Piezoelectric microvalve

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A normally closed microvalve is a very important component of a microfluidic system. The fabrication of an active, normally-closed piezoelectric microvalve useful for automated drug delivery or control of fluids in microreactor systems has been studied. The microvalve has dimensions of 19 mm × 19 mm × 7 mm, an inlet diameter of 200 µm, a dead volume of 0.33 µl and has a steady-state flow-rate of about 240 sccm.

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1 Introduction

Microvalves are one of the most important components of fluidic systems. They are the switching devices in a microfluidic system, analogous to transistors in electronic circuits. Most microvalves developed till now employed silicon processing techniques. The microvalve has been fabricated using polymer processing techniques. The valve is made by using AMANDA (surfAce microMACHining, Molding and Diaphragm transfer) process wherein microfluidic components can be made in a highly cost-effective way using established manufacturing techniques. This involves fabricating various components of microfluidic systems separately and then bonding them together.

In our work, the membrane is fabricated by surface micromachining and housings are made by micromolding; then the membrane is transferred onto the housings. The components can also be mass-produced further reducing the manufacturing costs per component. The piezoelectric microvalve uses a hydraulic mechanism based on a layer of silicone-gel to magnify the low deflection of the PZT (Lead Zirconium Titanate) unimorph actuator while transferring it to the membrane. The hydraulic mechanism also serves the purpose of keeping the valve normally-closed. The unimorph is made by gluing a PZT disc to a steel disc.

2 Operating Principle and Design

Fig. 1 shows the schematic of the microvalve. The silicone-gel layer sandwiched between the membrane and the PZT unimorph pushes the membrane onto the inlet of the valve due to the inherent pressure within the layer. The valve is thus normally-closed. The unimorph deflects upwards on application of a voltage between its top and bottom faces. This deflection is transferred to the membrane by the silicone layer in a magnified form. This magnification is normally referred to as a hydraulic mechanism, and can be explained as follows. Let \((A_m, \delta_m)\) and \((A_p, \delta_p)\) denote the (area, deflection) of the membrane and the PZT unimorph respectively (see Fig. 2). Since the volume of the silicone layer does not change even when its shape is altered due to deflection of the unimorph, we can write \(A_m\delta_m = A_p\delta_p\) or \(\delta_m = (A_p/A_m)\delta_p\).

A similar microvalve fabricated earlier had some manufacturability problems. A gluing mechanism...
used to hold the unimorph or actuator in place over the hydraulic layer presented difficulties in the manufacturing process. It was observed that, during fabrication, glue applied on the top of the unimorph (see Fig. 3) has a tendency to seep into the small gap between the walls of the actuator housing and the unimorph. This causes gluing of the PZT disc permanently to the housing, thereby, resulting in the failure of the actuation mechanism. In order to avoid this, a silicone lining was used to prevent seepage of glue in the earlier work. The problem with this approach was that if the quantity of the silicone used for the lining was insufficient the glue would still enter the gap and bond the PZT disc to the housing. On the other hand, if the quantity of silicone was in excess, the silicone would creep over the metal disc and prevent the glue from wetting the upper (steel) surface of the actuator properly. This would result in failure of the gluing mechanism. Thus, it is clear that, a precise control is required on the quantity of silicone to be applied as a lining in the actuator housing which is not practical.

Hence, the design of the valve to replace the gluing mechanism by a clamping technique has been modified, wherein an additional housing has been designed to clamp the PZT actuator to the actuator housing (see Fig. 4). We still use layers of silicone lining below and above the actuator. These layers provide a soft-seal mechanism and a flexible silicone suspension allowing the actuator to deflect freely.

2.1 Fabrication

The valve is fabricated using AMANDA process developed for fabricating MEMS devices which use a membrane. This technique is highly suitable for microfluidic devices as we can produce various components such as membrane, housings and actuation mechanism separately and bond them together to make a complete system. The fabrication process consists of following three stages.

Fabrication of Actuator and Membrane—The unimorph actuator is fabricated by gluing a 200 µm thick PZT disc of 10 mm diameter with a 100 µm thick steel disc using an epoxy glue which cures at 65°C in 20 min. A 1.2 µm thick membrane is fabricated by spin-coating polyimide over a gold-plated silicon wafer.

Fabrication of housings—There are four different housings in the microvalve assembly (see Fig 5); the valve-seat housing, the actuator housing, the actuator clamp housing, and the fluidic adaptor. The valve-seat housing is made of polysulphone and is produced by hot-embossing technique to obtain a valve seat with an inlet diameter of 200 µm and an outlet diameter of 400 µm. The actuator housing, actuator clamp housings and fluidic adaptor are fabricated by milling PMMA (poly methyl meta acrylate) sheets using a computer numerically controlled machine. The silicone chamber of the actuator housing has a diameter of 8.5 mm and is 800 µm high. All these components can also be fabricated using hot-embossing technique. Computer numerically controlled machining was used to demonstrate the improved design before the concept can actually be prototyped. Moreover, fabrication of the fluidic adaptors using computer numerically controlled machines is easy, since these adaptors have a simple structure.
Assembly of components—The components are assembled in the following steps. The membrane is glued to the valve-seat housing by Chamber Adhesive Bonding technique. The fluidic adaptor is glued to the non-membrane side of the valve-seat housing and the actuator housing is glued to the membrane side by capillary assisted gluing process using a UV curable glue. Chamber adhesive bonding is not used in this case, as it is not feasible to drill glue chambers by computer numerically controlled micromachining [the glue chambers can be incorporated while making a final prototype using hot-embossing technique for fabricating all housings (except fluidic adaptors)]. Later, a lining of silicone-gel is applied along the walls of the actuator chamber, and the actuator is mounted after the curing of silicone is complete. Then, a lining of silicone-gel is applied over the actuator. After curing of the gel, the actuator clamp housing is placed over the actuator and secured to the actuator housing with the help of steel plates and nuts and bolt arrangement. Tubes are glued to the silicone filling holes drilled in the valve-seat housing, valve inlet and valve outlet. Finally, silicone-gel is filled into the silicone chamber of the valve-seat housing at a pressure of 2 bars and cured.

The nut and bolt arrangement used for bonding the actuator clamp housing to the actuator housing can be replaced by a gluing technique, to reduce the valve size from 19 mm×19 mm×7 mm to 13 mm×13 mm×5 mm. For this purpose, the housings should be produced by hot-embossing technique capable of realizing a gluing chamber.

2.2 Characterization

The flow versus voltage characteristics of the microvalve fabricated, are shown in Fig. 6, for 0.5 bar pressure. At the opening voltage, the membrane is brought to a flat position over the valve seat and the nitrogen just begins to flow. As the voltage is increased further, the flow rises steeply and reaches a maximum value of about 240 sccm (standard cubic centimeters per minute). This is the flow that would result if there were no membrane to control the flow, and is limited by the dimensions of the inlet and outlet of the valve. When the voltage is reduced, the characteristics retrace themselves with a hysteresis so that the valve has a closing voltage which is less than the
opening voltage. The hysteresis is caused by the remanent polarization in the PZT material⁶.

3 Conclusions

A normally-closed piezoelectric microvalve was designed and fabricated using AMANDA process. Previous reliability problems associated with the valve were resolved by bonding the unimorph to the actuator housing using a mechanical clamp rather than glue. The clamping technique provides a silicone suspension system-cum-soft sealing for the unimorph wherein the unimorph can deflect freely, and avoids the possible failure of the actuator associated with the gluing process. The valve has overall dimensions of 19×19×7 mm, inlet/outlet of 200/400 μm diameter, silicone chamber of 800 μm height and 8.5 mm diameter. A steady state flow rate of about 240 sccm was attained with a low dead volume of 0.33 μl.

References

6 Uchino K, Piezoelectric actuators and ultrasonic motors (Kluwer, Boston) 1999.