A HIGH PRESSURE-RESISTANCE MICROPUMP USING ACTIVE AND NORMALLY-CLOSED VALVES

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ABSTRACT

A novel micropump that has two active and normally-closed valves was developed using micromachine technology. This micropump can pump in forward and backward direction, and hold the fluid without consuming energy even when the fluid source has some pressure. This normally-closed valve is manufactured in the way of filling up silicone rubber paste after bonding glass substrate and silicon substrate. This silicone rubber works as a "gate" for shutting off the flow. Therefore, high pressure-resistance micropump is realized with no influence of fabrication error. In this paper, basic characteristics of this micropump about flow rate, outlet pressure and pressure-resistance are described.

INTRODUCTION

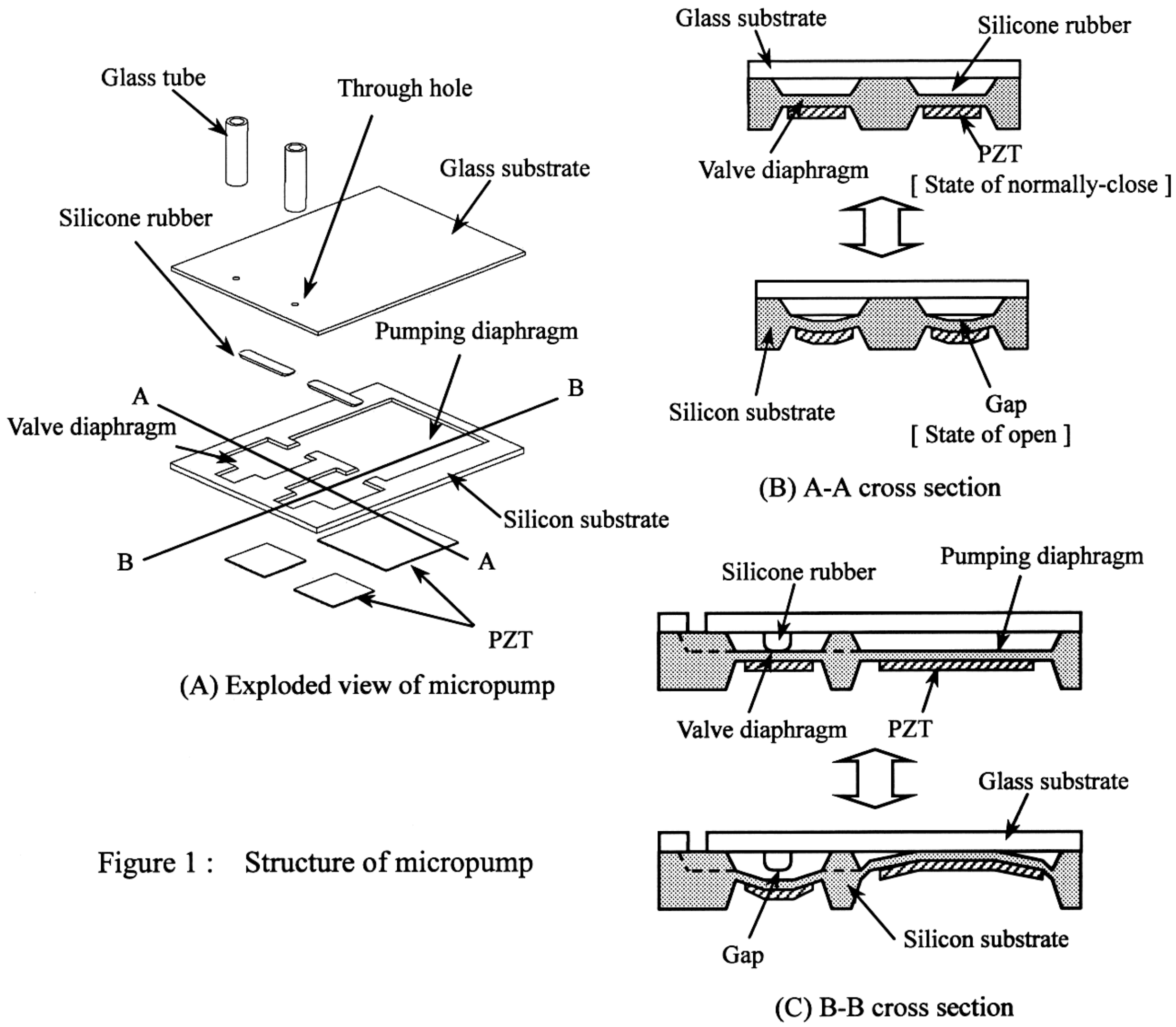
Micropump is one of the key devices of microfluidics. The application of microfluidics extends over wide range field, for example, Micro Total Analysis System, Drug Delivery System, etc. In these applications, requirement of micropump is not only pumping the fluid from one port to the other port. Various characteristics are needed to micropumps. For instance, bi-directional pumping ability is needed for micro-TAS because of handling samples in limited space. Ability of shutting off the flow is needed for Drug Delivery System because of preventing the leakage of drugs from tank. Furthermore, characteristic of low energy consumption is needed for all applications.

Most micropumps have two check valves [1-4]. The check valve works passively and allows the fluid to flow in one direction. These micropumps can pump the fluid in only one direction and their applications are limited. Furthermore, pressure-resistance of these micropumps depends on the direction, and it is especially low when the direction is from inlet port to outlet port. Therefore, they can not shut off the flows of fluid at inactive state in forward direction. Holding the fluid in forward direction is very important because there are many cases that inlet pressure is higher than outlet pressure. For instance, when tank of the fluid set on higher place, the fluid source itself has some pressure. On the other hand, there are some micropumps which do not use passive check valves and can pump the fluid in forward and backward direction [5-7]. However, they are still not designed to shut off the flow. The characteristic of this pressure-resistance tends to be overlooked although it is very important in practice. There are some examples of high pressure-resistance active valve [8-11], however they need some energy to keep close state because they are not normally-closed valves. Therefore, they must keep consuming power for shutting off the flow of the fluid. Besides, many micropumps are constructed from three or four layers, so that their structure becomes very complicated. This is a very important problem from the viewpoint of production.

The micropump we developed has two active and normally-closed valves. Therefore it is able to pump in forward and backward direction by changing the driving-sequence. Furthermore, it has no leakage from one port to the other port at inactive state even when the fluid source has some pressure. There is no energy consumption to keep blocking the flows of fluid because the valves in this micropump are normally-closed. This micropump is constructed from only two layers. This simple structure is one of the characteristics of it.

DESIGN

The micropump we developed is structured by only two layers; a silicon substrate and a pyrex glass substrate. It is a very simple structure compared with many other micropumps. Figure 1 (A) shows exploded view of the micropump. The silicon substrate has three diaphragms fabricated by anisotropic etching of silicon. Two of them are valve diaphragms for valves, and the other is a pumping diaphragm for moving the fluid. The glass substrate has two through holes, and glass tubes are placed over the holes. These are used as inlet and outlet port respectively. The silicon substrate and the glass substrate are bonded by anodic bonding method. Fluid is flowed in a small gap formed by anisotropic etching between silicon substrate and glass substrate. This gap



(A) Exploded view of micropump

(B) A-A cross section

(C) B-B cross section

Figure 1 : Structure of micropump

size is 50μm. PZT plates are glued onto diaphragms using epoxy resin, then silicon-PZT bimorph structures which work as driving actuators are fabricated. The whole chip size is $20 \times 15 \times 0.75$ mm^3. The valve diaphragm size is 5×5 mm^2, and the pumping diaphragm size is 10×10 mm^2. Overview of the micropump after packaging is shown in Figure 2.

Silicone rubber is packed between the glass substrate and the valve diaphragm. Silicone rubber and glass substrate are adhered, however, silicone rubber and valve diaphragms are not. Therefore, when the valve diaphragm deflects by applying voltage to bimorph actuators, a gap is appeared between the silicone rubber and the valve diaphragm, and then the valve becomes open state as shown in Figure 1(B). This silicone rubber works as a "gate" for shutting off the flow. This silicone rubber gate has elasticity and seals the flow path tightly without applied voltage. Thus, this structure works as a normally-closed valve. On the other hand, when pumping diaphragm deflects upward or downward by bimorph actuator, the fluid is pulled in or pushed out as shown in Figure 1 (C). This motion of pumping diaphragm is connected with open/close valves and it can pump the fluid from one port to the other port. Table 1 shows an example of driving actuators sequence. By repeating these six steps, the fluid is pumped from inlet port to outlet port. If driving-sequence is changed, it pumps in reverse direction.

FABRICATION

The micropump we developed has two normally-closed valves. There is silicone rubber gate between glass substrate and valve diaphragm. To realize the normally-closed valve, the silicone rubber gate must have the

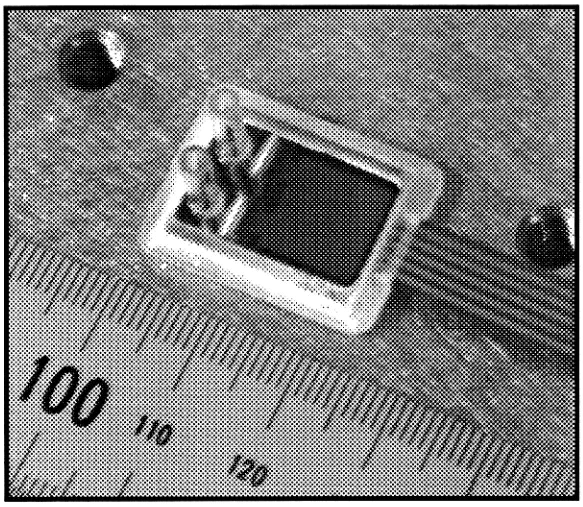
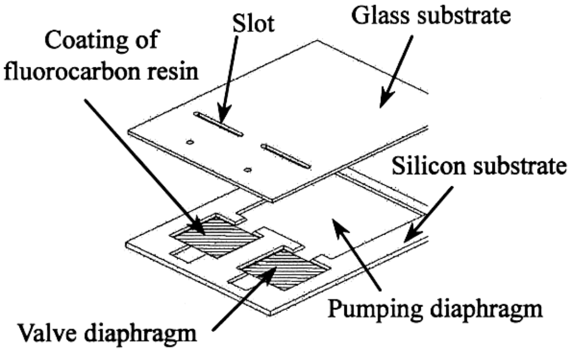


Figure 2 : Overview of micropump

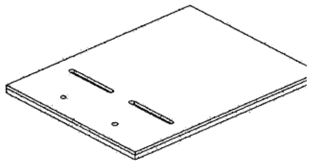
Table 1 : Driving sequence

	Intlet Valve	Pump	Outlet Valve	Status
Step1	Open	Up	Close	Open Inlet Valve
Step2	Open	Down	Close	Pull in the Fluid
Step3	Close	Down	Close	Close Inlet Valve
Step4	Close	Down	Open	Open Outlet Valve
Step5	Close	Up	Open	Push out the Fluid
Step6	Close	Up	Close	Close Outlet Valve

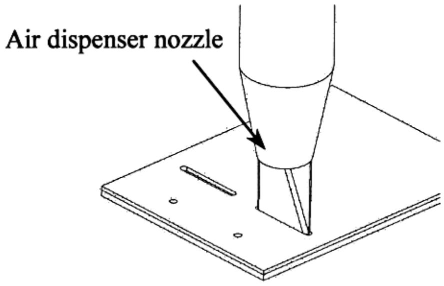
same thickness as the depth of the valve diaphragm. If the rubber gate is thinner than the depth of the valve diaphragm, it can not seal the flow path without applying voltage because of the gap between silicone rubber gate and valve diaphragm. If the silicone rubber gate is thicker than the depth of valve diaphragm, it is difficult to generate the gap between silicone rubber gate and valve diaphragm. However, to control accurately thickness of silicone rubber and depth of valve diaphragm is very difficult. In addition to this, there is some possibility of appearing gap by surface roughness. We fill up silicone rubber paste between them after bonding glass substrate and silicon substrate, and then polymerize silicone rubber. In this way, the thickness of the gate is always the same as the depth of valve diaphragm without influence of fabrication error. Fabrication process of normally-closed valve is shown in Figure 3. First, fluorocarbon resin is coated on the valve diaphragm before bonding. The purpose of this coating is to prevent silicone rubber from adhering to valve diaphragm. Next, slots for filling up silicone rubber are made on the glass substrate by sandblast (Figure 3 (A)). This glass substrate and the silicon substrate are bonded by anodic bonding technique (Figure 3 (B)). Next, silicone rubber paste is filled up from the slot using air dispenser (Figure 3 (C)). The quantity of silicone rubber paste is controlled by air pressure and filling time. After silicone rubber paste is filled up, it is polymerized at room temperature for 24 hours. This silicone rubber gate adheres to glass substrate, however, it easily separates from the valve diaphragm because of fluorocarbon resin. Therefore, when the valve diaphragm deflects by actuator, a gap appears between the silicone rubber gate and the valve diaphragm, and then the valve opens. As silicone rubber gate is on the side of the glass substrate, it does



(A) Fabrication of slot and Coating of fluorocarbon



(B) Bonding glass and silicon substrate



(C) Filling in silicon rubber paste

Figure 3 : Fabrication of normally-closed valve

not disturb displacement of valve diaphragm. Finally, PZT is glued on the back of the valve diaphragm, so that bimorph actuator is constructed. This valve has characteristics of simple structure, normally-closed and easy to open. To combine this normally-closed valve and pumping diaphragm, a high pressure-resistance micropump is realized.

EXPERIMENT AND RESULT

Measurement of flow rate

First, flow rate of the micropump was measured. The flow rate of micropump is calculated from the time needed for pumping 20μl of pure water in micropipette. The pumping the fluid is performed by the driving sequence in Table 1. Increasing the flow rate of the micropump is carried out with increasing the driving frequency. However, if driving frequency is too high, the fluid can not move with the movement of the pumping diaphragm for viscosity of the fluid. On the other hand, no movement of the fluid occurs with opening or closing valves. There is no problem to open or close valves in high speed. As stated above, it is necessary to select the most suitable driving speed to obtain the maximum flow rate. In following experiments, we apply that the time of open or close

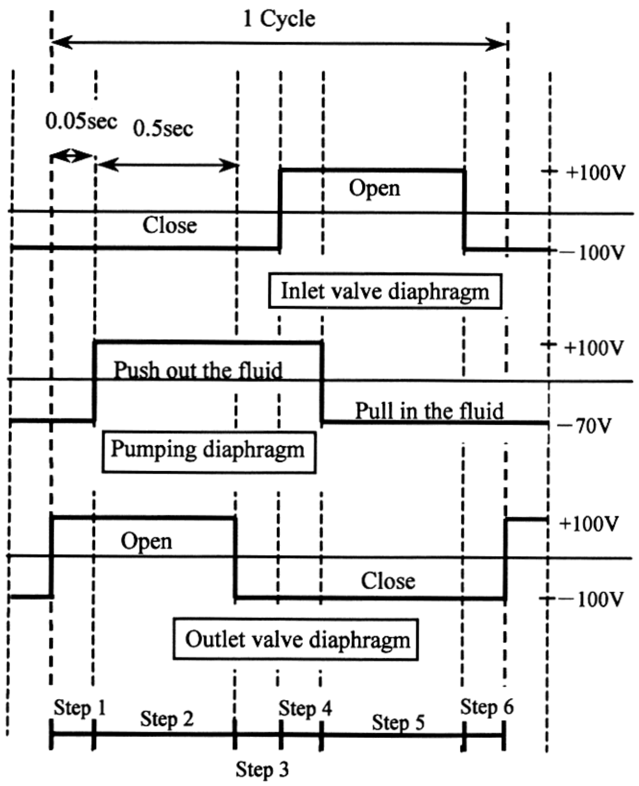


Figure 4 : Sequence of applying the voltage

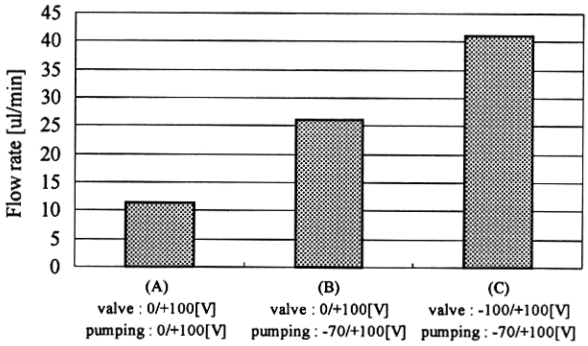


Figure 5 : Experimental result of flow rate

valves is 0.05sec, and the time of pumping is 0.5sec. At this time, the driving frequency of one cycle is about 0.83Hz.

On the other hand, it is necessary to consider the way of applying voltage to each actuator. The direction of each diaphragm's displacement depends on direction of applying voltage and polarization of PZT. This micropump is manufactured such that the valve opens and the pumping diaphragm pushes out the fluid when plus voltage is applied. The other way around, when minus voltage is applied, the valve closes more tightly and the pumping diaphragm pulls in the fluid more strongly compared with no voltage is applied to the actuators. Figure 4 shows the way of applying voltages and Figure 5 shows the result of the flow rate. This result shows that the flow rate of the micropump increases in the case of applying plus and minus voltage alternately. The reason is that pumping diaphragms deflect in both directions and the amount of flowing fluid increases in one cycle. Additionally, when valve diaphragm deflects upward, it is pushed onto silicone rubber gate more tightly. According to this, pumping efficiency becomes better. Currently, the maximum flow rate of this size of the micropump is about 40 μl/min.

Measurement of outlet pressure

Next, outlet pressure of the micropump was measured. Schematic of experiment is shown in Figure 6. When the micropump pumped a fluid from inlet port to outlet port, pressure was applied from outlet port using N_2 gas. With the increase of this pressure, amount of the fluid pumped to the outlet port decreases. When the pressure of N_2 gas increases even more, a backward flow arises from inlet port. This flow rate of leakage at inlet port was measured when applied pressures were changed. In this measurement, maximum outlet pressure of the micropump was calculated when the flow rate of leakage at inlet port was zero. Experimental result is shown in Figure 7. When outlet pressure is about 0.25 kgf/cm^2, pumping pressure of the

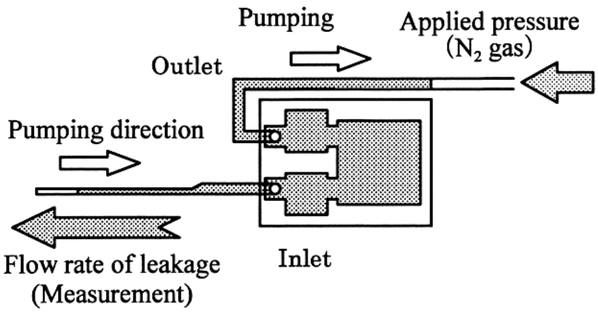


Figure 6 : Measurement of outlet pressure

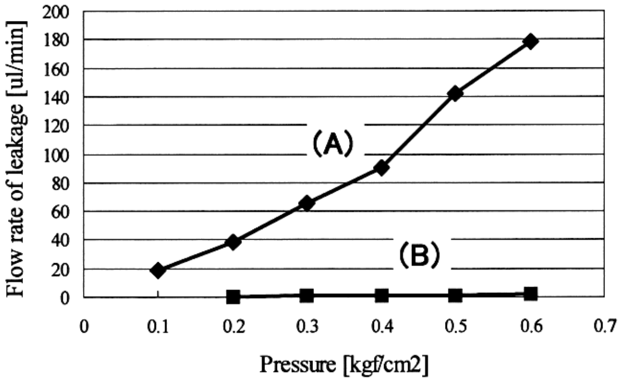


Figure 8 : Pressure resistance without applying voltage

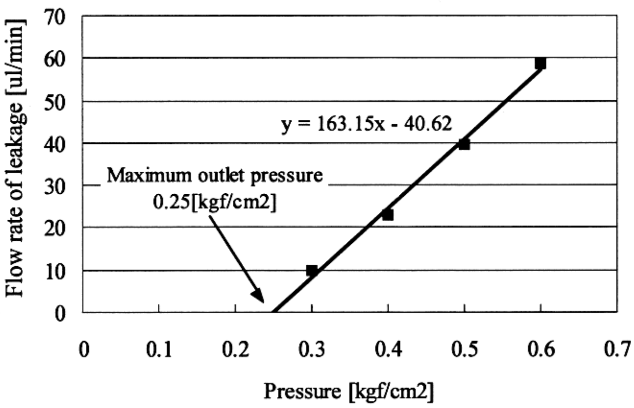


Figure 7 : Maximum outlet pressure obtained from leakage vs. applied pressure

micropump equals to the outlet pressure by N_2 gas. This result shows that the maximum outlet pressure of the micropump is about 0.25 kgf/cm^2.

Measurement of pressure resistance

In addition, pressure resistance of the micropump at no voltage applied to valve actuators was measured. The pressure using N_2 gas was applied from one port and flow rate of leakage at the other port was measured. We compared two different ways of closing the valves, Method (A) and Method (B).

Method (A)
Step1 : Open both valves by applying 100 V
Step2 : Close both valves by only turning off the voltage

Method (B)
Step1 : Open both valves by applying 100 V
Step2 : Close both valves by applying –100 V
Step3 : Turn off the voltage

Experimental result is shown in Figure 8. Horizontal axis shows applied pressure from one port, and vertical axis shows flow rate of leakage at the other port. There is much leakage using the closing Method (A). This result shows that it is difficult to shut off a flow with high pressure completely by only turning off the voltage. On the other hand, there is hardly any leakage in Method (B). It is possible that the closed state is kept under the high pressure condition by pressing valve diaphragm against the silicone rubber only once. This result indicates that the micropump we developed has excellent pressure resistance without applying voltage by using Method (B). This characteristic of shutting off the flow is very important point to use in practice, and it is definitely superior to the other micropumps

CONCLUSION

A high pressure-resistance micropump with active and normally-closed valves was developed. Every diaphragms for valves and pumping are actuated by silicon-PZT actuators. Therefore, this micropump can pump the fluid in both directions by only changing the driving sequence. The valve is normally-closed by fabrication process of filling up the silicone rubber paste. This fabrication process and elasticity of silicone rubber also realize high pressure-resistance. In addition to this, the micropump is constructed from only two layers, so that it has very simple structure and fabrication process becomes easy. These characteristics make this micropump extremely advantageous for application of Drug Delivery System, micro-TAS and so on. In the future, this micropump will be used in a wide range field.

REFERENCES

[1] D. Maillefer, H. Van Lintel, G.Rey-Mermet and R.Hirsch, “A High-Performance Silicon Micropump

for an Implantable Drug Delivery System, " Proc. MEMS '99, pp541-546, Orlando, Florida, USA.

[2] R.Linnemann, P.Woias, C.-D.Senfft and J.A.Ditterich, "A Self-Priming and Bubble-Tolerant Piezoelectric Silicon Micropump for Liquids and Gases, " Proc. MEMS '98, pp532-537, Heidelberg, Germany.

[3] K.-P.Kämper, J.Döpper, W.Ehrfeld, and S.Oberbeck, "A Self-filling Low-cost Membrane Micropump" Proc. MEMS'98, pp432-437, Heidelberg, Germany

[4] A.Olsson, O.Larsson, J.Holm, L.Lundbladh, O.Ohman and G.Stemme, "Valve-less Diffuser Micropumps Fabricated Using Thermoplastic Replication" Proc. MEMS '97, pp305-310, Nagoya, Japan.

[5] S.Matsumoto, A.Klein and R.Maeda, "Development of Bi-directional Valve-less Micropump for Liquid " Proc. MEMS '99, pp141-146, Orlando, Florida, USA.

[6] J.W.Choi, and Y.K.Kim, "Fabrication and Experiment of Novel Type Electrohydrodynamic Micropump" Transact. Of Institute of Electrical Engineering of Japan, Vol.117-E, No.3, pp170-174, 1997.

[7] S.H.Ahn, and Y.K.Kim, "Fabrication and Experiment of Planar Micro Ion Drag Pump" Technical Digest of the 15th Sensor Symposium, 1997, pp173-176

[8] T.Ohori, S.Shoji, K.Miura and A.Yotumoto, "Three-way Microvalve for Blood Flow Control in Medical Micro Total Analysis Systems (μTAS) " Proc. MEMS '97, pp333-337, Nagoya, Japan.

[9] X.Yang, C.Grosjean, Y.C.Tai and C.M.Ho, "A MEMS Thermopneumatic Silicone Membrane Valve " Proc. MEMS '97, pp114-118, Nagoya, Japan.

[10] K.D.Skrobanek, M.Kohl, and S.Miyazaki, "Stress-optimized Shape Memory Microvalves" Proc. MEMS '97, pp256-261, Nagoya, Japan.

[11] C.Grosjean, X.Yang, and Y.C.Tai, "A Practical Thermopneumatic Valve", Proc. MEMS'99, pp147-152, Orlando, Florida, USA.