A novel method for utilizing AIMS™ to evaluate mask repair and quantify over-repair or under-repair condition
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ABSTRACT

The ZEISS AIMS™ platform is well established as the industry standard for qualifying the printability of mask features based on the aerial image. Typically the critical dimension (CD) and intensity at a certain through-focus range are the parameters which are monitored in order to verify printability or to ensure a successful repair. This information is essential in determining if a feature will pass printability, but in the case that the feature does fail, other metrology is often required in order to isolate the reason why the failure occurred, e.g., quartz level deviates from nominal. Photronics-nanoFab, in collaboration with Carl Zeiss, demonstrate the ability to use AIMS™ to provide quantitative feedback on a given repair process; beyond simple pass/fail of the repair. This technique is used in lieu of Atomic Force Microscopy (AFM) to determine if failing post-repair regions are “under-repaired” (too little material removed) or “over-repaired” (too much material removed). Using the ZEISS MeRiT® E-beam repair tool as the test platform, the AIMS™ technique is used to characterize a series of opaque repairs with differing repair times for each. The AIMS™ technique provides a means to determine the etch depth based on through-focus response of the Bossung plot and further to predict the amount of MeRiT® recipe change required in order to bring out of spec repairs to a passing state.

KEYWORDS: AIMS™, Bossung plot, linewidth versus defocus, quartz height, EAPSM, repair verification, MeRiT™, Litho simulation

INTRODUCTION

The ZEISS AIMS™ aerial image measurement system is an absolutely necessary step in photomask qualification providing printability information based on the aerial image performance of the photomask at actinic wavelength. This printability information is utilized for defect disposition, in order to determine which defects require repair, as well as for repair verification, used to determine if the repair was successful. A repair is performed either by etching away excess opaque material or by depositing material in clear regions where the opaque material is missing. The MeRiT® electron beam based mask repair tool can remove and deposit material allowing it to perform both clear and opaque defect repairs. The printability measurement capability of the AIMS™ combined with the repair capabilities of the MeRiT® provide a powerful defect solution to mask manufacturers.

In the case that the feature of interest does not meet the specifications and results in a defect or failing repair, it is useful to know why. The reason for failure can help to determine the proper repair process as well as to provide feedback to the front end of the line (FEOL) for process optimization or yield improvement. In certain defect cases, such as when the quartz height deviates from the nominal value, this information cannot be discerned from the intensity plot and another metrology step utilizing an atomic force microscope (AFM) must be performed. As this additional AFM metrology step is time consuming it would be advantageous if it could be omitted and instead directly use the AIMS™ verification data to extract height information.

In this paper it will be shown that the AIMS™ verification data alone, namely the Bossung plot, can be used to qualify if a defective region has a deviation from the nominal quartz height and if that deviation lies below (in the quartz) or above
(in the opaque material) that level. Furthermore, the magnitude of the height above or below the nominal level is dependent on the slope of the centermost curve of the Bossung plot. Simulations are performed in order to support the experiments and to investigate the impact of different CD and defect type on this technique.

CONCEPT

In order to explain the effect utilized in this work, consider an embedded attenuated phase shift mask (EAPSM) with a line and space pattern. Three different cases of interest exist as shown in Figure 1, including the nominal case in which the quartz height is at the optimal target position, the overetch case in which the quartz level is below that of the nominal and the underetch case in which phase shifting material remains above the quartz level. For each case it is interesting to investigate the CD as a function of defocus, or the Bossung plot. The focus position will be defined as shown in the image with a negative (-) value referring to the intrafocal position when the objective is closer to the mask than at best focus. Conversely the extrafocal position, in which the objective is positioned farther from the mask than best focus will be denoted as positive (+).

![Figure 1. Definition of the over etch, nominal and under etch cases are shown in a simple mask structure. Intrafocal refers to an objective position closer to the mask than at best focus while extrafocal refers to a position farther from the mask than at best focus.](image)

The intensity plot obtained from each case, shown in Figure 2 below, is used to determine the CD. At best focus (black line) the intensity curve, and therefore the CD extracted for a specific threshold, remains relatively constant among the three different cases. As the objective lens is moved to the intrafocal position (red line) however, the over etched condition displays an inverted response to that of the under etched condition due to the difference in the optical path length. As the objective is positioned in the extrafocal position (blue line) the responses invert, but are again opposite with respect to the over etch and under etch cases.
In the ideal case there exists an optimal threshold value (the term threshold value will be used in this paper instead of exposure dose) which corresponds to a constant CD through focus, the so-called isofocal point (green line in Figure 2). A Bossung plot at this isofocal point will show slope of 0 for the nominal case as shown in the center graph in Figure 3. For the overetch condition however, the intensity plot in Figure 2 clearly shows that the linewidth increases going from the intrafocal position to the extrafocal position therefore producing a Bossung plot curve with a positive slope as shown in the left graph of Figure 3 below. The under etch condition, on the other hand yields a negative slope.

A Bossung plot with a positive slope therefore indicates an over etched condition in which the quartz level is below that of the nominal while a negative slope indicates a condition in which material (quartz or absorber) remains at a height above the nominal quartz level. The next section will present experimental results supporting this theory as well as demonstrate the fact that the magnitude of the Bossung plot slope is related to the magnitude of the deviation from the nominal quartz height.

**EXPERIMENTAL RESULTS**

In order to explore the feasibility of the proposed technique an experiment was designed and performed with a suite of tools in the Photronics nanoFab production line. All etches were performed with a ZEISS MeRIT® MG45 electron beam based repair tool and physical height data was verified via an external AFM. All aerial imaging data including the Bossung plot information was obtained with a ZEISS AIMSTM45 system.
The photomask used was a 193nm MoSi EAPSM designed for testing with various features and programmed defects. For the first part of the experiment a horizontal line and space array with a nominal CD of 230nm and a 1:1 pitch was utilized. Four programmed bridge defects, like the one shown in Figure 4, were etched using the MeRiT® with fixed times of 280 s, 240 s, 200 s and 190 s in order to provide two over etched repairs of different depth and two under etched repairs of different height. A summary of the times and deviation from the nominal quartz value are summarized in the table on the right in Figure 4.

<table>
<thead>
<tr>
<th>Etch time (s)</th>
<th>ΔZ from quartz (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>-3.9</td>
</tr>
<tr>
<td>240</td>
<td>-1.3</td>
</tr>
<tr>
<td>200</td>
<td>6.4</td>
</tr>
<tr>
<td>190</td>
<td>10.2</td>
</tr>
</tbody>
</table>

Figure 4. The two images on the left show SEM views of one of the programmed defects before and after etch. The table on the right summarizes the fixed etch times and deviation from the nominal quartz level as measured by AFM.

The Bossung Plots for each of the four etched sites were obtained with the AIMS™45 system and the linewidth vs. defocus curves for the optimum threshold of each etch were extracted. These curves are plotted in Figure 5 below.

Figure 5. The centermost Bossung curve for each of the 4 etches is plotted together. The over etched sites (red) both display a positive slope while the under etched sites (blue) display negative slopes. The magnitude of the slopes in both cases appear to scale with the deviation from the nominal.

First, it can be seen that for every etch there is a significant change in the linewidth across the focus range, indicating a non-optimal etch depth. Secondly, for the two over etched repairs plotted in red (280 s and 240 s) the slope is positive, while for the two under etched repairs plotted in blue (200 s and 190 s) the slope is negative. Therefore the claim made in the Concept Section that the direction of the slope extracted from the Bossung center most curve can tell whether a feature is above or below the nominal quartz etch holds true. The third important observation is that the magnitude of
the slope appears to correlate to that of the deviation from the nominal quartz value. The positive slope of the 280 s (-3.9 nm deep) etch is steeper than that of the shallower 240 s (-1.3 nm deep) etch. Similarly the negative slope of the 190 s etch (10.2 nm height) is steeper than that of the 200 s etch (6.4 nm height).

In order to further investigate this effect a linear regression line was fitted to each of the linewidth vs. defocus curves previously shown in Figure 5 and the slopes were extracted. These values were subsequently plotted against the respective etch times in a single graph, as shown in Figure 6.

![Figure 6](image.png)

**Figure 6.** This graph plots the slope of the centermost Bossung curve against the corresponding etch time for each of the 4 etch times performed. As the optimal etch time should have a slope of 0, a linear regression line was plotted and the etch time corresponding to slope = 0 extracted.

An optimum repair should have no change in linewidth through focus and therefore have a slope of 0 for the linewidth vs. defocus curve. A linear regression line was plotted and the regression line was solved for $y = 0$ (in this plot $y$ is the slope), yielding a theoretical optimum repair time of 222 s. In order to experimentally verify this etch time, another defect was etched with the MeRiT® using a fixed 222 s time and then the aerial image data was obtained with the AIMS™.

Figure 7 shows the AIMS™ data acquired for the optimized 222 s etch. The linewidth vs. threshold plot in the lower right shows a well-defined iso-focal point while the center Bossung curve in the lower left appears to have a slope near 0. These are both good indicators of a successful repair.
SIMULATION RESULTS

In the previous section experimental evidence was presented demonstrating that the slope of the center Bossung plot curve, , can be used to determine if a region has a quartz height deviation from the nominal value. It can also be determined if this height deviation is above or below the nominal value and as the relationship appears to be linear, a quantitative value can be extracted. Furthermore, the etch time required to reach the nominal height can be calculated.

In order to provide more data, investigate further aspects of this technique and provide a broader variety of test cases and variables than would be feasible experimentally, a simulation model was utilized. The simulation was set up in Panoramic® EM-Suit and run using the Rigorous 3D model ("Tempest pr2"). The template was set up with the same 230nm line and space feature with a 1:1 pitch and a bridge defect of similar shape and dimensions to that of the experimental setup. The model outputs the intensity distribution as a function of focal plane deviation from which the Bossung plots are constructed in the same way as for the experimental results section.

The first step in the investigation was to simulate the experiment in order to ensure agreement between the simulation and experimental data. Figure 8 below shows the simulated data which corresponds to that generated from the experimental setup in Figure 6. It can be observed that the general trend of the simulation indeed fits to that of the experiment. Positive values of the slope correspond to the over etched condition in which the quartz level is below the nominal, while negative slope values correspond to the under etched condition in which MoSi remains above the nominal quartz level. Furthermore it can be seen that with more data points added to the simulation, a linear relationship between the slope and etch time (or deviation from the nominal quartz value) can be seen for each region. This linear behavior supports the feasibility of the demonstrated method for calculating the nominal etch time as well as for extracting the actual deviation of the quartz or MoSi height from the nominal. This supports the ability to use the slope of the Bossung curve to extract relative height deviations if the slope of the material is known, without the use of the AFM.

One difference that can be seen between the simulated data in Figure 8 and the experimentally obtained data in Figure 6 is the relative difference between the slopes of the two differing regions. In the experimentally obtained data there are relatively few data points but while there appears to be a steeper positive slope in the under etch region (MoSi) than in the over etched region (quartz), this effect is much less pronounced than in the simulation. This slope difference is indeed explained due to two factors: 1) the difference in the refractive index of the two different materials (2.34 for...
MoSi and 1.56 for quartz) and 2) the difference in the etching rate of the two different materials (0.38 nm/s for MoSi and 0.065 nm/s for quartz). This discrepancy in the slope variation can be attributed to a difference in the refractive index used for the model and the experiment for the MoSi as well as optical differences and physical degradation due to cleaning, exposures, processing, etc. Additionally the true side wall angle of the MoSi can lead to different behavior as that predicted by the simulation which has been performed assuming a perpendicular side wall. One final note is that the slopes of the overetched or quartz regions match quite well, further supporting that the difference lies within the simulation of the MoSi.

In the experimental data a linear fit approximation was applied along the entire plot, fitting both the quartz and MoSi regions to the same line although they appear to have slightly differing slopes. In this case an optimum etch time of 222 s was extracted and provided an optimum etch. The simulation illuminates the fact that it is more appropriate to utilize a linear slope for each individual region separately. Doing so gives us an optimal etch time of 219 s from the underetch region and 223 s from the overetch region, therefore matching very well with the experimentally determined optimum etch time. Therefore, the conclusion is that the optimum etch time, or vertical deviation from the nominal level, can be calculated if the slope in either of the two regions is known.

![Simulated Bossung slope vs. Etch time](image)

Figure 8. Simulated Results of Experimental setup. The slope value of centermost Bossung line is Plotted against respective etch time.

The previous explanation for the difference in slope can be easily verified by converting the etch time axis to optical path difference. Plotting the slope with respect to height instead of etch time removes the etch rate component while multiplying by the refractive index eliminates the component due to the different optical properties. In Figure 9 below this conversion has been made and the slope plotted with respect to the optical path difference. A linear slope can be observed spanning the entire over etched and under etched regions and therefore confirming the assumptions. The line also crosses the origin indicating a slope of 0 would be obtained at the nominal height as the theory predicts.
In order to investigate the effect of feature size on this technique a second simulation was run with a 180 nm line and space pattern with a 1:1 pitch. This data is plotted in Figure 10 (blue points), together with the previous 230nm line and space results. Comparing these two data sets shows that while a smaller CD results in different Bossung slope magnitudes, the linear behaviour holds indicating this technique can be utilized for varying technology nodes. By finding the intersection of the two linearly fitted functions, it is possible to derive an optimal etch time for both the pitches. Assuming that etch rate is not size dependent, the resulting optimal etch time for both pitches provide the same result of 219 s. Future work will investigate different pitches and features as well.

Another interesting aspect, in addition to the effect of the pattern features, is the effect of the size and shape of the defect itself. In order to investigate this the original 230nm line and space pattern with 1:1 pitch template was utilized. The original bridge defect with a width of 230nm was plotted along with a smaller bridge defect of 115nm in width and an...
extension of 230 nm in width but bridging half of the space. Images of the defect layouts along with the plotted simulation data is shown below in Figure 11. Both the small bridge defect and the extension exhibit the same linear behavior as the original bridge, only with a smaller slope. This indicates that for a given pattern, at least in the case for lines and spaces, this technique is applicable for defects of various shape. One final observation is that the small bridge and extension defect, having the same size (230 nm by 115 nm each) but different shape with respect to the pattern, are overlaid with respect to each other. This indicates, from this limited data set, that the size of the defect has more influence than the shape does on the Bossung plot slope variation with respect to etch time or depth.

![Simulated Bossung Slope vs. etchtime](image)

**Figure 11. Study of different sized defects. LS 230 nm at 1:1 pitch.** The defects are SmallDefect width 1xCD and extension 0.5xCD, the HalfDefect width 0.5xCD and extension 1xCD, the Defect width 1xCD and extension 1xCD.

**CONCLUSIONS AND OUTLOOK**

In collaboration with Photronics nanoFab, it has been demonstrated that the Bossung plot output by the AIMS™ system can be used to extract useful information about the variation in z-height from the nominal quartz level for a specific etched feature. The slope of the Bossung plot provides immediate qualitative information as to whether the etched region is below or above the nominal. In the case that the Bossung plot has a positive slope, the quartz level lies below that of the nominal level corresponding to an over etch. A negative slope is, on the other hand, indicative of material remaining above the nominal level corresponding to an under etch. Furthermore, the magnitude of the slope of the Bossung plot correlates to the magnitude of the deviation from the nominal quartz height. As the absolute value of the slope becomes larger, the deviation from the nominal height, either below or above the quartz, becomes larger. This relationship has been shown useful in calculating the optimal repair process and can predict the height difference between a region of interest and the nominal height.
Simulation results have confirmed that a linear relationship between the slopes of the Bossung plots and the etch time for bridge defects does indeed exist, however this linearity may only hold valid within each underetched (MoSi) or overetched (quartz) region separately. The simulation results indicate that this linear relationship exists for line and space features of different CD as well as for defects of varying size and shape. Many aspects of this technique are yet to be investigated including the sensitivity and reliability across various mask materials, features and illumination settings as well as the applicability for quartz bumps and pits.

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REFERENCES