COMSOL Simulation of MEMS Piezoelectrically Actuated Micropump

Wei Zhan, Chengsi Li, Advisors: Prof. Xingguo Xiong, Prof. Prabir Patra, Prof. Junling Hu
Department of Biomedical Engineering, University of Bridgeport, Bridgeport, CT 06604

Abstract

In this poster, the design and COMSOL simulation of a piezoelectric micropump [1] with dome-shaped diaphragms and diffuser-nozzle fluid rectifiers is reported. The micropump uses piezoelectric ZnO film (less than 10μm thick) to actuate the vibration of a parylene dome diaphragm, so that microfluid can be pumped in and out of the chamber. The device is to be fabricated on silicon substrate with an IC-compatible process. Piezoelectric ZnO film is sputter-deposited on a parylene dome diaphragm with its C-axis oriented perpendicular to the dome surface. The micropump utilizes two symmetric dome diaphragms for improved pumping rate. Diffuser-nozzle elements are integrated with piezoelectrically actuated dome diaphragms to form a multi-chip micropump. Due to the MEMS (Microelectromechanical Systems) technology used, the proposed micropump has very small size (10×10×1.6mm^3) and consumes extremely low power. It also shows negligible leakage up to 700 Pa static differential pressure. The function of the proposed micropump is verified with COMSOL simulation.

Introduction

Micropumps are miniature fluid delivery devices which are capable of generating microfluid flow at finite pressure loads. Micropumps base on MEMS (Microelectromechanical Systems) technology have functional dimensions in the range of microns (1μm=10^{-6}m). Due to their small size, low cost, low energy consumption and high efficiency, MEMS micropumps have been widely used in many applications, such as Micro Total Analysis System (μTAS), Lab-on-a-chip, and micro drug delivery systems. MEMS micropumps can be divided into two categories: passive and active micropumps. Passive micropumps requires no external energy supply, while active micropumps need energy supply to operate. Micropumps based on different actuation techniques have been reported, such as magnetic micropumps, electrostatic micropumps, piezoelectric micropumps, thermodynamic micropumps, shape-memory-alloy micropumps, etc. Among them, piezoelectric micropumps are able to produce significantly large force with low power consumption. In this poster, a piezoelectric micropump with dome-shaped valveless membrane structure is designed and simulated. Valveless diffuser-nozzles are used for inlet and outlet ports. The pumping chamber is sealed by top and bottom dome-shaped parylene diaphragms. Piezoelectric ZnO actuators are deposited on the surface of each diaphragm. When AC driving voltage is applied, piezoelectric actuator expands and shrinks periodically, causing the diaphragm to bend up and down. Hence the microfluid is sucked into the chamber and pumped out periodically.

Design Consideration

The bulk-micromachined piezoelectric dome-shaped micropump design was reported in [1]. In this poster, we designed the micropump and uses COMSO to simulate its performance. It consists of two parts: dome-shaped diaphragm transducer (DSDT) and a cylinder chamber with diffuser-nozzle elements as inlet and outlet. As shown in Figure 1, the cylinder chamber is located in the center of this whole structure. Two dome-shaped diaphragms (20μm thick parylene) cover the top and bottom of the chamber. A 5μm ZnO film is coated onto the diaphragm to initiate the vibration. Each diffuser-nozzle element is located on the diameter line of the cylinder. When the piezoelectric material bends the diaphragm up/down, there will be a fluid through the whole structure.

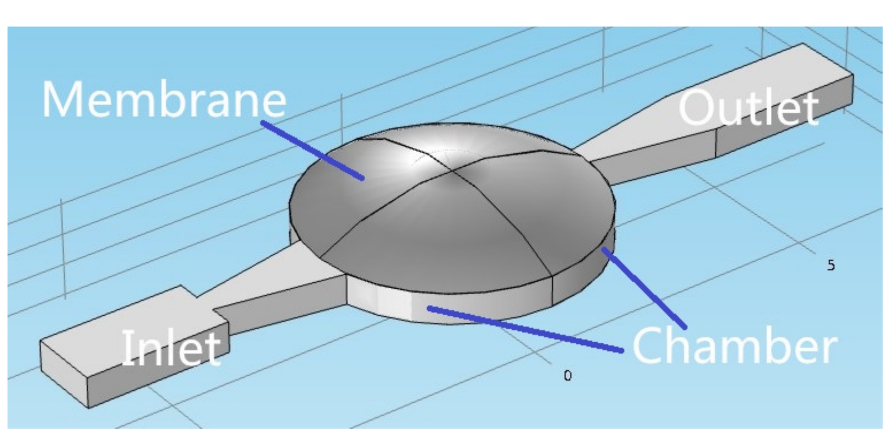


Figure 1. 3D view of the structure of a MEMS Piezoelectric Micropump

The micropump utilizes valveless design. No inlet/outlet valves are needed for the device operation. As shown in Figure 2, when membranes bend outwards in supply mode, liquid is sucked in from both inlet and outlet. However, more liquid goes through the inlet than outlet due to larger pressure loss at nozzle. Similarly, more liquid goes through outlet than inlet during pump mode. This ensures a net flow of microfluid from inlet to outlet during a complete pumping cycle.

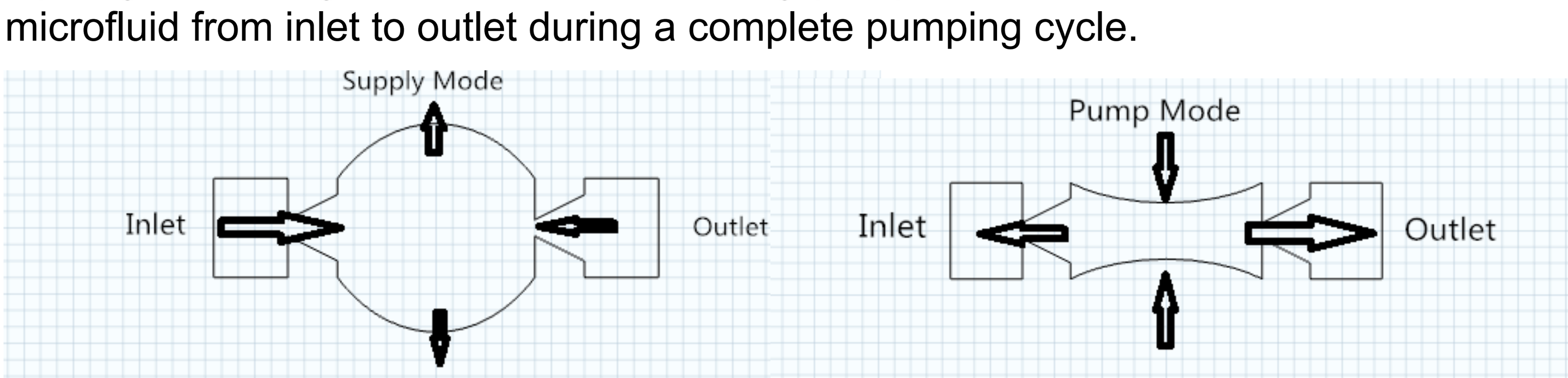


Figure 2. Operational modes of valveless piezoelectric micropump

Advantages of dome shaped diaphragm over a flat diaphragm include capability to release the residual stress of the diaphragm through volumetric change of its shape, efficiency of converting in-plane strain to volumetric deflection, structural stiffness and sturdiness, etc. When a flat diaphragm is curved into a dome shape, the diaphragm stiffness increases by a few orders of magnitude, and can be made large enough to pump liquid even with a very thin diaphragm of thickness less than 10μm.

The DSDT resonant frequencies are calculated with an equivalent Young's modulus based on 10μm parylene as diaphragm, 0.5μm aluminum for a bottom electrode, 5μm ZnO for piezoelectric actuation, 0.5μm parylene for insulation, and another 0.5μm aluminum for a top electrode. Calculation results verifies the effect of the dome curvature on the stiffness and resonant frequency.

COMSOL Simulation

To verify the correction function of valveless micropump, we simulate the operation of piezoelectric micropump in COMSOL with AC driving voltage $V_d=V_0\sin(2\pi f\ t)$, where V_0 is amplitude of driving voltage, and f is frequency. The velocity plot of both modes are shown in Figure 3. From Figure 3, we can see that with the AC driving voltage, the top and bottom diaphragms bends in opposite directions. In supply mode, both diaphragms bends outwards, chamber volume increases, liquid is sucked in from both inlet and outlet. However, due to pressure difference, more liquid is sucked in from inlet than outlet. This results in net flow from inlet into chamber. In pump mode, both diaphragms bend inwards, liquid is pressed out from both inlet and outlet. Due to pressure difference, more liquid is pressed out from outlet than inlet. This result in net flow from chamber to outlet. In a complete pumping cycle, a net amount of liquid is pumped from inlet to outlet. This verifies the correction function of valveless micropump.

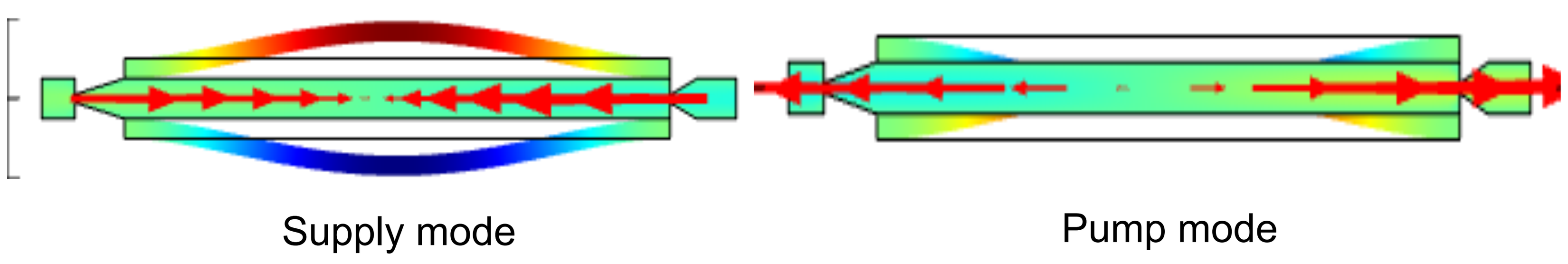


Fig. 3. COMSOL simulation of valveless micropump (velocity plot)

Furthermore, we use COMSOL simulation to verify that dome-shaped diaphragm leads to improved stiffness, hence it can work at higher frequency. As shown in Fig. 4, for flat membrane, when driving voltage frequency increases to 1000Hz, the diaphragm bends abnormally (it begins to twist). While for dome-shaped diaphragm shown in Fig. 5, it can bend normally under driving frequency f=1000Hz. Thus dome-shaped diaphragm can work at higher frequency than flat-shape diaphragm. This results in quicker response and improved pumping rate. That's the reason why dome-shaped diaphragm is used in the micropump design.

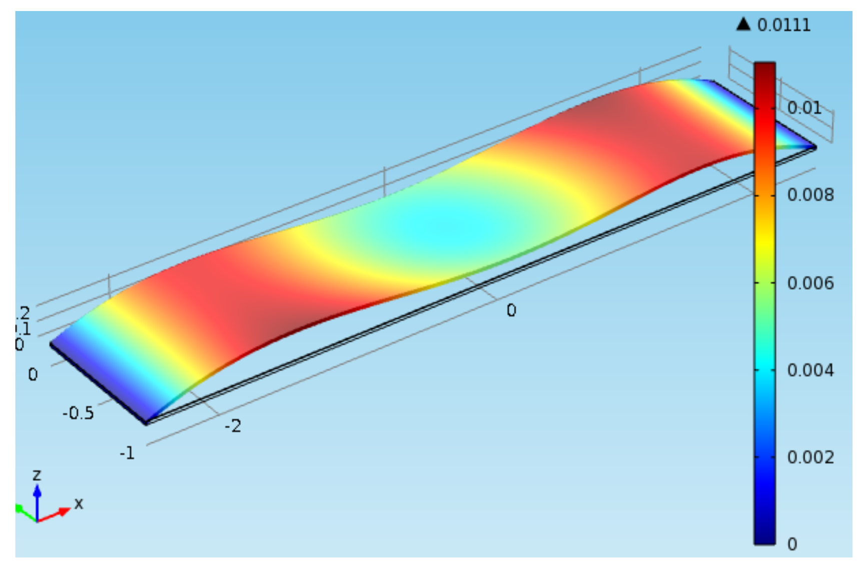


Fig. 4. Flat diaphragm, V_0=80V, f=1000Hz

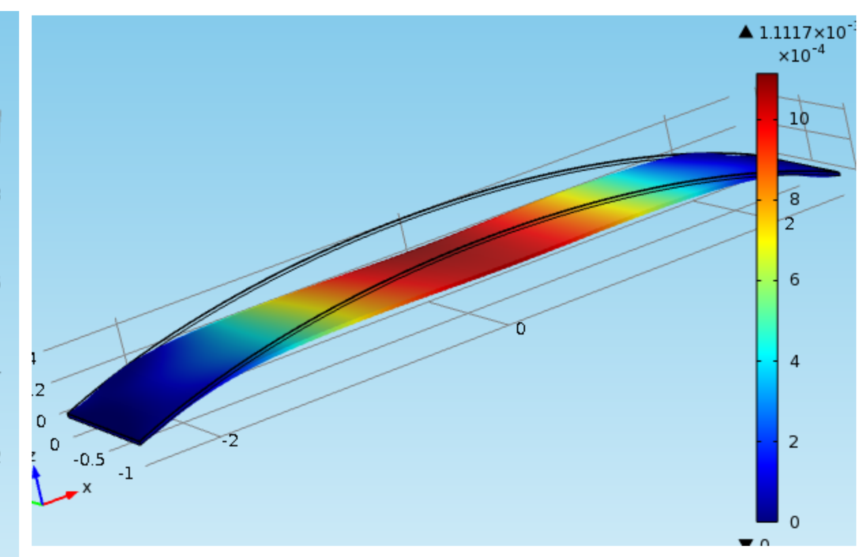
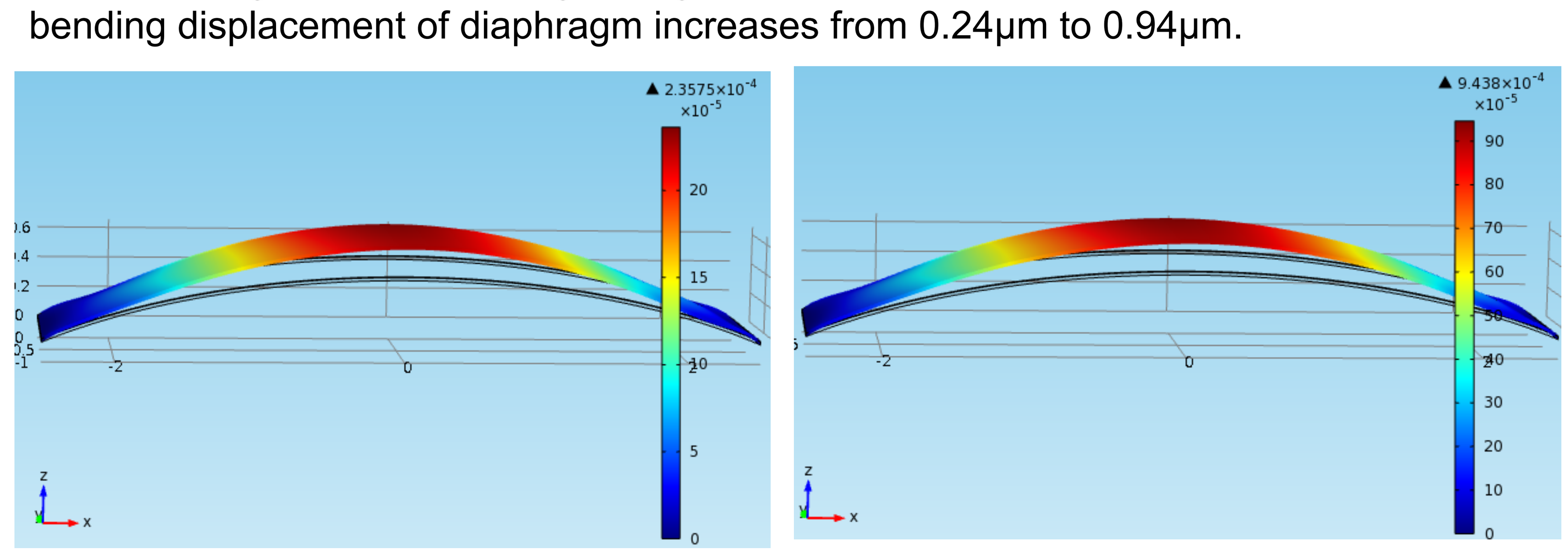


Fig. 5. dome diaphragm, V_0=80V, f=1000Hz

The bending displacement of micropump increases with driving voltage. This is verified in Fig. 7. When driving voltage is increased from 20V to 80V, the maximum bending displacement of diaphragm increases from 0.24μm to 0.94μm.



(a). V_0=20V, x_{d_max}=2.3575×10^{-4}mm (a). V_0=80V, x_{d_max}=9.438×10^{-4}mm

Figure 7. Diaphragm bending displacement increases with higher driving voltage (f=500Hz)

Device Fabrication

The device is fabricated with bulk-micromachining process [1] as shown in Fig. 8. The fabrication involves a wax molding and a two-dimensional array of large dome-shaped and thin diaphragms on a standard 3" silicon wafer. Besides, anisotropic plasma etching is used to fabricate the chamber and diffuser-nozzle parts. Then a DSDT wafer is aligned and bonded to the chamber wafer. The wafers are then diced into individual chips. This batch-process makes the manufacturing cost extremely low.

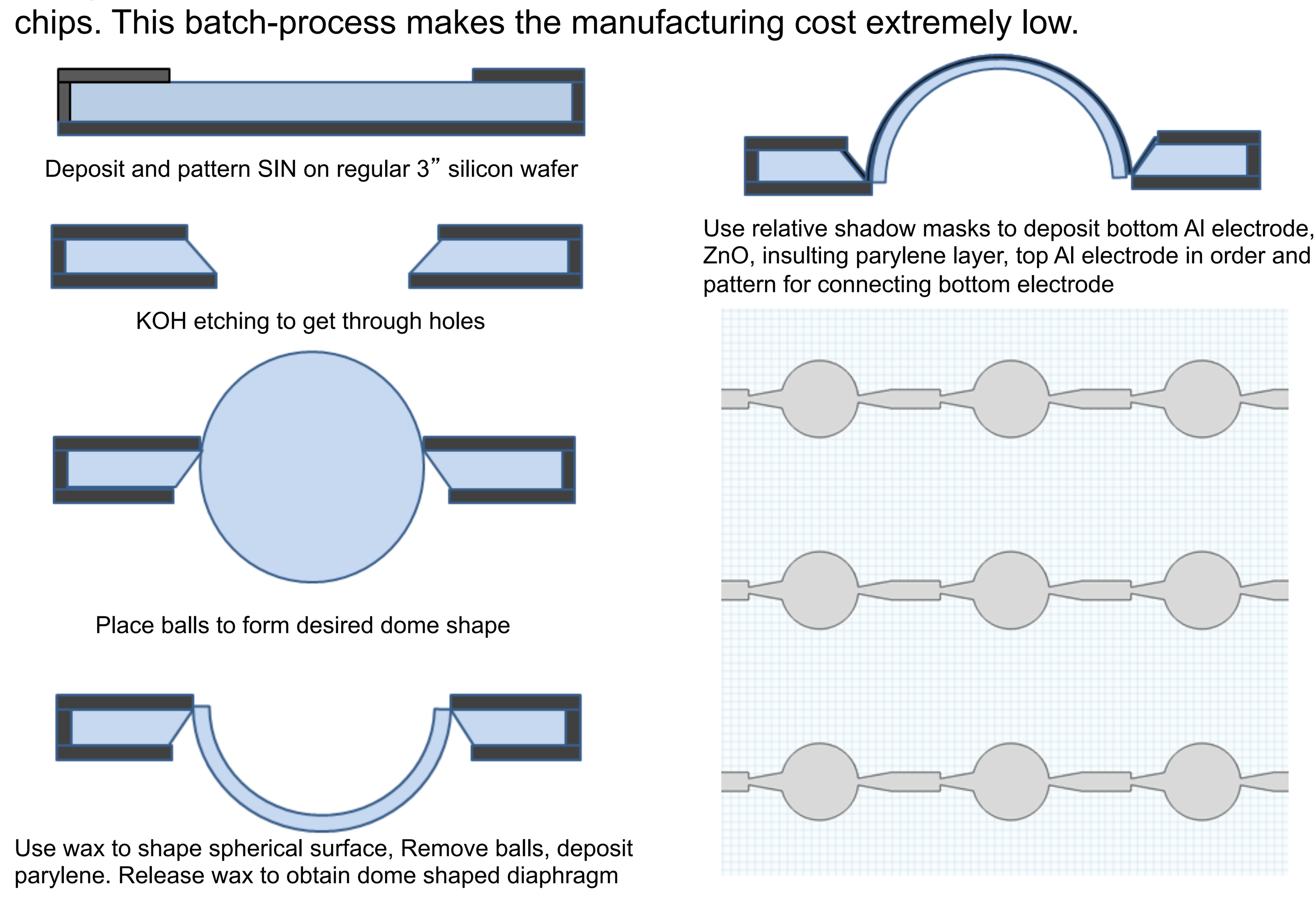


Fig. 8. Fabrication flow of piezoelectric micropump with dome-shaped diaphragm [1]

Conclusions and Future Work

In this project, COMSOL simulation of a bulk-micromachined piezoelectric micropump with dome-shaped diaphragms is proposed. The working principle of the micropump is analyzed in details. The dome-shaped diaphragm leads to better high-frequency response than flat-diaphragm. In the future, we will try other different structure designs of diaphragms increase the pumping rate even more.

References

[1] G.H. Feng, E.S. Kim, "Piezoelectrically Actuated Dome-shaped Diaphragm Micropump", IEEE Journal of Microelectromechanical Systems, Vol. 14, No. 2, Apr. 2005, pp. 192-199.