2015 Advanced Lithography :

Phase Measurements of EUV Mask Defects

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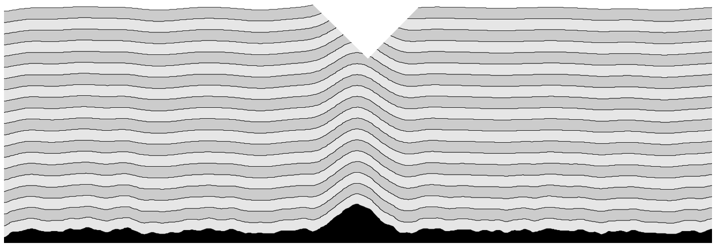
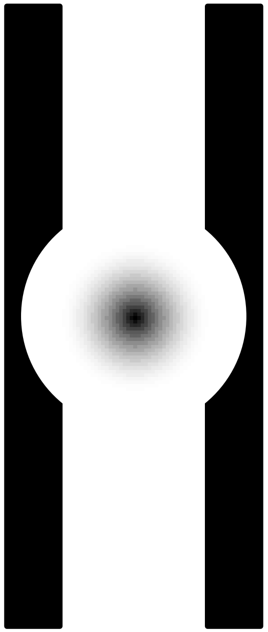
EUV Mask Defects

- Pits or particles in the substrate or multilayer will affect printing
- Can repair multilayer
- Can modify pattern
- Need to know what defect looks like
  - What is the phase/height?
  - What is the width?
  - Does it have amplitude?
- Want to measure using existing tools
  - AIMS tool





New Phase Retrieval Algorithm

Arbitrary Pupil
(aberrations)

+

Arbitrary Source
(partial coherence)

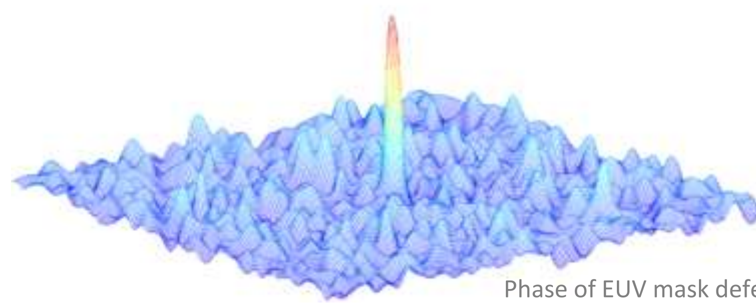
↓

Aerial Image Measurements

(focus series)

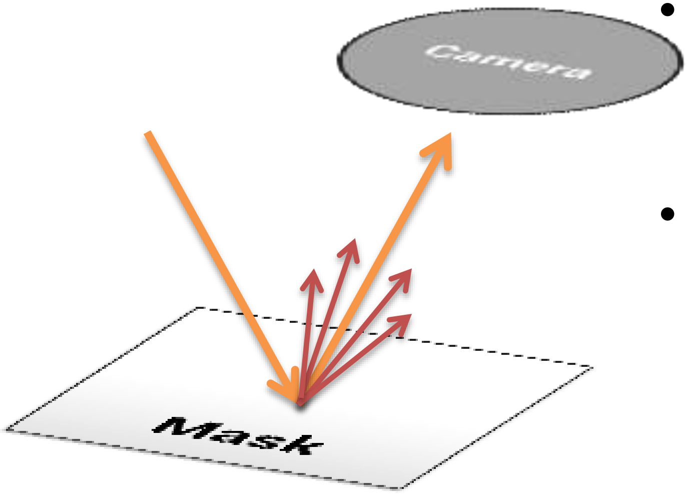
↓

Quantitative Phase & Amplitude



Phase of EUV mask defect

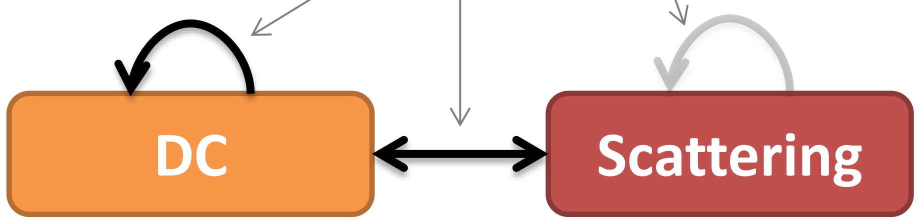
Weak Object Assumption



- 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

$$E = 1 + E_s$$

$$I = |1 + E_s|^2 = 1 + 2Re\{E_s\} + \cancel{|E_s|^2}$$



- For most objects *Scattering* ≪ *DC*
  - We can ignore *Scattering-Scattering*

Transfer Function

$$I = 1 + Re\{E_s\} * K_{re} + Im\{E_s\} * K_{im}$$

- For a weakly scattering object, we can express the intensity as two convolutions

$$F\{K_{re}\} = (P \cdot L) \star P + P \star (P \cdot L)$$
$$F\{K_{im}\} = (P \cdot L) \star P - P \star (P \cdot L)$$

P: pupil function, L: source shape

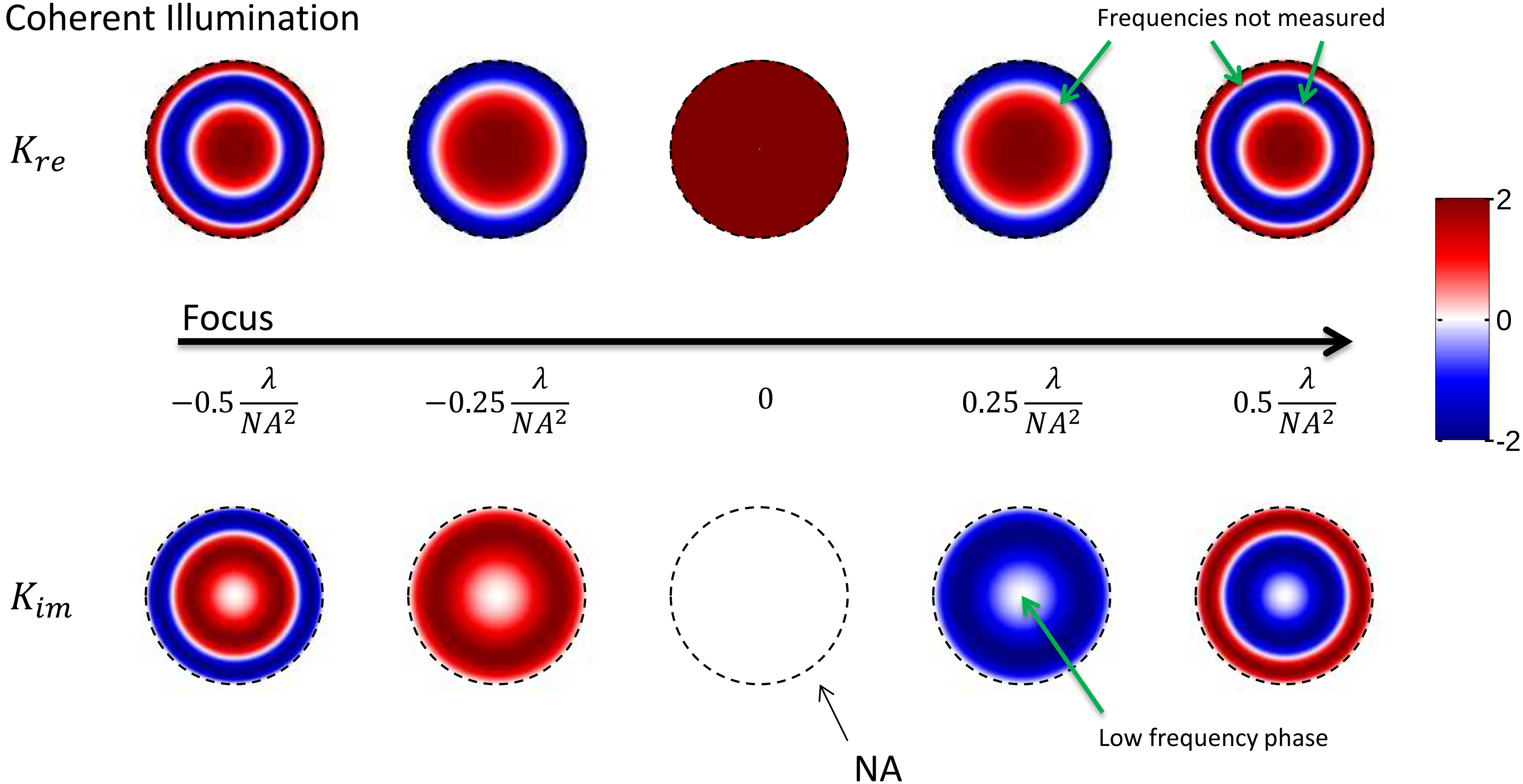
- $Re\{E_s\} \approx amplitude,\ Im\{E_s\} \approx phase$

$$E = (1 + A)e^{i\phi} \approx 1 + A + i\phi$$

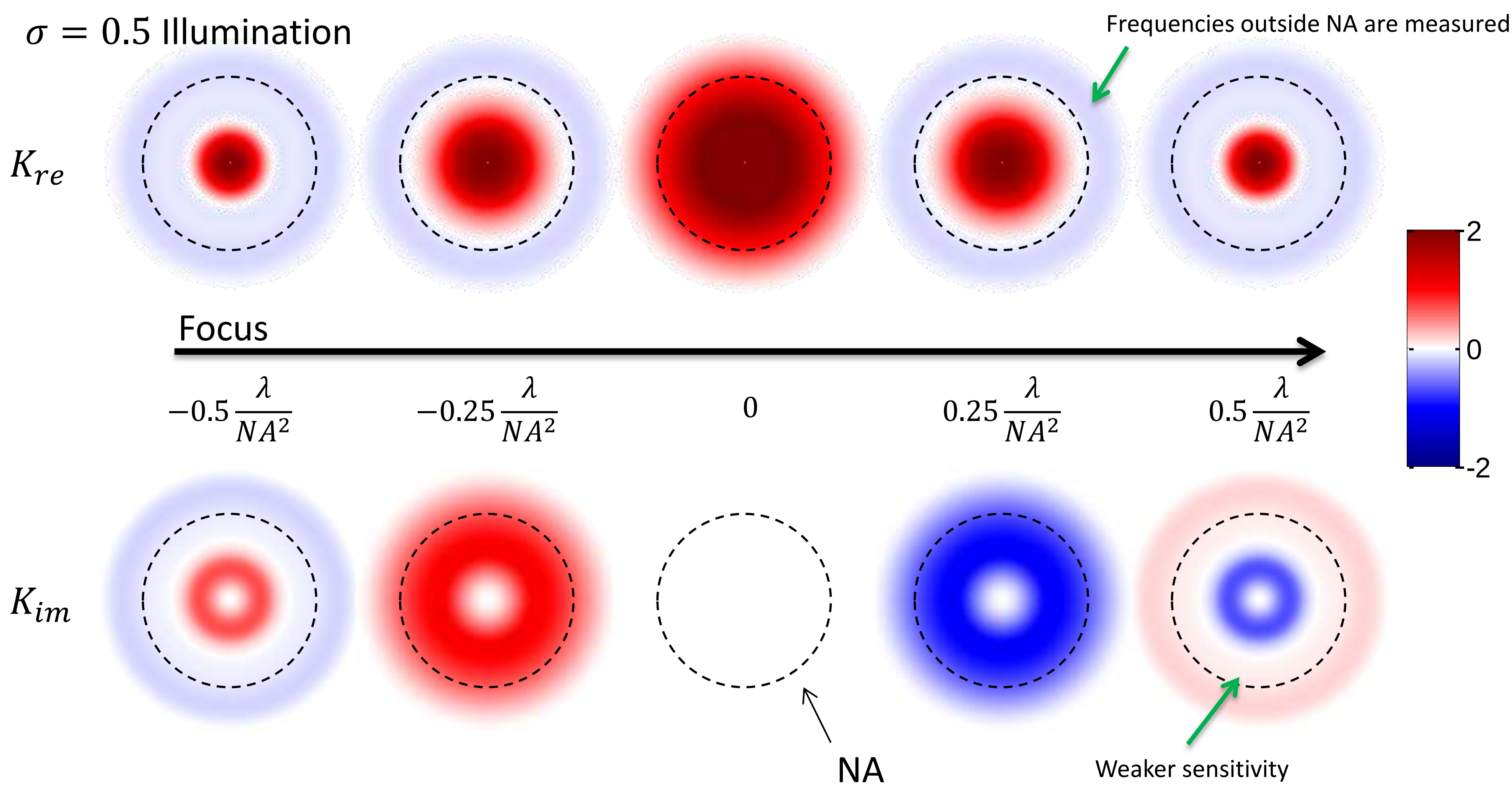
$Re\{E_s\}$ (amplitude) $Im\{E_s\}$ (phase)

Coherent Transfer Function

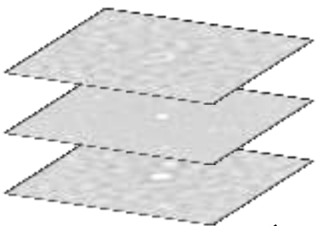
Coherent Illumination

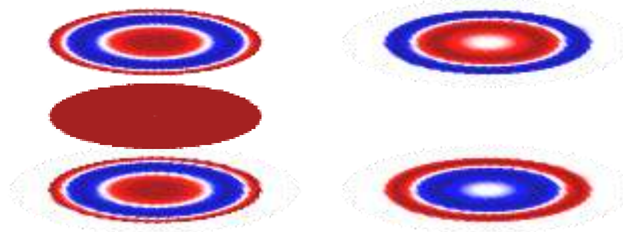


Partially Coherent Transfer Function



Inverting the Transfer Functions

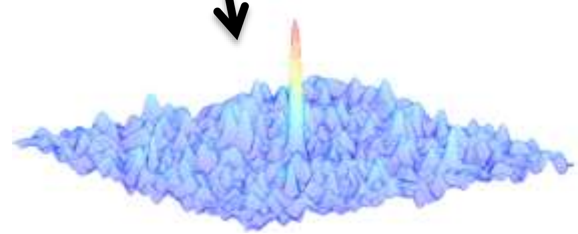




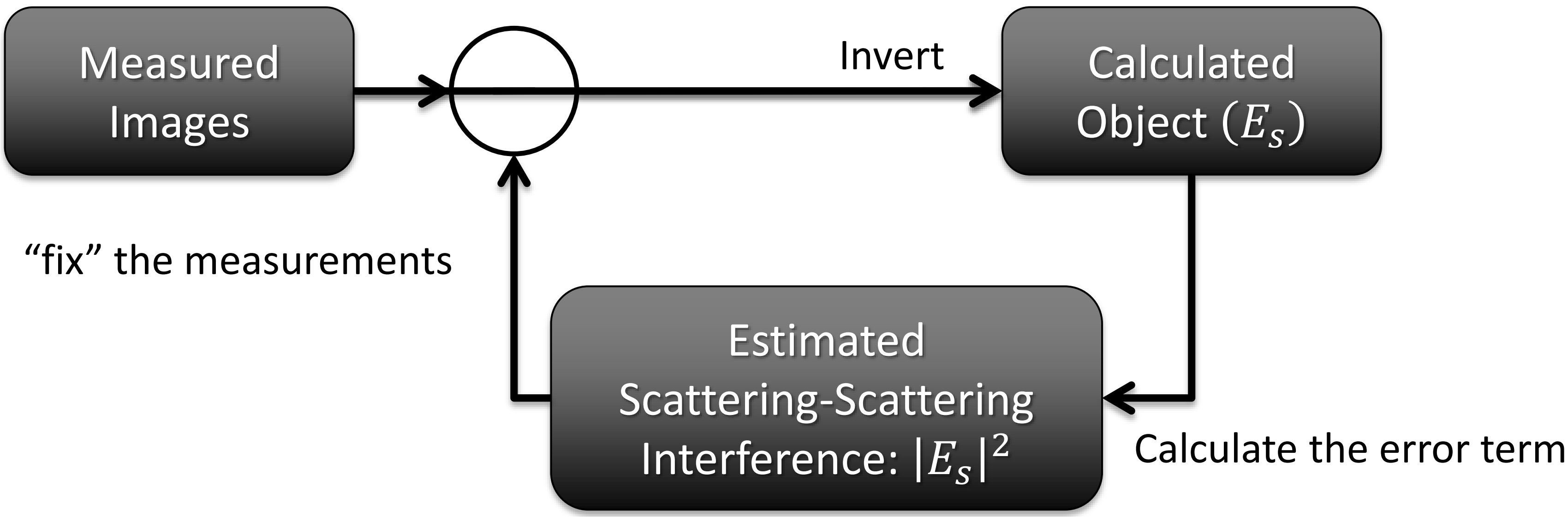
$$\begin{bmatrix} \tilde{I}_1\,(f_i) \\ \vdots \\ \tilde{I}_n\,(f_i) \end{bmatrix} = \begin{bmatrix} \widetilde{K^1_{re}}(f_i) & \widetilde{K^1_{im}}(f_i) \\ \vdots & \vdots \\ \widetilde{K^n_{re}}(f_i) & \widetilde{K^n_{im}}(f_i) \end{bmatrix} \begin{bmatrix} \widetilde{E_{re}}(f_i) \\ \widetilde{E_{im}}(f_i) \end{bmatrix}$$

Linear system of equations

Solve using least squares

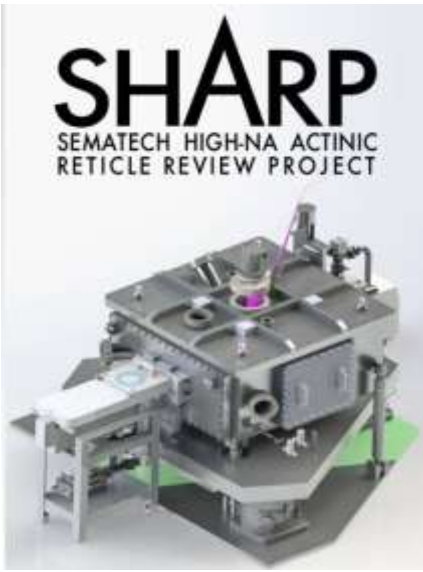


Iterative Algorithm



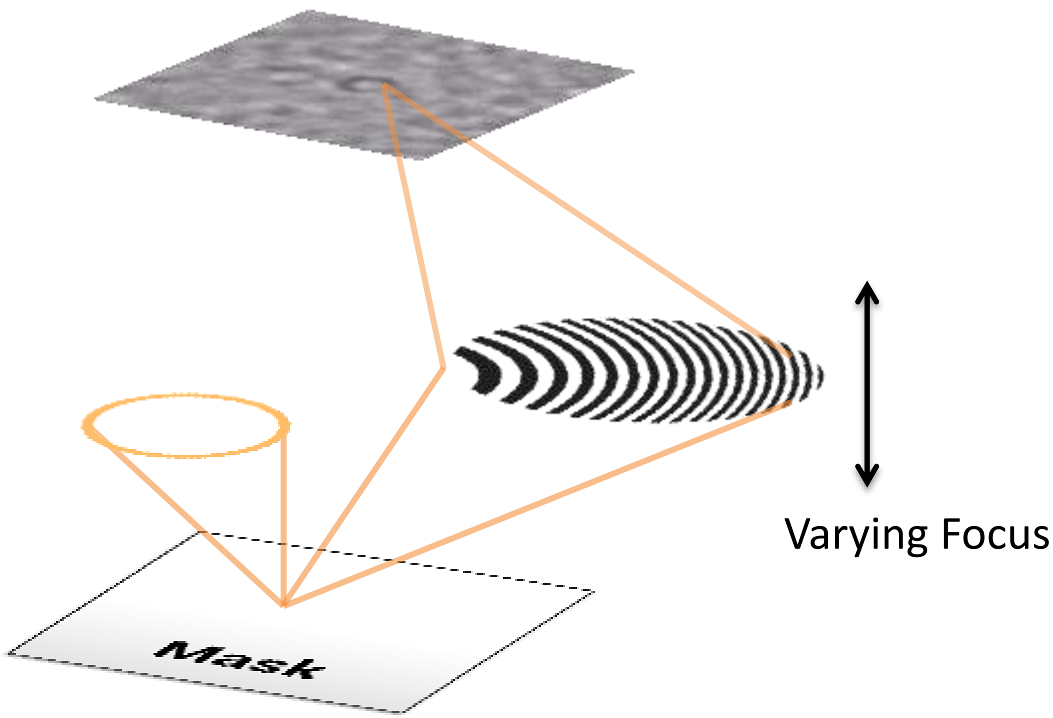
- Ideally scattering-scattering term is zero
  - Subtract term → becomes zero
- The iterative algorithm works reliably for defects even when they are large

SHARP



Zone Plate Microscope

- Pixel Size: 15nm
- NA: $0.33/4$ (0.0825)
- Wavelength:13.5nm
- Programmable illumination

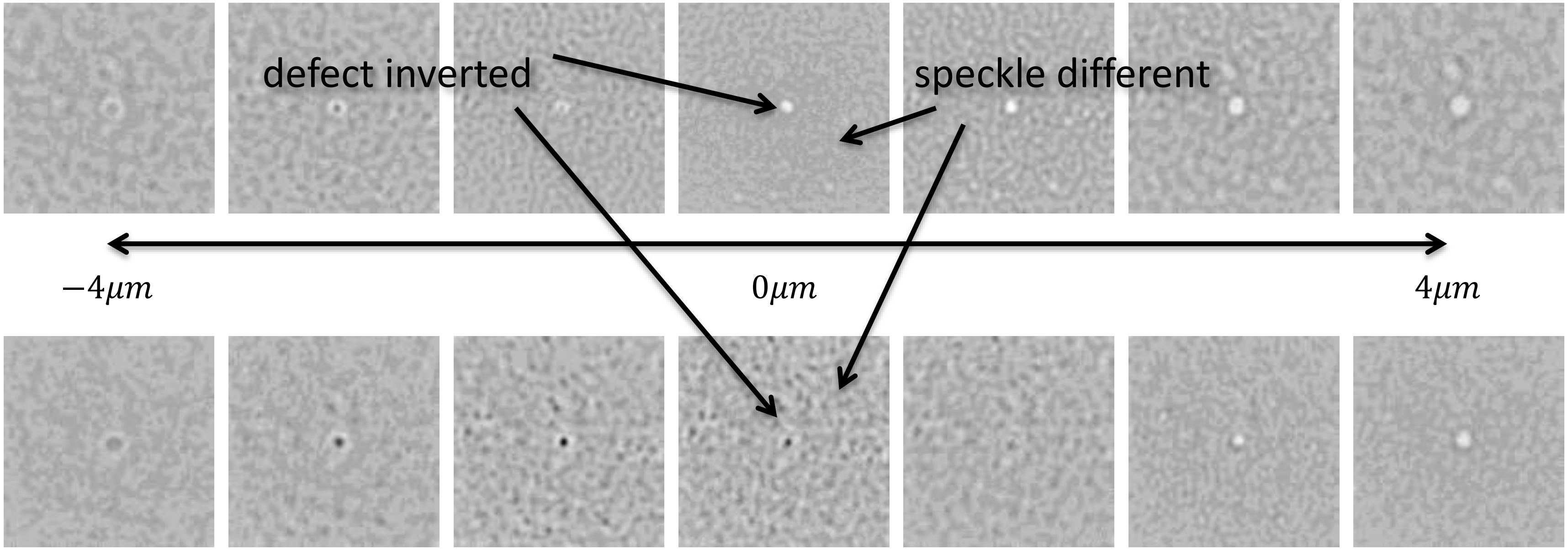


Phase Contrast vs Standard Data

- Measured same defect with different pupils
- Qualitatively very different measurements
- If the recovered object is the same, it's not an artifact

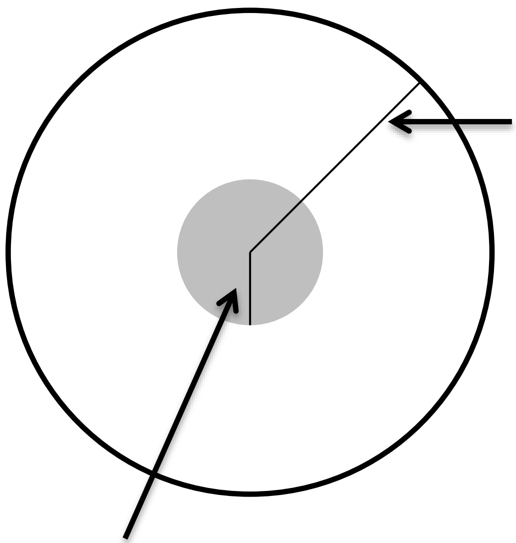
$NA: 0.33/4$
$\sigma = 0.25$ illumination

Standard Pupil



Phase Contrast Pupil

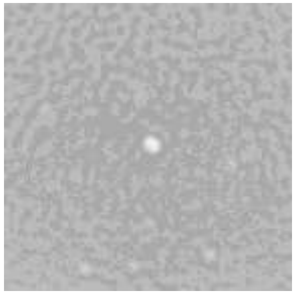
Phase Contrast Imaging

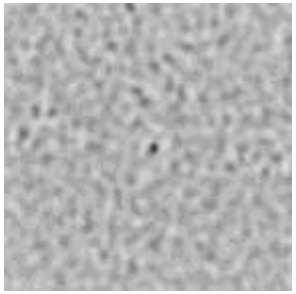


- A phase contrast pupil has a phase shifting region
- Effectively switches phase and amplitude information

At Focus:

Standard

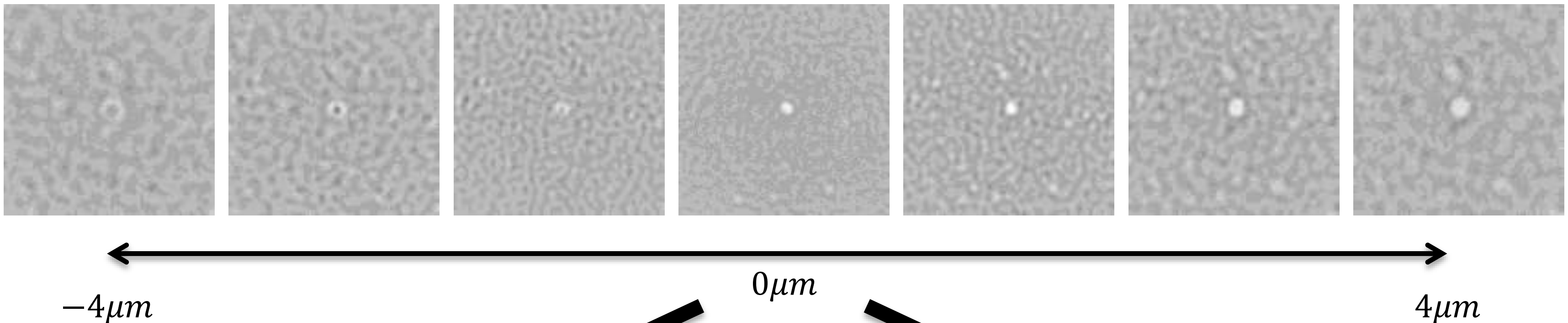




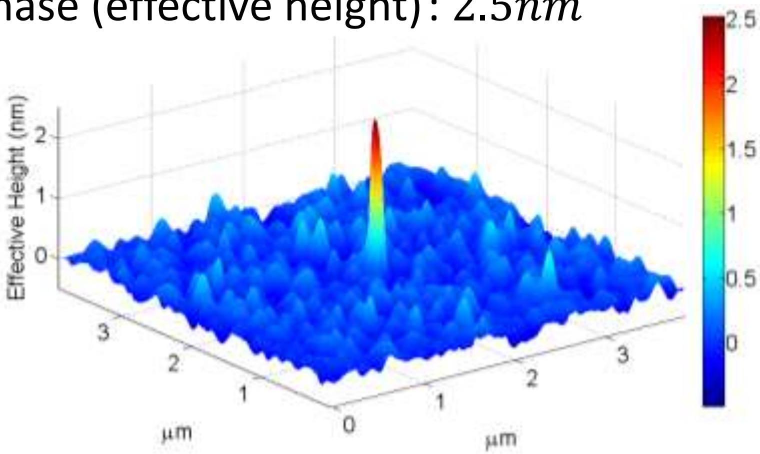
Phase Contrast

Y.G. Wang, "Enhancing defect detection with Zernike phase contrast in EUV multilayer blank inspection," SPIE Advanced Lithography (2015).

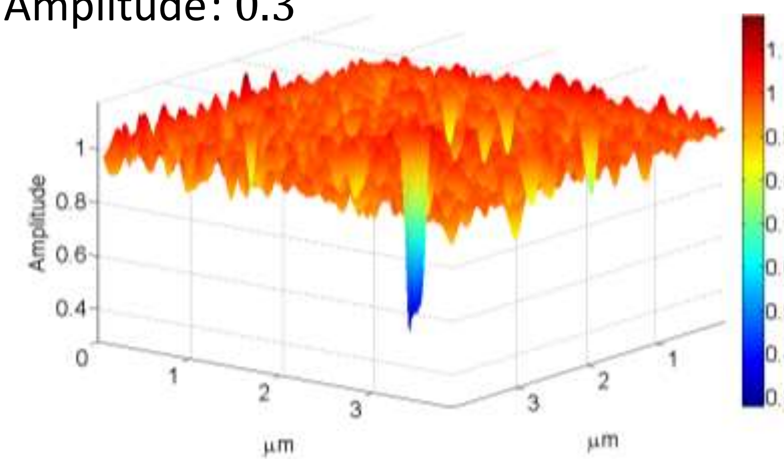
Standard Zone Plate Results



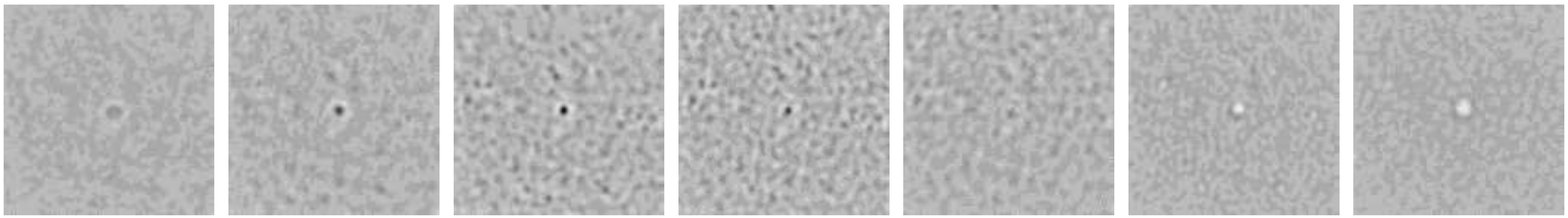
Phase (effective height): $2.5nm$



Amplitude: 0.3

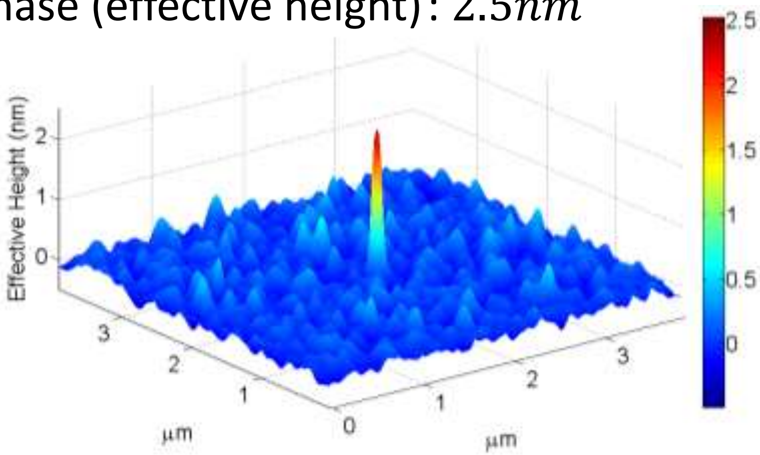


Phase Contrast Zone Plate Results

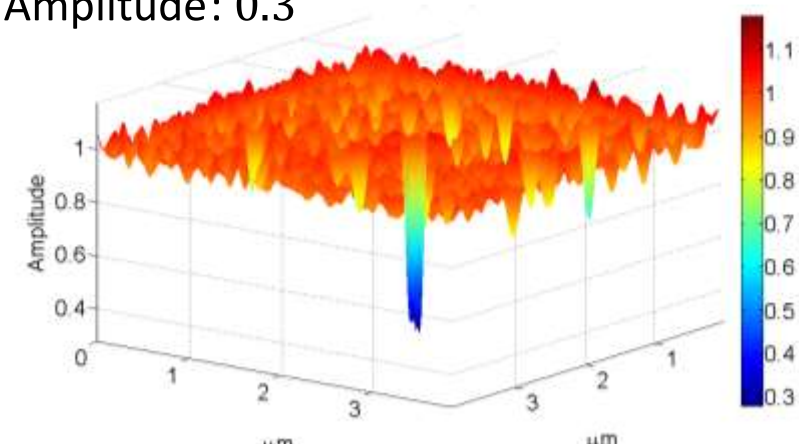


$-4\mu m$ $0\mu m$ $4\mu m$

Phase (effective height): $2.5nm$

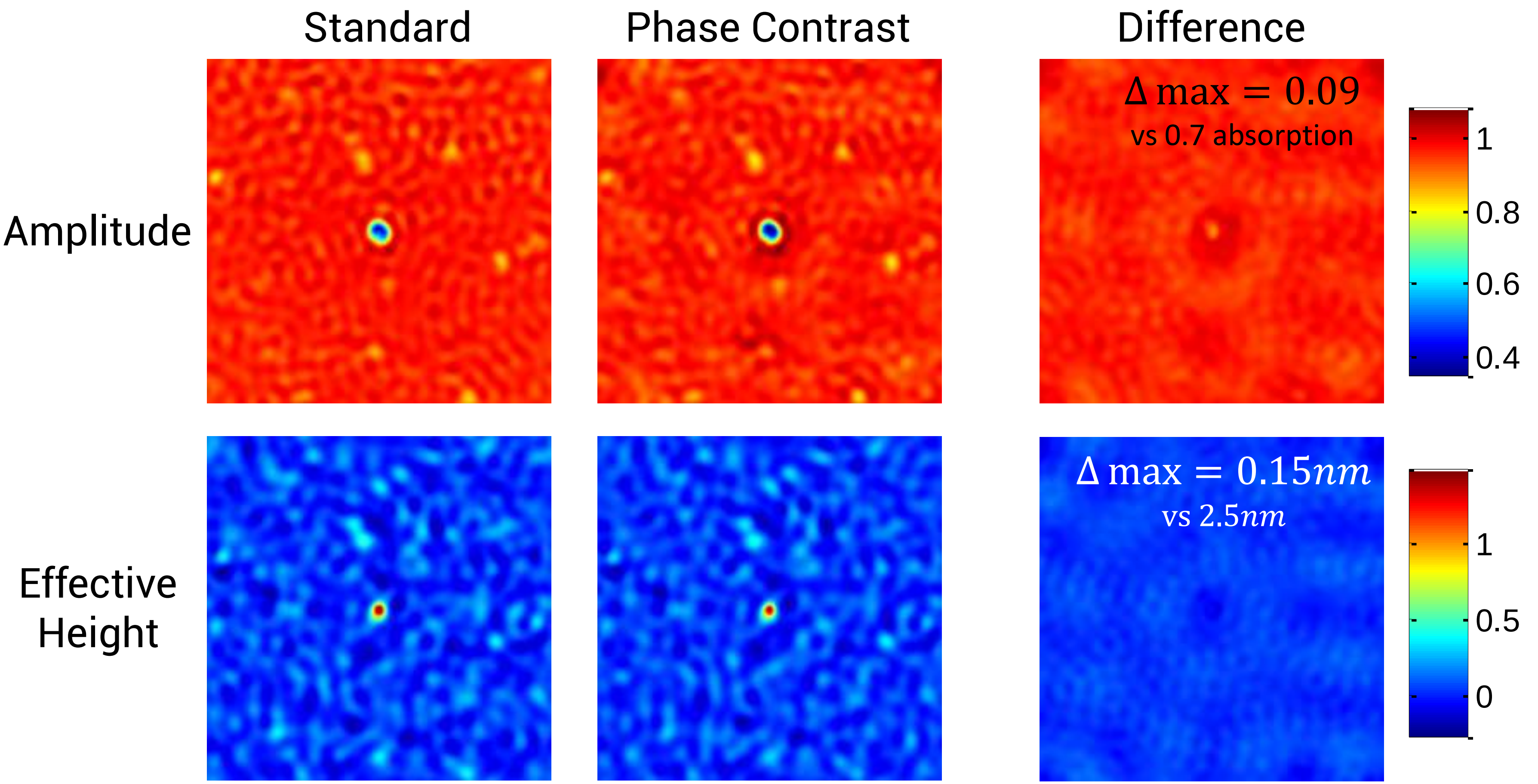


Amplitude: 0.3



Same Result

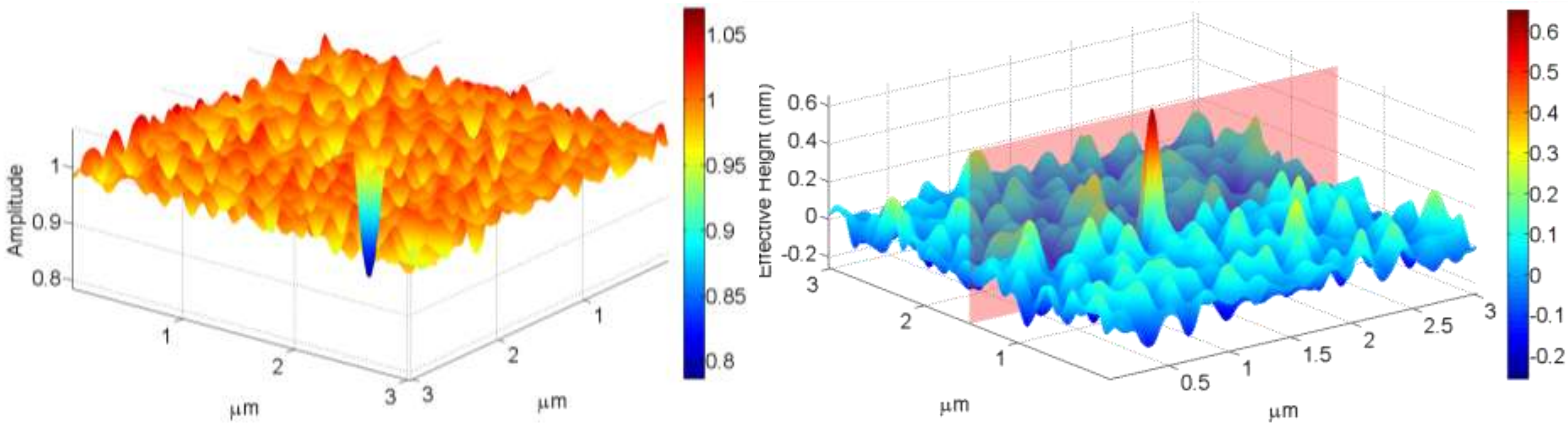
Comparing Results



Algorithm works for: complicated pupil and partial coherence ($\sigma = 0.25$)

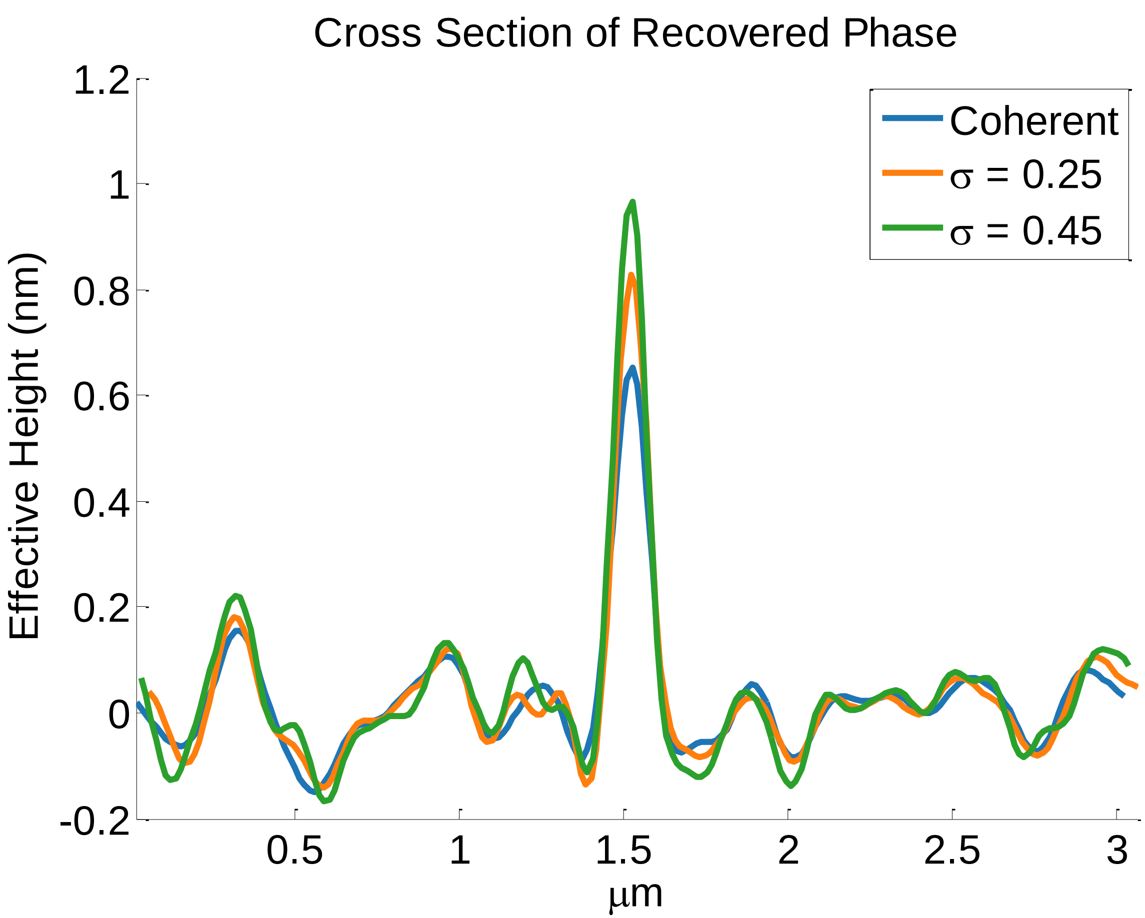
Resolution Limited Defect

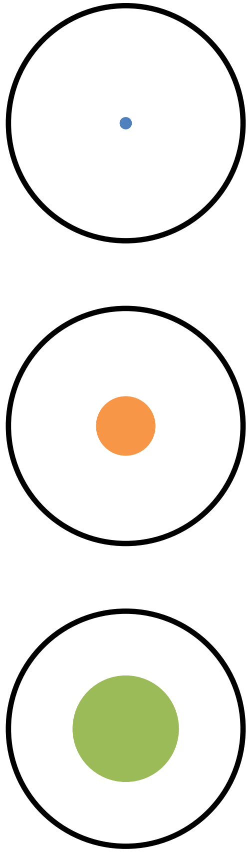
Very Small Native Defect
FWHM: $100nm$, Height: $0.65nm$, Absorption: 11%



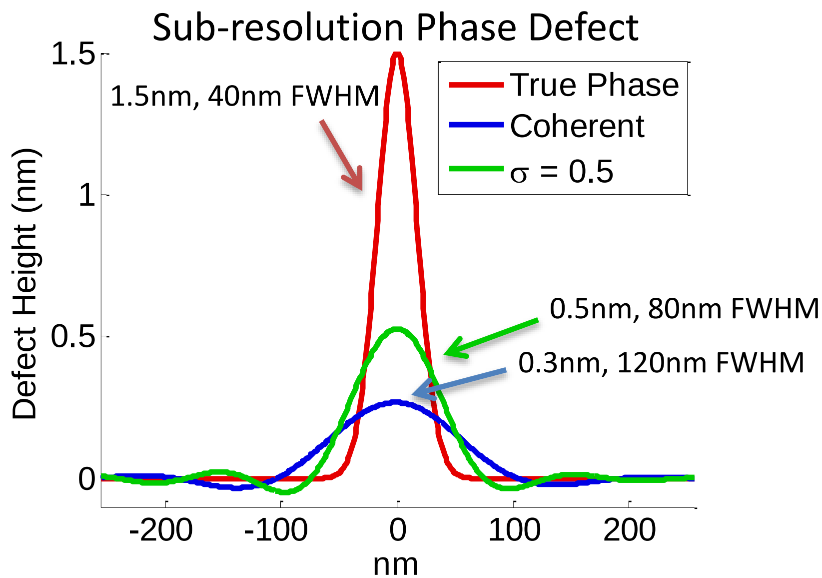
Coherent results

Partial Coherence and Resolution

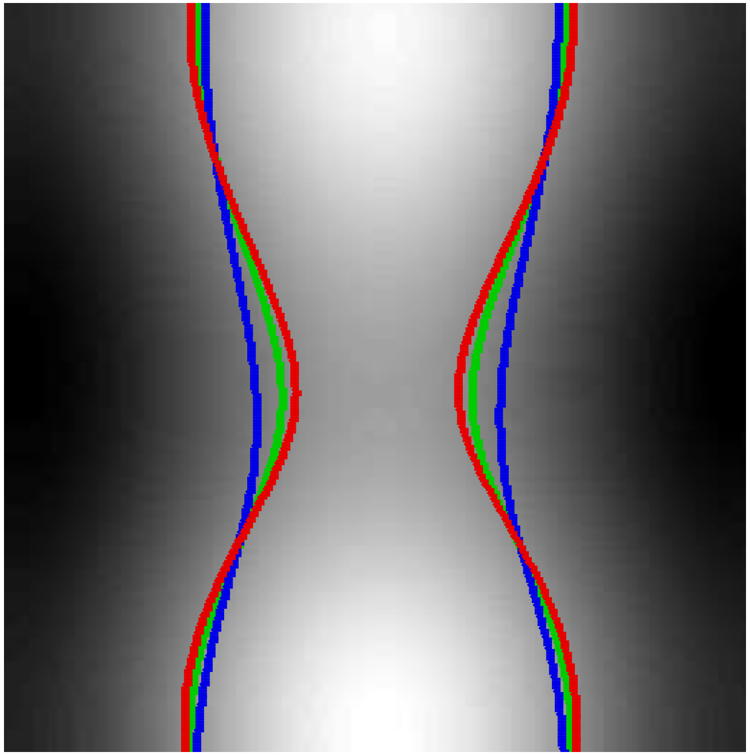




Sub-Resolution Defect Printability



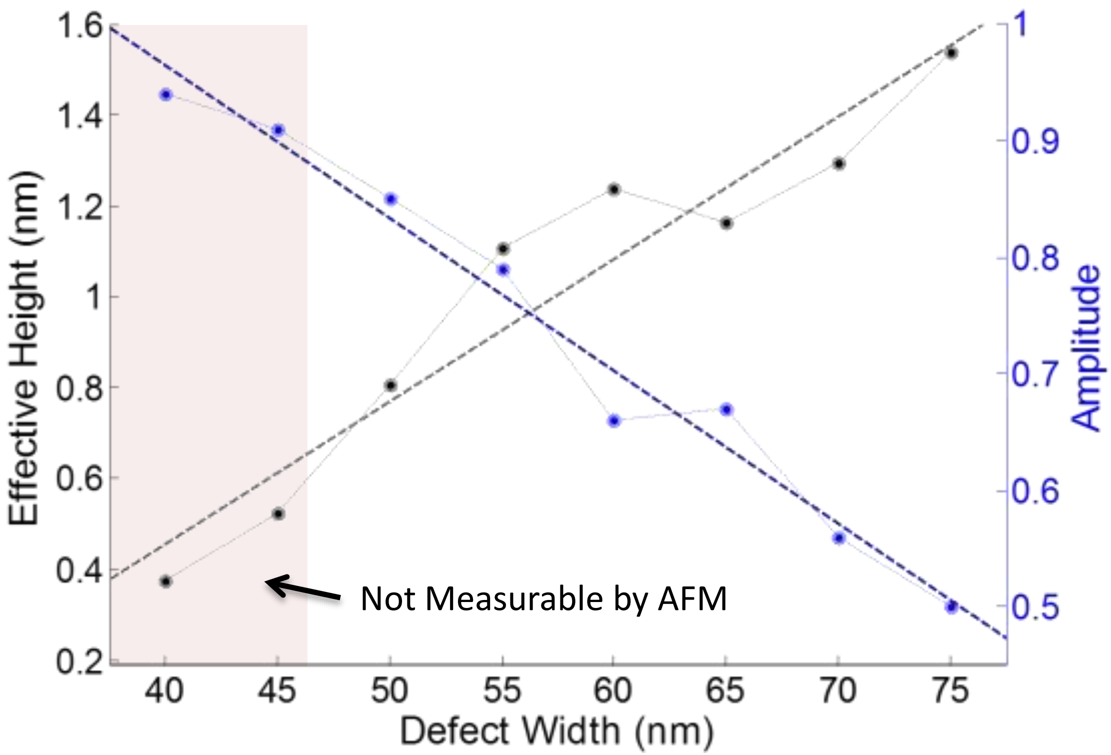
(Simulated Aerial Image)



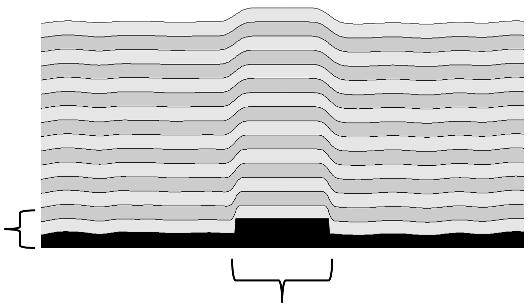
16nm lines, dipole illumination
65nm defocus

- Sub-resolution defects appear shorter and wider than they are under Coherent illumination
- Partially coherent measurements give a more accurate (higher resolution) phase result
- They print differently when patterned
- **Need to measure with partially coherently illumination or use higher NA inspection**

Programmed Defect Study



Programmed Defects



- Can measure EUV defects smaller than what AFM can see
- Defects are not pure phase defects

Y.G. Wang, "Enhancing defect detection with Zernike phase contrast in EUV multilayer blank inspection," SPIE Advanced Lithography (2015).

T. Liang, "Growth and Printability of Multilayer Phase Defects on EUV Mask Blanks," JVSTB (2007).

Conclusion

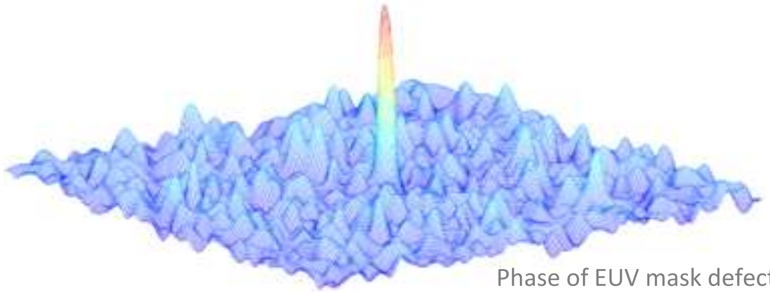
- We've developed a new algorithm to get the phase and amplitude from measurements
  - Can use partially coherent illumination
  - Verified using phase contrast zone plate
- Small defects may be larger on the mask than seen with AIMS
  - Can use partially coherent illumination to get higher fidelity measurement of the mask phase
- Mask defects are not pure phase defects
  - Large defects have higher absorption

Acknowledgement

IMPACT+
integrated modeling process and computation for technology

CXRO
THE CENTER FOR X-RAY OPTICS

BERKELEY LAB



Phase of EUV mask defect

Thank you for your attention!

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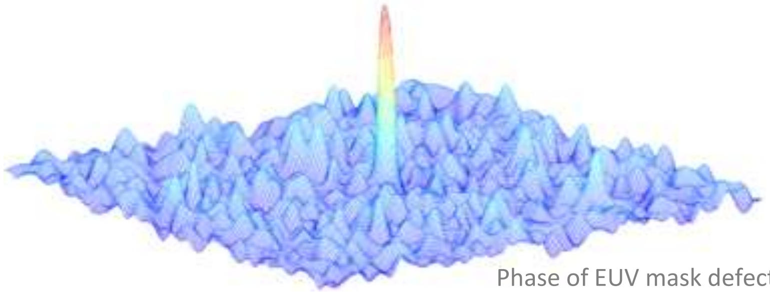

Phase of EUV mask defect

Questions?

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