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Micro thermal conductivity detector with flow compensation using a dual MEMS device

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ABSTRACT

A generic method to reduce the in-line flow dependence of thermal conductivity detectors (TCDs) is presented. The principle is based on a dual-MEMS device configuration. Two thin-film sensors on membranes in parallel in the gas stream on the same chip are differentially operated. Both micro-TCDs are designed to be identical in terms of contact with the main gas flow, however a different depth of the detection chamber results in a different response to the thermal conductivity of the sample gas. Static and dynamic simulations have been performed to characterize the design of the fabricated structures. Devices have been fabricated in a MEMS process using a combined surface- and bulk micromachining process. The devices have been characterized statically and dynamically. Measurements on prototypes show that depending on the range of gases, device size and flow range device the effect of flow on the thermal conductivity can be reduced by a factor 4–15.

1. Introduction

Gas sensors are increasingly used in the growing markets of the automotive industry and in environmental monitoring. The most common gas sensors are based on chemical interaction [1,2]. These sensors have a high sensitivity and can be low cost. Gas sensors based on physical principles, such as optical absorption, density and thermal conductivity detectors (TCDs) have also found many areas of applications, mainly because of their superior long-term stability. Gas detection based on thermal conductivity is widely used in process control for helium and hydrogen and in gas chromatography [3–5]. The operation of a TCD is based on the gas-specific thermal conductivity, which is measured by means of the temperature reduction in a heated element in the gas stream, due to the heat loss through the gas. The heat loss can be either by conduction or convection and in most devices both phenomena are present. If the heat loss is mainly by convection a TCD can also be used as a thermal flow sensor, however if the heat loss is mainly by conduction through the gas the device operates a gas sensor. Therefore the TCD and the thermal flowmeter [6,7] are closely related devices.

The most common and simplest TCDs are the so-called hot-wire devices [8,9] where the hot-wire acts as a heater and temperature sensor at the same time. An electric current through the wire produces Joule heating and, depending on the surrounding gas, the temperature of the wire changes and can be detected as a change in resistance. Instead of a wire, other heater geometries, such as thin metal sheets, are also been utilized [10], and based on these basic robust devices thermal conductivity detectors have grown into mature, commercially available devices [11]. When used for gas pressure measurements these sensors are also referred to as Pirani gauges or thermal conductivity gauges [12,13]. Recent advances in MEMS and integrated circuit (IC) technology enable the fabrication of many types of small, IC-compatible, high sensitivity and low cost thermal sensors and heaters [14]. Nowadays, TCDs can be miniaturized enabling low sample volumes and low cost [13]. MEMS TCD's have already replaced the traditional hot-wire and hot-strip sensors in many applications [14,15,16–18]. Micro-strip TCD's based on thin-film platinum wires have been published by several authors [12,19,20] and are also commercially available [10,13]. Most of these devices use bulk micromachining of the substrate for thermal isolation of the sensor. The basic TCD design as presented here is based on a combination of bulk- and surface-micromachining technology as has been used in our previous work on a sensor platform for natural gas composition measurement [21]. In these systems the fabrication of a TCD [22,23] and thermopile detector arrays [24] for infrared absorption spectroscopy on a single chip has been realized. In these TCD devices the separation of the heater and the temper-

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ature sensor enabled a more flexible design, a very small sample chamber, a short response time and a high sensitivity [23,25].

2. Flow compensation

One of the major issues of TCD sensors is their flow dependence [3]. In many cases it is necessary to keep the flow constant or to calibrate the sensor depending on the flow rate for every gas in the gas stream. For instance in a gas chromatography system, a flow independent design could avoid the time-consuming re-calibration for each gas. In gas chromatography the effect of flow velocity can be partly compensated by adding a reference channel with a reference gas flow [4,20] which results in extra components and adds to costs. Such a system using micro-TCDs has been described by [20]. In this system the temperatures are sensed by platinum resistors in a Wheatstone bridge configuration and a control loop is added for automatic gain control and imbalance compensation.

A single channel flow independent micro-TCD has been proposed by [19]. In this device the temperature of the gas stream is kept constant. A multi-stage TCD is used, where the gas is preheated in the first region to the operating temperature of the actual measurement TCD to minimize heat exchange by flow in the next TCDs. Another method could be the use of a differential calorimeter for gas flow rate measurement and deriving a flow independent parameter that may represent the thermal conductivity of the gas involved [6].

The basic idea of the flow-independent TCD, as presented here, has been already proposed by us in [26]. This work describes the basic concept, using two TCDs on a single die, supported by simulations. In the current paper the concept and realization is described in much more detail and the realization is also supported with measurements on pure gases and gas mixtures at different flow rates. The dual TCD principle will be explained in the following section.

3. Description of the device

The proposed dual-TCD is composed of two identical devices fabricated on the same substrate, as shown in Fig. 1. Each device consists of a resistive heating strips and thermopiles measuring the temperature difference between the membrane and the substrate at both sides of the heater. The heater/temperature sensor are integrated on a thin membrane. Each membrane covers a volume, which is the gas-filled detection chamber. Gas venting to the volume between the membrane and the substrate is possible via etching holes or slits in the membrane, as can be seen in Figs. 1 and 2. One of the chambers is relatively shallow, having a depth of 2 μm. while the other chamber is considerably deeper, having a full-wafer depth of 525 μm, as shown in Fig. 1(b). The sensor membrane size is typically 250 × 330 μm^2. The measurement principle relies on the change in effective thermal conductance between the sensitive area of the sensor (the membrane) and the substrate. In the shallow cavity device the dominant the thermal conductance originates from the thin layer of gas below the membrane, as shown in the cross-section of Fig. 2. The thin gas layer results in a high sensitivity for the gas thermal conductance.

3.1. Operating principle

Both heaters are connected to a voltage source and heat is produced by the Joule heating effect. The output voltages of the thermopiles on the left and right side of each TCD are added for measurement of the effective membrane temperature. The heat spreads over the thin membrane and the thermopiles measure the temperature difference between the heater and the substrate. Measurements and simulations have shown have shown that both devices are sensitive to the gas flow rate but not significantly to the x-y direction of the flow. However they should be placed in parallel in the gas stream to avoid pre-heating of gas at the downstream device by the upstream device. A control loop keeps the membrane temperature, as measured by the thermopiles, constant at a certain value above ambient by controlling the voltage V_{in} applied to the heaters. Fig. 2 shows the basic structure with the main heat flows.

For a thermal conductance G, the temperature rise in the membrane, ΔT, of the shallow cavity TCD-S device and the deep cavity TCD-D device is proportional to the dissipated power P

$$\Delta T = \frac{P}{G} \tag{1.1}$$

Neglecting radiation effects, the thermal conductance G can be split as follows

$$G = G_b + G_g + G_c \tag{1.2}$$

with G_b the thermal conductance of the supporting structure, G_g the thermal conductance through the gas, and G_c corresponds to the heat loss by convection. The difference in power fed to the shallow cavity TCD (TCD-S) and deep cavity (TCD-D) can be written as

$$\Delta P = P_S - P_D \text{with} \left\{ \begin{array}{l} P_S = \Delta T_S (G_{bS} + G_{gS} + G_{cS}) \\ P_D = \Delta T_D (G_{bD} + G_{gD} + G_{cD}) \end{array} \right\} \tag{1.3}$$

where the subscript $_S$ corresponds to the TCD-S and $_D$ corresponds to the TCD-D.

Since the beam conductivity and the heat loss due to convection are identical, the terms G_c and G_b are equal and when keeping both sensors at the same temperature ΔT the power difference can be written as

$$\Delta P = P_S - P_D = \Delta T \left(G_{gS} - G_{gD} \right) \tag{1.4}$$

where G_{gS} represents the conductance of the gas in the TCD-S and G_{gD} the conductance of the gas in the TCD-D. The thermal conductance of the gas layer G_g can be approximated by:

$$G_g = \frac{\lambda_g A}{d} \tag{1.5}$$

where λ_g is the thermal conductivity of the gas, A is the area of the membrane and d is the depth of the cavity. Substituting Eq. (1.5) in Eq. (1.4) yields for the power difference

$$\Delta P = \Delta T \left(\frac{\lambda_g A}{d_S} - \frac{\lambda_g A}{d_D} \right) = \Delta T \lambda_g A \left(\frac{1}{d_S} - \frac{1}{d_D} \right) \tag{1.6}$$

Since the depth of the cavity d_D is much larger than d_S, the second term of Eq. (1.6) can be disregarded, which results in:

$$\Delta P \approx \Delta P \frac{\lambda_g A}{d_S} \tag{1.7}$$

Eq. (1.7) shows that the power difference in the devices is proportional to the thermal conductivity of the gas λ_g, and independent of the conduction by the gas flow G_C and the thermal conduction G_B of the supporting structure. By substitution of some typical values of the presented structure it can be shown that the heat loss through the beam suspension is much lower than the heat loss by conduction through the gas. Eq. (1.6) also shows that TCD-S is very sensitive to the heat loss through the gas, while the TCD-D acts as a compensation device.

3.2. Design and modeling of the dual-TCD

The thermal conductivity sensor has been fabricated using IC compatible techniques on thin silicon-nitride bridges and membranes. Different structures have been fabricated as shown in Fig. 3. The heating element is a meander-shaped poly-silicon resistor in the middle of the membrane. N- and P-doped poly-silicon wires have been used for the thermocouples. The temperature difference