MEMS-based Micro Coriolis mass flow sensor

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Abstract
We have realized a micromachined micro Coriolis flow sensor consisting of a silicon nitride resonant tube of 40 µm diameter and 1.2 µm wall thickness. First measurements with both gas and liquid flows have demonstrated an unprecedented mass flow resolution in the order of 10 mg/hr at a full scale range of 1 g/hr. The sensor can simultaneously be used as a density sensor.

1 Introduction
Integrated microfluidic systems have recently gained interest in many applications requiring accurate, reliable, and cost-effective liquid and gas handling systems. Most MEMS flow sensors are based on a thermal measurement principle capable of measuring liquid flows down to a few nl/min [1,2]. However, an important drawback of the measurement is the highly dependency on temperature and fluid properties.

The Coriolis type flow sensor presented in this paper consists of a vibrating tube being driven at the torsional resonance frequency of 3.0 kHz by Lorentz actuation. A mass flow inside the tube results in Coriolis forces that cause a secondary deflection mode which can be detected. Figure 1 shows a schematic drawing. Because the Coriolis force is directly proportional to the angular velocity and the mass flow, the Coriolis sensor is sensitive to the true mass flow, independent of flow profile, pressure, temperature and properties of the fluid (density, viscosity, etc.). Mostly, Coriolis-flow meters [3,4] are used for large flow rates, since the relatively weak
Coriolis forces are correspondingly harder to detect for small flows. The resonant tube is actuated in a “torsion mode” as shown in Figure 1 indicated by $\omega$. A mass flow $\Phi_m$ inside the tube results in a Coriolis force $F_c$ that can be expressed by:

$$\vec{F}_c = -2L \omega \times \vec{\Phi}_m$$

(1)

Where $L$ is the length of the rectangular tube (see Figure 1). The Coriolis force induces a “flapping mode” vibration with an amplitude proportional to the mass flow.

![Figure 1: a) Rectangle-shaped Coriolis flow sensor. b) Measured torsion mode using a PolyTec laser vibrometer setup.](image)

2 Resonant tube design

Earlier attempts to realize micromachined Coriolis flow sensors [5,6] were aimed at using silicon as the material for the tube. This has the disadvantage that there is no complete freedom in the choice of the resonant tube shape, and the tubes have a rather thick wall (in the order of 100 $\mu$m). In this paper we propose to use silicon nitride, which results in a thinner tube wall so that the mass of the tube can be smaller compared to the mass of the moving fluid. In addition, channels completely made of silicon nitride ensure inertness of the resonant tube to virtually all chemicals.

The tube is designed for fluid flow rates up to 1 g/hr, with a maximum pressure drop in the order of 1 bar (using water). The dimensions of the tube outline shape are 2.5x4 mm, with an inner diameter of approximately 40 $\mu$m. The tube is actuated by Lorentz forces using a constant external magnetic field in combination with an alternating current through a platinum track on top of the channel.
3 Fabrication
The resonant tube structures were fabricated using the surface-channel technology described in [7,8] and outlined in Figure 2. A 500 nm thick silicon-rich nitride ($\text{Si}_x\text{N}_y$) layer is deposited on a silicon wafer. The nitride is patterned with arrays of 6x2 µm holes, spaced 2 µm apart. A RIE step is performed, as shown in Figure 2a, defining the channel shape. A second $\text{Si}_x\text{N}_y$ layer is deposited and forms the channel wall and seals the etch holes, as shown in Figure 2b. Subsequently a 10/100 nm layer of chromium/platinum is sputtered (Figure 2c) to create the metal track which will facilitate Lorentz force actuation of the structure. Finally, the structure is released (Figure 2d) by KOH wafer-through etching. Figure 3 shows a close-ups of the nitride.

![Fabrication Process Diagram]

Figure 2: Outline of the fabrication process. Left column: cross-section perpendicular to the resonant tube. Right column: cross-section along the length of the tube.

4 Measurements
Mass flow measurements have been performed using water, ethanol and nitrogen. The tube is actuated in torsion mode at an amplitude in the order of 4 mRad. Figure 1b shows an image of the resulting torsional vibration mode. Point P has been monitored by a laser vibrometer to measure the out-of-plane displacements of the tube due to the Coriolis force. At zero flow this point shows no out of plane motion. The torsional resonance frequency of the empty tube is approximately 3 kHz. This
frequency decreases to 2 kHz when filled with water. The vibration amplitude is linearly dependent on the actuation current. Figure 4a shows the displacement amplitude as a function of volume flow for both water and ethanol. The difference in the slope of the two lines is exactly equal to the relative density of ethanol compared to water, indicating that the device measures mass flow directly. The offset in the velocity/flow rate graph is due to non-perfect alignment of the tube to the external magnetic field, but that the effects on sensitivity of the sensor are negligible. The zero-stability of the sensor is better than 1% of the full-scale of 1 g/hr. Figure 4b shows the measured torsional resonance frequencies for water, ethanol and nitrogen.

Figure 3: a) SEM photograph (view from the bottom of the chip) of the resonant tube entering the silicon support. b) The complete resonant tube loop.

Figure 4: a) Measured resonance frequency as a function of the medium density. b) Measured output signal as a function of volume flow for water and ethanol.
Mass flow measurement have also been performed using argon gas resulting in a response of the sensor corresponding to the measurements using water. The Coriolis sensor also functions as a density sensor. Figure 4b shows the measured torsional resonance frequencies for water, ethanol, a 1:1 mixture of water and ethanol, and nitrogen. Very good $1/f^2$ dependency is observed.

5 Conclusions
We have successfully fabricated and tested a micro Coriolis mass flow sensor. The experiments show excellent linear behavior of the sensor, combined with good resolution in the order of 0.01 g/hour. Sensor output signal offset was observed and shown to be a result of non-perfect alignment of the sensor to the actuation magnetic field.

References: