

# Study on the postbaking process and the effects on UV lithography of high aspect ratio SU-8 microstructures

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**Abstract.** In recent years, a relatively new type of negative photoresist, EPON SU-8, has received a lot of attention in the MEMS field because of its excellent lithography properties. Significant research efforts have been made to study the lithographic properties of SU-8 to obtain high aspect ratio microstructures with good sidewall quality. Currently, selection of optimal wavelengths of the UV light for lithographic and reduction of the diffraction effects are believed to be the two most important factors for achieving high-quality lithography of SU-8 as reported in the literature. Other reported efforts also include modifications of the chemical properties of SU-8 for better lithographic quality. We report a study on stress reduction during the postbaking process and the effects on lithography of ultra-thick high aspect ratio SU-8 microstructures. Our research proves that aspect ratios up to 40:1 in isolated open field structures of thicknesses between 1 and 1.5  $\mu\text{m}$  can be obtained without any modifications of the resist chemistry or changes in light spectrum applied from a standard broadband UV source. The principal factor in this achievement is the reduction of internal stress during the postexposure bake process that eliminates large plastic deformations present during standard bake procedures. This process may be used for the fabrication of ultra-thick high aspect ratio microstructures that have to date only been obtainable using x-ray lithography-based LIGA processes. © 2004 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.1792650]

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## 1 Introduction

In the past few years, SU-8 has received a lot of attention in the MEMS field and is quickly becoming the preferred resist for high aspect ratio micromachining. Although the process required to produce SU-8 structures remains challenging, it can be used to expose 20 to 1500  $\mu\text{m}$  deep with aspect ratios greater than 10:1 using either optical<sup>1</sup> or deep x-ray<sup>2,3</sup> lithography. Until recently, SU-8's major competitor for optical lithography was AZ 4562. The AZ resist can be coated using multiple spins to produce structures more than 100  $\mu\text{m}$  thick.<sup>4</sup> Within the past year, structures as thick as 1.4  $\mu\text{m}$  have been lithographed with JSR THB-430N, but the aspect ratios are at about 5:1 and have relatively poor sidewall quality.<sup>5</sup> In comparison, microstructures with higher aspect ratios can be easily achieved using a UV lithograph of SU-8. Recent publications show the ability to expose 1-mm-tall isolated SU-8 structures with aspect ratios exceeding 10:1<sup>4,6</sup> and 1.5-mm structures with 15:1 aspect ratios.<sup>7</sup>

The aspect ratio and sidewall quality of microstructures obtained using UV lithography of SU-8 have been limited by many factors, as reported by many researchers. The reported results are often difficult to duplicate because the properties of the resist have made consistent processing a challenge for research labs. The published research results

suggest that there are two major factors that limited the aspect ratio and sidewall quality in UV lithograph of SU-8: 1. use of light source with suitable wavelengths; and 2. significant diffraction problems due to low uniformity caused by the difficulty in spin-coating uniform and thick resist on a substrate.

Exposing the resist with the proper light spectrum is one of the key requirements to achieve the best lithography results of SU-8.<sup>8,9</sup> The UV absorption of SU-8 resist is dominated by that of the photoinitiator content added in the SU-8. SU-8 resist has a very high absorption rate for wavelengths less than 350 nm. Shorter wavelengths tend to be absorbed at the surface of the resist, while the longer wavelengths have a much lower absorption rate, and therefore tend to be able to penetrate deeper and can be used for exposure of thick resist. Therefore if the light source used for the exposure has a wide spectrum, high frequency components will mainly be absorbed at the surface layer of the resist and only the lower frequency (longer wavelength) components of the light source will be able to penetrate to deeper and lower bottom parts of the resist. This overexposure at the surface layer by high-frequency UV light produces a skin effect on the resist, a layer of highly cross-linked polymer with a thickness ranging from two to a few tens of microns. This effect greatly distorts the pattern near

the surface and yields low-quality microstructures. Optical filters are therefore often used to eliminate unwanted wavelengths and to overcome the skin effect in SU-8 structures.<sup>8,9</sup> Dentinger et al.<sup>8</sup> has recently shown that complex patterned structures with high aspect ratios up to 700  $\mu\text{m}$  thick can be achieved by using a combined approach of optical filters for wavelength selection and modification of chemical properties of SU-8.

The second most important factor for the lithography of thick SU-8 resist is the diffraction effect, just as in any other optical lithograph process. This problem is much worse in comparison to optical lithography of AZ in the IC industry because of the increased resist thickness and non-uniformity of the prebaked resist. Direct casts of the resist<sup>7,10</sup> are currently required to obtain layers greater than 1 mm on a substrate. The second challenge is to overcome the residual stress in baked SU-8 films. Often, thick layers of SU-8 retain so much residual stress under the suggested bake parameters<sup>11</sup> that large exposed resist fields either debond from the substrate, bow, or even lead to cracks in silicon substrates after exposure.<sup>12,13</sup> Most thick SU-8 films have 5 to 10% error in the resist thickness across a 4-in. substrate due to extended contact with a nonlevel surface prior to exposure. The error in resist thickness causes gaps between the masks and the substrate during exposure, which are arguably present in almost all the thick SU-8 lithography results presented to date. In a recent work, Chuang, Tseng, and Lin<sup>14</sup> filled these gaps with glycerin during the exposure. Glycerin has nearly the same refractive index as SU-8. Their results showed a significant drop in diffraction during the exposure. Structures produced using glycerin showed significant improvement in the pattern quality of 100- $\mu\text{m}$  SU-8 exposures.

In published research results, very limited study is to be focused on the postbaking conditions and its effects on the lithography of very thick resist. Typical SU-8 procedures call for the resist to be cooled rapidly from 96 to 65 °C, held for a few minutes, and then removed from the heat source and cooled to room temperature.<sup>7,12</sup> This procedure does not fully remove the internal stress built up in thick resist films. To reduce the stress observed in thin SU-8 films under 100  $\mu\text{m}$  in height, Chang and Kim<sup>12</sup> suggested decreasing the temperature at a constant rate from 96 °C to room temperature. However, no study focused on the residual stress effects of the temperature reduction during postbaking, and optimization of the temperature reduction process has been reported in open literature.

We report a study on the stress reduction during the postbaking process and the effects on lithography of ultra-thick high aspect ratio SU-8 microstructures. It is well known that internal stress is always induced in the SU-8 layer during the resist baking processes, and it affects the overall pattern quality of the structures. However, the significance of this effect has not been well appreciated or carefully studied. The experiments described in this work were designed to study this important issue. A complete discussion of resist coating, baking, and exposure parameters is presented. The related residual stress reductions and effects on lithography quality during the bake cycle are examined in detail. We show how to obtain high aspect ratio structures through optimization of the bake process and exposure dose. The process described uses standard

Micro-Chem SU-8 100 with no additional additives. Attempts were made to follow the protocol of traditional optical lithographic processing, with as minimal human involvement as possible, in application of the resist. In addition, a multilayer spin-coating process was also developed to coat uniform SU-8 resist for a thickness up to 1.5 mm. Our research proved that aspect ratios up to 40:1 in isolated open field structures of thicknesses between 1 and 1.5 mm can be obtained without any modifications of the resist chemistry or changes in light spectrum applied from a standard broadband UV source.

## 2 Experiments

SU-8 has good adhesion to silicon, SiO<sub>2</sub> and aluminum, Al<sub>2</sub>O<sub>3</sub>, and gold films<sup>15</sup> and poor adhesion to most commonly used metals such as copper, titanium, nickel, or iron. This limitation has often been overcome by patterning the metal layer, or by increasing the surface roughness so that the substrate has a better mechanical hold on the resist. In our experiment, a 1-mm-thick 4-in. diameter machineable alumina substrate was used to develop this process. This substrate was chosen for two reasons: mechanical strength and surface roughness. The substrate shows excellent mechanical strength, and no significant deflection of the substrate was observed due to residual stress in the SU-8 film during process development.

### 2.1 Multiple Spin-Coat Process to Prepare Thick SU-8 Resists

The experiments were performed using MicroChem SU-8 100 with no chemical modifications. To obtain 1100  $\mu\text{m}$  of SU-8 on the substrate, 10 ml of SU-8 was applied to the center of the substrate and spun at 400 rpm for 25 sec. SU-8 layers thicker than 1200  $\mu\text{m}$  were obtained using two spin coats. To obtain a 1500- $\mu\text{m}$ -thick SU-8 film, a second layer of SU-8 100 was spun on a prebaked 1100- $\mu\text{m}$ -thick film. The second spin coat required 6 ml of SU-8 100 at 400 rpm on top of previously baked film. The resist was spun for 25 sec and care was taken to remove any excess resist from the edge of the substrate.

To maintain uniform resist thickness, the substrate had to remain on a level surface until after exposure. Pre-exposure baking on a surface with a slope of only 1 deg can cause significant error in the uniformity of the resist, and in extreme cases leads to overflow of the resist off of the substrate.

### 2.2 Prebake

All samples were prebaked in a temperature-controlled oven. The oven was ramped from room temperature to 96 °C over a 30-min time interval, and held for a specific period of time depending on the thickness of the resist. Our experiments show that each additional 100  $\mu\text{m}$  of resist thickness of SU-8 requires an additional 50 min of baking time at 96 °C. At the end of the bake process, the resist was cooled at a constant ramp rate. If necessary, additional spin coats were applied to achieve the desired resist thickness.

Multiple coatings required extended prebaking time for each additional layer. For example, two layers of resist were spin coated to obtain a 1500- $\mu\text{m}$ -thick resist as shown in our experiments. The second bake time was extended to

**Table 1** Optimum applied dose conditions for test structures.

Structure	Resist thickness ( $\mu\text{m}$ )	Optimum dose ( $\text{mJ}/\text{cm}^2$ )	Aspect ratio
Cross	1150/1500	3000/7000	45/40
Cylinders ( $l_d < 250 \mu\text{m}$ )	1100	2000	>24
Square cylinder	1100	2000	28
Round hole	1100	2000	<10
Line	1150/1500	3000/7000	18

13 h at  $96^\circ\text{C}$ , even though the second layer was only several hundreds of micrometers thick. The substrates were then cooled at a constant rate for 8 h to room temperature.

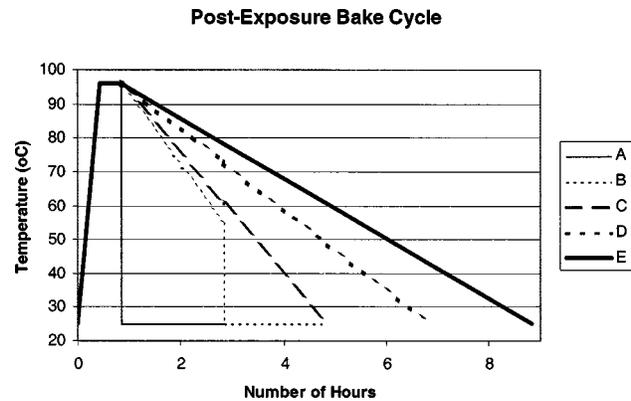
After evaluating several different temperature reduction schemes, it was found that the reduction of temperature at slow rates after the PB process does not significantly contribute to the overall pattern quality in open field exposures. The data suggest instead that a prebaked substrate can be removed from the hotplate or oven and cooled quickly to room temperature. To reduce pattern distortion using this process, we suggest a pre-exposure bake of 10 h, followed by a short relaxation period.

### 2.3 Exposure

The resist was exposed using a Quintel UL7000-OBS aligner with a 1000-W Hg lamp. No additional filters were used to optimize it for SU-8 exposures. The presence of a low but measurable power density from wavelengths below 350 nm. This resulted in some minor skin effects on the surfaces of the samples as expected. Test exposures were completed at various applied doses. The dose required to expose different patterns in the resist on the same substrate was significantly different. Open field structures such as crosses and squares required significantly higher dosages than close field holes in the resist. Similarly, cylindrical structures required different exposure times and longer development times than standard open field structures due to partial exposure by diffracting light from nearby mask patterns. The exposure doses provided were optimized to within  $100 \text{ mJ}/\text{cm}^2$ . Our experiments showed that variations of exposure dose by  $300 \text{ mJ}/\text{cm}^2$  from the correct dosage could result in significant reduction of pattern quality. Table 1 shows the different dosages used for a few commonly used feature types in resists of 1 to 1.2 mm and 1500 mm. Aspect ratios for these features are also presented.

### 2.4 Postbake

Experiments were designed and conducted to evaluate and optimize the temperature cooling conditions required after postexposure bake (PEB) processes. Figure 1 shows details of the temperature reduction rates evaluated. All of the samples were ramped from room temperature to  $96^\circ\text{C}$  over a 30-min period and baked for 25 min prior to cooling. For condition A, the substrate was removed from the oven at  $96^\circ\text{C}$  and cooled to room temperature using a cold plate. The substrate was then placed on a level surface and allowed to relax from internal stress for 2 h prior to exposure. Condition B required cooling the substrate to  $50^\circ\text{C}$  at a

**Fig. 1** Experimental procedure for ramp conditions after baking.

constant rate of  $23^\circ\text{C}/\text{h}$ . The substrate was then removed from the oven, cooled to room temperature on a cold plate, and allowed to relax for 2 h. Samples using conditions C, D, and E were cooled at a constant rate to room temperature at the rate of 17.5, 11.8, and  $8.8^\circ\text{C}/\text{h}$ , respectively.

Reduction in the cooling rate showed significant improvement in the overall quality of the printed resist pattern. Experimental bias due to increased bake times associated with slow cooling rates was compared to samples with longer bake times and ramp cycles. The data showed that there was no significant bias of the experimental results due to the increased bake time required for slow cooling of the resist.

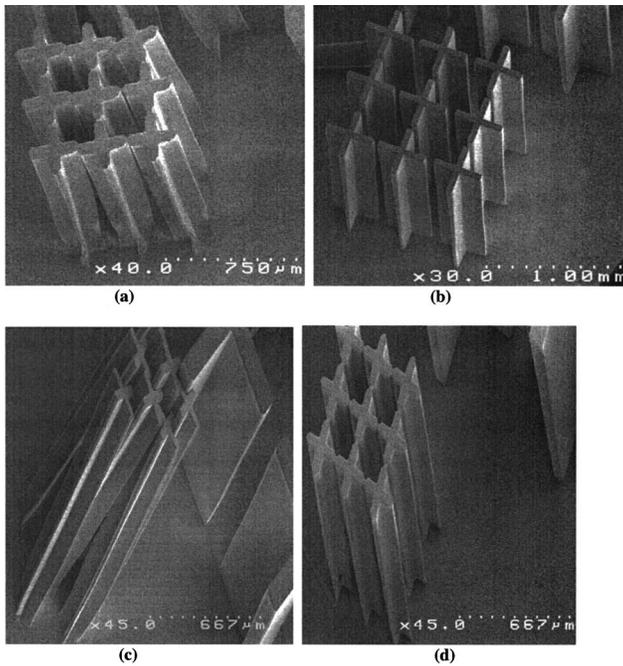
### 2.5 Development

All samples were developed in SU-8 developer for 12 h with no agitation. Substrates were rinsed using isopropyl alcohol and dried in an oven at  $40^\circ\text{C}$  for 5 min. Development without mechanical oscillation aids allows us to obtain high aspect ratio structures that might normally be deformed or debonded during development. Our experiments show that sonic development can be used to further improve the development rate while maintaining as little mechanical motion in the fluid as possible. Ultrasonic development often leads to debonding large exposed regions and destruction of smaller structures. However, higher frequency oscillation such as megasonic development oscillates the fluid at an acceptable frequency, yielding high aspect ratio structures and large exposed regions without fracture and debonding.<sup>16,17</sup>

## 3 Experimental Results and Discussions

For experimental purposes, a test mask was made with several common shapes such as crosses, line spaces, hollow cylinders, hexagons, posts, and closed field holes. Multiple exposures were performed on each substrate, with one dose often repeated on other substrates to reduce the probability of erroneous data. The data presented was observed for the same dose on at least two different substrates for process verification.

Figure 2 shows four SEM images of some typical microstructures obtained with a UV lithograph of a 1-mm-thick SU-8 layer under four different cooling conditions.



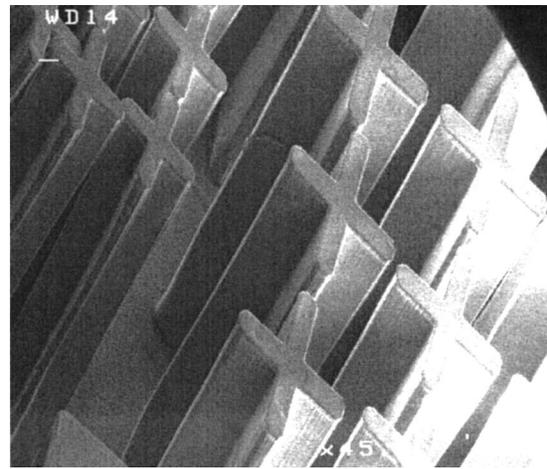
**Fig. 2** SEM images of 1-mm-tall microstructures obtained using the cooling conditions as presented in Fig. 1. The same prebaking, exposure dosage, and development conditions were used except the postbaking conditions. Crosses in (a) and (b) are  $35\ \mu\text{m}$  in width. The small crosses in (c) are  $25\ \mu\text{m}$  wide. The crosses in (d) are  $35$  and  $25\ \mu\text{m}$  in width and  $1200\ \mu\text{m}$  tall. (a) Cooled in minutes using a cold plate. (b) Cooled to  $25\ ^\circ\text{C}$  over 4-h period. (c) Cooled to  $25\ ^\circ\text{C}$  over 6-h period. (d) Cooled to  $25\ ^\circ\text{C}$  over 8-h period.

The same prebaking, exposure dose, and development conditions were used except the postbake cooling rate.

Figure 2(a) shows a SEM image for structures cooled using a cold plate. Significant deformations of structures and low sidewall quality can be observed. This is mainly caused by the significant difference between the thermal expansion coefficients of exposed SU-8 and the ceramic substrate. The residual stress concentrations cause large plastic deformations of the microstructures and sometimes debonding of fine features from the substrate. The smallest obtainable cross patterns,  $35\ \mu\text{m}$  wide, were twisted and distorted near their bases.

Figure 2(b) shows the same group of microstructures obtained using a constant cooling rate over a 4-h period immediately following exposure. The quality of microstructures was improved significantly. However, there were still structural deformations caused by residual shear stress. In addition, the finest features in the design were all debonded from the substrate as in the case of using a cold plate. The smallest obtainable cross pattern was  $35\ \mu\text{m}$  wide.

Figure 2(c) shows results obtained using a constant cooling rate over 6 h. These  $25\text{-}\mu\text{m}$ -wide microstructures represent the finest cross patterns remaining on the substrate after development. However, they were twisted and debonded from the surface due to the residual stress caused by mismatch in the rate of thermal contraction between the substrate and the resist. Larger patterns remained very similar to those produced using a 4-h cooling cycle.

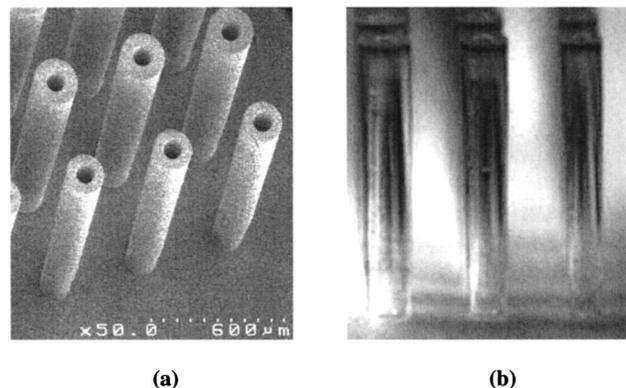


**Fig. 3**  $1500\text{-}\mu\text{m}$ -tall field of crosses. Small crosses on the right have width of  $35\ \mu\text{m}$  at the top of the structure. The recorded aspect ratio is greater than 42:1.

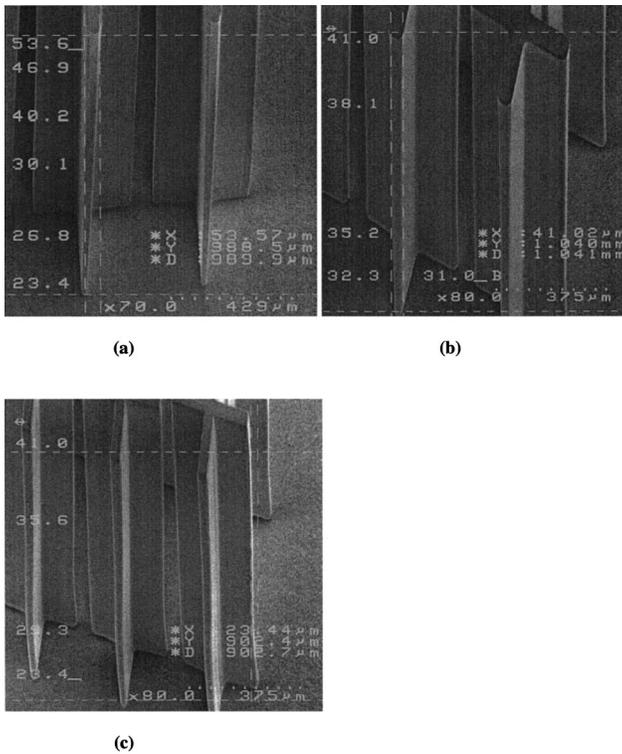
Figure 2(d) shows an image of the same group of  $25\text{-}\mu\text{m}$ -wide microstructures obtained using a cooling rate of  $8\ \text{h}$ . The structures in this particular image are  $1200\ \mu\text{m}$  tall. No debonding or significant deformation was observed. From these results, it can be seen that the really fine features with the highest aspect ratios are very sensitive to postbaking conditions and the resulting residual stress. As the feature sizes increase and aspect ratios reduce, the final results become less sensitive to variations of cooling rates.

No significant improvement in sidewall quality was observed, for  $1100\ \mu\text{m}$  thick SU-8 structure when cooling rates lower than  $8.5\ ^\circ\text{C}/\text{h}$  were used.

Figures 3 and 4 show SEM pictures of some microstructures fabricated using optimal postexposure processing. Figure 3 shows a set of open field crosses of SU-8  $1500\ \mu\text{m}$  tall produced by a single exposure. The optimal dosage for this structure was found to be  $7000\ \text{mJ}/\text{cm}^2$ . Figure 4 shows  $1150\text{-}\mu\text{m}$ -tall cylinders developed through to the substrate. The inner diameter of the smaller cylinders was less than  $85\ \mu\text{m}$  at the top and approximately  $100\ \mu\text{m}$  at the base. The observed aspect ratio based on measurements



**Fig. 4**  $1150\text{-}\mu\text{m}$ -tall cylinders. (a) SEM of cylinder walls. (b) Optical image showing complete development. Cylinders from left to right in (b) correspond to cylinders from top to bottom in (a).



**Fig. 5** Identical structures produced under different exposure conditions. (a) Structures made with broadband exposure; (b) structures made using broadband with glycerin for diffraction reduction; (c) structures made using I-line UV light source (filtered light, no glycerin used).

from the top of the pattern is approximately 24:1. The exposure doses required were  $2000 \text{ mJ/cm}^2$  for the cylinder and holes.

From the SEM images of these microstructures, significant distortions at corners and sidewall profiles can still be observed. Variations in thicknesses of the structures are also notable. These distortions are mainly caused by diffraction effect due to weak contact between the mask and substrate, and the shorter wavelength components (below  $365 \text{ nm}$ ) in the light source used in the lithographic processes.

To further study the effects of using glycerin for diffraction reduction and as a filtered light source, experiments were conducted using a filtered light source with an I-line filter and glycerin, respectively. In both cases, the same postbake cooling conditions were used ( $8.5^\circ\text{C/h}$ ). Figure 5(a) shows the SEM image of a group of microstructures fabricated using a broadband light source. Figure 5(b) shows a SEM image of the same cross structures made using glycerin coating between the mask and resist layer, and Fig. 5(c) shows a SEM image of the same cross patterns made using a filtered light source (I-line filter). The designed thickness of the cross is  $40 \mu\text{m}$ . The thickness of the structures in Fig. 5(a) shows the largest error from  $53.6$  to  $23.4 \mu\text{m}$ . The thickness of the structures in Fig. 5(b) varies from  $41 \mu\text{m}$  at the surface to  $32.3 \mu\text{m}$  at the bottom. The thickness of the structures shown in Fig. 5(c) changed from  $41 \mu\text{m}$  at the surface to  $23.4 \mu\text{m}$  at the bottom. Several observations can be made from these results: 1. using a filtered light source mainly contributes to improvement in

the surface layer; 2. using glycerin to reduce the diffraction seems to improve the precision in sidewall thickness significantly; 3. further improvement in lithography quality can be made by using a combined approach with a filtered light source, glycerin for diffraction reduction, and optimal postbake cooling conditions, as suggested by this reported study.

## 4 Conclusions

The experimental results reported in this work show that the aspect ratio and sidewall quality of microstructures obtainable in an SU-8 photolithography process are closely related to the cooling rate after postexposure bake. This is mainly due to the internal stresses induced in exposed microstructures during the cooling process. To produce fine feature sizes with high aspect ratios, the cooling rate during the postbake process has to be controlled carefully to allow for proper stress reduction. Our experiments show that patterns more than  $1000 \mu\text{m}$  tall with aspect ratios exceeding 40:1 and can be obtained by effectively reducing the residual stress with extended cooling time. Although cooling at slower rates may indeed allow for further reduction in residual stress, our experiments show that a plateau is eventually reached at roughly  $8.5^\circ\text{C/h}$ , and further reduction of the cooling rate seems to no longer affect the structure quality. The results also show that the best results can be obtained by using an optimal lithograph process that includes a filtered light source, glycerin for diffraction reduction, and an optimal cooling rate during the postexposure bake procedure. This process may be used for the fabrication of ultra-thick high aspect ratio microstructures that have to date only been obtainable using x-ray lithography-based LIGA processes.

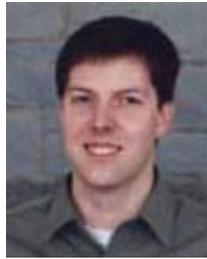
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