MEMS Micropump for a Micro Gas Analyzer

by

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Abstract

This thesis presents a MEMS micro-vacuum pump designed for use in a portable gas analysis system. It is designed to be pneumatically-driven and as such does not have self-contained actuation (the focus of future work). This research was carried out through a series of modeling, design, fabrication, and experimental testing tasks. Non-linear stress modeling tools characterizing the structural deformations of the micropump pistons and tethers, and fluid-flow modeling tools characterizing the vacuum generation and pumping rates were developed. A systematic design procedure based on these tools enabled the design and prediction of different valve and pump layouts to satisfy the stress limitations, and flow and power consumption requirements set forth by the MIT Micro Gas Analyzer project. The micropumps were fabricated using MEMS fabrication techniques, comprised of silicon and pyrex micromachining and bonding. Fabrication challenges, in particular the deep-reactive ion etching (DRIE) of the drive pistons and membrane structures, were overcome, and a completely computer controlled pneumatic testing platform for the rapid characterization of valve and micropump performance at different actuation pressures and frequencies was developed.

Valve leakage data for various valve designs was collected and compared with models, and a micropump capable of generating 258Torr of vacuum below atmosphere was demonstrated at 0.75Hz operation. The maximum frequency of operation for these devices was experimentally measured to be just above 2Hz, which was consistent with fluid flow models. This thesis presents vacuum generating micropump performance that comparables well with the best published to date, and explores future micropump designs and modeling/testing approaches that could improve overall performance and bring us closer to meeting the specifications set forth by the MGA project. Finally, general guidelines for micropump design and fabrication for any application are also presented.

Thesis Supervisor: Martin A. Schmidt
Title: Professor of Electrical Engineering and Computer Science
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First and foremost, I would like to thank my advisor, Dr. Martin Schmidt, for giving me the opportunity for this research, and mentoring and supporting me throughout the project. Additionally, his ability to always keep me looking one step ahead and making sure I clearly justify all the decisions I made along the path of my PhD work. I would also like to acknowledge my doctoral committee members, Dr. Tayo Akinwande, Dr. Jeffrey Lang for their advice and direction during this work. These interactions have helped me mature, both intellectually and personally. This project could not have been accomplished without the guidance of Dr. Hanqing Li and Dr. Luis Velasquez-Garcia, who taught me everything I know about micro-fabrication in the cleanroom.

I would also like to thank the Schmidt group for their friendship and support over the years - Ole Nielsen, Valerie Leblanc, Kerry Cheung, Hui Zhou, and Eric Lam; it has been a great experience working with them. I want to acknowledge Vicky Diadiuk and the Microsystems Technology Laboratories staff, especially Dennis Ward, Donal Jamieson, Dave Terry, and Eric Lim for their training and invaluable assistance in the cleanroom; and thank Debb Hodges-Pabon, Anne Wasserman and Carolyn Collins for their support and encouragement through out my PhD.

Finally, I would like to thank my Mom, Dad, and Sister - to whom I owe the most. None of this work could have been accomplished without the support.
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Chapter 1
Introduction and Background

1.1 Context

There are many advantages to miniaturizing systems for chemical and biological analysis. Recent interest in this area has led to the creation of several research programs, including a Micro Gas Analyzer (MGA) project at MIT. The goal of this project is to develop a new approach for detecting biological and chemical agents. Currently available portable gas analyzers are expensive, slow, bulky, and consume significant power [156-158]. New approaches that have the potential for instantaneous detection in the field that are low cost, portable, and consume very little power would be extremely useful. The possible advantages and applications of such a device are numerous: it could be deployed in remote locations (space research, terrestrial research), in laboratories and industry for chemical and biological agent analysis or as safety leakage detectors, and of course in the field in the hand or on the uniform of an inspector or intelligent robot/unmanned vehicle that is able to communicate with a base station. The MGA will consist
Chapter 1: Introduction and Background

of several key components that will themselves also be very useful in other areas of research, as well as find applications in industry.

A schematic of the proposed MGA device is shown in Figure 1-1. A typical gas analyzer based on mass spectrometry consists of the following key steps and components that perform the steps as shown:

- ionization of the gas species in a gas stream under reduced pressure (Ionizer)
- reduced pressure to increase the mean free path of the ionized species (Vacuum Pump)
- direction or re-direction of the ionized species towards the region of analysis (Ion Lens)
- separation of the ionized species by mass or charge to mass ratio (Time of Flight Mass Filter or Quadrupole Mass Filter)
- detection of the mass separated ions (Electrometer or Micro-channel Electron Multiplier + Ion Counter)

These components are well developed for macro-sized devices. Most chemical agent detection systems depend on a gas chromatograph or mass spectrometer scheme. Mass spectrometer schemes are usually based on a time-of-flight mass spectrometer or a quadrupole mass spectrometer that provides specific discrimination between various biological and chemical agents. Currently available systems are at the minimum shoebox size. The desired goal for the MGA project is to develop a micro-scale device that could occupy a total volume of 5 cm$^3$, operate in real-time, consume less than 1 J of energy per analysis, have a reduced false alarm rate, increased sensitivity and specificity, and work at higher vacuum pressures reducing the pumping requirements at the micro-scale. If such a system were developed, the possible advantages and applications are numerous.

My PhD work will focus on demonstrating that a MEMS Micro Vacuum Pump to meet the MGA project specifications can be made; these specifications call for the generation of 0.1 sccm flow rate with 1 W power consumption based on piezoelectric-
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Figure 1-1: Schematic of the proposed Micro Gas Analyzer system showing the key components. The aim of this thesis is to develop the micro vacuum pump shaded in blue.

stack actuation (for reference 1 sccm = 1mL/min). Typical large-scale instruments operate at rather low pressures (< uTorr) because of the requirement that ions suffer few collisions during mass analysis.

The mean free path of the ions is determined by the pressure and at any given pressure ions suffer fewer collisions as the device dimensions are reduced. Therefore, the additional benefit of making a “micro” gas analyzer is that analysis can take place at higher pressure levels compared to macro-scale mass spectrometers since the distances particles need to travel in the MGA are much smaller (5 mm mean free path can be achieved at 0.01 Torr vacuum level) [159]. Before taking a closer look at our MEMS micropump work it’s helpful and informative to review previous micropump research.

1.2.1 Reciprocating Displacement Micropumps

One of the first micropumps was developed by Jan Smits in the early 1980s for use in insulin delivery systems [2]. Since then micropumps have been developed for medical applications [3-7], microelectronic device cooling [8-10], and chemical and biological analysis [11-18], among other applications (e.g. space exploration).

As shown in Figure 1-2 the two main types of pumps are

- displacement pumps, in which boundaries moving the fluid create pressure differentials
- dynamic pumps, in which energy is added to the fluid to increase its momentum (centrifugal pumps) or its pressure (electroosmotic and electrohydrodynamic pumps)

The majority of micropumps published are reciprocating displacement pumps with a periodically moving surface (a diaphragm). A complete review and comparison of all the micropumps made is quite difficult. In this review we focus on reciprocating

Figure 1-2: Pump and micropump classification based on [22] and [132].
displacement micropumps since that is the type of pump we need. Other reviews of micropump technologies can be found here [19-21, 132, 148, 161].

In macroscale reciprocating displacement pumps, sealed piston structures are the moving boundaries. In most reciprocating displacement micropumps the moving surface is a deformable plate (the pump diaphragm) with fixed edges that are commonly made of silicon, glass, and plastic. Figure 1-3 shows a typical reciprocating displacement micropump with a pump chamber and diaphragm, an actuator, and two passive check valves at the chamber input and output. When the diaphragm is actuated to increase the pump chamber volume fluid is “sucked” into the pump, and when the diaphragm is actuated to decrease the pump chamber volume fluid is “pushed out” of the pump. Check valves open and close depending on the pressure differential across them and the direction of fluid flow. This piezoelectrically driven micropump design can be traced back to Demer’s patent in 1974 [160], but it was the publications of Van Lintel et al [23-25] and Smits [2] that marked the beginning of extensive research into MEMS micropumps. Van Lintel et al’s micropump was driven by the lateral strain in a piezoelectric disk, reported a maximum flow rate $Q_{\text{max}} = 0.008 \text{sccm}$, and produced a maximum pressure differential $\Delta P_{\text{max}} = 75 \text{ Torr}$ at a frequency $f = 1 \text{ Hz}$ and actuation voltage $V = 125 \text{ V}$.

Reciprocating displacement micropumps with a wide range of designs have been collected from review sources and summarized in Table 1-1. Although many designs only include a single pump chamber, some have multiple pump chambers arranged in series or parallel as mentioned in the table. A wide variety of drivers including piezoelectric, electrostatic, thermopneumatic, pneumatic, and others have been demonstrated. Many different valve designs have also been used including moving flaps and pistons, or fixed-geometry valves that rectify the flow in one direction (e.g. nozzles).
Chapter 1: Introduction and Background

1.2.2 Chamber Designs

In contrast to most reciprocating displacement micropumps, which have a single pump chamber, Smits' micropump had three pump chambers in series driven 120° out of phase with each other by piezoelectric actuators to generate flow. Micropumps with multiple chambers in series and without valves are called peristaltic micropumps. Smits' micropump consisted of a single silicon substrate between two glass layers, had a large package size \( S_p = 1.5 \text{ cm}^3 \), pumped water with \( Q_{\text{max}} = 0.1 \text{ sccm} \), and produced a maximum input to output pressure differential of \( \Delta P_{\text{max}} = 4.5 \text{ Torr} \) at an operating frequency \( f = 15 \text{ Hz} \) and voltage \( V = 100 \text{ Vp-p} \). Shoji et al reported a micropump with two piezoelectrically driven pump chambers in series using check valves [26]. This design, fabricated from glass and silicon, operated more effectively at higher frequencies than similar single-chamber micropumps. Its size was \( S_p = 4.0 \text{ cm}^3 \), \( Q_{\text{max}} = 0.018 \text{ sccm} \), and \( \Delta P_{\text{max}} = 80.25 \text{ Torr} \) operating at \( f = 25 \text{ Hz} \) and \( V = 100 \text{ V} \). Yun et al also demonstrated a series chamber design driven by electrowetting-induced oscillation of...
### Table 1: Micropump research summary

<table>
<thead>
<tr>
<th>Reference</th>
<th>Driver</th>
<th>Valves</th>
<th>Construction</th>
<th>Pump chamber</th>
<th>Diaphragm material</th>
<th>Diaphragm thickness (mm)</th>
<th>Working fluid</th>
<th>p max (Torr)</th>
<th>O max (l/sec)</th>
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<td>Water</td>
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<td>0 2</td>
<td>Water</td>
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<td>11 800</td>
<td>0 3</td>
<td>Water</td>
<td>250</td>
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<td>0 15</td>
<td>Water</td>
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<td>0 12</td>
<td>Water</td>
<td>50</td>
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<td>1600</td>
<td>0 35</td>
<td>Water</td>
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<td>n r</td>
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<td>0 15</td>
<td>Water</td>
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<td>n r</td>
<td>0 07</td>
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1 - Edited from [132]
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<td>Titanium</td>
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Chapter 1: Introduction and Background

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<th>Flap (diaphragm/plate)</th>
<th>Glass/PDMS-glass PDMS, glass</th>
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<th>PDMS</th>
<th>n.a.</th>
<th>0 254</th>
<th>Water</th>
<th>n.a.</th>
<th>1</th>
<th>225</th>
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<td>4 0</td>
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<td>Rubber</td>
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<td>34 5</td>
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<td>Silicone rubber</td>
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<td>0 2</td>
<td>Water</td>
<td>5</td>
<td>50</td>
<td>75</td>
<td>2 1</td>
</tr>
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<td>2 3</td>
<td>25</td>
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a mercury plug [27]. This micropump pumped water with \( Q_{\text{max}} = 0.07 \text{ sccm} \) and \( \Delta P_{\text{max}} = 5.25 \text{ Torr} \) operating at \( f = 25 \text{ Hz} \) and \( V = 2.3 \text{ V} \). While Berg et al [28] went on to demonstrate another phased actuation series chambers design without check valves, Shoji et al reported a parallel chambers design [26] with the aim of reducing the oscillation in the output flow produced by periodic driver actuation. Olsson et al demonstrated another parallel chamber design with drivers attached to both the top and bottom surfaces of the pump chambers [29, 30].

Although some performance improvements can be seen for multi-chamber designs [31] they are more difficult to fabricate and overall larger in size, which are two very important considerations.

### 1.2.3 Fabrication Materials and Techniques

Although these initial micropumps were quite large, Zengerle et al later reported a silicon four layer electrostatically driven micropump with \( S_p = 0.1 \text{ cm}^3 \) that pumped water with \( Q_{\text{max}} = 0.85 \text{ sccm} \) [32]. Stemme and Stemme demonstrated a piezoelectrically driven micropump made of brass that was \( S_p = 2.5 \text{ cm}^3 \) in size [33]. Olsson et al’s pump was also made of brass. Some current commercially available micropumps for implanted drug delivery use glass diaphragms [48, 68]. Other commercially available micropumps produced by thinXXS GmbH of Germany, are made of plastic [34, 35]. These micropump are \( S_p = 4.6 \text{ cm}^3 \) and produce \( Q_{\text{max}} = 2 \text{ sccm} \) and \( \Delta P_{\text{max}} = 262.5 \text{ Torr} \) at \( V = 450 \text{ V} \) and \( f = 20 \text{ Hz} \). Another plastic micropump design
includes the one by Bohm et al with \( Sp = 0.28 \text{ cm}^3 \) [45]. Carrozza et al used stereolithography of an ultraviolet-photocurable polymer to make a micropump with \( Sp = 1.3 \text{ cm}^3 \) that pumps water with \( \Delta P_{\text{max}} = 187.5 \text{ Torr} \) and \( Q_{\text{max}} = 2.7 \text{ sccm} \) at \( V = 300 \text{ V} \) and \( f = 70 \text{ Hz} \) [38]. Printed circuit boards have also been used to make micropumps [58].

Low frequency and/or low-force actuators (such as thermopneumatics) often require less stiff diaphragm materials such as mylar [45] and silicone rubber [59]. High frequency and high force drivers (such as piezoelectrics) require stiff diaphragms made of silicon and glass due to their fast mechanical response times.

1.2.4 Drivers

Piezoelectric drivers can be used in lateral and axial configurations as shown in Figure 1-3. In lateral configurations (such as van Lintel et al’s and Smits’ micropumps), one side of the piezoelectric disk is bonded to the chamber diaphragm and the other is left unconstrained. The application of an axial electric field across the piezoelectric disk causes the diaphragm to bow into the chamber or out of the chamber. Numerical modeling has been used to study the responses of piezobonded diaphragms and optimal designs of lateral strain piezoelectric micropumps [69-72]. In axial configurations (such as Esashi et al’s micropump [50]) both sides of the piezoelectric disk are bonded, one side to a rigid support and the other to the pump diaphragm. The application of an axial electric field causes the pump diaphragm to expand or contract the pump chamber.

Although piezoelectric drivers can typically only provide several microns of actuation, they can be driven at frequencies above 1 kHz. Olsson et al demonstrated a two-chamber design pumping water at \( f = 3 \text{ kHz} \) and \( Q_{\text{max}} = 2.3 \text{ sccm} \) [73, 41]. At MIT, Li et al developed a micropump that used multiple stacks of piezoelectric materials in the axial-configuration to pump silicone oil at \( Q_{\text{max}} = 3 \text{ sccm} \) and \( \Delta P_{\text{max}} = 2250 \text{ Torr} \) operating at \( f = 3.5 \text{ kHz} \) and \( V = 1.2 \text{ kV} \) [51]. This micropump was being developed for microrobotics and shoe strike power conversion, and had a package size \( Sp = 3.2 \text{ cm}^3 \).
To offset the increased fabrication complexity and cost of incorporating bulk piezoelectric actuators into micropumps, Koch et al demonstrated screen-printed PZT thick films that worked as lateral-strain drivers [75-77]. Please refer to [36, 47, 74, 78-82] for more examples of piezoelectrically driven micropumps.

A typical thermopneumatically driven micropump design is shown in Figure 1-4. Heating and cooling of an enclosed fluid usually with an integrated thin-film resistive heater causes it to expand and contract, thereby deflecting the pump diaphragm. The first thermopneumatically driven micro-valves were reported by Zdeblick et al [162, 163]. Van de Pol et al soon followed this work with the first thermopneumatically driven micropump made of three layers of silicon, two layers of glass, and an aluminum thin film heater that was $S_p = 4 \text{ cm}^3$ in size [83, 52]. It used air as the enclosed heating fluid and pumped water with $Q_{\text{max}} = 0.034 \text{ scm}$ and $\Delta P_{\text{max}} = 37.5 \text{ Torr}$ operating at $f = 1 \text{ Hz}$ and $V = 6 \text{ V}$. Thermopneumatically driven micropumps have several advantages including ease of fabrication, low voltages of operation, and large stroke lengths. However, they can typically only operate at relatively low frequencies because of the time it takes to heat and cool the enclosed pumping fluid. Considerable work has been done to maximize their frequency of operation and optimize their design [54-57, 84-86]. Bubble pumps are a subset of thermopneumatically driven micropumps and work by changing the phase of the fluid being pumped (instead of heating a secondary pumping fluid). Some examples include [60, 61].

**Figure 1-4:** Thermopneumatic actuator design. On the right side we see fluid flowing out of the pump chamber as it is actuated.
A typical electrostatically driven micropump design is shown in Figure 1-5. A voltage applied across the electrodes either attracts or repels them from each other causing the pump chamber to contract or expand. Zengerle et al demonstrated a highly compact design ($S_p = 0.1 \text{ cm}^3$) [32, 87]; it was completely micromachined and pumped water at high frequency – $Q_{\text{max}} = 0.850 \text{ sccm}$ and $A P_{\text{max}} = 217.5 \text{ Torr}$ operating at $V = 200 \text{ V}$ and $f = 800 \text{ Hz}$. Richter et al conducted a study comparing two similarly designed electrostatically and piezoelectrically driven micropumps [44]. The electrostatically driven micropump pumped water with $Q_{\text{max}} = 0.26 \text{ sccm}$ operating at $f = 400 \text{ Hz}$, and the piezoelectrically driven micropump pumped water with $Q_{\text{max}} = 0.7 \text{ sccm}$ operating at $f = 220 \text{ Hz}$. An impressive three chamber series design was demonstrated by Cabuz et al [88, 164]. This pump had a $Q_{\text{max}} = 30 \text{sccm}$, a package size $S_p = 0.225 \text{cm}^3$, and consumed about 8mW. Other examples of electrostatically driven micropumps include [89, 90-93].

A typical pneumatically driven reciprocating displacement micropump design is shown in Figure 1-6. External high and low pressure gases controlled by a high-speed switch actuate the pump chamber. Rapp et al used LIGA techniques to demonstrate this actuation scheme [62]. The Grosjean et al micropump discussed earlier performed better with pneumatic actuation ($Q_{\text{max}} = 0.1 \text{ sccm}$) than with thermopneumatic actuation ($Q_{\text{max}} = 0.0042$) [56]. As with thermopneumatic drivers, less stiff diaphragm materials are typically used in pneumatically driven micropumps. Other examples of pneumatically driven micropumps include [17, 64, 65].
Several other driving techniques have also been demonstrated: solenoid drivers and high pressure low pressure selector. Figure 1-6: Pneumatic actuator design. On the right side we see fluid flowing out of the pump chamber as it is actuated.

electromagnetically driven micropump made of thermoplastic molding [67], magnetic drivers and diaphragms [96], magnetoelastic drivers [100], shape-memory alloy drivers [66, 97], bimetallic drivers [98, 99], and a micropump driven by electrowetting [27].

1.2.5 Valve Designs

Valves at the chamber inlet and outlet are critical to performance. A few microvalve reviews include [101, 102, 133, 148, 149]. Most micropumps use passive (non-actuated) valve structures. Van Lintel et al’s micropump and several others used a flexible circular diaphragm with a central opening surrounded by a stiffening “ring mesa” [23, 34, 45, 51, 52]. Other micropumps have used check valves with a tethered-plate structure (like that shown in Figure 1-3) [26, 50, 66]. Cantilever based flap valves are also widely used [32, 44, 43]. Several papers have studied the mechanical response of passive flap valves [93, 95, 104-106], and observed that at operating frequencies greater than the mechanical resonance frequency of these valves (typically several hundred Hz), flow can reverse in direction [32, 103]. Ball-type check valves have also been demonstrated [38, 107].

Active valves that are opened/closed by an actuating force operated by an external control unit are more complex to fabricate but offer high frequency (kHz) performance.
Several active valve designs have been demonstrated including piezoelectric [50, 117], thermopneumatic [113-116], electrostatic [109-112], bimetallic [108], and others [102, 118-124].

Fixed geometry valves or valveless pumps refer to designs without moving parts that rectify flow in a particular direction based on geometry and fluid dynamic effects [29, 33, 37, 39, 57, 75-77, 125, 126-130]. They can be useful when the fluid being pumped contains particles that could get damaged or clogged by flow cutting valves.

1.3 Vacuum Micropumps

As we’ve seen there has been a great deal of research done in the area of micro pumping devices. However, only a handful were designed for vacuum generation. These include a thermal molecular pump (Knudson pump) by McNamara et al capable of pumping down 410Torr below atmosphere using 80mW at $1 \times 10^{-6}$ sccm. This pump required very narrow channels between the hot and cold chambers permitting only molecular flows to produce the required pressure drops - hence the unattractively low flow rates. Doms et al demonstrated a vapor-jet vacuum pump capable of pumping down 371Torr below atmosphere at an impressive 50sccm [166]; operating similarly to a macroscopic diffusion pump, a pumping fluid is heated and mixes at high speed (after passing through nozzles) with the incoming gas to be pumped, which gets accelerated to the output and experiences a pressure drop. The drawbacks of this design are the requirements for a heating element and the interaction of a high temperature pumping fluid with the incoming gas. Finally, Kamper et al demonstrated a piezoelectric displacement micropump capable of pumping down 263Torr below atmosphere at 3.5sccm (70Hz operation) [34]. Of the three vacuum generating micropumps this design is most attractive because of its simplicity and our experience developing similar piezoelectrically actuated micropumps for previous MIT projects, such as the micro energy harvester project.
1.4 Thesis Outline

To meet our goals for speed, power, and vacuum generation the most appropriate choice is an active valve reciprocating displacement micropump. Chapter 2 of this thesis will look at different design options. Computer models will be used to layout the final device and methods for testing the micropumps will be explored. Chapter 3 will review the results and progress made over the first four iterations of design, fabrication, and testing. In Chapter 4 lessons learned from these rounds will be applied to a more advanced model for the micropump and a new design yielding working micropumps that meet our modeling expectations. Finally, Chapter 5 explores future micropump designs and modeling/testing approaches that will bring us closer to meeting the specifications set out by the MGA project, and guidelines for micropump design and fabrication that hopefully can be used to produce a micropump for any application.
Chapter 2

Micropump Design and Testing

2.1 Introduction

Having reviewed the micropump research space, in this chapter we consider design options and select a final layout for our micropump to meet the goals set out by the MGA project, while leveraging our prior experiences and available fabrication facilities. Detailed computer models are built and used to properly dimension all aspects of the micropump layout to withstand the maximum stresses it will face during operation, while keeping its dead-to-pump volume ratio within the required range to generate low enough vacuum levels (covered in detail in section 2.2).

Finally, to be able to rapidly characterize the performance of our design and all future micropump designs, we consider several possible testing schemes and select the one that gives us the greatest flexibility. We then design, build, and characterize our testing platform in advance of building our micropumps, whose fabrication and characterization are covered in detail in the upcoming chapters.
2.2 Design Options

As we saw in Chapter 1 there has been a great deal of research done in the area of micro pumping devices. To meet our goals for speed, power, and vacuum generation the appropriate choice was to use an active valve reciprocating displacement micropump design. The majority of micro-valves are classified as either active or passive [135-149]. Passive valves (also called check valves) are not actuated by an external control unit; they are opened by pressure differentials and the direction of through-flow, and are mostly mechanical flap structures or flexible diaphragms [132, 150]. They are typically more susceptible to back flow problems and considered to be low frequency (i.e. < 500 Hz) [135].

On the other hand, active valves are actuated by an external operator and therefore consume power, but through-flow is completely controllable and almost independent of flow direction and pressure differential. Active valves also have a relatively quicker response time permitting higher frequency operation (for example, up to several kHz using piezoelectric drivers). To operate at the high frequency and low power consumption we require, piezoelectric stack drivers in particular are a great choice. They also provide the large forces necessary to open and close the pump pistons under vacuum. Beyond the pump type another important consideration was which designs can we fabricate at MIT’s Microsystems Technology Laboratories (MTL).

These criteria inspired a design conceptually similar the high flow rate piezoelectrically driven MEMS micropump reported by Li et al for pumping silicon oil [51], shown in Figure 2-1. Li’s device was fabricated at MIT with three small bulk cylindrical piezoelectric material elements that were integrated with micro-fabricated silicon-on-insulator (SOI) and glass micromachined substrates using eutectic bonding and anodic bonding processes. The hydraulic amplification chamber converted small displacements produced by bulk piezoelectric cylinders into much larger piston displacements.
Chapter 2: Micropump Design & Testing

Since we were looking to pump as much volume as possible as fast as possible, large pump chamber piston displacements were preferred. An alternative to using the difficult to fabricate hydraulic amplification chambers were piezo-stacks. For voltages in the 100 volt range we could achieve more than 6um of travel, not possible with bulk piezoelectric elements (which would require around 1000 volts). The piezo-stacks we considered for our micropump design are shown in Figure 2-2.

Given the availability of these stacks and the high complexity of our initial design we came up with a second more simple design shown in Figure 2-3. A further simplification step led to our final micropump design shown in Figure 2-4. It includes a piezoelectrically driven pump chamber and a pair of piezoelectrically driven active-valves, with single tether structures and input and output ports located on the actuation side (very useful as we will see later when discussing testing techniques).

For a single stage pump the minimum achievable vacuum pressure is given by $P_{\text{vac}} = (V_d/V_p)P_{\text{out}}$ where $V_p$ is the pump volume (with the chamber piston pulled all the way down) and $V_d$ is the dead volume (with the chamber piston pushed all the way up). The dead volume is a subset of the pump volume and includes the channels from the input/output valves to the pump chamber, and about half of the tether volume that is not evacuated during actuation as shown in Figure 2-5.
Chapter 2: Micropump Design & Testing

Table 2.1: Technical Data / Ordering Numbers

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<tr>
<th>Ordering Number</th>
<th>Dimensions A x B x L [mm]</th>
<th>Nominal Displacement [µm @ 100 V (±10%)]</th>
<th>Max. Displacement [µm @ 120 V (±10%)]</th>
<th>Blocking Force [N @ 120 V]</th>
<th>Stiffness [N/µm]</th>
<th>Electrical Capacitance [µF] (±20%)</th>
<th>Resonant Frequency [kHz]</th>
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<td>P-885.10</td>
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<td>9</td>
<td>900</td>
<td>115</td>
<td>0.6</td>
<td>135</td>
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</table>

Figure 2.2: Piezo-stack elements we considered for our micropump design give > 6 um of travel for 100 volts actuation [167]. (To be conservative we assumed 6um at 100V)

To arrive at the minimum pressure equation we begin by assuming that at pressure $P_{out}$ the pump volume $V_p$ contained $n_p$ moles of gas. As the pump chamber piston is actuated for one cycle to expel this gas it isn’t able to pump out the entire volume; the portion that remains we call the dead volume $V_d$ ($V_d$ is a subset of $V_p$). From the ideal gas law we know that $P_{out}V_p = n_pRT$ and $n_p = n_d + n_x$, where $n_d$ are the moles of gas in the dead volume and $n_x$ are the moles of gas that are expelled during pumping. After one cycle of pumping we have $P_{vac}V_p = n_dRT$. Since $n_d$ at pressure $P_{out}$ would occupy volume $V_d$, we can also say that $n_d = P_{out}V_d/RT$. Substituting this into the previous equation gives us $P_{vac}V_p = (P_{out}V_d/RT)RT = P_{out}V_d$, which can be rewritten as $P_{vac} = (V_d/V_p)P_{out}$. A two-stage micropump can be made by connecting two single-stage pumps in series, and would reduce the overall pressure and power consumed – the minimum achievable vacuum pressure in this case would be $P_{vac} = (V_d/V_p)^2P_{out}$.

Figure 2.3: Simplified micropump design.
Chapter 2: Micropump Design & Testing

2.3 Modeling and Design

With a schematic design for our micropump in hand the next step was to determine appropriate dimensions for all the components in Figure 2-4 using physical models, which could then be used to layout a detailed design for fabrication. The chamber height and input/output valve stroke was fixed to 6um from the piezo-stacks we had available (assumed 6 um although the specifications indicated larger possible displacements). Since the valve lip region and pump chamber were the sources of highest fluidic resistance (had the smallest effective cross-sectional heights), the largest fluidic resistances in the micropump were fixed in one dimension. Resistances depend on the cross-sectional surface area and length of the region the fluid travels through as we will see in Chapter 4, when the fluidic resistance model is covered in detail, but for now it is useful to note that fluidic resistances are proportional to $L/h^3$ where $L$ is the length of the region and $h$ is the smallest cross-sectional dimension.

We aimed to achieve a few Torrs of vacuum ($< 5$ Torrs) with a two stage cascade of our micropumps. This meant that the pump to dead volume ratio ($V_d/V_p$) needed to be less than $(760/5)^{1/2} = 8\%$. In the ideal case, the two regions contributing to dead volume are the channels between the input/output valves and the pump chamber, and roughly half of the tether volume during actuation as shown by the pink regions in Figure 2-5. The only ways of minimizing the channel volumes are to make them as narrow as possible.
and as short as possible. To minimize their length (L) we decided to have the valve openings at the edges of the input and output pistons (unlike Figure 2-5 where they are located at the piston centers). Making them narrow (h) beyond a certain point would bring their fluidic resistances into play during operation, which isn’t ideal. That point also depends on the tether dead volume as we will see a bit later. The tether dead volume depends on the tether widths and the diameter of the pump chamber piston, and we began by looking for appropriate tether widths and thickness.

![Figure 2-5: Dead volume in our micropump design represented by the pink regions.](image)

The tether region is a thin annular plate with a rigid central piston as shown in Figure 2-6, and the equation for its nonlinear bending under uniform external forces and pressures is well known (in cylindrical coordinates):

\[
\frac{d^3w}{dr^3} + \frac{1}{r} \frac{d^2w}{dr^2} - \frac{1}{r^2} \frac{dw}{dr} - \frac{N_r}{D} \frac{dw}{dr} = \frac{Q(r, Pch, Fte)}{D(E, \nu)}, \quad w(r = a) = 0, \quad \frac{dw}{dr} (r = a) = 0, \quad \frac{dw}{dr} (r = b) = 0
\]

where \( w(r) \) is the vertical deflection of the tether at radial position \( r \), with its outer radius clamped at \( r = a \), and inner radius guided at \( r = b \) by any applied forces or pressures (e.g. piezo actuators). \( N_r \) is the in-plane tension load per unit circumference, \( Q(r) \) is the shear force per unit length and is given by

\[
Q = \frac{Fte \cdot \frac{Pch(r^2 - b^2)}{2\pi r}}{2r}
\]

where \( Pch \) is the uniform pressure loading the tether region (pressure above minus pressure below) and \( Fte \) is the concentrated force guiding the tether at its inner radius \( r = b \). \( D \) is the flexural rigidity of the plate given by

\[
D = \frac{Et_o^3}{12(1-\nu^2)}
\]
where $t_{te}$ is the tether's thickness, $E$ is silicon's Young's modulus (165 GPa), and $v$ is silicon's Poisson ratio (0.22) [to be consistent with reference 134]. David Roberts covers the numerical solution to this problem in detail in Chapter 3 of his PhD thesis, which studies the design and fabrication of microvalves [134]. We modified his Matlab code to solve our design problem and that code is included in Appendix A.

![Diagram of tether and piston](image)

**Figure 2-6**: Variables included in our nonlinear model for the tether region.

The tether region was being made of the device layer of an SOI wafer with the buried oxide removed. A wide variety of device layer thicknesses are readily available from vendors. Thick device layers are too stiff to use as tethers, but tethers that are very thin can also be too fragile and compliant. We decided to focus on the 8 – 12 um thick tether range from prior project experience (such as the MIT Micro-Harvester project) – they were found to be thin enough to work as tethers, and not too fragile to handle during fabrication.

For the analysis that follows the in-plane tension load ($N_t$) is assumed to be zero (ideally). In reality it may be non zero depending on the wafer, its processing, and actuation mechanism. Figure 2-7 shows a plot of the maximum tensile stress experienced by tethers of different thicknesses – for a guided translation of 6 um at their inner edge, while the outer edge is clamped, and there is no pressure differential across the tethers (pressure above minus pressure below = 0). The stress plots are normalized to the critical value of 1 GPa identified experimentally by [134] and [151] as the average breaking stress of thin silicon membranes made from SOI device layers (the breaking stress was found to be approximately in the 0.5 - 1.5 GPa range depending on the quality of the SOI wafers.)
Figure 2-7: Left: plot of the maximum normalized stress (relative to 1GPa) experienced by tethers of different thicknesses (blue = 8 um, red = 10 um, black = 12 um) — for a guided translation of 6 um at their inner edge, while the outer edge is clamped, and zero pressure differential across the tethers. Right: plot of the shape of two 10 um thick tethers of widths 300 um and 600 um as they are translated by 6 um at their inner edge (and zero pressure differential).

and the membrane fabricated). The blue curve corresponds to an 8 um thick tether, the red curve corresponds to a 10 um tether, and the black curve corresponds to a 12 um thick tether. The plot on the right shows the shape of two 10 um thick tethers of widths 300 um and 600 um as they are translated by 6 um at their inner edge (with zero pressure differential). As we expect, the thinner tether experiences the lowest overall stress in this case. During pumping action the pressure differential will not be zero as vacuum is created in the pump chamber. Figure 2-8 helps us understand the stresses under non-zero pressure differentials ranging from 0 — 1 Atm absolute for the three tether thicknesses under consideration.

Figure 2-8: Maximum normalized stresses experienced by the different thickness tethers under non-zero pressure differentials ranging from 0 — 1 Atm absolute. Top curve in each case = 1 Atm and bottom curve = 0 Atm.
During pumping action we don’t expect the pressure differential across the tethers to ever be greater than 1Atm since this micropump will not be able to pump down that low and we don’t expect to use an actuation scheme that would apply any greater pressures.

The tether design goal was to use the narrowest width tethers to reduce dead-volume, with the lowest stresses to prevent failure, and the lowest compliance to minimize the impact on the pump chamber capacitance (or effective chamber volume). At zero pressure differential we aimed for the normalized stress during 6um of translation to be about 0.15 of the critical stress (1GPa). For 12um thick tethers this corresponds to a width of ~ 535um, for 10um thick tethers this corresponds to a width of ~495um, and for 8um thick tethers this corresponds to a width of ~450um. Going from 0 – 1Atm pressure differential the 12um thick tether normalized stress increased from 0.15 to 0.24. For the 10um thick tether it increased from 0.15 to 0.265, and for the 8um tether it increased from 0.1 to 0.3.

Figure 2-9 shows the modeled shape of tethers of different widths (300um to 600um in 30um steps) at 0.5Atm pressure differential and zero translation at their inner edge (i.e. piston not actuated). As expected the stiffer 12um tethers deflect the least. Comparing a 480um wide tether in each case (bold curve) shows a deflection of 0.29um by the 12um thick tether, a 0.48um deflection by the 10um thick tether, and a 0.9um deflection by the 8um thick tether. There isn’t a single optimal choice because other real-world variables...
(such as in plane stress and fabrication quality) haven’t been accounted for, but we felt that the 10um thick tethers provided a good balance of stress, compliance, and dead-volume. In particular, 480um wide by 10um thick tethers experienced relatively low stresses and low dead-volumes throughout the 0 – 1Atm pressure differential range (under 6um of translation), and so we chose these tether dimensions as a starting point for our fabrication.

We now had two micropump parameters defined - the valve/chamber height of 6um, and tethers that were 10um thick by 480um wide. Three more parameters remained – the valve chamber height around the valve lip, the channel cross-section, and the pump chamber radius as shown in Figure 2-10. To minimize the fluidic resistance of the valve chamber we decided to make it 5 times taller than the lip height – 30um total (since as we saw earlier resistance $\sim 1/h^3$). For a structurally robust valve lip we then decided to keep the lip height to width ratio close to 1:1, which set the lip width to be 30um as well.

Finally, to help us select the appropriate channel cross-section and pump chamber radius we plotted the dead-volume to pump volume ratio ($V_d/V_p$) as a function of these two variables, as shown in Figure 2-12. In each plot the y-axis corresponds to the width or height of the channel (square cross-section), and the x-axis corresponds to the pump chamber radius. Note that the pump chamber radius includes the 480um tether region and the rest is the pump chamber piston. Given the width of the tether region and a nominal SOI wafer thickness of 450um we noted that the channel lengths would be 2.2mm from CAD layouts, as shown in Figure 2-11.

![Figure 2-10: Closer view of the micropump schematic highlighting the valve chamber, valve lip, channel between the valve and the pump chamber, and pump chamber radius – which includes the tether region and the pump chamber piston.](image-url)
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Figure 2-11: Tentative CAD layout of our micropump showing the input/output valves, input/output ports, and the pump chamber. The blue channels connecting the input/output valves to the pump chamber are located at input/output piston edges and over the tether region of the pump chamber to minimize their length.

The plots in Figure 2-12 also assume channel widths/heights greater than 30um (which was the lip width) to minimize their resistance. The plot on the left is the dead-volume to pump volume ratio ($V_d/V_p$) with the blue region indicating 6% or less. We see that for a 30um wide channel the minimum pump chamber radius is about 7mm. Based on this plot we decided to use a 10mm radius pump chamber as this would allow for larger channel widths. To be conservative we opted for 90um wide by 90um tall channels (effective curricular cross-sectional radius of 50um). The plot on the right is the channel volume to tether volume ratio with the blue indicating 12% or less. We see that for our selected channel cross-section and pump chamber radius, the channels are only a small fraction of the micropump dead-volume – the greatest contributor is the pump chamber tether region.
All the micropump parameters were now defined:

- 5 layer design (L1 – pyrex, L2 – double sided polished silicon, L3 – silicon on insulator)
- Chamber height = 6um – set by piezo stacks (for 100V actuation)
- Chamber radius = 10mm (i.e. 9.52mm pump chamber piston radius and 480um wide tether), Valve opening = 90x90um (effective curricular cross-sectional radius of 50um), and Channel length = 2.2mm – for a reasonably small dead to pump volume ratio of 5.58% (i.e. $P_{min} = 0.0558 \times 760 = 42.39$Torr for a single stage and $P_{min} = (0.0558)^2 \times 760 = 2.36$Torr for a cascade of two stages)
- Tether width = 480μm and Tether thickness = 10μm – for reasonable stress levels without too much compliance under pressure or excessive dead volume

![Graph](image)

**Figure 2-12**: Left: plot of the dead-volume to pump volume ratio (Vd/Vp) with the blue region indicating 6% or less. Right: plot comparing the channel region volume to the tether region volume with the blue indicating 12% or less.

Finally, we tried to estimate the theoretical power consumption of our micropump design. The maximum mechanical work done by the pump chamber per cycle on the gas can in the simplest sense be approximated using the PV rectangle shown in Figure 2-13.
Chapter 2: Micropump Design & Testing

Figure 2-13: Approximation of the maximum mechanical work being done by the pump chamber per cycle on the gas.

Under ideal conditions:

- \( P_{\text{max}} = 760 \text{ Torr} = 101.33 \text{ kPa} \), \( P_{\text{min}} = \frac{V_d}{V_p}P_{\text{max}} = (0.0558)P_{\text{max}} \), where 
  \( V_p = \text{pump chamber volume} + \text{channel volume} = 6\mu m \times \pi (10\text{mm})^2 + 2 \times (90\mu m)^2 (2.2\text{mm}) \)
- \( W = \Delta P \times \Delta V = P_{\text{max}}(1 - 0.0558) \times V_p(1 - 0.0558) = 0.169 \text{ mJ} \) and therefore 
  \( P_{\text{mech}} = 0.162 \times 10^{-3} \times f \), where \( f \) is the frequency of operation

The second major component of power consumption is the power converted to heat in each piezo \( \Rightarrow P_{\text{heat}} \approx (\pi/4)\tan(\delta) \times f \times C \times V_{pp}^2 \), where \( \tan(\delta) \) is the dielectric loss factor \( (= 20 \times 10^{-3} \) from the PI specification sheets), \( C \) is the piezo capacitance (from the PI specification sheets), and \( V_{pp} \) is the applied peak to peak voltage. At 100 Volts (required to get 6\mu m displacement), for each valve and chamber piezo that we selected in Figure 2-2:

- \( P_{\text{heat-valve}} = 2.0420 \times 10^{-5} \times f \)
- \( P_{\text{heat-chamber}} = 9.4248 \times 10^{-5} \times f \)

Therefore the total power consumption estimate can be written as:

\[ P = P_{\text{mech}} + 2P_{\text{heat-valve}} + P_{\text{heat-chamber}} \]

\[ = 29.7 \text{mW at 100Hz operation and 297mW at 1kHz operation} \]

of which 45% is the total power consumed by the three piezo-stacks. This power estimate does not include power consumed by any electronics driving or monitoring the micropump’s operation.
2.4 Testing Method

Our micropump design consists of 5 layers (i.e. 5 wafers) but layers 1-3 define the ultimate performance since they contain the channels, chambers, pistons, and tethers connecting the pistons to the side walls. The aim of this thesis is to focus on the design and fabrication of these layers for testing. Layer 4 contains the piezos to drive the pistons and layer 5 provides structural support, both of which can be integrated to make the final device once a suitable design for layers 1-3 is found.

A testing facility for our devices did not exist and so we decided to build one in house. We considered three actuation schemes for driving the pistons during testing: piezo-electric, voice-coil, and pneumatic. Although piezo-stacks would be used in the final design, using them in the test platform would be quite involved. First, vertical alignment would be a serious issue – since the piezo-stacks can only provide a few microns of displacement, their surface roughness and vertical positioning would need to be accurate to the sub-micron level for complete closure of the valves and pump chamber during testing. Second, there would be no simple way to stick and then un-stick the piezos to the micropump pistons, which is necessary for low pressure operation where the pistons are pulled up by vacuum and need to be pulled back down; it would be too expensive and complicated to incorporate a new set of piezos each time a new pump die is tested. For voice-coils actuators vertical alignment is not an issue since they can provide millimeters of travel, but once again there is no simple way to stick/un-stick the voice-coils to the micropump pistons. Small voice-coils are also incapable of providing the forces necessary to actuate the pistons under large pressure differentials (e.g. 1 atmosphere). Pneumatic actuation, where the pump pistons are actuated by high and low pressure gases, appeared to provide the greatest flexibility. No alignment was necessary, uniform pressure of any magnitude could be applied, and the same testing platform could be used by all devices for rapid testing.
As we will see in the following two chapters, 6 rounds of micropump fabrication with improvements at each stage led to the final working pumps we have today. The testing setup went through just as many iterations of design, build, and characterization, but here we focus on describing the most recent and best working test setup for the benefit of the reader. A simplified schematic of our test setup is shown in Figure 2-14.

There are three main parts to the test setup: the fluidic connections, electronics and circuitry, and computer software. We begin by looking at the fluidic connections. The micropump dies to be tested are clamped using optical clamps onto the testing platform as shown in Figure 2-15b. Each pump die has 5 access ports: one input port, one output port (interchangeable), and three actuation ports for the input/output valves and the pump chamber (Figure 2-11). O-rings help seal the pump die ports against the testing platform (as well as support the pump die) as shown in Figure 2-15a.

![Figure 2-14: Simplified schematic of the pneumatic test setup used to characterize the layer 1-3 micropump devices, showing all key components and connections. (Photos of all components shown on the following pages)
Figure 2-15: a) Micropump testing platform with o-rings at the fluidic ports and 4 extra o-rings to support the pump die. b) Micropump clamped down using optical clamps and ready for testing. c) Parker pressure selector switch. d) Valve testing platform with a valve die clamped in and ready for testing.

Figure 2-16: High pressure channel components – a) Airgas sub-micron filter b) pressure gauge c) bleeder valve
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Figure 2-17: Low pressure channel components – a) Vacuum access valve b) bleeder valve. c) 2 Parker pressure sensors are used to make any high pressure and low pressure measurements, or to monitor actuation pressures.

Figure 2-18: a) Basic stamp micro-controller board with BJT and switch circuitry needed to drive the b) Omron relays. c) Three relay circuits power the three pressure selector switches attached the micropump testing setup, that require a d) 24volt supply to switch.

Figure 2-19: a) Ni-Daq breakout board used to relay any electrical signals to the computer for storage and analysis. b) Sierra, MKS, and Honeywell mass flow meters we used during testing – neither could register very small flows but were very useful for certain tests (for example the “pressure differential versus flow rate” test described in Chapter 3.)
Figure 2-20: LabView program we made to monitor the mass flow meter readings (top chart) and pressure sensor readings (bottom chart) while a pump die is being tested. Each pressure sensor (Figure 2-16c) and mass flow meter (Figure 2-18b) outputs a 0-5 volt analog signal that is connected to the Ni-Daq breakout board (Figure 2-18a) and transferred to computer. Our LabView program helps us capture, store, and analyze this data.

Access to the input and output ports is provided at the bottom of the testing platform shown in Figure 2-15a, and each of the three actuation channels leads to one edge of the platform where a pressure selector switch is attached. The testing platform was designed using CAD tools and machined at the MIT machine shop – a detailed dimensional drawing is provided in Appendix B along with a list of all test setup components. The pressure selector switches shown in Figure 2-15c are Parker-VA01PEP341UEF, and allow for the selection between vacuum and a high pressure channel. The switching time is approximately 5ms (from specifications) and requires 24 Volts to be supplied to the switching side. Both the high and low pressure sources are the MIT lab channels. The high pressure N\textsubscript{2} source is filtered using an Airgas-SS submicron filter shown in Figure 2-16a and controlled using a pressure gauge shown in Figure 2-16b. The vacuum source does not have a vacuum gauge but a simple access valve shown in Figure 2-17a. A vacuum bleeder valve shown Figure 2-17b in combination with a Parker-MPS-V3N
pressure sensor shown in Figure 2-17c are used to monitor the vacuum source (another Parker-MPS-L3N pressure sensor is used to measure positive pressures above an atmosphere). Two high pressure channels are used from the lab wall (both with their own filter, pressure gauge, and safety bleeder valves incase of pressure overload). One channel is directed to the pressure switches and the other is available to be connected to the input port if testing requires air to be flown through the device. Finally, the high and low pressure channels are also split off and connected to a pressure sensor. We monitor several pressures: the high and low pressures provided to the valve switches, the high pressure provided to the input port (when that is required), and vacuum generated at the output port during pumping. Depending on the type of test being performed the input or output port could be connected to one of our mass flow meters shown in Figure 2-19b. In all cases we opted to use thick walled plastic tubing to avoid any tube deformation (which could change measurements or become loose).

Figure 2-18 shows the Basic-Stamp micro-controller and circuitry used to drive the micropump during testing. The micro-controller (Figure 2-18a) can be programmed to output any on/off pattern to the three pressure switches (Figure 2-15c). The programs are written in Basic and then transferred to the micro-controller using a serial cable. The circuitry on the white circuit board attached to the micro-controller converts these small on/off signals to 5volt square waves using simple series BJT-resistor networks. The circuitry also includes two switches that allow us to manipulate the micro-controller programming – for example select the frequency of operation or stop the test. Samples of the Basic code used for testing are provided in Appendix C.

As mentioned earlier the pressure selector switches require 24volts to select either channel. Since the 5volts provided by the micro-controller circuit isn’t enough, the three 5volt channels are connected to three relay switches shown in Figure 2-18c. These relays (zoom-in shown in Figure 2-18b) control the pressure selector switches and, in response to the 0 - 5Volt square wave input they receive, send out a 0 - 24Volt signal to the pressure switches (powered by the lab supply shown in Figure 2-18d). Finally, any
electrical signals to be captured are read by the Ni-Daq breakout board shown in Figure 2-19a and transferred to the computer. These signals include pressure sensor and mass flow meter readings, or any other voltages we need to monitor. The Parker pressure sensors we used are shown in Figure 2-17c. The slower Sierra (0-4sccm) and MKS (0-2sccm) mass flow meters, and faster Honeywell (0-1slpm) mass flow meter we used are shown in Figure 2-19b. Each of these sensors has an analog output between 0-5Volts that is wired to the Ni-Daq breakout board. The data-acquisition card in the computer is then read using LabView software that we wrote for this application. Figure 2-20 shows a screen capture of one the programs we wrote. The top chart is monitoring a mass flow meter and the bottom chart is monitoring a pressure sensor. (To conduct a pressure differential versus mass flow experiment for example, the input pressure as a function of the output mass flow reading is needed). Our LabView program allows us to control the rate of data capture and saves all the data to excel spreadsheets that we can then read, plot and analyze using MatLab or Excel. The LabView programs we wrote for micropump testing are included in Appendix C.

Figure 2-15d shows the test platform used to test single valve dies. Since this platform requires all the same fluidic and electrical wiring, only the micropumps or the valves can be tested at any one time. In the chapters that follow the devices we fabricated and the tests we performed using our computer controlled pneumatic test platform are described in detail.
Chapter 3

Process Development

3.1 Introduction

With a detailed micropump layout in hand and testing facility ready to go, in this chapter we develop a process flow for the fabrication of our micropumps and review the first four rounds of build and testing. The lessons learned at each round lead to incremental improvements in the fabrication process flow and testing techniques that are applied to the next. By the fourth round these improvements finally yield devices with fully functioning parts almost capable of generating vacuum. In the chapter that follows we continue to improve the process flow and with some major advances produce our very first vacuum generating micropumps.

3.2 Process Flow

With the stress modeling complete and a set of MGA requirements in hand, we had calculated (in Chapter 2) the exact specifications for the micropump to be fabricated
shown in Figure 3-1:

- 5 layer design (L1 – pyrex, L2 – double sided polished silicon, L3 – silicon on insulator)
- Chamber height = 6um – set by piezo stacks (for 100V actuation)
- Chamber radius = 10mm (i.e. 9.52mm pump chamber piston radius and 480um wide tether), Valve opening = 90×90um (effective curricular cross-sectional radius of 50um), and Channel length = 2.2mm – for a reasonably small dead to pump volume ratio of 5.58% (i.e. \( P_{\text{min}} = 0.0558 \times 760 = 42.39\text{Torr} \) for a single stage and \( P_{\text{min}} = (0.0558)^2 \times 760 = 2.36\text{Torr} \) for a cascade of two stages)
- Tether width = 480\( \mu \)m and Tether thickness = 10\( \mu \)m – for reasonable stress levels without too much compliance under pressure or excessive dead volume

\[ \text{Figure 3-1: Below: schematic of our final MEMS micropump. Layers 1 and 4 are glass, Layer 2 forming the chambers and channels is double-side polished (DSP) silicon, Layer 3 forming the pistons and tethers is silicon on insulator, and Layer 5 is single-polished (SOI) silicon. Above: for this project we focus on fabricating and studying Layers 2-3. These main two layers and the half that will be used to review the process flow are shown, including some of the main etch steps.} \]
To review the process flow for the fabrication of our micropumps we focus on layers 2 and 3 since they contain the channels, chambers, pistons, and tethers connecting the pistons to the side walls, and involve the most work. We use schematics showing only one half of a micropump (top of Figure 3-1) since the device is symmetric. We start by reviewing the process flow for layer 2, the DSP layer. The main steps for this part of the fabrication are shown in Figure 3-2. A detailed version of the process flow with machines and recipes used is included in Appendix D. All etches are conducted using the deep reactive-ion etchers at MIT’s Microsystems Technology Laboratories (machine STS3 with the versatile “JBetch” recipe unless otherwise indicated).

![Figure 3-2: Review of the main steps in the process flow for layer 2, the DSP layer.](image)
Chapter 3: Process Development

After 0.3μm of thermal oxide is grown on the DSP and SOI wafers and alignment marks are etched on both sides (only one side show in Figure 3-2), the mask for the shallow 6μm chamber etch is applied and developed (B), and the exposed thermal oxide removed using BOE. Once the etch is complete (C) 4μm of oxide is deposited on both sides of the wafer (D) using a plasma-enhanced chemical vapor deposition system. The thick oxide helps create a nested mask, and the cross channel mask is applied on the top while the valve lip mask is applied at the bottom (E) – this mask also includes additional support posts for the piston that are at the same height as the valve lip.

Once the oxide is etched away using a dry oxide etching system, the through channel mask is applied on top (F). The through channels are then etched leaving behind approximately 30μm + cross channel thickness (90μm) from breaking through the bottom (G). The resist is removed and the cross channel is etched leaving just under 30μm to the bottom surface (H). Finally the 30μm valve lip and piston support post etch is completed from the bottom opening up the channel from the valve to the pump chamber (I). If we had etched through the wafer in step (H) the valve lips would have been damaged.

In parallel some work is done on the SOI wafer to prepare it for bonding with the DSP wafer as shown in Figure 3-3. After alignment marks are etched on both sides (J) (only one side shown), the input/output port mask is applied (K), and the exposed thermal oxide is removed using BOE. The donut shaped etch to create the input and output ports is then conducted for 10μm through the device layer till the buried oxide is reached (L).

Figure 3-3: Review of the main steps in the process flow for layer 3, the SOI layer before it is bonded to the completed DSP wafer in step (M).
Chapter 3: Process Development

At this point the wafers are ready for bonding, all the oxide is removed from both wafers using an HF dip and the wafers are bonded together (silicon-direct bonding) (M). The steps that follow are shown in Figure 3-4.

After the silicon-direct bonding is complete a blank pyrex wafer is anodically bonded on top of the stack to seal off the channels (N). This capping wafer doesn’t need to be pyrex, but pyrex gives us optical access to the channels if needed. The mask to open up the input/output ports and create the tethers and pistons is then applied to the SOI bottom and the etch is conducted (O). Once the tethers are fully formed the buried oxide is removed using HF vapor (P) since wet processing isn’t possible at this point (would clog

Figure 3-4: Review of the final steps in the process flow – etching the pistons and the tethers and incorporating the pyrex layers to complete the final device (T).
the channels and pump chamber). Once the buried oxide is removed from the tether region the stack is ready to be bonded to the bottom support pyrex layer. This bottom pyrex layer is a rest stop for the input/output and pump chamber pistons and allows pneumatic access to all ports. The first step in preparing the bottom pyrex layer is depositing silver alignment marks using eBeam lift-off (Q). The input/output and piston access ports are then cut out using a Resonetics laser system (R) [152]. Once complete, a shadow mask is used to eBeam a 0.3um layer of silver on top of a 0.03um Titanium adhesive layer in circular pads around the piston actuation ports to prevent the pistons from bonding to the bottom pyrex during the anodic bonding process (S) – these metal pads are slightly larger than the pistons in diameter. Finally, the completed bottom pyrex layer is bonded to the stack (T) and individual pump dies are cut out using the die-saw. As shown in Appendix D the entire process is about 65 steps long.

The process flow corresponds to a set of 8 masks and the CAD layout shown in Figure 3-5. A single stack contains 6 identical pumps. The stack and the pumps are perfectly symmetric to allow ease of fabrication and testing (in any direction). Note that the channels from the input/output valves to the pump chamber (blue) start at the valve edges to make them as short as possible and reduce the dead-volume. A series of support posts (purple) are used to hold the input and output pistons in place as the valve lips are sealed during actuation. Without these support posts the pistons would be tilted during actuation and possibly tear their tethers.

Figure 3-5: a) Single micropump mask layout (10mm radius pump piston and 3.2mm radius valve pistons). b) Can fit 6 pumps on a 6inch wafer stack.
3.3 Round 1

Figure 3-6 shows some of the photographs taken during various stages of the first round of processing. On the left we see processing of the DSP valve lips, chamber, and channel that connects the two, and on the right we see a completed tether etch of the SOI wafer before the buried oxide (blue-ish rings) is removed.

![Figure 3-6: Photos taken during different stages of fabrication; channel and valve lips on the left, and pistons and tethers on the right.](image)

We encountered several problems and learned a great deal during the first round of fabrication. The first problem was over etching of valve and pump chamber heights. They needed to be 6um but initial etching resulted in roughly 7.5um heights (as measured using a stylus profilometer), indicating the need for more process development. During actuation this over-etching would result in additional stressing of the tethers. From the modeling in Chapter 2 we see that under an ideal case of 6um translation with zero pressure differential across the tethers the maximum stress they experience is 15.9% of the 1GPa critical value (indicated by [134] and [151]). For a translation of 7.5um this jumps to 20.9%. The second and more serious problem was that half the pump pistons blew off during the piston tether etch. Figure 3-7 illustrates the problem – trapped gas in the pump chamber that got very heated during the etching process ended up blowing off pistons just as their tethers were being created.
Figure 3-7: Half the chamber pistons were blown off because of trapped gas (green) that was heated and expanded during the tether etch process.

We had also decided to deposit gold at the DSP-SOI interface to act as a gasket for the valve-lip seal, but during the high temperature anodic bonding of the bottom pyrex layer gold particles passed through the silicon and into the pyrex, causing the pistons to stick to the ceilings or the floors of the pump chambers as show in Figure 3-8. Finally, the Resonetics laser system we used to machine the bottom pyrex wafer access ports required several attempts to completely cut through the pyrex and left behind very rough edges. The best laser machining achieved is shown in Figure 3-8b.

We were still able to measure the pressure versus flow rate characteristics of one device (whose pistons were stuck down). During this test the output port was connected to a mass flow meter open to atmosphere and the input port was attached to filtered pressure source. A schematic of the test, and the data captured is shown in Figure 3-9.

Figure 3-8: a) Gold particles passed through the silicon and entered the pyrex layer. b) Resonetics laser did a poor job machining the bottom pyrex layer access ports.
Chapter 3: Process Development

Assuming fully developed flow, the flow rate equations for the different components of the micropump for a given pressure differential are shown in Figure 3-9 (pressures in Pa and flow rates in m$^3$/s). These equations can be found in most fluid mechanics textbooks and help approximate:

- $Q_1$ and $Q_5$: flow rate through a circular valve of inner radius $R$, height from the piston $h$, and valve-lip width $L_{ip}$.
- $Q_2$ and $Q_4$: flow rate through a circular channel of effective radius $R$ and length $L$. *In our case the horizontal portion of the channel (across the DSP top surface) was slightly over etched and that needs to be added to $R$.

$$Q_1 = \frac{\pi h (P_{in} - P_2)}{6\mu \ln \left( \frac{R + L_{ip}}{R} \right)}$$
$$Q_2 = \frac{\pi R^4 (P_2 - P_3)}{8\mu L}$$
$$Q_3 = \frac{W_{ch} R (P_3 - P_4)}{12 \mu L_{ch}}$$
$$Q_4 = \frac{\pi h (P_5 - P_{out})}{6\mu \ln \left( \frac{R + L_{ip}}{R} \right)}$$
$$Q_5 = \frac{\pi R^4 (P_4 - P_5)}{8\mu L}$$

$R = 50\mu m^*, R_{lip} = 30\mu m, L = 2.2 mm, L_{ch} = 17.72 mm, W_{ch} = 17.72 mm, h = 7.5 \mu m$, and $\mu = 1.79 \times 10^{-5} \text{ Ns/m}^2$

Figure 3-9: Plot of the measured flow rate through the micropump as a function of the pressure applied across its ports. The measured data compares quite well with the model shown above.
- $Q_3$: the flow rate through a rectangular plate of width $W_{ch}$, length $L_{ch}$, and height $h$ – rough rectangular approximation of the pump chamber.

All the flow rate equations in Figure 3-9 must be equal to each other ($Q_1 = Q_2 = \ldots = Q_5$). Since we know that Pout = 760Torr and Pin is our input variable, we have a set of five equations with five unknowns that can be solved using linear algebra. The solution to this set of equations is the model curve plotted in Figure 3-9. We see that it does approximate the experimental measurements quite well.

3.4 Round 2

For the second round of fabrication we improved the pump chamber and valve-lip etch precision by running several trials and identifying the correct etch times. More importantly, we added a new fabrication step ($L'$) to the original process flow, shown in Figure 3-3, to relieve the built up pressure underneath the pistons during tether creation. Once the donut shaped etch to create the input and output ports is run for 10um through the device layer down to the buried oxide (step L), the buried oxide is removed using BOE and the etch is continued 200um further (step $L'$). During step (O) when the tether/piston etch is being conducted this allows the input and output ports to open up well in advance of the tethers being created, relieving any built up pressure in the chamber volume and saving the pistons from being blown off.

We also refrained from using gold as a gasket material and used an external vendor (Bullen Ultrasonics) for precision machining of the bottom pyrex layer, which was then processed as usual (i.e. outsourced step R but continued with all the rest of the steps as usual).

![Figure 3-10](image_url): Additional pre-etch done on the SOI wafer to prevent pistons from blowing off from built up pressure during the tether etch.
These improvements saved all the pistons and led to the successful creation of a full stack of micropump dies. Unfortunately during the die-saw process, when all the micropumps were being cut out of the stack, water leaked in through the SOI-DSP interface and caused that critical bond to break, essentially separating the pumps in two as shown in Figure 3-11.

![Figure 3-11: Pump die that completed separated at the SOI-DSP bond interface during die-sawing (pump chamber piston also got damaged and fell off at that point).]

Only half the micropumps remained intact, but with some amounts of water in their chambers. We don’t have a good explanation for why this happened; clearly the SOI-DSP silicon direct bonding and annealing steps had some issues that we didn’t notice during fabrication (all the IR images taken after bonding looked fine). It’s also possible that die-sawing was too violent a process for our micropump stack to handle. After heating the devices that survived in a (non-vacuum) lab oven for three hours to evaporate any trapped water we were able to measure their pressure-flow characteristics. The best data from this round of fabrication is shown in Figure 3-12. The data shows that some pistons were partially working and that others were leaking, but there was no fully functional micropump.

To test the pistons we applied a constant pressure source at the input port and measured the output flow rate using a mass flow meter as we attempted to actuate the pistons. We only applied positive pressures to actuate the pistons (no vacuum to pull them down). Ideally for actuation pressures above the input pressure the pistons should actuate shut and the output flow should drop to zero. In Figure 3-12 the green data represents the input piston actuation tests, the red data represents the chamber piston
actuation tests, and the blue data represents the output piston actuation tests. While each piston was being tested the other pistons were left open (i.e. not actuated). Note that as the input and output pistons are actuated with positive pressures (indicated by the green and blue transparent vertical bars) the output flow rate is reduced, which is what we want. Unfortunately the output flow is not cutoff entirely for any actuation pressure up to 760Torr above atmosphere (we didn’t test at even higher actuation pressures because that would damage the tethers). As the chamber piston is actuated (indicated by the red transparent vertical bars) the output flow rate actually increases, signifying leakage in the pump chamber piston’s tether. Since positive pressure is applied during this test any tether leakage would show up as an increase in the output flow rate. Our best results were semi-working input and output pistons and a leaky tether pump chamber piston.

![Diagram of actuation tests and flow rates](image)

**Figure 3-12:** Best data from round 2 of fabrication. Air is input at the input port and the output flow rate is measured using a flow sensor. As the three pistons are actuated (indicated by the transparent vertical bars) we expect to see a complete cut off of any flow (green data for the input piston, red for the chamber piston, and blue for the output piston). Note that the input and output pistons do work to some degree but that the pump chamber tether is leaking air.
3.5 Round 3

For the third round of fabrication we removed the top pyrex wafer and replaced it with a silicon wafer so that the Si-DSP-SOI bond could be done in one shot (step N), and also annealed at a higher temperature (950°C compared to 850°C in round 2) to ensure bond strength. The more significant change was to use a 9th mask - a “cutting” mask that defined die-lines that we etched to cut-out the dies and avoid having to use the die-saw. The addition of this mask added a few extra steps to the process flow and increased the total processing time.

Once the dies were cut-out via etching they were anodically bonded to their bottom supporting pyrex layers using a die-level bonder. Unfortunately, even after many bonding set-up improvements, complete bonding of the pyrex pieces to the micropump dies was not possible and there always remained several unbonded regions as shown in Figure 3-13. The main reasons were most likely the SOI wafers weren’t perfectly polished enough (a supplier defect we noticed in this batch), and we couldn’t apply enough pressure to bond them to the pyrex pieces (tested > 330°C, > 1000Volts, > 301bs of pressure, and using graphite gaskets).

This made the testing of these devices very challenging because air could leak between ports along the pyrex-SOI interface, in particular between a port being actuated and the output port where measurements were taken. To try to overcome these problems we applied huge clamping forces to seal the Si-pyrex interface and eliminate leakage. To avoid cracking the devices we applied rubber padding both underneath and above the micropumps and a metal plate was placed on top of the rubber sheet before the clamps

![Figure 3-13: Pyrex bottom layer didn’t bond well to any micropump die. This allowed air to leak between the various ports and made testing very challenging.](image-url)
were applied – to evenly distribute the pressure, as shown in Figure 3-14. Using this approach we were able to eliminate leakage between ports for some time and make some useful pressure-flow measurements. One device proved to have all three pistons working with no leakage, the data from that device is shown in Figures 15-18. Figure 3-15 shows the tether leakage test, where pressure is applied at both the input and output ports and any leakage flow is measured underneath the input, output, and chamber pistons.

![Figure 3-14: Used rubber sheets, metal plates and huge clamps to seal off the air spaces between the pyrex and micropump dies. (In the image on the right the pump being tested is underneath the metal plate)](image)

![Figure 3-15: Tether leakage test where pressure is applied at the input and output ports and leakage flow is measured underneath the pistons. No leakage was measured using our most sensitive mass flow meter)](image)
Our most sensitive mass flow meter did not register any leakage. Figures 16-18 show the actuation tests of the input, pump chamber, and output pistons respectively. With a pressure source applied at the input port of the micropump so that a clear flow rate is measured at the output port using a mass flow meter, each piston is actuated with a positive pressure (indicated by the red transparent vertical bars). All three pistons showed to completely shut off flow as we hoped (to the point that could not be registered by the mass flow meters). For each piston the output flow rate versus actuation pressure is also plotted; all three pistons did cutoff flow when they were actuated with pressures slightly greater than pressures in the chambers above them. Unfortunately this performance didn’t last for very long as pump dies inevitably started to delaminate (i.e. separate from the pyrex layer) under the tremendous forces we were applying to them using the clamps. This precluded any actual pumping experiments for these devices because very few measurements were possible.

**Figure 3-16:** Actuation test results for the input valve showing a complete cutoff of output flow at an actuation pressure slightly greater that the pressure above the input piston (also the input pressure).
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Figure 3-17: Actuation test results for the chamber valve showing a complete cutoff of output flow at an actuation pressure slightly greater than the pressure above the chamber piston (also the input pressure).

Figure 3-18: Actuation test results for the output valve showing a complete cutoff of output flow at an actuation pressure slightly greater than the pressure above the output piston (also the output pressure, i.e. atmosphere).
3.6 Round 4

We had learned many lessons from the previous three rounds of fabrication and the testing of those devices. These all led to improvements in the fabrication process flow and testing setup. We felt that the next improvement was to use double side polished SOI wafers and repeat all the steps in fabrication round 3 knowing that the pyrex bonding issue would be resolved using a highly polished surface. This turned out to be the case but all round 4 micropumps showed to have some level of leakage during actuation, pointing once again to damaged tethers. Photos from round 4 of fabrication and testing are shown in Figure 3-19.

Figure 3-19: Left: DSP wafer after Etch 1 (pump chamber height and valve-lip height) and deposition of thick oxide. Middle: bottom pyrex wafer after through holes have been created, and metal pads have been deposited. Right: micropump dies being clamped to the testing platform using o-rings and optical clamps for testing.
Chapter 4

The Working Micropumps

4.1 Introduction

Although many improvements had been made over the first 4 rounds many micropumps were still coming out of fabrication with damaged tethers. Stress modeling (Chapter 2) suggested that the design wasn’t the source of failure, which pointed to fabrication methods. After a step by step re-examination of the fabrication process flow to identify potential sources of failure, several steps stood out.

The original process flow called for the creation of the tethers after the SOI wafer had been bonded to the DSP wafer with the chambers and channels already complete (step O in Figure 3-4). Considering these were some of the widest and thinnest tethers fabricated at the MIT Microsystems Technology Laboratories (MTL) we worried that they might not survive on their own without the support of the DSP wafer holding the pistons in place. Our modeling had originally suggested that the tethers were strong enough, and to test this idea we began a tether creation experiment, which ultimately lead
Chapter 4: The Working Micropumps

to the very first fully functioning vacuum pumps and a round 6 design that brought us closer to meeting the goals set out by the MGA project.

4.2 Round 5 Fabrication

Almost every standard etch recipe used to etch the 480um wide by 440um deep tether trenches etched faster at the edges than at the center. This left behind a mound of silicon in the middle of tether when the buried oxide was reached along the edges.

![Micropump die](image)

**Figure 4-1**: Typical SOI tether etch profile for all recipes on STS2 and STS3. The tether edges etch faster than the middle leaving behind a mound of silicon in the middle when the edges had reached the buried oxide. Image on the right shows an entire device.

To remove the silicon mound the process flow required us to continue etching, which invariably led to some undercutting/lateral etching of the silicon along the trench edges (as illustrated by Figure 4-1), which magnifies stresses at the silicon/buried oxide interface and compromises the overall strength of the structure. This lateral etching phenomenon is also called “footing” and is due to plasma charging effects at the silicon/buried oxide interface [153 – 155]. Since the SOI wafer had already been bonded to the DSP wafer (containing the pump chamber and flow channels), wet processing wasn’t an option to remove the buried oxide or any thermal oxide. To get around this, our process flow required the use of HF vapor to remove all oxide. We had run tests to determine the HF vapor oxide etch rates for a given temperature but there was no way to guarantee that condensation had not occurred - once condensed HF liquid could flow
sideways into the undercut regions, remove more buried oxide, and detach the SOI device layer from the rest of the wafer. Since the stack had already been created there was no way to evaluate any tether’s condition after this step in the process flow. We could look into the tether trench from above but there was no way to see the tether edges from the DSP side, especially around the undercut regions. Since many pumps were coming out of fabrication with damaged or leaky tethers it was quite likely we were ending up with weakened or cracked tether structures like those illustrated in Figure 4-2.

![Figure 4-2: Our hypothesis for the low yield - detached and/or cracked tethers due to undercutting of the silicon and the use of HF vapor. These problems were not noticeable from above, but also could not have been detected from below since the SOI and DSP layers had already been bonded together.](image)

The tether creation process flow definitely had to be rethought. The ideal tether etch would result in robust tether structures, with the trench and fillet profile shown in Figure 4-3. Very small fillet radii act as stress concentrators and very large fillet radii stiffen the tethers, making them hard to deflect. Fillet radii between 30 – 50um have been found to provide the required flexibility while minimizing stress concentrations [134]. Also using HF vapor to remove the buried oxide was not ideal because it was not very controllable, and condensation was always a concern. Since completed DSP layers had already been bonded to the SOI layers they were going to waste every time the tether process flow resulted in damaged tethers. If SOI wafers could be processed independently it would solve all of these problems, and that was the focus of our tether etch recipe investigation.

After trial and error we found that no standard etching recipe used on MTL etchers produced a trench different from the one shown in Figure 4-1, but some were better than others. By modifying the etch powers and gas conditions of the better recipes we were able to change the etch profile. After running several controlled trials we arrived upon a
recipe that finally etched faster at the center of the trench than at the edges and gave us the fillet profile we sought (Figure 4-3) – we called this customized recipe “Vtrench” and it’s parameters are given in the Appendix F. Although we were using our most uniform etcher, rotated the wafers every several minutes, and were very careful about measuring the etch depths after each step, it was still not possible to obtain perfect uniformity along a single pump chamber’s fillet (across the wafer was out of the question). In the best cases the tethers at their widest and narrowest points along a single pump chamber piston were approximately 20um apart. Once a valve or pump piston’s tether etch was complete, it was painted with photo-resist by hand so that it wouldn’t etch any further as the rest of the tethers on the wafer were being etched.

Figure 4-4 shows a SOI wafer with pistons and tethers completed. Unfortunately due to clamping stresses in our etchers the top and bottom chamber pistons were often damaged. The rest of the tethers and pistons were all in tact and survived vertical wet cleaning (nanostrip), oxide removal using BOE, and spin drying, as we had hoped. It was an exciting step towards the development of a working pump.

The tether etch recipe investigation led to 4 major improvements:

- A custom controlled recipe for tether creation
- Tethers with properly defined fillets whose condition could now also be observed from the device layer (not possible before due to bonding with the DSP layer)
- No need for HF vapor to remove the buried or thermal oxides, wet processing and the use of BOE was finally possible
Chapter 4: The Working Micropumps

- Ability to process the SOI layer independently of the other layers in the pump stack – thereby saving completed DSP wafers from being sacrificed.

The additional process flow steps to augment the original process flow presented in Chapter 3 are shown in Figure 4-5. With an improved process flow in hand we continued to complete the round 5 micropumps. More comfortable at this point with the integrity of our structures and their bonding we went back to using the die-saw to cut out our pump dies (die-saw tape was enough to prevent water or die-saw slurry from entering the devices).

![Image of a completed SOI wafer with piston and tether etches completed.]

**Figure 4-4:** Photograph of a completed SOI wafer with piston and tether etches completed.

- Silicon
- Photo-resist
- Thermal-oxide

**Figure 4-5:** New SOI process steps that replace the previous L-P steps presented in Chapter 3 (Figures 3 and 4). After the tether mask is applied to the SOI wafer (M), the tether region is etched and the buried oxide is removed (N). All resist and oxide is removed from the completed DSP and SOI wafers and they are bonded together (O), and immediately bonded to top capping wafer that seals the channels (P). The rest of the processing steps (Q-T) are the same as before.
4.3 Round 5 Results and Hypothesis

This round of fabrication led to a fully functioning set of vacuum micropumps. Using the test setup (described in Chapter 2) we performed the main set of tests on these devices:

- **Test 1:** Check for valve and pump chamber leaks by actuating the pistons and measuring any flows at the input or output ports
- **Test 2:** Check that all pistons can shut down flow by applying an external pressure source at the input and measuring the flow rate at the output as each of the pistons is actuated
- **Test 3:** Measure the flow rate through the device as a function of the pressure differential applied across it
- **Test 4:** Measure the micropump generated flow rate via the 6 stage pumping cycle shown below, as a function of operating frequency

![Pumping Cycle Diagram]

- **Test 5:** Measure the micropump generated vacuum at a frequency of operation in the micropump’s operating range indicated by **Test 4**

The implementation of Tests 1 – 3 have been described in Chapter 3 and these pumps showed to have working pistons with non leaky tethers, and a flow through characteristic
that we could predict using the model introduced in Chapter 3 (with a corrected chamber height of 5.7um). To improve upon the time independent models presented in Chapter 3 we will consider, later in this chapter, a circuit analysis technique to predict the flow rates and pressure distributions throughout the micropump device. The circuit model has the additional advantage of helping us predict the micropump’s maximum frequency of operation (a time dependent problem).

Having successfully completed Tests 1-3 we attempted for the very first time to measure the flow generated by these devices. After many attempts we realized that none of our mass flow meters (Figure 2-19b) were able to accurately measure the flow rates produced by our micropumps, even though their specifications indicated they should. The large fluidic resistances across them and day-to-day variations in their noise floors produced readings that weren’t reliable.

We then resorted to the simplest flow sensing experiment. With a water droplet in a plastic tube attached to the outlet port of the micropump we actuated the device to produce a forward direction flow and looked to see if the water droplet moved. This experiment showed that our micropumps were in fact pumping, a very exciting result. Snapshots from this experiment are shown in Figure 4-6.

Given the dimensions of the plastic tube and the displacement of the water droplet, the flow rate generated by our micropump as a function of frequency can be calculated. The results of 38 such experiments are plotted in Figure 4-7. Notice that although the flow rate initially increases linearly with frequency (as we expected), it eventually tapers off and starts to decline. Note also the wide band of error at all frequencies.

**Figure 4-6:** Five snapshots from the water droplet experiment for forward direction pumping. Backward direction pumping worked just as well.
After running over a 100 similar water droplet experiments we felt that a more accurate and repeatable flow measurement technique was needed. The friction between the water droplets and plastic tubing lead to inconsistent droplet travel times. Sometimes the droplet would be stuck in place until a certain amount of positive pressure was built up behind it after which it quickly raced along; and the center of the droplet also sometimes bubbled out to absorb pressure.

We then came up with and tested a third method of measuring the flow rate – at each frequency we actuated the micropump to generate vacuum in a closed and defined volume connected to the input port and took several measurements of the rate of change of the pressure drop, which we could then use to calculate the flow rate. The fixed volume we generated vacuum in was a stiff walled plastic tube connected at one end to the micropump input port, and the other end to a vacuum sensor. Starting at atmosphere in the tube, the micropump was actuated to generate vacuum and we measured the pressure drop for 10Torr – this gave us the $\Delta P/\Delta t$ the micropump can generate at a given frequency of operation. From the ideal gas law we know that $\Delta P V_t = \Delta nRT$, where $V_t$ is the fixed tube volume ($m^3$).
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The flow rate is defined as

\[ Q = \frac{\text{volume evacuated}}{\Delta t} = \frac{\Delta n}{\Delta t} \left( \text{molar volume} \right) \left[ \frac{\text{liters}}{\text{sec}} \right] \]

where the molar volume of air at room temperature and atmosphere is 24.79 L/mol. Therefore, given \( \Delta P/\Delta t \) in Torr/sec from the captured vacuum sensor data we can calculate the flow rate in sccm as follows

\[ Q = \left( \frac{\Delta P}{\Delta t} \frac{101325 \text{Pa}}{760 \text{Torr}} \frac{60 \text{ sec}}{\text{min}} \right) V_t \left( \frac{\text{molar volume}}{\text{RT L}} \right) \left[ \frac{1000 \text{cm}^3}{\text{L}} \right] [\text{sccm}] \]

where \( V_t \) is the fixed tube volume in m\(^3\), \( R = 8.314 \text{ m}^3 \text{ Pa} / \text{K mol} \), and \( T = 298 \text{K} \).

Our vacuum sensors worked very well in the ranges we were generating vacuum (between 0 – 20 Torr below atmosphere) and this method ended up giving us very repeatable measurements that are plotted in Figure 4-8. Note that the flow rate increases linearly with frequency till about the 1Hz mark and then starts to plateau-off reaching a maximum of about 0.024 sccm at 2.5Hz after which we found it begins to drop. As we will see later in this chapter when the flow-circuit model is covered, the fluidic resistance of the valve lips and pump chamber are the primary causes of this maximum frequency of operation.

![Figure 4-8](image-url)

**Figure 4-8:** Plot of the flow rate generated by the 6 stage pumping cycle as a function of operating frequency (calculated using the rate of change of vacuum generated in a fixed volume).
Figure 4-9 shows the vacuum generation performance of the micropump at 0.75Hz operating frequency – within the linear region of the micropump’s operating range. The best vacuum level we could generate was 163Torr below atmosphere. A comparison of this data with that compiled in Chapter 1 summarizing the micropump research space shows that our results stack up quite well and are not far from matching the best vacuum generating micropumps.

Several questions still remained. First, why can’t we pump down more than 163Torr below atmosphere when the micropump was designed to have a dead volume of 5.58% - indicating ideally the ability to pump down 718Torr below atmosphere? And second, why is our maximum frequency of operation around 2.5Hz and not higher? Are these problems due to imperfections in the fabrication, leaks at the valve seats, or piston bending under stress/pressure?

![Graph showing vacuum levels over time](image)

**Figure 4-9:** Best vacuum level generated below atmosphere during round 5 at 0.75Hz operation and 10psi actuation, in an external volume of ~6cm³.
Piston bending could answer some of these questions (as we will see) and our first indication that it was indeed an issue was when we optically profiled a few broken chamber pistons. As shown in Figure 4-10, chamber pistons were all curved by at least 1.6um to as much as 2.3um at their centers. Numerically calculating the volume of revolution of the plotted curve reveals that it is 31% of the total pump volume (chamber volume plus dead volume assuming a 6um tall pump chamber), which is a staggering amount.

Ideally the pistons would be perfectly flat but due to stresses across the wafer due to the SOI buried oxide they were always curving up into the pump chamber and reducing the possible pump volume - effectively increasing the dead volume (by up to 31% in the worst of cases), and diminishing the ability to generate a low vacuum level.

![Figure 4-10: Optical profile of a pump chamber piston at rest showing that it is quite curved due to wafer stresses.](image)

To get a better understanding of piston bending and its effects on performance we used Finite Element Analysis (FEA) to model piston deformation. To confirm that our FEA models were reasonable we compared them to solutions of the nonlinear differential equation for symmetrical bending of a circular plate under external stress introduced in Chapter 2 (where we used it to determine the optimal tether dimensions). Figure 4-11 compares both results, which match up quite well.
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Figure 4-11: Comparison of results from FEA analysis and numerical solutions to the nonlinear differential equation for the symmetric bending of a circular plate under an input stress. Both solutions match perfectly.

Although FEA modeling is more computationally intensive than solving the differential equation for symmetrical bending introduced in Chapter 2, it has the additional advantage of allowing us to model piston actuation with a bonded ceiling 6um above to stop travel – better representing our actual device. The results of the FEA modeling were quite revealing, they showed that for the actuation pressures we were using (8-12psi) the 440um thick pistons would actually curve quite a bit and not fully rest along the chamber ceilings. The piston centers would come in contact with the ceiling first with the rest only partially sealing radially outwards. For any range of reasonable actuation pressures up to 14.5Psi the edges of the pistons were not close to resting along the ceilings. Figure 4-12 shows the FEA modeling results for the input/output piston at 10psi actuation pressure. Note that the edge the piston is not in contact with the ceiling, and the valve opening at that edge leading to the pump chamber is not being sealed properly, resulting in valve leakage during pumping. Recall the valve openings were placed at the piston edges to reduce the channel dead-volume.

FEA modeling of the pump chamber showed similar results; with increasing actuation pressure it was possible to have more of the piston surface in contact with the chamber ceiling, thereby reducing the dead-volume, as shown in Figure 4-13. To have the pistons completely flat across the chamber ceilings, considerably larger pressures would be required, much larger than the tethers were designed to handle.
Speaking of tethers, it's interesting to note that in Figure 4-13 the tethers are only the 0.48mm regions at both edges of the plot (-9.52mm to 9.52mm is the piston) - we see that the tethers are not in fact translated by 6um at the inner edges that we had modeled and designed them for in Chapter 2, which points to potential room for optimization (use of narrower width tethers).

Figure 4-12: FEA modeling results for the input/output piston under 10psi of actuation pressure. Bright red indicates 6um of travel (contact with the ceiling stops) and blue represents 0um of travel. Note that the edge the piston is not in contact with the ceiling and the valve opening at the edge leading to the pump chamber is not being sealed properly.

Figure 4-13: FEA modeling of the pump chamber piston under different actuation pressures, showing that more of the piston surface comes in contact with the 6um high ceiling as the actuation pressure is increased.
The main takeaways from this modeling exercise are:

- The pistons curve during actuation and do not completely seal with the valve or pump chamber ceilings under normal actuation pressures (up to 2 atmospheres absolute that the tethers were designed for) – resulting in excessive dead-volume in the pump chamber and leakage at the input/output valves.

- With increasing actuation pressures it is possible to flatten more of the piston surfaces across the chamber ceilings, leading to greater pump rates (due to lower dead-volumes) and better vacuum generation (due to lower leakage).

These observations led to the following hypothesis - pistons with less stiffness would result in greater pump rates and lower leak rates at the same actuation pressures. In addition, positioning the input/output valve openings at the piston centers would lead to better valve-lip coverage and lower leakage. The latter is obvious from current modeling results. To investigate the former, two simple cases were considered: a wafer thick piston with several tether regions, and a thinned down piston design. The two options are compared in Figure 4-14.

Figure 4-14: Comparison of FEA modeling of two possible future designs actuated at the same pressure: thinned down piston (220um thick), and wafer thick piston (440um) with additional tether structures. Cross-sections of each design are shown in gray.
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The thinner piston design was attractive for two reasons, not only did it lead to better ceiling coverage (red region = 6um of travel and contact with the ceiling), but it was also easier to fabricate than the additional tether design. Tethers are very delicate structures and break often, and the process of creating them with proper structural integrity is also very involved. The thinner piston design would require additional masks and fabrication time but would be a higher yield option. Figure 4-15 shows how a thinner piston (220um thick) compares to a regular wafer thickness piston (440um) under the same actuation pressure. The difference is quite significant and should be measurable experimentally.

![Figure 4-15: Comparison of the FEA modeling of a thinner piston design (220um thick) with the original piston (440um thick) under 9psi of actuation pressure (tethers are the 0.5mm regions at the plot edges).](image)

With these modeling results in hand we came up with a new micropump design that would allow us to test and verify our hypothesis. The round 6 design shown in Figure 4-16, includes 8 identical micropumps with valve openings at the input/output piston centers, and pistons that are all 220um thick (half their original thickness). To support these pistons along the bottom pyrex surface and prevent more than 6um of travel, 400um wide (and 220um tall) support pillars are included along their circumference (movement much beyond 6um would result in tether breakage). The pump stack also has 8 valves for leak testing that includes 4 designs (all 150um inner radius) - valve opening at the piston.
edge, valve opening in between the piston edge and center (valve opening at the piston center is included in the pumps themselves), thick valve lip (60um thick) at the piston center, and thin valve lip (20um thick) at the piston center. The regular valve lip thickness included in the pumps themselves is 40um.

Figure 4-16: Round 6 design to test our hypothesis. The design includes 8 identical micropumps and 8 valves for testing, which consist of the 4 valve designs shown on the left.

A 3D rendering of a single micropump is shown above (10mm radius pump piston, 1.5mm radius valve pistons), and the green bars illustrate the air path through the device. Notice the thinned down pistons are supported by posts, and the valve openings are at the piston centers.
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It’s important to note that we’re fabricating round 6 to test our hypothesis for the performance of the round 5 micropumps. We hope the new pump and valve designs will yield experimental data which, after comparison with round 5 data, can help explain why the round 5 pumps performed the way they did, and illustrate the impact of the various design parameters on overall pump performance. In this way, the purpose of round 6 is to help us close the loop on our understanding of the round 5 design and is not the proposed direction for better micropump performance (although it is expected to perform better). In the following chapter we will present an optimized micropump design geared towards improving overall size, robustness, and performance (including frequency and vacuum level).

The specific goal for round 6 is to show that pistons that seal better against the ceilings for the same actuation pressures yield better overall performance (greater pump rates and lower leakages) – and the simplest way of achieving that is by thinning down the pistons. In addition, positioning the input/output valve openings at the piston centers should lead to better overall valve lip coverage. Having a semi-opened valve lip doesn’t allow us to pump down very far – eventually the pressure differential across the pump increases the leak rate to a point that balances with the pump rate, producing a floor of minimum achievable vacuum level.

4.4 Round 6 Fabrication

The new process flow steps incorporating the new masks needed to thin down the pistons and create the supporting post structures are shown in Figure 4-17. Included in the Appendix F are the parameters of the “MIT69a” recipe used to etch the tethers. We had previously designed the custom recipe “Vtrench” for this purpose, but it was no longer working after the machine had been re-tooled (i.e. taken-apart and re-built as part of yearly maintenance). Another exhaustive tether recipe search brought us to “MIT69a,” which gave us the tether and fillet profile we needed (shown in Figure 4-3). “MIT69a” has the drawback of ejecting many little fly-away particles of silicon from the surface that
land back on the etching areas resulting in a very rough pyramid like final surface as shown in Figure 4-18.

The most sensitive and time consuming step was the creation of the tethers. Once the buried oxide was reached, etches were done one minute at a time with fillet measurements taken after each etch. Since all the piston tethers had different etch rates

![Diagram showing the process steps](image)

**Figure 4-17:** New SOI process steps that replace the previous L-P steps presented in Figure 5 (or Chapter 3 Figures 3 and 4). After thick DCVD oxide is deposited on the SOI wafer (L2) it is patterned using the nested pillar-tether mask and the exposed oxide is removed (M1). Resist is then deposited and tether mask is applied (M2). The tether region is etched for half the wafer thickness (N1), after which the resist is removed and the etch is continued till the tethers are complete and the pistons are thinned down (N2). Finally all the thick and thermal oxide is removed from the completed DSP and SOI wafers and they are bonded together (O), and immediately bonded to a top capping wafer that seals the channels (P). The rest of the processing steps (Q-T) are the same as before.
once one was complete it had to be painted by hand and dried before any further processing was possible. The SOI wafer at this point was mounted on blue-tape and so using the oven to dry the resist wasn’t an option. We had to leave it to dry in air for 3hrs after every resist paint job. Figure 4-18 shows the tether creation photographs and Figure 4-19 shows a completed DSP wafer (with channels and chambers), near complete SOI wafer (with tether and thinned down piston regions being etched), and completed supporting pyrex wafer (with input/output and chamber actuation openings, and silver pads to prevent piston-pyrex bonding. Figure 4-21 shows completed valve and pump dies.

Figure 4-18: Photographs of the tethers being etched open from left to right. Note that sides of the filets are not very smooth. The “MIT69a” recipe creates a lot of fly-away particles that land back onto the silicon surface resulting in pyramids, some of which extend out into the tether region and could be a source of failure during actuation.

Once the SOI and DSP layers were completed they were bonded together with a capping silicon wafer to seal the micro-channels along the top surface of the DSP wafer. The bonding went very well and an IR photograph taken after annealing is shown in Figure 4-20. The final step was anodically bonding this 3 wafer stack to the bottom support pyrex layer that had circular pads of 0.2µm of silver (on top of 0.02µm of titanium adhesive layer) to prevent bonding of the piston support posts to the pyrex. Completed valve and pump dies are shown in Figure 4-21.

Up to the anodic bonding step the fabrication proceeded without a hitch and this step has always been problem free, but during bonding we observed many spikes in the current suggesting that there were arcs developing between the SOI wafer and the metal
Figure 4-19: Photograph top left: a completed DSP wafer with channels and chambers. Top right: near complete SOI wafer with tether and thinned down piston regions being etched. Bottom left: completed supporting pyrex wafer with input/output and chamber actuation openings, and silver pads to prevent piston-pyrex bonding. Bottom right: Close up of tethers and thinned down pistons being etched, and piston support posts viewed from above and at a shallow angle.

Figure 4-20: IR Photograph taken after annealing of a completed SOI wafer bonded with a completed DSP wafer and a capping Si wafer. The bonding went very well, and fringes in the pump chambers indicate the pistons are free to travel (un-bonded as we require). Unfortunately STS clamps damaged the top and bottom pump pistons of this stack and they did not survive processing.
on the pyrex. Once the bonding was complete we noticed that the very high temperatures generated by these arcs led to thermal expansion that cracked the pyrex, and burnt the silver and silicon layers, around the piston access ports as shown in Figure 4-21. In the following two sections we review the results of the valve and pump tests of the Round 6 devices.

![Figure 4-21](image)

*Figure 4-21: Photographs of completed pump and valve dies. Notice the burn damage on the silver and silicon surfaces, and cracking of the pyrex at the port openings – produced by arcing during the anodic bonding process.*

### 4.5 Valve Models and Characterization

We had 5 different valve designs to test:

- Thin lip width (20um) at piston center
- Thick lip width (60um) at piston center
- Normal lip width (40um) at piston center - in the micropumps themselves
- Normal lip width located halfway between piston center and piston edge
- Normal lip width located at piston edge

A schematic of the test setup used to conduct these experiments is shown in Figure 4-22. A vacuum sensor with a thick walled tube of fixed length is attached to the output port of the valve being tested. Vacuum is then pulled from the input port of the device. Once the desired vacuum level is read on the vacuum sensor the valve piston is actuated.
shut and the vacuum sensor readings are recorded with time - they represent the valve leakage data. A valve design with the lip at the piston edge is shown in Figure 4-22. The averaged data from these experiments is shown in Figure 4-23 for each valve design.

![Photograph of the valve testing platform with a valve die clamped in and ready for testing.](image)

**Figure 4-22**: Schematic and photograph of the valve test setup. A valve design with the lip at the piston edge is shown here.

Note that the vertical axis represents the vacuum sensor readings in Torr below atmosphere and the horizontal axis represents time in seconds. So in all cases 30Torr of vacuum was pulled on the vacuum sensor through the valve being tested before it was actuated shut with 10psi of actuation pressure. Once shut the pressure read by the vacuum sensor fell (i.e. moved towards 0Torr = atmosphere) as the valve leaked. Each graph is the average of two measurements and is accompanied by a picture of the valve design it represents. The thin lipped valve leaked the most and the thick lipped valve positioned at the piston center leaked the least, which was what we expected since the valve lip resistance increases with thickness. For the normal thickness valve lips the slope decreased (i.e. the leakage decreased) as the lip position was moved closer towards
Figure 4-23: Raw valve leakage data obtained for each valve design. 30Torr vacuum was pulled across each valve before it was actuated shut with 9psi actuation pressure, and the leakage of that vacuum across the valve is what is being plotted here.
the piston center, which also makes sense since we know that the piston sits flatter along the chamber ceiling (and therefore the valve lip). The results were what we expected and so we proceeded to compare them with known expressions for flow resistances through valve openings, to see if they followed trends that could be modeled.

Assuming laminar parabolic flow throughout the gap between the piston and valve lip, which holds true for small gaps [133], the fluidic resistance is well known and shown in Figure 4-24. (Recently a slightly modified version of this resistance equation with additional weighting/correction factors depending on the valve geometry has been published [156]).

![Figure 4-24: Fluidic resistance for a standard circular valve design, where η is the fluid viscosity and r2 - r1 is the valve lip thickness.](image)

$$R = \frac{6\eta}{\pi h^3} \ln\left(\frac{r_2}{r_1}\right)$$

The pressure differential (P1 - P2 in Pascals) and volumetric flow rate (in m³/s) are related to the resistance above by \(Q = \Delta P/R\) (covered in more detail in the following section). Since we have the slopes (ΔP) for the 3 valve designs located at the piston centers (thick lip, normal lip, thin lip) we can take their ratios and see how well they compare with the model above (\(\Delta P_2/\Delta P_1 = R_1/R_2\)).
Chapter 4: The Working Micropumps

Table 4-1: Comparison of the fluidic resistance ratios with the valve leakage slope ratios. (Errors correspond to the largest errors in optical measurements and maximum noise in vacuum sensor data)

<table>
<thead>
<tr>
<th></th>
<th>$R_1/R_2$</th>
<th>Error on calculation</th>
<th>$ΔP_2/ΔP_1$</th>
<th>Error on measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal vs. Thin</td>
<td>2.299</td>
<td>0.188</td>
<td>2.589</td>
<td>0.29</td>
</tr>
<tr>
<td>Thick vs. Thin</td>
<td>3.266</td>
<td>0.240</td>
<td>3.551</td>
<td>0.29</td>
</tr>
<tr>
<td>Thick vs. Normal</td>
<td>1.420</td>
<td>0.050</td>
<td>1.372</td>
<td>0.29</td>
</tr>
</tbody>
</table>

When the DSP layer was completed, the normal valve lip thickness was optically measured to be 42um on average, the thin valve lip thickness was measured to be 17um on average, and the thick valve lip thickness was measured to be 63um on average. These are the values used in Table 4-1 (along with channel inner radius $r_1 = 150$um), and the errors correspond to the largest possible errors in the optical measurements and maximum noise in the vacuum sensor slope data. The modeling results don’t exactly match the measurements but are reasonably close.

Finally, we compared the valves at the piston edges with the valves at the piston centers for different actuation pressures. The results for the valves at the piston edges are shown in Figure 4-25. Note that with increasing actuation pressure the leak rate drops significantly. This is because the piston seals better along the valve lip with increased actuation pressure, confirming our hypothesis. In comparison, the leakage slope (as was plotted in Figure 4-23) for the thick lipped valve located at the piston center changed

![Figure 4-25: Valve leakage test confirming that valves with openings at the piston edge leak less with increased actuation pressure.](image-url)
negligibly with increased actuation pressure, going from 0.0159 (0.00131 sccm) at 5 psi actuation, to 0.0156 (0.00128 sccm) at 10 psi actuation, to 0.0152 (0.00125 sccm) at 14.5 psi actuation.

4.6 Pump Models and Characterization

Many pumps broke during initial testing; often the pump chamber tethers cracked, which could have been made more fragile by the anodic bonding damage, or possibly stretched in too far during vacuum actuation to pull down the pump chamber pistons. To explain how this is possible, our process flow aimed to have 220 um thick pistons but they were closer to 170 um thick at their centers on completion. This was due to our recipe’s faster etch rates at the center of every structure than at the edges, and the additional etch time required to “open-up” the tether region once the buried oxide was reached. The thinner 170 um pistons are held above the bottom pyrex surface by 220 um tall posts at the piston circumference (as shown in Figure 4-16). When vacuum is applied to pull the pistons down it’s possible that they deform/curve-in and cause the tethers to stretch inwards. Under these conditions the tethers could break. During the valve tests vacuum actuation was never needed or applied and we didn’t observe any breakage. We did however end up with many broken pumps after pump testing. Figure 4-26 shows photographs of micropump tethers and pistons that were cracked only after testing.

Figure 4-26: Photographs of a cracked micropump piston (on the left) and tether (on the right) after pump testing. Notice also the rough “MIT69a” etch quality along the filet surface with leftover pyramids, some of which extend out into the tether region and are potentially a source of failure during actuation.
In the case of the round 5 micropumps the pistons sat on the pyrex layer and could not curve downwards to stretch the tethers. We also saw in Chapter 2 that 1Atm of differential pressure across the tethers (maximum actuation that we apply during testing) should not break them.

We were still able to test the vacuum generation capability of a working die and the best results are shown in Figure 4-27. At 0.75Hz operation (within the operating region shown in Figure 4-29) we generated a new low vacuum pressure of 258Torr below atmosphere. Our previous best result from round 5 was 163Torr below atmosphere.

To better understand why we achieved 163Torr in round 5 and 258Torr in round 6 we developed a simple “ball-park” model for our micropump that showed how the device parameters influenced the lowest achievable vacuum levels (computational fluid dynamics would be needed create a more detailed and accurate model). For a given frequency each of these parameters represents a volume that can be pumped out or cannot be pumped out (leaks and inaccessible pump volume represent extra dead
volume). By calculating the modified dead-to-pump volume ratio we can forecast the best possible vacuum level that each device can generate. In this simple model the minimum achievable vacuum pressure is

\[
P_{mn} = \left( \frac{V_d}{V_p} \right) 760 \text{Torr} = \left( \frac{V_{d-channels} + V_{d-curved-piston} + V_{d-valve-leakage}}{V_p} \right) 760 \text{Torr},
\]

- \( V_p \) is the total pump volume including the pump chamber and the channels from the pump chamber to the valves – region in blue shown below. For both round 5 and round 6 we modeled assuming 5.8um high chamber ceilings (as measured using a stylus profilometer), because it was not possible to etch exactly 6um and we made sure to stop short.

- \( V_{d-channels} \) is the total channel dead volume – region in red shown below. The channels in round 5 were approximately 50um in radius and 2.2mm long. The channels in round 6 were 150um in radius and 3.75mm long. In both cases the cross channels traveling horizontally across the DSP top surface were slightly over etched compared to the channels going straight down through the wafer, and this increase in channel volume was taken into account.

The valve lips in round 6 were located at the input/output pistons centers, and so we made their channels wider to reduce their flow resistance as we made them longer. (Recall that in round 5 the valve openings were at the piston edges and suffered a much higher leak rate than the valve openings in round 6).
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- $V_{d\text{-curved-piston}}$ consists mostly of A) the chamber volume that isn’t pumped out by the pump piston during actuation (tether and piston regions not in contact with the chamber ceiling) – red region shown below. This volume was extracted from FEA models of the round 5 and round 6 pump chamber pistons during actuation (shown in Figure 4-15).

![Image of curved piston](image)

And $V_{d\text{-curved-piston}}$ consists partially of B) the chamber volume lost due to the curvature of the pump piston while un-actuated – region in red highlighted below. This volume, as show in Figure 4-10, can be as large as 31% of the pump chamber volume, but we assumed it here to be about 15% on average for round 5 (from measurements), and 0% for round 6 (since we didn’t have measurements).

![Image of un-actuated piston](image)

- $V_{d\text{-valve-leakage}}$ is the pump volume leakage for the given valve geometry – arrows in red shown below. For round 5 (valves at piston edges) these were valve leak rates near 160Torr pressure differential, and for round 6 (valves at piston centers) they were valve leak rates near 260Torr pressure differential.

![Image of valve leakage](image)

With increasing frequency the valves are used for shorter portions of the pump cycle thereby reducing the effect of valve leakage on the minimum achievable vacuum level.
relative to the other dead volume contributors (i.e. the magnitude of the volume leaked through the valves per pumping cycle, $V_{d-valve-leakage}$, decreases with frequency).

The approximate contribution of $V_{d-valve-leakage}$ can be calculated as follows

$$
\Delta V = \Delta n \times \text{molar volume} \left[ \text{m}^3 \right] \text{ where } \Delta n = \frac{\Delta P \times V_i}{RT}, \text{ and } \Delta P = \text{slope/frequency}
$$

where $\Delta P$ is calculated at 0.75Hz frequency using the experimental leakage rates we had measured earlier for the round 5 and round 6 micropump valves at their respective maximum achievable pressure differentials (approximately 160Torr for round 5 and 260Torr for round 6). For example, we had measured the leakage slope for the round 6 micropump valves (40um thick) located at the piston centers to be 0.0214Torr/sec at 30Torr pressure differential. Therefore, the largest leakage slope we can expect here at 260Torr pressure differential is approximately $\Delta P = (260/30) \times 0.0214$ Torr/sec, which makes $\Delta P = (260/30) \times 0.0214/0.75$ Torr. Since we had measured this leakage slope for a fixed volume $V_i$ (1/8” inner diameter by 13cm long plastic tube) we can calculate the volume lost ($\Delta V$) over a single pumping cycle using the equation above.

Given these modeling parameters the results are presented graphically in Figure 4-28. Starting at atmosphere (the blue bar), the red bar represents the dead volume in the channels and the volume in the pump chamber that the pump piston cannot expel. The thinner pump piston in round 6, pumps out more pump chamber volume than the pump piston in round 5 (as shown by Figure 4-15), but because round 6 has more channel dead-volume the effect is offset and both devices have very similar dead-to-pump volume ratios. The major difference is the effect of valve leakage represented by the green bars, strongly suggesting that valve lip placement and width is an important factor in micropump performance. The round 6 pumps have their valve openings at the input/output piston centers and therefore leak a lot less, leading to better overall performance during vacuum generation. The ideal lowest vacuum levels predicted by this model for round 5 and round 6 are 187Torr and 279Torr, respectively. We measured
163Torr and 258Torr during testing. One point to note is that the test setup leakage (when assembled and pre-tested properly) was measured to be orders of magnitude less than the valve leakage, and was therefore not included in this model.

The measured flow rate as a function of the operating frequency (6 stage pumping cycle) is plotted in Figure 4-29. As before, at each frequency we generated vacuum in a closed and defined volume connected to the input port of the micropump and took several measurements of the rate of change of the pressure drop, which then gave us the flow rate ($\Delta P/t \sim \Delta m/\text{moles of gas}/t \sim Q$). Since 0.75Hz falls safely within the micropump’s operating region it was used as the pumping frequency for the vacuum generation experiment discussed earlier. Similar to round 5, the flow rate reaches a peak near 2.25Hz after which it starts to decrease. A search for a simple way to model this behavior and better understand the reasons for this maximum frequency of operation led us to electrical analogies for microfluidic components.

The equations of fluid mechanics in certain limits, for example long and narrow channels, can be simplified by replacing real systems with simplified mathematical expressions. Micro-systems approximate these limits very well. Although a complete
solution for a micro-channel flow problem can be quite involved, one dimensional models give us approximate solutions. So we can treat micro-channels as single dimensional elements, their intersections as nodes where flows combine, and model total fluid flows and pressures with circuit-like elements related by an Ohm’s law like equation, called the Hagen-Poiseuille law. This is a very useful result, and allows us to create simple circuit diagram approximations for flows in complicated fluidic networks.

These models of flow through micro-systems require that we are in the low-Reynolds number limit, which is most of the time a good assumption in micro-systems due to their short length scales. In this limit, we can approximate the flow as composed of Poiseuille and Couette like components only. The Poiseuille flow is generated by pressure differentials as given by the Hagen-Poiseuille law: \( \Delta P = Q/R \), where \( \Delta P \) is the pressure drop across the channel (in Pascals), \( Q \) is the volumetric flow rate through the channel (in \( \text{m}^3/\text{sec} \)) driven by the pressure differential, and \( R \) is the hydraulic resistance of the channel. Note how this expression is analogous to Ohm’s law: \( V = IR \), with pressures representing voltages, volumetric flows representing currents, and fluidic resistances representing electrical resistors.
Chapter 4: The Working Micropumps

The hydraulic resistance of a micro-channel in one dimension is approximated by

\[ R = \frac{8\eta L}{r^2 A_{\text{channel}}} \text{ where } r = \frac{2A_{\text{channel}}}{C} \]

is the hydraulic radius of the channel, \( A_{\text{channel}} \) is the cross-sectional area of the channel, \( C \) is the length of the perimeter of the channel, and \( \eta \) is the fluid viscosity. If the channel is circular, then \( r \) is equal to the radius of the circular cross-section. Derived from the flow rate equation for Poiseuille flow, the equation for \( R \) is only exact for infinitely long circular channels. For finite channels or non-circular cross-sections it's only an approximation, but most of the time a good one. We can now derive the hydraulic resistances for the elements in our micropump, and they are:

- **Input/output valves:** \( R = \frac{6\eta}{\pi h^2} \ln\left(\frac{r_2}{r_1}\right) \), where \( r_1 \) is the inner radius, \( r_2 \) the outer radius, and \( h \) the space between the valve lip and the piston.

- **Channels between the valves and pump chamber:** \( R = \frac{8\eta L}{\pi x^4} \), where \( L \) is the length of the channel, and \( x \) is the radius of the channel.

- **Pump chamber:** since the pump chamber is a circular disk, we are modeling it’s resistance as a parallel combination of thin rectangular strips along the flow lines going from the input of the pump chamber to its output, as shown in Figure 4-30. Each of these strips has resistance \( R = \frac{8\eta L}{wh^3} \), where \( L \) is the length of the strip, \( w \) is the width of the strip (100um), and \( h \) is the chamber height.

![Figure 4-30: Resistance model of our 10mm radius pump chamber. Each of the blue lines shown here represents a thin rectangular strip of width 0.5mm (used 0.1mm wide strips for calculating actual resistance) and height 6um going from the input of the pump chamber to the output.](image-url)
The final element we need to model is the pump volume, which acts as a capacitor that is charged by the incoming flow until the pressure matches the source (much like current charging a capacitor until its voltage matches the supply). The chamber capacitance is related to the flow and pressure by $Q = C \frac{dP}{dt}$ (analogous to $I = C \frac{dV}{dt}$). Now according to the law of conservation of mass, the time rate of mass entering the chamber through an inlet must equal to the increase of mass in the chamber, or $\rho Q = \frac{d}{dt} (\rho V)$ where $\rho$ is the fluid density and $V$ is the fixed pump volume. So we can re-write this expression as follows $Q = \frac{V}{\rho} \frac{d}{dt} (\rho)$. From the ideal gas law we know that $P = \rho R_{gc} T$, substituting $P$ for $\rho$ we see that the flow rate is related to the change in pressure by $Q = \frac{V}{\rho R_{gc} T} \frac{d}{dt} (P)$, which means that the chamber capacitance can be represented by $C = \frac{V}{\rho R_{gc} T}$, where $\rho$ is the fluid density, $V$ is the fixed pump volume (including the chamber and channel volumes), $R_{gc}$ is the ideal gas constant and $T$ is the temperature.

With these components in hand we can draw the simple circuit diagram for the charging and discharging of the micropump volume shown in Figure 4-31. Since the chamber piston tethers are compliant (as we saw in Figure 2-9) they also have an associated capacitance. This circuit has a time constant which represents the time it takes to fill or un-fill the pump volume. Given the micropump dimensions presented earlier for the round 5 and round 6 devices, the component values are:

- Round 5: R-valve = 8.5193x10$^{10}$, R-channel = 2.1502x10$^{10}$, R-chamber = 9.1505x10$^{11}$ (slice width = 100um), C-chamber = 1.8425x10$^{-14}$, C-tether = 8.7667x10$^{-16}$

- Round 6: R-valve = 4.2848x10$^{10}$, R-channel = 4.8202x10$^{8}$, R-chamber = 9.1505x10$^{11}$ (slice width = 100um), C-chamber = 2.5203x10$^{-14}$, C-tether = 8.7667x10$^{-16}$
Chapter 4: The Working Micropumps

![Circuit model](image)

**Figure 4-31:** Circuit model for the charging and discharging of the micropump chamber.

Plots of the pump volume pressure as a function of time are shown in Figure 4-32 for an input pressure of half an atmosphere. The first point to note is that they have relatively similar fill times, which we expected after the pump-down modeling results (i.e. similar dead-to-pump volume ratios). The second is that it takes approximately 158msec to fill and un-fill the round 5 pump volume, and approximately 200msec to fill and un-fill the round 6 pump volume. These fill times correspond to 8 time constants of

![Plots of pump volume](image)

**Figure 4-32:** Plots of the pump volume fill times for the round 5 and round 6 devices using our circuit model.
the RC circuit shown in Figure 4-31. A similar analysis of the test setup showed that it takes only a few microseconds to fill the channels in the testing platform that actuate the micropump pistons. In the 6 stage cycle actuating the micropump pistons to generate vacuum the pump chamber is filled once and un-filled once. During the rest of the four steps the input and output pistons are actuated shut or open, and held in place for a minimum of about 10msec. The pressure switches and associated drive circuitry in the test setup that actuate the pistons take approximately 5ms to respond (from their specification sheets). The combined times during pumping are:

\[
F_{\text{max}} = \frac{1000}{\text{pump fill time} \times 2 + 10 \times 4 + 5 \times 6} = 2.59\text{Hz} \text{ for round 5 and } 2.13\text{Hz} \text{ for round 6}
\]

which are quite close to the approximate maximum frequencies of operation we observed for the round 5 and 6 micropumps, shown in Figures 4-8 and 4-29, respectively.

To model the flow-rate at the micropump output versus pressure differential applied across its input–output ports (with the output open to atmosphere), we can use the circuit diagram shown in Figure 4-33. Unfortunately as discussed earlier, because our mass flow meters are not able to accurately measure very small flows we don’t have
experimental data to compare with our modeling results for the round 5 and 6 devices. The round 1 devices (covered in Chapter 3) had over etched ceilings (close to 7.5um tall) and their pistons were firmly stuck to the bottom pyrex layer, allowing overall for much larger and measurable flow rates. In Figure 4-34 their mass flow readings are plotted and compare relatively well with our circuit modeling results using the correct component values (i.e. 7.5um tall ceiling, etc.).

Figure 4-33: Circuit model for the flow rate observed at the output versus the pressure differential applied across its input-output ports.

Figure 4-34: Plot of the applied pressure differential versus measured and modeled flow rates observed at the micropump output port for the round 1 devices.
Chapter 5

Future Micropump Development

5.1.1 Summary of Work

After reviewing the micropump research space, we considered several micropump designs and settled on an active valve displacement micropump using piezoelectric actuation, to meet our goals for speed, power, and vacuum generation. Given the largest available piezo-stack actuation we used computer models to dimension the input/output valves, channels, and pump chambers to produce the dead-to-pump volume ratios needed to achieve a $< 5$Torr vacuum level with a cascade of two stages. We then used non-linear numerical models to study the maximum stresses faced by the tethers connecting the pistons to the chamber walls, and selected a tether width and thickness that aimed to minimize the operational stress as much as possible. This design exercise led to a final micropump layout geared to meet the goals set out by the MGA project, while leveraging our prior experiences and available fabrication facilities.
To be able to rapidly characterize the performance of our design and all future micropump designs we considered several possible testing schemes, but finally settled on a computer controlled pneumatic testing platform since it provided the greatest flexibility. We then designed, built, and characterized our testing platform in advance of building our micropumps.

During the first four rounds of fabrication we faced many challenges, a few of which included blown off pistons, pyrex layer and SOI-DSP interface damage, silicon-direct bonding failure, incomplete anodic bonding, stuck pistons, and very often damaged pump chamber tethers. Further investigation into the tether failure issue led to a new process flow that allowed for SOI layer fabrication independent of the DSP layer, and with well defined tether fillets for structural integrity. These improvements led to a round 5 generation of micropumps that not only had fully function parts but were also capable of generating flow and producing vacuum. These pumps showed an increase in flowrate with actuation frequency as expected, but up to a maximum frequency of operation near 2.5Hz. We were able to pump down by 163Torr below atmosphere at 0.75Hz (working within the linear region of operation) and 9psi actuation. To better understand why the round 5 micropumps performed the way they did we designed a round 6 generation of micropumps that allowed us to test 2 ideas:

- how much of a role does piston bending play in micropump performance - can flatter pistons decrease leakage and dead-volume, thereby leading to better overall performance?
- how does valve lip placement and geometry affect leakage and which designs perform better than others?

In this way, the purpose of round 6 was to help us close the loop on our understanding of the round 5 design and was not a proposed direction for better micropump performance (although it did perform better). In the following sections we will present an optimized micropump design and present guidelines for micropump fabrication for any application.
The working micropumps of round 5 and round 6 inspired many improvements in the test setup and the testing approaches we used since we finally had working devices (for example, using a micro-controller to accurately control pumping frequency, and pressure sensors as flow meters in place of MFM's or water droplet experiments). The analysis of their data also required better techniques and led to three advances in our computer modeling (in addition to our initial modeling work in Chapter 2):

- detailed FEA models of the pistons and tethers to understand their curvature during actuation,
- a simple minimum achievable vacuum prediction model that took valve leakage, piston bending, and micropump dimensions into account,
- and a flow-circuit model that helped us identify the largest flow resistances in our micropumps and their impact on the maximum frequency of operation.

The round 6 micropumps were also capable of operating at just above 2Hz and produced vacuum of 258Torr below atmosphere. These micropumps and valves helped us confirm our round 5 hypothesis, verify our models, and illustrate the relative impact of the various parameters we tried modifying (including piston thickness, valve lip width, and valve lip position). We now have a better understanding of our micropumps, which helps point the direction to future designs that will more closely match any desired specifications.

As we saw in Figure 1-2 there are great number of ways of designing reciprocating displacement micropumps (many valve, chamber, material, and driver options). So it's difficult to recommend a single design procedure that can be generally applied. In the following sections we will design a better future micropump that can be fabricated using the same tools and methods we have been using so far, but given a few initial constraints (important for limiting the number of possible design variables), and conclude with a list of recommended experiments that would further our understanding of these type of devices.
Before we begin the round 7 design exercise it’s worth recapturing some of the key observations, lessons learned, and do’s and don’ts for anyone looking to fabricate micropumps similar to ours. To simplify the discussion, we’ll separate the review into three parts: micropump fabrication, testing, and performance.

5.1.2 Notes on Micropump Fabrication

The process flows described in Chapters 3 and 4 (and included in the Appendix) show how to fabricate the round 5 and round 6 micropumps. For people familiar with micro-fabrication the simpler steps will immediately make sense, such as the use of thermal oxide to protect bonding surfaces, use of thick oxide nested masks to simply the fabrication of complex structures, and remembering to remove any left behind Teflon before running additional etch steps. The process flow order has slightly higher complexity and becomes clearer while fabricating, for example opening up the input/output ports on the SOI layer frontside before starting the tether etches, and making sure to machine the DSP layer valve lips last. Other “nitty-gritty” steps and concepts are harder to capture in the process flow and are sometimes the most important points to note for someone not experienced in micro-fabrication. We try to highlight those here:

- Always make sure to have dummy wafers running through all process flow steps before using your main wafers - cannot stress this point strongly enough.
- Always protect the backside of any wafer you are processing with photoresist even if it already has thermal oxide grown on it - some machines and process steps end up scratching the wafers and having two layers of protection is better than one.
- Make sure to rotate the wafers often during etching to maximize etch uniformity, and mounting wafers on blue-tape instead of quartz wafers during break-through etches leads to better heat distribution and etch uniformity. Blue-tape doesn’t provide the structural support that quartz wafers do so there
is small chance of wafer cracking. On the whole we’ve only had 2 wafers crack out of 18 during break-through etches using blue-tape. Any surface that will be exposed to blue-tape should have photoresist on it to avoid having the blue-tape come in direct contact with the wafer. Subsequent removal of the blue-tape in acetone becomes very straightforward.

- The DRIE etcher clamps, although far from the devices, produce enough stress to crack thin membranes - we often found the pump piston tethers at the wafer top and bottom were damaged because of this.

- Never run any short etches in one step (for example the 6um chamber height etch) - make sure to use the stylus profilometer to check the etch depth often. For long etches the interference microscope is useful. Always keep a depth map of your etches across the entire wafer to see where you are and if any parts need to be covered up with photoresist because they’re etching too fast.

- Make sure to check the etch rates for any deposited oxide (both in BOE and in the DRIE etchers) - they can vary widely depending on the oxide deposition recipe.

- Making sure you have alignment marks on both sides of all wafers might seem redundant but can come in very handy when one set of alignment marks is damaged or not properly machined. Also make sure to protect all alignment marks from etching with photoresist and Teflon tape. This will leave you with protected alignment marks that at the end will unfortunately have a lot of oxide on and near them - you will need to put a few drops of BOE on the alignment marks at the very end to thin down that oxide so that any future wafer-level oxide stripping step works (HF stripping would remove all oxide very quickly but you can’t use HF on the SOI wafers with exposed tethers, the only way of stripping the oxide on these wafers is BOE).

- The SOI tether and piston creation process is the most time consuming step. Make sure you are using an etch recipe that will allow you to etch fastest in
the trench center and control the fillet profile. Make sure the wafer is mounted on blue-tape. Once the buried oxide is reached anywhere on the wafer it’s important to cut down the etch times to 1-2min per etch and to measure the exposed tether widths after each step. All the tethers will etch open at different rates so it’s important to keep a proper etch map. Once a tether is complete you need to paint it with photoresist by hand, which means to drop some thin resist into the trench using a narrow gauge wire so that it sweeps around the trench to cover it up. Do not touch the trench/piston with the wire. After every paint job the photoresist needs to be dried, but since the wafer is mounted on blue-tape it can’t be put into the oven - you’ll need to dry it in air in safe place for roughly 3hrs after every paint job. If the photoresist is not fully dried before the next etch you’ll see bubbles form in the photoresist, which could result in exposed silicon. Completing all the tethers in this way can take over a week so it’s important to make machine reservations well in advance and be patient.

- After silicon-direct bonding make sure to use the IR camera to check the quality of the bond and map out where potential unbonded regions are. Do this again after annealing.
- During die-sawing use the thickest blade and make sure to put die-saw tape on both sides to prevent water and slurry from entering the micropumps. Also make sure to make as many vertical cuts as wafers in the stack with each cut going through each wafer and slightly below it (so as not to end up at a bonding interface). Start with a dummy cut and always cut at a slow speed - faster speeds, although save time, can be very violent for the micropumps.
5.1.3 Notes on Micropump Testing

With respect to the test setup and testing schemes there are several points to keep in mind:

- Don’t actuate with more than 1Atm below and above atmosphere since that’s all we have modeled the tethers to handle (and the range of our pressure sensors).
- Only use thick walled tubing (at least 1/16” wall thickness) - thinner tubing deforms under vacuum and high pressure and could leak at tube connections. It can also change the test volume being pumped.
- Use cable ties to minimize leakage over barb fittings.
- It’s important to use the pressure sensors to monitor the actuation pressures - the gas source gauges are very coarse.
- Always use bleeder valves along the high pressure and vacuum actuation lines incase of pressure buildup.
- Always use submicron filters ahead of any positive pressure sources - the critical heights in our micropumps are only 6um tall, and a micron-sized dust particle could easily block flow or impede actuation.
- O-rings
  - It’s important to check the condition of all the o-rings in the setup before beginning an experiment (o-rings connect the pressure switches to the testing platform and seal the micropump against the testing platform). O-rings lose shape and start to crack over time and could become a source of leakage.
  - If the micropump is not properly sealed against the testing platform before beginning an experiment the ultimate measurements made will certainly change. Since the start state is vacuum actuation (for all ports) listen to hear for any leakage.
o Make sure the o-rings are soft enough to absorb clamping pressure or the micropumps could break. Also make sure they are not too soft or the micropump surface will come in contact with the metal testing platform (you need to have something in between).

o Add additional o-rings around the micropump to allow it to sit flatly along the testing platform surface. Since most of the fluidic ports are only along the bottom half of the micropump, the top half goes unsupported otherwise.

o Overall do not clamp too hard - we found that optical clamps work very well; they allow for the right application of pressure on top of the actuation and input/output ports.

• After a new testing platform is machined make sure to clean the oil and metal debris left behind before using. It’s very important that the top surface is machined as flat as possible.

• Try to operate the testing platform in the cleanest space available (such as in a vented hood) to avoid exposure to dust and oil.

• Always store the micropumps facing down so that dust doesn’t enter any port.

• Micro-controllers are very useful for driving the actuation mechanism since they allow for very precise frequency control. The captured data on the other hand depends on the computer being used and how fast LabView is able to run on it (which changes as other processes run) - therefore it’s important to always make sure to capture the time stamp of any data value so that you know what was captured when (and process accordingly).

• The pressure switches take 5ms to switch. A circuit analysis (similar to that used to find the micropump maximum frequencies of operation) showed that the time it takes for the channels in the testing platform (underneath the micropump ports) to be filled with high pressure or vacuum (after switching)
is only a matter of microseconds - we therefore don’t consider this time in the micropump frequency analysis.

- Fluctuations observed in the high pressure actuation channels during operation are caused by the pressure selector switches, since they allow for vacuum to leak into the high pressure channels during switching.
- There is a great deal of electrical wiring in the test setup - make sure it is all labeled and held securely in place. It’s useful to routinely check to see that the actuation signals are as expected and that the power supplies are providing the required power with minimum fluctuation.
- It’s worth measuring the noise in the driver circuit and captured data and look for possible ways of reducing it.
- Our mass flow meters were not very useful due to their large resistances and slow response. For high speed operation with large flow rates the Honeywell MFM shown in Chapter 2 is recommended.
- There maybe some variations in performance due to operating temperature. During the day our testing area sees direct sunlight and at night the AC is always on so the testing setup temperature does fluctuate by several degrees.

5.1.4 Notes on Micropump Performance

Since we’re building a vacuum micropump we need to pay attention to the dead-to-pump volume ratio \((V_d/V_p)\), which often required the use of shallow chambers and narrow channels (i.e. narrow valve openings) - this made \(V_d\) small but the fluidic resistances large and therefore the maximum frequency of operation small. If we were building a standard micropump (not for vacuum generation) we wouldn’t need to minimize \(V_d\), and could use taller chambers (even with small actuation) and operate at higher frequencies.

We noted that pistons definitely bend during operation. This is partially due to the buried oxide which pre-stresses the wafers; but what is the effect of any left over oxide
on the tether region, and what if we deposit a thin film on the backside of the pistons to balance the buried oxide stress? Overall the bending of our pistons means that the tethers don't deflect by 6μm, which suggests that there may be room for optimization (i.e. narrower width tethers and less associated dead-volume). Pneumatic actuation doesn't help with piston bending due to its uniform application of pressure - piezo actuation around the piston edges could overcome this issue and wouldn't face the 5ms switching times that limit our pressure selectors.

We observed that most often the chamber piston tethers broke during operation (almost never the valve tethers). Kevin Turner's thesis [151] highlighted the impact of small defects in tether etching on overall integrity (and is where we obtained our 1GPa critical stress limit for SOI tethers). We saw that even with regular wafer rotation during etching uniform tether widths weren't achieved; across a chamber piston there was always at least a 20-30μm difference in tether width. We don't yet understand the impact of this variation - certainly the wider regions would actuate more than the narrower regions, leading to non-uniform actuation and stress distribution. More advanced FEA models are needed.

Having the pistons sit on the pyrex layer, as in round 5, is more attractive than having them float (220μm) above the pyrex layer, as in round 6. Since we often use the standard lab vacuum supply (-680Torr below atmosphere) and we know that pistons bend, it's conceivable that pistons are forced to deflect by more than 6μm downwards during vacuum actuation in round 6, which could cause piston/tether damage. Future designs should work with stiffer pistons that have rest surfaces in both actuation directions (like round 5).

Finally, note that all micropump and valve testing was conducted at 9-10psi actuation to be consistent and so that comparisons between designs and tests could be fairly made. At higher actuation pressures certainly more of the pistons would come in contact with the ceilings leading to overall lower chamber dead-volume ($V_d$) and lower valve leakage (since the valve lips would seal better). Although the maximum frequency
of operation would not change, this would likely result in lower achievable vacuum levels (lower than the 163Torr and 258Torr levels achieved in round 5 and 6, respectively). The tether stresses would be higher but still below the modeled values in Chapter 2.

5.2 Round 7 Design

Since there are great number of ways of designing reciprocating displacement micropumps (huge number of valve, chamber, material, and driver options) it’s not possible to recommend a single design procedure that can be generally applied. In this section we will try to design an optimized micropump geared towards improving overall size, robustness, and performance (including frequency and vacuum level) that can be fabricated using the same tools and methods we have been using so far given a few initial constraints (otherwise there are still too many design variables); and we will present guidelines for micropump design and fabrication that can hopefully be used to produce micropumps for any application. In the section that follows we will recommend experiments that should be conducted to further our understanding of these types of devices.

Although all the pump chamber and valve pistons we fabricated previously were designed to have similar tether widths and thicknesses, it was almost always the pump piston tethers that broke whenever failure was observed. Smaller pistons have a smaller tether area (most fragile region) that could be damaged. They also have closely matching fillet and tether widths since etch rates are more uniform over smaller etching regions. Given our experiences, we feel that future designs should aim to work with smaller radius pump pistons. The round 5 valve pistons were 3.2mm in radius, the round 6 valve pistons were 1.5mm in radius, and both designs worked quite well (compared to the 9.5mm radius pump chamber pistons that often suffered tether damage).

We will now work through a simple design exercise to layout a potential new micropump. An attractive design would

- pump down to a low pressure level – have a small dead-to-pump volume ratio
operate at high frequency – have low fluidic resistance components
be structurally robust – have a small tether area with widths, thicknesses, and fillets geared to handle the operating stresses

These considerations however are interlinked, and trying to maximize one property often reduces another. For example, using a smaller pump piston leads to a smaller pump volume and therefore larger relative dead-volume (i.e. inability to pump down to low pressures). To increase the pump volume given this smaller piston the actuation range needs to be increased. Although this allows for higher frequency operation (since the chamber height is the critical factor in determining its resistance), the tethers will experience greater stresses and could break.

Since there are many interlinked variables at play it makes sense to set some design goals and constraints and work to maximize the micropump’s performance given those. For example, based on our prior experience it makes sense to propose the following:

- pump chamber piston radius $\leq 3.5\text{mm}$ (much higher yield option, and much smaller overall micropump die)
- actuation height $< 9\text{um}$ (recall from Figure 2-2 our piezo-stacks can provide just below $9\text{um}$ of actuation at 120 volts)
- tether thicknesses $\geq 10\text{um}$ (since $10\text{um}$ was already quite fragile)
- maximum frequency of operation an order of magnitude greater than our current maximum, which is quite low (i.e. new maximum frequency near $25\text{Hz}$)
- generate a two stage absolute vacuum pressure $\leq 150\text{Torr}$, (a more reasonable target given our results to date)

These design goals and constraints cannot be satisfied without a relatively low dead-volume design. Starting with the round 5 layout (shown in Figure 2-4) our first attempt at minimizing dead volume yielded the design shown in Figure 5-1. The top schematic shows the micropump in the “pull air in” state, and the schematic on the bottom shows the micropump in the “push air out” state, with the total dead-volume highlighted in pink.
and red; the pink refers to the dead-volume in the channels and the red refers to the dead-volume in the tether region. Our original micropump design had 5 layers. This design has two additional layers and therefore slightly greater fabrication complexity, but the additional SOI layer (L3) allows for the placement of the input and output valves above the pump chamber – significantly reducing the channel length and associated dead-volume. Recall the round 5 channel length was 2.2mm and the round 6 channel length was 3.75mm; in contrast, this new design’s channel length is approximately 0.45mm (assuming a 450um thick L4 as in our original design).

Although the channel dead-volume (highlighted in pink) has been reduced significantly there is still a large amount of tether dead-volume all around the pump chamber piston (highlighted in red). Looking for a design that minimized the tether dead-volume brought us to the micropump layout shown in Figure 5-2. Again, the top schematic shows the design in the “pull air in” state, and the schematic on the bottom

![Figure 5-1: Micropump design with a minimal channel dead volume. Schematic on top shows the un-actuated piston state and on the bottom shows the actuated piston state. Red and pink regions refer to the tether and channel dead volumes, respectively](image)

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shows the design in the “push air out” state; with the total dead-volume highlighted in pink. In this design the tethers are deflected when the valves and pump chamber are being opened in contrast to before, and therefore the only dead-volume is that in the channels. This design has the smallest dead-volume of any of our prior proposals.

![Figure 5-2: Micropump design with a minimal channel and zero tether dead volume. Schematic on top shows the un-actuated piston state and on the bottom shows the actuated piston state. Pink regions refer to the channel dead volumes.](image)

Before we can estimate the performance of this design we need to determine the required tether widths. Figure 5-3 shows a plot of the maximum tensile stress experienced by tethers of different thicknesses – for a guided translation of 7um, 8um, and 9um at their inner edges, while the outer edges are clamped, and there is a 1Atm pressure differential across the tethers (pressure above minus pressure below = 1Atm – greater than the maximum they would ever face during operation). The stress plots are normalized to the critical value of 1GPa for SOI wafers identified by [134] and [151]. The red curves correspond to 10um thick tethers, the blue curves correspond to 12um tethers, and the black curves correspond to 14um thick tethers. In each case the bottom
curve is for 7um actuation, the middle curve is for 8um actuation, and the top curve is for 9um actuation.

![Graph showing normalized stresses for different tether thicknesses](image)

**Figure 5-3**: Maximum normalized stresses experienced by different thickness tethers under 1 Atm pressure differential for a guided translation of 7 - 9um at their inner edge, while the outer edge is clamped. Top curve in each case = 9um of actuation, middle curve in each case = 8um of actuation, and bottom curve in each case = 7um of actuation

Note that with increasing tether thickness the overall stress magnitude decreases. In contrast, the thinner the tether the smaller the tether width where the stress is minimized; the minimum stress point for the 10um thick tethers occurs at a narrowest tether widths (between 550-600um), and the minimum stress point for the 14um tethers occurs at the widest tether widths (between 670-730um). Our round 5 and round 6 designs used 480um and 500um tether widths respectively, and were some of the widest tether structures fabricated at the MIT Microsystems Technology Laboratories. Wide tethers are prone to fabrication irregularities and handling damage but since we need to work with them it's worth considering a thicker tether structure than what we've been using so far (10um). A good balance of thickness and width appears to be the 12um thick tethers, and in particular the 600um wide tethers that translate 8um (middle curve). Had we opted for a total travel of 7um we could have used a 500um wide tether with the same maximum stress level. So how do these options stack up? First we compare dead-to-pump volume ratios assuming that we are working with the widest chamber pistons.
available to us – 3.5mm radius, to maximize pump volume, and 150um radius channels as in round 6 (to be able to leverage that channel and valve data). We’ll call the 500um wide, 7um traveling tether option 1 and the 600um wide, 8um traveling tether option 2.

The dead volume in this design is given by

$$V_d = 2\pi R_{\text{channel}}^2 L_{\text{channel}}$$

where $R_{\text{channel}}$ is the channel inner radius (150um for both options), and $L_{\text{channel}}$ is the channel length (450um for both options). The total pump volume is then given by

$$V_p = V_d + \pi R_{\text{chamber}}^2 H_{\text{chamber}} + 0.5\pi \left( (R_{\text{chamber}} + W_{\text{tether}})^2 - R_{\text{chamber}}^2 \right) H_{\text{chamber}}$$

where $R_{\text{chamber}}$ is the pump chamber piston radius (3.5mm for both options), $H_{\text{chamber}}$ is the pump chamber height (7um for option 1 and 8um for option 2), and $W_{\text{tether}}$ is the tether width (500um for option 1 and 600um for option 2). Note we’re assuming that exactly half of the tether swept volume is part of the pump volume, which is a reasonable assumption under small pressure differentials. The dead-to-pump volume ratio ($V_d/V_p$) for option 1 is then 17%, and for option 2 is 14.8%. For an ideal single stage pump this means that option 2 can pump down $(0.17 - 0.148)760\text{Torr} = 16.7\text{Torr}$ below option 1. (For a cascade of two pumps this difference is $(0.17^2 - 0.148^2)760\text{Torr} = 5.3\text{Torr}$). Note that in general ($V_d/V_p$) could be plotted or differentiated over all its variables to find the “optimal design.” In this case we are using dimensions we have some familiarity with from prior fabrication rounds, to be able to leverage performance measurements and compare results.

We now look at how the two options compare in terms of fluidic resistances and chamber fill times. Recall that the design with the lowest fluidic resistance components can fill and un-fill the pump volume in the shortest amount of time, allowing for higher frequency operation. As we saw in Chapter 4, the key components to consider in this exercise are the valve resistance, channel resistance, chamber resistance, and chamber capacitance as shown in Figure 5-4 (we’re assuming for simplicity that the tether capacitance/compliance is minimal).
The hydraulic resistances of the elements in our new micropump design are:

- **Input/output valves**: \( R = \frac{6\eta}{\pi h l} \ln \left( \frac{r_2}{r_1} \right) \), where \( r_1 \) is the inner radius (150um for both options), \( r_2 \) the outer radius (190um for both options), and \( h \) the space between the valve lip and the piston (7um for option 1 and 8um for option 2)

- **Channels between the valves and pump chamber**: \( R = \frac{8\eta L}{\pi x h^2} \), where \( L \) is the length of the channel (450um for both options), and \( x \) is the radius of the channel (150um for both options)

- **Pump chamber**: since the pump chamber is a circular disk, we are modeling it’s resistance as a parallel combination of thin rectangular strips along the flow lines going from the input of the pump chamber to its output, as shown in Figure 4-30. Each of these strips has resistance \( R = \frac{8\eta L}{w h^3} \), where \( L \) is the length of the strip, \( w \) is the width of the strip (100um), and \( h \) is the chamber height (7um for option 1 and 8um for option 2)
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Figure 5-5: Resistance model of our 3.5mm radius pump chamber. Each of the blue lines represents a thin rectangular strip of width 0.1 mm and height 7um or 8um going from the input of the pump chamber to the output.

Note that for simplicity our model is only considering the volume above the 3.5mm radius pump chamber piston as the pump volume (and not including the tether region). We are also assuming that the pump chamber input and output are located at the piston edges to simplify calculations. Strictly speaking these assumptions are not accurate but a good place to start; in reality the pump chamber piston wouldn't be perfectly flat (making the height parameter \( h \) a function of \((x,y)\)), the tether region plays a role in reducing the resistance, and the input/output to the pump chamber would be located near the pump piston center (for faster filling/un-filling of the pump volume) since we get the greatest piston deflection there.

Finally, the pump volume capacitance is given by 

\[
C = \frac{V_p}{\rho R_{gc} T},
\]

where \( \rho \) is the fluid density, \( V_p \) is the pump volume (including the chamber and channel volumes), \( R_{gc} \) is the ideal gas constant and \( T \) is the temperature. Given all these component values we can estimate the pump volume fill/un-fill time as 8 time-constants of the circuit shown in Figure 5-4 (we found 8 time constants to be appropriate from our modeling work in Chapter 4):

\[
\text{Fill-time} = 8 \left( R_{\text{wall}} + R_{\text{channel}} + R_{\text{chamber}} \right) C.
\]

For option 1 the fill time = 16ms and for option 2 the fill time = 12.5ms. Considering both options have similar tether stress magnitudes, option 2 is more attractive both in
terms of dead-to-pump volume ratio and pump volume fill-time. In the 6 stage cycle actuating the micropump pistons to generate vacuum the pump chamber is filled once and un-filled once. During the rest of the four steps the input and output pistons are actuated shut or open for a short period of time.

There is no lower time limit for holding the valves in place during those four steps assuming that the actuation mechanism can support it (i.e. is faster). To be conservative lets assume that we hold the valves in place for 1msec and that the test setup has been re-engineered so that the driving mechanism actuating the pistons now only takes 0.5ms to respond. The maximum operating frequency for each design option can then be calculated as

\[
F_{\text{max}} = \frac{1000}{pump \ \text{fill time} \times 2 + 1 \times 4 + 0.5 \times 6}
\]

For option 1 \( F_{\text{max}} = 25.65 \text{Hz} \) and for option 2 \( F_{\text{max}} = 31.15 \text{Hz} \). So far both designs meet our goals but option 2 is more attractive.

In our former dead-to-pump volume ratio calculations we had assumed perfect conditions. To be more realistic we'll now try to take imperfect actuation and valve-leakage into account. In this case

\[
\frac{V_d}{V_p} = \frac{V_{d-\text{channels}} + V_{d-\text{valve-leakage}}}{V_{p-\text{carved-piston}}}
\]
where $V_{d\text{-channels}}$ is the total channel dead volume we had calculated before and $V_{p\text{-curved-piston}} = V_{d\text{-channels}} +$ the modified chamber volume due to the curvature of the pump piston during actuation, as shown by the purple region in Figure 5-6. To be very conservative we’ll assume the absolute worst, and set this modified chamber volume to be half its original (shown in Figure 5-2)

$$= 0.5\pi R_{\text{chamber}}^2 H_{\text{chamber}} + 0.25\pi (R_{\text{chamber}} + W_{\text{other}})^2 - R_{\text{chamber}}^2 \cdot H_{\text{chamber}}.$$

Finally, $V_{d\text{-valve-leakage}[f]}$ is the valve leakage volume that decreases with frequency, indicated by the red arrows in Figure 5-6. Since the pump chamber shape has changed, we can’t technically assume the same chamber resistance and maximum frequency of operation, and there isn’t a simple way to determine the resistance of the modified pump chamber without computational fluid dynamics. Once more to be very conservative, we’ll assume the change in shape is significant enough to have increased the chamber resistance by 50% (in reality it should be lower). In this case the maximum frequencies of operation become 18.2Hz for option 1 and 22.4Hz for option 2.

![Figure 5-6: More realistic micropump schematic showing valve leakage and a curved pump chamber piston during actuation (assuming half chamber volume lost).](image)

We can now approximate the contribution of $V_{d\text{-valve-leakage}}$ for both options at their respective maximum frequencies using the experimental leakage rates we had measured in Chapter 4 (since we’re working with the same valve design here). Given the minimum dead-to-pump volume ratio for a single stage is 14.8% (option 2), ideally the minimum
achievable vacuum level is \( (0.148 \times 760) \text{Torr} = 112.5 \text{Torr} \). In Chapter 4 we had measured the leakage slope for the normal thickness valve (40\,\mu\text{m} thick) located at the piston center to be \( 0.0214 \text{Torr/sec} \) at 30\,\text{Torr} pressure differential. Therefore, the highest leakage slope we can expect here at \( (760 - 112.5) \text{Torr} \) pressure differential is approximately \( (760 - 112.5)/30 \times 0.0214 = 0.4619 \text{Torr/sec} \). Since we had measured this leakage slope for a fixed volume \( V_t \) (1/8" inner diameter by 13cm long plastic tube) we can calculate the volume lost over a single pumping cycle as follows

\[
\Delta V = \Delta n \times \text{molar volume} \quad \left[ \text{m}^3 \right]
\]

where \( \Delta n = \frac{\Delta P \times V_t}{RT} \), and \( \Delta P = \text{slope/frequency} \).

We now have all the component values needed to calculate the modified dead-to-pump volume ratios for both options. \( (V_d/V_p)_{\text{modified}} \) for option 1 (at 18.2\,\text{Hz}) = 44.97\%, and for option 2 (at 22.4\,\text{Hz}) = 37.33\%, which means that the lowest achievable vacuum level for a single stage pump using option 1 = 341.7\,\text{Torr} and using option 2 = 283.7\,\text{Torr}. A cascade of two micropumps would obtain a minimum vacuum level of 153.7\,\text{Torr} using option 1 and 105.9\,\text{Torr} using option 2. Option 1 comes very close to meeting the goals that we had set out and is good choice because it works with the narrower tether widths we have successfully used before (500\,\mu\text{m}). If however we choose to work with the wider option 2 tethers (600\,\mu\text{m}) we can obtain an almost 45\,\text{Torr} improvement, which isn’t negligible. It’s useful to note that these are worst case projections and that hopefully in reality the results are even better.

Although this simple exercise has yielded an attractive future round 7 design that is worth investigating further, the point of this exercise was to briefly highlight the key steps in estimating the performance of any future micropump design before it’s fabricated.

### 5.3 Thesis Contributions and Future Studies

The work in this thesis has furthered our understanding of micropump design, fabrication, and testing. We see as its main contributions:
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- A MEMS vacuum micropump capable of generating 258 Torr below atmosphere.
- Detailed guidelines for the design of air micropumps, including
  - useful models and software tools for the analysis of plate/thin film bending/stress (Matlab, FEA), and for the analysis of fluid flow in MEMS devices (circuit models, Matlab),
  - detailed processes/best practices and etching recipes for the fabrication of reciprocating displacement micropumps, and in particular the generation of valves and very wide width tethers with proper fillets,
  - a complete pneumatic testing platform and effective testing techniques for the characterization of micropumping devices (including custom designed mechanical parts, electronics and software, as well as best practices from experiments),
  - experimental data demonstrating how the various design parameters influence pump and valve performance,
and finally, an attractive round 7 design that would bring us closer to meeting the MGA goals. In addition to these contributions, this thesis has also laid down the ground work for several areas of future investigation; to that end we propose the following mini-projects that should be undertaken to further our understanding of micropump development, and help us design the most appropriate micropump for any given application:

- Use computation fluid dynamics (CFD) to get precise resistance values for all the components as a function of their dimensions, and help estimate a more accurate maximum frequency of operation. CFD can also help model valve leakage and its dependence on valve geometry.
- Conduct a detailed tether fabrication study since they are the most critical components. This study should try to map out the tether width/thickness and fillet profile range within which we should work to obtain the deflection we

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need with lowest failure. Other tether materials should also be investigated – it's possible that another material may not be that much harder to use and lead to more robust micropumps.

- Look for ways of flattening the pump chamber piston, which curves due to the SOI buried oxide – perhaps by depositing an additional film on the backside of the piston. Or, is there any way to curve the pump chamber ceiling to better fit the pump piston and reduce dead volume?

- Conduct another valve leakage study investigating additional valve geometries (for example, concentric ring valve lips), and what materials can be deposited on the valve lips to reduce their leakage further (currently we have direct silicon to silicon contact).

- Investigate the possibility of incorporating pressure sensors into the design of the micropump to gauge the pressure levels in different parts of the pump.

- Incorporate piezo-stacks into the design by bonding them to the pistons to better understand what future work needs to be done with regards to drivers.

- Cascade two working micropumps together to see if the combination performs as expected and look for designs that could help optimize cascade performance (perhaps by sharing a valve, i.e. output valve of pump 1 is also the input valve of pump 2).

- Develop an order of magnitude faster testing setup that can also allow testing under different pressure conditions (for example, testing the micropumps under external vacuum).

- Run a power consumption study to understand the actual power consumption of these devices and see if they match our models.

All of these projects would go a long way towards furthering our understanding of micropumps and their development.
Appendix

Appendix A - Matlab Tether Stress Modeling Code, adapted from [134]

Plotmaxstress.m

% calculate normalized stress for different tether widths and
% stresses

clear all;
c1c;
numberofpoints = 15;
tw = zeros(1,numberofpoints+1);
nms = zeros(1,numberofpoints+1);

Dch = 10e-3;                  % m - chamber diameter
 tvb = 10e-6;
Pvm = 10*(14.6961*6894.7)/10; % 14.6961*6894.7 = 1atm
 yvc_imposed = 6e-6;

for wada = 1: (numberofpoints+1)
    tw(wada) = 400e-6 + (wada-1)*(500e-6)/numberofpoints;
    tether_width = tw(wada);
     NLLValveCapMembrane_CaseC;
     nms(wada) = maxstress;
     figure(2)
     hold on;
     r = ra:(rb-ra)/200:rb;
     r = r(2:end);
     plot(r*le3,fliplr(y')*le6,'r');
     plot(min(r)*le3,0,'.r');
     grid on;

end

figure(1);
hold on;
plot(tw/le-6, nms/le9, 'r');
grid on;

NLLValveCapMembrane_CaseC.m

% output:
% y,r,Vtotal,psi,theta,xi,thetaND,psiND,sigma_r_top,sigma_r_bot,
% yvc,Fvc,maxstress
% input: Pvm,yvc_imposed,rb,ra,tvm,E,nu,flagNL,No

% This Matlab code solves for the non-linear deflection behavior
% of the valve cap/membrane under loading Pvm and a desired valve
% cap deflection at %r=rb. The required Fvc to produce this
% deflection and the resulting deflection, slope, curvature,
Appendix

% swept volume, and membrane stress are calculated. Case C refers
% to the fact that we are applying Pvm and imposing a cap
% deflection, and then solving for the Fvc and the resulting
% structural response. Prior to calling this code, the user must
% define Pvm as a function of PHAC and P2. This Pvm loading is
% defined as follows:

% Pvm = PHAC-P2

% The plate/membrane is characterized by inner radius rb, outer
% radius ra, thickness tvm, and material properties E and nu. If
% flagNL=0, only linear theory will be considered. If flagNL=1,
% non-linear theory will be considered. No is the value of the in-
% plane pretension. In this file, yvc is the valve cap deflection
% (Zvc).

hold_val = 1;
plot_color = 'r';

flagNL = 1; % 1 means solve non linear problem

R = 8.314; % Pa*m^3/(K*mol) = kg*m^2/(K*sec^2*mol);
M = 28.97e-3; % kg/mol - mean molar mass of air at 273K and 1atm
= 101kPa
T = 293; % K

tvm = 10e-6; % m - tether thickness
Dch = 20e-3; % m - chamber diameter
E = 165e9; % Pa - Youngs modulus of silicon
nu = 0.22; % Poisson ratio of silicon

Po = 14.6961*6894.7; % 101kPa - initial chamber pressure

ra = Dch/2;
tether_width = 480e-6;
rb = ra-tether_width;

% Pvm = 0;
% Pvm = Po-Po/0.5;
No = 0; % in plane prestress

yvc_imposed = 6e-6;
D = E*tvm^3/(12*(1-nu^2));

%Convert Inputs to Dimensionless Quantities
Wb = yvc_imposed/tvm;
For the grid points from x to x, define the derivatives of 

derivative of inner radius

derivative of middle position

derivative of outer radius

\[ \left( \frac{\partial}{\partial r} \right) f(r) \]

\[ \left( \frac{\partial}{\partial z} \right) f(z) \]

\[ \left( \frac{\partial}{\partial \theta} \right) f(\theta) \]

where \( x \) and \( z \) are the coordinates of the grid points.

Parameters for finite-difference method

Section 2: Define grid spacing and coordinate transformation

\[ \beta = \sqrt{1 + \frac{\nu}{\nu + \rho} \frac{\partial}{\partial x}} \]

\[ \text{area} = \int r \, dr \]

\[ \text{moment of inertia} = \int r^2 \, dr \]

\[ \text{pressure} = \frac{\partial}{\partial r} \left( \frac{\partial}{\partial z} \right) f(z) \]

\[ \text{friction} = \int f(r) \, dr \]

\[ \text{moment of inertia} = \int r^2 \, dr \]

Across cap/membrane

Provision of boundary conditions and pressure

Appendix
\[ d2\eta(i) = \frac{-(0.5/\log(\phi))*m*(1+\phi)*(m2-2*\xi(i))}{(m*\phi-(\xi(i)-\xi_b))*(m+(\xi(i)-\xi_b))^2}; \]

%%Section 3: Finite-Difference Implementation

% Governing equations at internal points (from 2 to Npoints-1)
for i=2:Npoints-l,
  A(i,i-1) = \frac{(\xi(i)^2*d\eta(i)^2)/(hr^2) - \xi(i)*d\eta(i)}{2*hr};
  A(i,i) = -\left( \frac{(2*\xi(i)^2*d\eta(i)^2)/(hr^2) + (s^2+1) + \xi(i)^2*k^2}{2*hr}; \right);
  A(i,i+l) = \frac{(\xi(i)^2*d\eta(i)^2)/(hr^2) + \xi(i)*d\eta(i)}{2*hr};
  B(i,i-l) = \frac{(\xi(i)^2*d\eta(i)^2)/(hr^2) - 3*\xi(i)*d\eta(i)}{2*hr};
  B(i,i) = \frac{-2*\xi(i)^2*d\eta(i)^2/(hr^2)}{hr^2};
  B(i,i+l) = \frac{(\xi(i)^2*d\eta(i)^2)/(hr^2) + 3*\xi(i)*d\eta(i)}{2*hr};
  C(i) = 6*(1-nu^2)*P*(\xi(i)^3 - \xi(i)*(rb/ra)^2);
end

% Boundary condition equations at xi_b (grid point #1)
A(1,1) = 1;
B(1,1) = -3*\xi(1)*d\eta(1)/(2*hr) + (1-nu);
B(1,2) = 4*\xi(1)*d\eta(1)/(2*hr);
B(1,3) = -\xi(1)*d\eta(1)/(2*hr);
C(1) = 0;

% Boundary condition equations at xi_a (grid point #Npoints)
A(Npoints,Npoints) = 1;
B(Npoints,Npoints-2) = \xi(Npoints)*d\eta(Npoints)/(2*hr);
B(Npoints,Npoints-1) = -4*\xi(Npoints)*d\eta(Npoints)/(2*hr);
B(Npoints,Npoints) = 3*\xi(Npoints)*d\eta(Npoints)/(2*hr) + (1-nu);
C(Npoints) = 0;

% IMPORTANT: Since F is an unknown, an extra column and row are added to A to solve for F
% and therefore the added entry to C is the non-dimensional deflection Wb.

% Define entries in additional column of A
A(1,Npoints+l) = 0; % BC at r=rb
for i=2:Npoints-l % central points
  A(i,Npoints+l) = -6*(1-nu^2)*xi(i);
end
end
A(Npoints, Npoints+1) = 0; % BC at r=ra
A(Npoints+1, Npoints+1) = 0; % This is a meaningless entry so it must be zero.

% Define entries in additional row of A
A(Npoints+1, 1) = -(hr/2)/deta(1);
for i=2:Npoints-1
A(Npoints+1, i) = -(hr)/deta(i);
end
A(Npoints+1, Npoints) = -(hr/2)/deta(Npoints);

% Define additional entry in C
C(Npoints+1) = Wb;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Section 4: Provide an initial guess for the theta vector (plate slope), to be used in the finite-difference iteration procedure.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if k==0,
theta = (-0.75*(1-nu^2)*P*xi.*(1-xi.^2))'; % Linear result
theta = xi';
else
theta = xi';
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Section 5: Matrix Manipulation Procedure
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Niterations = 500; % Perform up to 500 iterations
tolerance1 = 1e-8;
tolerance2 = 1e-8;
omega = 0.45; % Under-relaxation parameter
if flagNL == 1 % This variable is passed into file.
NLoption = 1; % 0 = Linear solution; 1 = NonLinear solution
else
NLoption = 0;
end

for i=1:Niterations,
for j=2:Npoints-1 % Define D vector for each iteration
D(j) = -0.5*theta(j).^2;
end
D(1) = 0;

Appendix

D(Npoints)=0;
Sr = inv(B)*D'*NLoption; %Solve for Sr
v_Sr = 12*(1-nu^2)*xi'.^2.*Sr; %Calculate non-linear correction term v_Sr
v_Sr(Npoints+1) = 0; %Make v_Sr the proper length
A2 = A - diag(v_Sr,0); %Substract non-linear correction term from A
theta_new = inv(A2)*C'; %Calculate new theta vector
F_result = theta_new(Npoints+1); %Record the calculated value of F
theta_new = theta_new(1:Npoints); %Remove the F entry from the theta vector
inner_product = (theta_new'*theta)/sqrt(theta_new'*theta)/sqrt(theta'*theta);
length_ratio = sqrt(theta_new'*theta_new)/sqrt(theta'*theta);
if (1-inner_product) >= tolerance1 | (1-length_ratio) >=
tolerance2
theta = (1-omega)*theta + omega*theta_new;
else
break;
end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Section 6: Calculate Deflection, Curvature, Stress, and Swept Volume in this post-processing section.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%CALCULATE Fvcstar
Fvc = F_result*(pi*E*tvm^4)/(ra^2); %Dimensionalize the additional cap force
%Done

%PLATE DEFLECTION: Calculate plate deflection vector from the final theta vector,
%using 2nd-order forward, backward, and central difference methods to express
%theta in terms of W. Then, using matrix inversion to obtain the vector W.
i=l; %BC at rb
Wmatrix(i,i) = deta(i)*(-3/(2*hr));
Wmatrix(i,i+1) = deta(i)*(2/hr);
Wmatrix(i,i+2) = deta(i)*(-1/(2*hr));
for i=2:Npoints-1 %Inner grid points
Wmatrix(i,i-1) = deta(i)*(-1/(2*hr));
Wmatrix(i,i+1) = deta(i)*(1/(2*hr));
end

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end

% BC at ra --> Do not do for the outer boundary condition. We
% already know that
% the deflection at ra is equal to zero.

W = inv(Wmatrix(1:Npoints-1,1:Npoints-1))*theta(1:Npoints-1);
W=[W;0];
% Done

% PLATE CURVATURE: Calculate plate curvature vector from the final
% theta vector,
% using 2nd-order forward, backward, and central difference
% methods.
i=1; %BC at rb
psi(i) = deta(i)*(1/(2*hr))*(-3*theta(i) + 4*theta(i+1) -
theta(i+2));

for i=2:Npoints-1 %Inner grid points
psi(i) = deta(i)*(1/(2*hr))*(theta(i+1) - theta(i-1));
end

i=Npoints; %BC at ra
psi(i) = deta(i)*(1/(2*hr))*(3*theta(i) - 4*theta(i-1) + theta(i-
2));
% Done

% PLATE STRESS: Calculate the stress vectors in the plate.

for i=1:Npoints
Sro(i) = (k^2/(12*(1-nu^2)))*(1 + beta^2/(xi(i)^2));
sigma_r_top(i) = (E*tvm^2/ra^2)*(Sro(i) + Sr(i) -
(1/(2*(1-
u^2)))*(psi(i) + (nu*theta(i))./xi(i)));
sigma_r_bot(i) = (E*tvm^2/ra^2)*(Sro(i) + Sr(i) +
(1/(2*(1-
u^2)))*(psi(i) + (nu*theta(i))./xi(i)));
end
if max(sigma_r_top) > max(sigma_r_bot)
maxstress = abs(max(sigma_r_top));
else
maxstress = abs(max(sigma_r_bot));
end
% Done

% CONVERSION TO NON_DIMENSIONAL PARAMETERS
r=xi*ra;
y=W*tvm;
thetaND=theta*tvm/ra; %This non-dimensional theta is dw/dr
psiND = psi*tvm/(ra^2); %This non-dimensional psi is d2w/dr2

%PLATE SWEPT VOLUME: Calculate total swept volume under cap and membrane.
% V=0;
% for i=1:Npoints-1
% dV(i) = pi*(r(i+1)^2-r(i)^2)*0.5*(y(i+1)+y(i));
% V = V + dV(i);
% end
% yvc = y(1);
% Vcap = yvc*pi*rb^2;
% Vtotal = Vcap + V;
%Done

% if hold_val == 1
% figure(8); hold on;
% else
% figure(8); clf;
% end

% r = ra:(rb-ra)/200:rb;
% r = r(2:end);
% figure(8)
% plot(r*1e3,fliplr(y')*1e6,plot_color);
% grid on;
% xlabel('Radial Position [mm]')
% ylabel('Tether Deflection [um]');

% tether_thickness_um = tvm*1e6
% tether_width_um = tether_width*1e6
% normalized_max_stress = maxstress/1e9
Appendix B - Test Setup Components

Round 6 Micropump Test Platform

Top

Material: Aluminum
All units: mm
Circle diameters shown
Appendix

**Bottom**

- 6-32 screw hole
- 8-32 screw hole
- 16mm diameter channel
- 4mm diameter channel
- 10-32 screw hole

**McMaster small O-Ring**  
Part# 2418T113  
AS568A Dash # 007

**McMaster large O-Ring**  
Part# 2418T116  
AS568A Dash # 010
Round 6 Valve Test Platform

Top

- 6-32 screw hole
- 8-32 screw hole
- 1.6mm diameter channel
- 4mm diameter channel
- 10-32 screw hole

McMaster small O-Ring
Part #: 2418TI13
AS568A Dash # 007

McMaster large O-Ring
Part #: 2418T116
AS568A Dash # 010
Appendix

Bottom

- 6-32 screw hole
- 8-32 screw hole
- 1.6mm diameter channel
- 4mm diameter channel
- 10-32 screw hole

McMaster small O-Ring
Part# 2418T113
AS568A Dash # 007

McMaster large O-Ring
Part# 2418T116
AS568A Dash # 010
Test setup key components, vendors, and quantity (not all currently needed)

**MCMASTER CARR SUPPLY CO**  
473 RIDGE RD  
DAYTON NJ 08810-0317

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**THORLABS INC**  
BOX#366  
NEWTON NJ 07860-0366

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WARREN PIKE ASSOCIATES
109 SOUTH ST
HOPKINTON MA 01748-2206

Parker Valve - VA01PEP341UEF 4
Parker Valve Subbase - V34BM5 4
Parker Pressure Sensor - MPS-L3N-PGA 1
Parker Pressure Sensor - MPS-V3N-PGA 1

MOUSER ELECTRONICS
1000 N MAIN ST
MANSFIELD TX 76063

Relay, Part# 653-G6K-2P-Y-DC3 10
Relay, Part# 653-G5V-2-DC3 2
Relay, Part# 653-G6A-234P-DC3 2

CAMBRIDGE VALVE & FITTING
PO BOX 595
BILLERICA MA 01821-0595

Part # SS-4-VCR-2 4
Part # SS-4-VCR-6-400 2
Part # SS-2-HC-A401 2

RADIO SHACK

Basic Stamp Kit
Appendix C - Test Setup Code

*Basic stamp micro-controller code used to control the pressure selector switches and generate vacuum*

' Generating vacuum at ~ 1.0hz if 5ms switching times are not considered

' {$STAMP BS2}
' {$PBASIC 2.5}
' channel 13 = output valve, channel 14 = chamber piston, channel 15 = input valve

timeinbetweenFast VAR Word
timeinbetweenSlow VAR Word
freqcase VAR Byte
freqcase = 1

' timeinbetweenSlow used for when the chamber piston is being actuated otherwise use timeinbetweenFast

timeinbetweenFast = 100
timeinbetweenSlow = 300

' start-state output and chamber closed and input open

HIGH 13
  PAUSE timeinbetweenSlow
HIGH 14
  PAUSE timeinbetweenSlow
LOW 15
  PAUSE timeinbetweenSlow

DEBUG "Press button to start pumping...", CR, CR
DO
  PAUSE timeinbetweenSlow
LOOP UNTIL IN0 = 1

DO

  LOW 15
  PAUSE timeinbetweenFast

  LOW 14
  PAUSE timeinbetweenSlow
HIGH 15
  PAUSE timeinbetweenFast

LOW 13
  PAUSE timeinbetweenFast

HIGH 14
  PAUSE timeinbetweenSlow

HIGH 13
  PAUSE timeinbetweenFast

LOOP UNTIL IN0 = 1

' end-state everything open

LOW 13
  PAUSE timeinbetweenSlow
LOW 14
  PAUSE timeinbetweenSlow
LOW 15
  PAUSE timeinbetweenSlow

DEBUG "DONE!", CR, CR, CR
Appendix

LabView code used to capture MFM and pressure sensor data

Frontside
Appendix

Backside
Appendix D - Round 5 Masks and Process Flow

Round 5 Masks

M1 - Alignment Marks
M2 - DSP Cross-Channels

Micro Vacuum Pump
V. 01
Channels
Appendix

M3 - DSP Chamber Etch

Micro Vacuum Pump
V. 01
Top Wafer Recess
M4 - DSP Through Channels

Micro Vacuum Pump
V. 01
Chamber/Channel Ports
Appendix

M5 - DSP Valve Lip and Posts Etch

Micro Vacuum Pump
V. 01
Piston Stoppers
Micro Vacuum Pump
V. 01
Valves and Pistons
Appendix

M7 - SOI Input/Output Ports

Micro Vacuum Pump
V. 01
Valves Through Holes
M8 - Pyrex Through Holes (sent to Bullen Ultrasonics)
Appendix

M9 - Pyrex Shadow Mask

Micro Vacuum Pump
V. 01
Shadow Mask
Appendix

Round 5 Process Flow

- Make sure to protect alignment marks before all etch steps with photoresist and teflon tape

Layer 2 - DSP(450um Si)

1. Grow thermal oxide (0.3um) - preferably buy wafers with thermal oxide pre-grown
2. HMDS wafers, deposit thin resist on both sides, pre-bake, photo M1 (alignment marks) on topside, develop, post-bake
3. BOE for 4minutes, spin-dry wafers
4. Alignment mark etch topside using Almark recipe on STS2 or STS3 for 10sec
5. Strip resist using piranha, spin-dry wafers
6. HMDS wafers, deposit thin resist on both sides, pre-bake, photo M1 (alignment marks) on bottomside making sure they line up with topside alignment marks, develop, post-bake
7. BOE for 4minutes, spin-dry wafers
8. Alignment mark etch bottomside using Almark recipe on STS2 or STS3 for 10sec
9. HMDS wafers, deposit thin resist on both sides, pre-bake, photo M3 (6um chamber etch) on bottomside, develop, post-bake
10. BOE for 4minutes, spin-dry wafers
11. Etch pump chamber from bottom using Jbetch in STS3 till 6um chamber depth is obtained (measure using dektak profilometer), rotate wafers at least 4 times during etch
12. Strip resist using piranha, spin-dry wafers
13. Deposit 4um of thick oxide on both sides using ICL DCVD
14. HMDS wafers, deposit thick resist on both sides, pre-bake, photo M5 (valve lip and posts) on bottomside, photo M3 (cross channels) on topside, develop, post-bake
15. Etch 4.3um of oxide on both sides using ICL AME5000
16. Strip resist using piranha, spin-dry wafers
17. HMDS wafers, deposit thick resist on both sides, pre-bake, photo M4 (through holes) on topside, develop, post-bake
18. Etch through holes from the top by (450-30-channelwidth) microns using recipe MIT69A on STS2, make sure to rotate wafers often for etch uniformity
19. Strip resist using piranha, spin-dry wafers
20. Ash wafers for 1.5hours
21. HMDS wafers, deposit thick resist on bottomside, post-bake
22. Etch through holes and channels from the top by the channelwidth microns making sure to stop short of ~24um of breaking through the bottomside using recipe MIT69A on STS2, make sure to rotate wafers often for etch uniformity
23. Strip resist using piranha, spin-dry wafers
24. HMDS wafers, deposit thin resist on topside, post-bake
25. Apply blue-tape to topside
26. Etch from the bottom by slightly greater than 24um to create the valve lips, support posts, and open up the valve to pump chamber channels. Use recipe MIT69A on STS2, make sure to rotate wafers often for etch uniformity
27. Once complete place wafer in acetone till blue-tape comes off
28. Strip resist using piranha, spin-dry wafers
29. Ash wafers for 1.5 hours

Layer 3 - SOI (450um Si)

30. Grow thermal oxide (0.3um) - preferably buy wafers with thermal oxide pre-grown
31. HMDS wafers, deposit thin resist on both sides, pre-bake, photo M1 (alignment marks) on topside, develop, post-bake
32. BOE for 4 minutes, spin-dry wafers
33. Alignment mark etch topside using Almark recipe on STS2 or STS3 for 10 sec
34. Strip resist using piranha, spin-dry wafers
35. HMDS wafers, deposit thin resist on both sides, pre-bake, photo M1 (alignment marks) on bottomside making sure they line up with topside alignment marks, develop, post-bake
36. BOE for 4 minutes, spin-dry wafers
37. Alignment mark etch bottomside using Almark recipe on STS2 or STS3 for 10 sec
38. HMDS wafers, deposit thin resist on both sides, pre-bake, photo M7 (input/output ports) on topside, develop, post-bake
39. BOE for 4 minutes, spin-dry wafers
40. Etch input/output ports from the top by 10um until the buried oxide layer is reached using recipe MIT69A in STS2, rotate wafers at least 4 times during etch
41. Strip resist using piranha, spin-dry wafers
42. Deposit 4um of thick oxide on the bottomside using ICL DCVD
43. HMDS wafers, deposit thick resist on both sides, pre-bake, photo M6 (tethers) on bottomside, develop, post-bake
44. Etch 4.3um of oxide on bottomside using ICL AME5000
45. Strip resist using piranha, spin-dry wafers
46. HMDS wafers, deposit thin resist on topside, post-bake
47. Apply blue-tape to topside
48. Etch tethers from the bottom till the buried oxide is reached and the right tether width/fillet profile is obtained. Use recipe MIT69A on STS2. Make sure to rotate
wafers often for etch uniformity. Once any tether is complete paint it with resist by hand and let it dry in air for 3 hours before proceeding with etching other tethers - don't use oven.

49. Once tethers all completed place wafer in acetone till blue-tape comes off
50. Strip resist using piranha, spin-dry wafers
51. Ash wafers for 1.5 hours

Bottom Support Pyrex Layer

52. Get alignment marks, input/output and actuation ports machined by Bullen Ultrasonics using M8 (pyrex holes)
53. Make a shadow mask for the pyrex wafer: HMDS a blank Si wafer, deposit double layer of thick resist on the topside, pre-bake, photo M9 (shadow mask) on topside, develop, post-bake, mount on quartz wafer, and etch through the wafer till the shadow mask is complete using recipe Jbetch on STS2 or STS3
54. Unmount shadow mask from quartz wafer and clean using piranha, then spin-dry wafers
55. Align shadow mask to quartz wafer using bonding aligner and water droplets (to help wafers stick together)
56. Deposit 0.02um of Titanium adhesive layer followed by 0.2um of Silver in Ebeam

Bonding & Cutting

57. HF strip all oxide from DSP Layer 2
58. BOE strip all oxide from SOI Layer 3 - at the same time the buried oxide will also be removed (don't etch more than buried oxide thickness so make sure that all other oxide on the wafer is already thinner before beginning this step). Can't use HF on this layer.
59. Spin dry clean the pyrex bottom layer
60. RCA clean Layer 2, Layer 3, and a blank capping Si wafer (no HF)
61. Silicon direct bond blank capping wafer to Layer 2 to Layer 3
62. Anneal the 3 layer silicon stack for 1 hour at 950 degrees Celcius
63. Anodically bond stack to pyrex bottom layer
64. Die-saw the micropump dies using thickest black blade (use die-saw tape on both sides to prevent water/slurry from entering the devices)
Appendix E - Round 6 Masks and Process Flow

Round 6 Masks

M1 - Alignment Marks
Appendix

M2 - DSP Through Channels
Appendix

M3 - DSP Cross-Channels
M4 - SOI Input/Output Ports
Appendix

M5 - DSP Chamber Etch
Appendix

M6 - DSP Valve Lip and Posts Etch
M7 - SOI Thin Pistons Down and Support Posts
M9 - Pyrex Through Holes (sent to Bullen Ultrasonics)
M10 - Pyrex Shadow Mask
Appendix

Round 6 Process Flow

- Make sure to protect alignment marks before all etch steps with photoresist and teflon tape

Layer 2 - DSP(450um Si)

1. Grow thermal oxide (0.3um) - preferably buy wafers with thermal oxide pre-grown
2. HMDS wafers, deposit thin resist on both sides, pre-bake, photo M1 (alignment marks) on topside, develop, post-bake
3. BOE for 4minutes, spin-dry wafers
4. Alignment mark etch topside using Almark recipe on STS2 or STS3 for 10sec
5. Strip resist using piranha, spin-dry wafers
6. HMDS wafers, deposit thin resist on both sides, pre-bake, photo M1 (alignment marks) on bottomside making sure they line up with topside alignment marks, develop, post-bake
7. BOE for 4minutes, spin-dry wafers
8. Alignment mark etch bottomside using Almark recipe on STS2 or STS3 for 10sec
9. HMDS wafers, deposit thin resist on both sides, pre-bake, photo M5 (6um chamber etch) on bottomside, develop, post-bake
10. BOE for 4minutes, spin-dry wafers
11. Etch pump chamber from bottom using Jbetch in STS3 till 6um chamber depth is obtained (measure using dektak profilometer), rotate wafers at least 4 times during etch
12. Strip resist using piranha, spin-dry wafers
13. Deposit 4um of thick oxide on both sides using ICL DCVD
14. HMDS wafers, deposit thick resist on both sides, pre-bake, photo M6 (valve lip and posts) on bottomside, photo M3 (cross channels) on topside, develop, post-bake
15. Etch 4.3um of oxide on both sides using ICL AME5000
16. Strip resist using piranha, spin-dry wafers
17. HMDS wafers, deposit thick resist on both sides, pre-bake, photo M2 (through holes) on topside, develop, post-bake
18. Etch through holes from the top by (450-30-channelwidth) microns using recipe MIT69A on STS2, make sure to rotate wafers often for etch uniformity
19. Strip resist using piranha, spin-dry wafers
20. Ash wafers for 1.5hours
21. HMDS wafers, deposit thick resist on bottomside, post-bake
22. Etch through holes and channels from the top by the channelwidth microns making sure to stop short of ~24um of breaking through the bottomside using recipe MIT69A on STS2, make sure to rotate wafers often for etch uniformity
23. Strip resist using piranha, spin-dry wafers

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24. HMDS wafers, deposit thin resist on topside, post-bake
25. Apply blue-tape to topside
26. Etch from the bottom by slightly greater than 24um to create the valve lips, support posts, and open up the valve to pump chamber channels. Use recipe MIT69A on STS2, make sure to rotate wafers often for etch uniformity
27. Once complete place wafer in acetone till blue-tape comes off
28. Strip resist using piranha, spin-dry wafers
29. Ash wafers for 1.5hours

Layer 3 - SOI (450um Si)

30. Grow thermal oxide (0.3um) - preferably buy wafers with thermal oxide pre-grown
31. HMDS wafers, deposit thin resist on both sides, pre-bake, photo M1 (alignment marks) on topside, develop, post-bake
32. BOE for 4minutes, spin-dry wafers
33. Alignment mark etch topside using Almark recipe on STS2 or STS3 for 10sec
34. Strip resist using piranha, spin-dry wafers
35. HMDS wafers, deposit thin resist on both sides, pre-bake, photo M1 (alignment marks) on bottomside making sure they line up with topside alignment marks, develop, post-bake
36. BOE for 4minutes, spin-dry wafers
37. Alignment mark etch bottomside using Almark recipe on STS2 or STS3 for 10sec
38. HMDS wafers, deposit thin resist on both sides, pre-bake, photo M4 (input/output ports) on topside, develop, post-bake
39. BOE for 4minutes, spin-dry wafers
40. Etch input/output ports from the top by 10um until the buried oxide layer is reached using recipe MIT69A in STS2, rotate wafers at least 4 times during etch
41. Strip resist using piranha, spin-dry wafers
42. Deposit 4um of thick oxide on the bottomside using ICL DCVD
43. HMDS wafers, deposit thick resist on both sides, pre-bake, photo M7 (thin pistons) on bottomside, develop, post-bake
44. Etch 4.3um of oxide on bottomside using ICL AME5000
45. Strip resist using piranha, spin-dry wafers
46. HMDS wafers, deposit thick resist on both sides, pre-bake, photo M8 (tethers) on bottomside, develop, post-bake
47. Etch tethers from the bottomside for half the wafer thickness using recipe MIT69A on STS2, make sure to rotate wafers often for etch uniformity
48. Strip resist using piranha, spin-dry wafers
49. HMDS wafers, deposit thin resist on topside, post-bake
50. Apply blue-tape to topside
51. Etch tethers and thin down pistons from the bottom till the buried oxide is reached and the right tether width/fillet profile is obtained. Use recipe MIT69A on STS2. Make sure to rotate wafers often for etch uniformity. Once any tether is complete paint it with resist by hand and let it dry in air for 3 hours before proceeding with etching other tethers - don't use oven.
52. Once tethers all completed place wafer in acetone till blue-tape comes off
53. Strip resist using piranha, spin-dry wafers
54. Ash wafers for 1.5 hours

**Bottom Support Pyrex Layer**
55. Get alignment marks, input/output and actuation ports machined by Bullen Ultrasonics using M9 (pyrex holes)
56. Make a shadow mask for the pyrex wafer: HMDS a blank Si wafer, deposit double layer of thick resist on the topside, pre-bake, photo M10 (shadow mask) on topside, develop, post-bake, mount on quartz wafer, and etch through the wafer till the shadow mask is complete using recipe Jbetch on STS2 or STS3
57. Unmount shadow mask from quartz wafer and clean using piranha, then spin-dry wafers
58. Align shadow mask to quartz wafer using bonding aligner and water droplets (to help wafers stick together)
59. Deposit 0.02um of Titanium adhesive layer followed by 0.2um of Silver in Ebeam

**Bonding & Cutting**
60. HF strip all oxide from DSP Layer 2
61. BOE strip all oxide from SOI Layer 3 - at the same time the buried oxide will also be removed (don't etch more than buried oxide thickness so make sure that all other oxide on the wafer is already thinner before beginning this step). Can't use HF on this layer.
62. Spin dry clean the pyrex bottom layer
63. RCA clean Layer 2, Layer 3, and a blank capping Si wafer (no HF)
64. Silicon direct bond blank capping wafer to Layer 2 to Layer 3
65. Anneal the 3 layer silicon stack for 1 hour at 950 degrees Celsius
66. Anodically bond stack to pyrex bottom layer
67. Die-saw (use die-saw tape on both sides to prevent water/slurry from entering the devices)
Appendix F - Tether Etch Recipes

Mit69a on STS2 [currently tether etch recipe of choice]

Standby
Standby Gas - Argon: Flow rate 0 sccm
Standby:
  Pump down time: 20 sec
  Purge time: 10 sec
  Pump out time: 30 sec
Base Pressure: 0.0 mTorr
Pressure Trip: 94.0 mTorr
MIT 69 A
Process:
  Pump down time: 20 sec
  Gas stabilization: 10 sec
  Process time:
  Pump out time: 30 sec
Parameter Switching:
  Order: Pass First
  Time (s):
    Etch: 15.0
    Pass: 11.0
Pressure:
  Base: 0.0 mTorr
  Pressure trip: 94.0 mTorr
Gases:
  Etch          Passivation
  Flow(sccm)Tol(%) Flow(sccm)Tol(%)  
  C4F8 0 5 40 5
  SF6 105 50 0 5
R.F.:
  Platen Generator:
    Power: Etch 80W - Passivate 60W
  Coil Generator:
    Power: Etch 750W - Passivate 600W
Vtrench2 on STS3 [doesn’t work since STS3 was re-tooled]

Standby
Standby Gas - Argon: Flow rate 0 sccm
Standby:
  Pump down time: 20 sec
  Purge time: 10 sec
  Pump out time: 30 sec
Base Pressure: 0.0 mTorr
Pressure Trip: 94.0 mTorr
20 mT JB etch
Process:
  Pump down time: 20 sec
  Gas stabilization: 10 sec
  Process time:
  Pump out time: 30 sec
Switching Parameters:
  Phase: Etch (start) - Etch (end)
Parameter switching cycle times:
  Etch: 12.0
  Pass: 11.0
Pressure:
  Base: 0.0 mTorr
  Pressure trip: 94.0 mTorr
Presssure setting:
  Pressure: 16.0 mTorr
Gases:

<table>
<thead>
<tr>
<th></th>
<th>Etch</th>
<th>Passivation</th>
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<tbody>
<tr>
<td>C4F8</td>
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<td>5</td>
</tr>
<tr>
<td>SF6</td>
<td>105</td>
<td>25</td>
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</table>
R.F.:
  13.56MHz generator connected to coil:
    Power: Etch 800W - Passivate 600W
Platen generator connected to 13.56MHz
    Power: Etch 20W - Passivate 6W
HBC:
  Pressure: 9900 mTorr
Max Flow: 40 sccm
Min Flow: 10 sccm
HeLUR:
  Max leak rate: 15mTorr/min
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