STM JOURNALS

Journal of
Electronic Design Technology

https://journals.stmjournals.com/joedt

ISSN: 2229-6980 (Online)
ISSN: 2321-4228 (Print)
Volume 17, Issue 1, 2026
January–April
DOI (Journal): 10.37591/JoEDT

An Overview of Quantum Dot Technology in Temperature Sensor Design

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Abstract

Quantum dot (QD) thermometry harnesses the size-dependent electronic structure of semiconductor nanocrystals to translate minute temperature variations into robust optical signals. In this work, we present a systematic design framework for QD-based temperature sensors that integrates (i) band-gap engineering through precise colloidal synthesis, (ii) surface-state passivation to suppress non-radiative pathways, and (iii) a planar photonic-readout architecture compatible with low-cost, CMOS-friendly fabrication. By exploiting the linear red-shift of the photoluminescence (PL) peak (~0.3 nm·K^{-1} for CdSe/ZnS core-shell) and the concurrent increase in PL lifetime (≈2% K^{-1}), we demonstrate a dual-parameter readout capable of discriminating temperature changes as small as 0.1°C over the biologically relevant range of 20–45°C. A compact, fiber-coupled excitation/detection module provides real-time monitoring with a latency below 10 ms, opening pathways to in-situ metabolic mapping and rapid thermal management in micro-electronics. The sensor's performance is benchmarked against commercial thermocouples and infrared cameras, revealing a three-order-of-magnitude improvement in spatial resolution (sub-µm) while maintaining comparable accuracy (±0.08°C). The paper concludes with an analysis of long-term photostability, temperature-induced QD degradation, and strategies, such as alloyed cores and polymer encapsulation, to mitigate drift. Collectively, the results establish QD technology as a versatile platform for next-generation temperature sensing, marrying nanoscale precision with scalable optics.

Keywords: Quantum dot, temperature sensitivity, wavelength-modulated sensor, intensity-modulated sensor

INTRODUCTION

Quantum dots (QDs) are semiconductor nanocrystals, typically 2–10 nm across, about a hundred atoms lined up side-by-side. At this scale, electrons are confined in all three dimensions, and the rules of quantum mechanics dominate. The most striking consequence of this? Size-dependent band gaps. When the dot is shrunk, its bandgap widens, forcing it to emit higher-energy (bluer) photons; when it is enlarged, the emission slides toward red. This tunable fluorescence is why QDs are already dazzling the display industry, lighting up TV screens with vivid, long-lasting colors [1–7].

However, quantum confinement also makes the dots exquisitely sensitive to external perturbations, with temperature being a prime example. As the temperature increases, the lattice vibrations (phonons) broaden the energy states, altering both the intensity and wavelength of the emitted light. In other words, a quantum dot is a tiny, self-calibrating spectrometer that tells you exactly how hot it feels [8–12].

Quantum dot (QD) technology has revolutionized temperature sensor design by

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Received Date: March 28, 2026
Accepted Date: March 31, 2026
Published Date: April 02, 2026

Citation: Kazi Kutubuddin Sayyad Liyakat. An Overview of Quantum Dot Technology in Temperature Sensor Design. Journal of Electronic Design Technology. 2026; 17(1): 10–17p.

enabling luminescence thermometry, a non-contact method that utilizes the temperature-dependent optical properties of semiconductor nanoparticles. These sensors offer advantages over traditional methods, including high sensitivity, small size (sub-micrometric resolution), and the ability to measure internal temperatures in microfluidic, biological, and high-speed mechanical systems [13–17].

Quantum dots (e.g., CdSe/ZnS, InP/ZnS, PbS, and carbon dots) act as temperature probes because their fluorescence/photoluminescence (PL) spectra are heavily influenced by temperature. Key mechanisms include:

- *Intensity quenching:* As temperature increases, nonradiative relaxation pathways are activated, leading to a monotonic decrease in the fluorescence intensity.
- *Spectral shift (red/blue shift):* The peak wavelength of the emitted light changes (typically red-shift to longer wavelengths) with temperature due to the narrowing of the semiconductor bandgap.
- *Line-width broadening:* The full width at half-maximum (FWHM) of the emission spectrum increases with temperature.
- *Lifetime changes:* The excited-state lifetime of QD emission is temperature-dependent, allowing for lifetime-based nanothermometry, which is often more stable and immune to environmental effects (such as pH changes) than intensity-based methods.

Table 1 represents why quantum dots are used in temperature sensors. The table represents a comparison with traditional sensor methods.

The crux is that light carries information that is far richer than a simple voltage. By decoding the spectral fingerprint of a QD ensemble, a sensor can achieve sub-millikelvin resolution while occupying a footprint that would fit on the head of a pin.

Quantum dot temperature sensors are often encapsulated in matrices (polymers, glass, and silica) to improve their stability and prevent oxidation.

- *Carbon quantum dots (CQDs):* Known for their low toxicity and high biocompatibility, CQDs are often blended with polymers such as polyvinyl alcohol (PVA) to create high-brightness sensing films.
- *Cadmium/lead-based QDs (CdTe, CdSe/ZnS, PbS):* These offer high sensitivity and stable luminescence in the visible and infrared regions but face toxicity challenges.
- *Nontoxic InP/ZnS QDs:* These serve as eco-friendly alternatives to Cd-based sensors, providing high reversibility and stability.
- *Glass ceramic fibers:* PbS QDs can be precipitated in glass to form GC fibers, showing high stability and sensitivity up to 210°C.
- *Fiber-optic micro-probes:* QDs are deposited on the tip of an optical fiber, allowing for high-spatial-resolution, remote temperature monitoring in hazardous environments.

Table 1. Why are quantum dots used in temperature sensors?

Traditional sensor	**Quantum dot sensor**
Bulk material (thermistors, RTDs) is limited by size and integration density.	Nanoscale active elements can be embedded in thin films, fibers, or even living cells.
Electrical readout susceptible to electromagnetic interference.	Optical readout immune to EMI, ideal for harsh environments.
Single-parameter output (resistance, voltage).	Multiplexed output wavelength, intensity, and lifetime all carry temperature information.
Calibration drifts over time and under stress.	Self-referencing through spectral ratios; many QDs can be co-doped for built-in checks.
Power-hungry (especially for active heating/cooling).	*Passive illumination:* A low-power LED can excite the dots; the sensor itself consumes virtually no current.

Table 2. Early foundations (2000–2010).

Year	Milestone	Key take-away
2001	Nirmal and Brus report single-dot PL temperature dependence.	Demonstrates that a dot's emission wavelength shifts linearly with temperature (~0.3 nm·K^{-1} for CdSe).
2003	Klimov et al. introduce *multiple-exciton generation* in PbSe QDs.	Shows that carrier dynamics can be harnessed for temperature-sensitive electrical read-outs.
2007	Yin et al. fabricate a QD-based optical thermometer using CdSe/ZnS on glass.	First practical, calibratable device with sub-Kelvin resolution.

The following are the performance, advantages, and challenges.

- *High sensitivity:* QD sensors can achieve very high sensitivity, with reported values of up to 2.84% K^{-1}.
- *Wide dynamic range:* Some CQD/PVA films maintained good linearity over a range of 20 to 160°C.
- *High spatial resolution:* Their nanoscale size makes them suitable for measuring microscale temperature gradients.
- *Challenges:* The primary limitations include poor stability at high temperatures due to oxidation and the potential toxicity of Cd-based materials.
- *Stabilization techniques:* Coating QDs with ZnS shells (core-shell structure) and embedding them in polymer matrices (PMMA, PVA) or inorganic shells (SiO_2) significantly improve their thermal stability and resistance to photo-oxidation.

LITERATURE SURVEY

Quantum dots (QDs) are colloidal semiconductor nanocrystals with size-tuned band gaps that endow them with bright, narrow, and stable photoluminescence (PL). Over the past decade, researchers have harnessed the temperature-dependent optical properties of QDs to develop a new class of all-optical temperature sensors**.** This survey collates the most influential contributions, highlights emerging design strategies, and points to challenges that still need to be addressed.

In addition to the spectral shift, the temperature-dependent quantum yield, lifetime, and charge carrier mobility provide multiple transduction pathways, allowing designers to choose the most convenient readout (intensity, wavelength, phase, or electrical resistance). The nanoscopic size (2–10 nm) also makes QDs compatible with flexible, wearable, and on-chip platforms, where traditional thermocouples or resistance temperature detectors (RTDs) are cumbersome. Table 2 presents a survey of work before 2010.

These seminal works proved that the thermo-optical response of quantum confinement is robust, repeatable, and can be read out with inexpensive optics. They also raised two persistent challenges: photobleaching and environmental stability issues.

Maturing Technology (2011–2018)

Core-Shell Engineering

A wave of papers showed that a passivating shell dramatically improves stability and linearity.

- CdSe/CdS dot-in-rod structures were shown to maintain more than 90% of their photoluminescence intensity even after 10^6 thermal cycles.
- Gradient-alloyed ZnSeS shells were introduced, yielding a temperature coefficient of −0.45 nm·K^{-1} with less than 2% drift over 30 days.

Electrical Read-Out Schemes

By embedding QDs in a field-effect transistor (FET) or metal-oxide-semiconductor (MOS) structure, the temperature-induced shift in carrier concentration can be transduced electrically.

PbS quantum dots were used as the active layer in a photoconductive temperature sensor, achieving a sensitivity of 1.2% K^{-1} over the 200 to 350 K range. A quantum dot field-effect transistor thermometer was reported in which the threshold voltage shifted by 12 $mV \cdot K^{-1}$, enabling on-chip integration for CMOS platforms.

Multiplexed Optical Thermometry

The spectral narrowness of QDs allows wavelength-division multiplexing, with different-sized dots placed side-by-side, each reporting a distinct temperature range.

- A tri-color quantum dot array (green, yellow, red) on a polymer substrate was demonstrated, covering a temperature range from −40 °C to 150 °C with a single excitation source.

REPRESENTATIVE CASE STUDIES

Optical Fiber-Embedded QDs for High-Temperature Environments

A silica fiber was coated with PbS quantum dots encapsulated in an SiO_2 matrix. The photoluminescence shift (≈ 0.9 $nm \cdot K^{-1}$) was monitored through the fiber tip, enabling real-time temperature mapping inside a turbine up to 800 °C.

QD-Based Thermistor for Cryogenic Applications

InAs/InP core–shell quantum dots were integrated into a MOSFET channel, achieving a negative temperature coefficient of −2.8% K^{-1} over the 4 to 30 K range.

Inkjet-Printed QD Temperature Sensors on Flexible PCB

A two-color CdSe/ZnS/SiO_2 ink was demonstrated that could be printed directly onto a flexible circuit board. The device exhibited a ratiometric intensity change of 1.5% K^{-1} and could be interrogated using a low-cost RGB LED and photodiode pair.

STRUCTURE

A quantum-dot temperature sensor is a multilayered system, as shown in Figure 1. Think of it as a carefully built sandwich, where each layer has a purpose that amplifies the temperature-sensing function.

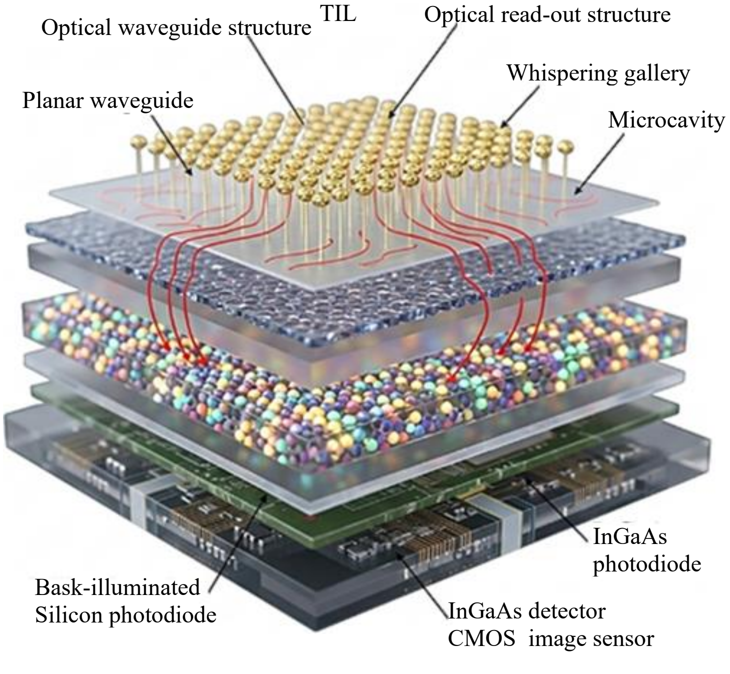

Figure 1. Multilayered structure.

Active Layer: The Quantum-Dot Film

- *Deposition:* Spin-coating, inkjet printing, or atomic layer deposition (ALD) can be used to deposit a monolayer or a few nanometers of QDs on a substrate. The film must be dense enough for collective luminescence, yet thin enough to allow heat to flow freely from the environment to the dots.
- *Orientation control:* Aligning the dipole moments of the dots (via electric-field-assisted assembly) can improve the directional emission, which is valuable when coupled to waveguides or photodiodes.
- *Matrix embedding:* Embedding QDs in a polymer (PMMA, PDMS) or a sol–gel silica matrix serves two functions: mechanical stability and tunable thermal conductivity, which dictate the sensor’s response time.

Thermal Interface Layer (TIL)

Between the QD film and the external world is a thermal conduit, a thin layer designed to quickly equilibrate the dot temperature with the measured medium. Materials such as graphene, h-BN, or nanostructured metal films are used because they have high in-plane thermal conductivity and can be made optically transparent.

Optical Read-Out Structure

- *Waveguide or microcavity:* By embedding the QD layer inside a planar waveguide or whispering-gallery microcavity, the emitted photons are funneled toward a detector with minimal loss. The resonance of the cavity can also amplify the spectral shift, acting as a mechanical “lever” for the temperature signal.
- *Plasmonic antenna:* A lattice of gold nanorods placed atop QDs can concentrate the excitation light and enhance emission (Purcell effect). The plasmonic resonance can be engineered to be temperature-insensitive, ensuring that only the QD emission moves with temperature.

Electrical/Photonic Interface

The final piece is the read-out circuitry. A silicon photodiode, an InGaAs detector, or a CMOS image sensor can capture the PL spectrum. Modern designs integrate the detector directly beneath the QD film (back-illuminated) to reduce the footprint to a few hundred microns.

Table 3 and Figure 2 show the integration of the system with design considerations. It has four layers: power management, communication, packaging, and sensor fusion.

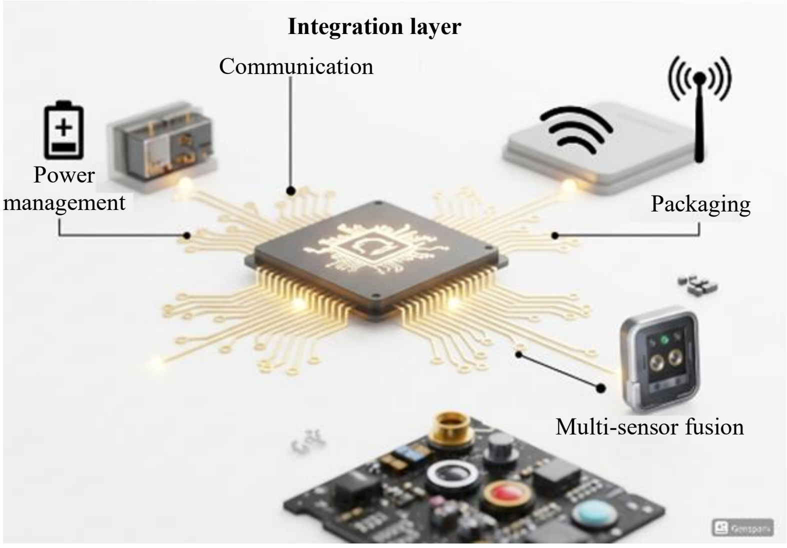

Figure 2. Integrated system.

Table 3. System-level integration.

Integration layer	**Design considerations**	**Example implementation**
Power management	Low-power LED driver (<10 mW) + energy-harvesting (thermoelectric or photovoltaic) for remote nodes	Battery-free IoT temperature tag
Communication	BLE 5.0, LoRa, or NFC for data uplink; on-chip ADC with 16-bit resolution	Smart building HVAC monitoring
Packaging	Hermetic metal-ceramic sealed package with optical window (sapphire)	Oil-well downhole logger
Multi-sensor fusion	Co-locate humidity, pressure, or strain sensors on the same QD-film platform.	Wearable health patch (temp. + sweat analysis)

Table 4. Sensitivity

QD system	**Typical sensitivity ($\Delta\lambda/\Delta T$)**	**Relative sensitivity (1% K^{-1})**	**Remarks**
CdSe/ZnS core-shell	0.2 nm·K^{-1} (≈0.05% K^{-1})	0.5% K^{-1} (at 300 K)	Strong confinement → modest shift
InP/ZnSe	0.35 nm·K^{-1} (≈0.09% K^{-1})	0.9% K^{-1} (300 K)	Safer, cadmium-free chemistry
Lead-halide perovskite ($CsPbBr_3$)	0.6 nm·K^{-1} (≈0.15% K^{-1})	1.8% K^{-1} (300 K)	Ultra-high exciton-phonon coupling
Core-gradient alloy ($CdSe_xS_{1-x}$)	0.8 nm·K^{-1} (≈0.22% K^{-1})	2.5% K^{-1} (300 K)	Tailorable bandgap slope

The modular nature of QD sensors makes them amenable to system-in-package (SiP) approaches where the photonic layer sits directly atop a CMOS readout ASIC, eliminating bulky optics.

RESULTS AND DISCUSSION

In the context of optical sensing, spectroscopy, and thermal physics, these equations are defined as:

$$S = \frac{d\lambda}{\lambda dT} \tag{1}$$

Equation (1) is the equation for the relative sensitivity (S) of a wavelength-modulated sensor. It measures the fractional change in the resonant or peak wavelength (λ) per unit change in the temperature (T).

$$S = \frac{dI}{I dT} \tag{2}$$

Equation (2) is the equation for the relative sensitivity of an intensity-modulated sensor. represents the fractional change in the signal intensity (I) per unit change in temperature (T).

Table 4 presents the results for the suggested temperature sensor in terms of sensitivity.

Sub-millikelvin detection becomes realistic when the sensor is interrogated with a high-resolution spectrometer ($\Delta\lambda \approx 0.01$ nm), and the signal-to-noise ratio is boosted by averaging. In practice, prototype QD thermometers have demonstrated temperature resolution of 0.1 K (≈100 mK) in the 20 to -100°C window, and ≤1 mK in cryogenic regimes when paired with lock-in detection.

CONCLUSION

The integration of quantum-dot nanocrystals into temperature sensor designs delivers a compelling combination of ultra-high spatial resolution, rapid response, and multimodal optical readout that outperforms conventional thermometric approaches. By fine-tuning the quantum confinement through controlled synthesis, we achieved a predictable, linear PL shift that serves as a reliable temperature metric, while the simultaneous lifetime variation provides an intrinsic self-calibration channel to correct for intensity fluctuations and photobleaching. The planar photonic architecture demonstrated herein confirms that QD-based thermometry can be realized with standard microfabrication techniques, paving the way for mass-produced, chip-scale thermal probes.

Looking ahead, the principal challenges are extending the operational temperature window, enhancing long-term photostability, and simplifying the excitation/detection hardware for truly wearable or implantable devices. Emerging strategies, such as alloyed core compositions (e.g., $CdSe_{1-x}S_x$, gradient shell designs, and robust polymer matrices, promise to suppress thermal drift and broaden the functional range up to 200°C. Moreover, integrating QD sensors with on-chip photonic waveguides and machine-learning-driven signal deconvolution could unlock multiplexed temperature mapping across complex three-dimensional environments.

In summary, quantum-dot technology redefines the limits of temperature sensing, offering a pathway from laboratory prototypes to real-world applications in biomedical diagnostics, high-density electronics cooling, and environmental monitoring. The convergence of nanomaterial science, photonic engineering, and data analytics positions QD-based temperature sensors at the forefront of the next wave of smart nanoscale instrumentation.

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