Multi-Height Precision Alignment With Selectively Developed Alignment Marks

Michael Heymann, Seth Fraden, and Dongshin Kim

***Abstract*— The alignment step in fabricating multi-height photoresist masters is a critical and time-consuming process. SU8 masters that combine very thin and thick layers can be difficult to align because of low contrast visibility. We increase visual contrast by selectively developing alignment marks to ease fabrication of masters with thick resist layers deposited on much thinner ones. In addition, we use a vernier calliper based alignment mark to achieve high precision alignment. [2013-0172]**

***Index Terms*— Microfabrication, microelectromechanical systems, microfluidics, lithography, alignment.**

MULTI-HEIGHT designs are both common and critical to a wide range of microfluidic applications, e.g. the chaotic herringbone mixer [1], surface tension guided drop storage [2], sub micrometer drop fabrication [3], *E.coli* trap device (“mother machine”) [4], elastomer stamping [5], electronically programmable membranes [6], and to pattern hydrophobicity on surfaces by using nanometer deep micro-patterns [7].

Fabricating multi-level masters is challenging and time consuming. Typically, after depositing, exposing and baking the first photoresist layer, a second level of photoresist is spun and soft baked onto the master. The photomask for the second layer is then aligned with the master using dedicated alignment marks exposed into the first resist layer (Figure 1, middle panel). Due to this sequential build-up of photoresist, the first layer alignment marks are always immersed by uncured photoresist of the second layer and therefore, their optical contrast is reduced. If the second layer is thicker than the first layer, the alignment marks may become too faint to be resolved in standard reflection microscopy. This approach also limits the number of additional layers to be built onto the master, since the second level mark becomes exposed into the resist.

To overcome these optical limitations, different techniques have been used. Mata *et al.* [8] dry etched their alignment marks directly into the silicon wafer to build masters with up to six photoresist layers. Alternatively, positive photoresist marks can be deployed onto a wafer in a first preparative step [9] (Figure 1, right panel). Because of their amber-red color, marks from positive resist (AZ or SPR) are easily seen through subsequently deposited negative resist layers. Both methods have the advantage that building the marks is independent from building the features and the heights of both can be chosen independently. However, silicon dry etching is a complex technique and not accessible to many microfluidics labs that mostly build PDMS devices outside of a traditional clean room. Furthermore, if one is constructing a multiheight photoresist master composed solely of negative resist, then both the dry etch and positive resist alignment methods require an independent manufacturing step. In each case it is desirable to save the labor time and material cost by building the alignment marks along with the features. Another disadvantage of both the dry etch and positive photoresist approaches is that the wafer has already been processed and the surface has to be cleaned again before depositing the first

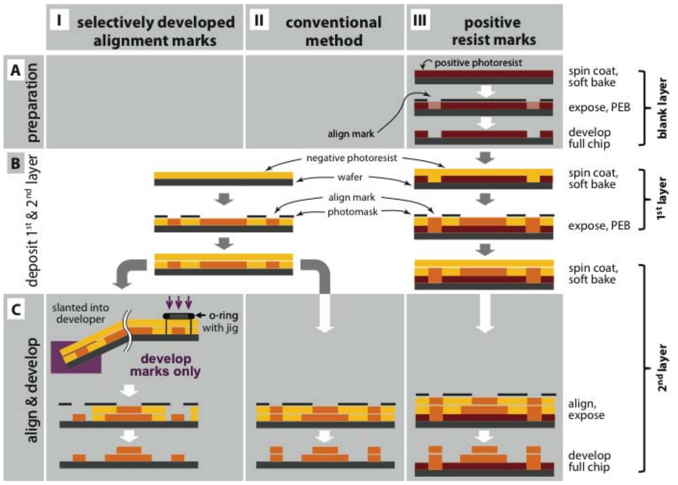

Fig. 1. Schematic comparison of methods to fabricate multi-height molds. The positive resist marks method (right column) uses the predefined alignment marks on an additional layer which the other two methods do not require (A). Our method to selectively develop alignment marks (left column) and the conventional method (middle column) share a common first step (B I&II): After the 1st layer photoresist was spun and exposed to UV the 2nd layer photoresist was spun. (C I) After soft baking the 2nd layer photoresist, the alignment marks were selectively developed as illustrated in Figures 3 to 5. Subsequent procedures including alignment, exposure and development were the same for all three methods. The center column (II) shows the conventional microfabrication method without selective development of alignment marks. The right column (III) shows how positive photoresist can be used to distinguish the alignment mark by its amber-red color [9].

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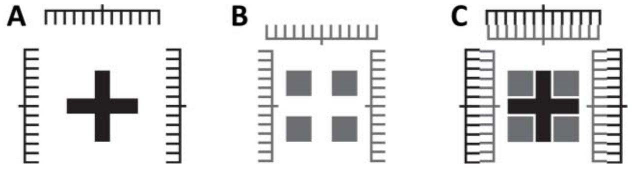


Fig. 2. Vernier caliper alignment mark for the first layer (A) mask, and second layer (B) mask. (C) View when mask (B) is aligned over the developed photoresist (A). Graduations are 90 μm wide and the squares (in B and C) have an edge length of 250 μm. The alignment precision of this vernier scale is 2.5 μm.

negative resist layer. Inevitably one ends up with a poorer surface than the original polished wafer, especially if a 'blank' foundation layer of positive resist is used [9].

In this paper, we introduce a new method for photo-mask alignment to make multiheight negative SU8 photoresist masters in which the alignment marks have high optical contrast and do not require additional spin coats of resist. We increase alignment mark visibility by developing the non-exposed (non-cross linked) photo resist in the region around the alignment mark. In the crudest implementation, we tilted the master in a bath of developer such that only the edge of the master with the alignment mark is submerged. Alternatively, we use a spin-coater to develop the mark in order to minimize the developed area. In a more sophisticated version, we constructed a jig to isolate the portion of the wafer containing the alignment mark for development. Our approach does not require extra resources or equipment and can be implemented easily in other labs. Another advantage is that no photoresist from the second layer remains over the first layer alignment marks so that the second layer alignment marks are not constructed on top of the first layer marks. Therefore, one can deposit multiple layers of features without obscuring the original mark.

We demonstrate the selective development of alignment marks method using a simple vernier scale alignment mark [10], [11], as shown in Figure 2. We match the size of our mark to fit into the field of view of our contact aligner (ABM Mask Aligner, ABM Inc.) equipped with a Zeiss MJM Split Field Microscope at 50× final magnification. With a 1 mm large mark we can achieve an alignment precision of 2.5 μm in both principal directions. If desired, even sub-micron precision can be achieved by re-scaling the vernier.

We manufactured several masters with alignment marks exposed into a 5 μm thick SU8-2005 layer. We then spin coated a second layer of SU8-2000 series negative resist of varying thickness. SU8 resists were purchased from MicroChem and processed as described by the product information. After the second level resist soft bake had been completed, we selectively developed the alignment marks using one of three different techniques:

(**1**) The master was carefully dipped sideways into a bath with developer so that the mark was immersed in developer solution, but the device features remained undeveloped (Figure 3). To prevent developer contacting the unexposed resist in the region about to be exposed to UV-light, the developer was only agitated very gently. Developing the alignment mark on a 100 μm thick SU8 master took about 10 minutes.

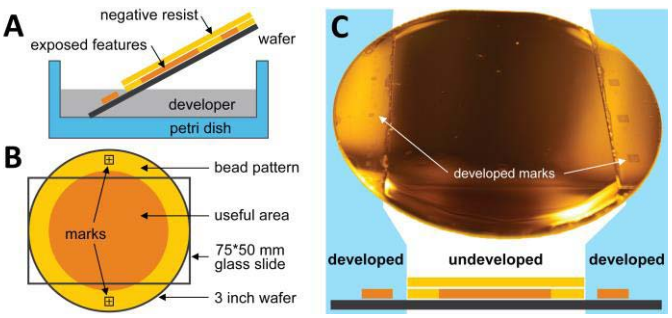


Fig. 3. Slanted wafer for selectively developed alignment mark method. (A) A wafer was dipped sideways into a bath of developer to selectively develop a 1 cm wide sector containing the marks. (B) Thick SU8 films form a pronounced edge bead, causing varying resist thickness within approximately 1 cm of the rim (yellow). While microfluidic channels are preferably not placed into this rim, it is well suited for alignment marks. Furthermore, most microfluidic devices adopt a rectangular footprint, so that essentially no 'useful' wafer space (orange) is consumed by the slanted wafer method. Top view (C) of an alignment mark test pattern on a 3-inch wafer after selective development, including a schematic cross section below. Developed areas are highlighted in blue.

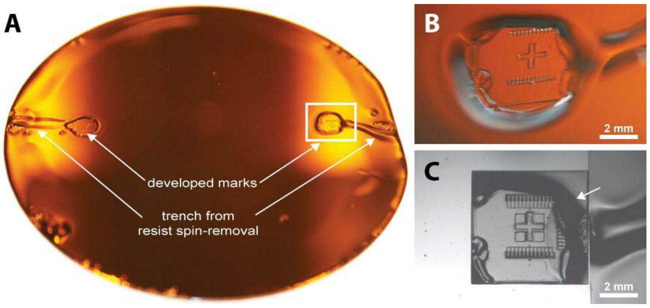


Fig. 4. Selective alignment mark development with spin-removal of developed resist. (A) 3 μl of developer was placed onto each alignment mark and allowed to soften the resist for 2 minutes. The resist was the removed using a spin-coater. (B) Mark after two cycles of development with spin-removal, prior to UV exposure. (C) Stereomicroscope image of final wafer after complete development and hard bake. The transition zone from developed area to unaffected resist (arrow) is about 1 mm thick.

(**2**) Using a Hamilton gas tight syringe we deposit a few microliter of developer solution over the mark. After a 2 min incubation, we remove the softened resist by spinning the wafer at 500 rpm for 5 seconds with acceleration of 100 rpm/second and subsequently 3000 rpm for 30 seconds with acceleration of 300 rpm/second on the spin-coater (Figure 4). We repeat these develop-and-spin cycles until the mark is sufficiently cleared for further processing. Usually two rounds suffice to remove a 100 μm resist layer to achieve good mark visibility for alignment. We then bake the wafer for 2 min at 65 °C and 2 min at 95 °C to evaporate away remaining developer.

(**3**) Alternatively, we use a dedicated clamp to further speed up the development process while also reducing the area developed around the mark (Figure 5). It was important to clean spilled resist from the backside of the master with a cloth soaked in developer and then dry with a stream of nitrogen gas. We placed the master on a glass plate and mounted it into a jig, where O-rings limited the developer solution to be in contact only with the region around the alignment mark. We then used a plastic Pasteur pipette to flush the mark

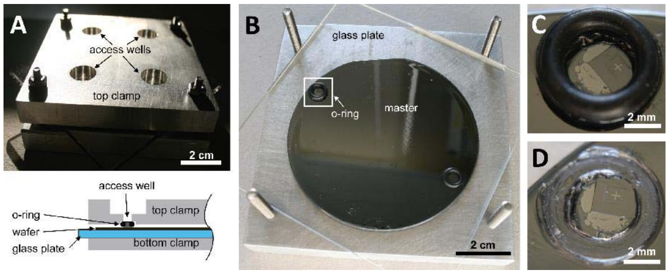


Fig. 5. Clamp to selectively develop alignment marks. (A) An aluminum clamp was machined with 4 access wells. The back of the master is cleaned to ensure an even and flat surface. (B) The master is then centered on a glass plate and the lid with the O-rings is carefully lowered onto the master and fixed in position by gently fastening the screw nuts manually. After the alignment marks were developed the clamp was disassembled. The white square (B) highlights the alignment mark before (C) and after (D) the O-rings were removed.

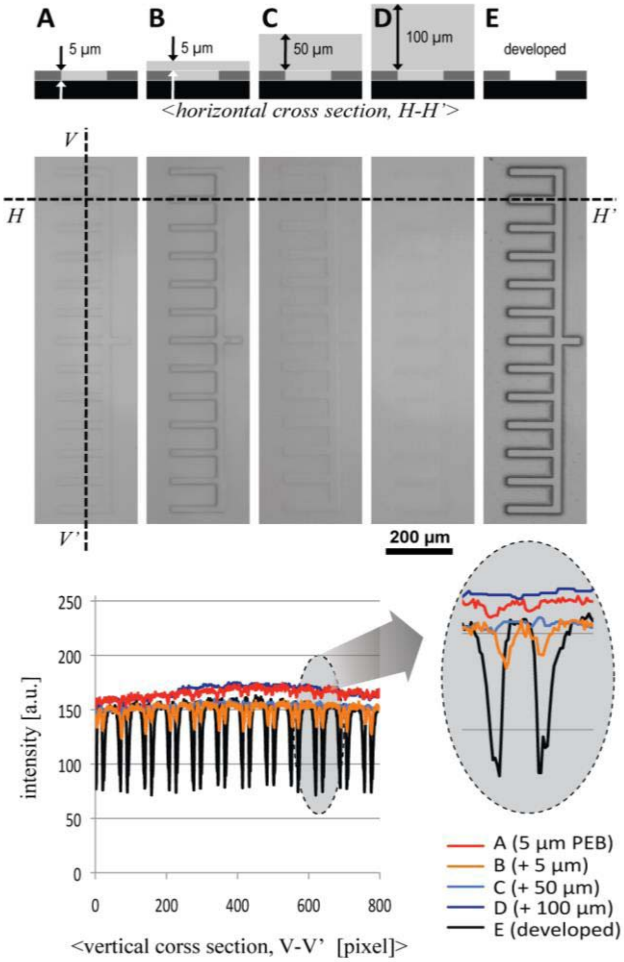


Fig. 6. Alignment mark visibility for 5 μm thick SU8-2005 after (A) post-exposure bake and after (E) partial development. For comparison a 5 μm thick SU8-2005 photoresist layer with a second layer of SU8-2000 series of thickness (B) 5 μm, (C) 50 μm, and (D) 100 μm after pre-exposure bake. The vertical line over the alignment vernier (V-V′ in A), indicate where the intensity profiles were scanned.

with developer and isopropanol by repeatedly aspirating and re-injecting the respective solutions. We found this process to be quite effective, as even a 100 μm thick SU8 layer was fully developed after 30 seconds. Residual isopropanol in the access well was dried away using a stream of nitrogen gas.

Using bright field reflection microscopy we compared the visibility of our masters (Figure 6). Because the optics of our contact aligner split field microscope could not resolve 5 μm thick marks covered with more than 25 μm SU8, we used an Olympus BX51 with an AVT Marlin firewire camera to image our masters. The illumination conditions were kept constant and only the focus was adjusted slightly to maximise contrast. We measured intensity profiles along the vernier using ImageJ [12]. The optical contrast deteriorated strongly with increasing thickness once the second resist layer was thicker than 10 μm (Figure 6). Only for the case of a thin second resist layer was the alignment mark visibility improved in comparison to the post exposure baked first resist layer. We attribute this to the fact that the low viscosity SU8 photo resist formulations, tailored for coating up to 10 μm thin films, contained enough solvent to dissolve the upper portions of the first resist layer, which was partially removed during spin coating of the second layer resulting in improved optical contrast. In all cases the visibility of the alignment marks was dramatically improved upon developing the alignment marks. We did not notice a significant difference in alignment mark visibility between the three techniques and all three methods can remove the uncured resist completely.

We found each of the three techniques to selectively develop alignment marks to be robust and reliable, however specific applications might favor one over the other. The transition from selectively developed portion to unaffected resist was smaller than 2 mm in all cases. The developer only affected the exposed region and we did not observe the developer to cut through or go under the photo resist.

While technically the easiest approach, the slanted wafer technique (Fig. 3) needs the most time to develop a given mark. Both marks have to be developed sequentially, but one can easily batch process wafers this way. The space consumed for this method roughly matches the smallest hemi-circle to contain the mark, plus a few millimetres safety margin (Figure 3B). Thick SU8 films form a pronounced edge bead and accordingly microfluidic channels are usually not placed within the approximately 1 cm wide rim zone of the wafer that is most affected by the edge bead. We place our alignment marks into this peripheral zone, because the edge bead does not affect alignment accuracy. Furthermore, most microfluidic devices adopt a rectangular footprint. For instance a design tailored for a standard 2 × 3 inch microscope slide, leaves an excess half-inch segment on each half of the 3 inch wafer. Each of these segments is large enough for selective development. As a result, no 'useful' wafer space is consumed.

The spin-removal technique (Fig. 4) consumes significantly less space on the wafer and also is faster than the slanted wafer technique, but requires more attention when applying the developer to the mark. For second resist layers thicker than 50 μm this technique requires multiple iterations. We get best results with depositing 3 μl to develop a mark with about 2 mm edge length. This method is sensitive to the amount of developer deposited, as too big a puddle will easily spread out beyond the target area. When spinning the softened resist away a trench remains, which limits this approach to marks placed on the perimeter of a design only.

The clamp-assisted method (Fig. 5) is the most controlled way to apply developer to defined regions. While this technique takes the most time to set-up, actual development proceeds the fastest, rendering this approach ideal for very thick resist layers of about 150 μm and thicker. The space consumed in this method exactly matches the outer diameter of the O-rings used. This clamp-assisted method is also useful in case one desires to use selective development with already old/previously designed photomasks that have the alignment marks in the middle of the design. If we can reuse photomasks, it will reduce the process cost which is especially a concern with expensive chrome photomasks.

Selectively developing the alignment marks makes the fabrication of multilevel masters simpler and more robust than current master preparation methods and facilitates the fabrication of large and complex chip designs with multiple resist layers. We showed three different techniques to selectively develop the marks and highlighted their respective advantages and disadvantages.

Independent of the specific optics available, our method allows the alignment of masks when the height of the second layer of resist is greater than the first layer with a minimum of extra processing steps. This ability will greatly benefit the microfluidics community in light of the many new rigid materials for making microfluidic devices that help to overcome the stringent height-to-width aspect ratio limitations of traditional PDMS features, which rarely exceed ratios of 1:10 height to width, e.g. microfluidic stickers (see Sollier *et al.* [13] for a review), sol-gel chips [14], and embossed plastics [15], which have recently been pioneered. The resolutions used in most microfluidic applications do not require clean rooms. Because it is less expensive and more convenient, the soft-lithography community is increasingly working outside of the clean room. The selective development of alignment marks method is intended for this community. This method is also intended for those facilities that do not possess dry-etchers, such as in smaller universities and in developing countries. To selectively develop alignment marks eases the fabrication of multiheight, high-aspect ratio devices.

REFERENCES

[1] A. D. Stroock, S. K. W. Dertinger, A. Ajdari, I. Mezic, H. A. Stone, and G. M. Whitesides, “Chaotic mixer for microchannels,” *Science*, vol. 295, pp. 647–651, Jan. 2002.

[2] S. Selimović, F. Gobeaux, and S. Fraden, “Mapping and manipulating temperature–concentration phase diagrams using microfluidics,” *Lab Chip*, vol. 10, no. 3, pp. 1696–1699, 2010.

[3] F. Malloggi, N. Pannacci, R. Attia, F. Monti, P. Mary, H. Willaime, P. Tabeling, B. Cabane, and P. Poncet, “Monodisperse colloids synthesized with nanofluidic technology,” *Langmuir*, vol. 26, pp. 2369–2373, Feb. 2010.

[4] P. Wang, L. Robert, J. Pelletier, W. L. Dang, F. Taddei, A. Wright, and S. Jun, “Robust growth of escherichia coli,” *Current Biol.*, vol. 20, no. 12, pp. 1099–1103, 2010.

[5] J. Tien, C. M. Nelson, and C. S. Chen, “Fabrication of aligned microstructures with a single elastomeric stamp,” *Proc. Nat. Acad. Sci. USA*, vol. 99, no. 4, pp. 1758–1762, 2002.

[6] S. Chemnitz, U. Tangen, P. Wagler, T. Maeke, and J. Mccaskill, “Electronically programmable membranes for improved biomolecule handling in micro-compartments on-chip,” *Chem. Eng. J.*, vol. 135, pp. S276–S279, Jan. 2008.

[7] L. Li, W. Du, and R. Ismagilov, “User-Loaded SlipChip for Equipment-Free Multiplexed Nanoliter-Scale Experiments,” *J. Amer. Chem. Soc.*, vol. 132, no. 1, pp. 106–111, 2010.

[8] A. Mata, A. J. Fleischman, and S. Roy, “Fabrication of multi-layer SU-8 microstructures,” *J. Micromech. Microeng.*, vol. 16, no. 2, pp. 276–284, 2006.

[9] Stanford Microfluidics Foundry. “Multi-Height Molds” [Online]. Available: http://www.stanford.edu/group/foundry/services/multi_height_molds.html, 2013.

[10] S. Farrens and S. Sood, “Precision wafer to wafer packaging using eutectic metal bonding,” SUSS Rep., Jul. 2008, pp. 6–11.

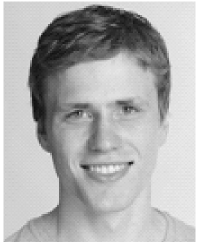
[11] C. Stuart, Q. Xu, R. J. Tseng, Y. Yang, H. T. Hahn, Y. Chen, W. Wu, and R. S. Williams, “Nanofabrication module integrated with optical aligner,” *J. Vac. Sci. Technol. B, Microelectron. Nanometer Struct.*, vol. 24, p. 539, Feb. 2006.

[12] W. S. Rasband. “ImageJ,” U.S. National Institutes of Health, Bethesda, MD, USA, imagej.nih.gov/ij, 1997–2012.

[13] E. Sollier, C. Murray, P. Maoddi, and D. Di Carlo, “Rapid prototyping polymers for microfluidic devices and high pressure injections,” *Lab Chip*, vol. 11, no. 22, pp. 3752–3765, 2011.

[14] M. B. Mikkelsen, A. A. Letailleur, E. Søndergård, E. Barthel, J. Teisseire, R. Marie, and A. Kristensen, “All-silica nanofluidic devices for DNA-analysis fabricated by imprint of sol–gel silica with silicon stamp,” *Lab Chip*, vol. 12, no. 2, pp. 262–267, 2012.

[15] A. Bhattacharyya and C. M. Klapperich, “Design and testing of a disposable microfluidic chemiluminescent immunoassay for disease biomarkers in human serum samples,” *Biomed. Microdevices*, vol. 9, no. 2, pp. 245–251, 2007.



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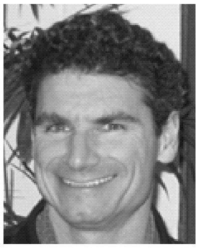

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