## Device Construction

Photolithography uses photoresist solutions, which are mixtures of UV-reactive polymers. Exposure to intense UV light through a photomask causes the polymers to cross-link (negative photoresist) or degrade (positive photoresist) in a specific pattern. Resists are applied to the wafer by spin coating *i.e.* the wafer is covered in a layer of photoresist and then spun for 30 seconds. Each resist has a specific viscosity and density, thereby giving a calculatable layer thickness after spinning at a specific speed. To construct the device, a silicon wafer is cleaned and spin-coated with photoresist. The coated wafer is aligned and exposed to patterned UV light. After exposure, the unlinked photoresist is removed with developer, exposing only the desired pattern in the resist. The process is repeated for every layer required to manufacture the device. Usually, the layers are applied in increasing order of thickness, but this is not always true (see second note on step 20). After all layers are constructed, the device is baked at an elevated temperature to ensure good bonding between the photoresist and the wafer. Finally, a release agent is applied to the wafer to facilitate easy removal of PDMS monoliths. Omission of the release agent can lead to premature mold failure and loss of feature fidelity.

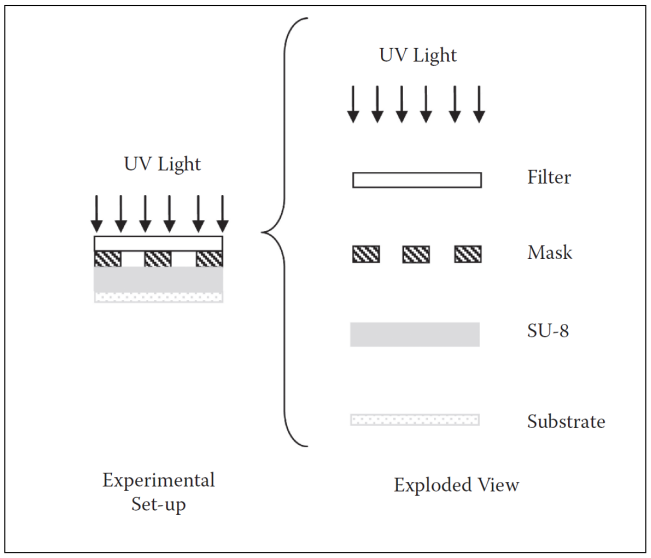


**Figure 1:** The order of contact for exposing photoresist. From Martinez-Duarte and Madou (2011).

## Preparation of the masks

The photomasks used in these processes are ordered specifically so that the silver coating is on the bottom of the mask, to place it in close contact with the SU-8 photoresist. The silver coating is printed onto a plastic sheet. This plastic will contract over time, usually more in one dimension than the other. Therefore, it is suggested that all masks from an order (and especially all masks for a specific device) are mounted at the same time, and as soon as possible after masks arrive from the vendor.

1. Trim the mask to the standard 5"x5" size using scissors or a razor blade, taking care to not scratch or damage the silver coating on the masks
2. Apply a small amount of cyanoacrylate adhesive to all four corners of a 5"x5" borosilicate glass square
3. Place the top of the mask (side without the silver compound) against the surface of the borosilicate glass, ensuring that none of the adhesive permeates to portions of the mask which will form structures in the final device, as the presence of adhesive can change the transmittance of the mask and therefore affect the fidelity of the final pattern
4. Allow the adhesive to dry, ensuring that the mask does not shift during drying
5. Store the masks until needed

## SU-8 photolithography

1. Clean the wafer with acetone, isopropanol, and blow dry with filtered $N_2$

2. Center the wafer on the spin coater
3. Apply enough photoresist to cover the entire wafer
4. Spin at 500RPM for 15 seconds (acceleration at 100RPM/sec) then at speed for 30 seconds (acceleration at 300RPM/sec) to reach final thickness
5. Soft bake at 95°C for a specific time based on layer thickness (see Table 1) on a hotplate
6. Let the wafer cool to room temperature (∼2-3 minutes)
7. Mount the correct mask to the mask aligner, ensuring that the mask is oriented correctly (emulsion down, top of the mask away from you)
8. Perform a 3 second flood exposure to check the exposure energy of the lamp (in $mW/cm^2$). This energy will be needed to calculate the exposure time in step 12.
9. Mount the wafer to the chuck of the mask aligner
10. Set the WEC setting. This establishes the force with which the mask contacts the wafer. Usually, a pressure of 2 bar is sufficient.
11. Set the exposure type. Usually, exposure is done under hard contact, which utilizes both physical force and pressurized nitrogen to keep the mask and wafer in contact (Martinez-Duarte and Madou, 2011). The more complete the contact, the less space between the mask and the photoresist, which in turn prevents the broadening of features (MicroChem, 2010; Martinez-Duarte and Madou, 2011). Usually, a 5 second hard contact is sufficient.
12. Set the exposure dose. Each thickness of photoresist has its own required exposure dose to ensure complete cross-linking of the features (see Table 1) (MicroChem, 2010). The exposure dose is given in $mJ/cm^2$, and dividing the exposure dose by the lamp exposure intensity (in $mW/cm^2$) gives the exposure time in seconds.
13. Align the wafer using the microscope on the mask aligner. Once aligned, initiate the exposure.
14. Remove the wafer after exposure
15. To complete the cross-linking reaction, a post-exposure bake is performed at 95°C on a hotplate for a specific time based on layer thickness (see Table 1). If the exposure dose is correct, a 'ghost' of the desired structure is visible in the photoresist after 15-30 seconds at 95°C (MicroChem, 2010).
16. Let the wafer cool to room temperature (2-3 minutes)
17. Immerse the wafer in SU-8 developer for 45-60 seconds to remove uncross-linked photoresist
18. Spray the wafer with SU-8 developer, followed with isopropanol, and blow dry with filtered $N_2$
19. Check the height of the features with the profilometer
20. Repeat the above steps for all required layers (beginning with step 2)

    Note: For thin layers (∼¡1$\mu$m), it is beneficial to hard bake these layers before applying the next layers. In this case, bake the wafer at 150°C on a hotplate for 5 minutes (the same as in step 21, and let cool before repeating steps 2- 18.

    Note: In constructing certain devices, a smaller layer must be applied after a taller layer, such as the addition of chaotic mixers on DAW devices (Ferry et al., 2011). In these cases, the development step is omitted after the taller layer is constructed, and the shorter layer is applied directly to the taller layer. After construction of the shorter layer, the unlinked resist from both layers is removed by developing as in steps 17 and 18.
21. After all layers have been constructed, the device should be hard-baked to solidify the features. The hard bake is performed at 150°C on a hotplate for 5 minutes for all devices, regardless of the number of layers (MicroChem, 2010).
22. Let the wafer cool to room temperature (4-6 minutes)

23. To protect the wafer and make PDMS removal possible, a release agent is applied ((tridecafluoro-1,1,2,2-tetrahydrooctyl)-1-trichlorosilane). The wafer is placed in a desiccator, and 3 drops of release agent are dispensed into a weigh boat in the desiccator. The desiccator is placed under vacuum for 5-10 minutes to evenly distribute the release agent.

    Note: To remove excess release agent, PDMS is applied to the wafer and removed in three rounds before the monoliths are used to construct devices.

| **Layer Thickness ($\mu$m)** | **Soft bake time (min)** | **Exposure Dose (mJ/cm$^2$)** | **PEB time (min)** |
|---|---|---|---|
| 0-2 | 1 | 60-80 | 1-2 |
| 3-5 | 2 | 90-105 | 2-3 |
| 6-15 | 2-3 | 110-140 | 3-4 |
| 16-25 | 3-4 | 140-150 | 4-5 |
| 26-40 | 4-5 | 150-160 | 5-6 |

**Table 1:** Manufacturing guidlines for SU-8 photoresist. Replicated from MicroChem (2010).

# Bibliography

Ferry, M., Razinkov, I., and Hasty, J. 2011. Microfluidics for synthetic biology: from design to execution. *Methods in Enzymology*, 497:295–372.

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