Research Article

Design and Fabrication of a PDMS-Based Manual Micro-Valve System for Microfluidic Applications

Tu N. Le,1 Van-Anh Nguyen,2 Giang L. Bach,3 Lam D. Tran,4,5 and Ha H. Cao2

1National Psychiatric Hospital No. 1, Hanoi, Vietnam
2School of Chemical Engineering, Hanoi University of Science and Technology (HUST), Hanoi, Vietnam
3Nguyen Tat Thanh University, Ho Chi Minh City, Vietnam
4Institute for Tropical Technology, Hanoi, Vietnam
5Graduate University of Science and Technology (GUST), Vietnam Academy of Science and Technology (VAST), Vietnam

Correspondence should be addressed to Ha H. Cao; ha.caohong@hust.edu.vn

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1. Introduction

Recently, the micro/nano-fluidic devices are interested in biomedical and chemical analyses. The micro/nanofluidics with very small channels (μm size) have advantages such as: reducing the consumption of agents; increasing sensitivity thanks to small volume (micro/nano litter) with large surface-to-volume ratio [1, 2]. In addition, the development of nanotechnology and micro/nano electromechanical system (MEMS, NEMS) helps to easily fabricate and integrate microelectronic components and functionalized modules. Therefore, the development tendency of microfluidic system is design and fabrication of a “Lab-on-a-chip” model by integrating with functionalized modules such as sample mixers, micro-reactors, sensors, etc. [3–5]. These chips are studied and applied in biomedical (e.g., DNA, cell, and PCR analysis) or chemical analyses [6, 7], and they will be power tools for many analysis processing. However, each biomedical or chemical analysis is used to carry out with many chemicals or biological agents, nanoparticles, etc); these agents are often introduced into a reactor, sequentially. Regarding a microfluidic system, the add-on devices connecting to the microfluidic needs to be miniaturized, and all agents are injected into micro-channels by micro-pumps; the sequence of flow needs to be controlled by a micro-valve system [8, 9].

Typical studies [9–11] on microfluidics reported that it was easy to control the on/off chip flows based on a valve structure. There are several commercial valve systems, e.g., the MUX WIRE system from Elveflow® company or LINEUP™ Series from Fluigent® company. These valves systems are professional but quite expensive. In the literature, some models of “Lab-made” valves were designed for controlling liquid flows of microfluidic system in laboratories [12, 13]. These valves were proved to be effective for controlling the flows in the microfluidic systems, and they had reasonable fabrication cost for end-users in laboratories. In generally, the microfluidic valves are used in some types of control structures: operating mechanics, pneumatic, electro-kinetic, phase changes, or introduction of external force [13]. The microfluidic valves
can be classified by two main types of valve states: the active valves and the passive valves depending on mechanical or non-mechanical moving parts [14].

The poly(dimethyl siloxane)—PDMS is one of the most popular materials for fabricating microfluidic systems and others components such as control valves or pumps in laboratories [14]. Concerning the “Lab-made” cheap valves, Zhang [12] reported the hydraulic valve design (using PDMS materials). This valve was integrated fully in microfluidics as an internal part, and it was controlled by adjusting the pressure in a displacement chamber on the pneumatic layer via a computer-regulated solenoid [12], Elizabeth Hulme [15] designed and fabricated screw, pneumatic and solenoid valves embedding directly into microfluidic devices. These valve systems were generated easily by a replica molding process and a PDMS rapid prototyping technique due to a soft lithography process [15]. The direction unit for the screws of these valves was made of cured epoxy that was filled on top of the PDMS slab to fix the screws. However, these valves do not work stably due to the deformation of the microchannels when the valve was screwed, directly interfering with the channels [16, 17]. Brett [9] designed and fabricated a manually actuated pin valve for controlling the fluid flow (on/off) within microfluidic channels [9]. This valve consisted of a simple pushing pin (a polydimethylsiloxane tip) and was integrated inside an inlet that connected to the microchannel. However, it cannot be separate from the microfluidic system, so that such valves are not reusable.

In this study, a valve was designed and fabricated as an individual part of a microfluidic system for different applications that needs the flows to be controlled. Besides, a specific multi-valve switch also has been designed and fabricated to manipulate flows that injects from syringe pumps into a multi-inlet channel. This switch is very useful to stop the flow existing in the channel and to control the multi-flows during the operation of the microfluidic system. Different to the single inlet case, this design avoids the tube plugging/un-plugging actions causing a certain mechanical force. It is very important because the flow inside the channel is very sensitive with this force due to the small volume of the channels. Moreover, it has absolute precision and rapid response time during the operation process, similar to expensive commercial products (e.g., the valve systems of Elveflow® or Fluigent®).

2. Materials and Equipment

The 2-inch silicon wafers were from The Institute of Electronic Materials Technology (ITME)—France. Poly(dimethyl siloxane) (PDMS) was in the Sylgard 184 Silicone Elastomer Kit, purchased from Dow Corning Corporation. PTFE tubes (0.8 mm ID) were supplied by Cole—Parmer. The photoresist SU-8 3050 was from MicroChem Corp. Teflon layer was a CYTOP® product (AGC Chemicals Company). Other chemicals were obtained from Sigma Aldrich Inc.

The fabrication processes were carried out in a clean room of The Nano and Energy Center (NEC)—VNU, Vietnam with a system consisting of: The OAI Model 800E Mask Aligner system for lithography process; and a Pico plasma cleaner system (Diener electronic GmbH) for the plasma treatment; all thermal treatments or bonding processes were performed in a MEMMERT heating and drying oven, and hot plates.

3. Results and Discussion

3.1. Design and Fabrication of the PDMS Manual Micro-Valve System

3.1.1. Description of the Manual-Controlled Valve System. The working principle of the valve is based on the mechanical structure (in Plexiglas® materials) and flexible materials (PDMS) as described in Figure 1.

The valve system has a working part including a micro-channel and a thin film made of the PDMS material (Figures 1(a) and 1(b)). The PDMS film was fabricated with 100 µm thickness and bonded on top of the channel by a plasma technique. The microchannel was fabricated with dimensions of $W \times D \times L: 1 \times 0.05 \times 10$ mm in PDMS via a soft lithography technique. The mechanical structure for opening and closing the flow of the valve was combined with two components: a screw (~3 mm of diameter, with 0.5 mm of thread pitch) is guided thanks to a threaded hole in Plexiglas slab fixing with second slab; a PDMS piece (~2.5 mm) is smaller than the screw hole and freely moves in this hole. The PDMS piece helps the screw head not crack the PDMS film during the working process.

Concerning the valve as shown in Figure 1(d), there are two main structures including PDMS and Plexiglas® parts. The PDMS part contained channels part (relevant to the channel valves) and an intermediate PDMS slab that had several holes with diameter the same as that of the screws. They were located onto the top of each channel-valve position. The two mechanical structures were fabricated using Plexiglas® material, including: the first part was designed with threaded array holes (as described above); the second part was a bottom support that combined with the first part (as a clamp) to fix all structures of the valve system.

3.1.2. Fabrication of the Manual-Controlled Valve. Firstly, the channel valve (PDMS material) was prepared by using the SU-8 master mold in the clean room. The SU-8 master mold of the channel valves was fabricated on a silicon wafer by the soft lithography technique. A 50-µm thick layer of the photoresist SU-8 3050 was spin-coated in two steps onto the silicon wafer (2 inches). The first spin step was at 500 rpm speed for 5~10 s with an acceleration of 100 rpm/s; the second spin step was at 3000-rpm speed for 30 s with an acceleration of 300 rpm/s. After the spin coating, the photoresist layer was soft-baked on a hotplate at 95°C for 15 min (a). Then it was exposed in UV radiation (with a transparent mask) at 250 mJ/cm² of power (b). After that, it was taken for a post bake at 65°C for 1 min, and at 95°C for 5 min. The development process was achieved by a SU-8 developer solution for 5 min. Finally, the mold was rinsed with isopropanol and dried in a nitrogen flow (c).

Secondly, the PDMS valve channels were fabricated by replica molding and the PDMS rapid prototyping technique.
The fabrication process was performed as follows: Step 1. The fresh PDMS was prepared by mixing uniformly two components: silicone elastomer base and curing agent at a ratio of 10:1 (wt./wt.). After mixing, the mixture was degassed in a vacuum chamber. Then, fresh PDMS was poured onto the mold (from Figure 2(c)), and cured at 90°C for 1 h or at 75°C for 2 h (Figure 3(a)); Step 2. The embossed channel was carefully released from the SU-8 mold (Figure 3(b)) and cut in a suitable shape; Step 3. Inlets and outlets of channels were drilled directly by PDMS tool kits (Figure 3(c)); In the last step (4), the valve channels were bonded to a 20-µm thick PDMS layer to close them. This PDMS layer was obtained by spin-coating the fresh PDMS (10:1 ratio) onto a silicon wafer with a certain 5-µm-thick of Teflon-coated layer (prepared by using the CYTOP® product (AGC Chemicals Company)) in order to easily peel off. Then, this PDMS layer was cured in an oven at 75°C for 1 h. The bond of PDMS valve channels to the PDMS layer was carried out by using oxygen plasma treatment in 1 min. The bonding step was taken by thermal treatment at 75°C for 1 hour. This bond was irreversible bonding.

3.1.3. Fabrication of Plexiglas® Clamps and Its Assemblage with the Valve System. Two clamps (Plexiglas® materials) of the valve were fabricated by the CNC (computerized numerical control) technique. The design of these clamps, with parameters of $W \times D \times L$: $3.5 \times 0.8 \times 7$ cm, is shown in Figure 4. One pair of clamps included a bottom support, Figure 4(b), and a top support that were used for operating
The valve system was connected to micro-syringe pumps and microfluidics via PTFE tubes (0.8 mm ID). The valve was tested for the mixing process using three liquid flows (Figure 6): two solutions of methylene blue (1st and 3rd flow) and DI water (the 2nd flow at the middle). The microfluidics was designed with multi-inlets and outlets that can be used for performing ELISA (The Enzyme-Linked Immunosorbent Assay) experiments.

Firstly, the three syringe pumps were set at the maximum flow rate of 150 μL/min to inject the liquids into the microchannels through the multi-controlled valves. Secondly, the three flows were controlled by setting the level of releasing or closing screws in three different modes (Table 1).

screws to generate a force on the PDMS layer Figure 4(a). The assemblage of the PDMS valve channels and clamp parts was shown in Figure 4(c). Four screws were used to fix the PDMS parts (including valve channels and PDMS support slap) by two clamps. These screws need to be fixed tightly enough to avoid blocking the channel valve.

3.2. Test of Controlling the Liquid Flow in the Microfluidic Device. The manual-controlled valve system was connected to a microfluidic system with multi-inlets for mixing purpose. The experimental setup for testing the liquid flows is shown in Figure 5.
The results of controlling the fluid flows by the valve with the purpose of mixing the liquid in the microchannels are shown in Figure 6.

By using the valve, the process inside the channels could be controlled thanks to either the stop-flow mode or the continuous-flow mode. It is very effective to perform a complex analysis working with multi-liquid flows that needs to be controlled (e.g., ELISA immunoassay in microfluidic system). In

(i) Mode 1: three flows were opened at the maximum flow rate.
(ii) Mode 2: the 1st and 3rd flows (methylene blue solution) were opened at the maximum flow rate, the 2nd one (DI water) was reduced from 150 to 0 (µL/min).
(iii) Mode 3: the 1st and 2nd flows were reduced from 150 to 0 (µL/min); the 3rd one was opened at the maximum flow rate.
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4. Conclusions

The “lab-made” manual micro-valve system was designed and fabricated successfully by the micro-fabrication technique. This valve consisted of two main components: Plexiglas® clamps and PDMS complex structures. The Plexiglas® clamps contained an array of screws for controlling the level of opening/closing flows. The PDMS component included an important PDMS film as the actuator part, and this film was fabricated easily in the step of closing valve channel. Significantly, the valve system was fabricated as a separated device, and easily connected to microfluidic system by tubes. The valves operated uniformly and performed reproducibly with repeated use in the mixing process experiments.

The valve system is compatible with multi modes of the operation, but it is recommended to use in fully opening/closing mode of the flow. The range of controlling the liquid flows depends on applications of the microfluidic system. It can be adjusted by changing the size of the channel valve. The valve system is also inexpensive because of the low costs of materials: Plexiglas clamps, general machine screw, PDMS, etc.

Data Availability

The data used to support the findings of this study are included within the article.
Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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