DESIGN AND PROTOTYPING OF A SURFACE MICROMACHINED PARYLENE MICROVALVE WITH HYBRID ACTUATION SCHEME: ON-CHIP THERMOPNEUMATIC INITIATION AND ELECTROSTATIC LATCHING
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ABSTRACT
We report a development of microvalve that combines the advantages of high-force thermopneumatic actuation and low-power nature of electrostatic actuation. Microvalve is the most important component in realizing programmable and multifunctional microfluidic systems. Many researchers seek to develop microvalves with small leakage, portability, and small footage. Dominantly, external pneumatic source is used as actuation source. This makes it difficult to be portable. Also, elastomer as dominant valve material has compatibility issues against other surface micromachined MEMS components. It is our motivation to develop a microvalve without such external dependence and limitations.

KEYWORDS: Electrostatic, Parylene, Thermopneumatic, Valve

CONCEPT
As shown in Figure 1, the power input to the heating element induces the pressure increase to move the valve membrane. Then relatively smaller electrostatic force can hold the valve membrane. For the valve to operate against higher-pressure, the power input to the thermopneumatic source can be simply increased accordingly.

The device is unique in the following: (1) wafer through-holes are used as inlets and outlets: minimizes leakages as there is no lateral passages (2) the whole fabrication process does not involve assembly or bonding process, (3) Parylene (Young’s modulus: 4 GPa) is used for valve membrane: low spring constant, (4) thermopneumatic actuation does not rely on phase change: no phase-change material needs to be filled and seed, (5) ZnO is used as sacrificial layer to elevate the heating element.

Figure 1. Schematic of the microvalve concept.
FABRICATION
The fabrication processes to realize the micro valve requires 8 masks and is described in the following (Figure 2). (a) First, through holes are drilled from the backside and 0.3-µm-thick Al layer is patterned to cover the through holes. (b) 0.3-µm-thick ZnO sacrificial layer is patterned prior to deposition of 1-µm-thick Si₃N₄ layer. (c) Bottom Au electrodes are patterned and first photoresist sacrificial layer is shaped to form heating and valve chambers followed by conformal 2.5-µm-thick Parylene deposition. (d) After top electrodes are formed, connecting vias are created by Oxygen plasma etching. Second photoresist layer is then patterned to form the chamber on top of the valve membrane followed by 4-µm-thick Parylene deposition. The Al layer is removed along with sacrificial photoresist layers. Finally, the acetone is interchanged with ethanol before releasing the device with supercritical drying. Figure 3 shows the released device.

ENGINEERING CHALLENGES AND SOLUTIONS
There were major engineering challenges in developing the presented device:
(1) The spring constant of the actuator membrane has to be reduced. We have employed a polymer called Parylene, which has comparably smaller Young’s modulus (4GPa) compared to the aforementioned materials. From Timoshenko’s “Shells and Plates”, the spring constant of a membrane can be modeled as a function of its area and the material thickness. Spring constant of the Parylene is modeled to be actuated with 1 psi of pressure. (For 250 µm membrane, 2.5 µm thick Parylene is used.)
(2) However, the releasing of the membrane in acetone caused collapse of the membrane as the surface tension of the solvent pulled in the membrane as it dried up. This was solved by introducing liquid phase CO₂ to change the media.
Isolating the heating element from the substrate is essential for the array of the devices not to have any cross talking. Amorphous structure ZnO was used as the sacrificial layer to create nitride membranes. For the device presented, Silicon Nitride layer has been deposited with PECVD (Plasma Enhanced Chemical Vapor Deposition. One unique feature of ZnO is that it can be etched away with any acid with 5 times faster lateral etch rate than that of vertical one. Our parametric study has shown 0.5% HCL solution will etch ZnO layer with 300 Angstrom’s rate but will not etch Aluminum.

Finally, DC actuation of electrostatic device causes charge injection problem to the dielectric. The Parylene is not free from this problem, either. Testing of the device with DC actuation at 180 V\textsubscript{pp} (only electrostatic actuation) confirmed this problem by collapsing only after 10 actuations operated at 1 Hz. To reduce the charging problem, bipolar waveform was used as actuation signal.

TESTING AND RESULTS

The hybrid actuation scheme was tested by sending a pulse (300ms, 2W) to the heating element to deflect the membrane and the minimum required voltage to latch the membrane was measured. The voltage required to latch the membrane with the hybrid scheme was reduced to 45V\textsubscript{pp} from 180V\textsubscript{pp} when only electrostatic actuation is employed. Figure 4 confirms the optical interferometer graph for the valve membrane for open and closed state. The hybrid actuation scheme was tested against increasing pressure as shown in Figure 5. It was found both the power input and electrostatic voltage need to be increased at higher pressure. Nitrogen was used for leakage tests (Figure 6) and the amount of leakage increases as the pressure is raised with a constant latching voltage at 100V\textsubscript{pp}. The surface roughness of the membrane could have caused passages for the gas to leak even with the actuator membrane latched. With the current design, the leakage issue can be levitated by either increasing the holding voltage or by decreasing the gap between the two electrodes. Future areas of work include integrating a valve seat for better sealing, a method to improve charge injection problem, and lifetime analysis of the device.

Figure 5. Both power(-) and the latching voltage increase at higher pressure.

Figure 6. Leakage test with latching voltage constant at 100 V\textsubscript{pp}

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