

Polymer micro piezo valve with a small dead volume

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Abstract

A polymer valve with a small dead volume in the range of 6 nl and a response time faster than 1 ms is presented. The valve structure is simple and therefore easy to fabricate by injection molding or hot embossing. A layer of silicone rubber applied by a stamping technique not only promotes the sealing of the valve but also defines the gluing area during assembly. The fabrication is based on the AMANDA-process, which allows low-cost batch production of polymer micro devices.

1. Introduction

The main specification of almost all valves is a small dead volume and a short switching time, in addition to low costs which are always desirable. These properties allow e.g. quick movements of pneumatically driven robots and rapid accurate dosing of liquids. The demand for small dead volume even increases when small amounts of liquids or gases are to be dosed. Therefore, micro valves have been receiving a lot of attention in recent years and several valve concepts were and are still under investigation. There are micro valves with electrostatic [1–6], piezoelectric [7, 8], thermo-pneumatic [9–12], thermo-mechanic [13] and SMA [14, 15] actuators. The basic materials used range from silicon to a variety of plastics.

Other important advantages of micro valves are low power consumption, small outer dimensions and low weight. Therefore, the importance of designing precise valves on the base of low-cost fabrication processes should not be underestimated.

In this paper a polymer valve is presented with a small dead volume. A silicone pattern between the valve seat and the valve membrane serves as a seal during operation and also prevents glue from entering fluid channels during fabrication. The fabrication process is based on the AMANDA⁴-process [16], which allows low-cost batch fabrication.

2. Analysis of micro valves dead volume

Micro valves usually have a diaphragm and chamber structure including a valve seat. The diaphragm is pressed onto the valve seat to close the valve and is deflected to open the valve, as shown in figure 1. A dead volume between the diaphragm and the housing cannot be avoided except in some cases, where a double membrane driven by electrostatic force is used [17].

When a micro valve is being opened or closed, the dead volume has to be filled or emptied, which leads to inaccurate fluid flow through the valve at the moment of switching, and an increased switching time, which correlates to the time necessary to move the fluid out of or into the chamber.

Additionally, the dead volume cannot be constant for different valves with the same design and fabrication process, because tolerances in production are necessary in general. In particular, when parts are manually assembled comparatively large changes in dead volume may occur [18]. The error is difficult to compensate during operation, when the error is large and is distributed over a wide range. Typically, the error is proportional to the dead volume. Therefore, the realization of a small and stable dead volume is important for the precision of micro valves.

3. Valve structure with low dead volume

The dead volume and its error can be reduced by decreasing the radius of the area of the moving membrane. This is achieved in the work presented here by a small silicone pattern on the valve seat.

Following the concept of the AMANDA-process [16] a membrane is packed between two plastic housing shells. In

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⁴ Acronym for German 'Abformung, Oberflächenmikromechanik und Membranübertragung' or English 'surface micromachining, molding and diaphragm transfer'.

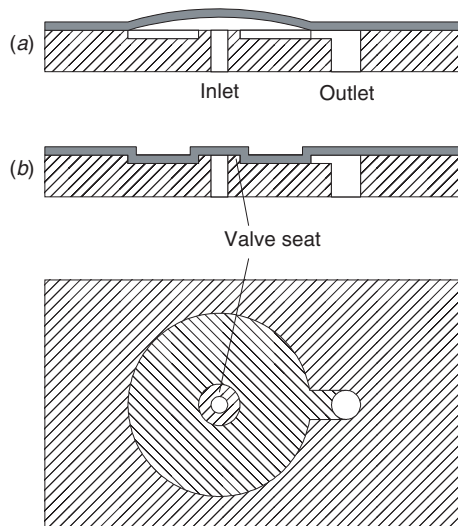


Figure 1. Schematic of a typical micro valve: (a) open valve and (b) closed valve.

this case, the membrane is not patterned at all. The housing shells (figure 3) can be made by hot embossing [19] or injection molding. Two micro channels with a cross-section of $200 \times 150 \mu\text{m}$ are separated by a $50 \mu\text{m}$ wide separation wall as shown in figure 3(b) and (c). Silicone is printed on top of the separation wall in the fabrication process. The silicone adapts to the form of the separation wall (cf figures 2(c) and 4(a)). A $3 \mu\text{m}$ thick polyimide membrane is glued to the housing except for the area where the silicone pattern is placed (see description of the fabrication process below). Thus, the movable part of the membrane is restricted to the part on top of the silicone pattern (figure 2(c)). When the diaphragm deflects upwards, the two channels are connected and the valve is open. If the pressure above the diaphragm is higher than the pressure in the fluid channels, the diaphragm is pressed onto the wall. In this way, the two channels are separated and the valve is closed.

As shown in figure 2(a), we use a piezo actuator to drive the valve, which is based on the work of Rogge [8]. This actuator is glued into the upper housing shell of the valve and is deflected upwards when an electric field is applied. The chamber between the piezo actuator and the valve membrane is filled with a silicone gel (Silgel from DRAWIN Vertriebs-GmbH), which is incompressible and can be easily deformed. When the valve is closed the silicone gel is at an enhanced pressure. This keeps the valve closed against a pressure applied to the inlet of the valve. When the actuator deflects upwards, the diaphragm is deflected off the separation wall and the valve is opened.

The circular silicone covers the rough surface of the separation wall and forms a smooth valve seat surface. During valve operation, the silicone rubber improves the tightness of the valve, because it is soft and can adapt to foreign particles.

4. Fabrication of the micro valve

The fabrication of the micro valve is shown in figure 3. The lower housing shell of the valve is fabricated by milling

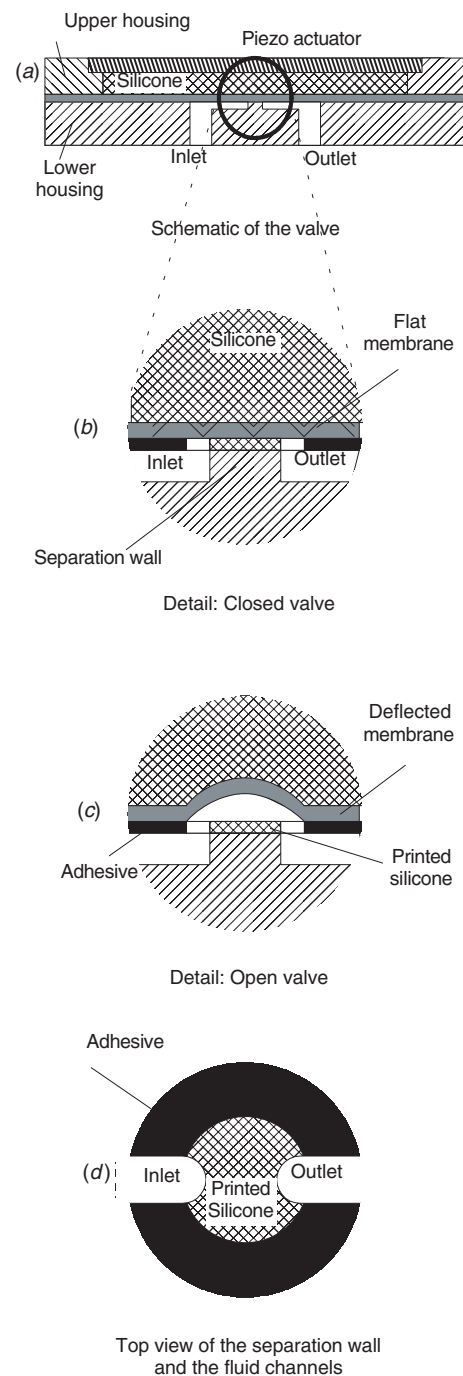


Figure 2. Schematic cross-sections of the micro valve.

PMMA, but can also be produced by hot embossing later. A circular area of silicone (Silgel from DRAWIN Vertriebs-GmbH) is printed on the surface of the lower housing, where the two channels are separated. (see figure 3(a), also refer to figures 3(b) and (c)). For printing we use a rubber-printing tool, which is fabricated by molding. The printing process is similar to that in [20], which can reach $1 \mu\text{m}$ resolution. The silicone is cured at room temperature.

A silicon wafer with a diameter of 100 mm is covered with 100 nm low-adhesive gold and $2 \mu\text{m}$ polyimide by sputtering and spin-coating respectively, as described in [16]. After the silicone pattern on the separation wall of the valve

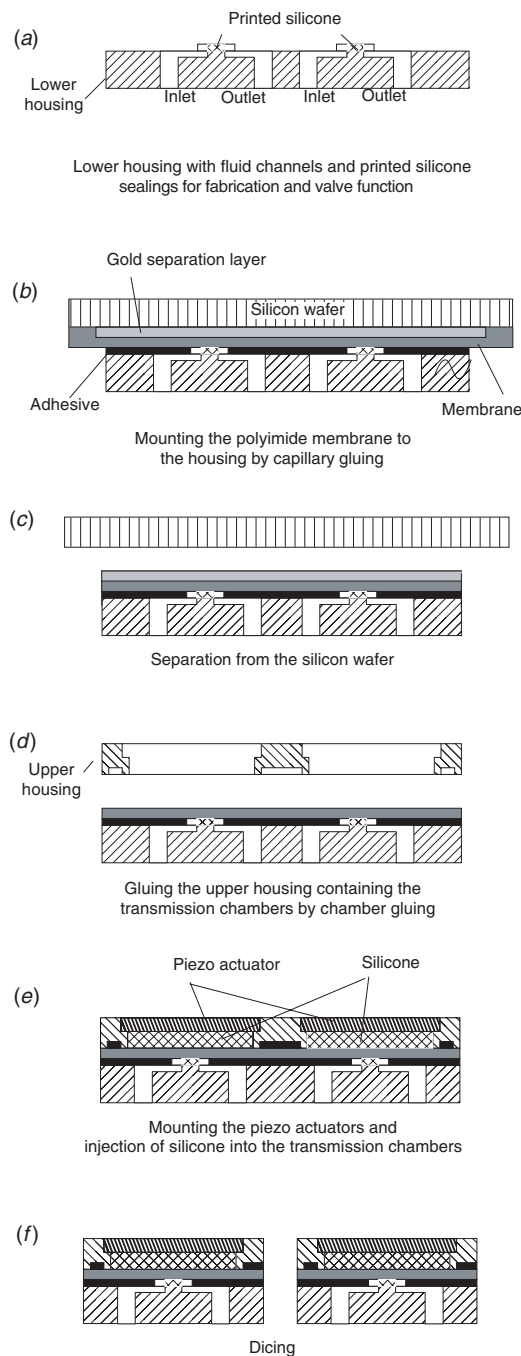


Figure 3. Valve fabrication process.

is to some extent cured, the housing is pressed onto the polyimide layer on a silicon wafer (figure 3(b)), then the silicone pattern is cured completely (at room temperature). To connect the membrane to the housing, low viscosity epoxy glue is added to the gap between the membrane and the housing and spreads by capillary force. The glue flow is stopped at the valve channel because capillary forces do not act there. It is stopped at the silicone pattern as well, as silicone is hydrophobic and repels the glue. In this way the glue is prevented from entering the fluidic channels and the polyimide is bonded to the housing everywhere except the area covered by silicone.

After curing the glue, the housing shell and the membrane are lifted from the silicon wafer. The old layer with low adhesion to the silicon and necessary for the separation of the membrane from the silicon wafer, is sticking to the backside of the polyimide membrane (figure 3(c)). It is removed by wet etching.

The actuator housing shell is glued to the membrane (figure 3(d)). A piezoelectric disk with a diameter and thickness of 10 mm and 200 μm respectively, is adhesively bonded with the epoxy EPO TEK 353ND from Polytec GmbH to a 200 μm thick steel disk and forms a bimorph actuator. Electrical connections to the piezo disk are made by gluing wires to it with electrically conducting adhesive. After inserting this piezo actuator and gluing it to the housing shell, the silicone gel is injected into the actuator chamber and cured while the piezo actuators are deflected by an applied voltage (figure 3(e)). The final fabrication step is dicing of the batch of eight valves (figure 3(f)).

The lower housing shell is shown in figure 4. The picture (figure 4(a)) shows the fluid channels separated by a wall and the silicone pattern. The inlet and the outlet channels are 200 μm wide and 150 μm deep and are fabricated by milling. Smaller channels can be fabricated by hot embossing. The diameter of the circular silicone pattern is 600 μm . The following pictures were taken after a polyimide membrane with a thickness of 2 μm had been glued to the housing shell. Figure 4(b) shows the closed valve, figure 4(c) the opened valve.

After gluing the actuator housing shell, the silicone is injected into the actuator chamber and cured while the actuator plates are deflected upwards with a voltage of 200 V. When the voltage is removed, the pressure in the silicone chamber increases. For the sake of simplicity, the process was demonstrated on a batch of two valves only. The two normally closed valves are shown in figure 5.

5. Experimental results

The dead volume of the micro valve was determined in a displacement experiment. A small tube with an inner diameter of less than 200 μm was connected to the outlet. The valve and the connected tubes were filled with water, while the valve was kept open. No bubbles were lead through the valve. The inlet tube was closed and the valve was periodically opened and closed at different voltages. The water, almost incompressible, was moved in and out to and from the outlet capillary. The meniscus was observed under a microscope. The movement of meniscus was measured to be 200 μm , 150 μm and 100 μm at 300 V, 250 V and 200 V actuator driving voltage, respectively, which results in dead volumes of 6.2 nl, 4.7 nl and 3.1 nl, respectively.

The nitrogen flow through the micro valve was investigated as a function of the voltage supplied to the piezo actuator. No flow could be observed when the pressure difference over the valve was less than 50 kPa. At a pressure of 50 kPa, the relation of the flow rate and the voltage on the piezo disk is shown in figure 6. The valve can be opened at 200 V and closed at 100 V. The maximum flow rate for nitrogen at that pressure is about 70 sccm.

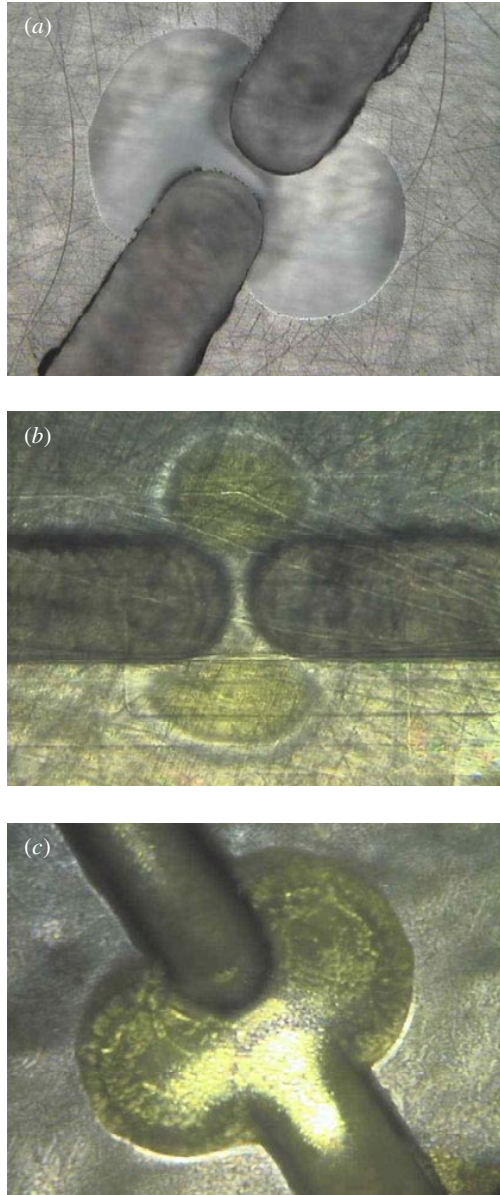


Figure 4. Critical structure of the small dead volume valve observed with an optical microscope: (a) two $200\ \mu\text{m}$ wide channels in the lower housing shell with the silicone pattern, (b) two channels in the lower housing shell with the silicone pattern under a polyimide membrane and (c) polyimide membrane deflected by fluid pressure in the channel.

In order to measure the response time of the valve, the outlet was connected to a pressure sensor, and a throttle. If a fluid flow is passing the valve, the pressure increases in the capillary at the valve outlet. The pressure falls to atmospheric, when the valve is closed. The control signal and the signal of the pressure sensor were observed with an oscilloscope. The valve was driven at a frequency of 20 Hz and a voltage of 300 V. The applied pressure at the valve inlet was about 50 kPa.

The signals are shown in figures 7 and 8. The first diagram contains several switching cycles to show the shift between the control signal for the valve and the pressure rise at the sensor. The experimental result is a response time of 0.7 ms.

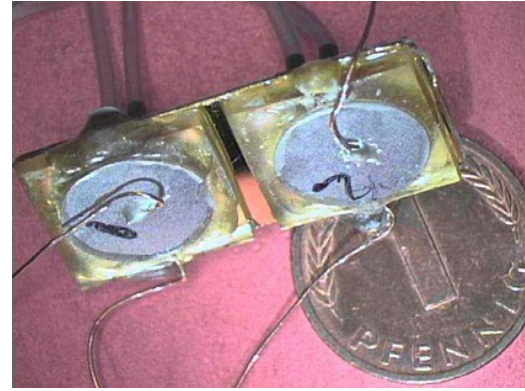


Figure 5. Two piezo valves with small dead volume in comparison to the smallest former German coin. Outer dimensions of one valve are $13 \times 13\ \text{mm}^2$.

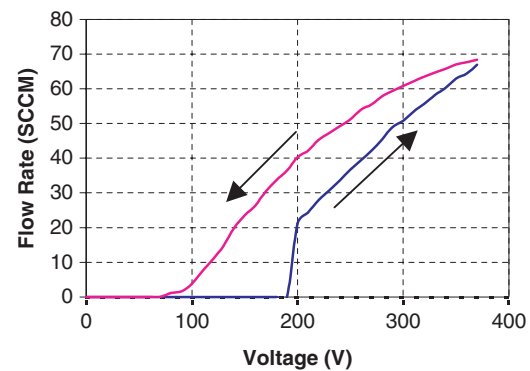


Figure 6. Relation between the flow rate and the voltage.

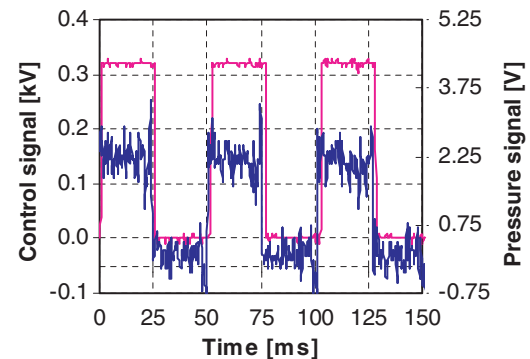


Figure 7. Control signal to drive the piezo actuator and the response of the pressure sensor.

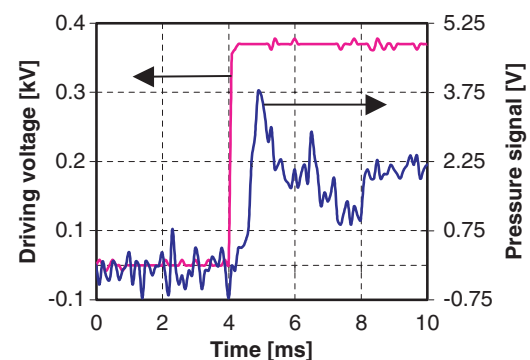


Figure 8. Detail of the control signal to drive the piezo actuator and the response of the pressure sensor. The delay is 0.7 ms.

6. Conclusions

A valve with a simple structure and the appropriate fabrication process is presented. The simplicity permits the design of small dimensions in the critical structure of the valve, and thereby a small dead volume of 6 nl was achieved. The small stroke of this micro valve results in a very short switching time of 0.7 ms which is an important condition for exact dosing of small amounts of liquids and gases. As a consequence the maximum flow through the valve is limited to 70 sccm nitrogen at a pressure difference of 50 kPa.

A precise but low cost printing process is employed to fabricate a silicone rubber pattern between the membrane and the valve seat, which ensures the precision of the dead volume and promotes the sealing of the valve. This silicone pattern is also used to define the gluing area, where the membrane is bonded to the housing shell and improves the reliability of the gluing process.

The very small response time of less than 1 ms, the small dead volume and the small energy consumption combined with the low-cost fabrication make this micro valve suitable for precise dosing applications.

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