DESIGN CHALENGES FOR STEPPER MOTOR ACTUATED MICROVAVLE BASED ON FINE AND MICRO-MACHINING

Imran Fazal and Miko Elwenspoek

Mesa + research institute, University of Twente, P. O. Box 217, 7500 AE, Enschede, The Netherlands.

i.fazal@ewi.utwente.nl

Abstract — *we present a normally open stepper motor actuated microvalve based on micro and fine-machining technique. In this paper, first we have described how the larger controllable flow range can be achieved with simple micromachining techniques and secondly we have presented the results which show how the performance of the microvalve can be improved by using combination of different metal screws for mechanical transmission of power to deflect the membrane to control the flow of gas..*

.

Key Words: *Microvalve, fine machining, micromachining.*

I INTRODUCTION

This paper is the continuation of the stepper motor actuated microvalve [1]. Certain modifications have been made to enhance the performance of the microvalve presented earlier. The cross-sectional view of the previous design is shown in figure 1. Earlier, the membrane boss with exact size could not be realized by using KOH time stop etching and the needed resistance to control the flow of gas could not be achieved. In this paper we present the modifications made to the previous design. Additionally it is described how the performance of the valve can be affected by the wear in the screw threads during valve operation.

A study to design the microvalve for different operational modes has been carried out and all the modeling details have been presented earlier [1-3]. Based on the derived specifications, microvalve has been realized and characterized. The flow rate is measured as a function of gap height. Figure 2 shows the measured volume flow rate at a pressure difference of 4 bars for a microvalve with a static resistance length of 24 mm. It can be seen from figure 2 that the flow rate exceeds a flow of 200 ml/min at a gap height of approximately 9 μm instead of 22 μm. It has been explained earlier that it was due to small static resistance offered by the channels [1]. In fact, the channels with higher static resistance were not properly etched.

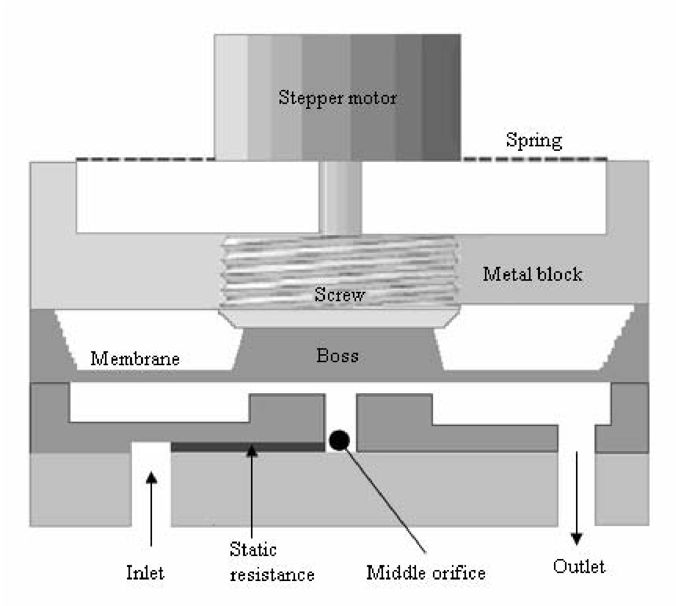

Figure 1: Schematic cross sectional view of the microvalve.

Figure 2 also shows the flow rate change is steeper as compared to the model (see figure 3). This is due to the lesser variable resistance offered by the small size membrane boss. In fact model shows that the lesser variable resistance results in a steeper change in flow. We could not realize the membrane boss with required dimensions of 2 mm^2 (see figure 4).

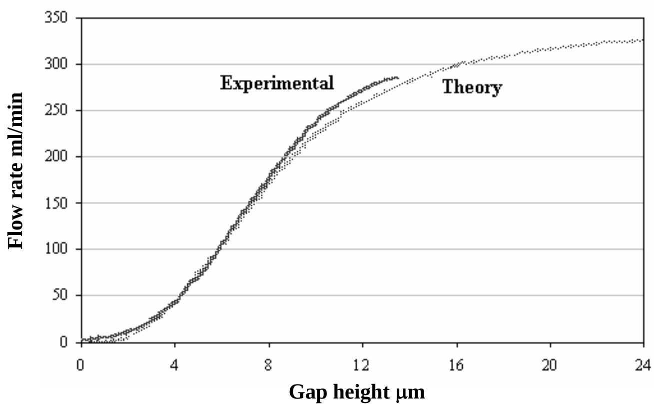

Figure 2: Flow reaches its maximum value at a gap height of 9 μm instead of 22 μm due to less static resistance available.

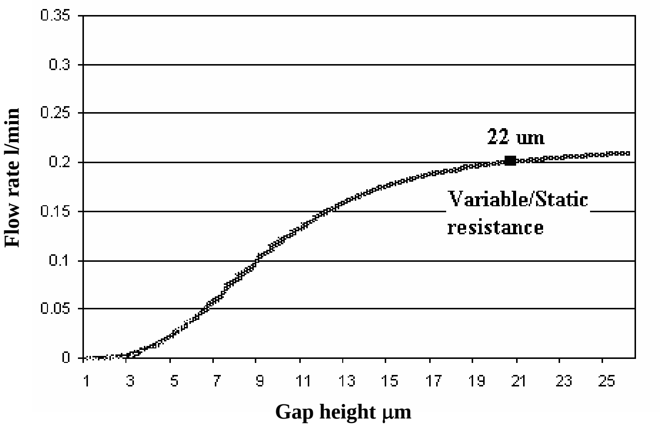

Figure 3: variable resistance provides more linearity and less steep flow behavior

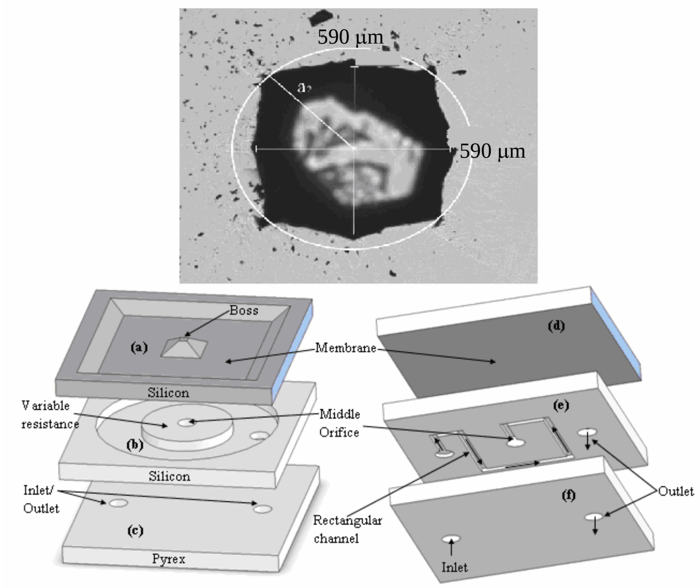

Figure 4: Square boss with required size could not be realized with KOH time stop etching

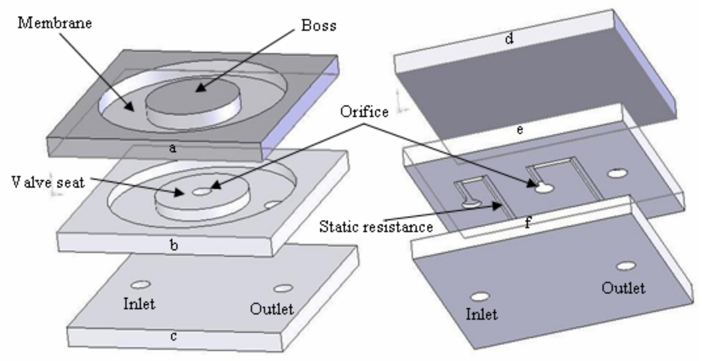

Figure 5: Three dimensional view of microvalve with circular boss

So in order to optimize the performance of the microvalve, square boss is replaced with the circular boss (see figure 5). In the following section fabrication of the micromachined part is described in detail.

II FABRICATION

The fabrication process of the valve is straightforward as it includes standard micro-machining steps. It includes the micro machining of three wafers as shown in figure 6. The fabrication is started with silicon membranes. They are fabricated primarily by patterning the mask layer of 908/35 photoresist. Using the photoresist as a mask layer, 100 µm thick circular membrane with circular boss is etched using BOSCH process for 28 minutes. Finally the photoresist is removed by 100% HNO_3 to get the membrane with the boss as shown in figure 6a.

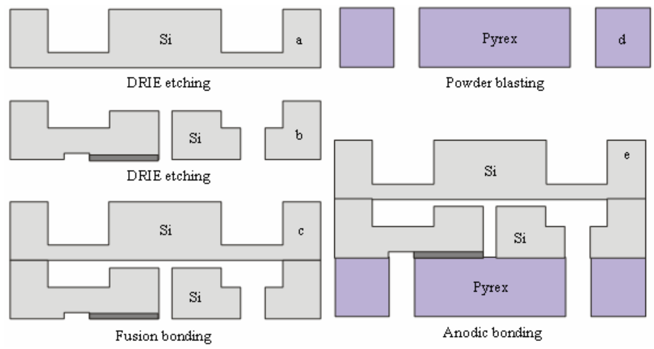

Figure 6: Fabrication of micromachined part

To realize the channels, the variable resistance and the orifices, a double-sided polished Silicon <100> substrate is used. As a first step, photo resist (917/17) as a mask layer, is patterned on the backside of the substrate. Using the photo resist as a mask layer, 60 µm rectangular channels are etched using the BOSCH process (B Fast) for 5 minutes (see figure 4e, 6b).

To fabricate the variable resistance and the orifice, three different layers are realized on the topside of the substrate. 1) A 1.2 µm layer of SiO_2 is grown by wet oxidation of silicon at 1150 °C. The SiO_2 layer is patterned which defines the square chamber around the valve seat. With this step the height between the valve seat and the membrane is defined. A 50 nm layer of chromium is deposited using a sputtering process (90 sccm Ar. flow, 5.0 E-3mbar, 200W). The chromium layer is patterned which defines the shape of the valve seat in the second etching step. Finally a layer of photo-resist (907-17) is patterned. This mask layer defines the orifice and outlet of the valve. Then the three etching steps are followed to realize the variable resistance, chamber and orifice with the BOSCH process. The parameters used for the BOSCH process are: Temperature: 10°C, C_4F_8 (2sec, 10 sccm, valve 100%), SF6 (13sec, 400 sccm, valve 15%), ICP: 2500W, CCP: 10W, SH: 110mm, He: 0.7sccm. Figures 6b and 2e show the middle wafer with channel, variable resistance, chamber and orifice. The inlet and the outlet are realized in the Pyrex wafer by powder blasting (particles 32 µm ALO_2) as shown in figure 6d.

The two silicon wafers are fusion bonded at 1100 °C in N_2. An Electronic Visions Aligner is used to align and to pre-bond the wafers. The final step is to anodic bond the fusion bonded silicon wafers and Pyrex wafer (see figure 6c, 6e). The anodic bonding is performed on a hot plate setup.

III RESULTS AND DISCUSSIONS

The flow rate is measured as a function of gap height. A schematic of the measurement setup is shown in figure 7.

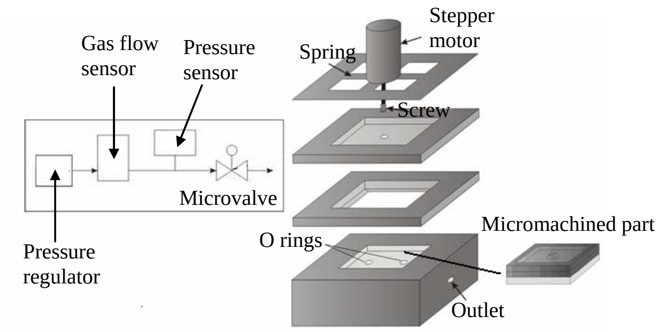

Figure 7: Experimental set up

A Bronkhorst flow meter is used to measure the flow of gas. The precision of the flow meter is 1% of the maximum flow. In front of the flow meter, a filter is placed to purify the air from dust particles, to avoid congestion of the valve. The pressure is measured by the pressure gauge in between the flow meter and the valve.

The measurement procedure starts by mounting the micromachined part into the holder as shown in figure 7. Then the stepper motor (120:1) is actuated in clockwise direction to rotate the screw downward till it came into contact with the membrane boss. Afterwards the membrane is deflected further till the volumetric flow of air reached the value of 0.5 ml/min. Then the valve is gradually opened by turning the stepper motor in anti clockwise direction till the flow reached its maximum value of 220 ml/min. The step size is set to 75 nm approximately. The volumetric flow rate is measured at a pressure difference of 4 bars between inlet and outlet. Figure 8 shows the measured volumetric rates at a pressure difference of 4 bar for a valve with a static resistance of 34 mm in length. It can be seen that the results predicted by the incompressible flow model of gas are in good agreement with the measurement. It can be observed that the introduction of the circular boss provides necessary resistance to avoid the steeper change in flow. Additionally the realization of the higher static resistance proved to be vital to achieve the larger controllable flow range.

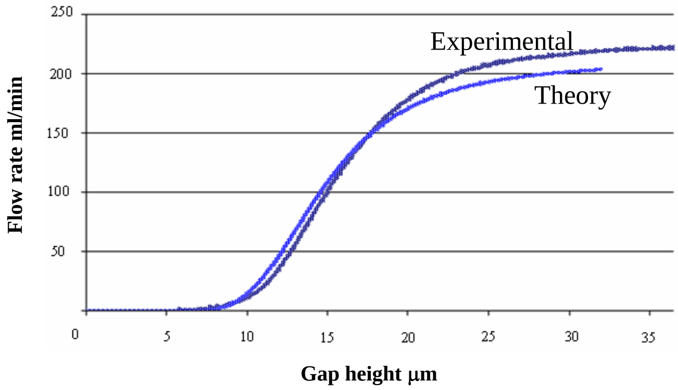

Figure 8: Experimental results are in accordance with the theory.

To examine the performance of the microvalve, wear tests have been performed for different metallic screws. The typical tensile strengths of several materials are given in the table 1.

Table 1: Typical tensile strength of some materials

Material	Yield strength (MPa)	Ultimate strength (MPa)
Brass	180	250
Titanium Alloy (6% Al, 4% V)	830	900
Structural steel ASTM-A36	250	400
Steel, high strength alloy ASTM A-514	690	760
Aluminum Alloy 2014-T6	400	455

Brass and Titanium (male) screws are characterized to examine the wear during valve operation. The maximum stress on the screw threads for a closed valve with pressure difference of 4 bar is calculated. The stress is calculated for a screw with a basic diameter of 2 mm and is given in table 2. The force on the bottom of the screw calculated previously (see table 2).

Table 2: Force and stress on the screw [4]

$F_{Pressure} = 1.88$ N $F_{Deflection} = \mathbf{0.6\ N}$	F_{Total} 2.48 N	Stress area for screw $A_t = \frac{\mu}{4}(D - 0.938194P)$
Stress $\sigma = F_{total}/A_t$	1.4 MPa<<180 MPa (Brass) 1.4 MPa<<830 MPa (Titanium)	

To examine the wear in the screw threads, the microvalve was set to operate back and forth for five days. It was opened, closed and kept in different intermediate states to observe any difference in the flow rates due to wear in the screw threads.

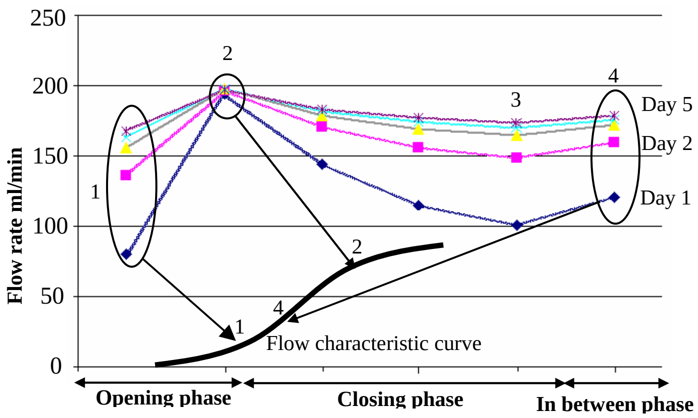

Figure 9: Combined effect of Hysteresis in stepper motor, change in ambient conditions and wear in the screw threads cause high difference in flow rates.

It can be observed that the there is considerable difference in flow at certain points. This high difference in flow rates is basically the combined effect of hysteresis in stepper motor, change in ambient conditions and little wear in the screw threads. If we will closely examine the results then we can attribute this change mainly to the characteristic flow behavior of the microvalve. Because at points 1, 3 and 4 a little change in gap height gives steeper change in flow as compared to the change at point 2 (see figure 9). Additionally the hysteresis in the stepper motor and change in ambient conditions affect the flow behavior. Silicon membrane boss and titanium screw tip were examined to see any damage. It was observed that both the membrane boss and the screw tip were not damaged. Further experiments were also performed with the screw made of brass. Similar behavior in flow was observed. Surfaces of both membrane boss and screw tip was examined. It can be seen clearly that the tip of the brass crew was damaged (see figure 10).

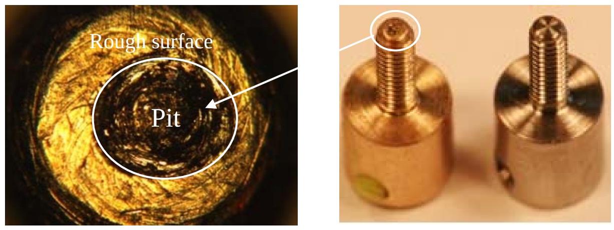

Figure 10: A part of the brass screw was eroded

The flat surface of the screw become extremely rough and a part of it is eroded. It happened due to the friction in between the silicon boss and the bottom of the brass screw. Due the continuous rotary movement of the screw on the top of the silicon membrane boss, friction increases and makes the screw surface rougher which ultimately eroded the bottom part of the screw (see figure 10). Silicon membrane was undamaged as it is harder material than the brass (see table 1).

IV CONCLUSIONS

We have presented a stepper motor actuated microvalve with an improved performance. The replacement of square boss with circular one proved to be critical to control the flow precisely and provide larger flow controllable range. The use of screw made of strong metals is vital for the continuous operation of the microvalve and improve its robustness.

REFERENCES

[1] I. Fazal, M. C. Louwerse, H. V. Jansen, Design, fabrication and characterization of a novel gas microvalve based on micro and fine-machining *J. Micromech. Microeng. 16 (2006) 1207-1214.*

[2] F. C. M. Van der Pol, A pump based on micro-engineering techniques 90-9003024-7 1989, University of Twente, Enschede, The Netherlands.

[3] J. P. Khatait, W. Lin and W. J. Lin, Design an development of orifice type aerostatic thrust bearing SIMTech Technical Reports 2005 Volume 6, No 1.

[4] A. M. Howatson, P. J. Lund and J. D. Todd, Engineering tables and data, 2nd Edition, 0412389703, 1992.