Proportional Microvalve Using A Piezoelectric Unimorph Microactuator

Gunda, Arun; Özkayar, Gürhan; Tichem, Marcel; Ghatkesar, Murali

Publication date
2019

Document Version
Final published version

Published in
Proceedings of the 4th International Conference on MicroFluidic Handling Systems (MFHS 2019)

Citation (APA)
Gunda, A., Özkayar, G., Tichem, M., & Ghatkesar, M. (2019). Proportional Microvalve Using A Piezoelectric Unimorph Microactuator. In D. Alveringh (Ed.), *Proceedings of the 4th International Conference on MicroFluidic Handling Systems (MFHS 2019)* (pp. 45-48). Twente University.

PROPORTIONAL MICROVALVE USING A PIEZOELECTRIC UNIMORPH MICROACTUATOR

A. Gunda[1], G. Özkayar[1], M. Tichem[1], and M.K. Ghatkesar[1]
[1] Delft University of Technology, Delft, The Netherlands

ABSTRACT

Microvalves are important flow-control components in many standalone and integrated microfluidic circuits. Although there is a large body of work regarding microvalves, there is still a need for an easy-to-fabricate, small-footprint, low-power device that can control both liquids and gases at moderate pressures. This paper details the development of a piezoelectric microvalve compatible with both liquids and gases with a maximum driving pressure of $1\,\text{bar}$. A novel combination of accessible methods like 3D-printing and laser-cutting has been used to realize this device. The device has a flow range of 0 - $90\,\mu\text{L}\,\text{min}^{-1}$ at $1\,\text{bar}$ inlet pressure. When fully closed, a leakage of $0.8\,\%$ open-flow was measured with a power consumption of $37.5\,\mu\text{W}$.

KEYWORDS

microvalve, proportional, piezoelectric, 3D-printing, unimorph

INTRODUCTION

The need for techniques that more efficiently utilize chemical and biological reagents in chemical analysis systems led to the introduction of micro-total analysis systems (μTAS) [1]. The versatility of miniaturizing fluidics was realized and subsequently utilized in applications like drug-delivery [2], lab-on-a-chip devices [3], and even micro- and nano-spacecraft thermal cooling and propulsion systems [4].

An essential component in integrated microfluidic devices is the microvalve. In conjunction with a pressure source, it is used to control, direct, or regulate the pressure or flow rate of media within microfluidic circuits. Valves that operate in the μm- to cm-length scales are generally classified as microvalves and they are usually fabricated using microfabrication techniques like (soft-)lithography, etching, etc. Conventional microvalves consist of a microchannel that is obstructed by an active/passive element. Active microvalves, as opposed to their passive counterparts, have a controllable element within the device. These valves are usually classified by the working principle of the active element.

In this work, an active proportional microvalve was designed, fabricated and characterized. It is based on a piezoelectric actuation method that uses a commercially available piezoelectric plate as the active element. As the active element functions without any further processing, all the advantages of piezoelectric actuation were retained while the usual manufacturing disadvantages of thin-film piezo-MEMS (Micro Electromechanical Systems) devices were eliminated. The valve deflection was controlled by applying a desired voltage across the piezoelectric material. Thus, the fluid flow-rate in the microvalve was proportionally controlled. The following sections detail the design, fabrication, and characterization of the microvalve.

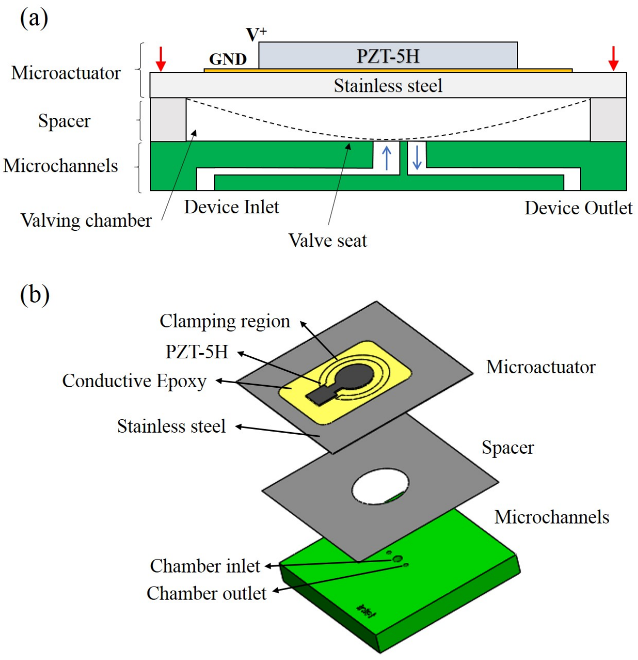

Figure 1: (a) Schematic of the microvalve: It consists of a piezoelectric unimorph microactuator, a spacer, and 3D-printed microchannels. The microactuator is placed on top of the microchannels with an intermediate spacer and the entire assembly is clamped. Red arrows indicate the direction of the clamping force. Black dashed lines indicate the membrane deformation when actuated. (b) Exploded 3D view of the microvalve.

DESIGN AND FABRICATION

A piezoelectric microvalve with a small footprint of $5\,\mathrm{mm} \times 5\,\mathrm{mm} \times 1.8\,\mathrm{mm}$ that can withstand a pressure of $1\,\mathrm{bar}$ and compatible with both liquids and gases was developed in this work. As shown in Fig. 1 (a), the piezoelectric microactuator bows down on the application of a voltage and blocks the inlet orifice. This modulates the flow-rate in the microvalve. The downward displacement of the microactuator is magnified with respect to the lateral displacement of the piezo-layer because of the clamped geometry of the structure. This type of structure, where an active layer (in this work, Lead Zirconate Titanate, PZT-5H) is bonded to a passive substrate (in this work, stainless steel) is called a unimorph.

The design shown in Fig. 1 was optimized for two objectives. The first one was to maximize the microactuator displacement for a given voltage. This was done to decrease the voltage required to close the valve. An analytical approach was adapted from the work done by Mo et al [5]. A constrained optimization study was performed to find the optimal PZT dimensions where the central displacement of the actuator is maximized.

The second aspect that was optimized was the fluid flow-rate through the microvalve; de-ionized (DI) water was used as it was the test fluid. Due to a low range of the liquid flow sensor that was available, it was desired to have a maximum flow-rate of $90\,\mu\mathrm{L\,min}^{-1}$ at the maximum pressure of $1\,\mathrm{bar}$. The fluid flow was modelled analytically using an electrical-analogue approach [6]. It was found that the thickness of the spacer was the primary control variable.

Numerical modeling using COMSOL Multiphysics v5.3 were used to validate both the analytical models mentioned above. This resulted in the final dimensions as shown in Table 1. Some dimensions were not realizable with the available facilities, so the closest possible values were used.

Table 1: Microvalve Design Parameters

Parameter	Analytical	Numerical	Fabricated
PZT diameter	4 mm	4.2 mm	4 mm
PZT thickness	76 µm	68 µm	127 µm
Epoxy thickness	-	< 5 µm	< 15 µm
Steel diameter	5 mm	5 mm	5 mm
Steel thickness	25 µm	25 µm	50 µm
Spacer thickness	3.5 µm	3.6 µm	5 µm

The top part in Fig. 1 (b) is the actuator designed in this work. It consists of a thin PZT-5H plate that is laser-cut to the desired shape and then glued with con-

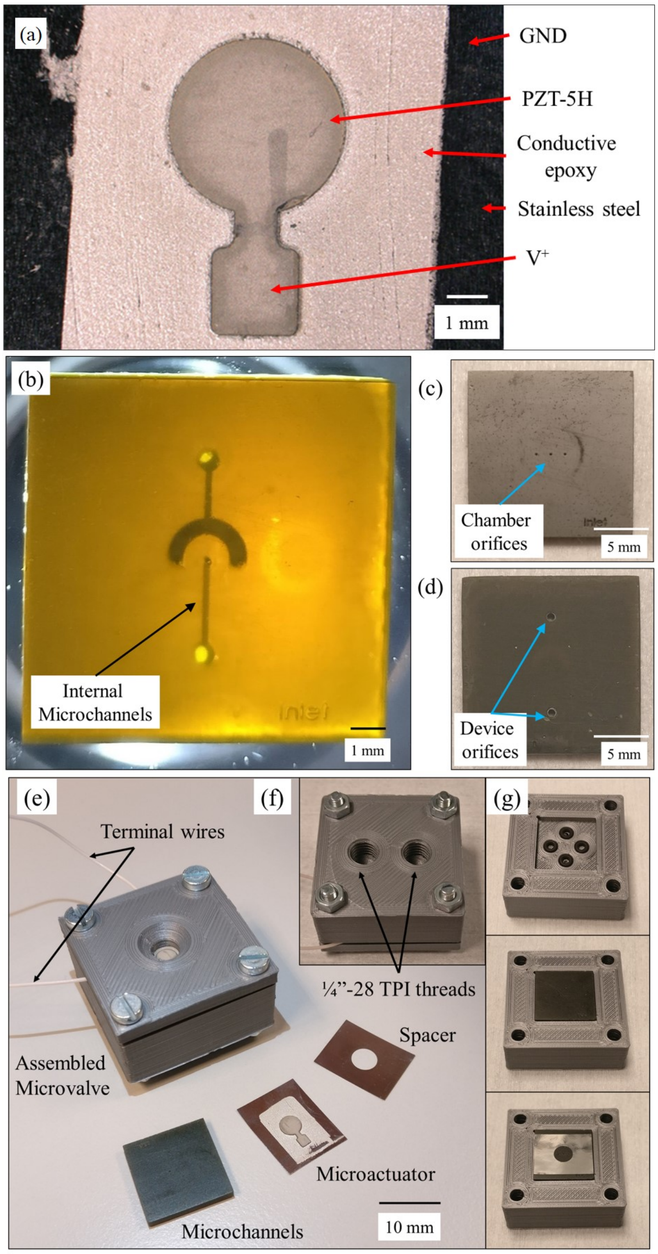

Figure 2: (a) Fabricated microactuator with a laser-cut PZT part bonded to a stainless steel membrane using conductive epoxy. Positive (V^+) and Ground (GND) terminals are indicated. Wires were attached using conductive tape (bottom terminal) and a press-fit (top terminal) (b) Microchannels with a light source underneath to illuminate the internal channels (c) Top view: Central orifice is the valve chamber inlet, neighbouring orifices are chamber outlets (d) Bottom View: Top orifice is the device inlet, bottom orifice is the device outlet, surface is sanded with 1000-grit sandpaper (e) Assembled microvalve holder with constituent parts. Terminal wires are copper with $0.5\,\mathrm{mm}$ diameter. (f) Bottom view of the holder (g) First step: O-rings placed in grooves, Second step: Microchannels placed in groove, Third step: Spacer placed over microchannels, Fourth step (not shown): Actuator is placed and then assembly is clamped.

ductive epoxy to a stainless steel (SS) plate to form a unimorph piezoelectric microactuator (UPM). The fabricated UPM is shown in Fig. 2 (a).

The microchannels (bottom part in Fig. 1 (b)) were 3D-printed using stereolithography, a technique that uses UV-light to selectively polymerize a UV-sensitive resin layer-by-layer. The fabricated microchannel part is shown in Fig. 2 (b-d). The material used is a hard polymer called HTM-140 (High-Temperature Mold) and is proprietary to the EnvisionTec SLA printer that was used. The spacer in the middle defines the initial separation between the actuator membrane and valve seat. It was made using $5\,\mu\text{m}$ thick shim-steel that was laser-cut.

The entire assembly shown in Fig. 1 (b) needs to be clamped for the actuator to function and for the assembly to be leak-tight. A valve holder that can clamp the entire microvalve and enable fluidic and electrical interfacing was designed and is shown in Fig. 2 (e-g).

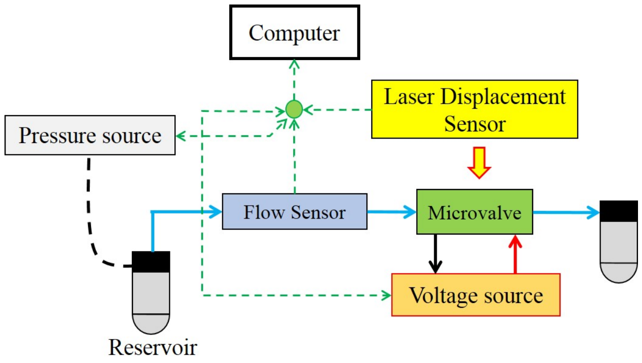

Figure 3: Layout of the test set-up for measuring flow-rate and displacement of the microvalve: Green dashed arrows are signal wires, red and black arrows are terminal wires of the microvalve, blue arrows are microfluidic tubing, and the black dashed line is tubing from the pressure source.

A test-setup was used to interface with the valve holder. A schematic is shown in Fig. 3. It was used to apply fluid pressure across the valve, measure fluid flow through the valve, apply voltage to the UPM, and measure the displacement of the UPM. The UPM was controlled by a high-voltage, current-limited, programmable DC power-supply (Delta Elektronika ES0300-0.45). The central displacement of the UPM was measured using a high-resolution laser displacement sensor (Keyence LC-2420 sensor-head with a Keyence LC-2400W laser displacement meter). The microvalve was connected to a microfluidic circuit consisting of a pressure source (Elveflow OB1 Mk3+) which could apply pressure from $-1\,\text{bar}$ to $6\,\text{bar}$, and a thermal flow-sensor (Elveflow MFS3) which could measure a maximum flow-rate of $90\,\mu\text{L}\,\text{min}^{-1}$ (accuracy: 5% measured value).

RESULTS AND DISCUSSION

The main results from this work are related to the flow-rate behaviour of the microvalve. They are shown in Fig. 4 and Fig. 5. DI water was used for all experiments.

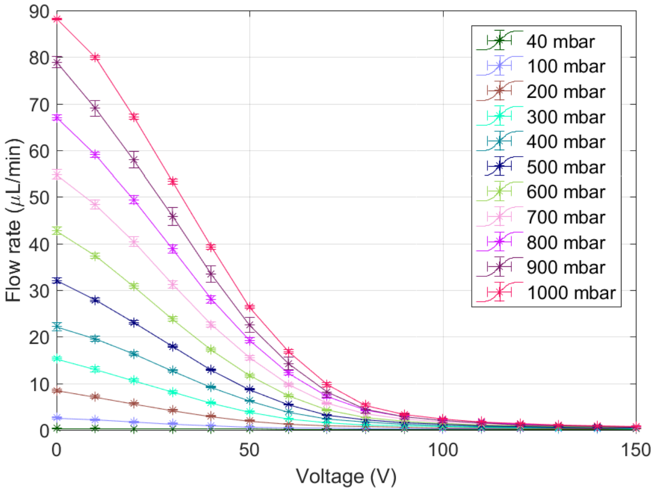

Figure 4: Proportional control of flow rate at different pressures. Error-bars indicate one standard-deviation of three measurements.

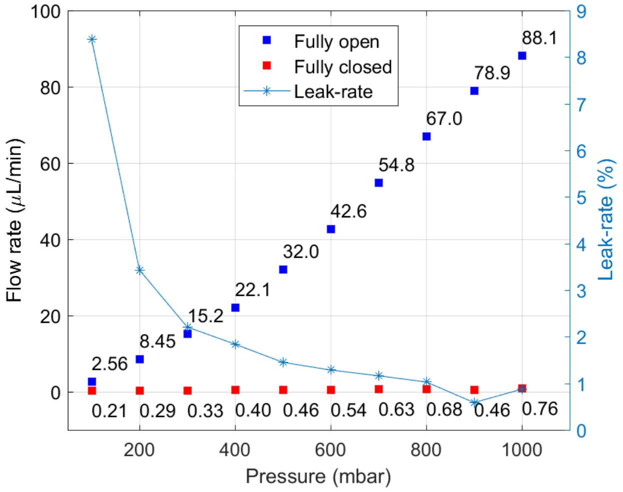

Figure 5: On-off behaviour and leak-rate of the microvalve at different pressures: The numbers are the flow rates at those data points. Leak-rate is the ratio of closed and open flow rates.

The main objective of this work was to prove proportional control of fluid flow. This is shown clearly in Fig. 4. For a set pressure, the voltage was increased from $0\,\text{V}$ to $150\,\text{V}$ and the flow rate was measured. A uniform upward shift in the flow rate curve is seen as the pressure increases. The small standard deviation (error bars) shows that there is good repeatability of the valving behaviour. It can also be seen that, at all pressures, a bulk of the valving is done from 0 - 100 V. The slope changes rapidly from 90 V and the flow rate appears to asymptotically decrease to zero. The residual flow observed even at a high voltage might be due to valve seat defects that could not be blocked by the actuator membrane.

The leakage behaviour of the microvalve is shown in Fig. 5. Here, leakage rate is defined as the ratio of closed and open flow rates. The industry standard is to measure leakage using Helium gas but this facility was not available. A high leakage-rate is observed at low pressures; this is because flow rate at open condition is low, but a constant leakage is always present due to valve seat defects. As pressure increases, open flow rate increases while closed flow rate remains relatively constant, effectively decreasing the leakage-rate. Some methods to decrease leakage include decreasing the valve-seat area by using a knife-edge contact and introducing a soft material like PDMS or a parylene layer to the actuator or valve-seat.

CONCLUSION

A proportionally-controlled piezoelectric microvalve was designed, fabricated and characterized. De-ionized water at room temperature was used for characterization. Most piezoelectric devices use MEMS fabrication techniques which are not very accessible. Here, a novel combination of accessible rapid-prototyping methods were used to fabricate an active piezoelectric microfluidic device. The specifications of the final microvalve are given in Table 2.

Table 2: Obtained Microvalve specifications

Specification	**Measured value**
Flow range	0 - 90 μL min^{-1}
Flow control resolution	0.2 μL min^{-1} at 500 mbar
Leakage	0.8% open-flow at 1000 mbar
Max. differential pressure	1 bar
Static power consumption	37.5 μW
Operating voltage	0 - 150 V
Typical response time	40 ms
Dimensions (effective)	5 mm × 5 mm × 1.8 mm

Due to limitations in the available flow sensor, the full potential of the microvalve could not be explored. The projected flow-range for this microvalve is 0 - 750 μL min^{-1} (DI water). A low power consumption of 37.5 μW has been measured, which, to the best of the author's knowledge, is the lowest reported in literature for this pressure range.

REFERENCES

[1] A. Manz, N. Graber, and H. á. Widmer, "Miniaturized total chemical analysis systems: a novel concept for chemical sensing," *Sensors and actuators B: Chemical*, vol. 1, no. 1-6, pp. 244–248, 1990.

[2] S. Böhm, B. Timmer, W. Olthuis, and P. Bergveld, "A closed-loop controlled electrochemically actuated micro-dosing system," *Journal of Micromechanics and Microengineering*, vol. 10, no. 4, p. 498, 2000.

[3] P. S. Dittrich and A. Manz, "Lab-on-a-chip: microfluidics in drug discovery," *Nature reviews Drug discovery*, vol. 5, no. 3, p. 210, 2006.

[4] C. M. Marrese-Reading, J. Mueller, and W. C. West, "Microfluidic electrospray thruster," Oct. 7 2014. US Patent 8,850,792.

[5] C. Mo, R. Wright, W. S. Slaughter, and W. W. Clark, "Behaviour of a unimorph circular piezoelectric actuator," *Smart Materials and Structures*, vol. 15, no. 4, p. 1094, 2006.

[6] I. Fazal and M. C. Elwenspoek, "Design and analysis of a high pressure piezoelectric actuated microvalve," *Journal of micromechanics and microengineering*, vol. 17, no. 11, p. 2366, 2007.

CONTACT

- G. Ozkayar, g.ozkayar@tudelft.nl
- M. K. Ghatkesar, m.k.ghatkesar@tudelft.nl