Importance of EUV mask research to provide high contrast images

- Extreme ultraviolet (EUV) lithography has been developed as the next-generation lithography technique for manufacturing semiconductor devices at 5 nm node and beyond.
- The increased importance of stochastic defects and mask 3D effects at smaller feature sizes places further demands on mask
- To mitigate stochastic defects and mask 3D effects, it is crucial to optimize the aerial image contrast.

Simulation setting

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>13.53 nm</td>
</tr>
<tr>
<td>Numerical aperture</td>
<td>0.33</td>
</tr>
<tr>
<td>Chief ray angle</td>
<td>6°</td>
</tr>
<tr>
<td>Pupil</td>
<td>Mag 4x</td>
</tr>
<tr>
<td>Source shape</td>
<td>Monopole &amp; dipole illumination</td>
</tr>
</tbody>
</table>

Analysis of the relationship between diffraction orders and EUV absorber

- Two-beam imaging for high-resolution imaging of dense lines is performed using only the 0th and 1st diffraction orders that contribute to the imaging.
- The shift of the two images that are generated by the two monopoles making up the dipole illumination system, resulting in a loss of contrast → Image split.
- The relationship between the zeroth and first diffraction order is crucial for EUV imaging performance.

Absorber conditions setting

- Refractive index : $0.87 \leq n \leq 0.92$ (absorbers with low-n)
- Extinction coefficient: $0.01 \leq k \leq 0.08$
- Absorber thickness: $30 \leq \text{Thickness} \leq 40$ (thin mask)
- The range in which the effect of the phase shift of the absorber appears well.
Relationship between phase delta and image split in EUV mask

\[ E = \sum A_m e^{i\left((m \frac{2\pi}{p}) + \theta_m\right)} \quad I = uu^* = A_0^2 + A_k^2 + 2A_0A_k \cos \left(\frac{2\pi}{p}x + \theta_1 - \theta_0\right) \]

- In the Kirchhoff model, the effect of the amplitude and phase of the interference wave on the intensity distribution of the image can be observed. However, it is somewhat different from the Rigorous 3D model.

- The intensities and phases of the diffraction orders in the Kirchhoff model:

\[ I = uu^* = A_0^2 + A_k^2 + 2A_0A_k \cos \left(\frac{2\pi}{p}x + \theta_1 - \theta_0\right) \]

where:
- \( A_m \): mth diffraction order
- \( p \): pitch
- \( \theta_m \): The amplitude of mth diffraction order
- \( \theta_0 \): The phase of mth diffraction order

- Phase effects by absorber optimization in EUVL

- In the Rigorous 3D model, there is a special phase delta value that minimizes the image split.

- Additional simulations of the Opt. phase delta

- Phase delta vs. n, k, Thickness of the absorber at 0.33NA 18 nm half pitch patterns, k=0.01

- Phase delta vs. n, k, Thickness of the absorber at 0.55NA 12 nm half pitch patterns, k=0.01

- By optimizing the phase delta, the image split can be reduced, finally improving the imaging quality. (In the above graph, only the case of k=1 is shown, but optimization is possible in all absorber conditions.)

- Imaging performances can be improved by controlling the optical and geometric properties of the absorber to have an optimal phase delta value for each pattern size.
In the low-n ($n < 0.92$) mask-absorber materials, the influence of pattern size on amplitude is insignificant, so the range of improved amplitude balancing is almost similar.

In addition, since the graph trend by n value for each pitch is similar, it is seen that the influence of k value on amplitude balancing is dominant compared to n value.

### Imaging quality optimization by EUV mask absorber

- There is a difference between the condition of the absorber with good amplitude balancing and the condition of the absorber with improved imaging performance.
- As a result, in the low-n PSM, improved imaging performance can be optimized through phase control, and k value must be such that the intensity transmission is not negligible and offers a better amplitude balancing.

### CONCLUSION & FUTURE WORK

- Diffraction properties such as phase and amplitude of diffraction orders can be used to explore advanced masks with enhanced image contrast.
- In terms of phase, it is possible to improve the imaging performance by using the optimal phase delta for each pitch, and in terms of amplitude, it is necessary to study the relationship with imaging performance as well as improving amplitude balancing.
- By optimizing the diffraction properties of the absorber, it is expected to be used not only to search for a single material but also to apply it to alloy materials to research various materials to improve mask performances.