

A Comparative Evaluation of Temperature Sensing Technologies: RTDs, Thermocouples, Thermistors and Semiconductor Temperature Sensors

¹S Keerthana, ²A Amarnath Kumar

¹Student, Computer Science and Engineering, Sir M Visvesvaraya Institute of Technology, Bengaluru, Karnataka, India.

²Assistant Professor, Sir M Visvesvaraya Institute of Technology, Bengaluru, Karnataka, India

Abstract - This work presents a comparative evaluation of the four major temperature-sensing technologies, namely, RTDs, thermocouples, thermistors and semiconductor-based temperature sensors. Temperature measurement is essential across industrial, automotive, medical, environmental and scientific applications. Not one technology is best for every criterion or use. RTDs showcase strong performance in terms of accuracy, stability, repeatability and linearity, making them particularly suitable when precision is the primary requirement. Thermocouples have an advantage in wide and extreme temperature measurement and hence, are suitable for harsh and high-temperature environments. Thermistors are highly sensitive and provide rapid responses, making them applicable for monitoring relatively small temperature changes. Semiconductor temperature sensors are well suited for compact electronic systems due to their potential for miniaturization, electronic integration and signal processing. This work provides an application-oriented basis for selecting an appropriate temperature-sensing technology rather than declaring one sensor to be superior over the others.

Key Words: temperature sensing, RTD, thermocouple, thermistor, semiconductor temperature sensor, temperature measurement, sensor comparison

1. INTRODUCTION

Accurate temperature measurement underpins a broad range of engineering processes and operations, from industrial process control and nuclear-plant safety instrumentation to wearable health monitoring and lowpower integrated circuit thermal management. None of the sensing technologies satisfy every application simultaneously, since the requirements of accuracy, response speed, operating range, cost and mechanical form factor often trade off against one another. Common temperature sensors include thermistors, resistance temperature detectors (RTDs), thermocouples and semiconductor-based sensors, each suited for different applications depending upon sensitivity, measurement range and operating environment [1]. Similarly, industrial

practice groups temperature sensors into integrated circuit(IC)/semiconductor sensors, thermistors, RTDs and thermocouples, with sensor size and measurement range generally increasing along this progression [13]. The choice of sensors is rarely trivial. In machining research, for instance, the main criteria for selecting a temperature measurement technique include the expected temperature range, the sensor's sensitivity to noise, its responsiveness and its cost [5]. Since no single methodology has proven ideal for every machining operation, the appropriate technique must be selected according to the specific experimental requirements [5]. This same reasoning is applicable across domains: nuclear-grade RTDs are chosen for stability and regulatory compliant response time [3], flexible thermocouples are chosen for their combination of fast response and mechanical compliance [6], printed thermistors are chosen for low cost and high sensitivity in wearable patches [10,11], and semiconductor (MOS/CMOS) sensors are chosen for on-chip integration and micro-power operation. This review consolidates recent literature (2022-2026) on four major temperature-sensing families-RTDs, thermocouples, thermistors, and semiconductor-based sensors. For each family, the underlying physical principle, representative implementations, and reported performance are summarized. A structured comparative evaluation is then presented across accuracy, operating range, sensitivity, response time, linearity/stability, and cost/integration, followed by application-based sensor-selection guidance, a discussion of open challenges and concluding remarks.

2. LITERATURE SURVEY

2.1 Resistance Temperature Sensors (RTDs)

RTDs are considered as reliable and accurate sensing elements that operate on the principle of measuring the near-linear change in electrical resistance in metals with temperature [2]. The resistance of an RTD changes predictably with temperature, allowing the temperature to be determined from the measured resistance. The basic sensing mechanism is shown in Fig. 1.

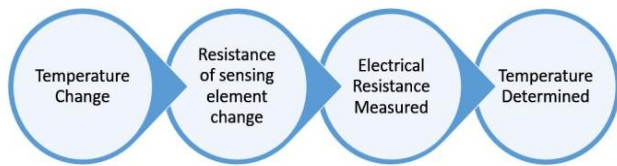


Fig 1. Basic Operating Principle of an RTD

Platinum, nickel and copper are the most commonly used metals, that offer accurate and reliable measurement across a wide range (-200 °C to 850 °C), together with high conductivity, sensitivity, and resistance to strain, shock, pressure and vibration [2]. Platinum was found to remain most accurate and stable choice owing to its low reactivity, high melting point, and chemical stability, whereas copper is prone to oxidation at higher temperature despite good linearity and low cost, and nickel becomes markedly nonlinear above 300 °C despite offering high output and lower cost than platinum [2].

Response time is a safety-critical parameter for RTDs used in nuclear reactor coolant instrumentation, governed by standards like Regulatory Guide 1.118 and NUREG-0800 [3]. Beyond the sensing element itself, the accuracy of an RTD measurement chain depends heavily on the temperature transducer (TT) that converts sensor resistance into a voltage or digital signal, since nonlinearity, gain, zero and supply voltage errors in the TT can dominate overall system error [4].

Overall, the reviewed literature indicates that RTDs provide a strong combination of accuracy, repeatability, stability, and predictable response, making them particularly suitable for precision-oriented temperature measurement. However, their response characteristics, construction cost, and susceptibility to installation-related errors must be considered when selecting them for a specific application.

2.2 Thermocouples

Thermocouple exploit the Seebeck effect: an electromotive force is generated across the junction of two dissimilar conducting materials when a temperature gradient exists between the hot and cold junctions [7]. They are valued for their design simplicity, robustness, low cost, and the ability to measure a wide range of temperatures without an external excitation source [6]. A thermocouple generates a thermoelectric voltage when its junctions are maintained at different temperatures. The basic measurement principle is illustrated in Fig. 2.



Fig. 2. Basic Operating Principle of a Thermocouple

Common types of thermocouples include K (nickel chromium/nickel-silicon), J, T, E, R, S, and B, each with a distinct usable temperature range depending on the alloy pair [6]. In metal machining, thermocouples remain the most common conductive temperature-measurement technique because they are durable, relatively inexpensive, and able to operate over a wide temperature range [5]. However, tool work thermocouples are unsuitable when coolants/lubricants are used and are limited to non-indexable tools, while embedded thermocouples are destructive to the work piece, provide only average interface temperatures, and show insufficient response to rapid temperature transients [5]. Traditional wire thermocouples are too bulky and slow for wearable or micro-scale sensing. Flexible thinfilm thermocouples combine small heat capacity and fast response with mechanical flexibility, ultrathin form factors, and compatibility with wearable electronics, healthcare, and smart-detection systems [6]. Experimental characterization of type K thermocouple connected in series demonstrated that thermocouple arrays can generate usable low-level voltages for control applications [7]. Thermocouples are also widely deployed as low-cost overheat-protection sensors in rotating machinery [8].

Overall, the reviewed literature indicates that thermocouples are particularly advantageous when a wide or extreme operating-temperature range is required. Their principal strength is therefore their temperature-range capability, whereas measurement accuracy can depend strongly on sensor construction, calibration, installation, and the surrounding thermal environment.

2.3 Thermistors

Thermistors are resistive temperature sensors whose resistance changes markedly- far more than metallic RTDs- with temperature. Following either a negative temperature coefficient or positive temperature coefficient [9,10,12]. Some of the desirable properties of thermistors include high sensitivity, fast response, and good linearity within its calibrated range [10]. Thermistors exploit the strong dependence of electrical resistance on temperature, enabling small temperature variations to be detected. This sensing behavior is illustrated in Fig. 3.

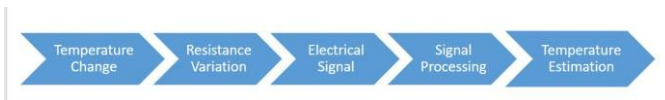


Fig. 3. Basic Operating Principle of a Thermistor

A key historical limitation of PTC thermistors is that very high sensitivity is typically confined to a narrow temperature span, below about 10 °C, limiting their use in systems requiring broad-range coverage [9]. An inkjet-printed interdigitated-electrode (IDE) thermistor on polyimide and Epson glossy-paper substrates achieved sensitivities of 3.202%/ °C (PI) and 1.462%/ °C (paper) over a 28-50 °C range relevant to human body-temperature monitoring, with linear response and repeatability confirmed over five thermal cycles, and demonstrated bendability suitable for wearable use [11].

A novel thermally-coupled chip-thermistor device (TCCT), combining a self-heating input thermistor with a passive output thermistor in thermal- but not electrical- contact, was characterized for input/output resistance, self-heating current stability, and heat-transfer behavior, with an exponential factor $B \approx 3908\text{K}$ and nominal resistance $R_0 \approx 2600 \Omega$ [12]. Devices of this kind are proposed for microelectronic applications requiring electrical isolation combined with thermal coupling of slowly changing signals, such as power to-voltage or temperature-to-voltage conversion circuits [12].

Overall, the reviewed literature indicates that thermistors are particularly attractive when high sensitivity, rapid response, compact size, and low cost are important. However, their relatively limited temperature range, nonlinear response, self-heating, and stability considerations can make them less suitable for applications requiring a broad operating range and long-term precision.

2.4 Semiconductor-Based Temperature Sensors

Semiconductor-based approaches exploit the temperature dependence of carrier transport (MOSFET threshold voltage/mobility, subthreshold current, gate leakage), diode/thermionic emission physics, or surface-conductance changes in wide-bandgap compounds, offering the strongest potential for on-chip integration and micro-power operation [13,16]. Semiconductor temperature sensors use temperature dependent electrical characteristics of semiconductor devices to obtain a temperature-related output. A simplified sensing mechanism is shown in Fig. 4.

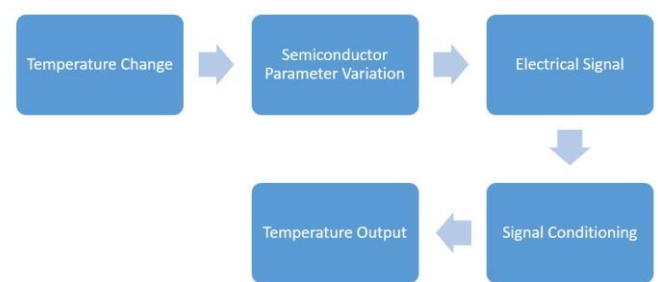


Fig. 4. Basic Operating Principle of Semiconductor Temperature Sensor

A comprehensive review classifies MOS-based temperature sensors into three types: Type I, which includes logic/saturation/linear MOSEFT operation, Type II, which includes the subthreshold MOSEFT operation and Type III, which includes the gate-leakage-based sensors [13]. Although developed primarily as gas sensor, II-VI compound semiconductors are relevant to temperature-dependent semiconductor sensing because their conduct-metric response is strongly temperature-sensitive and their surface chemistry, doping, and Nano structuring (0D-3D) govern sensitivity and response time [14].

Overall, semiconductor temperature sensors offer an important alternative to conventional resistive and thermoelectric sensors, particularly when compactness, electronic integration, and application-specific device design are required.

3. COMPARATIVE EVALUATION

3.1 Evaluation Criteria

Based on the recurring metrics reported across the reviewed literature, six criteria are used to compare the four sensor families: accuracy and measurement performance, operating temperature range, sensitivity, response time, linearity and stability, and cost/integration capability [1-16]. These criteria mirror the nine accuracy-governing features, identified specifically for RTDs [2] and the sensor-selection criteria identified for machining thermocouples [5], generalized here across all four technology families.

3.2 Accuracy and Measurement Performance

RTDs remain the accuracy benchmark among contact resistive sensors: platinum RTD accuracy classes reach 0.35 [2], and intelligently signal-conditioned platinum RTD systems can achieve an expanded measurement uncertainty as low as 0.02 °C at 99% confidence [4]. Thermocouples are comparatively less accurate as

standalone sensors and are prone to calibration drift [5], though cold-end compensation and characterization procedures can improve practical accuracy [7]. Thermistors offer high local accuracy within a narrow, well-characterized range owing to their large resistance-temperature slope, but nonlinearity outside the range and environmental sensitivity can degrade accuracy unless compensated. Semiconductor sensors show a very wide accuracy spread depending on design: MOS-based sensors reviewed span from sub-degree inaccuracies after multi-point trims to several degrees for single-point calibrated designs, with self-heating error negligible relative to resolution [13].

3.3 Operating Temperature Range

RTDs offer the widest standardized industrial range, from 200 °C to 850 °C [2], with flexible/printed variants typically validated over a narrower practical span [1]. Thermocouples, depending on type, can exceed RTD ranges at the high temperature extreme, and TFTCs specifically target flexible, moderate-range sensing for wearable and aerospace/engine applications [6]. Thermistors are inherently range-limited compared with RTDs and thermocouples: conventional low temperature NTC chip thermistors operate over roughly -50 °C to +250 °C and hightemperature variants over +250 °C to +1000 °C [12], while the RF-interfaced flexible PTC thermistor extended usable range to 30-205 °C specifically to overcome the traditional narrow-range limitation of PTC devices [9].

Semiconductor sensors are typically confined to moderate ranges suited to electronics and human-adjacent applications- the vacuum-diode sensor operated over approximately 273 325K [16], reflecting the constraints of silicon device physics and packaging rather than the sensing mechanism itself.

3.4 Sensitivity

Thermistors exhibit the highest raw sensitivity of the four families by a wide margin, with the RF-interfaced PTC thermistor demonstrating resistance sensitivity above 1000% °C⁻¹ [9], versus TCR values around 0.4-0.7%/°C for interdigitated PEDOT: PSS thermistors [10,11] and roughly 0.35-0.67% /°C-equivalent for RTD metal [2]. Semiconductor sensors report sensitivities in the low-single-digit mV/K range (0.61-7.6mV/K) [16], while TFTC thermocouple sensitivity is reported in the tens of mV/ °C, and RTD-type sensitivity is best expressed through TCR [2] rather than an absolute mV output, since RTDs require external excitation and signal conditioning [4] to produce a usable voltage signal.

3.5 Response Time

Response time is dominated by thermal mass and sensor geometry rather than by sensing principle alone. Thin-film and printed device consistently outperform bulk devices: the encapsulated printed RTD achieved a 2.7s response time [1]; 3D-printed thermistors showed response times of roughly 27 31 s (recovery 48-54 s) [10]; and flexible TFTCs were shown to respond faster than a standard K-type wire thermocouple in a turbine-engine test due to their reduced thermal conductivity and mass [6]. For bulk industrial RTDs, response time is a safety-relevant, separately-measures parameter- the LCSR in-situ method achieved response-time estimates within ±10% of plunge-test values, complying with nuclear instrumentation standards [3]. Semiconductor sensors are effectively instantaneous at the transduction level, but printed read-out electronics currently limit the overall signal chain to bandwidths on the order of 1kHz [15].

3.5 Linearity and Stability

RTDs and printed RTDs demonstrate the strongest inherent linearity, matching a reference Pt100 with negligible IV. APPLICATION-BASED hysteresis and confirming stable operation after 1000 bending cycles and six months of storage [1]; nickel RTDs, by contrast, become notably nonlinear above 300 °C [2]. Thermistors display good linearity within their calibrated span but are markedly more sensitive to environmental stability factors, particularly humidity-induced drift [10] and hysteresis up to 3% [10]. Thermocouples are robust but subject to calibration drift over time and require cold-junction compensation for stable absolute-temperature accuracy [5,6]. Semiconductor sensors depend heavily on calibration strategy for stability: process and power-supply variations are primary error sources for MOS-based sensors, motivating a shift towards selfcalibrated, differential architectures [13], while surface-state instability was identified as the central long-term reliability limitation for II-VI semiconductor devices [14].

3.6 Cost and Integration Capability

Thermocouples remain the lowest-cost option for wide-range, rugged industrial and protective monitoring applications, being simple to implement and relatively inexpensive [5,8]. RTDs are moderately costed but benefit from low-cost, scalable printing fabrication routes that reduce cost while retaining accuracy [1]. Thermistors, particularly printed and 3D-printed variants, offer some of the lowest fabrication costs and the simplest integration into flexible/wearable form factors owing to additive-manufacturing compatibility [10,11]. Semiconductor

sensors offer the highest integration capability of all four families, since MOS-based designs can be embedded directly on-chip alongside digital logic with micro-watt power consumption [13], and fully-printed oxide TFT read-out electronics point toward complete, self contained, low-voltage printed sensor-and-electronic patches [15]-at the cost of typically narrow operating ranges and, in emerging materials such as II-VI compounds, unresolved long-term stability challenges [14].

3.7 Overall Assessment

Table I Comparative Characteristics Of Temperature Sensing Technologies

Criteria	RTDs	Thermocouples	Thermistors	Semiconductor
Accuracy	Highest	Moderate	High	Designdependent
Range	Wide	Very Wide	Limited	Limited
Sensitivity	Low Moderate	Moderate	Highest	Low
Response	Fast	Fast	Fast	Very Fast
Cost	Moderate	Low	Low	High

4. APPLICATION-BASED

4.1 Industrial Process and Nuclear Transformation

Platinum RTDs remain the standard where wide range, high accuracy, and regulatory-compliant dynamic response are required, supported by in-situ-response-time verification methods such as LCSR [3] and intelligent auto-calibrating transducers [4].

4.2 Metal Machining and High-Speed Manufacturing

Embedded or tool-work thermocouples are preferred for their low cost and simplicity where average interface temperature is acceptable while fiber-optic infrared thermometry is favored when fast response and non-contact measurement are required despite higher cost [5].

4.3 Wireless Sensing

RF-interfaced flexible thermistors enable passive, wide range wireless temperature sensing via RFID/microwave resonator readout, overcoming the traditional narrow-range limitation of PTC thermistors [9].

4.4 Rotating Machinery Protection

Simple, rugged thermocouple-based overheat monitoring and shutdown systems are well suited to community/industrial motor-protection applications where cost and reliability outweigh the need for high precision [8].

4.5 Emerging Sensing Engines

Nanoscale vacuum-diode sensors represent a promising, CMOS-compatible alternative to solid - state diode temperature sensors for applications demanding both high sensitivity and harsh-environment robustness [16], while II VI semiconductor-based devices, despite favorable intrinsic sensitivity, are currently better suited to gas - sensing research than to commercial temperature-sensing deployment given their surface-stability limitations [14].

5. CONCLUSION

This review synthesized sixteen recent papers on RTDs, thermocouples, thermistors and semiconductor-based temperature sensors. RTDs offer the best accuracy, linearity, and range, especially in platinum and printed forms [4]. Thermocouples remain simplest and cheapest for widerange and protected monitoring [5,7,8]. Thermistors deliver the highest sensitivity, particularly RF-interfaced and printed forms, suited to compact wireless wearables [9-12]. Semiconductor temperature sensors provide unmatched on chip integration and micro-power operation, though within narrower ranges and, in some materials, unresolved stability issues [13-16]. Overall, sensor selection should be application-driven, with fabrication technique, encapsulation, and intelligent signal conditioning being the key levers for improving real-world performance across all four families.

REFERENCES

- Retolaza, A. et al. "Flexible printed RTD sensors for wearable temperature monitoring," Sensors and Actuators: A. Physical, 406 (2026) 117876.
- Kako, S.A. "A Comparative Study about Accuracy Levels of Resistance Temperature Detectors RTDs Composed of Platinum, Copper, and Nickel," Al-

- Nahrain Journal for Engineering Sciences (NJES), 26(3), 216–225, 2023.
- 3) Song, Y.; Liang, Y.; Zhang, Z.; Su, G.; Su, M. "In Situ Response Time Measurement of RTD Based on LCSR Method," *Sensors*, 25, 4826, 2025.
 - 4) Miczulski, W.; Krajewski, M.; Sienkowski, S.; Kawecka, E.; Perec, A. "Intelligent Transducer for Temperature Measurement with Two-Wire or Three-Wire Platinum RTD," *Sensors*, 24, 7689, 2024. Leonidas, E.; Ayvar-Soberanis, S.; Laalej, H.; Fitzpatrick,
 - 5) S.; Willmott, J.R. "A Comparative Review of Thermocouple and Infrared Radiation Temperature Measurement Methods during the Machining of Metals," *Sensors*, 22, 4693, 2022. Zhang, Z.; Liu, Z.; Lei, J.; Chen, L.; Li, L.; Zhao, N.; Fang, X.;
 - 6) Ruan, Y.; Tian, B.; Zhao, L. "Flexible thin film thermocouples: From structure, material, fabrication to application," *iScience*, 26, 107303, 2023.
 - 7) Igwilo, O.C.; Mathurine, G.; Onyegbadue, I.A.; Azike, R.U. "Experimental Design, Characterization, coupling and calibration of type k thermocouple," *UNIZIK Journal of Engineering and Applied Sciences*, 2(3), 388–399, 2023.
 - 8) Firdaus, A.A.; Sobhita, R.A.; Nugraha, A.T. "Implementation of an Overheat Monitoring and Protection System for Community Empowerment Programs Using Thermocouples," *Journal for Maritime in Community Service and Empowerment*.
 - 9) Wagih, M.; Shi, J.; Li, M.; Komolafe, A.; Whittaker, T.; Schneider, J.; Kumar, S.; Whittow, W.; Beeby, S. "Wide range soft anisotropic thermistor with a direct wireless radio frequency interface," *Nature Communications*, 15, 452, 2024.
 - 10) Cicek, U.I.; Southee, D.J.; Johnson, A.A. "The development and characterisation of 3D-printed multi material thermistor," *Additive Manufacturing*, 94, 104510, 2024.
 - 11) Khalaf, A.M.; Ramírez, J.L.; Mohamed, S.A.; Issa, H.H. "Highly sensitive interdigitated thermistor based on PEDOT:PSS for human body temperature monitoring," *Flexible and Printed Electronics*, 7, 045012, 2022.
 - 12) Bodić, M.Z.; Aleksić, S.O.; Rajs, V.M.; Damnjanović, M.S.; Kisić, M.G. "Thermally Coupled NTC Chip Thermistors: Their Properties and Applications," *Sensors*, 24, 3547, 2024.
 - 13) Xie, S. "The Design Considerations and Challenges in MOS-Based Temperature Sensors: A Review," *Electronics*, 11, 1019, 2022.
 - 14) Korotcenkov, G. "II–VI Semiconductor-Based Conductometric Gas Sensors: Is There a Future for These Sensors?" *Sensors*, 24, 3861, 2024. Pradhan, J.R.; Priyadarsini, S.S.; Nibgoor, S.R.; Singh, M.;
 - 15) Dasgupta, S. "Oxide semiconductor based deep subthreshold operated read-out electronics for allprinted smart sensor patches," *Exploration*, 5, 20230167, 2025.
 - 16) Shen, Z.; Wang, X.; Li, Q.; Ge, B.; Jiang, L.; Tian, J.; Wu, S. "A High-Sensitivity Vacuum Diode Temperature Sensor Based on Barrier-Lowering Effect," *Micromachines*, 13, 286, 2022.