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Micromachined Flow Sensors Enabling Electrocalorimetric and TOF Transduction

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Abstract

A novel thermal flow sensor is presented featuring three spatially separated micromachined silicon-nitride membranes. A thin-film heater is embedded in the central one, while the others carry thermistors. This advanced sensor structure enables two different transduction modes. The electrocalorimetric mode exhibits high resolution and quick response at the expense of high power consumption. For slowly varying flows, the Time-of-Flight mode with low duty-cycles allows for power-saving operation but suffers from less sensitivity and slower response.

Keywords: Micromachined flow sensor, electrocalorimetric transduction principle, Time-of-Flight.

1. Introduction

Flow measurement is one important application where micromachined sensors seem to be most promising. Adopting thermal transduction principles, micromachining enables high sensitivity, quick response and low power consumption, making thermal flow sensors superior for low volume liquid flow and for gas flow[1]. The micromachined thermal transducers typically comprise thermally isolated structures (membranes) with embedded heater(s) and temperature sensors. Basically there are three different types of thermal flow sensors[2]:

- Hot-wire or hot-film flow sensors which exploit directly the cooling effect of the passing fluid on a heater.
- Calorimetric flow sensors utilize the flow dependent asymmetry of the temperature profile around the heater.
- Time-of-Flight flow sensors which measure the passage of a heat pulse over a known distance.

This paper presents first results obtained with a novel thermal flow sensor suited to perform the second as well as the third transduction method alternatively. It comprises three spatially separated and thermally isolated micromachined silicon-nitride membranes. A thin-film heater is embedded in the central one, while the others carry thermistors. Applying a constant power to the heater, the sensor evaluates the distortion of the temperature distribution due to convective heat transfer (standard electrocalorimetric mode). The second operation mode utilizes pulsed heat generation. Due to membrane segmentation, heat is transferred almost exclusively by the fluid through

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heat diffusion and convection. At the thermistors the broadened heat pulses are registered with some time-of-flight (TOF) delay. As the TOF depends on magnitude and direction of the flow, these values can be extracted from the difference of temperature responses of the upstream and downstream thermistor.

The electrocalorimetric mode exhibits high resolution and quick response. However, due to the very slow thermal equilibration, the heater must be supplied permanently with a constant voltage causing high power consumption in this mode. Therefore, for slowly varying flows, the TOF-mode with low duty-cycles enables power-saving operation at the expense of less sensitivity and slower response.

2. Sensor design

A typical calorimetric flow sensor features a single membrane carrying a miniaturized heat source and symmetrically arranged temperature sensors[3]. Such designs show a rather slow approach to the thermal steady-state, which makes intermittent operation as a power saving technique impossible. The new design embeds actuator and thermistors in three separate membranes. Fig. 1a shows the schematic cross section of the flow sensors. Two micromachined membranes carrying thin film Ge-thermistors (MT1/MT2) are placed symmetrically to a central membrane with an embedded chromium heater (H). The fluid temperature can be measured with two additional thermistors arranged on the substrate area between the membranes (ST1/ST2).

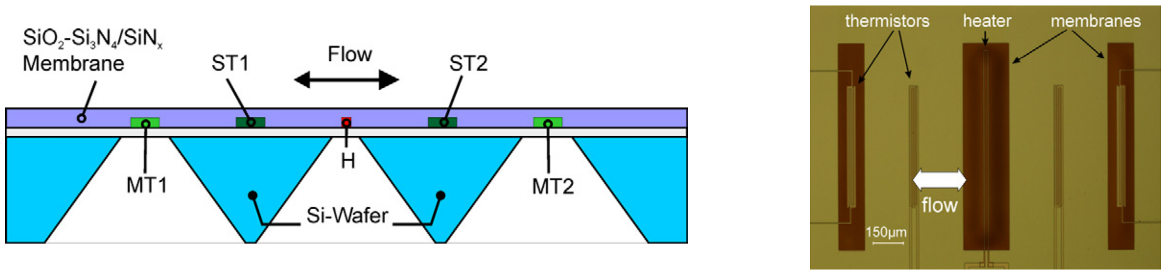

Fig. 1. (a) Schematic cross section of the flow sensor comprising three silicon-nitride membranes. H denotes the heater, MT1 and MT2 the membrane thermistors. The substrate thermistors (ST1 and ST2) measure the fluid temperature; (b) Photomicrograph of the flow sensor arrangement. The mean distance between adjacent membranes is 675 µm, the overall chip size is 3 × 6 mm².

Because of symmetrical arrangement, the sensor features a bidirectional characteristic. Fig. 1b depicts a photomicrograph of the membrane arrangement. The dimensions are 0.1 × 1 mm² for the thermistor membrane and 0.2 × 1 mm² for the heater membrane. The mean distance between two adjacent membranes is 675 µm and the overall chip size amounts to 3 × 6 mm².

For the measurement of nitrogen gas flow rates, the silicon chip was incorporated in the wall of a miniaturized flow channel (Fig. 2). A PCB (Printed Circuit Board) of about 0.8 mm thickness forms the bottom of a rectangular flow channel (1.2 mm width and 1 mm height). A milled recess accommodates the sensor chip flush with the surface of the PCB.

3. Measurements and results

For both operation modes the difference of the temperature responses of the up- and downstream thermistor must be evaluated (thermistor bias 0.5 V, gain $6.6 \cdot 10^7$ V/A). In the electrocalorimetric mode its magnitude is flow dependent, whereas in the TOF mode its delay with respect to the heating pulse corresponds to the flow velocity.

3.1. Electrocalorimetric mode

Applying a constant voltage to the heater the sensor is operated in the calorimetric mode. Without flow, the generated temperature profile around the heater is symmetrical and consequentially both temperature sensors measure the same value. Convective heat transfer induced by the media flowing across the sensor surface disturbs the thermal symmetry. The temperature difference of the membrane thermistors depends on the flow velocity and the power dissipated by the heater. The output characteristic for 5.4 mW heater power is depicted in Fig. 3.

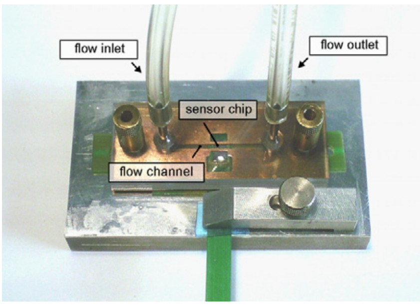

Fig. 2. Sensor chip incorporated in the wall of a miniaturized rectangular flow channel with cross-sectional dimensions 1.2 × 1 mm².

Due to permanent acquisition, signal averaging is feasible yielding high-resolution measurements with reasonable speed of response. However, continuous calorimetric operation wastes energy if slowly varying flows are to be monitored. Where power-saving matters, the TOF-mode with heating pulses of suitable duration and repetition rate should be used.

3.2. TOF mode

In the TOF mode, a pulse signal with low duty-cycles is applied to the heater. The upstream thermistor is affected mainly by conductive heat transfer through the membrane, which is practically independent of the flow velocity. On the other hand, the downstream thermistor registers conductive heat transfer through the membrane as well as the flow dependent convective heat transfer by the fluid. Thus, evaluating the difference of the thermistor responses, the conductive part can be eliminated. The output signal exhibits a flow dependent delay with respect to the falling edge of the heating pulse, as illustrated in Fig. 4a for two different flow velocities. Electrical crosstalk generates sharp peaks at the end of exciting pulse which has no influence on the TOF but could be utilized conveniently to trigger delay measurements.

By tuning the duration of the heating pulse, the response peak can be shaped appropriately to enable sufficiently accurate peak delay measurements. Longer heater pulses produce output signals with higher magnitude but flat peaks, which is detrimental to precise time measurement (Fig 4b).

The TOF mode was characterized by applying 5 V pulses signal to the heater with 5 ms pulse duration and 20 ms repetition rate (corresponding to 25 % duty-cycle). The reciprocal TOF, as plotted in Fig. 5, constitutes an appropriate output quantity of the TOF operation mode.

At very low flow rates, the convective contribution to heat transfer is too small to generate a resolvable difference of the upstream/downstream thermistor signals. Thermal diffusion and dissipation to the substrate cause considerable spreading and shrinking of the propagating heat pulses, hampering precise delay time measurements (Fig. 4a). Accordingly, this appears to be a lower limit for measurement range (about 5 cm/s for the current sensor design).

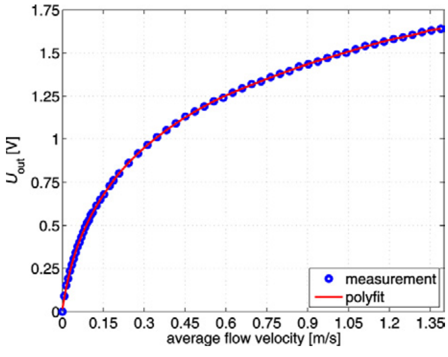

Fig. 3. Output characteristic measured in calorimetric mode. Temperature difference of the membrane thermistors serves as output signal (heater voltage and resistance are 4 V and 3 kΩ, respectively)

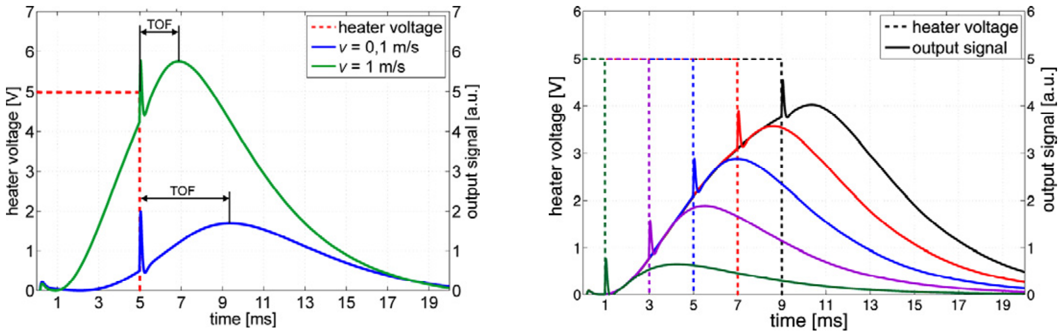

Fig. 4. (a) TOF measurement for two different flow velocities. At lower flow rates, the thermal diffusion and dissipation to the substrate cause spreading and shrinking of the heat pulse; (b) Influence of the heating pulse duration on the shape of the output signal. Longer heater pulses produce output signals with higher magnitude but smoothed peaks.

At high flow rates, the short passage times demand for high precision TOF estimation. Signal averaging techniques may be required in order to suppress noise, at the expense of extended response time. The related tradeoff leads to an upper limit for the practical measurement range. The average power consumption could be reduced arbitrarily using extremely low duty-cycles at the cost of considerable dead times. Very long acquisition periods must be accepted, if high accuracy by means of averaging is desirable.

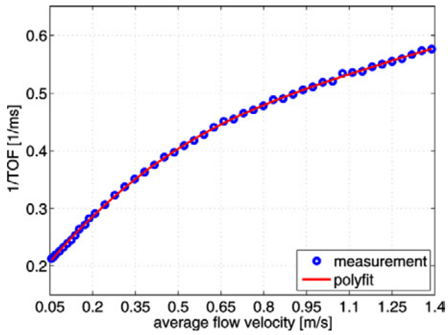

Fig. 5. Measured transduction characteristic TOF-mode. The reciprocal of the TOF serves as output quantity.

4. Conclusion

We presented a novel thermal flow sensor enabling electrocalorimetric and TOF transduction. Applying constant power to the heater, the sensor evaluates the flow dependent asymmetry of the temperature profile around the heater (standard electrocalorimetric mode). The magnitude and direction of the flow can be extracted from the difference of temperature responses of the upstream and downstream thermistor. The second operation mode utilizes pulsed heat generation. The output signal exhibits a flow dependent delay with respect to the heating pulse. The electrocalorimetric mode exhibits high resolution and quick response at the expense of high power consumption. For slowly varying flows, the TOF-mode with low duty-cycles enables power-saving operation but suffers from less sensitivity and slower response.

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