MICRO CORIOLIS MASS FLOW SENSOR WITH PIEZOELECTRIC TRANSDUCERS FOR BOTH ACTUATION AND READOUT

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ABSTRACT

We have realized a micro Coriolis mass flow sensor with piezoelectric transducers for both actuation and readout, resulting in lower power consumption and improved robustness to shock in comparison to the current actuation and readout methods. The PZT thin film in the parallel plate piezoelectric transducers was deposited by pulsed laser deposition (PLD). This paper presents the design, fabrication process and initial characterization results with mass flow of water and nitrogen.

KEYWORDS

Coriolis mass flow sensor, Piezoelectric transducers, PZT.

INTRODUCTION

Micro Coriolis mass flow sensors are based on vibrating microfluidic channels. Fluid flow inside the channel results in Coriolis forces that induce a secondary vibration with an amplitude proportional to the mass flow [1]. Micro Coriolis mass flow sensors with electrostatic actuation [2], [3], Lorentz force actuation [4], [5] and piezoelectric actuation [6] have been reported. The channel movement was measured optically [2], [7], capacitively [1], [8] or by resistive strain gauges [9]. However, the above mentioned actuation and sensing methods have their respective limitations. Electrostatic actuation requires either a high actuation voltage or a high quality factor to achieve enough amplitude. Lorentz force actuation results in relatively large power consumption and heating of the channel [6]. Furthermore, external components are needed to generate the magnetic field. Optical measurement requires an external measurement setup and is up to now only used in a lab environment [2], [7]. A capacitive readout typically requires a high frequency carrier signal and demodulation circuitry [10], limits the actuation amplitude due to nonlinearity [11], and results in a relatively fragile device that can be damaged by external shocks. To address these issues it was proposed to use resistive strain gauges, however this resulted in significantly lower sensitivity [9].

This paper presents a device that uses piezoelectric transducers for both actuation and readout. The piezoelectric actuation is compact and has low power consumption [6]. A piezoelectrically actuated Coriolis flow sensor can operate in atmospheric pressure with less than 0.5V actuation voltage. The piezoelectric readout structure is resistant to shocks, produces a strong signal, and requires a relatively simple electronic interface circuit, resulting in a further reduction of power consumption. The direct and inverse piezoelectric effects can be exploited so that both the actuation and readout can be integrated on one chip.

DESIGN AND OPERATION PRINCIPLE

A photograph of the micro Coriolis mass flow sensor with PZT piezoelectric transducers is shown in Figure 1. The rectangular loop of the microfluidic channel is actuated with the piezoelectric actuators marked 1 and 2, which are 1.5 mm long to enable a large displacement. Three parallel transducers are used to allow underetching during the release etch of the channel. The microfluidic channel loop is suspended from one side at two anchor points. The displacement and bending of the channel are sensed by the two piezoelectric transducers 3 and 4 near the anchor points. The transducers for sensing are shorter to increase sensitivity. To avoid crosstalk, the sensing transducers are placed away from the actuators and the silicon substrate is grounded. Figure 2 shows a cross sectional drawing of a piezoelectric transducer, which is on top of a silicon nitride support structure. The transducers consist of platinum top and bottom electrodes with a 1µm thick PZT layer in between, exploiting the transverse piezoelectric effect. One side of the silicon nitride support is connected to the silicon body and the other side is connected to the suspended channel.

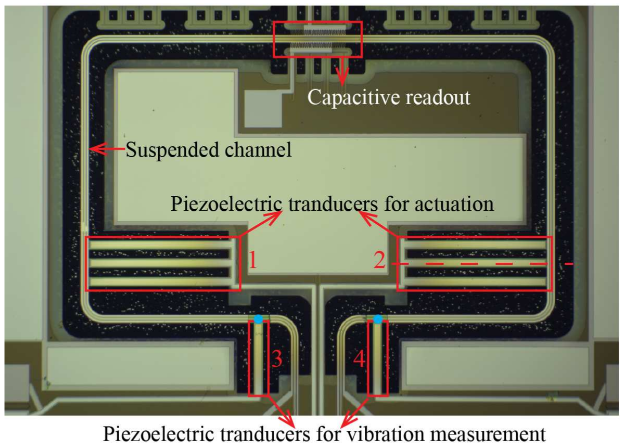

Figure 1: Microscope photograph of the fabricated micro Coriolis flow sensor with piezoelectric actuation and readout. Transducers 1 and 2 are used for actuation and 3 and 4 are used for sensing. The blue dots indicate the points that were used for vibrometer measurements.

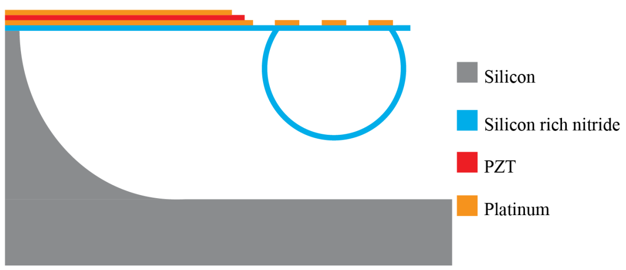

Figure2: Cross-sectional drawing along the red dashed line in Figure 1. All piezoelectric transducers have a similar cross section.

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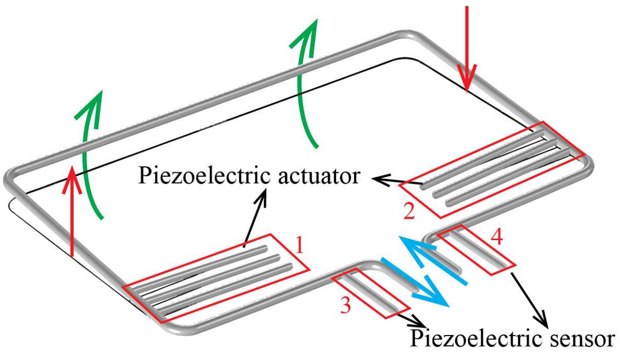
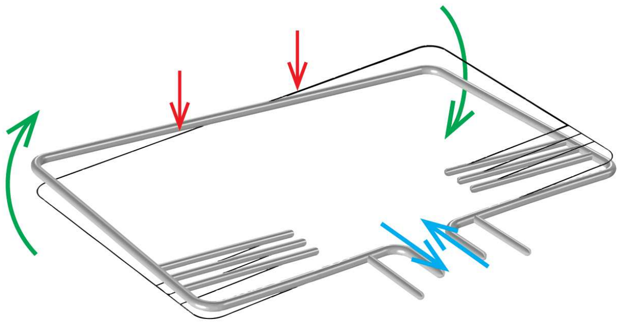
Figure 3 shows schematic drawings of the channel and the actuation modes. The structure is actuated in swing mode by driving the two actuator sets with the same sinusoidal signal, and in twist mode by driving with two signals with 180° phase shift. When actuated in swing mode the Coriolis forces due to mass flow will result in a twist mode vibration, and vice versa. The two piezoelectric sensors are sensitive to both vibration modes, but the swing mode results in a common signal and the twist mode results in a differential signal. When there is no fluid flow inside the channel, the phase difference between the output signals is close to 0° in the case of swing mode actuation and close to 180° in the case of twist mode actuation. A fluid flow inside the channel will result in an additional phase shift between the two signals which is proportional to the mass flow.



(a) Swing mode actuation



(b) Twist mode actuation

Figure 3: Illustration of the two possible actuation modes and their corresponding Coriolis mode. The thin black lines indicate the tube shape at rest. The blue arrows indicate the fluid flow direction. The green arrows indicate the actuation mode and the red arrows indicate the direction of the Coriolis force.

FABRICATION

The fabrication process of the device is based on [6] with some adjustments to integrate the PZT transducers. An outline of the process is shown in Figure 4.

First, a 500 nm thick layer of silicon-rich silicon nitride (SiRN) and a 500 nm thick layer of SiO_2 are deposited on a silicon wafer. The SiO_2 acts as a hard mask for SiRN patterning. The SiO_2 and SiRN layers are patterned with rows of slits of 5 by 2 µm (Figure 4a). The silicon underneath is isotropically etched through the slits to form the channel shape.

Next, a layer of silicon dioxide is deposited to temporarily protect the channel walls (Figure 4b). Then fluidic inlets are etched from the backside of the wafer using deep reactive ion etching, stopping on the silicon dioxide layer. Subsequently the silicon dioxide layer is totally removed (Figure 4c).

Next, another layer of SiRN is deposited to form the channel wall and close the slits in the first SiRN layer. Then, a Ta/Pt/LNO/PZT/Ta/Pt stack is deposited on the top surface (Figure 4d). Ta and LNO are used as adhesion layer and not shown in the figure. The PLD deposition of the LNO/PZT layers was presented in [12].

Next, the material stack was patterned to form the piezoelectric transducers and metal structures (Figure 4e). Finally, a layer of Al_2O_3 was deposited as hard mask and with the hard mask, the suspended microfluidic channel was released by etching openings in the SiRN layer followed by isotropic etching of silicon through these openings (Figure 4f).

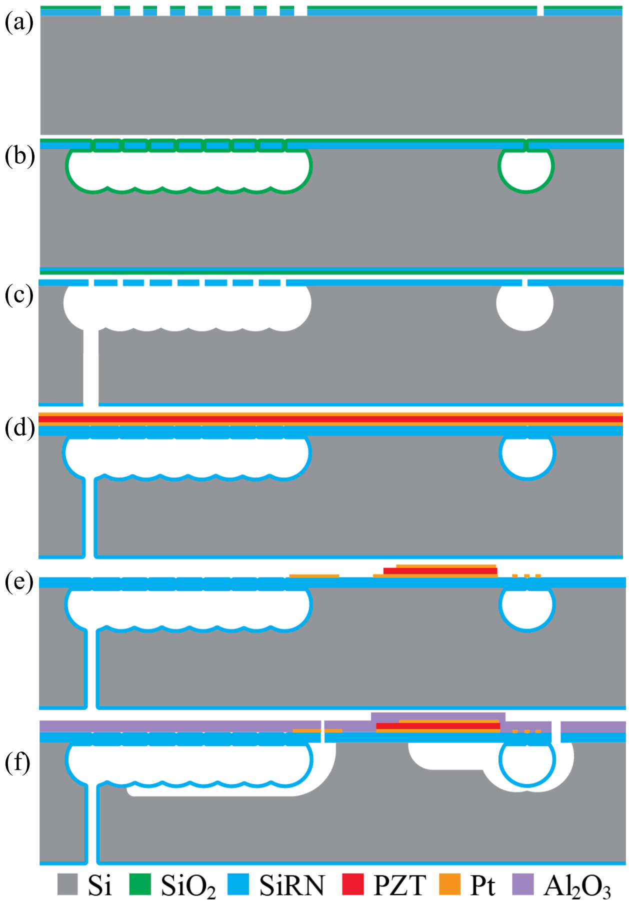


Figure 4: Schematic cross section of the wafer during the fabrication process. The left half shows the cross section along the channel, the right half shows the cross section perpendicular to the channel.

MEASUREMENT SETUP

Figure 5 shows a schematic drawing of the fluidic and electric setup to measure the response of the device to mass flow. The figure shows the situation when measuring water flow with the device actuated in twist mode. Water and nitrogen were used as measurement medium. In case of water flow, a Bronkhorst µ-FLOW flow controller was used to control and maintain a stable flow. In case of nitrogen flow, a Bronkhorst EL-Flow flow controller was used and the pressurized nitrogen source was directly connected to the flow controller.

During the measurements the sensor was actuated in both swing and twist mode. When actuated in swing mode, a sinusoidal signal with an amplitude of 0.3V was applied to both actuators. When actuated in twist mode, a sinusoidal signal with an amplitude of 0.2V was applied to one of the piezoelectric actuators and an inverted signal was connected to the other actuator as shown in Figure 5. Before performing the flow measurements, the resonance frequencies and vibration amplitudes of the swing mode and twist mode with nitrogen and water were measured with a Polytec MSA-400 laser Doppler vibrometer using the measurements points indicated by the blue dots in Figure 1. The frequencies and vibration amplitudes are summarized in Table 1.

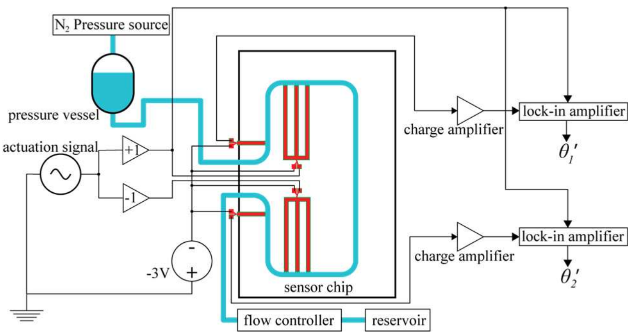


Figure 5: Schematic of the actuation and readout circuit and fluid path. This setup is for measuring water flow with the device actuated in twist mode. θ_1 and θ_2 represent the phase difference between the actuation signal and signal from the charge amplifier.

The output signals of the piezoelectric transducers were amplified by charge amplifiers and then measured using two Stanford SR830 lock-in amplifiers. In all measurements, the time constant of the lock-in amplifiers was set to 1s with the output also recorded every 1s. In the case of swing mode actuation, the Coriolis forces actuate the twist mode and the phase outputs of the lock-in amplifiers θ_1' and θ_2' relate to phase shift θ as follows:

$$2\theta = \theta_1' - \theta_2' \qquad (1)$$

In the case of twist mode actuation, the relationship is written as:

$$2\theta = \theta_1' - \theta_2' - \pi \qquad (2)$$

The measured phase shift is influenced by both the fluid flow and the fluid density. In order to measure the mass flow independent of the fluid density, the time delay Δt between the two signal needs to be calculated [13]:

$$\Delta t = 2\theta/(2\pi f) \qquad (3)$$

Where f represents the frequency of the actuation signal.

RESULTS AND DISCUSSION

Figure 6 shows the measured time delay versus mass flow for nitrogen and water in the case of twist mode actuation. Water flow was applied from 0.2 g/h to 1.6 g/h in steps of 0.2 g/h. Nitrogen flow was applied from 2 mln/min to 16 mln/min in steps of 2 mln/min, which corresponds to a mass flow range from 0.155 g/h to 1.24 g/h. For each flow rate, the flow was kept constant during 300 s and the phase shift was recorded 300 times.

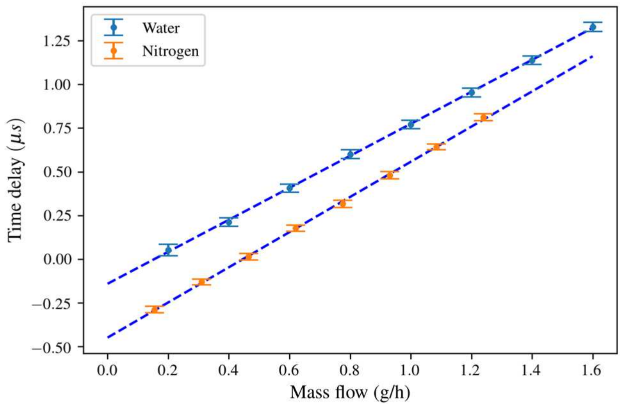


Figure 6: Measured time delay in case of twist mode actuation as a function of nitrogen and water mass flow. The error bars indicate two times the standard deviation of 300 samples taken at each flow rate.

The measured time delay shows a very good linearity with a sensitivity of 0.915 µs/(g/h) for water flow and 1.01 µs/(g/h) the nitrogen flow. The difference in offset between the water and nitrogen measurements may be induced by asymmetry due to fabrication inaccuracies, the difference in actuation frequency, or the compressibility of nitrogen and the resulting uneven mass distribution. The standard deviation of the measured time delays at each flow rate was below 0.03 µs for water and 0.02 µs for nitrogen. The latter is slightly smaller because of the higher resonance frequency.

Figure 7 shows the measured time delay versus nitrogen and water flow when the device was actuated in swing mode. The measurement protocol was similar to the twist mode actuation measurements.

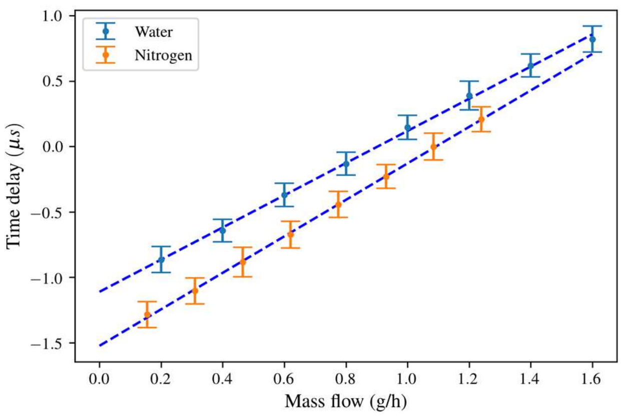


Figure 7: Measured time delay in case of swing mode actuation as a function of nitrogen and water mass flow. The error bars indicate two times the standard deviation of 300 samples taken at each flow rate.

Again the time delay is proportional to mass flow. The sensitivities are 1.23 µs/(g/h) and 1.39 µs/(g/h) for water and nitrogen, respectively. The standard deviation for nitrogen and water measurements were both around 0.1 µs. Due to the lower amplitude and lower actuation frequency when the device is actuated in the swing mode, the standard deviation for the measurements in swing mode is higher than in twist mode.

The sensitivities to mass flow in case of swing mode actuation and twist mode actuation mode are very similar and both relatively low. This is because the vibration amplitude in the Coriolis mode is a lot smaller than in the actuation mode [14], [15]. The measurement results show that the piezoelectric sensing transducers have a similar sensitivity to both swing mode and twist mode. In order to reach a higher sensitivity to mass flow, the design of the sensing transducers needs to be adjusted so that the actuation mode results in a smaller contribution to the output signal [16], [17].

A summary of the measurement results is given in Table 1. The time delay per unit mass flow of nitrogen is slightly higher than that of water for both swing mode and twist mode. This is probably because the mode shapes are slightly dependent on the density of the fluid inside the tube [13].

CONCLUSION

We have successfully fabricated and characterized a micro Coriolis mass flow sensor that uses piezoelectric transducers for both actuation and readout. The sensor operates with low actuation voltage and low power consumption and does not require additional components like external magnets or optical setup. The current design shows good linearity for both water flow and nitrogen flow and both swing mode actuation and twist mode actuation. Future work will focus on improving the piezoelectric transducer design and readout electronics for sensitivity improvement.

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Table 1: Measured phase shift for piezoelectric transducers

Mode	Twist		Swing	
Fluid	Water	Nitrogen	Water	Nitrogen
Actuation frequency (Hz)	1644.6	2479.2	1016.9	1594
Amplitude (nm)	331	147.5	162.3	41
Time delay per mass flow (μs/(g/h))	0.915	1.01	1.23	1.39

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