

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

Jamila Boudaden¹, Syed Fahad Ali¹, Heerenkumar Vadadoriya¹, Nnaemeka Michael Mbachu¹, Fatemehsadat Parpanchi¹, 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 liquid and gaseous environments. The device comprises two sensing areas, each capacitively coupled to a MOSFET and OpAmp readout via a floating gate. The CCSFET is flip-chip packaged onto a flexible substrate, which improves mechanical robustness and ensures reliable signal acquisition. As a demonstration, we investigate sensing capacity of CCSFET at room-temperature in both liquid and gas environments. We present the sensing characteristics of pH with Ta₂O₅ sensing layer and hydrogen sensing using a thin Pd layer deposited on two different sensing layers, Si₃N₄ and Ta₂O₅.

Keywords: CCSFET, MOSFET, OpAmp, pH sensing, H₂ sensing, CMOS technology

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 [1–2]. Our objective is to demonstrate, on a single-chip platform, hydrogen detection in air at atmospheric pressure and room temperature using both sensing systems, Pd on Ta₂O₅ and Pd on Si₃N₄, integrated on the same CCSFET chip.

Description of CCSFET

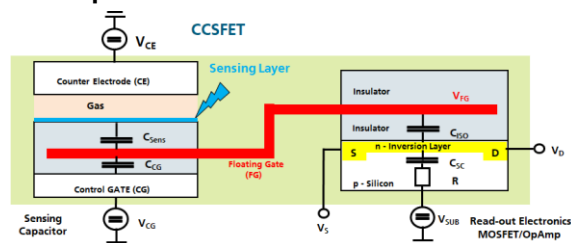


Fig. 1. Schematic of CCSFET device with sensing area, counter electrode, floating gate, control gate and MOSFET and OpAmp read-out.

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 Si₃N₄ and Ta₂O₅, are capacitively coupled to a MOSFET and OpAmp readout via floating gate. Si₃N₄ was deposited by PECVD. 50nm Ta₂O₅ was sputtered on Si₃N₄ grown by LPCVD.

To improve robustness and simplify handling, the CCSFET is flip-chip bonded onto a flexible foil, as described in [3]. This hybrid packaging approach yields a compact and mechanically compliant sensor module. Only the sensing areas are exposed to the fluid 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 H₂ at room temperature, the gold 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 Si₃N₄ and Ta₂O₅ enables detection of H₂ 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). With Ta₂O₅ layer deposited on the sensing electrode, the CCSFET is capable of monitoring the

concentration of H^+ ions, enabling effective pH detection. The counter electrode, when coated with Ag/AgCl paste, serves as a stable reference electrode, eliminating the need for an additional external reference electrode. By applying a 20 μ L droplet of a liquid solution onto the sensing area, pH values ranging from 2.7 to 10 were successfully detected. Figure 3 presents the source-drain current as a function of control gate voltage for different reference voltages, demonstrating the device's response to various pH levels.

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 on Ta_2O_5 and Pd on Si_3N_4 .

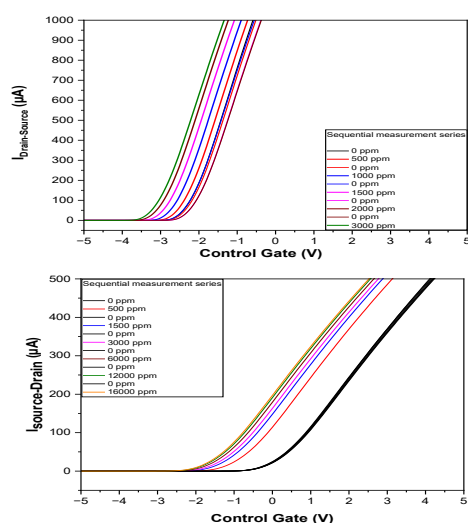


Fig. 2. CCSFET input characteristics: Source-drain current (I_{SD}) vs control gate voltage for sensing system Pd on Ta_2O_5 (Top) and Pd on Si_3N_4 (Bottom).

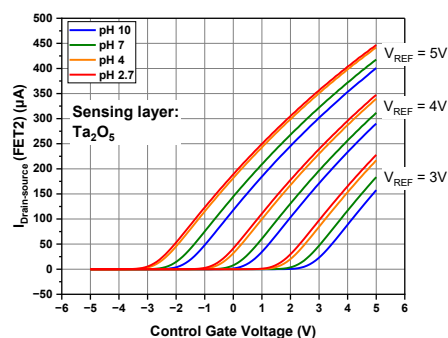


Fig. 3. MOSFET input characteristics for $V_{Drain}=200mV$ using on-chip reference electrode (Ag/AgCl paste). A 20 μ L droplet of pH buffer solution (pH 2.7, 4, 7, and 10) was placed on the sensing area for each measurement. The $I_{Drain-Source}$ was recorded as a function of $V_{ControlGate}$ for various V_{REF} .

CCSFET is adapted to sense both pH and H_2 . For both, a shift of the MOSFET threshold voltage V_{th} to lower values is observed with increasing H_2 concentration and an increase to higher values for sensing pH in liquid. V_{th} is correlated

with the chemical interaction of H_2 with the Pd on Ta_2O_5 and Pd on Si_3N_4 sensing systems, as well as to detecting H^+ ions in liquid 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 as well as OpAmp (will be presented).

Only the Pd on Si_3N_4 system shows reversible and reproducible sensing behavior toward H_2 at room temperature (Fig. 2, bottom). The detection limit reaches 1.2%. In contrast, Pd// Ta_2O_5 system doesn't recover after H_2 exposure: the sensing error exceeds 5%, restricting reliable measurements to about 0.3% H_2 . Our results contrast with recently published work [4], which reports reversible H_2 sensing for a Pd on Ta_2O_5 system. We attribute the irreversibility observed in Fig. 2 top, to the fact that both Pd and Ta_2O_5 are permeable to hydrogen, whereas Si_3N_4 remains essentially impermeable to H_2 . In the Pd on Si_3N_4 system, H_2 absorbed in Pd can rapidly desorb once the H_2 atmosphere is removed. In contrast, H_2 captured in Ta_2O_5 likely requires elevated temperatures (around 150 $^{\circ}C$) for efficient release, as suggested in [4]. To the best of our knowledge, no prior experimental or theoretical studies report H_2 detection using Pd on Ta_2O_5 and Pd on Si_3N_4 sensing systems at room temperature.

Conclusion

The CCSFET introduces a new class of CMOS-compatible field-effect devices for dual chemical sensing, pH and H_2 , in liquid and gaseous environments at room temperature. Charge formed at the sensing layer, from the reaction of H_2 with Pd or from H^+ ions at the Ta_2O_5 surface, is capacitively coupled to a floating gate connected to both a MOSFET and an OpAmp readout, enabling robust electrical detection. Critically, the H_2 sensitivity and reversibility of the Pd sensing layer depend strongly on the composition of the underlying dielectric on which it is deposited.

References

- [1] I. Eisele, J. Boudaden and K. Neumeier, IEEE Sensors Journal, vol. 25, no. 20, pp. 37622-37629, 15 Oct.15, 2025, doi: 10.1109/JSEN.2025.3596216
- [2] I. Eisele, J. Boudaden, K. Neumeier, "Sensor Device and Corresponding Methods," Patent application EP24191571.9, 2024.
- [3] M. Steinmaßl, J. Boudaden, W. Hell, C. Kutter, "Simple and powerful encapsulation through hybrid packaging for electrochemical transducers," Smart Systems Integration (SSI) Conference, 2021.
- [4] J. Tong, Y. Lv, Z. Zhuang, J. Yang, B. Feng, J. Zhao, S. Huang, D. Zhang, Y. Zhu, G. Cuniberti, L. Wang, Sensors & Actuators: B. Chemical 451 (2026) 139432.