A PLANAR MICROPUMP UTILIZING THERMOPNEUMATIC ACTUATION AND IN-PLANE FLAP VALVES

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ABSTRACT

The micropump presented in this paper demonstrates advancements made both in performance and fabrication over most existing mechanical micropumps. The pump is planar and fabricated using a wafer-level, four-mask process, making it attractive for integration into micro total-analysis systems. Its design utilizes thermopneumatic actuation and two in-plane flap valves with fluidic-resistance ratios greater than 1300 to reach maximum pressures of 16 kPa and maximum flow rates of 9 µL/min at an average power consumption of 180 mW (20% duty cycle, 5 Hz). Pressures as high as 20.2 kPa were achieved at an average power consumption of 200 mW (20% duty cycle, 10 Hz). This performance is better than most micropumps utilizing in-plane or out-of-plane valves [1], [2].

1. INTRODUCTION

The expected boom in the microfluidic market continues to draw out new micropump designs from both industry and academia. Applications ranging from micro total-analysis systems to drug delivery have been tagged as potential beneficiaries of this effort. Each application dictates unique specifications for pumping pressures and flow rates and it is this range of needs that drives the differentiation of pump designs.

This specific mechanical pump was designed for high pressure/high flow rate applications such as drug delivery and cryogenic systems but could work equally well for other applications where low flow rates and precise volume control are necessary.

Thermopneumatic actuation was chosen for this pump as resistive heaters could easily be integrated into the design. This form of actuation has been shown to be quite effective for micropumps due to the high pressure and high expansion rate caused by the phase change of the heated liquid [3]. However, the pump design is not limited to this form of actuation, as problems with thermopneumatic actuation exist. High power consumption and overall heating of the device during continuous long-term operation are drawbacks. The planar valves used in this pump design are compatible with any pulsatile actuation mechanism, such as piezoelectric- or electrostatic-driven pistons.

It is important to note that the pump is a planar design and wafer-level fabricated using a simple four-mask process. This allows easy integration with other planar fluidic components, such as mixers and sensing elements, facilitating system design.

2. PUMP DESIGN AND FABRICATION

Design

The planar micropump, as shown in Fig. 1, consists of flow channels and two in-plane flap valves structured into a silicon-on-insulator wafer and an anodically bonded Pyrex® cover with two platinum resistive heaters (2.3 kΩ). Cyclic pulsing of the resistive heaters causes a bubble to expand and collapse in the bubble chamber. Thus, the bubble serves as the piston of the micropump. The bubble chamber is separated from the flow channel by a buffer channel to avoid direct heating of the working fluid, Fig. 1. Capillary tubes glued into in-plane fluid ports serve as fluidic interconnects.

The in-plane valves consist of a flexible flap that covers a hole etched through the wall of the valve inlet, Fig. 2. This geometry has been shown to create well-sealing valve seats [4]. The flap is attached to a bi-stable suspension that is flipped before wafer bonding, applying a preload on the flap and holding the valve in its normally closed position, Fig. 2. The mathematics used to design the bi-stable suspension is discussed in [5]. The bi-stable suspension is also a fabrication necessity since it is not possible to fabricate an in-plane flap valve in its closed position. Doing so would require etching a submicron thin trench to separate the flap from the valve seat while ensuring maximum sealing. The bi-stable suspension compensates for this short fall. It allows the valve to be closed after fabrication by flipping the bi-stable structure.

The suspension also serves as an anchor for the flaps, ensuring that none of the moving parts are lost after they have been released.

Figure 1: Photo (top view through the Pyrex® cover onto the silicon substrate) of the planar micropump utilizing two platinum heaters (including one “backup” heater, 2.3 kΩ resistance) for thermopneumatic actuation and two in-plane flap valves.

Figure 2: This geometry has been shown to create well-sealing valve seats [4]. The flap is attached to a bi-stable suspension that is flipped before wafer bonding, applying a preload on the flap and holding the valve in its normally closed position. The mathematics used to design the bi-stable suspension is discussed in [5]. The bi-stable suspension is also a fabrication necessity since it is not possible to fabricate an in-plane flap valve in its closed position. Doing so would require etching a submicron thin trench to separate the flap from the valve seat while ensuring maximum sealing. The bi-stable suspension compensates for this short fall. It allows the valve to be closed after fabrication by flipping the bi-stable structure.
Previous planar micropump designs have suffered low yield rates due to free-floating valve components being lost during fabrication [6].

![Figure 2: SEM images of the in-plane flap valve before (top, middle) and after (bottom) flipping the bi-stable structure into the normally closed position.](image)

Fluid flow in the forward direction causes the flap to bend open while the bi-stable structure remains flipped, Fig. 3. The preload from the flipped bi-stable structure combined with the restoring moment of the bent flap returns the flap to the seat for stopped or reversed flow conditions. Since fluid drag is not required to close the valve, the transition time from open to close is minimized which improves the efficiency of the pump.

![Figure 3: Photo (top view thorough the Pyrex® cover) of the flap (bent in the open position) during fluid flow through the "hole-in-the-wall".](image)

Previous planar micropumps utilizing valves with moving parts had poor performance mainly due to the low fluidic-resistance ratios of these valves. To create in-plane flexures or moving parts, a sacrificial layer needs to be removed from below the moving part and a recess is required in the cover. This opens up leakage paths below and above the flexure that previous planar valves could not address. The "hole-in-the-wall" design seals off this leakage around the moving flap, Fig. 4, and greatly enhances performance of the valve and the pump.

![Figure 4: Cross-sectional view of the valve seat showing that all leakage paths around the valve seat are sealed.](image)

The pumping process has two steps. Powering the heater causes a bubble to expand in the bubble chamber, forcing fluid through the outlet valve of the pump. During the cooling step the bubble collapses, drawing fluid through the inlet valve. No working fluid is drawn into the bubble chamber since the volume of the fluid displaced by the bubble is less than the volume of the buffer channel.

**Fabrication**

The pump is wafer-level fabricated with a four-mask process utilizing the "hole-in-the-wall" fabrication method, which is described in detail in [4]. First, trenches of two different depths are etched (DRIE, vertical sidewalls) in the device layer of an SOI wafer (100 µm thick device layer and 4 µm buried oxide) using a two-layer oxide/photoresist mask. The deeper channels are etched completely down to the buried oxide while the shallow trenches are etched only half way through. The deeper channels make up the majority of the fluidic pathways whereas the shallow trenches are only necessary to create the valve seat.

Conformal silicon dioxide is grown in a wet oxidation step to passivate all exposed silicon. The wafer is then subjected to a directed SiO₂ plasma etch to remove the oxide from the bottom of the shallow channels.

![Figure 5: Schematic diagram of the "hole-in-the-wall" process. The final isotropic silicon etch punctures the sidewall so that the valve seat is formed.](image)
An isotropic silicon etch (plasma etch in SF₆ atmosphere) is used to form the valve seat by undercutting the thin silicon wall, see Fig. 5. This timed etch is halted when the thin wall separating the shallow and deep channels is punctured. Finally, the silicon oxide is removed in HF, which also releases the moving portions of the flap valves.

Shallow trenches are etched 20 µm in the Pyrex® cover, ensuring that the free-moving parts do not anodically bond to the glass cover. Additionally, the metal meander-shaped heaters, bond pads and connecting traces are patterned in these trenches. Thus, the metal heaters are recessed into the Pyrex®, so that the two wafers are in close contact for the anodic bonding. Due to its inert nature and temperature stability, platinum is used for the heaters. A thin titanium film serves as an adhesion layer between the platinum and the Pyrex®.

After anodic bonding, the wafer stack is diced from both sides half way through the silicon and Pyrex so that the fluidic channels remain sealed while dicing, Fig. 6. This prevents particles from entering the pump, which may cause the pump to malfunction. The wafer-stack easily breaks into chips, which opens the in-plane fluid ports. The chip design also allows easy bond pad access after wafer dicing. Since the bond pads are located in shallow trenches in the Pyrex®, the silicon overlapping the bond pads remains unbonded [7]. Thus, the overlapping silicon breaks off readily after dicing the wafer stack, giving access to the bond pads.

4. RESULTS AND DISCUSSION

Assuming the fluidic system behaves as a simple flow resistor, the pressure drop

\[ P = \frac{1}{C_1} \dot{V} + C_2 \]

across the pump is a linear function of the flow rate \( \dot{V} \) through the pump. In this test setup, this pressure drop is equal to the hydrostatic pressure

\[ P = h g \rho, \]

where \( g \) is the acceleration of gravity and \( h \) the height of the liquid in the capillary. The flow rate

\[ \dot{V} = A \frac{dh}{dt} \]

corresponds to the change in height of the liquid in the capillary with the cross-sectional area \( A \). Equations (1-3) can be combined and formulated into the differential equation

\[ P = A \frac{dP}{dt} + C_2. \]

The solution of this equation describes the time dependence of the hydrostatic pressure

\[ P = C_1 + C_1 \exp(C_1 C_2 t), \quad C_1 = \frac{g \rho}{A}. \]

Figure 7: Isopropanol is pumped into a glass capillary (ID 250 µm). The liquid height is measured by a pressure sensor placed at the bottom of the tube.

Figure 6: Schematic diagram of the dicing sequence. This sequence prevents particles from contaminating the pump since all channels remain sealed while dicing. Furthermore, it enables bond pad access after wafer-level anodic bonding.

3. EXPERIMENTAL

Isopropanol (density of \( \rho = 790 \text{ kg/m}^3 \)) was pumped into a vertically mounted glass capillary (ID 250 µm), as shown in Fig. 7. A pressure sensor was placed directly above the pump at the bottom of the tube to measure the pressure increase as the pump continuously ran. The height difference between the pressure sensor and the Isopropanol level in the reservoir was added to the sensor reading. The capillary effect of the glass tube was accounted for as a negative pressure offset of 0.39 kPa.
Curve fitting of the measured pressure-time curve, Fig. 8, yields the parameters $C_1$ and $C_2$ necessary to compute the pressure-flow rate characteristics for different average power consumptions shown in Fig. 9.

![Figure 9: Pressure-flow characteristic for Isopropanol (IPA) at different power consumptions (one heater powered, 10 Hz, 20% duty cycle).](image)

The maximum pressure for different power consumptions and pumping frequencies is shown in Fig. 10.

![Figure 10: Maximum pressure for Isopropanol at different frequencies and average power consumptions (one heater powered, 20% duty cycle).](image)

The maximum pressure as a function of the pumping frequency, as shown in Fig. 11, suggests an optimum operation frequency between 2.5 and 7.5 Hz for 150 mW average power consumption (20% duty cycle, one heater powered).

![Figure 11: Maximum pressure for Isopropanol at different frequencies (150 mW average power consumption, one heater powered, 20% duty cycle).](image)

No significant decrease in pump performance could be measured within 12 h of continuous operation.

5. CONCLUSIONS

A reliable planar micropump with well-sealing planar flap valves has been fabricated based on the ‘hole-in-the-wall’ process. The four-mask process can easily be integrated with other planar fluidic components to create micro total-analysis systems. The new valve design eliminates leakage paths around the moving part resulting in superior performance over previous planar valves. A bi-stable suspension attached to the flap allows the valve to be closed after fabrication by flipping the suspension. This enables the fabrication of a planar flap valve. In addition, a preload is applied to the flap holding the valve in its normally closed position. Since fluid drag is not required to close the valve, the transition time from open to close is minimized which improves the efficiency of the pump.

Flow rates up to 9 µL/min and pressures up to 16 kPa have been achieved at an average power consumption of 180 mW (10 Hz, 20% duty cycle, one heater powered). A maximum pressure of 20.2 kPa is reached at an average power consumption of 200 mW (5 Hz, 20% duty cycle, one heater powered).

REFERENCES


