FLCC Seminar
Part 1: Fast Simulation of EUV Masks with Buried Defects

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Chris Clifford
Challenge for Extreme Ultraviolet Lithography

- Buried defects in masks are a major roadblock to the implementation of EUV lithography
- Accurate and fast simulation of the reflected electric field is critical to overcome these defects
  - Determine tolerable defect sizes and positions
  - Develop compensation strategy
New Simulation Strategy: RADICAL

Transmission through absorber features

Reflection from multilayer

Thin Mask Model

Ray Tracing

Incident Wave

Absorber Layout Simulator

Absorber Pattern Specifications

Defect and Multilayer Specifications

Multilayer Simulator

Plane Wave

Near Field

Final Result

Absorber Layout Simulator

Near Field FT

Near Field FT

Example Simulation

- Example simulation for 22nm lines on wafer (88nm lines on mask and 4x demagnification)
- Modularity allows intermediate fields within the mask to be studied

<table>
<thead>
<tr>
<th>Absorber</th>
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<tbody>
<tr>
<td>Line Width (On Mask)</td>
<td>88nm</td>
</tr>
<tr>
<td>Absorber Height</td>
<td>75nm</td>
</tr>
<tr>
<td>Absorber Capping Layer Height</td>
<td>12nm</td>
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<td>Absorber Refractive Index (TaN)</td>
<td>0.948 - j*0.032</td>
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<td>Capping Refractive Index (ARC)</td>
<td>0.957 - j*0.023</td>
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<table>
<thead>
<tr>
<th>Multilayer</th>
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<tbody>
<tr>
<td>Number of Bilayers</td>
<td>40</td>
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<tr>
<td>Silicon Thickness</td>
<td>4.17nm</td>
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<tr>
<td>Molybdenum Thickness</td>
<td>2.78nm</td>
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<tr>
<td>Capping Layer Thickness</td>
<td>2.5nm</td>
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<tr>
<td>Silicon Refractive Index</td>
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<td>Molybdenum Refractive Index</td>
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<tr>
<td>Capping Layer Refractive Index</td>
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<table>
<thead>
<tr>
<th>Defect</th>
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<tr>
<td>Defect Shape</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Defect FWHM</td>
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<tr>
<td>Defect Height</td>
<td>30nm</td>
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<td>Smoothing Process</td>
<td>V1286 from [2]</td>
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<th>Incident Wave</th>
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<tr>
<td>Wavelength</td>
<td>13.5nm</td>
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<tr>
<td>Incident Angle</td>
<td>6°, perpendicular to absorber pattern</td>
</tr>
<tr>
<td>Polarization</td>
<td>Transverse Electric</td>
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</tbody>
</table>
Simulator Output

Intermediate Field Magnitudes Between Multilayer and Absorber
- Downward Traveling
- Upward Traveling

Final Magnitude and Phase Reflected from Mask
Accuracy and Computational Requirements

- Aerial image CD change accurate to within 1.5nm compared to FDTD simulation (32nm line)

- Runtime Comparison
  - RADICAL: 1 minute 40 seconds (1 processor)
  - FDTD: 13 hours 32 minutes (4 processors)
  - RADICAL is 487 times faster than FDTD
Project Summary

• New simulation strategy for EUV masks can predict the field reflected from an EUV mask with a buried defect over 450 times faster than FDTD, with comparable accuracy

• Issues going forward
  – Verifying accuracy of RADICAL for small features
    • Accuracy of FDTD questionable for lines smaller than 32nm on wafer
    • Experimental results not available for small features
  – Runtime is pattern dependent due to Fourier transform
    • Exploitation of symmetry by recycling results decreases dependence
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Part 2: Lateral Interactions between Standard Cells using Pattern Matching

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Lynn Wang
Industry Challenge

• There are interactions between circuits which are critical to electrical performance.
  – Poly: Electrical data have shown that the context in which the cell is placed affects cell’s circuit gate-centric performance, i.e. $I_{ON}$, with the worst-case variation of 10% [1].

• This paper proposes to understand and mitigate the nature of the interactions between standard cells.

Novel Concept

- Identify through focus interactions via fast-CAD pattern matching
- The Pattern Match Factors (PMF) are based on the Pattern Matcher by Gennari [2] scaled from 0-1.

\[
PMF\left(i + \frac{X}{2}, j + \frac{Y}{2}\right) = \sum_{y} \sum_{x} Layout(x + i, y + j) \cdot Pattern(x, y)
\]

- Accuracy of the pattern matcher is shown via the correlation of PMF and edge placement change.

Confirms with the physical model of defocus, which is a quadratic relationship.

Approach

• An aberration is approximated as:

\[ 1 + j \cdot OPD \]

• The 1st term is the diffraction limited electric field. The 2nd term is an additive electric field and its lateral pattern is a Fourier transform. The electric field influence at an observation point from a surrounding pattern is the convolution (C) of the surrounding pattern with electric field spread function weighed by the focal shift (\( \Delta d \)).

• The total electric field is:

\[ E_0 + j(\Delta d) \cdot C \]

• The intensity is:

\[ \text{Re}\{(E_0 + j(\Delta d) \cdot C)(E_0 + j(\Delta d) \cdot C)^*\} \]

• For a binary mask, \( E_0 \) is real and for an even aberration like focus the Fourier transform is real.

• Thus the intensity is:

\[ E_0^2 + (\Delta d \cdot C)^2 \]

• A quadratic behavior with focus is expected.
Example

Match Factors: 0.143 to 0.190. Lateral interactions increases match factor to 0.220.

*Disclaimer: To avoid proprietary issues in the data, we have only utilized a small selection of cells and not examined process induced edge placement errors in the context of the multiple layers in the process flow and the resulting electrical performance. We have also deliberately induced modifications and design rule violations such as utilizing negative cell to cell placements.
Results and Conclusions

• Cell Interaction Characterization:
  – Victim cell and aggressor cells can be quickly identified

• Cell Distance Characterization:
  – Saves Area: The oscillations indicate that lithography hotspots that arise from neighboring cell interaction may be intelligently mitigated by moving the aggressor standard cell to an optimal distance away from the victim standard cell.
  – Oscillation period corresponds to the size of the rings
Self-Critique of Concept and Approach

- Assumes cell layouts are designed for binary masks
  - The standard cell layouts were likely to be designed for phase-shift-masks (PSM) in the poly layer

- Assumes coherent on-axis illumination
  - Because off-axis enhances the printing of a particular period at the expense of other periods, the spacing effects will likely be more severe for small shift distances
  - Because off-axis has multiple illumination angles, more averaging will occur as the distance increases. Thus the impact versus separation will likely be even more oscillatory initially and then damp out faster

- Pattern matching technique can be generalized for these effects.

- Further validation of pattern matching is needed. (i.e. outliers, slope in edge placement shift).
The Challenge

• The industry challenge is to monitor focus electronically to get a large amount of data over the field easily.
• The sign of the focus is also required.
Approach: Aberration Monitoring with Electrical Testing

Contact Pad + Thin line of conductive material = Open circuit created when aberration present

Defocus = 0.0
Defocus = 0.02
Defocus = 0.2
Design of monitors via Simulation

- Six parameters were varied with all combinations placed on the layout
- Designs were staggered to account for misalignment

- Linewidth
- Number of rings
- Chrome neck size
- Chrome gap width
- Probe size
- Ring bias
Rings are cutting through the line and spot is not bright enough.

+ Focus (each step is 0.04µm)

Linewidth: 0.25 µm (1.1 k₁) (large)
Ring Bias: Off
# Rings: 3 (small)
Probe Radius: 0.23µm (1.0 k₁) (small)
Chrome Gap: 0.45 µm (small)
Chrome Neck: 0.55 µm (small)

Conventional illumination with \( \sigma = 0.3 \), \( NA = 0.85 \), \( \lambda = 0.193\mu m \).
The other values for probe neck and probe radius reduced the sensitivity.

Conventional illumination with $\sigma=0.3$ NA=0.85, $\lambda=0.193\mu m$

Optimal Combination

Linewidth: 0.15 $\mu m$ (0.66$k_1$) (small)
Ring Bias: Off
# Rings: 4 (large)
Probe Radius: 0.23$\mu m$ (1.0 $k_1$) (small)
Chrome Gap: 0.7 $\mu m$ (large)
Chrome Neck: 0.55 $\mu m$ (small)

Focus (each step is 0.04$\mu m$)

0$\mu m$ +0.04$\mu m$ +0.08$\mu m$ +0.12$\mu m$

-0.012$\mu m$ -0.08$\mu m$ -0.04$\mu m$
Analysis of Sensitivity

Simulation shows that the pattern and probe should theoretically be much more sensitive than a probe alone.

The linear behavior exhibited in simulation may become more parabolic due to edge effects, which cause the intensity curve to become rotated.
Critique of Technique

- Sensitivity to focus of 0.3RU were demonstrated.
- This technique could be improved to include targets both with and without probes in order to predict the sign of the defocus.
- This technique uses nominal conditions and could be used with an ordinary double exposure process.
- The benefit it has over bossung plot generation is that it is electrical, and can be generated at any time to determine the process conditions across the field.
- The chrome gap needed to be larger than calculated in simulations, due to the additive effect of the two exposures.
- A thick mask model for the probe would be beneficial.
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Part 3: Characterization and Monitoring Photomask Edge Effects

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Marshal Miller
Industry Challenge

• As feature sizes shrink, thick mask electromagnetic effects have larger impact on imaging
• Currently for ALT-PSM, 180° phase shift can only be produced for one pitch
  – Bob Gleason, Intel BACUS ‘06
• Boundary layer methods have been shown as a useful method for adding a correction to a thin mask model
• We present a simple method for calculating these correction biases
Approach: simulation vs. experimental

• Simulate transmission through various mask stacks
  – Change duty cycle and pitch
  – Look at field amplitude transmitting through mask

• Experimental setup
  – Mask created with gratings of various duty cycle and pitch
  – Look at square root of transmission intensity
  – Use measured data to back out edge contributions to see if experiment matches simulation
Simulation Results: MoSi Attenuating PSM

- **MoSi Attenuating PSM**
- E-Field Intensity
  4.998%
- Phase Difference:
  176.8° (limited by cell grid)
- By ratio of intensities:
  min should be at 18.3% duty
- Thickness: 77.20 nm

Simulations run with periodic BC in horizontal direction and PML on top and bottom to minimize unwanted reflections
Simulation Results: Glass Alternating PSM

- **Glass CPL**
- Lossless
- Phase Difference: 180.8° (limited by cell grid)
- Min should be at 50% duty
- Etch Depth: 193nm

\[ C_{ER} = \Delta f \frac{\text{Period}}{\lambda} \]
\[ C_{EI} = \frac{E_{\text{min}}}{2} \frac{\text{Period}}{\lambda} \]

Use offset from the expected minimum location to calculate real \( (C_{ER}) \) and the height of the offset for imaginary \( (C_{EI}) \) contributions of thick mask in terms of boundary layers with width in nm.
Data summary: values in nm per edge

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<th>Period</th>
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<th>$3\lambda$</th>
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<td>TE-C$_{EI}$</td>
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<td>TM-C$_{ER}$</td>
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<td>21.3</td>
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- Data represents width in nm of box with transmission of 100%
Conclusions/Looking Ahead

• Developed method for calculating real and imaginary edge contributions from thick mask

• Future work:
  – Look at off axis illumination
  – Examine coherence effects and possible cross-polarization
  – Compare results from 2-D method to 3-D structures
    • Are 2-D simulation results accurate enough?
  – Verify effect of 0\textsuperscript{th} order correction on higher diffraction orders
    • Does correcting 0\textsuperscript{th} order sufficiently fix higher orders?
  – Change etch depths (ALT-PSM) and absorber thickness (ATT-PSM) to look at correction techniques
  – Test experimental results with FLCC mask
    • Gratings of varying duty cycles printed on mask
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Part 5: Parameter Sensitive PSM Patterns for Scatterometry Monitoring

Jing Xue

Yu Ben, Marshal A. Miller,
Prof. Costas J. Spanos, Prof. Andrew R. Neureuther
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Defocus Sensitive Pattern Design

Mask with 90° test line

90° trench

Normal Incidence
Monopole radius 0.1

Twice the focus aberration lobe spacing

P = 1.14\(\lambda/NA\)

Test line image

Center line prints!

Focus contributed spillover has 90° phase and adds

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Defocus Sensitive Pattern Design (c.n.d)

The maximum defocus slope is ~0.78 with 45nm test line.
The electric field contribution from test line, pattern line and spillover due to defocus is well quantified by phasor model.

Refer to G. Robins, PhD 2005
Defocus Sensitive Pattern Design (c.n.d)

Photo-resist Focus Exposure Testing

defocus

dose

<table>
<thead>
<tr>
<th></th>
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<td></td>
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</tbody>
</table>

Test line begins to appear
ODP Calibration and Library

- ~10^5 models
- Calibration Model
  (profile is described by 6 floating variables)
- ~10^5 spectra
- Spectrum data

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ODP Calibration

Defocus: -0.2 RU, dose: 5units
GOD: 0.9985, Res: 0.0228

Defocus: -0.3 RU, dose: 5units
GOD: 0.9973, Res: 0.0249

Defocus: -0.4 RU, dose: 5units
GOD: 0.9989, Res: 0.0157

9/10/2007
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## ODP Calibration Test (data in nm)

<table>
<thead>
<tr>
<th>df (R.U.)</th>
<th>Pattern Top CD</th>
<th>Pattern Bot. CD</th>
<th>Pattern Depth</th>
<th>Test Top CD</th>
<th>Test Bot. CD</th>
<th>Test Depth</th>
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<td>51 56</td>
<td>200 194</td>
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<td>-0.4</td>
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<td>6 6</td>
<td>48 50</td>
<td>84 86</td>
<td>61 62</td>
<td>200 198</td>
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<tr>
<td>Max Error</td>
<td>6.7%</td>
<td>-</td>
<td>12.9%</td>
<td>9%</td>
<td>9.8%</td>
<td>3%</td>
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</table>

- 6 Variables seem to describe this profile well
- Reasonably compact library can be built for this pattern
- Good sensitivity to defocus is captured by the library
- Experimental verification needed

*Conclusion based on simulated results*