Fabrication of a Thermopneumatic Valveless Micropump with Multi-Stacked PDMS Layers

Ok-Chan Jeong*, Dae-Jung Jeong and Sang-Sik Yang****

Abstract - In this paper, a thermopneumatic PMDS (polydimethlysiloxane) micropump with nozzle/diffuser elements is presented. The micropump is composed of nozzle/diffuser elements as dynamic valves, an actuator consisting of a circular PDMS diaphragm and a Cr/Au heater on a glass substrate. Four PDMS layers are used for fabrication of an actuator chamber, actuator diaphragm by a spin coating process, spacer layer, and nozzle/diffuser by the SU-8 molding process. The radius and thickness of the actuator diaphragm is 2 mm and 30 μm, respectively. The length and the conical angle of the nozzle/diffuser elements are 3.5 mm and 20°, respectively. The actuator diaphragm is driven by the air cavity pressure variation caused by ohmic heating and natural cooling. The flow rate of the micropump in the frequency domain is measured for various duty cycles of the square wave input voltage. When the square wave input voltage of 5 V DC is applied to the heater, the maximum flow rate of the micropump is 44.6 μl/min at 100 Hz with a duty ratio of 80% under the zero pressure difference.

Keywords: Flow rate, nozzle/diffuser Thermopneumatic PMDS (polydimethlysiloxane) micropump,

1. Introduction

Recently, various micro fluidic devices with no mechanical moving parts have been fabricated with a PDMS (polydimethlysiloxane) elastomer for a polymerase chain reaction (PCR), a micro fluorescence activated cell sorter (μFACS), micro total analysis systems (μTAS) and various other bio-medical applications [1-3]. The key merits of using PDMS material are a simple molding fabrication process as well as a pile-up process for the multi-PDMS layers through an irreversible bonding process between soft cured PDMS layers [4]. Moreover, the thickness of PDMS layers can be controlled easily by the spin coating process. If all components of the micropump are fabricated using a PDMS elastomer, the internal flow fields of the fabricated transparent structure can be observed and measured by a micro PIV (Particle Image Velocimetry) system. It is possible to investigate flow features using a micro PIV system for the optimal design rule of the micropumps.

Micropumps with mechanical actuators have been developed with various kinds of membrane materials such as p+ silicon, silicone rubber, Parylene and etc. [5-7]. The flexibility of an actuator material is one of the most important factors in defining the performance of the actuator. The silicon and/or metallic diaphragms are stiffer than other candidates, and are unable to make a large displacement. In the case of a p+ silicon diaphragm, the performance of the actuator deteriorates because of the residual tensile stress of the actuator diaphragm [8].

Fig. 1 depicts the load-deflection curves of the two diaphragms calculated by using the equations of Scheeper et al. [9]. The material properties and dimensions of the diaphragm materials are shown in Table 1. The diaphragm size is set to 4 mm x 4 mm. Young's modulus of PDMS is small compared with *p+* silicon, spin-coated silicon rubber, and deposited Parylene. Assuming that no residual stress exists in the diaphragm, the ratio of the applied pressure to the steady-state deflection for the PDMS layer is smaller than any other material. The actuator having a PDMS diaphragm is expected to be useful in actuator construction because of its remarkable flexibility and simpler fabrication process. If necessary, multi-stacked PDMS can be easily accomplished by adjusting the spin coating process for the thickness of the PDMS layer and the curing process for the irreversible bonding between PDMS layers. Consequently, it is adequate for the actuator diaphragm of a micropump. If a thermopneumatic actuator with PDMS material is fabricated, it can create a large deflection with relatively low input voltage.

Generally, microvalves are classified into two types such as passive valves [10-12] and active valves [13-15]. Active valves precisely control the flow rate under some pressure difference, but have complex structures including the

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Received November 4, 2003 ; Accepted March 4, 2004

additional actuation circuit. Passive valves operate only with forward pressure and have simple structures. However, passive check valves are unable to follow the typical high frequencies of the thin membrane of the actuator. Since nozzle/diffuser elements such as dynamic passive valves have no mechanical moving parts and have broad frequency range, it is possible to apply the high frequency of up to several kHz [16].

This paper is evaluated for the new fabrication approach of the membrane-type micropump with transparent body. It can be applicable to the investigation of the flow features by the micro PIV techniques for analysis of the velocimetry within the micropump. The PDMS micropump with nozzle/diffuser elements is fabricated through the simple fabrication process and tested by the thermopneumatic actuation method. Other actuation methods are available, but the thermopneumatic actuation method is applied to create a high micropump flow rate. The flow rates of the micropump under various actuation frequencies and duty ratios were measured.

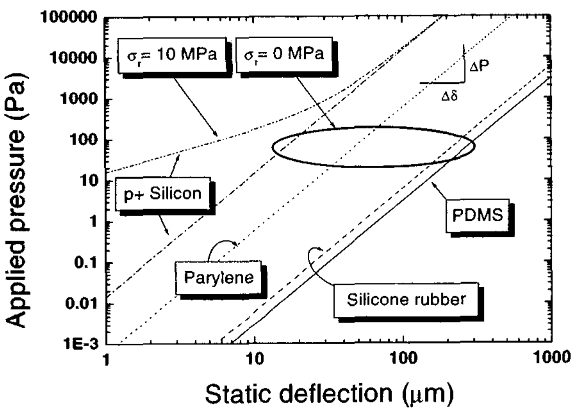


Fig. 1 Typical load-deflection curves.

Table 1 Mechanical properties and sensitivities of the materials for the actuator diaphragm.

Material	Young's modulus	Poisson's ratio	Thick -ness	ΔP/Δδ (Pa/μm)
p+ Si	125 GPa	0.25	1 μm	116.3722
Parylene	4.5 GPa	0.40	1 μm	4.67567
Silicone rubber	1.5 MPa	0.45	30 μm	0.04925
PDMS	750 kPa	0.45	30 μm	0.02462

2. Structure and working principle

Fig. 2 illustrates the schematic view of the thermopneumatic PDMS micropump with nozzle/diffuser elements. All components are fabricated with PDMS except the micro heater on a glass substrate. The micropump consists of a thermopneumatic actuator as well as nozzle/diffuser elements as dynamic passive valves. The radius of the outlet and inlet port for the fluidic tube connection, r is 1 mm. The length of nozzle/diffuser elements, L is 3.5 mm and the conical angle, α is 20°. The radius and thickness of the actuator diaphragm is 2 mm, and 30 μm, respectively. The height of the actuator air chamber and spacer are 500 μm. The depth of nozzle/diffuser elements as a fluidic channel is 30 μm.

When the square input power is applied to the micro heater, the ohmic heating and the natural cooling of the air in the actuator chamber result in a pressure change within the cavity. This periodic pressure change vibrates the PDMS diaphragm, and the flow rate of the micropump is generated by the flow resistance difference between the nozzle/diffuser elements. For that reason, the fluid is repeatedly sucked in and spouted out of the micropump through the nozzle/diffuser elements.

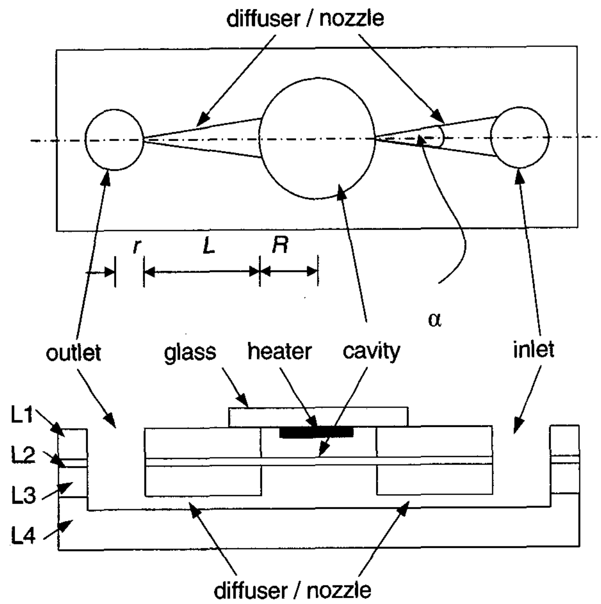


Fig. 2 Schematic view of the micropump. L1: actuator chamber, L2: actuator diaphragm, L3: spacer, L4: diffuser / nozzle

3. Fabrication process and assembly sequence

The fabrication method for all components of the micropump is a combination of SU-8 molding for nozzle/diffuser elements and the PDMS coating/curing/bonding process. All of PDMS layers are fabricated, bonded and sealed via the spin coating process and the two-step curing process that are known as the irreversible bonding process [8].

Fig. 3 shows the fabrication process and assembly sequence for a micropump with stacked PDMS layers. Firstly, a 10:1 mixture of PDMS prepolymer and curing agent (Sylgard 184, Dow Corning, Midland, MI) was stirred thoroughly, and degassed for 10 min in a vacuum chamber. The prepared PDMS mixture for the formation of layer 1 and layer 3 was poured on the silicon wafer and spun at 500 rpm for 10 seconds. After curing at 75°C for 60 min, the soft cured PDMS layers of 500 μm thickness were peeled off and a throughhole for an actuator chamber of 2 mm radius was punched out. The prepared PDMS mixture for the actuator diaphragm layer was poured on the silicon wafer and spun at 3000 rpm for 10 seconds. The soft curing process was carried out at 65°C for 15 minutes. The fabricated PDMS layers under this spin coating condition were measured and found to be 30 μm thick. The actuator chamber layer was aligned on the soft cured PDMS layer 2 for the actuator diaphragm, and carefully lowered onto it. The flexible PDMS layer 1 for an actuator chamber provides continuous contact with the PDMS layer 1 for an actuator diaphragm to prevent any bubbles from forming at the interface. And then, the stacked PDMS structure was baked for 10 min at 65°C. After the soft bonded PDMS layer was peeled off and bonded with the soft cured PDMS layer 3 again at the same soft baking process condition, two access throughholes for the fluidic access were punched out. The adhesive strength of the soft baked PDMS layers was sufficient to maintain their stacked shape prior to the entire PDMS curing process. The nozzle/diffuser layer was fabricated by an SU-8 mold, with a height of 30 um. The prepolymer mixture was poured onto the SU-8 master for nozzle/diffuser elements and cured for 15 minutes at 65°C. Following the soft curing process, the PDMS replica was peeled from the SU-8 master. Finally, the stacked PDMS layer was aligned and carefully lowered onto the PDMS layer for the nozzle/diffuser elements. The stacked PDMS layers were then placed on the hot plate, and loaded with a 200g weight. The entire PDMS layers were cured at 100°C for 60 min. For fabrication of the micro heater, a Cr/Au (500 Å/1500 Å) layer was deposited on Pyrex glass (#7740) by using a thermal evaporator, and then that was patterned and etched. Finally, a glass substrate with a micro heater was bonded and sealed with a PDMS structure by using the additional PDMS mixture at 100°C for 60 min. The fabricated PDMS pump is shown in Fig. 4.

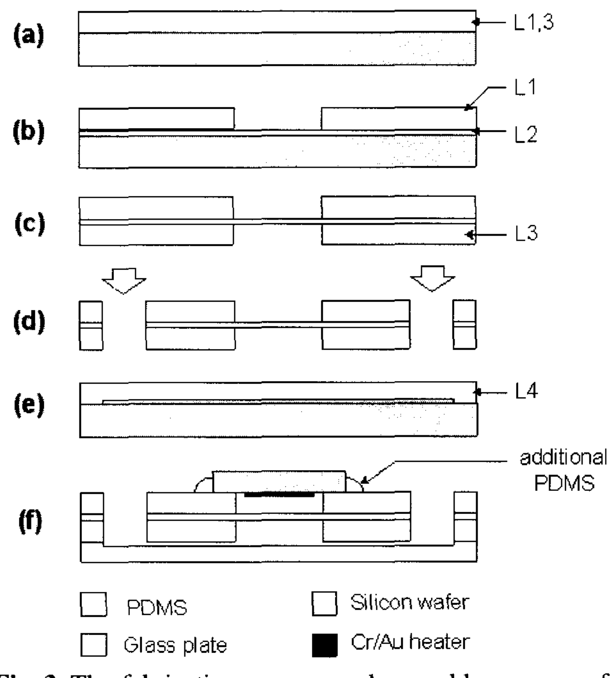


Fig. 3 The fabrication process and assemble sequence for the micropump
(a) PDMS spin coating and soft curing for L1 and L3, (b) Punching a throughhole for the actuator cavity of L1 and an irreversible bonding process of L2 and L1, (c) PDMS layer 3 with a punched hole is irreversibly bonded with the bonded structure in step (b), (d) Punching two throughholes for a fluidic connection in step (c), (e) PDMS pouring on SU-8 formed on a silicon wafer for L4, (f) Irreversible bonding process of L4 and the bonded structure in step (d).

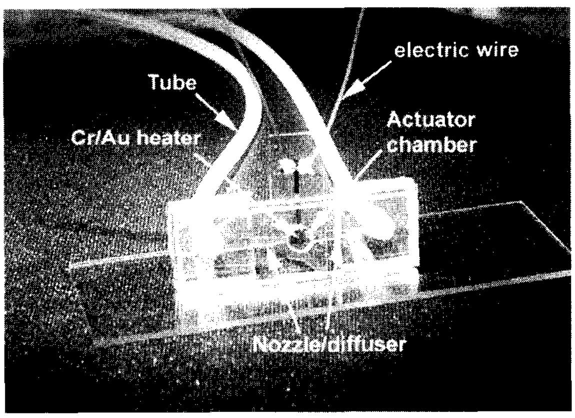


Fig. 4 Photograph of the fabricated micropump.

4. Flow rate measurement

Fig. 5 shows the measurement system for the flow rate of the fabricated micropump. The square wave input voltage is supplied to the micro heater, which is generated by the DC power supply, function generator, and FET driver. The heater resistance is about 12 Ω at room temperature, and the resistance increases about 10% when the input voltage is 5V DC. The temperature variation of the glass substrate with the micro heater pattern is approximately +13°C. While the micropump operates by thermopneumatic force, displacement of the meniscus in the capillary tube is observed and recorded using a video microscope (Hi-scope KH-2200, HiRox) and a videocassette recorder. The flow rate of the micropump is calculated through an analysis of the recorded displacement data.

Fig. 6 shows the capillary images captured with a video microscope every 0.5 second for two different inputs. Oscillation of the meniscus in the capillary tube is clearly observed at 1 Hz. As the operation frequency increases, the oscillation decreases. The oscillation is hardly observed for the input of 50 Hz. Because the nozzle and the diffuser contain no mechanical moving parts, there is no limitation in the operation frequency as a dynamic passive valve. The flow resistance difference between the nozzle and the diffuser makes a net forward flow. Fig. 7 illustrates the mean flow rates of the micropump for various input frequencies and duty ratios when the pressure difference between the inlet and the outlet is zero and the input voltage is 5 V. The mean flow rate increases as the duty ratio increases, and the mean flow rate increases as the frequency increases up to 100 Hz. The thermal capacitance of the thermopneumatic actuator causes the flow rate of the micropump to decrease at the operation frequency over 100 Hz. The maximum flow rate is 44.6 μl/min when the duty ratio and the frequency are 80% and 100 Hz, respectively.

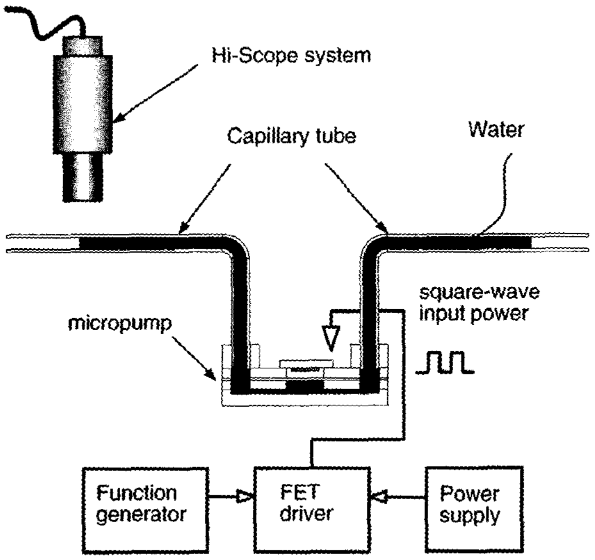
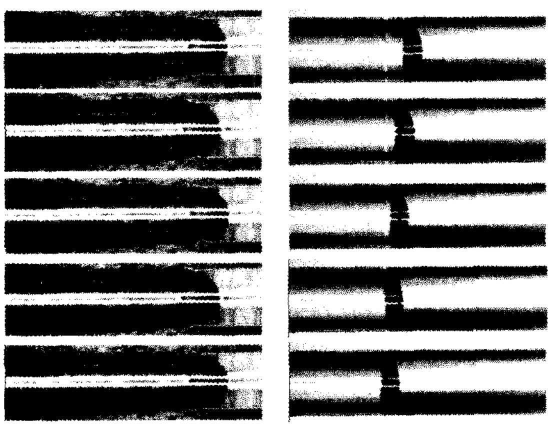


Fig. 5 The flow measurement system of the micropump



(a) (b)

Fig. 6 Captured images of the water flow in the capillary tube every 0.5 seconds.(a) 1Hz, 20%, 5V DC, (b) 50Hz, 80%, 5V DC

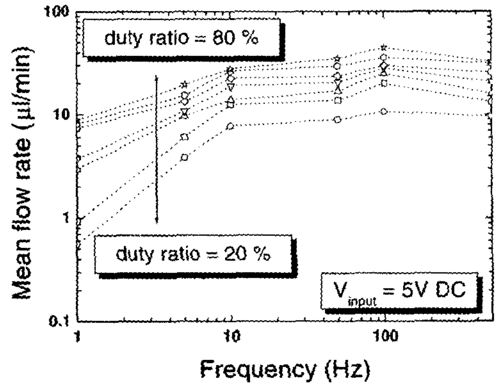


Fig. 7 Mean flow rate of the micropump.

5. Conclusions

In this paper, a thermopneumatic valveless micropump with four PDMS layers has been fabricated through a spin coating, curing, and irreversible PDMS to PDMS bonding. Under the zero pressure difference between the inlet and outlet, the flow rate of the micropump has been measured. Because of some advantages of PDMS material such as its mechanical properties, simple fabrication process, and low production cost, it is a practical method to make a micropump with a membrane type actuator.

As a future work, the flow fields within the fabricated transparent structure is planned for observation and measurement by the micro PIV (Particle Image Velocimetry) system.

Acknowledgment

This work was supported by a grant from the Nano Bioelectronics and Systems Research Center of Seoul National University, which is an ERC supported by the Korean Science and Engineering Foundation (KOSEF).

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