Phase shift mask etch process development utilizing a scatterometry-based metrology tool

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ABSTRACT
Phase, along with defect levels and CD, must be closely monitored on 45nm technology node masks. The final phase shift of a mask is highly dependent on the ability of the etch tool to stop at precisely the correct depth. Developing etch processes and endpoint recipes for successful phase shift processing depends on rapid and accurate measurement of etch depth. In many mask shops, these measurements are made by either direct phase measurement tools or atomic force microscopes (AFM). These tools have relatively low throughput. In the case of the direct phase measurement tool, the large measurement spot size precludes the measurement of the small features most interesting to mask makers. A need exists for a relatively fast measurement tool that can be applied to features <1\(\mu\)m in size.

As part of Oerlikon USA’s continuous etch process improvement efforts, the etch depth measurement capabilities of a scatterometry based metrology tool were explored. Phase shift masks (one EAPSM, one AAPSM) were created to act as standards for our experiments. Regions of each mask were etched to various depths using an Oerlikon Mask Etcher system, and then measured with both a commercial AFM and an n&k Technology 1700-RT scatterometry tool. Using this data, recipes capable of measuring quartz trench features, partially-etched MoSi trench features, and bulk MoSi films were developed on the n&k 1700-RT. Phase uniformity data taken from actual etch experiments will be provided, as well as data showing the repeatability of each system, and a comparison of the relative measurement times.

1. INTRODUCTION
Photomask process development and qualification on a new etch system can be a daunting task. Timelines are often short, and there is great pressure to minimize the number of masks run due to the costs associated with the mask blanks, write time, and metrology. It would be advantageous to be able to simplify the development cycle by using masks without patterns, thus saving write time. Further, the ability to re-use previously etched MoSi masks for phase uniformity screening experiments would significantly reduce development costs. Short measurement times would maximize efficiency and allow the process development cycle to move more quickly.

Scatterometry-based metrology tools offer these capabilities and other advantages as well. As scatterometry tools are significantly faster than AFM, the number of points measured can be increased to allow for accurate regression analysis. Scatterometry tools are also capable of measuring much narrower trenches than can be accommodated by the current generation of phase tools. This capability provides an advantage when production-qualifying an etch process, as the metrology data is obtained from features much more similar to the feature of interest on a mask than is ordinarily possible. In addition to trench measurement capability, it is also possible to measure unpatterned samples. This capability allows the re-use of previously etched masks for etch rate uniformity experiments.

Although much work in recent years has focused on the study of the CD measurement capability of scatterometry based metrology tools, relatively little work has been presented on the potential for these tools to supplement AFM or direct phase measurement tools.\textsuperscript{1,2} As part of the Oerlikon Mask Etcher V development program, an n&k 1700-RT scatterometry-based metrology system from n&k Technology, Inc. was employed to help obtain an optimized MoSi etch recipe. The Mask Etcher V is an advanced etch system (targeted at 45nm and below technology nodes), and offers multiple adjustments for neutralizing radial, linear, and loading dependent non-uniformity signatures. With the increased capability of these adjustments comes an increase in the complexity of any process development program. Using an n&k
Technology metrology system greatly simplified the process development cycle, allowing for the rapid creation of a process capable of easily meeting 45nm process goals.

2. METROLOGY

2a. n&k Methodology

For the current study we used a commercially available spectrophotometer-based instrument, n&k 1700-RT manufactured by n&k Technology Inc., capable of collecting continuous broadband reflectance and transmittance spectra at the same location on the sample. The broadband light source consists of a tungsten filament lamp, providing visible and near-IR light, and a deuterium arc lamp, providing deep-UV radiation. Each detector (reflectance and transmittance) consists of a holographic diffraction grating which separates the incident polychromatic beam into its constituent wavelength components, and a photodiode array which records the reflected spectrum. The angle of incidence is 9º from normal and the measurement spot diameter is 50 µm for reflectance and 400 µm for transmittance at the sample surface. Data acquisition time is one second, consisting of ten averaged consecutive measurements. Figure 1 depicts the schematic diagram of the optical path of the instrument.

![Optical path of the n&k 1700-RT](image)

After the raw data is collected, both reflectance and transmittance spectra are simultaneously analysed using the Forouhi-Bloomer dispersion relations (1) and (2), in conjunction with rigorously coupled wave analysis (RCWA), to extract the values of $n$ and $k$, film thickness, and trench dimensions.

\[
n(E) = n(\infty) + \sum_{i=1}^{q} \frac{B_i E + C_i}{E^2 - B_i E + C_i} \quad (1)
\]

\[
k(E) = \sum_{i=1}^{q} \frac{A_i (E - E_i)^2}{E^2 - B_i E + C_i} \quad (2)
\]
The analysis model generates calculated reflectance and transmittance spectra using the nominal parameters, and then optimizes the values, using nonlinear regression analysis in order to obtain the best match between the measured and calculated spectra. Each parameter in the model can be either varied or fixed at a known value. The dimensions obtained upon the convergence with the highest obtainable goodness of fit parameter are reported as the dimensions of the grating structure.

While library-based scatterometry tools have been successfully employed in production environments, the \( n \& k \) model-based method offers a significant advantage in an R&D environment. The wide range of results that are often generated during development programs would be challenging to fully describe using a previously generated result library. The model based approach can accommodate more variation in the incoming samples, providing accurate results even when faced with novel conditions.

2b. Measurement Repeatability and Accuracy

In order to develop the etch process, it was necessary to measure MoSi blanks, trenches in MoSi, and trenches in quartz. To determine measurement accuracy, series of samples including MoSi trenches, quartz trenches, and MoSi blanks were created. Trenches in both MoSi and quartz were measured by both AFM and the \( n \& k \) tool. The DI-5000 AFM was considered to be the relative standard for accurate depth measurement in these experiments, as it is calibrated using a 1000Å NIST-traceable step height standard. It was observed that there was a measurement delta in each type of trench measurement between the two instruments. Rather than attempt to change the \( n \& k \) measurement recipes, a simple linear correction was applied to all \( n \& k \) MoSi and quartz trench measurements to bring the data into line with the AFM-measured values.

![AFM/n&k Comparison on MoSi Trenches](image1)

\[
\begin{align*}
y &= 0.9299x + 25.44 \\
R^2 &= 0.9998
\end{align*}
\]

![AFM/n&k Comparison on Quartz Trenches](image2)

\[
\begin{align*}
y &= 1.1646x - 150.1881 \\
R^2 &= 0.9980
\end{align*}
\]

Figure 2: Accuracy testing of the \( n \& k \) 1700-RT vs. DI 5000 AFM

As the AFM requires trench features to measure, we were unable to determine the true thickness of the MoSi layer independently of the \( n \& k \) measurement on MoSi blanks. Instead we created standards by performing partial etches of the bulk film using an etch process with a previously characterized etch rate. Using this method, the \( n \& k \) measurement confirmed the etch depths.

Short term gage studies were run for each sample type to determine the measurement repeatability. Each sample was measured three times by three different operators. On the \( n \& k \) 1700-RT, the \( 6\sigma \) gage error for MoSi trenches measured at 6.2Å while for quartz trenches gage error was 7.4Å. MoSi blanks showed a gage error of 4.0Å. By comparison, the AFM gage error was determined to be 34.5Å.

2c. Measurement time

For the \( n \& k \) 1700-RT, measurement speed is primarily limited by the data analysis, as the multi-parameter model fitting can be quite complex. Typical measurement times (including the move, acquire, measure, and analyze steps) were on the order of 10s per data point. In contrast, the manually operated AFM used in this experiment required approximately 120s per data point. Although not entirely a fair comparison given that the AFM was not fully automated, much of the
time was spent simply in AFM vertical tip positioning and the actual scanning of the tip across the feature. Even when compared to a fully automated AFM, the n&k 1700-RT measurement time is expected to be significantly shorter.

3. EXPERIMENT
Our experiment was aimed at testing whether a scatterometry-based metrology tool could be used to enhance process development on embedded phase shift masks. To that end, a simple experimental plan was devised:

a) Use partial etches on blanket MoSi films to identify etch parameter that has most significant influence on phase uniformity (as determined through etch depth analysis)
b) Perform detailed study of identified parameter on both MoSi and quartz phase uniformity
c) Select optimized recipe and verify phase performance with a full etch on patterned mask

Initial process development experiments focused only on characterizing the phase uniformity response of the MoSi process, so unpatterned MoSi blanks were used. For later experiments requiring CD measurement, patterned masks were required. In order to simplify the measurements as much as possible, a single pattern was chosen for all such experiments. This pattern (named “Clearwater”) is a low load (0.6%) pattern exposed by e-beam in FEP171. This pattern has 64 sites, with each site having a large 500nm line/space array (1:1 pitch) for n&k measurement.

Initial MoSi Process Development – Phase Uniformity
As a starting point, a standard SF$_6$-based MoSi etch recipe was adapted for the ME-V. Utilizing the n&k 1700-RT, it was possible to quickly run several experiments to study the phase uniformity response to several processes. Radial non-uniformity was the primary area of interest, as linear non-uniformities can be easily corrected on the ME-V after a process has been developed. The experiments are summarized in figure 4:
3b. Detailed study of pressure response

Of the parameters explored, pressure was the most significant. Holding all other parameters constant, a change in process pressure could move the phase uniformity signature from center fast to edge fast. The change in pressure required to produce a change in the uniformity signature was small, but within the control capability of the etch tool. Further testing (shown in figure 5) determined that the change in uniformity fit a nearly linear trend, enabling relatively simple control of the radial component through process pressure.

![Figure 5: Blanket MoSi film radial uniformity response to pressure](image)

Standard commercially available MoSi films are designed to produce a phase shift of only 178°. Some overetching beyond the MoSi into the quartz is necessary to achieve a full 180° phase shift in a typical MoSi phase shift mask etch process. The final phase uniformity of the mask is a combination of the MoSi film phase uniformity and the quartz etch portion of the MoSi process. For this reason, we chose to study the quartz etch using NTAR7 binary Cr masks with the Clearwater pattern as a test vehicle. Each mask was Cr etched, then resist stripped to best simulate the sample conditions during the MoSi etch. The binary masks were then exposed to the preliminary MoSi etch process for a fixed time, Cr stripped, and finally measured for quartz trench depth using the n&k 1700-RT. After the first mask etched showed a radial signature reminiscent of what was observed on the MoSi, further experiments exploring the quartz trench radial etch rate uniformity response to pressure were performed:
Based on these results shown in figure 5, a roughly 5mT process would be most likely to produce a uniform MoSi etch depth. The quartz data in figure 6 suggests that the quartz etch rate uniformity will be somewhat center fast at that pressure. However, the high selectivity and shallow etch depth of the quartz should still allow for an acceptable phase uniformity.

3c. Verification of the Optimized MoSi Etch Process

Using the preceding data, a 5mT process was selected for full etch testing in the Mask Etcher V MoSi chamber. A Clearwater pattern mask was prepared, with initial CDs measured by KLA-8100XPR CDSEM and the initial reflectance of the Cr measured using the n&k 1700-RT. The plate was then etched using the selected process. Endpoint determination was made using a broadband reflectance-based technique, with the process terminated automatically after a 5% overetch past endpoint. In our experiment, the etch process ran for 70s, with a 3.5s overetch. Following etch, the Cr reflectance was again measured. The Cr mask was then dry stripped in preparation for post etch CD measurement and AFM depth uniformity measurement.

Changes in reflectance are to be avoided if possible, as increases in the stray reflection from the mask during exposure operations can degrade mask performance. Some mask makers etch MoSi phase shift parts with the photoresist intact (following Cr etch) to act as a protective coating for the mask’s antireflective layer. However, the presence of photoresist during the MoSi etch could potentially impact defect levels in the etch chamber. One goal of the MoSi etch process development program was to avoid significant changes to the Cr reflectance as measured at a wavelength of 193nm.

Figure 7 shows the results of the Cr reflectance measurements. In these plots, the dark squares represent measurements that are larger than the average, while white squares represent measurements below the average. Prior to this experiment, it was assumed that etching of the antireflective layer during the MoSi process would result in an increase of the overall reflectance. However, it was observed during this experiment that the average reflectance actually decreased very slightly.
The CD data in figure 8 represents the etch contribution to CD of the selected MoSi process. Initial and final CD measurements were taken on the 500nm line/space features. Although the CD bias is negligible, a small radial signature is observed.

Cross section SEM images were taken from both the center and corner of the mask (figure 9). These features were preserved during the dry strip of the Cr mask, making it possible to image the post-MoSi etch features with Cr intact. The profiles appear largely vertical with no significant undercut, although some Cr footing is observed in the image taken of the center of the mask.

Phase uniformity (figure 10) of fully etched trenches was determined through AFM measurement of etch depth. Multiple measurements were averaged to reduce the measurement error. Because the etch process included a short overetch into the quartz, the total etch depth measurements each represent a superposition of the initial MoSi film uniformity and the quartz uniformity. The initial blanket MoSi film uniformity has been measured at ~2Å, indicating that the primary source of non-uniformity observed here is in the quartz. The 9.6Å range observed would translate to a
Presented at the SPIE Photomask Japan 15th Annual Symposium, April 16-18, 2008, Yokohama, Japan

Phase uniformity of less than 1°. Regression analysis of the signature indicates that the non-uniformity is mostly a linear (corner to corner) signature, which can be easily optimized on the Mask Etcher V with further experiments.

Figure 10: Etch depth uniformity

4. DISCUSSION

Utilizing the n&k 1700-RT, it was possible to develop a new Mask Etcher V MoSi etch process with superior phase uniformity without compromising CD uniformity. While these results only show the initial work performed in the new process development project, they confirm the capability of the Mask Etcher V to meet 45nm node goals:

<table>
<thead>
<tr>
<th>Etch Rate</th>
<th>ME-IV Standard MoSi Process Result</th>
<th>ME-V New MoSi Process Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photo:Quartz</td>
<td>2:1</td>
<td>2.5:1</td>
</tr>
<tr>
<td>MoSi:Cr</td>
<td>10:1</td>
<td>&gt;15:1</td>
</tr>
<tr>
<td>Phase Uniformity</td>
<td>&lt;3° range</td>
<td>&lt;1° range</td>
</tr>
<tr>
<td>Profile</td>
<td>&gt;87°</td>
<td>&gt;88°</td>
</tr>
</tbody>
</table>

Figure 11: Summary of etch results

As demonstrated here, the n&k 1700-RT tool greatly assisted in the rapid development of a new MoSi etch process through accurate and repeatable measurements of:

1) Unpatterned MoSi blanks
2) Partially etched MoSi trench features
3) Etched quartz trench features
4) Initial and post etch Cr reflectance

The use of MoSi blanks for the initial rough process development was instrumental in reducing costs. Previously etched MoSi masks could be repurposed for development and used as an even less expensive alternative to unetched MoSi blanks. The ability to measure partially etched MoSi and quartz trenches allow for the decoupling of the MoSi and quartz etch signatures. This capability makes it possible to target the specific causes of phase non-uniformity and address them directly in the process. The Cr reflectance measurements confirm that the new etch process did not significantly damage the antireflective layer.

Although scatterometry tools are often seen as useful in production, their use in research and development has been limited. The dependence of many of these tools are carefully developed data libraries has made the tools difficult to employ in any setting where the incoming measurement samples may vary widely across several characteristics (etch depth, profile, and CD, for example) at the same time. The demonstrated ability of the n&k 1700-RT to accept the wide range of samples during the development of the Mask Etcher V MoSi etch process is an example of how these issues can
be overcome to produce a positive result. It is likely that as familiarity with scatterometry tools grow, and as the tools themselves mature, they will become more prevalent in R&D environments.

5. REFERENCES

