Exploration of Large Scale Manufacturing of Polydimethylsiloxane (PDMS) Microfluidic Devices

by

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ABSTRACT

Discussion of the current manufacturing process of polydimethylsiloxane (PDMS) parts and the emergence of PDMS use in biomedical microfluidic devices addresses the need to develop large scale manufacturing processes for the fabrication of said devices. Casting PDMS parts is found to be the best mass production process after evaluating several different production methods.

Automation of the manufacturing process is introduced as a solution to the need for mass production. Changing variables within the production process and its effects are also discussed with the recommendation being made for using low viscosity pre-cured PDMS, high temperature curing and high vacuum degassing techniques to produce high quality parts at high production rates. The further development of producing two-sided PDMS parts is recommended by investigating the usage of a non-closed aspect limited casting process.

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Chapter 1. Introduction to Polydimethylsiloxane

The capability to mass produce microfluidic devices is essential to bringing bio-mechanical devices to society at large. There have been positive results from researchers attempting to develop microfluidic devices using polymers. One polymer that has exhibited good characteristics for use in these bio-mechanical devices is polydimethylsiloxane or PDMS.

The most widely used PDMS kit is Dow Corning Sylgard Elastomer 184. PDMS is an elastomer that is made by combining a siloxane base with a curing agent. The two parts must be mixed together and cured to form PDMS. When the two parts are mixed an organometallic crosslinking reaction cures the product into PDMS. The siloxane base oligomers have vinyl groups while the crosslinking oligomers have at least three silicon hydride bonds each. The curing agent contains a platinum based catalyst that aids in the formation of SiH bonds across the vinyl groups to form $Si-CH_2-CH_2-Si$ linkages. The presence of multiple bonding sites allows for the development of three-dimensional crosslinking throughout the cured PDMS.[1]

PDMS has several properties that make it suitable for use in microfluidic devices. When casting PDMS its low viscosity allows it to spread over large areas and to conform to nonplanar deformations on the master. The cured PDMS can be removed from the masters easily due to its elasticity. It is also chemically inert, homogenous, isotropic and durable. Cured PDMS can also be treated with surface preparations in order to adhere it to other certain materials.[2]

Virtually all of the advances that have been achieved in making microfluidic devices from PDMS have been on the laboratory scale. While these advances should not be overlooked, in order to bring PDMS microfluidic devices to a more marketable position, procedures must be formulated to mass produce these devices. Currently, the technology to realize this has not yet been developed.

The aim of this thesis is to first explore current methods of manufacturing PDMS microfluidic devices. It will then present a method for automating the process of making parts for microfluidic devices for use in implementation in a mass production system. Because of the lack of automated processes for producing PDMS devices right now, the processes that are drawn up will have to be tested on a small scale before full implementation.

Chapter 2. Application of PDMS to Microfluidics

Microfluidic devices have only started to be developed since the 1990s. These devices are comprised of pumps, channels and valves on the micrometer scale. Several applications of microfluidics are micro-thermal and propulsion technologies, and biomedical technologies such as lab-on-a-chip, DNA microarrays, drug screening, gene analysis and cell culturing.[3, 25]

Microfluidic devices are currently being manufactured from materials such as polymethylmethacrylate (PMMA), polyurethane and silicon. The main drawback for using these hard materials in microfluidic devices is their hardness.[26] Creating moving parts, such as valves, using these materials is possible but only by increasing the size of the device to allow for the inclusion of structures such as membranes and valve seats. Furthermore, it is difficult to incorporate soft materials with silicon which is a necessary process to create microfluidic devices using silicon.[26]

The main property that makes PDMS better suited for microfluidic applications over hard materials is elasticity. PDMS is also able to form complex patterns on the micrometer scale which is essential in microfluidics. These complex patterns can be formed using casting techniques while hot embossing and micromachining is primarily used with hard plastics.[26] Elasticity is important to the creation of pumps and valves while complex patterns are needed to shape the channels for the fluids. To help quantify what was stated previously, the softness of PDMS elastomer is superior to that of silicon and hard plastic based devices in that the area of the valves and pumps can be reduced by greater than two magnitudes.[4] This is an important property since size is a critical factor in microfluidic devices.

2.1 Valves

Valves can be created by utilizing the elasticity of PDMS. If a fluid were being pumped through a channel, there are several ways of stopping the flow. The simplest way is to apply pressure to the PDMS channel until the wall pinches shut and stops the flow. This is similar to stepping on a garden hose. For example, see Figure 1 below.

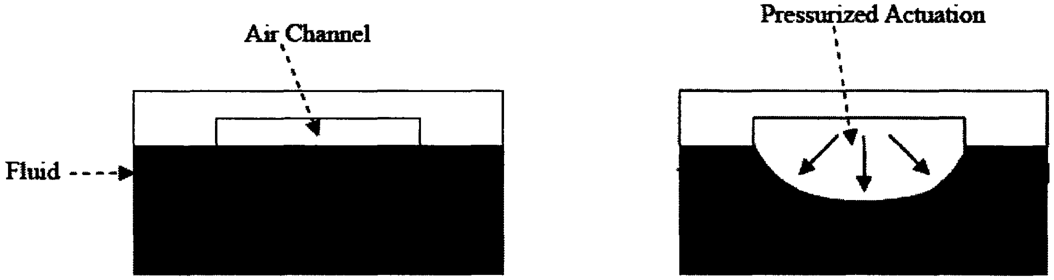

Figure 1: Diagram exhibiting a simple valve made with PDMS [5]

In Figure 1, the three layers are all made of PDMS. When the valve is not engaged, the fluid flows freely, however when air pressure is applied in the upper channel, the middle PDMS layer deforms downward to cut off the fluid flow.

More complex valves have been created using PDMS such as diaphragm and flap check valves. The main goal of the diaphragm and flap check valves is to prevent backflow of the fluid. These valves involve more intricate designs and fabrication techniques than the simple valve. Similar to the construction of the simple valve in Figure 1, the diaphragm and flap check valves are made by stacking three layers of

PDMS. However, these layers are not just flat films or single channel membranes. For illustration, see Figures 2 and 3 below.

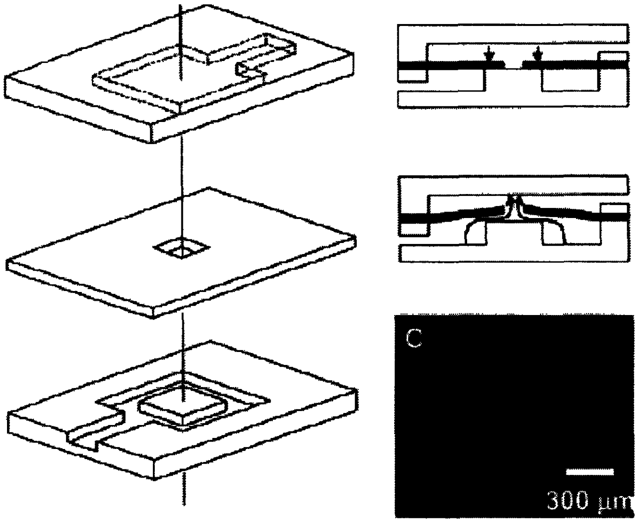

Figure 2: Illustration showing the separate PDMS layers and operating principle of a diaphragm valve [22]

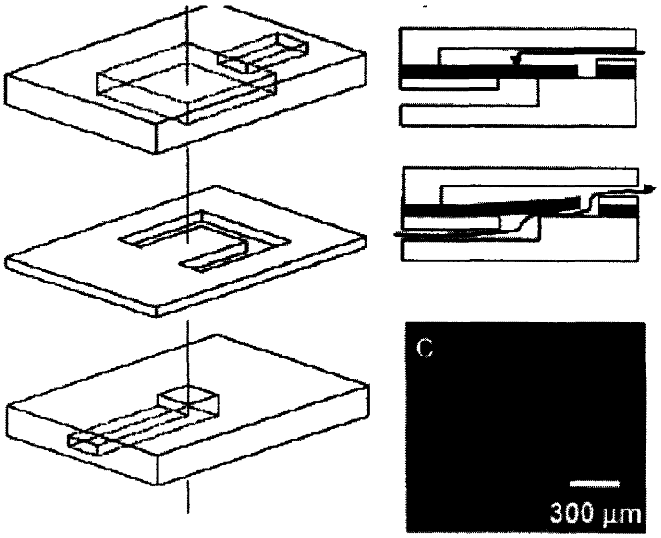

Figure 3: Illustration showing the separate PDMS layers and operating principle of a flap check valve [22]

There are many more ways to incorporate the elasticity of PDMS into the manufacture of valves, these few examples are just the beginning of what is possible.

2.2 Pumps

Peristaltic pumps can be formed by putting several simple PDMS valves in sequence. Fluid is passed within a channel of PDMS and the sequential actuations of valves causes the fluid in the channel to flow. This type of pump is useful because the fluid being pumped never touches anything outside of the PDMS channel. A cross-section and full drawing of a peristaltic pump is shown below in Figure 4.

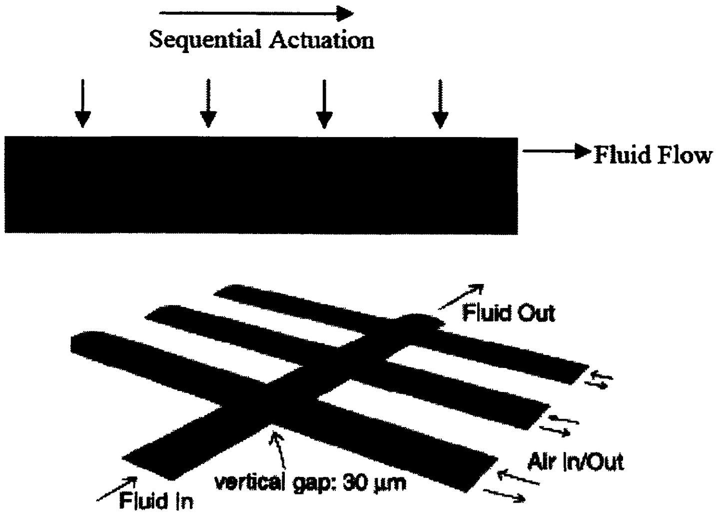

Figure 4: A cross-section and diagram of a peristaltic pump made with PDMS [4]

The above pump was fabricated and tested in a laboratory setting. The pump performed well and the PDMS showed no sign of wear or fatigue after more than 4 million actuations.[4]

2.3 Fluid Networks

The fluid networks that are needed for microfluidic devices are often very complex with small features. What makes PDMS a good material is that by utilizing replica molding, features as small as 30 nm can be achieved.[2] This is a much higher resolution than is needed for microfluidic applications. Shown below in Figure 5 is an optical micrograph of a fabricated valve grid.[4]

Figure 5: Optical micrograph of a valve grid consisting of 30μm control line and a 50μm flow line. Scale bar is 200μm.[4]

These channels are representative of the capabilities of PDMS in creating microchannels and valves.

2.4 Biomedical Devices

Microfluidic devices are gaining interest in the biomedical community because of their small size and ability to transport both liquids and gases. PDMS in particular is being investigated because it is chemically inert, thermally stable, easy to handle and gas permeable.[6] Combining its microfluidic capabilities and biological compatibilities, PDMS is very appealing to the BioMEMs community.

For example, MIT Professor Todd Thorsen is currently investigating the feasibility and production of a PDMS-based artificial respiration system.[6] This technology is aimed to provide a self-contained, mobile oxygen unit to support a disabled lung. A diagram of the proposed system is shown in Figure 5.

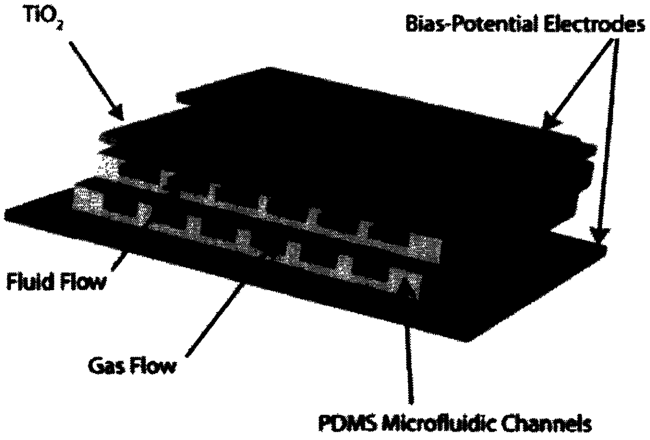

Figure 6: Diagram of microfluidic artificial respiration device [6]

The bias-potential electrodes are used as photolytic elements to generate oxygen directly from water that is present in blood plasma.[6] Blood is pumped through the fluid flow channels and the generated oxygen is pumped through the gas flow channels. By utilizing the gas permeability of PDMS, oxygenation of the blood is realized.

There has been a growing interest in using PDMS to create structures that can be used for growing bacterial and cell cultures. Biochips consisting of PDMS and silicon have been tested for long term batch culture of bacterial cells and were observed to be successful in culturing *Listeria innocua* and *Escherichia coli.*[27] Other mammalian cells have been tested for culture in a PDMS-made devices. At the University of Tokyo, researchers used PDMS to create a microdevice to culture Hepatocarcinoma liver cells.[28] The use of PDMS was advocated by the researchers because oxygen could easily diffuse through the membrane to feed the cells and the transparency of the material allowed direct observation of cell growth.[28]

Another application of PDMS in biomedical microfluidic devices is for use in gene amplification and capillary gel electrophoresis.[20] Microchips were made to perform polymerase chain reaction, capillary gel electrophoresis and separation of components. Results were found to be successful in that the PDMS microchip was able to have polymerase chain reaction and capillary gel electrophoresis performed on it.[20] The PDMS was chosen over use of silicon, glass or quartz to reduce cost and to test for possible use as a single-use device.

These are only a few of many examples of ongoing research into incorporating the microfluidic properties of PDMS with biomedical applications. With so much research being done on this topic, it is important that when products are designed, we have the capability to make them.

Chapter 3. Current Manufacturing Methods

After thorough research, documentation has not been found regarding methods for mass producing PDMS microfluidic devices. The devices that are being fabricated in laboratories are made by hand in a time consuming fashion and cannot be replicated exactly. In order to properly determine the best way to automate the manufacture of PDMS microfluidic devices, the current process must first be understood.

The method of fabricating parts from PDMS is called soft lithography. Soft lithography was developed primarily by Professor George M. Whitesides at Harvard University.[2] It is a relatively easy and simple procedure to manufacture polymeric parts using replica molding.

3.1 PDMS Bench Top Fabrication

To create a part with a certain pattern, the 2-D pattern must be drawn in a CAD program and printed on a transparent polymer sheet. A silicon wafer is then spin coated with photoresist, usually MicroChem SU-8. The printed pattern is then transferred to the photoresist by aligning the pattern on the wafer and exposing it to ultraviolet light, a step called contact printing. The photoresist is then etched away to reveal the pattern that was designed. What is left is the patterned master. An illustration of these steps is shown in Figure 7 below.

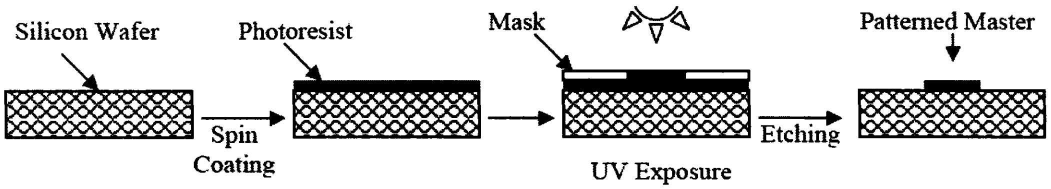

Figure 7: Illustration showing the steps to make a master

This master must be the negative of the desired part because when the PDMS is cast over this master, the inverse of the master will be created. Hence, if the PDMS part is supposed to have a channel, it would show up as a protruding ridge on the negative master.

There are several intermediate steps involved in the PDMS casting step. PDMS comes in two components that must be mixed and then poured. The most widely used PDMS product for laboratory use is Dow Corning Sylgard 184. This product comes with a polymer base and a curing agent. Dow Corning suggests mixing the two parts in a 10:1 mass ratio to produce PDMS.[7] The two parts are mixed together and then placed in a vacuum to degas the mixture. When the liquid has been properly degassed, anywhere from 15 minutes to 2 hours, the liquid is then either poured or spun-coat onto the master. Figure 8 below shows a visual representation of the mixing process.

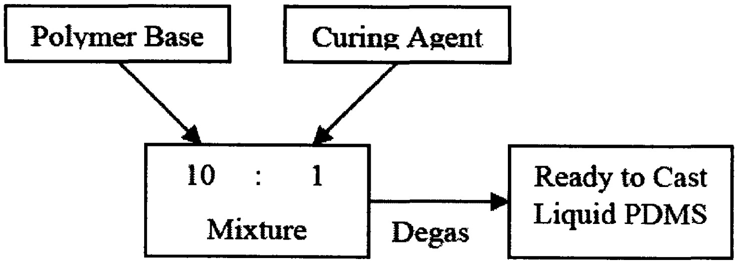

Figure 8: Illustration outlining the PDMS mixing process

The master and PDMS are then heated to speed the curing process. When the PDMS has fully cured, it is peeled off the master. This is PDMS part that is used to create microfluidic devices.

3.2 Joining Layers of PDMS

In order to make multilayer microfluidic devices, layers of PDMS must be stacked on top of each other. These stacked layers often contain crossing channels in order to create valves and pumps within the device. Examples of this can be seen in Figures 3 and 4. Both diagrams depict bonded layers of PDMS.

There are two main methods that are currently used to join layers of PDMS. The first is mainly used only for bonds in which the tolerance needed is fairly low. It involves taking the two layers of PDMS and sticking them together before they are fully cured. By doing so, each layer is still sticky and will bond to each other. However, since each layer of PDMS is not yet fully cured, the possibility exists for the parts to deform while being handled. Because deformation of the uncured part may cause the part to be of different shape or dimension than intended after curing, this method should not be used for assembling parts which require low tolerance fittings.

The other method that is used for joining layers of PDMS is by surface treatments. Each layer is exposed to oxygen plasma.[8] The oxygen plasma changes the surface chemistry of the PDMS by oxidizing it. This oxidized layer is now able to adhere to the other oxidized surface of the PDMS. In addition to allowing PDMS-PDMS adhesion, treatment by oxygen plasma allows PDMS to be bonded to other substrates such as silicon or glass.

3.3 Replica Molding

In replica molding, a master is made and used to make many exact replicas of it, hence its name. To make the master, the same procedure that was described in Section 3.1 is followed. Once the master has been made, PDMS is cast over it and cured. When the cured PDMS is removed from the master, it can now be used as a mold. It is from this mold that exact replicas of the master can be made. Usually the replicas are made by pouring polyurethane (PU) against the secondary PDMS mold.[9, 14] This method is better than conventional methods because the elastomeric mold allows the replica to be released easily.[2] Figure 6 below shows the replica molding concept.

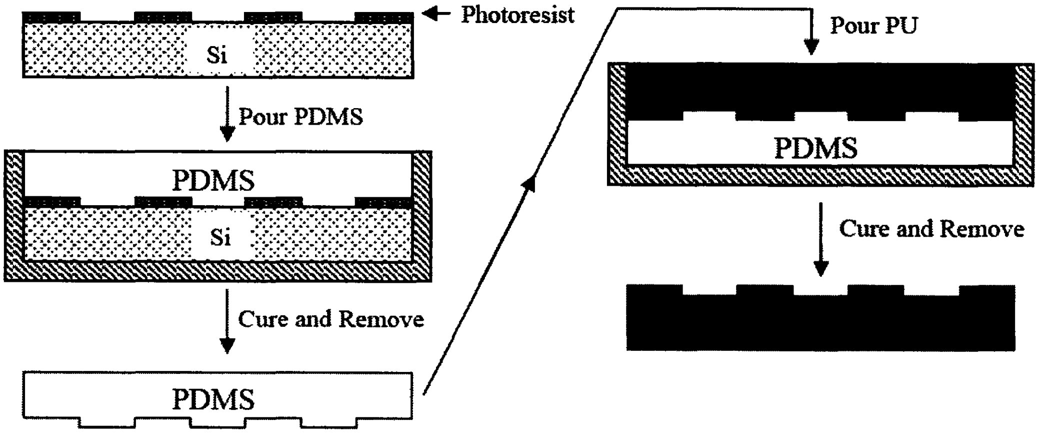

Figure 9: Schematic Illustration of Replica Molding from Si Master to PDMS Mold to Polyurethane (PU) Replica of Master

Although replica molding is the method of choice for producing many parts made from polymer, it is not the best solution for producing microfluidic devices using PDMS. Replica molding primarily uses PDMS as an intermediate material to get from a silicon based master to a polyurethane replica. The PDMS is never meant to be the final product. Instead, the favorable properties of PDMS such as elasticity and low surface energy are used to cast polyurethane.[2] Polyurethane cures into a rigid polymer thus it is much easier to have an elastic mold which can be peeled off of it. If the polyurethane were to be cast directly on to the silicon wafer, trying to separate the two rigid materials from each other would be difficult and most probably result in a cracked wafer. PDMS could be cast onto the PDMS mold but the mold would have to undergo certain surface treatments before casting or else the poured PDMS would adhere directly to the mold. Another issue that arises with molding PDMS against PDMS is that both the mold and the cast part are elastomers. This means that both materials can deform very easily and if casting is not performed very carefully, deformed parts will be made.

Chapter 4. Mechanizing Manufacturing Methods

The current manufacturing methods for producing microfluidic devices from PDMS are highly manual, time-consuming and not repeatable. In order to take a product to market, an automated method of mass producing it must be developed. During the development of this method in Section 4.2, the core competencies of rate, quality, cost and flexibility will be considered to aid in the optimization of the manufacturing method. The following section explores each step in the PDMS device making process and possible solutions for automation.

4.1 Steps to Cast PDMS Parts

Casting PDMS parts has two main steps. The first is to fabricate the negative of a master that is to be replicated. The second is to cast and replicate the parts. For simplicity, the two steps will be investigated separately.

4.1.2 Making Masters

Making a master takes only a few hours. Since only one master is needed to make a certain design, the process of making a master can still be done manually as it is not a limiting factor for mass production. The following is a more detailed walk through of the master making process than what was outlined in Section 3.1.

Step 1: Drawing. The design of the master must first be draw with a CAD program. This 2-D design is then printed directly on to polymer sheets using commercial laser-assisted image-setting systems.[2] The printer should have a resolution of at least 5000 dpi to allow for feature sizes of 50 μm. The use of polymer based masks is more economical and time-saving than using more commercially available chrome masks. The chrome masks are more durable but are also on the order of 200 times more expensive per square inch than polymer masks.[2]

Step 2: Wafer Cleaning. Now that the design has been printed onto a mask, the material that the master will be made from must be prepared. The base for the master is a silicon wafer, which must be prepared for use. The silicon wafer is soaked in acetone for five minutes, then soaked in methanol for five minutes and then soaked in deionized water for five minutes. The wafer should then be washed under running deionized water for 30 seconds and spun dry.[8]

Step 3: Drying. The cleaned wafer must now be dried to ensure that no moisture remains on the surface in order to prevent poor adhesion to the surface. The wafer should be baked in a convection oven at 150°C for 15 minutes.[8]

Step 4: Spin Coating. A layer of photoresist is then spun onto the wafer. This is done by holding the wafer in a vacuum chuck and spinning the wafer anywhere from 3000-6000 rpm for 15-30 seconds depending on the type of photoresist used and the required thickness of the photoresist.[8] A diagram of the spin coating process is shown below in Figure 7.

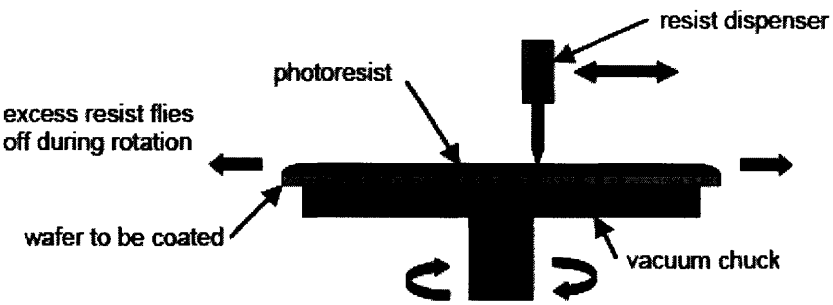

Figure 10: Schematic of spin coating photoresist onto a silicon wafer[8]

The governing equation for determining photoresist thickness is as follows in Eq. 1

$$t=\frac{kp^2}{\sqrt{w}}, \tag{1}$$

where t is the thickness of the layer, k is the spinner constant, p is the resist solids content in percent and w is the spinner speed in rpm/1000.[8] For the following times and temperatures, it is assumed that the photoresist is MicroChem SU-8 25 and is 40 μm thick. For different thicknesses and types of photoresist, the bake times and temperatures will be different.

Step 5: Pre-bake. The photoresist is then pre-baked in a convection oven at 65°C for five minutes and then at 95°C for 15 minutes. This step is needed to evaporate some of the solvent in the photoresist.[10]

Step 6: Alignment and Exposure. The printed mask is then aligned over the wafer using an alignment machine.[8] This step can take a skilled human operator 30-45 seconds using an Oriel Aligner whereas current automatic alignment systems can perform this step in 1-5 seconds, significantly faster than a skilled human.[8] With both systems, registration accuracy is approximately 2 μm.[29] Marks such as the ones seen in Figure 8 below are used to align the mask above the wafer.

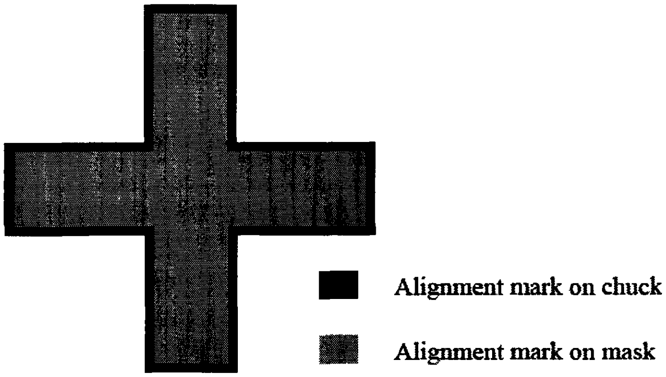

Figure 11: Typical marks used to align the mask above the wafer

The alignment marks on the chuck holding the wafer and the mask must line up and then the mask is brought into contact with the wafer. This process is called contact printing. When the mask is properly aligned and lowered onto the wafer, the wafer is exposed to ultraviolet light (350-400nm)[10] for 30 seconds to develop the photoresist.

Step 7: Post-exposure Bake. The wafer is then put back in the convection oven for the post-exposure bake to harden the photoresist. The wafer is baked at 65°C for one minute and then at 95°C for four minutes.[11]

Step 8: Development. The wafer is then immersed in MicroChem SU-8 Developer which consists of 1-methoxy-2-propanol acetate.[20] To aid in the etching and development of the photoresist, the bath should be agitated for 40 minutes.

Step 9: Rinse. After developing, the wafer should be removed from the developer and rinsed with isopropyl alcohol. A gentle stream of dry nitrogen gas should then be used to dry the wafer.[10]

Step 10: Post-bake. To ensure that the photoresist has fully cured and to further cross-link the material, the wafer should be post-baked at 65°C for one minute, then at 100°C for two minutes and finally at 150°C for seven minutes.[10]

Step 11: Silanize. Finally, the master needs to be silanized in order to reduce the chance of PDMS to stick to the mold during casting. A Petri dish with a few drops of silanizing agent (tridecafluoro-1, 1, 2, 2-tetrahydrooctyl trichlorosilane)[21] and the master should be placed in a vacuum dessicator for one hour.

At this point the master has been completed. This process has taken about 3 hours for one master. The wafer now has the desired pattern on it and is ready to be replicated.

4.1.2 Casting PDMS Against the Master

PDMS will now be cast against the master to produce the parts that are desired. There are two sub processes that are integral to casting against the master. The first is to properly prepare PDMS for the casting process. The second is the actual process of using the PDMS to cast on the master. As in Section 4.1.1, these processes will be outlined in detail, much more so than in Section 3.1.

Step 1: Mixing. PDMS comes in two base components, a prepolymer siloxane base and a curing agent. The most widely used PDMS kit is Dow Corning's Sylgard 184. The base and curing agent must be mixed to start the curing process of the PDMS. Dow Corning suggests a mixing ratio of 10:1, base to curing agent by mass.[7]

The two parts must be mixed together thoroughly to ensure that the mixing has been uniform. This can be achieved by pouring the base and curing agent into a vessel and agitating the mixture until it is thoroughly mixed. In order to reduce the amount of air introduced into the mixture it is recommended that the mixer operates at a speed great enough to properly blend the two parts but low enough such that minimal bubbles are formed.

Step 2: Degassing. This is a critical step in the PDMS casting process. During the mixing of the base and curing agent, air is introduced into the fluid. If air is present in the mixed fluid and then cast, the air will produce unwanted cavities in the cured product. In order to prevent this, the fluid is degassed.

The mixed batch of base and curing agent should be pumped to another vessel for degassing. This vessel must be at least four times larger than the fluid to be degassed in volume. A vacuum of approximately 14 psi should be applied to the vessel for a duration of 30 minutes.[7] The viscosity of the fluid requires the degassing time to be long, however 30 minutes should allow sufficient time for the air bubbles that are trapped in the fluid to escape. At this point the PDMS has been properly degassed and is ready for casting. The working time for a batch of mixed PDMS is approximately two hours.[7]

Step 3: Casting the Master. A part will now be cast from the master using PDMS. The master is placed in a silanized glass mold container. The registration of the glass and the silicon is not of great importance and will be discussed later in Step 6. A calculated volume of PDMS is poured onto the master in order to produce a part that is of the desired thickness. The fluid at this point will have a low enough viscosity such that it will fill the channels and other etched features of the master.[16]

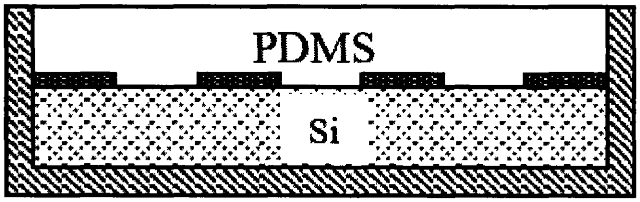

Figure 12: Casting PDMS over the master

Step 4: Curing the PDMS. PDMS will cure under room temperature, but cure time can be greatly accelerated by increasing the temperature. In this case it is suggested that the cast master be heat cured in a convection oven at 150°C for 10 minutes.[7]

Step 5: Releasing the PDMS from the Master. The master/PDMS should be removed from the oven and be prepared for separation. The proposed method for automated separation is by vacuum. When separating the PDMS from the master by hand, a peeling motion is used to aid in the ease of separation.[2] Similarly, a vacuum should be applied to one edge of the mold and by drawing it back at an angle, the same peeling motion is imitated. This is done twice, once to remove the PDMS and silicon from the glass mold container and once to separate the silicon from the cured PDMS.

Step 6: Post Casting Processes. At this point there are bits of excess PDMS on the cast part that are unwanted from weak registration of the master in the glass mold and possible flash from overfilling of the mold. The trouble spots that are of note are highlighted in the figure below.

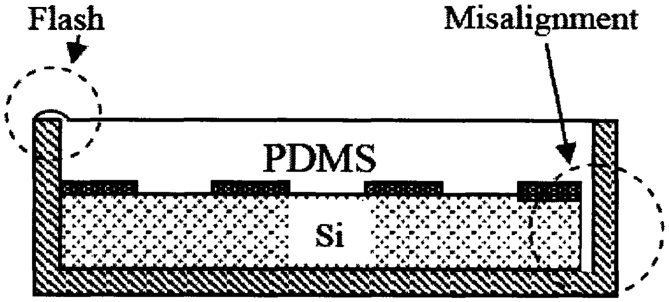

Figure 13: Illustration highlighting trouble spots that may require post-casting trimming

One method of taking care of the unwanted bits of flash and jagged edges is to use a punch and die set. The alignment of the die would be given by the positioning of where the vacuum pulled the PDMS from the master. Another commonly performed process is sterilization if the part is to be used in biomedical applications.[13]

4.2 Exploring Rate, Quality, Cost and Flexibility of Manufacture

At this point, one mold has been made from one master. It takes approximately three hours to make one master. The cycle time to make one mold from one master is approximately 12 minutes, allowing 30 seconds for the casting of the PDMS, 10 minutes for cure time, and one and a half minutes for cooling and separation. For a large-scale production of a PDMS device, we suggest that a production rate of at least 120 units per hour would need to be realized. This coincides with a feasible weekly manufacture rate of approximately 10,000 units, operating 16 hours a day for five days per week.

In order to meet this goal, one PDMS casting must be completed every 30 seconds. Given that the cycle time to make one mold from a master is 12 minutes, there must be at least 24 masters in the production circuit. Having more masters is an easy solution, but if cycle time can be reduced, than the amount of masters needed may also be reduced. Seeing as the cycle time to produce a master is 3 hours, it is more advisable to reduce the number of masters needed.

The first two steps in the casting process involve the mixing and degassing of the PDMS components. The time it takes to properly mix the pre-polymer and the curing agent is dependent upon the amounts being mixed, but given its dynamic viscosity of 3,900 mPa·s[7], it should not exceed five minutes. However, the degassing step takes longer than the mixing step, approximately 30 minutes. Combining the first two steps into what can be called PDMS preparation, it takes around 35 minutes to prepare a batch of PDMS for casting.

As mentioned previously, the working time for a batch of PDMS is two hours. When the working time has been exceeded, the viscosity of the PDMS has increased such that it no longer flows as easily and will not conform to the master as readily. To accommodate this working time limitation it is suggested to have two vacuum vessels that can be swapped in and out. With a setup like this, the usage of the mixing and two vacuum vessels would be represented by the bars in Figure 9.

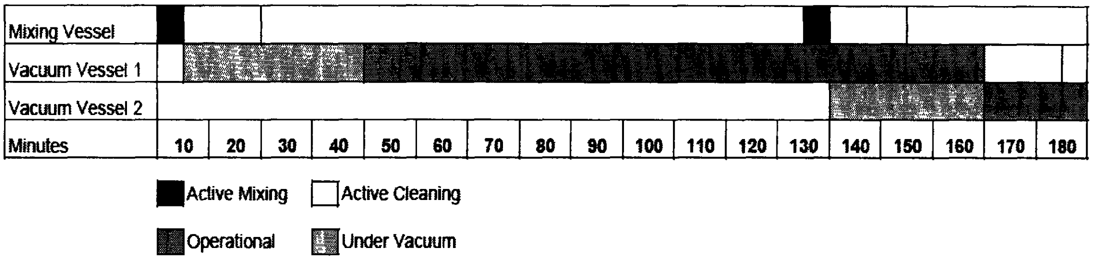

Figure 14: Gantt Chart Representation of Vessel Activity

As can be seen in Figure 14 above, the mixing vessel will be used for all mixing while the vacuum vessels will switch on and off for each batch. This allows each vessel to have ample cleaning time between batches and for there to be a continuous supply of PDMS for the casting process.

Looking at the following steps, it is not obvious to see where any gains in reducing cycle time can be found. The casting step itself is fairly quick as a calculated shot size (volume) of PDMS is cast onto the mold. The mold with PDMS on it then works its way into the curing oven and must stay in the oven until it is cured. The mold is then removed from the oven and cooled before separating the glass container, master and PDMS.

Here is where a gain in time can be had. Instead of waiting for the mold to cool passively on its own, an active cooling solution may be implemented. This could range from something as simple as blowing a fan across the top of the mold. This would aid in cooling the mold more quickly and allow the PDMS to be peeled off the mold faster.

Attempting to mimic human fingers peeling off the PDMS is something difficult. However, it is thought that because PDMS is not bonded to the silicon substrate due to low surface energy as well as the master being silanized, a vacuum applied to one of the edges would start to lift and separate one edge up from the wafer. The peeling action is further imitated by pulling away from the mold at and angle, similar to the way a hand would. This step is estimated to take on the order of 30 seconds.

The steps in the casting process that involve the master have now all been looked at to see if any streamlining could be done. However, it seems that if each step is completed as specified, the process will be running as smooth as possible. It then looks as if time savings must be looked for on the master making process. In order to achieve the target production rate of 120 units per hour, 24 masters will need to be produced.

Every step in the master making process must take the instructed amount of time. If the wafer must be baked for 40 minutes, it must be, any shorter or longer and the wafer will suffer from reduced quality.[10] However, the process can be streamlined to make sure that the time to process 24 masters is as short as possible. In this way the cycle time for each master is the same, at approximately three hours, but the production time is vastly reduced.

There are two steps in the master making process that cannot be continuously fed. They are steps four and six. Step four is spin coating the photoresist on to the wafer and step six is the alignment of the photomask and ultraviolet exposure. Since step four has a duration of about a minute while step six only takes about 30 seconds,[8] the limiting step in the master making process is step four.

Now that step four has been identified as the limiting factor in the production time of the masters, let us see how quickly the masters can be produced. Spin coating photoresist on to a silicon wafer takes about one minute. If the silicon wafers are fed through the spin coating apparatus back to back, the effective time it will take to process 24 wafers is about 24 minutes.

However, the last step of the master making process does not work well under continuous feed. In order to properly silanize the wafers the masters must be held under vacuum while the vapor from the silanizing agent covers the wafer.[17] This silanizing step takes about one hour, easily the longest step in the master making process. The best way to determine how to work around this limitation is to look ahead at the casting process.

The casting process takes about 30 seconds which is twice as fast as the limiting spin coating step in the master making process. In order to cause no backup in the casting process, there is one way to configure the silanizing step. The silicon wafers should be silanized in batches of eight. This way, it takes four minutes for a batch of eight silanized wafers to be cast at 30 seconds per casting. Eight minutes later, the next batch of eight wafers starts to be cast while the first eight wafers are two-thirds of the way through the 12-minute casting process. Eight minutes after that, the final batch of eight wafers is ready to be cast and due to the timing of the casting and silanizing, it lines up perfectly with the gap in the casting process, causing no lost time being spent in a cue.

However, this setup requires two parallel silanizing stations for the master making process. Although this will call for an additional investment of capital to install, it is probably a good choice. The silanizing chambers do not have to be as large and in case of failure of one chamber, the other can still be used without having to take the master making process offline.

The masters can be made with very good accuracy. Photolithography has been in use in the semiconductor industry for years and has been tested and refined many times over. Given a certain pattern and specification of depth, a master can be created and replicated with accuracy to within 3 µm.[34] For the resolutions needed to produce quality microfluidic devices, this accuracy is sufficient.

The thickness of the spin coated photoresist layer is of importance because it represents the height of the features of the master. The behavior of the thickness of the photoresist during spin coating was given in Eq. 1. It has been observed that through the strict monitoring of spinner speed and photoresist viscosity, the layer thickness repeatability is on the order of 5%.[34]

The lifetime of a master mold is currently not known. With proper handling and silanization of the master, the life of the master should be at least 50 molding cycles. In order to ensure that the PDMS does not adhere to the photoresist and dislodge it from the silicon wafer, it is suggested that the masters be resilanized every 10 molding cycles. This is something that must be tested in the field as the quality of the masters directly affects the quality of the PDMS parts.

There is substantial variability that may be present during the PDMS molding steps. The thickness of the PDMS molded part must be regulated such that it satisfies the design requirements of the part. When a thickness is specified, it should be converted into the volume of PDMS needed to be cast in the mold to attain that thickness. This is simply a mathematical derivation using the volume of the master and the size of the mold container. It has been proposed in Section 4.1.2 to use a dispenser that deposits the calculated volume of PDMS onto the mold each time. Shot-size accuracy in the injection molding industry has reached levels of ±0.1%.[35] If the technology used to feed injection molding molds can be transferred over to the proposed open casting method by even a magnitude of 10, the PDMS parts can be molded to an accuracy of 1%.

Levelness is also a consideration to keep in mind when tracking quality of the PDMS parts. If the molds are not held level when the PDMS is cast and cured then the final parts will end up uneven and sloped. This problem is also applicable to the fabrication of the masters. The photoresist and mask alignment steps must be done on a level surface or sloping will occur. This is undesirable because parts are often layered and need to be of uniform thickness. It is thus imperative that during the construction of the manufacturing lines all the machines are made level to reduce imperfections in thickness variability during manufacturing.

Deformation is an concern during the post-processing step of cutting away extra PDMS due to flash and misalignment. The suggested method of trimming is to use a punch and die set. A punch and die uses shear to cut an object to shape. Because PDMS is a very soft elastomer, there may be deformation problems during this process. The PDMS part may stretch and produce irregular patterns during the trimming process. While this issue cannot be quantified right now, it is a quality issue nonetheless.

There are certain cost issues that must be addressed when designing a production line. Some of these have already been brought up such as running two parallel lines for degassing and silanization. While adding another line for these two steps increases the initial capital costs, their presence allows a continuous stream of parts to be made as well as continued production if one line were to fail. There is also an inherent cost correlation to tolerance. It will cost more to make sure that all the machines are perfectly level rather than level to within one degree. The same is true for using a PDMS casting machine that has a shot-size accuracy of 0.1% or one accurate to 1%. The balance must be struck between the capital costs to install such machinery and the quality that is demanded by the products and its customers.

There are other variable costs associated with PDMS production such as material and tooling costs. The material costs lie with the amount of silicon wafer, photoresist, and PDMS needed. If a customer is willing to use a master for more mold cycles, than the end cost per unit will be lower than if the master was used for less. However, there is an effect on quality as the masters do degrade over use. The majority of the variable tooling cost is the fabrication of the punch and die. For most microfluidic devices it will be of a simple shape so its complexity and relative cost will be low.

There is a need for this type of production system to be very flexible. New designs can come through the door at any moment wanting to be fabricated. The beauty of the production process is that it is very adaptive and able to respond quickly. The turnaround time from receiving a specified pattern and design to production of the first unit is less than a day. As outlined in Section 4.1, a master can be made in approximately three hours and the subsequent production of PDMS parts from the master can start immediately in 12-minute casting cycles. The actual time between accepting an order and production of the first part is dependent on current manufacturing status. If the lines are already being used to produce another part, that production run must be finished before the new order can be started.

To reduce storage of used masters and maintain flexibility, once a production run has been completed the masters should be destroyed. However, the computer drawings of each manufactured part should be archived to allow quick access in case of reorder. If it is known that a customer will reorder at some point, several new masters may be fabricated in advance such that when the order comes through the masters can be introduced to the production line immediately, saving at least a three hour lead time of master manufacturing.

4.3 Other Production Methods

There are several other production methods which are used in the mass production of polymer based parts. Some popular methods are injection molding, reaction injection molding and machining.[18] Each of these methods is used in the rapid manufacturing of products such as toys, cups, car bumpers and plastic housings. The usage of these methods brings the question of whether or not one of them can be brought to manufacture microfluidic devices from PDMS. Let us take a look at each process separately.

Injection molding is perhaps the most widely used mass production method for thermoplastics. In injection molding, pellets of plastic are heated and then injected into an enclosed mold. The plastic is held for a specific amount of time to allow the part to sufficiently cool. The mold is opened, the part ejected from the mold and then the process repeats itself.[12] A typical injection molding machine is shown below in Figure 15.

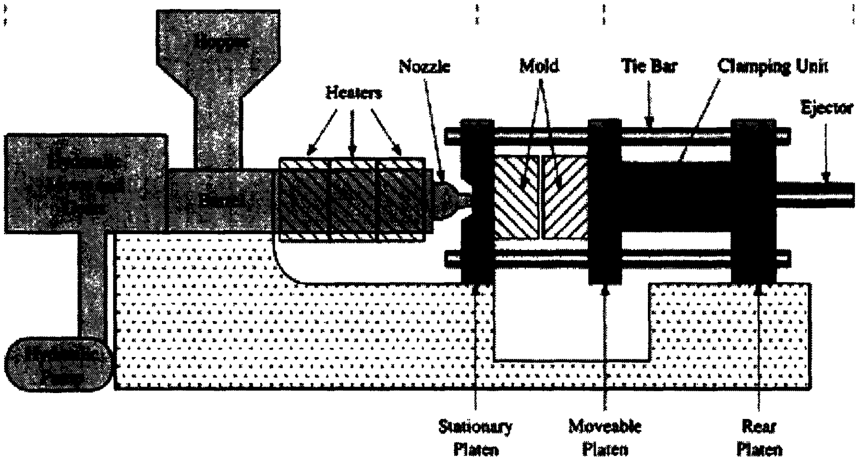

Figure 15: A typical injection molding machine[12]

For thermosets, such as PDMS, the molds are normally heated to greater temperatures to aid in the polymerization and crosslinking of the polymer.

The main reason injection molding is not a viable production method for PDMS products is that the parts are formed in a sealed mold. One of the greatest difficulties in working with PDMS is that during the curing process, gasses must be allowed to escape.[7] If the gasses are unable to escape, cavities will form during the curing stage. These bubbles are highly unwanted and their presence will render the part useless and the material wasted.

There have been recent reports of manufacturers using mold-evacuation hardware during injection molding.[30] This hardware draws a vacuum on the molds in order to removed the trapped air and gases. This would help solve the previously stated problem with injection molding PDMS. However, another problem with injection molding is the time that is necessary for the PDMS to cure. It takes a minimum of 10 minutes[7] to cure the PDMS which is very long for an injection molding system.

Although the conventional injection molding process has several drawbacks that makes it unsuitable for PDMS manufacturing, reaction injection molding may seem to be a better choice. The premise behind reaction injection molding is that two base components are violently injected into the mold simultaneously.[19] The speed at which the components are injection into the mold causes them to mix thoroughly within the mold. This mixed polymer undergoes several rapid chemical reactions and solidifies into a thermoset part.[19] A schematic of the reaction injection molding process is shown below in Figure 16.

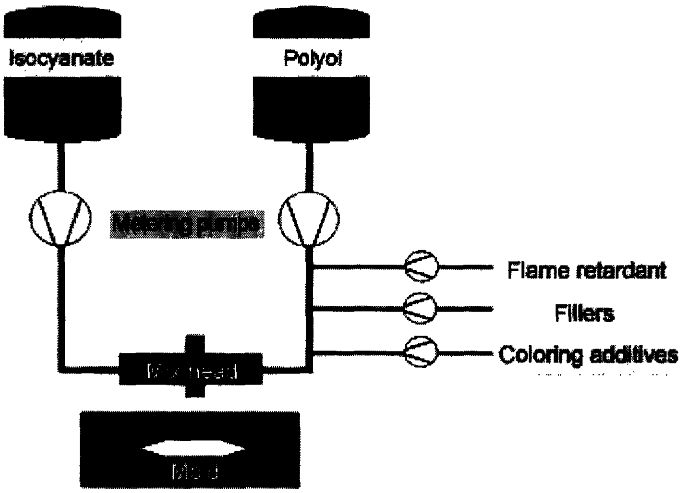

Figure 16: Reaction injection molding setup. Isocyanate and polyol are two reactants that when combined in the mixhead at extremely high pressure and velocity from the metering pumps, and then allowed to flow into the mold at atmospheric pressure cures into polyurethane[31]

What makes reaction injection molding relevant to PDMS part manufacturing is that PDMS must also have two base ingredients mixed together before it can be molded and cured. If the prepolymer base and curing agent could be simultaneously injected into a mold, the mixing stage would be eliminated and a time savings would be gained. However, this method of manufacturing suffers from the same problems that ordinary injection molding does. The crucial step in PDMS manufacturing is the degassing stage. Without a degassing stage the part will cure with bubbles contained in it.[7] The degassing step would be even more necessary for reaction injection molding because the turbulence that the base and curing agent experience will cause more gas to be trapped in the fluid than in an injection molding process utilizing degassed PDMS. Ultimately reaction injection molding suffers from the same problem as conventional injection molding, an inability to release gases during the curing stage. Mold-evacuation hardware would not applicable to reaction injection molding since the molds are temperature-controlled and at atmospheric pressure.[19,31]

To manufacture parts out of plastic on the inch scale, standard machining processes can be used. Typically these involve milling, planing and shaping. For microfluidic devices, the feature sizes of the parts are usually between 10 and a few hundred micrometers.[15] To allow for resolutions that small, standard machining processes and tooling cannot be used. There has been development of micromachining for use in fabrication of microelectromechanical systems (MEMS) in the past few years. These micromachining operations usually involve chemical etching[18] which is very similar to the process used to manufacture the master in Section 4.1.2. Although chemical etching allows for features on the micrometer scale to be produced, it is not a process that is done on polymers. Thus, PDMS parts cannot be directly manufactured using chemical etching micromachining processes.

Three other manufacturing processes were investigated for use in producing PDMS parts for fabricating microfluidic devices. Each of these processes had inherent flaws in them which made it unsuitable for this task. Although casting is more time-consuming and has a longer cycle time compared to both conventional and reaction injection molding, it is the only process that will produce PDMS parts of the necessary quality.

4.4 Effects of Changing Variables

There are several variables which can be altered in the PDMS casting process. Each variable that is changed will have a corresponding effect on the on either the quality of the cast PDMS part or the rate of manufacture. Given that each of these variables can be independently changed, the effects should be known in order to properly optimize the manufacturing process and the product itself.

4.4.1 Pre-polymer Base:Curing Agent Ratio

The manufacturer suggested mixing ratio for the pre-polymer and curing agent is 10:1 respectively.[7] However, there is no reason that the mixing ratio cannot be changed. By changing the mixing ratio of the two parts it is expected that there will be significant changes in the workability and final properties of the cured PDMS. There is experimental data which has been collected that will allow us to study the effects of changing the ratio.[13]

Sometimes spin-coating is used to produce thin films of PDMS to be used as backings or covers in microfluidic devices. Using the same exact spin-coating process, the resulting thickness of the PDMS film differed for different ratios of base and curing agent.[13] An increase in the amount of curing agent leads to a decrease in the thickness of the spin-coated film. This can be attributed to the different viscosities of the pre-polymer base and the curing agent. The pre-polymer base has a kinematic viscosity of 0.0050 m^2/s while the curing agent has a kinematic viscosity of 0.0011 m^2/s.[13] By increasing the amount of curing agent, the resulting fluid mixture is less viscous. Referencing Equation 1, the thickness of a spin coated film is proportional to the square of the percent solids content, or viscosity of the fluid. Therefore the less viscous fluid is able to flow more easily over the wafer during spin coating resulting in a thinner film.

The reduction in viscosity as the amount of curing agent is increased is also relevant to the casting process. The ability of the fluid to conform to the designs imprinted on the silicon wafers is of great importance in order to fabricate useful parts.[2] If the fluid cannot flow easily over the structures, a poor imprint will be made. Intuition tells us that a lower viscosity fluid will flow more readily over and into the imprinted structures resulting in higher quality PDMS parts. In addition, the working time of a batch of PDMS is also increased. Generally the working time is dependent on how long it takes the fluid to double in viscosity. However, say the viscosity of a 10:1 ratio is X and the viscosity of a 10:3 ratio is Y. Using the previous information on the relative viscosities of pre-polymer base and curing agent, X must be greater than Y. Thus, to reach the working time limit of $2X$, it will take the 10:3 ratio mixture longer than it takes the 10:1 mixture, making the effective working time of the 10:3 ratio longer compared to the 10:1 mixture. Data could not be found that links the amount of curing agent to cure rate that would refute or confirm this assumption. However, literature warns that increasing the amount of curing agent increases the amount of final crosslinking within the cured PDMS and that using too much curing agent will cause the PDMS to become hard and inelastic.[32]

Another property that changes with differing mixing ratios is the ultimate tensile stress of the cured PDMS. This property can be important if the PDMS is to be subjected to tensile forces. It has been observed that increasing the amount of curing agent increases the ultimate tensile strength but if too much curing agent is used it will decrease.[13] Figure 17 shows the increasing then decreasing trend in ultimate tensile strength. The bars of note are the solid colored ones on the left of each subgroup.

PDMS1 has the lowest ratio of pre-polymer base to curing agent while PDMS has the highest.

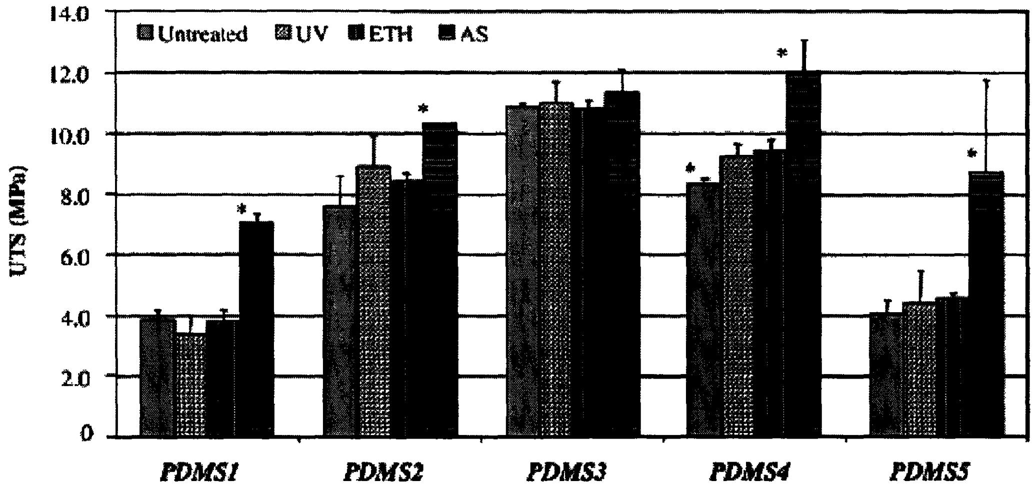

Figure 17: Graph showing the ultimate tensile strength for samples of PDMS that were mixed at various ratios of pre-polymer base to curing agent.[13]

Laboratory results suggest that the greatest ultimate tensile strength is achieved at a pre-polymer base to curing agent ratio of approximately 7:1.[13] The effect of changing the mixing ratio to ultimate tensile strength should be considered if it will affect the performance of the resulting PDMS part.

4.4.2 Temperature

There are several temperature dependent steps in both the master making and PDMS casting process. Given the ease with which the temperature of convection ovens can be set, the effects of temperature on each step in the process should be investigated. The effects on both time and quality with regard to temperature change will be noted.

Before the silicon wafer is coated with photoresist, the wafer must be completely dried. The current method calls for the wafer to be dried in a convection oven at 150°C for 15 minutes. The temperature for this step can be widely varied. Some procedures call for the wafer to be dried at 200°C for six minutes while others call for it to be dried at 90°C for 15 minutes.[8] There is definitely a correlation between the drying temperature and its duration. No documentation has been found to suggest that high temperature, short time drying is better or worse than low temperature, long exposure drying. For this step it is suggested that the drying temperature be adjusted such that the drying time fits best into the production process.

The parameters of the pre-bake, post-exposure bake and post-bake of the photoresist are outlined explicitly in the manufacturer's specifications.[10] These times and temperatures are dependent upon the thickness of the layer of photoresist. However, it should be noted that a lower initial bake temperature allows the solvent in the photoresist to evaporate at a more controlled rate which results in better coating fidelity and silicon-photoresist adhesion.[8] The length of exposure should remain the same as outlined in the procedure, however the method of heating should be changed to reduce the stress in the curing photoresist and increase its quality. Instead of stepping the temperatures from 65°C to 95°C for the pre-bake and post-exposure bake and from 65°C to 100°C to 150°C for the post-bake, a steady ramped increase in baking temperature should be used.[10]

Curing the PDMS under elevated temperatures greatly decreases the cure time. PDMS cures chemically by forming $Si\text{-}CH_2\text{-}CH_2\text{-}Si$ linkages within itself.[1] By increasing the temperature the linkages form more quickly, this in turn causes the cure time to decrease. PDMS will cure completely at room temperature in approximately 48 hours. If the PDMS is held in an oven at 100°C the cure time decreases significantly to

45 minutes. PDMS cures even more quickly at 125°C in 20 minutes and quickest at 150°C in 10 minutes.[7] There is no evidence to suggest that an elevated cure temperature and shortened cure time degrades the quality of the resulting PDMS. With this in mind, and the need to have short production cycle times, the highest cure temperature should be used in order to ensure the cycle time is as short as possible.

4.4.3 Vacuum Pressure

There are two steps in the manufacturing process that require the use of a vacuum. The first is during the silanization of the silicon master. The vacuum is needed in order to vaporize the silanizing agent (tridecafluoro-1, 1, 2, 2-tetrahydrooctyl trichlorosilane) such that the vapor will deposit a layer onto the silicon.[21] The higher the vacuum pressure, the more easily the silanizing agent will be vaporized. This increase in vaporization will allow the silicon wafer to be silanized at a faster rate. The degassing process is performed under a vacuum to aid in the release of air from the mixed fluid. If the vacuum applied to the vessel containing the fluid was increased, the air bubbles would come out faster. To aid in the process of degassing, the vessel may be agitated gently while under vacuum. But in order to decrease the processing time in these two steps, the applied vacuum pressures should be as high as possible.

Chapter 5. Two-Sided PDMS Molding

One of the drawbacks of open-faced or atmospheric casting is that features cannot be formed on both sides of the cast part. The top side is always just left open to the atmosphere and cured with a flat surface. This is slightly problematic when trying to assemble microfluidic devices because features on both sides of a part are often desired. Current methods to simulate two sided parts involve joining two separate layers with features together. However, this solution is not optimal as the dual layering significantly increases the thickness of the device, doubles the part count and requires an assembly step. In microfluidic devices, size is at a premium and this increased thickness is not an optimal solution.

In general, the only way to mold parts that have specified features on both sides in one step is by using a closed mold.[18] This method ensures that the part being made is in contact with the desired features on both sides. When the part has solidified and cured, the mold is opened and the two sided part is removed. Typically, this process is achieved by injection molding. However, as discussed in Section 4.3, injection molding is not a viable manufacturing process for PDMS parts.

This limitation of not using injection molding techniques forces the formulation of a unique manufacturing process. The fundamental needs of this process are that there must be features on the top and bottom of the part, degassing must be allowed during curing and it must be repeatable. To satisfy these three needs a process was developed. This process involves a standard silicon wafer substrate with features as well as a secondary silicon wafer with features. The secondary wafer is to be used as the mold for the top features. The limitation of this design is that the width of the top mold can be as wide as twice the height of the cast PDMS at the maximum. This is to allow any air bubbles that may be present at the bottom of the PDMS at 45° angle of escape to the surface. To facilitate the removal of any air that may be trapped between the two layers, the filled mold should be exposed to a vacuum before and during the heat cure process. A diagram of what the dual mold design will look like is shown below in Figure 14.

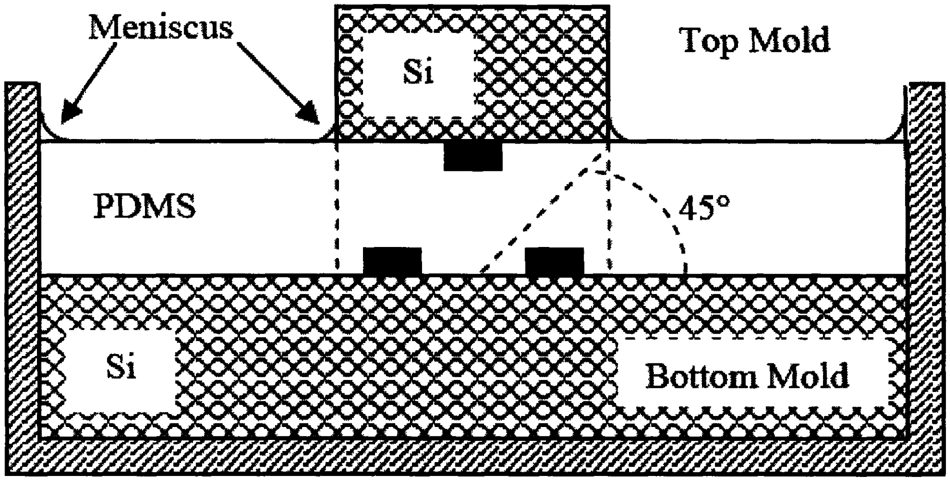

Figure 18: Diagram showing the two silicon molds and the PDMS to be cast

The bottom mold rests in a container made of silanized glass and the top mold is held in place by a vacuum chuck. The liquid PDMS will probably form a meniscus around the edge of the upper mold and container due to surface tension between the two materials. To in order to remove these top defects after separation from the molds, the cured PDMS should be cut along the two vertical dotted lines. This will ensure that both the upper and lower surfaces of the PDMS part are smooth.

The 2:1 ratio of width to height of the final PDMS part is severely limiting as microfluidic devices are usually comprised of layers from 40-500 μm thick and of widths of approximately 10 mm.[4,27] However, this ratio is only a proposed limitation as a stepping stone to increasing the ratio. For example, if it is found that no gas is trapped under the top mold using a 2:1 ratio, then the ratio should be increased and the molding process tested again. The goal is to eventually be able to mold parts with a width to height ratio on the order of 250:1.

As discussed in Section 4.4, temperature can be varied greatly during the molding process. If it is found that air bubbles are trapped using a 2:1 ratio while being cured at 100°C, then the temperature should be lowered. Here is where the trade-offs between rate and quality matter. A higher curing temperature increases the rate of cure, but it may be at the expense of the quality of the product. If the PDMS in the mold is allowed to cure for a longer time at a lower temperature under vacuum, it gives the bubbles more time to escape from between the top and bottom molds.

This process should be better than current method of joining two layers together because the final part is one unit and there is no chance of layers becoming separated. However, this method of two sided PDMS manufacturing is limiting in that the width of the part can only be twice as wide as the cast part which underscores the need for the further development of two-sided PDMS manufacturing.

Chapter 6. Ultimate Goal – One Step, Two-Sided PDMS Part with Through-Holes

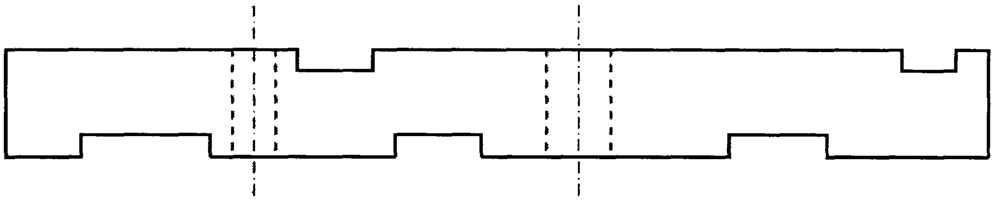

Figure 19: Example of a two-sided part with through-holes made with PDMS

The development of an automated process to manufacture PDMS microfluidic devices is in its infancy stage. The vast majority of research going into this field is still in the laboratory stage; attempting to determine what microfluidic devices to make as opposed to how to make microfluidic devices. There will come a time when someone will want to make a certain microfluidic device from PDMS in bulk and when that time comes, we want that technology to exist. Thus, it is of great importance to know what the ultimate goal is such that the technology can be developed.

There are several properties that a PDMS part may need to exhibit for use in microfluidic devices. The part must be defect free in that no surface abnormalities or trapped air bubbles can exist. For the simplest parts, no features are needed on either side of the PDMS part. However, for more complex parts, features will need to be present on both sides of the part. This is where the discussion in Section 5 on two-sided PDMS molding is relevant. The solution that was presented in Section 5 is simple and easily testable. At first glance it seems to solve the degassing issues present with closed molds while achieving the same results. However, experimental testing must be done before it can be said to be the solution to the problem.

One more feature that has not been covered yet is a through-hole. Some microfluidic devices require through holes to be present in a layer. This is harder to produce than it sounds because this is not as simple as casting the PDMS around a cylinder that is higher than the cast layer. If that method is used, a meniscus similar to the one pictured in Figure 18 will form resulting in a defect. However, combining the solution presented in Section 5 with the use of posts between the molds, through-holes may be created.[33]

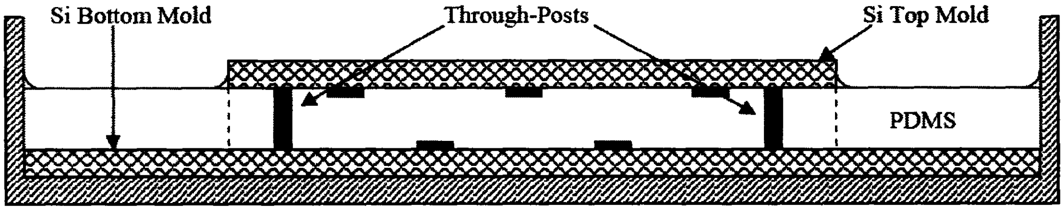

Figure 20: Diagram illustrating possible solution to forming two-sided PDMS parts with through-holes[33]

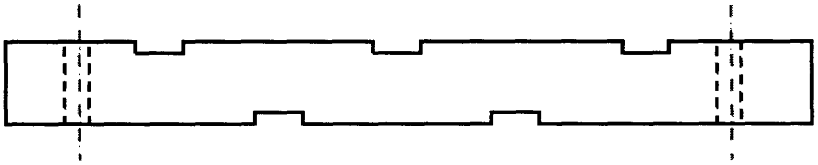

Figure 21: Expected shape of PDMS part after removal from mold in Figure 16 and trimming of edges (magnified view)

In Figure 20 above, through-posts lie between the top and bottom mold. It is theorized that the PDMS will mold around these posts and when cured and removed, through-holes will remain. This configuration should not result in a meniscus being formed around the tops of the holes because they are molded flush against the molds. It is expected that the PMDS from the two-sided mold with through-post inserts will look like the part in Figure 21.

Automation is the final step. The ultimate goal is to take a design of a PDMS part that has features on both sides and through-holes, input it into the computer and collect the made part at the output of the process without having any intermediate human interaction. When this process is available, the mass production of PDMS-based microfluidic devices will be possible.

Chapter 7. Steps Forward

The steps that should be taken forward from here should always have the outlined ultimate goal in mind. It is making the jump from a manual process in which a one sided PDMS part is made one at a time to a fully automated process in which PDMS parts having features on both sides with through holes are produced on a continuous basis.

By no means is the solution to the ultimate goal going to be discovered overnight, it will be a long process that will need to be refined over time. However, there are several logical next steps to be investigated. The first is to determine the best ways of automating each individual step of the master and casting process. This does not have to be a ground up endeavor.

There are automated technologies that exist to produce patterned silicon wafer masters in use in the semiconductor industry. These processes are often performed in a clean room environment because microelectronic devices are affected greatly by contaminants.[23] The resolution to which the masters in this case must have is not nearly as stringent. While many semiconductor manufacturing plants use Class 1 clean rooms[24] a PDMS microfluidic device plant would require a Class 10,000 or 1,000 clean room. The technology present in the semiconductor industry is more than adequate to handle the requirements of automated master making and should be investigated for adaptation.

Many steps in the casting process have already been developed. Mixing vessels and vacuum chambers can be found in many manufacturing plants. The one step in this process that should be looked at first is the removal of cured PDMS from the silicon master. It is more difficult to remove the elastomeric PDMS than say hard polyurethane from a mold because of its elastic nature.[18] Ejection pins do not seem like the best option because they are used primarily with rigid parts. A possible solution was proposed in Section 4.1.2 that uses a vacuum to separate the PDMS and the master. The basis for this solution is that a peeling motion is used when manually removing the cast PDMS. Applying a vacuum to one edge of the part and pulling back at an angle mimics the peeling motion. This can be tried on a laboratory scale to determine whether or not this is a viable solution to automating this step.

These are just two specific steps that need to be investigated in order to make the jump to automation. Other intermediate steps involve the testing of PDMS for durability in microfluidic applications, adaptation of traditional automated casting methods to the microscale and controlling the variables mentioned in Section 4.4 to produce parts that have the best properties possible at a high rate.

Further development and testing of the manufacturing solutions proposed in Sections 5 and 6 regarding two-sided and through-hole molding should be performed. These attributes are important to microfluidic devices and will need to be perfected before implementation in an automated line. While this level of complexity is above that of automating single-side featured PDMS parts, it should be kept in mind because it will be needed.

Conclusion

As advances are made in developing successful microfluidic devices from PDMS, significant attention must be devoted to the fabrication of these devices on a mass production scale. A great idea that can only be made in a laboratory setting stays a great idea until it can be brought to consumers. When this happens, the great idea becomes realized on a greater scale and becomes truly revolutionary. Biomedical microfluidic devices have significant potential to revolutionize healthcare.

The technology that currently exists is not suitable for the production of PDMS-based biomedical microfluidic devices. There are some processes used today in other industries that can be adapted for this use. Other processes must be developed with the production of PDMS as its main focus. Only through the proper investment of time and research into developing these new processes can large-scale manufacturing of PDMS microfluidic devices be realized.

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