A MICRO CONTROL VALVE WITH INTEGRATED CAPACITIVE SENSING FOR AMBULANT BLOOD PRESSURE WAVEFORM MONITORING

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ABSTRACT

We have designed and fabricated the first single-wafer proportional micro control valve with built-in capacitive displacement sensing. The displacement sensor can facilitate high-speed active proportional control of gas flow through the valve. This is an essential requirement for non-invasive blood pressure waveform monitoring based on following the arterial pressure with a counter pressure. We demonstrate a near-linear relation between valve plate displacement and inverse capacitance. The valve shows monotonously increasing flow with decreasing capacitance and increasing pressure.

KEYWORDS: Microvalve, Capacitive, MEMS, Proportional Control, Blood Pressure Waveform

INTRODUCTION

Cardiovascular disease and hypertension are partners in a vicious circle leading to death. Predisposition to hypertension expresses itself in the morphology of the arterial blood pressure waveform. Non-invasive, real-time monitoring of the blood pressure waveform can therefore be used to screen for cardiovascular disease.

A proven technology for blood pressure waveform monitoring applies a controlled gas pressure in a finger sleeve to keep the volume of the unloaded artery constant. This is done by measuring the finger's phototransparency, and ensures that the counter pressure equals the arterial pressure (see Figure 1) [1]. Current solutions for ambulant applications remain bulky, and further downscaling is currently limited by the flow control system. Apart from small dimensions, this flow control system primarily requires a high control bandwidth to closely follow the blood pressure waveform. Provided the relation between displacement and gas flow is characterized accurately, high-speed capacitive displacement sensing can offer improved fluidic control bandwidth through position-based feedforward control of the valve. Capacitive readout has previously been achieved using bonded wafer designs [2]. Proportional, active control valves with integrated capacitive displacement sensing have not yet been reported using a single-wafer fabrication process.

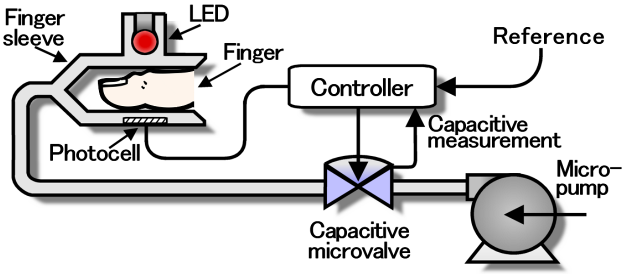


Figure 1: Application of the capacitive microvalve in a portable blood pressure sensing device. The microvalve controls flow to keep the photocurrent equal to the reference [1].

This paper describes the design, fabrication and characterization of an SOI-based microvalve with capacitive displacement sensing for proportional control of gas flow, for application in ambulant, real-time blood pressure waveform monitoring systems.

DESIGN AND FABRICATION

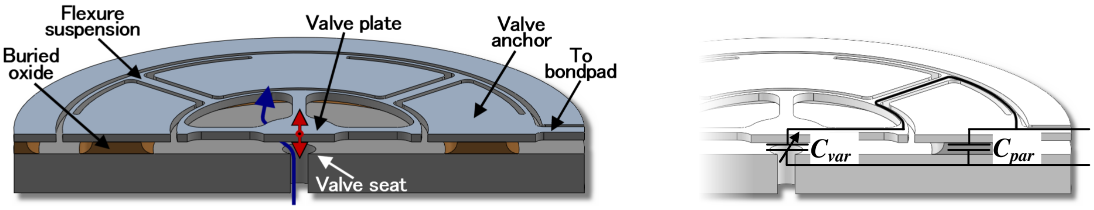
A schematic cross-sectional drawing of the microvalve design is shown in Figure 2a. A translating plate design is chosen as it allows very large design freedom to simplify fabrication [3]. The valve plate is suspended by electrically conducting flexure beams, separated from the valve seat by the thickness of the buried oxide. The conducting beams are contacted through a bond pad on the outer edge of the chip, allowing capacitive measurements across the microvalve. The electrical model of the valve consists of a variable capacitance C_{var} between plate and seat, connected in parallel to constant parasitic capacitances C_{par} between the top and bottom layers (see Figure 2b).

The measured capacitance between the valve plate and seat $C_{meas} = C_{var} + C_{par}$ is an inverse measure for the valve separation. A normalized capacitance C_n compensating for the parasitic capacitance is defined as:

$$C_n = \frac{C_{meas} - C_{par}}{C_0 - C_{par}} \tag{1}$$

Where C_0 is the initial capacitance at maximum valve-seat separation.

Fabrication of the capacitive microvalve is relatively straight-forward, similar to the process reported in [4]. It requires two deep reactive ion etching (DRIE) steps in a silicon-on-insulator wafer (400 µm handle layer, 50 µm device layer), and one sacrificial etch of the buried oxide. The oxide layer is 4 µm thick, to allow for large displacements for increased flow. This also means the valve is normally open. Given a good control over the etching speeds during DRIE and HF etching, this fabrication process is very robust and near-perfect yields can be achieved. The realized microvalve chip, shown in Figure 3, is 7.5 mm in diameter and 0.5 mm thick, which is suitable for ambulant applications but can be further miniaturized if so required.



(a) **(b)**

Figure 2: (a) Cross-sectional schematic view of the valve design. Gas flow is indicated in blue, valve movement in red. (b) Electrical model of the capacitive microvalve.

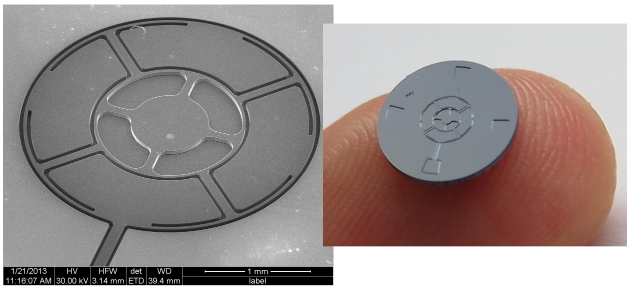


Figure 3: Close-up SEM micrograph (left) and full device photograph (right) of the realized microvalve.

CHARACTERIZATION

To use the capacitive displacement sensing in any feedforward configuration, an accurate characterization of the flow behavior of the microvalve is essential. The flow behavior has therefore been measured as a function of valve capacitance and differential gas pressure, using the measurement scheme shown in Figure 4. A PI P-603.3S2 piezoelectric actuator is controlled in feedback with an integrated strain gauge displacement sensor, capable of controlling the actuator displacement with 8 nm resolution. A PC software program controls this external actuator to change the valve plate displacement. The force applied to the microvalve is measured with a Futek LSM250 loadcell at 10.00 V supply voltage, and is transferred to the valve plate through a stiff glass needle.

A Bronkhorst P-602CV pressure controller is used to control a dry nitrogen gas flow through the microvalve, which is measured using a Bronkhorst F-111B gas flow meter with a maximum flow range of 22.4 sccm. Capacitance is measured using an HP 4194a impedance analyzer at 100 kHz.

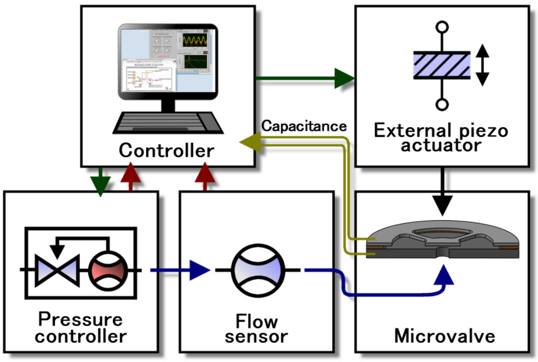


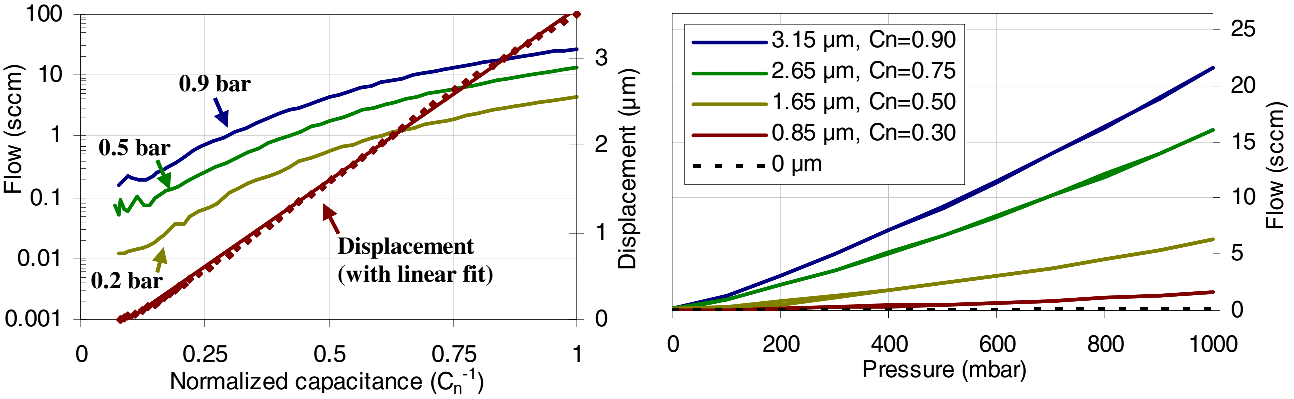
Figure 4: Schematic view of the setup used to characterize the microvalve flow behavior.

As the pressure is increased, a change in valve plate displacement is expected due to the pressure acting on the valve plate. To avoid this influencing the characterization process, the built-in capacitive displacement sensing is used to keep the valve plate displacement constant. For each separation value the capacitance is measured at zero pressure, and as the pressure is ramped up this capacitance is kept constant using the piezoelectric actuator.

EXPERIMENTAL RESULTS

Figure 5a shows the valve plate displacement and the gas flow as a function of the inverse of normalized capacitance C_n. A near-linear relation exists between displacement and inverse normalized capacitance, with a nonlinearity (standard linear regression error) of less than 0.03. Both gas flow and valve plate displacement show a smooth, continuous increase with decreasing capacitance, which is essential for proportional control applications. At very low C_n^{-1} values (closed valve) the flow is slightly unstable because of high sensitivity to variations in valve plate displacement at that point.

Keeping the displacement constant and ramping the gas pressure up and down results in the flow profiles shown in Figure 5b. Again a smooth, monotonously increasing flow profile is measured for all valve separation values. At 3.15 µm valve plate displacement ($C_n = 0.9$) and 0.5 bar inlet pressure the gas flow is 9.3 sccm. The maximum flow is strongly dependent on the displacement, so using a pulling actuator to increase valve plate displacement beyond the buried oxide thickness (4 µm and more) should allow for significantly larger gas flows. The maximum leak flow when the valve is closed is measured to be less than 0.07 sccm at 0.5 bar.



(a) **(b)**

Figure 5: (a) Gas flow and valve plate displacement as a function of inverse normalized capacitance. (b) Gas flow as a function of inlet pressure, measured at decreasing displacements (right).

CONCLUSION

A micromachined control valve for use in ambulatory blood pressure waveform measurements has been designed and realized. The valve has built-in capacitive displacement sensing, which has been used in flow characterization measurements to keep valve plate displacement constant with changing gas pressures. Flow characterization has shown monotonously increasing flow with increasing pressure and increasing valve separation. A near-linear relation between valve separation and inverse capacitance has been found. With these results, the potential of using the microvalve in proportional control of gas flow has been demonstrated.

The chip can be further optimized for smaller dimensions and higher flow rates. Future work will focus on integrating an actuator in the microvalve, characterizing the dynamic control properties and decreasing the leak flow.

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REFERENCES

[1] J. Peňáz et al., *Beitrag zur fortlaufenden indirekten Blutdruckmessung*, Zschr. inn. Med. 31, pp. 1030-1033 (1976)
[2] H. Scheurenbrand et al., *Micro-valve with capacitor plate position detector*, U.S. patent no. 6,182,941 (2001)
[3] M.S. Groen et al., *Design considerations for a micromachined proportional control valve*, Micromachines 3, pp. 396-412 (2013)
[4] M. Hu et al., *A silicon-on-insulator based micro check valve*, J. Micromech. Microeng. 14, pp. 382-387 (2004)

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