

# ***(Invited)* System-on-Chip Sensor Integration in Advanced CMOS Technology**

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## **Abstract**

### **1. Introduction**

While aggressive device scaling has taken the front stage in the semiconductor industry for many decades, there is currently an ever-increasing demand for functional integration in a single device. The rise of the Internet of Things is a clear indicator of this trend. Connecting different dies using bonding wires can negatively impact performance and power dissipation, since long wires result in high RC delay and increased circuit resistance. The highest efficiency is reached when all functionalities are fabricated on a single substrate – deemed System-on-Chip (SoC). The use of silicon as a substrate material allows for the efficient integration of MEMS and CMOS structures into a truly monolithic device. This is highly challenging, since the typical high temperature associated with sensor fabrication negatively influences front end of line devices and metalization. We discuss the integration of MEMS gas sensors within an advanced CMOS technology, for which all fabrication steps, required for the MEMS sensor fabrication, are below 450°C.

### **2. Approach**

The SoC integration of gas sensors requires many forms of interconnections; however, the key enabler is the capability to fabricate all desired functionalities, such as a sensing element, on a Si wafer technology. We will analyze the sensing layer itself and the micro-heater, both essential components for ensuring that the gas sensing functionality is compatible with SoC integration. The sensing layer, which is a metal-oxide, must be heated up to temperatures in the range between 300°C and 500°C in order to operate as a sensor. For this reason, a micro-heater must be implemented underneath the sensing element.

#### *2.1 Fabrication*

The fabrication of the full sensor device has been achieved on a silicon wafer. First, an isolating silicon dioxide is deposited using low temperature oxidation techniques. A sacrificial Polyimide is spin-coated and subsequently selectively etched to form the sensor cavity ([Figure 1](#)) [1]. The membrane material is composed of a Tantalum-Aluminum (TaAl) micro-heater, sandwiched between two silicon nitride (SiN) layers. SiN is deposited using low pressure chemical vapor deposition (LPCVD), while TaAl is patterned using physical vapor deposition (PVD) and

subsequent plasma etching. The sensing material is deposited on top of the membrane, followed by the metal contacts [2]. The sensing layer is tin dioxide (SnO<sub>2</sub>), one of the most promising metal-oxide materials for gas sensor applications. SnO<sub>2</sub> can be deposited using a variety of techniques: CVD, sputtering, pulsed-laser deposition, sol-gel process, and spray pyrolysis.

## 2.2 Operation

With regard to the micro-heater operation, we concentrate on its power dissipation, thermo-mechanical properties, and mechanical stability [3], while the SnO<sub>2</sub> metal oxide is discussed in terms of its conductive response in the presence of various gases in the environment [4]. Two micro-heater designs with low-power operation have been achieved at our research group: a dual-hotplate (requiring 8mW of power for operation at 350°C) and a micro-heater array (requiring 9.31mW of power for operation at 350°C), as shown in Figure 2 and Figure 3, respectively. In Figure 2 we see the thermal distribution along the active sensor area, which varies by only a few percent minimizing the influence of high thermal gradients on the heater's and sensor's sensitivity and reliability. In Figure 3 the displacement of the membrane due to the intrinsic and thermal stresses is depicted.

The electrical conduction of the SnO<sub>2</sub> layer is modeled using a drift-diffusion equation, where only electrons, the majority carriers, are considered. The electron concentration and the mobility vary significantly with temperature in an inert environment, as depicted in Figure 4. The ionosorption of gas molecules attracts electrons from the SnO<sub>2</sub> bulk, resulting in band-bending at the interface between the material and the surrounding gas. The amount of band bending is proportional to the effective concentration of localized surface electrons  $N_{eff}$  [5].  $N_{eff}$  is the sum of the intrinsic electrons which gain enough power to reach the surface and the external electrons donated from ionosorbed gas ions, such as O<sup>-</sup> or O<sup>2-</sup>. In Figure 5, the effective surface charge density is plotted versus time at various temperatures in a synthetic air environment. We further use this result to model the change in the SnO<sub>2</sub> layer's conductivity in air and during its exposure to other gases of interest such as H<sub>2</sub> or H<sub>2</sub>S.

## References

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- [4] A. Fort et al., *Sens. Actuators, B* **124** (1), pp. 245-259 (2007).
- [5] G. Tuzer et al., *Nanotechnol.* **24** (31), pp. 315501(10) (2013).

## Footnotes

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**Figures**



Figure 1: Two-dimensional cross section cut through the material stack making up the micro-heater. The primary materials are shown, including the sacrificial Polyimide, which, when removed, forms the air cavity and the suspended membrane, ensuring thermal isolation between the membrane micro-heater and the underlying Si wafer.

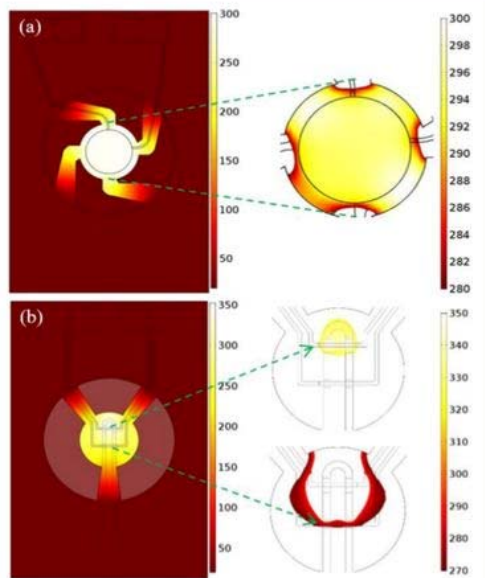


Figure 2: Thermal distribution [°C] of two micro-heater designs: (a) dual-hotplate and (b) micro-heater array. A highly even temperature distribution along the active sensor region can be observed.

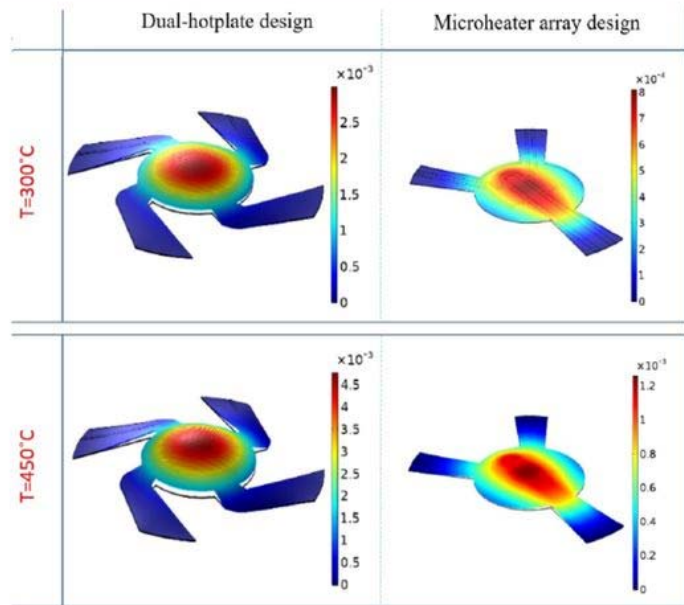


Figure 3: Total displacement (mm) of the membrane stack at different operating temperatures. Frequent thermal cycling results in stress build-up and relaxation leading to membrane deformation. This frequent deformation can eventually lead to micro-heater failure.

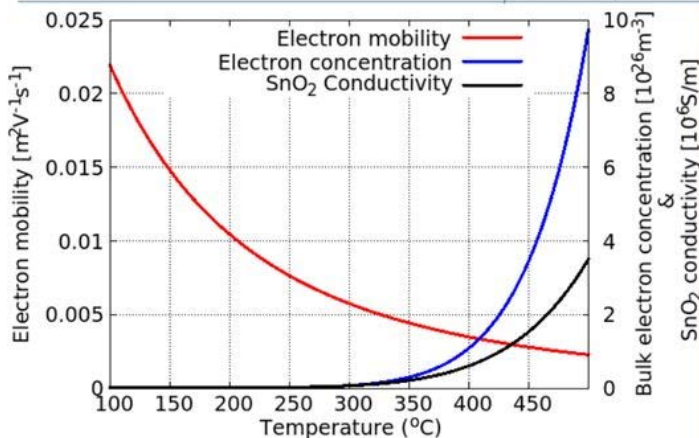


Figure 4: Temperature dependence of the electron concentration  $n_e$  and mobility  $\mu_e$  in  $\text{SnO}_2$ . The conductivity  $\sigma$  is a combination of both by  $\sigma = q \cdot \mu_e \cdot n_e$ .

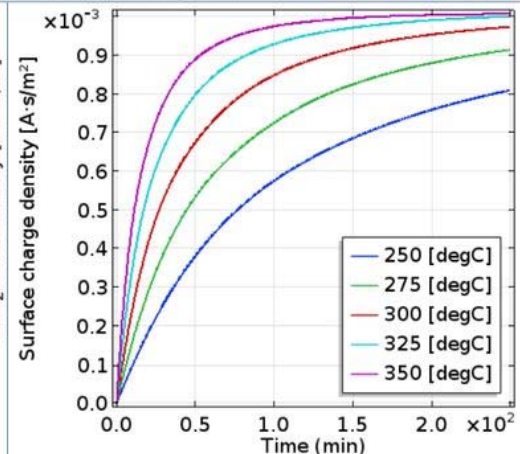


Figure 5: Surface charge density [A·s/m²] in a synthetic air environment, with 80%  $\text{N}_2$  and 20%  $\text{O}_2$ .