Microlens formation using heavily dyed photoresist in a single step

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ABSTRACT

The work described here produced a new method of forming microlenses which requires fewer processing steps, eliminates the need for reflow or photoresist etching steps, and can be used with an inexpensive mask to form arrays. In this new method, a strongly absorbing dye is added in high percentage to a normal positive i-line photoresist. This photoresist is then processed at a much higher exposure dose than the normal photoresist. This paper describes simulated microlens structures as predicted by PROLITH as well as actual lens structures that were produced with the new method. This newly developed method is designed to enable the formation of microlenses at significant cost savings and with increased process control.

Keywords: microlens, photoresist, array, reflow, dye

1. INTRODUCTION

In an imaging sensor device, the optical-to-electrical conversion area is smaller than the pixel size. By using a microlens above each photodetector, it is possible to collect light from an area larger than the area of the detector. This design increases the signal-to-noise ratio, reduces crosstalk, and thus improves the overall sensitivity of the device.

As the spatial resolution of image sensors becomes ever higher, materials having higher refractive indexes are needed to form the microlens. The focal length of a microlens needs to be relatively short, on the order of a few microns. This requirement calls for a microlens having a certain curvature and thickness. The curvature and thickness will cause aberrations, especially off axis, which degrade the image. High refractive index materials reduce the required curvature and thickness and thus improve image quality.

Typically microlenses are made in one of three ways. One current patent suggests exposing positive i-line photoresist to form structures that form round pillars. Subsequently the exposed pillar-shaped resist feature is heated at exactly the right temperature for the exact time needed to reflow the resist to form a convex lens shape (Fig. 1). This method is not preferred because of the imposed tight controls of baking temperature and time, the two-stage process needed to form the microlens, and image spreading. Reproducibility could also be affected where lens arrays are concerned.

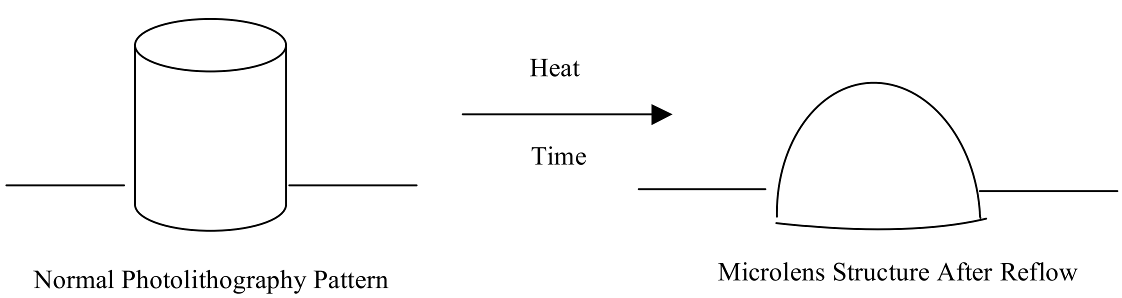


Figure 1. Method for forming microlens structure using polymer reflow techniques.

Another method that is currently used is to perform defocused exposures in negative photoresist to cause the photoresist profile to resemble a silo shape. This silo-shaped photoresist profile is then subjected to reactive ion etching (RIE), which shrinks the photoresist in height to form a microlens structure (Fig. 2). This method is not preferred because it requires an additional etch step, the etch time must be controlled very tightly, and focus requirements are very stringent.

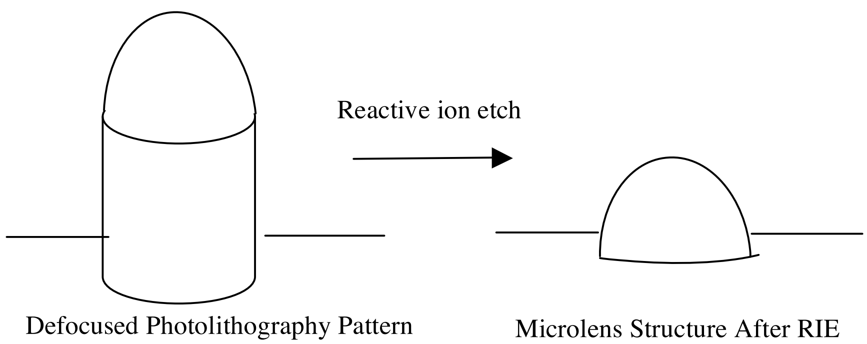


Figure 2. Method for forming microlens structure using RIE techniques.

A third method used to produce microlens structures is by the use of gray-scale photomasks. However, the expense of the photomask may be cost prohibitive and arrays are difficult to achieve.

In the new method described here, a strongly absorbing dye is added in high percentage to a normal positive i-line photoresist. This photoresist is then processed at a much higher exposure dose than the normal photoresist. The resultant photoresist pattern is in the shape of a microlens. This method is preferred because it requires only one step; no reflow step or etch step is needed to form the microlens structure. Also an inexpensive binary, square, pixilated mask can be used to form microlens arrays.

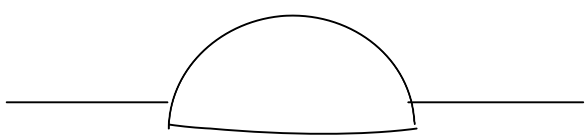


Figure 3. Method for forming microlens structure after a single photolithography step.

In addition to describing the method, we will show simulated microlens structures as predicted by PROLITH modeling as well as actual lens structures that were produced using this new method.

2. METHODOLOGY

2.1. PROLITH simulations

2.1.1. Typical i-line photoresist modeling setup

A model film stack was set up using silicon as a substrate and a typical i-line photoresist as the model photoresist. Modeling parameters were as follows:

Substrate: silicon

Photoresist Type: i-line

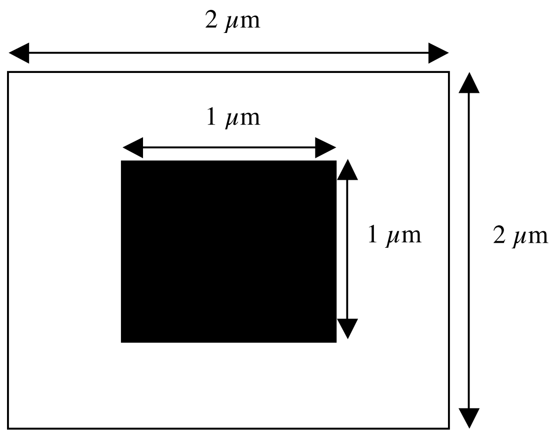
Photoresist Thickness: 800 nm

Photoresist Optical Parameters: refractive index n = 1.724 and imaginary refractive index k = 0.034274. Imaginary refractive index k can be converted to optical density (OD) by the following equation: $OD = (4 \times \pi \times k)/(\ln 10 \times \lambda)$ where λ = the wavelength of light in µm.

Photoresist OD: 0.51/µm

Photomask Design: square island 1 µm wide by 1 µm long.

Photomask Drawing:



Photoresist Post-Application Bake: 90°C for 60 seconds

Exposure Energy: 200 mJ

Exposure Focus: 0.0 µm offset

Exposure Wavelength: 365 nm

Post-Exposure Bake: 110°C for 90 seconds

Photoresist Development: PD523AD (0.26N TMAH in water) for 60 seconds at 23.0°C

2.1.2. Heavily dyed i-line photo resist Prolith set up

A second model film stack was set up using silicon as a substrate with a modified i-line photoresist that would mimic a very heavily dyed photoresist as the model photoresist. The model set up is as follows:

Substrate: silicon

Photoresist Type: very heavily dyed resist

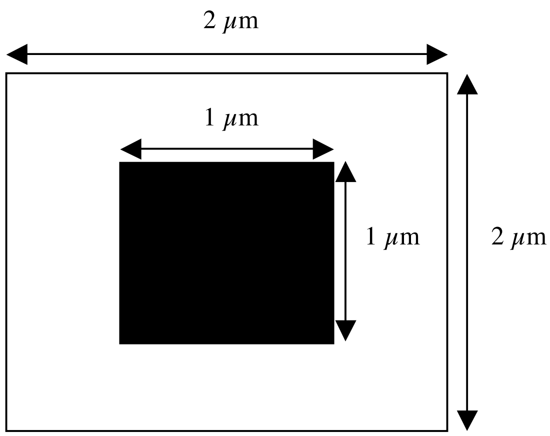
Photoresist Thickness: 500 nm

Photoresist Optical Parameters: refractive index n = 1.74 and imaginary refractive index k = 0.2336

Photoresist OD: 3.49/µm

Photomask Design: square island 1 µm wide by 1 µm long.

Photomask Drawing:



Photoresist Post-Application Bake: 90°C for 60 seconds

Exposure Energy: 2000 mJ

Exposure Focus: 0.5µm offset

Exposure Wavelength: 365 nm

Post-Exposure Bake: 110°C for 90 seconds

Photoresist Development: PD523AD (0.26N TMAH in water) for 60 seconds at 23.0°C

2.2. Formulating a heavily dyed resist
A commercially available i-line photoresist was measured for percent solids using a percent solids analyzer. The resist was determined to have 22.15% solids. A solution was prepared by combining 30.00 grams i-line photoresist, 1.99 grams CC2484-70-1 dye, and 30.35g ethyl lactate.

The physical properties of the dye are as follows: λ_{max} = 381 nm; Molar extinction coefficient ($MEC_{365)}$) = 22,100; soluble in 0.26N $TMAH/H_2O$, propylene glycol monomethyl ether (PGME), and ethyl lactate (EL).

2.2.1. Wafer coating
For this experiment, the films of the dyed and undyed photoresists were spin cast onto 4-inch silicon wafers previously coated with EXP04054, a proprietary high refractive index material from Brewer Science, Inc., to yield films with thicknesses of 550 nm and 650 nm and optical densities of 2.30/µm and 0.39/µm, respectively. The following conditions were used to apply the photoresists:

	Dyed	Undyed
Spin Speed:	1000 rpm	5000 rpm
Acceleration:	10,000 rpm/s	10,000 rpm/s
Spin Time:	60 seconds	60 seconds

The resist-coated wafers were then baked on a hot plate at 100°C for 60 seconds.

2.2.2. Exposure, post-exposure bake, and development
The wafers coated in step 2.2.1. were photo-patterned using an i-line stepper with pixel arrays in 5 x 5, focus-exposure matrices. Focus ranged from –1 to +1 µm for both resists, and exposure doses ranged from 1000 to 3000 mJ for the dyed resist and 154 to 242 mJ for the undyed resist. Both exposed films were then baked on a hot plate at 112°C for

60 seconds. The undyed resist was then developed by immersion in 2.38% TMAH/H_2O surfactaded developer for 20 seconds, spray rinsed in deionized (DI) water, and spin dried. The dyed resist sample was developed in the same manner, with the exception of the developer being diluted 1:1 with DI water and the develop time extended to 60 seconds. The two samples were then examined by confocal and scanning electron microscopy.

3. RESULTS

3.1. PROLITH simulation results

3.1.1. Normal photoresist profile as predicted by PROLITH simulations

In Figure 4, a normal, undyed photoresist profile as predicted by PROLITH is shown. This photoresist profile was modeled using an exposure dose of 200 mj with a focus offset of 0.0 µm.

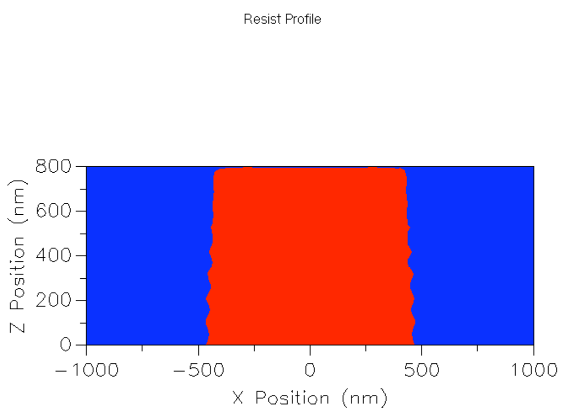


Figure 4. A normal i-line photoresist pattern as predicted by PROLITH.

3.1.2. Heavily dyed photoresist profile as predicted by PROLITH simulations

In Figure 5, a heavily dyed photoresist profile as predicted by PROLITH is shown. This photoresist profile was modeled using an exposure dose of 2000 mj with a focus offset of -0.5 µm. Instead of a straight photoresist profile similar to that shown in Figure 4, we see a profile that resembles the shape of a convex lens.

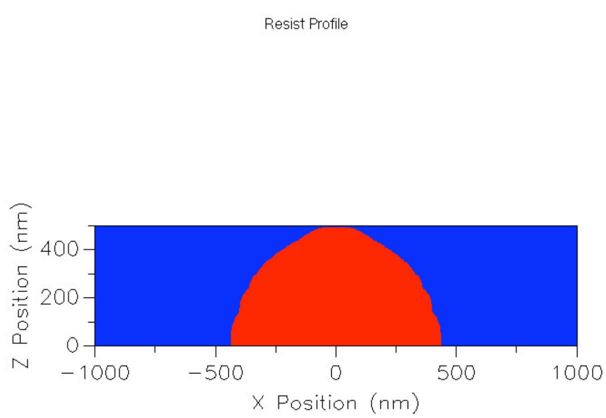


Figure 5. A heavily dyed i-line photoresist pattern as predicted by PROLITH.

3.2. Lithographic patterning results

3.2.1. Normal i-line photoresist results

Figure 6 shows the profile of a normal i-line photoresist coated over the Brewer Science high refractive index material on a silicon substrate. The photoresist profile shows straight sidewalls, which one would expect when processing normal photoresist. These straight sidewalls in the photoresist were also predicted from PROLITH modeling. The exposure dose to achieve these profiles was 242 mj. Focus offset is 0.0 µm. Target pixel size is 1 µm.

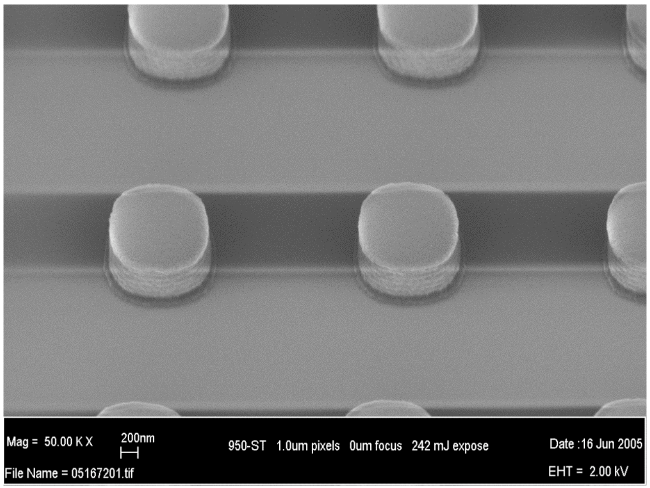


Figure 6. SEM photo of ~1-µm pixels using normal, undyed photoresist. Exposure dose: 242 mJ. Focus: 0.0 µm.

3.2.2. Heavily dyed i-line photoresist results

Figures 7, 8, and 9 show the photoresist profile, across focus, of a heavily dyed i-line photoresist coated over the Brewer Science high refractive index material on a silicon substrate. The photoresist profile shows a convex lens shape as predicted by PROLITH simulation. The exposure dose required to form the lens shape is 2500 mJ, which is very close to the 10X increase predicted by Prolith modeling. The lens size is ~ 1 µm.

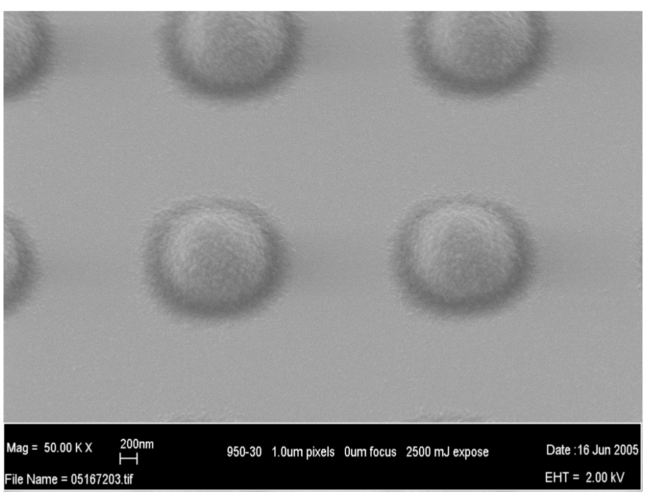


Figure 7. SEM photo of ~1-µm pixels using heavily dyed photoresist. Exposure dose: 2500 mJ. Focus: 0.0 µm.

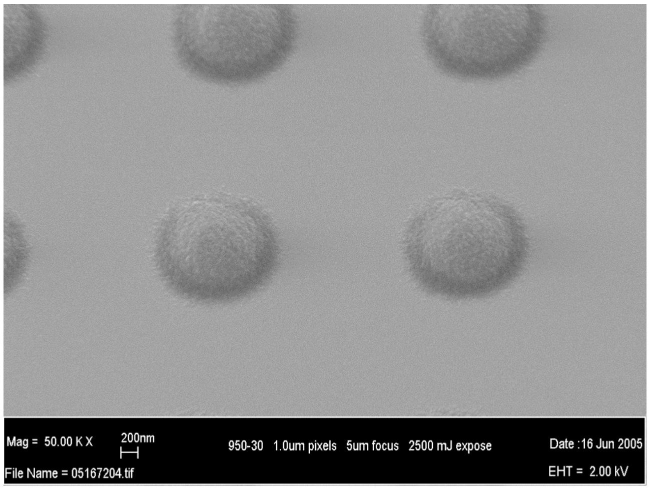


Figure 8. SEM photo of ~1-µm pixels using heavily dyed photoresist. Exposure dose: 2500 mJ. Focus: +0.5 µm.

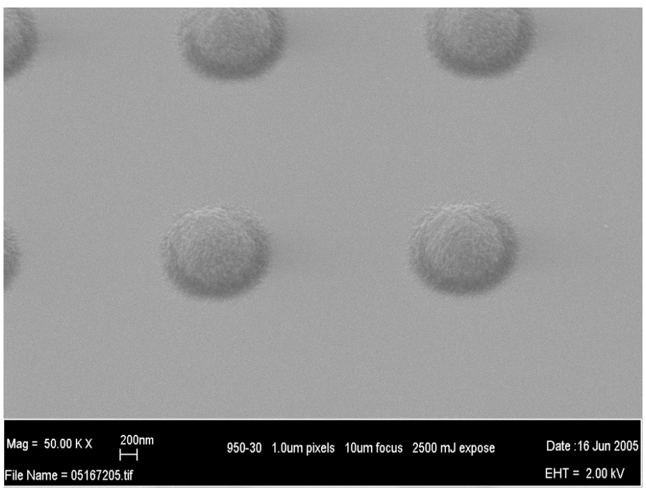


Figure 9. SEM photo of ~1-µm pixels using heavily dyed photoresist. Exposure dose: 2500 mJ. Focus: +1 µm.

4. CONCLUSION

While there is still a great deal of work remaining to obtain a manufacturing-friendly process (i.e., lower exposure energy, dense array formation, and etch integration), these initial results look promising. From the data presented within this paper it can be concluded that it is possible to form microlens structures using a heavily dyed photoresist with a conventional square pixilated mask. It can also be concluded that using PROLITH as a modeling tool provides a good approximation of real-world results. Furthermore, through PROLITH modeling, an optimum dye loading based on resist OD should be attainable. This optimum dye loading should still result in microlens resist structures, but with a lower exposure energy required to form them.

5. ACKNOWLEDGMENTS

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