Harnessing the extreme ultraviolet for critical dimension metrology

Bryan M. Barnes
Lead, “EUV Scatterometry” project

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National Institute of Standards and Technology
U.S. Department of Commerce

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Agenda

- Motivation and Project Goals
- Trends in prior work
- Results from our project
    - EUV Scatterometry
    - Ellipsometry in the EUV
- Perspectives


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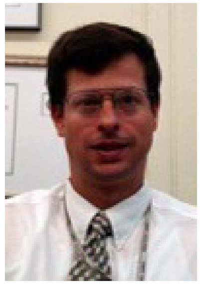
Martin Sohn


Aaron Chew


Thom Germer

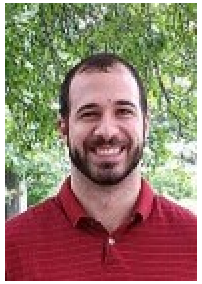

Eric Shirley


Stephanie Moffitt


Purnima Balakrishnan

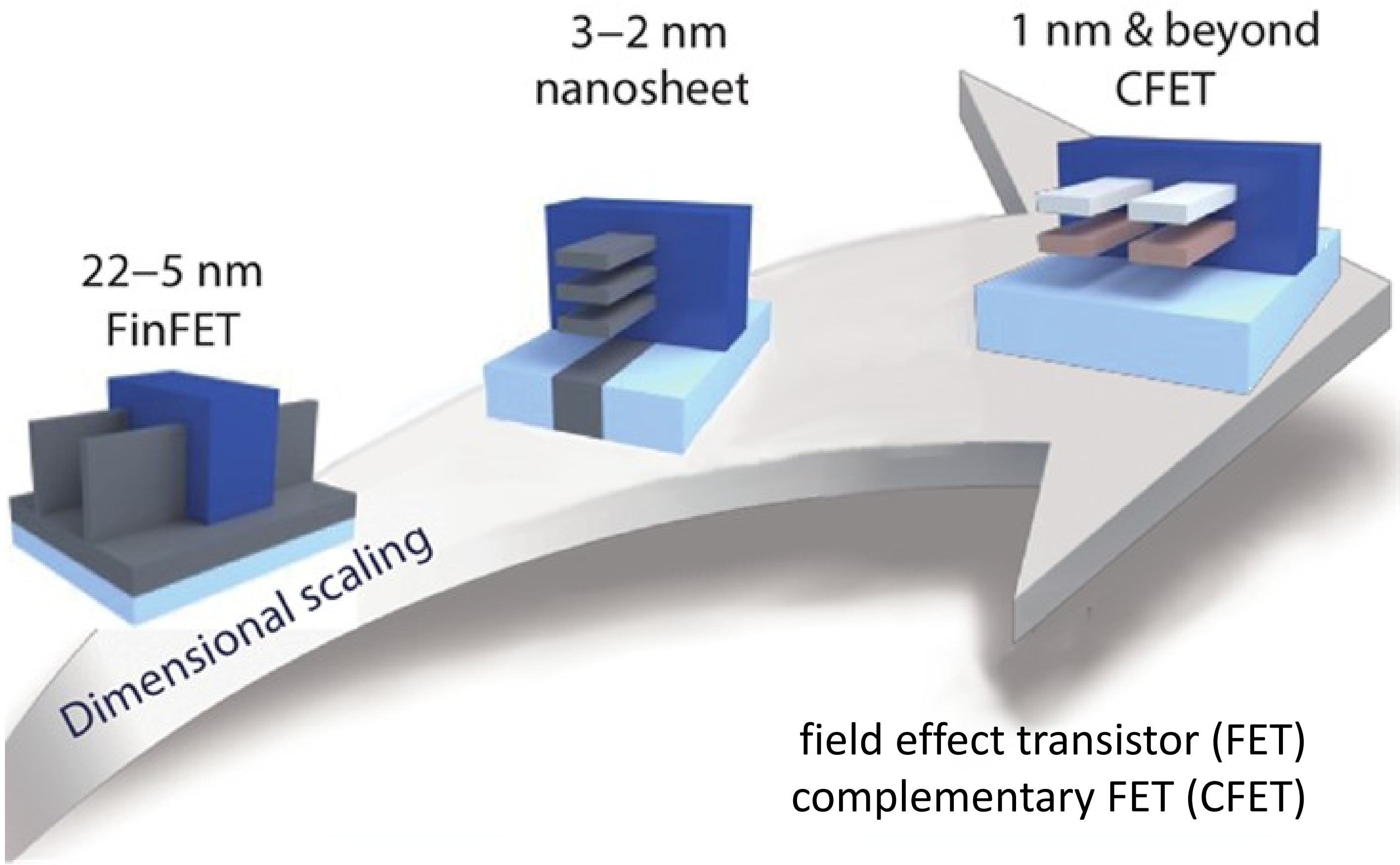

Steven Grantham


Colton Dudley

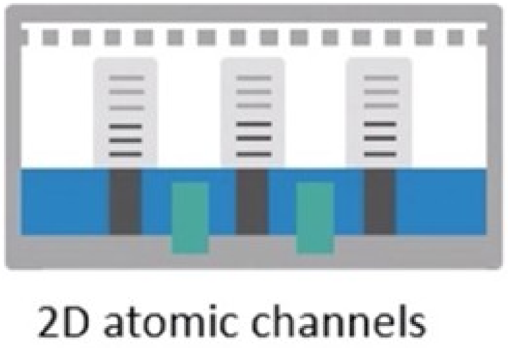

Daniel Sunday

Motivation and Project Goals

Motivation



field effect transistor (FET)
complementary FET (CFET)



Current optical approaches to measuring device dimensions are barely adequate.

Han and Hao, Journal of Semiconductors, 2021, 42(2): 020301 (2021).

Samavedam *et al.*, *2020 IEEE International Electron Devices Meeting (IEDM)* pp. 1.1.1-1.1.10

"Scatterometry"

"Scatterometry" in the literature means –

Spectroscopic ellipsometry

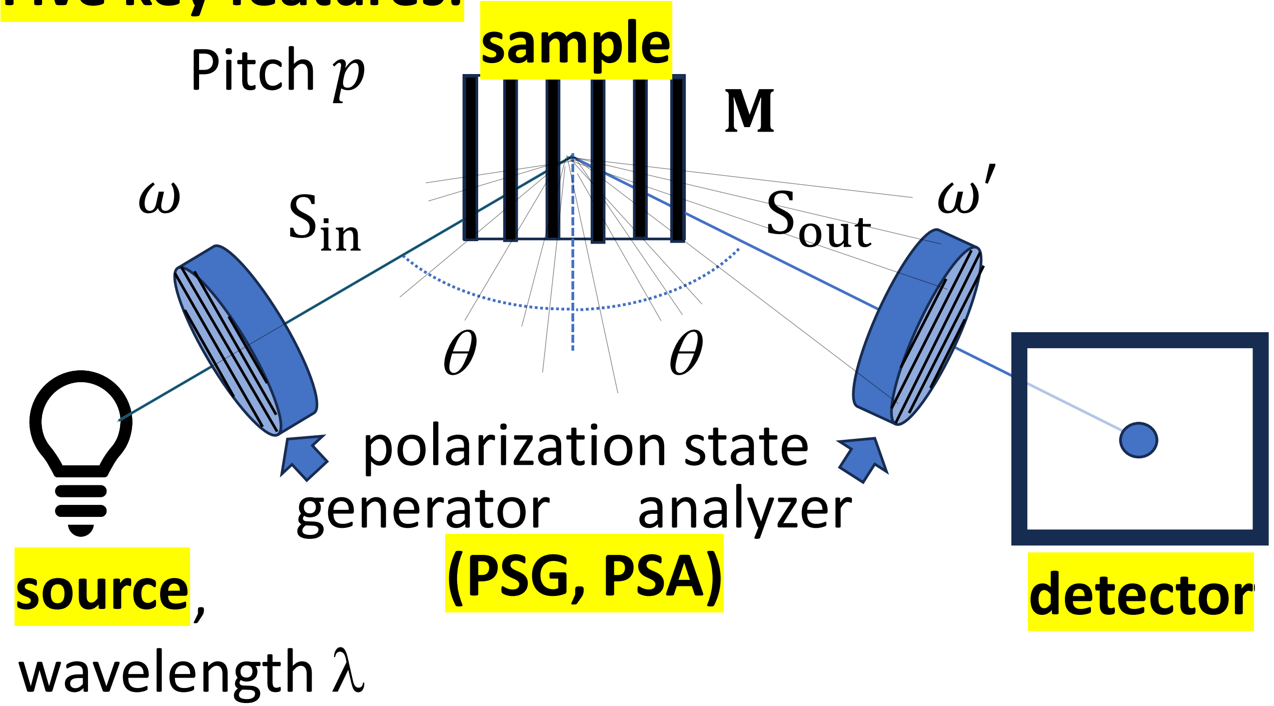
- (visible or UV)

Mueller Matrix Spectroscopic Ellipsometry

$$S_{out} = S_{in}\mathbf{M}$$

$$\mathbf{M} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix}$$

Five key features:



$$p \ll \lambda$$

Profile for OCD : from **modeling**

"EUV Scatterometry"

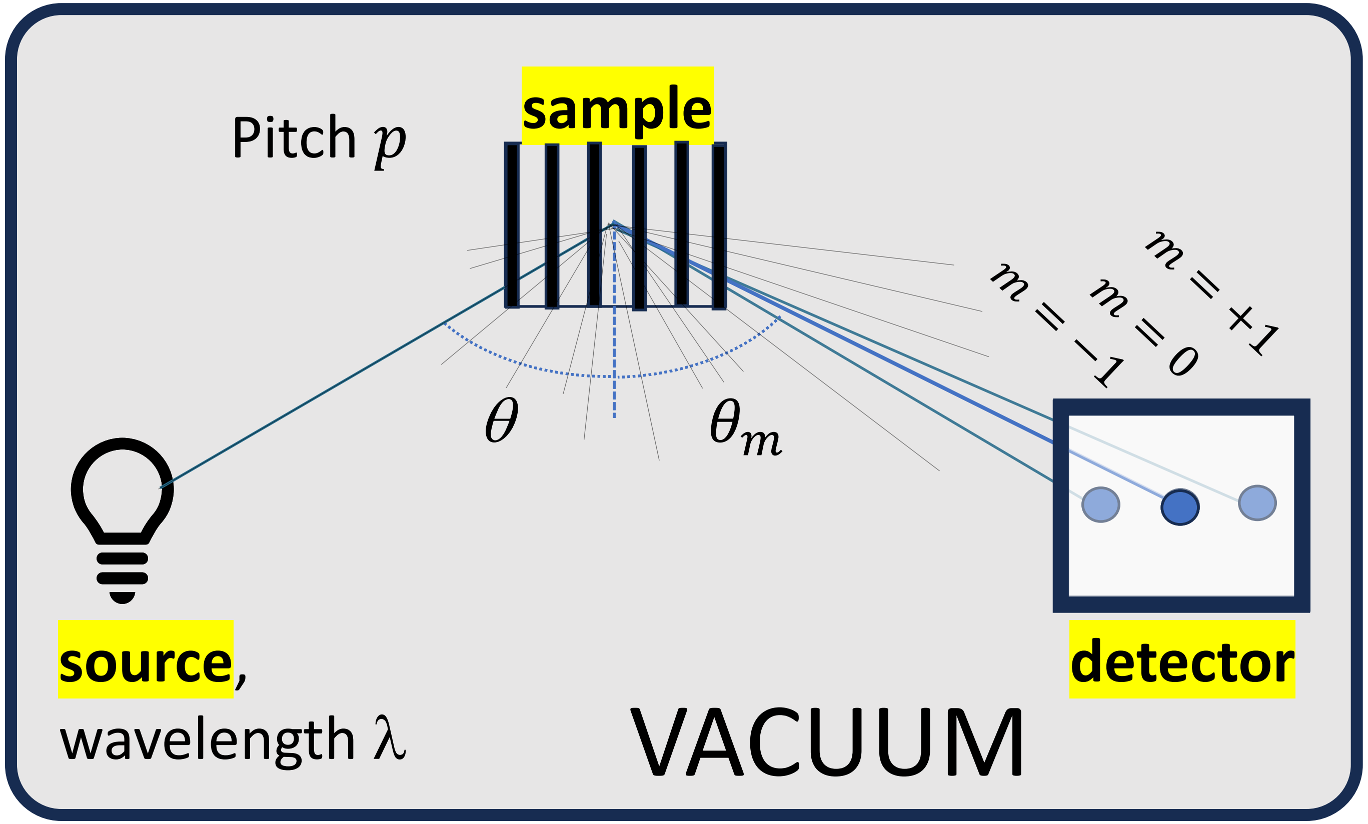
"Scatterometry" in the literature means –

Spectroscopic ellipsometry

- (visible or UV)

Diffractometry

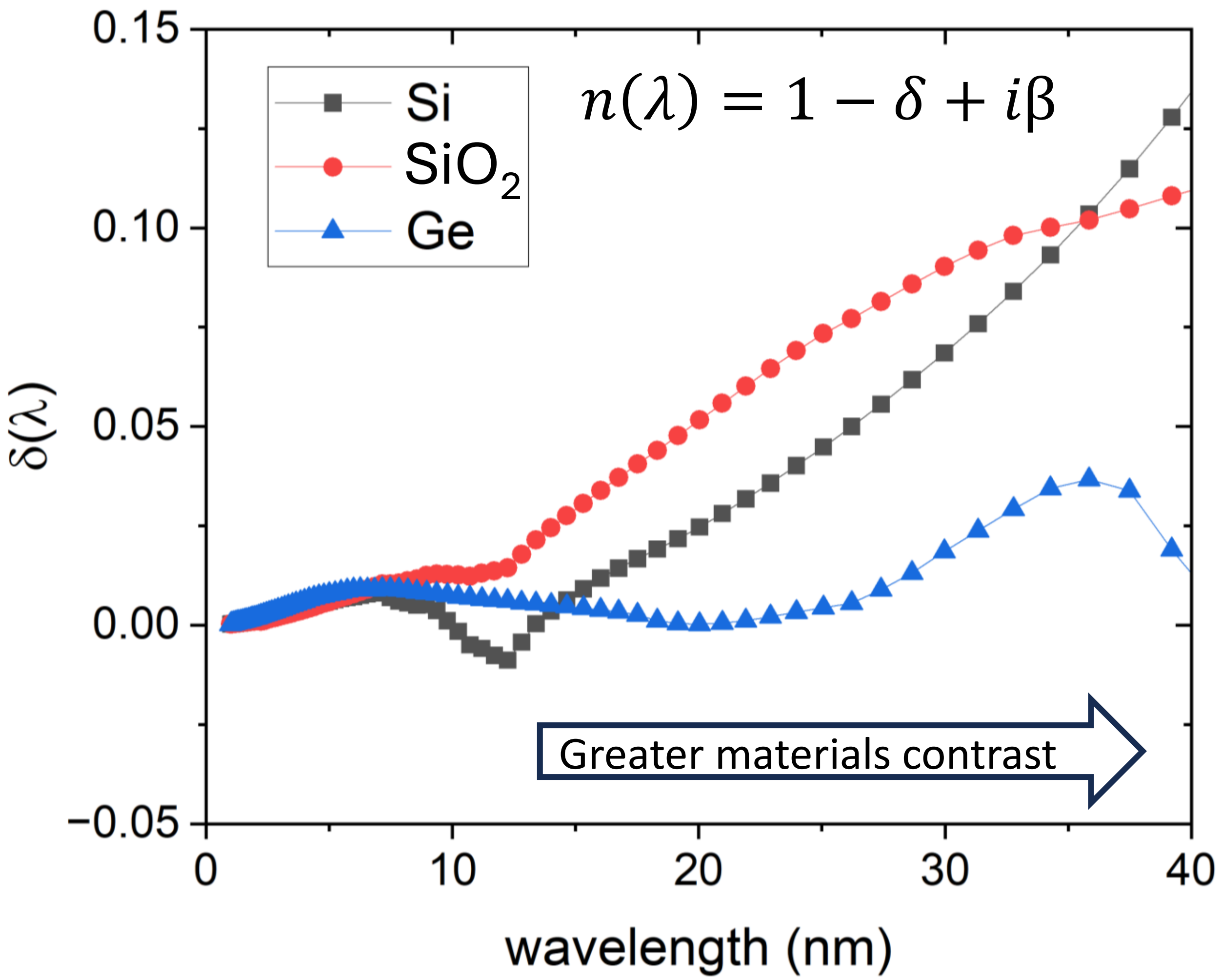
- (EUV)



Angle : $m\lambda = p\,(\sin\theta + \sin\theta_m)$

Profile for OCD : from **modeling**

Role of the EUV



Vacuum and extreme ultraviolet

VUV (> 50 nm) to EUV (10 nm to 50 nm)

- Greater materials contrast
- Wavelength comparable to pitch

Soft-x-ray region

SXR (0.1 nm to 10 nm range)

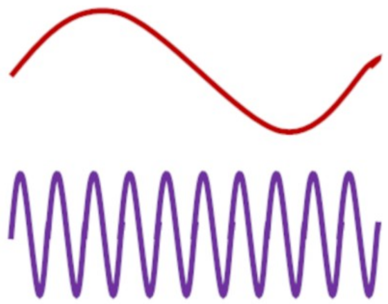
- Less materials contrast
- Wavelength comparable to feature dimensions

B.L. Henke, *et al.* Atomic Data and Nuclear Data Tables Vol. **54**, 181-342 (1993).
after C.-H. C. Tseng, Metrology, Inspection, and Process Control XL (2026).

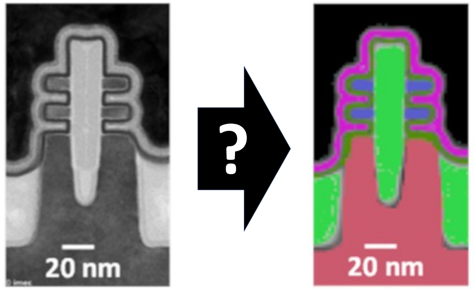
Project Goals

Our project at NIST is aiming for "EUV scatterometry" that....

Reduces wavelengths



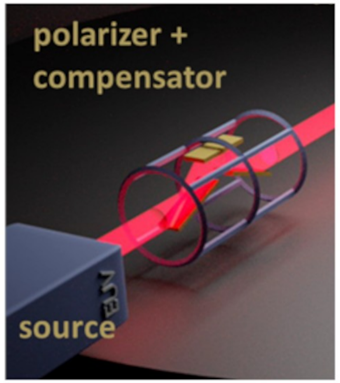
Harnesses chemical sensitivity



Samavedam *et al.*, *2020 IEDM*

False coloring for illustration

Provides polarization state controls



We are pursuing

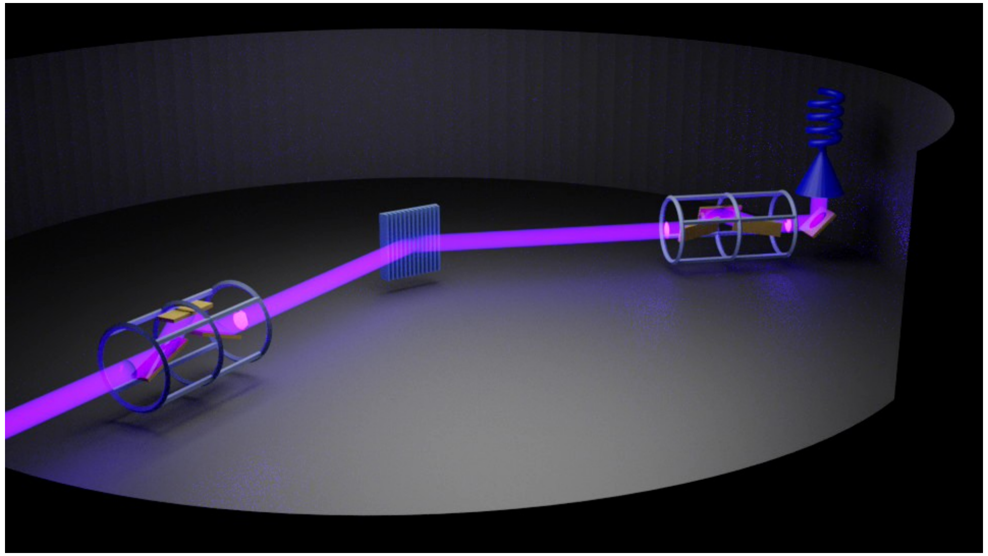
EUV spectroscopic ellipsometry, and

EUV diffractometry.

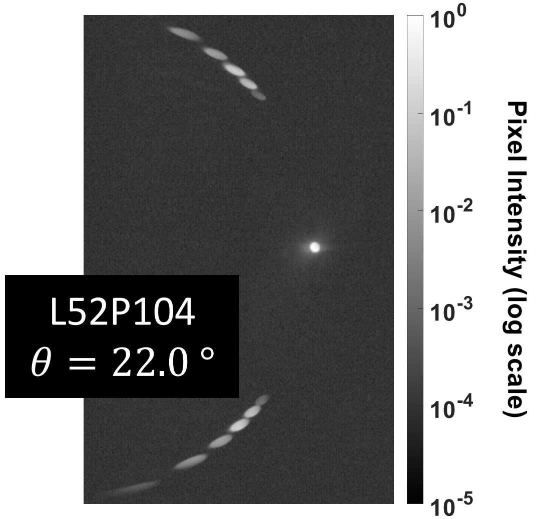
Project goals

- **EUV Spectroscopic Ellipsometry (EUV SE)**
  - Implementing VUV/EUV phase retarders to create a Mueller Matrix ellipsometer invented by a team member.
- **EUV Diffractometry**
  - Harnessing EUV diffraction-based metrology at selectable orthogonal polarizations at these shorter wavelengths.

We are building a novel **proof-of-concept EUV scatterometer** to demonstrate its feasibility in the 5 nm to 150 nm spectral region.



T.A. Germer, US Patent 12,352,687 (2025).



Initial results through a collaboration with the Murnane Group at CU-Boulder.

Barnes *et al.*, Proc. SPIE 134261V (2025).

Trends in prior work

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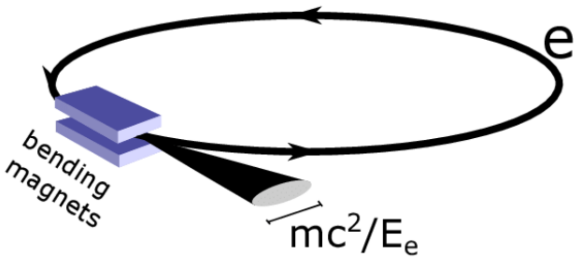
Selections from published prior work

Year	Effort	Type	Reference(s)
2007	PTB	EUV Scatterometry	F. Scholze, *et al.*, Proc. SPIE **6617**, 66171A (2007).
2013	RIKEN	EUV Scatterometry	Y. Nagata, *et al.*, Proc. SPIE **8849**, 884914 (2013).
2014	PTB	Ellipsometry in the EUV	M.D. Neumann, *et al.*, Rev. Sci. Instrum. **85**, 055117 (2014)
2016	ITRI	EUV Scatterometry	Y.-S. Ku, *et al.*, Optics Express **24**, 28014 (2016).
2020	ELI	Ellipsometry in the EUV	S. Espinoza *et al.*, Appl. Surf. Sci. **421** B, 378-382 (2017). S. Espinoza *et al.*, J. Vac. Sci. Technol. B **38**, 024005 (2020).
2021	CU-Boulder	EUV Scatterometry	M. Tankaslava, *et al.*, Science Advances **7**, eabd9667 (2021).
2022	ASML	EUV Scatterometry	C. Porter, *et al.*, FCMN 93-95 (2022) & FCMN 96-98 (2024). C. Porter, *et al.*, Proc SPIE **12496**, 124961I (2023).
2022	CU-Boulder	EUV Scatterometry	Y. Esashi, *et al.*, FCMN 236-238 (2022); Y. Esashi, *et al.*, Rev. Sci. Instrum. **94**, 123705 (2023).
2025	NIST/CU	EUV Scatterometry	B.M. Barnes, *et al.*, Proc. SPIE **13426**, 134261V (2025).
2025	imec	EUV Scatterometry	V. Krasnov, *et al.*, EPJ Web of Conf. **335**, 01019 (2025).
2026	Nat'l Tsing Hua U.	Ellipsometry in the EUV	I-H. Li., *et al.*, Optics Letters **51**, 845-848 (2026).
2026	NIST	Ellipsometry in the EUV	P. Balakrishnan *et al.*, Proc SPIE **13981** (2026).

EUV Sources

Synchrotron radiation (SR)

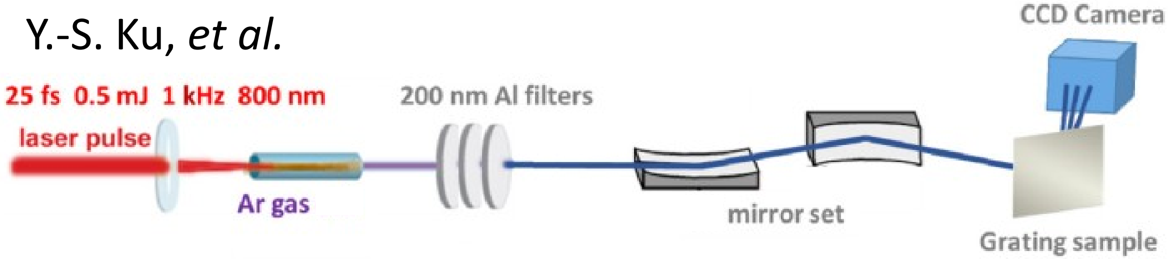
- High brightness
- Linear polarization in plane of beam
- Ultra-high vacuum



High-harmonic generation (HHG)

- Tabletop
- Polarization from IR laser
- High vacuum

Y.-S. Ku, *et al.*



HHG using HHG for EUV scatterometry:
RIKEN, ITRI, imec, CU-Boulder, ASML, NIST/CU

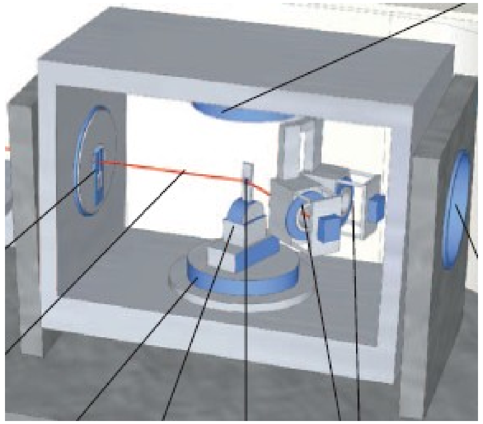
HHG for ellipsometry in the EUV:
ELI, Nat'l Tsing Hua Univ.

- In these efforts, the predominant source is HHG.
- **Laser produced plasmas (LPP)** will be discussed in the following talk.

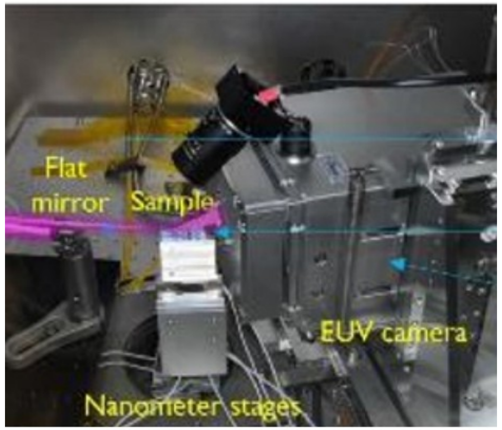
Sample (Mounting)

Perpendicular to floor

M.D. Neumann, *et al.*

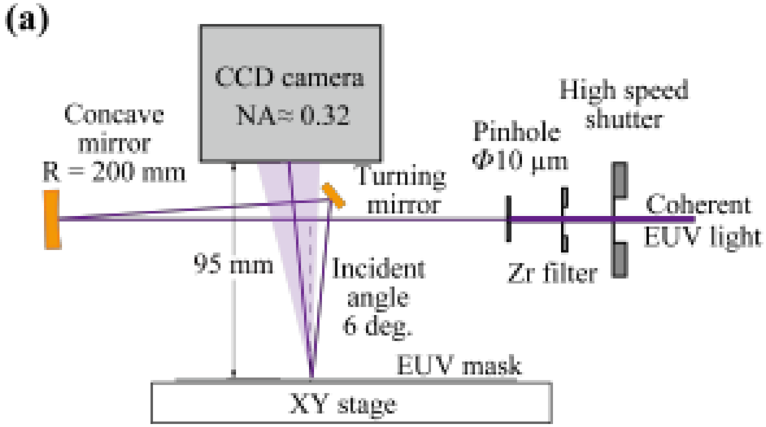


V. Krasnov, *et al.*

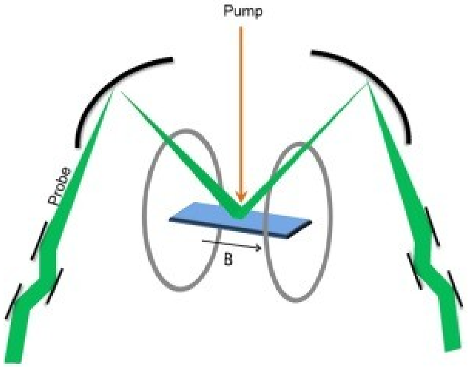


Parallel with the floor

Y. Nagata, *et al*.



S. Espinoza *et al.,* Appl. Surf. Sci.



Perpendicular, EUV scatterometry:
PTB, ITRI, imec, CU-Boulder, NIST/CU
for ellipsometry in the EUV:
PTB, NIST

Parallel mounting for EUV scatterometry:
RIKEN
For ellipsometry in the EUV:
ELI

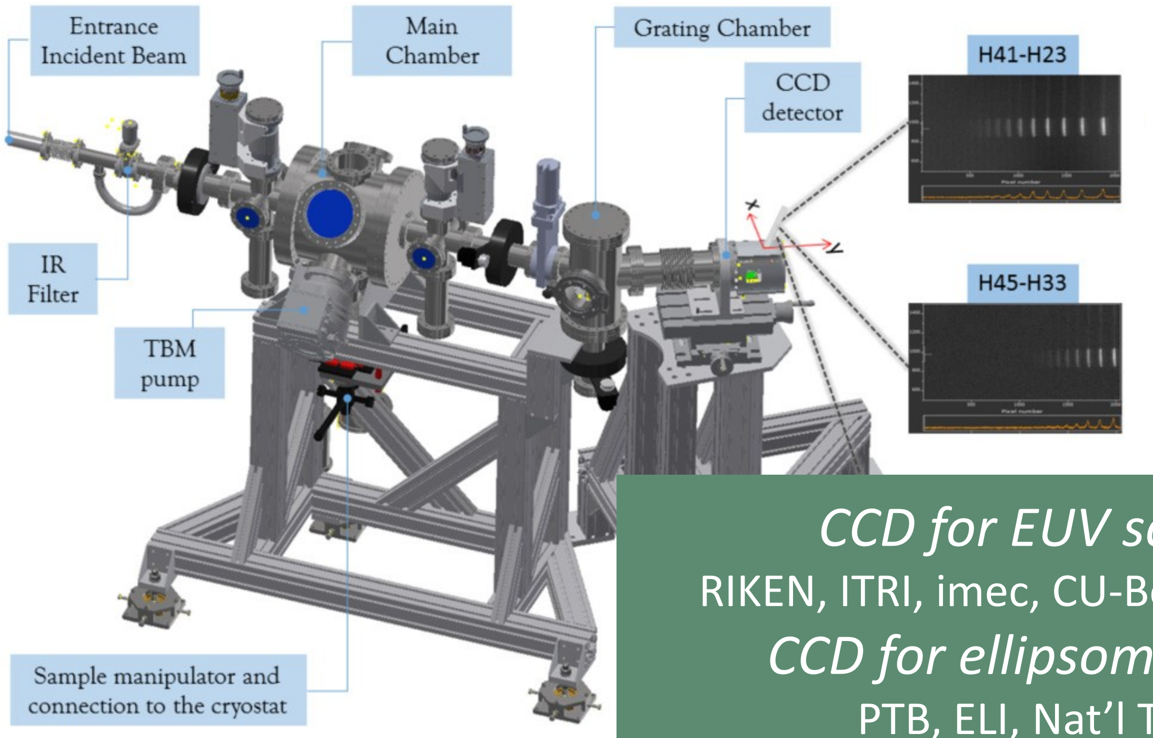
- Most efforts have perpendicular mounting with little room for industrial samples.

EUV Detectors

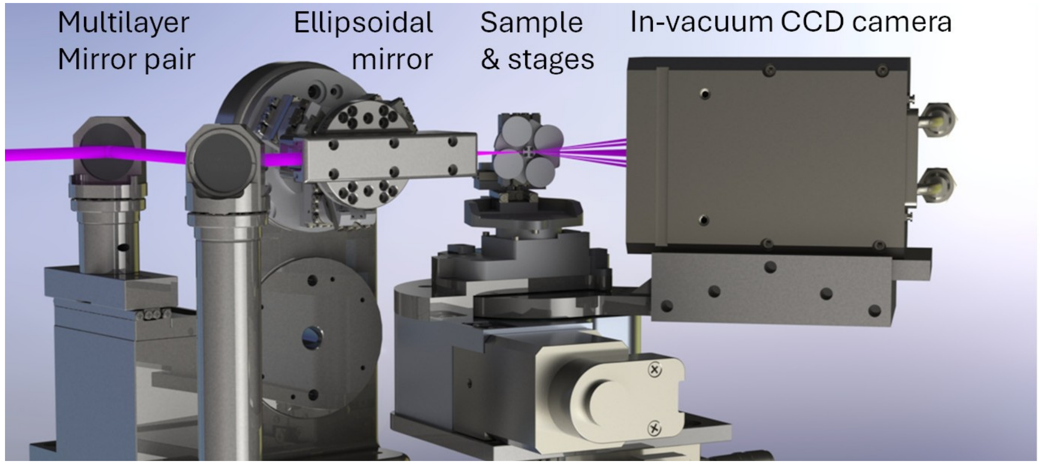
Charge-coupled devices (CCD)

Flange-mounted:

S. Espinoza *et al.* JVSTB



or in-vacuum:



Y. Esashi, *et al.*, RSI
M. Tankaslava, *et al.*

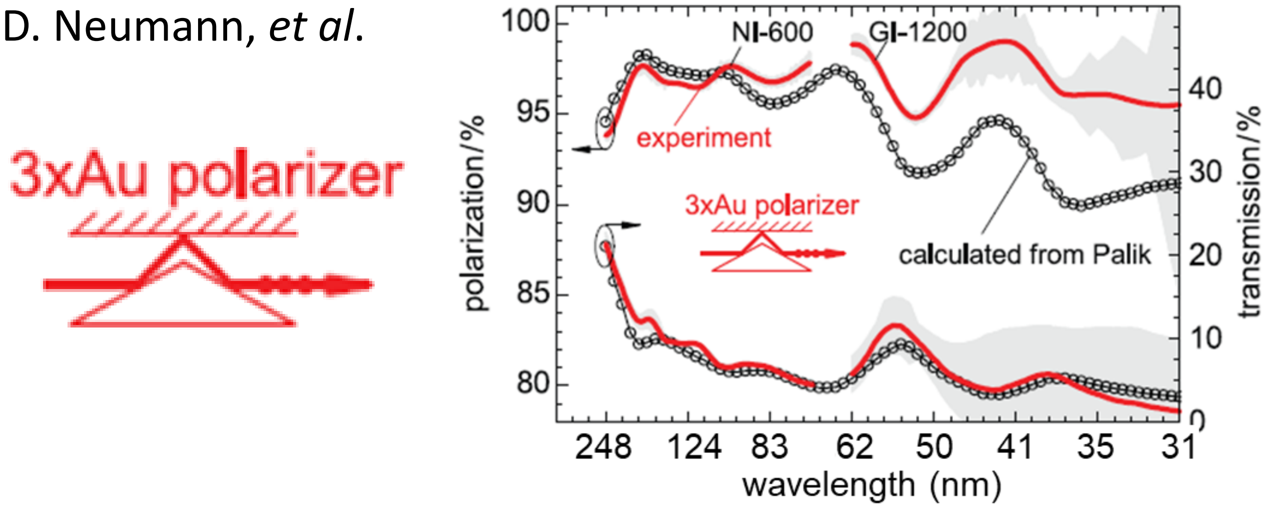
CCD for EUV scatterometry:
RIKEN, ITRI, imec, CU-Boulder, ASML, NIST/CU
CCD for ellipsometry in the EUV:
PTB, ELI, Nat'l Tsing Hua Univ.

- CCD cameras are ubiquitous in these efforts.

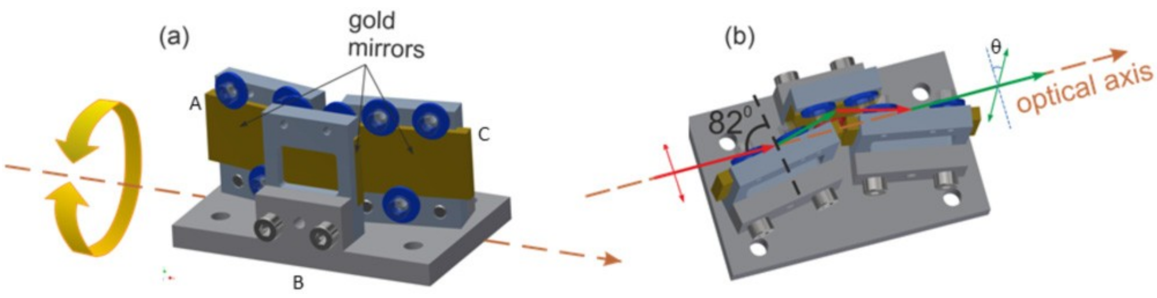
PSG and PSA

Rotating reflective polarizers and analyzers

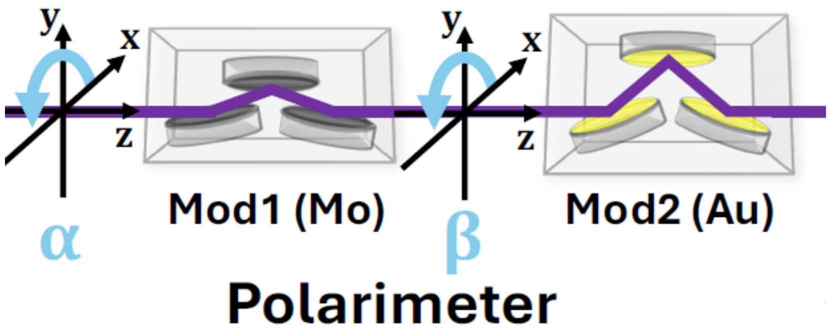
M.D. Neumann, *et al.*



S. Espinoza *et al.* JVSTB



I-H. Li., *et al.*



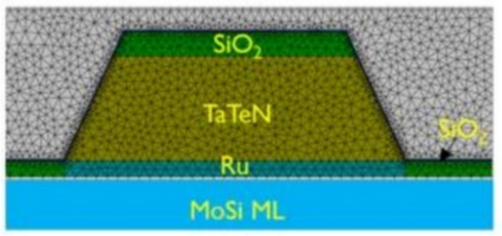
PSG, PSA for ellipsometry in the EUV:
PTB, ELI, Nat'l Tsing Hua Univ.

- EUV HHG sources have polarization control through the IR beam.
- PSG and PSA are features of EUV ellipsometric experiments.

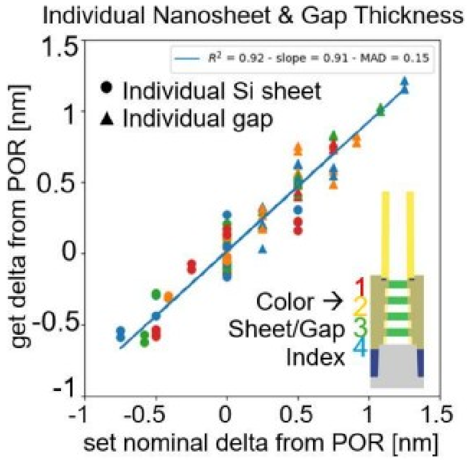
EUV Modeling

Numerical Maxwell Eqns. Solvers

V. Krasnov, *et al.*

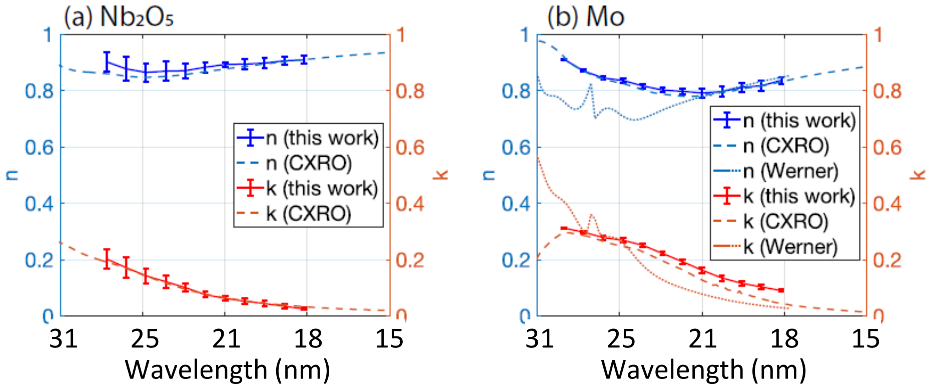


C. Porter, *et al.* FCMN 2024



Analytic solutions (*e.g.*, for n & k)

I-H. Li., *et al.*



Numerical modeling, EUV Scatterometry:
PTB, RIKEN, imec, CU-Boulder, ASML, NIST/CU

Analytic sol'n, ellipsometry in the EUV:
PTB, ELI, Nat'l Tsing Hua Univ.

- Thus far, ellipsometry efforts in the EUV have yet to employ numerical solutions.

Results from Our Project

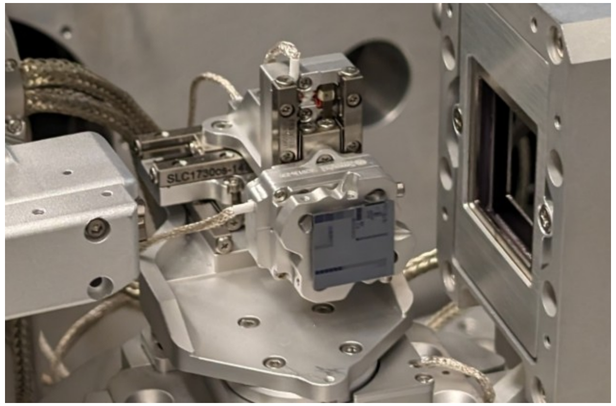
National Institute of Standards and Technology
U.S. Department of Commerce

Results: EUV Scatterometry

Collaboration with CU-Boulder

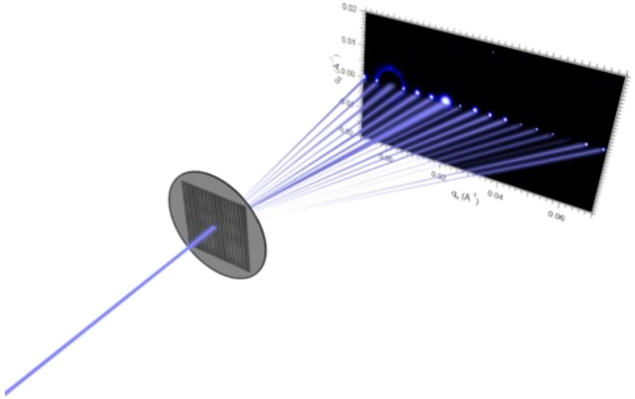
Nick Jenkins, Clay Klein, Henry Kapteyn, Yunzhe Shao, Margaret Murnane

EUV diffractometry



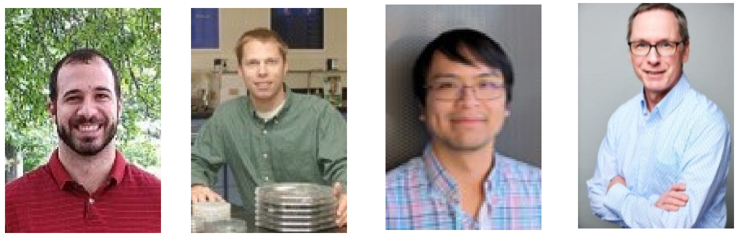
- In-laboratory
- $\lambda \approx 30\ \mathrm{nm}\ (E \approx 42\ \mathrm{eV})$

Critical dimension small angle x-ray scattering (CD-SAXS)



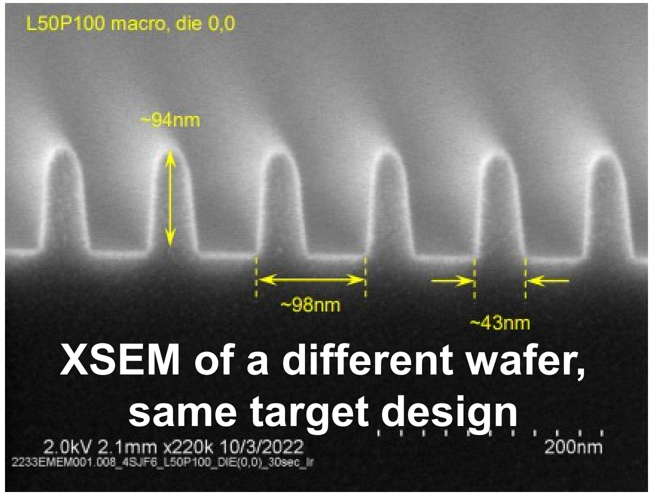
- At synchrotron
- $\lambda < 0.1\ \mathrm{nm}\ (E > 10\ \mathrm{keV})$

Source:	an existing EUV HHG source
Mounting:	perpendicular
Detector:	in-vacuum CCD camera
PSG, PSA:	*none*
Modeling:	`pySCATMECH` package by T.A. Germer, NIST; rigorous coupled-wave approach (RCWA)

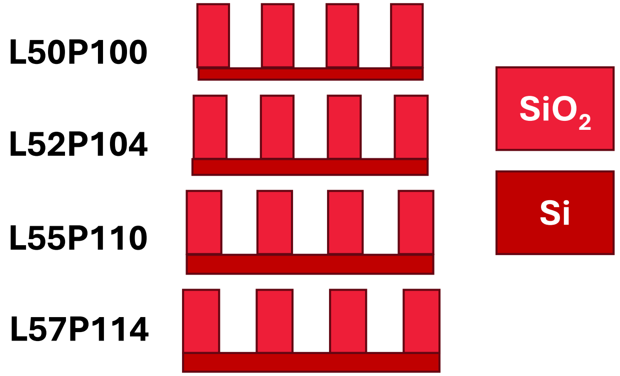


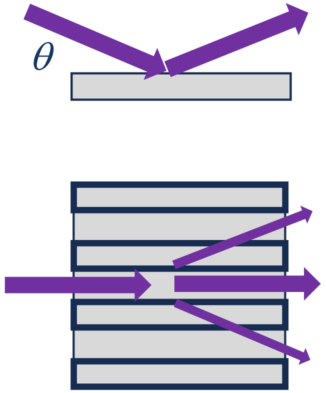
Daniel Sunday, Joe Kline, Aaron Chew, Thom Germer

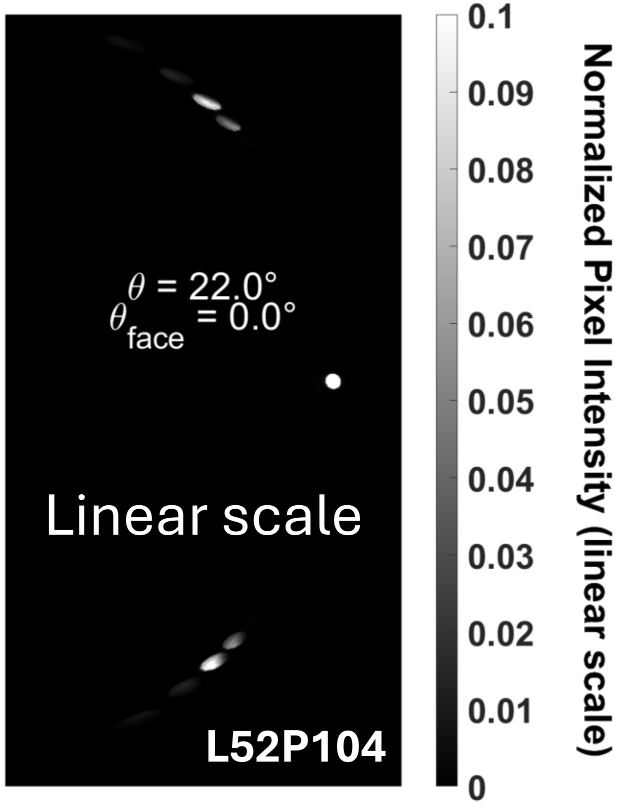
Results: EUV Scatterometry



www.amagnm.com





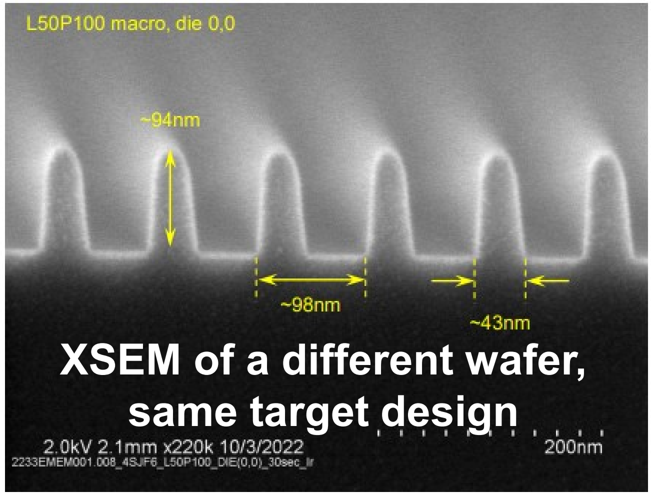


- The brightest point is the 0th order.
- Above and below are the 1st orders.
- On linear scale, 1 wavelength dominant.
- On log scale, 5+ wavelengths are visible in the 1st orders.

- Extract the total intensity from the ROI for each (m, λ, θ).
    - Normalize ($m=\pm1$, λ, θ) by ($m=0$, λ, θ).

B.M. Barnes, *et al.*, Proc. SPIE **13426**, 134261V (2025).

Results: EUV Scatterometry



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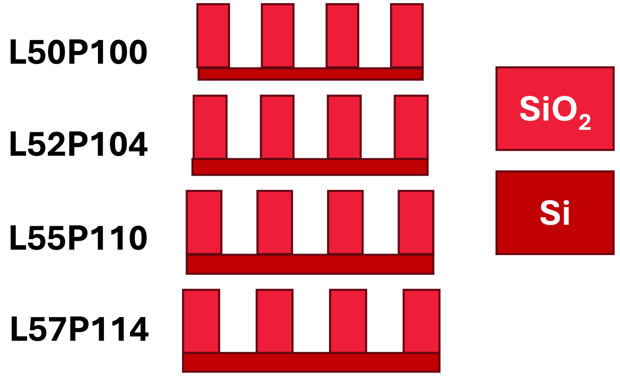

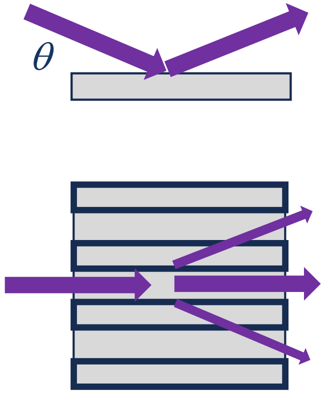

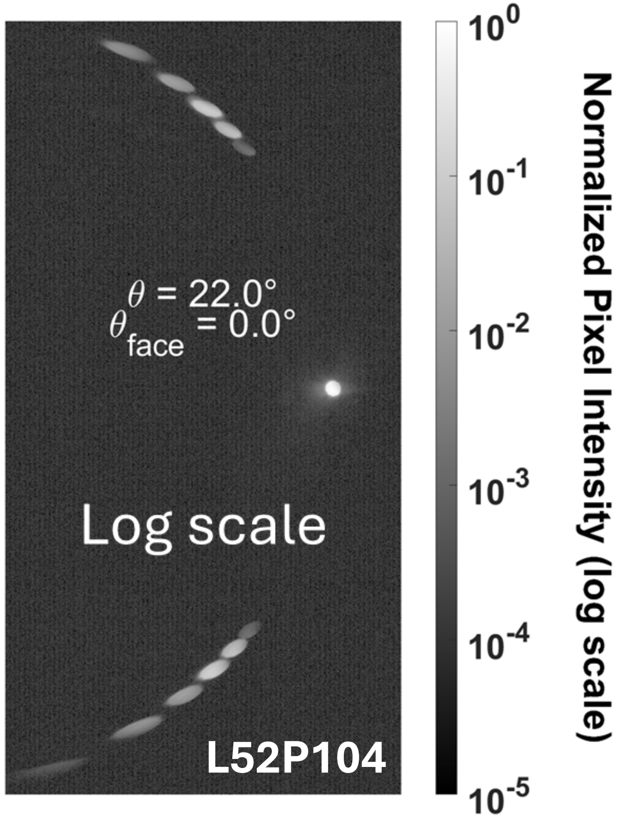

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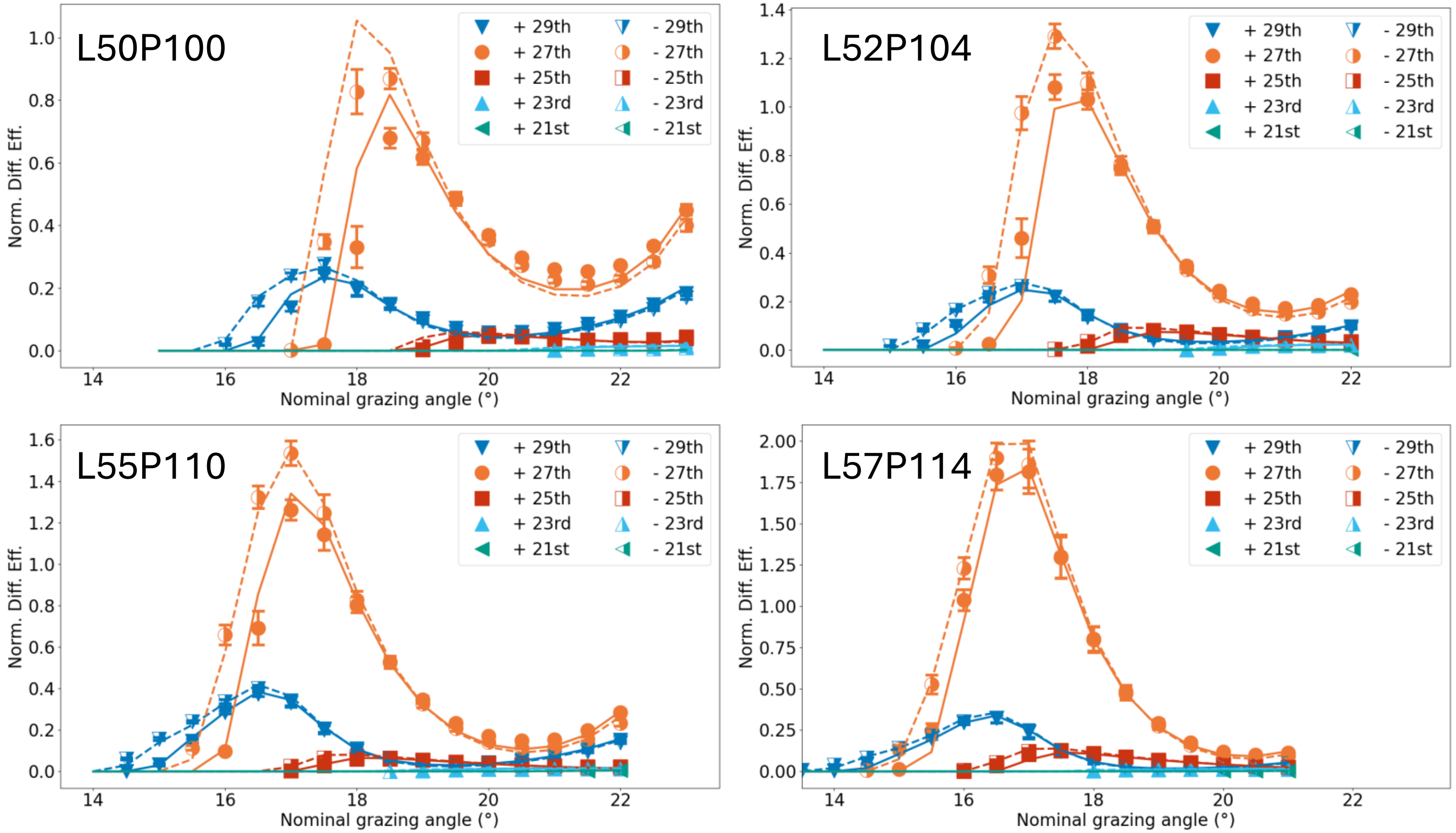
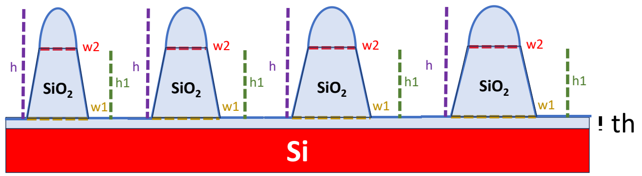
B.M. Barnes, *et al.*, Proc. SPIE **13426**, 134261V (2025).

Results: EUV Scatterometry

Normalized diffraction efficiencies with fits from a parallel regression





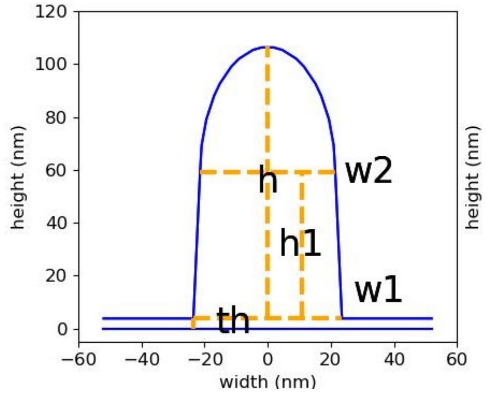
- 8 per target (x 4 targets):
  - 4 dimensional parameters *per target*,
  - 4 relative intensities *per target*.
- 4 common floated parameters:
  - 1 oxide thickness
  - 3 tilt angles

B.M. Barnes, *et al.*, Proc. SPIE **13426**, 134261V (2025).

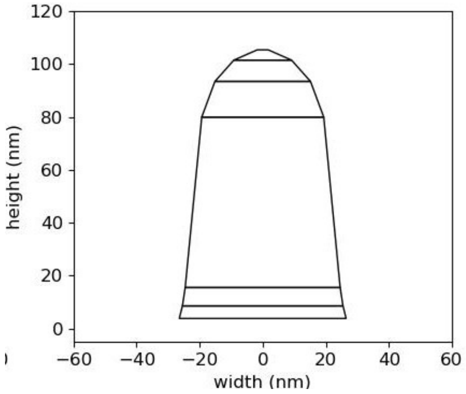
Results: EUV Scatterometry vs CD-SAXS

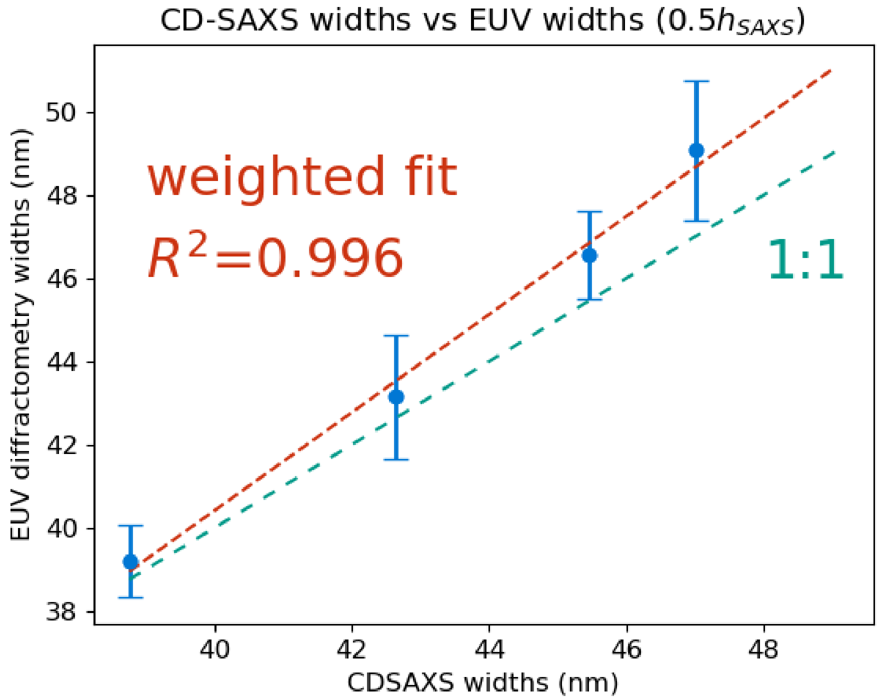
Parametric geometries

EUV Diffractometry



CD-SAXS

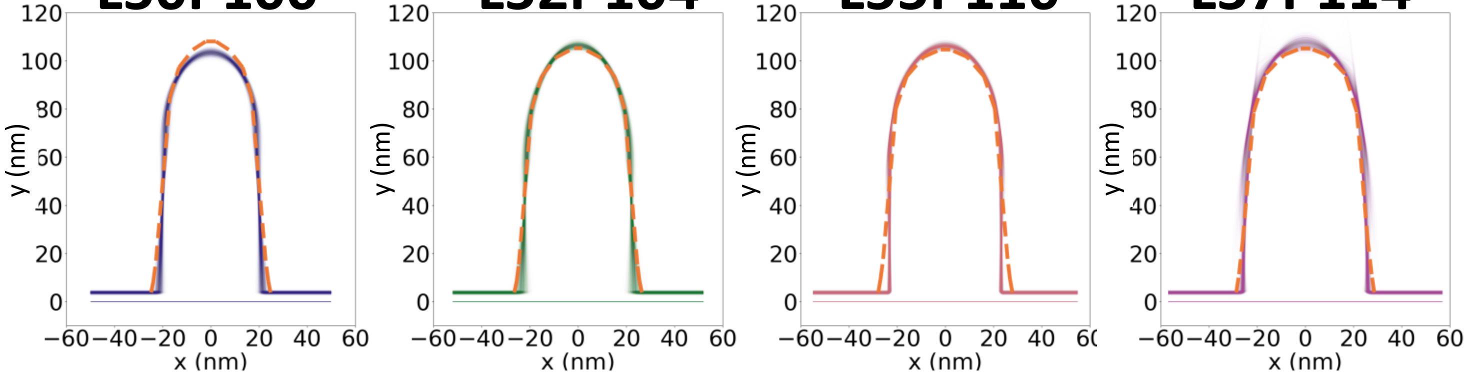




EUV uncertainty envelope

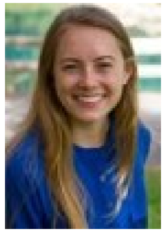
CD-SAXS with $2\sigma = \pm\ 0.01$ nm

L50P100 **L52P104** **L55P110** **L57P114**



B.M. Barnes, *et al.*, Proc. SPIE **13426**, 134261V (2025).

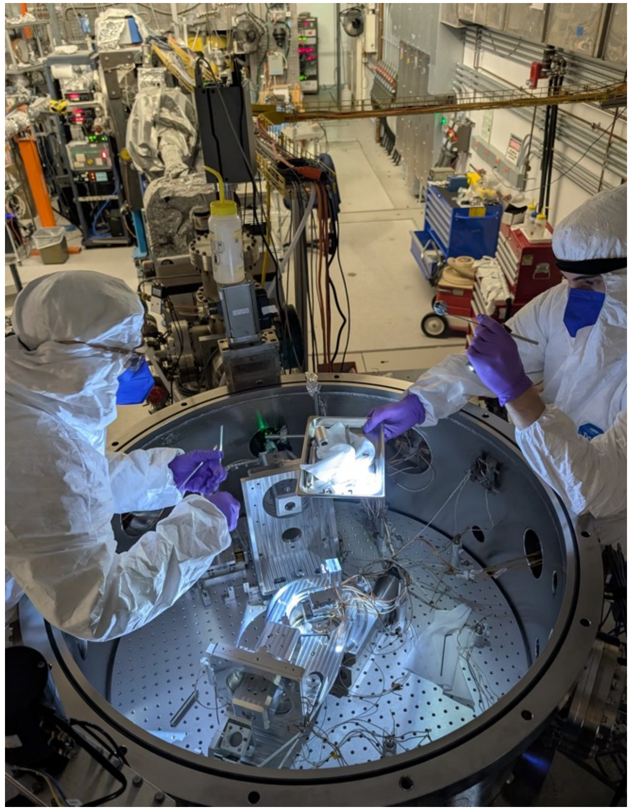
Results: Ellipsometry in the EUV



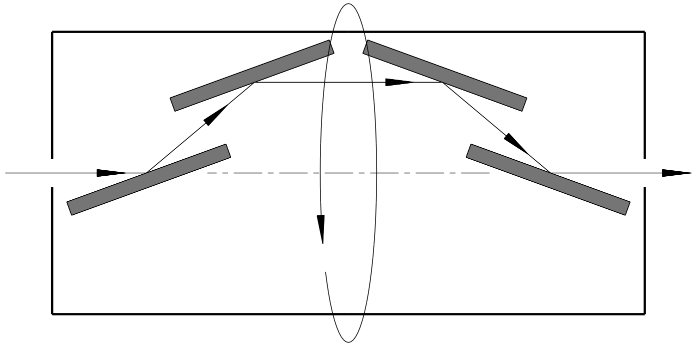


Stephanie Moffitt | Purnima Balakrishnan | Steven Grantham | Colton Dudley | Thom Germer

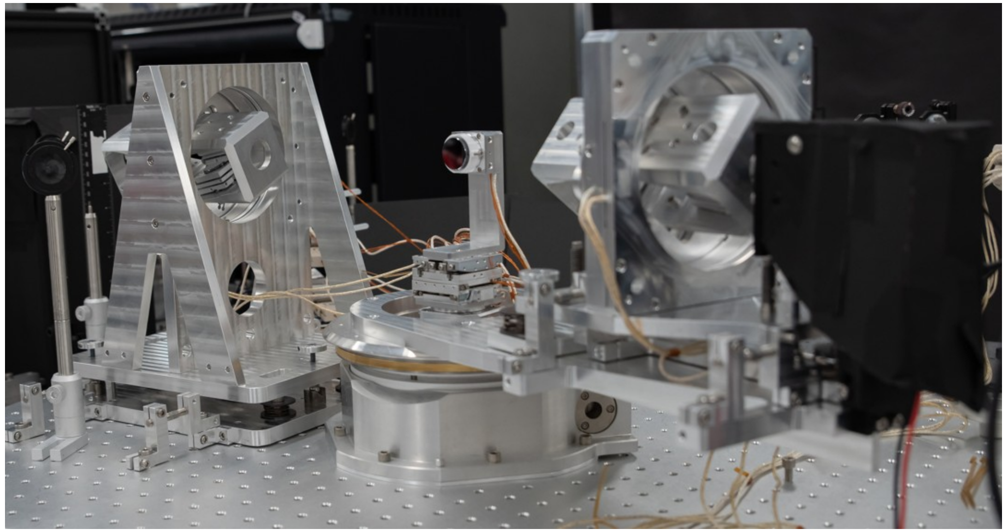
Source: SURF-III synchrotron
Mounting: perpendicular
Detector: EUV photodiode
PSG, PSA: (2) 4-bounce Si + 1 Au



4-bounce Si mirrors @ 80°



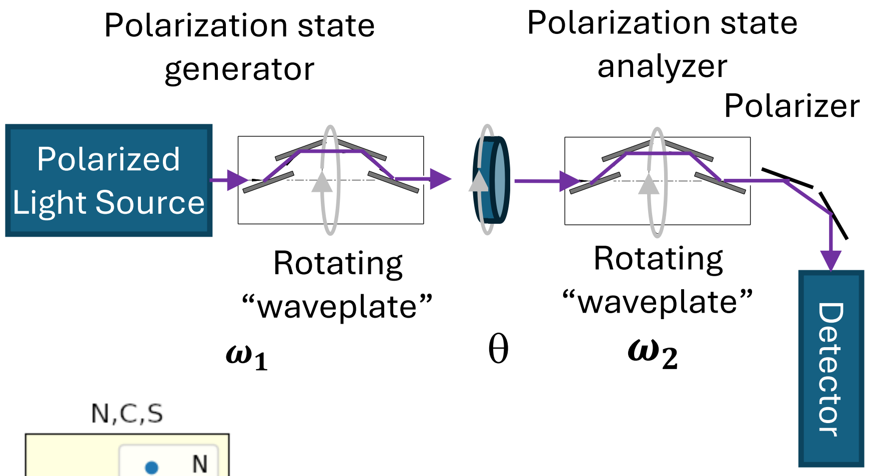
PSG Sample PSA

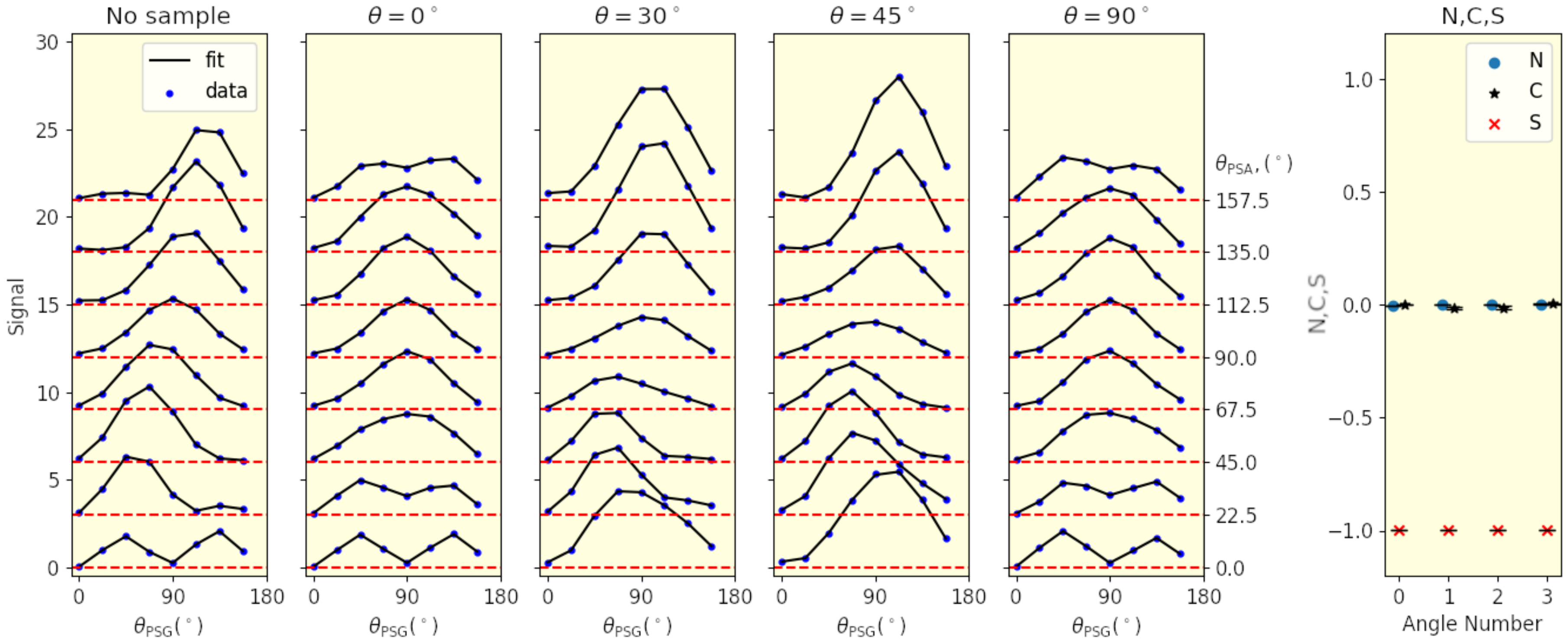


Results: Ellipsometry in the EUV

On the testbench: λ = 266 nm

Quarter-wave plate at 4 rotation angles





$$\mathbf{M} = \begin{bmatrix} 1 & -N & 0 & 0 \\ -N & 1 & 0 & 0 \\ 0 & 0 & C & S \\ 0 & 0 & -S & -C \end{bmatrix}$$

$N = 0$

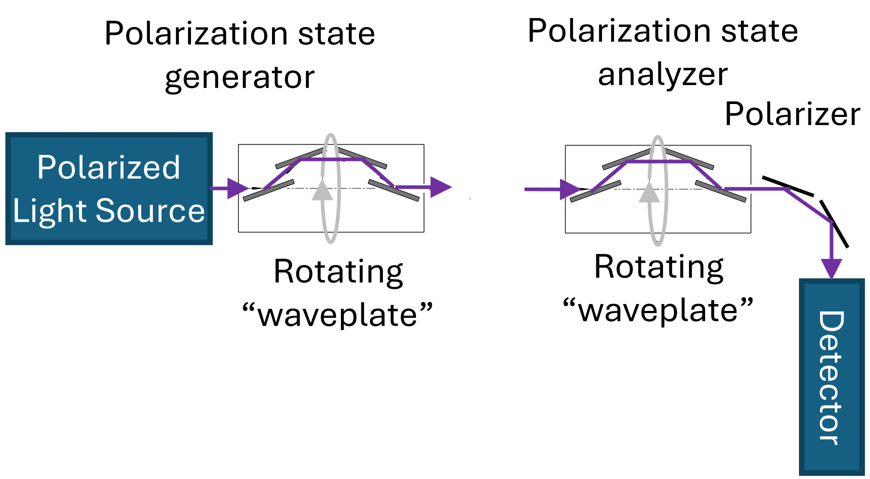
$C = 0$

$S = -1$

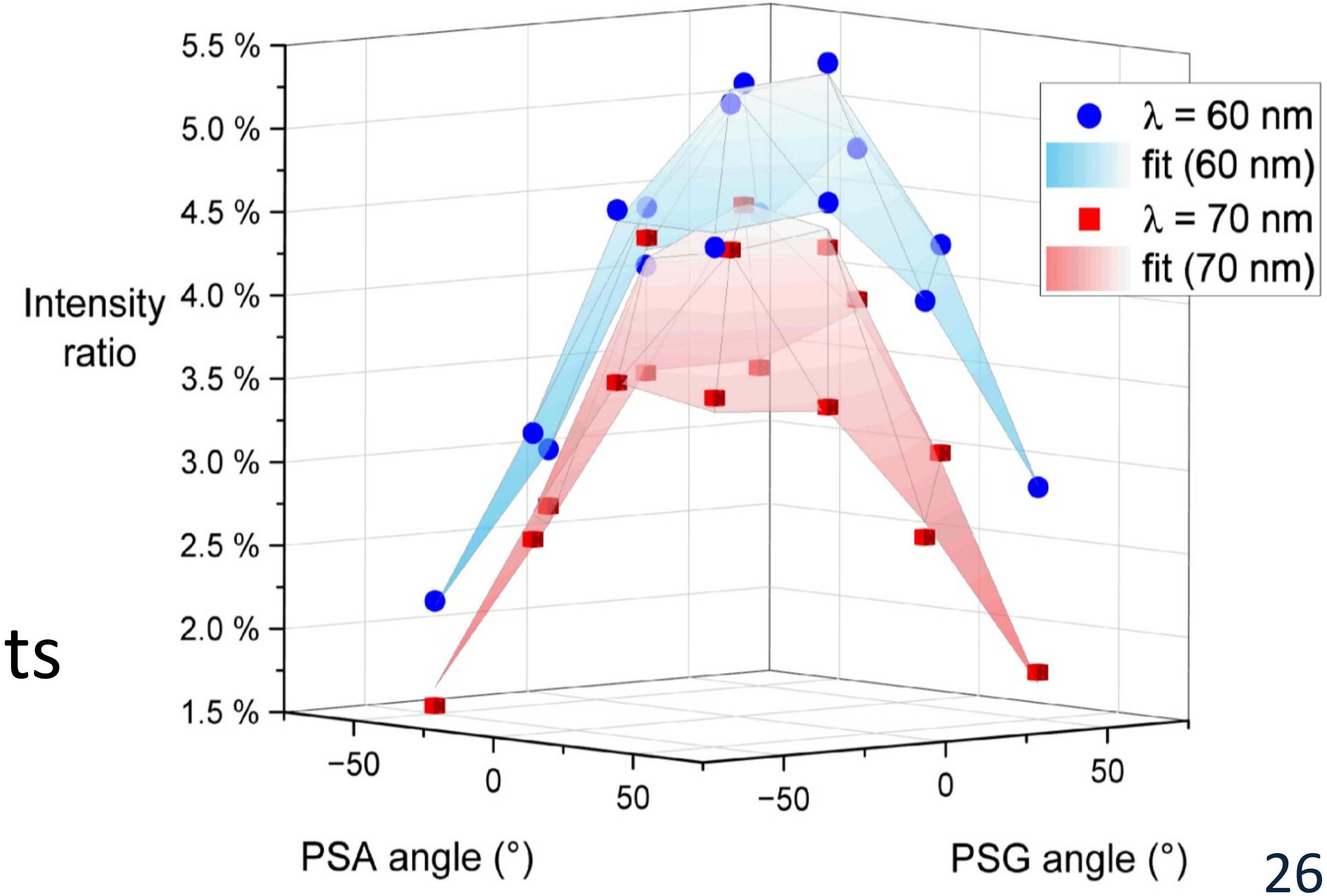
Results: Ellipsometry in the EUV

Commissioning an EUV ellipsometer

✓ Demonstrating polarization control



P. Balakrishnan, *et al.*



❑ Calculating optical constants

- ❑ Au being measured now.

Perspectives

Goal: Scatterometry in the EUV

Commissioning ~~an ellipsometer in the EUV~~

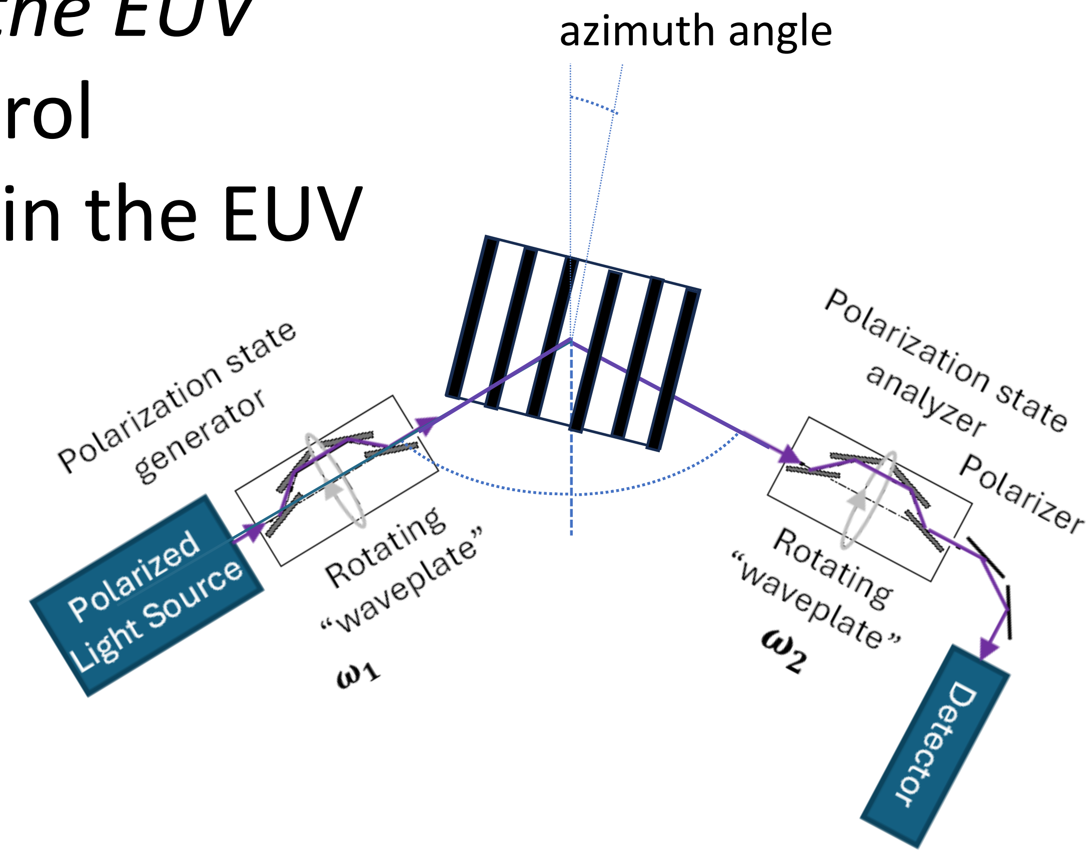
a scatterometer in the EUV

✓ Demonstrating polarization control

❑ Measuring a full Mueller Matrix in the EUV

$$\mathbf{M} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix}$$

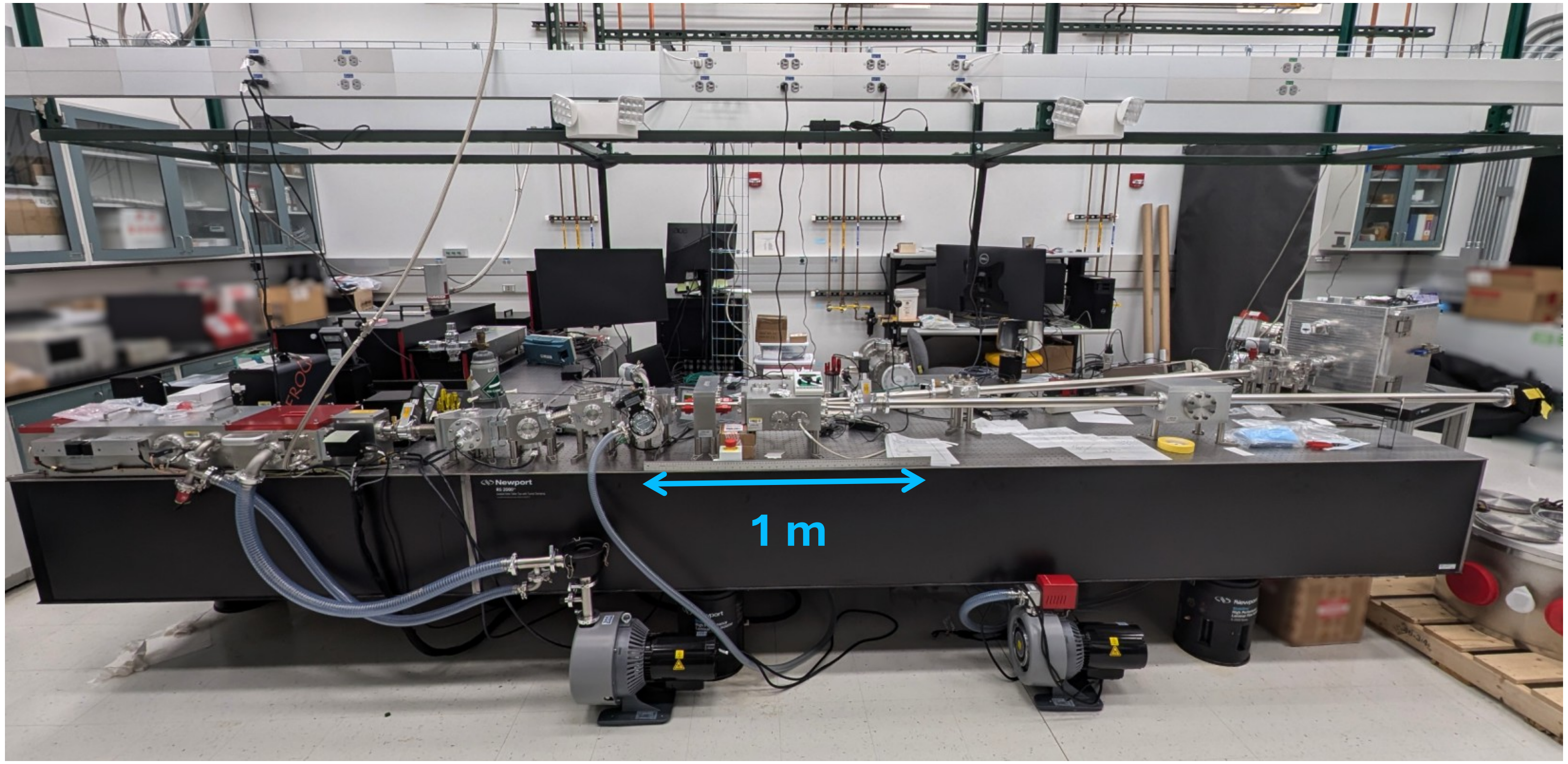
all off-diagonal elements non-zero
for 0° < azimuth angle < 90°



Goal: Laboratory-based scatterometry

Utilizing NIST's new EUV HHG Source

- Two beamlines : λ = 10 nm to 150 nm
  λ = 13.5 nm



- In-lab experiments will demonstrate in-fab feasibility and extensibility.

Harnessing the EUV for CD metrology

We are building a novel proof-of-concept EUV scatterometer to demonstrate its feasibility in the 5 nm to 150 nm spectral region.

- Initiated EUV diffractometry (“EUV scatterometry”) work with CU-Boulder.
- Realizing ellipsometry into the VUV and EUV.
- Building towards “scatterometry in the EUV” using patterned samples.