Table-top, full-field, actinic microscope for extreme ultraviolet lithography mask characterization

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Department of Electrical Engineering
Dissertation
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• **Opportunity:** Extreme Ultraviolet Lithography – EUVL

• **Challenge:** Characterization of EUVL masks

• **Project Goal:** Development of a table-top microscope for EUVL mask

• **Accomplishments:** Microscope and mask characterization

• **Future opportunities:** System improvements and mask studies
Since 1965 the semiconductor industry has been following Moore’s Law

"The number of transistors incorporated in a chip will approximately double every 24 months." — Gordon Moore, Intel Co-founder

Critical dimension:

\[
CD = \frac{K \lambda}{NA}
\]

- \(K\): process constant
- \(\lambda\): printing wavelength
- \(NA\): numerical aperture of printer

MOORE'S LAW

2300 transistors

1.7 billion transistors

nano-taiwan.sinica.edu.tw/.../index.htm
Current lithography uses 248 nm - 193 nm deep UV light

\[ \lambda \]: Krypton fluoride and argon fluoride excimer lasers

NA: immersion lithography

K: high quality resists, double patterning schemes

Current technology is reaching CD limit at around 32 nm

Industry will move to EUV wavelengths
Extreme Ultraviolet Lithography is based on reflective optics in a vacuum environment.
EUV Lithography will use 13.5 nm wavelength due to availability of mirrors and sources.

Mo/Si multilayer mirrors present high reflectivity around 13.5 nm wavelength.

Lithium, Tin, and Xenon plasmas emit at this wavelength.

Beta printing tools have demonstrated printability of wafers and functional devices using EUVL.

- AMD demonstrated a functional SRAM device with critical-layer patterning.

- The University of California, Berkeley, showed 26 and 22 nm patterning capabilities from their micro-exposure tool (MET).

- The Paul Sherrer Institute in Switzerland demonstrated 11 nm printed features.
Several technological issues challenge EUVL

Source power > 180 W at intermediate focus, acceptable utility requirements through increased conversion efficiency and sufficient lifetime of collector optics and source components

Cost control and return on investment

Resist with < 1.5 nm 3s LWR, < 10 mJ/cm² sensitivity and < 20 nm ½ pitch resolution

Fabrication of Zero Printing Defect Mask Blanks
Establishing the EUVL mask Blank infrastructure (Substrate defect inspection, actinic blank inspection)
Establishing the EUVL patterned mask infrastructure (Actinic mask inspection, EUV AIMs)

Controlling optics contamination to achieve > five-year lifetime

Protection of EUV masks from defects without pellicles

Fabrication of optics with < 0.10 nm rms figure error and < 7% intrinsic flare

International Technology Roadmap for Semiconductors

2009 report
Different defects can be present in EUVL masks

- 6” × 6” Mo/Si multilayer coated mask
- Absorber pattern

Current values and goals:

- Currently: 0.3 defects/cm²
  Goal: 0.003 defects/cm²

- Currently: 70 defects/mask
  Goal: 0.7 defects/mask
Defect type, size, and location determine printability

Mochi, EUVL Symposium (2009)

225 nm  160 nm

phase defect
(11.9 nm \times 57.6 \text{ nm})

Three actinic (at-wavelength) tools for EUVL mask inspection are needed.

- **Mask blank inspection tools**: capable of scanning a masks before pattern deposition
  - Source brightness: 10 – 500 W/(mm$^2$sr)

- **Aerial image microscopes**: capable of imaging regions of interest on masks
  - Source brightness: 100 - 200 W/(mm$^2$sr)

- **Patterned mask inspection tools**: capable of scanning patterned mask
  - Source brightness: 300- 2500 W/(mm$^2$sr)

*Actinic*: term coined from early photography were it was used to distinguish light that would expose a film from light that would not
Several approaches to Full-field microscopy of EUVL masks have been proposed:

- EUV mirror system with secondary magnification
- Zone plate based system
- All EUV mirror system

<table>
<thead>
<tr>
<th>System</th>
<th>Source brightness</th>
<th>Top challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUV + Visible</td>
<td>750</td>
<td>Source brightness</td>
</tr>
<tr>
<td>EUV + PEEM</td>
<td>700</td>
<td>Source brightness</td>
</tr>
<tr>
<td>Zone Plates</td>
<td>26</td>
<td>Source bandwidth</td>
</tr>
<tr>
<td>All EUV</td>
<td>32</td>
<td>Small sub-apertures</td>
</tr>
</tbody>
</table>

NewSUBARU (operational)  
Osugi, JJAP 47 (2008)  
Zeiss (proposed 2013)  
Feldman, SPIE 2010  
AIT (operational)  
Goldberg, SPIE 2010
Aerial image microscopes currently operate at synchrotrons facilities.

**SEMATECH Berkeley**
Actinic Inspection Tool (AIT)

**NewSUBARU EUVM**


Osugi et al., JJAP 47, 4872-77 (2008)
Synchrotron-based Full-field actinic microscopes can capture high quality images in shot exposure times.

175 nm half-pitch

Resolution > 88 nm
Exposure time: 10 - 20 sec

300 nm half-pitch

Resolution > 200 nm
Exposure time: 40 - 120 sec

225 nm half-pitch

500 nm and 400 nm half-pitch

Osugi et al., JJAP 47, 4872-77 (2008)
Project Goal: develop a compact AIM microscope

Develop a table-top full-field actinic microscope for in-house EUVL mask characterization

Strategic plan:

- Compact EUV laser at CSU
- Optics from CXRO

Design
Implement
Characterize microscope
Study mask patterns
The EUV laser pulses are generated by creating a plasma from solid target using a Ti:Sapphire laser.
The characteristics of the laser beam make it well suited for EUVL mask inspection.

**Cadmium target**

13.2 nm

\[ P = 1 - 10 \, \mu W \]
\[ \theta = 7 - 10 \, \text{mrad} \]
\[ \Delta \lambda/\lambda < 10^{-4} \]

Diffraction-based optics are a good alternative for laser-based microscopy


\[ NA = \frac{\lambda}{2 \Delta r} \]

resolution = \[ k_1 \frac{\lambda}{NA_{obj}} = 2k_1 \Delta r \]

\[ f = \frac{4N(\Delta r)^2}{\lambda} \]

\[ DOF = \pm \frac{\lambda}{2 (NA_{OZP})^2} = \pm \frac{2(\Delta r)^2}{\lambda} \]

SEM Images

zone plates
made by electron beam lithography
The full-field microscope is designed to mimic the imaging conditions of an EUVL stepper

- angle of illumination (6 deg normal)
- numerical aperture of the objective (1/4 of 0.25 NA)
- coherence of the system (matching NA for objective and condenser)
The condenser zone plate was designed to fit the geometrical constrains of the reflection mode design.

- An open area must be left next to the condenser to clear the path for the image to form at the CCD.

- $\Delta r = 100$ nm
- Diameter = 5 mm
- Diameter central stop = 1.6 mm (b)
- NA = 0.066
- Focal distance = 38 mm
- 100 nm Si$_3$Ni$_4$

Zone plates fabricated at CXRO
Off-axis zone plate allows normal incidence imaging of samples

- $\Delta r = 40 \text{ nm}$
- Diameter = 120 $\mu$m
- NA = 0.0625
- Diameter parent = 330 $\mu$m
- Focal distance = 1 mm
- $\text{Si}_3\text{N}_4$ Membrane etched to 40 nm
A set of diagnostic ports are used for microscope alignment and optimization

- A: laser input
- B: beam imaging
- C: transmission
- D: reflection
- E: laser intensity

microscope housed in a 70×45×40 cm³ chamber
Photon budget indicates that images are obtained with a reasonably short exposure time.

<table>
<thead>
<tr>
<th>Laser Power (µW)</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput of 0.1 µm Zr filter</td>
<td>0.7</td>
</tr>
<tr>
<td>Throughput of Mo/Si turning mirror</td>
<td>0.5</td>
</tr>
<tr>
<td>Throughput of condenser</td>
<td>0.05</td>
</tr>
<tr>
<td>Sample reflectivity</td>
<td>0.5</td>
</tr>
<tr>
<td>Throughput of (objective+window)</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Total throughput of the system</strong></td>
<td>4.4E-4</td>
</tr>
<tr>
<td><strong>Output power (nW)</strong></td>
<td>0.21875</td>
</tr>
<tr>
<td><strong>Number of photos/sec</strong></td>
<td>1.5E7</td>
</tr>
<tr>
<td><strong>Diameter of beam at sample plane (µm)</strong></td>
<td>20</td>
</tr>
<tr>
<td><strong>Magnification</strong></td>
<td>1080</td>
</tr>
<tr>
<td><strong>Diameter of beam at image plane (µm)</strong></td>
<td>21600</td>
</tr>
<tr>
<td><strong>Area of the beam at image plane (µm²)</strong></td>
<td>3.7E+08</td>
</tr>
<tr>
<td><strong>CCD pixel size (µm)</strong></td>
<td>13.5</td>
</tr>
<tr>
<td><strong>area of CCD pixel (µm²)</strong></td>
<td>182</td>
</tr>
<tr>
<td><strong>Number of illuminated pixels</strong></td>
<td>2.0E+06</td>
</tr>
<tr>
<td><strong>Number of photons/(sec*pixel)</strong></td>
<td>7</td>
</tr>
<tr>
<td><strong>Number of counts/photon</strong></td>
<td>4.4</td>
</tr>
<tr>
<td><strong>Number of counts/(sec*pixel)</strong></td>
<td>32</td>
</tr>
<tr>
<td><strong>Exposure time for 600 counts/pixel (sec)</strong></td>
<td>19</td>
</tr>
</tbody>
</table>

50 nm half pitch grating

\[ \lambda = 13.2 \text{ nm}, \ 20 \text{ sec} \]

trans_{ref} = 0.5 \text{ trans}_{trans}

exp_{ref} = 2 \text{ exp}_{trans}
Monochromatic light at 13.2 nm allows for correct evaluation of EUVL masks

- Mo/Si multilayer
- N=40
- d=7.06 nm
- G=0.4
- F=6 deg
- 2% increments
Two masks were available for characterization of the microscope:

**CXRO sample:**
Absorber lines on a reflective background
Easier to locate and characterize the illumination

- 1:1 gratings, 80 nm to 500 nm lines
- 1:2 gratings, 60 nm to 500 nm lines
- 1:1 elbow patterns, 80 nm to 400 nm lines

**GLOBALFOUNDRIES Mask:**
Courtesy Bruno La Fontaine
Reflective lines on an absorber sample
Usually results in nicer images by avoiding flare and masking beam non-uniformities.
Periodic structures 120 nm – 500 nm
Images of dense grating patterns can be used to evaluate the resolution of the microscope.

20 sec exposure images of elbow patterns

80 nm features are fully resolved

M > 60%

80 nm features are fully resolved

20 nm on wafer
Due to lack of smaller gratings, other tests were used to estimate the spatial resolution of the system.

Knife-edge

Half-pitch resolution ~ 55 nm

Correlation method

120 nm half period – (53 ± 10) nm resolution
The Modulation Transfer Function of the microscope
Removing the central stop of the condenser improves the uniformity of the illumination

Solutions to uniformity

- No central stop
- Better zone plate writing
- Condenser motion during acquisition
The new zone plate greatly increases the uniformity of the illumination

180 nm half-pitch elbow

200 nm half-pitch grating

175 nm half-pitch grating
The coherence of the microscope was evaluated using the Talbot effect.

The position of max modulation is given by the Talbot expression:

\[ Z_t = 2 \frac{a^2}{\lambda} \]

Through-focus simulation for a 120 nm half-pitch grating.
The coherence parameter of the system is $\sigma \sim 0.25$

200 nm half-pitch grating

$\sigma \sim 0.25$

Stepper: 0.5
AIT: 0.1 - 0.2
LER and NILS provide information on quality of printed lines

**NILS** Normalized image log-slope:
measured as the derivative of the logarithm of the image’s intensity, assesses the steepness of the intensity slope along the imaged features. Line edge roughness

**LER** Line-edge roughness:
is a statistical measure of the variation of a feature’s edge along the feature’s extent and is typically expressed as three times the standard deviation, $3\sigma_{\text{dev}}$.
LER measurements are below 10% CD

<table>
<thead>
<tr>
<th>CD (nm)</th>
<th>1:1 threshold</th>
<th>NILS</th>
<th>$3\sigma$ (nm)</th>
<th>$100 \times 3\sigma/CD$</th>
</tr>
</thead>
<tbody>
<tr>
<td>175</td>
<td>0.395</td>
<td>3.58</td>
<td>13.55</td>
<td>7.75</td>
</tr>
<tr>
<td>225</td>
<td>0.442</td>
<td>3.32</td>
<td>20.86</td>
<td>9.27</td>
</tr>
</tbody>
</table>
The extent of the focal spot can be tailored by redesigning the condenser zone plate

Grating equation:
\[ d (\sin \theta_m + \sin \theta_i) = m \lambda \]

- \(d\) = grating spacing
- \(\theta_m\) = diffraction angle
- \(\theta_i\) = incident angle
- \(m\) = diffraction order
- \(\lambda\) = illumination wavelength

\[ d \sin \theta_m = \lambda \]

The illuminated region is formed by the superposition of the 1\textsuperscript{st} order diffraction of each sub-region of the zone plate

Proposed condenser zone plate design must have same diameter, focal length and numerical aperture

- Concentric rings with periodic gratings
- Ring width equal to desired spot size
- Each ring with integer number of zones

- focal spot: ~15 µm
- focal length: 38 mm
- diameter: 5 mm
- number of rings: 164
- size of smallest grating: ~100 nm
Phase defects change the local intensity in the image disrupting the quality.

<table>
<thead>
<tr>
<th>Defect Size</th>
<th>Image Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 nm × 56.6 nm</td>
<td></td>
</tr>
<tr>
<td>7.2 nm × 55.7 nm</td>
<td></td>
</tr>
<tr>
<td>8.2 nm × 56.6 nm</td>
<td></td>
</tr>
<tr>
<td>9.7 nm × 55.6 nm</td>
<td></td>
</tr>
<tr>
<td>11.9 nm × 57.6 nm</td>
<td></td>
</tr>
</tbody>
</table>


- □ absorption defect
- ◆ phase defect

Programmed defects help determine the effect of defects on printed wafers
• Designed a compact reflection mode microscope that emulates a 0.25 NA EUVL stepper

• Measured spatial resolution better than 80 nm on mask (20 nm for 4× reduction)

• Estimated spatial resolution of 55 nm on mask (14 nm for 4× reduction)

• Exposure times of 5 to 90 seconds (comparable to Synchrotron-based microscopes)

• Performed the first measurements of LER and NILS on an EUVL mask using a compact actinic microscope

• The microscope now can be used to study EUVL mask defect and pattern printability
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Committee members

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