SINGLE CHIP FLOW SENSING SYSTEM WITH A DYNAMIC FLOW RANGE OF MORE THAN 4 DECADES

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ABSTRACT

We have realized a micromachined single chip flow sensing system with an ultra-wide dynamic flow range of more than 4 decades, from less than 0.1 up to more than 1000 µl/h. The system comprises both a thermal and a micro Coriolis flow sensor with partially overlapping flow ranges.

KEYWORDS

Integrated microsystems, thermal flowsensors, Coriolis flow sensors, surface channel technology

INTRODUCTION

In [1, 2] we presented a surface channel technology that can be used to realize both thermal [3] and Coriolis [4] flow sensors.

Thermal flow sensors are capable of measuring liquid flow down to a few nl/min by accurate measurement of very small flow-induced temperature changes [3, 5]. However, their upper flow range is limited due to the transition from the calorimetric to the anemometric heat transfer regime. On the other hand, Coriolis flow sensors are capable of measuring large flow rates, but their resolution is limited due to the extremely small Coriolis forces. In [4] we presented a micro Coriolis mass flow sensor with a very thin (1 µm) tube wall made of silicon nitride, resulting in a significant improvement in resolution compared to earlier devices [6, 7]. This has opened the possibility to combine a thermal and a Coriolis flow sensor on a single chip with partially overlapping flow ranges in order to obtain a combined dynamic range of more than 4 decades.

SYSTEM STRUCTURE

The single chip flow sensing system, as shown in figure 1, comprises a fluidic inlet, a Coriolis mass flow sensor, a thermal mass flow sensor, and a fluidic outlet. Fluid flow enters the system through the inlet holes, first goes through the Coriolis flow sensor, then through the thermal flow sensor, and leaves the system through the outlet holes.

THERMAL FLOW SENSOR

The thermal flow sensor, as shown in figure 2a, consists of a silicon nitride microchannel that is freely-suspended over an etched cavity in the silicon substrate.

The channel crosses the cavity two times in order to eliminate external temperature gradients. Two resistors, that fulfill both the heating and sensing function, are positioned on each channel segment.

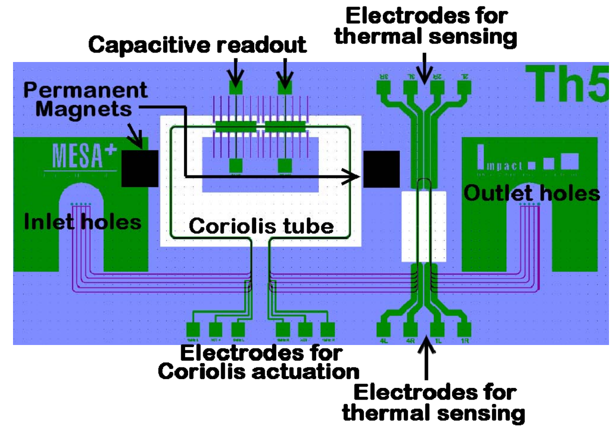
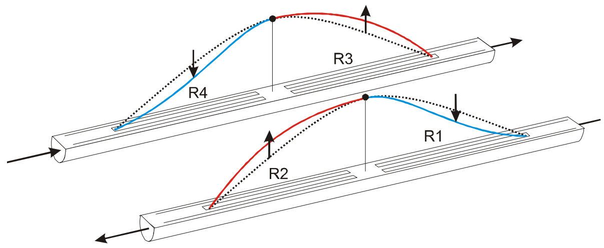
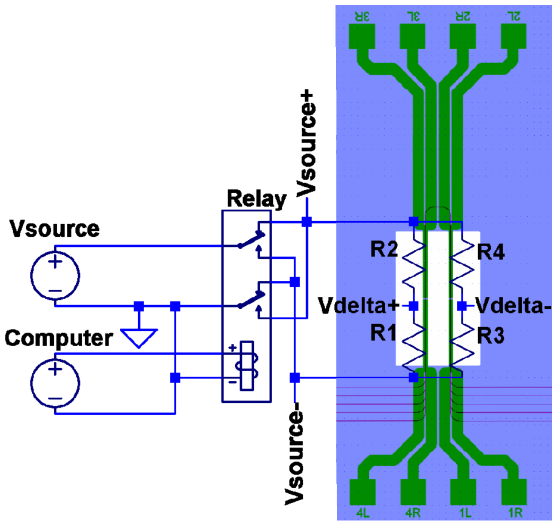


Figure 1. Structure of single chip flow sensing system.



(a)



(b)

Figure 2: (a) Thermal flow sensor with (b) Wheatstone bridge configuration.

The resistors are connected in a Wheatstone bridge configuration, as shown in figure 2b. A flow through the channel results in a corresponding output voltage of the Wheatstone bridge.

CORIOLIS FLOW SENSOR

The Coriolis type flow sensor consists of a vibrating tube. Fluid flow inside the vibrating tube results in Coriolis forces that can be detected.

Figure 3 shows a schematic drawing of a Coriolis sensor based on a rectangular tube shape [4]. The tube is actuated in a torsional mode indicated by ω_{am}, using the Lorentz force on an electrical ac-current i_{act} flowing through a metal track on top of the tube and a static external magnetic field B imposed by two permanent magnets. A mass flow Φ_m inside the tube results in a Coriolis force F_c. The Coriolis force is capacitively detected by its induced out of plane vibration mode with an amplitude proportional to the mass flow.

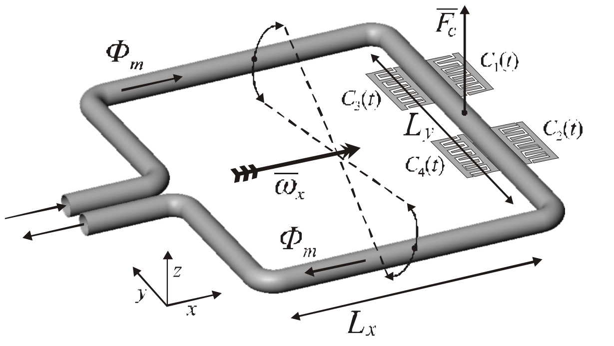


Figure 3: Coriolis flow sensor.

Figure 4 shows a schematic diagram of the complete sensor system with actuation and readout electronics [4]. The comb-shaped readout capacitors are indicated by C_1 through C_4. The combs that are attached to the moving sensor tube are connected to a signal source with frequency $F_{carrier}$ equal to 1.4 MHz. The fixed combs are connected to charge amplifiers and the resulting amplitude modulated signals are demodulated by multiplication with an in-phase reference signal. Low pass filters with relatively high cut-off frequency of 100 kHz are used to prevent phase shift at frequencies below 3 kHz, i.e. the vibration frequency of the tube.

The measured mass flow can be extracted from the phase difference between the two output signals S_{out1} and S_{out2}.

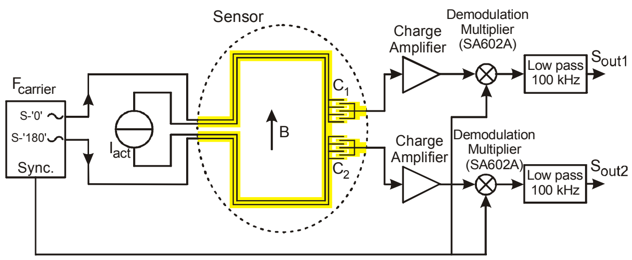


Figure 4. Schematic diagram of the actuation and readout electronics.

FABRICATION TECHNOLOGY

Both flow sensors consist of a silicon nitride microchannel that is freely-suspended over an etched cavity in the silicon substrate, for either thermal insulation (thermal flow sensor) or to allow the tube to vibrate (Coriolis flow sensor).

Here we give a brief summary of the fabrication process. A more detailed description can be found in [4].

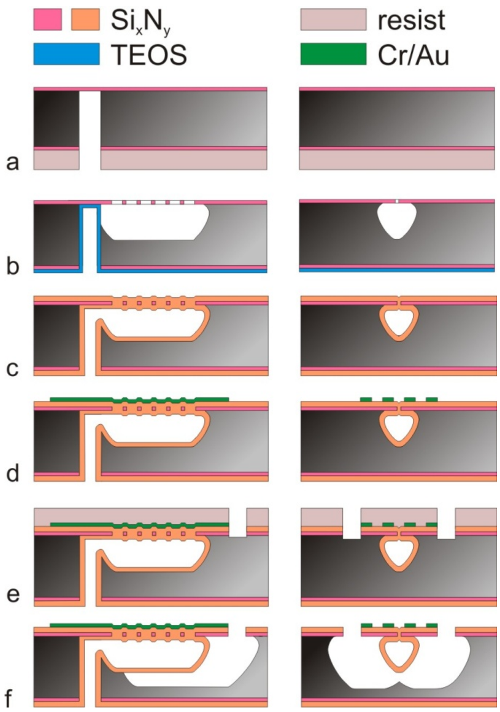


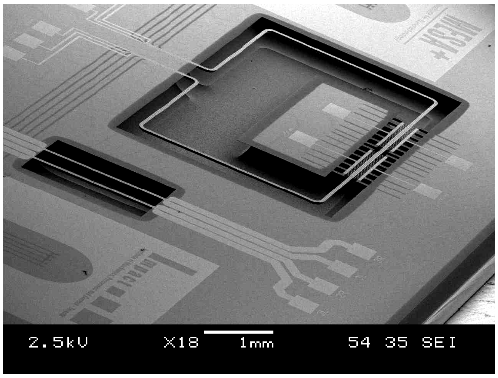
Figure 5: Outline of the fabrication process. Left column: cross-section along the length of the tube. Right column: cross-section perpendicular to the sensor tube.

Starting with a highly doped <100> p++ wafer, a 500 nm thick low stress LPCVD silicon-rich silicon nitride (Si_xN_y) layer is deposited. Then the fluidic inlet/outlet holes are etched from the backside of the wafer using the Si_xN_y layer at the top side as etch stop (Fig. 5a). Next, a 1 µm thick TEOS (tetraethyl orthosilicate) oxide layer is deposited and removed from the front side of the wafer. Then a 50 nm layer of chromium is sputtered on the front side of the substrate. This chromium layer is patterned using a mask containing arrays of 5×2 µm holes, spaced 3 µm apart. This pattern forms the centerline of the final channel. The pattern is then transferred into the nitride layer by reactive ion etching and subsequently the channels are etched in the silicon using isotropic plasma etching (Fig. 5b). The TEOS layer and chromium mask are then removed and another Si_xN_y layer is grown with a thickness of 1.8 µm to form the channel walls and seals the etch holes in the first nitride layer (Fig. 5c). A 10/200 nm layer of chromium and gold is sputtered (chromium serving as the adhesion layer for gold) and patterned to create the metal electrodes for actuation and readout (Fig. 5d).

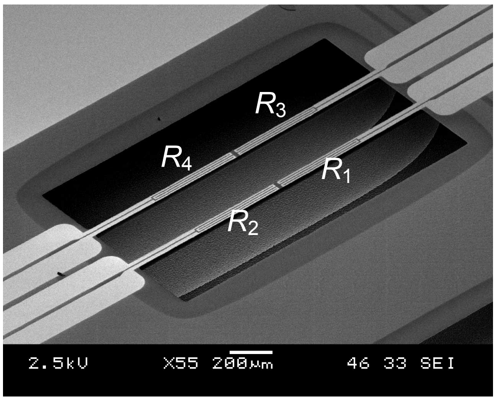
Next, the release windows are opened by reactive ion etching of the Si_xN_y layer (Fig. 5e) and the structure is released by isotropic silicon plasma etching (Fig. 5f)).

The realized single chip flow sensing system is shown in figure 6a, with the thermal and Coriolis flow sensor shown in more detail in figures 6b and 6c, respectively. The tube diameter is approximately 40 µm. The entire chip measures 7.5 mm × 15 mm.

A picture of the single chip flow sensing system mounted on a printed circuit board is shown in figure 7.



(a)



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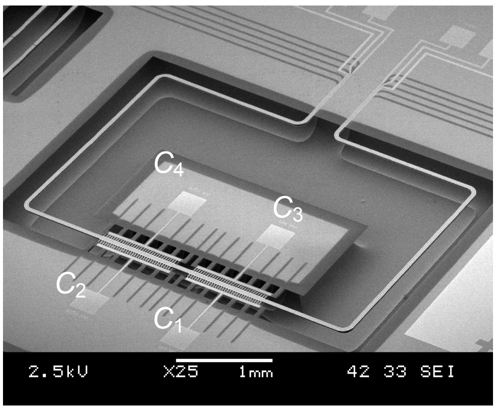

(c)

Figure 6. SEM photographs of the combined single chip thermal/Coriolis flow sensing system: (a) Overview of the chip, (b) thermal flow sensor and (c) Coriolis flow sensor.

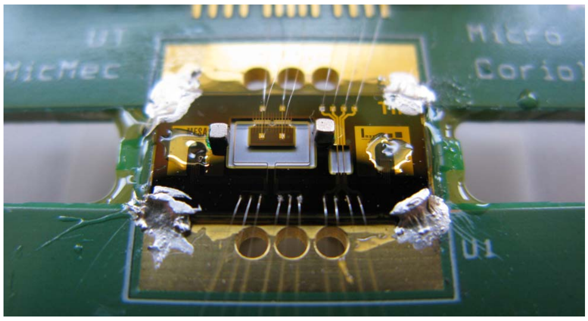

Figure 7. Single chip flow sensing system, mounted on a printed circuit board.

MEASUREMENT SET-UP

A syringe pump system, as shown in figure 8, was used to generate water flows in the range of 0.1 up to 2100 µl/h through the chip. During the measurements the output signals of both the thermal and the Coriolis flow sensor were recorded simultaneously, together with the output signal of a precision balance, which is used as a reference for the mass flow rate.

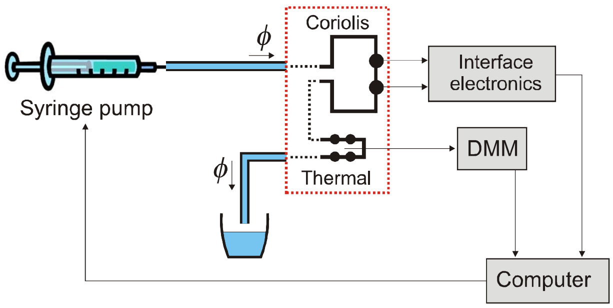

Figure 8. Measurement set-up. Water flow is provided by a syringe pump and checked with a balance.

MEASUREMENT RESULTS

The measurement results of the single chip flow sensing system are shown in figure 9. In this figure, the volume flow as measured by both the thermal and the Coriolis mass flow sensor are displayed versus the flow rate as set by the syringe pump.

The thermal flow sensor provides an almost linear output signal from the lowest flow of 0.1 µl/h through approximately 5 µl/h. Then, the curve flattens and reaches its top at approximately 40 µl/h, after which the output signal decreases with further increasing flow. The limitation of the upper flow range is due to the transition from the calorimetric to the anemometric heat transfer regime [8].

The low flow limitation of 0.1 µl/h is caused by the size of the syringes used (10 µl). Smaller syringes (1 µl) have been ordered to measure even lower flows. The absolute minimum detectable flow rate will eventually be determined by the signal to noise ratio of the thermal flow sensor.

The measurable flow range of the thermal flow sensor was found to be from 0.1 up to 40 µl/h.

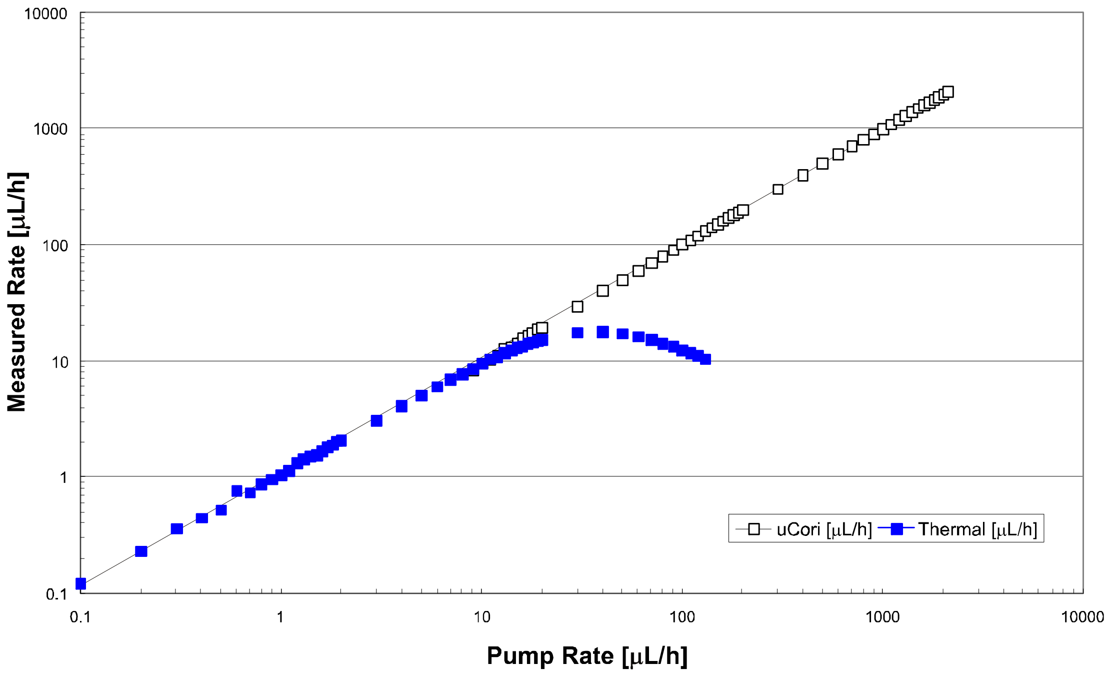

Figure 9. Measurement results demonstrating a dynamic range of more than 4 decades.

The Coriolis flow sensor provides a linear output signal from the lowest measurable flow of 10 µl/h up to the highest measurable flow of more than 2100 µl/h.

The low flow limitation of 10 µl/h is caused by the limited zero-stability of the Coriolis flow sensor due to the extremely small Coriolis forces [4].

The high flow limitation of 2100 µl/h is caused by the size of the syringes used (10 µl). Larger syringes (100 µl) have been ordered to measure higher flows. The absolute maximum detectable flow rate will eventually be determined by the maximum pressure at the inlet.

The combination of the thermal and the Coriolis flow sensor into a single chip flow sensing system results in a measurable flow range of 0.1 up to 2100 µl/h, a dynamic flow range of more than 4 decades.

CONCLUSIONS

We have designed and realized a micromachined single chip flow sensing system covering an unprecedented ultra-wide dynamic flow range of more than 4 decades, from 0.1 up to 2100 µl/h. The system comprises both a thermal and a micro Coriolis flow sensor with partially overlapping flow ranges.

The thermal flow sensor consists of a silicon nitride microchannel with resistors positioned on it, which function both as heater and sensor, and are connected in a Wheatstone bridge configuration. Its measurable flow range goes from 0.1 up to 40 µl/h.

The Coriolis flow sensor consists of a vibrating tube. Fluid flow inside the vibrating tube results in Coriolis forces that are capacitively detected. Its measurable flow range was found to be 10 up to 2100 µl/h.

The flow sensing system was realized using thin-walled silicon nitride channels.

ACKNOWLEDGMENTS

This research was financed by the Dutch MicroNed, PIDON High Tech Factory and Kenniswerkers programs. The authors would like to thank the industrial partners in these projects for many fruitful discussions.

REFERENCES

[1] M. Dijkstra , M.J. de Boer , J.W. Berenschot , T.S.J. Lammerink , R.J. Wiegerink and M. Elwenspoek, *J. Micromech. Microeng.* **17** (2007) pp. 1971-1977

[2] R.J. Wiegerink, T.S.J. Lammerink, M. Dijkstra and J. Haneveld, *Procedia Chemistry, 1 (1)* (2009), pp. 1455-1458

[3] M. Dijkstra, T.S.J. Lammerink, M.J. de Boer, R.J. Wiegerink and M. Elwenspoek, *Proc. MEMS* (2009) pp. 479-482.

[4] J. Haneveld, T.S.J. Lammerink, M.J. de Boer, R.G.P. Sanders, A. Mehendale, J.C. Lötters, M. Dijkstra and R.J. Wiegerink, *J. Micromech. Microeng.* **20** (2010) 125001

[5] Y. Mizuno, M. Liger, Y-C. Tai, *Proc. MEMS* (2004), pp. 322-325.

[6] P. Enoksson, G. Stemme and E. Stemme, *J. MEMS* 6 (1997), pp. 119-125.

[7] D. Sparks, R. Smith, J. Cripe, R. Schneider, N. Najafi, *Proc. IEEE Sensors Conference* (2003), pp. 90-92.

[8] M. Dijkstra, M.J. de Boer, J.W. Berenschot, T.S.J. Lammerink, R.J. Wiegerink, M.C. Elwenspoek, Sensors and Actuators A: Physical (2008), 143 (1). pp. 1-6

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