Fabrication of Eight Level Micro-lenses

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Abstract—**As imaging and photonics technology is advancing to smaller and complex devices there is increasing interest in applications that make use of small micro-level optical elements such as micro-lenses. Micro-lens fabrication is useful in developing diffractive optical elements (DOE's) that are used in optical communication, optical storage, optical interconnection, optical information processing and micro-optical sensors. Another area where micro-lens fabrication can be used is in characterization and optimization of illuminating sources of lithographic projection systems. The objective of this project was to fabricate eight level micro-lenses on a 5"X5" quartz substrate designed for the 193nm exposing wavelength. A micro-lens is fabricated as a Fresnel Zone Target (FZT) pattern which can be used to characterize and optimize the illuminating source of a lithographic projection system. Developing a fabrication procedure for eight level micro-lenses will be helpful for further research work in manufacturing micro-optical elements at Rochester Institute of Technology's Semiconductor and Microsystems Fabrication Laboratory.**

Index Terms—**Diffractive Optical Elements, Fresnel Zone Target, Micro-lens, Reactive Ion Etching**

I. Introduction

Fabrication of micro-lenses is useful in developing diffractive optical elements which are commonly known as DOE's. DOE's have a varied scope of applications such as optical communication, optical storage, optical interconnection, optical information processing and micro-optical sensors. Another useful application of micro-lenses is the characterization and optimization of illuminating sources of lithographic projection systems. A micro-lens can be fabricated as a Fresnel Zone Target (FZT) that can be patterned on an image plane when it is exposed through an illuminating source. This high resolution pupil diagram can be studied and characterized to make adjustments to improve the illuminating source.

The MEBES e-beam writer was used to create all patterning on the quartz substrate. A layer of Aluminum was obtained using the CVC 601 sputterer to reduce charging on the non-conductive substrate. IP3600 resist was used as an e-beam resist and coated using a spinner with a quartz plate chuck. Plasma etching was performed on the DryTek Quad reactive ion etching tool using a CHF_3 plasma to etch quartz. The two metrology tools that were used for obtaining etch rate and profile topography measurement were Tencor P2 Profilometer and the WYKO phase measuring interferometer. The P2, a stylus profilometer, was used to monitor the etch depth on the etch rate monitors after each etch. Since stylus profilometery cannot be useful in determining the etch depth across features that are less than 1 micron wide, the WYKO phase measuring interferometer was used to obtain step height and 3-D profile of the micro-lenses. The etch depth data was compared between the P2 profilometer and the WYKO phase measuring interferometer.

II. Theory

A. Etch Methodology

A micro-lens was fabricated using a series of three subsequent plasma etch processes that approximated the curvature of a lens in a staircase type fashion with eight steps, called levels on the lens. The maximum etch depth in a substrate for a 2π phase shift is given by equation 1.

$$d_{\max} = \frac{\lambda}{n-1} \quad [1]$$

where, λ is the wavelength of exposure and n is the refractive index of the substrate.

However, in order to reach the maximum etch depth giving eight different steps, a three etch methodology was devised. Therefore, etch depth after each etch is given by equation 2.

$$d_M = \frac{\lambda}{2^M (n-1)} \quad [2]$$

where, M is the number of etch steps.

The progression of the fabrication sequence is presented in the following figures. Figure 1, Figure 2 and Figure 3 represent the first, second and third etch steps of $d_{max}/2$, $d_{max}/4$ and $d_{max}/8$ respectively.

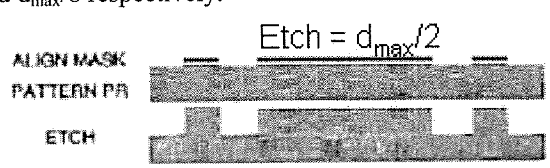

Fig. 1. Deepest etch first with an etch of $d_{max}/2$ giving a 2-step lens profile.

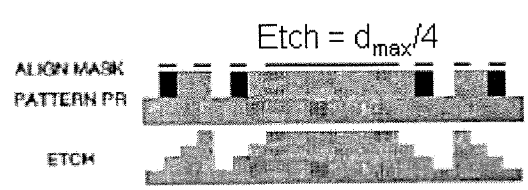

Fig. 2. Second etch of $d_{max}/4$ giving a 4-step lens profile.

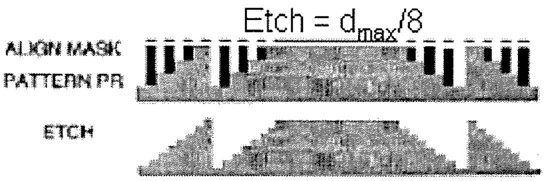

Fig. 3. Third and final etch of $d_{max}/8$ giving an 8-step lens profile.

B. *Fresnel Zone Target*

The curvature of a micro-lens can be approximated by considering the lens as a Fresnel Zone Target and calculating the radius of each Fresnel zone using equation 3.

$$\sqrt{r_k^{\,2} + f^2} - f = k\lambda / N \qquad [3]$$

where, r_k is the radii of kth fresnel zone designed for a lens of focal length f at N^{th} phase level.

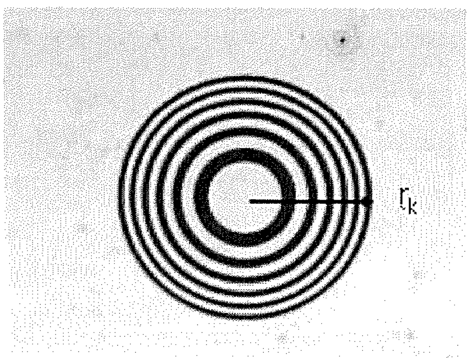

Fig. 4. Representation of the radius of Fresnel Zones as shown on the first fabricated level of the micro-lens process sequence.

C. *Mask Layout*

The layout for the micro-lenses was designed on AutoCAD. As shown in Figure 5, the mask contained an array of nine lenses which were designed for an exposure wavelength of 193 nm with focal lengths ranging from 4 mm to 40 mm and radius ranging from 250µm to 400µm. The minimum CD on the mask was designed as 0.78µm.

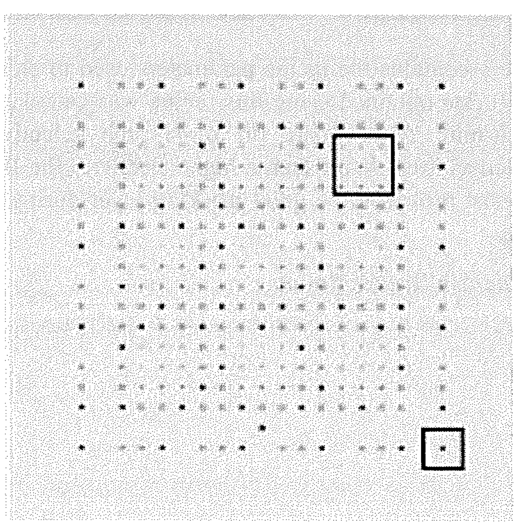

Fig. 5. Mask layout with a) periodic array of nine micro-lenses and b) etch rate monitors.

Etch rate monitors were periodically placed in groups of three, one etch rate monitor for each etch as an etch rate monitor is sacrificed after that particular etch. The etch rate monitor has 200 microns equal lines and spaces in order to perform stylus profilometry on it to measure etch depth. Figure 6 represents a microscopic view of the etch rate monitor.

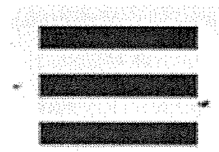

Fig. 6. Etch rate monitor.

Figures 7 through 9 represent the patterns used to perform plasma etch in respective order. Using equations 1 and 2, the target etch depths were calculated as 172nm, 86 nm and 43 nm for the 1st, 2nd and 3rd etch steps respectively.

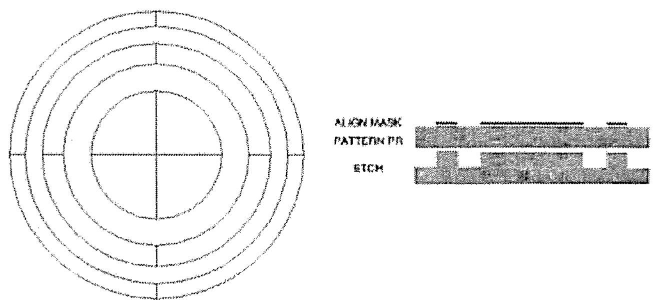

Fig. 7 Phase level 2 a) top down view of mask design b) cross-section view of etched profile.

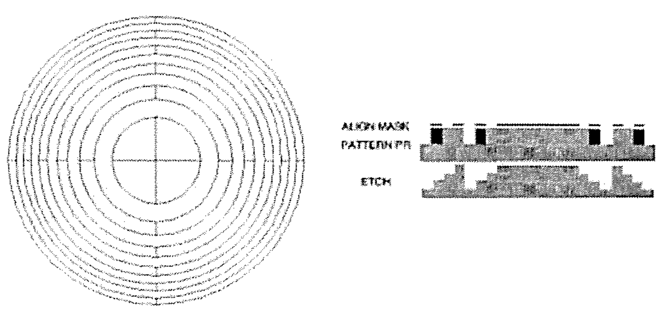

Fig. 8 Phase level 4 a) top down view of mask design b) cross-section view of etched profile.

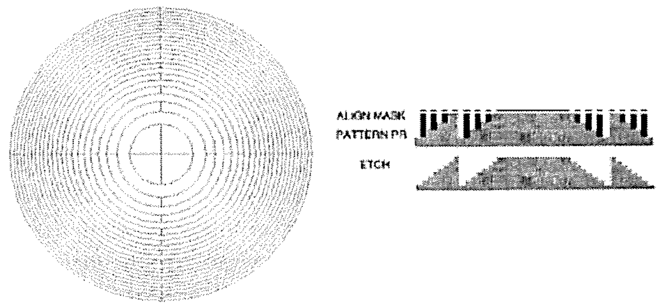

Fig. 9 Phase level 8 a) top down view of mask design b) cross-section view of etched profile.

III. Fabrication Procedure

Level 0 was the initial masking step, which provided windows (aperture) in the chrome-coated mask plate to provide the area where micro-lenses were to be fabricated. Resist was used for pattern development. Exposures were conducted on the MEBES1 (Manufacturing Electron Beam System).

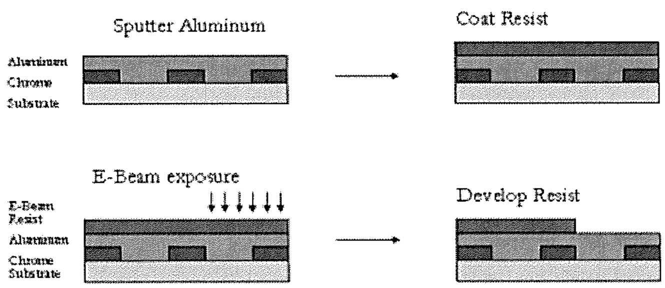

Fig. 10. Fabrication procedure diagram from sputtering aluminum to developing resist.

Following the initial chrome-etching step, the micro-lens fabrication sequence was performed on the windows of quartz. 100 Å of aluminum was sputtered on the substrate. This was followed by spin coating IP3600 e-beam resist. The resist thickness was calculated to be 2500 Å. The MEBES was then used to write the first level.

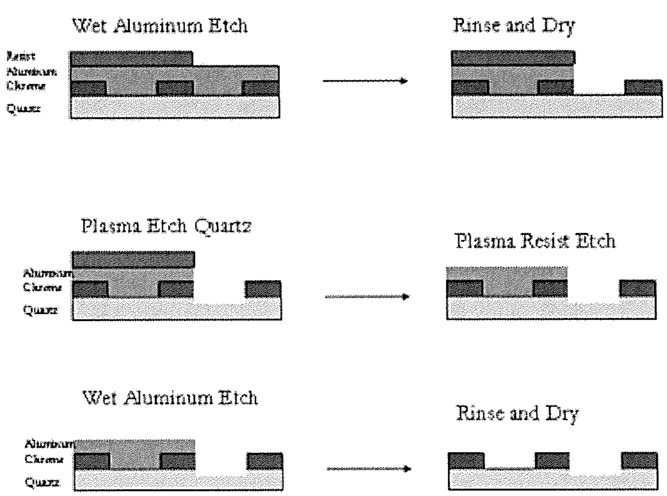

Fig. 11. Fabrication procedure diagram from wet aluminum etch to rinse and dry step.

After developing the quartz plate, a hard bake step was performed at 150°C for 5 minutes. A wet aluminum etch was performed by a 2 sec dip in Aluminum etch solution of 16 parts phosphoric acid, 1 part nitric acid, 1 part acetic acid and 1 part water. After a rinse and dry step the quartz plate was plasma etched. In order to reach the required etch depth, a series of short etches were performed so that no over etch occurs. The resist and aluminum were then stripped in respective etch processes. The quartz plate was rinsed and dried and sent for a level 1 pattern write.

This entire procedure was repeated for level 2 to make a four-level micro-lens and finally on level 3 to fabricate an eight-level micro-lenses.

IV. Results and Discussions

A. *Plasma Etch Results*

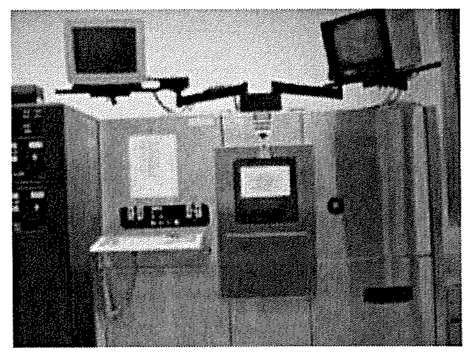

Fig. 12. DryTek Quad RIE etcher.

TABLE I
PLASMA ETCH RECIPE PARAMETERS

Parameter	Value
Power	400 W
CHF3 flow	100 sccms
Ar flow	50 sccms
O2 flow	5 sccms
Pressure	300 mTorr
Etch Rate	107.5 Å/min

Table 1 contains the recipe parameters used to etch quartz. The etch rate obtained using this recipe was calculated to be 107.5 A/min. Also, quartz to resist etch selectivity was calculated as 40:1. With such a high selectivity the IP3600 e-beam resist proved to be good masking layer during the etch process.

B. *Aluminum Sputter Results*

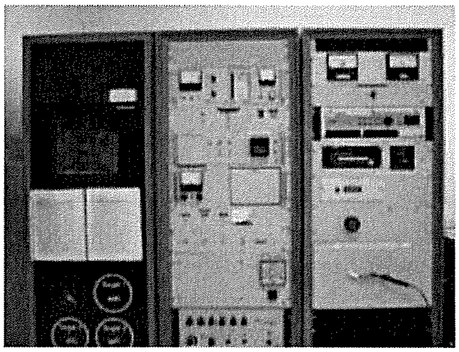

Fig. 13. CVC 601 sputterer.

TABLE II
ALUMINUM SPUTTER RECIPE PARAMETERS

Parameter	Value
Pre Sputter time	300 s
Base Pressure	5E-5 Torr
Sputter Gas	Argon
RF Power	2000 W
Pressure	5 mTorr
Deposition Rate	390 Å/min

Aluminum layer was required as a conductive layer on quartz in order to prevent charging effects during e-beam exposure. In absence of a conductive layer, during e-beam exposure there is enough charge build up on quartz which deviates the beam distorting the writing pattern.

C. Challenges at the Aluminum Etch Step

After level 0 patterning 1500 Å of aluminum was deposited on the quartz plate. A wet aluminum etch step was performed in Aluminum etch solution of 16 parts phosphoric acid, 1 part nitric acid, 1 part acetic acid and 1 part water. The etch rate of this solution at 50°C was calculated to be 2600 Å/min and hence a 36 sec etch was performed. After the etch, it was observed under a microscope that resist was cleared completely along with Aluminum. The possibility of lift off was boiled down to three causes. Firstly, absence of hard bake step, secondly, poor adhesion of resist to Aluminum and thirdly the measure of undercutting was higher than the CD's. An experiment was designed to determine if any of these factors have an effect on resist adhesion to aluminum. In this experiment only 100 A of Aluminum was deposited on the four substrates. It was found that the substrate with HMDS prime and a hard-bake of 110°C for 1 min showed a much better adhesion during the wet aluminum etch step.

Since quartz is not a good conductor of heat and much thicker substrate than silicon wafer, the hard bake step was set at 150°C for 10 minutes.

D. Microscope Pictures of Micro-lens

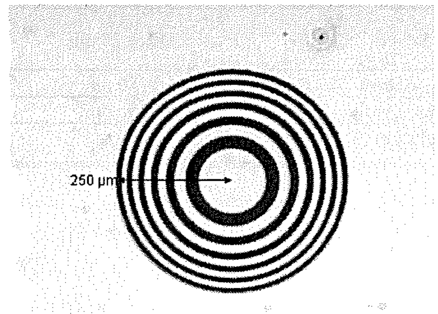

Fig. 14. Two level Micro-lens with a radius of 250 microns.

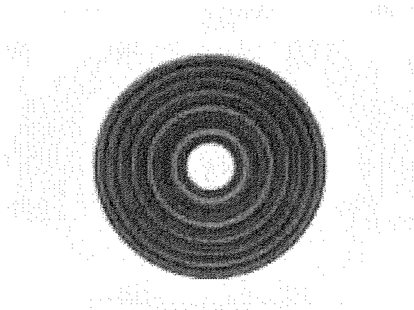

Fig. 15. A microscopic picture of a 4 level micro-lens.

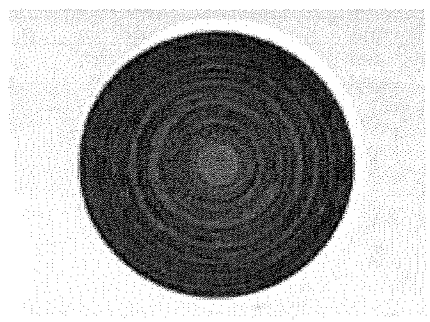

Fig. 16. A microscopic picture of eight level micro-lens.

E. P2 Profilometer Results

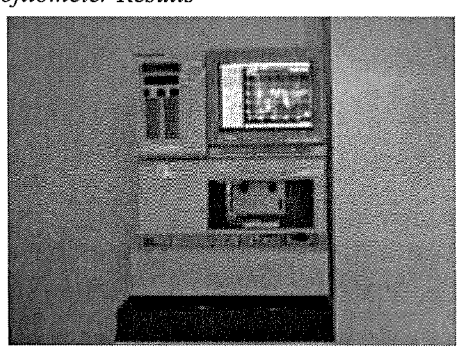

Fig. 17. P2 profilometer.

The P2 profilometer was used to measure the etch depth after each etch step. Table III represents the etch data for each level of micro-lenses.

TABLE III
P2 PROFILOMETER ETCH RESULTS

Level	Etch Depth
Two Level	750 nm
Four Level	350 nm
Eight Level	190 nm

F. *WYKO Phase Measuring Interferometer Results*

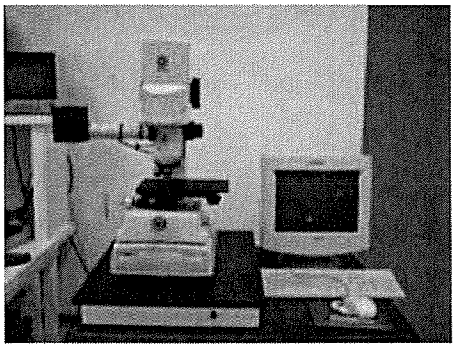

Fig. 18. WYKO phase measuring interferometer

TABLE IV
WYKO ETCH RESULTS

Level	Etch Depth
Two Level	650 nm
Four Level	427 nm
Eight Level	252 nm

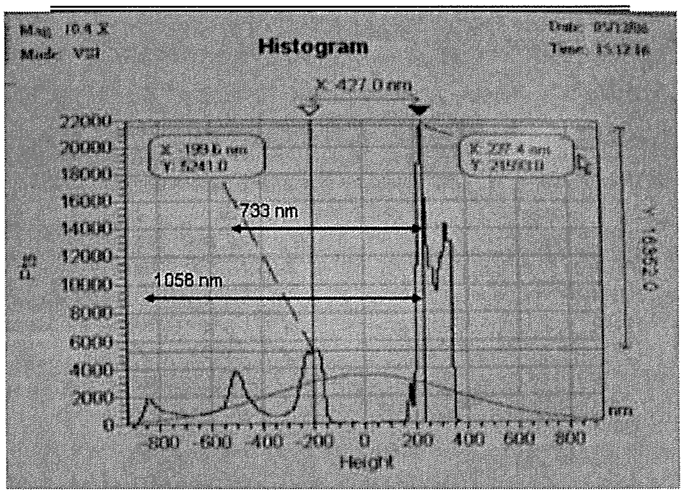

Fig. 19. An etch depth plot representing 4 levels of the micro-lens from the WYKO phase measuring interferometer.

Figure 19 represents the 4 steps of a four-level micro-lenses as measured on the phase measuring interferometer. Each peak is representing a level and hence it can be observed that the respective etch depths of each level considering the top quartz as the first level, is 427nm, 733nm and 1058nm. The peak to right represents the chrome layer on top of the quartz substrate.

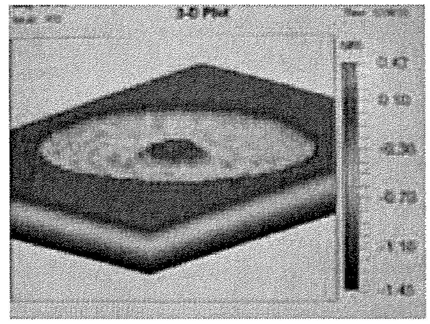

Fig. 20. 3-D plot of an eight level Micro-lens.

The 3-D profile of the eight level micro-lenses did not look very uniform. This was due to an over etch at level 1 which was 750 nm deep etch. According to the design of the micro-lenses the first desired etch depth was 172 nm. Due to scheduling limitations and time constraints, the fabrication was continued with deeper etch steps, perhaps useful as a micro-lens at a different operating wavelength.

V. CONCLUSION

In conclusion, eight-level micro-lenses were fabricated at the RIT's Semiconductor and Microsystems Fabrication Laboratory. A dry etch process was developed to fabricate the eight level micro-lenses. The etch depth attained at the first etch step was calculated as 750 nm on the WYCO tool and 650 nm on the P2 profilometer. Step height for 4 level micro-lens was 427 nm on WYKO and 350 nm on P2 profilometer and after the final etch, the step height for eight level micro-lens was 252 nm on WYKO and 190 nm on P2 Profilometer.

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