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A fully polymeric micropump with piezoelectric actuator

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Abstract

This paper presents a new concept of designing and fabricating polymeric micropumps. The micro pump is made of SU-8 photoresist and polymethylmethacrylate (PMMA). The key elements of the micropump are the micro check valves, which are fabricated in a 100-μm-thick SU-8 film. The SU-8 part is designed as a disc with 10-mm diameter. The check valves are 1-mm discs suspended on a compliant orthoplanar spring with four arms. The cross section of the spring beam has a dimension of 100 μm × 100 μm. The pump is designed as a stack of different layers, which are made of PMMA and SU-8. In contrast to their silicon counterparts, the low spring constant of the SU-8 check valves allows the use of relatively low drive voltages on the order of several 10 V for the piezodisc, which works as the pump's actuator. Pump rates up to 1 ml/min and back pressures up to 200 mm water have been achieved. The pump design shows the feasibility of our current effort to make microfluidic systems based on the lamination of different polymeric materials.

Keywords: Microfluidics; Micropumps; Polymeric micromachining; SU-8; PMMA

1. Introduction

The development of pumping devices in microscale is a part of the emerging research field of microfluidics [1]. Besides stand-alone micropumps, simple pump designs are required for integration in miniaturized chemical analyzers, which are often called micro total analysis systems (μTAS) or lab on a chip (LOC). The trend of a disposable system in form of a plastic test cartridge leads to the need of simple polymeric micropumps, which can be easily implemented in the fabrication process of the test cartridge. Furthermore, low-voltage and low-power actuating schemes for the pump are needed for the use in hand-held devices, which are usually powered by batteries.

The development of micropumps has a history of more than two decades. Generally, micropumps can be categorized as mechanical pumps and nonmechnical pumps [1,2]. While mechanical pumps apply conventional concepts in microscale, nonmechanical pumps utilize effects which are dominant in microscales such as surface tension and electrokinetics. Since the size of the above mentioned test cartridges is in the mesoscale, mechanical pumps are still relevant. References [1,2] give detailed description of different micropump concepts.

With the need of polymeric microdevices, polymer-based micromachining techniques have been established recently as new alternatives in microtechnology. The basic polymer-based micromachining techniques are thick resist lithography, polymeric surface micromachining, soft lithography, micro stereolithography and micromolding [1]. The advantage of polymer-based micromachining is the possible use of different polymeric materials, which may offer μTAS good biocompatibility and chemical resistance.

A significant advantage of polymers over silicon is their relatively low Young's modulus, which is 50-100 times smaller than that of silicon. Thus, check valves made of polymers require less pressure for operating. Furthermore, the softer polymeric material offers much better sealing characteristics. A number of works on polymeric check valves was reported. Check valves were fabricated in polyimide [3–6], polyester [7], parylene [8], and silicone rubber [9]. In some cases the check valves are simply made of manually punched polymer film [7,9]. SU-8 is a negative thick-film photoresist, which has been widely used for making microchannels [1]. In this paper, we report the first SU-8 check valves with movable structures. The structures are fabricated and released with the so-called polymeric surface micromachining technique [1], which can make freely moveable polymeric microstructures. More importantly, we demonstrate in this paper the layered concept for making microfluidic systems. This concept lays the foundation for

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the lamination technique, which is currently developed by our research group.

2. Micropump design

Fig. 1 depicts the assembly concept of our micropump. The pump consists of six layers of different materials. The first polymethylmethacrylate (PMMA) plate has an opening at the center for the piezodisc. This plate is used for fixing the piezodisc. The piezodisc works as both actuator and pump membrane. The characteristics of the piezodisc were described previously in [10]. The pump chamber is defined by the piezodisc and a second PMMA plate, which has two access holes for inlet and outlet. The next two layers are identical and made of SU-8. The check valves are integrated in these layers and have the form of a suspended disc. The design and fabrication of the SU-8 check valves are discussed in the next section. The PMMA parts are fabricated with conventional cutting and milling techniques. The stack of these six layers is fixed with four screws. The assembled device is shown in Fig. 2.

This assembly concept combines different fabrication techniques. While precision elements such as check valves and microsprings are fabricated with photolithography of SU-8, other elements can be fabricated with conventional techniques such as cutting, milling, laser machining, or injection molding. One of the serious problems of μTAS is the relatively large size of the chip, which increases the cost if the chip is entirely fabricated in batch with silicon-based microtechnology. The assembly concept used in this paper allows mass production of microfluidic cartridges at a relatively low cost, while keeping the size of microparts reasonable for batch fabrication.

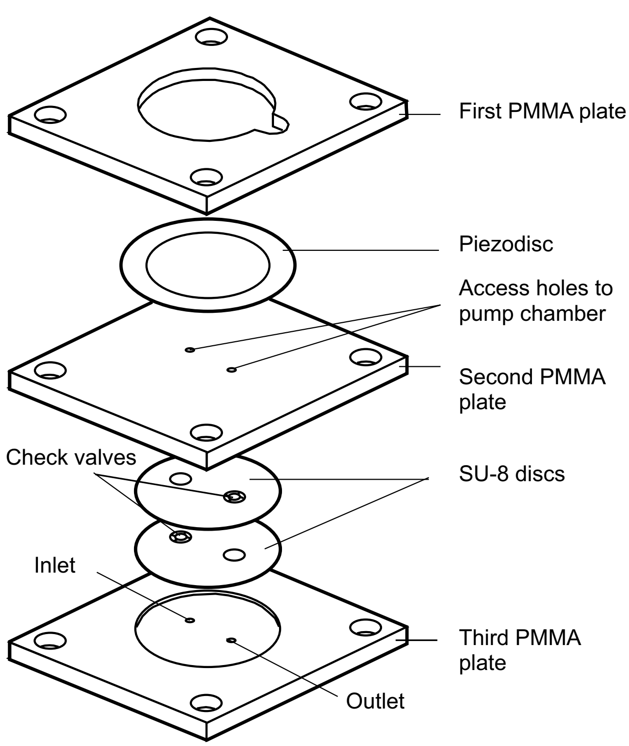

Fig. 1. Stacked concept of the micropump.

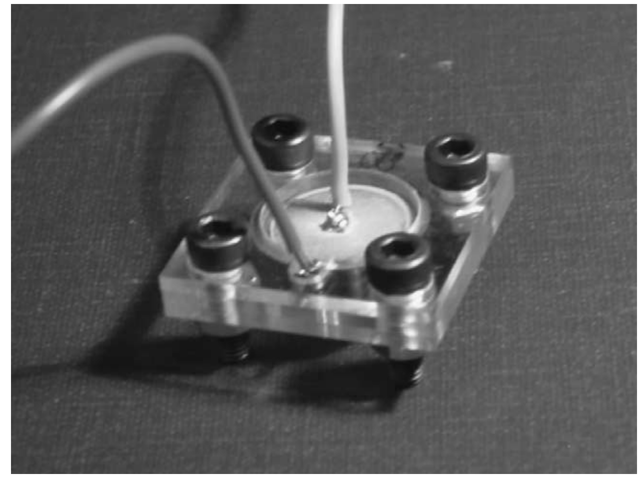

Fig. 2. The assembled micropump.

3. Design and fabrication of the SU-8 check valves

3.1. Design

Fig. 3 depicts the most important geometry parameters of the SU-8 disc. The disc is 100-μm thick and has a diameter of 10 mm. The check valve consists of a 1-mm circular plate suspended on four folded springs. The spring design is called the compliant orthoplanar spring [11]. This design assures that the valve plate is displaced in parallel to the disc surface, Fig. 4. The valve springs are folded beams with a cross section of 100 μm × 100 μm. The circular hole next to the spring structures works as a spacer for the check valve on

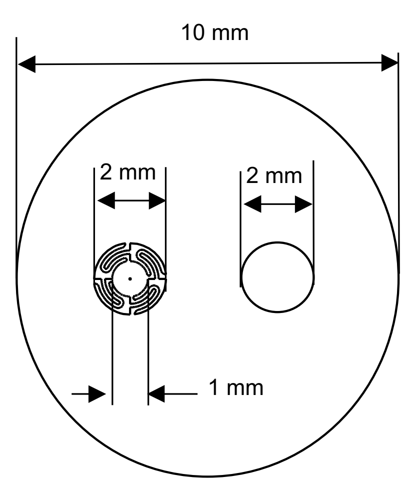

Fig. 3. Geometry of the SU-8 disk containing the valve and a hole.

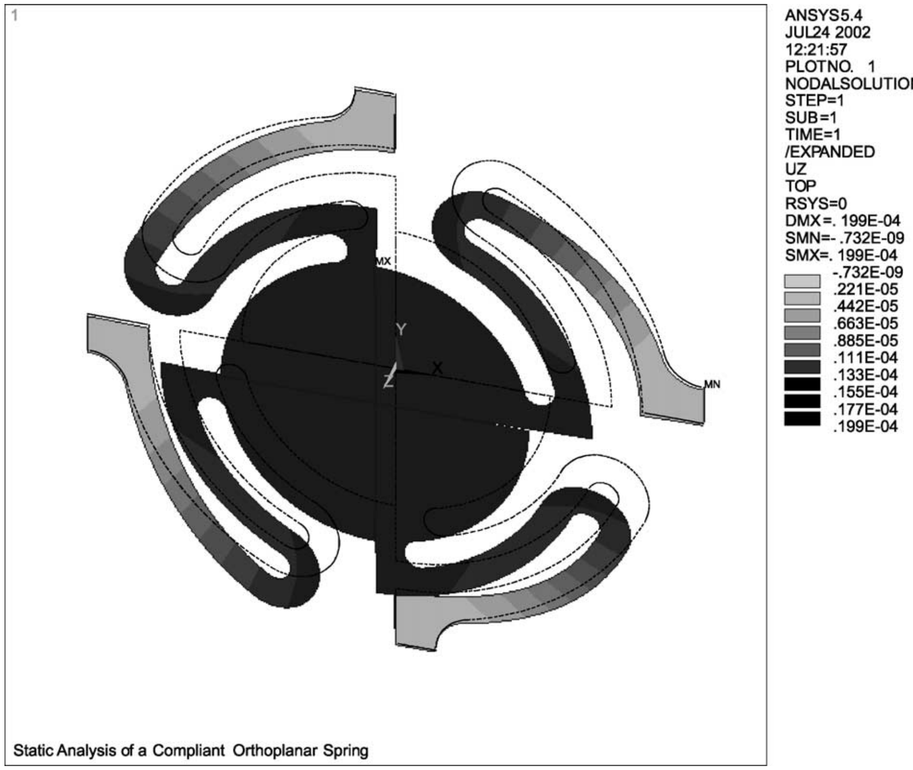

Fig. 4. Deflection analysis of the check valve using FEM.

the another SU-8 disc as shown in Fig. 1. Because the two SU-8 discs in Fig. 1 are identical, only one design is needed.

Fig. 4 shows the simulation results of FEM analysis with ANSYS. Because of the relatively low Young's modulus, a drag pressure of 3 mbar is able to displace the valve disc by almost 4 μm. Since the hole on the SU-8 disc works as a spacer, the maximum deflection is limited under 100 μm, which is the thickness of the spring beam. Thus, a linear deflection model can be assumed. Using a Young's modulus of 4.02 GPa [12] the design results to a stiffness of 613.59 N/m. This stiffness is then used for the subsequent coupled fluid-structural simulation of the check valve.

The prediction of the behavior of the check valve requires a coupled fluid-structural simulation. The usual approach is to run the structural and flow analysis separately with two different solvers [13,14]. The deflection of the valve is used for shaping the grid of the fluid domain. In turn, the pressure distribution from the flow analysis is used as the boundary condition for the structural analysis. The multiphysics feature of ANSYS also allows this coupling approach. However, this simulation approach is time consuming. For complicated structures such as the orthoplanar spring in our case, a complex three-dimensional model is necessary for the simulation. The three-dimensional coupled fluid-structural simulation is more time consuming.

Because the valve disc in our case moves parallel to its surface, the behavior of the valve displacement is straight forward. A linear model with a constant stiffness can be assumed. Only one structural analysis needs to be carried out for determining the stiffness. This stiffness can then be used for a semi-analytical coupled simulation.

The fluid-structural coupling was realized in an iteration loop written as a macro script in the ANSYS batch file. First, the flow analysis was carried out for an initial gap between the valve disc and the inlet. The pressure distribution across the valve disc was used with the known stiffness for calculating the displacement analytically. The new gap between the valve disc and the inlet was then updated. The flow model was subsequently meshed again with the new geometry, readied for the next iteration. The iteration loop stopped, if the displacement difference reached a given convergence condition which was in our analysis 10 nm. On average the coupled simulation stopped after three or four iterations. The simulation of our two-dimensional rotation-symmetric model with 14336 elements required about 20 min on a Pentium IV personal computer with a clock frequency of 1.8 GHz. Fig. 5 shows the simulated flow field in forward and backward direction. The simulation results are discussed later with the measurement results in Section 4.

3.2. Fabrication

The SU-8 structures were fabricated with the polymeric surface micromachining technique [1], where SU-8 works as the functional material. First, we used single crystalline silicon directly as the sacrificial material. SU-8 was coated

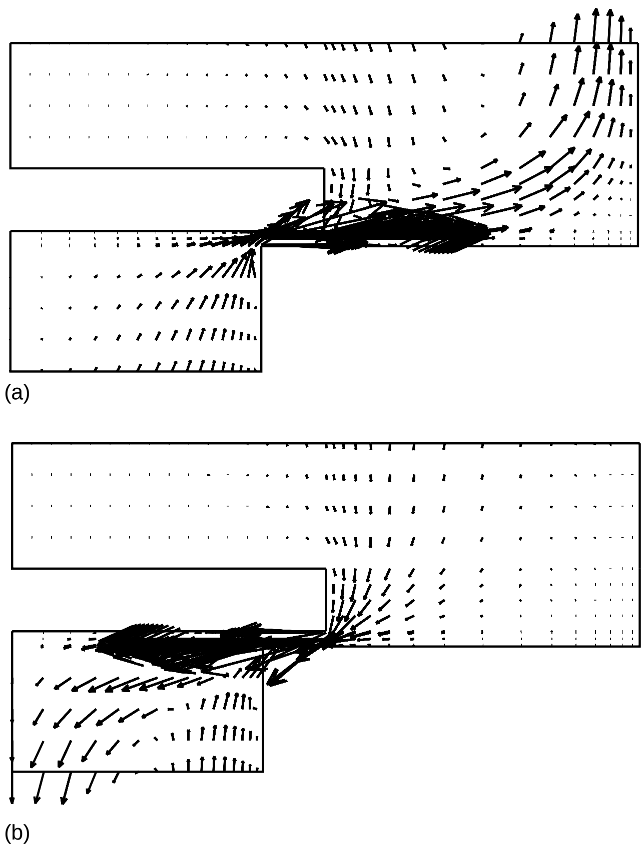

Fig. 5. Simulated velocity field in the micro check valve: (a) forward and (b) backward (inlet diameter: 0.8 mm, outlet diamter: 2 mm, initial gap: 24 μm, rotation-symmetric model with less computational elements for clarity).

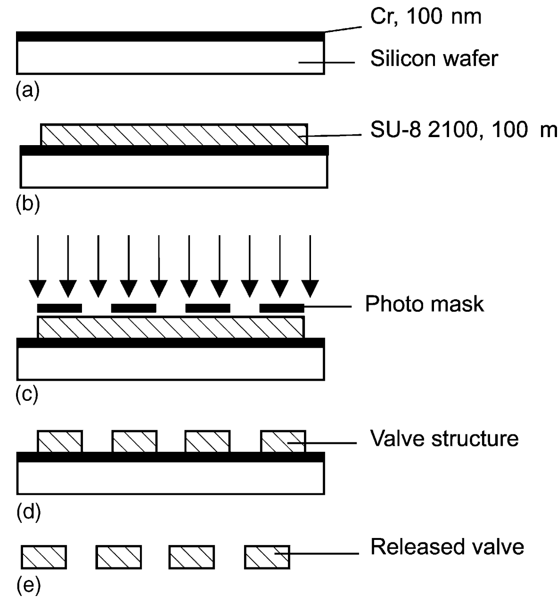

Fig. 6. Fabrication process for the SU-8 check valve.

on a silicon wafer. After developing and hard bake, the SU-8 part was released by dissolving the silicon wafer in a 30% KOH solution. This method requires a long etching time of almost 10 h. The long exposure time in KOH caused curling of the SU-8 disc, which led to difficulties in the subsequent assembly process.

In order to avoid the long etching time, a thin chromium layer was used as the sacrificial layer. The process is depicted in Fig. 6. First, a 100-nm thick chromium layer was sputtered on the silicon wafer. The next step was coating and developing SU-8. The valve was released by chromium etchant in 2 h. Access holes were incorporated into the SU-8 disc to speed up the release etch and to arrest microcracks.

3.3. *SU-8 process*

We used SU-8 2100 (Microchem Corp., http://www.microchem.com), that belongs to a new SU-8 family. SU-8 2000 family uses cyclopentanone (CP) as solvent instead of gamma-butyrolactone (GBL) in the old SU-8 formulation. According to the company, SU-82000 improves wetting on silicon, glass, and metals. Edge bead can be cleanly removed immediately after spin-coating. SU-8 2000 family offers faster drying for film thickness up to about 50 μm [15]. The fabrication process for SU-8 2100 microvalves is discussed in detail in the following sections.

3.3.1. *Substrate preparation*

The silicon wafer was first RCA-cleaned. Prior to applying the resist, the wafer was sprayed with acetone, then with DI water. It was blown dry with nitrogen then baked at 200 °C for 30 min in a convection oven. This step is important because untreated wafer surface can cause bubbles or pinholes on the SU-8 layer in the later process.

3.3.2. *Dispensing*

Dispensing is crucial for obtaining an uniform film and process repeatability. For high viscous resists like SU-8 2100, dispensing is very difficult. As a rule of thumb, about 1 ml of resist is needed per 1 in. of substrate diameter. Thus, a 4-in. wafer needs about 4 ml. First, we heated the SU-8 bottle at 60 °C for 30 min to reduce viscosity and bubbles. The piston of the syringe was then removed. Four milliliters of the resist was poured into the syringe. After placing back the piston, SU-8 is allowed to cool down to room temperature. The resist is then dispensed at the center of the cleaned wafer. We observed that there were bubbles in the dispensed resist. Using larger syringe orifice may reduce bubbles as suggested by Microchem.

3.3.3. *Spin-coating*

To achieve thickness of 100 μm, we experimented with three different recipes listed in Table 1. We spun SU-8 with a spin coater (P6708, Specialty Coating Inc.) in two steps: spread cycle and spin cycle. In the spread cycle, we ramped the speed up to 500 rpm in 5 s and kept the constant speed for 5 s. In the spin cycle, we ramped the speed up to 3000 rpm

Table 1
Spin recipes for SU-8 2100, room temperature at 24 °C

Process step	Recipe 1	Recipe 2	Recipe 3
Ramp 1 (s)	5	5	5
Speed 1 (rpm)	500	500	500
Time 1 (s)	5	5	5
Ramp 2 (s)	10	10	10
Speed 2 (rpm)	3000	2100	2000
Time 2 (s)	22	22	22
Ramp 3 (s)	20	20	20
Thickness (μm)	67	100	110

(or 2100and 2000 rpm in other recipes) in 10 s, and kept the speed constant for 22 s. At the end, the speed was ramped down in 20 s. After developing the thickness of different spin recipes was measured with the Wyko 32 Profiler. The results are shown in Table 1.

3.3.4. Planarizing

After spinning, the SU-8 surface was not very uniform. We still could observe footprint of the dispensed amount in the wafer center. To achieve a good uniform thickness, we placed the wafer on an even surface for 30 min to 1 h. During this process, the wafer was covered to avoid contamination and evaporation.

3.3.5. Soft bake

In the next step, we baked the wafer in a convection oven (Fisher Scientific) at 65 °C for 10 min and subsequently at 95 °C for 40 min. The wafer was then allowed to cool down to room temperature before exposure. During the soft bake process, SU-8 continues to flow so it is important to place the wafer on a planar surface. In our experiment, we developed a small leveling table with three adjustable legs and placed them inside the oven. With these measures, a thickness variation of ±2 μm was achieved for the 100-μm film.

3.3.6. Exposure

The resist was exposed at 525 mJ/cm^2 using the mask aligner system EV 620. The mask was printed on a polymeric transparency used in press industry. The resolution of 8000 dpi was acceptable for our purpose.

Post exposure bake: Following exposure, a post exposure bake (PEB) must be performed to selectively cross-link the exposed portions of the film. We baked the exposed SU-8 2100 at 65 °C for 5 min and subsequently at 95 °C for 10 min. The oven was then switched off allowing the wafer to cool down from 95 °C to room temperature of 25 °C in about 1 h. After PEB, SU-8 is readily cross-linked and can result in high residual stress, which causes microcracks. The slow cooling process is crucial to minimize these micro cracks.

3.3.7. Developing

At the end, the SU-8 layer was developed with Microchem SU-8 developer propylene glycol methyl ether acetate (PGMEA). The final structure was then rinsed with isopropyl alcohol (IPA) and dried with nitrogen gun. The fabricated valve is shown in Fig. 7. In order to take the image with scanning electron microscopy (SEM), the SU-8-structure was coated with an aluminum layer. The holes for etch access and stress relieve are visible in Fig. 7.

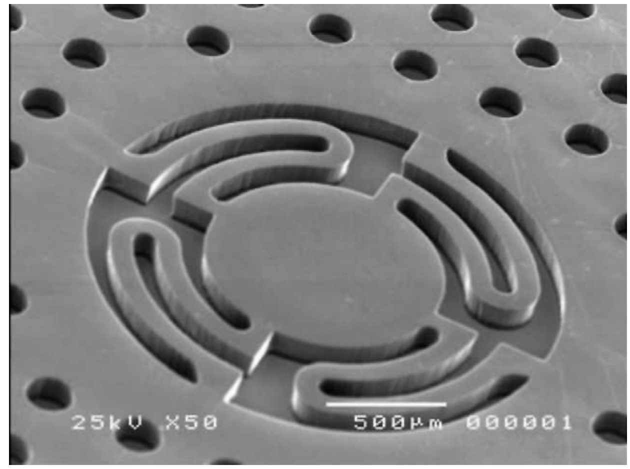

Fig. 7. The fabricated SU-8 check valve.

4. Characterization results

The micro check valve was first characterized. A large water reservoir with variable surface heights was used for adjusting the pressure across the micro check valve. The large reservoir ensures a constant height and a constant inlet pressure during the measurement. The pressure was measured with a pressure sensor (Honeywell 22PC-Series, ±1 psi) which was calibrated for a pressure range from 0 to 6000 Pa. The flow rate was measured by determining the velocity of the water/air interface in the outlet tube. Fig. 8 shows the measurement results of the valve. The negative pressures and flow rates represent the characteristics of the reverse flow. The measurement results show that the valve is leaky in the reverse direction. This fact can be explained by an initial gap between the inlet and the valve disc, which could be caused by assembly tolerance or the non-planar milled surface of PMMA-material.

Simulation results of the model described in Section 3.1 with different initial gaps of 23, 24 and 25 μm are shown in Fig. 8 for comparison. The simulation results show that a small change in the gap could cause a shift in the valve characteristics. For an initial gap of 24 μm and an inlet pressure of 3000 Pa the deflections of the valve disc in forward and reverse directions are 3.27 and 3.58 μm, respectively. The small deflection causes a relatively large leakage flow rate. However, the rectification characteristics of the valve still can be used in a reciprocating micropump. The smaller measured leakage and larger forward flow rate indicates that the actual valve spring is softer, and the actual Young's modulus

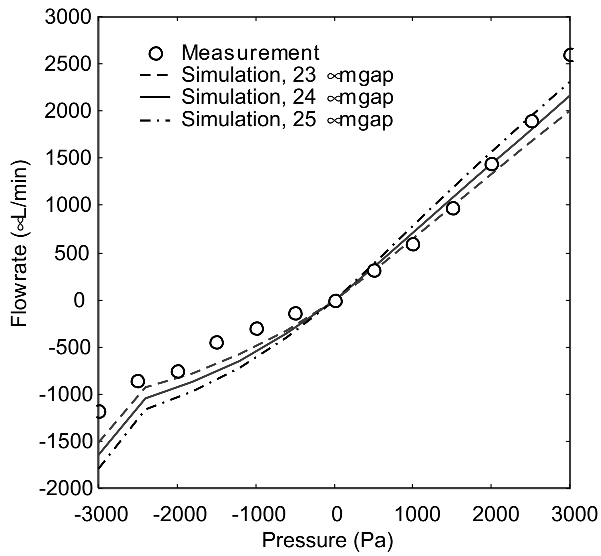

Fig. 8. Measured and simulated behavior of the check valves.

of the processed SU-8 may be less then 4.02 GPa as assumed for the simulation.

The pump was characterized using a simple setup described in a previous paper [10]. The pump was tested with DI water. Fig. 9 shows the flow rates versus the actuating frequencies at different peak voltages. The pump characteristics are similar to those of diffuser/nozzle pumps using the same type of piezodisc as actuator [10]. However for the same peak voltage, the micropump with SU-8 check valves can achieve flow rates, which are twice of those delivered by the previous diffuser/nozzle pump.

Fig. 10 shows the flow rates versus back pressures. While the flow rates are twice as large as those of the diffuser/nozzle pump reported in [10], the back pressures are only a half of those of the diffuser/nozzle pump. That means, the pump with SU-8 valves deliver with the same actuator almost the same pumping power, which is calculated as [1]:

$$P_{\text{pump}} = \frac{Q_{\max} \times p_{\max}}{2} \tag{1}$$

where P_{pump} is the pumping power, $p_{\max}$ and $Q_{\max}$ are the maximum back pressure and the maximum flow rate, respectively.

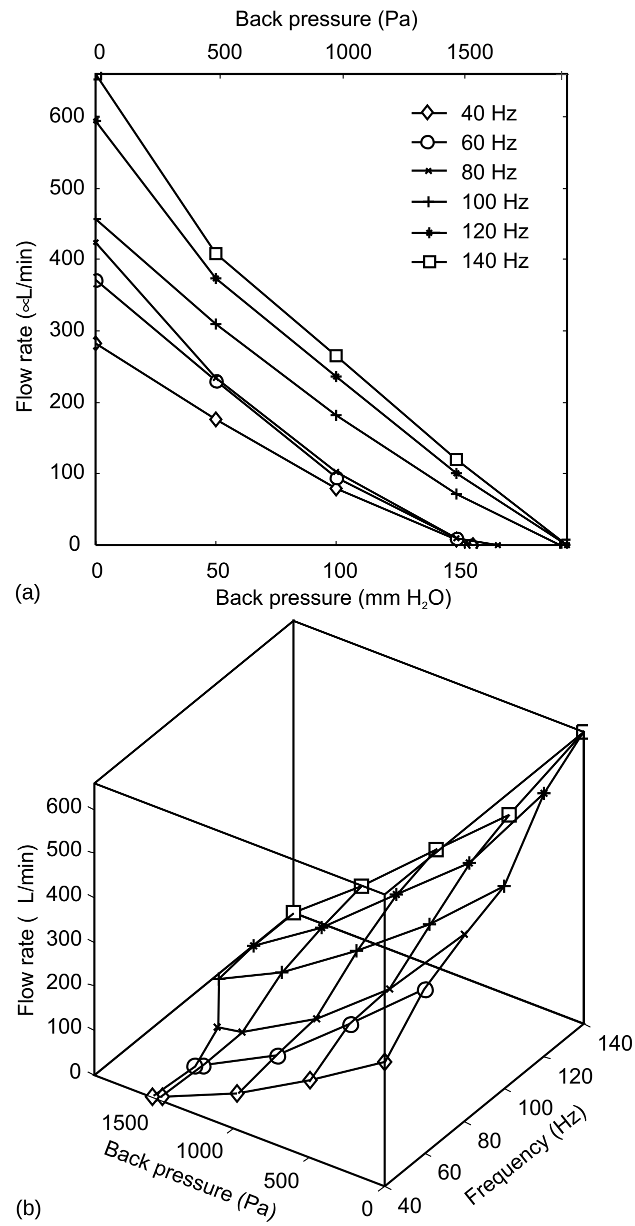

Fig. 10. Flow rates vs. back pressures ($V = \pm 100$ V): (a) flow rate as a function of back pressure and (b) flow rate as a function of back pressure and drive frequency.

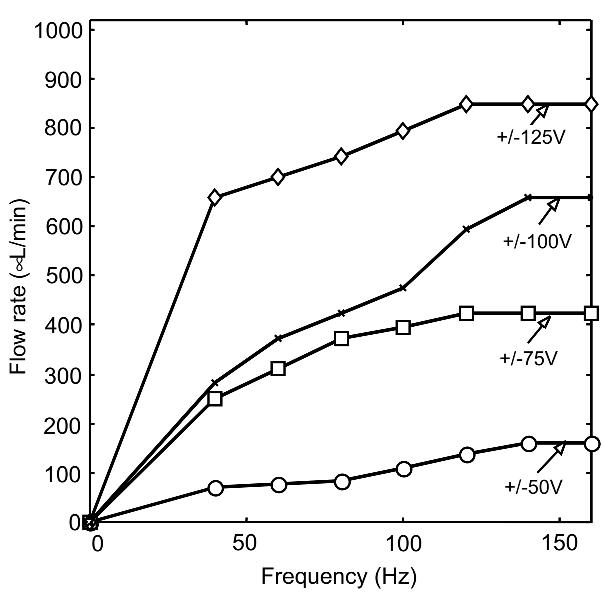

Fig. 9. Flow rate vs. frequency.

5. Conclusion and future works

We have designed, fabricated and characterized a fully polymeric micropump with piezoelectric actuator. The most important parts of the pump are the two micro check valves, which are fabricated in a 100-μm-thick SU-8 film using a one-mask lithography process. The valves feature the compliant orthoplanar spring design. The other parts such as pump chamber and housing are machined using conventional cutting and milling techniques. The pump achieves flow rates and back pressure up to 1 ml/min and 200 mm water, respectively. It can work with voltages as low as 50 V, which is half the drive voltage of other piezoelectric micropumps [10]. The fabrication of this pump demonstrates the layered concept, which lays the foundation for the lamination technique for polymeric microfluidic devices.

The coupled fluid-structural simulation and measurement of the micro check valve show that a softer spring design is needed for a deflection on the order of 100 μm under a back pressure on the order of 3000 Pa. We recently tested several softer valve designs. The results show a much larger ratio between forward flow and the leakage. Further more, a valve design with pre-strained spring may avoid the effect of the initial gap and the large leakage.

Precise alignment of various parts, especially the two check valves, is important for a high-performance pump, yet is difficult to achieve. We are working on different approaches, such as fabricating discs with alignment holes or integrating the two check valves in the same fabrication process. We recently successfully implement lamination techniques for packaging the valves, the piezodisc, and the pump housing, in order to further reduce material, fabrication, and assembling costs.

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Biographies

Nam-Trung Nguyen was born in Hanoi, Vietnam, in 1970. He received his Dip.-Ing. And Dr. Ing. degrees from Chemnitz University of Technology, Germany, in 1993 and 1997, respectively. In 1998, he worked as a postdoctoral research engineer in the Berkeley Sensor and Actuator center (UC Berkeley, USA). Currently he is an assistant professor with the School of Mechanical and Production Engineering of the Nanyang Technological University in Singapore. His research is focused on microfluidics and instrumentation for biomedical applications. He published a number of research papers on microfluidics. His recent book "Fundamentals and Applications of Microfluidics" co-authored with S. Wereley was published in October 2002.

Thai-Quang Truong was born in Vietnam in 1972. He received the MSc in electronics engineering in 2001 from Nanyang Technological University, Singapore. He is currently working towards the PhD degree in microtechnology at the School of Mechanical and Production Engineering of the Nanyang Technological University in Singapore.