C-DEN
Center for Design-Enabled Nanofabrication
Berkeley UCLA UCSD

Workshop
Patterning
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Quantitative phase imaging for EUV masks

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Motivation

- EUV photomasks reflect light with both attenuation and phase delay
- The phase impacts imaging, especially with regard to aberrations (defocus)
- Both the real and imaginary parts of the complex electric field must be known accurately before SMO

1

Objectives

- Measure the real and imaginary parts of the mask reflection function to the highest possible accuracy
- Explore the potential and limitations of scatterometry vs traditional imaging vs coded-aperture imaging

2

The Problem

- Optical phase cannot be directly observed, but can be recovered computationally
- We explore several hardware and software solutions for line-space gratings that can be implemented at CXRO

3

Traditional phase-retrieval

- Solve for phase from multiple intensity images using nonlinear least-squares
  - Susceptible to error in initial guess

$$\min_E \sum_i \left\| \sqrt{I_i} - E * H_i \right\|_2^2$$

- I_i – measured intensity image
- E – mask's complex field
- H_i – Imaging system PSF
- Multiple images w/different H_i needed

Algorithmic improvement: PhaseLift

- Computationally intensive, but not susceptible to error in initial guess
- Images are *linear* in *rank-1 matrix* EE^*:

$$I_i = \mathrm{diag}\left[F^* \mathrm{diag}\left[\widetilde{H}_i\right] \tilde{E}\tilde{E}^* \mathrm{diag}\left[\widetilde{H}_i^*\right] F\right] = \mathcal{L}_i\{\tilde{E}\tilde{E}^*\} = \mathcal{L}_i\{\mathrm{X}\}$$

$$\min_{\mathrm{X}} \alpha \mathrm{Trace}[\mathrm{X}] + \sum_i \|I_i - \mathcal{L}_i\{\mathrm{X}\}\|_2^2$$

Small trace promotes low-rank solutions — Data consistency term (least-squares)

Ref: Candes, E. J., Strohmer, T., & Voroninski, V. (2013). Phaselift: Exact and stable signal recovery from magnitude measurements via convex programming. Communications on Pure and Applied Mathematics, 66(8), 1241-1274.

Hardware improvement: coded aperture

- Self-referencing interferometry:
  - If you can phase-shift *only* the DC (carrier), phase can be solved directly:

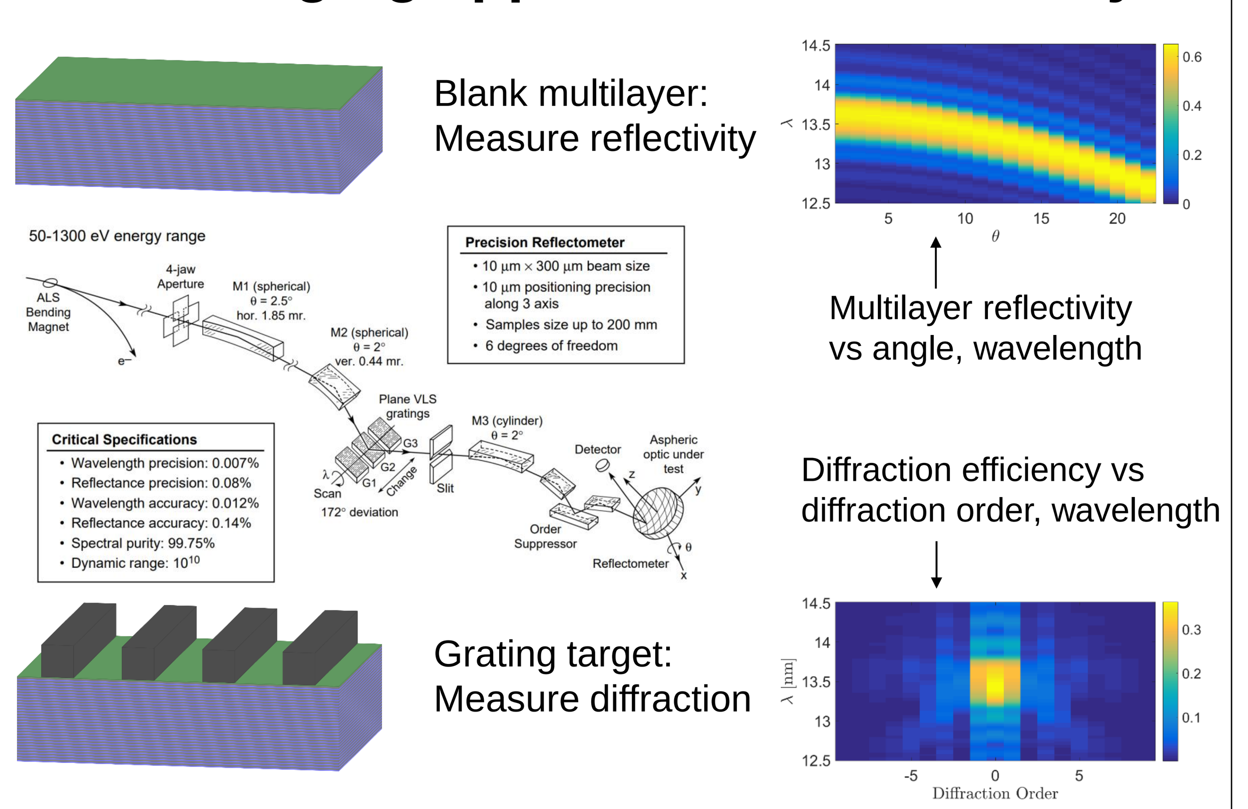
$$I_{\phi_i}[x_j] = (1, \cos\phi_i, \sin\phi_i) \begin{pmatrix} a_{1,j} \\ a_{2,j} \\ a_{3,j} \end{pmatrix}$$

$$a_{2,j} \propto \mathrm{Re}(E[x_j]), a_{3,j} \propto \mathrm{Im}(E[x_j])$$

- Implementation with coded-apertures
- Insight into coded-aperture design

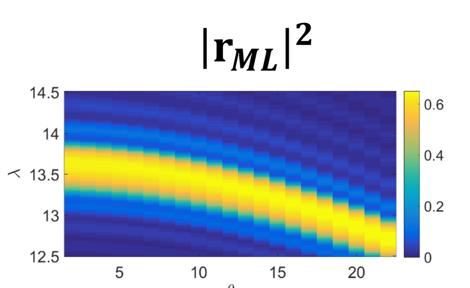
Ref: Bon, P., Maucort, G., Wattellier, B., & Monneret, S. (2009). Quadriwave lateral shearing interferometry for quantitative phase microscopy of living cells. Optics express, 17(15), 13080-13094.

Non-imaging approach: scatterometry



Ref: E. M. Gullikson, S. Mrowka, and B. B. Kaufmann, "Recent developments in euv reflectometry at the advanced light source," in Emerging Lithographic Technologies V, 4343, pp. 363–374, International Society for Optics and Photonics, 2001.

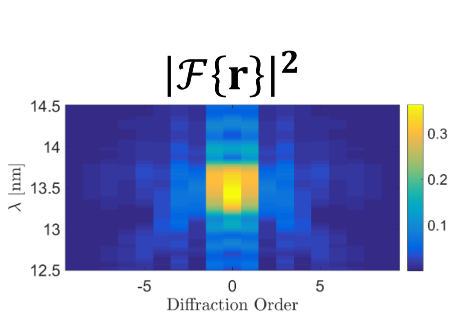
Scatterometry analysis



Multilayer phase retrieval, **either**:
1. Fit directly to layer thicknesses
2. Extrapolation + Kramer's-Kronig
3. Neural net "learned" Kramer's-Kronig

r: Reflected field
t: Absorber transmission
$\mathbf{r}_{\mathbf{ML}}$: Multilayer reflection

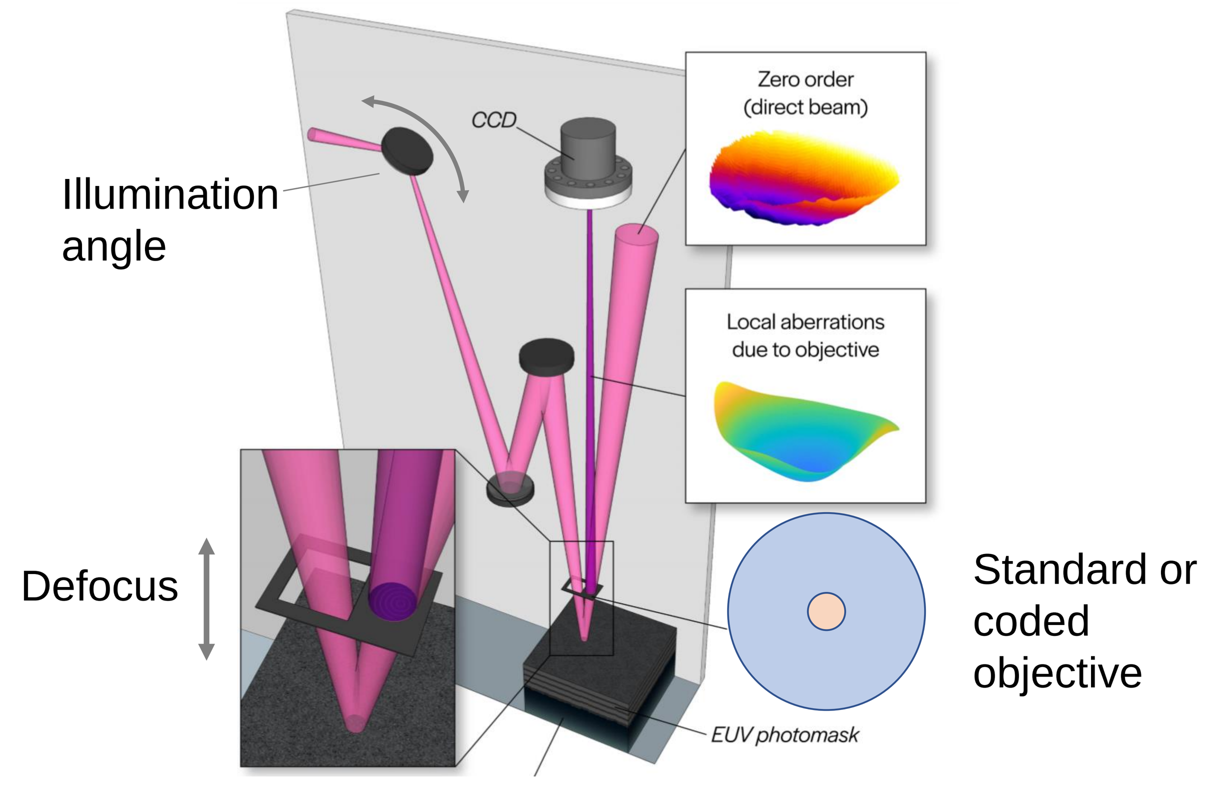
$$\mathbf{r}[\theta_0] \approx \mathbf{t} \circ \mathcal{F}^{-1}\{\tilde{\mathbf{t}} \circ \mathbf{r}_{\mathbf{ML}}[\theta_0]\}$$



Absorber transmission estimation via transmission-reflection-transmission model: regression for **t** given estimate for $\mathbf{r}_{\mathbf{ML}}$ and measured $|\mathcal{F}\{\mathbf{r}\}|^2$

Ref: Sherwin, S., Neureuther, A., & Naulleau, P. (2018, October). EUV mask characterization with actinic scatterometry. In *International Conference on Extreme Ultraviolet Lithography 2018* (Vol. 10809, p. 108090T). International Society for Optics and Photonics.

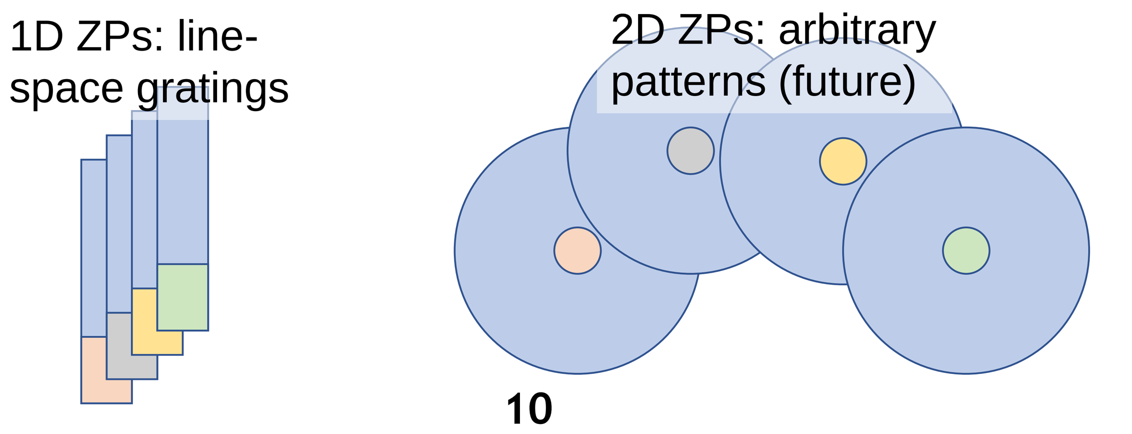
SHARP EUV imaging system



Ref: [pre-print] G. Gunjala, A. Wojdyla, S. Sherwin, A. Shanker, M. Benk, K. Goldberg, P. Naulleau, & L. Waller. Extreme ultraviolet microscope characterization using photomask surface roughness.

Coded aperture: phase-shifting DC

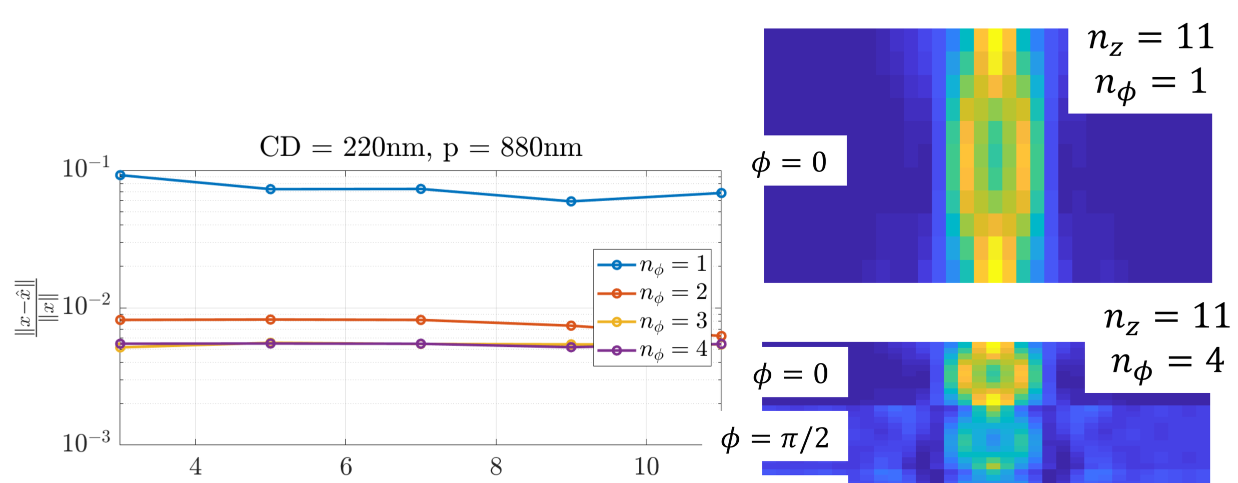
- SHARP: custom zone-plate (ZP) objectives
- Set of coded ZPs for phase retrieval
- 0 order passes through phase-shifted region, scattered light imaged normally



10

Initial studies using PhaseLift

- Key result: coded aperture improves accuracy over defocus for larger pitch



n_z: number of z planes
n_ϕ: number of coded apertures
y-axis: reconstruction error

11

Future Goals

- Fabricate set of DC phase-shifted zone-plates
  - 1D, 2 orientations for H/V features
- Conduct experiments at ALS using measurement modalities discussed

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12