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# Continuously Adjustable Micro Valve Based on a Piezoelectric Actuator for High-Precision Flow Rate Control

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**Abstract:** A MEMS-based micro valve fitted with a piezoelectric actuator is presented in order to achieve a continuously adjustable flow rate control. The micro valve is realized using a cost-effective fabrication scheme with simple polyimide (PI) bonding, which has an average shear strength of up to 39.8 MPa, indicating a relatively high reliability. The simulation results based on the finite element method (FEM) show that the valve membrane is able to seal the inlet and cut off the flow successfully with a piezoelectric force of 3N when the differential pressure is 200 kPa. The measurement of the flow rate through the outlets shows that the micro valve can control the flow rate effectively in a large range under different actuation voltages and differential pressures. When the actuation voltage is 140 V, the measured leak flow of the closed micro valve is smaller than 0.5 sccm with a differential pressure of 200 kPa.

**Keywords:** micro valve; piezoelectric actuator; flow rate control; continuously adjustable

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## 1. Introduction

Micro valves are important components for microfluidic systems, such as drug delivery systems [1–3], biochemical detection systems [4,5], biological analytical systems [6,7], and liquid level sensors [8]. Micro valves can be categorized into two types: active and passive micro valves, which are equipped with and without an active actuator, respectively. In the field of microfluidics, an accurate and continuously adjustable control of flow rate is in great demand. In order to meet this requirement, it is important to fabricate the whole micro valve system with a fitted active actuator, which is able to regulate the state of the micro valve easily and control the flow rate continuously and precisely. Moreover, it is also crucial for the micro valve to be manufactured in a small form factor with a high reliability, low cost, and simple fabrication.

For flow rate control, micro valves with a high response speed that are electrostatic driven, electromagnetic driven, and piezoelectric driven are the most commonly used active micro valves. As electromagnetic-driven micro valves suffer from large chip areas [9,10] and the electrostatic-driven micro valves typically operate in binary mode, which requires a relatively large valve array to control the flow [11–13], piezoelectric-driven micro valves are utilized in this work to achieve continuously adjustable and high-precision flow rate control. However, the piezoelectric-driven micro valves usually require a complex fabrication process [14–16]. Yang [17] demonstrated a simplified two-wafer fabrication process with wafer bonding, but it still requires seven lithographic mask steps.

In this paper, a MEMS-based micro valve fitted with a piezoelectric actuator is investigated for flow rate control. The simulation results of the valve membrane displacement, the fabrication scheme with simple polyimide (PI) bonding, the reliability evaluation of the PI bonding, and the experimental results of the flow rate are presented. It is validated that the realized micro valve performs well for controlling the flow rate with a high reliability. The rest of this paper is organized as follows. Section 2 introduces the structural design of the device. Sections 3 and 4 discuss the simulation and fabrication results, respectively. The experimental results are presented in Section 5, and Section 6 provides the concluding remarks.

## 2. Structure Design

Figure 1 shows the structure of the micro valve, which consists of two silicon wafers with a PI bonding layer. A flexible membrane with a circular plate, which is prepared for the integration of the piezoelectric actuator, is bonded to the valve seat through the PI layer. The radial flow channel with one inlet and two outlets embedded inside the valve seat lays between the valve membrane and the valve seat. The height of the radial channel can be changed through the vertical movement of the valve membrane, which varies the flow resistance of the valve and adjusts the flow rate.

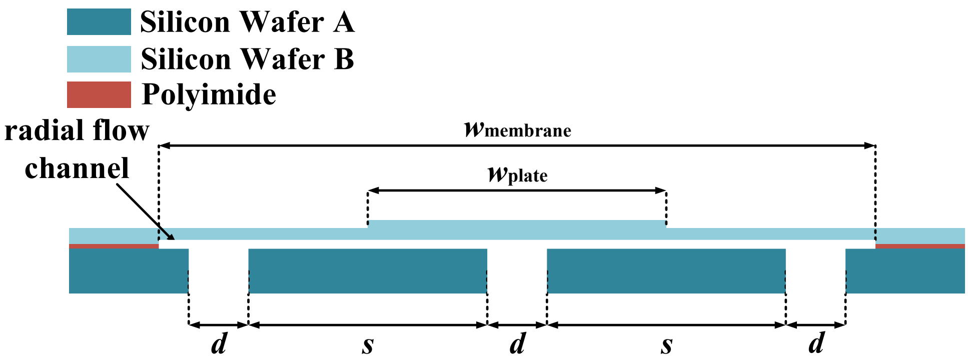


**Figure 1.** Schematic of the micro valve.

The dimensions mentioned in Figure 1 are summarized in Table 1. The diameter of the valve membrane is 4.8 mm, with a thickness of 80 µm. The diameter of the valve plate above the membrane is 2 mm, with a thickness of 50 µm. The size of the radial flow channel underneath the membrane is designed to have a diameter of 4.8 mm with a height of 15 µm, which depends on the etching depth and the thickness of the PI bonding layer. The height of the radial flow channel determines not only the maximum flow rate through the outlets of the micro valve, but also the required deformation for the valve membrane to fully close the valve inlet. The circular flow inlet and outlets are fabricated inside the valve seat, with a diameter of 400 µm, a height of 300 µm, and a spacing of 1.6 mm. The diameters of the inlet and outlets are much larger than the height of the radial flow channel, which ensures that the flow resistance of the inlet and outlet channels is negligible compared with the valve resistance. In addition, with the relatively large spacing between the inlet and the two outlets, the leakage paths from the inlet to outlets can be avoided effectively.

**Table 1.** Summary of the micro valve dimensions.

| Parameter | Variable | Value (µm) |
|---|---|---|
| Inlet/outlet diameter | $d$ | 400 |
| Inlet/outlet height | $h$ | 300 |
| Inlet/outlet spacing | $s$ | 1600 |
| Membrane diameter | $w_{\text{membrane}}$ | 4800 |
| Plate diameter | $w_{\text{plate}}$ | 2000 |
| Membrane thickness | $t_{\text{membrane}}$ | 80 |
| Plate thickness | $t_{\text{plate}}$ | 50 |
| Channel diameter | $d_{\text{channel}}$ | 4800 |
| Channel height | $h_{\text{channel}}$ | 15 |

## 3. Simulation

The finite element method (FEM) tool FEMLAB (COMSOL Inc., Stockholm, Sweden) was utilized to analyze the 3D structural performance of the micro valve. The main concern is the displacement of the valve membrane under the piezoelectric force and the inlet pressure. Figure 2 depicts the simulation model where the inlet and outlets are not shown. The dimensions of the FEM model are the same as those mentioned in Table 1. The Young's modulus and Poisson's ratio of the silicon were set to be 170 GPa and 0.28, respectively. As long as the piezoelectric force was large enough, the valve membrane would move downwards, even if a differential pressure was applied through the inlet. Figure 2 shows the simulation result of the vertical displacement of the deformed valve membrane when a piezoelectric force of 7 N and an inlet pressure of 200 kPa were applied. Note that the displacement at the center region of the valve membrane was up to 37.9 µm, which is larger than the height of the radial flow channel.

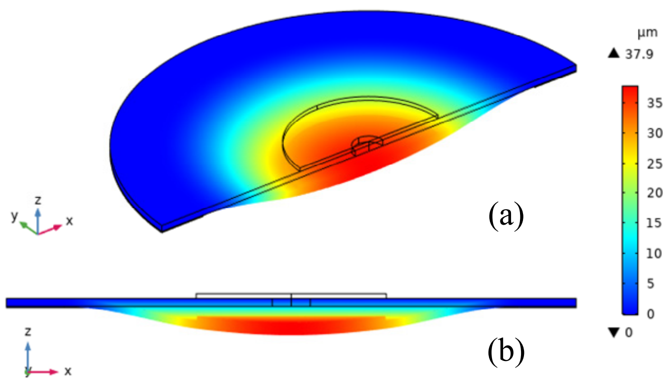


**Figure 2.** Simulation results of the vertical displacement with a piezoelectric force of 7 N and a differential pressure of 200 kPa. (**a**) Three-dimensional view. (**b**) z–x plane view.

The vertical displacements of the valve membrane under various piezoelectric forces with a fixed inlet pressure of 200 kPa are shown in Figure 3. The positions of the *x* axis correspond to different points along the radius from the center to the edge of the membrane. As the displacement of the membrane is constrained by the height of the radial flow channel, when a piezoelectric force is applied to the valve plate, the valve membrane will be deformed and the center region of the membrane will come into close contact with the inlet to seal the inlet effectively. It can be seen from Figure 3 that, even with a piezoelectric force of 3N and a pressure of 200 kPa, the contact region of the valve membrane is large enough to seal the inlet (d = 400 µm) and cut off the flow successfully.

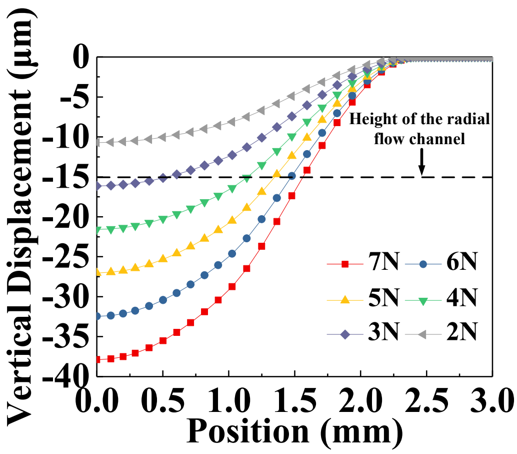


**Figure 3.** Vertical displacement of the valve membrane under various applied piezoelectric forces with a differential pressure 200 kPa.

## 4. Fabrication Results

### *4.1. Fabrication Process*

The fabrication process of the micro valve is shown in Figure 4. The process started with a 4-inch p-type <100> silicon wafer A with a thickness of 300 µm (Figure 4a). After patterning (Figure 4b), the inlet and outlets were etched through a deep reactive ion etcher (DRIE) using a Bosch process with a diameter of 400 µm (Figure 4c). Then, the patterning was performed on another 4-inch p-type silicon wafer B (Figure 4d) to prepare for the cavity etching, as shown in Figure 4e. For the cavity etching, the DRIE was adopted again to achieve a cavity depth of 10 µm (Figure 4f). Next, the polyimide was firstly deposited on the surface of wafer B using a conventional spin coating approach and pre-curing process (Figure 4g), and was then patterned to remove the PI inside the cavity by wet etching, as shown in Figure 4h. After that, wafer A and B were permanently bonded together with the PI acting as the adhesion layer (Figure 4i). After the bonding, the total height of the radial flow channel was around 15 µm. Then, the silicon grinding and chemical mechanical polishing (CMP) were performed to reduce the thickness of the wafer B to 140 µm, as indicated in Figure 4j. Finally, after patterning (Figure 4k), the valve plate with a thickness of 50 µm was realized through DRIE (Figure 4l).

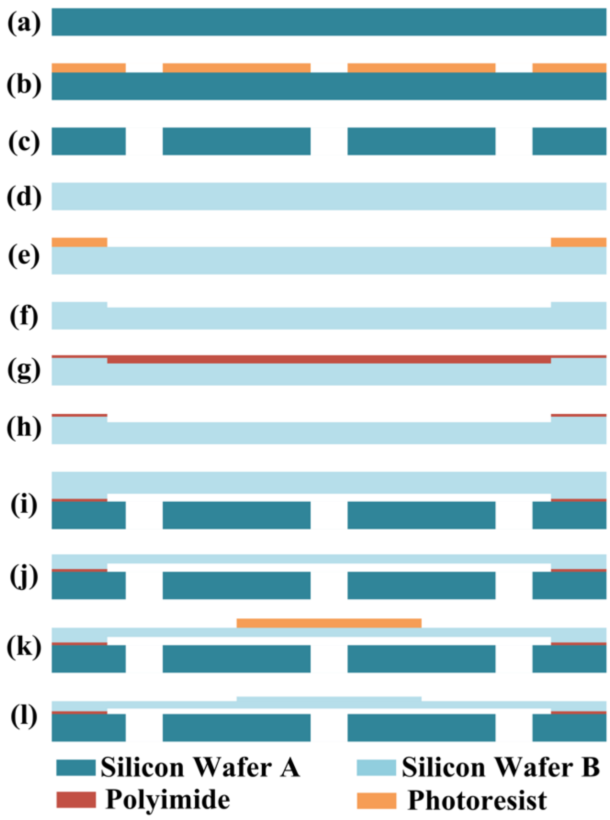


**Figure 4.** Fabrication process of the micro valve.

### *4.2. Fabrication Results*

Figure 5a–d shows the scanning electron microscope (SEM) images of different parts of the micro valve. Figure 5a shows the top view of the circular valve plate with a diameter of 2 mm. The image of the valve membrane and the outlet are shown in Figure 5b, from which it can be seen that the diameter and thickness of the outlet are 401 µm and 300 µm, respectively. The valve membrane was ground and polished to a thickness of 80 µm. Figure 5c shows the radial flow channel with a height of 20.2 µm, including the PI bonding layer of 5.2 µm, as shown in the enlarged view of Figure 5d. Note that the dimensions of the micro valve are quite similar to the designed values.

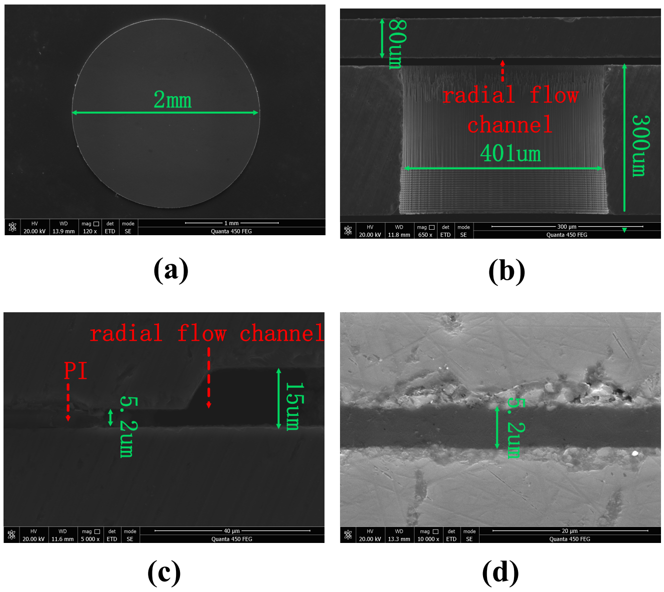


**Figure 5.** SEM images of different parts of the micro valve. (**a**) Top view of the valve plate. (**b**) The valve membrane and the outlet. (**c**) The radial flow channel. (**d**) The PI bonding interface.

It is worth mentioning that PI is employed as the adhesion layer between two wafers. For the bonding process, the recommended heating condition is 50 °C to 100 °C higher than the glass transition temperature (Tg) of the PI layer [18,19]. As the Tg of the PI layer used is around 300 °C, the bonding temperature was set to 375 °C. Bonding pressure is also an important factor for determining the quality of the bonding. In order to obtain a void-free bonding interface, the bonding pressure was set to 200 kPa, which ensures the high-quality bonding of the contact gap formed as a result of the bending of the silicon wafer. Moreover, during high temperature bonding, the PI layer is expected to release gas, which has a great influence on the bonding performance. Therefore, it is necessary to pre-cure the PI layer properly before bonding, which not only releases the gas, but also ensures the fluidity of the PI layer for reliable bonding. Figure 5d shows a bonding interface with a 5.2 µm thick PI adhesive layer. It is clear that there is no void existing in the interface. For the purpose of assessing the mechanical strength of the bonded structure, the shear strength test is applied to the PI bonding samples with a test area of 0.5 mm × 5 mm. The shear strength results for eight samples are shown in Figure 6 and the average shear strength is up to 39.8 MPa, which indicates sufficient mechanical strength for the micro valve.

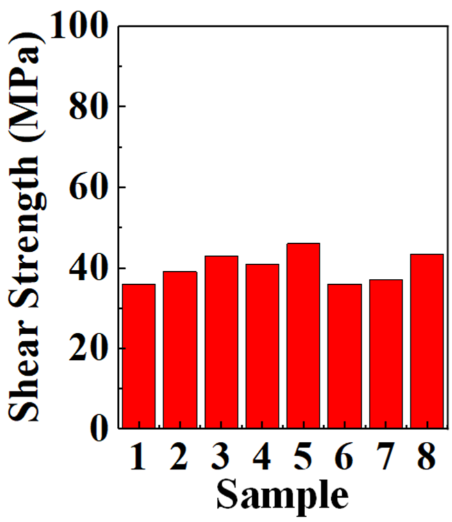


**Figure 6.** Shear strength of the PI bonding samples.

## 5. Experimental Results

Figure 7 shows the test structure of the fabricated micro valve with an integrated piezoelectric actuator. A piezoelectric thin slice (PZT-5A) with a thickness of 210 µm was first glued onto the thin copper slice (115 µm in thickness), and then embedded into the PMMA holder (Figure 7a). The electrical connections for the piezoelectric actuator were made directly through the wires. The micro valve was fixed into another PMMA holder (Figure 7b). The micro valve holder and the piezoelectric actuator holder were assembled together mechanically. For the test structure, the height and maximum width were 47 mm and 60 mm, respectively (Figure 7c).

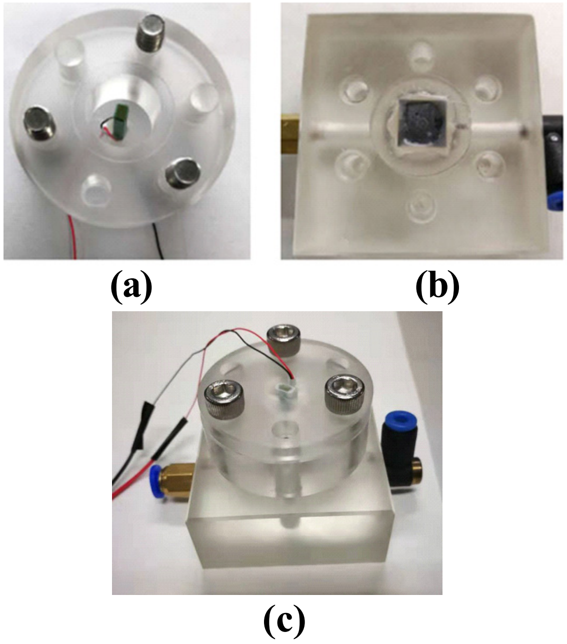


**Figure 7.** Photograph of the test structures. (**a**) The PMMA holder with the piezoelectric actuator. (**b**) The PMMA holder with the micro valve. (**c**) The whole structure after assembly.

The measured flow rate through the outlets of the micro valve was measured as a function of the differential pressure through the inlet with actuation voltages varying from 60 V to 140 V. During the test, all measurement data were recorded after stabilization of the inlet pressure and the driven voltage of the piezoelectric actuator. The inlet pressure gradually increased from a small value to prevent any sudden change in pressure. It is shown in Figure 8a that the flow rate scaled nearly linearly with the pressure. It is shown in Figure 8b that the flow rate decreased with the increasing actuation voltage. With an actuation voltage of 60 V, the flow rate reached 256 sccm at a pressure of 200 kPa. It was possible to obtain a larger flow rate range by increasing the pressure or decreasing the actuation voltage further. When the actuation voltage increased to 140 V, the flow rate was smaller than 0.5 sccm, even though the pressure through the inlet was as high as 200 kPa. A larger actuation voltage could be applied to further reduce the flow rate to nearly zero under an inlet pressure of 200 kPa, indicating that the valve membrane is capable of sealing the inlet and can cut off the flow effectively. It can be seen from Figure 8 that the flow rate can be adjusted continuously by tuning the actuation voltage or pressure.

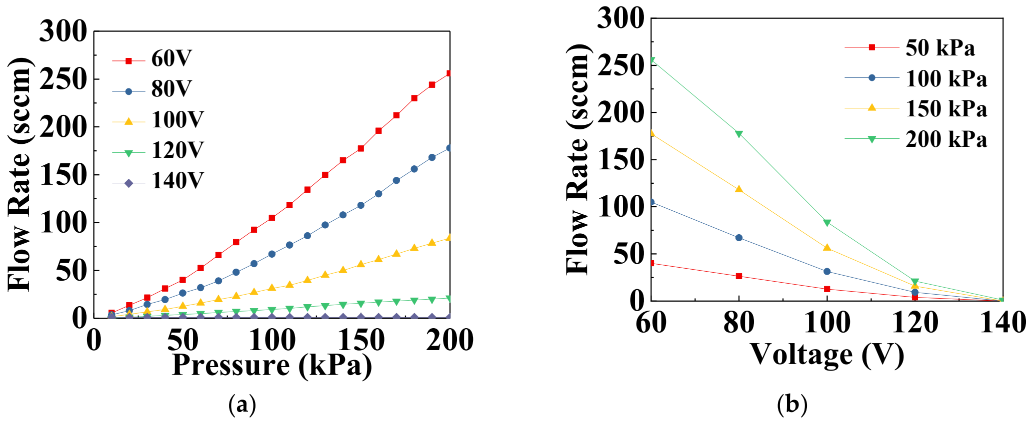


**Figure 8.** Measured flow rate as a function of (**a**) differential pressure under various actuation voltages and (**b**) actuation voltage under various differential pressures.

## 6. Conclusions

In this work, a MEMS-based micro valve fitted with a piezoelectric actuator is realized for the continuous control on the flow rate. A cost-effective fabrication process is proposed with simple PI bonding. The simulation with the FEM tool demonstrates that the valve membrane is able to seal the inlet and cut off the flow successfully with a proper piezoelectric force at a pressure of 200 kPa. Moreover, the PI bonding utilized here has an average shear strength of up to 39.8 MPa, which ensures high reliability. During the experiment, the flow rate through the outlets covered a large range with different actuation voltages and pressures. The leak flow was smaller than 0.5 sccm when a 140 V actuation voltage and a differential pressure of 200 kPa were applied.

**Author Contributions:** Conceptualization, simulation, experiment, and writing—original draft preparation, Y.D.; validation and writing—review and editing, Y.C.; supervision, project administration, funding acquisition, and writing—review and editing, Y.L. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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