HÁSKÓLI ÍSLANDS

Fabrication of integrated optical and microfluidic devices

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Abstract

This study aimed to develop a methodology for fabricating microfluidic devices on different substrates. We describe all necessary steps in fabricating a PDMS (Polydimetylsiloxane) microfluidic device using standard microfabrication techniques. We manufactured devices that could be combined with an integrated optical circuit designed by the supervisor. Bonding and combining to three different substrate materials; Si, glass and CYTOP, were evaluated where an irreversible bond was desired. The method described is low cost, low temperature and suitable for combining with other fabrication technologies.

1 Introduction

The field of microfluidics has expanded rapidly in recent years with applications in a host of other fields including chemical analysis and medicine. While significant research has been conducted towards microfluidics internationally, microfluidic circuits have not been fabricated in Iceland before. We devised a methodology for fabricating microfluidic circuits at the University of Iceland and combined a microfluidic component with an optical waveguide designed by our supervisor. The fabrication process for the optical circuit is described in detail in [1].

Plastics have become increasingly popular as a structural material for microfluidic devices mainly because of low fabrication costs. We chose PDMS (Polydimethylsiloxane) for fabricating the microfluidic devices. PDMS is the most commonly used material for this process and has many favorable properties, such as biocompability, optical transparency and elasticity.

The fabrication of microfluidic devices using PDMS typically involves micromolding, a casting process to transfer patterns from a master mold to the PDMS. Other methods to define microchannels have been suggested such as dry and wet etching[2]. The negative photoresist SU-8 is commonly used in microfluidics because it can be deposited in thick layers required for defining microfluidic channels on the master mold[3].

The PDMS microfluidic component contains an open structure of the microchannels but needs to be sealed to a substrate in order to form enclosed channels and thus sealing is a critical step in the fabrication process. Different bonding techniques have been suggested in literature such as lamination and adhesives[4], thermal bonding[4][5] and surface modification by plasma treatment[5][6][7]. A successful bonding procedure needs to preserve channel integrity and withstand high pressures for fluid injection. A low temperature (<100 °C) process is preferred in our case because of possible damage to the optical circuit by overheating. Vlachopulou *et al.* [5] reported a method of sealing PDMS to substrates using surface treatment with aminopropyltriethoxysilane (APTES). M. Kanai *et al.* [6] spin coated CYTOP, a thermoplastic polymer, on the PDMS component to promote an irreversible seal to a CYTOP substrate.

The process described was carried out in the cleanroom at the University of Iceland because of delicate microchannel structure and to minimize possible blocking or deformation. The fabrication method presented is quick and simple to implement and results in an irreversible bond between components.

2 Materials and methods

Here follows a description of the materials used and an outline of the fabrication process. A more detailed step-by-step fabrication guide is listed in appendix A, which includes a list of all processing equipment.

2.1 Materials

The PDMS was supplied from Dow Corning (Sylgard 184) and was prepared by mixing the silicone base polymer with the curing agent in a 10:1 weight ratio. The SU-8 2035 negative photoresist used for preparing the master mold was supplied from Microchem Corporation and developed in mr-Dev 600 developer. According to the datasheet [8] a spin coated SU-8 layer at 2000rpm yields a thickness of 60 μm but can be varied by changing the spin

rate. Silicon wafers (2in.) were supplied from Silicon Quest International.

The CYTOP (CTX809AP2) polymer, from Asahi glass company, has a refractive index close to that of water and is thus suitable for biochemical applications. Both unmixed and mixed solutions (1:3 with a fluorinated solvent) were used. A 5% solution of APTES (aminopropyltriethoxysilane) was used for surface treating the CYTOP substrates. They were developed in ma-D 331 developer. O_2 and Ar gases were used for plasma treatment in a 1:1 ratio. The Ar gas should in principle not be needed for the plasma treatment but helped ignite the plasma. Other materials included IPA (Isopropyl alcohol), acetone and methanol, mainly used for cleaning substrates and pure N_2 gas for blow drying.

A regular red colored food dye was used when testing the microfluidic circuits on glass, but a 1:10 solution of carboxylate-modified microspheres called FluoSpheres was used when evaluating the integrated microfluidic and optical device using a fluorescence microscope.

2.2 Silicon master mold

The master mold was prepared by applying the SU-8 2035 photoresist to a clean Si wafer by spin coating at 2000rpm for 30s. The wafer is subsequently baked at 65°C for 130 seconds and then at 95°C for 7 minutes on a hotplate. A mask of the circuit (see Figure 1(a)) is placed on top of the wafer and the photoresist is exposed with a UV-light dosage of $150 - 215\,\mathrm{mJ/cm^2}$ using a mask aligner. After exposure the wafer is baked again on a hotplate (post exposure bake), first at 65°C for 60 seconds and then at 95°C for 6 minutes. A visible latent image on the film should be seen within 5–15 seconds after being placed on the hotplate. The wafer is then developed by immersing in mr-Dev 600 developer for 6 minutes and rinsed with IPA and blow dried with N_2 gas.

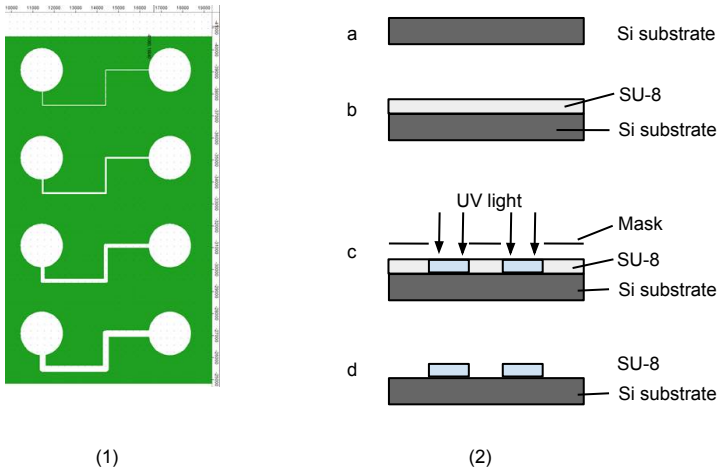


Figure 1: (1) The mask used for defining the microfluidic channels, channels are 50, 100, 200 and 300μm wide respectively. The reservoirs are 2mm in diameter; (2a) A clean Si wafer; (2b) SU-8 polymer is spin coated on Si wafer; (2c) The wafer is exposed with UV light under the mask; (2d) Unexposed SU-8 is removed with the developer resulting in a complete master mold.

2.3 Preparing the PDMS

The PDMS is prepared by mixing the silicone base polymer with the curing agent in a 10:1 weight ratio. The PDMS mixture was then degassed in vacuum for 10–15 minutes to help remove any air bubbles. Like illustrated in Figure 2 the degassed PDMS mixture is then cast on the SU-8 master mold. The PDMS was either let stand overnight or to shorten the curing time, put in an oven at 65°C for two hours. After carefully peeling of the PDMS from the SU-8 master the PDMS contains an inverted structure of the microchannels. Holes are then punched with blunt needles on the reservoirs for injecting media. The component is then cut to pieces with a surgical blade as desired.

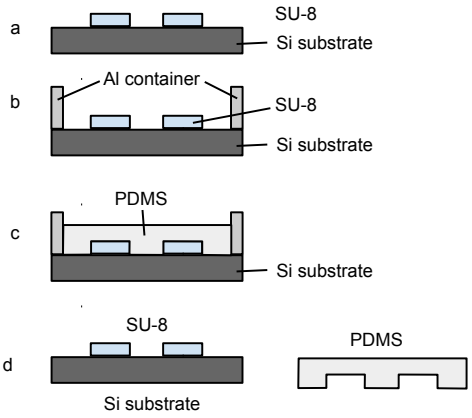


Figure 2: Process illustration for casting PDMS on the SU-8 master: (a) A reusable SU-8 master mold; (b) An aluminum container to contain the PDMS is put on top; (c) The PDMS is poured over and cured; (d) A molded PDMS is seperated from the SU-8 master mold.

2.4 Bonding experiments

PDMS is a hydrophobic and overall a non-reactive material, making it difficult to bond with other substrates. The PDMS surface can be made hydrophilic and reactive by exposing the PDMS to an oxygen plasma, resulting in an irreversible bond when it encounters glass or silicon[7]. Taking into account that PDMS returns to a hydrophobic state within hours[9] and to ensure optimal surface hydrophillicity of the samples, plasma treated surfaces were bound together immediately after plasma treatment.

2.4.1 Bonding PDMS to glass

The bonding procedure is illustrated in Figure 3. After cleaning a glass slide with acetone, IPA and methanol respectively and blow drying with N_2 gas, both the PDMS component and glass are plasma treated for 30 seconds. Immediately after the plasma treatment the components are put in contact with each other and they let stand for five minutes. The components form an irreversibly bonded microfluidic device.

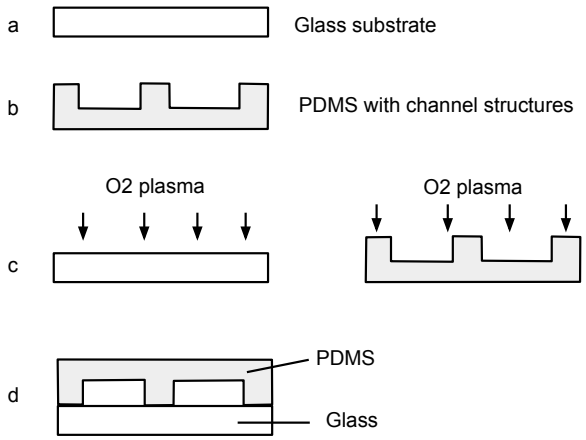


Figure 3: Bonding process for bonding PDMS to a glass substrate: (a) A cleaned glass slide; (b) A molded PDMS; (c) Both the glass and PDMS components are plasma treated; (d) Treated surfaces are bonded together to form a complete microfluidic device.

2.4.2 Bonding PDMS to Si

A. Kroatech *et al.* [7] report that PDMS can be irreversibly bonded to a silicon substrate using the same method to bond PDMS to glass. The same procedure was followed as described above with subsequent thermal treatment experiments. After plasma treating the PDMS and Si substrates they were put in contact with each other and then heated at different temperatures in an oven for 30 minutes, at 80°C, 90°C and 100°C respectively.

2.4.3 Bonding PDMS to CYTOP

Experiments on sealing PDMS to CYTOP substrates were conducted in order to bond microfluidic channels on the integrated optical circuit, consisting of a CYTOP top layer.

A clean CYTOP substrate was plasma treated for 1 minute for better adhesion to the APTES layer. A diluted APTES solution was then spin coated on the CYTOP substrate at 3000 rpm for 30s. The CYTOP substrate was then baked in an oven at 80° C for 30 min. After cooling the sample it was plasma treated along with a structured PDMS component. The treated surfaces were then put in contact and let stand for 1 hour. The device was then filled with a 1:10 fluorescent FluoSpheres solution.

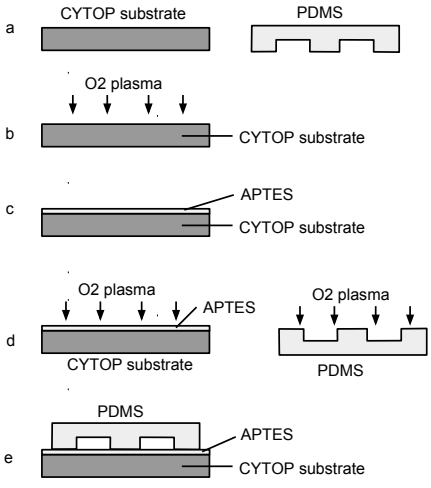


Figure 4: Bonding process for bonding PDMS to a CYTOP substrate: (a) A clean CYTOP substrate and a molded PDMS with open micro-channels; (b) The CYTOP substrate is plasma treated for 1 min; (c) APTES is spun on the plasma treated surface; (d) After heating the sample is plasma treated along with the PDMS component; (e) The treated surfaces are bonded together.

3 Results and discussion

3.1 SU-8 master and PDMS preparation

The microchannel thickness was measured using a profilometer. The thicknesses were in the range of $35-45\,\mu$m for all 4 SU-8 master fabricated. The channel walls were straight and uniform as is shown in Figure 5.

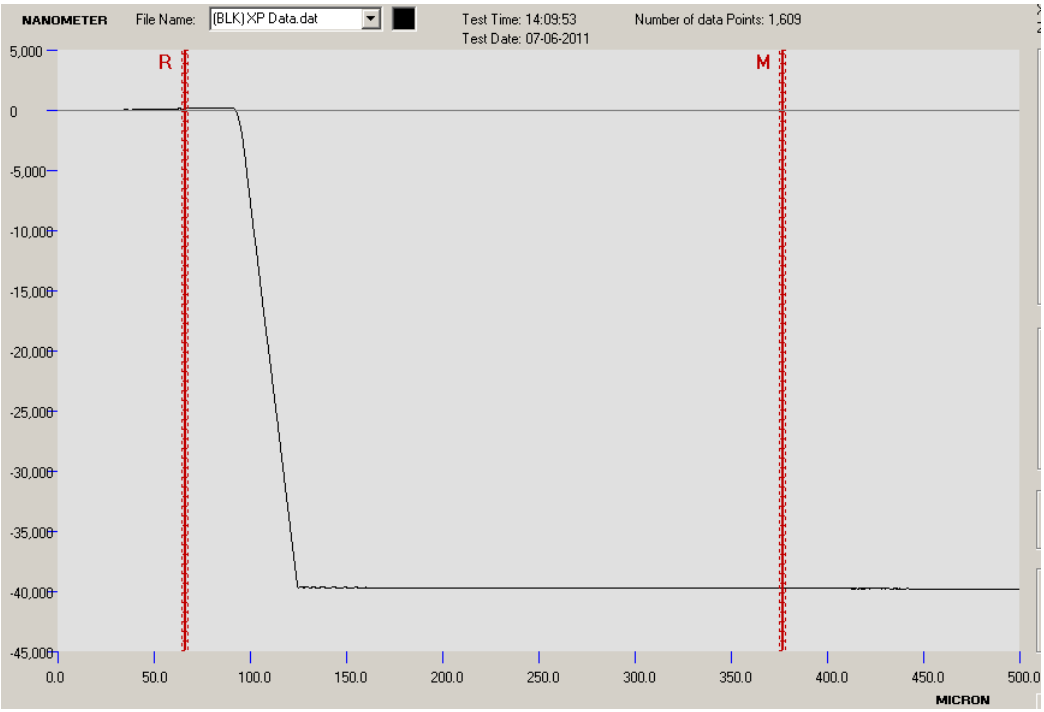
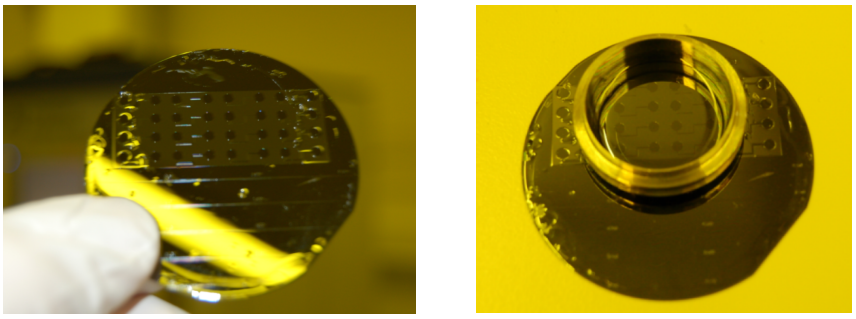


Figure 5: A microprofile of one of the SU-8 master molds, taken using a profilometer. The slope is not vertical on the graph resulting from the shape of the profilometer needle.

According to the SU-8 datasheet [8] the correct exposure dosage for $60\,\mu$m thickness was $150-215\,\mathrm{mJ/cm^2}$. The power amplitude from the mask aligner was measured to be in the range of $12.5-13.8\,\mathrm{mW/cm^2}$ so the exposure time was adjusted accordingly and set to 15–16 seconds.

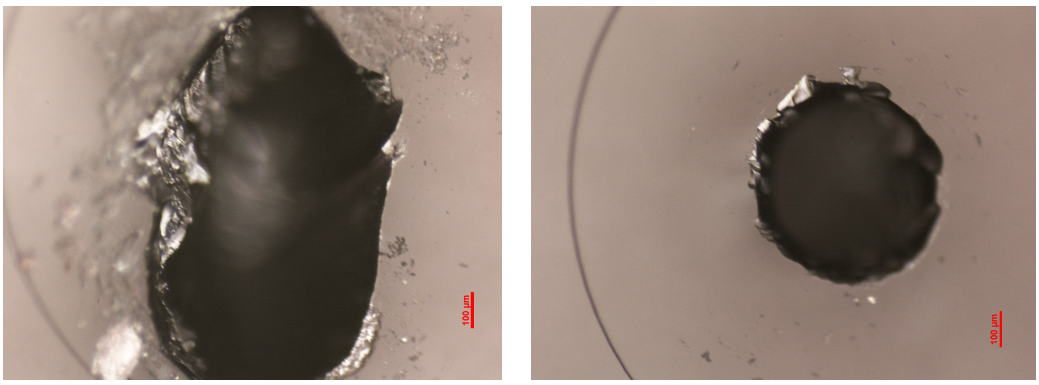
The SU-8 master proved to be effectively reusable, provided all excess PDMS was removed after each curing process, reducing fabrication time. Figure 6 shows a single fabricated master along with a photo of the mold during curing of the PDMS component.



(1) (2)

Figure 6: A fabricated SU-8 master mold: (1) A clean SU-8 master mold; (2) SU-8 master mold, Al container and PDMS during curing.

Holes needed be made for injecting media into the reservoirs on the microfluidic devices. Two approaches where tried. We tried using a epoxy glue to glue Al pellets (2.5mm in diameter) on the reservoirs on the SU-8 master, before casting the PDMS on the master. This resulted in difficult separation of the molded PDMS and master and an uneven PDMS slab. We also tried punching holes through the PDMS reservoirs using needles. Figure 7 shows the effect of using (1) a sharp surgical needle and (2) a blunt needle. The blunt needle gave a better result, no leakage was experienced when injecting fluid through them because of good adhesion between the injection needle and the PDMS slab.



(1) (2)

Figure 7: Punched holes on PDMS reservoirs. The scale is the same, the red line indicating 100 μm; (1) Hole punched with a sharp surgical needle; (2) Hole punched with a blunt needle.

While preparing the PDMS, the base elastomer and curing agent were mixed in both a 10:1 weight ratio and a 10:1 volume ratio. Woo-Jin Chang *et al.* [10] conducted experiments on different mixing ratios, showing effects on PDMS flexibility and liquid absorbability. No obvious difference in bonding strength was found in our experiments.

3.2 Bonding

Several bonding experiments were conducted, aiming for an irreversible bond between the PDMS and the substrate. All successful methods, methods resulting in an irreversible bond, included a plasma treatment at some stage in the process. T. Maturos *et al.* [11] describe that PDMS treated with oxygen plasma results in the formation of hydroxyl groups at the surface which can form a covalent bond with a glass-like substrate.

K. C. Tang *et al.* [12] reported that bonding quality deteriorated with longer plasma activation time, so we used a plasma activation time of 30 seconds. Two different processing equipment were used for plasma treatment, a plasma asher and a RIE chamber. All bonding experiments using the RIE chamber for plasma treatment were unsuccessful. This was particularly because of long venting time after turning off the plasma, weakening the reactiveness of the treated surfaces and thus resulting in a weaker bond. Plasma activation by the plasma asher yielded much stronger bonds, as samples could be quickly taken in and out of the asher.

All bonding experiments on bonding PDMS to a silicon substrate resulted in little or no adhesion between components. Low temperature ($< 100°C$) heat treatments were tested following the plasma surface treatment. They had little effect on bonding strength. A possible next step would be to try oxidizing the silicon wafer giving a thicker SiO_2 glass layer, possibly encouraging better bond strength.

The same bonding methods to bond PDMS to CYTOP with subsequent heat treatments with varying heat and treatment time, where tried, all resulting in little or no adhesion between components. Kanai *et al.* [6] reported spin coating a thin (0.2-5μm) layer of CYTOP on the PDMS microfluidic

device resulted in a strong CYTOP to CYTOP-substrate bond, unlike our experiments, yielding no adhesion.

Spin coating a thin layer of APTES on a plasma activated CYTOP substrate yielded a successful PDMS to CYTOP bond. In order to facilitate a good adhesion of APTES on the CYTOP substrate the CYTOP was plasma treated for 1 min prior to spinning. The APTES layer was precured at 80°C for 30 min for surface functionalization. After bringing the surface treated components in contact they were let stand for at least one hour before fluid injection. This was to prevent the surface activated channel ceiling from bonding to the APTES floor.

We combined a PDMS microfluidic component to the optical circuit, having a CYTOP top layer. Figure 8 show the images of the complete device, obtained with a fluorescence microscope, when using a fluorescent solution of FluoSpheres mixed in a 1:10 ratio. Figure 8(3) is imaged using the evanescent tail of a light propagating in the waveguide [1]. Details of fluorescence imaging setup are given in [13].

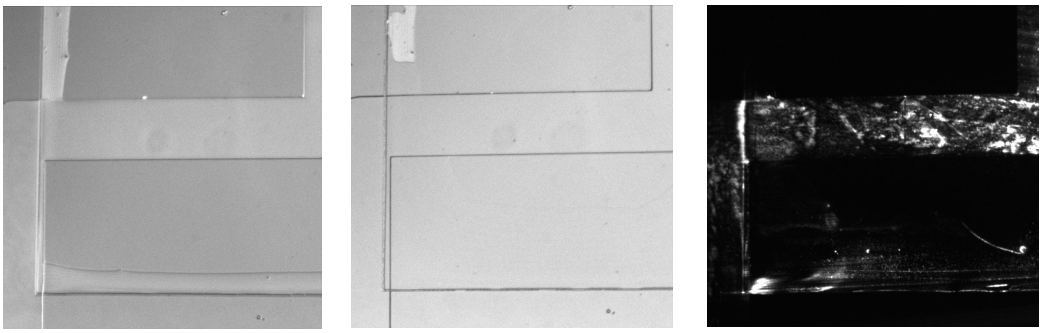


Figure 8: Photos of a PDMS microfluidic channel bonded to the optical circuit; (1) Photo taken in whitelight before fluid injection; (2) Photo taken in whitelight after injection of a fluorescent solution; (3)After fluid injection, taken while propagating a green 532nm laser light through the optical circuit.

Figure 9 shows a complete microfluidic device, containing a bonded PDMS component to a glass slide. The figure shows a simple leak test, employed to test if leakage occurred with increasing pressure. Even when the fastening screws fastening the needles to the tubes gave away, no leakage between the bonded surfaces was found.

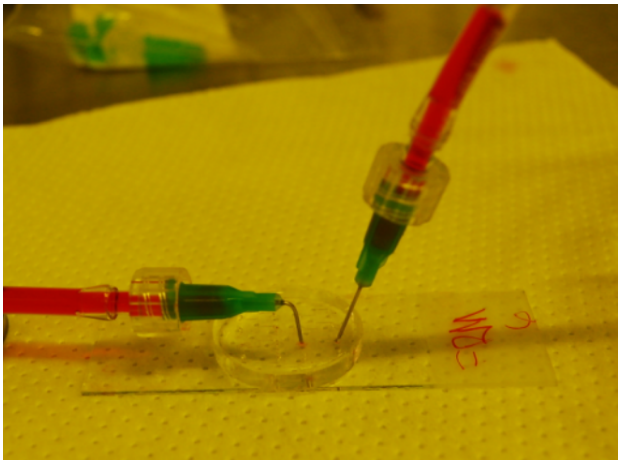


Figure 9: A complete microfluidic device; PDMS irreversibly bonded to a glass slip. No leakage was found between bonded surfaces.

4 Conclusions

We successfully fabricated PDMS based microfluidic devices. We report a method for fabricating a complete PDMS microfluidic device were an irreversible seal is desired. An irreversible bond to glass and CYTOP substrates was achieved. In the case of a Si substrate, some adhesion was confirmed but not sufficient for our applications. The microfluidic device was tested on an optical circuit giving positive results but testing for full use is pending.

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HÁSKÓLI ÍSLANDS

Microfluidics Procedure

Summer 2011

Tools and equipment

1. **You'll need access to these devices in the cleanroom, book them in advance:**
   - Spinner and hotplate
   - Mask aligner
   - Profilometer
   - Microwave
2. **Other equipment include:**
   - Scale
   - Mask, defining the microchannels
   - Blunt needles and surgical blade
   - Syringes and tubes
   - Plastic cups
   - Container for containing PDMS on the master mold
   - Pipettes
3. **List of materials, found in cleanroom:**
   - 2 in Silicon wafer
   - SU-8 2035 photoresist from Microchem Corp.
   - mr-Dev 600, SU-8 developer from Micro Resist Technology
   - Sylgard 184 silicone base elastomer and curing agent
   - CYTOP (CTX809AP2) from Asahi glass comp.
   - APTES (aminopropyltriethoxysilane) from Sigma-Aldrich – found in changing room cooler.
   - Glass slides

Procedure

2.1 Master mold

This is a procedure description for making the master mold for casting a microfluidic device using SU-8 2035. The aimed thickness was 60μm. Measured thickness was in the range of $35 - 45\mu$m. If another thickness is desired check the datasheet from MicroChem; http://www.microchem.com/Prod-SU82000.htm

1. **Spin SU-8 2035:** Ramp up to 500rpm in 5s and keep for 5 s. Then ramp up to 2000rpm in 5 s and keep for 30 s.
   - SU-8 is too thick to be dispensed with a pipette. You can either cut the tip of a pippett, using the wider part or use a disposable beaker to dispense the SU-8 since it is very hard to clean off.
   - Apply approximately 1 ml for each inch of substrate diameter.
2. **Soft bake** on hotplate at 65°C for 130s and then at 95°C for 7 min.
3. **Expose** with dosage of $150 - 215\,\mathrm{mJ/cm^2}$.
4. **Post Exposure Bake (PEB)** should take place directly after exposure. Bake on hotplate at 65°C for 60s and 95°C for 6 min.
   - A visible latent image on the film should be seen within 5–15s after being placed on hotplate.
5. **Develop** in SU-8 developer (MR–Dev 600) for 6 mins and then rinse with IPA. Dry off IPA with N_2 gas.

PDMS

3.1 Preparing the PDMS

1. PDMS is mixed with curing agent at a weight ratio of 10:1.
   - For 10 grams of Sylgard base silicone elastomer you add 1 gram of Sylgard curing agent.
   - Place the PDMS in vacuum for 10 min to help remove air bubbles.
2. Place the containing frame on the master and pour the PDMS carefully over the master.
3. Cure the PDMS by letting it stand overnight.
   - Curing time can be shortened to under 2 hours by baking at 65°C in oven.
4. Carefully lift the PDMS off the master.
   - If required, carefully cut the PDMS to desired pieces with a surgical blade.
5. Using blunt needles punch holes in the reservoirs.
   - Be sure to remove all excess PDMS from the holes.
6. Blow away excess debris with N_2 gas.

3.2 Bonding PDMS to glass

1. Clean glass cover slip with acetone, IPA and methanol and dry with N_2 gas.
2. Put the glass slide and the PDMS face up in the microwave.
3. For plasma treatment follow the microwave procedure.
    - The plasma exposure time should be adjusted to 30s so cooling water is not needed.
    - Adjust both Ar and O_2 to 4 SCFH air flow.
4. Place the glass and the PDMS in contact with each other as soon as possible after the plasma is turned off to get a stronger bond.
5. Let stand for 5 minutes.

Extra notes:

- After a few minutes, the hydrophilicity of the device will decrease making it more difficult for the liquid to enter the channels.
- If the plasma treatment is successful the PDMS should be irreversibly bonded to the glass.

3.3 Bonding PDMS to Cytop

1. Put a clean CYTOP sample in plasma for 1 min. For plasma treatment follow the microwave procedure.
2. Spin coat APTES 5% solution onto sample at 3000rpm for 30s.
3. Bake at 80°C for 30 mins.
4. Put both CYTOP and PDMS samples in plasma for 30s.
5. Combine PDMS and CYTOP samples as soon as possible after removing them from plasma.
6. Let samples stand for 1 hour.
    - The long wait is to reduce the effect of the plasma treatment. If a needle is punched through the holes in the PDMS right away the reservoir ceiling will collapse and bond with the CYTOP.
7. Place the glass and the PDMS in contact with each other after the plasma is turned off.
8. Place in oven shielded with Pyrex glass for 30 min at 100 C.