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PDMS Based Thermopneumatic Peristaltic Micropump for Microfluidic Systems

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Abstract. A thermopneumatic peristaltic micropump for controlling micro liters of fluid was designed and fabricated from multi-stack PDMS structure on glass substrate. Pump structure consists of inlet and outlet, microchannel, three thermopneumatic actuation chambers, and three heaters. In microchannel, fluid is controlled and pumped by peristaltic motion of actuation diaphragm. Actuation diaphragm can bend up and down by exploiting air expansion that is induced by increasing heater temperature. The micropump characteristics were measured as a function of applied voltage and frequency. The flow rate was determined by periodically recording the motion of fluid at Nanoport output and computing flow volume from height difference between consecutive records. From the experiment, an optimum flow rate of 0.82 $\mu\text{l}/\text{min}$ is obtained under 14 V three-phase input voltages at 0.033 Hz operating frequency.

1. Introduction

A micropump can be considered as the most important part for a micro total analysis system (Micro-TAS) or a lab-on-a-chip. Micropumps are integrated to lab-on-chip in order to inject chemical in liquid state with controllable flow rate. Previously, a number of micropump has been reported with varieties of actuation mechanisms such as piezoelectric, electrostatic [3], electromagnetic, shape memory alloy (SMA) [4], electro-osmotic, and thermopneumatic actuation.

Polydimethylsiloxane (PDMS) is one of the most useful materials for fabrication of various microfluidic devices for bio-chip and lab-on-a-chip applications because of its bio-compatibility, low cost, flexibility, and bonding ability. However, most reported PDMS based structures are not mechanically active and the moving parts for the microfluidic systems including micropump and microvalve are usually fabricated from silicon-based micromachining process [1-2]. The cost of such a system is relatively high and hence they are not practical for commercial use in general bio-clinical or biochemical laboratory. In this work, a low-cost microfluidic system employing multi-stack PDMS microchannel with peristaltic micropump structure on a glass substrate is developed.

In this work, a low-cost microfluidic system employing multi-stack PDMS microchannel with peristaltic micropump structure on a glass substrate is developed. Micromachining technology including photolithography, electroplating, thermal evaporation, PDMS casting and bonding was applied for device fabrication. The device performance was then tested by applying three-phase driving voltage and measuring flow rate of pumped fluid at different frequencies.

2. Structure and operating principle

The peristaltic micropump consists of three main components including microchannel, actuation diaphragm attached to actuation chambers, and heaters on glass slide. The cross-sectional view of micropump is depicted in Fig 1.

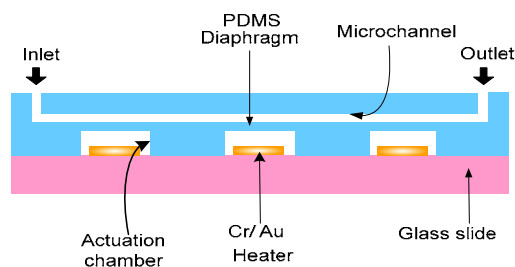


Figure 1. Cross-section view of peristaltic thermopneumatic Micropump.

Fig. 2 demonstrates the operating principle of the peristaltic micropump. Initially, each of heaters is supplied with driving voltage to its corresponding electrical pad. The temperature of heater is increased by Joule's heating effect causing the air inside actuation chamber to expand and the flexible actuation diaphragm to move up to drive the fluid along microchannel (Fig 2 A). Three heaters are driven by three-phase driving voltage (Fig 2 B), causing actuation diaphragms and fluid to move periodically in a wavelike motion. The three-phase control voltage is designed such that the diaphragms are flexed in five successive steps as shown in Fig. 2 A.

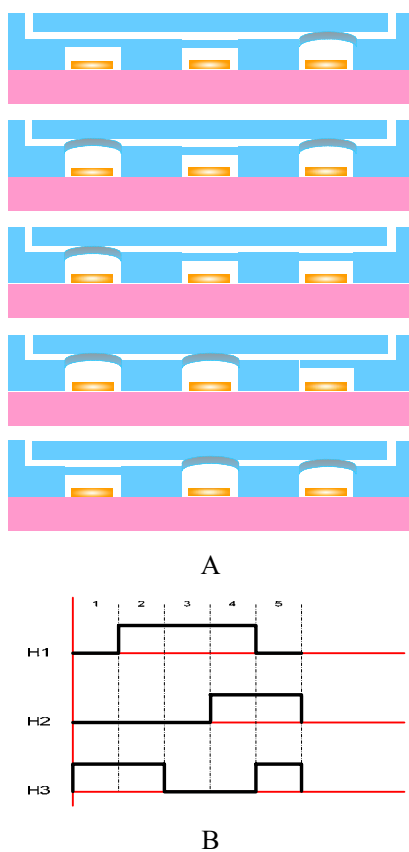


Figure 2. Operating principle of a micropump.

- (A) Working of pump can operate by peristaltic motion of actuation diaphragm
 (B) Three-phase driving voltage for three heaters.

3. Fabrication process

The fabrication process of micropump is depicted as shown in Fig 3. First (Fig 3.A), SU-8 mold has been constructed on silicon wafer for casting PDMS microchannel. 50 μm -thick photoresist are spin-coated on a cleaned silicon wafer and patterned by the standard photolithography. Then, 10:1 of PDMS (Dow Corning Sylgard 184) base and curing agent has been mixed and degassed for filling up the SU-8 mold. Next, the PDMS was soft-cured at 90 $^{\circ}\text{C}$. PDMS Microchannel replica is then peeled off from mold and holes for inlet/outlet ports are punched at both ends of the microchannel. The microchannel is ~ 100 μm wide and 50 μm deep.

The next stage is the fabrication of the PDMS actuation diaphragm (Fig 3.B). PDMS diaphragm can be fabricated by spinning technique on glass slide. The spinning speed and spinning time are dependent on the PDMS material and specific lab equipment. Different spinning speed and time can yield different thickness of PDMS layer. Higher spinning speed produces thinner PDMS membrane. After spinning PDMS on a glass slide, soft curing is performed in order to strengthen cross-link of PDMS polymer. In this design, the thickness of PDMS diaphragm is controlled to be ~ 30 μm .

The PDMS actuation chamber (Fig 3.C) is then made by the spinning technique similar to the process of making diaphragm. However, the thickness of this PDMS layer is much thicker and it is controllable by lowering spinning speed. In this design the thickness of chamber should be about 500 μm . PDMS layer is then soft-cured and striped off from the glass slide. Three punched holes are made to form actuation chambers, which has circular shape with radius of ~ 2 mm.

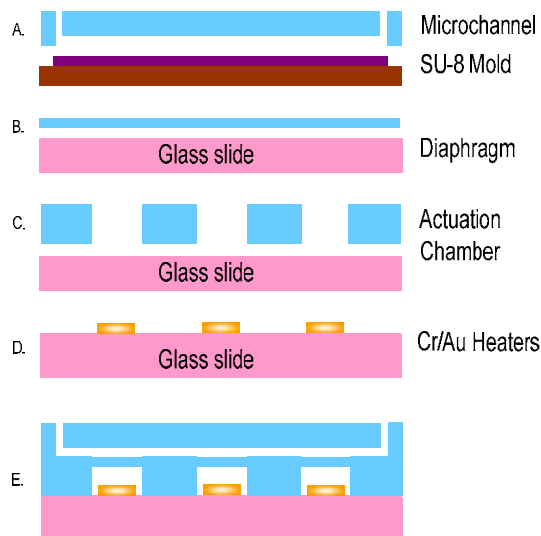


Figure 3 Fabrication processes.

- (A) PDMS microchannel&inlet/outlet
- (B) PDMS actuation diaphragm
- (C) PDMS actuation chamber
- (D) Cr/Au heaters on glass slide
- (E) Assembled a peristaltic thermopneumatic micropump

Next, Cr/Au heaters are fabricated by thermal evaporation through microshadow masks. Firstly, Ni-mask has been designed and constructed by Nickel electroplating process. This mask is used as shadow mask in thermal evaporation process. Before loading glass slide into chamber, glass slide should be cleaned by Piranha solution to get rid of organic contaminations. Cleaned glass slides with mask are thermally evaporated with 30 nm-thick Cr layer and 200 nm-thick Au layer, respectively. The resistances of fabricated heaters (Fig. 3 D) are in range of 120-140 Ω .

After all components have been created, the oxygen plasma bonding technique is applied for bonding PDMS to PDMS and PDMS to glass slide. The conditions (i.e. pressure, operating time, and power) of bonding depend on specific tool. Before bonding process, the surface of PDMS and glass slide should be cleaned with methanol. All PDMS layers and heaters on glass slide are assembled as shown in Fig. 3 E. Finally, inlet/outlet ports by Nanoports kit and Teflon tube are installed. The Nanoport is used to reduce backing pressure along the channel.

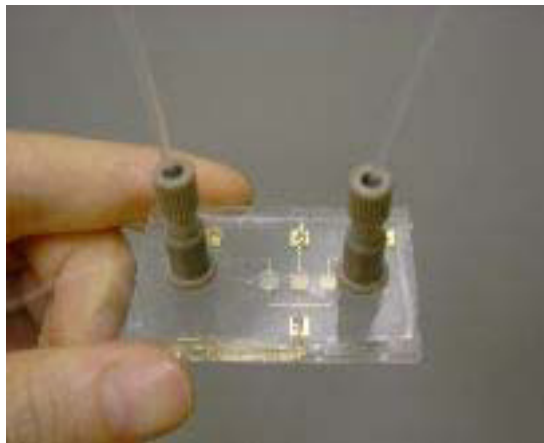


Figure 4. Fabricated thermopneumatic peristaltic micropump was installed with Nanoports and Teflon tube.

4. Measurement

The measurement has been set up as shown in Fig 5. In order to measure accurate flow rate, methanol is chosen to be the test fluid for the PDMS microchannel because it has suitable surface tension such that it can fill the channel easily with no bubble. The three-phase pulse driving power supply is controlled by FPGA (Field Programmable Gate Array) circuit. After the pulse voltage is applied to Cr/Au electrical pads, peristaltic diaphragms start pumping methanol from Nanoport inlet through microchannel to Nanoport outlet.

To measure the characteristics of a peristaltic micropump, a digital camera is used to capture the image of fluid movement at the exit Teflon tube. For flow rate measurement, captured image of fluid flowing in tube is done for every 5 minutes. The flow volume can be determined from the height difference of fluid between two consecutive images and the flow rate is obtained by dividing flow volume with the time between two records. It should be noted that the height scale of image is calibrated against the known inner diameter of Teflon tube of 0.75 mm. Two consecutive images of fluid and height difference are illustrated in Fig. 6.

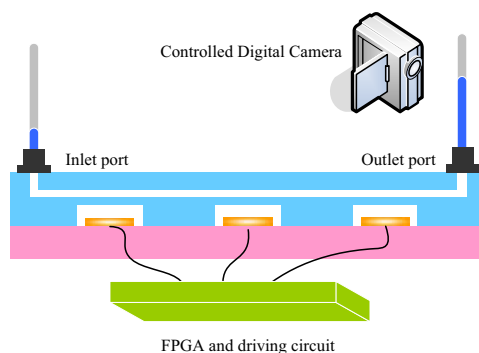


Figure 5. Set up experiment for flow rate measurement. Digital camera was used for capture image. FPGA board was connected to micropump for controlling supply power.

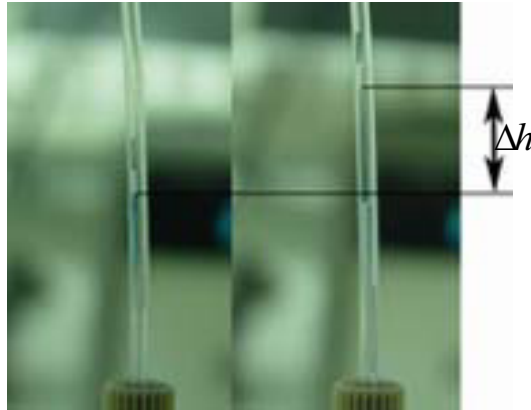


Figure 6. Compared consecutive images for measurement the height difference of fluid flow in outlet Nanoport.

The micropump characteristics are studied as a function of applied voltage and operating frequency because the applied voltage and pulse duration have tremendous effects to temperature inside the actuation chamber. In this experiment, the applied voltage and the operating frequency are varied from 6 volts to 14 volts and from 0.025 Hz to 0.668 Hz, respectively. Fig. 7 shows the flow rate versus applied voltage for various operating frequencies. From the figure, it is seen that flow rates at various frequencies tended to increase linearly as a function of applied voltage. In addition, the slope of increasing flow rate is considerably depending on the applied frequency. It can be noticed that as the frequency increases, the slope of increasing flow rate is reduced considerably. This effect can be explained from the fact that as the frequency increases, heating time in each cycle is reduced. As a result, the diaphragm deflection and pumping rate decrease.

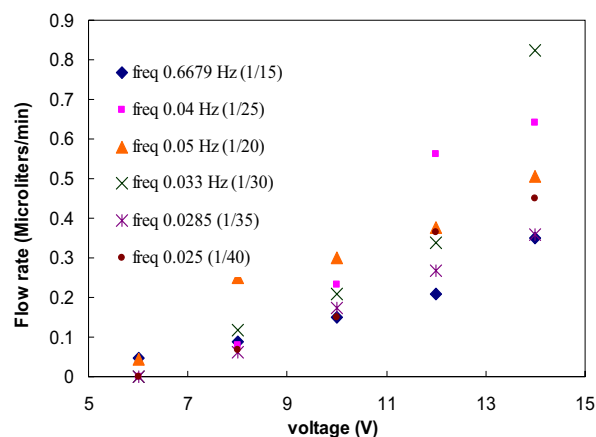


Figure 7. Flow rate vs. voltage for different driven frequencies of the PDMS peristaltic micropump.

The flow rate characteristic as a function of operating frequency for various applied voltage are shown in Fig. 8. The frequency of three-phase voltage is limited in the very low frequency range between 0.025 Hz and 0.668 Hz because the heater in the actuation chamber requires a long time to heat up and cool down. From Fig 8, there is an optimum frequency where the flow rate is maximized at each applied voltage. In addition, the optimum frequency is reduced as the applied voltage increases. In this experiment, the maximum flow rate of 0.82 $\mu\text{l}/\text{min}$ is obtained at 0.033 Hz at applied voltage of 14 volts. It should be noted that flow rates would drop after reaching their

maximum frequencies according to actuation mechanism that required a specific range of time to let heaters heat up and cool down.

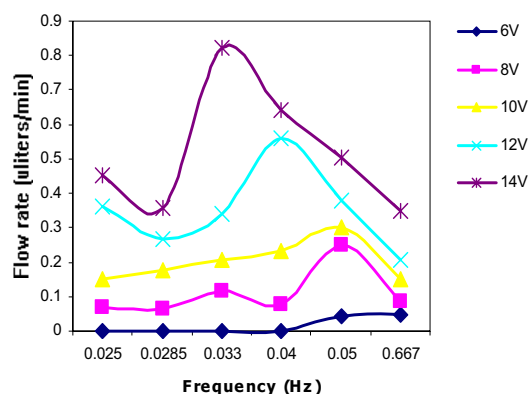


Figure 8. Flow rate vs. frequency for different supplied voltage.

5. Conclusions

In conclusion, PDMS-based thermopneumatic micropump integrated on microfluidic glass chip has been developed. The micropump has been fabricated by low cost processes including PDMS casting, oxygen plasma bonding, electroplated micromasking, and thermal evaporation. The flow rate of micropump had been measured by means of consecutive image captures along transparent Teflon tube and characterized as a function of applied voltages and operating frequency. It was found that the flow rate increased linearly as a function of applied voltage. In contrast, flow rate does not always increase as the operating frequency increases and there is optimum frequency where maximum flow rate is reached at a given applied voltage. The fabricated peristaltic micropump was able to produce a maximum fluid flow rate of 0.82 $\mu\text{l}/\text{min}$ with 14 V maximum applied voltage. Therefore, the developed PDMS based micropump is applicable for nano/micro liter scale control in Lab-on-chip and drug delivery system.

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