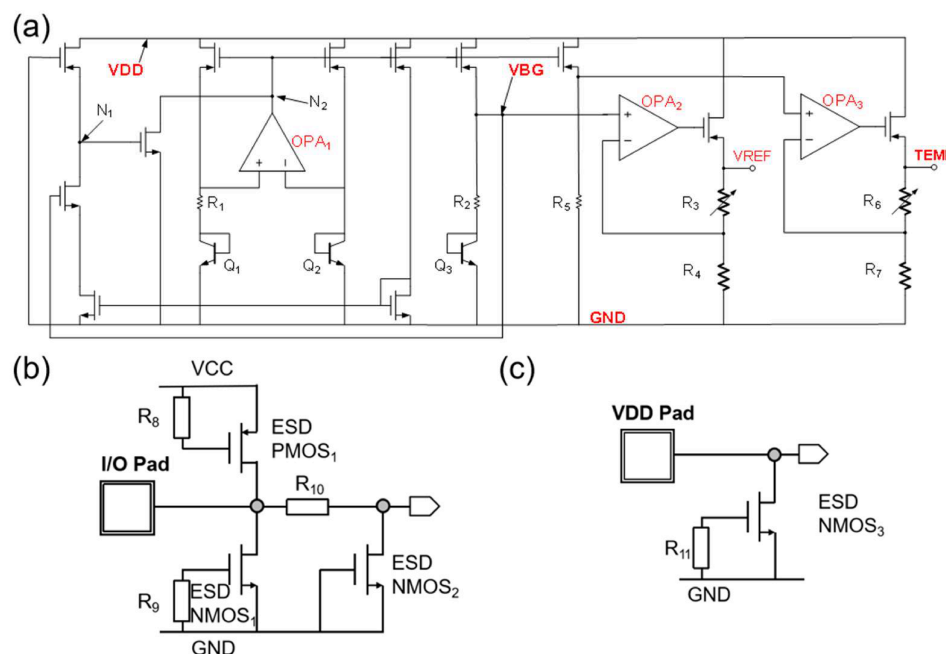


Figure 2. Circuit schematic. (a) Schematic of the circuit generating the reference output and temperature sensing signals; (b) schematic of the ESD protection path for the input/output pins; (c) schematic of the ESD protection path for the power supply pins.

The circuit schematic of the sensing die is shown in Figure 2a. From left to right, it sequentially integrates a soft-start circuit (to suppress power surge impact), a bandgap reference core, a V_{BE} circuit combining PTAT/CTAT currents, and a buffer amplifier circuit (implementing voltage proportional amplification through a resistor feedback network, respectively driving the reference output V_{REF} and the temperature signal TEMP).

To raise the bias voltage and achieve layout matching, the parallel count ratio of Q_1 to Q_2 is selected as 16:2. The voltage division on resistor R1 in the bandgap reference core is expressed as follows:

$$\Delta V_{BE} = V_{BE(Q_2)} - V_{BE(Q_1)} \quad (1)$$

where V_{BE} represents the voltage difference between the base and emitter of the transistors. For bipolar transistors with emitter-area ratio N operating at the same collector bias current, this base-emitter voltage difference follows the well-known bandgap relation

$$\Delta V_{BE} = \left(\frac{kT}{q} \right) \times \ln(N) \quad (2)$$

where k is Boltzmann's constant, T is the absolute temperature, q is the elementary charge, and $N = 8$ is the effective emitter-area ratio set by the 16:2 parallel arrangement of Q_1 and Q_2 . Substituting $N = 8$ shows that ΔV_{BE} grows linearly and predictably with absolute temperature, which is the physical basis for the PTAT (proportional-to-absolute-temperature) current subsequently generated in the reference core.

According to the current mirror current replication relationship, the following holds in the PTAT/CTAT fusion circuit:

$$(\Delta V_{BE}/R_1) \times R_2 + V_{BE(Q3)} = V_{BG} \quad (3)$$

where IPTAT is the PTAT current generated by the bandgap reference core, copied to the branch Q_3 through a current mirror, forming a PTAT voltage across the resistor R_2 . The transistor Q_3 provides the CTAT voltage. By adjusting the ratio between R_1 and R_2 , the first-order temperature coefficient of V_{BG} can be corrected. Because $V_{BE(Q3)}$ decreases with temperature at approximately $-2 \text{ mV}/^\circ\text{C}$ (the CTAT term) while $(V_{BE}/R_1) \times R_2$ increases with temperature, the zero-temperature-coefficient condition for V_{BE} is obtained by setting the total derivative with respect to temperature to zero:

$$\partial/\partial T \left[\left(\frac{\Delta V_{BE}}{R_1} \right) \times R_2 \right] + \partial V_{BE(Q3)}/\partial T = 0 \quad (4)$$

which, after substituting the linear approximations for both temperature-dependent terms, yields the practical resistor-sizing constraint

$$R_2/R_1 \approx \left[\frac{\partial V_{BE(Q3)}}{\partial T} / [(k/q) \times \ln(N)] \right] \quad (5)$$

This ratio directly determines the R_2/R_1 resistor sizing implemented, and explains why precise resistor matching rather than absolute resistor accuracy governs the $20 \text{ ppm}/^\circ\text{C}$ temperature-drift performance reported in Section 3. The output reference voltage is given by

$$V_{REF} = V_{BG} \times (R_3 + R_4)/R_4 \quad (6)$$

The resistor ratio circuit constructed by OPA2 enables the V_{REF} pin to have both strong driving capability and high input impedance, without affecting the voltage value of the V_{BG} circuit. The temperature sensing pin is expressed as

$$V_{TEMP} = (\Delta V_{BG}/R_1) \times R_5 \times (R_6 + R_7)/R_7 \quad (7)$$

Differentiating V_{TEMP} with respect to temperature gives the sensor's temperature-to-voltage sensitivity, S :

$$S = dV_{TEMP}/dT = [(k/q) \times \ln(N)] R_1 \times R_5 \times (R_6 + R_7)/R_7 \quad (8)$$

With R_5 , R_6 , and R_7 sized to give $S \approx 5 \text{ mV}/^\circ\text{C}$, the value subsequently evaluated experimentally in Section 3, the sensor provides a directly usable analog signal. The TEMP output can therefore be interfaced with an external analog-to-digital converter (ADC); however, integration with a specific battery management system (BMS) was not experimentally evaluated in this study.

Here, I_{PTAT} is the PTAT current generated by the bandgap reference core and copied via a current mirror to the R_5 branch, forming a PTAT voltage across R_5 . Additionally, because the resistor-ratio circuit is constructed by OPA3, the TEMP pin possesses high input impedance and output-driving capability.

Figure 2b illustrates the ESD protection paths for the I/O pins, including VREF and TEMP. A p-channel metal-oxide-semiconductor (PMOS) AND n-channel metal-oxide-semiconductor (NMOS) bidirectional discharge structure is adopted, with a secondary NMOS discharge path and current-limiting resistor introduced to improve transient robustness. Figure 2c shows the ESD protection path for the power pins; VDD is connected

to a large-size NMOS discharge transistor to ground, with a gate-integrated current-limiting resistor to reduce false triggering. The dual-path network was designed to improve component-level ESD robustness. The experimentally applied human body model (HBM), charged device model (CDM), and machine model (MM) stress levels and the corresponding test results are reported in Section 3; these results should not be interpreted as formal automotive ESD qualification.

Before fabrication, the circuit was evaluated using transistor-level simulations based on the commercial 180 nm CMOS process process design kit (PDK). Process, voltage, and temperature (PVT) analyses and Monte Carlo simulations were used to examine startup behavior, loop stability, reference-voltage temperature dependence, and process-related statistical variation. Figure 3 summarizes these simulation-based evaluations and should be distinguished from the physical-device measurements presented in Section 3.

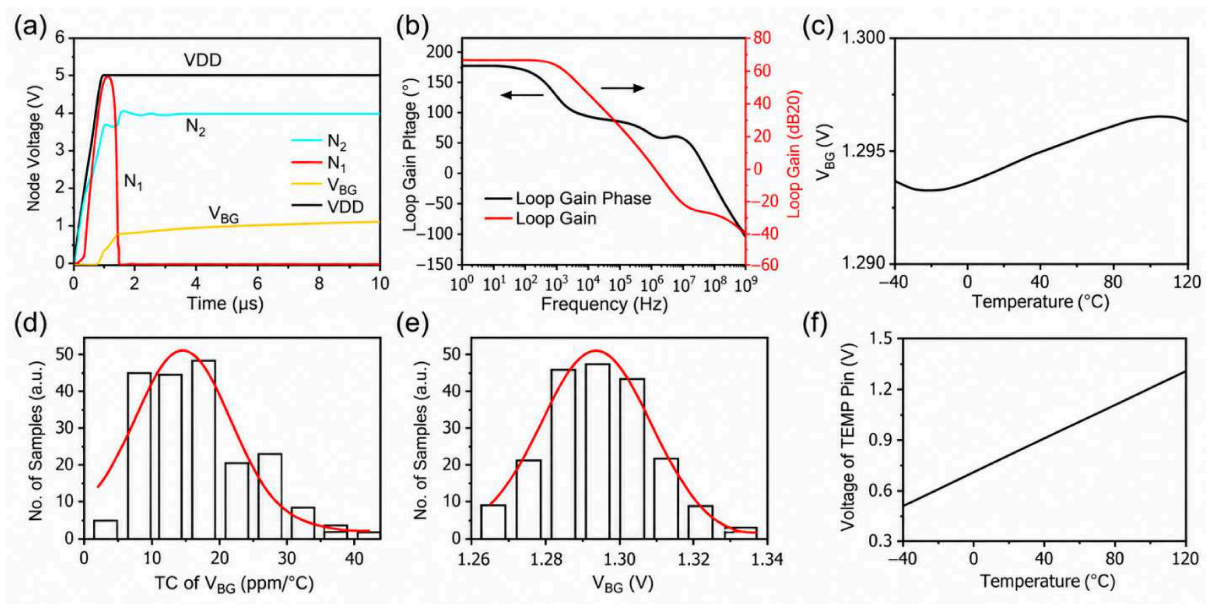


Figure 3. Simulation analysis of the schematic based on the foundry PDK. (a) Transient timing simulation of the startup circuit; (b) stability simulation of the bandgap reference core loop; (c) relationship between bandgap reference voltage and temperature; (d) distribution of the temperature coefficient of the bandgap reference voltage based on Monte Carlo simulation; (e) distribution of the bandgap reference voltage based on Monte Carlo simulation; (f) relationship between the output voltage at the temperature output pin and temperature.

Circuit simulation based on the commercial 180 nm CMOS process PDK shows that, under a $5 \text{ V}/\mu\text{s}$ power-supply slew rate, Figure 3a predicts normal startup of the bandgap reference core with an overshoot below 5%. Loop-stability analysis in Figure 3b gives a phase margin above 55° . Figure 3c predicts a typical reference-voltage temperature coefficient of $20 \text{ ppm}/^\circ\text{C}$ over -40 to 125°C . PVT and Monte Carlo simulations in Figure 3d,e indicate a worst-case temperature coefficient of $\leq 45 \text{ ppm}/^\circ\text{C}$ and a reference-voltage deviation below 8 mV (3σ). Figure 3f shows the simulated TEMP-output response over the full temperature range, with an output voltage of approximately 0.83 V at 25°C and a simulated sensitivity of approximately $5 \text{ mV}/^\circ\text{C}$. These quantities are simulation results and are therefore not treated as experimentally measured device characteristics. The simulation results were used to guide circuit and layout optimization prior to fabrication; experimental thermal performance is evaluated separately in Section 3.

Following circuit-level verification, the design was translated into a physical layout compliant with the target CMOS process. Figure 4 illustrates the resulting die layout,

highlighting the placement of the matched bandgap core, the ESD protection network, and the bond-pad interface subsequently wire-bonded onto the flexible substrate described in Figure 5.

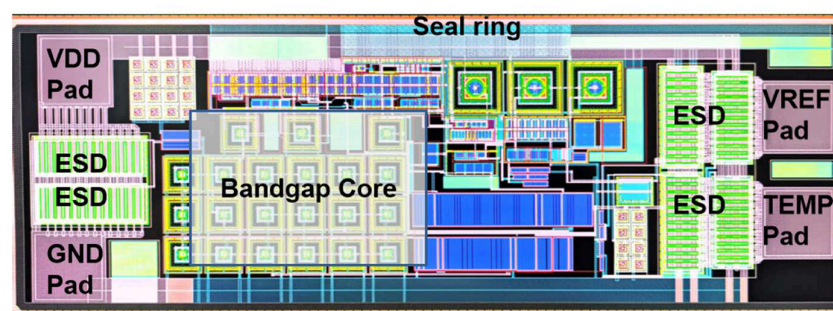


Figure 4. Layout of the temperature-sensing die based on the foundry PDK.

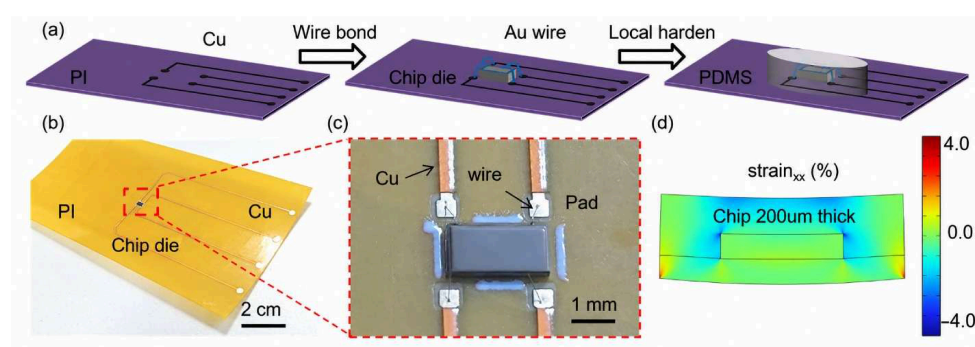


Figure 5. Fabrication of the flexible hybrid-integrated temperature sensor. (a) Process flow of flexible hybrid integration; (b) photo of the flexible hybrid-integrated temperature sensor based on the FPC board; (c) photo of the temperature sensing die mounted on the FPC board; (d) schematic diagram of the strain distribution in the x direction when the die mounted on the FPC board is bent with a 10 mm radius.

The layout strictly follows the 180 nm CMOS process design rules. The core area includes the bandgap reference source, occupying 0.08 mm^2 and using a common-centroid matched layout to suppress gradient errors; a dual-path ESD protection network, with large-size clamp transistors integrated at the VDD/GND pins and accounting for 22% of the area; and four aluminum-copper alloy pins (VDD/GND/TEMP/ V_{REF}), each with a width of $80 \text{ }\mu\text{m}$. The periphery is equipped with a double-layer seal-ring structure, $20 \text{ }\mu\text{m}$ wide, to provide mechanical stress buffering. Key signal routing employs shielding, with temperature-sensing lines having a width of $3 \text{ }\mu\text{m}$ and spacing of $2 \text{ }\mu\text{m}$, while the reference-voltage path is routed using a differential symmetric arrangement to reduce crosstalk. The entire layout design rule check (DRC) and layout versus schematic (LVS) with zero errors, confirming consistency with the target process design rules and enabling subsequent fabrication and flexible-device assembly.

Once the CMOS die was fabricated, it was integrated into a flexible hybrid package for curved-surface mounting. Figure 5 summarizes the fabrication process, photographs of the completed sensor, and a finite-element simulation used to estimate the strain distribution in the die and bonding region under the specified 10 mm bending condition. The mechanical simulation is used here as a design assessment and not as evidence of long-term fatigue or automotive vibration qualification.

The fabrication process of the flexible hybrid-integrated temperature sensor is shown in Figure 5a. Based on a standardized process, a $1.2 \times 0.6 \text{ mm}^2$ CMOS sensing bare die is integrated with a flexible printed circuit board. A photograph of the flexible sensor is

shown in Figure 5b, and close-up photographs of the gold-wire bonding and encapsulation are shown in Figure 5c. To reduce strain on the die during bending, the back of the die is polished to a thickness of 200 μm before assembly. As a result, the overall thickness of the flexible sensor is 0.3 mm. Finite-element simulation indicates that, at a bending radius of 10 mm, the maximum strain in the x direction in the die region is below 0.5%, while the corresponding strain at the bonding points is below 3%. These simulated values characterize the mechanical response of the package under the specified bending configuration and should not be interpreted as demonstrating long-term mechanical reliability or automotive vibration durability. The adopted fabrication approach is compatible with a conventional fabless CMOS and FPC-integration workflow; production-scale manufacturing and automotive qualification were not evaluated in this study.

3. Results

Having established the electrical design and flexible packaging of the proposed sensor, this section experimentally evaluates its electrical response under controlled laboratory bending and temperature conditions. The bending experiment assesses short-term output stability under repeated deformation, whereas the temperature experiment evaluates the steady-state temperature-dependent output of the fabricated device. These tests characterize the prototype only under the specified laboratory conditions and are not equivalent to automotive vibration, fatigue, electromagnetic compatibility (EMC), or environmental qualification. Figure 6 presents the experimental setups and corresponding bending and temperature measurements.

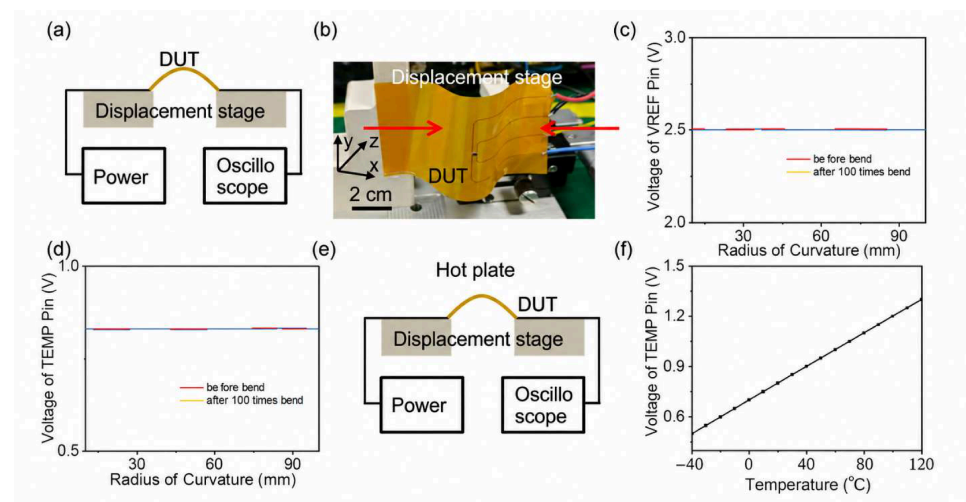


Figure 6. Testing of the flexible hybrid-integrated temperature sensor. (a) Schematic diagram of the bending-test experimental setup; (b) photograph of the bending-test experimental setup; (c) relationship between the reference-voltage output and bending radius before bending and after 100 bending cycles; (d) relationship between the TEMP-pin voltage output and bending radius before bending and after 100 bending cycles; (e) schematic diagram of the temperature-characterization setup; (f) relationship between the TEMP-pin output voltage and device temperature.

The bending-test setup is shown in Figure 6a,b. A digital power supply provides adjustable voltage signals (1.8, 2.5, 3.3, and 5 V) to the sensing die. An oscilloscope records the output-voltage time-domain signal, while a multimeter monitors the static voltage. Both ends of the flexible device are mounted on a bidirectional displacement platform, and controlled displacement along the x-axis produces bending. A microscope positioned along the y-axis is used to observe the device contour and determine the bending radius at the sensing-die location.

Figure 6c,d compare the reference-voltage and TEMP-pin outputs before bending and after 100 bending cycles. For bending radii of 10 mm and above, no substantial change in either output is observed within the resolution of the reported measurements. These results demonstrate short-term mechanical and electrical stability under the specified laboratory bending condition only. The 100-cycle test does not establish long-term fatigue or automotive vibration reliability, and no automotive vibration, thermal-cycling, humidity, or EMC qualification was performed in this study. The temperature-characterization setup is shown in Figure 6e. The sensor is placed on a hot plate, and the temperature at the sensing-die location is varied under controlled conditions. At each temperature point, the device is allowed to stabilize for 20 min before the TEMP-pin output voltage is recorded. The experimental documentation currently available for preparation of this revision confirms the use of hot-plate heating and a 20 min stabilization period at each temperature point before recording the TEMP-pin output voltage. However, the retained documentation does not identify the model and calibration traceability of the reference-temperature sensor, the number of devices subjected to the temperature characterization, the number of repeated measurements at each temperature point, or a formal measurement-uncertainty budget. The documentation currently available also does not preserve the calculation definitions used for the previously stated ± 1 °C temperature error and 0.99% linearity. These methodological details have therefore not been reconstructed retrospectively. Accordingly, the present revision limits quantitative interpretation to the temperature-dependent electrical characteristics directly supported by the retained experimental record and does not treat the previously reported ± 1 °C and 0.99% values as independently verified metrological performance metrics. Accordingly, the present experiment characterizes steady-state temperature performance rather than dynamic thermal response. The response time of the packaged sensor was not measured; therefore, no numerical response-time value is claimed, and controlled temperature-step testing is required before performance in time-critical thermal-warning applications can be established.

As shown in Figure 6f, the TEMP-pin output is approximately 0.825 V at the reported 25 °C operating point, and the measured voltage–temperature characteristic corresponds to a sensitivity of approximately 5.0 mV/°C over the reported –40 to 125 °C temperature range. After 100 bending cycles at a 10 mm radius, the reported TEMP-output shift remains within ± 0.5 °C under the tested laboratory conditions. Because the experimental documentation currently available does not preserve the reference-temperature calibration traceability, repeated-measurement statistics, measurement-uncertainty analysis, or calculation procedures underlying the previously stated ± 1 °C temperature error and 0.99% linearity, these two values are not retained in the present revision as independently verified performance claims. The experimentally observed TEMP-output characteristics should be distinguished from the 20 ppm/°C reference-voltage temperature coefficient obtained from the circuit-level simulation presented in Figure 3. Additionally, five samples were subjected to component-level ESD stress testing. The available experimental documentation reports applied stress levels of HBM 4 kV, CDM 500 V, and MM 200 V, with no failure reported for the tested pins at these levels. The exact test standard and edition, stress polarity and pin-combination sequence, number of stress applications or repetitions, and post-stress electrical pass/fail criteria are not specified in the records currently available for this revision and have therefore not been reconstructed retrospectively. Accordingly, these results are reported as component-level laboratory ESD observations under the applied stress conditions and are not claimed as compliance with a specific JEDEC Solid State Technology Association (JEDEC)/ESD Association (ESDA) protocol or as formal Automotive Electronics Council (AEC) Q100.

4. Discussion

The combined simulation and experimental results demonstrate the complementary roles of the CMOS sensing die and the flexible hybrid-integration structure. Compared with representative Pt- and Ni-based flexible temperature sensors [20,21], the proposed approach retains the electrical characteristics of a process-controlled CMOS sensing die while using die thinning, conductive-epoxy attachment, and polydimethylsiloxane (PDMS) encapsulation to accommodate bending of the FPC substrate. Carbon-based and printed flexible temperature sensors can provide high mechanical compliance but may exhibit material- and process-dependent limitations in wide-range linearity and stability [23,24]. In the present work, circuit-level simulation predicts a typical reference-voltage temperature coefficient of 20 ppm/°C over -40 to 125 °C, whereas the experiments verify the TEMP-output response and its stability under the specified thermal and bending conditions. The experimentally characterized TEMP output exhibits a sensitivity of approximately 5.0 mV/°C over the reported temperature range, while the reported temperature-equivalent TEMP-output shift after 100 bending cycles at a 10 mm radius remains within ± 0.5 °C under the tested laboratory conditions. The previously stated ± 1 °C temperature error and 0.99% linearity are not used as independently verified performance metrics in the present revision because the currently available experimental documentation does not provide the reference-temperature calibration traceability, number of devices and repeated measurements, measurement-uncertainty evaluation, or calculation definitions required to substantiate those quantities. Accordingly, the temperature results are interpreted as steady-state laboratory voltage-temperature characterization rather than a traceable absolute-temperature calibration. These results should be interpreted as laboratory-level electrical and short-term bending validation rather than evidence of long-term mechanical or automotive reliability. Because the thermal measurements were recorded after a 20 min stabilization period at each temperature point, they characterize steady-state temperature-sensing performance. The dynamic thermal response time of the packaged sensor was not measured in the present study; therefore, no response-time claim is made, and controlled temperature-step characterization is required to assess suitability for time-critical thermal monitoring.

To place these results in context, Table 1 compares the proposed sensor with representative flexible temperature-sensing approaches reported in the literature. The comparison is intended to identify differences in sensing principle, flexibility, integration, and demonstrated validation rather than to establish a unified quantitative benchmark. Because device structures and test conditions differ among the cited studies, numerical values should be interpreted only within their respective experimental contexts.

For EV-related thermal monitoring, the sensor architecture presents several potential use cases rather than demonstrated production applications. Its 1.2×0.6 mm² sensing die and 0.3 mm flexible package may facilitate conformal placement on geometrically constrained surfaces such as PMSM end-windings, battery-module surfaces, or curved busbars. The experimentally characterized analog TEMP output could provide a temperature input to a motor controller or battery-management system through an appropriate analog-to-digital conversion interface. For multi-point monitoring, multiple analog TEMP outputs could, at the system level, be digitized by a multichannel ADC and processed by a host BMS or motor controller, with subsequent communication implemented through an appropriate digital interface, such as vehicle-level Controller Area Network (CAN) or local Serial Peripheral Interface (SPI)/Inter-Integrated Circuit (I²C/I²C). These digital interfaces are not integrated into the present sensing die, and such a multi-sensor communication architecture was not implemented or experimentally validated in this study. Similarly, the integrated ESD structure was evaluated in component-level testing at the reported HBM, CDM, and MM stress levels; these observations are limited to the laboratory test conditions

documented in this study. However, these characteristics establish technical feasibility only; operation on an actual traction motor, battery pack, or power-electronic module was not evaluated.

Table 1. Qualitative comparison of representative flexible and rigid temperature-sensing approaches with the sensor reported in this work. Ranges for prior approaches reflect typical values reported in the corresponding cited literature and are not from a single unified benchmark test; they are included to contextualize, not to statistically compare, the present results.

Sensing Approach	Typical Accuracy/Linearity	Typical Temp. Range (°C)	Mechanical Flexibility	ESD/EMI Robustness	Automotive Qualification Status
Pt/Ni thin-film RTD on flexible substrate	High accuracy; drift with film cracking/delamination	−40 to 150 (typical)	Moderate; degrades with repeated bending	Not integrated; external protection needed	Not typically automotive-qualified
Carbon-based/organic semiconductor	Moderate; linearity limited over wide range	0 to 100 (typical)	High compliance and stretchability	Not integrated	Not automotive-qualified
Printed/solution-processed	Variable; sensitive to ink/curing/aging	−20 to 100 (typical)	High; low cost, large area	Not integrated	Not automotive-qualified
Commercial rigid NTC/Pt1000	$\pm(0.5\text{--}2)^\circ\text{C}$ typical	−40 to 150	None; rigid package, poor curved-surface conformability	Package-level, standards-qualified	Widely automotive-qualified
This work: flexible hybrid-integrated CMOS bandgap sensor	TEMP sensitivity $\approx 5.0\text{ mV}/^\circ\text{C}$; absolute error and linearity are not independently established.	−40 to 125	High; stable after 100 cycles at 10 mm radius	On-die dual-path ESD; five devices passed HBM 4 kV, CDM 500 V, and MM 200 V laboratory-level testing.	Not yet formally qualified; laboratory-level validation only

Abbreviations: CMOS, complementary metal-oxide-semiconductor; ESD, electrostatic discharge; EMI, electromagnetic interference; RTD, resistance temperature detector; NTC, negative temperature coefficient; Pt1000, platinum resistance thermometer with $1000\ \Omega$ at 0°C ; HBM, human body model; CDM, charged device model; MM, machine model.

Several limitations therefore define the scope of the present results. The thermal and bending experiments were performed under controlled laboratory conditions, and the 100-cycle bending test demonstrates only short-term mechanical stability at the specified 10 mm bending radius. It should not be interpreted as equivalent to automotive vibration, mechanical-shock, or long-term fatigue qualification. Moreover, no system-level tests were conducted on actual traction motors, battery packs, or power-electronic modules, and automotive vibration, thermal-cycling, humidity, and electromagnetic-compatibility tests were not performed. The reported HBM, CDM, and MM results likewise represent component-level ESD validation rather than formal automotive qualification. Consequently, the present results demonstrate the feasibility of combining CMOS temperature sensing with flexible hybrid integration, while extended mechanical-fatigue testing, environmental qualification, EMC evaluation, and validation on representative EV components remain necessary before automotive deployment can be established. Future work should therefore include controlled temperature-step measurements to quantify dynamic response, extended mechanical and environmental reliability testing, and system-level evaluation of ADC and digital-interface integration for multi-point motor or battery temperature monitoring.

5. Conclusions

In summary, this paper presents a flexible hybrid-integrated temperature sensor based on a customized CMOS sensing die. Through the collaborative design of the bandgap reference circuit and dual-path ESD protection within the die, circuit-level simulation predicts a typical reference-voltage temperature coefficient of 20 ppm/°C over -40 to 125 °C, while the temperature-sensing output is experimentally evaluated over the tested temperature range. By combining bare-die-level flexible printed circuit (FPC) hybrid integration technology, the mechanical mismatch between the rigid CMOS die and flexible substrate is mitigated. Experimental characterization shows a TEMP-output sensitivity of approximately 5.0 mV/°C over -40 to 125 °C and a reported temperature-equivalent output shift within ± 0.5 °C after 100 bending cycles at a 10 mm radius. Because the available test records lack the traceability, repeatability, uncertainty, and calculation details required to verify the previously reported ± 1 °C error and 0.99% linearity, these values are not claimed as independently verified performance metrics. These results demonstrate short-term mechanical stability under the specified laboratory bending conditions and should not be interpreted as long-term fatigue or automotive vibration qualification. Five samples withstood HBM 4 kV, CDM 500 V, and MM 200 V without reported failure. Because the test protocol, repetitions, and acceptance criteria were unavailable, these results are reported only as laboratory-level ESD observations, not formal standards or automotive qualification. Compared with existing flexible temperature-sensing approaches, the proposed design combines CMOS sensing performance with flexible FPC conformability and component-level ESD robustness, providing a laboratory-validated sensing platform with potential applicability to wearable health monitoring, electronic skin, dynamic thermal sensing in robotics, and curved or space-constrained thermal monitoring in electric vehicle systems. No validation was performed on actual traction motors, battery packs, or power-electronic modules; therefore, automotive deployment requires further vibration, thermal-cycling, humidity, and EMC qualification. Future work will focus on multi-point sensor networking with a standard automotive digital interface and extended qualification under combined vibration and thermal-cycling conditions representative of full EV service life, to support the transition of this technology from laboratory validation toward production-grade vehicle integration.

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References

1. Lajunen, A.; Yang, Y.; Emadi, A. Recent Developments in Thermal Management of Electrified Powertrains. *IEEE Trans. Veh. Technol.* **2018**, *67*, 11499. [\[CrossRef\]](#)
2. Lei, S.; Xin, S.; Liu, S. Separate and integrated thermal management solutions for electric vehicles: A review. *J. Power Sources* **2022**, *550*, 232133. [\[CrossRef\]](#)
3. Asim, M.; Baig, T.; Riaz Siddiqui, F.; Khan, S.; Ali Khan, S.; Babar, H.; Said, Z.; Zhao, J.; Abidi, I.H. Advancements in thermal management solutions for electric vehicle high power electronics: Innovations, cooling methods, and future perspectives. *J. Energy Storage* **2025**, *111*, 115344. [\[CrossRef\]](#)
4. Zhu, Z.-Q.; Liang, D. Perspective of Thermal Analysis and Management for Permanent Magnet Machines, with Particular Reference to Hotspot Temperatures. *Energies* **2022**, *15*, 8189. [\[CrossRef\]](#)
5. Shuai, Z.; He, S.; Xue, Y.; Zheng, Y.; Gai, J.; Li, Y.; Li, G.; Li, J. Junction temperature estimation of a SiC MOSFET module for 800V high voltage application in electric vehicles. *eTransportation* **2023**, *16*, 100241. [\[CrossRef\]](#)
6. Zhang, Z.; Dyer, J.; Wu, X.; Wang, F.; Costinett, D.; Tolbert, L.M.; Blalock, B.J. Online Junction Temperature Monitoring Using Intelligent Gate Drive for SiC Power Devices. *IEEE Trans. Power Electron.* **2019**, *34*, 7922–7932. [\[CrossRef\]](#)
7. Koshkouei, M.J.; Saniee, N.F.; Barai, A. Thermocouple selection and its influence on temperature monitoring of lithium-ion cells. *J. Energy Storage* **2024**, *92*, 112072. [\[CrossRef\]](#)
8. Cheng, A.; Xin, Y.; Wu, H.; Yang, L.; Deng, B. A Review of Sensor Applications in Electric Vehicle Thermal Management Systems. *Energies* **2023**, *16*, 5139. [\[CrossRef\]](#)
9. Jinasena, A.; Spitthoff, L.; Wahl, M.S.; Lamb, J.J.; Shearing, P.R.; Strømman, A.H.; Burheim, O.S. Online Internal Temperature Sensors in Lithium-Ion Batteries: State-of-the-Art and Future Trends. *Front. Chem. Eng.* **2022**, *4*, 804704. [\[CrossRef\]](#)
10. Liu, L.; Dou, Y.; Wang, J.; Zhao, Y.; Kong, W.; Ma, C.; He, D.; Wang, H.; Zhang, H.; Chang, A.; et al. Recent Advances in Flexible Temperature Sensors: Materials, Mechanism, Fabrication, and Applications. *Adv. Sci.* **2024**, *11*, e2405003. [\[CrossRef\]](#) [\[PubMed\]](#) [\[PubMed Central\]](#)
11. Kuzubasoglu, B.A.; Bahadir, S.K. Flexible temperature sensors: A review. *Sens. Actuators A Phys.* **2020**, *315*, 112282. [\[CrossRef\]](#)
12. Liu, S.-Z.; Guo, W.-T.; Chen, H.; Yin, Z.-X.; Tang, X.-G.; Sun, Q.-J. Recent Progress on Flexible Self-Powered Tactile Sensing Platforms for Health Monitoring and Robotics. *Small* **2024**, *20*, 2405520. [\[CrossRef\]](#)
13. Hegde, C.; Su, J.; Tan, J.M.R.; He, K.; Chen, X.; Magdassi, S. Sensing in Soft Robotics. *ACS Nano* **2023**, *17*, 15277–15307. [\[CrossRef\]](#) [\[PubMed\]](#) [\[PubMed Central\]](#)
14. Oh, J.Y.; Lee, Y.; Lee, T.-W. Skin-Mountable Functional Electronic Materials for Bio-Integrated Devices. *Adv. Healthc. Mater.* **2024**, *13*, 2303797. [\[CrossRef\]](#)
15. Du, Y.; Kim, J.H.; Kong, H.; Li, A.A.; Jin, M.L.; Kim, D.H.; Wang, Y. Biocompatible Electronic Skins for Cardiovascular Health Monitoring. *Adv. Healthc. Mater.* **2024**, *13*, 2303461. [\[CrossRef\]](#)
16. Kenry; Yeo, J.; Lim, C. Emerging flexible and wearable physical sensing platforms for healthcare and biomedical applications. *Microsyst. Nanoeng.* **2016**, *2*, 16043. [\[CrossRef\]](#)
17. Brody, R.; McIntyre, M.; Grainger, B. Online Permanent Magnet Temperature Estimation in Permanent Magnet Machines Using Nonlinear Observer With Enhanced Parameter Estimation to Minimise Risk of Demagnetisation. *IET Electr. Power Appl.* **2025**, *19*, e70043. [\[CrossRef\]](#)
18. Zhu, L.; Zhu, L.; Wang, S.; Chen, H. A fast real-time motor temperature estimation method taking less than 0.2 s. *Therm. Sci. Eng. Prog.* **2025**, *57*, 103103. [\[CrossRef\]](#)
19. Khan, F.I.; Moinul Hossain, M.; Lu, G. Sensing-based monitoring systems for electric vehicle battery—A review. *Meas. Energy* **2025**, *6*, 100050. [\[CrossRef\]](#)
20. Liu, Z.; Tian, B.; Zhang, B.; Liu, J.; Zhang, Z.; Wang, S.; Luo, Y.; Zhao, L.; Shi, P.; Lin, Q.; et al. A thin-film temperature sensor based on a flexible electrode and substrate. *Microsyst. Nanoeng.* **2021**, *7*, 42. [\[CrossRef\]](#)
21. Nam, V.B.; Lee, D. Evaluation of Ni-Based Flexible Resistance Temperature Detectors Fabricated by Laser Digital Patterning. *Nanomaterials* **2021**, *11*, 576. [\[CrossRef\]](#)
22. Liu, R.; He, L.; Cao, M.; Sun, Z.; Zhu, R.; Li, Y. Flexible Temperature Sensors. *Front. Chem.* **2021**, *9*, 539678. [\[CrossRef\]](#)
23. Shi, L.; Zhang, N.; Li, L.; Ding, S.; Li, W.; Li, K. Printed flexible temperature sensors: Principles, materials, processes, and applications. *Appl. Mater. Today* **2025**, *43*, 102665. [\[CrossRef\]](#)
24. Ma, Y.; Zhang, Y.; Cai, S.; Han, Z.; Liu, X.; Wang, F.; Cao, Y.; Wang, Z.; Li, H.; Chen, Y.; et al. Flexible Hybrid Electronics for Digital Healthcare. *Adv. Mater.* **2020**, *32*, 1902062. [\[CrossRef\]](#)
25. Xie, S. The Design Considerations and Challenges in MOS-Based Temperature Sensors: A Review. *Electronics* **2022**, *11*, 1019. [\[CrossRef\]](#)
26. Meijer, G.C.M.; Wang, G.; Fruett, F. Temperature sensors and voltage references implemented in CMOS technology. *IEEE Sens. J.* **2001**, *1*, 225–234. [\[CrossRef\]](#)

27. Wang, G.; Meijer, G.C.M. The temperature characteristics of bipolar transistors fabricated in CMOS technology. *Sens. Actuators A Phys.* **2000**, *87*, 81–89. [[CrossRef](#)]
28. Szermer, M.; Jankowski, M. Analysis of a PTAT Sensor and Bandgap Reference with Emphasis on Their Mutual Influence in a CMOS ASIC. *Electronics* **2025**, *14*, 4947. [[CrossRef](#)]
29. Wu, H.; Huang, Y.; Yin, Z. Flexible hybrid electronics: Enabling integration techniques and applications. *Sci. China Technol. Sci.* **2022**, *65*, 1995–2006. [[CrossRef](#)] [[PubMed](#)] [[PubMed Central](#)]
30. Somarathna, U.S.; Pathirana, O.V.; Wickramasinghe, G.C.; Alhendi, M.A.; Weerawarne, D.L.; Poliks, M.D. Evaluation of Electromechanical Reliability of Flexible and Stretchable Electronics. *Annu. Rev. Mater. Res.* **2026**, *56*, 257–282. [[CrossRef](#)]
31. Xie, L.; Deng, E.; Yang, S.; Zhang, Y.; Zhong, Y.; Wang, Y.; Huang, Y. State-of-the-art of the bond wire failure mechanism and power cycling lifetime in power electronics. *Microelectron. Reliab.* **2023**, *147*, 115060. [[CrossRef](#)]

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