Reflecting on inspectability and wafer printability of EUV mask absorbers

Kazunori Seki¹, Karen Badger², Emily Gallagher², Gregory McIntyre³, Toshio Konishi¹, Yutaka Kodera⁴, Satoshi Takahashi⁴, Vincent Redding⁵

¹ Toppan Photomasks Inc., 1000 River Street, Essex Junction, VT, 05452
² IBM Microelectronics, 1000 River Street, Essex Junction, VT, 05452
³ IBM Microelectronics, 257 Fuller Road, Albany Nanotech, Albany, NY, 12203
⁴ Toppan Printing Co., Ltd. 21-33 Nobidome 7-chome, Niiza-shi, Saitama 352-8562
⁵ KLA-Tencor Corporation, 1 Technology Drive, Milpitas, CA, 95035

ABSTRACT

Four EUV film stacks are prepared and evaluated from multiple points of view: mask fabrication, blank inspection, non-actinic inspection, actinic inspection and wafer print. Mask linearity measurements show very good results for all of four blanks. Blank inspection results reveal similar inspectability. Blank roughness and reflectivity at 193nm wavelength were also measured. Some types of defects were evaluated with both non-actinic inspection tools and simulations. It was found that the thinner low reflectivity (LR) stack shows higher defect sensitivity than the thicker ones for pattern defects at 193nm inspection wavelengths. Phase defect evaluations indicate that thinner total film stacks (LR plus absorber) have an advantage for phase defect detection. Defect printability was evaluated through focus by imaging on an EUV microscope and defect printability was shown to be equivalent among the four stacks. Then the appropriate film stacks are discussed from the wafer point of view. Finally the appropriate stack was chosen based on evaluations from all the various points of view.

Keywords: EUVL, blank inspection, mask inspection, wafer printability, defect sensitivity, actinic image

1. INTRODUCTION

EUV (Extreme Ultraviolet) lithography is one of the most promising techniques for imaging 7-nm node wafer features. There are several challenges associated with moving EUV lithography from development to manufacturing and mask defectivity is one of the largest.[1] EUV mask inspection may require more advanced approaches than those currently employed on optical masks.[2, 3] Where both transmitted and reflected light are used for optical mask inspection, only reflected light is available for EUV because the masks are reflective.[4] EUV blanks consist of many layers: LTEM (Low Thermal Expansion Material) substrate, backside conductive layer, front side reflective stack of 40 of Mo/Si bilayers, a Ru protective cap, and the Ta-based absorber material and Ta based low reflective material. The thickness of both the absorber and the low reflectivity layer are very important for both wafer print and mask fabrication process. From the wafer point of view, phase shift and reflected intensity are a function of the total thickness and with impact on MEEF and NILS as well. [5, 6] From the mask fabrication point of view, it is confirmed that defect inspectability and defect sensitivity vary with film thickness.[7] Four different EUV blanks are prepared for this study. These blanks are evaluated from many points of view and the best blank was identified.

2. MATERIALS

Figure 1 shows the EUV film structures used for this study. They are labeled Stack_A, Stack_B, Stack_C and Stack_D. All of four stacks have same configuration from capping layer to the back side material: 2.5nm of Ru-capping layer, 40 pairs of Mo/Si bi-layers on the substrate and 20nm CrN on the back side. The only difference between the stacks is the...
film height of the low reflective material and absorber. Stack_A is the thinnest blank of the four, with the thinnest LR and absorber. Stack_B is the thickest stack of all four blanks, coupling the thinnest LR layer with the thickest absorber. The total height of Stack_C is same as Stack_B, but it has a thicker LR and a thinner absorber. Stack_D has the thinnest LR and a moderate absorber; the total stack height is thicker than Stack_A and thinner than Stack_B.

3. MASK FABRICATION

Mask linearity is measured to compare mask process capability. The results are shown in Figure 2. Isolated clear patterns between 50nm to 500nm in size, as well as nested clear and isolated opaque patterns were used for these measurements. All four masks demonstrate very good, and similar, linearity. It is confirmed that all four of the stacks are appropriate in terms of the mask fabrication process.

4. BLANK INSPECTABILITY AND FACTORS

4.1 Blank inspectability comparison

The blank inspection at 193nm wavelength [8] used an algorithm developed to detect phase defects located in or under the multilayer. Figure 3a shows the blank inspectability comparison result. Defect sensitivities are optimized to minimize nuisance detections, the very small sub-specification defects and false defects. The same inspection settings are applied to all four blank and compared. Figure 3a shows the defect count comparison result. Stack_A shows slightly higher defect counts than others, and the defects appear to be real defect as shown in Figure 3b. These are likely the result of bumps or pits in or under multilayer, but without failure analysis, there is no way to confirm the real defect shape. In any case, the defects are not considered a consequence of the absorber stack.
4.2 Blank roughness comparison
The purpose of this study is to determine whether there is a roughness difference among the four different film stacks because blank roughness may impact blank inspectability.[9] Figure 4 shows the blank roughness result of all four film stacks. Stack_A, B, C and D have Root Mean Square (RMS) values of 0.308nm, 0.393nm, 0.388nm and 0.336nm respectively. All these numbers are the essentially the same since they are within normal variability.

Power Spectral Density (PSD) analysis showed no significant difference in all frequency regions (low frequency, middle frequency and high frequency). Based on these results, there should be no blank inspectability difference among film stacks.
The defect counts also indicate that defect reduction will be required for all of film stacks because acceptable defect count should be 20 or lower to enable defect avoidance by pattern shift. [10] However, these blanks were engineering grade, so with focus we anticipate improvements to defect level.

5. DEFECT SENSITIVITY

5.1 Defect analysis at 193nm wavelength

Table 1 compares the two 193nm wavelength inspection tools, used for this evaluation, Tool_1 and Tool_2. Only die to database mode was used. Tool_1 uses circular illumination with a single, fixed focal plane and Tool_2 use circular or off-axis illumination with two focal planes. Optimized light calibration settings were used for both tool evaluations. Tool_1 uses one focal plane with a fixed offset by default for all masks, and Tool_2 uses two focal planes with a fixed delta between them. These two planes are optimized on a programmed defect test mask for a particular substrate type. For modeling Tool_1 uses standard modeling algorithms that are based on optical mask modeling. Tool_2 uses sophisticated EUV modeling algorithms that adjust film properties on observed optical images during the setup.[11] The defect sensitivity was also optimized for fewer than 50 false detection settings.

Figure 5 shows the inspection result from Tool_1. Programmed opaque extension defects on 72nm L/S and on 128nm hole patterns were used for this study. The defect signal, represented by the gray scale difference of 2x2 pixels between reference and defect pattern, is compared across the four stacks. Stack_D shows the highest defect signal for most defect types, followed by Stack_A and Stack_B. Stack_C shows the lowest defect signal. It is considered that the defect sensitivity difference is due to the reflectivity difference shown in Figure 6. Stack_C shows lower reflectivity than others due to the thickness of LR.

Table 1. 193nm wavelength tool settings

<table>
<thead>
<tr>
<th>Optimization Parameter</th>
<th>Tool_1</th>
<th>Tool_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspect Mode</td>
<td>Database</td>
<td>Optical</td>
</tr>
<tr>
<td>Illumination</td>
<td>Circular</td>
<td>Circular + Off-Axis</td>
</tr>
<tr>
<td>Light Calibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Focus Offset Plane(s)</td>
<td>Standard</td>
<td>Advanced</td>
</tr>
<tr>
<td>Modeling</td>
<td>&lt; 50 Off-grid</td>
<td>&lt; 50 Off-grid</td>
</tr>
</tbody>
</table>

Figure 5. Defect signal comparison results (Tool_1)
Figure 7 shows the inspection results from Tool_2. The results are more complex than Tool_1 because Tool_2 is a two focal plane system. This means that the defect signal is the combined result of two focal planes (the higher signal was plotted for each defect). Overall, Stack_D shows the highest defect signals. Stack_A and B show the second highest defect signals. The results are similar to Tool_1’s, shown in Figure 5. These results indicate that the thicker LR has a lower defect signal than thinner LR.

5.2 Phase defect analysis at 193nm wavelength
Phase defect detection is one of the most difficult challenges for non-actinic inspection tools. The 193nm light does not penetrate very deep into the multi-layer, so a relatively low defect signature on the surface of the absorber or multi-layer may be detected.[2] There may also be differences between the 13.5nm actinic phase impact and what can be seen at the 193nm wavelength. Simulation was used for this phase defect evaluation to ensure that the same size of phase defect is evaluated on all four blanks. The simulation setup uses the following assumptions; a simple high-NA microscope, 193nm inspection and NA of 0.95. Figure 8 shows the pattern and defect location information used for this study. The full with at half maximum (FWHM) of 47nm and a 2nm deep pit defect was simulated at five locations: center of the clear line, near the absorber edge, partially under the absorber edge, just under the absorber edge, and completely under the absorber.

Figure 9 shows the simulation results. This result assumes pure intensity measurements and no phase tricks within the inspection system. All images are at best focus. The defect images were created by subtracting the reference image from the defect. When the defect is located in a space (no shift and a small shift of 28nm), the defect intensity is higher than 5% for all four stacks, which means the 193nm wavelength tool should detect these defects. When the defect is located under the absorber, or partially under the absorber (shifts of 56nm, 84nm and 112nm), the defect intensity is lower than...
5% and should be difficult to detect. Overall, Stack_A shows the highest defect signal and Stack_D shows the second highest. The defect intensity of Stack_A is more than 20% and is almost double of that of Stack_C. The results indicate that thinner absorbers have higher defect signals than thicker ones. It is considered that the thinner absorber is good for phase defect detection for the 193nm inspection tool.

5.3 Actinic (EUV) imaging with SHARP

The purpose of this study is to estimate inspectability based on EUV wavelength imaging on the four different EUV film stacks. Actinic inspection tools are several years away from production so inspectability is compared using EUV microscope images which were captured by the SHARP tool. SHARP, The Sematech High-NA Actinic Reticle review Project, is a microscope operated at the Center for X-Ray Optics at the Lawrence Berkeley National Laboratory. Figure 10 shows the microscope images of the 128nm hole pattern and the cross section profile of each image. For these images, pattern contrast was calculated and compared. These four images look similar and all show good contrast. Based on the imaging, inspectability at EUV wavelengths should be similar for the four film stacks. A more detailed evaluation will be required when a commercial EUV inspection tool is available.

6. WAFER PRINTABILITY

6.1 Through focus analysis with SHARP

Through focus analysis was done with the SHARP tool to compare defect printability across the four different film stacks. Programmed defects of the same size were analyzed with various steps of focus, and their printability evaluated. Figure 11 shows the through focus evaluation result of an opaque extension defect on 72nm line/space pattern. Dipole illumination with practical initial settings for the NXE3300B, and -100 to +100nm focus was used for this measurement. Wafer printability is very similar among the four film stacks, not only at best focus but also at both negative and positive focus settings.
Figure 12 shows one more example of through focus evaluation. An opaque extension defect on the 128nm hole pattern was analyzed with a -150 to +150nm focus range. Quasar illumination with NXE3300B settings was used. The defect printability is similar for the four different film stacks as well. Defect printability of these four blank appears to be identical.

6.2 Wafer process point of view
Wafer printability and wafer process including yield is one of the most important parameters for blank selection. Gregory McIntyre et al. reported that there are many trade-offs between thinner and thicker films.[5,6] Generally, a thinner stack reduces 3D mask effects, however there are other considerations. Figure 13 shows two important absorber-driven parameters for wafer print: reflectivity of the absorber should be low and the absorber phase shift should be near 180 degrees. This result indicates that relative Anti-Reflective Coating (ARC) thickness has no impact on wafer printing, which means we can choose ARC thickness based on mask inspectability, repairability or cleaning durability. The total thickness impacts both reflected intensity and phase shift. Based on these analysis, Stack_D is chosen as the best blank of all four stacks and Stack_B and C is the second best. Stack_A is not appropriate in terms of wafer print.

Figure 12. Through focus analysis with SHARP (Hole pattern)

Figure 13. Reflected intensity and Phase shift value with various film thickness
7. SUMMARY

Four film stacks were evaluated from various points of view as is documented in Table 2. The mask fabrication process shows very good performance for all of four blanks. Blank inspectability was evaluated by blank inspection, absorber roughness measurement, and PSD profiles and scored yellow for all of four stacks because no inspectability difference was seen but all blanks had many real defects. Stacks_A, B, D that have thinner LR, are all appropriate for non-actinic pattern inspection. Stacks_A and D have thinner total thickness and are appropriate for phase defect detection on a 193nm inspection tool. For EUV inspection, actinic images are used to estimate EUV inspectability and no significant difference was seen among the four blanks. Defect printability was compared using through focus images and the conclusion is that the defect printability was identical among four blanks. Finally the stacks were evaluated based on the wafer impact. Stack_D is the best overall blank among the four blanks. This study concluded that the thickness of LR, absorber and total thickness is very important and that impact on mask inspectability, defect sensitivity and wafer imaging.

Table 2. Summary of this study

<table>
<thead>
<tr>
<th></th>
<th>Stack_A</th>
<th>Stack_B</th>
<th>Stack_C</th>
<th>Stack_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>LR: Thin</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
</tr>
<tr>
<td>Abs: Thin</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
</tr>
<tr>
<td>Total: Thin</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
</tr>
<tr>
<td>Mask Process</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
</tr>
<tr>
<td>Blank Inspection</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
</tr>
<tr>
<td>Pattern Defect</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
</tr>
<tr>
<td>Phase Defect</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
</tr>
<tr>
<td>EUV Imaging</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
</tr>
<tr>
<td>Through Focus</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
</tr>
<tr>
<td>Wafer Perspective</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
<td>🧐</td>
</tr>
</tbody>
</table>

ACKNOWLEDGMENTS

The authors would like to thank the following for their contributions to this paper: Kenneth Goldberg of Lawrence Berkeley National Laboratory and the SHARP (The SEMATECH High-NA Actinic Reticle review Project) team for EUV microscope imaging, KLA-Tencor engineering and application team for 193nm tool evaluation and good discussions, Isao Yonekura and Shinya Morisaki of Toppan Printing for blank roughness measurements and helpful advice, John Leonard, Chad Normand and Reg Bowley of IBM for 193nm tool evaluation, SEM measurement and good discussions, and Yosifumi Sakamoto of Toppan Photomask for advice. Finally we would like to thank the IBM and Toppan management and technical teams for support of this project.
REFERENCES


