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Simulation and Fabrication of Piezoelectrically Actuated Nozzle/Diffuser Micropump

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***Abstract*—Micropumps are one of the most important parts of a microfluidic system. In particular, for biomedical applications such as Lab-on-Chip systems, micropumps are used to transport and manipulate test fluids in a controlled manner. In this paper, a low-cost, structurally simple, piezoelectrically actuated micropump was simulated and fabricated using poly-dimethylsiloxane (PDMS). The channels in PDMS were fabricated using patterned SU-8 structures. The pump flow rate was measured to be 9.49 µL/min, 14.06 µL/min and 20.87 µL/min for applied voltages of 12 V, 14 V and 16 V respectively. Further, we report finite element analysis (FEA) simulation to confirm the operation of the micropump and compare favorably the experimentally obtained flowrate with the one predicted by simulation. By taking these flow rates as a reference, the chamber pressure was found to be 1.1 to 1.5 kPa from FEA simulations.**

Keywords—Micropump, Diffuser, Nozzle, Microfluidics, PDMS, Flowrate.

I. Introduction

With the miniaturization of electronic devices and the advent of next-generation wearable electronics [1-4], the concept of a miniature laboratory for instantly analyzing biofluids has become possible [5-7]. Micropumps play one of the most important roles in the making of microelectromechanical systems (MEMS) based microfluidic systems [8, 9]. Micropumps have significant applications in lab-on-a-chip systems as well as embedded medical devices to exert bodily fluids, insert medicine in the body and help liquid flow [10]. While there are many designs for microfluidic pumps in the literature, one of the simplest designs is the valveless nozzle-diffuser pump which employs a central chamber connected to the inlet and outlet through two flow diodes [11-13] (Figure 1a). When the central chamber is repeatedly pressurized, the fluid flows preferentially from inlet to outlet. Generally, the chamber is pressurized using a flexible piezoelectric disc. The diffuser/nozzle structure of inlet and outlet channels allows more flow in one direction than the other. When the chamber expands, inlet behaves as diffuser and outlet behave as the nozzle. As a result, more flow is obtained through the inlet into the chamber than through outlet out of the chamber. When the chamber contracts, inlet behaves as nozzle and outlet behave as the diffuser. Thus, more flow is obtained through the outlet out of the chamber. The principle of operation of the micropump is shown in Figure 1b.

In this work, a PDMS-based piezoelectrically actuated micropump is fabricated and simulated using finite element analysis (FEA). The fabricated micropump has a typical design (as shown in Figure 1) with a central chamber, inlet and outlet reservoirs, and diffuser/nozzle structure all made of PDMS molded using patterned SU-8 structures. A piezoelectric disc is used to actuate the vibration of the chamber to obtain fluid flow. The flow rate of the micropump is measured to characterize its performance for different applied voltages, and the same is compared with the results obtained from FEA simulations.

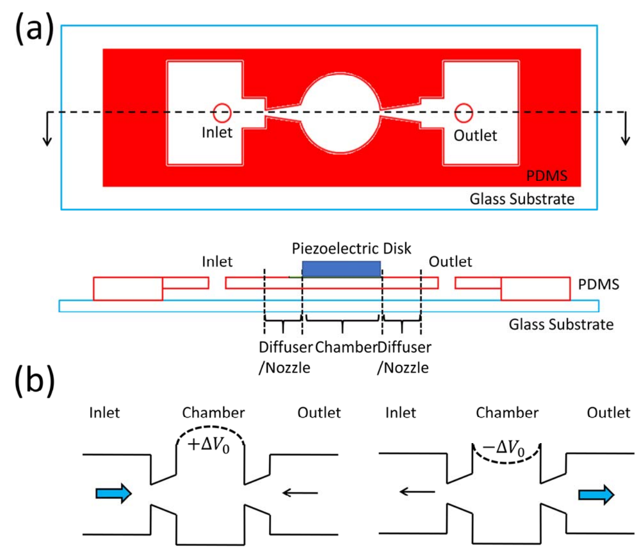

Fig. 1. (a) Structure of the diffuser/nozzle micropump. (b) Principle of operation of the micropump.

II. Simulation Analysis

The micropump was simulated using COMSOL™ Multiphysics by applying different pressures on the chamber assuming that the pressure is uniformly distributed on the circular shape of the chamber. The pressure distribution and fluid flow from a trapezoidal diffuser/nozzle structure were simulated for various applied pressure difference. As expected from theory, for the same applied pressure difference, the fluid flow was found to be less in case of nozzle and more in case of diffuser configuration. This difference in fluid flow is the cause of the net fluid flow from the inlet to the outlet in the micropump design (Figure 1b). The pressure distribution for the trapezoidal structure as diffuser and nozzle is shown in Figure 2. The length of the trapezoid structure was 1500 µm,

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while the width of the two ends were 40 µm and 200 µm. For an applied pressure difference of 1000 Pa, the flow rate was found to be 53.7 µL/min in case of the diffuser and 45.7 µL/min in case of the nozzle configuration. The difference between these is proportional to the net flow rate in a given actuation cycle.

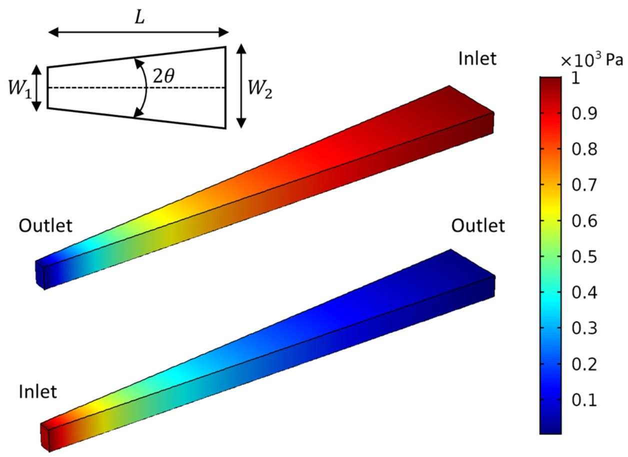

Fig. 2. Results of FEA simulations for pressure distribution in a trapezoidal microfluidic channel with L=1500 µm, W_2=200 µm, W_1=40 µm, as diffuser and nozzle.

We simulated the net flow rate for various applied pressure differences by observing the difference in the flow rates for the diffuser and nozzle structures. The change in flow rate for a nozzle/diffuser pump with respect to pressure is shown in Figure 3. The difference between the two flows (highlighted in Cyan) gives the net flow in case of the nozzle/diffuser micropump.

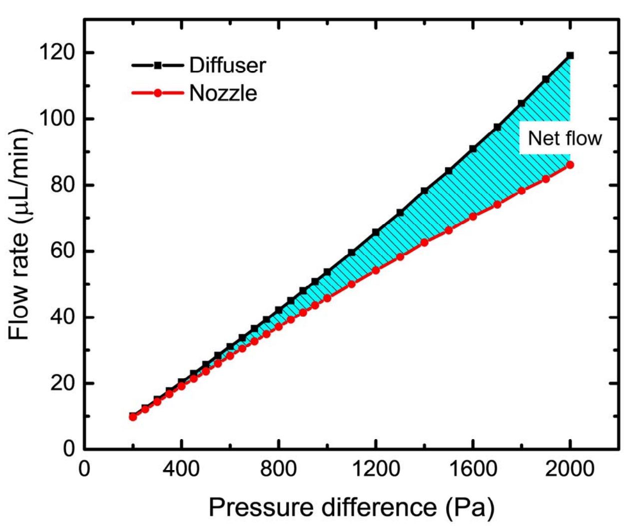

Fig. 3. Results of FEA simulations for flow rate in a diffuser and nozzle structure as a function of applied pressure. Simulated for L=1500 µm, W_2=200 µm, W_1=40 µm.

III. Fabrication And Process

A. *Fabrication of SU-8 mold*

For fabrication, a thick layer of SU-8 was patterned on a silicon substrate to make the chamber, channels and inlet-outlet design. SU-8 was chosen as the mold material because it can be easily handled, can be photo patterned, is chemically stable and does not react with PDMS. SU-8 2025 was spun on the wafer at 1250 rpm for 40 seconds to obtain a film of 70 µm thickness. The wafer was exposed using i-line UV at 250 mJ/cm^2 exposure dose, followed by post-baked at 65 °C for 1 minute and 95 °C for 6 minutes. The pattern was then developed using Microchem SU-8 developer bath for 6 minutes. Figure 4b shows the Scanning Electron Microscopy (SEM) images of the patterned SU-8 layer, which confirm that SU-8 side-walls obtained using the above recipe were smooth and straight.

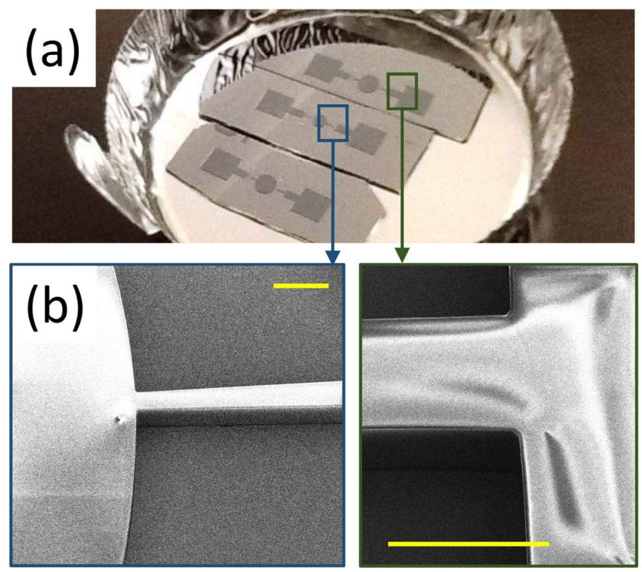

Fig. 4. (a) Optical images of finished SU-8 molds on a silicon substrate. (b) Scanning electron microscopy (SEM) images of the SU-8 mold. Scale bars are 100 µm.

B. *Fabrication of PDMS micropump*

The PDMS prepolymer mixture was created by mixing Sylgard 184 (Dow Corning Inc.) and curing agent in the ratio of 10:1 by weight. The mixture was then poured in aluminum weigh boats containing the SU-8 molds of the micropump as shown in Fig. 4a. The mixture was then degassed in a vacuum oven, while simultaneously being cured at 110 °C for 30 minutes. The PDMS layer thus formed was peeled off and cut into pieces to obtain a single micropump design.

C. *Final assembly*

The PDMS layer was bonded to a glass substrate by surface activation method. Both the PDMS surface and the glass surface were exposed to oxygen plasma in a reactive ion etching (RIE) tool for 40 seconds at a pressure of 70 mTorr, with oxygen flow of 25 sccm. After the plasma exposure, the activated PDMS surface was firmly pressed against the glass surface to affect the bonding. Figure 5 shows an assembled micropump with a colored die in the chamber and inlet/outlet reservoirs. Two small cavities were made in the PDMS layer using syringes to serve as inlet and outlet of the fluid.

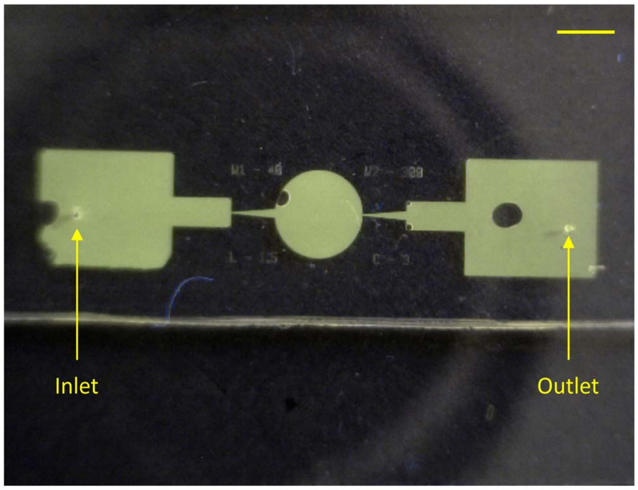

Fig. 5. Optical image of the final fabricated micropump with inlet and outlet syringe cavities, filled completely with colored die. Scale bar is 2 mm.

IV. Results And Discussion

The final assembly of the micropump was used to measure the flow rate for various applied voltages. The flow rate was determined by measuring the time taken to transport a known volume of liquid (200 µL) from inlet to outlet. These measurements were done for a micropump with chamber size of 3 mm. The diffuser inlet width, its length, and its outlet width were 40 µm, 1500 µm, and 200 µm respectively. Given the dimensions of the nozzle/diffuser assembly and assuming the same pressure difference during positive and negative actuation, the efficiency of the nozzle/diffuser structure, η, can be calculated from the following equation [14, 15]:

$$\eta = \left(\frac{19}{20}\right)\left(\frac{W_2}{W_1}\right)^{0.34} \tag{1}$$

From the above equation, the value of η was found to be 1.642, for W_1=40 µm and W_2=200 µm. Now, the net volume flow rate of the nozzle/diffuser structure has been derived as [16]:

$$Q = 2\,\Delta V\,f\left(\frac{\eta^{\frac{1}{2}}-1}{\eta^{\frac{1}{2}}+1}\right) = 2\,\Delta V\,f\,C \tag{2}$$

where Q is the net flow rate, ΔV is the volume change per each actuation cycle, f is the frequency of actuation and C is the rectification factor calculated as,

$$C = \left(\frac{\eta^{\frac{1}{2}}-1}{\eta^{\frac{1}{2}}+1}\right) \tag{3}$$

Thus, C as calculated to be 12.33% for the fabricated micropump with W_1=40 µm and W_2=200 µm. The term ΔV in the above equation depends on the deflection of the diaphragm, which in turn depends on the applied voltage in case of a piezoelectric actuator. Hence, because C is a constant for given micropump dimensions, the net flow rate Q only depends on the applied pressure difference. This is also evident from the FEA analysis reported earlier.

To verify the simulation and analysis, we fitted the experimentally obtained flow rate to the net flow rate obtained from FEA simulations for various pressures. In case of the piezoelectric actuator, the independent variable is the applied voltage which was mapped to applied pressure using a constant multiplier because these quantities are linearly dependent. Figure 6 shows experimental and simulation results for the micropump with L=1500 µm, W_2=200 µm, W_1=40 µm. By fitting experimental results to the simulation, the scaling factor for the applied voltage was found to be 97.24 Pa/V. Thus, the pressure in the micropump chamber was found to be in the range of 1.1 to 1.5 kPa (Figure 6).

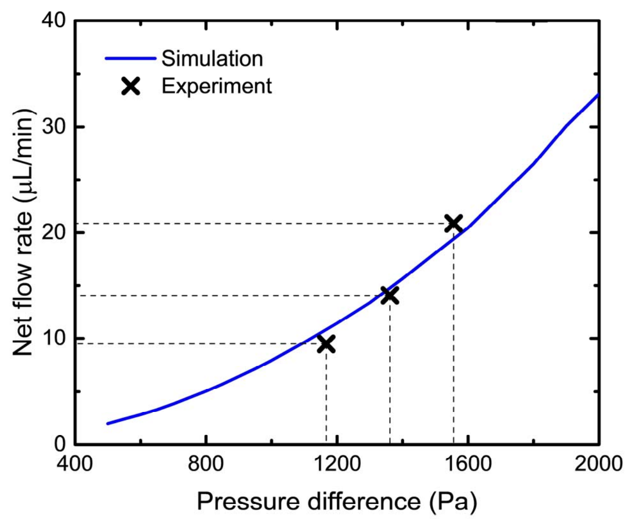

Fig. 6. Experimental flow rate compared to the FEA simulation results for the fabricated micropump.

V. Conclusion

In this work, a process for fabrication of piezoelectrically actuated diffuser micropump was presented, together with FEA simulation of the flow rates for nozzle/diffuser micropumps. The micropump thus fabricated was characterized by measuring flow rate against various applied input voltages. It was established that a working micropump with a rated flow rate of 10 µL/min, at an applied voltage of 12 V, can be fabricated using the given process. The pump efficiency was calculated to be 1.642, while the rectification factor was calculated to be 12.33%. The chamber pressure was found to be in the range 1.1 to 1.5 kPa using the flow rates to calculate the pressure in the chamber by fitting experimental results with the simulation. The micropump fabrication process established in this work can be repeated in the future for various combinations of diffuser/nozzle dimensions. Further characterizations of the fabricated micropumps can be done by measuring backpressure and chamber deflection for given voltage and frequency of the piezoelectric actuator.

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