Characterization of an integrated multibeam laser mask-pattern generation and dry-etch processing total solution

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ABSTRACT

As mask specifications continually tighten with the ever-present progression of Moore's law, mask manufacturing specifications have become increasingly difficult to achieve. Global process optimization from coat to etch is critical for achieving the required mask performance. As an Applied Materials company, Etec is in a unique position within the maskmaking industry to introduce mask manufacturing solutions that are optimized across a number of process steps. Working with the Applied Materials photomask etch team, Etec's laser mask-patterning product group characterized and implemented an integrated process recipe for the deep ultraviolet (DUV), raster-scan, continuous-wave, laser mask-patterning ALTA® 4000 system and the Applied Materials Tetra™ Photomask Etch System.

Using a photomask recipe already developed by Etec, commercially manufactured DX1100P photoresist-coated masks were patterned on the ALTA 4000 system, the latest optical pattern generator released by Etec Systems, and were subsequently used for integrating a dry-etch process with the Centura Photomask Etch system. The newly developed photomask process solution includes an anti-reflective resist top coat (patent pending), post-exposure bake (PEB), develop, dry etch, and resist strip steps. The areas investigated to optimize dry etch included partial pressure and flow rates of reactant gases, chamber pressure, overetch, and focus ring geometry. The characterization primarily focused on those parameters directly affecting the productive yield of the maskmaker, including critical dimension (CD) mean error, CD uniformity, process bias, selectivity, and micro-loading. This paper documents the results of Etec's implementation and characterization of an integrated mask manufacturing process, which is optimized across many process steps, creating a Total Solutions™ concept for maskmaking.

Keywords: CAR, dry-etch, DUV, integrated process recipe, PEB

1 INTRODUCTION

As requirements for critical layer CD control on the wafer become more stringent, photomask CD control emerges as a crucial technological challenge. To support the manufacturing of reticles for 0.13µm technology, it is essential to have a high precision, high resolution, and high throughput pattern generator, as well a photomask process that accurately transfers the pattern into the chrome layer. Plasma etch of binary (chrome on quartz) photomasks has emerged as the process of choice for reticles with CD's below 0.25µm. Historically, the photomask etch process has been based on the classic Cl_2/O_2 chemistry[1] [2] . With these reactants, both chlorine and oxygen combine with chrome to form the volatile CrOxCly [3]. Some have added He as a dilutant gas[4], and recently, other reactive gasses have been used[5].

Etec Systems Inc., an Applied Materials company, has recently introduced the ALTA 4000 pattern generator, utilizing a 257nm wavelength laser, to meet the precision, resolution, and throughput requirements of the industry. Applied Materials has developed a state of the art photomask etcher, the Tetra Photomask Etch System, based on its vast experience in plasma etch technology in VLSI wafer fabrication. In this paper we present the results of reticles exposed with the ALTA 4000 system and processed with Etec's current DUV process. Etec's current DUV process provides a complete process solution that will demonstrate the lithography performance of the ALTA 4000 pattern generation system and provide a starting point for customer production processes. Areas of new innovation will be highlighted, including environmental protection with top coating and resist profile enhancement. Further, this paper will show the integration of the ALTA 4000 system and the Tetra etch performance to date, as Etec strives to provide Total Solutions to the maskmaker.

2 EXPERIMENTAL

The photomasks used were standard commercially coated binary chrome masks (chrome oxide / chrome oxynitride / chrome) with chrome and anti-reflective (ARC) layers having a total thickness of 1000Å. The mask blanks were coated with DX1100P photoresist at Hoya, the mask blank vendor. Plates were kept in clean controlled environments (with < 10 ppb mw airborne base contamination) and shipped and stored in clean gasket sealed boxes.

Prior to exposure, the resist coated plates were coated with an AQUATAR™ a top coat, commercially available from AZ-Microelectronics, a division of Clariant Corporation.

Exposure was preformed on an Etec Systems ALTA 4000 pattern generator, which uses a 257nm laser source with improved CD precision and resolution better than 400nm lines and spaces. Patterns printed to characterize the process included "Exposure/ Focus", "Load28" and "ALTA 4000 ATP". Some patterns had special iso – dense test structures, known as "Paddles". All exposures were done at isofocal dose (typically 21 mJ/cm²) and best focus, as determined by an exposure focus plot. Following exposure, plates were post exposure baked (PEB) at 70°C. All plates had a post exposure delay (PED) of 60 minutes between the end of print and PEB. Plates were developed in 2.38% TMAH (AZ 300 MIF Developer).

Plasma etch was performed in two steps: TRIM (patent pending), and then etch. The TRIM process, discussed in further detail below, reshapes the resist sidewall to yield a vertical slope. We found the resist CD measurement without a TRIM process was not robust, yielding an intensity profile which was difficult to use in top down CD SEM metrology. Therefore, all resist measurements in the CD SEM were done post TRIM.

Results showing the culmination of Etec's current DUV process are shown in section 3.1. The resist strip was done using a sulfuric acid and peroxide solution. For CD metrology a CD-SEM and/or a Leica LWM was employed. Photoresist thickneses were measured on an n&k Analyzer, post develop, post TRIM, and post etch.

The % open area (chrome load) for these patterns is between 20 – 30%. For both patterns, the metrology features were printed in a constituent fashion (same combination of beams and polygon facets in the ALTA system), to minimize the tool CD error contributions and in order to focus on process contributions to CD uniformity. The Load28 pattern, shown in Figure 1, is comprised of alternating rows of fully isolated and fully dense (chrome loaded) metrology features. The 400nm design CD was measured in resist (post TRIM) and in chrome on a CD-SEM. CD's from both the loaded ("L") regions and unloaded ("U") regions were measured.

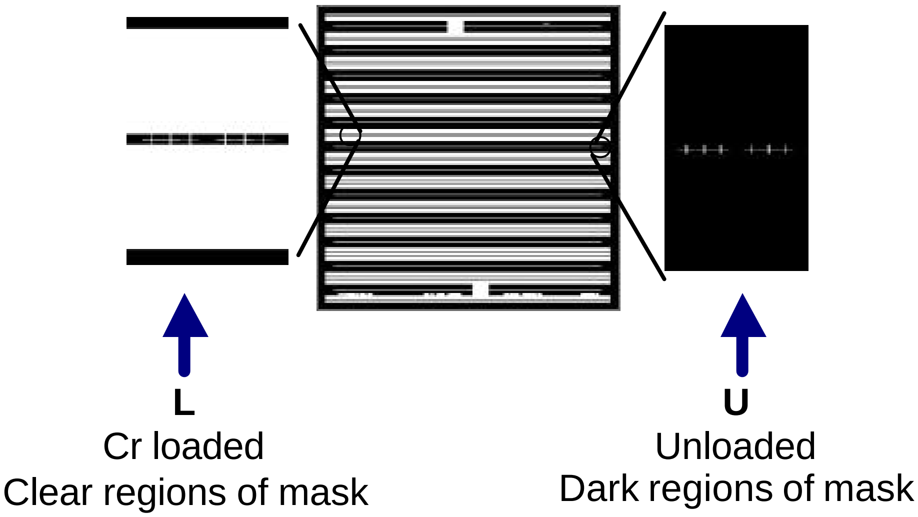


Figure 1. The Load28 pattern with both chrome loaded features (expanded view on left) and isolated features (expanded view on right). The CD's have an extent of 120 x 132 mm.

The acceptance test pattern (Figure 2) consists of an 11 × 11 array of test marks embedded within a larger pattern of features. Note how the first, center and last columns, as well as the center row, all have a different background loading (more sparse) than the remaining test points. In order to create an acceptance test that evaluates system performance similar to real production reticles, Etec has included variable pattern density into our ALTA 4000 ATP pattern.

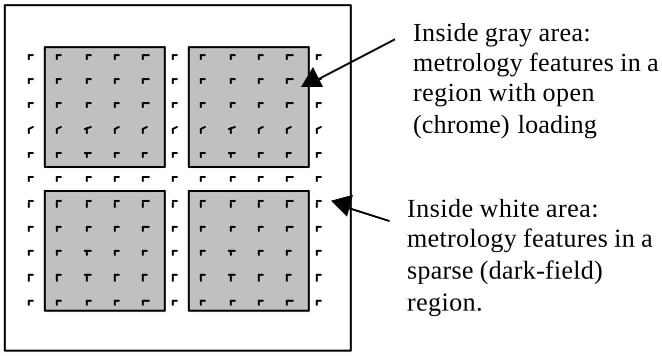


Figure 2. ALTA 4000 ATP pattern layout. Each mark represents a test point on the 11´11 CD array, with an extent of 132 x 110 mm. The areas shaded gray are high-density chrome fields with clear features. The white areas are low-density chrome fields with clear (dark-field) features.

An iso –dense test structure was created to verify the process. This "paddle" shaped structure, shown in Figure 3, has spaces in a dark-field region of a test reticle. The center clear space is measured in the isolated and dense parts of the structure.

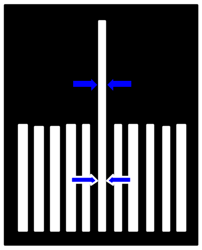


Figure 3. The "paddle" structure for verifying iso-dense process performance.

The process flow is comprised of the modules shown in Figure 4. The AQUATAR top coating activity was done as a precaution to control environmental contamination effects at the mask blank and to improve the mean CD control. The DX1100 photoresist is chemically amplified and although it is relatively robust with respect to environmental contamination (compared to other resist systems), the top coat activity enhances its insensitivity to environmental contamination.

Operation	**Comments**
AQUATAR Coating	Top coat
ALTA 4000 Expose	Isofocal Dose
Post Exposure Delay	60 minutes
Post Exposure Bake	70C
Develop	2.38% TMAH. Removes AQUATAR and develops resist.
TRIM	Remove resist footing
Resist CD Metrology	Optional
Plasma Etch	Cl_2, O_2, He chemistry
Resist Strip and Clean	Sulfuric Acid, Peroxide
Chrome CD Metrology	CD SEM and / or optical metrology

Figure 4. Plate process for the ALTA 4000 exposed masks.

More recent process development data was collected using the Applied Materials Tetra Photomask Etch System (section 3.2). For comparison, some current DUV process results are also discussed. The etch gas chemistry included Cl_2, O_2 , He, and an "Assist Gas", termed: "Gas A". The Applied Materials H.O.T. ™ Pack endpoint system (an optical emission spectrometer) was used for Tetra etch system, monitoring the plasma intensity at 3600Å.

The experiments were designed, analyzed and modeled using Design Expert 6.0.3 software (Stat-Ease, Inc.). ANOVA was used to verify the significance of the factors and the validity of the models. Only statistically significant effects and models, with f-values less than 0.05 were used in the analysis.

3 RESULTS AND DISCUSSION

Current process results are presented, with focus on the novel processes, namely AQUATAR top coat, and TRIM. The performance of the complete process is demonstrated. The development work to integrate the Tetra photomask etch system is presented by a DOE and process verification. Finally, the direction for current and future work is shown.

3.1 ALTA 4000 Process Results

3.1.1 The AQUATAR Process

The AQUATAR top coat is applied on to the DX1100 resist layer in order to improve mean CD control. Although the DX1100 resist has good stability, it becomes more sensitive to the environment after exposure (Figure 5a). By applying the AQUATAR top coat, the post exposure sensitivity to the environment is reduced (Figure 5b), thus enabling its use in a wide range of environments, as used at various customer sites. The time between AQUATAR coating and exposure is controlled, in an analogous manner as used in wafer fabrication.

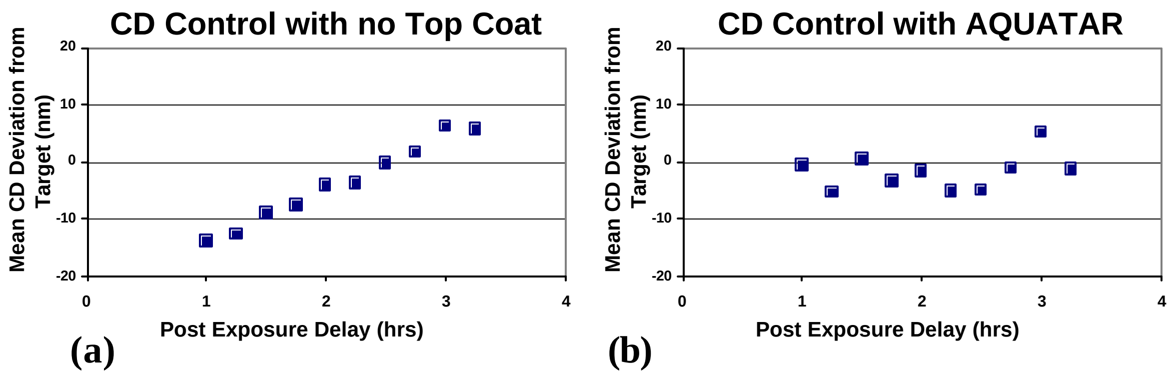


Figure 5. Improvement of CD mean control with AQUATAR. (a) CD mean control without a topcoat, and (b) CD mean control with AQUATAR top coat.

3.1.2 The TRIM Process

The TRIM process reshapes the resist sidewall to yield a vertical slope. A resist foot, observed post develop, is believed to be caused predominantly by chemical interaction between the DX1100 resist and the CrO_xN_y ARC layer on the mask[6]. The TRIM process is designed to (1) improve the resist profiles prior to etch, by eliminating the resist foot at the resist / chrome interface, and (2) remove any scumming from the open (developed) areas. The resulting profiles are vertical resist sidewalls, enabling the following chrome etch process to properly transfer the pattern into chrome. Another important feature of this process step is that by eliminating the foot, it enables reliable resist CD metrology prior to etch.

The TRIM process utilizes high energy ions in the plasma etcher, accelerated in a direction normal to the photomask surface. The ions remove the foot by both physical (sputtering) and chemical means. Etec's TRIM process removes a minimum amount of resist uniformly across the mask, and maintains the desired CD, without introducing process bias.

In a typical effective TRIM process, resist loss is on the order of 1000Å, leaving sufficient resist thickness for the subsequent etch process. The effect of the TRIM process on the resist profile is shown in Figure 6(a-c). Figure 6a shows the resist profile in the after develop condition. The image shows a resist foot at the base of the profile. After TRIM (Figure 6b), the resist sidewalls are vertical. Note that the space CD did not grow in this process. Similarly, after etch (Figure 6c), the space CD did not change.

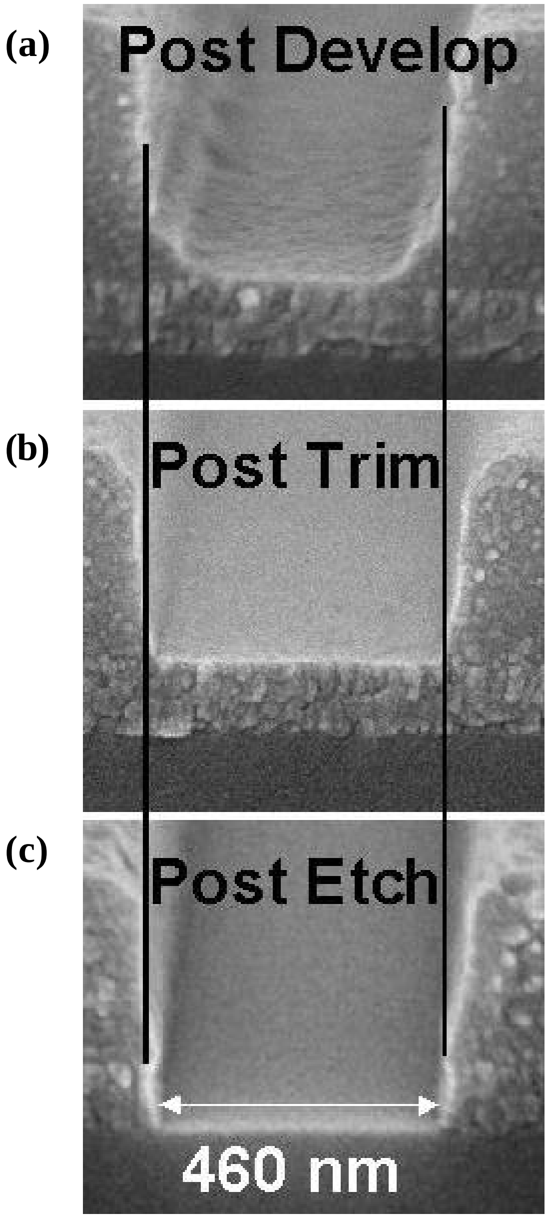


Figure 6. SEM cross sections post (a) Develop, (b) TRIM, and (c) Etch. The CD is maintained throughout these process steps. The profile becomes vertical at the TRIM step, and the subsequent chrome sidewall is vertical.

3.1.3 Print and Process Performance

Print window results are shown by Bossung plots in Figure 7. The mask was processed as per the process flow shown in Figure 4. The isofocal dose was 21 mJ/cm2. The CD sensitivity to dose was 2.3 nm/mJ, showing excellent performance at the isofocal dose. The total process bias (including etch bias) was below 50nm.

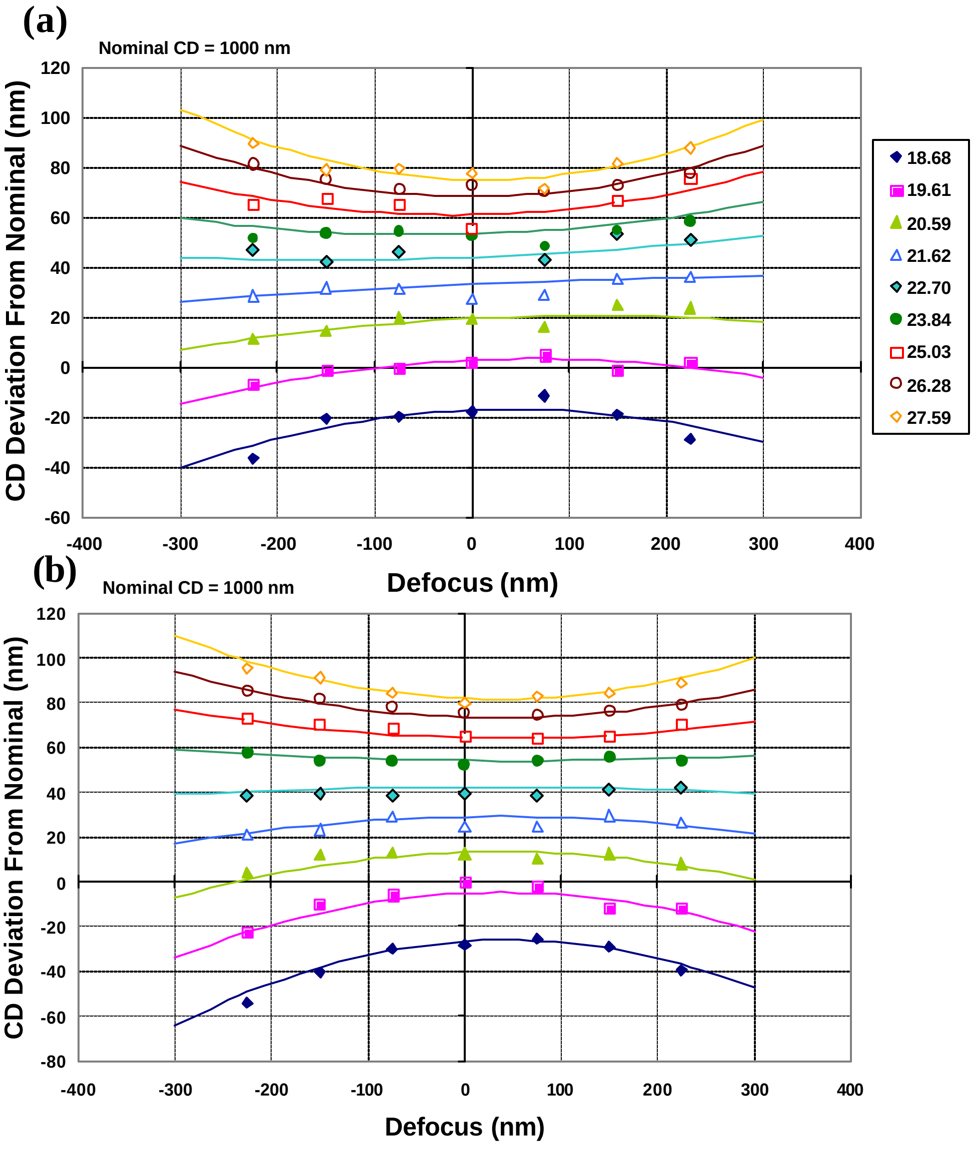
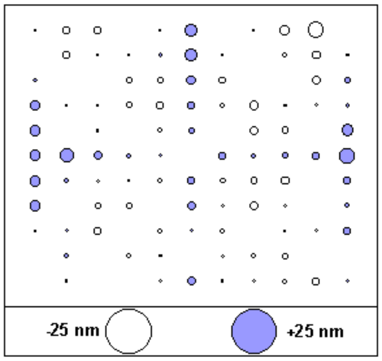


Figure 7. Exposure – Focus plots for DX1100 film stack exposed on the ALTA 4000 system. Shown are stripe direction (a), scan direction (b). The CD dose sensitivity was 2.3nm/%, and the total process bias was 42.4 nm.

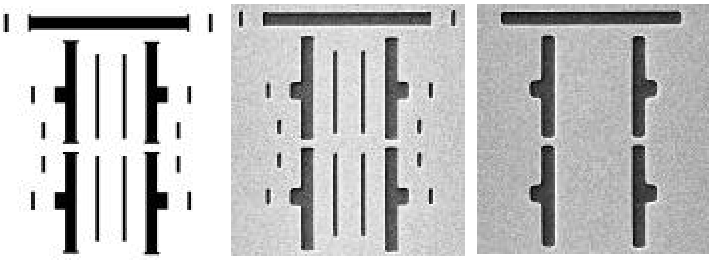
In order to specifically characterize the performance of the process, a constituent test structure was created, purposely designed to minimize CD errors from tool effects. The layout of this structure was described in Figure 2. The resulting raw CD uniformity plot (measured in chrome), is shown in Figure 8. The resulting 3σ is 10.4 nm. Although the total CD error from this process is small, the observed CD errors are attributed to the unloaded regions of the pattern, indicating some micro-loading effect of process. The etch process factors affecting micro-loading are discussed below.



Mean = 391.1 nm
Max = 8.4 nm
Min = -8.8 nm
3s = 10.4 nm

Figure 8. CD uniformity plot covering a 132 x 110 mm field. The test structure is constituent, designed to minimize CD errors from exposure and highlight errors associated with plate and process.

The resolution performance of the ALTA 4000 system with the process of record is shown in Figure 9. The 200nm scattering bars resolve. The imaging performance of the ALTA 3700 system is shown for comparison.



Input data ALTA 4000 ALTA 3700

Figure 9. OPC decorated 680nm lines. The large horizontal lines are 760nm, the large vertical lines are 680nm, and the scattering bars (small vertical lines) are 200nm in width. Note how the ALTA 4000 system resolves these patterns (images are in resist).

3.2 Plasma Etch Process Development on the Applied Materials Tetra Photomask Etch System

The advantages the Tetra photomask etcher include high range of operating pressures, excellent plasma uniformity from the dome chamber lid and the conforming power delivery antenna. In this section we discuss the integration of this design with a chrome plasma etch process.

3.2.1 The Etch Process Development

The etch process on the Tetra was optimized by the Response Surface Method (RSM) DOE, using a Central Composite Design (CCD). The experiment had 20 experimental runs, six of which were center-point repeats (for pure error evaluation). The experiment was designed to explore the effects and interactions of three factors: %O_2, Pressure, and %Gas A (A is the “Assist Gas”), with:

$$\%O_2 = \frac{O_2\ \text{sccm}}{(O_2 + Cl_2 + A)\ \text{sccm}}$$

And

$$\%A = \frac{A\ \text{sccm}}{(A + Cl_2)\ \text{sccm}}$$

The exposure pattern was Load28. All plates were TRIM’d with a fixed process, to remove the foot and enable resist CD-SEM measurements prior to etch. The etch process was performed in the Tetra, using a ¼ inch focus ring. The effect of the factors on Mean CD Shift is shown in perturbation plot,
Figure 10. The Mean CD Shift was calculated by point to point subtracting the post TRIM resist CD from the final chrome CD (both measured on a CD-SEM). This minimizes the effects of errors present prior to etch, in the analysis.

Figure 10 shows how the Mean CD Shift is affected by the factors. Higher pressure lowers the mean CD shift, indicating a more anisotropic etch. Classic ion (sputter) etch models favor an anisotropic etch mechanism at lower pressures, where there are less scattering events for the accelerated ions. In this case we see the opposite effect, indicating the dominant mechanism is not driven by the ion kinetic energy.

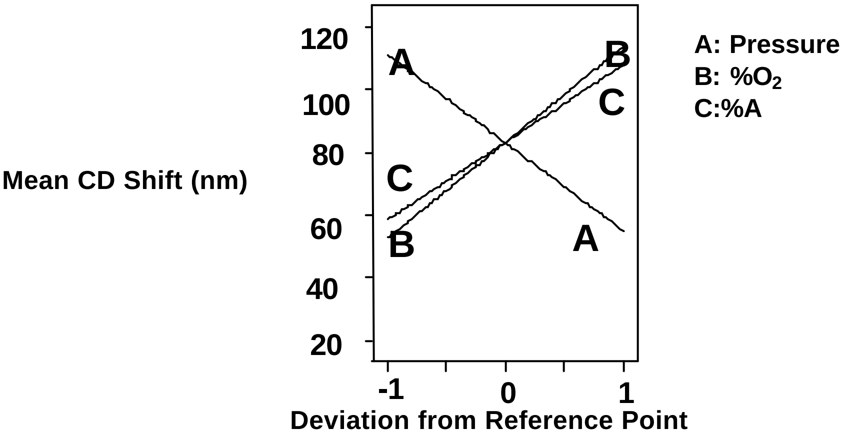


Figure 10. Effects of DOE factors on Mean CD Shift (Cr-Resist CD's).

The staticical model indicates an interaction between pressure and %O_2, where addion of O_2 yields a a smaller mean CD shift at higher pressures compared to lower pressures, as seen in Figure 11.

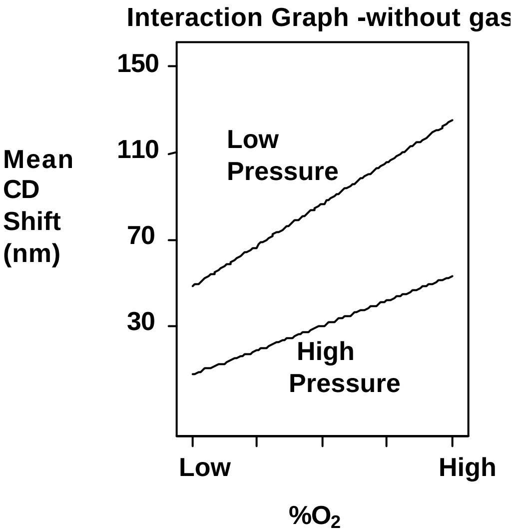


Figure 11. Interaction graph showing the effects of %O_2 and Pressure on Mean CD Shift.

The effect of the experimental factors on CD uniformity was evaluated using the 3-Sigma value after point to point subtraction of resist CDs (post TRIM) from chrome CDs, in the same fashion as the Mean CD Shift evaluation. The results, shown in Figure 12, indicate CD uniformity is improved with higher %O_2, and higher pressure. Increasing %O_2, however, also increases the Mean CD Shift, as seen in Figure 11. On the other hand, increasing pressure has the benefit of lower Mean CD Shift as well as improved CD uniformity. One of the strengths of the Applied Materials Photomask Etcher is its ability to operate over a wide range of pressures. Processing of photomasks at pressures higher than 30mTorr is achieved without difficulty.

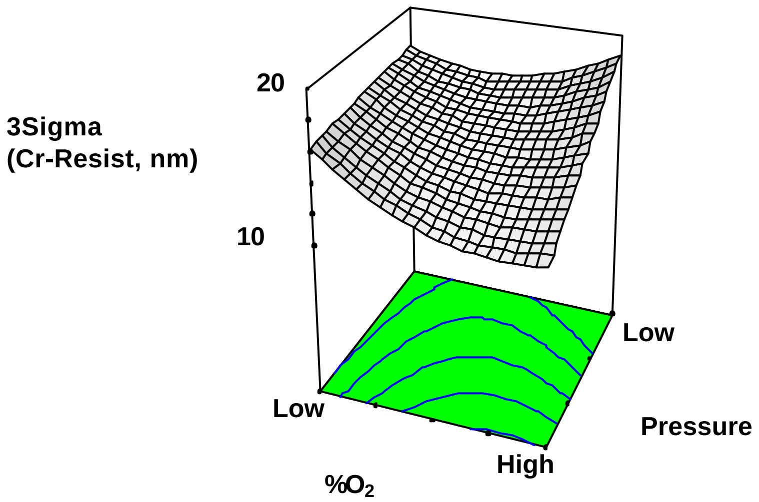


Figure 12. Effect of Pressure and %O_2 on CD Uniformity (3Sigma, chrome-resist)

The addition of Gas A to the plasma improved CD uniformity, as shown in Figure 13.

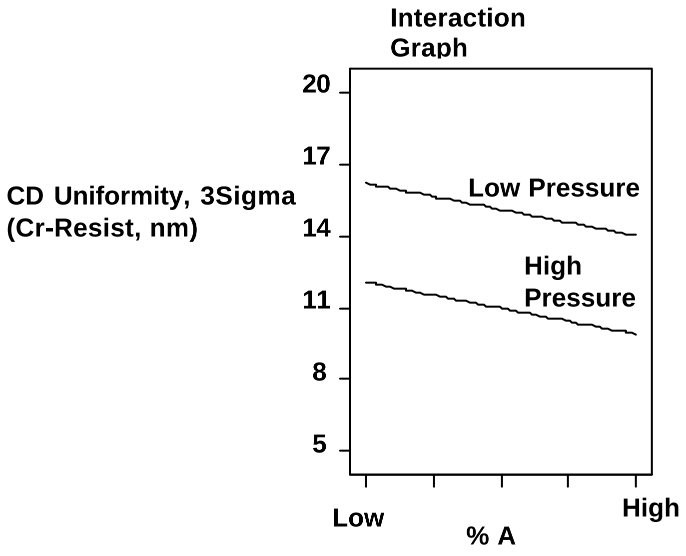


Figure 13. Addition of Gas A improves CD Uniformity.

3.2.2 Micro-loading and Gas A

To quantify the effect of micro-loading, the Load28 test pattern was used. A micro-loading parameter, L-U was defined as average CD from chrome loaded regions , “L” (clear-field), minus the average CD from unloaded regions, “U” (dark-field). The values of L-U were evaluated as a response in the DOE analysis. Results indicate a process space shown as the dark regions of Figure 14. These regions indicate the process space (in terms of %O2 and pressure) where both L-U is within +/- 2 nm and 3 sigma less than 13 nm. Note how the addition of gas A increases the available process space. Recall, however, that the etch bias worsens with gas A additions (Figure 10), indicating a trade off.

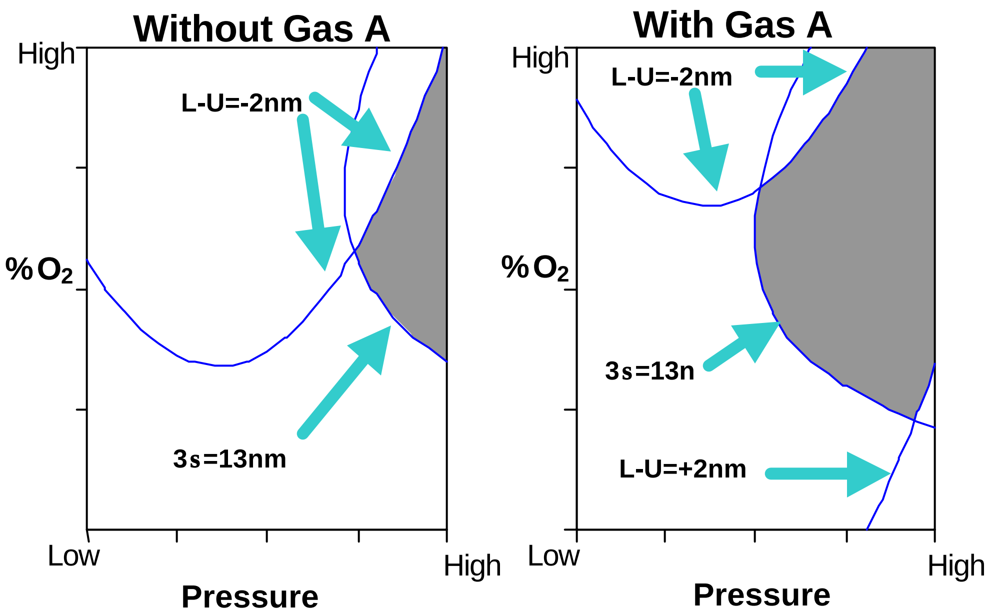


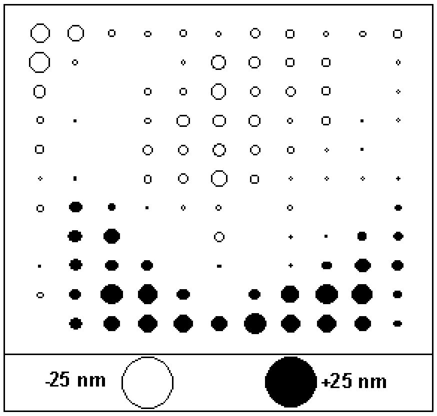
Figure 14. Addition of Gas A on increases the process space with respect to micro-loading.

3.2.3 Result Verification on the ALTA 4000 ATP Pattern with the Applied Materials Photomask Etcher

Based on the development work with the Load28 pattern, process performance was verified using the constituent ALTA 4000 ATP pattern described above. The first results show comparable CD uniformity, as seen in

Figure 15, with a 3σ of 14.8 nm. With this Tetra etch process, the CD uniformity signature shows less micro-loading from the isolated regions (compare CD uniformity plots and

Figure 15 to the design pattern shown in Figure 2), but exhibits a top to bottom CD uniformity signature (discussed further in section 3.2.4). The process bias of these results is currently ~80nm. Further reduction of process bias by increasing process pressure is currently under investigation. The Iso-Dense bias is seen is in Figure 16, showing the impressive performance from this combination of ALTA 4000 system and the Tetra Photomask Etch System.



Mean	431.5 nm
3s	14.8 nm
Max =	10.3 nm
Min =	-9.8 nm

Figure 15. CD uniformity plot of Acceptance Test Pattern Cross1 features etched on the Tetra system.

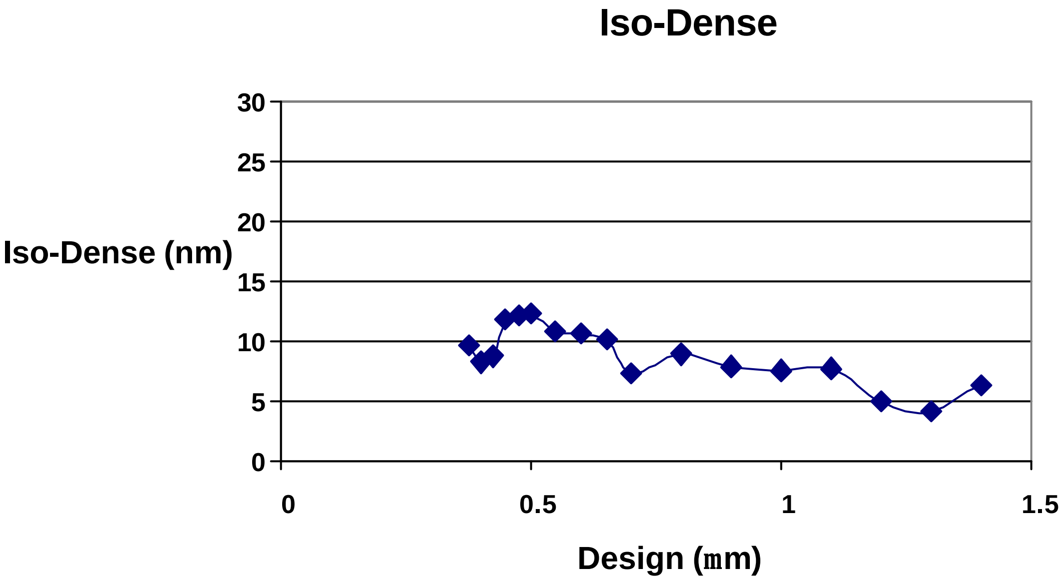


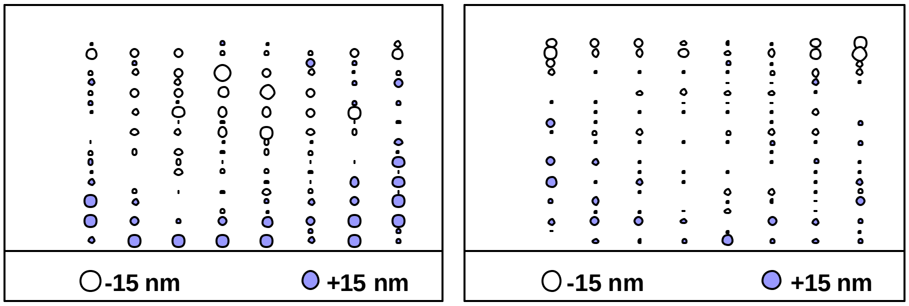
Figure 16. Verification of the Tetra process in terms of iso-dense bias. These data are from a "Paddle" structure, described in Figure 3.

3.2.4 Effect of Focus Ring Geometry

To further improve the CD uniformity, the effect of focus ring geometry was evaluated. The standard Tetra process uses a ¼ inch focus ring. The resulting CD uniformity signature is seen in

Figure 15, as a top-bottom effect. Using the Load28 pattern as a test vehicle, a comparison of CD uniformity signatures was done, while varying the focus ring height.

Figure 17 shows the results from using the ¼ inch focus ring, and the 1 inch focus ring. The 1 inch ring had a positive affect on the CD uniformity, by lowering the top-bottom effect. This encouraging result indicates that optimizing focus ring geometry can lead to better uniformity. This is currently being evaluated.



¼ Inch Focus Ring
3s = 16 nm

1 Inch Focus Ring
3s = 12 nm

Figure 17 Effect of focus ring height on the signature of CD uniformity. The 1 inch focus ring reduces the top – bottom signature, and improves the CD uniformity. The pattern was Load28 and the CD's for this case had an extent of 120 x 104 mm.

4 CONCLUSIONS

We have shown a DUV process solution for the ALTA 4000 pattern generation system, demonstrating excellent CD control and resolution. Two key enabling process steps were the AQUATAR coating for post exposure CD control, and the TRIM process for improving sidewall profiles. The integration of the Tetra Photomask Etch System into the DUV process was described, showing good uniformity and iso-dense performance.

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Pattern data courtesy of the Reticle Technology Center LLC - part of a joint partnership.

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