THERMAL BASED FLOW SENSOR WITH NEARLY ZERO TEMPERATURE DEPENDENCE AND MID-BASED FLOW CHANNEL

Florian T. Krogmann, Christoph J. Hepp, Mirko Lehmann, and Jiri Holoubek
Innovative Sensor Technology- IST AG, Ebnat-Kappel, SWITZERLAND

ABSTRACT

For the first time, a resistance based flow sensor is presented, which shows nearly zero temperature dependence in the flow output signal without the need of complex compensation, due to both the unique sensor design and a new packaging technology approach. The improvements are achieved by designing a full Wheatstone bridge out of four platinum resistors and driving the sensor with a constant current source. Moreover, a Molded-interconnected-device (MID) fabricated housing is introduced, defining a highly reproducible flow channel and allowing an easy integration into systems by simply soldering the sensor system to a Printed Circuit Board (PCB).

INTRODUCTION

Thermal based flow sensors are used since decades for measuring flow velocity or mass flow of fluids [1]. Applications as diverse as mass flow-controllers, control of the air-intake of combustion systems, spirometers or HVAC use successfully thermal based flow sensors. The measurement principle is basically based on a heating element, which is cooled by the fluid flow. Several techniques can be used in order to measure a the flow velocity or mass flow; either the amount of transferred energy over the fluid to a temperature sensing element is used to calculate the flow by evaluating the resulting temperature at the temperature element or the amount of energy which is transferred to the fluid is measured and serves as sensing mechanism [1].

MEMS-based thermal based flow sensors are typically based on silicon technologies on which the active components are placed on membranes [2]. Mostly, a heater out of doped silicon or a metal is used for heating and temperature sensors are implemented by the use of thermopiles or resistive temperature detectors. Other systems based on different membrane materials (e.g. polyimide [3] or Parylene [4]) are known, too, but are less common.

All systems have one major drawback: the systems typically have to be calibrated in two dimensions. On the one hand, a calibration to the flow velocity or mass flow is necessary; on the other hand a calibration in the temperature regime is necessary. While the calibration for the flow velocity can be done relatively easy and fast, the compensation for temperature needs a lot of more resources and time. Therefore, a sensor with no temperature compensation would ease the calibration process dramatically and with this reduces the cost of thermal based flow sensors.

In this work a system is presented which shows nearly zero temperature dependence in the output signal in a wide temperature range between 7°C and 55°C.

CONCEPT

The basic principle behind thermal based flow sensors is the heat dissipation due to forced convection of the flowing fluid. The more flow is flowing over the sensors, the more heat is transferred to the fluid and the lower is the resulting temperature of the heater. According to Joule's heating the total dissipated power in a resistance is

$$P=U^2/R = I^2*R \tag{1}$$

with P = power in Watt, U= voltage in Volts, I = Current in Amperes and R= resistance in Ohms.

In no-flow conditions, the heat is transferred to the fluid by heat conduction and natural convection. Unfortunately, the heat conduction coefficient of air increases with increasing temperature [5]. This leads to a higher heat loss of the heater at higher ambient temperatures, resulting in a lower increase of the heaters' temperature (ΔT) at elevated temperature. Since the output signal of a thermal flow sensor is based on the energy transferred to the fluid, it is obvious, that the output signal differs at different temperatures.

The idea of this work is to compensate for the changes in heat conduction over temperature in a physical way, not by electronic compensation. Therefore, the system has to increase the temperature of the heater with increase of ambient temperature in a way, that the higher heat transfer to the fluid is compensated.

In general, the easiest electronic to drive sensors is by constant voltages sources. Assuming this and taking eq. 1 into account, the ratio P*R must maintain constant. This would mean that with increase of R – which is equal to an increase of ambient temperature – would lead to a decrease of power. Power and resulting temperature are coupled by the equation

$$\Delta T = P/E_k \tag{2}$$

With E_k = self-heating coefficient in W/K.

The result would therefore be a decrease in the heater temperature, not an increase.

Taking a constant current source into account, the following situation occurs

$$P/R= I^2 = \text{const.} \tag{3}$$

This means, that for driving the sensor by a constant current, the ratio P/R must remain constant.

Combing eq.3 and eq. 2

$$\Delta T * E_k / R = I^2 = \text{const.} \quad (4)$$

In a first approximation the self-heating coefficient can be taken as constant, so that finally the system temperature behavior can be described as

$$\Delta T / R = \text{const.} \quad (5)$$

From this, one can easily see that using a constant current source leads to a system which increases the temperature of the heater (ΔT) with increase of the ambient temperature (R).

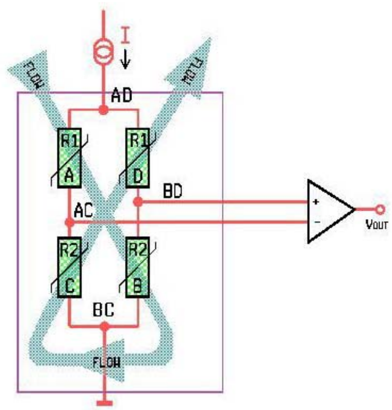

Figure 1: Corresponding equivalent circuit of the sensor

In order to form a sensitive flow sensor, the sensor concept is based on a full-Wheatstone bridge out of platinum resistors on a membrane. Wheatstone-bridges are known to be very sensitive to resistance changes and therefore allow to easily detecting minimal variations in the resistance; a fact which is implemented also in other sensors, e.g. pressure or force sensors. Implementing a membrane helps to increase response time due to the lower thermal mass of the heating elements. An equivalent circuit of the sensor can be seen in Figure 1, the corresponding design schematic in figure 2.

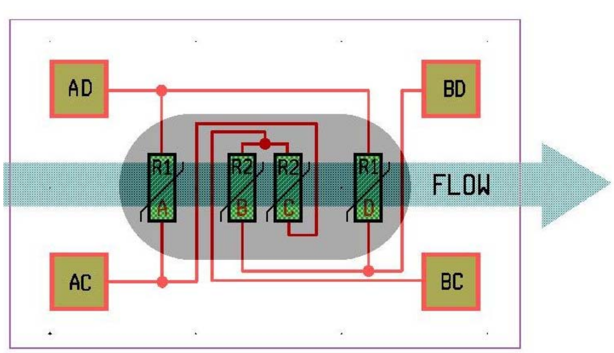

Figure 2: Corresponding design schematic of the sensor

In this configuration, the flow is measured by a shift in the heat cloud which is formed over the four resistances. With no-flow the heat cloud uniformly heats all four resistances so that an output signal of around 0mV is obtained. When flow occurs, the resistances A and B are cooled down more than C and D, which leads to a disbalance of the Wheatstone-bridge and therefore to a voltage signal, typically in the range of some tenth of millivolts.

DESIGN & FABRICATION

Design

The sensor design can be seem in Figure 3. The sensor is based on platinum resistors. Four of them are structured to resistances of 500 Ohms +/- 10% and connected in order to form a full Wheatstone bridge. All four resistors act finally as heaters and temperature dependent elements. Two resistors are next to each other in the middle of the membrane, left and right from them a resistor is placed with a distance of 200 µm. Only four connection pads are necessary in order to drive the circuit and extract the output signal: to AD and BC the constant current source is connected, contact AC and BD are used to measure the bridge signal.

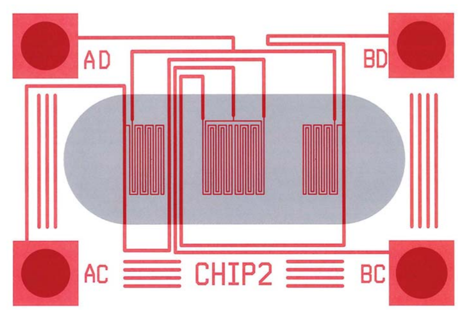

Figure 3: Chip layout; the connection lines between the resistors are optimized for equal resistance.

Special interest was taken to the connection lines between the resistances. Due to their internal resistance, the connection lines act as parasitic resistances. As mentioned before, Wheatstone-bridges act very sensitive to resistance variations. Small changes in the resistance of the connection lines can therefore disbalance the bridge and yield to an offset in the output signal, even at zero flow. Moreover, the connection lines act as small heat sources which can affect the output signal, too. Therefore, the connection lines were design for exactly the same resistance value.

Fabrication

The sensor was fabricated on a Foturan substrate (thickness: 0.5mm). Foturan is a photosensitive glass and can be structured with UV-light exposure through a mask and annealing it at temperature of approximately 600°C. This generates crystalline glass structures in the areas where it was exposed while maintaining its amorphous structure in non-exposed areas. Since the crystalline glass has a much higher etch rate in diluted hydrofluoric acid, this process can be used to selectively structure the substrate.

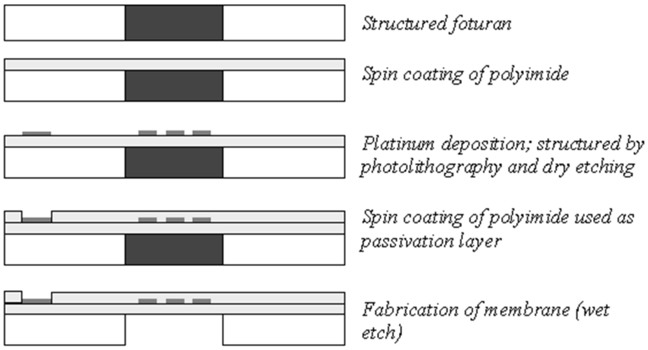

Figure 4: Fabrication process.

In our work, we used this to form a membrane area on the chip. For this, the substrates were exposed and annealed, followed by spin-coating of a polyimide (see Figure 4). After curing the polyimide at 350°C for 1h, a 220nm thick platinum film was sputtered. The layer was structure by photolithography and ion-etching of the platinum, leading to the final resistance structure. To ensure a good soldering, the pads were additionally covered by a 200nm Gold layer. Besides the soldering pads, all other areas were covered again by spin-on polyimide in order to protect the resistance structures from environmental influences (e.g. humidity). Subsequently, the crystalline structures of the Foturan glass were etched in 10% hydrofluoric acid, leading to a membrane in the resistance area of 10µm thickness. Last, the contacts were pre-soldered by printing SAC305 solder paste to it and melting it in a solder oven. An overview of the fabrication process is shown in figure 4.

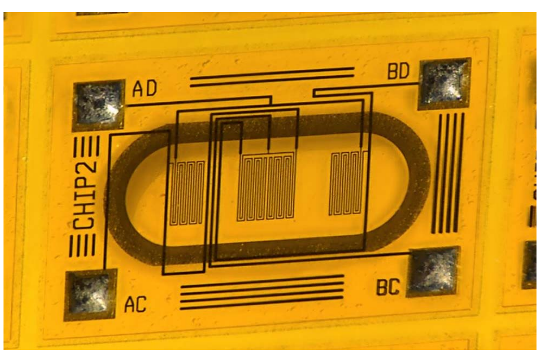

Figure 5: Photography of the front side of the final sensor chip. In the middle, the four resistances can be seen, on the pad, the soldering depot is visible.

Images of the final sensor can be seen in figure 5 and 6. On the front side, the resistor structures as well as the solder on the pads are clearly visible, on the backside the membrane area and the surrounding Foturan substrate can be seen.

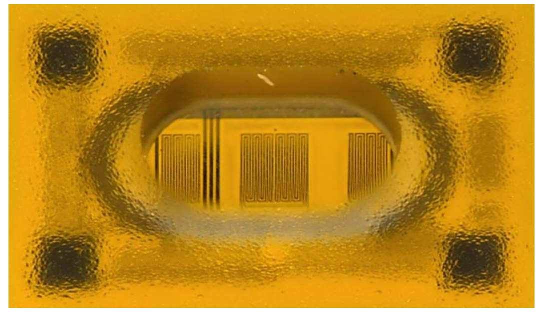

Figure 6: Photography of backside of the chip. The precisely etched membrane is visible in the middle of the chip.

PACKAGING

Packaging is a crucial element in flow sensor systems. Often, the sensor is cheaper as the assembly method in order to form an accurate and precisely controlled flow profile over the sensor. For this reason, we used a molded interconnected device (MID) which acts as sensor housing and which forms the flow channel.

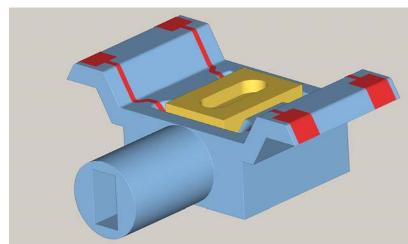

Figure 7: Layout of the MID housing; in red the connection for the soldering can be seen, on the left the inlet for the fluid is shown. The chip (yellow) is placed on the bottom.

MID systems are known for years [6]. They allow structuring polymeric based housings with metallization layers. The big benefit of MID systems is that even 3D metallization on the polymer housings can be achieved.

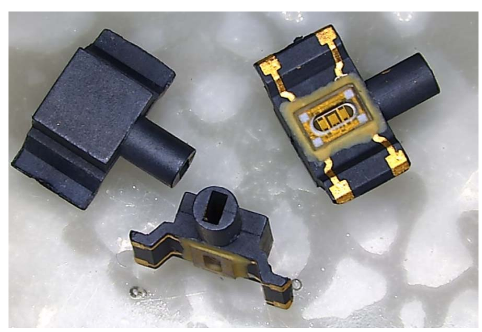

Figure 8: Photography of the final sensor system. The golden contacts are solderable, so that the system can be easily mounted onto a PCB.

In our work, the sensor is placed into a MID housing which was designed to form a flow channel with dimensions of 0.5 x 1.5 mm square (W x H). A schematic of the housing can be seen in Figure 7. It features a flow inlet (left) and metallic connections (red) from the chip (yellow) to bottom of the housing. The metallic connections are solderable in order to allow an easy connection to an electronic.

The sensor itself is also soldered into the housing, allowing a robust and cheap assembly technology. For closing residual gaps, the surrounding of the sensor is filled UV-curing epoxy by dispensing around the chip edges. A picture of the final sensor system can be seen in figure 8.

EXPERIMENTAL RESULTS

The sensor system was measured using a mass flow controller (MFC) unit (MKS Model 1179) as reference and normal dry air as fluid. A 4mA constant current source (Keithley SourceMeter Model 2420) was applied to the sensor and the bridge signal was measured using a standard DMM (Keithley Model 2000). For changing the temperature of the fluid, the experiment was build up in a climatic chamber, allowing changing the temperature of the fluid and the sensor from 7 to 55°C. In figure 9 the result of these measurements can be seen. The bridge voltage vs. the normal volume flow of air shows only a slight change due to ambient temperature variations.

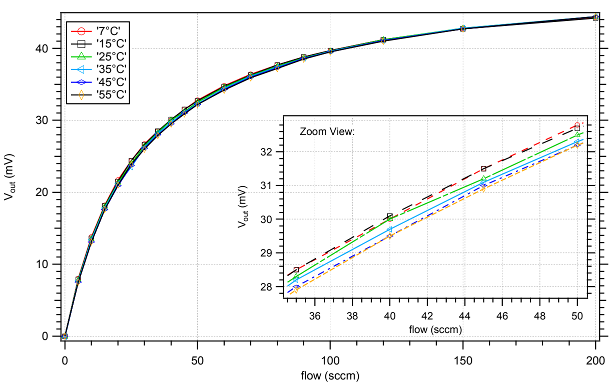

Figure 9: Measured bridge output signal vs. normal volume flow of air for temperatures between 7°C and 55°C at 4mA driving current.

Taking the 25°C flow curve as calibration curve, the obtained deviations without any external temperature compensation is plotted in figure 10. As can be seen, a maximum error of less than 5% of the reading and less than 1.6% full-scale was achieved between 7°C and 55°C.

DISCUSSION

The shown result of the experimental measurements proofed that the concept is working. The temperature dependence of the output signal is reduced to a minimum, allowing temperature uncalibrated accuracies in the norm volume flow of less than 5% of the reading. The flow profile itself follows the typical exponential form like known from other flow sensors. In the future, the behavior of different gases and the behavior in higher and lower temperatures will be investigated.

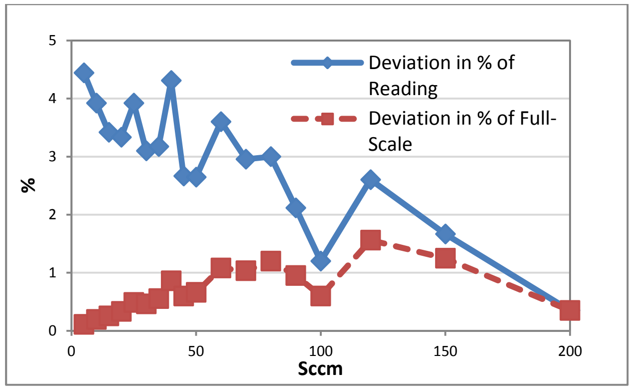

Figure 10: Resulting maximum deviation between 7 and 55°C of the flow sensor in % at every measurement point when calibrating the flow signal at 25°C.

CONCLUSION

A sensor system is presented which is capable to meet the needs of many applications without a temperature calibration. Moreover, the requirements to the electronics for driving the sensor are simple and cheap, making it a perfect approach for low-cost applications. Last, the use of a MID-housing allows to integrate the sensor in a highly automatic way, making it a good choice even for high volume applications.

REFERENCES

[1] N. T. Nguyen, “Micromachined flow sensors – a review”, Flow Meas. Instrum, Vol. 8, No.1 pp. 7-16, 1997

[2] M. Ashauer, H. Glosch, F. Hedrich, N. Hey, H. Sandmaier, W. Lang, “Thermal flow sensor for liquids and gases based on combinations of two principles”, Sensor and Actuators A: Physical, Vol. 73, Issues 1-2, pp. 7-13, 1999

[3] C. Hepp, F .Krogmann, G. Urban, “Flow Rate Independent Sensing of Thermal conductivity in a Gas Stream by a Thermal MEMS-Sensor – Simulation and Experiments”, Sensors and Actuators A: Physical, 2016, http://dx.doi.org/10.1016/j.sna.2016.11.009

[4] E. Meng and Y. Tai “A parylene MEMS flow sensing array”, in *Digest Tech. Papers Transducers‘03 Conference*, Boston, June 8-12, 2003, pp. 686-689.

[5] K. Stephan and A. Laesecke, “The Thermal Conductivity of Fluid Air”, J. Phys. Chem. Ref. Data, Vol. 14, No. 1, 1965

[6] Peitz, T. „Methodik zur Produktoptimierung mechanisch elektronischer Baugruppen durch die Technologie MID“. PhD Thesis, Fakultät für Maschinenbau, University Paderborn. Paderborn: HNI-Verlagsschriftenreihe, Band 221; 2007.

CONTACT

*Florian T. Krogmann, tel: +41-71-9920-100;
florian.krogmann@ist-ag.com