3D Printing-Assisted Fabrication of Microfluidic Pneumatic Valves

Seyda Keles
Department of Bioengineering
Izmir Institute of Technology
Izmir, Turkey

Betul Karakuzu
Department of Bioengineering
Izmir Institute of Technology
Izmir, Turkey

H. Cumhur Tekin[1,2]
[1]Department of Bioengineering,
Izmir Institute of Technology, Izmir, Turkey
[2]METU MEMS Center, Ankara, Turkey

2023 Medical Technologies Congress (TIPTEKNO) | 979-8-3503-2896-7/23/$31.00 ©2023 IEEE | DOI: 10.1109/TIPTEKNO59875.2023.10359176

***Abstract*—Pneumatic valves have a crucial place in the fluidic control in microfluidic systems. Pneumatic valves containing polydimethylsiloxane (PDMS) membrane structures are used in microfluidic systems such as cell separation, and cell manipulation due to their flexible structure, and ease of production. This study demonstrates the rapid and straightforward fabrication of pneumatic valve structures using PDMS membranes, achieved through the utilization of 3D-printed molds. As a result of our experiments, we observed valve closure in a fluidic channel with a height of 150 µm. This closure was achieved by utilizing 400 µm × 800 µm PDMS membrane with a thickness of 66 µm positioned between the fluidic and control channels, while applying 1.5 bar of pressure to the control channel. When the pressure is removed, the opening time of the valve is only 0.02 s, and this response time allows rapid valving function. The presented valve fabrication strategy would allow easy and low-cost production of sophisticated microfluidic chips.**

Keywords—Pneumatic valve; microfluidics; PDMS membrane; flow control

I. Introduction

Microfluidic systems have played a remarkable role in a wide range of applications, from chemical analysis to biomedical diagnostics [1-2]. In the basis of microfluidic systems, pneumatic valves, especially valves in which polydimethylsiloxane (PDMS) membranes are used, provide microscale fluid manipulation play and an important role for fluidic automation [2-3]. Additionally, due to their excellent on-off and leak-proof qualities, pneumatic valves are highly useful for lab-on-chip (LOC) devices that are often employed in biomedical applications [3]. The valves can also be used for drug delivery systems for the injection and adjustment of medication dosages [4].

Biological analytes such as protein can be purified and analyzed in microfluidic chips produced using multiple PDMS valve structures [5-6]. PDMS membranes are very advantageous thanks to their flexible structure and biocompatibility [7-8]. These membranes can have different sizes and thicknesses, fabricating using the soft lithography method [8-9]. In cell manipulation and cell sorting applications, these valves containing PDMS membrane offer controlled and easy analysis in microfluidic chips [10-11]. However, to fabricate these valves, expensive infrastructures and cleanroom environments are necessary that limits their usages. The fabrication strategy developed here with 3D printing offers rapid and low-cost fabrication of pneumatic valves with PDMS membranes using 3D printed molds. With this study, it is envisioned that affordable microfluidic chips with integrated valves can be realized for automated fluidic operations with the proposed fabrication strategy.

II. Methods

The pneumatic microfluidic valves in different sizes were realized in 2-layer PDMS composed of fluidic and control channels. When the air pressure is applied to the liquid-filled control channel, the flexible thin PDMS membrane at the top of the fluidic channel collapses and blocks the fluidic flow (Fig. 1). The molds for PDMS layers were printed at a resolution of 25 µm by a 3D printing system (Formlabs Form 3, High Temp). Afterwards, post-cure was carried out for 120 minutes at 80ºC. 200, 400, and 800 µm channel widths were chosen for control and fluidic channels. Channel heights were 150 µm. The PDMS mixture was prepared by mixing the PDMS base and the curing agent with 10:1 (w/w) ratio [12]. The fluidic channels were fabricated by spin-coating PDMS mixture at 500 rpm, for 30 second to realize 216 µm thick PDMS [13]. The control channels were fabricated by pouring PDMS mixture of 2 mm thickness. Then, PDMS mixtures on molds were cured in an incubator for 1 hour at 100ºC. The cured PDMS layer for control channels was peeled off from the mold, and holes were punched for inlets using 15-gauge needles. The air plasma was then applied for 1 min at 100 W and 0.5 Torr (ZEPTO, Diener), on PDMS layers of control and fluidic channels to bond them. By doing so, thin PDMS membranes with a thickness of 66 µm were realized on the overlapping control and fluidic channels. Then, holes were punched for the inlets and outlets of fluidic channels. Air plasma treatment was applied to bond PDMS layers and a glass substrate seamlessly for realizing a monolithic microfluidic chip (Fig. 2). To eliminate air penetration through PDMS membranes, the control channels were filled with deionized water. Pressurized nitrogen gas was applied on the control channels for valving purposes.

979-8-3503-2896-7/23/$31.00 ©2023 IEEE

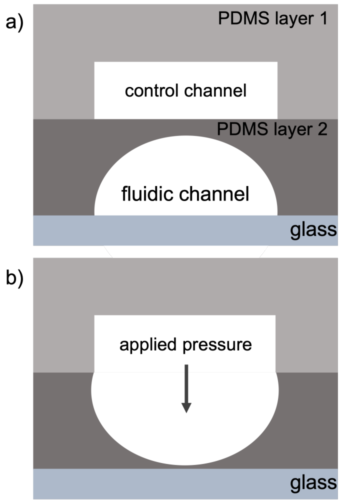

Fig 1. Pneumatic microfluidic valve structure a) without and with b) applied pressure on the control channel.

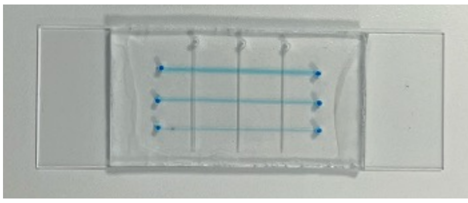

Fig 2. Photograph of fabricated microfluidic chip composed of control and fluidic channels filled with water and blue color solution, respectively.

III. Results And Discussion

Control and fluidic channels with different widths were fabricated on their 3D printed molds. The channel widths designed in the mold were 200, 400 and 800 µm. However, the widths of fabricated PDMS channels were 346.031 µm, 489.083 µm, and 887.311 µm for fluidic channel, and 310 ± 47 µm, 468 ± 60 µm and 868 ± 64µm for control channels (Fig. 3).

Valving was realized by applying 1.5 bar pressure on different channel sizes without a fluidic flow (Fig. 4). Valve closure was observed in the configuration for fluidic channel with 800 µm width, and control channels with 400 µm and 800 µm widths. As the PDMS membrane enlarged, the valves could be closed. We also checked the valving with fluidic channels having 800 µm width in different pressures while introducing 0.5 mL/h flow rate in fluidic channels (Fig. 5). We observed that valving still was realized with 1.5 bar for control channels having 800 µm width and 2 bar for control channels with 400 µm width. These pressure values are lower than the PDMS bonding strength of 4 bar [14]. It means that these valves can be safely used in microfluidic systems. Moreover, when the pressure is removed, the valve opening time is approximately 0.02 seconds (Fig. 6). Thus, this valving strategy can also offer fast fluidic manipulation in microfluidic systems.

The valve with an 800 µm control and flow channel has a dead volume of approximately 96 nL. Therefore, these valves offer no significant samples losses. Elliptical channels were successfully worked for valving without the need of additional processing [15]. Unlike 3D printed channels [16], printed molds offer the advantage of reusability for the fabrication of channels. Furthermore, our fabrication strategy with 3D printing eliminates the need for a cleanroom environment and photolithography steps as in traditional soft lithography methods, which require long and expensive processes. Consequently, the integration of microfluidic valves into various designs becomes effortless, meeting the growing need for automating complex protocols at the chip level.

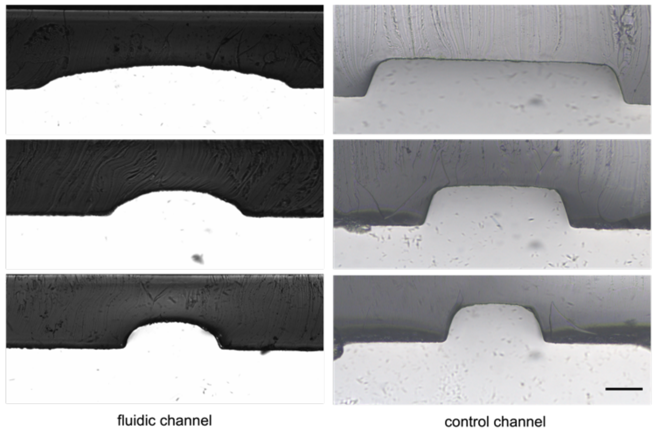

Fig 3. Micrographs of cross-sectional area of PDMS channels. Scale bar: 100 µm

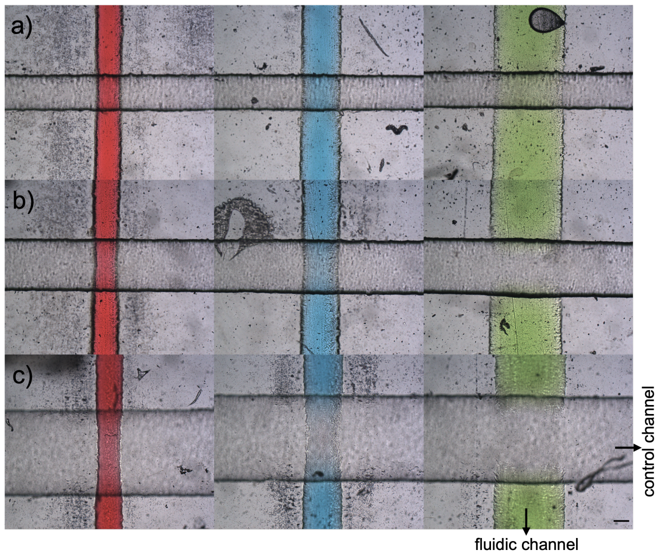

Fig 4. Micrographs of valves with 1.5 bar applied pressure on control channels: a) fluidic channel of with a width of 200 µm and control channels with widths of 200 µm, 400 µm, and 800 µm respectively, b) fluidic channel with a width of 400 µm and control channels with widths of 200 µm, 400 µm, and 800 µm respectively, c) for fluidic channel with a width of 800 µm and control channels with widths of 200 µm, 400 µm, and 800 µm respectively. Food dye solutions were filled in fluidic channels. Scale bar: 200 µm

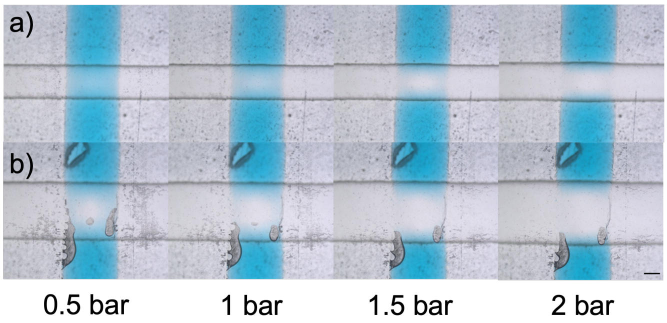

Fig 5. Micrographs of valves under different control pressures and a fluidic flow of 0.5 mL/hr. The valves are composed of control channels with a width of 800 µm and fluidic channels with a width of a) 400 µm and b) 800 µm, respectively. Fluidic channels are filled with a blue food dye solution. Scale bar: 200 µm.

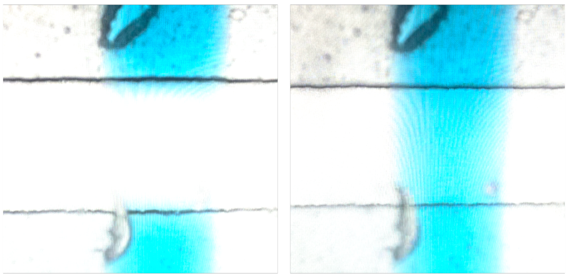

Fig 6. Micrographs of valves after pressure is removed. The valves are composed of control channel and fluidic channel with a width both of 800 µm. The fluidic channel is filled with a blue food dye solution.

IV. Conclusion

In this study, the rapid and affordable fabrication of pneumatic microfluidic valves from PDMS using 3D printed molds were shown. By using a thin (66 µm) and a wide (at least 400 µm × 800 µm) PDMS membrane between control and fluidic channels, valving can be achieved with an applied pressure of ≥1.5 bar on control channels. The rapid recovery of the valve, when the applied pressure is removed, allows the repeated and instant usage of these valves. Since the fabrication of pneumatic microfluidic valves has been facilitated with 3D printing molds, as they do not require expensive and complex manufacturing methods, we expect that the findings presented in this study will contribute to the broader adoption and dissemination of pneumatic valves.

Acknowledgment

H.C.T. acknowledges financial support from The Scientific and Technological Research Council of Turkey (22AG032), and Science Academy (BAGEP). S.K acknowledges financial support from The Scientific and Technological Research Council of Turkey (2210-C BIDEB graduate scholarship). B.K. acknowledges financial support from Turkish Council of Higher Education (100/2000 CoHE doctoral scholarship), The Scientific and Technological Research Council of Turkey (2211-A BIDEB doctoral scholarship).

References

[1] M. G. Toudeshkchoui *et al.*, "Microfluidic devices with gold thin film channels for chemical and biomedical applications: a review," *Biomed Microdevices*, vol. 21, no. 4, 2019, doi: 10.1007/s10544-019-0439-0.

[2] Y. Yang, Y. Chen, H. Tang, N. Zong, and X. Jiang, "Microfluidics for Biomedical Analysis," *Small Methods*, vol. 4, no. 4. 2020. doi: 10.1002/smtd.201900451.

[3] K. W. Oh, "Lab-on-chip (LOC) devices and microfluidics for biomedical applications," in *MEMS for Biomedical Applications*, Elsevier, 2012, pp. 150–171. doi: 10.1533/9780857096272.2.150.

[4] M. R. Ahmad Fuaad, M. N. Hasan, M. I. Ahmad Asri, and M. S. Mohamed Ali, "Microactuators technologies for biomedical applications," *Microsystem Technologies*, Jul. 2023, doi: 10.1007/s00542-023-05489-8.

[5] H. C. Tekin, M. Cornaglia, and M. A. M. Gijs, "Attomolar protein detection using a magnetic bead surface coverage assay," *Lab Chip*, vol. 13, no. 6, p. 1053, 2013, doi: 10.1039/c3lc41285g.

[6] H. C. Tekin, V. Sivagnanam, A. T. Ciftlik, A. Sayah, C. Vandevyver, and M. A. M. Gijs, "Chaotic mixing using source–sink microfluidic flows in a PDMS chip," *Microfluid Nanofluidics*, vol. 10, no. 4, pp. 749–759, 2011.

[7] R. Ariati, F. Sales, A. Souza, R. A. Lima, and J. Ribeiro, "Polydimethylsiloxane composites characterization and its applications: A review," *Polymers*, vol. 13, no. 23. 2021. doi: 10.3390/polym13234258.

[8] S. B. Campbell, Q. Wu, J. Yazbeck, C. Liu, S. Okhovatian, and M. Radisic, "Beyond Polydimethylsiloxane: Alternative Materials for Fabrication of Organ-on-a-Chip Devices and Microphysiological Systems," *ACS Biomaterials Science and Engineering*, vol. 7, no. 7. 2021. doi: 10.1021/acsbiomaterials.0c00640.

[9] M. A. Eddings and B. K. Gale, "A PDMS-based gas permeation pump for on-chip fluid handling in microfluidic devices," *Journal of Micromechanics and Microengineering*, vol. 16, no. 11, 2006, doi: 10.1088/0960-1317/16/11/021.

[10] Y. C. Tung, Y. S. Torisawa, N. Futai, and S. Takayama, "Small volume low mechanical stress cytometry using computer-controlled Braille display microfluidics," *Lab Chip*, vol. 7, no. 11, 2007, doi: 10.1039/b708187a.

[11] H. Tavakoli *et al.*, "Recent advances in microfluidic platforms for single-cell analysis in cancer biology, diagnosis and therapy," *TrAC - Trends in Analytical Chemistry*, vol. 117. 2019. doi: 10.1016/j.trac.2019.05.010.

[12] D. Armani, C. Liu, and N. Aluru, "Re-configurable fluid circuits by PDMS elastomer micromachining," in *Technical Digest. IEEE International MEMS 99 Conference. Twelfth IEEE International Conference on Micro Electro Mechanical Systems (Cat. No.99CH36291)*, IEEE, 1999, pp. 222–227. doi: 10.1109/MEMSYS.1999.746817.

[13] M. Long *et al.*, "Robust and thermal-healing superhydrophobic surfaces by spin-coating of polydimethylsiloxane," *J Colloid Interface Sci*, vol. 508, pp. 18–27, Dec. 2017, doi: 10.1016/j.jcis.2017.08.027.

[14] S. Kecili and H. C. Tekin, "Adhesive bonding strategies to fabricate high-strength and transparent 3D printed microfluidic device," *Biomicrofluidics*, vol. 14, no. 2, Mar. 2020, doi: 10.1063/5.0003302.

[15] N. Compera, S. Atwell, J. Wirth, B. Wolfrum, and M. Meier, "Upscaling of pneumatic membrane valves for the integration of 3D cell cultures on chip," *Lab Chip*, vol. 21, no. 15, pp. 2986–2996, Aug. 2021, doi: 10.1039/d1lc00194a.

[16] X. Jiang and P. B. Lillehoj, "Pneuamtic Microvalves Fabricated by Multi-material 3D Printing" IEEE Nanotechnology Council and Institute of Electrical and Electronics Engineers, *IEEE NEMS 2017 : the 12th IEEE Annual International Conference on Nano/Micro Engineered and Molecular Systems : April 9-12, 2017, Los Angeles, California, USA.*