Classification and printability of EUV mask defects from SEM images

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ABSTRACT

EUV lithography is starting to show more promise for patterning some of the critical layers at the 5nm technology node and beyond. However, there still are many technical challenges to overcome before it can be implemented into high volume manufacturing (HVM) and one of them is the production of defect-free EUV masks.

Mask shops today typically use their cutting-edge 193nm inspection tools to detect defects on patterned EUV masks, since no EUV actinic pattern inspection or even e-beam mask inspection tools are available. The 193nm inspection tools have limited resolution on mask dimensions targeted for EUV patterning. The theoretical resolution limit for 193nm mask inspection tools is about 60nm HP on 4X masks, which means that main feature sizes on EUV masks will be well beyond the practical resolution of 193nm inspection tools. Nevertheless, 193nm inspection tools with various illumination conditions to maximize defect sensitivity and/or main-pattern modulation are being explored for initial EUV defect detection. Due to the generally low signal-to-noise in 193nm inspection imaging of EUV masks, these inspections often need to be run “hot” resulting in hundreds or thousands of defects getting detected. Each one of these detections then need to be accurately reviewed and dispositioned. Manually reviewing each defect is difficult due to poor 193nm resolution. In addition, the lack of a reliable aerial image dispositioning system makes it even more challenging to disposition for printability.

In this paper, we present the use of SEM images of EUV masks for higher resolution review and disposition of defects. In this approach, most of the defects detected by the 193nm inspection tools are first imaged on a mask SEM tool. These images together with the corresponding post-OPC design clips are provided to KLA-Tencor’s Reticle Decision Center (RDC) platform which provides a comprehensive SEM ADC (Automatic Defect Classification) analysis of every defect. First, a defect-free or reference mask SEM image is rendered from the post-OPC design, and the defective signature is determined from the difference image. The defective signatures help assess the true nature of the defect as seen under e-beam imaging; for example, excess or missing EUV absorber, line-edge roughness, contamination, etc. Next, the defect and reference contours are extracted from the grayscale SEM images and fed into the simulation engine with an EUV mask and scanner model to generate corresponding EUV defect and reference aerial images. These are then analyzed for printability and dispositioned using RDC’s Aerial Image Analyzer application to automatically measure and estimate the impact of the mask defect to wafer CDs. By integrating the SEM ADC application into the EUV inspection and review flow this way, every defect is characterized for its type and printability. Such defect characterization is essential not only for determining which defects are nuisance or critical, but also for monitoring the performance of EUV mask process tools.

With EUV lithography progressing towards volume manufacturing and progress being made in the area of e-beam based mask inspectors, the EUV SEM ADC software solution will continue serving an essential role of dispositioning defects off e-beam imaging.

Keywords: EUV mask inspection, mask defects, ADC, Automatic Defect Classification, defect SEM review, mask SEM, reticle SEM, SEM ADC, Aerial Image Analyzer, AIA, Reticle Decision Center, RDC
1. MOTIVATION

The availability of defect-free EUV masks is crucial to inserting EUV lithography into HVM (High Volume Manufacturing). There have been many studies done on developing viable inspection solutions for EUV patterned masks. Currently 193nm optical inspection tools are still the workhorse for detecting pattern defects on EUV masks. However, pattern sizes on EUV masks are expected to be beyond the limit of resolution of 193nm inspection tools. Figure 1 shows an example of such an EUV test mask pattern. At the native EUV wavelength of 13.5nm, these patterns print as expected. However, under the best available resolution on 193nm inspection tools today, one can hardly recognize the mask patterns.

![EUV Mask, Wafer aerial image, 193 inspection image](image1)

**Figure 1.** Simulated imaging of a test mask at EUV 13.5nm versus 193nm wavelength

On these tools, one can setup the inspection either to maximize the signal of defects, often resulting in the associated main features not resolving or vice versa, i.e., maximize main feature modulation but with somewhat lower defective signal strength. Figure 2 shows an example of such a compromise in imaging performance one needs to consider when inspecting EUV mask geometries on 193nm inspection tools.

![Optimized for patterns, Optimized for Defects](image2)

**Figure 2.** 193nm inspection imaged for main pattern contrast vs. defect signal

Furthermore, main patterns barely resolve in 193nm imaging at 88nm HP for example, and are completely unresolved at 64nm HP and below as shown in Figure 3.

![88 nm HP, 64 nm HP, 52 nm HP](image3)

**Figure 3.** Resolution of mask patterns in 88nm HP vs. 64nm HP vs. 52nm HP line-space patterns on 193nm inspection tool
Lastly, under 193nm imaging, main patterns and sometimes defects too show a reversal of tone or color which makes it very difficult to classify. Figure 4 shows how both contact holes (generally bright in optical inspection) and posts (generally dark in optical inspection) look similar under 193nm imaging.

For 193nm optical masks, computational review of mask defects has successfully been deployed into mask manufacturing [1, 2]. For EUV masks inspection on 193nm inspection tools, there also is a need for an Automated Defect Classification system especially since the tools end up being setup quite “hot” resulting in hundreds, if not thousands, of defects being detected. However, due to the challenges of defect and main pattern resolution, and tone inversion, ADC performance may be limited to filtering some false and nuisance defects. Hence, there is need for a higher resolution defect review system such as a mask CD-SEM or review SEM tool to better image the remaining detections, and also for a corresponding ADC system to better characterize and disposition defects imaged by the SEM tools.

2. SEM ADC WORKFLOW

From the 193nm optical inspection report, test SEM images are first captured on a mask review or CD-SEM tool. The defect-free or reference SEM images are rendered from the corresponding post-OPC design database clips in a die-to-database type approach. The SEM ADC workflow then involves three main steps as shown in Figure 5: Defect isolation, Classification and Printability.

Step1. The original images from the SEM tool are first de-noised and refined to improve the quality of the images. Then, the post-OPC design database at the same location as the defect are clipped, and a SEM model applied to render a defect-free reference SEM image. The de-noised test and rendered reference SEM images are aligned and also subtracted to generate a grayscale difference image which is then used to isolate the defect site by local gray level integration.

Step2. Binary contours are extracted from the de-noised SEM test image to generate the Test Binary mask containing the defect, and also from the rendered SEM image to generate the Reference Binary mask. A binary difference image is then generated by subtracting the Reference Binary from the Test Binary mask. The gray and binary difference images thus generated are used to calculate defect metrics from the defect isolated in Step1, for example, defect area, size, gray-level intensity, percentage of defect lying on the multilayer, etc. This information is saved in a DefectInfo table, and then some rules-based guidelines are applied to generate the final defect classification code.

Step3. The EUV Defect Printability Simulator (DPS) mask model 0 is then applied to both the Test and Reference binary masks with the associated scanner exposure conditions to generate Test and Reference EUV Aerial images. The Aerial Image Analyzer (AIA) Error! Reference source not found,[5] is then run to compute printability of all features within the Field of View (FOV).
2.1 SEM ADC Classifications

Figure 6 shows the different classification bins provided through SEM ADC along with some examples (Fig 6). Absorber defects are categorized into hard-defect or line-edge roughness (LER) based on the defect size and geometric topologies affected by the defect. Contamination or particle type defects are categorized into on-absorber or on-ML (multi-layer). On-absorber means the defect is completely on top of the absorber surface and away from any ML by a certain distance, and hence should not have any impact on printability. On-ML means the defect is fully or partially lying on the ML and may have printability impact. Depending on the defect-type identified, a more comprehensive analysis is then done for each classification:

![Classification examples](image)

Figure 6. Classification examples. 6a. Hard-defect, 6b. Line-edge roughness, 6c. Contamination or Particle on Absorber, 6d. Contamination or Particle affecting ML

a. Hard-Defect

When a defect is classified as an absorber hard-defect, its size and area are extracted (Figure 7b) as one of the metrics to judge defect severity, and also its printability impact is reported as shown in Figure 7c.
b. LER

In the SEM image of Figure 6b, there is no obvious defect seen and SEM ADC classifies it as LER. However, when upon zooming into the SEM (Figure 8b) and binary difference (Fig 8c) images, tiny extensions on the absorber edge are evident. SEM ADC classification does not react to tiny absorber defects, instead its printability in the EUV aerial image plane is considered to determine its criticality. In the example shown in Figure 8, both absorber edges on either side of the ML space have small extensions and even through each extension is small, the sum of its impact to print CD is seen to be quite large. This is a good example of why SEM ADC has both classification and printability checks in the flow.

c. On Absorber

Although On-absorber defects are supposed to be completely on top of the absorber and should not have any impact on printability, SEM ADC still checks its printability for conformation (Figure 9). In this case, all contact CD errors are less than 5% and also the size of the defect on ML is 0 nm² so SEM ADC can clearly disposition this as a nuisance.

d. On ML

When a defect lies on the ML, its area and size are computed (Fig 10b). Even though contamination and particle defects are not of the same material as absorber defects, SEM ADC considers them as full-height absorber (Figure 10c) and predicts their worst-case printability (Figure 10d) providing a conservative wafer print estimate.

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**Figure 7a.** Hard-defect result from Fig 6a. 7b. Binary difference to measure the defect size, 7c. Printability simulation result

**Figure 8a.** LER result from Fig 6b. 8b. Zoom-in SEM of defect site at 8a red box, 8c. Zoom-in binary difference at defect site, 8d. Printability simulation result
3. RESULTS

3.1 Performance on defect classification

Figure 11 shows SEM ADC performance (in blue) on programmed defects (left) and naturally occurring defects in product-like masks (right). Also shown in red is the same for Optical ADC. It can be seen that the classification performance on programmed defects is almost the same but on natural defects, SEM ADC classification accuracy is substantially better than Optical. The poor resolution of main-features and defects in 193nm optical images causes defects to be cautiously classified as absorber hard-defects whereas using the SEM images, defects can be more precisely placed into their individual classification bins.

Figure 12 shows some examples of real defects as imaged and classified in the 193nm optical and SEM images. The resolution of defects at 193nm do not lend itself to be sufficiently differentiated and hence are often conservatively classified as being on edge, i.e., critical. However, in the SEM images, the defect signatures are a lot clearer resulting in a more accurate and finer classification of not just absorber but also particles and contaminations that are on the absorber material and don’t affect printability.
### Correct bins

**SEM / Optic**

<table>
<thead>
<tr>
<th>Real defect types</th>
<th>Programmed Defect</th>
<th>Natural Defect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Absorber Defects</td>
<td>Absorber Defects</td>
</tr>
<tr>
<td>Dark Ext</td>
<td>67 / 68</td>
<td>152 / 172</td>
</tr>
<tr>
<td>Clear Ext</td>
<td>16 / 15</td>
<td>20 / 977</td>
</tr>
<tr>
<td>Pin Dots</td>
<td>53 / 51</td>
<td>945 / 0</td>
</tr>
<tr>
<td>Pin Holes</td>
<td>44 / 42</td>
<td>20 / 1</td>
</tr>
<tr>
<td>Contam/Particles</td>
<td>1 / 0</td>
<td>20 / 1</td>
</tr>
</tbody>
</table>

**SEM ADC works better. Optical ADC works OK.**

- Matching ratio, SEM 99.5% vs. Optical 97.2%

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**3.2 Performance on defect printability**

The printability performance of SEM ADC engine was verified with respect to another simulation engine as shown in Figure 13. This comparison was performed for many natural defects on product-like masks, and shows a fairly good correlation. The simulated aerial images (right) also show generally good matching between the two EUV defect modeling engines.

![ADC images comparison](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)
4. CONCLUSIONS

For EUV defect characterization and disposition, a SEM-based ADC solution provides the desired accuracy and precision of classification and estimated printability. 193nm optical inspection images clearly lack the resolution to accurately classify naturally occurring defects on EUV patterned masks. The EUV SEM ADC product is now qualified to support initial EUV mask manufacturing R&D and ramp. We plan to next correlate its print accuracy with actual wafer prints. Over the next few years, as EUV technology is expected to ramp up, SEM ADC is expected to be just as effectively used in HVM to better characterize defects and reduce post-inspection defect loading on downstream repair and review tools.

REFERENCES


Figure 13. Comparing EUV defect printability estimation from SEM ADC with another EUV simulation engine for natural defects