A High-Frequency, High-Stiffness Piezoelectric Micro-Actuator For Hydraulic Applications

David C. Roberts*, J. Lodewyk Steyn*, Hanqing Li*, Kevin T. Turner*, Richard Mlcak**,
Laxman Saggere*, S. Mark Spearing*, Martin A. Schmidt*, and Nesbitt W. Hagood*
*Massachusetts Institute of Technology, Cambridge, MA 02139 USA
**Boston MicroSystems, Inc., Woburn, MA 01801 USA

SUMMARY

A piezoelectric micro-actuator capable of high stiffness actuation in micro-hydraulic systems was fabricated and experimentally tested to frequencies in excess of 100 kHz. The actuator was fabricated from a bonded stack of micromachined silicon-on-insulator (SOI) and borosilicate glass layers. Actuation was provided by 1mm sized piezoelectric cylinders, which were integrated within a tethered piston structure and electrically and mechanically attached using a thin-film AuSn eutectic bond. Die-level anodic bonding techniques were developed to assemble the supporting structural silicon and glass layers. The microfabrication, device assembly, experimental testing procedures, and actuator performance are discussed in this paper. Issues such as piezoelectric material preparation, requisite dimensional tolerancing, micromachining of the silicon tethered structures, and integration of multiple piezoelectric elements within the micro-actuator structure are detailed.

Keywords: actuator, piezoelectric, micromachined

INTRODUCTION

In order to realize high specific power transducers, a novel approach integrating micro-hydraulics, piezoelectric materials and micromachining technology is being developed [1,2,3]. These micro-hydraulic transducers (MHT) rely on a high frequency fluid pumping mechanism and equally fast actively controlled valves to achieve high system flow rates (~1ml/s) against large differential pressures (~1-2MPa). The pumping and valving functions in MHT systems require a positive-displacement micro-actuator structure that can produce fluid volume oscillations at high frequency (10-20 kHz) and exhibit high structural stiffness so as to minimize compliance against the large differential system pressures. The actuator is required to be compact, low mass, and amenable to integration with other micromachined components of the hydraulic system. Motivated by the need for such an actuator for use in MHT technology, and potentially, other similar microhydraulics applications, a novel piezoelectrically driven micro-actuator has been developed and tested. The paper highlights the development of this actuator.

Conceptually, the proposed micro-actuator incorporates a circular piston structure supported from beneath by one or more small bulk piezoelectric cylinders and suspended circumferentially from a surrounding support structure by thin annular micromachined tethers. This unique design provides the actuator not only the desired performance characteristics, but also enables higher specific actuation authority (force per unit mass) than a similar class of piezoelectrically-driven micro-actuators using tall stacks of piezoelectric layers or thick piezoelectric films previously reported [4,5]. In addition, the integration of high performance single-crystal PZN-PT piezoelectric material over standard polycrystalline PZT-5H piezoelectric material allows for enhanced actuation capabilities [6].

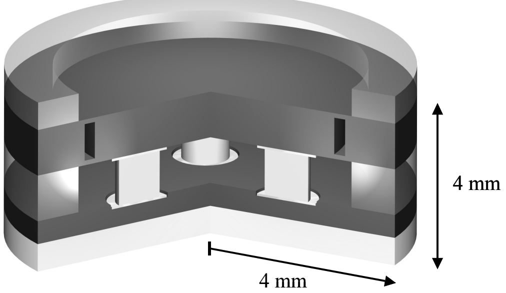


Figure 1: Schematic of a micro-actuator device, with three piezoelectric material cylinders beneath a double layer micromachined piston and tether structure.

Development of the actuator reported in this paper involved overcoming several technical challenges including (1) reliable bonding of bulk piezoelectric material to silicon using a thin-film AuSn eutectic bond, (2) tight control tolerances of piezoelectric cylinder lengths and surface roughness, and (3) controlled Si etching of the thin tether structures. The following sections present the details of design, microfabrication, and assembly of the actuator, and experimental validation of the actuator performance.

DEVICE DESIGN

The micro-actuator device is illustrated in Figures 1 and 3. It consists of one or more piezoelectric cylinders sandwiched between a rigid bottom silicon layer and a top micromachined silicon piston/tether structure. Each of the piezoelectric cylinders has a thickness of 1mm and a diameter of 1mm. The top and bottom surfaces of each piezoelectric element are coated with a eutectic bond layer consisting of 50nm Ti, 250nm Pt, 4000nm AuSn alloy, and 20nm Au. The Ti serves as an adhesion layer to the piezoelectric material, the Pt serves as a diffusion barrier, and the Au serves as a capping layer to ensure no oxidation of the Sn. The bottom silicon layer incorporates an etch seat for each of the piezoelectric elements, to allow for tolerancing of the elements with respect to the surrounding glass layer. The tethered piston (diameter=6.2mm) is created by wafer fusion bonding two micromachined SOI layers together. In response to a sinusoidal voltage, the piezoelectric material expands and contracts, thereby actuating the piston against an external load. In a typical MHT system that incorporates this actuator element, hydraulic fluid above the piston and tether would be pressurized and depressurized, for the purpose of either pumping fluid [1,3] or actuating a valve head [2].

DEVICE FABRICATION

Piezoelectric Material Virgin piezoelectric materials, both PZT-5H and PZN-PT, are obtained in plate form and subsequently double-side polished to a thickness of 1mm±10µm. The surface roughness after polishing is 0.5µm. This ensures adequate roughness for adhesion of the eutectic film, yet sufficient smoothness for surface contact between the piezoelectric and Si surfaces during bonding. The Ti-Pt-AuSn-Au multi-layer film (as described in the previous section) is sputter-deposited onto both sides of the substrate plate. From this plate, 1mm diameter cylinders are core-drilled, cleaned, and measured.

Piston and Tether Structure The piston/tether structure is created by Deep Reactive Ion Etching (DRIE) of a SOI wafer. The tether thickness (~10µm) is defined by the SOI device layer, and the buried oxide acts as the etch stop. Control of the fillet radii at the base of the etch trench is critical for the minimization of stress concentrations and is accomplished with a carefully timed deep etch. Double layer drive pistons are desired to minimize piston bending during actuation. This is accomplished by individually etching two SOI wafers, each 400µm thick, and then fusion bonding them together. Vent channels are included within the piston structure to prevent pressurization between the tethers during wafer annealing (see Figure 2).

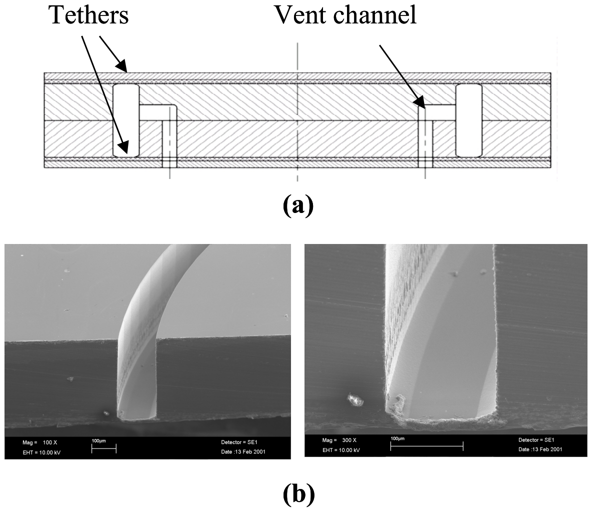


Figure 2: Micromachined tethered piston structure: (a) cross section schematic view of a double-layer piston and (b) Scanning Electron Micrograph of cross-sectioned single layer piston wafer. Note fillet radius features at base of tether.

Glass Layers All glass layers are Pyrex 7740 and are patterned by conventional diamond core drilling. The middle glass layer is measured for tolerancing purposes when integrating the piezoelectric elements.

Piezoelectric Cylinder Etch Seats The bottom silicon layer is 400µm thick and contains etched cavity seats for placement of the piezoelectric cylinders. The depth of these seats is determined by the thickness mismatch between the middle glass layer and the piezoelectric cylinders. It is desired to size the cylinders slightly larger (~1-2µm) than the glass and seat depth so as to create a preload during assembly, thereby ensuring that the eutectic bond remains in compression. Reactive Ion Etching (RIE) was used to etch the cavities down to the required depth. The top surface of the etch seats and the bottom surface of the piston are coated with 50nm Ti, 250nm Pt, and 50nm Au to facilitate adhesion of the eutectic bond layer. This film is deposited by electron beam evaporation, on the die level, through a shadow mask. After this deposition step, the subcomponents are ready for assembly.

DEVICE ASSEMBLY

As illustrated in Figure 3, the final assembly of the device requires multiple layers to be bonded. First, die level anodic bonds between the top and bottom silicon layers and the glass packaging layers (not shown in

Figure 3) are completed at a temperature of 300°C and an applied potential of 1000V. The middle glass layer, bottom silicon layer and piezoelectric cylinders are selected to provide the proper preload on the piston and piezoelectric element. A die level anodic bond between the bottom silicon layer and middle glass layer is then carried out under the conditions identified previously. The piezoelectric cylinders are inserted in the center cavity and aligned within the etched seats in the bottom silicon layer. The top silicon layer, which contains the tethered piston structure, is aligned and clamped to the lower structure. The clamped structure is heated to 300°C and a voltage of 1000 V is applied to form an anodic bond between the top silicon layer and the middle glass layer.

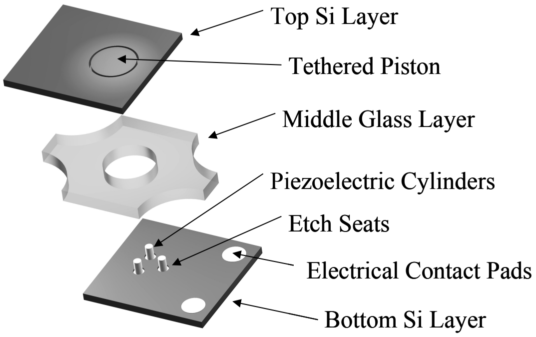
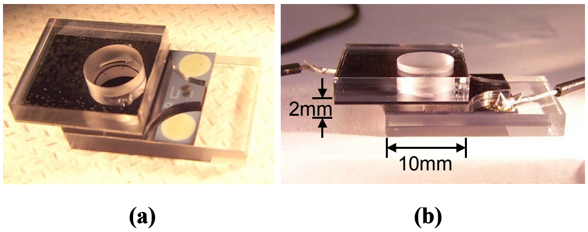


Figure 3: Exploded view of primary layers in single-layer piston micro-actuator structure (top and bottom support glass layers not shown).

The 300°C temperature allows the AuSn eutectic alloy to melt. The alloy flows and wets the Ti-Pt-Au film on the top and bottom silicon layers. The 4µm thick eutectic film is sized to be sufficiently thick to compensate for the dimensional tolerance (±1µm) of the piezoelectric elements. Upon cooling, the AuSn alloy solidifies and bonds the piezoelectric cylinders to the silicon layers in the device. Following the final bonding step, lead wires, which provide electrical connection to the piezoelectric element, are soldered to gold contact pads on the upper and lower silicon layers. Poling of the piezoelectric material within the device is performed following the assembly procedure. This is accomplished by heating the device to approximately half the Curie temperature and applying an electric field equal to twice that of the coercive field of the piezoelectric material, which in the case of PZT-5H are 90°C and 1100V, respectively.

TESTING AND RESULTS

Three distinct micro-actuator devices have been fabricated and tested. The first and second devices incorporate a centrally-located PZT-5H cylinder and PZN-PT cylinder, respectively, beneath a single layer piston. The third device incorporates three PZT-5H cylinders evenly spaced beneath a single layer piston. Work on integrating three PZN-PT cylinders in conjunction with double layer pistons is currently in progress. Device 1 is shown in Figure 4.

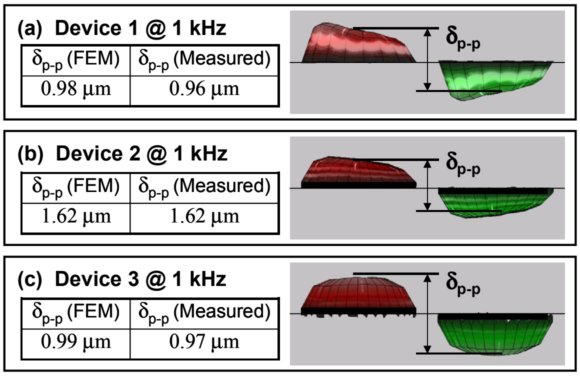


(a) (b)

Figure 4: Close-up photographs of Device 1: (a) w/o electrical leads, (b) with electrical leads.

Each of the fabricated devices was tested using a scanning laser vibrometer system. To determine quasi-static performance, a sinusoidal voltage of 500V ± 500V was applied at a frequency of 1 kHz. The piston center point peak-peak displacement $\delta_{p\text{-}p}$ was recorded to evaluate the voltage-displacement response of the device. To observe higher-order dynamic modal behavior, a reduced sinusoidal voltage was applied over a range from 1 kHz to 500 kHz and mode shape frequencies were recorded. For both the quasi-static and modal experiments, recorded data was compared to results from finite-elements models.

Figure 5 displays the quasi-static deformation of each of the three devices at 1 kHz and a comparison of expected $\delta_{p\text{-}p}$ to experimentally measured $\delta_{p\text{-}p}$. Ideally, a perfect micro-actuator device would exhibit flat piston motion as it transverses a complete cycle of deflection. As can be seen in Figure 5a and Figure 5b, the piston for each of the single piezoelectric cylinder devices tilts as it cycles, due to imperfect placement of the cylinder beneath the piston. Non-uniform fillet radii or membrane tether thickness around the piston could also contribute to this behavior, however, for these two devices, careful measurement and evaluation of the membrane structures prior to device assembly revealed very uniform etch profiles. Figure 5c illustrates the piston deformation for Device 3. As compared to the single cylinder devices, incorporation of three PZT-5H cylinders beneath the piston enables closer to ideal flat piston actuation throughout a cycle. The measured deflections of all three devices correlate well with those predicted by finite-element analyses.



(a) Device 1 @ 1 kHz

δ_{p-p} (FEM)	δ_{p-p} (Measured)
0.98 μm	0.96 μm

(b) Device 2 @ 1 kHz

δ_{p-p} (FEM)	δ_{p-p} (Measured)
1.62 μm	1.62 μm

(c) Device 3 @ 1 kHz

δ_{p-p} (FEM)	δ_{p-p} (Measured)
0.99 μm	0.97 μm

Figure 5: Quasi-static side-view deformations at 1 kHz: (a) Device 1, (b) Device 2, and (c) Device 3. Devices 1 and 2 exhibit tilted piston behavior whereas Device 3 operates with a more uniform flat profile.

Dynamic modal behavior of these devices can provide important insight into how well a given device has been fabricated. The frequency response and selected mode shapes for Device 1 are shown in Figure 6 as an example. The first mode shape at 32 kHz (see Figure 6b) is characterized by uneven tilting of the piston. Finite-element models predict this first mode to occur at 50 kHz. The discrepancy is most likely due to an un-centered piezoelectric cylinder. Figures 6c and 6d illustrate a plunge mode at 79 kHz and a higher order 2Θ mode at 131 kHz. Predictions for these modes from finite-element models are 80 kHz and 125 kHz, respectively. For Device 3, modal behavior is not observed until frequencies in excess of 70 kHz, due to the additional stiffening effects provided by multiple piezoelectric cylinders beneath the actuator piston.

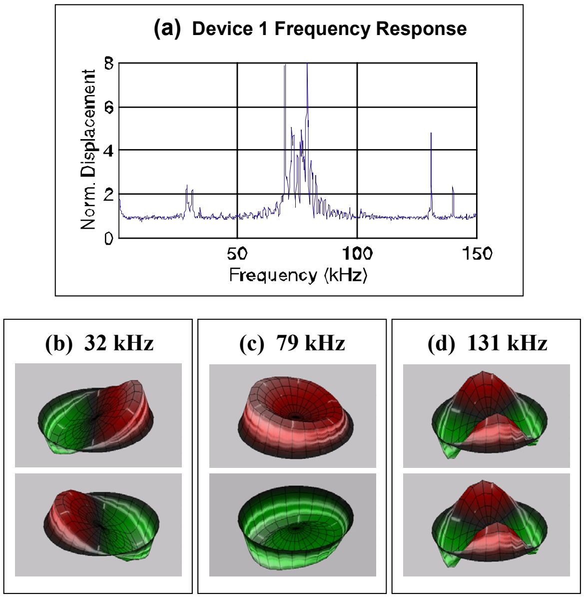


Figure 6: Device 1 modal behavior: (a) selected frequency response between 1kHz and 150kHz, (b) mode shape at 32kHz, (c) mode shape at 79kHz, and (d) mode shape at 131kHz.

CLOSURE

A novel piezoelectric micro-actuator device for use in high frequency fluidic pumping applications has been developed. Small bulk piezoelectric material cylinders were integrated within a microfabricated tethered piston structure using a AuSn eutectic bond to provide high stiffness actuation. A series of micro-actuator devices has been fabricated and experimentally tested. Benefits of incorporating high performance PZN-PT material rather than standard PZT-5H piezoelectric material and the incorporation of multiple piezoelectric cylinders beneath the actuator piston rather than a single centrally-located cylinder have been demonstrated. Development of actuators incorporating multiple piezoelectric cylinders beneath double layer piston structures to further improve actuator performance is underway.

ACKNOWLEDGEMENTS

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