

Surface-Micromachined 3-Omega Gas Sensor

Philipp Raimann¹, Guy Laurent Tchoffo¹, Frank Hedrich¹, Sophie Billat¹, Alfons Dehé^{1,2}

¹ Hahn-Schickard, 78052 Villingen-Schwenningen, Germany,

² Georg H. Endress Chair for Smart System Integration, Department of Microsystems Engineering–IMTEK, Albert-Ludwigs-University Freiburg, 79110 Freiburg, Germany

Summary:

In this paper a miniaturized thermal gas sensor with a n-doped polysilicon heating element on a thin silicon nitride membrane is presented. The sensor's thermal response is dominated by the gas properties, leading to a signal minimum in the out-of-phase component at a frequency proportional to the gas concentration. Operation at excitation frequencies between 3 and 9 kHz minimizes intrinsic 1/f noise sources and allows frequency-based control strategies with linear sensitivity.

Keywords: Thermal Gas Sensor, SNR improvement, 3-Omega-Method, Surface Micromachining, Lumped-Element-Modelling

Motivation

Micro-machining enables the fabrication of highly miniaturized thermal gas sensors with low power consumption. However, the performance of thermal conductivity sensors is often limited by intrinsic noise and non-linear signal behavior. N-doped polysilicon is widely used for micro-fabricated heaters due to its long-term stability and tunable temperature coefficient of resistance (TCR), but exhibits significant 1/f noise [1]. Therefore, optimizing thermal gas sensors for higher frequency operation is a key strategy to improve sensor performance and enables new possibilities for sensor signal evaluation, particularly through frequency-based analysis approaches.

Description of the New Method

Surface micromachining is employed to reduce the thermal time constant of the sensor, enabling an operation at higher modulation frequencies. Heat transfer between the heater and the surrounding structure occurs primarily through a well-defined gap, which is determined by the thickness d of a sacrificial silicon oxide layer used during fabrication. This controlled geometry ensures reproducible and well-defined thermal coupling to the surrounding gas. To enable accurate signal extraction, a half-bridge configuration is utilized, in which one structure is released by etching and suspended in the gaseous medium, while the other remains fixed on the bulk silicon. This arrangement suppresses the excitation component (1ω) and facilitates precise measurement of the 3ω response.

Sensor Theory

The 3-omega method is a powerful frequency modulation technique for detecting gases [2]. In this paper, the heater is driven with an AC voltage (1ω) at different frequencies and the resulting in- and out-of-phase components of the 3ω signal are detected with a lock-in amplifier.

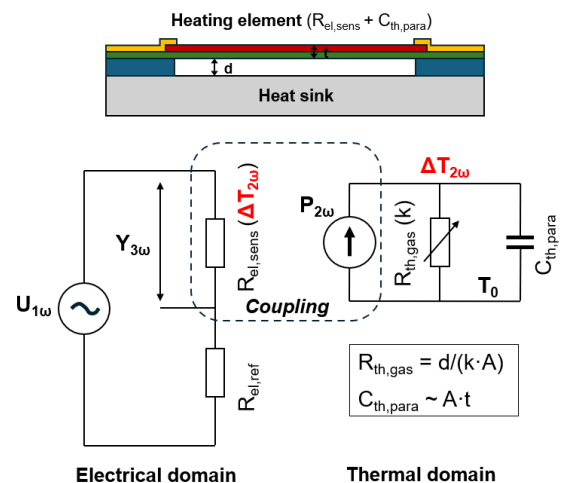


Fig. 1. Lumped element model of the thermal gas sensor with a single thermal time constant.

The low-pass behavior can be effectively captured using a thermal lumped-element model, which accounts for both parasitic contributions and gas-dependent thermal parameters.

$$\tau = R_{th,gas} \cdot C_{th,para} \sim k^{-1} \quad (1)$$

Due to the high degree of miniaturization, the thermal time constant τ is primarily determined by the thermal conductivity k dependent thermal resistance $R_{th,gas}$ and the parasitic thermal capacitance $C_{th,para}$ of the sensor structure.

Analyzing the temporal thermal behavior offers the advantage of a reduced influence on the applied heating power [3]. Gauthier [2] describes a signal minimum in the out-of-phase-component (Y-signal), which corresponds to dominant thermal frequency of the system.

Fabrication Process

The fabrication begins with the growth of a 1 μm sacrificial thermal oxide layer. A low-pressure chemical vapor deposition (LPCVD) silicon nitride layer is then deposited to form the membrane. The heater is defined in n-doped polysilicon and patterned in a honeycomb geometry for mechanical robustness. Perforations enable etchant access for controlled release and gas access to the cavity for sensing. A PECVD passivation layer protects the membrane during vapor HF (vHF) etching and is removed in the release step. The final device consists of an n-doped polysilicon heater suspended on an 80 nm-thick membrane with reduced thermal mass for enhanced gas sensitivity.

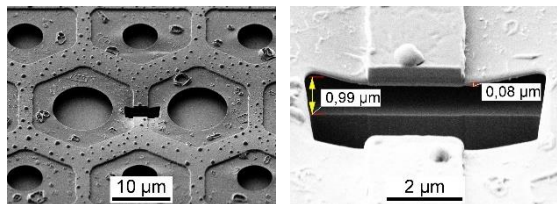


Fig. 2. Honeycomb-shaped heater structure (left) and FIB cross-section for structural analysis (right).

Experimental Results

The half-bridge is excited with a frequency sweep with a 3 V_{pk} input voltage, and the 3ω is recorded using a lock-in amplifier from Zurich Instruments.

Tab. 1: Overview of different sensor designs

A (mm^2)	$R_{\text{el,sens}}$ (Ω)	$f_{1\omega}$ @ $Y_{3\omega, \text{min}}$ (kHz)
0.011	384 ± 15	$3,02 \pm 0,10$
0.0165	588 ± 28	$3,14 \pm 0,05$
0.022	802 ± 40	$2,95 \pm 0,09$

Despite variations in sensor dimensions, a minimum in the Y-component at similar frequencies is observed, indicating that the thermal response is predominantly governed by the gas properties. This behavior can be explained by the fact that an increase in the area is accompanied by a proportional reduction of the gas thermal resistance (see Fig. 1), resulting in a nearly constant characteristic frequency, corresponding with the calculated frequency of approximately 3.3 kHz for N_2 .

In contrast to conventional steady-state thermal conductivity sensors, which exhibit a $1/k$ -dependence and thus reduced sensitivity at higher thermal conductivities [4], the characteristic frequency of the Y-component minimum shows a linear dependence on the gas concentration. This is attributed to the dynamic measurement principle, where the excitation frequency is inversely proportional to the dominant thermal time constant and therefore directly linked to the effective thermal conductivity of the gas mixture.

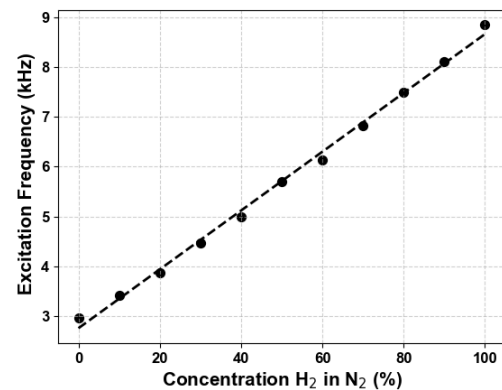


Fig. 3. Excitation frequency $f_{1\omega}$ at the $Y_{3\omega}$ minimum for N_2/H_2 mixtures using a sensor chip with an active area of $A = 0.022 \text{ mm}^2$.

Outlook

The potential of surface micromachined sensor for frequency modulated thermal gas detection has been successfully demonstrated. Further optimization of the fabrication process is required, as selectivity issues during vHF etching necessitate the use of a front-side nitride passivation layer. Although this layer is fully removed during etching, it can leave residues on the surface, which need to be addressed in future process refinements.

References

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