TRANSFER PRINTED MECHANICAL MEMS

BY

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THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Mechanical Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2011

Urbana, Illinois

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Abstract

Most Microelectromechanical Systems are primarily created using integrated circuit (IC) fabrication techniques and photolithography. These techniques and procedures are time consuming and exhaustive in the amount of steps needed in their creation. Also, fabrication processes often limit the materials, chemicals, and temperatures allowed throughout the extensive creation process in order to ensure cross compatibility with all materials in the device. As such, compromises to optimal design are common in many current commercial MEMS products. Current processes and manufacturing techniques are also very expensive.

Elastomeric transfer printing offers solutions to these challenges by introducing the ability to assemble individual modularized components of these devices. Transfer printing frees fabricators to simplify and optimize the creation process by breaking down the devices into unique individual parts. Transfer printing also allows for the use of a wider field of materials as well as the ability to use previously incompatible chemicals, temperatures, and other process parameters in pursuit of perfecting each part individually before final assembly. These parts can then be assembled individually or in an assembly line fashion at potentially a significant decrease in manufacturing cost.

This thesis examines three examples of transfer printed MEMS that span the areas of microfluidics, mechatronic, and optical/thermal. The microfluidic example is silicon microfluidic nozzles printed onto PDMS microchannels as a means to create simple modularized micro nozzle arrays. This process vastly cuts down on the steps needed to fabricate traditional MEMS Microfluidic nozzles as well as offers a means to potentially exchange damaged nozzles from existing microfluidics arrays. For the mechatronic area, silicon micro gears are transfer printed onto silicon shafts. These gears then demonstrated interdependent actuation. Transfer
printing gears allows MEMS designers new flexibility in micro mechatronic design that was previously limited due to photolithography processes. Lastly, for the optical thermal example, microbolometers are created and transfer printed onto a read-out test bed. Bolometers are a good example of the potential of modularized assembly of 3D MEMS. These devices are resistance-based sensing devices found at the heart of infrared thermal imaging devices. One critical parameter in a microbolometer membrane is the temperature coefficient of resistance (TCR) which is a measure of the bolometer’s sensitivity. Optimally, the TCR should be as negative as possible. Bolometers with a TCR of around -2%/°C are common in industry today and are fabricated directly on the readout integrated circuit (ROIC) which limits the thermal processing that can be done to optimize the bolometer membrane due to the risk of damaging the readout integrated circuit (ROIC). A solution to this problem is to fabricate the bolometer membranes separate from the ROIC, then combine them using transfer printing. Separating the processes allows for the use of high temperature annealing to be performed on the bolometer membrane that would have otherwise damaged the ROIC. This annealing allows the vanadium oxide in the membranes to achieve a much lower TCR of up to -4%/°C. Transfer printing then provides a unique method for assembling the bolometer membrane on the ROIC.

Transfer printing is a means for the optimization of MEMS assembly because it removes previous design constraints on MEMS creation and allows manufacturers to modularly and optimally create and assemble MEMS components into enhanced integrated devices.
To my family, my research group, and my advisor for their support and help in all of my academic pursuits.
Acknowledgements

I would like to thank my Advisor, Placid M. Ferreira for his mentorship and help throughout the last two years while working on this research. I would also like to thank my research group for all their continued help and assistance with all the experiments and in helping me work through challenges.

Specifically, I would like to thank Andrew Carlson with his help in teaching me microfabrication techniques and his help in making samples and masks for me. He also was instrumental in fabrication of all my stamps and many of the devices that I used in my experiments. He also was a partner in all of the PDMS sheer and adhesion testing we did.

I would also like to thank Numair Ahmed with his help in getting the transfer printer up and running as he was instrumental in the Labview automation programming interface. He also taught me many things pertaining to transfer printing concepts and techniques.

I would like to thank Greg Eisenmann for his help in the design, creation, CAD work, and printing of the micro gears and for being a willing support in those efforts. He also did a significant amount of work with me on the bolometers.

I would like to thank Jonathan Grim for teaching me how to use Pro Engineer and for his help in the development of many of the CAD files that we used in the creation of the Transfer Printer.

Lastly, I would like to thank the Army and West Point for making all of this possible through the Advance Civil Schooling Program.
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<td>A</td>
<td>Area</td>
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<tr>
<td>$A_h$</td>
<td>Hamaker constant</td>
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<td>C</td>
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<tr>
<td>$\rho$</td>
<td>Number of atoms per unit volume in two interacting bodies</td>
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<tr>
<td>$\sigma$</td>
<td>Interatomic distance</td>
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Chapter 1: Introduction

1.1 Purpose and Motivation

The purpose of this thesis is to demonstrate the use polydimethylsiloxane (PDMS) based transfer printing to build 3D microelectricalmechanical (MEMS) devices \([1][2][3]\). There is a need in industry to effectively automate the assembly of micro devices or find an alternative method to MEMS assembly. Manual labor is still extensively used to assemble many currently used micro devices such as small bearings and motors for use in dental work. Also, almost all MEMS devices are fabricated on silicon wafers using complex and cumbersome 2D photolithography techniques that almost always require rigid substrates and are design limited by process steps. Current fabrication techniques that use sacrificial layers and undercut etching are highly restrictive (in terms of geometry), often have low yields, are sometimes difficult to replicate, require extensive man hours to create, and ultimately are very expensive \([4]\). The ability to create a process that would allow the assembly of such devices without the need of human interaction or simplified photolithography would allow for an expansion in MEMS manufacturing production. This technology would also have the potential to expand beyond the micro assembly into the nano scale.

In order to make this technology a feasible option for the assembly of 3D devices, we built a micro transfer printing tool capable of manipulating the modular assembly pieces. This tool is explained in detail in Chapter 3. The micro transfer printer uses micro-size PDMS stamps that adhere to the micro assembly pieces. This initial connection is called “on” adhesion. The pieces are then moved to a destination substrate or device and accurately deposited or released from the PDMS stamp. This release from the PDMS stamp is called “off” adhesion. The key to
successful transfer printing lies in being able to control this on/off adhesion mechanism between the PDMS stamp and the micro parts. Therefore, after creating a machine capable of transfer printing, we then examined the intermolecular forces that affected the adhesion of PDMS to other materials, primarily examining its adhesion to silicon as most of our research is focused on the transfer of silicon based semiconductor materials. Understanding these forces helped in the customization and design of functional PDMS stamp tips that complement the varying geometry and surface textures of the printable devices. We also experimented extensively with varying modes of crack propagation along the device PDMS stamp interface so as to better understand how to optimally pick up and release various materials.

Using the transfer printer and the lessons learned from the study of PDMS, we then proceeded to design and fabricate MEMS parts for use in the creation of 3D MEMS and demonstrate assembly of these parts using the transfer printer. The three areas we focused on were microfluidics, mechatronic, and optical/thermal. The devices from these areas will be discussed in detail in Chapters 4 through 6.

1.2 Challenges of MEMS Manufacturing

MEMS devices are primarily made up of silicon, polymers, and metals. MEMS fabrication is currently accomplished primarily through photolithographic processes. Photolithography consists of using photo curable polymers and selective UV exposure to pattern desired features in mass arrays. This patterning often occurs on flat substrates such as silicon wafers. Once patterned, materials are either deposited or etched away to form the desired features. These processes are time consuming, require expensive equipment and chemicals, and restrictive [5].
Primarily a 2-D patterning process, photolithography can severely constrain the design process. For instance, material selection may be hindered due to incompatible chemicals, temperatures, and other process parameters. At times, more expensive materials may be required than would be desirable, such as the need to use platinum over nickel because nickel etchant would adversely affect other nickel components or metals in the proposed device. Also, at times, optimum material characteristics may not be achieved because all the features or components must be sequentially constructed on a single handle substrate. For example, high temperature oxidation of a feature may adversely affect other metals or polymers in the MEMS device. These are just a couple of examples of the challenges currently faced in MEMS creation using traditional photolithography methods.

1.3 Transfer Printing MEMS

Transfer printing MEMS offers many solutions to the current design challenges of MEMS devices. Transfer printing opens up the possibility of assembly line style creation of MEMS through the “printing” of modular MEMS parts together into a fully functions MEMS device. This can benefit the overall production in many ways. First, the design can be simplified to allow for the optimal creation of individual parts of a MEMS device. For instance, one can optimally design gears for a MEMS assembly without the need to consider how those processes may adversely affect the drive mechanism and vice versa.

In order to make transfer printing a viable commercial manufacturing process for MEMS, a few challenges to the actual transfer printing process need to be addressed and studied. One of the biggest challenges to transfer printing is the ability to fully control the on/off adhesion of PDMS to various devices and destination substrates. To address this issue, one must first understand the basic premise of transfer printing. This topic is addressed in Chapter 2.
Chapter 2: Transfer Printing

2.1 Elastomeric Transfer Printing

PDMS, an elastomeric material, is commonly used for the creation of stamps that are used in transfer printing micro/nano materials. Some of these materials include single-walled carbon nanotubes, solar cells, and micro devices such as light emitting diodes. These devices or “ink” are transferred from their fabricated material to desirable foreign substrates such as flexible elastomers, glass, plastics, or onto other micro devices as shown in Figure 1 [2]. Figure 1 illustrates this process.

![Figure 1: Large area mass transfer printing of silicon “ink” pads. (a) Silicon “ink” on origin substrate, (b) PDMS stamp after “ink” removal, (c) Transfer printed array of “ink” on flexible substrate](image)

The ability to transfer these inks from their origin to foreign substrates is very desirable for a number of applications to include but not limited to the realization of flexible/transparent electronics and displays, the creation of new types of micro devices, and the ability to manufacture micro devices in three dimensions [1]. The realization of these goals hinges on the ability of the PDMS stamps to not only effectively pick up and transport their desired source materials, but also to accurately position and reliably release those materials and devices onto the destination substrates or devices.
PDMS is currently used as the primary material for transfer printing because of its ability to natively adhere to most micro/nano materials via van der Waals atomic and molecular force interactions. These interactions are strong enough to lift the device free of its native substrate as long as the devices or materials are sufficiently undercut or passively resting where they were created. The real challenge arises in overcoming these forces in order to print these materials onto target substrates. This printing can only be achieved by breaking or interrupting this adhesion force. This challenge has been overcome in the past via the use of adhesive coatings on the target substrate [5]. This solution works for many applications, but a more desirable solution would be to print these inks in high yield without the need for an intermediary coating as these coatings may not be conducive to electrical contacts or other potential features on printed devices. These coatings also may prevent the ability to post process electrical interconnects in the case of creating LED displays or in the case of micro devices, prevent the devices from operating correctly [3]. Therefore, the ideal method for transfer printing is referred to as dry or adhesiveless transfer printing.

Adhesiveless transfer printing has been approached from many angles in research. Some of these methods include the modification of stamp surfaces, modifying the dynamics involved in the collection and deposition of the inks, and taking advantage of the viscoelastic nature of PDMS [5]. All of these modifications rely on finding ways to maximize the intermolecular forces in freeing and lifting off inks from their donor substrates while modifying or manipulating their release when desired. An in-depth study of the intermolecular forces between PDMS and the transfer materials will aid in achieving the goal of effective adhesiveless transfer printing stamps and techniques.
2.1.1 Elastomeric Stamp Fabrication

Another reason PDMS is used is because of its ability to mold into most any shape. Most transfer printing posts currently used in the transfer printing process are considered “flat” stamps, or micro-formed cubes of PDMS on a larger PDMS backing as shown previously in Figure 1. These flat stamps are most often created by first spinning a photo curable polymer such as SU-8 onto a flat silicon wafer. This photo curable polymer is spun on so it achieves a designated thickness that will become the thickness of the final post or array of posts, usually in the range of 50-100μm thick. This polymer is then patterned via a mask that has the desired dimensions of the post, usually the same size as the devices it will eventually pick up. After patterning, the polymer is developed; this process selectively removes portions of the polymer creating cavities down into the polymer in the shape of the mask. These cavities extend to the very flat surface of the silicon. The polymer is then cured and hardened. This polymer/silicon platform then becomes the die that will form the PDMS posts. Liquid PDMS is poured onto the polymer coated silicon and it enters into the square cavities and then left to cure. Once fully cured, the PDMS is then peeled back from the polymer/silicon die and all of the micro structures are then replicated as micro “posts” along the surface of the PDMS. The posts can then be cut out and applied to a desired backing in preparation for use in the transfer printing machine\textsuperscript{[6]}\textsuperscript{[5]}. 
2.2 Force Mechanisms of Transfer Printing

PDMS is a silicone organosilicon compound. Its chemical formula is \( \text{CH}_3[\text{Si}(\text{CH}_3)_2\text{O}]_n\text{Si}(\text{CH}_3)_3 \), where \( n \) is the number of repeating monomer units. It can be manufactured in many viscosities ranging from liquid when \( n \) is very low to a thick rubbery semi-solid when \( n \) is very high. Thermal curing of PDMS results in a hardened transparent rubber. PDMS used in transfer printing is most often cured between 75-100 °C. After polymerization and cross-linking, PDMS samples will possess a hydrophobic smooth external surface \(^4\). Hydrophobicity can be enhanced by creating micro pillars on the surface of the PDMS. When these pillars are patterned on the surface, there is an increase in hydrophobicity as indicated by an increase in a water droplet’s contact angle; there is also an increase in adhesion of the water droplet to the patterned PDMS surface. These results also indicate an increase in intermolecular forces introduced as a result of the micro pillars on the PDMS surface \(^2\). A similar effect was recorded by Lloyd Spielman in 1969 \(^7\).

The potential intermolecular forces involved in transfer printing include van der Waals forces, adhesion effects, and surface roughness effects. The primary or dominant attractive forces to explore are the van der Waals forces between the PDMS and the silicon. Van der Waals forces consist of more than one force and usually are only effective in proximity of less
than 100nm. A portion of those forces is called London forces or dispersion forces, another portion is called dipole-dipole interactions, and the last portion is made up of Debye forces. [8]

London forces involve temporarily induced dipoles. Attractions are electrical by nature and in dipoles these forces take on specific orientation and charge. Symmetrical molecules on average do not seem to have any electrical bias, but there are instantaneous induced dipoles as instances of negative temporary dipoles in molecules attract temporary positive instances in other molecules. Synchronization of lattices of these molecules is what makes up dispersion forces. These forces are small compared to intramolecular forces, but they are proportional to the size of the monatomic molecules. As the number of electrons in molecules increases, the radius of the atom increases. As the radius increases, so does the ability of the electrons to increase distance over which they can move which, in turn, allows for larger temporary dipoles and therefore bigger dispersion forces. In a similar manner, the shape of a molecule will also affect these forces. Long thin molecules, as found in polymers such as PDMS, will have bigger temporary dipoles than more compact molecules. Dipole-dipole or Keesom forces have permanent dipoles. They are often fairly minor when compared to dispersion forces, but are noticeable when comparing similarly sized molecules with the same number of electrons [8], [9]. Lastly, Debye forces are permanent-induced dipoles and are often the least influential of the van der Waals forces. Table 1 [9] shows a list of compounds and the percentage contributions from the various van der Waals forces that reinforces the concept that London forces are usually the most prevalent of the van der Waals forces—water being the noteworthy exception to this rule.
The most common scenario of PDMS on Silicon as used for transfer printing can be modeled as two surfaces. The van der Waals force contribution to the adhesion force for two flat surfaces is

\[ F_{vdw} = -\frac{A_h}{12\pi D^2} \]  \hspace{1cm} (2.1)

The pressure can also be calculated using:

\[ P = \frac{A_h}{6\pi D^3} \]  \hspace{1cm} (2.2)

\( A_h \) is the Hamaker constant which is defined by

\[ A_h = \pi^2 C \rho_1 \rho_2 \]  \hspace{1cm} (2.3)
D is the approximate interfacial cut-off distance, C is the coefficient in the atom-atom pair potential, and $\rho_1$ and $\rho_2$ are the number of atoms per unit volume in two interacting bodies. For most polymers,

$$Ah \sim 0.4 - 4 \times 10^{-21} J^{[10]}$$

The ability to manipulate these variables is the key to perfecting transfer printing.

Perhaps the easiest variable in these equations to control is the distance. Van der Waals forces are very dependent on distance, beginning around 100nm and strengthening as molecules move into contact. Maximizing this force is ideal for adhering the PDMS stamp to the inks. This force needs to be strong enough to break any anchor bonds, potential stiction, or any residue from undercut processes the inks may possess. As mentioned previously, greater adhesion can also be achieved through micro or nano patterning of the PDMS surface as well. It would be an interesting experiment to determine if this adhesion affect would be present if one were to nano pattern silicon $^{[12]}$.

Picking up ink with PDMS posts has shown to be very repeatable as long as the devices are fabricated and undercut correctly$^{[2]}$. A greater challenge in the transfer printing process is finding ways to release the ink from the PDMS stamp surface onto the desired target substrate or device. Most of the desirable receiving substrates such as silicon and glass do not generate enough intermolecular forces to overcome the adhesion between PDMS and ink samples without some external assistance such as a sticky adhesive coating. The key is to separate the PDMS from ink by initiating crack propagation across the PDMS/device interface by introducing shear forces at the interface or perhaps changing the geometry of the stamps to be able to somehow maximize initial pick up adhesion, but then have a built in mechanism to reduce interfacial
surface area to a minimum thus and thereby reducing the energy needed to break the remaining intermolecular forces\textsuperscript{[13]}. Effectively achieving this goal is the key to unlocking the potential of adhesiveless transfer printing and thereby enabling the reality of mass assembled 3D MEMS.

2.3 PDMS on Silicon Adhesion Testing

It is important to understand the PDMS/silicon interface. Silicon was chosen as the substrate because it is the most common material in MEMS. Meitl et al\textsuperscript{[3]} reported on the benefits of the viscoelastic rate dependent adhesive nature of PDMS during the pick-up phase of transfer printing. Specifically, separation energy between PDMS and a microstructure is smaller when moved slowly as compared to faster movements. Understanding this concept has been a key to transfer printing. Pick up velocities need to be high (between 1-3 cm/s) in order to achieve maximum adhesion. Conversely, release velocities need to be slower so as to lower the interfacial energy and allow for effective printing\textsuperscript{[3]}.

Even with optimizing the release velocity, it can be difficult to print micro devices onto many desirable substrates, especially if those substrates have a micro roughness such as

![Diagram of Interface Adhesion as it relates to velocity at the stamp/ink interface\textsuperscript{[3]}](image_url)
diamond. It is difficult at times to print onto even silicon because the adhesion energy between silicon and silicon is less than the adhesion energy between silicon and PDMS. As such, it is beneficial to determine another means to promote device release that would provide the ability to print on a greater variety of substrates as well as improve printing yields without the use of an applied adhesive. One method to accomplish this goal is to introduce shear strain at the structure/PDMS interface so as to break the intermolecular forces and introduce release enabling crack propagation if possible. The following experiments were designed to address the challenge of on/off adhesion for PDMS and devices and to determine the effect of induced shearing at this interface.

2.4 PDMS on Silicon Shear Experiment

The first purpose of this experiment was to determine the effect of induced shear strain on the PDMS/Silicon interface. The second purpose was to determine whether or not the aspect ratio of the post’s surface area to its depth plays a factor in the ability of the stamp to delaminate from a silicon substrate. The test setup included the following: a load cell with sensitivity up to 1/1000 lb was attached directly to the PDMS stamp arrays as shown in Figure 3.
The PDMS stamp arrays consisted of posts set at a uniform height of 50\(\mu\)m aligned in a square pattern. This height served as the aspect ratio control measure in the experiment. The surface areas of the square stamps were varied using lateral dimensions ranging from 75\(\mu\)m to 300\(\mu\)m. The array of PDMS stamps were leveled planar to the silicon substrate to tolerance of +/- 5 \(\mu\)m across the entire array. The silicon and PDMS were cleaned using scotch tape so as to ensure a clean dust free environment between the PDMS and silicon. The PDMS stamp arrays attached to the Z-stage were brought down into contact with the Silicon substrate mounted on the Y and X linear stages. All stages have a resolution of 1\(\mu\)m. All samples were preloaded with a 1N force to ensure uniform contact across the entire array. Shear strain was induced via moving the silicon substrate’s Y-stage parallel to the square of the array of posts. Shear strain applied in these experiments is defined as \(D_s/L\), where \(D_s\) is the distance the substrate moved. Aspect Ratio (AR) is defined as length over height (L:H_s). Once shear is introduced in the “Y” lateral direction, the stamp is pulled at a steady 1mm/s in the positive “Z” direction and the force is measured from the strain gauges that have a mN resolution.
Figure 4 illustrates the results of these tests and indicates, as one would expect, a definite loss of adhesion as shear strain is induced along the silicon/PDMS interface. Additionally, as the aspect ratio is increased, the amount of shear strain needed to eliminate adhesion decreases significantly. Therefore, the larger the surface to depth ratio for our PDMS stamps, the better the ability to introduce crack propagation along the silicon/PDMS interface and thereby an increased ability to release silicon objects. Designing stamps with these high ratios will aid in the ability of flat stamps to more readily deposit ink onto desired substrates.
Chapter 3: Micro Transfer Printer Tool

3.1 Transfer Printing Tool Origins

In order to further the study of transfer printing, we designed a tool that would be able to achieve our goals and realize the transfer printing automation process. The newest tool was designed and assembled in 2009. The previous tool was completed in 2007. It was designed to meet the following specifications [15]:

- X & Y stage accuracy of 1-5μm over 150-200mm
- Z stage accuracy of 1-3μm
- Controller that can resolve movements to meet the accuracy specifications of the stages as well as accurately control the acceleration and federate of the stages so as to take advantage of the viscoelastic nature of PDMS
- A tip/tilt stage mounted to the substrate to ensure the PDMS stamps and substrates are completely parallel
- An independent XYZ stage mounted optical microscope system with video feed for alignment and calibration

3.1.1 Model 2007 Transfer Printing Tool

The transfer printer tool with these specifications was assembled in 2007. The frame was made out of aluminum and most of the interconnecting pieces were made from rapid prototype polymers with the exception of the stamp holder that was machined from aluminum. The tool was mounted to a vibration dampening table to limit the amount of external vibrations affecting
the tool. The breakdown of parts is shown in Figure 6 and the assemble product is shown in Figure 7\textsuperscript{[15]}.

\textbf{Figure 6: Model 2007 transfer printing tool components} \textsuperscript{[15]}
The final tool was a success in many ways, but fell short in a few areas. The overall accuracy of the system was \( \pm 15\mu m \)\textsuperscript{15}. This error is significant as it represents 15% error on a 100\( \mu m \) device, or up to 60% error on a 25\( \mu m \) device. For purposes of alignment and the creation of MEMs this is not an acceptable error. It was determined that the X-axis of the stage produced the greatest error due to a torsional binding torque induced at the point where the X-axis stage bolted into the X-axis drive bearing.

The design of stamps used in this transfer printer was problematic. The stamps were curved with the posts protruding out of the center of curvature as shown in Figure 8.

\textbf{Figure 7: Assembled Model 2007 transfer printing tool}\textsuperscript{15}
These curved stamps were difficult and time consuming to fabricate because of all of the necessary alignment and because they required thin glass backings molded into the center and used a pressurized chamber to bow the stamps. Even with extra care placed into their creation, often the posts would fail to be at the apex of curvature as shown in Figure 8a. This error would result in the need to adjust the tip tilt stage under the substrate up to 6°. Though relative parallelism between the substrate and stamp was usually achieved, even a small 1° angular adjustment in the tilt of the stage at the left side of the 150mm substrate stage equated to a significant undesired 2.61mm rise in the Z-height of the opposite side of the stage.

Another limitation to this particular stamp design was the difficulty one had in locating the micro posts in the middle of the 125mm PDMS backing as shown in Figure 9:

Figure 8: Curved stamp with posts out of perfect alignment (a/b), and adjusted tip/tilt compensation (c)\textsuperscript{[15]}
These stamps were also very difficult and time consuming to remove and replace on the machine because they were mounted securely to the machine’s stamp holder using 18 individual screws. Changing out stamps for a different array or size would take around 15-25 minutes.

Automation on this particular tool was limited to manually generated (G-code) programs. There was no graphic user interface for optimizing the process or for easy automation. Each project needed to be custom programmed into the machine and then tested in advance of the actual printing to ensure the code was accurate. Even then, due to the inaccuracy of the stages, researches would have to resort to slow and tedious manual printing and substrate fiducial marks to ensure accurate printing of the devices. Figure 10 shows the inaccuracy of relying on the automated stages to print without manual placement or the use of destination fiducial marks.

![Figure 10: Graphic showing the vertical error of the deposited GaAs chiplets in relation to a straight lithographically deposited line of Au](image)

Figure 10: Graphic showing the vertical error of the deposited GaAs chiplets in relation to a straight lithographically deposited line of Au [15]
Additional optimizations to the original design included the ability to rotate the devices or stages in an automated fashion as part of the printing process instead of the use of manual rotation stages. Scalability to the size of printed substrate or the number of simultaneous device donors or receivers is also desirable.

3.2 Model 2009 Transfer Printer Concept and Design

The Model 2009 transfer printer design used the lessons learned from the creation of the Model 2007. Highest priority was given to the accuracy and repeatability of this tool. Ease of use was also a high priority in the design. The following were the design specifications:

- X & Y stage accuracy and repeatability of \( \leq 1\mu m \) over 200mm
- Z stage accuracy of \( \leq 1\mu m \) with enough vertical travel (150mm) to be able to integrate multiple accessories and large substrates if desired
- Rotational stage with accuracy of \( \leq 0.001\degree \)
- Versatile controller that can resolve movements to meet the accuracy specifications of the stages as well as accurately control the acceleration and federate of the stages so as to take advantage of the viscoelastic nature of PDMS
- Precision mounted XYZ stages to ensure perfect orthogonal and parallel alignment
- A tip/tilt stage mounted to XY platform for additional parallel alignment flexibility between the PDMS stamps and substrates
- An independent XYZ stage mounted optical viewing system with video feed for alignment and calibration capable of resolutions down to \( \leq 5\mu m \) with the largest zoom possible to enable macro views of device and stamp arrays
• Stamp holder mount capable of quick and easy exchange and alignment of PDMS stamps
• Modifiable substrate platform capable of securely mounting substrates of varying size, geometry, and texture

3.3 Printer Stages and Controller

The printer’s stages were found based on the design criteria. The following stages and controller from Aerotech® were chosen for integration into the final tool:

<table>
<thead>
<tr>
<th>Component</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Control</th>
<th>Type</th>
<th>Accuracy</th>
<th>Travel Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Stage</td>
<td>Aerotech</td>
<td>ALS20020</td>
<td>Automated</td>
<td>Linear Servo Motor</td>
<td>±1μm</td>
<td>200mm</td>
</tr>
<tr>
<td>Y Stage</td>
<td>Aerotech</td>
<td>ALS20020</td>
<td>Automated</td>
<td>Linear Servo Motor</td>
<td>±1μm</td>
<td>200mm</td>
</tr>
<tr>
<td>Z Stage</td>
<td>Aerotech</td>
<td>PRO225-150</td>
<td>Automated</td>
<td>Ball/screw</td>
<td>±1μm</td>
<td>150mm</td>
</tr>
<tr>
<td>θ Stage</td>
<td>Aerotech</td>
<td>ALAR-100-LP*</td>
<td>Automated</td>
<td>Direct drive Rotary</td>
<td>±1°</td>
<td>360°</td>
</tr>
<tr>
<td>Tip/Tilt</td>
<td>Aerotech</td>
<td>Custom</td>
<td>Manual</td>
<td>Screw</td>
<td>--</td>
<td>±3°</td>
</tr>
<tr>
<td>Motion Controller</td>
<td>Aerotech</td>
<td>A3200</td>
<td>6 AXES</td>
<td>Firewire to PC</td>
<td>±1pm</td>
<td>--</td>
</tr>
</tbody>
</table>

*The ALAR-100-LP was later exchanged for the ALAR-150-LP due to the increased capability of the larger 150mm aperture.

All of these components were purchased through Aerotech® and the stages were professionally mounted and aligned to a 750lb granite base to provide for extra vibration damping of higher frequencies. Figure 11 shows the base components mounted to the granite stage from Aerotech®.

® Registered tradename of Aerotech Corporation
Upon receipt of the unit, a PC capable of handling the user interface for the A3200 controller was designed and built according to the specifications in Table 3:

Table 3: CPU specifications for Transfer Printer

<table>
<thead>
<tr>
<th>Computer Type</th>
<th>OS</th>
<th>Processor</th>
<th>Speed</th>
<th>RAM</th>
<th>Storage</th>
<th>Monitors</th>
<th>Control Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>Windows XP</td>
<td>AMD Quad Core</td>
<td>2.9Ghz</td>
<td>8GB</td>
<td>1TB</td>
<td>2 X 23&quot;</td>
<td>Firewire</td>
</tr>
</tbody>
</table>

The tool was moved into the transfer printing lab and placed on a vibration dampening table capable of holding 4 tons of weight. Once placed on the table, all cables were connected from the transfer printer to the controller and the controller was connected to the PC via a firewire interface.
3.4 Optical Microscope Assembly

Once the base tool was fully assembled, the optics and optics mount were designed to match the printer hardware. The optics were designed with the following hardware:

<table>
<thead>
<tr>
<th>Component</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Control</th>
<th>Type</th>
<th>Accuracy</th>
<th>Travel Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Stage</td>
<td>Zaber</td>
<td>T-LS28M</td>
<td>Auto/Man</td>
<td>Linear Motor</td>
<td>±15μm</td>
<td>28mm</td>
</tr>
<tr>
<td>Y Stage</td>
<td>Zaber</td>
<td>T-LS28M</td>
<td>Auto/Man</td>
<td>Linear Motor</td>
<td>±15μm</td>
<td>28mm</td>
</tr>
<tr>
<td>Z Stage</td>
<td>Zaber</td>
<td>T-LSR150B</td>
<td>Auto/man</td>
<td>Ball/screw</td>
<td>±8μm</td>
<td>150mm</td>
</tr>
</tbody>
</table>

The optics were designed to be independently actuated from the transfer printers primary stages. As such, an aluminum platform was designed and mounted to the granite base of the transfer printer. Figure 12 is a schematic of the design for this arm. It was designed to mount direct to the predrilled holes in the granite base and then fabricated locally.

![Figure 12: Aluminum optics platform](image-url)
The optics were designed to be able to travel 150mm in the z direction to match the travel of the Z-axis of the Aerotech® stage. The rotation stage was mounted to the z-stage upside down. The rotary stage initially had a 100mm in diameter aperture at the center of rotation as shown in Figure 13. This aperture allows the optics assembly to move through the center of the rotary stage down to the correct focal length above the stamp and sample.

![Diagram of the transfer printer rotary stage](image)

**Figure 13: Diagram of the transfer printer rotary stage**

The rotary stage was later upgraded from the 100mm aperture stage to a 150mm aperture stage due to equipment safety considerations to allow for coaxial lighting and to allow for future hardware expansions or functionality upgrades such as the ability to integrate laser hardware or e-jet capability to the transfer printer. The components were all assembled and the optics were mounted and aligned coaxial with the center of the rotary aperture as shown in Figures 14 & 15.
Figure 14: Optical assembly coaxially mounted through rotary stage's aperture

Figure 15: Completed Model 2009 transfer printer
3.5 Stamp Holder

As previously mentioned, one area of challenge was the fabrication of stamps. The large composite stamps as shown in Figure 9 were tedious to fabricate and it was difficult to get a large array of stamps to align perfectly on the apex of curvature. Also, in order to get a rigid backing for the stamp, an additional fabrication step of inserting a glass slide backing was required. Lastly, the composite stamps were cumbersome and difficult to exchange with the printer requiring the removal of the entire stamp holder assembly from the printer as well as manually interchanging 18 small fastening screws.

The goal for this new printer was to create a simple solution to all of these challenges. We designed a rigid, readily swappable stamp system using common 1X3” glass slides. It is important to keep the PDMS portion of the stamp as small as possible due to fact that PDMS shrinks ~1.5% during curing [17]. The greatest issue that arises from this shrinkage is potential lateral movement of features of up to 5% due to residual stress relaxation after curing [18]. Therefore, the key to successful stamp design is to create PDMS stamps as small as possible to reduce the shrinkage effect, but still have a solid backing layer for support. Microscope glass slides provide a reliable and affordable solution to this problem.

3.5.1 New Stamp Design

Instead of the creating complex multi-step composite stamps, we simplified the stamp creation process as described and illustrated in section 2.2. The backing to the posts is determined by how much PDMS is deposited onto the level silicon/SU-8 mold. Depositing thin layers of 2mm or less onto the mold create stamps small enough to limit relaxation, but thick enough to manually manipulate with a pair of tweezers. Leveling of the mold in advance is
essential to this process as the top surface of the deposited PDMS will determine the flatness of
the stamp. The posts are often too small to see with the naked eye; therefore fiducial marks are
fabricated along with the posts that indicate location of the posts in the cured PDMS. After the
PDMS is demolded, one can simply locate the posts using the fiducial marks and then, with a
sharp blade, manually cut out of the PDMS a square area that includes the post features. The
surface area of this newly cut stamp matters for two reasons. First, a larger surface area means a
greater ability for the upper surface of the stamp to adhere to the glass slide’s surface. However,
the larger the stamp, the more pronounced are errors in flatness across the stamp’s surface. The
final dimensions of the cut out stamp vary, but an area of 2X2mm has proven more than
sufficient to adhere the stamp to the surface of a glass slide without the need for any additional
adhesives. Van der Waals forces between the PDMS and glass are more than sufficient to hold
the stamp steady throughout the transfer printing process.

Not only are these new stamp designs easier to fabricate, but they have other mechanical
benefits as well. The natural adhesion of the PDMS stamp to the glass slide allows for easy
application, adjustment, and removal of stamps to slides. These smaller stamps are easy to store
and organize as well. A secondary benefit of having smaller stamps is that it is easy to see the
cut edges of the stamp through the microscope. This is very advantageous for finding the posts
of the stamp during the setup phase of transfer printing. With the Model 2007 transfer printer,
one had to scan back and forth and through multiple focal lengths to try and find the micro posts.
At times it would take up to 20 or 30 minutes to locate these tiny features in the 125mm diameter
sea of PDMS. With these smaller stamps, it is much easier to find the posts, because the edges
of the stamp are easily found with the microscope and then when the X and Y bounds of the
stamp are determined, one can then confidently use adjustments in focal depth to find the micro-

post within the stamp limits. With the new stamps and holder, this setup process now routinely only takes approximately 2-4 minutes. Figure 16 depicts the stamp on glass slide setup.

![PDMS Stamp and Glass Slide](image)

**Figure 16: PDMS Stamp on glass slide**

The final benefit to this stamp design is that because the stamps are so small and formed perfectly flat, that there is no need to manually adjust the tip tilt on the transfer printer. The transfer printer’s Z stage is precision calibrated to be parallel to the X&Y stages. When we introduce these stamps on glass backing, the stamps are flat enough that we have found no need to adjust tip/tilt on the stage despite the shallow 50μm depth of most post features on the stamps’ surfaces. Again, the self-aligning simplicity of this design has eliminated a mandatory 5-15 minute calibration step on the Model 2007 transfer printer.

3.5.2 Stamp Holder Assembly

Using the stamp on glass slides solved the challenge of ease in manufacturing the stamps. The other challenge to address in the stamp holder was the way the stamps mounted to the transfer printer. The new stamp holder was designed for simplicity and scalability. Instead of using 18 screws to fasten the stamp to the transfer printer’s stamp holding stage, we chose to use vacuum suction instead. We built the stage to have a 1/16” plate designed with a 1”X3” aperture at the center that would perfectly fit the glass slide. This aperture fits directly over two vacuum
ports that are large enough to securely hold the glass slide in place on the bottom of the stamp holder assembly. These two ports are on either side of a large hole in the holder directly above where the stamp and posts are centered. This center hole allows the transfer printer to view down through the glass and stamp. Figure 17 shows this new stamp holder design.

![Figure 17: Transfer Printer Model 2009 Stamp Holder](image)

The stamp holder’s lower plate with the 1”X3” aperture is designed to be removable and swappable with modular plates of varying sizes and shapes to allow for scalability and flexibility in the mountable stamp backing substrates. In experiments, we have found the new stamp holder to function as designed, securely and accurately holding the glass slides centered in place.

The last part of the stamp holder’s design was to include the ability to sense contact both above and below the stamp holder’s platform. The reason for this functionality is to protect the independently controlled optics from the stamp holder rising up and colliding with them. The sensors on the bottom of the stamp holder were put there to protect substrates from being crushed by the force of the z-stage pushing down too forcefully onto the substrate due to human input error. The switches we installed on the transfer printer were wired to shut off power to the optics stages as well as send an immediate shut off signal to the Aerotech® A3200 controller. This fault
is then corrected manually on the optics stages. These switches have proven invaluable in keeping the equipment safe from accidental collisions during experiments.

3.6 Substrate Platform

The substrate platform is essentially a set of vacuum chucks designed for modularity as well. Two platforms were created. The first was created out of steel and consisted of 6 independent vacuum ports that fed 5 substrate holders on its surface, 4 smaller 1” waffle orifices and two feeds going to a larger 3” target shaped orifice in the center. This design is shown in Figure 18.

![Steel Substrate Holder](image)

**Figure 18: Steel substrate holder**

This steel substrate holder was limited in size measuring 5”X8” and therefore did not exploit the full 8”X8” travel of the transfer printer’s X and Y stages. The size also limited the ability to place larger substrates on it if needed. It was also not flexible as to the location of suction sites.
The second design was fabricated out of aluminum. This platform covers the entire 8”X8” printing area and also has a 1” buffer in both the X+ and X- axis direction. The platform also extends 4” in the Y+ and Y- axis directions. These extensions offer secure vacuum support for substrates that may extend beyond the immediate printing area of the transfer printer. This platform also has a uniform grid of holes throughout its surfaces so as to allow for the mounting of modular plates designed independently for use with various types and sizes of substrates. These plates can be mounted anywhere on the ½” pitch grid. The modular mounting plates are hollow inside and thereby connect to one of 8 available vacuum ports on the surface of the platform. Figure 19 shows the platform. The top plate shows the internal vacuum channels that feed the 8 external vacuum ports on the surface of the bottom plate; all other holes are for mounting the two plates together and to the transfer printing tool.

Figure 19: Modular aluminum transfer printing substrate holder
3.7 Testing the Transfer printer

Once the Model 2009 transfer printer was fully assembled, we conducted tests to measure accuracy and precision of the transfer printing process. The stages were rated for at least 1µm for accuracy, but the accuracy of the system when coupled with PDMS stamps was still unknown. In order to assess the accuracy of this system, we used an array of GaAs LEDs still anchored to their original Si donor substrate as shown in Figure 20.

![Array of GaAs LED chiplets on original Si substrate](image)

Figure 20: Array of GaAs LED chiplets on original Si substrate

16 of these chiplets were chosen for transfer printing. The SEM in Figure 20 was analyzed by measuring each of the 16 chosen LED chiplets at two points on each of its 4 sides to determine gap distance between the chiplets to within ±250nm. Once the donor substrate was fully
measured, the chiplets were then transfer printed to a receiver substrate shown in Figure 21. They were transfer printed manually by the use of a single flat PDMS post with the dimensions of 100µmX100µm.

The receiver substrate was a 2”X3” glass slide coated in 25µm of 10:1 PDMS. The PDMS on the receiver substrate served as an adhesive layer for printing. After printing the 16 chiplets they were then measured on the receiver substrate in the same manner as the donor substrate. The data as shown in Appendix A was then consolidated and analyzed. The greatest error was .75µm. The average error was .18µm and the standard deviation for the data was ±.2. This data supports the assumption that the use of PDMS in transfer printing on the Model 2009 transfer printer does not induce error greater than the error threshold of the printer’s stages of 1µm.
3.8 Transfer Printing Automation

The Model 2007 transfer printer used a PMAC® that was directly programmable through the use of G-code. For the Model 2009 transfer printer, we opted to create a graphic user interface (GUI) that would make this tool more user-friendly. We designed the interface using Labview software. Aerotech included some basic labview interface modules for use with their A3200 controller interface that we modified and enhanced. We included the following functionality in the final transfer printing GUI.

- System initialization and termination
- Master universal abort button
- Manual enabling, homing, moving of all stages to include modulating stage velocity
- Stage free run and step incremental runs are options for movement
- Real time position readout of all stages
- Remote load cell readout and tool safety integration such that if a load cell comes close to its max allowable load, then the stage will stop movement automatically
- Boolean input array for customizing the printout design
- Real time readout of controller system status and errors
- Customizable transfer printing automation to include:
  - Defining donor substrate ink array for automatic retrieval of ink
  - Defining receiver substrate for automatic printing of predefined rectangular arrays or customized print design
  - Definable print modes that include normal and shear printing modes

® Registered trademark of Delta Tau Systems Inc.
- Definable stage speed and automated velocity adjustment to take advantage of the tunable viscoelastic adhesive characteristics of PDMS stamps

The final GUI is shown in Figure 22:

![Figure 22: Transfer printer Model 2009 graphical user interface](image)

3.9 Transfer Printer Conclusions

The Model 2009 transfer printer successfully fixed most of the issues present in the Model 2007 transfer printer to include the following:

- Reliable and accurate printing that reduced the stage error from ±15µm to ±1µm
- Automated rotary control
- New and improved stamp design:
o Eliminates the need for tip/tilt calibration
o Introduces simplistic stamp swapping technology using vacuum suction
o Easy alignment of stamps and post
o Easy post locating and reduced initialization calibration steps

• Modular customizable printing platform
• Automated GUI interface for ease of use
• Safety features built in to protect the tool from human error

Overall, the printer has proven to be a success and continues to aid in the research of many multidisciplinary groups at the University of Illinois.
Chapter 4: Micro Nozzles

4.1 Introduction

With the Model 2009 transfer printer assembled, we started experiments that determine the feasibility of using transfer printing as an assembly method for 3D MEMS. The ability of heterogeneous integration of micro devices fabricated in silicon into other materials is the key motivation for this assembly. One of the greatest challenges to the realization of heterogeneous integration is the ability to manipulate and assemble items at the micro scale or below. This is one of the reasons that MEMS have predominantly been manufactured using 2½D photolithographic processes. Many groups have attempted to build micro grippers with some success, but they are still largely difficult to use and thereby difficult to scale for manufacturing purposes \[19\]. Elastomeric transfer printing is perhaps the first feasible tool for use in the bottom-up assembly of 3D MEMS.

Transfer printing has proven effective in the printing of many types of materials to include LEDs and solar cells onto multiple substrates through the use of flat PDMS stamps \[2\], \[3\], \[15\]. LEDs and solar cells are flat and smooth and thereby adhere easily to flat PDMS stamps. MEMS parts are not always flat or ideally smooth; therefore, PDMS stamps need to be custom designed to optimally match the shape of the part it needs to pick up and deposit.

To illustrate this concept, we chose E-jet micro nozzles as an example. Micro nozzles are normally fabricated using purely photolithographic processes. The nozzles are patterned on one side of a silicon wafer and then the microfluidic channels and reservoirs are patterned on the back side of the same wafer using expensive deep reactive ion etching (DRIE) ICP etching throughout the entire 500-600μm thick wafer. As an alternative, we fabricated a dense array of micro-nozzles on an silicon on insulator (SOI) wafer that could then be transfer printed to PDMS
formed micro fluidic channels and reservoirs. The PDMS channels are much more economical
to fabricate as they can be repeatedly molded from the same silicon/SU-8 die. Additionally, the
actual nozzle creation is reduced from over 20 steps to just 9 with no wasted space required for
large backside reservoirs or micro-fluidic channels. The dense array of nozzles can relatively
quickly be printed into hundreds of custom arrays of nozzles from a single wafer compared to
just a few using current fabrication processes. These out of plane silicon nozzles are integrated
into a PDMS-based microfluidic substrate for ease of use in and supply of fluids.

4.2 Nozzle Fabrication

The nozzles were fabricated on an SOI wafer that consisted of a 50\(\mu\)m thick device layer
and a 3\(\mu\)m thick SiO\(_2\) box layer. The fabrication consisted of the following steps as illustrated in
Figure 23:

1. Deposit 1\(\mu\)m of SiO\(_2\) on top of the wafer using plasma enhanced chemical vapor
deposition (PECVD)
2. Pattern the SiO\(_2\) with AZ5214 photoresist and etch the exposed SiO\(_2\) using RIE
3. Pattern the round nozzle head on the SiO\(_2\) squares with AZ5214
4. DRIE etch the wafer using the SiO\(_2\) and AZ5214 as a mask to a depth of 15\(\mu\)m
5. Remove the SiO\(_2\) using 6:1 or 10:1 H\(_2\)O:HF, Buffered Oxide etch (BOE)
6. Continue the DRIE etch until it reaches the SiO\(_2\) box layer
7. Remove the SiO\(_2\) box layer using BOE until the chiplets are undercut ~1-2\(\mu\)m
8. Spin coat AZ5214 but do not pattern, just flood expose it (the undercut portion will not
be exposed and will act as an ‘anchor’ for the chiplets to the handle layer of the SOI)
9. Continue BOE or pure HF undercut to remove all residual SiO\(_2\) box layer and thereby
suspend the nozzles
The final product after fabrication is shown in Figure 24.
The final dimensions are shown in Figure 25:

![Figure 25: Dimensions of microfluidic nozzles](image)

Due to side wall angle from the DRIE in fabrication, the dimensions of the surface area of the nozzles decreased from 100μmX100μm to approximately 80μmX80μm or 6400μm².
4.3 Nozzle Shaped Posts

After fabricating the nozzles, the next test was to determine how to best print the nozzles using PDMS. The ability of PDMS to successfully adhere to a surface is dependent on the amount of surface contact between the PDMS and the device or micro part. The greater the surface area, the greater the adhesion through van der Waals interactions; and therefore, greater the ability to break the photo resist anchors. If there is insufficient surface to PDMS contact, then the devices will remain anchored to the donor substrate.

The shape of the nozzle proved a challenge to transfer printing using a conventional flat stamp. The extruding nozzle from the larger base prevented the use of a regular flat stamp, as a flat stamp would only contact the very top surface of the nozzle with a surface area of only 471μm². This is a small value compared to the nozzle’s base surface area of approximately 6000μm². We decided to create a custom stamp to accommodate the geometry of the nozzles. These stamps were fabricated in the same manner as described in Section 2.11 with the exception of the insertion of a round cavity in the center of the post to accommodate the entire nozzle as shown in Figure 26.

![Diagram of PDMS hollow nozzle post fabrication](image)

(a) (b)

**Figure 26:** PDMS hollow nozzle post fabrication: (a) SU-8 mold, (b) PDMS stamp extracted from mold
The hollow posts allow the bulk of the PDMS post to adhere to the bulk of the nozzle base’s surface area and thereby maximize the adhesion force between the PDMS post and the micro nozzle. The posts were fabricated as a square 100X100µm with a height of 50µm. The round hollow cavity was fabricated to be 2.5 times the diameter of 20µm nozzles and extended the entire 50µm height to the base of the PDMS stamp backing. This size proved more than enough space to allow the 30µm tall nozzles fully inside the hollow of the post.

4.4 Microfluidic Nozzle Transfer Printing

Using the hollow posts and the newly fabricated array of micro nozzles, the nozzles were first transfer printed onto a flat bed of PDMS on glass and then onto micro channels fabricated in PDMS on glass. Both experiments were a success as we were able to successfully print some of the nozzles onto flat PDMS as well as onto PDMS micro fluidic channels as shown in Figures 27 and 28. This experiment also proved the feasibility of using customized PDMS as a means to pick up 3D micro structures.

![Image](Image)

Figure 27: Progression of transfer printed micro nozzle from silicon donor to PDMS substrate: (a)Micro nozzle on silicon donor, (b)Hollow PDMS post above MS receiver substrate, (c) Post above micro nozzle, (d) Post in contact with nozzle, (e)Released post on receiver substrate, (f)Transfer printed micro nozzle
4.5 Conclusions

Transfer printing has proven a versatile option for the creation of hybrid MEMS 3D microfluidic arrays. Challenges to this process as a viable assembly method include determining the best way to anchor the devices to enable the flow of highly pressurized liquids as well as defining the best way to make the nozzles electrically conductive so as to be able to E-jet liquid. These experiments have clearly shown that PDMS is a versatile substance capable of transfer printing devices with complex geometries.

Figure 28: Microfluidic nozzle printed onto PDMS microfluidic channel
Chapter 5: Micro Gears

5.1 Introduction

Mechatronics is another prominent area of MEMS. In order to demonstrate the use of transfer printing in this area, we chose to design micro gears on one substrate and micro posts on another substrate. The ability to create parts on separate substrates and then print them together allows fabricators flexibility in the fabrication process. It allows them the ability to fine-tune processes to optimize the creation of each specific part without needing to compromise fabrication due to consideration on how those processes might adversely affect separate components in the MEMS device.

5.2 Concept and Design

To further prove the printer’s ability to assemble 3D micro structures we plan to fabricate single crystal silicon gears and then directly print them onto silicon structures. The design of the micro gears is shown in Figure 29. We will fabricate the gears separately from the inner gear posts and then attempt to transfer print the gears onto the silicon posts in arrays of 2, 3, and 4. We hope to be able to create fully functional arrays demonstrating the micro assembly potential of adhesion-less transfer printing.
Masks were created for the gears and the posts. The posts were spaced at 52μm apart to allow for the gears to actuate each other once printed on the cylindrical posts.

5.3 Micro Gear Fabrication

Once the masks were created, the gears and posts were fabricated using an undoped SOI wafer with a 50μm device layer and a 2μm SiO₂ box layer. The fabrication steps illustrated in Figure 30 are as follows:

1. Deposit 1μm of SiO₂ onto the top surface of the silicon wafer using plasma enhanced chemical vapor deposition at 250°C
2. Pattern the gears and posts on top of the SiO₂ surface
3. Etch the SiO₂ using 6:1 BOE
4. Etch Si 50μm down to the box layer using DRIE ICP vertical etch using the remaining PR and SiO₂ as an etch mask. The posts are complete at this point.

5. On the gears wafer only, etch the box layer SiO₂ using 6:1 BOE until the gears are undercut ~2μm.

6. Spin coat the wafer with AZ5214 photo resist (PR) and then flood expose it to develop all the PR except the small amount trapped in the ~2μm undercut under the gears.

7. Undercut the SiO₂ box layer under the micro gears using 6:1 BOE or HF until the features are fully undercut and resting only on the residual PR.

The fabrication was a success and the SEM of the gear array is shown in Figure 30. The SEM of the post array is shown in Figure 31. The micro posts are shown in Figure 32.

![Figure 30: Silicon micro gears](image)
Device Substrate

- Deposit SiO₂ via PECVD (1μm)
- <110> Si Device layer (50μm)
- SiO₂ Silicon Nitride PECVD deposition (2μm)
- <110> Si handle Layer (~500μm)

Pattern AZ 5214 PR on SiO₂
Pattern SiO₂

DRIE Etch Silicon to box layer

Etch SiO₂ with BOE

Deposit AZ5214 and flood expose

Etch remaining SiO₂ with BOE and remove PR with Acetone

Top View

Figure 31: Micro gear and micro post fabrication steps
5.4 Micro Gear Transfer Printing

Upon completion of the micro gear and post fabrication, they were placed on the transfer printer to attempt transfer printing of the gears to the silicon micro posts. A flat 50x50x50μm PDMS post was used to pick up the 60μm diameter micro gears. Two gears were successfully retrieved from the donor gears substrate and transfer printed to the micro posts. The process is shown Figure 33.

Figure 32: Silicon micro posts
Figure 33: Micro gear printing progression. (a) Position stamp above gear (b) contact stamp with gear (c) pick up gear (d) move gear and align directly above silicon micro post (e) place gear on micro post (f) shear PDMS stamp off of gear to release, (g) transfer printed gear remains on the silicon micro post

Figure 34 shows the two successfully transfer printed micro gears:

Figure 34: Silicon micro gears printed on silicon micro posts
Once these two gears were transfer printed, the transfer printer was used to actuate the gears by using 50μm stamp to interact with the gears. Actuating one of the gears in this manner rotated the second gear as expected. Figure 35 shows this experiment:

![Figure 35: Actuating two micro gears using transfer printer's 50μm PDMS post. Red and yellow dots show rotational progression of the gears](image)

5.5 Conclusions

The successful transfer printing of micro gears demonstrates the ability of the transfer printer to assemble mechatronic MEMS. The next logical step would be to transfer print the gears onto a self-actuating MEMS. One potential driver for these gears would be a comb drive. Further improvements can be made in optimizing the design of the gears and posts so that they have tighter tolerances. Considerations for friction and other factors would also need to be part of a new design. The ability to transfer print the gears into functional arrays frees up this design process because it allows the designer the flexibility of optimizing each component independent of the MEMS as a whole.
Chapter 6: Air Cooled Microbolometers

6.1 Introduction to Air Cooled Microbolometers

Microbolometers are the primary sensors in infrared thermal imaging devices and therefore a thermoelectric MEMS device. There is significant military and commercial demand for these devices. Most commercial devices and those used in a wide array of military uses are cryogenically cooled photonic IR detectors and have been around for a few decades. They are often bulky, expensive and unreliable\[20]. Another type of infrared detector is the thermal detector. These detectors differ from photonic detectors primarily in their ability to operate at room temperature\[21]. By eliminating the cryogenic cooler, these sensors need less energy to run making them more reliable and the size is greatly reduced as well\[22].

Vanadium oxide is often selected as the material of choice when making uncooled microbolometers because of its large Temperature Coefficient Resistance (TCR).

\[
TCR = \left( \frac{1}{R_b} \right) \left( \frac{dR_b}{dT} \right) \times 100\%
\]

Vanadium oxide also has a decent electrical resistance and low 1/f noise. In the past, the vanadium oxide has been deposited onto membranes using reactive ion beam sputtering at a temperature below 200°C so as to not damage the Complimentary Metal-Oxide-Semiconductor Readout Integrated Circuit (CMOS ROIC)\[20]. Bolometers fabricated in this manner are shown in Figure 36:
Microbolometers created with vanadium oxide at 200 °C are sub optimal because the TCR of the vanadium oxide at this temperature is only around -2.2%/°C. It has been shown that a superior TCR of -4.4%/°C can be achieved when the vanadium oxide is annealed at 400 °C for 3 hours after it has been reactive ion beam sputtered[23]. The issue is that the 400 °C temperatures will damage the CMOS ROIC circuit; therefore, a compromise in microbolometer vanadium oxide sensitivity was the solution.

Transfer printing offers a unique answer to this issue. Transfer printing allows the bolometer membranes to be fabricated and optimally processed independent of the CMOS ROIC. Once fabricated, the membranes can then be transfer printed to the CMOS ROIC to complete the MEMS thermo electric sensor array.
6.2 Microbolometer Concept and Design

In order for a microbolometer to function, its membrane needs to be thermally isolated from its environment. Figure 37 shows the basic components of a microbolometer. The membrane is typically created out of vanadium oxide and sometimes uses silicon nitride (Si₃N₄) as a scaffold support layer. Si₃N₄ is used because it is invisible in the desired infrared sensing spectrum of λ= 8-12μm used for thermal imaging[^24]. To maintain isolation between the bolometer’s membrane and its environment, the vias between the membrane and the readout integrated circuit (ROIC) are designed to be as small as possible. These vias are created out of various materials, but they need to have at least one layer of a conductive metal that will send a constant voltage through the vanadium oxide. As photons strike the vanadium oxide, the ROIC will detect the change in resistance that occurs in the membrane and relay that to a visual display as a single pixel. Therefore, the more negative the TCR the better as this means that even small changes in temperature as sensed by the bolometer will register as large changes in resistance[^25].

![Figure 37: Bolometer schematic](image)

[^24]: Reference to the figure or diagram
[^25]: Reference to the figure or diagram
The preferable thermal isolation gap between the membrane and the bulk surface of the ROIC is measured at the desired sensing wavelength $\lambda$ divided by 4. The surface of the ROIC needs to be coated with a material that is reflective in the IR spectrum. This reflective surface, usually created out of Cr or Ti, reflects any IR light that may have passed through the thin (100nm) thick Vanadium Oxide membrane back up to the membrane to get reabsorbed. The distance of $\frac{\lambda}{4}$ is ideal for trapping the reflected IR light and allowing it to propagate horizontally, reflecting between the mirrored surface and the membrane enabling the microbolometer to capture as much of the IR light as possible from any given light source [20].

Current microbolometer designs are created by depositing the vanadium oxide membranes directly onto a $\frac{\lambda}{4}$ thick sacrificial layer that is deposited directly on the CMOS ROIC. This sacrificial layer is later removed in order to thermally isolate the membrane. This traditional process is shown in Figure 38:

![Figure 38: Traditional bolometer fabrication process flow (a) deposition of sacrificial layer on ROIC wafer; (b) deposition of bolometer materials; (c) patterning of bolometer materials; (d) via formation; (f) etching of sacrificial layer [24]](image)

This process has proven effective in current designs, but is limited in its potential because of the inability to anneal the vanadium oxide membrane at high temperatures to achieve optimal TCR.

6.2.1 Transfer Printed Bolometer Design

The transfer printable bolometer design was fabricated so as to maximize the Vanadium Oxide membrane’s TCR. The membranes were created separate to the readout circuit. As such,
we were able to achieve a higher TCR by virtue of annealing the Vanadium oxide at a higher temperature than is allowable for CMOS ROIC. The fabrication is discussed in detail in section 6.3.

6.3 Transfer Printable Microbolometer Fabrication

6.3.1 Bolometer Chiplet Fabrication

The bolometer membranes were created using a <111> silicon wafer as the primary substrate. 1μm of Si₃N₄ was deposited on the silicon wafer using PECVD. This layer serves as the scaffolding/support layer for the Vanadium Oxide. Next, 50nm of vanadium oxide was deposited onto the Si₃N₄ by using DC driven reactive ion sputtering of 99% pure vanadium in an oxygen rich environment. The result is a mixture of V₂O₂ and V₂O₅. The entire substrate was then annealed at 400 °C for 3 hours [23]. After annealing the vanadium oxide, CrAu contact pads were sputtered onto the surface of the vanadium oxide and the substrate was tested to determine a TCR of -3.3%/°C for the vanadium oxide thin film. This value is better than the industry average of ~2%/°C, but less than our goal of ~4%/°C [23]. After testing the vanadium oxide, we then patterned chrome collector bars directly onto the vanadium oxide surface and then patterned the membrane shape on top of the collector bars by etching the vanadium oxide and the Si₃N₄ down to the silicon wafer surface. We then etched 3μm into the silicon substrate to create an opening for a KOH etch. KOH was then used as a directional anisotropic etch to undercut the bolometers, completely leaving them suspended by Si₃N₄ anchors. This process is shown in Figure 39 and the process parameter as shown in Table 6:
Figure 39: Microbolometer chiplet fabrication process (a,b) PECVD silicon nitride deposition; b) 50 μm vanadium oxide deposition; c) patterned 50 nm chrome deposition; d) Etch down to 3 μm into silicon; e) Use KOH to preferentially etch along <111> planes to undercut membrane [26]

Table 6: Vanadium oxide sputtering parameters

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6.3.2 Bolometer Testbed ROIC Fabrication

The test bed was fabricated using CrAu on glass. The pattern in Figure 40 was then created using AZ5214 photoresist (PR). Next, 20nm of chrome was deposited onto the glass/PR followed by 60nm of Au. The pattern was then created using liftoff of all PR and undesired metal.
Once the readout test bed was fabricated, a sacrificial layer of AZ5214 PR was deposited with a thickness of $\frac{\lambda}{4}$ or 2.5µm. This PR was then patterned to create via holes at the points where the bolometers need to connect to the readout pads. This fabrication process is shown in Figure 41:
6.4 Micro Bolometer Transfer Printing

Once the bolometer chiplets and the readout test bed were fabricated, the chiplets were then transfer printed onto the PR layer of the readout test bed. Figure 42 shows the print progression of the microbolometers:

![Figure 42: Microbolometer transfer printing progression. (a) Readout test bed coated in PR with via holes; (b) Readout testbed with one printed bolometer; (c) Readout test bed with 4 printed bolometers](image)

The 50μm microbolometers were transfer printed to the readout test bed using a 50μm PDMS flat stamp. They printed readily onto the AZ5214 photoresist.

6.5 Micro Bolometer Post Processing

After transfer printing the bolometers, the next step is to connect the bolometers to the test bed through the via holes in the AZ5214 PR sacrificial layer. The devices were sputter coated with 300nm of gold and then the gold was etched everywhere except for the via holes. The Au connected the readout circuit to the Cr connector bars on the bolometers. The last step
was to etch all of the remaining photo resist on the substrate. This was accomplished using acetone and Nano-Strip® etchant.®

Figure 43: Printed microbolometer suspended above the readout test bed via gold connections

Once the bolometer test bed was complete, we attempted to test the bolometers, but we were unable to find any functional devices. A few potential issues to resolve are ensuring the sacrificial layer is fully undercut and the via connectors are fully contacting the collector bars and the underlining probe lines.

6.6 Conclusions

These experiments show that bolometers can indeed be fabricated separately and transfer printed to a foreign substrate. Some work needs to be completed to figure out how to effectively connect the bolometers to the readout circuitry, but the overall concept is valid as a means to

® Nano-Strip is a registered trademark of the Cyantek Corporation
optimize vanadium oxide membranes and boost the overall performance of microbolometer infrared sensing arrays.
Chapter 7: Conclusions

7.1 Summary and Conclusion

Transfer printing is an effective method of printing MEMS devices. This thesis has shown that mechatronic, micro fluidic, and microthermal sensing devices can all be modularly created and assembled through the use of the transfer printer tool.

The Model 2009 transfer printing tool successfully corrects most all of the faults of its predecessor making it an effective and precise pick and place instrument; its hardware and software are both scalable and customizable.

Continued studies on PDMS intermolecular forces, stamp design and printer automation will help expand the transfer printers capabilities and further its potential at becoming a valid manufacturing technique for the creation of newer and more complex forms of 3D MEMS.
References


### Appendix A: Transfer Printer Characterization Data

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