2015 Advanced Lithography:
Measuring Aberrations using EUV Mask Roughness

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Aberrations change the results from an EUV actinic inspection system
  – Want to measure aberrations
  – Want to measure from images directly
• Could use a programmed object (ex: contact array)
• We present a way to use existing mask roughness
  – Aberrations can be measured on any mask
Measuring Aberrations

- Unknown test object
  - Calculate object from model + measurements
- Unknown aberrations
- Minimize residual error by guessing different aberrations
New Phase Retrieval Algorithm

Arbitrary Pupil (Aberrations) + Arbitrary Source (partial coherence)

Aerial Image Measurements (focus series)

Quantitative Phase & Amplitude

More details in:
Weak Object Assumption

- Consider a rough mirror (or mask)
  - Most of the light is reflected
  - Some of the light is scattered
- The electric field leaving the mask can be expressed as the sum of these components
  \[ E = 1 + E_s \]
  \[ I = |1 + E_s|^2 = 1 + 2Re\{E_s\} + |E_s|^2 \]
- For most objects \( Scattering \ll DC \)
  - We can ignore \( Scattering-Scattering \)
Recovering the Field

Write the intensity as a sum of convolutions:

\[
I = 1 + E_{re} \ast K_{re} + E_{im} \ast K_{im} + \mathcal{O}(|E_s|^2)
\]

\[
\tilde{I} = 1 + \vec{E}_{re} \cdot \vec{K}_{re} + \vec{E}_{im} \cdot \vec{K}_{im}
\]

Transfer functions:

\[
\vec{K}_{re} = (P \cdot L) \ast P + P \ast (P \cdot L)
\]

\[
\vec{K}_{im} = (P \cdot L) \ast P - P \ast (P \cdot L)
\]

More details in:
Aberration and Coherent Imaging

- Under coherent illumination, the object & aberrations are not linearly independent
- Partial coherence can solve the problem

\[ I = |E_1 \ast P_1|^2 \]

\[ I = |E_2 \ast P_2|^2 \]
Partial Coherence Improves Sensitivity

Simulated 21 through-focus images of speckle with astigmatism:

- Model Astigmatism
- Residual Error
- Coherent
  \[ \sigma = 0.2 \]
  \[ \sigma = 0.5 \]

- Partial Coherence Improves Sensitivity

Assumed Astigmatism (waves)

Residual Error
SEMATECH Berkeley SHARP

- Actinic mask inspection system at LBNL
- Zone plate lens as objective
  - Less expensive than multilayer optics
  - Easy to test different lenses
  - Single lens system
  - Strong field dependent aberrations
  - Aberrations vary with focus
Aberrations Vary With Focus

Object moves with focus

Aberration is not constant with focus

RMS Aberration (milli waves)

Focus (μm)

Astigmatism

Coma

Defocus: -2757 nm
• Instead of modeling aberrations at each position we model the zone plate
  – rotation of zone plate
  – position of zone plate
  – illumination angle
• Calculate aberrations using ray tracing
• Consider physical measurement
  – “Zone plate was moved 500nm up per image”
  – Captures how aberrations change in each image
  – Captures how object moves
• Fewer parameters to optimize
Calibrating the Zone Plate

Illumination: $\sigma = 0.25$, monopole

Examine small areas → aberrations are approx constant

• Where is the center of the field?
• What is the tip/tilt of the zone plate?

Wasn’t able to automatically optimize the parameters
• Small stage drift
• Field dependent illumination

Guessed good parameters
Reduced Residual

Sample Measurement → Zone Plate Pupil

Simulated Measurement

Residual Error (Δ)

Ideal Pupil (considers only defocus)
Reduced Residual

Zone Plate Pupil

Sample Measurement

Ideal Pupil (considers only defocus)

Simulated Measurement

Residual Error ($\Delta$)

aberration error
Improved Results with ZP Model

Ideal pupil fits “average aberration” → fits best at center of the stack
Uncorrected Aberrations Affect the Object

Recovered Object:

Zone Plate Pupil

Ideal Pupil

Amplitude

Phase
Uncorrected Aberrations Affect the Object

Recovered Object:

Amplitude

remaining aberration

Phase

remaining aberration
Conclusion

- Presented new algorithm to measure aberrations
  - Unknown test object (ex: EUV mask roughness)
  - Use partial coherence to improve sensitivity
- Used a physical model for the zone plate on SHARP
  - Removed zone plate aberrations
  - Recovered field from aberrated images
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IMPACT+

integrated modeling process and computation for technology

CXRO

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Thank you for your attention!

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