HIGH-SPEED AND BI-STABLE Electrolysis-Bubble Actuated Gate Valves

Alexandros P. Papavasiliou, Albert P. Pisano, and Dorian Liepmann
Berkeley Sensor and Actuator Center, University of California Berkeley
497 Cory Hall, Berkeley CA 94720
alexip@me.berkeley.edu

SUMMARY

High-speed and bi-stable electrolysis-bubble actuated planar micro gate valves are demonstrated in this paper. The speed of previous low power planar microvalves was limited by the bubble collapse process. In addition bi-stability was unreliable. In this work, surface tension is used to physically remove the bubble from the actuation chamber allowing operation as fast as 3 Hz while requiring as little as 112µJ per actuation. Buckling beams are used to suspend valves that have been shown to be mechanically bi-stable.

Keywords: Microvalve, Microfluidics, Micro-bubble

INTRODUCTION

Background/Previous Work

The utility of previous low-power planar microfluidic valves has been limited by their long cycle times and limited bi-stability. As shown in [1] planar, integrable valves have been actuated with electrolysis bubbles using as little as 4.3µW. The residual electrolysis bubble prevented reciprocation until catalysis of the gasses collapsed the bubble. This limited the valve speed to 1 cycle every 120 seconds.

In addition, to being slow, the previous valves rely on friction between the gate an the substrate for their stability. On the micro-scale, body forces are negligible in comparison to frictional forces, making the previous valves fairly stable once actuated. However, normal operating conditions such as the application of a gravitational field in conjunction with vibration could change the valve position.

In this work valve designs are presented that 1) take advantage of surface energy to physically remove the actuation bubble from the actuation chamber allowing rapid reciprocation and 2) suspend the gates on buckling beams that make the valve mechanically stable in both the closed and open positions.

Surface Energy

While surface effects can often be taken to be negligible in macro-scale applications, they can dominate over viscous and inertial effects on the micro-scale. An imbalance in attractive forces at surfaces of liquids requires the addition of energy in proportion to surface area. When systems act to minimize this energy by minimizing surface area, the resulting effect is similar to a tension perpendicular to the surface. As the length scale of a system decreases, the surfaces effects, proportional to length squared, become much more important than the body forces which are proportional to length cubed.

Previous work by the authors [2] has shown that surface tension makes bubbles effective micro actuators. Work by Lin [3] and Evans [3] has shown that surface tension can also be used to move micro-bubbles. Bubbles in fluid will minimize their surface energy by forming a sphere. Bubbles in confined spaces with hydrophilic walls can be forced to adopt shapes that do not minimize their surface area. When allowed to move to a less confined space where surface area can be minimized bubbles, will do so. As shown in Figure1, a diverging channel can provide the kinetic path necessary to allow a bubble to minimize surface energy by moving out of a confined space. As a bubble moves a differential amount along the diverging channel, the surface area, and thus

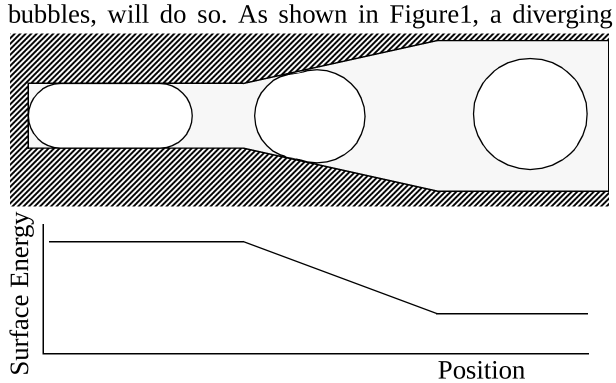

Figure 1. Surface energy of bubbles in confined channels with hydrophilic walls.

energy, of the bubble decrease. This energy gradient results in a force that pushes the bubble along the channel.

VALVE DESIGNS

Two designs that use surface effects to solve the problem of removing the actuating bubble from the actuation chamber thus allowing for reciprocation, as well as a valve in which buckling beams are used to make the valve mechanically bi-stable have been used in this work.

Enlarged Electrode Valve

The enlarged electrode design valve, shown in Figure 2, uses much larger electrode generation chambers than have been used previously [1]. Only a small portion, labeled the actuation chamber, must be cleared to allow reciprocation. After actuation the platinum electrodes in the bubble generation chamber rapidly catalyze the volume of gas necessary to empty the actuation portion of the chamber. Surface tension draws the bubble through a diverging channel, out of the actuation chamber leaving the valve free to reciprocate.

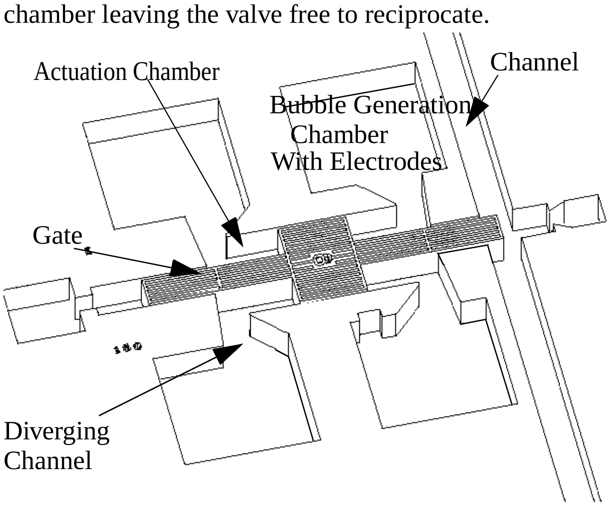

Figure 2. Enlarged Electrode Area Valve Design

Bubble Ejection Valve

The bubble ejection valve, shown in Figure 3, also relies on a diverging channel to remove bubbles from the actuation chamber. In this design, the bubbles are generated over fairly small electrode arrays in the actuation chamber. The movement of the valve opens a diverging channel. The actuation bubble expands into this channel and ejects from the actuation chamber to a side chamber that is lined with platinum.

Due to the fact that only a small actuation chamber must be filled with gas, this valve will require less power for

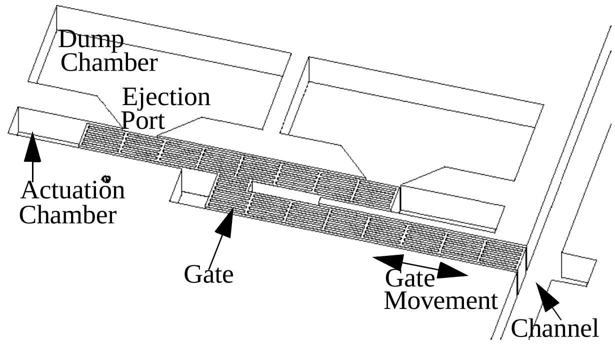

Figure 3. Bubble Ejection Valve Design

the initial actuation than the enlarged electrode area valve. In addition, since reciprocation is not dependent on reaction of the ejected bubble, the cycle frequency of this valve is only dependent on bubble generation rate. However if a sufficient number of cycles in a short period of time can quickly fill the dump chamber, restricting reciprocation. In addition the asymmetry involved in this particular valve design makes it prone to jamming.

Bi-Stable Buckling Beam Valve

The Bi-Stable Buckling Beam Valve, shown in Figure 4, was designed to solve the problem of bi-stability. Instead of a free floating gate, this valve has a gate suspended by four beams that are designed to make the valve stable in both the open and closed positions.

The beams hold the valve stable in the fabricated, open, position. If the valve is forced toward the closed position, the beams buckle, storing energy in bending. As shown in Figure 6, if the beams are then forced farther towards the closed position, the bending energy reaches a maximum and then decreases. This energy gradient provides a restoring force holding the gate stable in the closed position.

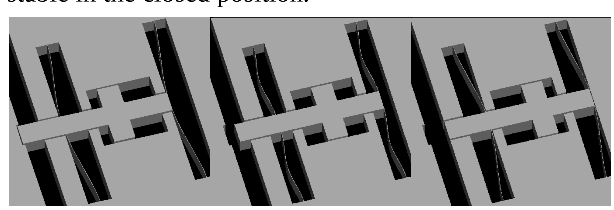

Figure 4. Bi-Stable Buckling Beam Valve Concept

An elastic buckling analysis was performed on the bi-stable buckling beam shown in Figure5. The shape of the beam was solved for a variety of displacements and the bending energy in the beam was solved each shape. Plots of the shape and resultant bending energy are shown in Figure 6.

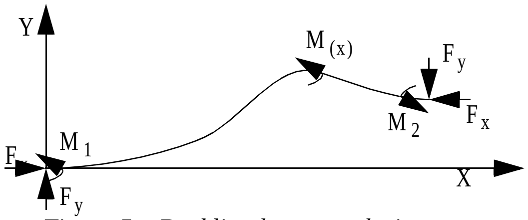

Figure 5. Buckling beam analysis

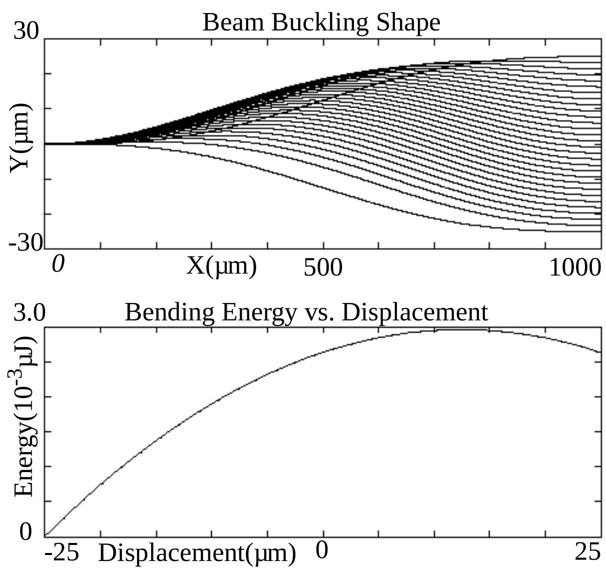

Figure 6. Results of Buckling beam analysis

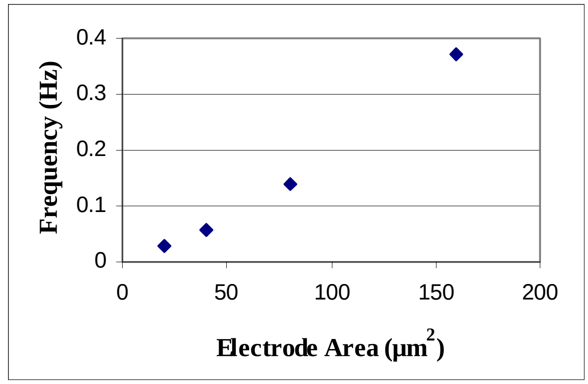

Figure 7. Large Electrode Area Valve Frequency vs. Electrode Area

VALVE TESTING

The two high-speed valve models were tested for cycle frequency and power consumption and the bi-stable valve was tested for stability

Enlarged Electrode Area Valve

Tests were performed on models of the enlarged electrode area valve, with four different electrode areas. The maximum actuation frequency for each model was found by increasing the actuation frequency until the gas in the actuation chambers could no longer be removed quickly enough to allow reciprocation. The results, shown in Figure 7, show that the actuation frequency is roughly proportional to electrode area. This design of valve was operated up to 0.37 Hz, however this increased speed comes at a cost in energy consumption.

At a constant electric potential, the energy required per actuation is proportional to the amount of gas needed per actuation. The amount of gas necessary to fill the bubble generation chamber should be proportional to the electrode area. However, during continuous operation the electrode area never completely empties and only enough gas to fill the actuation chamber need be added.

The energy necessary to operate the valve was tested at 5 volts for both the condition where the entire bubble generation chamber must be filled and continuous operation case where only the actuation chamber need be filled. The results, shown in Figure 8, agree with the theory. The initial-actuation case shows energy roughly proportional to electrode area and the continuous operation case shows energy as a much weaker function of electrode area. For initial actuation the energy required is as high as 1.69 mJ where as in continuous operation the valves require at most 411 µJ.

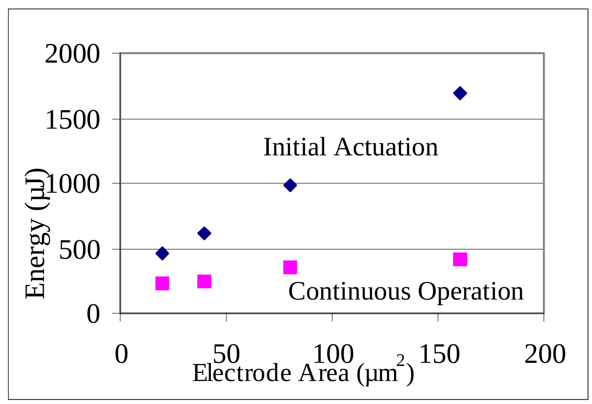

Figure 8. Large Electrode Area Valve Energy vs. Electrode Area.

Bubble Ejection Valve

Speed and energy consumption were also measured for the bubble ejection valve. Since the bubble is destroyed outside of the valve, the cycle frequency is only a function of bubble growth speed. Bubble growth speed is a function of actuation potential. Higher potential produces bubbles faster. Since the amount of gas needed to actuate the valve is constant, merely that needed to fill the actuation chamber and advance the bubble into the ejection port, actuation speed can be increased by increasing actuation energy.

A plot of cycle frequency as a function of actuation energy is shown in Figure 10. As expected. Increasing actuation energy will produce bubbles more quickly and the valve will actuate more rapidly. The speed of these

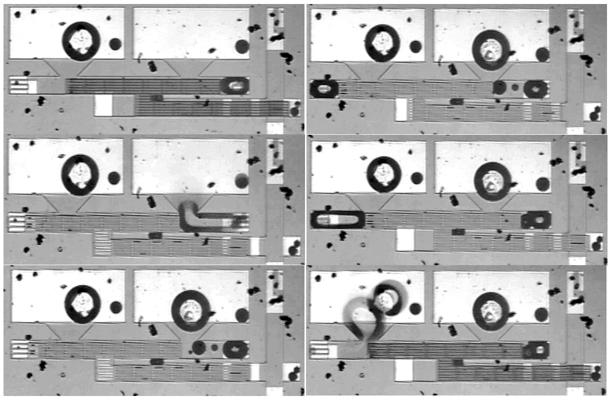

Figure 9. Bubble Ejection Valve Sequence

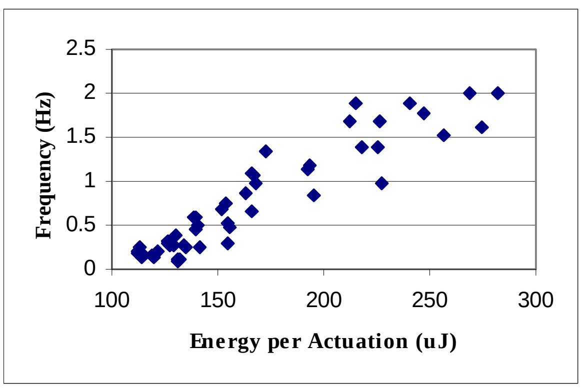

Figure 10. Bubble Ejection Valve Frequency vs. Energy Consumption

valves ranges from 0.137 Hz at 112 μJ to 2.00 Hz at 282μJ. The valve has been operated at frequencies up to 3 Hz. Unlike the increased electrode area valve which is automatically centered by actuation bubbles, the reliability of this asymmetric valve is limited to jamming caused by off axis forces.

Bi-Stable Buckling Beam Valve

The buckling beam valve was tested for stability. The valve was actuated by bubbles and shown to have a stability point in both the open, fabricated, position as well as the closed position as demonstrated in Figure 11. The valve was also tested in a dry environment to prove that stability was not caused by residual bubbles. The valve was moved by probe tip and again demonstrated a small but real stability region in the closed position.

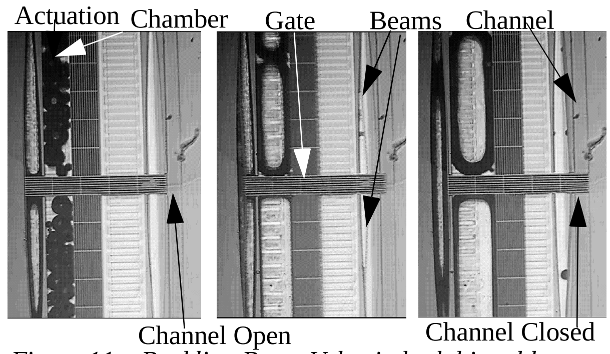

Figure 11. Buckling Beam Valve in both bi-stable positions

CONCLUSIONS

This work has demonstrated low-power planar valves with moderately rapid cycle times as well as valves that are truly mechanically bi-stable. High-speed valves were demonstrated up to 3Hz. The enlarged electrode valves were shown to have higher power consumption and slower cycle times, but were not affected by the jamming that limited the reliability of the faster and lower-power asymmetric bubble ejection valve. The bi-stable valves were shown to be stable in both the closed and open positions. All the elements have been developed to combine the buckling beam valve with the bubble ejection valve to create a bi-stable high-speed low-power valve.

ACKNOWLEDGMENTS

This research was funded by Becton Dickinson and DARPA.

REFERENCES

[1]Papavasiliou, Pisano, and Liepmann, "Electrolysis-Bubble Actuated Gate Valve, *Solid State Sensor and Actuator Workshop, (Hilton Head 2000)*, p. 48-51, 2000

[2]Papavasiliou, Liepmann, and Pisano, "Fabrication of a free floating Silicon Gate Valve," *Micro-Electro-Mechanical-Systems (MEMS), 1999 ASME IMECE*, Vol 1., p435-40, 1999

[3]L. Lin, A.P. Pisano, and A.P. Lee, "Microbubble powered actuator." *1991 International Conference on Solid-State Sensors and Actuators. Digest of Technical Papers (Transducers '91)*. p.1041-4, 1991

[4]J. D. Evans and D. Liepmann, "The Bubble Spring and Channel (BSaC) valve: An Actuated, Bi-stable, Mechanical Valve for In-plane Fluid Control," *10th International Conference on Solid-State Sensors and Actuators, (Transducers '99)*. pp 1122-1125, 1999