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Thermal and Coriolis type micro flow sensors based on surface channel technology

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Abstract

Recently, we proposed a fabrication technology to realize fluidic channels at the surface of a silicon wafer [1]. The channels have semi-circular cross section and a flat top so that low hydraulic resistance is combined with easy integration of actuation and readout structures. In this paper we present a number of flow sensors that have successfully been realized using this technology. Thermal flow sensors were realized in which heating resistors and thermopile sensors were integrated on top of freely suspended channels. With these sensors, a resolution in the order of nl/min can be achieved. Furthermore, Coriolis type flow sensors have been realized in which a freely suspended channel is brought into vibration so that the moving fluid experiences Coriolis forces. The Coriolis forces excite another vibration mode which can be detected optically or capacitively.

Keywords: flow sensors; surface channel technology; thermal sensors; Coriolis flow sensor

1. Introduction

Integrated microfluidic systems have gained interest in recent years for many applications including (bio)chemical, medical, automotive, and industrial devices. A major reason is the need for accurate, reliable, and cost-effective liquid and gas handling systems with increasing complexity and reduced size. In these systems, flow sensors are generally one of the key components.

Most MEMS flow sensors are based on a thermal measurement principle. It has been demonstrated [1, 2] that such sensors are capable of measuring liquid flow down to a few nl/min. These sensors require accurate measurement of very small flow-induced temperature changes. The accuracy of thermal flow sensors is limited by drift in material properties of the thin film materials that are used and by the influence of external temperature gradients. In this paper, we will show a sensor design that is insensitive to drift by using power control in combination with thermopile measurement of the flow-induced temperature difference. Furthermore, the influence of external temperature gradients is cancelled by a meandering tube design.

A general problem of thermal flow sensors is that the measurement is highly dependent on fluid properties like density and specific heat so that the sensor needs to be calibrated for each specific fluid and cannot be used for varying mixtures of fluids. Therefore, research has been done towards a micro Coriolis flow sensor, i.e. a flow

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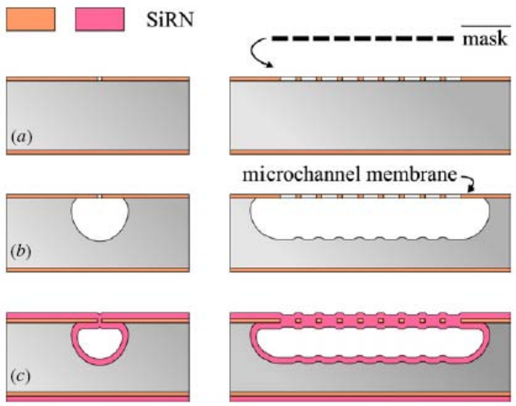
sensor containing a vibrating tube segment in which a mass flow is subject to Coriolis forces. The Coriolis forces are directly proportional to the mass flow and independent of temperature, pressure, flow profile and fluid properties.

2. Surface channel technology

The continuing downscaling of MEMS fluidic devices requires the fabrication of small microchannels with the ability to integrate various types of solid-state transducer structures. Often these structures need to be in close proximity to the fluid. For instance, in thermal applications the fluid should be heated or the fluid temperature has to be measured. Moreover, the microchannels often need to be suspended freely to achieve thermal isolation from the heat-conducting substrate or to allow the channel to move or vibrate. For this purpose, a surface channel technology was developed resulting in almost semi-circular channels embedded in the silicon substrate [3].

Surface microchannels are fabricated using a one-mask process scheme as indicated in Fig. 1. The mask layout defines etch holes, 2 μm in width, combined into segmented lines, where each line defines a microchannel. The mask layout is transferred into a 500 nm tensile low-stress (<300 MPa) silicon-rich silicon nitride (SiRN) layer deposited by LPCVD (Fig. 1(a)). The channels are isotropically etched through the etch holes, leading to the coalescence of neighbouring etch surfaces, resulting in long channels with semicircular profiles (Fig. 1(b)). Applying etch holes in a slightly tensile SiRN layer ensures the mechanical stability of the SiRN microchannel membranes formed during etching. This means that the etch holes can be properly sealed by a second LPCVD SiRN deposition (Fig. 1(c)). The inside surfaces of the microchannels are uniformly coated by SiRN during the deposition, where the thickness is limited by the sealing of the etch holes.



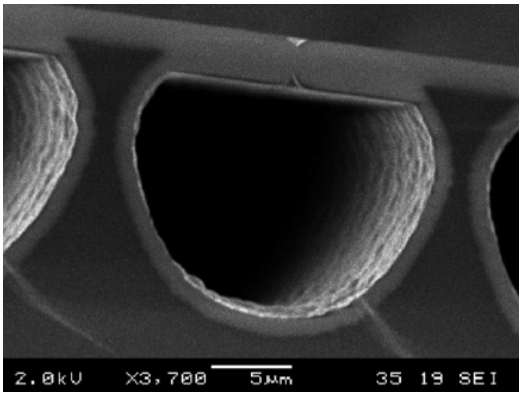


Fig. 1. Surface microchannel process scheme, applying a single mask defining etch holes in a 500 nm SiRN layer and a SEM photograph of the resulting micro channels.

3. Low drift thermal flow sensors

Important problems limiting the accuracy of micromachined thermal flow sensors are drift in the electrical resistance of thin-film metal layers used for heating, and temperature sensing, and the influence of external temperature gradients [4]. Previously, it was proposed to use a thermopile in combination with feedback operation to eliminate drift [5, 6]. In fact, a feedback loop is not necessary and the same result can be obtained by exploiting the linear relation between the applied heating powers and the resulting thermopile voltage. Furthermore, a special symmetrical flow channel layout can be used to eliminate the influence of external temperature gradients [7]. A meandering layout is used for the fluidic microchannel so that the temperature gradients due to fluid flow and ambient temperature can be distinguished from each other as indicated in Fig. 2. The meandering thermopile adds-up the contributions from fluid flow but cancels the contributions from ambient gradients. Furthermore, the thermopile direction is perpendicular to the flow channels and in first order does not reduce sensitivity due to parasitic heat flow through the thermopile material. Different designs are however possible.

Fig. 3 shows the thermopile voltage V_{TC} dependency on water flow rate Q up to 550 $nl \cdot min^{-1}$ at various applied heating powers. The sensor shows linear sensitivity up to flow rates of about 100 $nl \cdot min^{-1}$. The heater temperature decreases at higher flow rates, causing the sensor output to decrease according to King's law. The dashed lines show fitted FEM results after scaling calculated temperature differences to measured voltages.

A temperature-gradient measurement setup was constructed in order to determine the influence of external temperature gradients on the thermopile voltage. The setup consists of a 5 mm thick Cu plate, which is heated from one side by a resistor dissipating 25 W, while the other side is connected to a large aluminum plate acting as heat sink, thus creating a well defined temperature gradient of approximately 2.8 $K\cdot cm^{-1}$. An ambient temperature-gradient compensated flow sensor and an uncompensated single-microchannel flow sensor, for comparison, were measured, with both sensors having nearly equal amounts of thermopile junctions. The ambient temperature-gradient compensated flow sensor shows to be completely compensated for external temperature gradients (Fig. 3). The uncompensated flow sensor shows a figure-of-eight sensitivity pattern, because the sensor is only sensitive to temperature gradients parallel to the microchannel.

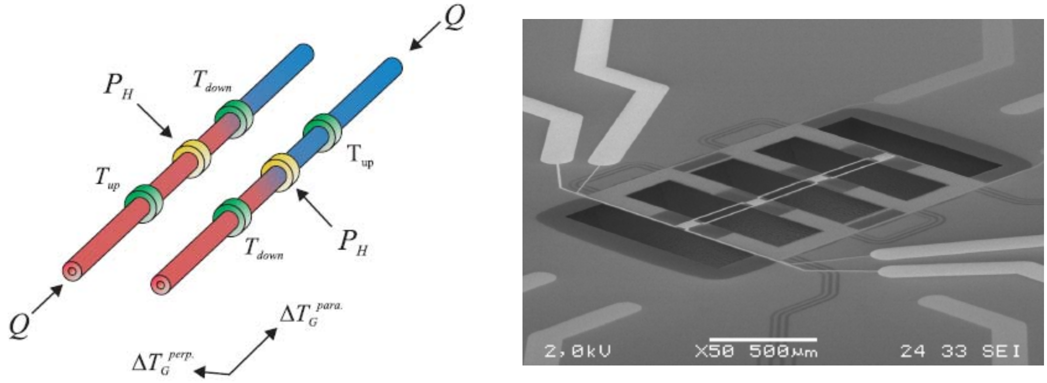


Fig. 2. Thermal flow sensor compensated for gradients in ambient temperature. Left: Principle of operation with fluid flow *Q*, and heating elements P_H. Fluid flow generates a temperature difference between the up- and down-stream sensors whereas an additional gradient due to ambient is cancelled. Right: Photograph of a realized sensor with four parallel channels and integrated Al heater resistors and Al/poly Si++ thermopiles.

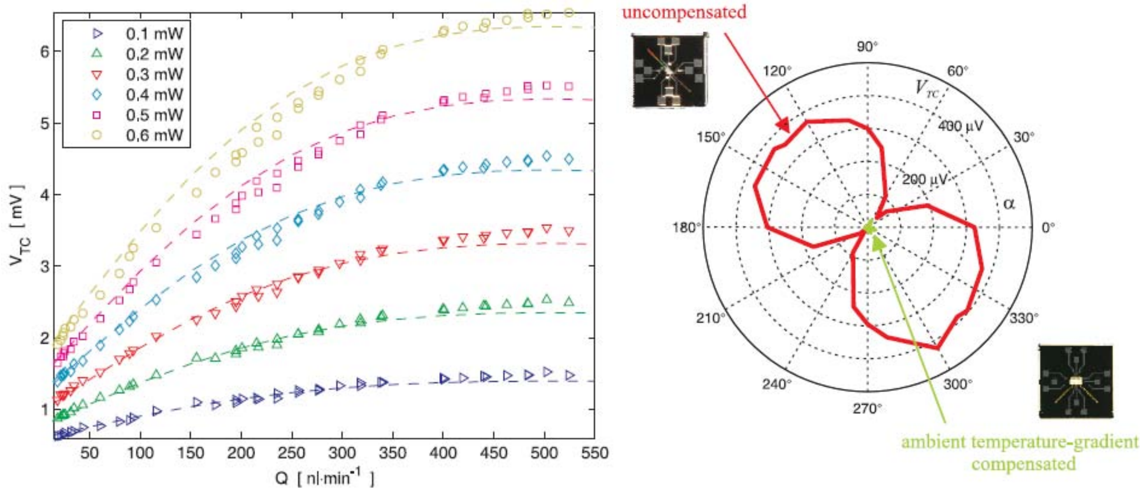


Fig. 3. Left: Flow sensor thermopile-voltage V_{TC} dependency on water flow rate *Q* at various applied total heating powers. Dashed lines show fitted FEM results. Right: External temperature-gradient sensitivity of the thermopile voltage V_{TC} measured for a compensated sensor and a single-microchannel uncompensated flow sensor.

4. Coriolis flow sensor

An important advantage of Coriolis sensors is that they are sensitive to the true mass flow, independent of flow profile, pressure, temperature and properties of the fluid (density, viscosity, etc.). Fig. 4 shows a SEM photograph of a realized Coriolis sensor [8] based on a rectangular tube shape. The tube is actuated in a torsion mode. The Coriolis force induces a "flapping mode" vibration with amplitude proportional to the mass flow. The movement of the rectangular sensor tube is measured capacitively using electrodes on a parallel tube which does not move. Flow measurements of the Coriolis movement were done for water, ethanol and white-gas, for liquid flows up to 1.2 ml/hr, see Fig. 4. The sensor output shows excellent linearity, and a comparison of the output signals for the three liquids confirms that mass flow is indeed measured: the slopes of the three graphs are proportional to the density of the measured medium.

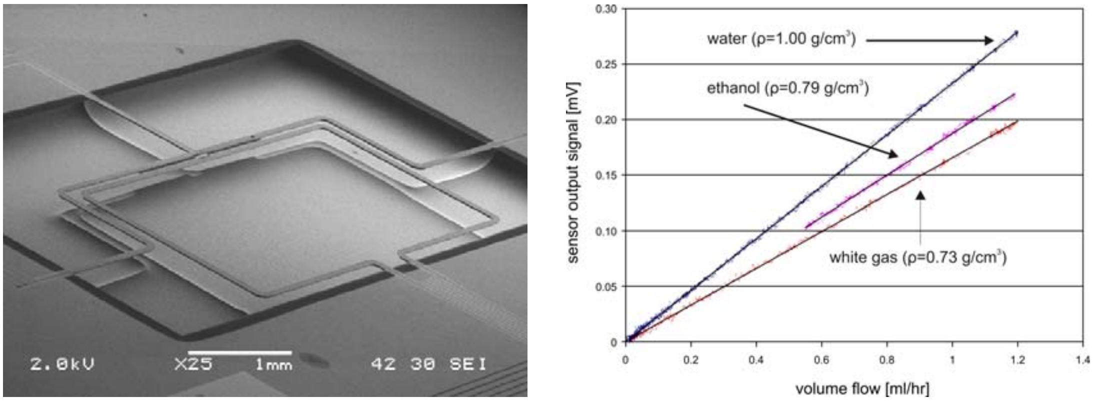


Fig. 4. Left: SEM photograph of a realized Coriolis flow sensor. Right: Measurement results for three different fluids: water, ethanol and white gas, demonstrating that the sensor indeed measures real mass flow (the output signal is proportional to the volume flow times the density of the fluid; independent of the fluid).

5. Conclusion

A recently proposed fabrication technology for semi-circular surface channels proofs to be very suitable for realization of both thermal and Coriolis type flow sensors. In the case of thermal flow sensors, the channels provide low hydraulic resistance in combination with thermal isolation from the substrate. A special meandering channel design almost completely eliminates the influence of external temperature gradients. Although less sensitive than thermal flow sensors, Coriolis type sensors can still be very useful because the mass flow is measured, independent of fluid properties and temperature.

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