

## Fabrication of microfluidic devices using polydimethylsiloxane

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Polydimethylsiloxane (PDMS) is nearly ubiquitous in microfluidic devices, being easy to work with, economical, and transparent. A detailed protocol is provided here for using PDMS in the fabrication of microfluidic devices to aid those interested in using the material in their work, with information on the many potential ways the material may be used for novel devices. © 2010 American Institute of Physics. [doi:[10.1063/1.3259624](https://doi.org/10.1063/1.3259624)]

### I. INTRODUCTION

Polydimethylsiloxane (PDMS) has come to be the most widely used material in microfluidic device fabrication due to its many advantages in fabrication ease, physical properties, and economy. Using the material to create even complex structures is a simple affair, although achieving good results requires experience with a reliable technique. The purpose of this brief article is not to review the many uses of PDMS in its application to microfluidics—this was provided by the group of Whitesides<sup>1</sup> some time ago, not to mention the incredible variety of articles that apply the material in specific devices<sup>2–13</sup>—nor is it to review the many ways PDMS may be used in the larger field of micro- to nanofabrication, certainly well covered by past researchers.<sup>14,15</sup> Recognizing that entry into microfluidics is predicated upon having fabrication experience and that many lack it, a simple protocol for fabricating a microfluidic device with PDMS is provided.

### II. METHOD

Although there are many methods for fabricating structures in PDMS, we focus on the most common approach here and encourage the reader to refer to other works<sup>16,17</sup> for special needs. The process outlined here and in Fig. 1 presumes the work is being conducted in a clean environment; the use of a clean room is not absolutely necessary except for the most demanding fabrication requirements. However, avoiding surface contamination is essential; *Pirahna* etch with subsequent rinse using de-ionized water is ideal for cleaning tools and substrates.

#### A. PDMS

The classic choice of PDMS for microfluidics is Dow and Corning's Sylgard 184, a two-part system with mix ratio of cross-linker/curing agent A: siloxane B = 1 : 10. Increasing the cross-linker ratio in the mix is known to increase the rigidity of the PDMS produced,<sup>18</sup> and some changes to the cure cycle can be performed to alter the PDMS' mechanical properties. Further, mixing in other materials can alter the mechanical properties of the PDMS (Ref. 19) or offer novel features not possible with standard PDMS.<sup>20</sup> Coating with other media gives similarly broad possibilities.<sup>21</sup>

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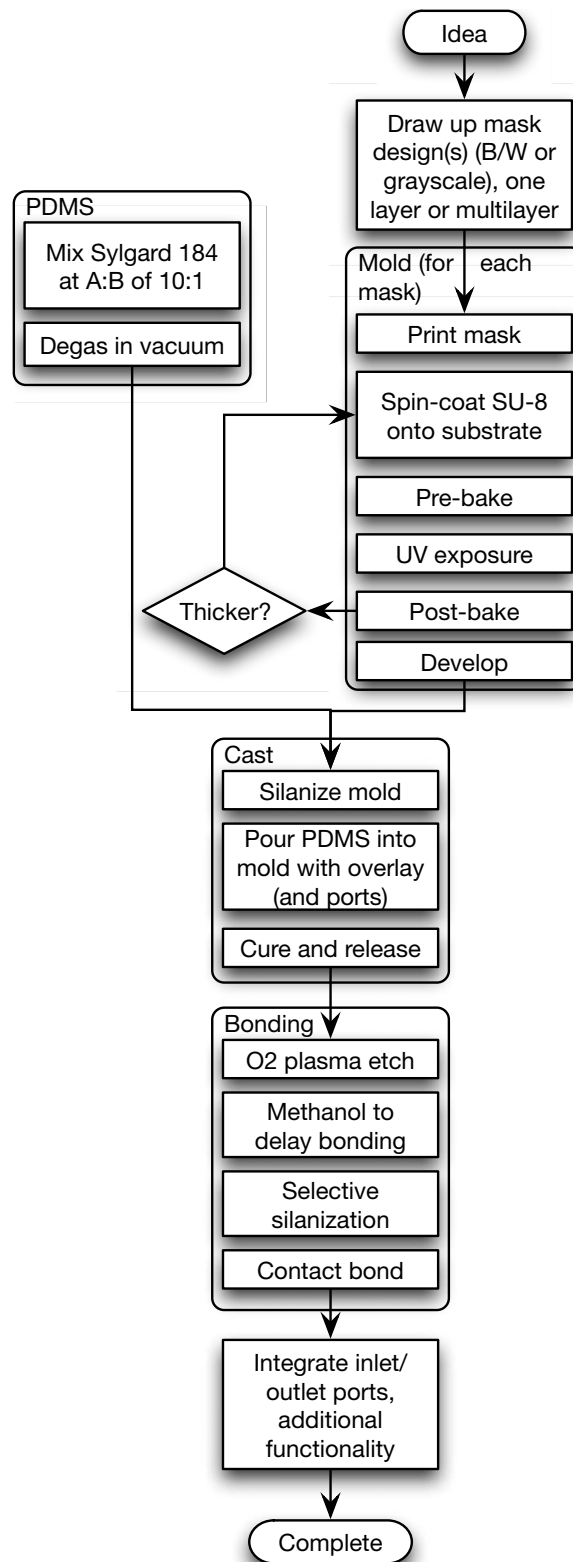


FIG. 1. Process of making microfluidic devices with PDMS. (Enhanced online.) [URL: <http://dx.doi.org/10.1063/1.3259624.1>]

Upon mixing, the PDMS must be degassed in a vacuum chamber for best results, and an Erlenmeyer flask or large beaker with cover is recommended to avoid a mess from the typically violent boiling off of the gas from the PDMS. The PDMS may be worked with for around 2 h after mixing, although its viscosity will gradually increase over this time.

## B. Casting

PDMS, as an elastomer, is known for its mold-release properties and ability to replicate features down to the nanoscale, with low shrinkage during cure (around 1%) and excellent elastic properties. Myriad structures may be fabricated casting the PDMS into preformed molds, the construction of which is an important first step in the process.

### 1. Molds

Using photolithography to form a mold for casting the PDMS structure requires a *mask* and *light source* to pattern a photosensitive resist polymer to match the features of the mask. Depending on resolution needs, the mask may be simply a laser-printed overhead transparency (1200 dpi or 250  $\mu\text{m}$  resolution), a high-resolution print on thin polymer transparency film 10000 dpi/30  $\mu\text{m}$ , or a laser quartz photomask print in chromium deposited on the quartz (420 000 dpi/600 nm). The highest resolution masks are several orders of magnitude more expensive and restrict the size of the overall microfluidic device to around 100 mm on a side.

Typically the mold is a *negative* mold, with the PDMS poured into it and filling the regions left open by the mold. This limits the potential configuration of the cast structure in some specific ways.

- The cast PDMS must be contiguous if the mold is to be reused. If the mold is to be used and then sacrificed (dissolved away), topologies with multiple holes and three-dimensional structures may be cast.<sup>22</sup>
- The size of feature's cast must accommodate the resolution limits of the mask and illumination system.
- Feature height-to-width aspect ratios of 1:1 are straightforward, while higher aspect ratios may be achieved either through multiple spin-coat/exposure cycles before final development of the mold or very expensive Lithographie, Galvanoformung, Abformung (LIGA).<sup>17</sup> Features with lower aspect ratios than about 1:4 are difficult due to sagging of the PDMS in use; unless the PDMS is made more rigid it is likely that the feature will not appear properly.

The mold for casting the PDMS may be made of a wide variety of materials, even for photolithography with many different photoresists available, but we will choose SU-8 (SU-8 2000, MicroChem, Newton MA USA); note that even in selecting SU-8, there are many formulations suitable for forming different layer thicknesses. The SU-8 is the most common molding media used for PDMS-based microfluidic structure fabrication. Using SU-8 with a single spin coat limits our maximum mold thickness to around 250  $\mu\text{m}$ ; here we will aim for a thickness of 200  $\mu\text{m}$ . The process is as follows.

- (1) Spin coat SU-8 polymer photoresist as poured onto a wafer substrate; Si is ideal for this purpose. Spin curves available from the vendor are useful for estimating the appropriate spin rate to obtain the desired thickness of 200  $\mu\text{m}$ ; here we ramp up to 500 rpm spin rate and hold for 15 s to flatten the resist, followed by a 30 s spin at 1250 rpm which gives us a final film thickness of  $205 \pm 3$   $\mu\text{m}$ . The spin acceleration is 100 rpm/s throughout.
- (2) Any bubbles seen in the photoresist must be removed, preferably by degassing the photoresist prior to use. Heating the resist to 50–60 °C will help.
- (3) Prebake (soft bake) the SU-8 to evaporate its solvent in preparation for exposure. Here we prebake the SU-8 coated wafer at 90 °C on a polished Al hot plate for 75 min; we ramp up the temperature to this temperature at 5 °C/min to give improved film adhesion. Generally the thicker the film, the longer it takes to complete evaporation of the solvent; this represents one limit in the maximum thickness of the spun-on film.

- (4) Mount SU-8 covered wafer with mask atop it and expose it with UV radiation with a wavelength of 350–400 nm. The vendor should provide an exposure energy estimate versus film thickness graph, but it will be at best an estimate and requires some trial and error to obtain good results. Our approach uses 500 mJ/cm<sup>2</sup> of exposure energy on a standard mask aligner (MA-6/UV400, SUSS Microtec, Garching, Germany) with 350–400 nm UV light source.
- (5) Making thicker structures can be accomplished by repeating steps 1 to 4 and then continuing onward.
- (6) Postexposure baking aids in cross-linking the exposed portions of the SU-8 in preparation for its development. This step will also require some trial and error; we ramp up to a bake of 15 min at 90 °C at 5 °C/min and ramp down after this time at the same rate. Care in ramping the temperature up and down in baking will reduce the appearance of cracks and bowing from internal stresses.
- (7) Development using MicroChem's SU-8 developer is straightforward, requiring about 16 min for immersion development, leaving the finished mold for use in casting.

## 2. Casting, curing, and releasing PDMS from the mold

With the appropriate PDMS on hand, the casting process is as simple as placing the mold in a heat-tolerant plastic tray or Al boat and pouring PDMS onto the mold. Control of the thickness may be made by using spacers of the appropriate thickness (or the SU-8 itself) to come into contact with a glass or Si overlay placed atop the freshly poured PDMS with a weight placed on top of the stack to squeeze out excess PDMS. Placing the result in an oven at 65 °C for 24 h cures the PDMS, which may then be peeled away from the mold and cut as desired. Silanization of the mold may be needed in some cases where the PDMS sticks to the SU-8 or Si, for example, exposure to the vapor of dimethyloctadecylchlorosilane in a desiccator for 15 min.<sup>23</sup>

## C. Bonding

The PDMS as cast will not stick to any other structures and it will be strongly hydrophobic. There are methods for treating the PDMS to reduce its hydrophobicity in addition to other characteristics, such as gas permeability, but to aid bonding the most common approach is to expose the surface to be bonded to oxygen plasma for about 10 min. The PDMS may then be placed—as soon as possible and in less than a minute—against a similarly cleaned Si, glass, or another PDMS layer to form a permanent bond. To aid in alignment, a small amount of methanol can be used to keep the surfaces separate for a short time. Selective exposure to liquid silanes can make it possible to have effective PDMS release in specific regions, i.e., for valves.<sup>22</sup>

## D. Interfacing and integration

Naturally the structure will require inlet and outlet connections; many researchers pierce especially large open regions within the bonded PDMS structure using needles for temporary applications, but more permanent applications require hose bibs or grommets cocured into the PDMS structure. An interesting alternative is the use of vacuum to draw the PDMS against a plate with prealigned inlet and outlet ports;<sup>24</sup> such a bond is strong yet easily released. Integrating microheaters, sensors, electro-osmotic fluid pumps, and many other devices may be accomplished with a few additional steps<sup>25</sup> to provide inexpensive and complete microfluidic devices with remarkable capabilities.

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