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# Fabrication of a Free Floating Silicon Gate Valve

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## ABSTRACT

**This paper introduces an active planar microvalve with free floating moving pieces and a novel process for fabricating that valve. The valve presented has all of its moving pieces and actuation in the plane of the wafer in which it is microfabricated. The valve can be moved up to 100 μm using thermally generated vapor bubbles to provide actuation. The fabrication process involves bonding a thin (~100μm) wafer to a handle wafer with epoxy. The moving pieces are then defined with DRIE etching and released from the epoxy bond with an oxygen plasma. The theoretical performance of the valve is presented as well as experimental results.**

## NOMENCLATURE

| | |
|---|---|
| $A$ | Cross sectional area [$l^2$] (equation2) |
| $b$ | One dimension of a rectangular channel [l] (equation5) |
| $C$ | Flow conductance of a channel [$l^4$] (equation3) |
| $c$ | 2nd dimension of a rectangular channel [l] (equation5) |
| $F$ | Force [$ml/t^2$] (equation2) |
| $l$ | Length of a channel [l] (equation4) |
| $t_d$ | Device wafer thickness [l] |
| $t_e$ | Epoxy thickness [l] |
| $t_g$ | Gap between gate and housing [l] |
| $t_L$ | Lattice thickness[l] |
| $p$ | Pressure [$m/t^2l$] (equation1) |
| $Q$ | Volume flow rate [$l^3/t$] (equation3) |
| $R$ | flow resistance of a channel [$m/l^2t$] (equation4) |
| $r$ | radius of curvature of bubble [l] (equation1) |
| $\mu$ | dynamic viscosity [m/lt} |
| $\sigma$ | surface tension [$m/t^2$] (equation1) |

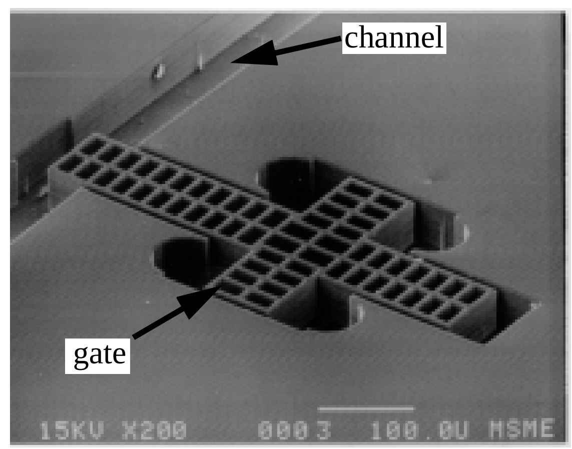


**Figure 1. An SEM of the gate valve. The flow channel is approximately 100 μm in width and 75 μm deep.**

## INTRODUCTION

### Need for microvalves

Micro-valves will be critical to any complex micro fluidic system. Micro-mixers, chem/bio sensors, drug delivery and micro total analysis systems all require active control of fluid flow. A number microvalves have been fabricated and there are even some commercially available. However, none of these valves provide the capability for active control in a planar configuration.

The microfluidics group at Berkeley is currently developing a drug delivery system under the auspices of the DARPA microfLUMES program. The system must have integrated fluid control including valves, pumps and mixers. These later two devices also need valves in order to operate. Although efficient operation is desirable, valves do not need to provide perfect seals for many applications, including the proposed system. They must, however, be fabricated in the same process as the rest of the device and minimize the number of bonding steps in order to make the complete system cost effective. In addition, because the system will be battery-powered, the valves must use as little power as possible. These design requirements demand the development of planar valves that are stable in at least one configuration.

### Existing Valves

There are many valves which involve the deflection of a membrane out of the plane of the valve. Perhaps the best example of these valves was presented by Henning (1997). They have excellent flow controlling characteristics. However, valves like this and Smith and Hok's (1991) out of plane check valve, require multiple wafer aligning and bonding steps making them quite expensive and difficult to integrate. Henning's valve also requires a relatively large amount of power.

Planar "No-Moving-Parts" valves such as the diffuser and nozzle from Olssen's (1995) "valveless pump" or Forster's (1995) Tesla valve are cheaper and easier to integrate than the valves with out of plane movement. These types of valves have been shown to allow more flow in one direction than the other and have been demonstrated to be effective as check valves in piezoelectrically actuated pumps. The development of higher-efficiency positive displacement pumps will require better flow rectification than current "No-Moving-Parts" valves can deliver.

The first attempt to create a planar valve at Berkeley was presented by Evans (1997). It consisted of a thermally-generated (steam) bubble constrained inside a converging passage or, for two-directional flow, a "cage." Surface tension forces block the flow by providing a pressure gradient across the bubble because of the different radii of curvature. While bubble valves will have some applications, they require too much power to remain "closed" because constant heat must be provided to keep the thermal bubble inflated. Thus another solution was sought.

## DESIGN OF THE VALVE

The simplest way to make a valve in the plane of the wafer is to simply move a piece of silicon into a flow channel and block it, i.e. create a microscopic gate or pin valve. Such a valve is shown in Figure 1. The flow channel is visible in the upper left section of the SEM and is approximately 100 microns wide and 75 microns deep.

A critical design requirement is to minimize the energy required to operate the valve. Specifically, it should remain open or closed without requiring any additional energy. In the current design, friction forces keep the gate valve in place after it has been moved. Unlike the valve presented by Evans (1999) where the gate was tethered to a spring, the gate valve presented here is free floating. Since the moving gate is free to rub against it's housing, the actuation must overcome friction to move close the valve. Once the actuation power is removed friction will keep the valve in place. In addition, the fluid flow is normal to the direction of gate travel so that viscous friction will not open the gate.

### Bubble Actuation

The fluid environment offers interesting advantages and disadvantages. Conventional MEMS actuators are impractical in a fluid environment. Electrostatic actuators will not work in a fluid with mobile ions and thermal actuators require more power in a conductive liquid than they do in air or a vacuum. However, one can take advantage of two other phenomena: One, there is a great density differential which accompanies a phase change and two, surface tension forces become much more significant at small scales. Together these can be used to make a bubble actuator.

The surface tension between the vapor in the bubble and the liquid outside it will tend to maximize the radius of curvature of the interface. In addition, the angle that this interface makes with the surface of any solid it encounters is fixed by the surface physics. These two factors combine in a chamber made of a hydrophilic material (such as silicon coated with a native oxide) to make it possible to use the pressure in a bubble to push micromechanical devices as Lin (1991) demonstrated. The limiting pressure is determined by capillary forces necessary to hold the bubble in the chamber and not squeeze through the gaps.

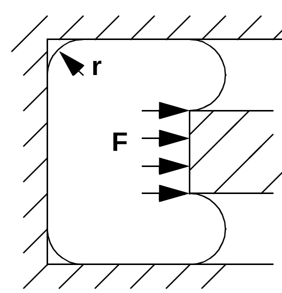


**Figure 2. A bubble in a small closed chamber.**

In this valve, one of the walls of the chamber containing the bubble, is a moving part of the valve. When the pressure in the bubble is increased by evaporating more fluid through heat input, the additional pressure pushes the valve forward. The bubble will not leak through the gaps until sufficient pressure has been achieved to force the bubble into the gaps.

The pressure inside the bubble is a function of surface tension $\sigma$ and radius of curvature of the bubble $r$.

$$\Delta p = \frac{2\sigma}{r} \quad (1)$$

Thus the force on the moving gate is given by:

$$F = \frac{2\sigma}{r} \times A \quad (2)$$

Where $A$ is the cross sectional area of the part of the gate in contact with the actuating bubble.

For the valve presented here, the largest gap for the bubble to leak through should be the lithographically defined gap between the gate and it's housing. The smallest radius of curvature that this gap can maintain is half the gap width. The maximum force should be $F = 1.07 \times 10^{-4} N$ .

### Valve Operation

As shown in Fig. 3, one set of heaters creates two bubbles that push the valve into the flow channel, block the channel and close the valve. Another set of heaters generates two bubbles that can subsequently open the valve.

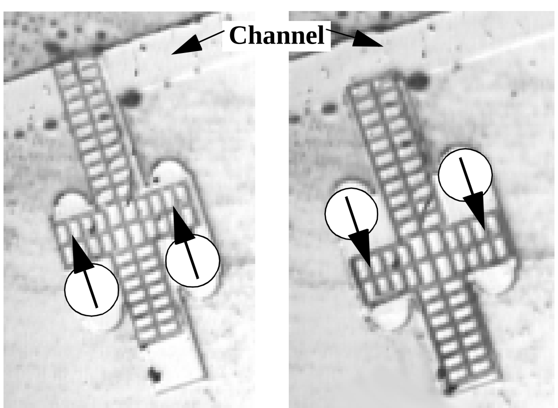


**Figure 3. Actuation of the valve to close and open the 100x75 μm channel. Bubbles formed on one side of the valve push it open, bubbles formed on the other side push it closed**

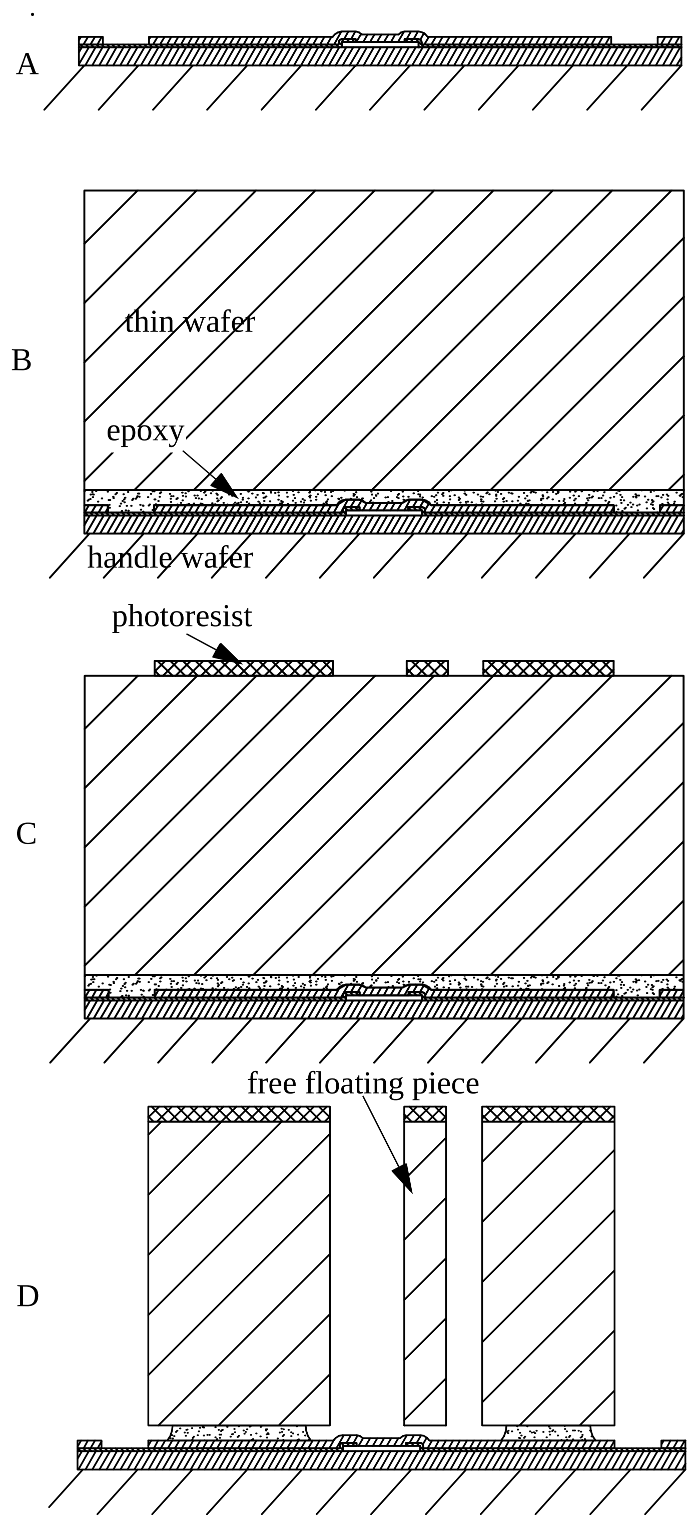


**Figure 4. The fabrication process. A) surface machined features on the handle wafer. B) Device wafer bonded on with Epoxy. C) Features defined on device wafer, aligned to buried features with I.R. light. D) Valve features etched and released.**

## FABRICATING THE VALVE

The fabrication process starts with a conventional silicon wafer dubbed the "handle" wafer. The polysilicon heating elements that generate bubbles are fabricated on this wafer. While the current system is actuated with vapor bubbles and consists of only a valve, virtually any surface micromachined structures can be fabricated on the handle wafer, including electrodes for electrochemical bubbles, other sensors, and CMOS for controlling circuitry. Thus this fabrication process is capable of creating complete microfluidic systems

Next, a thin (~100 μm) "device" wafer is bonded on the front surface of the handle wafer. The bonding is accomplished with a layer of 2-component epoxy which is spun on the handle wafer. The two wafers are actually joined under a vacuum to minimize the formation of voids between the two wafers. The epoxy is allowed to cure 24 hours.

The features on the surface of the handle wafer are now buried under 100μm of silicon and epoxy. A mask is aligned to these buried features with infrared light, allowing valves and channels to be defined in photoresist on top of the device wafer. The features are then etched into the silicon device wafer with an STS deep reactive ion etcher.

The devices are then put in an oxygen plasma to remove epoxy from the open areas and release the moving structures. Finally a cover plate is clamped over the top of the valve. However, the cover plate could have been bonded to the device using epoxy, but was not done because the goal of these experiments was to demonstrate a moving valve.

## PREDICTED VALVE PERFORMANCE

This gate valve is inherently leaky. Removing epoxy from underneath the gate leaves a gap. For the valve presented here, the epoxy thickness, $t_e$ is about $5\mu m$. The leakage through this gap was estimated by modeling the lattice work of the valve as contractions in the flow channel. As a first approximation, the flow was modeled as Pousille flow. Since the flow through the contractions is not fully developed, the resistance of the valve to flow should be higher than that predicted with pousille flow. A CFD model was created to get a more accurate estimate of the performance of the valve. The open valve is simply a portion of a long rectangular channel. The flow through this can accurately be modeled as fully developed pousille flow.

### Pousille Flow.

As discussed in Rosenhead (1963), the fully developed volume flow rate in an arbitrarily shaped channel is a function of the dimensions of the channel, the viscosity of the fluid and the pressure drop per unit length.

$$\boldsymbol{Q} = -\frac{C}{\mu} \times \frac{dp}{dx} \qquad (3)$$

Where $C$ is a function of cross-sectional shape.

For a given length, $l$, of channel filled with fluid with viscosity $\mu$,

$$\Delta p = \frac{Q\mu l}{C} = RQ \qquad (4)$$

Where $R$ is a channel's resistance to flow. Exact solutions for $C$ have been found and cited by Rosenhead (1963). For a rectangular channel,

$$C = \frac{1}{12}cb^3 - \frac{b^4}{2}\left(\frac{2}{\pi}\right)^5 \sum_0^{\infty} \frac{1}{(2n+1)^5} \tanh\left((2n+1)\frac{\pi c}{2b}\right) \qquad (5)$$

where $b$ is one dimension of the rectangle and $c$ is the other dimension.

The open valve is a channel with where the height of the channel is $b = t_e + t_d$, the width of the channels is $c = w_c$,and the length $l = w_v$, the width of the valve in the direction of flow. The closed valve can be approximated as three shorter rectangular channels in series where $b = t_e$, $c = w_c$, and $l = 3t_l$, the sum of the widths of the beams.

For the valve in this paper, the resistance to flow was predicted to be $R_{open} = 2.89\times10^{10} Pa \cdot s/m^3$ and $R_{closed} = 2.67\times10^{13} Pa \cdot s/m^3$.

### CFD Model

A model of the valve was simulated using CFD-ACE, a commercially available package from CFD Research Corporation that has extensions for MEMS design and microfluidics. As expected, the resulting resistance, $R_{closed} = 4.89\times10^{13} Pa \cdot s/m^3$, was higher than that calculated by Pousille flow by almost a factor of two.

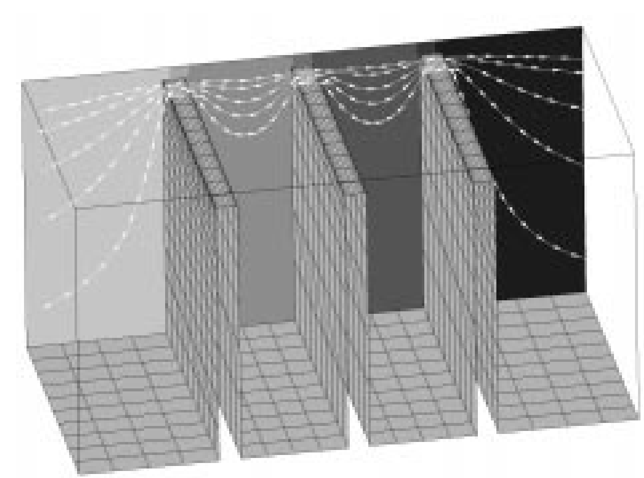

**Figure 5. The CFD-ACE model. Pressure is represented by the grey scale on the back wall. The streamlines are shown in white.**

## EXPERIMENTAL RESULTS

The micro-valve was successfully opened and closed. Figure 6 shows the valve being pushed closed by a thermally generated bubble.

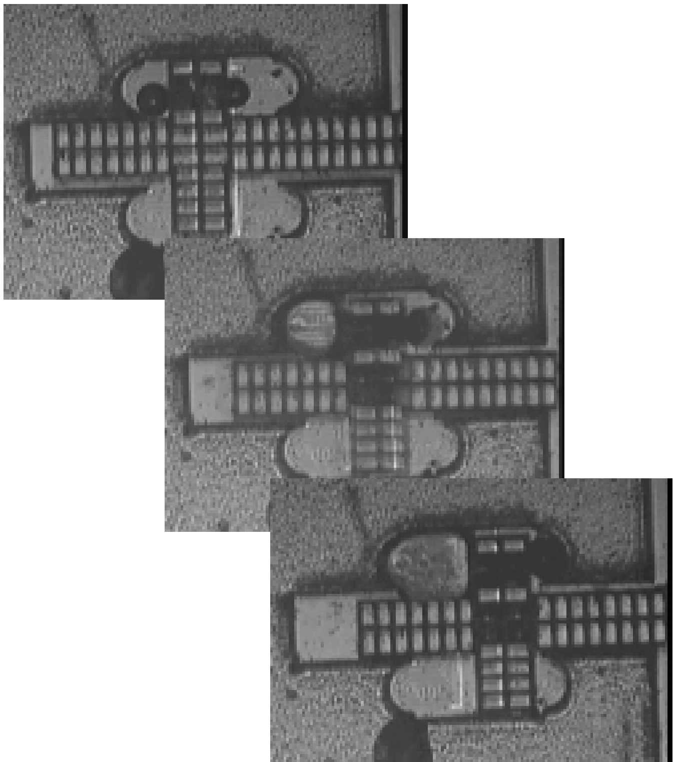

**Figure 6. Demonstration of valve closure using a single thermally generated bubble.**

### Observations on the operation of the valve.

1) Often only a single bubble forms. However, a single bubble is sufficient to move the valve because it is designed in such a way that an off axis force will not jam it.

2) As discussed by Evans (1999), thermally generated bubbles do not completely disappear when the heater is turned off. Formation of the thermal bubbles brings dissolved gasses out of solution. Although the bubbles do not disappear completely, they shrink sufficiently so that a second bubble can push the valve the opposite way.

3) The performance is of the valve depends on the epoxy removal step using the oxygen plasma. because the degree to which the epoxy has been cleared away affects the friction at the bottom of the valve. If the epoxy has not been sufficiently removed from underneath the lattice structure, the bubble actuation may not provide enough force to move the valve.

### Flow Resistance Measurement Setup

For the flow rate experiments, a polystyrene cover plate was clamped in place, then epoxy was applied around the edges of the plate sealing it. Holes were bored through the polystyrene. Blunt 20 gauge needles were inserted into the holes and sealed with epoxy. A syringe pump provided constant flow rates. A conventional differential pressure sensor measured the pressure drop across the entire device. The pressure drop was measured at various flow rates with the valve open, and the valve closed.

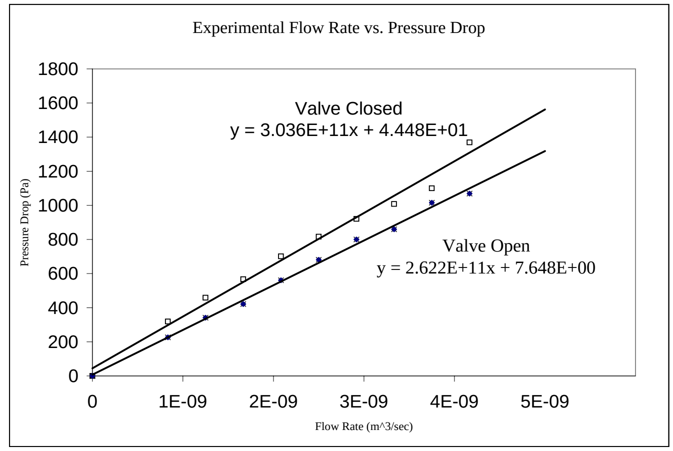


**Figure 7. Pressure drop across the device as a function of flow rate with the valve open and the valve closed.**

### Results

The results of this experiment are shown in figure 7 As expected, the pressure drop across the closed valve is higher than that across the open valve. The magnitude of the flow resistance was drastically lower than predicted. The difference is in large part due to the extremely poor sealing between the cover plate and the surface of the die. While measurements were being taken, it was clear that there was flow not only through the channel, but across a several millimeter wide area of the face of the die. The measurement of the pressure drop shown here serves only to demonstrate that the valve does actually affect fluid flow. The predicted flow resistances should be an indication of the performance which can be expected when the issue of sealing the channel is solved.

***Table 1: Flow Resistances***

| | Flow Resistance |
|---|---|
| Pousille Flow | $R_{closed} = 2.67\times10^{13} Pa \cdot s/m^3$ |
| CFD model | $R_{closed} = 4.89\times10^{13} Pa \cdot s/m^3$ |
| Experimental | $R_{closed} = 4.14\times10^{10} Pa \cdot s/m^3$ |

## CONCLUSIONS

A planar bi-stable microvalve has been demonstrated. The valve has been shown to open and close when actuated with thermally generated microbubbles. It has been shown to remain in position without requiring additional power between actuations. The measured performance of the valve is drastically worse than predicted due to poor sealing. However, the valve has been shown to affect fluid flow in the manner predicted.

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## ACKNOWLEDGMENTS

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***Table 2: Parameters used in this paper***

| Parameter | symbol | value | units | source |
|---|---|---|---|---|
| Viscosity of water | $\mu$ | $1.12\times10^{-3}$ | $\frac{N \cdot s}{m^2}$ | Munson 1990 |
| surface tension of water at 100 C | $\sigma$ | $58.9\times10^{-3}$ | $Pa \cdot m$ | Weast 1988 |
| Thickness of epoxy layer | $t_e$ | ~ 5 | $\mu m$ | Optical measurement |
| Width of channel | $w_c$ | 100 | $\mu m$ | Photolithography |
| Thickness of lattices | $t_L$ | 8 | $\mu m$ | Photolithography |
| Width of valve | $w_v$ | 100 | $\mu m$ | Photolithography |
| Gap between valve and housing | $t_g$ | 8 | $\mu m$ | Photolithography |
| Thickness of device wafer | $t_d$ | 73 | $\mu m$ | Optical Measurement |