# A screw-actuated pneumatic valve for portable, disposable microfluidics

Yizhe Zheng, Wen Dai and Hongkai Wu\*

Received 7th July 2008, Accepted 6th October 2008 First published as an Advance Article on the web 7th November 2008 DOI: 10.1039/b811526e

This work describes a simple and inexpensive approach for controlling the pneumatic valves that were invented in Quake's group to miniaturize the whole system for portable and disposable microfluidic devices. The valves are assembled from two parts. One is the polydimethylsiloxane (PDMS) channels formed by multilayer soft lithography. The other is a polymethylmethacrylate (PMMA) frame with machine screws for pressure control. Turning the screws into the control channel inlet (filled with water and covered with a thin PDMS membrane) actuates the valve by creating pressure in the control channel. This method avoids the bulky and expensive external pressure-control facilities and can be easily integrated into portable and disposable devices.

This work describes the fabrication of miniaturized pneumatic microvalves that are conveniently actuated with small machine screws. As the whole valves are very small in size and only require machine screws and polymethylmethacrylate (PMMA) plates, we demonstrate their use in portable and disposable microfluidic devices.

Microfluidics has grown into a flourishing field that holds the promise to offer better solutions for various areas such as bioanalysis and biomedical sciences with a number of advantages: small quantities of samples and reagents; high resolution and sensitivity of separation and detection; low cost; short times for analysis; and small size for portable devices.<sup>1-5</sup> There have been two contributions that are considered particularly important to the development of this field.<sup>2</sup> One is the development of soft lithography in polydimethylsiloxane (PDMS) as a method for fabricating prototype devices. The use of PDMS greatly reduces the cost and time for fabricating a microfluidic device; this material also offers a number of unique properties that are compatible with optical detection and biological samples (e.g., biomolecules and cells).<sup>6-9</sup> The other is the development of a simple method of fabricating pneumatically activated valves on the basis of soft-lithographic procedures developed by Quake et al.<sup>10</sup> This valve is fabricated in PDMS with two perpendicular microchannels in different layers that are separated by a thin PDMS membrane. The bottom layer is the fluidic channel. The top is the control channel that is connected to a pressure regulator; the pressure applied to the top channel can press the inbetween membrane down into the bottom channel and close it. Thus, the valve can control the fluid flow by changing the pressure in the top channel. Although many other types of valves have also been developed,<sup>11-17</sup> this monolithic, pneumatic valve has become the most widely used and offers a number of advantages: simple to fabricate; easy to be integrated; fast in response time and easy to manufacture in high density. In addition, this valve does not generate dead volume and its operations can be programmed under computer control.<sup>10,18-20</sup>

Department of Chemistry, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China. E-mail: chhkwu@ust.hk; Tel: (+852)2358-7246 However, it also has two major limitations: it requires bulky and expensive external hardware (usually gas cylinders with pressure regulators) for controlling pressure; and the off-mode of the valve requires constant pressure.<sup>10,18–20</sup> These limitations hinder the applications of this valve in portable and disposable micro-fluidic devices. Alternatively, Whitesides, *et al.* demonstrated a torque-actuated valve that directly uses small machine screws to press on PDMS microchannels for controlling fluid flows.<sup>21</sup> Although the whole device is convenient with portable size, the large size of screws (~1 mm) makes it impossible to fabricate valves in high density. Also, each valve on a microchip needs to be treated individually during the fabrication.

Here we describe a simple and inexpensive approach for controlling the pneumatic valves of Quake to miniaturize the whole system for portable and disposable microfluidic devices. Fig. 1 schematically illustrates the fabrication process of the

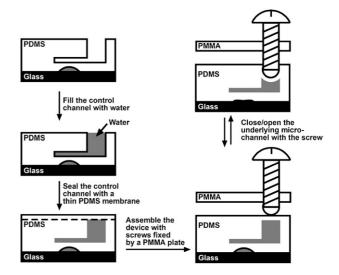
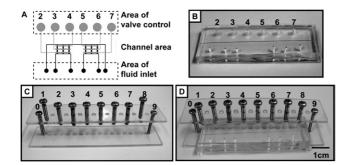


Fig. 1 Schematic illustration of the fabrication process of the screwassisted pneumatic valve. This schematic starts with a multilayer microfluidic structure that is created with soft-lithography. The dashed line in the third drawing shows the bonding interface of the control channel and the top membrane.

screw-actuated pneumatic valve. The fabrication of the two layers of channels and their bonding are similar to those of the monolithic, pneumatic valves with multilayer soft lithography.<sup>10</sup> The completion of the valve control layer is different. In a normal pneumatic valve, the control channel is connected to an external pressure source (e.g., gas tank and pressure regulator). In our approach, after the control channels are completely filled with water, their inlets are permanently sealed with a thin ( $\sim$ 300 µm) PDMS membrane to enclose the water. Adding a small amount of surfactant such as sodium dodecyl sulfate (SDS) in the water makes it much easier to fill into the channel. To prevent water evaporation from the control channel, the whole chip is placed in an environment saturated with water vapor during the sealing process (70 °C in an oven). After this sealing, the PDMS chip is completed and needs to be assembled with the pressure-control part. A machine screw is used to generate the pressure to close the underlying microfluidic channel by twisting it into the inlet of the control channel.

In order to hold the screws in position, that is right above each inlet of the control channels, the microfluidic chip is placed between two parallel PMMA plates. For convenience of operations, the chip pattern is arranged into three grouped areas: control channel inlets are on one side; fluidic channel inlets on the other side and the channels in the middle (Fig. 2). A set of threaded holes are drilled through the plates; the positions of these holes correspond to that of the control channel inlets. Two screws at the sides (screws 0 & 9) are used to hold the two plates together and adjust the space between them. After the PDMS chip is placed between these two plates with the inlet of each control channel right under each threaded hole, screws 1 & 8 are used to clamp the chip tightly in position. Other screws (# 2–7) can be twisted clockwise into the holes and press into the inlets. The whole device is now assembled and ready for use.

In our experiments, the control channel inlets are generated with a 3-mm-diameter cork borer, thus 3-mm-diameter screws are used accordingly. The critical depth of the screws pressing into the inlets for complete valve closure is dependent on (1) the thickness of the PDMS membrane that separates the two channel



**Fig. 2** Assembly of the PDMS chip with the valve control frame. (A) Typical design of a microfluidic chip with pneumatic valves. The inlets of control channels and fluidic channels are intentionally separated into two sides of the design. (B) Photograph of the formed PDMS chip from design shown in A. The inlets of control channel are numbered (2–7) to match with the screws shown in C. (C) Photograph of PMMA frame with screws. The screws are numbered (0–9). (D) Assembly of the PDMS chip in B and the frame in C. The numbered inlets are placed into the positioned right under the screws with the same number.

layers – we found 100–200  $\mu$ m is the proper thickness (thinner membranes are easy to collapse and stick to the bottom surface of the fluid channels and thicker ones require high pressure to close the valve), and (2) the volume of the control channel inlet – an inlet (dia. ~3 mm) with height ~6 mm is optimal. Although the thickness of the PDMS membrane covering the control channel inlets does not affect this critical depth, 300  $\mu$ m is the optimal thickness for our experiments: thinner membranes are easy to break and thicker ones are not elastic enough. To avoid the possible damage of this membrane from the rough surface of the screw, small amount of epoxy is applied to the bottom of each screw and cured to form a rounded surface; a thin layer of grease on the epoxy surface facilitates the turning of the screws.

Fig. 3 shows the photographs of three pneumatic valves that are controlled with screws on the same microchip. For comparison, only the middle valve is shown in both the open and the closed states. The screw closes the valve completely with a depth of 2 mm into the control channel inlet; a smaller penetration depth partially closes the valve. This capability of partially closing valves with easy control may be useful in some applications (e.g., filtering particles and trapping cells). We evaluate this valve in four aspects. The first is the effectiveness of the closed valve. The solutions can remain isolated in the separate channels for at least 12 hours without leakage past the valves; the valve can continue to be used without any impairment. The second is its repeatability. The valve can be opened and closed for over dozens of times without failing. The third is its response time. When the control channel is filled with water (viscosity  $\sim 1$  mPa s at room temperature), the valve responds immediately to the pressure from the screws. Liquids with higher viscosity (e.g., silicone oil and NOA optical adhesives) will slow the response of the valve. A valve with silicon oil of a viscosity  $\sim$ 350 mPa s increases the response time to over 1 min during valve close/open, which is unwanted in most applications. We use water to fill the control channel for all our experiments, and the total response

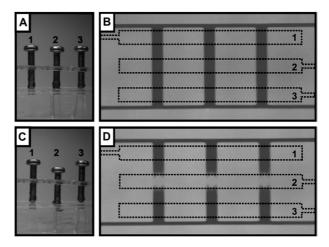
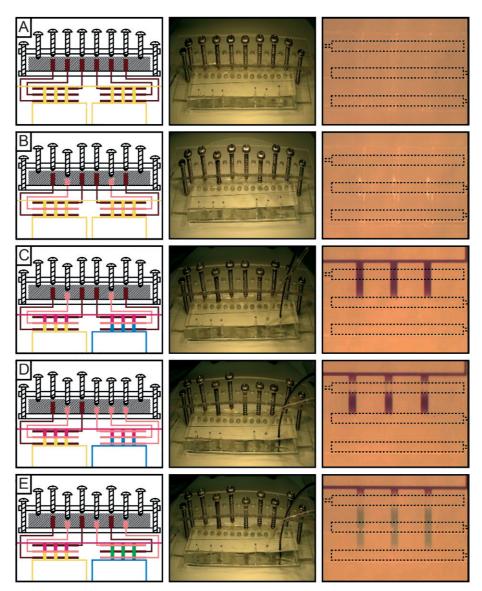


Fig. 3 Photographs of functioning valves. Three screws (A) control three valves (B), and each valve controls three channels with the design shown in Fig. 2. The screws and the valves are numbered according to their relation. When the middle screw (#2) is twisted into the control channel inlet for  $\sim$ 2 mm (C), the corresponding valve (#2) is closed completely (D). The dashed lines in B and D indicate the positions of corresponding valves.

time is dependent on how fast we can turn the screw, which takes a couple of seconds to reach a 2 mm depth. The fourth is the storage of the chip because the water in the control channels may evaporate and damage the function of the valve. Simply adding a few drops of water into a closed Petri dish creates a humid environment; our chips show no obvious evaporation of water from the control channel even for 10 days in this Petri dish.

To demonstrate the capability of this valve, we performed a base-acid reaction in a closed chamber on a PDMS chip. We choose this reaction because the performance of this reaction includes the basic steps for other types of reactions, *i.e.*, metering and isolating reagents, mixing the reagents and monitoring the reaction. The base-acid reaction can be easily monitored by color with proper pH indicators. In Fig. 4, the device (with total size of  $\sim$ 3 cm wide and 8 cm long) includes two microfluidic systems with the same design; each system has three microreactors synchronized by three groups of valves, which are controlled independently by three screws. The fluidic flow channels at the valve region have a cross section of a curved profile (150 µm wide and 10 µm tall), and the control channels are 150 µm wide and 50 µm tall. Solutions are pumped manually or with a syringe pump. We deliver three aliquots of sodium hydroxide solution with volume of  $\sim$ 400 pL into the top microchambers by closing the center valves (twist the middle screw down) and opening the



**Fig. 4** Performing a base-acid reaction on a portable chip with screw-assisted valves. We use the chip design with two identical parts (each having three microreactors controlled by valves), as shown in Fig. 2. The left column gives the schematics of the device; the middle is the photographs of the device and the right is the microphotographs of the valves on the right part of the device. The dashed lines in the right column indicate the position of the valves. (A) The assembled device with all six valves open. (B) For performing the reaction, the middle valves are closed by twisting down the screws 3 & 6. (C) NaOH solution (1 mM, with 0.1 M Crystal violet) and sulfuric acid solution (0.5 M) are injected into the top and bottom channels, respectively. (D) All valves in the right design are closed and the valves in the left design are left untouched for comparison. (E) The middle valve in the right design is opened to allow the solutions to mix. The solutions in all three microchambers change color from purple to green, indicating the reaction is taking place. The valve (#3) in the left design shows no leakage of solutions. Valves with pink and brown colors in the schematics on the left column indicate close and open states, respectively.

other two valves. After the top chamber is completely filled, the top valves are closed with screw 5. Sulfuric acid solution is delivered into the bottom microchambers with similar procedure by using screws 6 & 7. The middle valve is finally opened to mix the base and acid. The pH indicator changes color and the images are collected.

In this work, we have demonstrated convenient pneumatic valves for microfluidic devices that are actuated mechanically by machine screws. The method uses machine screws to replace the normally bulky external pressure source to mechanically actuate the pneumatic valves fabricated with multilayer soft lithography. We apply pressure on the water enclosed in the control channel by turning the screws to collapse the underlying microfluidic channels. The PMMA frame does not significantly increase the size of the chip (increasing the dimension in z direction by the thickness of two PMMA plates and screws). Smaller screws would further shrink the chip size.

This screw-actuated pneumatic valve has two major disadvantages: (1) it is relatively slow because of the manual operation in the current design (it takes a couple of seconds to rotate the screw to close or open a valve); and (2) the current design is not electronically controlled. In the future, we suggest that typewriter pins can be used to replace the screws and to electronically control the valve with fast speed. The Braille system by Takayama represents one example of electronically-controlled valves.<sup>22</sup> However, the future version should further lower the cost for disposable devices with better performance, *e.g.*, fast response time (reduced from seconds to ms by choosing control fluid with proper viscosity) and better registration than the Braille system.

Compared to the normal actuation with external pressure source, this actuation method does not change the way the pneumatic valve functions. Thus, it retains most merits of this valve: simple to fabricate; easy to be integrated; no dead volume; and ready to gain high density. In addition, this method greatly miniaturizes the whole device and makes the devices portable (small size) and disposable (cheap materials) without external facilities. This valve also has a power-off mode by turning the screws to the right position. Because the PMMA frame can be disassembled from the PDMS chip, it can be recycled for different chips to further lower the cost. This valve should be of interest to the scientists who work in the general areas of microfluidics, biotechnology and diagnostics.

## Experimental

#### Fabrication of the microfluidic chips

We fabricated the device in PDMS (GE Silicones RTV 615, Wilton, CT, USA) with multilayer soft photolithography.<sup>6,7,10</sup> The silicon masters for control channels and fluidic channels were generated with SU-8 2025 (MicroChem, Newton, MA) and AZ 4620 (Clariant Corp.), respectively, by standard photolithography. AZ 4620 patterns were reflowed at 120 °C for 10 min to be rounded.

PDMS prepolymer (A : B = 10 : 1) was used to mold replica of the control channels in a 70 °C oven for 1 h. A cork borer (3 mm diameter) was used to make inlets of the control channels. PDMS prepolymer was spin-coated (500 rpm for 48 s) onto the mold

with fluidic channels and partially cured at 70 °C for 10 min. The PDMS mold of control channels was placed onto this membrane and permanently bonded at 70 °C for 1 h. A syringe needle ( $\sim$ 1 mm diameter) was used to punch holes in this bonded PDMS piece as the inlets and outlets for the fluidic channels. This PDMS piece was finally enclosed by bonding with a glass slide after plasma oxidization.

A separate PDMS thin membrane was prepared by spincoating a layer of PDMS prepolymer on a glass slide at 500 rpm for 18 s and cured at 70 °C for 1 h. On top of this membrane, another layer of PDMS prepolymer was spin-coated at 500 rpm for 9 s plus 2000 rpm for 30 s and partially cured at 70 °C for 10 min. After the control channels were completely filled with a 5% SDS solution, this PDMS membrane was placed onto the control channels and permanently sealed the solution in the control channels within a enclosed Petri dish (with a few water drops inside) at 70 °C for 20 min.

#### Acknowledgements

This work was supported by the Li Foundation, the DuPont Young Professor Grant, the Nanoscience and Nanotechnology Program and UGC (SBI 07/08.SC04) at HKUST.

### References

- 1 D. J. Beebe, G. A. Mensing and G. M. Walker, *Annu. Rev. Biomed. Eng.*, 2002, **4**, 261–286.
- 2 G. M. Whitesides, Nature, 2006, 442, 368-373.
- 3 D. R. Reyes, D. Iossifidis, P. A. Auroux and A. Manz, *Anal. Chem.*, 2002, **74**, 2623–2636.
- 4 H. Craighead, Nature, 2006, 442, 387-393.
- 5 D. Janasek, J. Franzke and A. Manz, Nature, 2006, 442, 374-380.
- 6 D. C. Duffy, J. C. McDonald, O. J. A. Schueller and G. M. Whitesides, *Anal. Chem.*, 1998, **70**, 4974–4984.
- 7 Y. N. Xia and G. M. Whitesides, Angew. Chem., Int. Ed., 1998, 37, 551–575.
- 8 J. C. McDonald, D. C. Duffy, J. R. Anderson, D. T. Chiu, H. Wu, O. J. A. Schueller and G. M. Whitesides, *Electrophoresis*, 2000, 21, 27–40.
- 9 H. Wu, T. W. Odom, D. T. Chiu and G. M. Whitesides, J. Am. Chem. Soc., 2003, 125, 554–559.
- 10 M. A. Unger, H. P. Chou, T. Thorsen, A. Scherer and S. R. Quake, *Science*, 2000, 288, 113–116.
- C. Yu, S. Mutlu, P. Selvaganapathy, C. H. Mastrangelo, F. Svec and J. M. J. Frechett, *Anal. Chem.*, 2003, **75**, 1958–1961.
  N. L. Jeon, D. T. Chiu, C. J. Wargo, H. K. Wu, I. S. Choi,
- 12 N. L. Jeon, D. T. Chiu, C. J. Wargo, H. K. Wu, I. S. Choi, J. R. Anderson and G. M. Whitesides, *Biomed. Microdevices*, 2002, 4, 117–121.
- 13 W. H. Grover, R. H. C. Ivester, E. C. Jensen and R. A. Mathies, *Lab Chip*, 2006, 6, 623–631.
- 14 B. J. Kirby, D. S. Reichmuth, R. F. Renai, T. J. Shepodd and B. J. Wiedenman, *Lab Chip*, 2005, 5, 184–190.
- 15 D. J. Beebe, J. S. Moore, J. M. Bauer, Q. Yu, R. H. Liu, C. Devadoss and B. H. Jo, *Nature*, 2000, **404**, 588–590.
- 16 W. Gu, X. Y. Zhu, N. Futai, B. S. Cho and S. Takayama, Proc. Natl. Acad. Sci. U. S. A., 2004, 101, 15861–15866.
- 17 A. Terray, J. Oakey and D. W. M. Marr, Science, 2002, 296, 1841– 1844.
- 18 J. W. Hong and S. R. Quake, Nat. Biotechnol., 2003, 21, 1179-1183.
- 19 T. Thorsen, S. J. Maerkl and S. R. Quake, *Science*, 2002, 298, 580– 584.
- 20 H. Wu, A. Wheeler and R. N. Zare, Proc. Natl. Acad. Sci. U. S. A., 2004, 101, 12809–12813.
- 21 D. B. Weibel, M. Kruithof, S. Potenta, S. K. Sia, A. Lee and G. M. Whitesides, *Anal. Chem.*, 2005, **77**, 4726–4733.
- 22 W. Gu, H. Chen, Y. C. Tung, J. C. Meiners and S. Takayama, *Appl. Phys. Lett.*, 2007, **90**, 033505/1–3.