Gauging The Performance Of An In-situ Interferometer

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ABSTRACT:
Recently an insitu technique for measuring exposure tool projection lens aberrations was introduced by Litel Instruments. In this study we attempt to gauge the performance of the interferometer through comparison of simulated lithographic patterns using the wavefronts measured by the interferometer, with experimental data collected from printed wafers. Our results compare simulation and experiment for cases of field curvature, lithographic astigmatism, linewidth abnormality, and dense-is0 bias. As an additional gauge, we show that the change in the measured focus and 3rd order spherical aberration terms follows the theoretical trend for changing position along the optical axis.

Key Words: Interferometer, Aberration

1. INTRODUCTION:
The effects of aberrations on the lithographic imaging process have previously been extensively described. Although much is known about the effects of aberrations on projection imaging, it is generally not possible for the lithographer to use the theory in practical applications because the aberration content of the projection lens is not known. The aberrations in the projection lens are well characterized in the factory, but the effects of shipping and other environmental factors is unknown, and so the actual aberration content in the field is uncertain.

The insitu interferometer produced by Litel Instruments provides one technique for measuring aberration content of the projection lens in the field. Knowing the aberration content of a lens in the field would presumably allow one to use this information in a lithography simulator to more accurately predict printing on the wafer.

In this paper, we wish to make an initial probe into whether or not the wavefronts measured by the Litel interferometer can improve the modeling of the lithography. We begin in Section 2.0 by describing the experimental conditions for this work. In Section 3.0 we show and discuss the results of our testing.

2. EXPERIMENTAL CONDITIONS

2.1.1 Pattern Metrics
Considering only the simulator, the correlation of simulated patterns with printed wafer patterns is a function of all of the model parameters input into the simulator. This means that our results will be strongly impacted by not only the aberrated wavefronts, but also...
by our resist and developer models. We chose to look at 4 standard lenses that we felt would highlight certain aberration effects.

**Field curvature**: The difference in best focus between isolated lines with the same orientation at the center and edge of an exposure field.

**Lithographic astigmatism**: The difference in best focus between horizontal and vertical lines at the same field position.

**Line width abnormality (LWA)**: The difference between the left and right CD's of a five bar pattern divided by their sum.

\[
LWA = \frac{CD_{\text{leftbar}} - CD_{\text{rightbar}}}{CD_{\text{leftbar}} + CD_{\text{rightbar}}}
\]

**Dense-iso line bias**: The difference in CD between a L/S and an isolated line pattern of the same orientation at the same field point.

### 2.1.2 Process For Pattern Metrics

We used the following process conditions for our experiment:

<table>
<thead>
<tr>
<th>Resist</th>
<th>UV110</th>
</tr>
</thead>
<tbody>
<tr>
<td>BARC</td>
<td>DUV42</td>
</tr>
<tr>
<td>Substrate</td>
<td>Si Pilots</td>
</tr>
<tr>
<td>Nominal pattern sizes</td>
<td>180nm</td>
</tr>
</tbody>
</table>

**Table 1** Process conditions for our tests.

Simulations were performed assuming top hat type effective sources. Our resist model was tuned to match our process.

### 2.2 Stage Position Metric

**Stage position vs theoretical focus and 3rd order spherical aberration:**

This test is meant to demonstrate that the wavefronts of the Litel interferometer change according to theory as the z position of the stage is changed. The stage is moved in the z direction in five 1/2um increments, and the wavefront for the 5 field positions is measured at each of these increments. The trends of the focus and the 3rd order spherical aberration terms are plotted versus the commanded z stage position. This test will be more qualitative than the pattern tests. Our analysis will be limited to visual inspection of the plots.

### 3. RESULTS AND DISCUSSION

#### 3.1 Pattern Metrics

In this section we describe 3 test case examples using 3 different lenses described as Lens A, Lens B, and Lens C. Each of the test cases highlights at least one of the pattern metrics.
3.1 Case A: Field Curvature Comparison

The wavefront for Lens A was measured at two locations in the lens field using the Litel interferometer. Field point 1 was chosen at the edge of the field, and field point 2 was chosen at the center of the field. Unitless relative phase error plots at each position are shown in Figures 2 and 3 respectively.

Lens A was selected to demonstrate the ability of the simulator to predict field curvature using the aberrated wavefronts measured by the Litel interferometer. We printed an isolated line at both positions using the full NA and .3 sigma using an exposure dose set to print 180nm L/S patterns within 10% of the nominal 180nm. Both lines were measured using an SEM. The SEM measurement results as well as our simulation results are shown in Figure 4. Both the simulation and the SEM measurements show similar amounts of field curvature.

3.1.2 Case B: L/S Lithographic Astigmatism Comparison

The wavefront of Lens B was measured at a single position near the center of the field. The relative phase error plot is shown in Figure 5. Using this lens we printed nominal 180nm 5 bar L/S pattern in both the horizontal and vertical directions using the full NA and .3 sigma. The center line of each 5 bar pattern was measured through focus. The measured and simulated data is shown in Figures 6 & 7. Both the simulation and the SEM measurements show similar amounts of astigmatism.

3.1.3 Case C: Isolated Line Lithographic Astigmatism, LWA, and Dense-Iso Bias Comparison Using Multiple Illumination Conditions

The wavefront of Lens C was measured at a single position near the center of the field. The relative phase error plot is shown in Figure 8. For this case we wished to vary the sampling of the pupil at a single lens position by using different illumination conditions. We exposed wafers using the full NA at .4 sigma, .75 sigma, and ½ annular illumination respectively.

Isolated Line Lithographic Astigmatism:
For this test we printed 180nm isolated lines using the dose required to print the center bar of a 180nm L/S pattern within 10% of 180nm. The SEM measurements and the simulated data are plotted in Figures 9-14. For each illumination condition, the measured difference between the best focus of the 180nm horizontal and vertical isolated line structures is well predicted by the simulation performed using the aberrated wavefronts. In all cases, the measured astigmatism values are within 20nm of the simulated values.

LWA:
We printed 180nm L/S patterns for this test using the exposure dose required to print the center bar at within 10% of 180nm. The measured and simulated LWA data is shown in Figures 15-20. For all illumination cases, both the vertical and horizontal simulated values are within .013 of the measured values at best focus, and at +/- .1um from best focus. For a nominal 180nm line on the left side of the five bar pattern, an LWA of .01 translates into a measured right line value of ~176nm as shown in Figure 1.
LWA vs. Right Linewidth

(Left Linewidth is fixed at 180nm)

A 4nm difference is within the estimated measurement error of the SEM used to collect the data, and so we conclude that near best focus, the simulation matches the experimental data. The through +/- .1um focus comparison is summarized in Table 2.

<table>
<thead>
<tr>
<th>LWA</th>
<th>Vertical</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BF - .1um</td>
<td>Best .1um</td>
</tr>
<tr>
<td>0.4 Sigma</td>
<td>-0.005</td>
<td>-0.002</td>
</tr>
<tr>
<td>0.75 Sigma</td>
<td>-0.007</td>
<td>-0.013</td>
</tr>
<tr>
<td>½ annular</td>
<td>0.004</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Table 2 Comparison of the differences between simulation and measured values of LWA

Dense-ISO Bias:
We measured the structures printed for the astigmatism and LWA tests for the dense iso bias test. The measured and simulated dense-iso bias data are shown in Figures 21-23. In addition to the simulations performed using the aberrated wavefront, we've added simulations showing dense/iso bias for the non-aberrated lens as a baseline check.

.4 sigma illumination: The simulation of the dense-iso bias using the aberrated wavefront matches the SEM data to within < 8nm at best focus and at +/- .1um from best focus. In addition, the different behavior through focus of the horizontal and vertical lines is predicted. The behavior of the simulated dense-iso bias using a non-aberrated lens is not as well matched to the experimental data. The through +/- .1um focus comparison is summarized in Table 3.
The simulated dense-iso bias using the aberrated wavefront is within ~12nm of the data at best focus and at +/- .1µm from best focus, however the matching becomes poor at relatively large values of negative focus. The simulations for the non aberrated lens case is actually more closely matched to the measured data, but similarly does not predict the negative focus trend. The through +/- .1µm focus comparison is summarized in Table 4.

<table>
<thead>
<tr>
<th>Dense-Iso Bias [nm]</th>
<th>BF - .1µm</th>
<th>Best Focus</th>
<th>BF + .1µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aberrated - Meas Vert</td>
<td>12.0</td>
<td>5.8</td>
<td>9.0</td>
</tr>
<tr>
<td>Non Aber - Meas Vert</td>
<td>10.7</td>
<td>-0.1</td>
<td>-0.8</td>
</tr>
<tr>
<td>Aberrated - Meas Horz</td>
<td>5.8</td>
<td>1.9</td>
<td>6.0</td>
</tr>
<tr>
<td>Non Aber - Meas Horz</td>
<td>1.3</td>
<td>-2.8</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 4 Comparison of the differences between simulation and measured values of dense iso bias for .75 sigma illumination.

3.1.4 Pattern Metrics Summary

The data in Table 6 summarizes typical differences seen between simulation performed using the Litel measured wavefronts and experimental data.

<table>
<thead>
<tr>
<th>Summary of Typical Difference Between Simulation and SEM measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Litho Astigmatism</td>
</tr>
<tr>
<td>LWA</td>
</tr>
<tr>
<td>Dense/Iso Bias</td>
</tr>
</tbody>
</table>

Table 6 Summary table of typical data for simulation using the Litel wavefronts and SEM measurements.
3.2 Stage Metrics Summary

When the stage is moved vertically, in addition to the focus Zernike term changing, the 3rd and higher order spherical aberrations change as well. The eikonal ($\chi$) is the phase term in the exponent of the reticle to wafer transfer or Green function and is equal to (with appropriate sign conventions):

$$\chi(x,y,z;n_x,n_y) = \phi(n_x,n_y) - k*z*\sqrt{1 - n_x^2 - n_y^2} + k*(n_x^n + n_y^n)$$ (2)

Here, $\phi(n_x,n_y)$ represents the imaging objective aberrations as a function of the exit pupil transverse direction cosines ($n_x,n_y$) or equivalently, the exit pupil coordinates, $k=2\pi/\lambda$, $(x,y)$ the wafer transverse positions, and $z$ the wafer vertical position. At a fixed z position, the effective aberration experienced by lithographic features is represented by the combination of the aberrations, $\phi(n_x,n_y)$, and the effect of z-height displacement $-k*z*\sqrt{1 - n_x^2 - n_y^2}$. The phase measured by the in-situ interferometer is the sum of these two terms. Since Zernike polynomials are the conventional way of expressing aberrations, we need to express the z-height displacement term in terms of Zernike polynomials. Then when the lens aberrations are also expressed in terms of Zernike polynomials, we need only add corresponding Zernike coefficients together to express the effective aberration. Because the z-height dependent part is a function of $n_x^2+n_y^2$ only, we can express it as a sum of circularly symmetric Zernike polynomials as:

$-k*z*\sqrt{1 - n_x^2 - n_y^2}=-(b_4*Z_4(n/\sqrt{N_A})+b_{11}*Z_{11}(n/\sqrt{N_A})+b_{22}*Z_{22}(n/\sqrt{N_A})+...)$

where $n=\sqrt{n_x^2+n_y^2}$, $N_A$=imaging system numerical aperture, $Z_4,Z_11,Z_{22}$...are the Zernike polynomials in the Noll ordering, and $b_4,b_{11},b_{22}$...can be calculated based on the orthonormality of the Zernike polynomials as:

$$b_4(N_A) = \int_0^{\frac{\pi}{2}} \frac{dn+n}{N_A^2} \sqrt{1 - n^2} * Z_4(n/\sqrt{N_A})$$ (4)

and similarly for $b_{11},b_{22}$, etc. Table 7 lists these coefficients as a function of $N_A$.

<table>
<thead>
<tr>
<th>$N_A$</th>
<th>$b_4(N_A)$</th>
<th>$b_{11}(N_A)$</th>
<th>$b_{22}(N_A)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>-0.057593</td>
<td>-0.00164558</td>
<td>-0.00009377</td>
</tr>
<tr>
<td>0.63</td>
<td>-0.064288</td>
<td>-0.00207776</td>
<td>-0.00013301</td>
</tr>
<tr>
<td>0.65</td>
<td>-0.069043</td>
<td>-0.00241936</td>
<td>-0.00016779</td>
</tr>
<tr>
<td>0.68</td>
<td>-0.076650</td>
<td>0.00302787</td>
<td>0.00023656</td>
</tr>
<tr>
<td>0.7</td>
<td>-0.082061</td>
<td>-0.00350892</td>
<td>-0.00029668</td>
</tr>
<tr>
<td>0.73</td>
<td>-0.090735</td>
<td>-0.00436758</td>
<td>-0.00041569</td>
</tr>
<tr>
<td>0.75</td>
<td>-0.096923</td>
<td>-0.00304895</td>
<td>-0.00052013</td>
</tr>
<tr>
<td>0.8</td>
<td>-0.114027</td>
<td>-0.00725217</td>
<td>-0.00091332</td>
</tr>
</tbody>
</table>

Table 7 Focus, 3rd and 5th order spherical aberration influence coefficients as a function of $N_A$.

The effect of changing the wafer position, z, is then to change the appropriate Zernike polynomial coefficient as:

$$focus, \quad a_4 \rightarrow a_4 - k*z*b_4(N_A)$$ (5)

$$3^{rd} order spherical, \quad a_{11} \rightarrow a_{11} - k*z*b_{11}(N_A)$$ (6)

$$5^{th} order spherical, \quad a_{22} \rightarrow a_{22} - k*z*b_{22}(N_A)$$ (7)
The effect of changing the z-stage on spherical aberration can be seen in figure 25. There $a11-\langle a11 \rangle$ is the 3rd order spherical aberration as measured by the interferometer. $\langle a11 \rangle$ is just the average of the measured spherical aberration values at all 5 focal positions (-1, -0.5, 0, 0.5, 1um). The linear trend in $a11-\langle a11 \rangle$ is evident, and when the theoretical value for the contribution of the z-stage height is removed (equation 6) the resulting plot exhibits vertical scatter of size on the order of the interferometer reproducibility.

Wafer height change will effect the focus $(a4)$ aberration linearly with a slope equal to:

$$\frac{da4}{dz} = -k*b4(NA)$$

(8)

and we can also define an inferred z-height using the interferometer as:

$$zisi = a4 / \frac{da4}{dz}$$

(9)

where $a4$ is the measured focus aberration at a given field point. In figure 24 we have plotted $zisi - \langle zisi \rangle$ where $\langle zisi \rangle$ is the average of $zisi$ at all measured focus heights against the commanded stage height, zstage. The effect of the subtraction of $\langle zisi \rangle$ is to remove the effect of lens field curvature.

4.0 CONCLUSIONS

By incorporating the aberrated wavefronts measured by the Litel interferometer into our simulation software we were able to more closely predict the behavior of the printing process as measured by an SEM, for the pattern metrics of field curvature, lithographic astigmatism, and LWA. In each of these cases, the difference between the measured data and the simulated data was very close to experimental measurement error near best focus. We conclude that for the cases described in this paper, and for these metrics, using the wavefronts measured by the Litel interferometer can improve the ability of a simulator to predict the lithography on the wafer.

The results for predicting dense/iso bias were mixed. We found that simulation matched measurement for small sigma illumination, but not for large sigma or annular illumination. We expect that the predictions can be improved by further tuning of our resist model and by incorporating the exact effective source, but further work is necessary to understand the reason for the difference.

The stage test demonstrates that the sensitivity of the Litel interferometer outputs of the Zernike terms for focus and 3rd order spherical aberration is sufficient to detect the given stage movements, and that the change in the value of the coefficient with respect to the stage position matches the theoretical trend.

REFERENCES


CASE A: Field Curvature Comparison

![Image of Figure 2](image2.png)

**Figure 2.** Phase error plot at field point 1 of Lens A.

![Image of Figure 3](image3.png)

**Figure 3.** Phase error plot at field point 2 of Lens A.

![Image of Figure 4](image4.png)

**Figure 4.** Simulated and measured isolated lines through focus at field points 1 & 2.
CASE B: Dense Line Lithographic Astigmatism Comparison

Figure 5. Phase plot of Lens B.

Figure 6. Simulated dense line lithographic astigmatism produced by Lens B.

Figure 7. Measured dense line lithographic astigmatism produced by Lens B.
Case C: Isolated Line Astigmatism, LWA, and Dense-Iso Bias Using Multiple Illumination Conditions

I. Isolated Line Lithographic Astigmatism

Figure 8 Phase error plot of Lens C.

Figure 9 Simulated isolated line astigmatism produced by Lens C using .4 sigma.

Figure 10 Measured isolated line astigmatism produced by Lens C using .75 sigma.
Figure 11 Simulated isolated line astigmatism produced by Lens C using .75 sigma.

Figure 12 Measured isolated line astigmatism produced by Lens C using .75 sigma.

Figure 13 Simulated isolated line astigmatism using 1/2 annular illumination.

Figure 14 Measured isolated line astigmatism using 1/2 annular illumination.
II. LWA

**Figure 15** Simulated and measured LWA produced by Lens C using .4 sigma.

**Figure 16** Simulated and measured LWA produced by Lens C using .4 sigma.

**Figure 17** Simulated and measured LWA produced by Lens C using .75 sigma.

**Figure 18** Simulated and measured LWA produced by Lens C using .75 sigma.

**Figure 19** Simulated and measured LWA produced by Lens C using 1/2 annular illumination.

**Figure 20** Simulated and measured LWA produced by Lens C using 1/2 annular illumination.
III. Dense-Iso Bias

**Figure 21** Simulated and measured dense-iiso bias. No aberration case is also shown.

**Figure 22** Simulated and measured dense-iiso bias. No aberration case is also shown.

**Figure 23** Simulated and measured dense-iiso bias. No aberration case is also shown.
Figure 24 Plot showing z-positions as converted from the focus term of the aberrated wavefront versus the z stage position as defined by the exposure tool.

Spherical Aberration

Figure 25 Plot showing change in 3rd order spherical aberration with change in z position for 5 field points. Also shown is the residual aberration level with the theoretical trend removed.