Printability of buried extreme ultraviolet lithography photomask defects

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Abstract. Native acting phase-programmed defects, otherwise known as buried program defects, with attributes very similar to native defects, were successfully fabricated using a high-accuracy overlay technique. The defect detectability and visibility were analyzed with conventional amplitude and phase-contrast blank inspection at 193-nm wavelength, pattern inspection at 193-nm wavelength, and scanning electron microscopy. The mask was also printed on wafer, and printability is discussed. Finally, the inspection sensitivity and wafer printability are compared, leading to the observation that the current blank- and pattern-inspection sensitivity is not enough to detect all of the printable defects. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JMM.15.2.021004]

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1 Introduction

Mask defects that matter are the ones that print during exposure at 13.5 nm. To support extreme ultraviolet lithography (EUVL) development and production schedules, mask defectivity must be reduced to be at or near optical mask defect levels. This task is complicated by the fact that actinic EUV inspectors and EUV aerial image measurement system are not readily available. In the absence of these tools, all available methods of detecting and characterizing defects and their printability must be deployed. While programmed defect macros (PDMs) can be used to characterize the printability and inspectability of absorber-type defects, analogous techniques to characterize buried defects in the multilayer are problematic. Understanding the lithographic tolerances for these defects and the mask maker's sensitivity to them without actinic inspection is essential to refining mask and substrate supplier roadmaps.

As discussed above, PDMs can be generated to characterize the mask inspection and lithographic impact of absorber defects. Standard mask patterning processes, applied to the substrate prior to multilayer and absorber deposition, has been demonstrated as a method for creating programmed buried defects. However, these defects were rectangular or cubic in shape and are typically uniformly equal in height to the standard films. More importantly, it has been reported that defect printability is very different among native defects and programmed defects. Therefore, it is necessary to develop a method for systematically evaluating programmed buried defects with current state-of-the-art inspection and exposure tools.

We have developed an approach for fabricating buried programmed defects with attributes more similar to naturally occurring defects located beneath the multilayer. A test mask containing such defects was developed and used in a study that explores current capabilities in defect characterization, inspection sensitivity, and wafer printability at 13.5-nm wavelength of buried defects. This mask was named EUV new defect evaluation activity vehicle for optimization, utilization, and reflectivity (ENDEAVOUR) study.

2 Materials

Figure 1 shows a typical image of (a) a buried programmed defect that is created by conventional mask patterning and (b) one created by the novel fabrication method described here. As mentioned previously, it has been shown that defect printability is very different for programmed defects compared to native defects. One of the primary reasons for the difference in printable behavior between native and programmed defects may be defect shape. For instance, programmed buried defects created by a typical mask patterning process will appear rectangular and ridged in morphology, with orthogonal edge profiles [Fig. 1(a)] as compared to native defects which typically have a smooth surface morphology and edge gradation [Fig. 1(b)]. A novel programmed defect fabrication methodology is used in this work, which resulted in buried defects that better represent the smooth morphology of what naturally occurs during the substrate defect formation process [Fig. 1(b)], as opposed to the ridged rectangular defects seen in past programmed defect approaches. These defects will be called “native acting phase-programmed defects” (NAP-PDs).

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Figure 2 shows the approach to fabricate the NAP-PDs on the ENDEA VOUR test mask with more naturally contoured defects. First, a quartz blank capped with Ta-based film is prepared and fiducial marks are patterned with a 50 kV E-beam writer and a standard mask process. Seed defects are then added to the substrate with a microfabrication method. Both bump- and pit-type defects are fabricated, with Cr as the additive material to create bump defects. After the placement of these seed defects, 40 alternating layers of Mo/Si are deposited, followed by a Ru protective cap, and a Ta-based absorber material. Finally, arrays of 128-nm contact-hole patterns are placed over the seed defects with a novel high-accuracy overlay method. A highly accurate overlay technique is required because it is critical that the hole pattern is centered on each seed defect. If the “seed defect” width is 100 nm, the overlay error has to be less than 14 nm; otherwise, the defect would be printed under the pattern edge or under the absorber. To avoid that situation, the overlay target was set to 14 nm.

3 Defect Characterization

3.1 Defect Types and Sizes

Figure 3 shows examples of NAP-PDs, fabricated through our process. On the ENDEA VOUR test mask, there are 240 types and sizes of NAP-PDs. This figure shows the defect size and height of each NAP-PD. The defect sizes reflect measurements taken on the substrate before multilayer and absorber deposition. The defect width range is from 30 to 700 nm, and the height or depth is from 0.5 to 65 nm. During this study, we primarily focused on small defects (100 nm or smaller defect width and 2-nm or lower defect height) because it is expected that those defect sizes will be difficult to detect during inspection and represent borderline printable/nonprintable on wafer. The scanning electron microscopy (SEM) pictures show examples of the various types of NAP-PDs, including shallow and sizeable defects. Shallow defects are very short and have widths that are significantly greater than their heights. Sizeable defects are those in which widths and heights are both significantly large. Printability of these defects is discussed later in this document.

3.2 Overlay Accuracy

Figure 4 shows the overlay accuracy result between defects under the multilayer and patterns on the absorber. All of the buried defects were created on the substrate before multilayer and absorber deposition. After film deposition, 128-nm contacts were subsequently patterned and etched into the absorber. The center of gravity was measured for both defects and patterns, then overlay accuracy was calculated. Both $X$ and $Y$ errors were calculated for each defect. The four SEM images shown in Fig. 4 provide typical overlay analysis and results for a representative set of defects (A, B, C, and D). Overlay error was found to be 1.4, 2.9, 11.1, and 9.2 nm, respectively, indicating high overlay accuracy was achieved with our approach, easily meeting our target of <14 nm.
3.3 Blank Inspection Sensitivity

Figure 5 shows the distribution of defects found using an amplitude and phase-contrast blank inspection tool at 193-nm wavelength. The mask was inspected after absorber deposition, but before absorber patterning. High inspection sensitivity was used to understand what defects could possibly be detected. Results of this inspection indicate that most defects with 150-nm or larger width and 2-nm or higher height are detectable. On the other hand, defects in which widths are 150 nm or smaller and heights are 2 nm or lower are difficult to detect. The detectable ratio of those small defects is about 39%. When the defect width is less than 50 nm, the detectable ratio reduces to 0%.

3.4 Pattern Inspection Sensitivity

Figure 6 shows the patterned inspection result of the ENDEAVOUR mask. It was inspected on a 193-nm wavelength inspection tool after patterning. Similar to blank inspection, a higher inspection sensitivity was applied to understand what defects could be detected. This result shows that postpatterning inspection is able to detect defects 400 nm or larger in width and 10 nm or higher height defects. Conversely, there is a very low probability of detecting defects smaller than 200 nm, as indicated by the 6.5% detection ratio. If the defect width is less than 60 nm, the detectability is reduced to 0%. The data indicates that it is preferable to detect NAP-PDs during blank inspection prior to mask patterning.

3.5 Scanning Electron Microscopy Visibility

Figure 7 shows the visual analysis results of SEM images. SEM images for the NAP-PDs were captured by a critical dimension (CD)-SEM at 75,000× magnification. Defect detectability is judged based on a visual inspection of those SEM images. If there is a visual difference between

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**Fig. 4** Overlay analysis result between defect and patterns.

**Fig. 5** Blank inspection result at 193-nm wavelength inspector.

**Fig. 6** Pattern inspection result at 193-nm wavelength inspector.

**Fig. 7** Scanning Electron Microscopy Visibility result.
reference and programmed defect locations, as shown in the SEM pictures of Fig. 7, it is labeled as a detectable or visible defect. Most of the NAP-PDs tested were invisible in the SEM images (no difference is seen when compared with a reference image). The data indicate that the visibility of buried defects with a height of 20 nm or less is difficult to identify by SEM. It is expected that these NAP-PDs will be difficult to detect on an E-beam inspection tool.

4 Wafer Printability Analysis

The ENDEAVOUR mask was exposed with quasar illumination on an ASML NXE3300B11 to optimally image the contact arrays. Figure 8 shows an example of the wafer print analysis. The left figure shows an AFM image of the programmed defect as it appears on the quartz substrate. The defect type is a bump, with a width of 129.2 nm and the height of 10.3 nm. The center picture shows the AFM and blank inspection images after multilayer and absorber deposition. The defect size slightly changed as compared to the defect size on substrate. The defect was detectable during 193-nm blank inspection and showed a high defect signal. The right figure shows the SEM and patterned inspection images. The defect could be visually identified from the SEM image; however, a low defect signal was recorded during patterned inspection. This means the defect is detectable with low sensitivity during blank inspection but requires high sensitivity settings during patterned inspection. The bottom figures show the wafer images from the NXE3300B. The defect was analyzed with three focus settings: best, positive, and negative focus. Here, positive focus represents a focus offset into the mask, while negative focus is an offset away from the mask. Strong impact is observed from the wafer images, especially for positive focus. The defect was judged as printable.
Figure 9 shows another example of defectivity printing. The left figure shows the seed defect AFM image on the quartz substrate. The defect type is a pit, with a width of 57.7 nm and the height of 1.4 nm. The center image shows the defect AFM image after multilayer and absorber deposition. Blank inspection was performed after absorber sputtering; however, the defect was undetectable. The right figure shows SEM images after absorber patterning. A defect could not be visually identified from the SEM image. Pattern inspection at 193-nm wavelength was also performed, but similarly, no defect signal was observed. The bottom figures show the wafer print images. This data indicates that the defect was printable, with strong effects especially for negative-focus images, even though the defect was not visible by SEM or blank/mask inspection.

Figure 10 shows the focus dependence (Bossung tilt) of NAP-PDs. The impact of focus was measured on wafer for both pit- and bump-type defects. X and Y axes show the focus position and measured wafer CD, respectively. Wafer CD without a programmed defect is labeled as “reference” and represented by the blue line. Three representative bump and pit defects and their impact on wafer CD are shown in Fig. 10. All pit defects show stronger impact on negative focus images as compared to best and positive focus [Fig. 10(a)]. In contrast, bump defects show stronger CD impact from positive focus [Fig. 10(b)]. This is consistent with the view that the programmed defect shifts the multilayer surface such that out-of-plane film distortions can be compensated for by a negative (bump) or positive (pit) defocus.

Figure 11 indicates which of the fabricated NAP-PD defects negatively impact wafer imaging. Defect printability was analyzed for each NAP-PD based on wafer CD measurements. In the graph below, the green diamond and the red circle indicate “nonprintable” and “printable” defects, respectively. A defect is deemed printable if it influences the wafer CD by greater than 10% from the reference CD. As Fig. 10 shows, most of the NAP-PDs were printable, even if the defect height is less than 1 nm.
5 Wafer Printability Versus Inspection Sensitivity

Inspection sensitivity and wafer printability of NAP-PDs are summarized and shown in Fig. 12. The area represented in yellow indicates “unknown territory,” meaning, it was not possible to quantify buried defect detectability or printability due to fabrication and characterization limitations of such small defects. The blue color area represents the detectable buried defect region by conventional blank inspection or patterned inspection at 193-nm wavelength. The white color area indicates a region of buried defects that are undetectable using conventional 193-nm wavelength inspection. Despite printable defects within this region, it was not possible to detect defects of such small dimensions using either conventional blank and patterned inspection methods. A solution for detecting such defects is required.

6 Summary

New types of buried programmed defects, NAP-PD, were successfully created using a novel deposition and etching methodology and a high-accuracy overlay method. The overlay accuracy between the programmed buried defect and absorber pattern was less than 14 nm, ensuring excellent spatial correlation between defect and pattern.

Detectability and visibility of NAP-PDs were analyzed with current inspection and SEM tools. Table 1 shows the summary of detectable versus printable defect sizes. Blank inspection at 193-nm wavelength was performed after absorber and multilayer deposition, and confirmed that the blank inspection is able to detect most large defects, but unable to identify defects with 150-nm or smaller widths, and 2-nm or shorter heights. Patterned inspection at 193-nm wavelength was also evaluated postpatterning 128-nm contact arrays. There is very little chance of detecting defects of 200-nm or smaller width, and 10-nm or shorter height, via patterned inspection. SEM metrology was also evaluated postpatterning. Buried defects were not visible in the SEM image if the defect height is 20 nm or less.

Relative to wafer printability, it was confirmed that most NAP-PDs were printable, even if the defect height is less than 1 nm. It was also shown that there was a focus dependence. Pit defects showed a stronger CD impact at negative focus as compared to best and positive focus. In contrast, bump defects showed a stronger CD impact from a positive focus.

Finally, defect detection sensitivity and printability were compared. Results indicate there is a gap between defect detectability and wafer printability. Current 193-nm wavelength blank and patterned inspection systems were unable to detect small buried defects despite having a ≥10% CD impact on wafer. Therefore, there is no practical approach for detecting all multilayer defects with nonactinic inspection wavelengths.

The results from this study were made possible by knowing the “programmed” locations of the buried defects. If these defects had been “naturally occurring,” analysis could only be done on those defects detected within the penetration distance of the 193-nm inspection wavelength (roughly the first three layers of the multilayer). To detect tiny defects buried deep within the multilayer, an actinic wavelength blank or pattern-inspection tool, capable of “seeing” through all levels of the multilayer, is required. This gap must be addressed before high volume manufacturing.

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Table 1 Summary of detectable versus printable defect size.

<table>
<thead>
<tr>
<th>Defect Type</th>
<th>Detectable/visible defect size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank phase-contrast inspection</td>
<td>Width: &gt; 150 nm, height: &gt; 2 nm</td>
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<tr>
<td>(193-nm wavelength tool)</td>
<td></td>
</tr>
<tr>
<td>Pattern inspection</td>
<td>Width: &gt; 200 nm, height: &gt; 10 nm</td>
</tr>
<tr>
<td>(193-nm wavelength tool)</td>
<td></td>
</tr>
<tr>
<td>SEM visibility (Mag: 75,000×)</td>
<td>Width: &gt; 400 nm, height: &gt; 20 nm</td>
</tr>
<tr>
<td>Minimum printable defect size</td>
<td>Width: &lt; 35 nm, height: &lt; 1 nm</td>
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</tbody>
</table>

Fig. 11 Wafer printability analysis.

Fig. 12 Wafer printability versus inspection sensitivity.
References


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