A NOVEL PASSIVE NORMALLY CLOSED MICROFLUIDIC VALVE

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Abstract: Microfluidic systems require numerous control valves in order to function properly. These valves form the basic unit of fluid handling within the microfluidic system. Many different valves have been designed and manufactured, both active and passive. The current paper investigates a novel passive valve that works on the principle of hydrostatic pressure. This normally closed valve can also be used in a toggle valve combination, where only one external actuation source is required to yield two valves that open and close sequentially. The first valve is an active valve, operated pneumatically. The second valve operates purely on the pressure applied by the fluid in the microfluidic channel at the valve entrance. One valve is thus always closed, while the other is open. By changing the valve entrance properties, the valve can be designed to operate at different actuation pressures.

The valve mechanism, which consists of four layers of polydimethylsiloxane (PDMS), was designed and manufactured using the SU-8 lithography and replication molding processes. It was successfully implemented, and initial results show the relationship between the applied pressure and flow rate.

In addition to being used as a toggle valve, this design also allows for the passive valve to be used as a stand-alone pressure valve and as a one way valve, which would restrict fluid flow to a single direction. This may give rise to the possibility of designing entirely passive microfluidic devices, which would be advantageous from a circuit complexity and energy usage perspective.

Key words: microfluidics, normally closed passive microvalve, soft lithography, polydimethylsiloxane (PDMS)

1. INTRODUCTION

Microfluidic devices have advanced considerably over the last 20 years. They have evolved from simple, single channel devices to complex devices which integrate numerous components and functions. In this way, high density microfluidic chips have been developed [1]. In contrast to the expensive equipment which was typically required for the bulk and surface micromachining of silicon, the development of the soft lithography technique for fabrication has led to the ability to rapidly fabricate and test these circuits [2, 3]

Microfluidic valves and pumps are critical to the successful implementation of these devices, typically referred to as lab-on-chip devices. In fact, the successful commercialisation of microfluidic technology is often believed to have been delayed by the lack of reliable microfluidic components [4]. Although much progress has been made in the development of these components, there is still a lot of scope for the improvement of microfluidic components.

The valve is often thought of as the basic unit of fluid handling functionality, much the same way as the transistor in semiconductor electronics [5]. Valves are often categorised as either active or passive. Active valves are further characterised as mechanical (e.g. moving membranes), non-mechanical (e.g. intelligent materials) or external (e.g. pneumatic). Passive microvalves can be characterised as either mechanical or non-mechanical [4, 6].

In this paper, the idea of a normally closed passive microfluidic valve is explored. The great advantage of successfully developing such a valve is the reduction of external power sources for driving a microfluidic circuit. A number of researchers have worked on developing normally closed microfluidic valves. Grover et al [7] have developed a three-valve circuit which forms a latching microfluidic valve. The control for the latching valve is connected to two additional valves. This design allows for an elegant control of numerous latching valves utilising microfluidic logic structures. This configuration is primarily used as an active valve. Yang and colleagues [8] have developed a pneumatic micropump which is incorporated with a normally closed microfluidic valve. The valve, formed from a floating block in the microfluidic channel, operates when the hydraulic pressure inside the channel is higher than a certain critical pressure.

In this study, a different mechanical structure is utilised for the development of a normally closed passive microfluidic valve. In addition to this valve being utilised in a stand-alone mode, it can then also be utilised as one valve in a toggle valve combination (Figure 1). The second valve is a pneumatically actuated active microfluidic valve. Hydrostatic pressure from an external pump source opens the passive valve when the pressure exceeds a certain threshold resulting from the closing of the active valve.

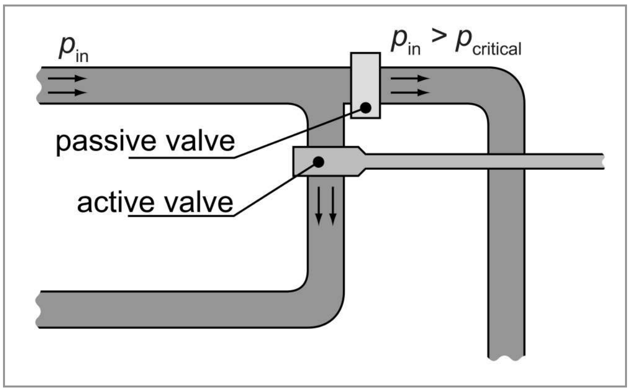

Figure 1: Passive valve being used in a toggle valve configuration

2. FUNCTIONAL PRINCIPLE

2.1 Active Valve

The most common type of active valve being utilised with soft lithography techniques is called the monolithic micromechanical valve. One layer of PDMS contains the fluid channel, while a second layer of PDMS contains the channels for pneumatic actuation. The two layers are bonded together with a thin middle membrane, such that the two channels are crossed. In this way, when a pneumatic pressure is applied to the actuation layer, the membrane is deflected into the fluid channel, thereby closing it [9, 10]. This is typically the valve which will be utilised with the passive valve described in this paper (see Figure 1).

Grover et al have described a normally closed active microfluidic valve, which can be used to form a latching valve combination. Figure 2 shows a schematic of this valve design. When a vacuum is applied to the control channel (via the pressure connection), the PDMS membrane is pulled downwards into the bottom chamber. Fluid is then free to flow through to the output channel (Figure 2b).

Although the authors mention the actuation of the valve purely by hydrostatic pressure, they do not explore this concept further.

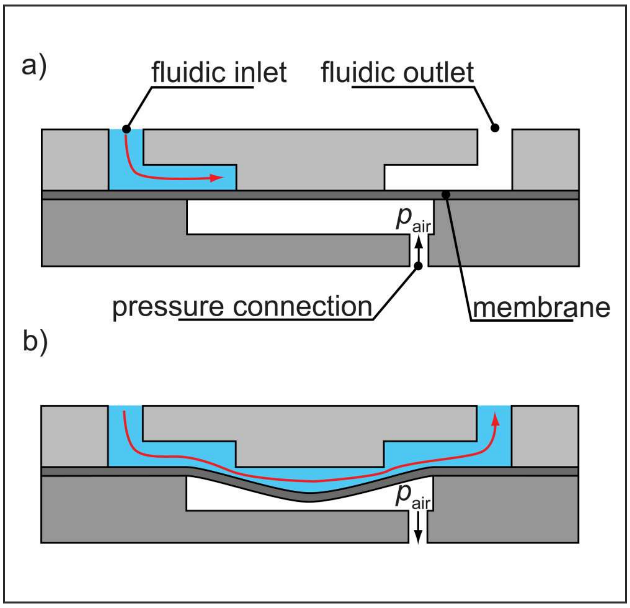

Figure 2: Principle of the normally closed active valve.

2.2 Passive Valve

A passive valve operating with hydrostatic pressure would have a number of advantages. Most importantly, no external control would be required, and this greatly diminishes the power requirements on a microfluidic circuit. Figure 3 shows the functional principle of a passive valve.

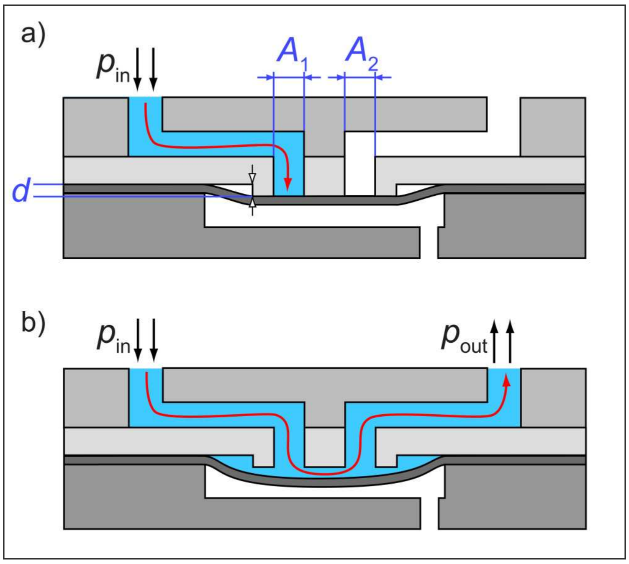

Figure 3: Functional principle of the passive normally closed microfluidic valve

A_1 represents the surface area in contact with the input fluid. A_2 is the surface area of the output side of the valve. 'd' represents the distance by which the membrane is depressed before actuation. This stretches the membrane to give it a pre-tension. Thus, when the pressure is removed from the inlet, the membrane returns to its original position, thereby closing the valve. This also determines the pressure, $p_{critical}$, required to depress the membrane for actuation.

Actuation occurs once the pressure from the input fluid reaches $p_{critical}$, the membrane is depressed and fluid flows freely from the inlet to the outlet. A reduction of the inlet pressure below $p_{critical}$ closes the valve due to the tension force on the membrane.

2.3 Design

The device consists of four PDMS layers. The bottom layer contains the atmospheric pressure chamber which allows the PDMS membrane to deflect downward. The schematic shows an inlet into this chamber. This is for testing purposes and does not play a functional part of the valve. The membrane is attached directly to this chamber (making out the second layer). The top layer contains the fluidic channel and the fluid inlets and outlets. Sandwiched between the membrane and the top layer is a layer which contains two tubes connecting the fluid inlets and outlets and a block ensuring pre-tension on the membrane. This third layer is seen in Figure 4 as the block with two protruding cylinders.

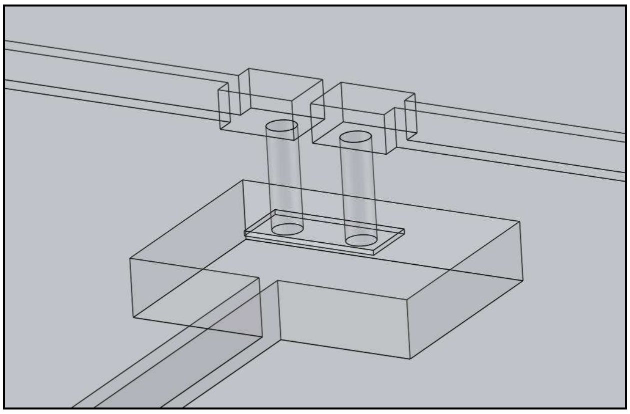

Figure 4: Schematic of the four level valve

3. PROCESS FLOW

3.1 Fabrication of the valve

Figure 5 is a schematic of the fabrication process, showing the SU-8 lithography stage (mold fabrication) together with the replication molding process (part manufacture).

The process is as follows (note that spin coat, baking and exposure parameters are photoresist thickness dependant – values given are for the 150 µm thick top and bottom layers):

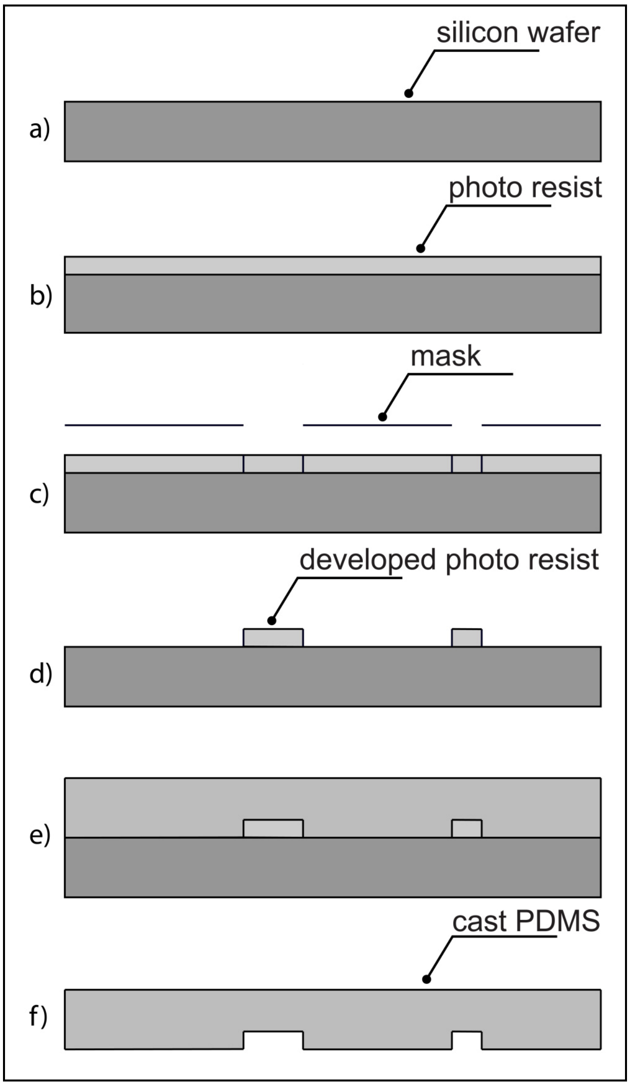

Figure 5: Flow of the manufacturing process

1. Clean silicon wafers in acetone in ultrasonic bath for 15 minutes. Dry with nitrogen (Figure 5a)
2. Oven bake at 200 ^{0}C for 30 min
3. Spin coat SU-8 negative photo resist onto a 4 inch silicon substrate (spin speed 1850 rpm, SU-8 2100) (Figure 5b).
4. Soft bake (5min @ 65 ^{0}C, 30 min @ 95 ^{0}C)
5. Expose with mask aligner (i-line 365nm, 260mJ/cm^2) (Figure 5c)
6. Post exposure bake (PEB, 5 min @ 65 ^{0}C, 12 min @ 95 ^{0}C)
7. Develop with SU-8 developer (visual check, approximately 15 min) (Figure 5d)
8. PDMS (silicone elastomer and curing agent mixed in a 10:1 ratio) is poured onto the mold template (Figure 5e)
9. Degassing of the PDMS utilising a vacuum pump and desiccator.
10. PDMS cured (@ 65 ^{0}C for 1 hour)
11. PDMS inverse structure peeled off mold (Figure 5f)
12. Structure mounted to laser cut Perspex templates and holes punched for fluidic inlets and outlets

13. Finally, PDMS structures are bonded together after being treated by oxygen plasma.

Figure 6 shows the top layer mold after step 7 above. Note that this test mold had numerous valves, which allows for testing of various valve configurations, such as different pillar diameters or series of valves in parallel. Figure 7 shows the mold made for creating the tube and block structures for the middle layer. The pillars in this scanning electron microscope (SEM) image are 200µm in diameter.

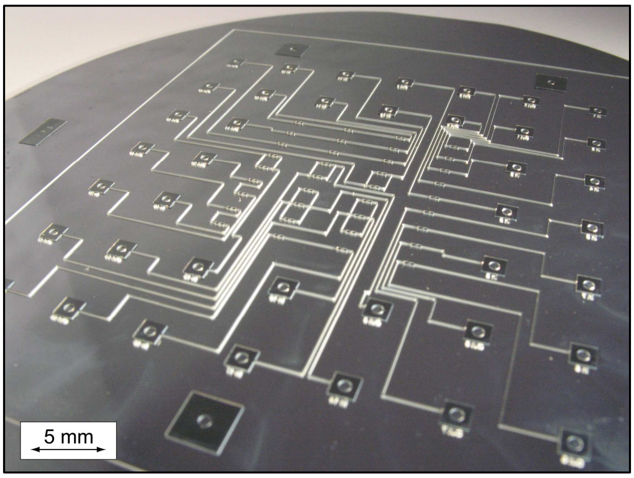

Figure 6: Microscope image of the top layer mold

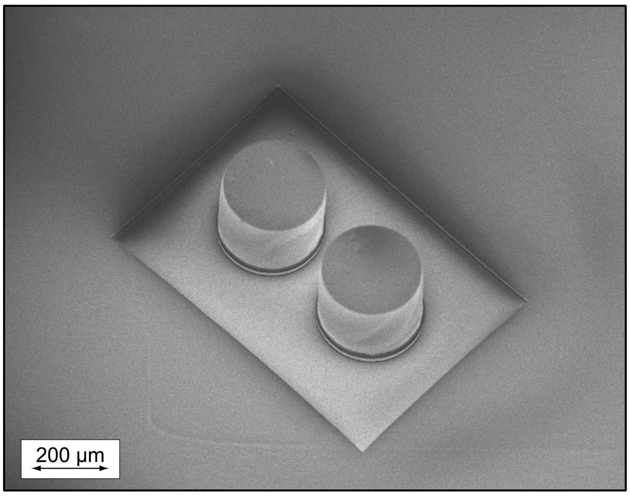

Figure 7: SEM image of the pillar structures on the middle layer mold.

In order to manufacture the PDMS structures, Perspex jigs are laser cut and placed onto the wafers. PDMS is cast into these jigs. The top layer is manufactured with a thickness of 3mm, as is the bottom layer. A thin layer of polycarbonate foil is placed on top of the jig to ensure the top surface also being flat. The middle layer is manufactured in a similar way, but this time the foil is placed on top of the pillars to ensure that channels are formed (and not blocked by a too thick layer of PDMS). The membrane is spun coated onto a Perspex base plate.

3.2 Assembly of the valve

The assembly of the valve involves a number of steps.

Firstly, the top and middle layers are aligned and bonded after treatment with oxygen plasma. A stereo microscope is used for the alignment. Once bonded, the structure is inspected to ensure that the channels are open after casting on the pillars. In some cases, it is necessary to cut open the very thin PDMS layer closing the channels.

Secondly, the bottom layer is bonded to the membrane on the base plate.

Lastly, the two structures are bonded to each other. The device is ready for testing.

4. EXPERIMENTAL SETUP AND RESULTS

Figure 8 shows a photograph of the experimental setup which was utilised for measuring the flow rate through the valve. A hydrostatic column was used to mount the fluid (food colorant mixed with water). This column had a maximum height of 1.5m. The PDMS structure was mounted vertically, and the outlet of the valve was then taken along a measurement platform where the distance travelled per unit time could be measured. The Figure 8 enlargement shows the inlet and outlet together with the path of the fluid through the test structure.

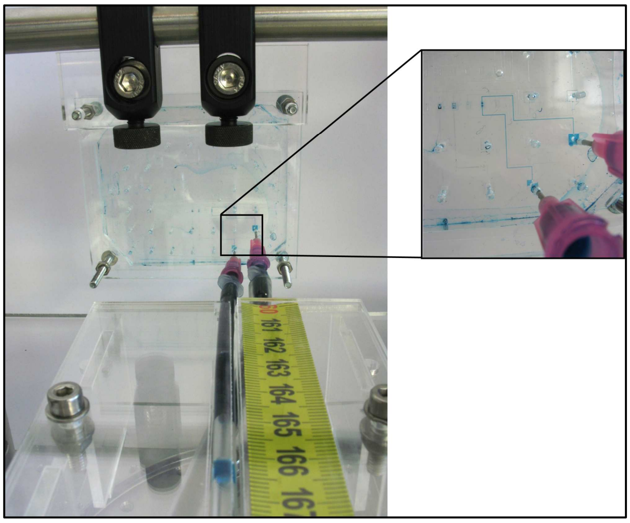

Figure 8: Photograph of the experimental setup used for the valve flow tests

As stated earlier, the valves are first tested using active actuation in order to determine whether the valves are correctly manufactured. The most important parameter to check is whether there is flow going through the device, as the current manufacturing method can leave a thin membrane in the tube structures which blocks flow.

Figure 9 shows a photograph of the valve before (a) and after (b) actuation.

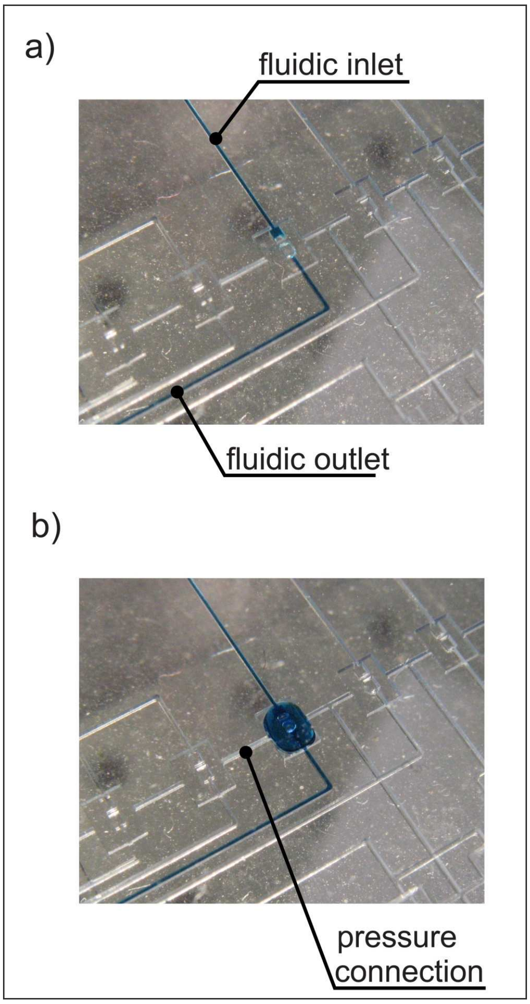

Figure 9: Photographs showing the valve (a) before and (b) after actuation.

Figure 10 shows a graph of the flow rate through the valve as a function of actuation pressure (hydrostatic pressure). The valve shown in this graph had tube diameters of 200 µm. The valve opens at 2 kPa, after which the flow rate is linear. This linear flow rate is expected.

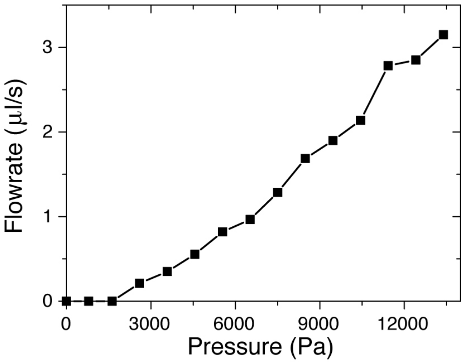

Figure 10: Graph of the flow rate as a function of pressure for a 200µm valve structure.

5. CONCLUSIONS AND OUTLOOK

This paper described the design and implementation of a normally closed passive microfluidic valve. It works on the principle of hydrostatic pressure and enables one to create a toggle valve configuration using only one external actuation mechanism. Preliminary results confirm the principle and show that the flow rate is a direct function of applied pressure.

To refine the concept and optimise the valve, several aspects need further investigation. These include:

- The manufacturing process needs to be fine-tuned. Currently, blocked valves result due to the formation of a thin membrane on top of the pillar structures on the mold. This will be investigated further.
- Precise alignment of the system for placement of the four layers is crucial to ensure functional valves. Making the system more robust to misalignment will reduce the number of rejected valves.
- A complete characterisation of the valve will be done with respect to flow rate, tube diameter and length, and membrane thickness. From this, the functional pressure range will be determined.
- Lastly, combinations (both serial and parallel) of valves will be tested, as well as the novel idea of a toggle valve.

Successful implementation of this valve could lead to a number of passive chip designs. Reducing the number of external actuation sources required per chip has a positive knock-on effect on the infrastructure surrounding the chip as well as the power requirements of the chip itself. These developments will assist in making point-of-care medicine a reality.

6. REFERENCES

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