Cds : SiO2 nanocomposite as a luminescence-based wide range temperature sensor

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A wide range (20–560 K) temperature sensor is devised for the first time from Cds : SiO2 nanocomposite thin films grown by pulsed laser deposition. Highly intense, stable, and broad red emission observed from the Cds : SiO2 nanocomposite is employed to obtain a luminescence thermometer. Nearly monodisperse and small sized Cds nanocrystals (~3 nm) in a SiO2 matrix, as viewed by transmission electron microscopy, may be accountable for the absence of band edge emission even at 20 K. The sensor exhibits almost linear behavior in all cryogenic, physiological, and high temperature ranges. The average sensitivity and resolution of the sensor reported here were \( \approx 10^{-2} \) K \(^{-1} \) and \( 10^{-4} \) K, respectively, with a maximum relative sensitivity of \( \approx 8.4\% \) K \(^{-1} \) at 120 K.

1. Introduction

Temperature is a fundamental thermodynamic quantity, measurement of which is crucial for a wide range of applications and it is a key quantity in diverse subject areas from biological sciences to space sciences. Thermometry has been carried out by employing various properties of materials, including changes in resistance, thermal expansion of a solid or liquid, change in pressure of a gas, or measurement of infrared energy emitted by an object in radiation type thermometers. Among all these, only radiation type thermometers operate in non-contact mode. To realize the temperature measurement in the micro/nano scale with high resolution and sensitivity, luminescence thermometry is the most widely applicable.

Optical temperature sensors are important in many thermometry applications because they provide immunity to electrical noise and exhibit better sensitivity, selectivity, and fast response. A variety of devices have been reported utilizing various methods, such as optical fiber sensing,\(^{1}\) surface plasmon resonance (change in dielectric constant and refractive index),\(^{2}\) photoluminescence (change in intensity, peak position, and lifetime),\(^{3,4}\) and shift in optical absorption edge,\(^{5}\) to realize optical thermometers in different ranges. In particular, photoluminescence (PL) based temperature sensors are widely applicable because of their low-cost, simple preparation, easy instrumentation, noninvasive operation, and nondestructive technique for the detection of temperature even for living or cancer cells.\(^{6}\) The PL intensity or luminescence intensity ratio (LIR) is a parameter that can offer versatility for sensing in different environments compared to other techniques.\(^{7}\) This ability to glean the temperature is demonstrated by certain luminescent materials including II–VI semiconductor quantum dots (QDs),\(^{8,9,10,11}\) carbon dots,\(^{12}\) lanthanide based complexes,\(^{13,14,15}\) and metal–organic-frameworks (MOFs).\(^{16,17}\) Among these, II–VI semiconductors (especially Cd-containing QDs) and their nanocomposites are used outstandingly. In the report by Walker et al., a luminescence intensity based thermometer was realized by Cds QDs with a Zns over-layer [(Cds)Zns] in poly[lauryl methacrylate] (PLMA) matrix in the temperature range from 100 to 315 K and a relative sensitivity of 1.3% per °C was observed.\(^{8}\) P. A. S. Jorge et al. devised a (Cds) Zns core–shell-doped bulk glass temperature sensor (287–316 K) with a resolution of 0.3 °C for intensity based sensing, and a wavelength shift sensitivity of 0.2 nm °C \(^{-1} \) was observed.\(^{7}\) Local temperature sensing (297.4–316.6 K) using single QDs of (Cds) Zns coated with a layer of organic polymer and conjugated with streptavidin was reported by S. Li and co-workers, which exhibited sensitivity of \( \approx 0.1 \) nm °C \(^{-1} \) using a PL spectral shift.\(^{10}\) A Cds(Zns) : SiO2 nanocomposite based high temperature sensor (295–525 K) was demonstrated. The optical thermometer worked on the principle of the variation of the emission wavelength with temperature and exhibited a sensitivity of \( \approx 0.11 \) nm °C \(^{-1} \). The core–shell structure of Cds(Zns) QDs with \( E_{\text{Cds}} = 2.04 \) eV and \( E_{\text{Zns}} = 2.72 \) eV encapsulated with SiO2 was employed to obtain a high yield and intense emission in the visible range.\(^{11}\) Maestro et al. demonstrated the potential use of Cds QDs as fluorescent nanothermometers for two-photon fluorescence microscopy. This nanothermometer displayed not only an enhancement in spatial resolution for multiphoton excitation processes but also considerably higher temperature sensitivity for two-photon (near-infrared) excitation as compared to that under one-photon (visible) excitation. In addition, the peak emission wavelength was also found to be temperature sensitive.\(^{12}\) A temperature sensor (296–353 K) based on ultrathin film system of mercapto-succinic acid modified CdTe QDs and positively charged layered double hydroxide nanosheets with high response sensitivity

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matrix such as SiO$_2$ provides multifold recompenses like diodes, the intense room temperature luminescence from the multifold enhancement in emission intensity to this system. Transmission electron microscopy (TEM) imaging. Before the n-type (110) silicon substrate and carbon-coated Cu grids for synthesis and characterization of CdS QDs is published elsewhere. Therefore, it is a challenge to devise new types of QDs based temperature sensors with a wide temperature range, thermal stability, reproducibility, and better sensitivity.

In this article, we report a simple and low-cost CdS : SiO$_2$ nanocomposite system that is chemically pure, thermally stable and offers a broad red luminescence, which opens new channels for futuristic photonic, optoelectronic and sensing devices. In particular, this study is about the fabrication of a versatile range temperature sensor based on emission from this system. CdS is a direct band gap (for bulk CdS $E_g = 2.42$ eV) II–VI$^{\text{th}}$ semiconductor that exhibits tunable optical properties and emission, which covers the full range of visible spectrum. Due to this property, CdS QDs are extensively used in diverse applications, including photodetection, light-emitting diodes, solar cells, lasers, waveguides, bio-imaging, and photoelectrochemical sensors. An optically transparent matrix such as SiO$_2$ provides multifold recompenses like stabilization of emission, prevention from contamination and oxidation, which can extensively affect the emission. The encapsulation of CdS with SiO$_2$ in the form of a nanocomposite provides thermal resistance, transparency, stability, and multifold enhancement in emission intensity to this system. The intense room temperature luminescence from the CdS : SiO$_2$ nanocomposite motivates for future research towards diverse applications of this system. A wide range luminescence based thermometer obtained out of it is just a step for harnessing the extraordinary emission properties of this composite system.

2. Experimental details

2.1 CdS QDs and target preparation

CdS QDs were synthesized by a chemical co-precipitation method using Cd(NO$_3$)$_2$ and Na$_2$S as precursors procured from Sigma Aldrich Ltd. (USA). The detailed report on the synthesis and characterization of CdS QDs is published elsewhere. The target for the laser ablation of CdS QDs was prepared by pressing and sintering the CdS QDs powder, while the target of SiO$_2$ was purchased from Sigma Aldrich Ltd. (USA).

2.2 Sensor fabrication

The nanocomposite thin films were grown by pulsed laser deposition (PLD) using a target swapping method, followed by thermal annealing at 400 and 500 $^\circ$C in an Ar atmosphere for 3 hours to obtain the crystalline phase of CdS. The swapping frequency is the key parameter to determine the final composition of the nanocomposite system. A Nd:YAG laser (continuum) operating in the $3^{\text{rd}}$ harmonic mode with wavelength $\lambda = 355$ nm is directed towards the rotating target of CdS and SiO$_2$ for the layer-by-layer deposition of CdS and SiO$_2$ on an n-type (110) silicon substrate and carbon-coated Cu grids for transmission electron microscopy (TEM) imaging. Before the ablation of the targets, the stainless steel chamber was evacuated to $5 \times 10^{-6}$ mbar. The energy of the laser beam was maintained at 200 mJ, and the repetition rate and pulse width were 10 Hz and 10 ns, respectively, for this experiment. The details of the sample preparation method and structural confirmation by X-ray photoelectron spectroscopy, glancing angle X-ray diffraction, and Raman spectroscopy are discussed elsewhere.

2.3 Sensor characterizations

Bright field TEM (BFTEM) imaging of the nanocomposites was carried out using a Tecnai G20-stwin microscope operating at 300 kV equipped with LaB$_6$ filament and a charge-coupled device camera having a point resolution of 1.44 $\AA$ and a line resolution of 2.32 $\AA$. Photoluminescence (PL) spectroscopy studies were carried out in the temperature range of 20 K–560 K using a Jobin Yvon Triax 550 monochromator combined with a liquid-nitrogen cooled InGaAs detector with a resolution of $\approx 10^{-3}$. The samples were excited at a wavelength of 325 nm obtained from a He–Cd laser.

3. Results and discussion

The room temperature PL (RTPL) of the as-grown, nanocomposites annealed at 400 $^\circ$C and 500 $^\circ$C are shown in Fig. 1. The RTPL exhibits an emission peak centered at $\sim 630$ nm with a small hump at $\sim 605$ nm for the as-grown nanocomposite, both are related to red emission (RE) without any sign of band edge emission. Dib et al. suggested that the band-edge PL band ($\sim 515$ nm for bulk CdS) appears due to the direct excitonic recombination in quantum dots (QDs) a diameter larger than 3 nm. Other QDs (the majority) are either non-luminescent, due to non-radiative processes, or luminescent at a higher wavelength by recombination of the trapped charge carriers, because in the strong confinement, the only allowed transition is from singlet states and other transitions are forbidden. Thus, the absence of band edge emission indicates that the dominating process in the present study is surface state recombination, which may be attributed to a very narrow size distribution with large number of small nanocrystals. The similar feature is well visualized in TEM micrographs, as discussed elsewhere in detail. It is well established now that the origin of trap emission occurs because of the high amount of surface defects, site-substitutional impurities, or vacancies. The RE from CdS originate from the transition of bound electrons from surface states to the valence band (VB). The defects responsible for such transitions are sulfur vacancies ($V_{\text{S}}^{2-}$) and cadmium vacancies ($V_{\text{Cd}}^{2-}$).

Thermal annealing of the nanocomposite causes enhancements in the emission intensity with a maximum shift of $\sim 15$ nm in peak position towards higher wavelength. The enhancement in intensity by annealing may be resulted by the alteration of Interface conditions of CdS QDs and SiO$_2$ matrix in the nanocomposite, i.e. coalescence of very tiny particles, thereby improving the crystallinity and formation of a large amount of surface defects such as cadmium and sulphur vacancies due to ionic displacements during recrystallization.
effects accountable for the observed intense RE in nano-composites are the interaction of CdS nanoparticles with the SiO2 matrix at their interfaces and thermal annealing. In the present study, the temperature sensing is performed only on the nano-composite annealed at 500 °C because it offers the highest emission intensity.

BFTEM studies envisage the formation of almost monodisperse CdS nanoparticles with a size of ~3 nm in SiO2 matrix after annealing at 500 °C, as shown in Fig. 2. The average inter-particle separation is ~12 nm, which is crucial to obtain highly intense and pure emission. The inset shows the corresponding particle size distribution histogram, which indicates that the size of the CdS nanoparticles ranges from 1.5 to 6 nm. The lognormal fitting to the histogram suggests the average particle size to be 3.0 ± 0.2 nm, indicating almost monodispersity in the nano-composite system. Selected area electron diffraction (SAED) pattern confirms the hexagonal phase of CdS with d-spacings of 3.54 Å, 3.34 Å and 3.12 Å, corresponding to the (100), (002) and (101) crystal orientations, respectively (inset Fig. 2).

The stability of PL intensity at room temperature for the present sensor was also studied with respect to time, and is shown in Fig. 3. It is clear that the intensity remains almost unchanged over the course of time. For better visualization, the upper part of the spectra is shown in a magnified view. It is illustrated that the rate of intensity reduction for first six months is relatively larger than later, and it almost saturates after two years (inset, Fig. 3). It is significant to note that even after two or more years, the PL intensity is preserved at 95% of its initial value.

The evolution of RE intensity with lowering of temperature is shown in Fig. 4a. The emission intensity enhances gradually, as the temperature is decreased to 20 K. This enhancement in intensity is usually due to the thermal deactivation of non-radiative transitions. The spectra do not show evolution of any new peak even at 20 K, implying that the only possible traps that contribute to emission are either sulfur vacancies (V_S^2+) or cadmium vacancies (V_Cd^2-) or both. The shift in the peak position is marginal, being maximum up to 15 nm at 20 K stating a high stability in the trap emission in the lower temperature range. It is observed that at room temperature, the emission intensity is sufficiently high to study the temperature dependency of the emission spectra above room temperature. The stagnation of the PL intensity is observed with increasing temperature and is shown in Fig. 4b. The peak shift is relatively larger (~35 nm) in this case as compared to the lower temperature side, but still trivial. Therefore, the emission is considerably stable in both the temperature regions. The data is obtained in reversible and repetitive manner to check the repeatability and reliability. This PL behavior gears-up to be utilized as a probe for temperature.

Fig. 5 depicts the linear behavior of the temperature sensor studied as a function of inverse temperature according to the standard expression:

$$\frac{1}{T} = \frac{\Delta H}{k_B} + \frac{1}{T}$$

where \(\Delta H\) is the activation energy for the transition between two energy levels, and \(k_B\) is Boltzmann’s constant. The graph shows a good linearity with a slope indicating the activation energy for the emission process.

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**Fig. 1** Room temperature photoluminescence of as-grown CdS : SiO2 nanocomposite system along with annealed at 400 °C and 500 °C.

**Fig. 2** TEM image of CdS : SiO2 nanocomposite temperature sensor. Inset shows the particle size histogram and SAED pattern.

**Fig. 3** Room temperature photoluminescence of the CdS : SiO2 nanocomposite temperature sensor recorded at various course of time. Inset: intensity variation as a function of aging time.
linear function \( \ln P = -\frac{\varepsilon}{kT} + \ln A \), deduced from the variation of integrated intensity with respect to temperature according to the following equation:

\[
I_T = \frac{B}{A e^{-\varepsilon/kT} + 1}
\]

where \( A \) and \( B \) are constants, \( \varepsilon \) is the activation energy, \( k \) is the Boltzmann constant and \( P = (B/I_T) - 1 \). The variation of integrated intensity is plotted as a function of temperature and is shown in the inset of Fig. 5. The constants were determined by fitting the experimental data with the above mentioned equation and were found to be \( A = 42.7 \), \( B = 2.565 \, 282 \) and \( \varepsilon = 0.043 \) eV. The linear behavior of the intensity with the inverse of temperature suggests its potential application as a temperature sensor. For clarity, the linear behavior of the temperature sensor above room temperature is shown separately in Fig. 5 (inset).

The sensor response is also studied in terms of the full width at half maximum (FWHM) of the PL spectrum and is plotted as a function of temperature, which is shown in Fig. 6. Intensity gives a direct interpretation of temperature, whereas FWHM is analytical. The collective effect of homogeneous and inhomogeneous broadening results in the increase in FWHM of the PL spectrum with increasing temperature. The underlying reasons for such broadening are: (i) broad distribution of intraband states caused by different trapping sites, (ii) distribution in trapped e–h distances (iii) carrier–phonon interactions due to scattering of excitons with acoustic and longitudinal optical (LO) phonons and (iv) nanocrystallites size distribution induced inhomogeneous broadening. Broadening of the PL spectrum is mainly originated by (iii) and (iv) sources. The third one causes homogeneous broadening, whereas the fourth is responsible for inhomogeneous broadening in the PL spectrum due to thermal treatment. The solid curve is obtained using a modified Toyozawa’s equation, which is stated as follows:

\[
\text{FWHM}(T) = \frac{A}{(e^{E_{LO}/kT} - 1)} + BT + C
\]

where \( A \) is the temperature independent linewidth parameter for the exciton-LO phonon-coupling strength; \( E_{LO} \) is the LO-phonon energy for the fundamental mode in the Raman spectrum of CdS.

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**Fig. 4** Temperature-dependent PL of the CdS : SiO\(_2\) nanocomposite temperature sensor (a) below room temperature and (b) above room temperature.

**Fig. 5** Linear fitting to intensity as a function of inverse temperature as \( \ln \left( \frac{B}{I_T} - 1 \right) = -\frac{\varepsilon}{kT} + \ln A \). Inset: variation of integrated intensity with increase in temperature. The linear fit to the experimental data is shown by the red line.

**Fig. 6** FWHM dependency on temperature. The solid curve represents fitting to the experimental data according to eqn (2).
QDs, taken as 37.2 meV; $B$ is the exciton-acoustic phonon coupling coefficient; $C$ is the inhomogeneous broadening, which is temperature-independent and it is due to distribution in size, shape, composition of the nanocrystals. The other parameters obtained by fitting the abovementioned equation to FWHM are listed in the table shown in the inset of Fig. 6. The exciton-LO phonon-coupling coefficient is smaller than 180.6 meV in single crystal CdS due to the confinement of excitonic polarization in small QDs in the nanocomposite system.

Temperature sensing in the cryogenic, physiological, and high temperature range has been studied with various sensing materials. Nevertheless, there is rarely any report on such a wide range temperature sensor using inorganic compounds and simple fabrication processes. The efficiency of the temperature sensor reported here can be attributed to high sensitivity and resolution. The sensitivity of the sensor is related to the slope of the linear fit and defines the rate of change of intensity/FWHM with respect to the change in temperature. The average sensitivity of the sensor in two temperature ranges is calculated using the relation $\Delta I/\Delta T$, where $\Delta I$ is the change in In $P$/FWHM, corresponding to the change in temperature $\Delta T$. The resolution of the sensor is deduced from the detector resolution and the calculated sensitivity. The sensitivity of the sensor deduced from intensity studies is plotted with temperature and is shown in Fig. 7. The sensitivity decreases with increasing the temperature due to the drastic change in emission intensity in the lower temperature regime and stability at higher temperatures. The calculated sensitivity and resolution in the two temperature ranges are given in inset of Fig. 7. The average sensitivity and resolution of the sensor were calculated to be $\sim 0.06$ K$^{-1}$ and 0.0002 K, respectively, from the intensity, while $\sim 0.389$ meV K$^{-1}$ from the FWHM measurements. The relative sensitivity of the sensor, i.e.

$$R_s(T) = \frac{1}{P} \frac{dP}{dT}$$ (3)

reaches as high as $\sim 8.4%$ K$^{-1}$ at 120 K (shown in Fig. 7) while better resolution of $\sim 0.003$ K is observed in the high temperature regime.

Table 1  Brief summary of the performance of the luminescence-based temperature sensors

<table>
<thead>
<tr>
<th>Sensing material</th>
<th>Temperature sensing method</th>
<th>Temp. range</th>
<th>Absolute/relative sensitivity</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rare-earth element doped $\gamma$-Fe$_2$O$_3$@TEOS/APTES NPs</td>
<td>Luminescence intensity ratio</td>
<td>10 K–350 K</td>
<td>0.5% K$^{-1}$</td>
<td>1</td>
</tr>
<tr>
<td>Eu$^{3+}$ doped TiO$_2$ NPs</td>
<td>Fluorescence intensity ratio and life time</td>
<td>307 K–533 K</td>
<td>0.17–2.43% K$^{-1}$</td>
<td>3</td>
</tr>
<tr>
<td>Mixed-lanthanide MOF</td>
<td>Luminescence intensity ratio</td>
<td>10 K–300 K</td>
<td>—</td>
<td>5</td>
</tr>
<tr>
<td>(CdSe)ZnS QDs in PLMA</td>
<td>Luminescence intensity</td>
<td>100 K–315 K</td>
<td>1.3% °C$^{-1}$</td>
<td>6</td>
</tr>
<tr>
<td>(CdSe)ZnS QDs doped bulk glass</td>
<td>PL spectral shift</td>
<td>287 K–316 K</td>
<td>0.2 nm °C$^{-1}$</td>
<td>7</td>
</tr>
<tr>
<td>Single QDs of (CdSe)ZnS</td>
<td>PL spectral shift</td>
<td>297.4 K–316.6 K</td>
<td>0.1 nm °C$^{-1}$</td>
<td>10</td>
</tr>
<tr>
<td>CdSe(ZnS) nanocomposite</td>
<td>PL spectral shift</td>
<td>295 K–525 K</td>
<td>0.11 nm °C$^{-1}$</td>
<td>11</td>
</tr>
<tr>
<td>CdSe QDs</td>
<td>Luminescence intensity and spectral shift</td>
<td>303 K–333 K</td>
<td>0.16 nm °C$^{-1}$</td>
<td>12</td>
</tr>
<tr>
<td>CdTe quantum dots-layered double hydroxide ultrathin films</td>
<td>Luminescence intensity</td>
<td>296 K–353 K</td>
<td>1.47% °C$^{-1}$</td>
<td>13</td>
</tr>
<tr>
<td>[ZnCd]S : Ag powder</td>
<td>Luminescence decay time</td>
<td>263 K–423 K</td>
<td>—</td>
<td>14</td>
</tr>
<tr>
<td>Carbon dots</td>
<td>Luminescence intensity</td>
<td>288 K–333 K</td>
<td>—</td>
<td>15</td>
</tr>
<tr>
<td>Tb$^{3+}$ doped crystalline oxide powders</td>
<td>Luminescence intensity ratio</td>
<td>303 K–773 K</td>
<td>2.8 $\times$ 10$^{-4}$ to 9 $\times$ 10$^{-4}$ °C$^{-1}$</td>
<td>16</td>
</tr>
<tr>
<td>Er$^{3+}$ doped BaTiO$_3$ NCs</td>
<td>Fluorescence intensity ratio</td>
<td>322 K–466 K</td>
<td>$\leq$0.0052 K$^{-1}$</td>
<td>17</td>
</tr>
<tr>
<td>Eu$^{3+}$ doped $Y_2$Mo$<em>6$O$</em>{17}$</td>
<td>Luminescence intensity</td>
<td>20 K–500 K</td>
<td>7% K$^{-1}$</td>
<td>18</td>
</tr>
<tr>
<td>Eu$<em>3$(Tb$</em>{1-x}$)MOF</td>
<td>Luminescence intensity ratio</td>
<td>100 K–450 K</td>
<td>1.325% K$^{-1}$</td>
<td>19</td>
</tr>
<tr>
<td>Cds : SiO$_2$ nanocomposite</td>
<td>Luminescence intensity &amp; FWHM</td>
<td>20 K–560 K</td>
<td>Intensity; 0.06 K$^{-1}$/8.4% K$^{-1}$</td>
<td>Present work</td>
</tr>
</tbody>
</table>
A brief review on the luminescence-based thermometers is presented in Table 1 for comparison. It includes studies on diverse range of materials to realize nanothermometers with high sensitivity. In most of the studies, the luminescence intensity ratio in rare earth doped compounds/complexes or alternatively PL intensity/spectral shift in Cd-containing QDs are studied with respect to temperature. In particular, for Cd-containing QDs temperature sensors, the sensitivity is not very satisfactory with the maximum being 1.47% °C−1 for CdTe quantum dots-layered double hydroxide ultrathin films with a limited range of temperature response. Some sensors are useful at cryogenic temperatures, some at physiological, while others are good for the high temperature range. Nevertheless, such a wide range temperature sensor that covers all the temperature zones has not yet been reported. The sensitivity and resolution of the present sensor is considerably better in all temperature regimes, according to the intensity study. The study of luminescence intensity with temperature for the present sensor is a direct and significant method as compared to others because a single peak is observed in the PL spectrum. The advantage here is that the temperature can be sensed directly by the observation of lowering or evolution of the PL spectrum intensity. Usually in most temperature sensors, like rare earth doped complexes, there are two sharp peaks for which the intensity ratio varies with temperature, and a direct linear or natural log based linear relation can be obtained for temperature sensor. Instead, for the CdS : SiO2 nanocomposite temperature sensor, there is no need to observe the ratio of PL peaks, which is not easy to perceive. We have also performed FWHM studies as a function of temperature and found that the sensor works with better sensitivity for luminescence intensity. The highest value of relative sensitivity (~8.4% K−1) is maximum, which is 1.2 times greater than the maximum achieved sensitivity to date for luminescence based molecular thermometers. The present temperature sensor is a good choice in the cryogenic region for better sensitivity, whereas in high temperature zones it offers better resolution.

4. Conclusion

In summary, a low-cost, highly efficient, sensitive and stable wide range temperature sensor using CdS : SiO2 nanocomposite is reported here for the first time. The emission intensity and thereby the performance of the device is unprecedented even after long periods of time. The possible mechanism of pure, intense, and stable RE is discussed by considering the role of surface defects, monodispersity of CdS nanocrystals and SiO2 matrix. The linearity of the sensor follows the trend of the variation of ln P with inverse of temperature as ln P = − [(506.96 ± 10)/T] + (3.74 ± 0.07). The average sensitivity and resolution of the temperature sensor were ~0.06 K−1 and 0.0002 K, respectively. The maximum relative sensitivity of 8.4% K−1 was observed at 120 K. Alternatively, the FWHM gives an analytic sensitivity of ~0.388 meV K−1 for this sensor. The achieved range, sensitivity, and resolution are considerably better than previous reports.

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