ABSTRACT
With the stringent requirements on image placement (IP) errors in the sub-50-nm regime, all sources of mask distortion during fabrication and usage must be minimized or corrected. For extreme ultraviolet lithography, the nonflatness of the mask is critical as well, due to the nontelecentric illumination during exposure. This paper outlines a procedure to predict the IP errors induced on the mask during the fabrication processing, e-beam tool chucking, and exposure tool chucking. Finite element (FE) models are used to simulate the out-of-plane and in-plane distortions induced during each processing step. The FE results are compiled to produce a “Correction Table” that can be implemented during e-beam writing to compensate for these distortions and significantly increase IP accuracy.

INTRODUCTION
The tolerance on image placement (IP) errors is becoming increasingly severe as lithography technology drives the minimum integrated-circuit feature size below 50 nm. According to the International Technology Roadmap for Semiconductors, meeting the requirements for critical dimensions (CD) and overlay at the lower nodes may be one of the most difficult technical challenges in lithography. The goal of this research is to investigate the IP errors induced during mask fabrication and usage for one of the leading NGL candidates – extreme ultraviolet lithography (EUVL). The basic concept is that if repeatable IP errors (due to fabrication and usage) can be predicted to a reasonable accuracy, it may be possible to correct for these errors when the mask is initially patterned in the e-beam writer. This paper describes the finite element (FE) models that have been developed to simulate the response of the EUVL mask during the fabrication process, as well as when it is chucked in both the e-beam and exposure tools. The FE predictions of the mask response are then used to determine the “Correction Table” to be implemented when e-beam patterning is performed.

A schematic of a simplified fabrication process flow is shown in Fig. 1. For modeling purposes, the individual processing steps are grouped by load steps that are used in the FE simulations. The first step is the deposition of the multilayer stack, absorber stack, photoresist, and backside layer. Typical values for the thicknesses and stresses of these layers are listed in Table I. Load Step 2 is the mechanical mounting of the mask in the e-beam tool for patterning. The development of the resist, etching of the absorber, and removal of the resist have all been grouped into Load Step 3. Finally, the mask is electrostatically chucked in the exposure tool at Load Step 4.

FIGURE 1. Simplified EUVL mask fabrication process flow.
**TABLE 1.** Typical EUVL mask fabrication parameters.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (nm)</th>
<th>Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multilayer Stack</td>
<td>280</td>
<td>400 (Compressive)</td>
</tr>
<tr>
<td>Absorber Stack</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>Photoresist</td>
<td>250</td>
<td>10</td>
</tr>
<tr>
<td>Backside Layer</td>
<td>63</td>
<td>150</td>
</tr>
</tbody>
</table>

**DESCRIPTION OF EXAMPLE CASE**

Full 3-D FE models have been developed to predict the response of the EUVL mask under the load steps given in the simplified fabrication process flow. The mask substrate was low-thermal expansion material (LTEM) with the standard size of 152 mm × 152 mm × 6.35 mm; here the Quality Area is defined as the central square region with side dimensions of 142 mm. The flatness of the EUVL mask is a key issue to minimize IP errors due to the nontelecentric illumination during exposure. SEMI Standard P37 [1] specifies the flatness of the frontside, backside, and thickness variation of the substrate in terms of the class of substrate. In essence, the Quality Area must be flat to within 30 nm to 100 nm peak-to-valley (p-v) for these classes.

As an example case, an interferometric measurement from an actual LTEM substrate was used to represent the nonflatness of the surfaces that result from the polishing procedures. Figure 2(a) shows the interferometric data displayed in 2-D and 3-D plots for the frontside surface of the reticle. The nonflatness is 50 nm p-v over the entire area. For this example case, the backside surface was assumed to have the same shape, but opposite sign, as shown in Fig. 2(b). Thus, the thickness variation was easily calculated by subtracting the backside flatness data from the frontside flatness data. The thickness variation, which has a maximum value of 100 nm, is shown in a 2-D contour plot in Fig. 3.

To input the initial nonflatness of the substrate into the FE structural models, the interferometric data were fitted with an 8 × 8 matrix of Legendre polynomials. Legendre polynomials have been identified as effective means to represent experimentally measured EUVL substrate surface shapes.

**FIGURE 2.** Nonflatness assumed for the EUVL mask substrate due to polishing procedures (shown in 2-D and 3-D plots). (a) Frontside surface (p-v = 50 nm) and (b) backside surface (p-v = 50 nm).
FIGURE 3. Thickness variation of the EUVL mask substrate (maximum = 100 nm).

The FE models can also be used to simulate the effects of stress nonuniformities that may be present in the thin film stacks. For the example case here, all the thin films were uniform with the thicknesses and stresses as given in Table I, except for the multilayer stack. It was assumed that the multilayer had a compressive stress of 450 MPa on one half of the substrate with the other half at a compressive stress of 350 MPa (as shown in Fig. 4). This is a worst case scenario that is used for illustration purposes only.

FIGURE 4. Stress nonuniformity assumed in multilayer stack. Compressive stresses are 450 MPa and 350 MPa for dark and light gray area, respectively.

SIMULATING THIN FILM DEPOSITION (LOAD STEP 1)

After generating the FE model of the EUVL substrate with the frontside and backside nonflatness, the deposition of the nonuniform stressed layers is simulated. Figure 5 shows the out-of-plane distortion (OPD) of the reticle displayed in 3-D and 2-D contour plots. The maximum bow of the reticle is 1310 nm p-v; the convex shape is consistent with that fact that the net stresses are compressive. The nonuniform stress distribution causes a bowed shape that is not truly spherical, as shown in the 2-D contours of Fig. 5(b). It is not necessary to calculate in-plane distortions (IPD) at this load step.

FIGURE 5. FE simulation of thin film deposition (Load Step 1). OPD contours of the entire reticle illustrating the resulting bow of 1310 nm (p-v) in (a) 3-D and (b) 2-D plots.

SIMULATING E-BEAM TOOL CHUCKING (LOAD STEP 2)

The SEMI Standards Committee originally recommended the development of an electrostatic chuck for use in the e-beam tool (SEMI P40) [2]. However, the industry prefers to retain the use of a three-point mount during patterning. Figure 6 shows a schematic of a typical three-point mount; support conditions consistent with this mount are included in the FE model.

Load Step 2 of the FE simulation predicts the response of the reticle when it is positioned in the three-point mount under gravitational loading. Consequently, the FE results for this load step include the initial nonflatness of the substrate and the nonuniform stress distribution, as well as the gravitational distortions. Figure 7(a) illustrates the OPD contours in 3-D, where the initial bow of 1310 nm has now increased to 1421 nm due to the effects of gravity. The corresponding IPD plot of the frontside surface is shown in Fig. 7(b); the value of the maximum IPD is 114 nm. The location of the mounting supports is indicated on the figures.
FIGURE 6. Schematic of the three-point mount in the e-beam tool (units in mm).

FIGURE 7. FE simulation of e-beam tool chucking (Load Step 2). (a) OPD plot of entire reticle (1421 nm p-v) and (b) IPD plot of reticle frontside surface (maximum = 114 nm).

The IPD results shown in Fig. 7(b) are repeatable distortions that must be compensated for during patterning. It should be noted that this IPD map does not contain the thermomechanical distortions due to the actual e-beam writing. FE models to predict the thermomechanical response of the reticle during e-beam exposure have been developed in previous research conducted at the UW-CMC [3]. If patterning distortions are found to be repeatable and significant, they can be vectorially added to IPD in Fig. 7(b).

SIMULATING THIN FILM ETCHING AND DEVELOPING (LOAD STEP 3)
In the Example Case, Load Step 3 includes the development of the resist, the etching of the absorber stack, and the removal of the resist. Previous analyses at the UW-CMC have shown that the change in OPD and IPD due to these processing steps is roughly 3 nm. However, if the fabrication process included the etching of the multilayer stack, FE simulations should be performed to identify the corresponding change in OPD and IPD. In fact, pattern-specific distortions can be predicted via the use of equivalent modeling techniques and submodeling procedures.

SIMULATING EXPOSURE TOOL CHUCKING (LOAD STEP 4)
It has been proposed to use a “pin-type” electrostatic chuck (e-chuck) in the exposure tool to ensure the mask is flattened and to minimize the effects of particles. Specifications on the e-chuck are given in SEMI P40, the EUVL Mask Chucking Standard: stiffness $\geq 30$ kN-m, clamping pressure = $15\pm1.5$ kPa, and nonflatness limited to $\sim 50$ nm (p-v). Full 3-D FE structural models have been developed to simulate the response of the EUVL mask during electrostatic chucking. The model capabilities include: nonflatness of the chuck, gap-dependent pressures, contact friction, chuck stiffness, and any support constraints. Consequently, the FE simulations are able to predict the final shape of both the frontside and backside of the reticle, the deformation of the chuck, and the remaining gap at the interface.

Electrostatic chucking of the mask was simulated using the interferometric measurements from an actual chuck, where the nonflatness was 263 nm p-v. Since this chuck was not within the SEMI P40 specifications, the magnitude of the nonflatness was scaled down to 50 nm p-v (as shown in Fig. 8). A clamping pressure of 15 kPa was used, the coefficient of friction was assumed to be relatively small, and the chuck was relatively stiff so chuck deformation was negligible.
Figure 8. Interferometric measurement of the electrostatic chuck surface scaled down to a nonflatness of 50 nm p-v shown in (a) 3-D and (b) 2-D plots.

Figure 9 shows the final OPD and IPD of the reticle frontside surface after e-chucking. Here the maximum OPD was 125 nm, and the corresponding IPD had a maximum value of 49 nm.

During the FE simulations of the EUV mask fabrication and chucking, the maximum OPD and IPD from the distortion maps are tracked as a function of the process step (or FE load step). For example, Fig. 10(a) illustrates the effects of employing a three-point mount instead of an electrostatic pin chuck during e-beam patterning. The effects are even more dramatic when considering the maximum IPD, which is shown in Fig. 10(b). Pattern transfer IPD is defined as the vectorial difference between the IPD field during e-beam chucking and the IPD field during exposure chucking. If an electrostatic pin chuck could be used for both e-beam writing and exposure scanning, the maximum distortion would be only a few nanometers. However, when the three-point mount is used in the e-beam tool, the final pattern transfer IPD has a maximum value of 72 nm, as shown in Fig. 10(b). Again, the pattern transfer IPD is repeatable and must be corrected during e-beam patterning.

Figure 9. FE simulation of exposure tool chucking (a) 3-D OPD plot of reticle frontside surface (125 nm p-v) and (b) 2-D IPD plot of reticle frontside surface (maximum = 49 nm).

Figure 10. Maximum (a) OPD and (b) IPD as a function of the individual processing steps.
To calculate the final Correction Table, it is necessary to consider the IP error at the wafer level. Because the exposure tool uses nontelecentric illumination, both the pattern transfer IPD and the OPD of the reticle after e-chucking will contribute to the total IP error at the wafer. These error components are expressed in Eqs. (1) and (2). Here the magnification factor ($M$) is 4 and the angle of incidence ($\beta$) is $6^\circ$. Consequently, the total IP error at the wafer is the vector addition of these two components. Figure 11 shows the final IPD map that must be compensated for during e-beam patterning. To accommodate the e-beam tool software, the FE code would produce these results in tabular form as needed. The tabular data from this map (multiplied by the magnification factor) constitutes the Correction Table.

\[
(IP\ Error)_{ipd} = \frac{\text{Pattern Transfer IPD}}{M} \tag{1}
\]

\[
(IP\ Error)_{opd} = \frac{\text{OPD} \times \tan\beta}{M} \tag{2}
\]

**FIGURE 11.** Final IP error at the wafer level for x-direction scanning (maximum = 20 nm).

**SUMMARY AND CONCLUSIONS**

FE simulations were used to identify the response of the EUVL mask during fabrication processes and chucking. To replicate the fabrication process flow, structural FE models simulated the deposition and etching of the various thin film layers. OPD and IPD were tracked as a function of the various processing steps. Both the initial nonflatness of the mask and the nonuniform stress distribution in the multilayer were included in the numerical simulations. The final mask configuration after processing was predicted as a function of the material properties and the inherent thin film stresses and thicknesses.

Chucking of the EUVL mask was considered separately, as the e-beam writer consists of a three-point mount, and the exposure tool utilizes an electrostatic pin chuck. FE models were first used to predict the distortions of the reticle in the three-point mount under gravitational loading. The electrostatic chucking simulations included the nonflatness of the EUVL reticle, gap-dependent pressures, and contact friction. The final OPD map of the frontside surface was modified to account for telecentric effects, then combined with the pattern transfer IPD map to obtain the Correction Table. An experimental program has been initiated with SEMATECH to verify and benchmark the FE modeling procedures associated with the individual load steps.

It should be noted that the Correction Table could also be modified to include thermomechanical distortions during scanning exposure. Previous research at the UW-CMC has shown that the magnitudes of the thermomechanical distortions are highly dependent on the contact conductance and the coefficient of friction between the reticle and the e-chuck. When more data becomes available on these specific parameters, the corresponding OPD and IPD will be included in the Correction Table as well.

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**REFERENCES**

