

Charge and Capacitance Sensitive Field-Effect Device for Room-Temperature Hydrogen Sensing

Jamila Boudaden¹, Nnaemeka Michael Mbachu¹, Karl Neumeier¹, Ignaz Eisele^{1,2}

¹ Fraunhofer Institute for Electronic Microsystems and Solid State Technologies EMFT, GERMANY

² Center Integrated Sensor Systems (SENS), Universität der Bundeswehr München, GERMANY
Jamila.boudaden@emft.fraunhofer.de

Summary:

We present the sensing properties of a CMOS-compatible Charge- and Capacitance-Sensitive Field-Effect Transistor (CCSFET) operated in gaseous environments. The device comprises two sensing areas, each integrating a chemically sensitive capacitor and a potential probe that together form the floating gate of a MOS transistor. In addition, the potential probe is connected to an operational amplifier (OpAmp), enabling robust electrical readout via both the MOSFET and the OpAmp. The CCSFET is flip-chip packaged onto a flexible substrate, which improves mechanical robustness and ensures reliable signal acquisition. As a demonstration, we investigate room-temperature hydrogen sensing using a thin Pd layer deposited on two different sensing layers, Si_3N_4 and Ta_2O_5 of CCSFT.

Keywords: CCSFET, MOSFET, OpAmp, H_2 sensing, CMOS technology, $\text{Pd}/\text{Si}_3\text{N}_4$, $\text{Pd}/\text{Ta}_2\text{O}_5$

Background, Motivation and Objective

In this work, we introduce the CCSFET, a fully CMOS-compatible device concept for sensing application that overcomes the limitations of previously proposed miniaturized systems as it is designed to operate in both liquid and gaseous environments. The CCSFET measures changes in both charge and capacitance of chemically sensitive layers [1–3]. Our objective is to demonstrate, on a single-chip platform, hydrogen detection in air at atmospheric pressure and room temperature using both sensing systems, $\text{Pd}/\text{Ta}_2\text{O}_5$ and $\text{Pd}/\text{Si}_3\text{N}_4$, integrated on the same CCSFET chip.

Description of CCSFET

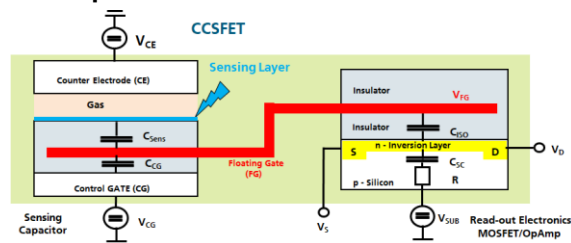


Fig. 1. Schematic of CCSFET device with sensing area, counter electrode, floating gate, control gate and MOSFET and OpAmp read-out.

The CCSFET is fabricated in CMOS technology on a 200 mm silicon substrate. The chip has a footprint of $4.5 \times 4.5 \text{ mm}^2$ and incorporates two circular sensing areas with diameters of 820 μm

and 520 μm (Fig. 1). The sensing areas, consisting of Si_3N_4 and Ta_2O_5 , that are capacitively coupled to a MOSFET and OpAmp readout via a floating gate. Si_3N_4 was deposited by PECVD. 50nm Ta_2O_5 was sputtered on Si_3N_4 grown by LPCVD. The gold counter electrode acts as Faraday cup for gas. CCSFET configuration has the advantage of a clear separation between the sensing areas and the electronic readout.

To improve robustness and simplify handling, the CCSFET is flip-chip bonded onto a flexible foil, as described in [4]. This hybrid packaging approach yields a compact and mechanically compliant sensor module. Only the sensing areas are exposed to the gas to be sensed, while the contact pads and interconnects remain protected. This design reduces parasitic effects and enhances long-term stability in real environments.

For sensing H_2 at room temperature, the counter electrode is connected to a grounded Faraday cup, which provides shielding and prevents chemical reactions at the cup surface from influencing the sensor response. This is particularly important because the gas capacitance is very small, and parasitic effects must be minimized. A 5 nm Pd layer sputtered on Si_3N_4 and Ta_2O_5 enables detection of H_2 between 500 ppm and 1.6% in synthetic air at atmospheric pressure. The sensors are placed inside a tight PEEK gas chamber. The counter electrode is grounded,

and the control gate is used to define the operating point of the CCSFET and to extract the MOSFET input characteristics (Fig. 2).

Results

In Fig. 2, we show the MOSFET input characteristics as a function of control gate voltage for different hydrogen concentrations for both sensing systems, Pd//Ta₂O₅ and Pd//Si₃N₄. In Fig. 3, we plot the change in control gate voltage, extracted at $I_{\text{source-drain}} = 300 \mu\text{A}$, as a function of H₂ concentration.

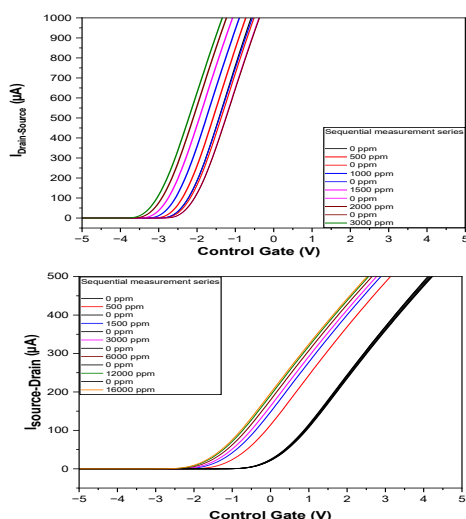


Fig. 2. CCSFET input characteristics: Source-drain current (I_{SD}) vs control gate voltage for sensing system Pd//Ta₂O₅ (Top) and Pd//Si₃N₄ (Bottom).

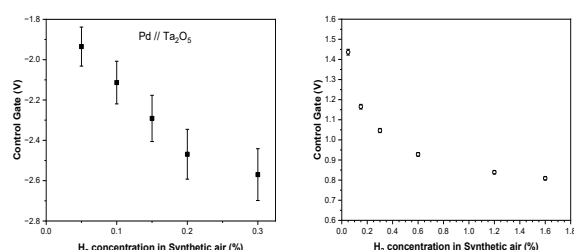


Fig. 3. Control voltage versus H₂ concentration at $I_{\text{source-drain}} = 300 \mu\text{A}$ for sensing system Pd//Ta₂O₅ (Left) and Pd//Si₃N₄ (Right).

For both sensing systems, a shift of the MOSFET threshold voltage V_{th} to lower values is observed with increasing H₂ concentration, demonstrating a clear response to the presence of hydrogen. V_{th} is correlated with the chemical interaction of H₂ with the Pd//Ta₂O₅ and Pd//Si₃N₄ sensing systems, which induces charges at the sensing areas and leads to a potential change at the floating gate. This potential shift is then converted into a measurable electrical response by the MOSFET readout.

Only the Pd//Si₃N₄ system shows reversible and reproducible sensing behavior toward H₂ at room temperature (Fig. 2, bottom). The detection limit reaches 1.2%. In contrast, Pd//Ta₂O₅ system doesn't recover after H₂ exposure: the sensing error exceeds 5%, restricting reliable measurements to about 0.3% H₂.

Our results contrast with recently published work [5], which reports reversible H₂ sensing for a Pd//Ta₂O₅ system. We attribute the irreversibility observed in Fig. 2 top, to the fact that both Pd and Ta₂O₅ are permeable to hydrogen, whereas Si₃N₄ remains essentially impermeable to H₂. In the Pd//Si₃N₄ system, H₂ absorbed in Pd can rapidly desorb once the H₂ atmosphere is removed. In contrast, H₂ captured in Ta₂O₅ likely requires elevated temperatures (around 150 °C) for efficient release, as suggested in [5]. To the best of our knowledge, no prior experimental or theoretical studies report H₂ detection using Pd//Ta₂O₅ and Pd//Si₃N₄ sensing systems at room temperature.

Conclusion

The CCSFET introduces a new class of CMOS-compatible field-effect devices for sensing charge formation in the sensing layer induced by the reaction of H₂ with Pd. The H₂ sensitivity of Pd depends strongly on the composition of the underlying layer on which Pd is sputtered. Among the investigated systems, Pd//Si₃N₄ emerges as a promising sensing stack for room-temperature H₂ detection.

References

- [1] I. Eisele, J. Boudaden and K. Neumeier, "Charge and Capacitance Sensitive Field Effect Transistor (CCSFET) for Chemical Sensing," in *IEEE Sensors Journal*, vol. 25, no. 20, pp. 37622-37629, 15 Oct.15, 2025, doi: 10.1109/JSEN.2025.3596216
- [2] I. Eisele, "Fluid Sensor and Method for Examining a Fluid," US patent 9,716,140 B2, 2017.
- [3] I. Eisele, J. Boudaden, K. Neumeier, "Sensor Device and Corresponding Methods," Patent application EP24191571.9, 2024.
- [4] M. Steinmaßl, J. Boudaden, W. Hell, C. Kutter, "Simple and powerful encapsulation through hybrid packaging for electrochemical transducers," *Smart Systems Integration (SSI) Conference*, 2021.
- [5] J. Tong, Y. Lv, Z. Zhuang, J. Yang, B. Feng, J. Zhao, S. Huang, D. Zhang, Y. Zhu, G. Cuniberti, L. Wang, Wafer-Scale Pd-decorated Ta₂O₅/SnO₂ Heterojunction Sensor for Ultrafast and Sensitive Hydrogen Detection, *Sensors & Actuators: B. Chemical* 451 (2026) 139432.