

Electrical Characterization of CeO₂/SnO₂ Hydrogen Sensors: Influence of Temperature on Baseline Sensor Currents

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Abstract

Growing environmental and energy sustainability challenges are driving increased interest in hydrogen as an emerging clean energy carrier and practical alternative to fossil fuels. Effective monitoring of H₂ concentrations in air is a critical requirement to ensure the safe operation of H₂-based technologies. Metal oxide (MO_x)-based resistive sensing is widely investigated, but their elevated working temperatures, often exceeding 300°C, lead to substantial increases in power consumption and reduce device longevity. Therefore, achieving H₂ sensing at or near room temperature is desirable for durable and scalable use. In this work, we report the use of CeO₂ and SnO₂-based heterostructures as potential sensing materials capable of lowering the operating temperature for H₂ detection in air. With this objective, we characterise the electrical behavior of the fabricated sensor devices under varying voltage and temperature conditions to assess baseline sensor currents. The gas sensing performance is also evaluated upon exposure to a 1% H₂/air mixture.

1 Introduction

In recent decades, significant efforts have been made to establish a sustainable energy economy to address global climate change and the depletion of fossil fuel reserves. In this regard, hydrogen, owing to its abundance and high energy efficiency, has emerged as a reliable and accessible green energy fuel. However, its wide explosion limits in air (4%-75%) under ambient conditions pose safety challenges that hinder large-scale commercialization [1]. As a consequence, reliable monitoring of hydrogen concentrations in air is crucial, driving the development of novel sensing materials and sensor prototypes. Numerous gas sensing mechanisms are based on physicochemical interactions between the target gas and the sensor's active layer [2]. Among all, resistive sensors based on reactive metal oxides are widely investigated due to their ease of fabrication, compatibility with integrated circuits, and high sensitivity. However, their operating temperatures are typically above 300°C, which increases power consumption and affects their long-term use [3]. Therefore, our current work focuses on reducing the working temperatures required to detect hydrogen in air.

The main working principle of resistive gas sensing relies on changes in the electrical current of the MO_x active layer upon exposure to analyte gas molecules. Based on this mechanism, several oxides and their combinations have been investigated and reported in the literature [4]. Nanostructured oxides, typically fabricated by techniques such as sol-gel, offer improved sensitivity due to their high surface-to-volume ratio. However, their deposition methods generally show poor compatibility with standard microelectronics processes, limiting their integration. As an

alternative, in this work, we present thin-film deposition techniques for cerium oxide, tin oxide, and their heterostructures as post-processes compatible with CMOS fabrication. The metal-oxide channels are patterned and contacted using photolithography. The resulting sensor structures are electrically characterized, and the influence of temperature on the sensor's baseline currents is investigated. In the end, as a proof of concept, the current variation to 1% H₂/air mixture is also reported.

2 Device Fabrication

MO_x-based H₂ sensors typically have a simple structure, consisting of a sensing layer that interacts with the target gas and electrodes that act as transducing elements. Additionally, microheater platforms are incorporated into the sensor design to achieve elevated operating temperatures. In microfabrication, Atomic Layer Deposition (ALD) and Radio Frequency Magnetron Sputtering (RF-MS) are commonly employed to deposit MO_x thin films. MS is advantageous for producing relatively thick layers within short processing times, while ALD is preferred for precise thickness control and highly conformal coatings, with a slower growth rate. Earlier studies have demonstrated the deposition of CeO₂ active films using both MS [5] and ALD. Notably, ALD-grown CeO₂ has been shown to exhibit a measurable response to H₂ even at room temperature [6]. In our case, microsensor chiplets were fabricated, mounted on a customised microheater (**Figure 1a**), and then wire-bonded to a Dual-In-Line package (DIL-24), as shown in **Figure 1d and 1e**. For the fabrication of CeO₂/SnO₂-based H₂ sensors, Si/SiO₂ substrates patterned with planarized interdigitated tungsten from IHP's cleanroom were used for

deposition using a shadow mask. **(Figure 1b)**. SnO₂-doped CeO₂ layers of roughly 100 nm were deposited using a water-cooled 13.56 MHz RF-MS system over 60 minutes. A 99.99% (4N) CeO₂ target of 2" diameter with Sn wires on its surface was sputtered at an RF power of 10W. Ar (10 sccm) was used as the sputter gas at a working pressure of 10⁻² mbar. Each fabricated sensor chiplet has two interdigitated electrode sets configured in a T-structure sharing a single common electrode. Further, for comparison, SnO₂-only channels were fabricated at IHP's Rapid Prototyping Lab (RPL) using maskless photolithography (Smart Print UV, Microlight 3D) as shown in **Figure 1c**. The process involved patterning the MO_x channel layer on SiO₂/Si substrates, followed by thermal evaporation of approximately 100 nm of Sn. The samples were then annealed in air at 300°C for an hour to oxidize the Sn. Finally, subsequent lithography steps were followed to pattern Ti/Au interdigitated electrode contacts.

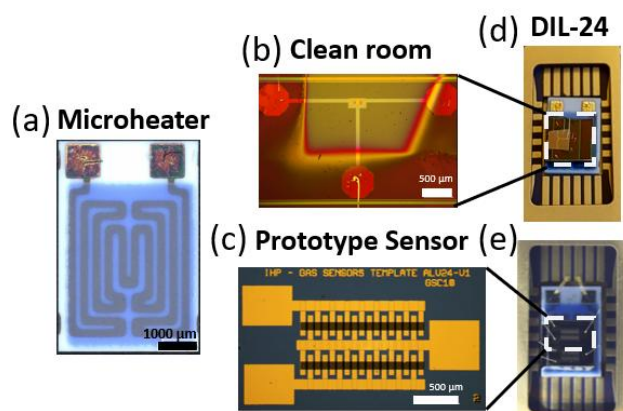


Figure 1 (a) Microheater, (b) CeO₂/SnO₂-based sensor chiplet, (c) SnO₂-based sensor chiplet, (d and e) sensor chiplets integrated with microheater and wire-bonded to a DIL-24 socket.

3 Electrical Characterization

CeO₂ exhibits versatile oxidation-state behavior under both reductive and oxidizing conditions, making it a highly suitable material for sensing applications. It is also being extensively investigated for the detection of H₂ at moderate operating temperatures, especially in heterostructures with more conductive oxides such as SnO₂ [7]. MO_x-based sensors exhibit time-dependent current variations due to aging and oxidation effects. Also, the electrical characterization of previous samples had a reduction in current by orders of magnitude. Current drifts in MO_x-based sensors have also been reported in literature [8] [9], attributed to oxygen vacancies and intrinsic material properties. In the present work, electrical characterization of our sensors has been carried out to evaluate the baseline sensor behavior over time under the influence of temperature and H₂ exposure. This baseline characterization helps eliminate possible misinterpretations in sensor responses. The results have been compared between CeO₂/SnO₂ devices and SnO₂-only devices.

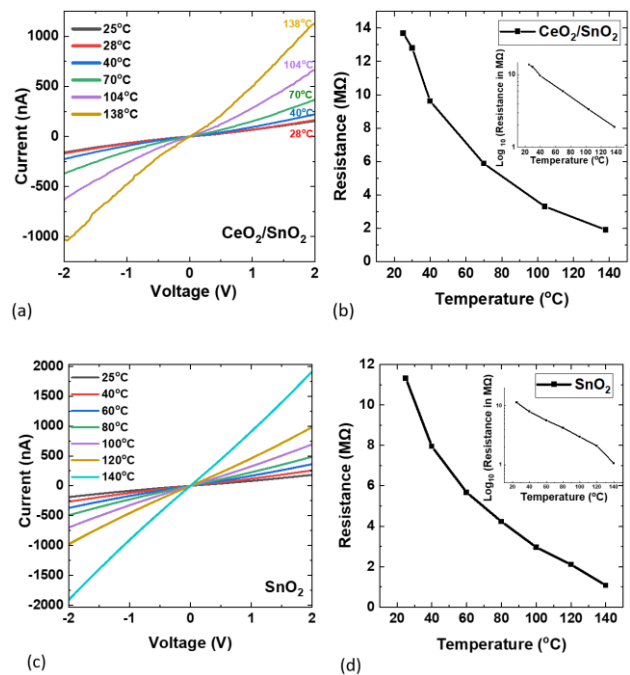


Figure 2 Effects of temperature on both CeO₂/SnO₂ and SnO₂-only structures. I-V characteristics with heating **(a)** CeO₂/SnO₂ (micro-heater voltage) and **(c)** SnO₂. **(b and d)** Resistance variation with temperature increase in CeO₂/SnO₂ and SnO₂-only structures, respectively. Inset: log (resistance) vs. temperature.

The influence of temperature on sensor current was evaluated based on current vs voltage (I-V) measurements. **Figure 2a** presents the I-V characteristics of the CeO₂/SnO₂ channels measured at increasing temperatures, controlled by varying the microheater voltage. Within the measured voltage range (-2 V to 2 V), all the I-V curves exhibit nearly linear behavior with a coefficient of determination (R^2) of approximately 0.99, indicating predominantly ohmic conduction. As the temperature increases, the additional thermal energy enhances charge transport, resulting in steeper I-V slopes. Consequently, the device resistance decreases significantly with temperature (**Figure 2b**), with the value at 138°C (1.9 MΩ) dropping to nearly 15% of the room-temperature resistance (13.7 MΩ). A logarithmic plot of resistance versus temperature (**Figure 2b inset**) was inserted to clearly illustrate this thermally activated conduction. Similar measurements were carried out for the SnO₂-only channels using the PMV200 electrical characterization tool. To evaluate the effect of temperature, the samples were heated to the desired temperatures using the PMV200 heater. The resulting I-V curves (**Figure 2c**) showed a consistent trend with temperature, with currents increasing from 190 nA to 1900 nA across the measured range (25°C-140°C). **Figure 2d** confirms the material's semiconducting behavior via the non-linear decrease in resistance with temperature. Furthermore, the log (resistance) (**Figure 2d inset**) shows a sharp drop in resistance for only a 20°C rise in temperature between 120°C and 140°C, emphasizing the strong temperature dependence.

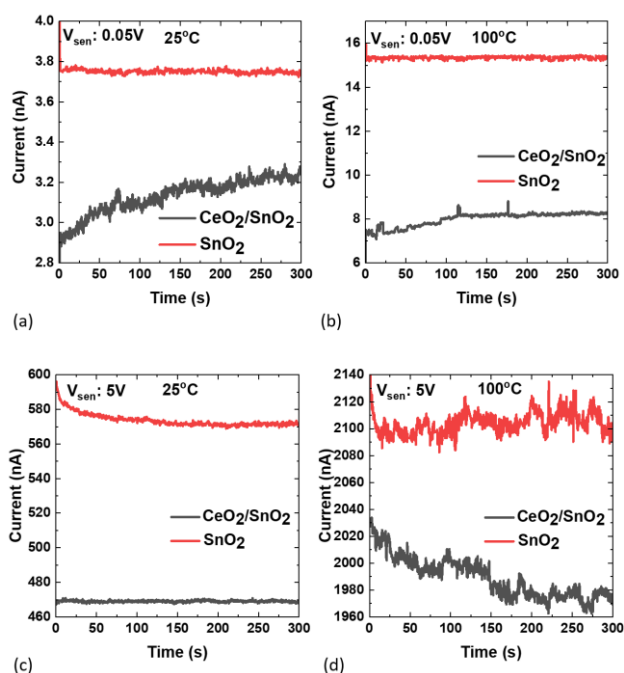


Figure 3 Observations of current drift in the CeO₂/SnO₂ channel (black) and the SnO₂-only channel (red) at low voltage (a and b) and high voltage (c and d) at room temperature and 100°C, respectively.

| Condition | Current Drift (pA/s) | |
|---------------|------------------------------------|------------------------|
| | CeO ₂ /SnO ₂ | SnO ₂ -only |
| 0.05 V, 25°C | + 0.99 | - 0.05 |
| 0.05 V, 100°C | + 2.48 | + 0.61 |
| 5 V, 25°C | + 2.03 | - 81.92 |
| 5 V, 100°C | - 198.79 | - 106.53 |

Table 1 Current drift values at each voltage and temperature condition for the CeO₂/SnO₂ and SnO₂-only channels.

A current drift analysis was carried out for both MO_x-based channels to assess current variations at very low (0.05 V) and relatively high (5 V) sensor voltages under different temperature conditions (25°C and 100°C) (**Figure 3**). For this purpose, current values were recorded for 5 minutes to examine whether the currents stabilized over time. Based on the measurements, current drift values were calculated in each case and tabulated (**Table 1**). The CeO₂/SnO₂ channel shows a modest increase in current under low voltage operation, rising from around 1 pA/s at 25°C to higher values at elevated temperatures (**Figure 3a and 3b**). At high voltage and 100°C, however, the drift becomes significantly negative (~199 pA/s), indicating reduced stability. In comparison, the SnO₂-only channel remains relatively stable at low voltages but shows pronounced negative drift at high voltage conditions. (**Figure 3c and 3d**). Overall in both cases, while the current behavior under mild conditions remains fairly stable, there is substantial instability under high voltage and elevated temperature operation.

In the end, the current variation in the MO_x channels due to a 1% H₂/air gas stream was measured at temperatures suitable for the surrounding electronics (**Figure 4**). As shown in **Figure 4a**, there is a 12% current variation upon

gas exposure at 50°C for the CeO₂/SnO₂ channel, whereas the SnO₂-only channel (**Figure 4b**) exhibits a slightly lower change of 6% at 70°C. Although the current ratio between before-exposure (I_0) and after-exposure (I) to the H₂ mixture is relatively low compared to previously reported values, achieving a measurable response at these low working temperatures represents a step toward reduced power consumption. The literature reports an increase in current in the MO_x layer when exposed to a reducing gas such as H₂; however, our results show an unexpected decrease in measured current. The mechanism behind this current behavior remains unclear and is under ongoing investigation. In future work, ultra-thin (< 20 nm) MO_x films and their heterostructures will be deposited by ALD, and their performance will be compared with that of sputtered films.

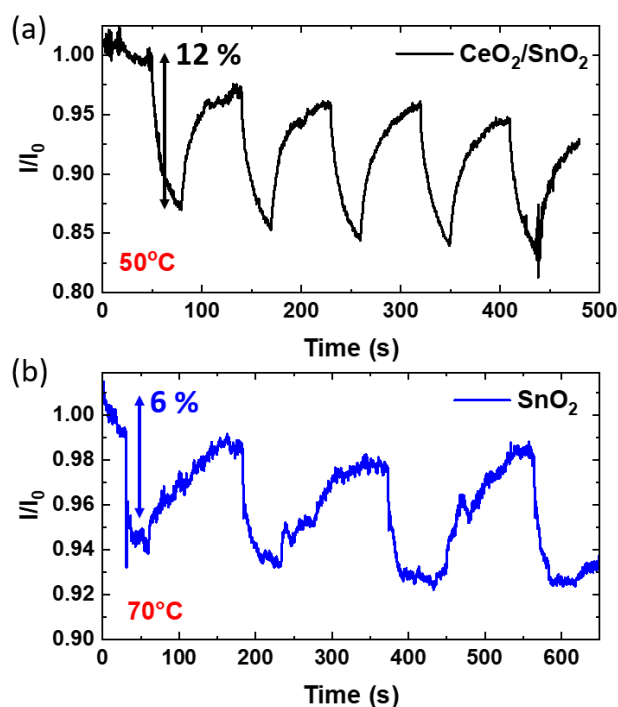


Figure 4 Current variation upon exposure to 1% H₂/air gas mixture at different temperatures in (a) CeO₂/SnO₂ sample and (b) SnO₂-only sample.

4 Conclusion

In this study, we report a thin film deposition method for CeO₂/SnO₂ heterostructures as a post-processing step that can be integrated with CMOS procedures. For comparison purposes, SnO₂-based sensor device fabrication was also done following rapid prototyping procedures via maskless photolithography. The sensor chiplets were then integrated with a custom microheater and wire bonded to a DIL-24 socket for electrical characterization at elevated temperatures. I-V measurements reveal a significant temperature dependence with reduced resistance at high temperatures. The current drift analysis indicates notable instability under high voltage and high temperature operation. Finally, from the results of gas exposure to a 1% H₂/air mixture, with detectable current variation at 50°C, the CeO₂/SnO₂-based device demonstrates better performance than the

SnO₂-only device. Although current changes remain low, these baseline results provide a reference for the electrical behavior and guide further optimization of the MO_x active layer and sensor performance.

5 Acknowledgements

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6 Literature

- [1] T. Hübert, L. Boon-Brett, W. Buttner, *Sensors for Safety and Process Control in Hydrogen Technologies*. in 2018. CRC Press.
- [2] T. Hübert, L. Boon-Brett, G. Black, and U. Banach, "Hydrogen sensors – A review," *Sens. Actuators B Chem.*, vol. 157, no. 2, pp. 329–352, Oct. 2011, doi: 10.1016/j.snb.2011.04.070.
- [3] P. Wang, S. Xu, X. Shi, J. Zhu, H. Xiong, and H. Wen, "Recent Advances in Resistive Gas Sensors: Fundamentals, Material and Device Design, and Intelligent Applications," *Chemosensors*, vol. 13, no. 7, p. 224, Jun. 2025, doi: 10.3390/chemosensors13070224.
- [4] N. Goel, K. Kunal, A. Kushwaha, and M. Kumar, "Metal oxide semiconductors for gas sensing," *Eng. Rep.*, vol. 5, no. 6, p. e12604, Jun. 2023, doi: 10.1002/eng2.12604.
- [5] A. Hayat *et al.*, "Structural and morphological properties of CeO₂ films deposited by radio frequency magnetron sputtering for back-end-of-line integration," *Thin Solid Films*, vol. 807, p. 140547, Oct. 2024, doi: 10.1016/j.tsf.2024.140547.
- [6] C. Morales *et al.*, "Hydrogen Sensing via Heterolytic H₂ Activation at Room Temperature by Atomic Layer Deposited Ceria," *ChemSusChem*, vol. 18, no. 13, p. e202402342, Jul. 2025, doi: 10.1002/cssc.202402342.
- [7] D. E. Motaung *et al.*, "Ultra-high sensitive and selective H₂ gas sensor manifested by interface of n–n heterostructure of CeO₂-SnO₂ nanoparticles," *Sens. Actuators B Chem.*, vol. 254, pp. 984–995, Jan. 2018, doi: 10.1016/j.snb.2017.07.093.
- [8] G. Müller and G. Sberveglieri, "Origin of Baseline Drift in Metal Oxide Gas Sensors: Effects of Bulk Equilibration," *Chemosensors*, vol. 10, no. 5, p. 171, May 2022, doi: 10.3390/chemosensors10050171.
- [9] N. Dennler, S. Rastogi, J. Fonollosa, A. van Schaik, and M. Schmuker, "Drift in a popular metal oxide sensor dataset reveals limitations for gas classification benchmarks," *Sens. Actuators B Chem.*, vol. 361, p. 131668, Jun. 2022, doi: 10.1016/j.snb.2022.131668.