Combinatorial Multilevel Mold Insert Using Micromachining and X-ray Lithography

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Summary

The present technology advancement in biomedical, micro-electro-mechanical systems (MEMS) engineering, bio-MEMS, healthcare, etc. is driving the need to fabricate devices with multi-level, high aspect ratio and complex microstructures which in turn requires high quality mold inserts with all these features. This research addressed fabrication challenges of a PMMA mold insert template containing multi-level microstructures with smallest features of 10µm and aspect ratios up to 50 using a process combination of micromilling and x-ray lithography. Initial plating tests verified that the fabricated templates built on a copper substrate with oxidized surface are suitable for making metal molds from nickel.

Introduction

Researchers in micro-electro-mechanical-systems (MEMS) have strong interest in developing mold inserts with complex, multilevel, quasi 3-dimensional contours and varying high aspect ratio (HAR) microstructures for a wide range of applications including microfluidic, microoptics, microreactors, and sensor and actuator devices [1,2,3,4,5,6,7,8,9,10,11]. Multilevel mold inserts have been fabricated using single as well as a combination of MEMS technologies including x-ray lithography, Si etching, electroforming, hot embossing, and micromilling to name a few [12,13,14,15,16,17]. While their results are promising the work reported was addressing mainly specific designs and applications and did not aim for maximum aspect ratio possible. In the present research we have explored process combination of micromilling with x-ray lithography aiming for a maximum aspect ratio while attempting to make structures as small as 10µm [18].

Fabrication and Results

Copper (Cu) was the first choice and compared to other potential materials [18,19,20] that can be used as substrates, owing to relative ease of machining and selective etching versus nickel. Schematic shown in Figure 1 illustrates two different approaches to fabricating plating templates. In the first approach (a) a Cu substrate is initially micromachined (milling or fly cutting) to define several height levels on the substrate. Subsequently, surface modification [18,21] and bonding of poly(methyl_methacrylate) (PMMA) resist followed. Gluing on substrates with topology requires some optimization in order to avoid trapping of air. The resist thickness was controlled by fly-cutting and ranged from about 300-600µm in different areas of the pre-structured substrate. Then, x-ray lithography was performed using a micro-milled PMMA sheet as flexible height filter to ensure that the thickness in each area is the same and thus exposure conditions, too. Initial dose studies covered a bottom dose range from 2500 to 4000 J/cm^3. Development of the exposed structures in GG developer completed the fabrication of the plating template [more details are found in 18].

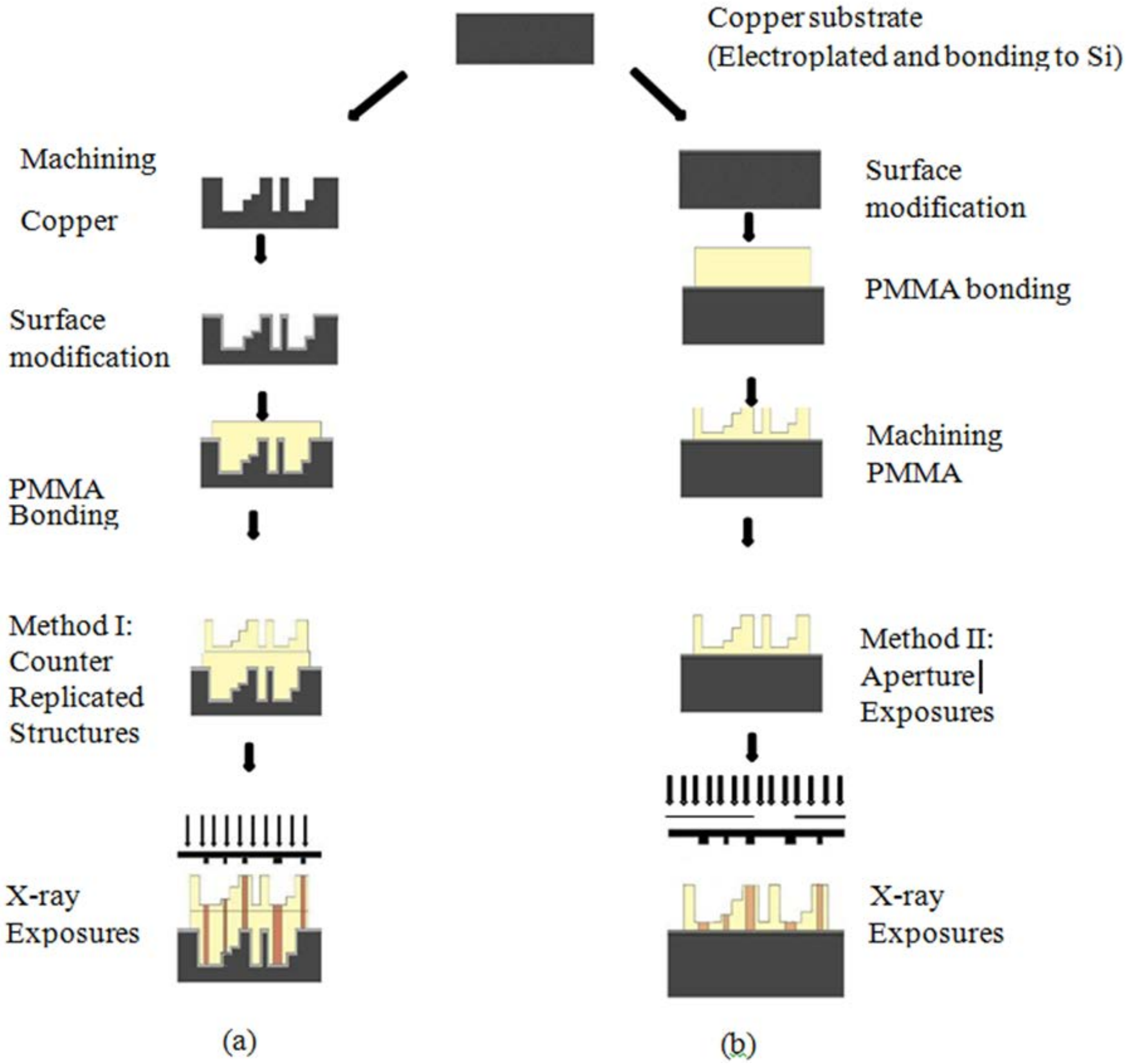


Fig. 1: Overview of fabrication approaches investigated in this research using a combination of micromachining and x-ray lithography [details in 18].

In the second approach (b) the process started out with a silicon wafer with seed layer onto which a thick Cu layer was electroplated. Cu substrates used were electroplated for about 30 to 45hrs to the thickness ranging from 500 to 700µm in a copper sulfate bath. The plated Cu was planarized by means of fly-cutting followed or micromilling/ fly-cutting was utilized to define multi height levels with step height ranging from 50 to 300µm as illustrated in Figure 2.

Surface modification and PMMA bonding followed the same procedure as in (a) but was simpler as the substrate did not have a topology. Next, micromilling of height levels into the PMMA resist completed the substrate preparation followed by x-ray lithography. Figure 1 is showing an alternative method of adjusting the bottom dose, namely using apertures defining areas which are then exposed with the appropriate dose. Note that this approach is only possible if areas are large enough and there is some tolerance in aligning mask/substrate and apertures A typically example is shown in Figure2, left, where each field can be exposed with the optimum dose by setting the apertures of the DEX 02 scanner accordingly. Exposures were performed at DEX02 scanner using ‘white’ synchrotron light from the CAMD bending magnet (http://www.camd.lsu.edu/aboutcamd.htm). The mask used for the tests is shown in Figures 3 and its fabrication is described in [16]. It consists of a graphite substrate (150µm thick) with 6 identical test fields of ~20mm x 20mm. Absorber pattern are made in about 25µm thick gold and dimensions of the microstructures from 10 to 200µm. Coarse alignment is realized by looking through holes drilled into the graphite substrate and adjusting the mask position relative to simple cross-hair pattern on the substrate.

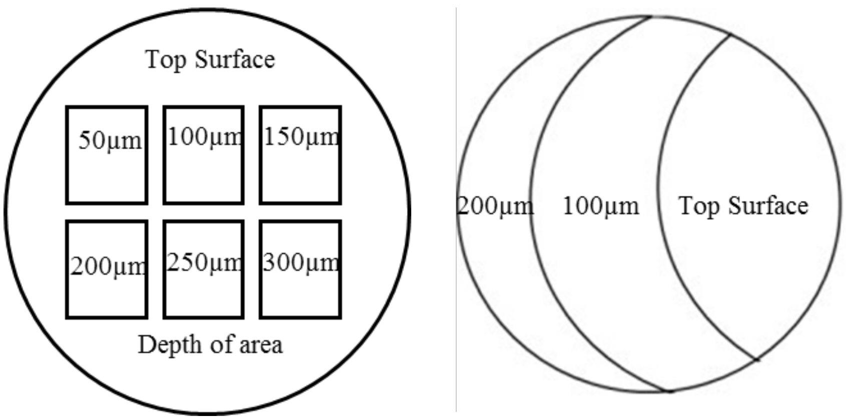


Figure 2:

Left – micromachined Cu pattern with 6 different height levels.

Right – flu-cut pattern with 3 different height levels.

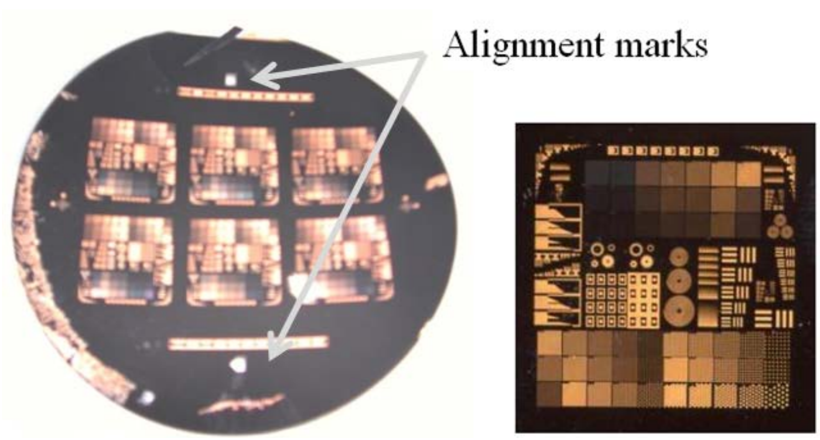


Figure 3:

Graphite x-ray mask with 6 fields of identical test pattern which are copied onto the pre-structured substrates. Close up shows test pattern mainly post arrays, gratings, finger pattern, and some typical MEMS designs (gears, spirals)

Results achieved on Cu substrates were compared with exposures on standard Si substrates coated with TiO_2 seed layer onto which the PMMA resist is bonded. These substrates are routinely used and aspect ratios of 30 are possible with small, free-standing structures. Initial dose screening studies performed on both substrates resulted in a best bottom dose of about 3000 J/cm^3. When using a lower bottom dose structures cannot be completely developed while higher dose resulted in poor adhesion mainly due to secondary radiation from the substrate interface causing additional exposure of the resist from the backside also in absorber covered areas [22]. These initial findings indicate the importance of similar bottom dose and the use of the structured pre-filter matching the step height of the substrate. In addition, development was done using a cycling approach changing developer and rinse baths in an effort to minimize time spent in the more aggressive developer. This prevents overdeveloping resulting in washed off structures.

PMMA samples with thickness ranging from 200 to 500µm were processed with optimized parameters and hexagon, circular and rectangular posts as well as finger structures with dimensions ranging from 10 to 100µm and the gap/spacing between the structures also varying from 10 to 100µm were inspected.

In Figures 4a&b SEM images of PMMA hexagon posts 450 µm tall with design diameter of 10 µm with gaps of 10 µm, too (aspect ratio AR =45 or AR 45) on Cu and Si substrates demonstrate comparable bond strength to either surface. Both micrographs were taken from the same area and x-ray mask cell in order to ensure good comparison. It can be noted that these arrays start to collapse especially near the outside edges of the arrays likely caused by resist residues not fully removed and causing sticking between posts. Zoomed in insets don't show any debonding between posts and substrate. It is noticeable that the oxidized copper surface appears much rougher suggesting that the bond strength is further improved via mechanical anchoring of the glue layer [23].

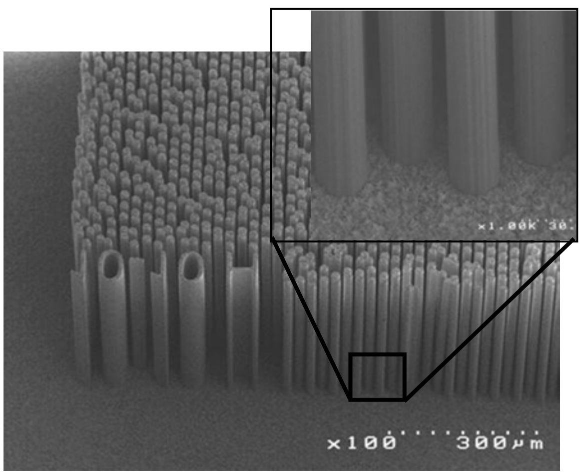


Fig.4a: 10-10H AR 45 on Cu substrate.

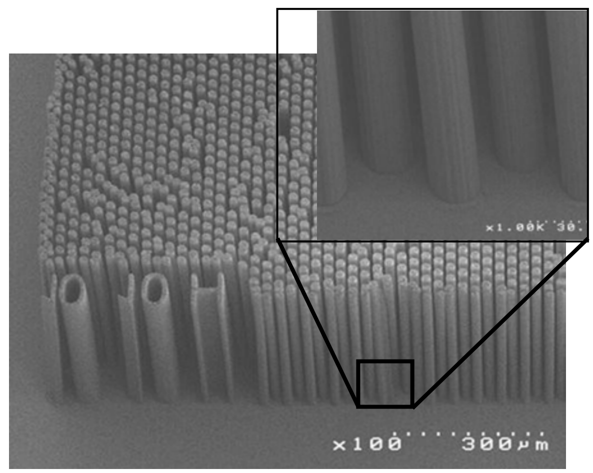


Fig.4b: 10-10H AR 45 on Si substrate.

Geometry and array density play a role on the performance and structure stability as is indicated in Figures 5a&b. Here again 10µm wide posts are arranged in an array with larger gaps of 50µm. The larger gap between the structures will allow the developer and rinse to easily approach the interface and eventually weaken the bond washing away columns (overdeveloped). This is especially a problem when working with both designs on the same mask/substrate. In this case structures with large gaps are developed faster and overdevelop while densely packed areas with small gaps still need longer development time to fully remove the exposed resist. From Fig. 6a it seems that post bonded to the rough copper surface have better adhesion and can tolerate longer development times while identical posts on Si/TiO_2 surfaces are washed off. This suggests that additional mechanical anchoring and thereby the use of the copper substrate will give better results for multilevel patterning as overdevelopment of areas with less thick resist will always be developed faster and thereby expose the substrate/resist interface to an extended developer attack.

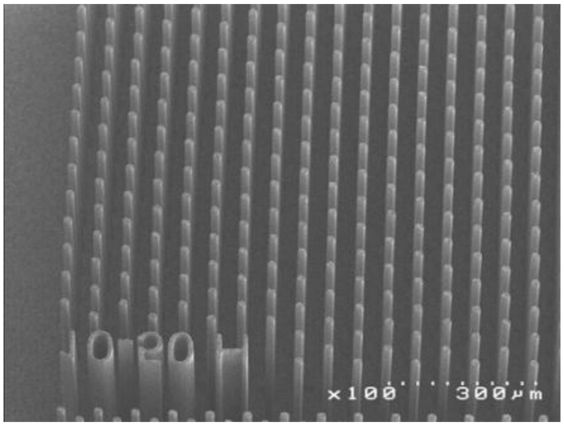


Fig.5a: 10-50H AR 45 on Cu substrate.

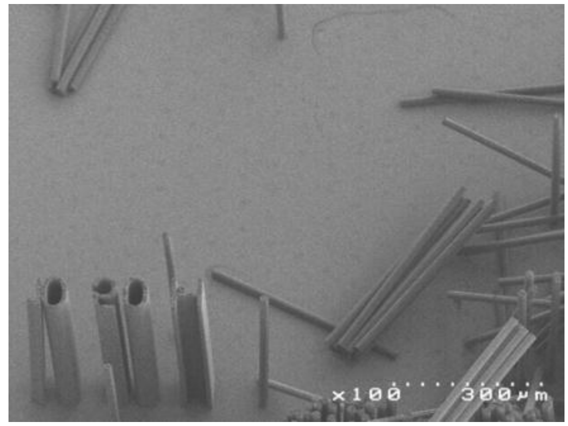
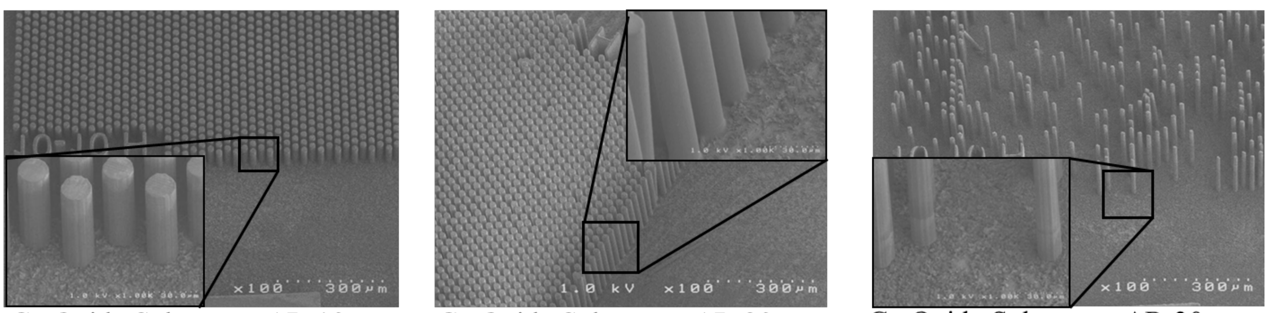


Fig.5b: 10-50H AR 45 on Si substrate.

Parallel patterning of structures with different aspect ratios on the same substrate is shown in Figures 6 for hexagonal posts of 10µm diameter with 10µm gap on a copper substrate using the height-adjusted filter to establish identical exposure conditions, As can be seen the extended development time for lower post heights is not leading to any adhesion problems while there are structure losses on the AR30 structures in part caused by mask defects on this particular cell.



Cu Oxide Substrate AR-10 Cu Oxide Substrate AR-20 Cu Oxide Substrate AR-30

Figure 6: 10µm PMMA posts in 100 µm (left), 200µm (center), and 300µm (right) height suing the adjusted filter height exposure setting.

Using the aperture setting and optimizing the exposure dose for each cell - employ lower dose for thinner resist requiring longer time to develop to the substrate-resist interface while a higher dose and thus faster development time is used for the thicker areas – results can be improved as is shown in Figure 7. However, it was not possible to pattern the entire height range from 100 to 500µm with this very demanding pattern. For practical usage and reliable patterning the aspect ratio range needs to be limited to something like a factor of 3.

Not shown are first attempts to electroplate Ni into the resist template using nickel sulfamate bath. While the process works in principle it was obvious that clean development was not always achieved resulting in many defects (holes) in areas where plating didn't start from the seed layer.

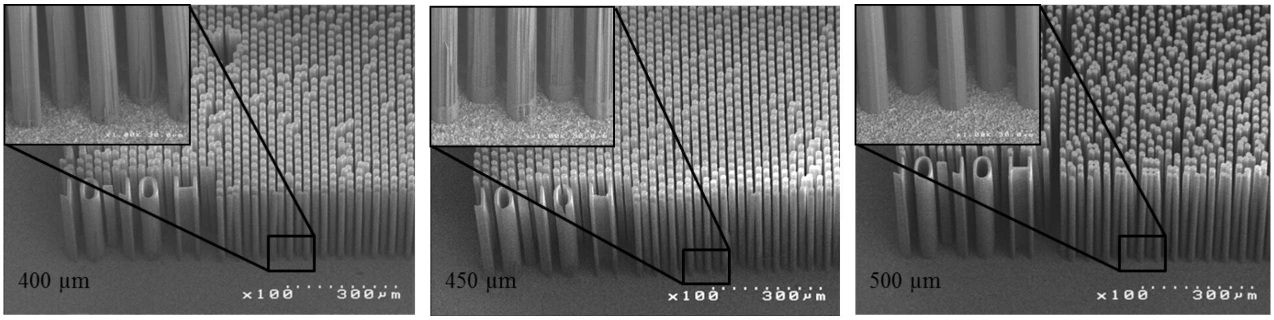


Figure 7: 10µm PMMA posts in 400 µm (left), 450µm (center), and 500µm (right) height using the aperture exposure setting.

Conclusion

We demonstrated the fabrication of a multi-level mold insert template with complex and challenging high aspect ratio microstructures using a process combination of micromilling and x-ray lithography. Good results have been achieved with electroplated copper substrates with an oxide layer where mechanical anchoring in the rough surface supports good adhesion and permits to some degree overdeveloping in areas with thinner resist pattern. The range of aspect ratios is limited to about a factor of 3. Highest aspect ratios of about 50 for 10µm posts could be routinely fabricated.

Acknowledgements

We would like to thank State of Louisiana for the partial funding of this project. Also, we would like to thank CAMD staff for their support and help. Further, we would like to thanks Dawit Yemane for his help in some of the X-ray lithography experiments, Jason Guy in micromilling of the Cu and PMMA samples.

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