Proceedings of IMECE'03
2003 ASME International Mechanical Engineering Congress & Exposition
Washington, D.C., November 16-21, 2003

IMECE2003-41213

MICROFABRICATED PDMS CHECK VALVES

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ABSTRACT

This paper presents two types of novel micro check valves that are based on PDMS. The valves consist of a thin flap and a flow restriction block inside a microchannel. The flap is perpendicular to the flow and lies near the block, which forms a restricted fluid path inside the channel. The valves are fabricated entirely from PDMS through replica molding techniques and can be readily integrated in PDMS-based complex microfluidic systems. Testing results show that for a reverse flow, the 2D valve has a saturated leakage rate at higher pressures, leading to an interesting "fluid diode" phenomenon, while the 3D valve has zero leakage at higher pressures.

KEYWORDS:
Microfluidics, microfluidic diode, microvalve, PDMS, replica molding, soft lithography.

INTRODUCTION

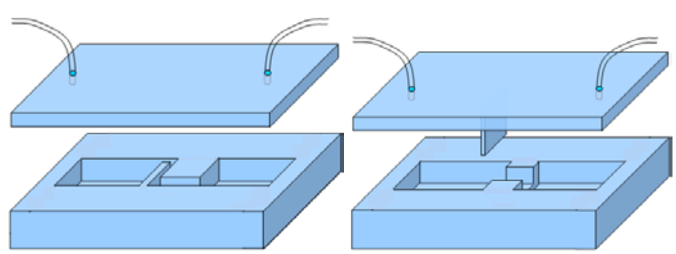
Check valves are passive devices in a fluidic circuit that open for forward flow and close for reverse flow. They are commonly required in microfluidic systems to direct flows. Micro check valves, as well as active valcves, have commonly been fabricated on silicon substrates using micromachining technology [refs]. Recently, alternaltive materials, such as polyimide and parylene and other polymers, have also used for micro valves [1, 2].

In recent years, PDMS (polydimethylsiloxane) has been widely used in microfluidics due to its numerous advantages, such as ease of fabrication, optical transparency, low Young's modulus, and excellent sealing properties [3]. PDMS has been also used as a microvalve material [4-6]. However, most of these microvalves are hybrid structures of PDMS and other materials, and require rather complex fabrication procedures. Microvalves fabricated entirely from PDMS have been scarce [7], even though they can be very useful in PDMS-based microfluidic systems.

This paper presents two types of micro check valves fabricated entirely from PDMS. These novel micro check valves, which are embedded in a microchannel, have relatively simple geometries and can be fabricated using procedures that are completely compatible with commonly used PDMS microfabrication techniques [3, 8]. Thus, the valves can be readily integrated within a PDMS microfluidic system for flow regulation without consumption of power.

DESIGN

Two types of micro check valves are designed. The schematic of these valves are shown in Figure 1. They respectively can be roughly characterized as having two- and three-dimensional arrangements of valving elements, and will be referred to as "2D" and "3D" valve designs hereafter.



(a) (b)

Figure 1. Schematics of two types of check valves. (a) Valve design with a 2D arrangement of valving elements. The flap sits in the microchannel. (b) Valve design with a 3D arrangement of valving elements. The flap is fixed to the cover PDMS sheet.

The PDMS micro check valves consist of a thin flap and a flow restriction block sitting within a microchannel. The flap is perpendicular to the flow and is located near the block, which forms a restricted fluid pathway inside the microchannel. For forward flow, hydrodynamic force pushes the flap away from the restriction step, allowing fluid passage. For reverse flow, the flap is pushed towards and into contact with the block, creating a restriction and thus shutting off the flow. For both valve designs, the bottom PDMS sheet contains the channel features, while the top sheet serves as a cover plate. The microchannel is formed by bonding these two PDMS sheets.

For the 2D valves, the microchannel is 200 μm in width and 250 μm in height. Both the flap and restriction block sit within the microchannel on the bottom PDMS sheet, and have the same height as the channel. The flap is anchored to one channel sidewall as well as the channel floor, while the block fixed to the other sidewall, forming a 50 μm × 250 μm flow restriction area.

The second valve design has a 3-D arragement of valving elements. The micronchannel on the bottom sheet is 300 μm wide and 400 μm high. The restriction block sits on the bottom PDMS sheet with a 75 μm × 200 μm flow restriction area. The flap is fixed to the cover PDMS sheet. This valve design would allow the restriction channel to be completely sealed by the flap. Therefore it drastically reduces the leak rate for reverse flow, as will be confirmed by the testing results below.

FABRICATION

The replica molding technique [3, 8] has been used for fabrication. This involves first making a master mold on a silicon wafer that has inverted features of the microvalve, then pouring a liquid prepolymer onto the mold, and finally curing to obtain a solidified PDMS sheet. Figures 2 and 3 show the fabrication processes for the bottom and cover PDMS sheets of the 3D valve design. To make the photolithography mask, the layout is drawn using CAD software and then printed onto transparency films using a high-resolution laser printer with a 3600 dpi resolution. These transparency films are used as masks in contact photolithography with a high-aspect ratio, negative tone photoresist (MicroChem SU-8 50, Newton MA). The resulting pattern from the lithography serves as the master mold for the prepolymer.

Fabrication of Molds. The fabrication steps will be described using the bottom PDMS sheet of the 3D valve as an example (shown in Figure 2). We first pattern the shallow depth features of the master (the reverse feature of restriction block channel in this case) by spincoating a 200 μm thick photoresist layer (SU-8 50) onto the wafer and exposing it to UV light through a high-resolution transparency mask. Without developing the un-crosslinked photoresist, we spin-coat a second layer of SU-8 photoresist (200 μm) on top of the first photoresist layer. We align a second high-resolution transparency mask to the crosslinked features and exposed the photoresist to UV light again. The second transparency contains patterns for the large-depth features (the reverse feature of the main fluid channel in this case). Then both layers of photoresist are developed in a single development process, with the resulting pattern giving the master for the bottom PDMS sheet. To facilitate the release of the cured PDMS sheet, a very thin detergent layer is coated on the master mold.

Replica Molding with PDMS. A curing agent and PDMS prepolymer (Sylgard 184 Silicone Elastomer Kit, Dow Corning) are thoroughly mixed in a 1:10 weight ratio. After being degassed for 1 hour to remove any air bubbles, the mixture is poured onto the master mold. A transparency film is carefully lowered onto the prepolymer mixture to prevent bubbles from forming at the interface. It also serves as a handling tool to remove the PDMS replica from the master mold after curing. The master-prepolymer-transparent film stack is clamped between two plates and cured for 3 hours at 100 °*C***.** Finally, the PDMS replica is peeled off from the master.

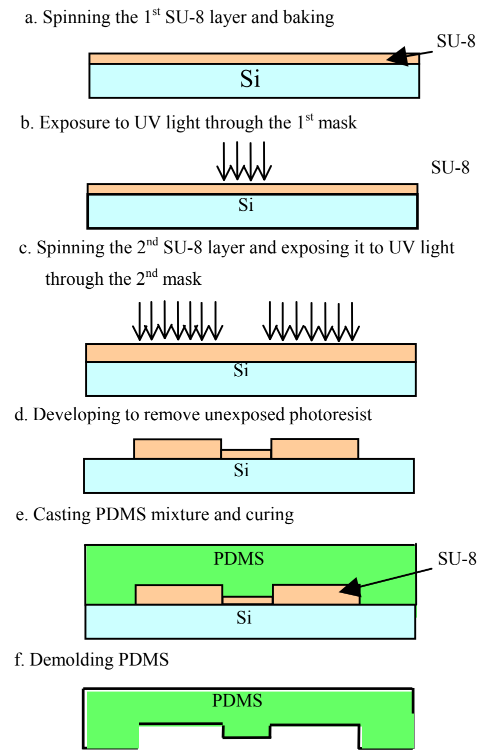


Figure 2. Fabrication process for the bottom PDMS sheet in the 3D valve design.

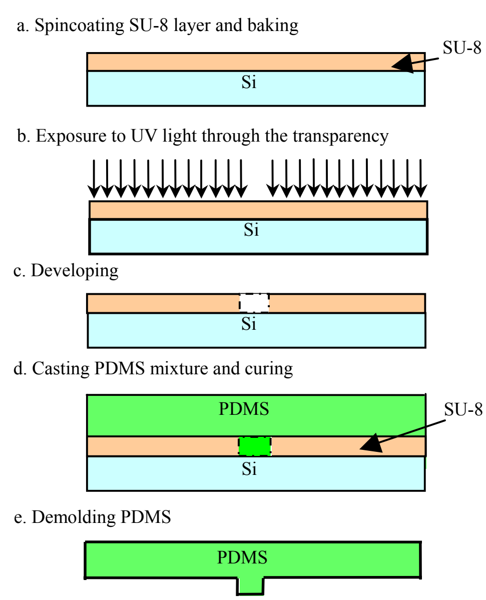


Figure 3. Fabrication process for the cover sheet in the 3D valve design.

Figure 3 shows the fabrication process of the cover PDMS sheet for the 3D valves. The process is similar to that for the bottom PDMS sheet, although only one UV exposure is necessary and no alignment is needed due to its simplified geometry.

Assembly and Fluidic Interconnection. After the bottom and cover PDMS sheets are cleaned by ultrasonic agitation with acetone, they are placed into a shallow container with methanol, which serves as a surfactant for alignment. Five small holes and pillars of the same size (180 μm diameter) are fabricated on the bottom and cover sheet respectively, to facilitate alignment of features during assembly. The two sheets are aligned and assembled manually under a microscope. After methanol evaporates, the surfaces of the two sheets are reversibly bonded together.

The fluidic interconnections are made on the cover sheet. Inlet and outlet connections are created by puncturing the cured PDMS sheet using a gauge needle (about 500 μm inner diameter). Epoxy glue is used to connect Tygon tubing to the cover sheet. To prevent the epoxy glue from entering the punctured holes on the cover sheet, a short polyimide tubing of small outer diameter is used as a coupler between the punctured holes and the Tygon tubing. Figure 4 shows micrographs of the fabricated valve elements.

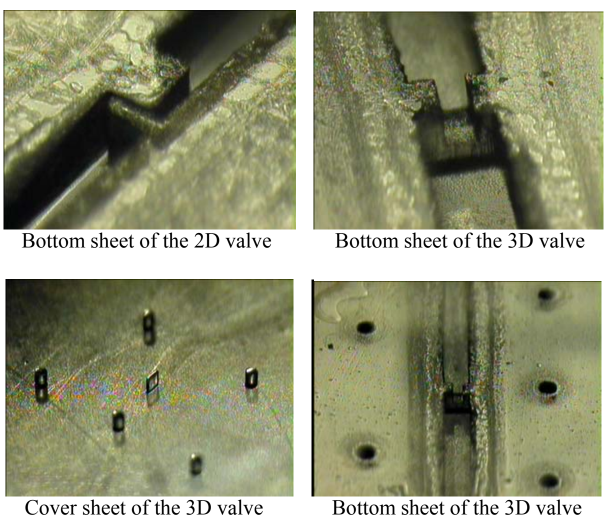


Figure 4. Micrographs of the fabricated valves before assembly.

TESTING RESULTS

We now present the results from the testing of our PDMS micro check valves. Water is used to test the valves. A syringe pump (KD Scientific 210, New Hope, PA) is used to pull water from the outlet channel with a precise flow rate. The pressure is measured with a digital vacuum pressure gauge. The testing setup is shown in Figure 5.

Two valves (valves A and B) with the 2D design have been tested. The flap of valve A is 175 μm wide and 60 μm thick, and is located 15 μm from the block. The flap of valve B is 160 μm wide and 80 μm thick, and is 25 μm from the block. Two valves (valves C and D) have also been tested for the 3D design. The flap of valve C is 100 μm wide and 25 μm thick, and is at a distance of 10 μm from the step. The flap of valve D is 100 μm wide and 37.5 μm thick, and is 5 μm from the step. For both valves C and D, the flaps are 300 μm long.

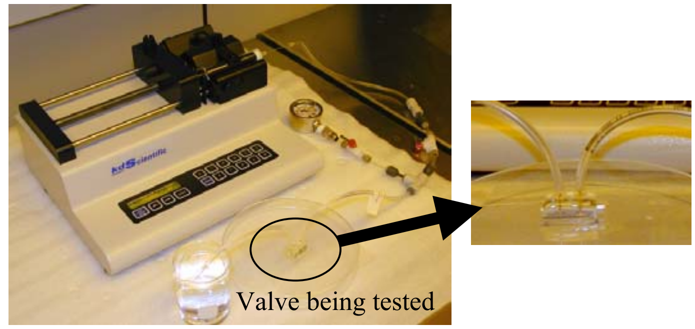


Figure 5. Test setup for the microvalves.

Since the bottom and cover PDMS sheets are not irreversibly bonded together, the syringe pump is operated in withdrawal mode to generate a pressure difference across the valve. Shown in Figure 6 is the flow rate as a function of the applied pressure for the 2D valves (valves A and B, respectively). The flow rate is almost linear with the applied pressure for the forward flow. This verifies that forward flow is largely Poiseuille in nature. For the reverse flow, the flow rate increases much more slowly as the pressure is increased. When the reverse pressure is larger than 40 kPa, the leakage flow rate almost remains a constant, at about 0.3 and 1 ml/min for valve A and B, respectively. These relatively large leakage rates are mainly due to the nature of the design where the flap is not as freely movable.

For the 2D valves, the testing results show that valve A has a smaller saturation leakage rate (about 0.3 ml/min) than valve B (about 1.0 ml/min). The reason is that the gap between the flap and the flow restriction block for valve A (15 μm) is less than that of valve B (25 μm). Therefore the smaller the gap between the flap and the flow restriction block, the smaller the saturation leakage flow rate for a reverse flow.

The 3D valves have a better performance due to its more sophisticated design. Shown in Figure 7 is the measured flow rate as a function of the applied pressure for the 3D valves (valves C and D, respectively). Similar to the 2D valve, the flow rate is almost linear with the applied pressure for the forward flow. But for the reverse flow, as the pressure increases the flow rate first increases and then decreases down to zero. This means that the 3D valves can be sealed completely at high pressures while undergoing reverse flow.

For the 3D valves, testing results show that valve D has a better performance than valve C. For reverse flow, when the pressure varies from 10 to 45 kPa, the flow rate for both valves C and D almost remains constant, which is similar to the 2D valves. When the pressure is increased to larger than 45 kPa, the leakage flow rate decreases until reaching zero. The cutoff pressure is 71.5 and 96.2 kPa for valves D and C, respectively. The difference in the cut-off pressure for the two valves is mainly because the gap between the flap and the flow restriction block for valve D (5 μm) is less than that of valve C

(10 μm). The stiffness of the flaps also influences the cut-off pressure difference.

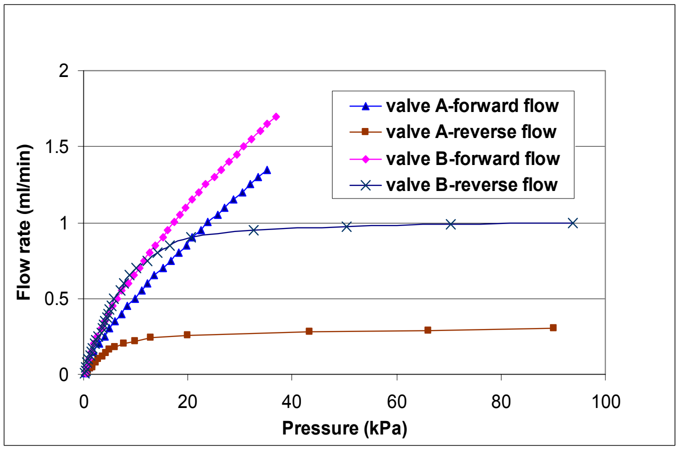


Figure 6. Testing results for the 2D valves

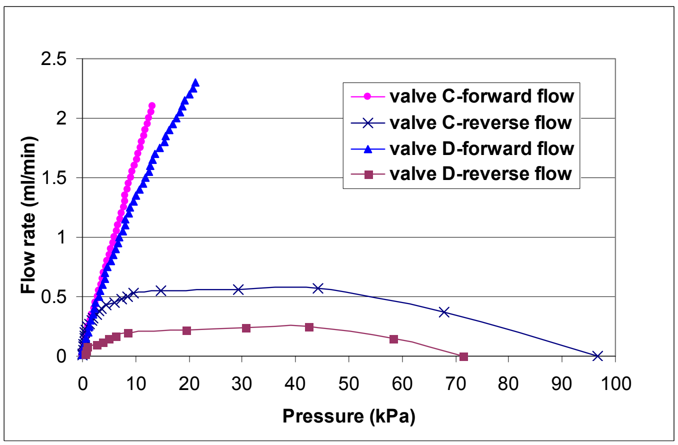


Figure 7. Testing results for the 3D valves

We have also measured the positive pressure required to reopen the 3D valves after they are completely sealed by the reverse pressure. Pressures ranging from 9 to 11 kPa are required to reopen the valves. The value is dependent on the valve configuration. This reopening pressure is very small, which means that only a small positive pressure is needed to push the flap away from the restriction block, thus easily opening the valve. This is a desired property for check valves.

Interestingly, the 2D valves show a "fluidic diode" behavior in that, in reverse flow mode, flow rate is virtually a constant at varying pressures. Although the 2D valves do not perform very well in valving, they are excellent fluidic diodes that may be very useful in many applications, such as microdialysis research. To our knowledge, this is the first time microfabricated passive fluidic diodes are reported. This fluidic diode behavior can be explained by a dynamic relation between the flow resistance and applied pressure. In reverse flow mode, as pressure increases the flap is pushed closer to the flow restriction block. This leads to a reduced effective area of flow passage and increased flow resistance, therefore the flow rate is not sensitive to the applied pressure. Detailed modeling of this fluidic diode behavior is currently under way.

CONCLUSION

Two types of PDMS check valves have been presented in this paper. The first type has a 2D arrangement of valving elements and the second type has a 3D configuration. The valves consist of a thin flap and a block inside a microchannel. Multilayer photolithography has been employed to fabricate the master for the valves, and the replica molding technique used to fabricate the micro valves from the master. The 2D valves have a pressure-insensitive leakage flow rate and behave like a fluidic diode. The 3D valves allow the restriction channel to be completely closed by the flap, leading to excellent passive valving.

ACKNOWLEDGMENTS

The authors would like to thank the MEMS Lab in the Department of Electrical and Computer Engineering at Carnegie Mellon for generously granting access to the fabrication and testing facilities.

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