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LETTER

A Flow-Insensitive Thermal Conductivity Microsensor and Its Application to Binary Gas Mixtures

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A microsensor fabricated using CMOS technology is presented along with preliminary measurements that demonstrate its ability to identify the concentration of gas constituents in selected binary gas mixtures. By virtue of its structural topology, the microsensor is insensitive to flow, operates at low input power and temperature (2 mW and 70°C at STP), and has an almost 100% transduction efficiency due to negligible parasitic heat losses.

1. Introduction

Thermal microsensors are employed in a variety of applications which include sensing of gaseous species, flow rate and pressure (or vacuum). Their advantages over large-scale counterparts lie in their small size, low operating power and temperature, and fast thermal response time. Such microsensors can be fabricated using silicon integrated circuit (IC) technologies yielding good performance due to the favorable thermal scaling laws and the high thermal isolation achievable with silicon micromachining.

In particular, with thermal-based gas microsensors,[(1–4)] the heat transfer from a resistively heated (active) element to a cooler sensing (passive) element is modulated by the thermophysical properties of a gas (*e.g.*, thermal conductivity, heat capacity) and also by its flow rate. The sensitivity to thermophysical properties is governed by heat transfer through conduction, whereas sensitivity to flow rate is due to forced convection. As a result, selectivity to one or the other measurand is undermined since both contribute to the output response of the microsensor. Thus, by design, a flow-insensitive microsensor must maximize the conductive heat transfer component and yet, at the same time, minimize or eliminate any contributions from heat transfer by forced convection. Such design attributes are crucial for high transduction efficiency.

In this letter, we report a microsensor designed to be flow insensitive at relatively low flow rates of 1.2 *l*/min that yields a high sensitivity to gas thermal conductivity. The microsensor, fabricated using an industrial CMOS fabrication process, is based on a thermally isolated twin polysilicon meandering coil topology (Fig. 1) and exhibits an almost 100% transduction efficiency.[5] The high efficiency stems from the large thermal resistance associated with the coil geometry and, more importantly, from the close proximity of the active and passive coils. Thus heat transfer from the active coil to the neighboring passive coil is predominantly lateral; in fact, from the viewpoint of conductive heat transfer, the arrangement yields a thermal short circuit. This feature makes the microsensor insensitive to gas flow and provides the capability to measure thermal conductivities with high sensitivity. The microsensor operates at very low power (2 mW) near atmospheric pressures with less than 1% of input power dissipated in terms of heat loss by conduction along coils and by radiation. High accuracies have been obtained for the gases tested in this work (*e.g.*, He, Ar and N_2).

2. Microsensor Physical Description and Theory of Operation

A cross-sectional view of the twin coil thermal conductivity microsensor is shown in Fig. 1. Each coil comprises an electrically conducting polysilicon layer to provide resistive-heating and temperature-sensing functions. The polysilicon is encapsulated in a dielectric sandwich of field oxide, intermetal oxide and passivation layers. The spacing between coils is 8 μm and each coil is approximately 1200 μm long.

The microsensor was fabricated using Northern Telecom's 1.2 μm CMOS technology. It was designed for micromachining compatibility without the requirement of additional masking steps. Post-processing (micromachining) for thermal isolation of the coils was performed in-house using an ethylenediamine pyrocatechol (EDP) solution at 97°C. Due to the structural (coil) topology, the anisotropic etch time was less than one hour and the exposed pad metallization was left virtually intact. The area defined for thermal isolation was approximately 210 μm by 280 μm. The coils were surprisingly robust; a high yield was obtained under special dicing conditions. A scanning electron micrograph of the microsensor is shown in Fig. 1.

Heat transfer from active to passive coils is governed by the thermal conductivity of the gas surrounding the coils; the passive coil senses the modulation of heat transfer by virtue of its resistance change with temperature. Since the thermal conductivity of the gas depends on pressure (or vacuum), this structure can be employed as a Pirani gauge.[5] In fact, its sensitivity to pressure at the vicinity of one atmosphere is one of the largest

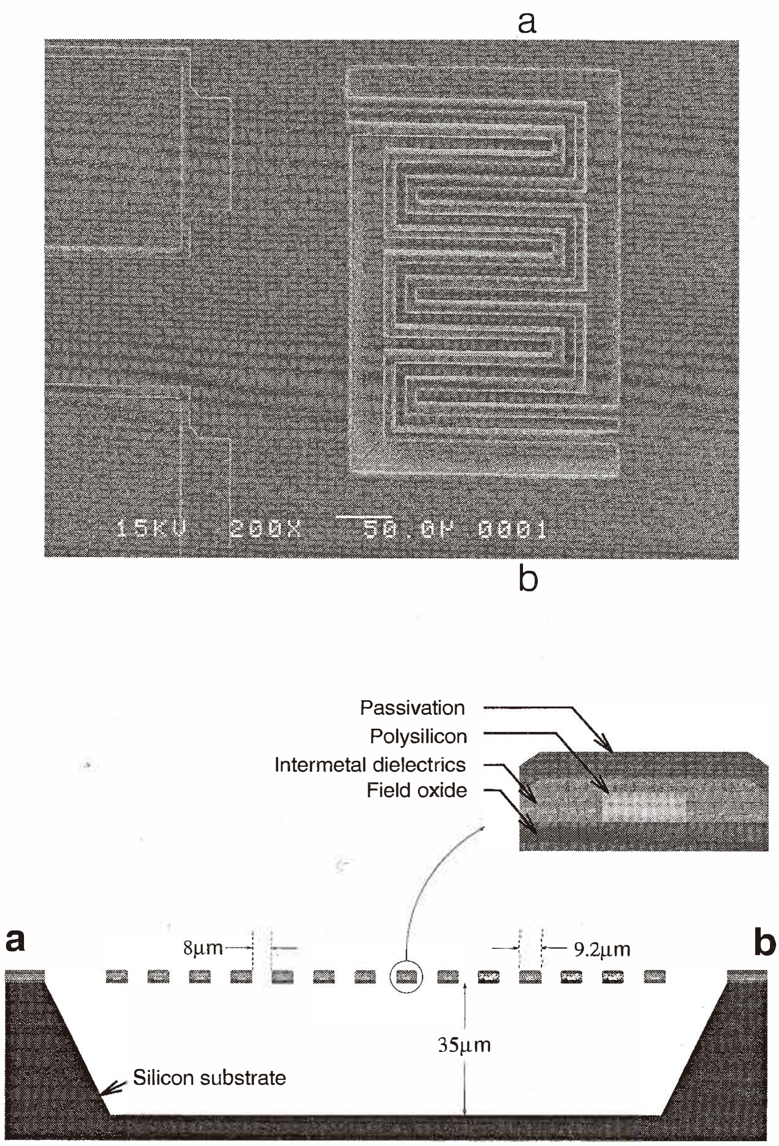

Fig. 1. Photomicrograph and cross-sectional view (at **a-b**) of the flow-insensitive thermal conductivity microsensor.

reported to date.[6] Alternatively, at constant pressure, its sensitivity to thermal conductivity may be used for discrimination of gases in mixtures of known constituents. This constitutes the objective of the present work.

The thermal conductivity of a gas can be determined using the following method. The heat flux between active and passive coils can be approximated as

$$\frac{q}{A} = -\kappa \frac{\partial T}{\partial x}. \tag{1}$$

Here, q denotes thermal power and A is the cross-sectional area (orthogonal to direction, x) across which heat flows. The derivative can be approximated using the average temperatures of the active and passive coils and an effective inter-coil spacing, d

$$\frac{q}{A} = -\kappa \left[\frac{T_{passive} - T_{active}}{d} \right]. \tag{2}$$

The quantities A and d in eq. (2) cannot be determined exactly in view of spatial nonuniformities in the inter-coil thermal resistance. However, instead of approximating these quantities separately, they can be combined into a characteristic length, *viz.*, $L = A/d$, which can be assumed independent of gas-type. The characteristic length can be retrieved experimentally by using the following equation

$$\frac{q}{L} = -\kappa \left[T_{passive} - T_{active} \right] \tag{3}$$

where q is determined by the input electrical power, T_α from precalibrated resistance-temperature measurements, and κ from measurements using a known gas. The various terms in eq. (3) have the following units: q (W), L (m), T_α (K), and κ (W/m/K).

3. Measurement Results and Discussion

Characterization of the microsensor was performed using a flow channel and pressurized gases which were suitably regulated to produce relatively small flow rates. Electrical biasing of the microsensor and associated measurements of coil resistance were obtained using a computer-controlled Keithley 236 source-measurement unit (SMU).

The flow channel was constructed from smooth sheets of plexiglass milled to produce a rectangular channel measuring 30 mm by 3 mm in cross-sectional area with a length of approximately 2.2 m (see Fig. 2). The gas inlet was located at one end of the channel in such a way that the initial gas flow was perpendicular to the direction of flow in the channel. The microsensor was located approximately 1.9 m from the gas inlet on the bottom of the flow channel. The flow was assumed to have a fully developed boundary

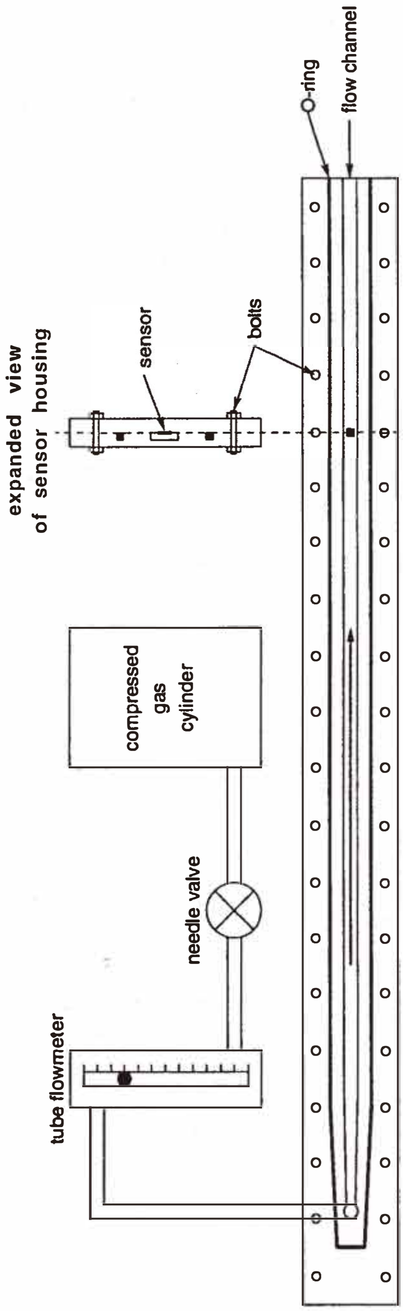

Fig. 2. Experimental set-up of the flow channel (duct) employed in the measurement of thermal conductivity.

layer by the time it reached the leading edge of the microsensor. The flow was regulated and measured using a needle valve followed by a tube flowmeter between the pressurized gas cylinder and the flow channel.

The microsensor response in terms of the temperature difference between active and passive coils, *viz.*, $\Delta T = T_{active} - T_{passive}$, as a function of input power for four different gases is shown in Fig. 3. Here, the input power to the active coil was varied by stepping the applied voltage over the range of 0.5 V to 10 V. Input power was calculated by measuring the current supplied through the SMU for each voltage step. The temperatures of the active and passive coils were retrieved from precalibrated measurement of the temperature dependence of the coil resistance. Due to the relatively low microsensor operating temperatures, radiative heat loss is negligible as observed from the high linearity in ΔT for the range of input powers considered. The values of thermal conductivity for different gases, retrieved from the slopes of the various curves using eq. (3), are given in Table 1. Here, the characteristic length was obtained by fitting measured results with the accepted value of the thermal conductivity of air under zero flow conditions. The values of thermal conductivity retrieved from measurements show 3.4%, or better, agreement with the accepted values for the different gases considered.

The flow insensitivity of the microsensor at flow rates (below 1.2 l/min) is shown in Fig. 4. Here, the same experimental set-up was used except for the addition of another gas cylinder with associated regulators. The flow rates for the two gases used, Ar and N_2, were measured using Matheson Gas Company type R-2-15-A tube flowmeters. In order to obtain a sufficiently high output signal, a large bias voltage was employed on the active coil. The voltage was pulsed with a 50% duty cycle signal of period 200 ms (>> the

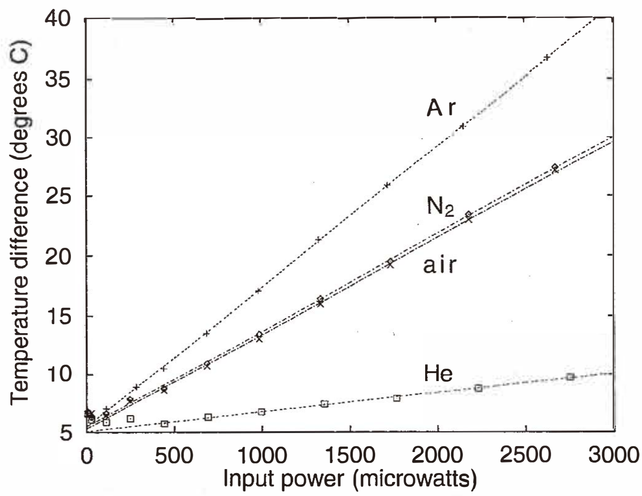

Fig. 3. The temperature difference between active and passive coils as a function of input power for various gases. Values retrieved for the thermal conductivities are given in Table 1.

Table 1
Comparison of measured and accepted (literature) values of thermal conductivity, κ [units: W/(mK)] for different gases retrieved from Fig. 3 with the heat transfer characteristic length calibrated to measurements for air.

Gas	Measured	Accepted	Discrepancy (%)
Ar	0.01789	0.01772	1.0
N_2	0.02656	0.02598	2.2
Air	0.02614	0.02614	calibration
He	0.14487	0.14990	3.4

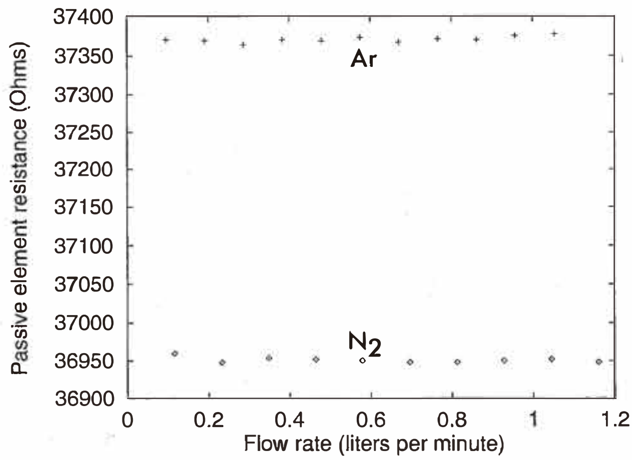

Fig. 4. Demonstration of flow insensitivity for argon and nitrogen at low flow rates.

measured microsensor thermal time constant of 3 ms) from 0 V to 10 V. Due to the large electrical resistance of the coil geometry, no adverse effects on electrical behavior were observed. The passive coil was biased with a constant current of 100 μA. For the range of flow rates considered (Fig. 4), there was no observable variation in the measured passive coil resistance for Ar and N_2. Any flow-induced convective heat transfer between coils falls within measurement error. Due to the insensitivity to flow rate, the microsensor lends itself to direct sensing of thermal conductivity of a flowing gas. If the flowing gas is a known binary mixture, the concentration of gas constituents can also be retrieved if there is sufficient difference in thermal conductivities. Figure 5 shows the variation in passive coil resistance in response to varying concentrations (% by volume) of N_2 in a flowing gas mixture of Ar and N_2. For this pulsed mode of operation, the change in passive coil resistance is approximately 400 Ω for variation in thermal conductivities in the range 0.01772 (Ar) W/(mK) to 0.02598 (N_2) W/(mK).

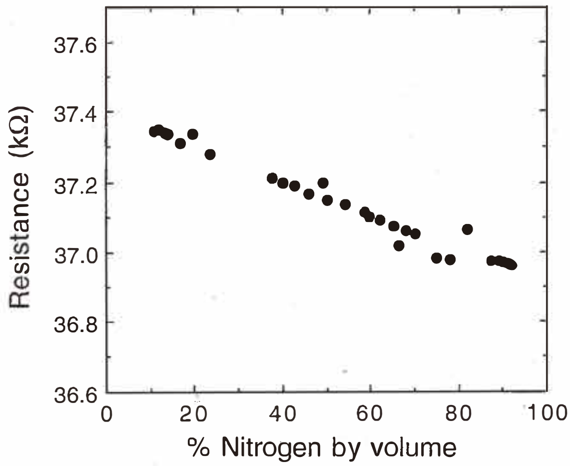

Fig. 5. Passive coil resistance in response to varying concentrations of N_2 in a flowing binary mixture of Ar and N_2.

4. Conclusion

We developed a flow-insensitive microsensor fabricated using CMOS technology that enables sensitive measurement of gas thermal conductivity, which is thought to be useful in gas separation applications or in microfluidic systems. Due to its small thermal time constant (~ 3 ms) and the very low inter-coil (fluidic) thermal resistance, the microsensor is capable of relatively high-speed operation in pulsed thermal mode, thus enabling other thermophysical properties (*e.g.*, diffusivity) to be retrieved. This is expected to extend its applications, in particular, in conjunction with artificial neural networks, to ternary (or higher) mixtures of known gas constituents.

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