



Plasma etching uniformity control for making large and thick dual-focus zone plates [☆]

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ABSTRACT

A typical zone plate structure is composed of concentric rings with a radially decreasing feature size such that the path of light through every second zone to the focus differs by one optical wavelength. In order to minimize the wavefront error, the etching depth has to be controlled uniformly across the whole substrate area to a phase difference of one half wavelength between adjacent zones. In this study, an optimized plasma etching process has been developed to minimize the feature size variation effect and a Teflon ring has been made to eliminate the edge effect on thick fused silica. A large phase type dual-focus zone plate with varied concentric ring sizes with good etching profile and better than 2.0% etching depth uniformity was successfully made.

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1. Introduction

A dual-focus zone plate has been designed for the measurement of radius-of-curvature (ROC), especially that of intermediate radii [1]. In this study, a nested dual-focus zone plate like the one shown in Fig. 1 was designed to measure the radius of a concave spherical mirror with 50 mm diameter and a nominal radius of 10 m. The Fresnel phase zone plate at the center of the nested zone plate has a diameter of 10 mm and a focal length of 190 mm. The outer region of the zone plate between 10 mm and 50 mm radius is a Fresnel phase zone plate with a focal length of 9810 mm. In order to achieve the highest possible diffraction efficiency, the etching depth in fused silica has to be controlled uniformly across the whole substrate area to get a phase difference of one half wavelength between adjacent zones. The variation of etching depth is one of the sources of errors in the wavefront. The maximum pattern height variation allowed was approximately 30 nm in our design.

However, it is a challenge to etch a dual-focused zone plate uniformly on thick quartz substrate [2] by using reactive ion etching (RIE) because the feature size of the concentric rings varies from tens of μm to hundreds of μm , the pattern density is not uniform from the center to the outer edge, and the fused silica substrate is both non-conductive and thick (5 mm).

Previous work has demonstrated that the plasma etching depth or rate varies with feature size and distribution length scales [3–5]. Jurgensen presented a simple angular distribution model that is qualitatively consistent with the shape of etching profiles and the magnitude of RIE-lag effect, and scales with pressure [6].

In this study, the plasma power and chamber pressure are optimized to reduce the microloading and aspect ratio effect. The edge effect was studied and an extension adapter was made to minimize the macro-loading effect.

2. Experimental

A 5.0 mm thick fused silica wafer 50.0 mm in diameter was used as our substrate. A chrome-on-glass photomask was fabricated by direct laser writing. The zone plate pattern was fabricated by Photolithography. In photolithography, photo-resist (S1813) was spin coated and exposed on a contact aligner by using the fabricated photo-mask. The exposed area was removed by MF-319 developer to leave the zone plate structures in photo-resist. The fabricated surface zone plate patterns were then transferred into the fused silica substrate by RIE using O_2 ($5.0 \text{ cm}^3/\text{min}$) and CHF_3 ($45.0 \text{ cm}^3/\text{min}$) gases. The 13.56 MHz RF power was varied from 100 W to 600 W and the chamber pressure from 1.3 Pa to 6.7 Pa.

Etching rate was characterized by using scanning electron microscope (SEM) on pattern cross-section images. The cross-wafer uniformity was measured with a profilometer after stripping off the residual photo-resist. The uncertainty in the profilometer measurements is dominated by the $\pm 2.0 \text{ nm}$ stage noise. The resolution of the profilometer itself is $0.1 \text{ nm}/6.5 \mu\text{m}$ as given by the manufacturer. Two orthogonal lines through the substrate center

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were scanned yielding the corresponding profiles. More than 40 points were sampled with non-uniform intervals along each individual test line: a higher density of sample points were scanned at the edge of the substrate.

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3. Results and discussions

Non-uniformities in plasma etch for zone plates are due to several factors: the feature size of individual pattern, the pattern density and the substrate thickness. The greatly varying line spacing across the zone plate and non-even distribution of concentric rings is one of the critical factors leading to etching non-uniformity. The settings of the etching process chamber, the breakdown of the feed gas into plasma, the strength of the electric field across the sheath, and the pressure within the chamber were studied to control the etching uniformity. RF power along with chamber pressure determines the breakdown of etching gas and the DC bias. With a fixed pressure, higher RF power leads to higher DC bias and faster etching rate but also to larger etching rate variation (as shown in Fig. 2). To control the etching rate variation while keeping an acceptable rate, 300 W RF power was selected for the process. With a fixed RF power, the chamber pressure was adjusted to minimize the feature size dependence because the chamber pressure determines the relative influence of mechanisms such as Knudsen transport, ion shadowing, neutral shadowing, and differential charging

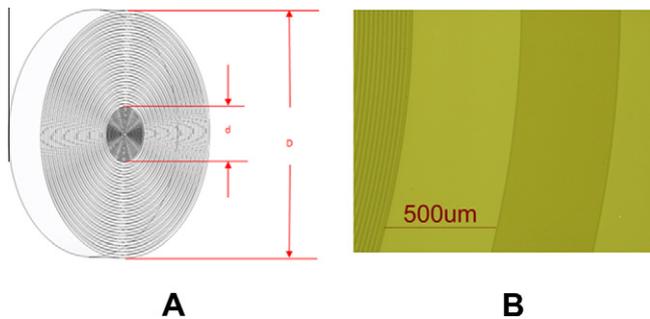


Fig. 1. Nested dual-zone pattern; (A) pattern diagram $d = 12.7$ mm, $D = 50.0$ mm; (B) zoom in view of the dual-zone zone plate.

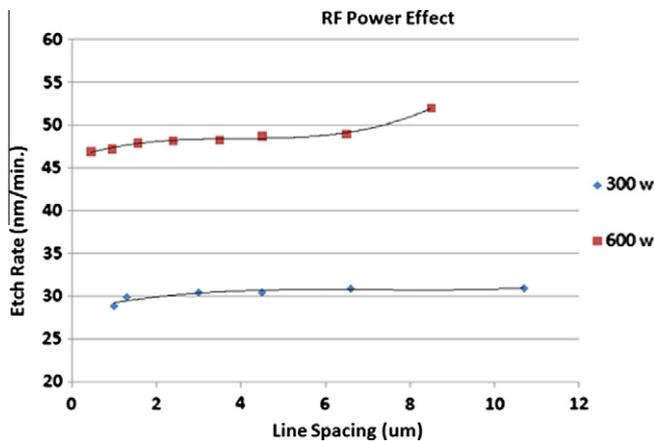


Fig. 2. Effect of RF power on etching uniformity at 1.3 Pa chamber pressure.

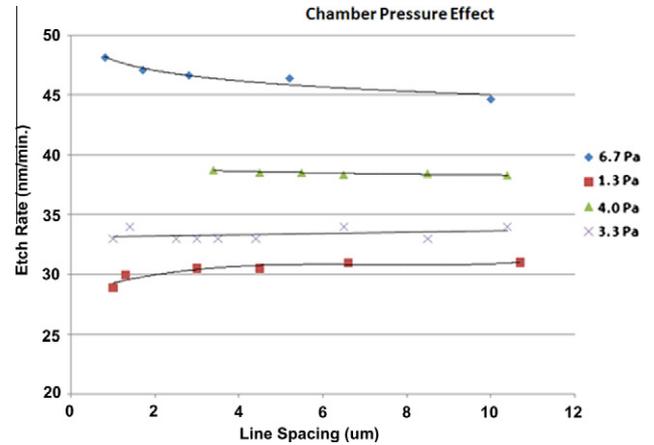


Fig. 3. Effect of chamber pressure on etching rate variation with feature size.

on etching uniformity [7]. We started the process at a chamber pressure of 6.7 Pa. Fig. 3 shows that the etching rate tends to decrease with increasing line spacing. In other words, the etching rate increases with feature aspect ratio at 6.7 Pa. This acceleration in reaction rate with increasing aspect ratio phenomenon is called “reverse” or “negative” RIE lag [8]. This “abnormal” behavior might be due to a negative charge on the pattern sidewall. During RIE etching, the collisions of electrons with the photo-resist mask can introduce a negative charge on the surface [9]. The negatively charged surface can accelerate the ion bombardment and increase the etching rate. Low chamber pressure, 1.3 Pa was tested later to reduce the feature aspect ratio dependence. Fig. 3 shows that the etching rate variation of 1.3 Pa is smaller than that of the 6.7 Pa but it is still there. The etching rate seems to increase with the line spacing at 1.3 Pa although not clear. This “normal” etching rate variation is mostly caused by the lack of enough reactant or diminishing quantity of reactants reaching the bottom of the narrow structure [10]. It is interesting to see that the trend of etching rate with feature size can either increase or decrease by simply adjusting the chamber pressure. To minimize the above “positive” and “negative” RIE lag effects, the midrange chamber pressure of 3.3 Pa and 4.0 Pa was tested. As expected, the etching rate is independent of line spacing under the midrange chamber pressure, as shown in Fig. 3.

In addition to influencing etching uniformity, the chamber pressure also affects the etching rate and profile. From Fig. 3, it is clear that the etching rate increases with the chamber pressure. Fig. 4a shows that sidewall is straight but the bottom is not flat at high pressure. Lowering the chamber pressure leads to sloping the sidewalls and trenches at the corners as shown in Fig. 4b. This behavior is called microtrenching which has been observed when fabricating microscopic features in SiO_2 layers using low pressure, high-density fluorocarbon plasmas. Microtrenching has been explained either as due to ion scattering from sloped sidewalls or negative charging of the sidewalls by electrons, and the influence of the associated electric field on ion trajectories [11]. By balancing the chamber pressure to the midrange, 4.0 Pa, the sidewall becomes straight and the bottom is flat (Fig. 5). Chamber pressure (4.0 Pa) was finally selected for etching our zone plate.

Another challenge for etching dual-focus zone plates uniformly is the thickness of the substrate. Commercially available RIE equipment is typically designed for etching 0.5 mm range thick wafer substrates. For a thick fused silica substrate, e.g. 5.0 mm, the sheath distance is different from the normal thickness wafer (e.g. 0.5 mm). This sheath distance change affects the energy of charged particles colliding on the silica surface. Since there is a jump on sheath distance and charge density from the fused silica edge to

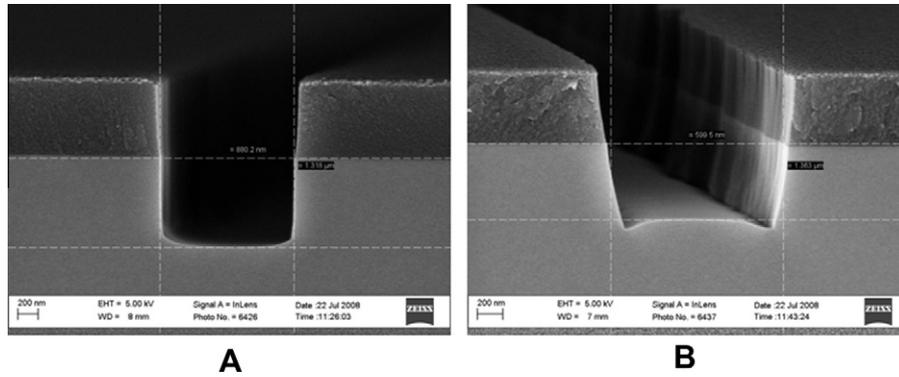


Fig. 4. Etching profile variation with the chamber pressure (a: 6.7 Pa; b: 1.3 Pa) after 20 min etching.

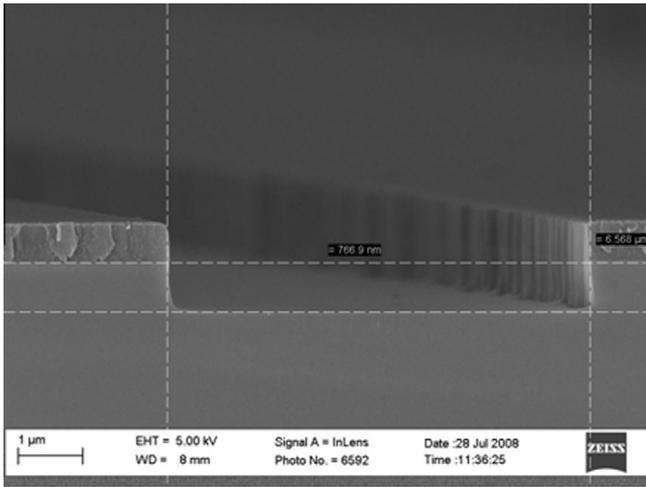


Fig. 5. Etching profile at chamber pressure 4.0 Pa.

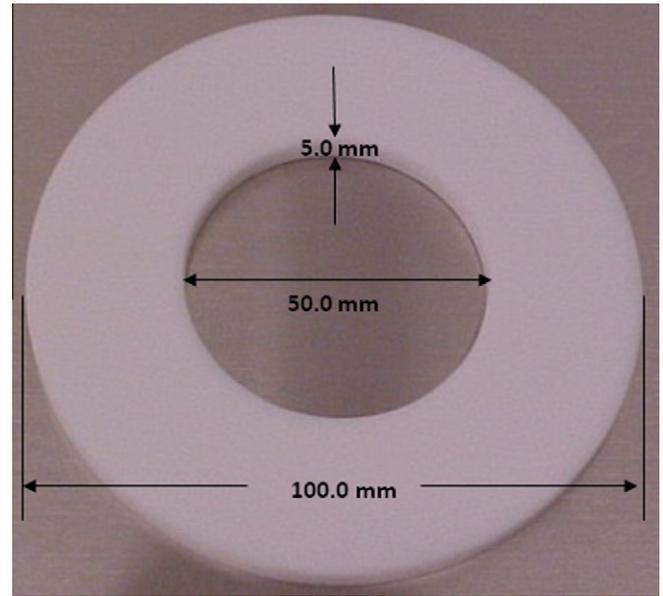


Fig. 7. PTFE adapter for 50.0 mm substrate.

the outside electrode, the self-bias varies from the center to the edge. This non-uniform distribution of self-bias above the substrate will lead to non-uniform etching depth from center to edge because the non-uniform electric field distribution contributes to a variation in ion acceleration and distribution across the wafer. The cross-wafer uniformity was measured with a profilometer after stripping off the residual photoresist. Two orthogonal lines through the substrate center were scanned with the corresponding

profiles shown in Fig. 6. More than 40 points were sampled with non-uniform intervals along each individual test line and a higher density sample points were scanned at the edge of the substrate. A strong edge effect was observed with nearly 20.0% etching depth variation on 5.0 mm thick fused silica in each test line. To prove that this cross wafer variation is due to the substrate thickness, a 0.5 mm fused silica wafer was patterned with the same mask,

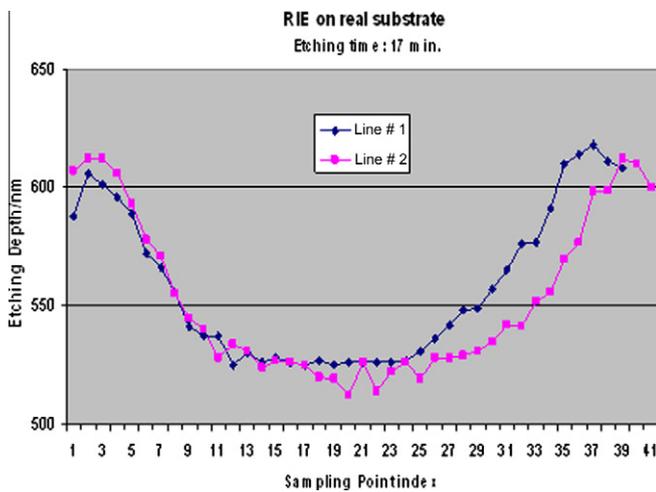


Fig. 6. Etching depth variation over the whole wafer.

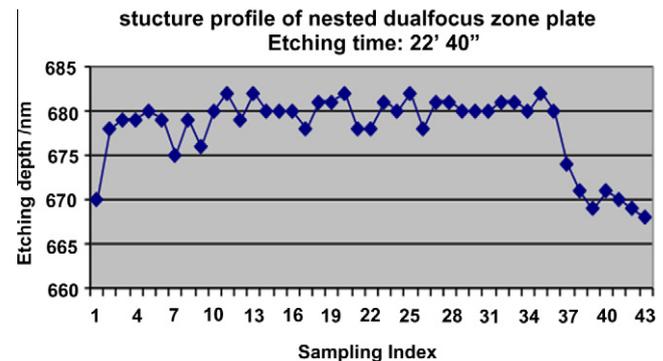


Fig. 8. Final etching depth across thick dual-focus zone plate. The uncertainty in measurement is ± 2.0 nm as described in the text.

and etched with the same recipe for the same etching time. The etching depth non-uniformity on 0.5 mm thick quartz across 100 mm diameter was 2.0%. Clearly, the edge non-uniformity increases with substrate thickness. Comparing the etching rate variation over the whole wafer, the slope of etching rate in the center is much smaller than that at the edge (Fig. 6). To enlarge the center uniform area, a Teflon annular disk was made to extend the thick fused silica size (Fig. 7). The same etching process was repeated on a thick substrate with the Teflon annular disk in place: the etching rate across the whole wafer is shown in Fig. 8. Clearly, the center uniform area has extended to the whole wafer area and the edge effect is moved out to the Teflon annular disk.

4. Conclusion

In summary, an optimized plasma etching process has been developed and a Teflon ring has been made to minimize the feature size variation effect and eliminate the thick glass edge effect. Large

phase type dual-focus zone plate with good etching profile and better than 2.0% etching depth uniformity was successfully made, which is acceptable for the error tolerance of the ROC measurement.

References

- [1] Q.D. Wang, G. Gao, U. Griesmann, *OF&T* (2008) 91.
- [2] C.J. Mogab, *J. Electrochem. Soc.* 124 (1977) 1262–1268.
- [3] C.J. Mogab, *J. Electrochem. Soc.* 124 (1977) 1262–1268.
- [4] R.A. Gottscho, C.W. Jurgensen, *J. Vac. Sci. Technol. B* 10 (5) (1992) 2133–2147.
- [5] J.W. Coburn, H.F. Winters, *Appl. Phys. Lett.* 55 (26) (1989) 2730–2732.
- [6] E.S.G. Shaqfeh, C.W. Jurgensen, *J. Appl. Phys.* 66 (5) (1989) 4664–4675.
- [7] K.O. Abrokwah, *Characterization and Modeling of Plasma Etch Pattern Dependencies in Integrated Circuits*, Thesis, Massachusetts Institute of Technology, 2006.
- [8] I.W. Rangelow, *J. Vac. Sci. Technol. A* 21(4) (2003) 1550–1562.
- [9] M. Schaepekens, G.S. Oehrlein, *Appl. Phys. Lett.* 72 (11) (1998) 1293.
- [10] J.W. Coburn, H.F. Winters, *Appl. Phys. Lett.* 55 (26) (1989) 2730–2732.
- [11] Marc Schaepekens, Gottlieb S. Oehrlein, *Appl. Phys. Lett.* 72 (11) (1998) 1293.