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Characterization and Modeling of Thermal MEMS for Selective Determination of Gas Properties

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Summary:
This work presents the characterization and modeling of thermal MEMS for the determination of gas properties. The sensor consists of thermopiles arranged on a membrane, which allow the determination of the gas property-dependent temperature response of an electrically excited heating element. Experimental data are used to demonstrate the applicability of a lumped-model for the modeling of a thermoelectric gas property sensor. The calculated sensor's sensitivity for small quantities of hydrogen in nitrogen is about 0.7mV per % H_2 at a heating power of 6 mW.

Keywords: MEMS, Thermal gas sensor, Thermal modeling, Lock-in amplifier techniques, Gas analysis.

Background and Motivation

Measurements of gas properties are becoming increasingly important in industrial and environmental applications to clarify process-related and safety-relevant issues [1]. Here, thermal MEMS have decisive advantages over other measurement principles due to low-cost manufacturing, non-consumable operation, wide measurement range, fast response times and low power consumption. Often thermal conductivity sensors with thin metal wires made of platinum [2] or tungsten [3] are used, which also act as detector elements. However, in order to distinguish specific gases or unknown components in gas mixtures, an independent determination of further gas properties is necessary. For example, the thermal conductivity of argon is only 7% higher than that of carbon dioxide, while the volumetric heat capacity of argon is about half that of carbon dioxide (see Tab. 1).

Tab. 1: Thermal conductivity k (mW m^{-1} K^{-1}) and volumetric heat capacity cv (kJ m^{-3} K^{-1}) of different gases at 293 K and 1 bar [4].

Gas	Ar	CO_2	N_2	He	H_2
k	17,50	16,25	25,47	153,5	183,4
cv	0,855	1,536	1,197	0,852	1,181

In this paper, the thermal response ΔT of a heater structure with different gases is analyzed using an equivalent model and the applicability of the model for the optimization of future thermal gas property sensors is demonstrated.

Description of the System

The direct heat transfer of a polysilicon heater to the surrounding gas is measured with polysilicon/aluminum thermopiles with their hot junctions located close to the heater (see Fig. 1). In contrast to the measurement of the temperature-dependent heater resistance R, this approach allows higher sensitivity in addition to galvanic isolation.

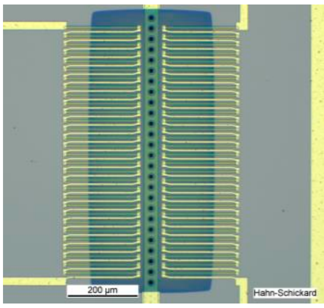

Fig. 1. MEMS thermal gas property sensor.

For detection of gas properties, the perforated heater is periodically excited with an electrical voltage U and the resulting response signal of the thermocouples U_{TP} is measured with a lock-in amplifier.

Lumped-Element-Model

An equivalent circuit composed of discrete components [2] describes the temperature response ΔT of the heater caused by Joule heating (see Fig. 2).The thermal equivalent parameters are of the form (1) and (2) and depend on the characteristic length L_i, the cross-sectional

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area A_i, the volume V_i and the thermal properties k_i and cv_i.

$$R_{th,i} = L_i / (k_i \cdot A_i) \quad (1)$$

$$C_{th,i} = cv_i \cdot V_i \quad (2)$$

These formulas apply to the parasitic heat transfer through thin film structures (e.g. membrane, heater) and to the surrounding gas.

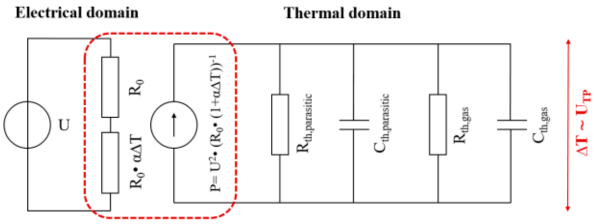

Fig. 2. Lumped model of the thermoelectric sensor.

Results and Outlook

Since a low excitation power P is chosen, the effect of the heater's temperature coefficient of resistance (TCR) is neglected. Thus, the measured thermopile signal is proportional to the thermal impedance of the system (see Fig. 3). Fitting the obtained signals to the RC-low pass model yield the respective fit parameters X_1 and X_2, which are proportional to the thermal impedances R_{th} (K/W) and C_{th} (J/K), respectively.

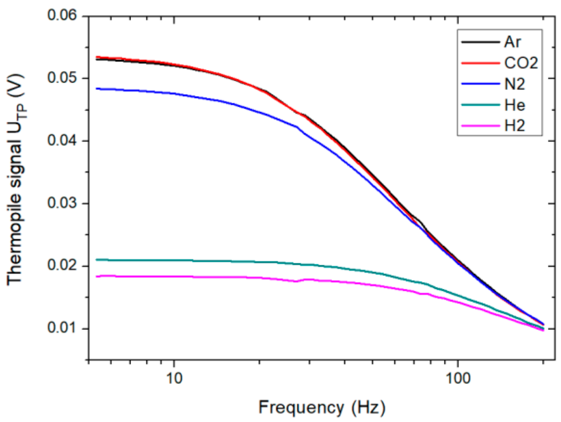

Fig. 3. Single-sided thermopile signal measured for different gases. This signal is fitted with the model function U_{TP}= ((1/X_1)^2+(2•π•f•X_2)^2)^-0.5 to derive the thermal equivalent parameters X_1 and X_2.

The resulting fit parameters can be described in both cases as a function of the gas properties using the formulas (1) and (2). Figure 4 shows that X_1 decreases with increasing thermal conductivity of the gas. The highest sensitivity is achieved at low thermal conductivities (e.g. small amounts of H_2 in N_2). Figure 5 depicts the linear dependence of X_2 with volumetric heat capacity. Since the volumetric heat capacity depends on the density, X_2 varies with pressure. X_1, on the other hand, is unaffected by pressure in a first approximation.

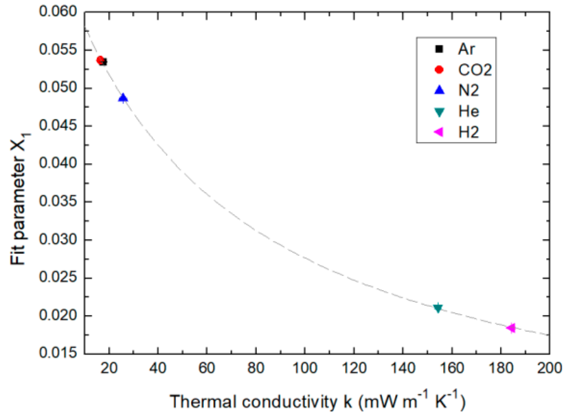

Fig. 4. Dependency of the fit parameter X_1 on the thermal conductivity of the surrounding gas.

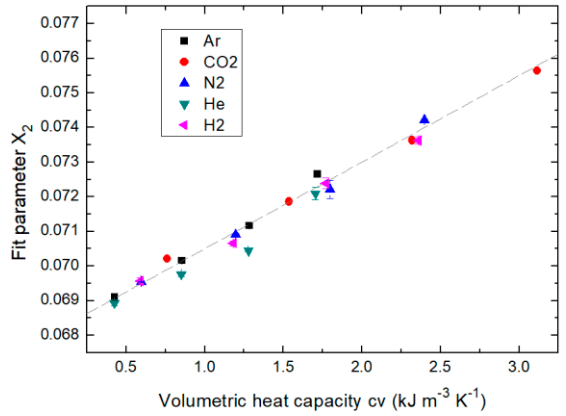

Fig. 5. Dependency of the fit parameter X_2 on the volumetric heat capacity of the surrounding gas. For additional changes of the volumetric heat capacity, pressure variations are used.

Based on this knowledge, miniaturized gas property sensors with a high selectivity towards individual properties are to be developed and combined with thermal flow sensors to address novel applications in the field of hydrogen technologies, smart grid, domotics or medicine.

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