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Low-cost silicon sensors for mass flow measurement of liquids and gases

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Abstract

A low-cost silicon sensor for measuring the mass flow rate of gases and liquids has been developed. Its operation is based on heat transfer from heated resistors to a flowing fluid (electrocaloric principle). The difference between the temperature of the sensors on the chip, the heating power, and the heater temperature can be used to measure the mass flow. It is important to realize that sensors are produced in silicon through the usage of micro-technology. Nitrogen and water are used for testing the sensor. The sensor has a high dynamic response and is suitable for dynamic fluid measurements. The possible measuring flow rates range from 0 to 500 ml/min for gases and 0 to 500 or 0 to 10 ml/min for liquids.

Keywords: Silicon sensors; Electrocaloric principle; Mass flow rates; Micro-technology

1. Introduction

The measurement of fluid flow is an important field in sensor technology of process controls. This consists of a wide variety of measurement tasks including measuring fluids. Important applications of a flow sensor can be found in mechanical engineering, medical equipment, semiconductor fabrication, and automobile industry. Since it is widely applied, a low-cost flow sensor was to be developed, which should have a high flexibility for measuring fluids and a fast dynamic response.

In recent years many thermal flow sensors were published [1–14]. Some of them were designed for only one kind of fluid [1,2,6,7], and all of them used only one operation mode.

In this paper, a thermal flow sensor for gases and liquids is presented. The sensor can perform in four different modes, enables the measurement of flow rates of different kinds of fluids, and provides a flexible measuring range. The sensor design with a micro-channel avoids direct contact between the fluid and the temperature sensors as well as the heaters and can measure aggressive fluids.

The sensor is made by standard technology used for the fabrication of silicon resistances, anisotropic etching, and anodic bonding. The advantages of this technique are that the electronic devices can be placed directly into the sensor chip, the device is small and the fabrication costs are low.

2. Principle and structure of the sensor

The principle of the sensor is based on convective heat transfer from a heated resistance structure to the flowing fluid. The flow causes a cooling of the heated resistance at constant heating power or an increase of the heating power at constant heater temperature. The expression 'constant heater temperature' is used in this paper to indicate that the heater temperature is maintained at a constant value above ambient temperature.

Analytical models of the principle have been often reported [1,4,7,10]. The present sensor operation principle combines the hot-wire principle [3,6,12] and the displacement of the temperature distribution [1,2,4,7]. There are four possible operation modes, see Fig. 1.

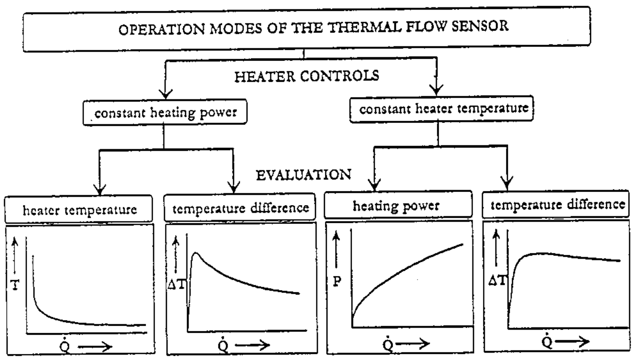

Fig. 1. Operation modes of the flow sensor.

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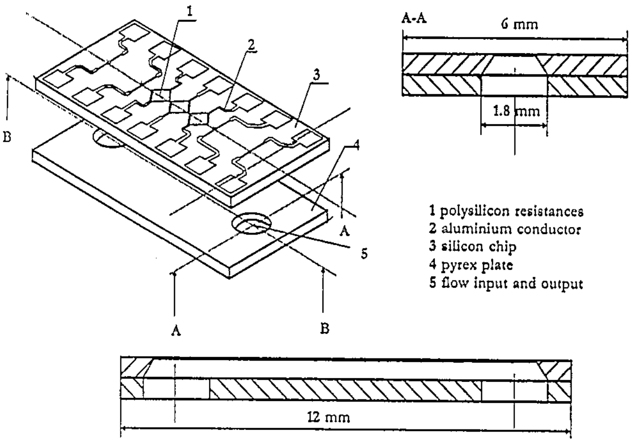

Fig. 2. Structure of the flow sensor.

Fig. 2 shows the structure of the sensor. The thermal flow sensor contains polysilicon heaters and measurement resistances on a diaphragm. The fluid flows in an anisotropically etched micro-channel with a cross-section of 0.6 mm^2 and a length of 10 mm. The channel is covered with a Pyrex glass plate by anodic bonding. A small thermal response time from 1 to 4 ms is reached with a diaphragm thickness from 10 to 30 μm. In the operation mode 'constant heater temperature' the dynamic response only depends on the heater control circuit and lies in the micro-second range.

3. Fabrication

To start with, a <100>-oriented silicon wafer polished on both sides is used. With standard processes the polysilicon resistances are deposited and patterned. Aluminium as an electrical conductor is applied. After the fabrication of resistance and conductor structures a silicon nitride passivation layer is used for protecting this structure. The next steps are the opening of the etching mask and the anisotropic etching using KOH. After removing the etching mask the silicon chip is bonded anodically on a Pyrex plate (800 V, 450 °C, Fig. 3.)

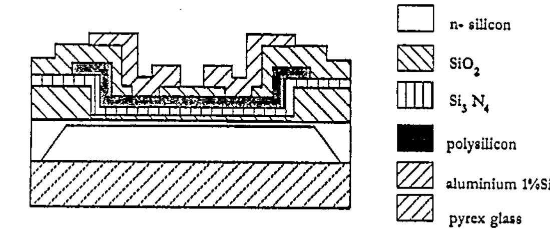

Fig. 3. Cross-section of the sensor.

4. Experimental results and discussions

Fig. 4 shows the experimental set-up for testing the sensor. The measuring system consists of two parts, one for liquid flow and the other for gas flow. All devices are connected to the control computer by means of a multi I–O card and other conventional computer interfaces. All components of the measuring system are programmed as virtual instruments using the graphical oriented program LABVIEW©. It allows free programmable measuring and automatic recording of experimental results. Water and nitrogen are used for testing the sensor. The measurements are carried out at room temperature (25 °C).

The electronics consist of two circuits. The first circuit controls and measures the heater resistances using its own resistance and a reference resistance [6]. The second circuit is used for measuring the temperature difference between the sensor downstream and the sensor upstream by a Wheatstone bridge and a chopper amplifier [4]. The combination of two circuits allows the use of all four operation modes.

Fig. 5 shows the voltage ouput for water flow by evaluating the heating power at constant level of heater temperature. The voltage is proportional to the heating power and shows a square-root like characteristic. The maximum heating power is nearly one watt.

The output voltage from the Wheatstone bridge for water flow and constant heat power is shown in Fig. 6. For low flow rates the output voltage is linear with flow rate. At 10 ml/min the output voltage reaches a maximum. For higher flow rates the sensor output voltage decreases with increasing flowrate.

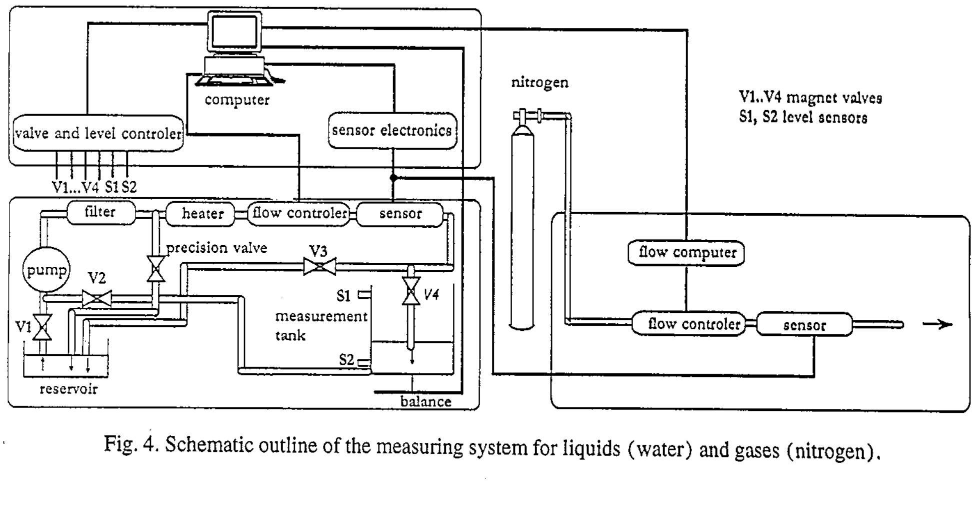

Fig. 4. Schematic outline of the measuring system for liquids (water) and gases (nitrogen).

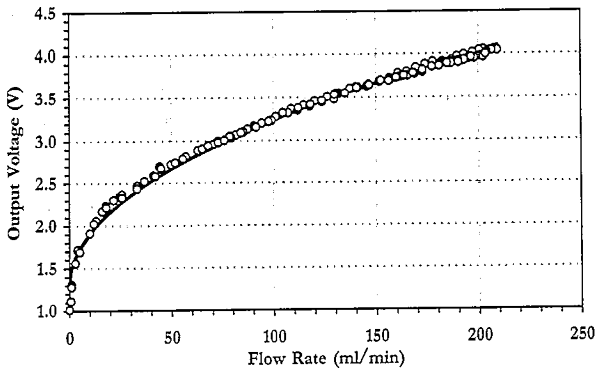

Fig. 5. Sensor signal vs. the water flow (constant heater temperature ΔT = 30 K, power evaluation, 1 V ~ 1/3 W).

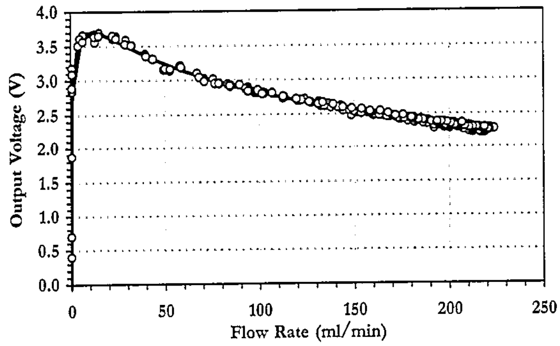

Fig. 6. Sensor signal vs. the water flow (constant heating power P = 300 mW, evaluation of temperature difference).

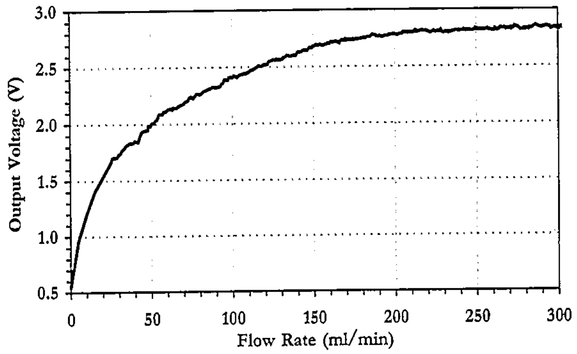

Fig. 7. Sensor signal vs. nitrogen flow (constant heater temperature ΔT = 30 K, evaluation of temperature difference).

The experimental results for the behavior of water flow have also been observed by Kuttner et al. [6] and Lammerink et al. [7].

It is not necessary to measure heating power at constant heater temperature by gases because gases have low heat conductivity and it leads to a low output signal level. Fig. 7 shows the sensor output voltage versus nitrogen flow rate. For high flow rates the output signal reaches saturation because the heater temperature is kept constant. This behavior for gases has also been observed by Johnson and Higashi [2].

5. Conclusions

A low-cost micro-channel thermal flow sensor has been designed, fabricated and tested. The measurement results show that it is possible to utilize a flow sensor for liquids and gases with only one chip. One of four possible operation modes can be used for measuring different fluids with different scopes. Future work can link the flow sensors to other micro-systems (micro-pumps, micro-valves). With good dynamic response the flow sensor can be used for dynamic investigations of fluid systems and components.

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References

[1] Canqian Yang and Heinrik Soeberg, Monolithic flow sensor for measuring millilitre per minute liquid flow, *Sensors and Actuators A, 33* (1992) 143–153.
[2] R.G. Johnson and R.E. Egashi, A highly sensitive silicon chip microtransducer for air flow and differential pressure sensing applications, *Sensor and Actuators, 11* (1987) 63–67.
[3] R. Kersjes, J. Eichholz, A. Langerbein, Y. Manoli and W. Mokwa, An integrated sensor for invasive blood velocity measurement, *Sensors and Actuators A, 37–38* (1993) 674–678.
[4] R. Kiehnscherf, N.T. Nguyen and M. Schulze, Elektrokalorischer Durchflußmengensensor für Gase und Öle, *F&M Feinwerktechnik Mikrotechnik Messtechnik, 9* (1994) 402–406.
[5] F. Kohl, A. Jachimowicz, J. Steurer, R. Glatz, J. Kuttner, D. Biacovsky and F. Olcaytug, A micro-machined flow sensor for liquid and gaseous fluids, *Sensors and Actuators A, 41–42* (1994) 293–299.
[6] H. Kuttner, G. Urban, A. Jachimowicz, F. Kohl, F. Olcaytug and P. Goiser, Micro-miniaturized thermistors arrays for temperature gradient, flow and perfusion measurements, *Sensors and Actuators A, 25–27* (1991) 641–645.
[7] T.S.J. Lammerink, N.R. Tas, M. Elwenspoek and J.H.J. Fluitman, Micro-liquid flow sensor, *Sensors and Actuators A, 37–38* (1993) 45–50.
[8] D. Moser and H. Baltes, A high sensitivity CMOS gas flow sensor on a thin dielectric membrane, *Sensors and Actuators A, 37–38* (1993) 33–37.
[9] B.W. van Oudheusden and J.H. Huijsing, Integrated flow friction sensor, *Sensors and Actuators, 15* (1988) 135–144.
[10] B.W. van Oudheusden, The thermal modelling of a flow sensor based on differential convective heat transfer, *Sensors and Actuators, 29* (1991) 93–106.
[11] B.W. van Oudheusden, Silicon thermal flow sensors, *Sensors and Actuators, 30* (1992) 5–26.
[12] Tong Qin-Yi and Hoang Jin-Biao, A novel CMOS flow sensor with constant chip temperature (CCT) operation, *Sensors and Actuators, 12* (1987) 9–21.
[13] J. van der Wiel, C. Linder and N.F. de Rooij, Liquid velocity sensor based on the hot-wire principle, *Sensors and Actuators A, 37–38* (1993) 693–697.
[14] You-Chong Tai and Richard S. Muller, Lightly-doped polysilicon bridge as a flow meter, *Sensors and Actuators, 15* (1988) 63–75.

Biographies

Richard Kiehnscherf was born in Genthin, Germany, in 1950. He received the Dipl.-Ing. and Dr.-Ing. degree in electronic engineering from the Technical University Karl-Marx-Stadt (Chemnitz), in 1972 and 1984. Subsequently he was engaged in research on NC-controls. He is currently a co-worker at the faculty of Microsystem and Device Engineering of the Department of Electronic Engineering and Information Technology at the Technical University of Chemnitz-Zwickau. He is the leader of the mentioned project.

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