Measuring the Complex Behavior of Phase in the EUV Regime and Implications for Phase Shift Masks

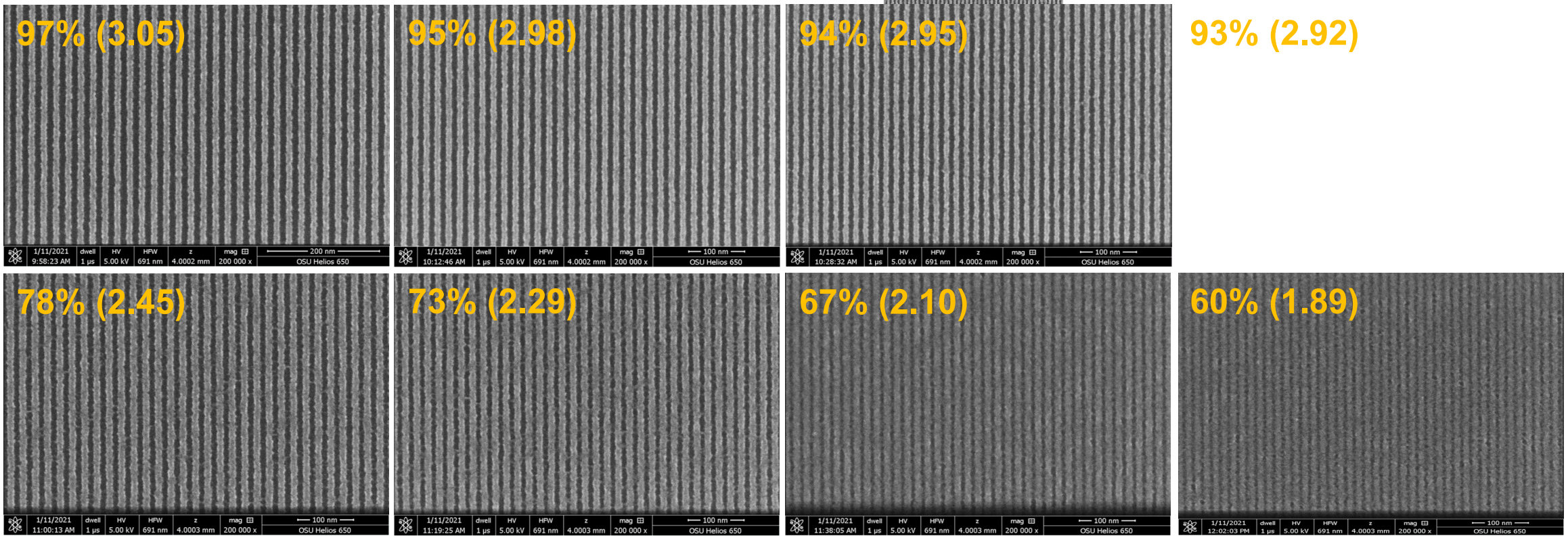
Matt Hettermann
EUV Tech Inc.

Agenda

- Motivating phase shift masks
- Phase control in the EUV regime
- How do we define the phase of an EUV mask?
- Measuring the full phase behavior of EUV masks

EUV resists require high bar for NILS

	11 nm	10 nm	9 nm	8 nm
TE (H)	97% (3.05)	95% (2.98)	94% (2.95)	93% (2.92)
TM (V)	78% (2.45)	73% (2.29)	67% (2.10)	60% (1.89)



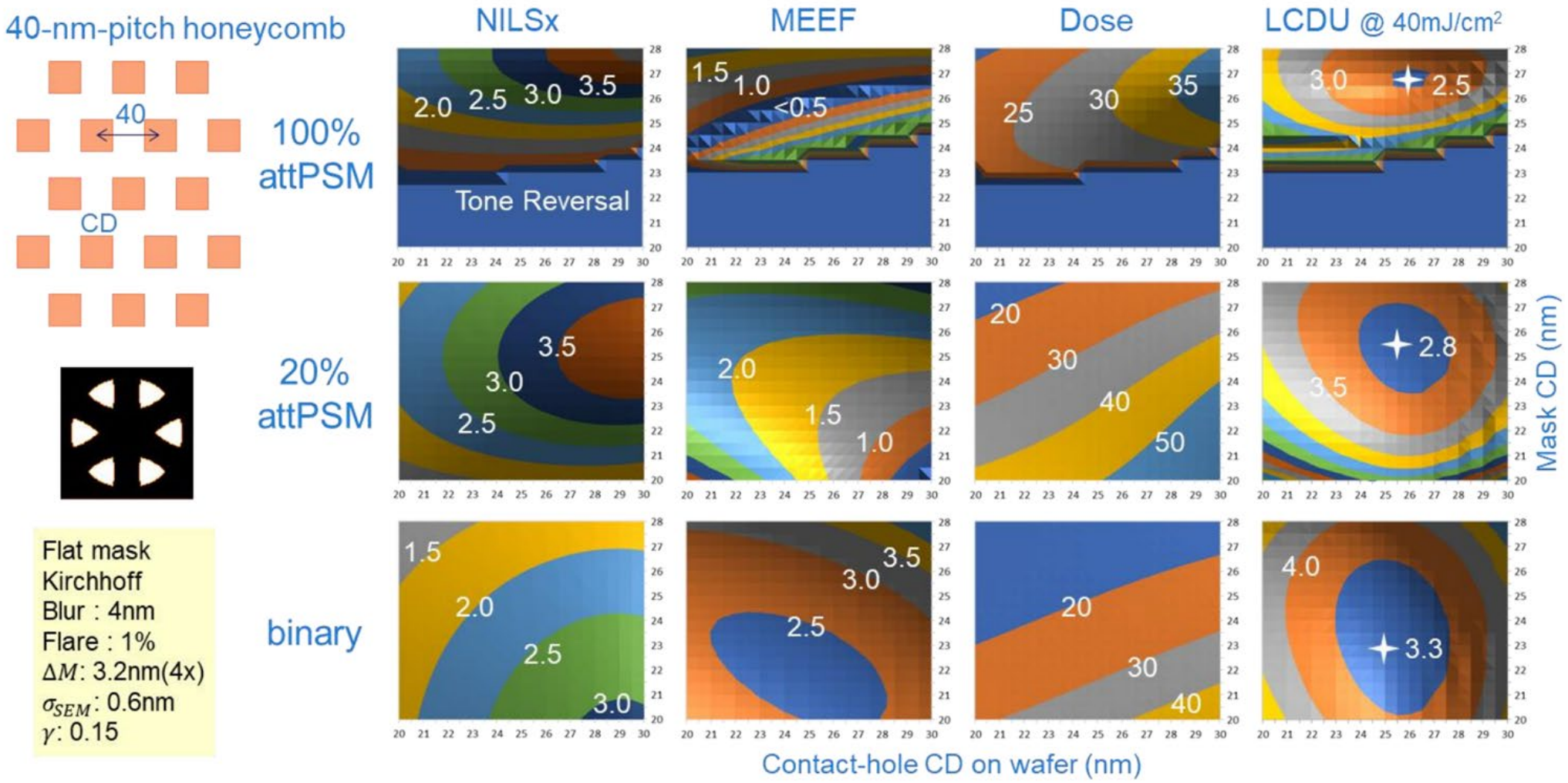
Simulated contrast (NILS) values in orange

BMET Exposures

CXRO

euvtech

Phase masks needed for current NILS target



Chang-Nam Ahn, Dong-Seok Nam, Nakgeuon Seong, Anthony Yen, Proc. SPIE **11609**, 116090D (2021); doi: 10.1117/12.2583462

Phase mask NILS benefit demonstrated on NXE

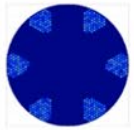
Initial experimental LCDU results: 15% reduction with low-n mask

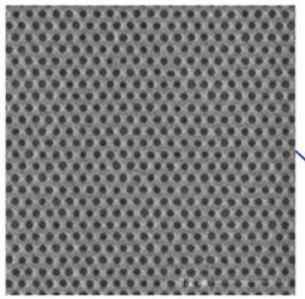
ASML

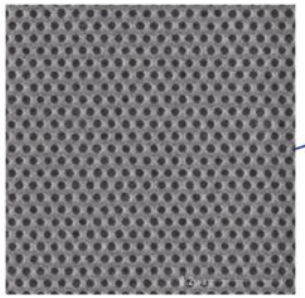
Public

HOYA 01-2021

Hexagonal contact holes





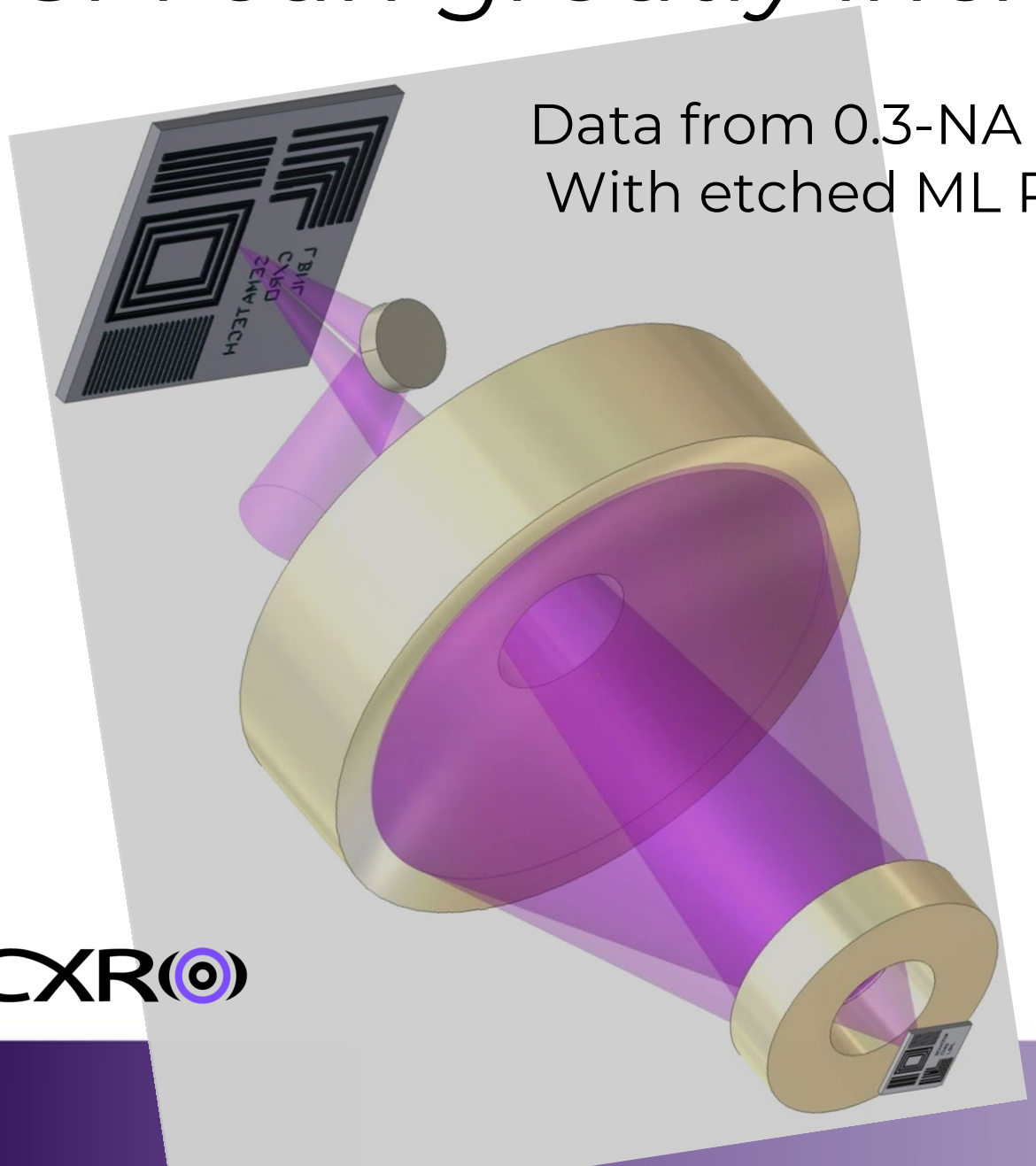


Pitch (nm)	Design mask bias (nm)	Dose (mJ/cm²)	LCDU (nm)	
			Ta mask	Low-n mask
38	3	48	3.41	2.89
40	3	48	3.09	2.63

LCDU numbers include mask contribution

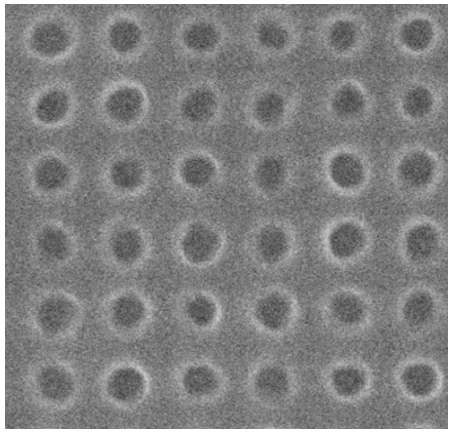
Claire van Lare, et al., Proc. SPIE **11609**, 116090A (2021); https://doi.org/10.1117/12.2584725

PSM can greatly increase throughput



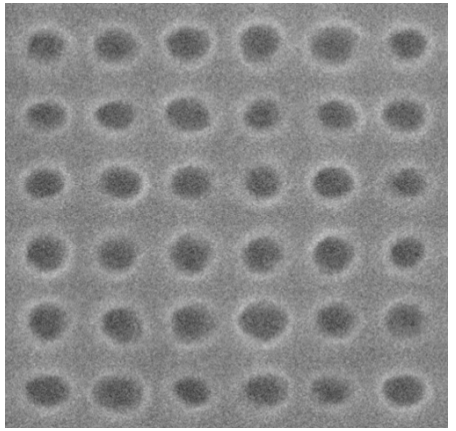
PSM

13 mJ/cm^2



TaN

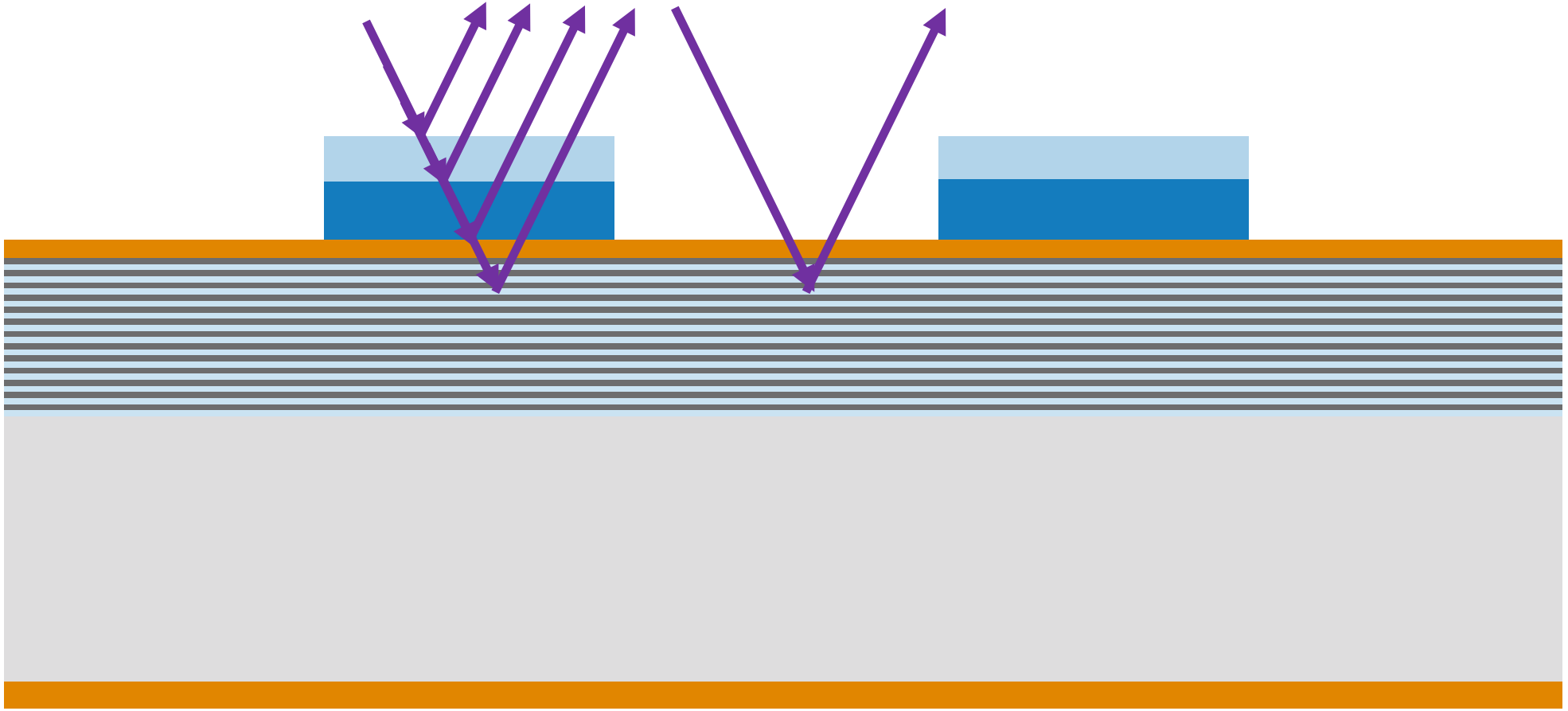
94 mJ/cm^2



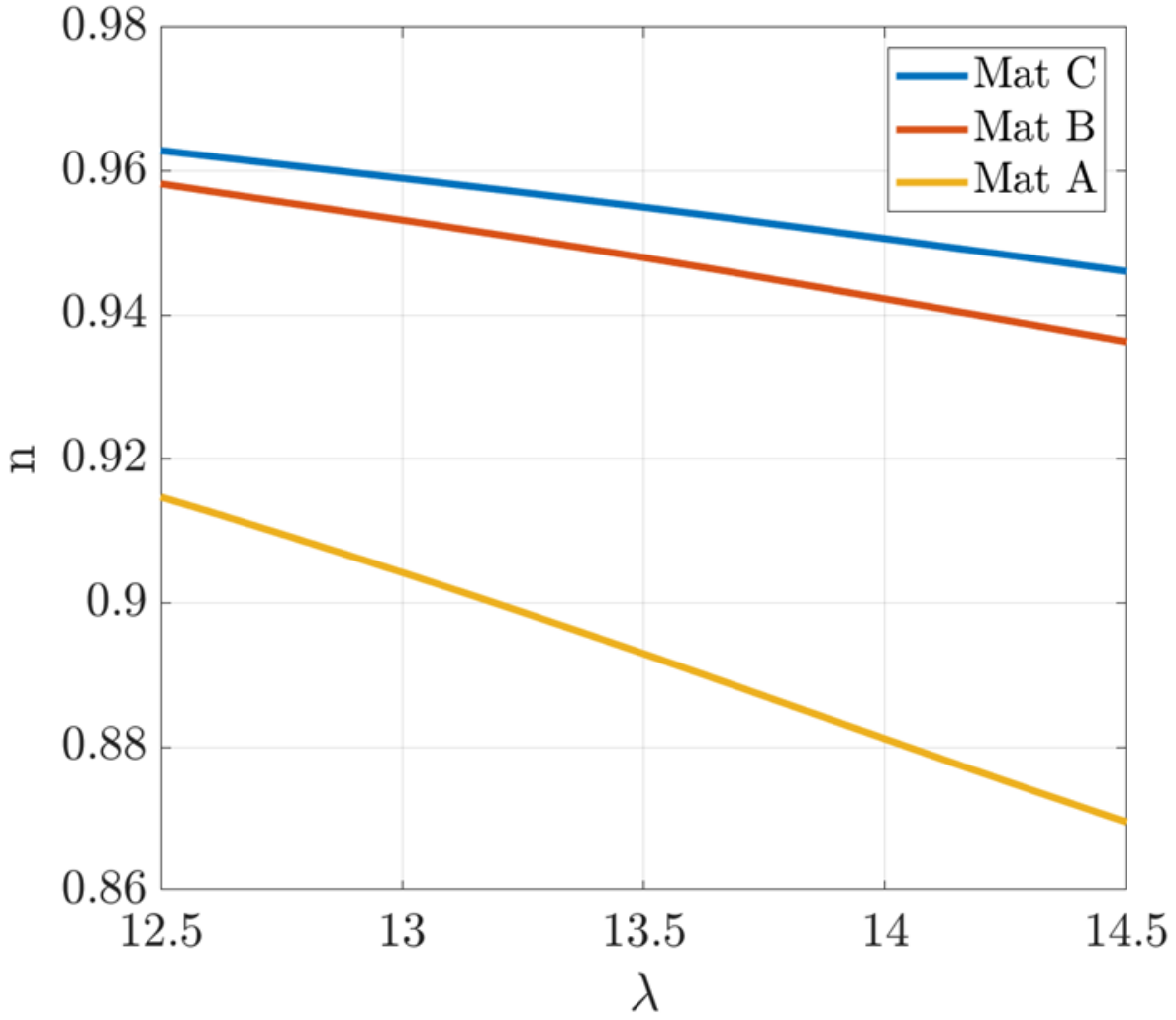
CXRO

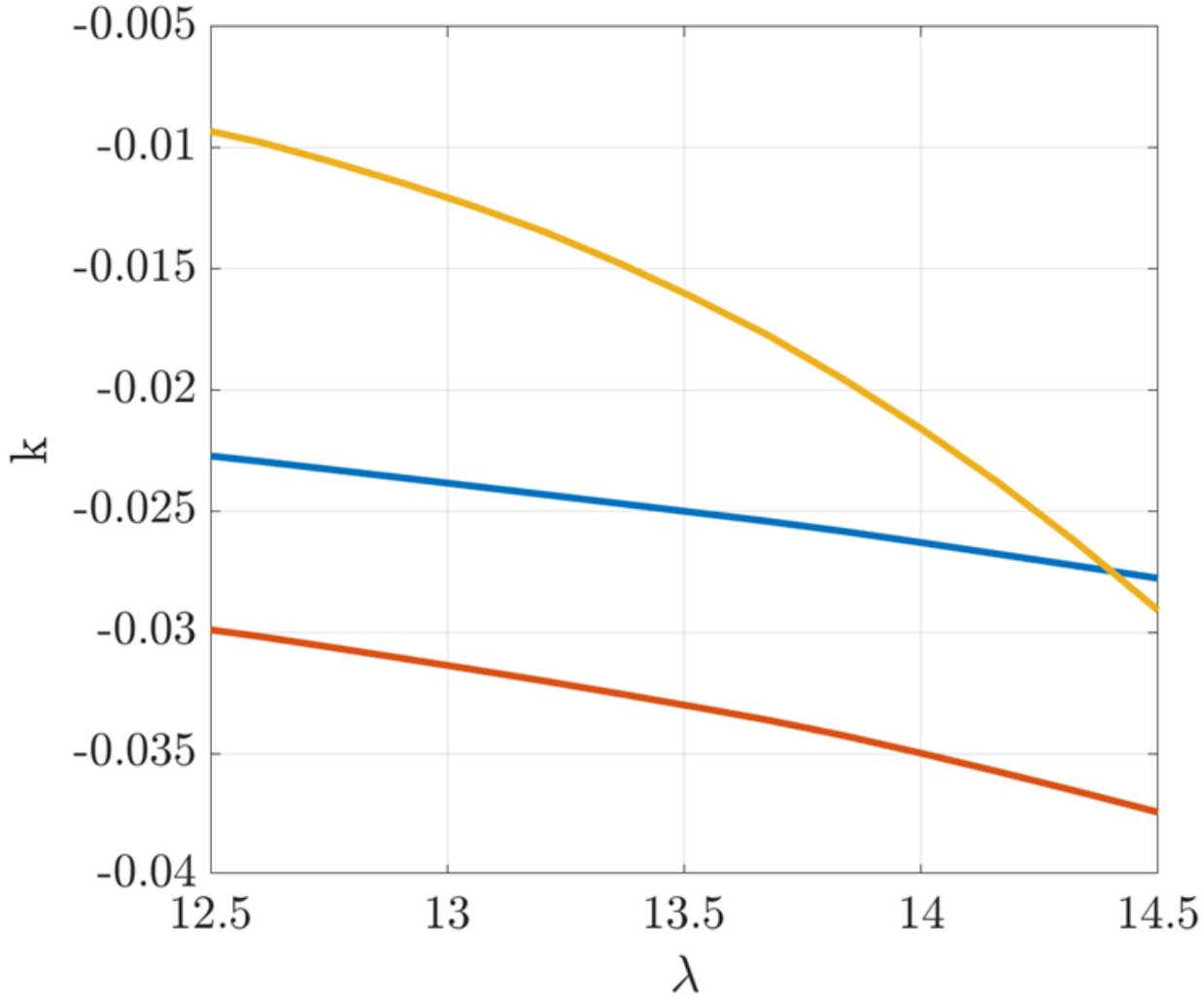
euv tech

EUV mask phase depends on refraction and thin-film effects



Materials very dispersive in the EUV regime

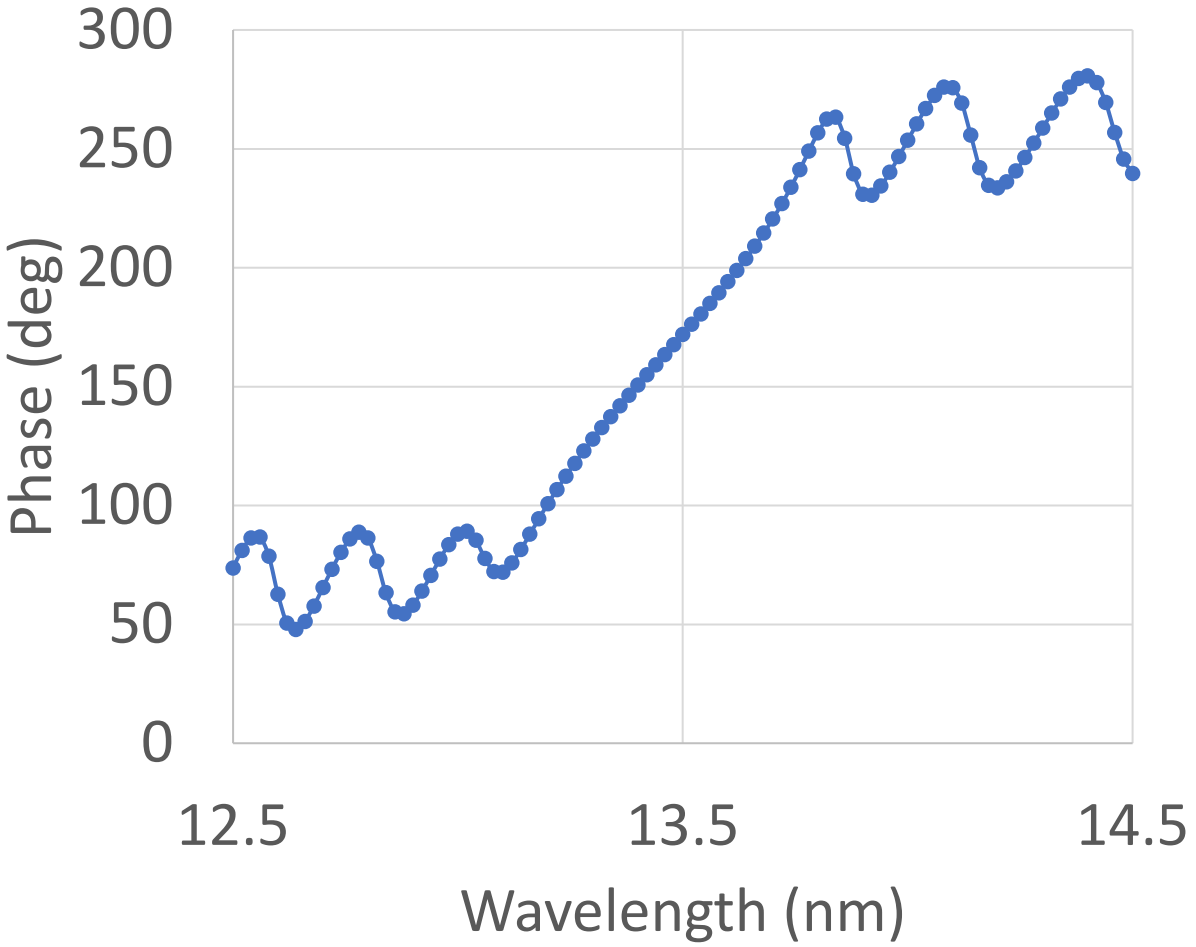


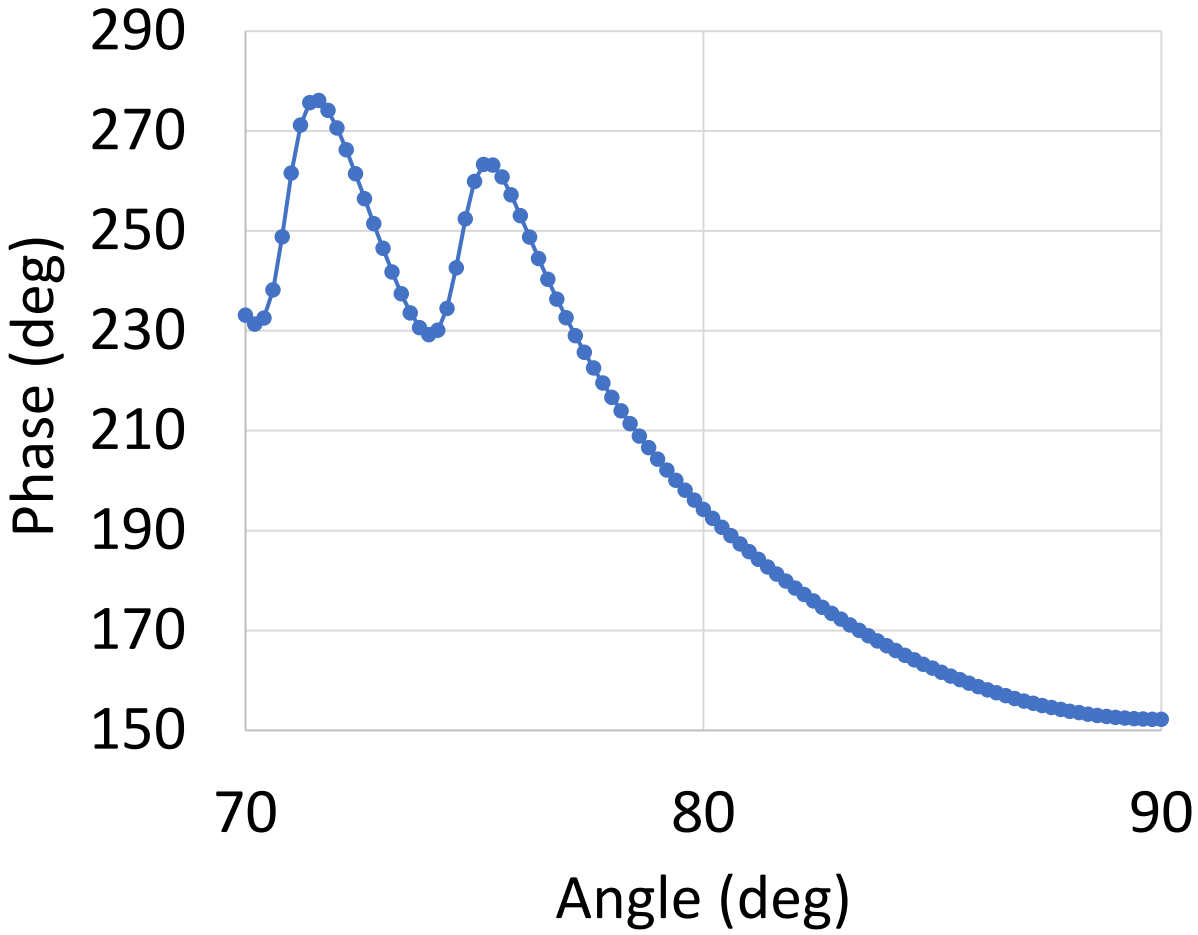


Measured using EUV Tech ENK tool

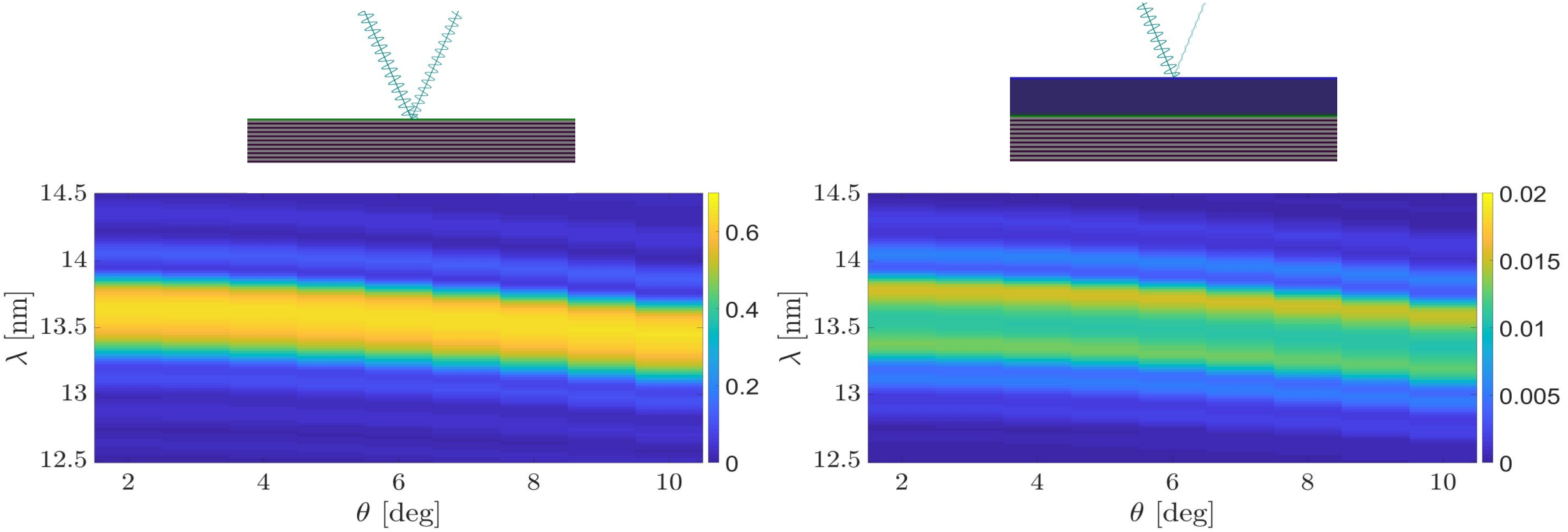
euv tech

Multilayers lead to rapidly evolving phase





Relative phase can be measured through spectroscopic variable angle reflectometry



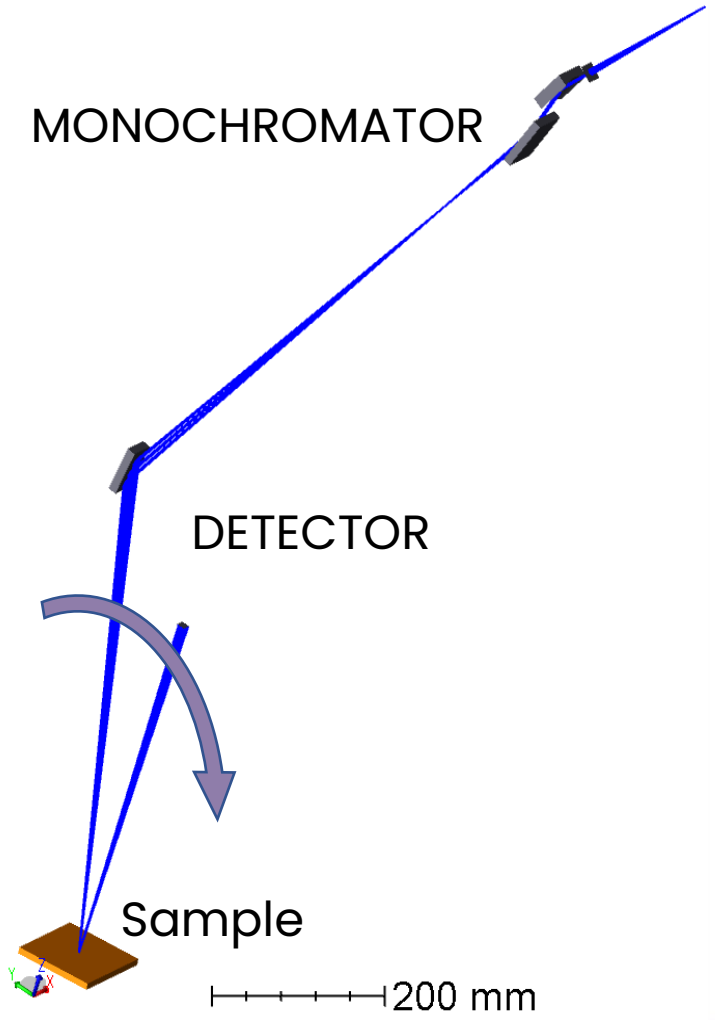
S. Sherwin, E. Gullikson, M. Hettermann, D. Houser, C. Perera, P. Naulleau,
"EUV phase monitoring applications with actinic reflectometry," Proc. SPIE **PC12494**, (2023)

Measured using EUV Tech ENK tool

euvtech

EUV Tech ENK tool: a spectroscopic variable angle reflectometer/scatterometer

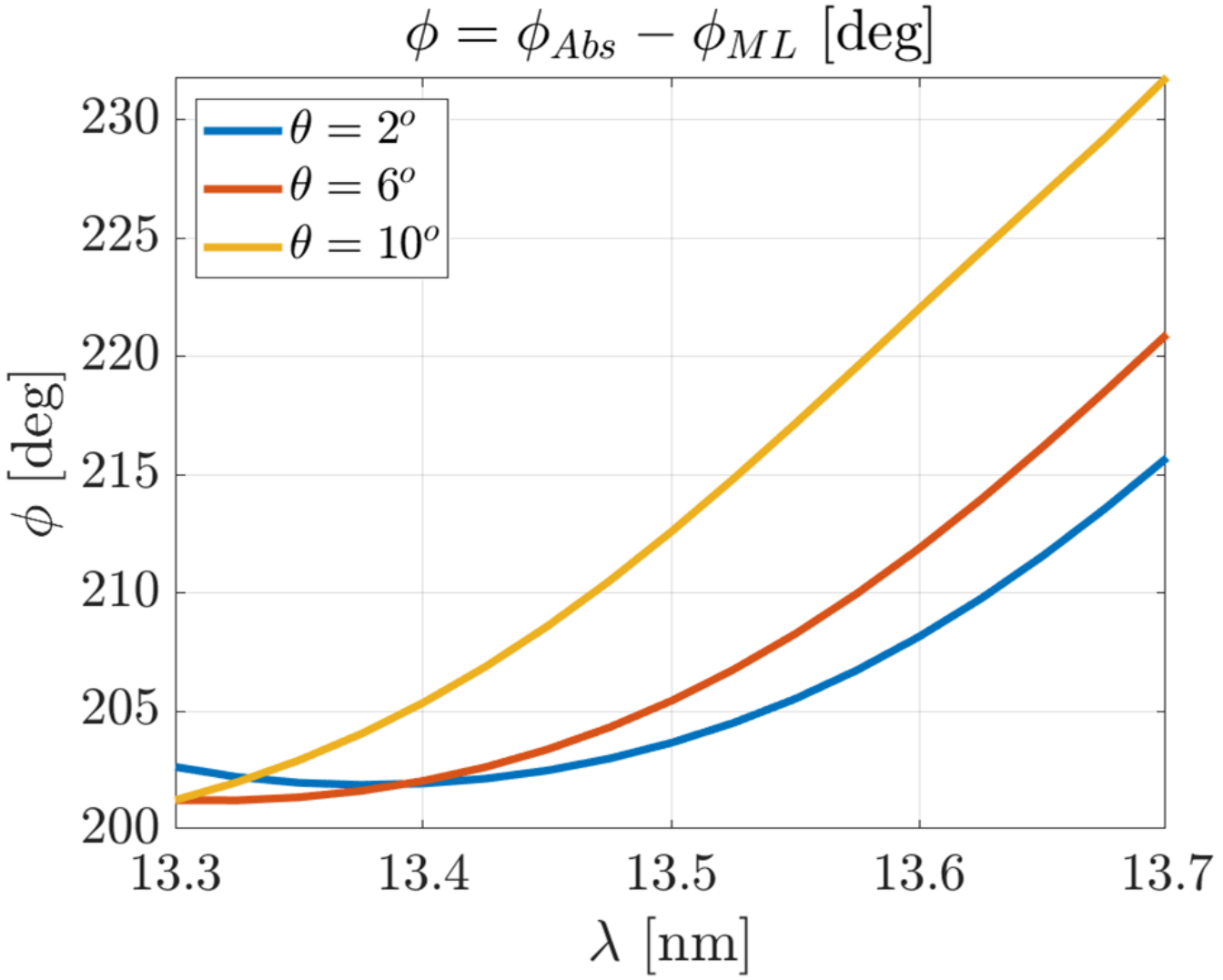
- Utilize EUV Tech's proven high-brightness and high-stability EUV source to implement an angle resolved spectroscopic reflectometer/scatterometer
- Measure n and k of individual films (including dispersive term)
- Measure film thickness and bulk phase
- Measure relative phase of full absorber stacks (including thin film effects)
    - Angle dependent phase
    - Wavelength dependent phase
- Measure full absorber and multilayer stack parameters
- Scatterometry mode to measure pattern phase



EUV Tech ENK tool: a spectroscopic variable angle reflectometer/scatterometer

- Production tool supporting HVM requirements
- Semi S2/S8 certified
- OHT- and AGV-compliant (SEMI E84)
- Supports full-factory automation (SECS-GEM & customer-specific protocols)

Relative phase rapidly evolving

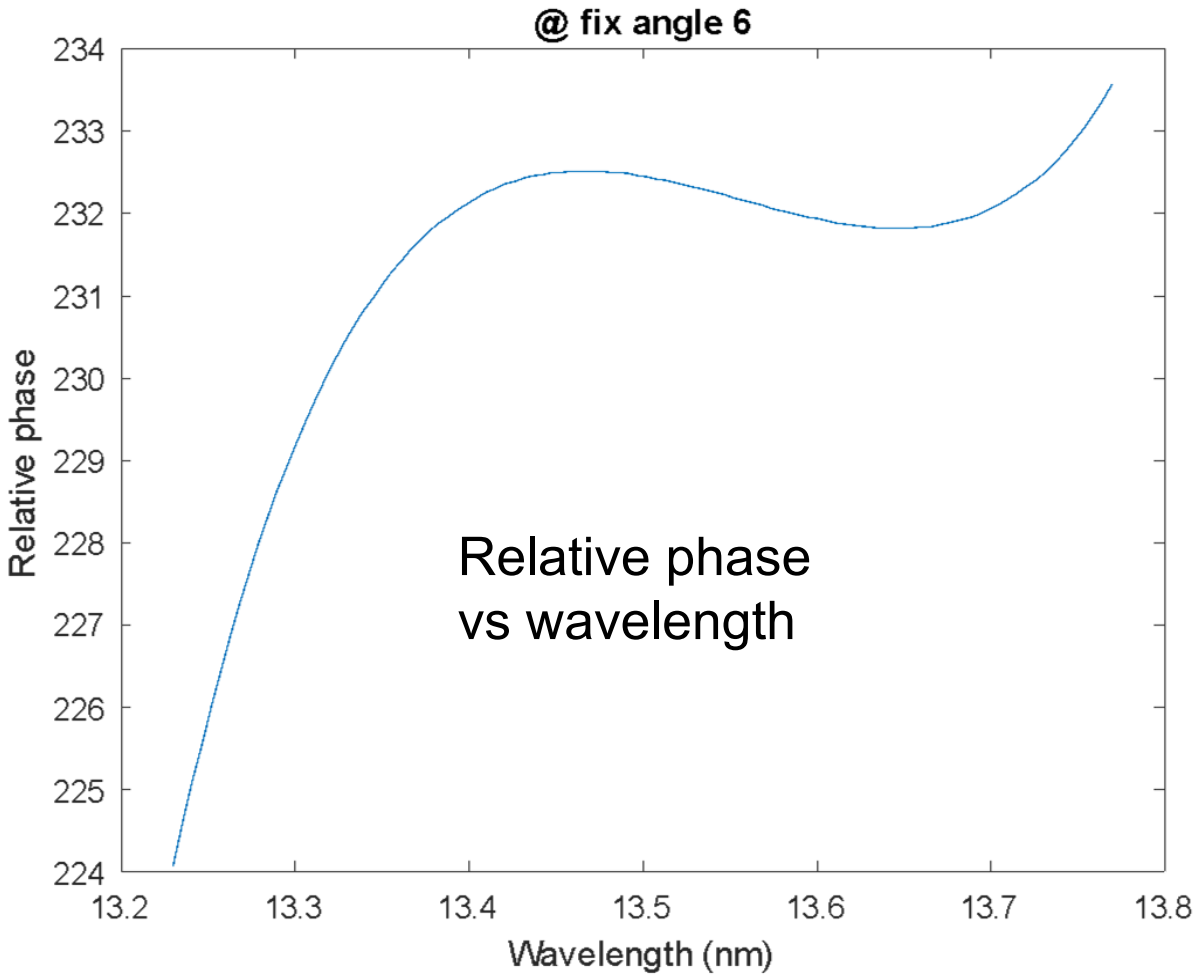


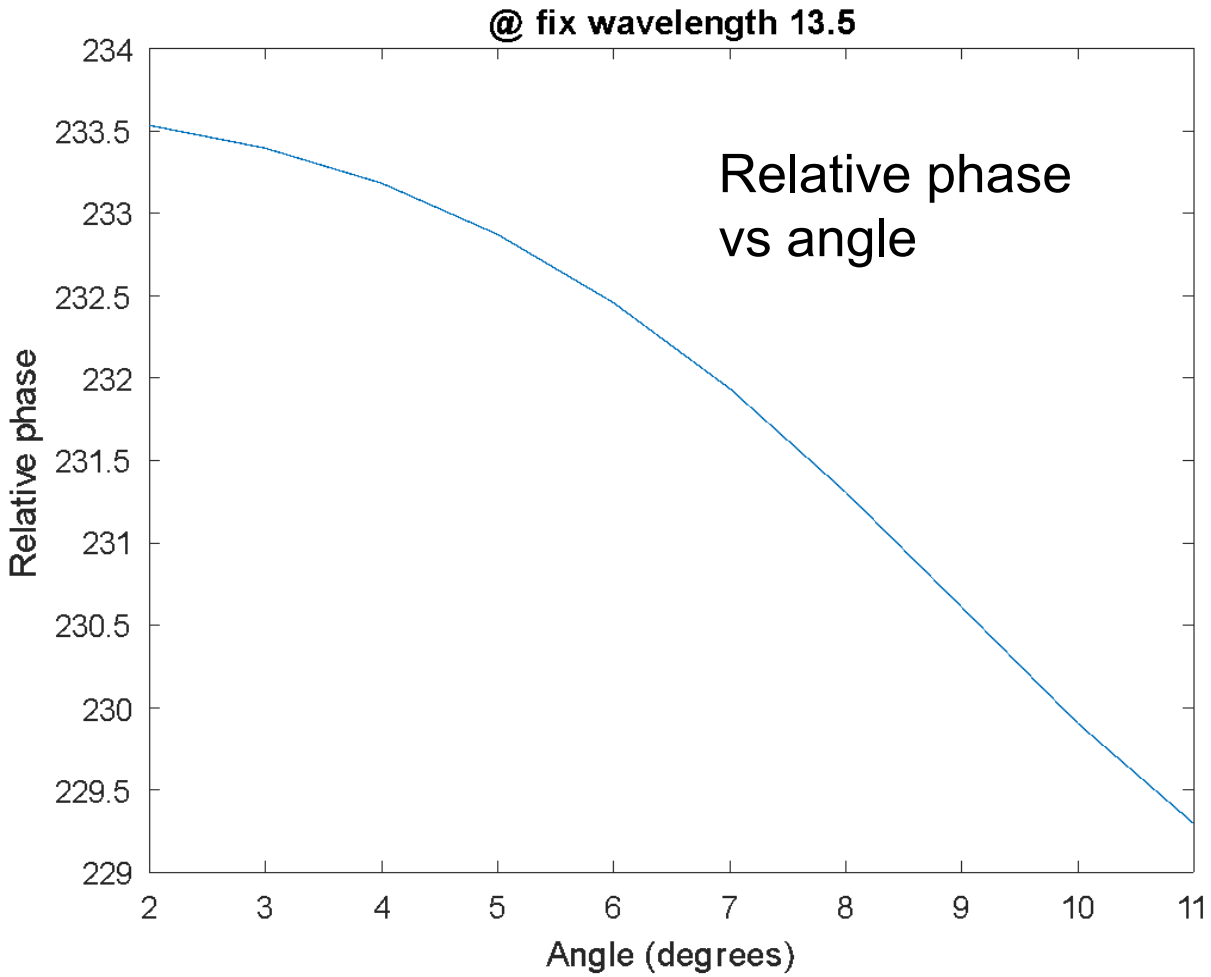
- Up to 30 degrees across passband
- Up to 15 degrees across illumination angle range

Measured using EUV Tech ENK tool

euv tech

Phase evolution highly material dependent

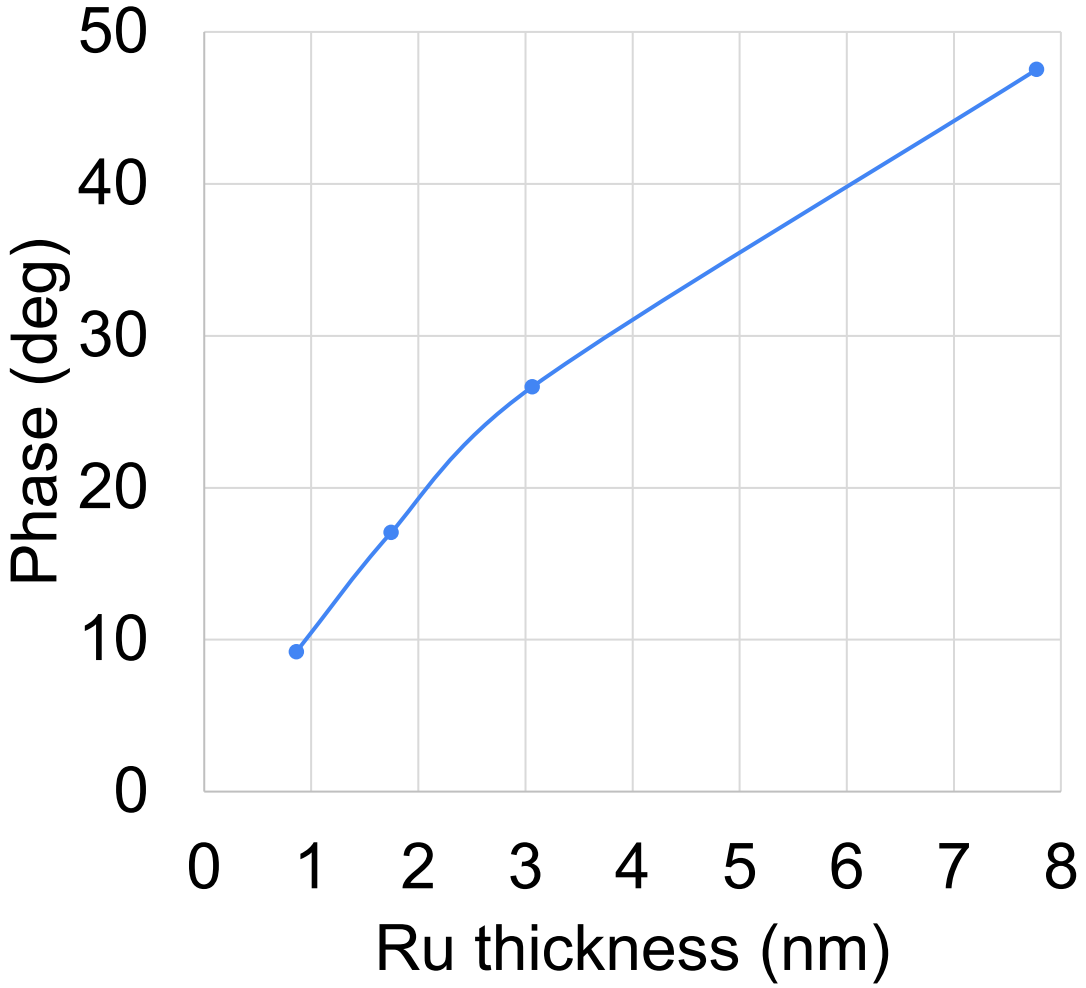


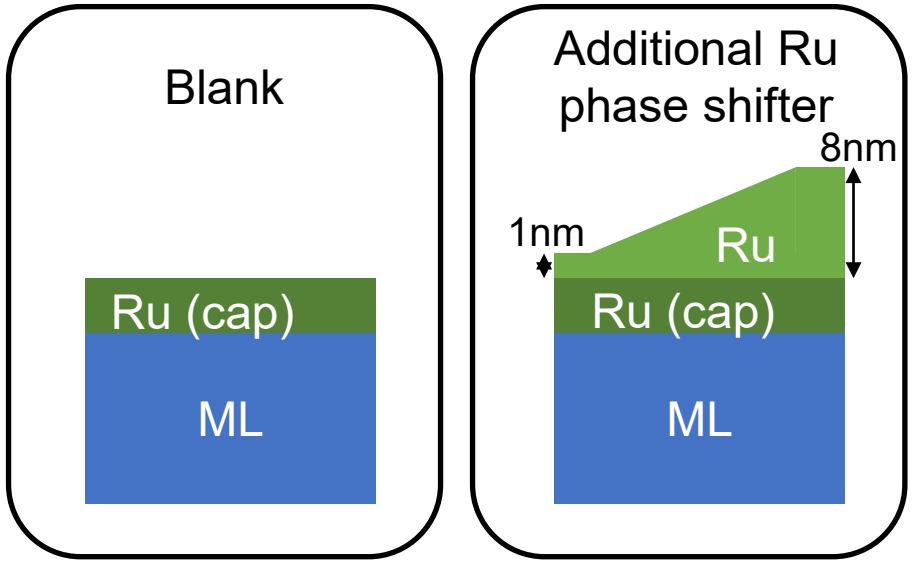


Measured using EUV Tech ENK tool

euvtech

Phase highly dependent on thin film effects



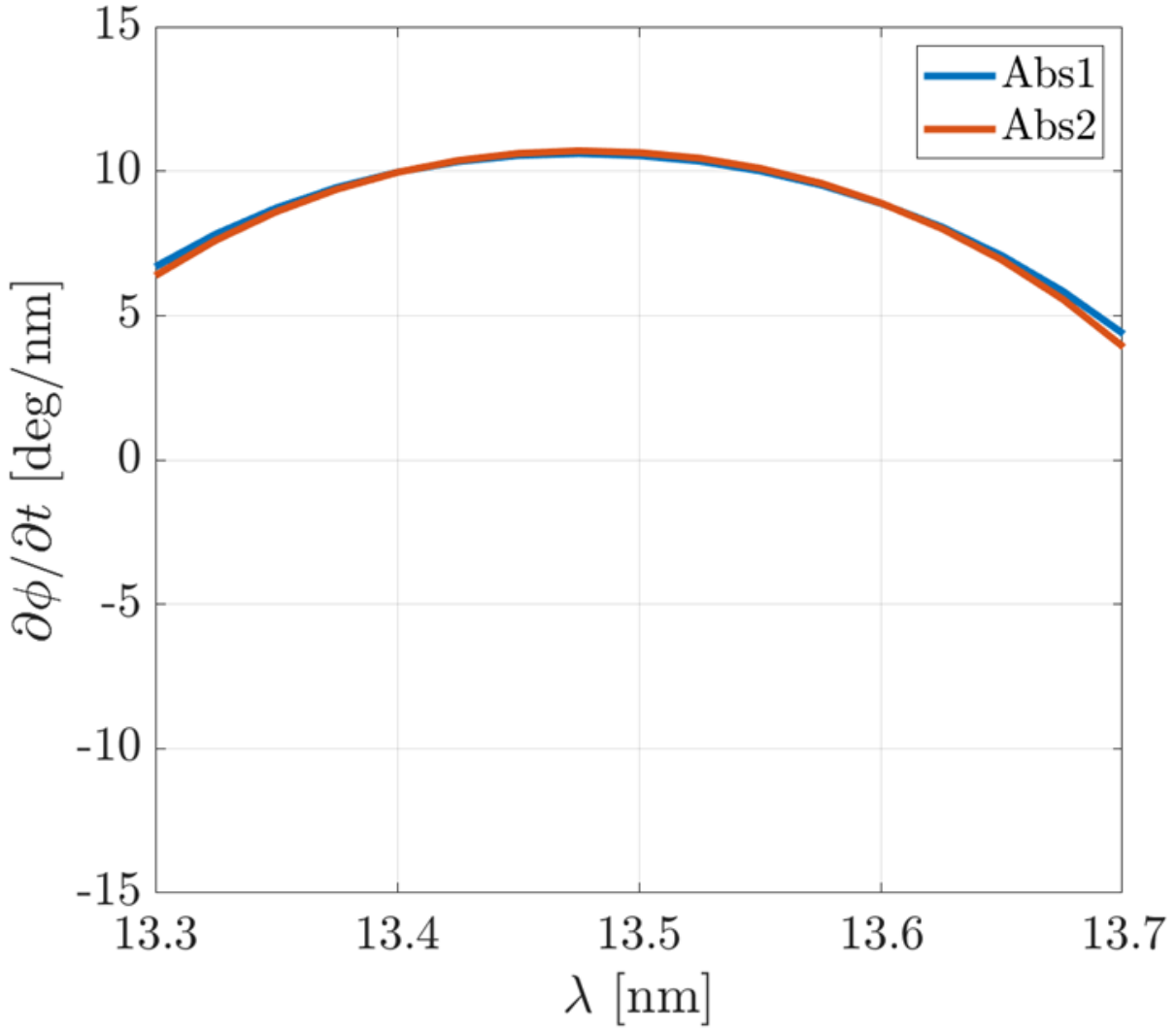


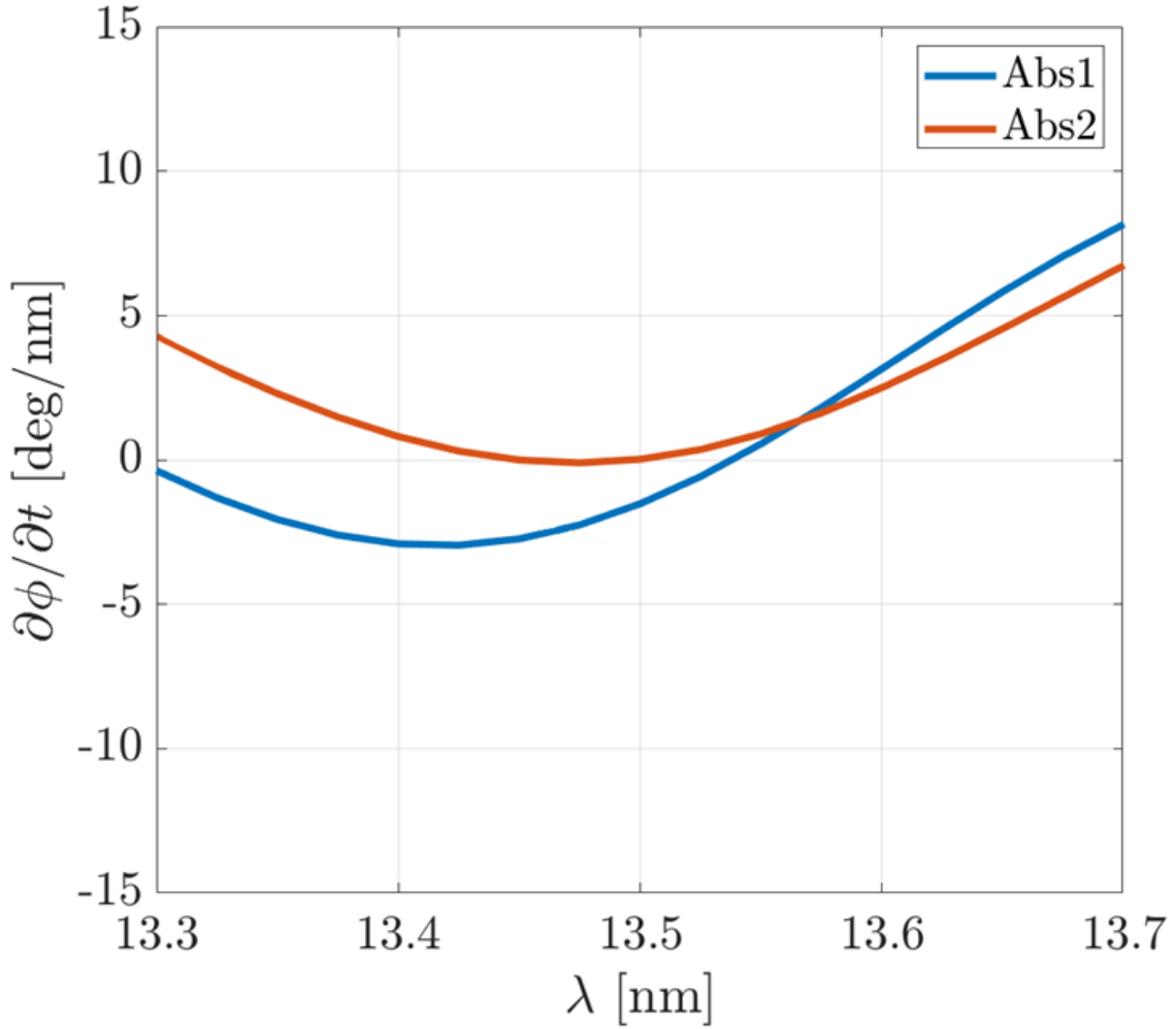
- Up to 10-degrees per nm phase sensitivity

Measured using EUV Tech ENK tool

euvtech

Multilayer absorbers can compound the effect

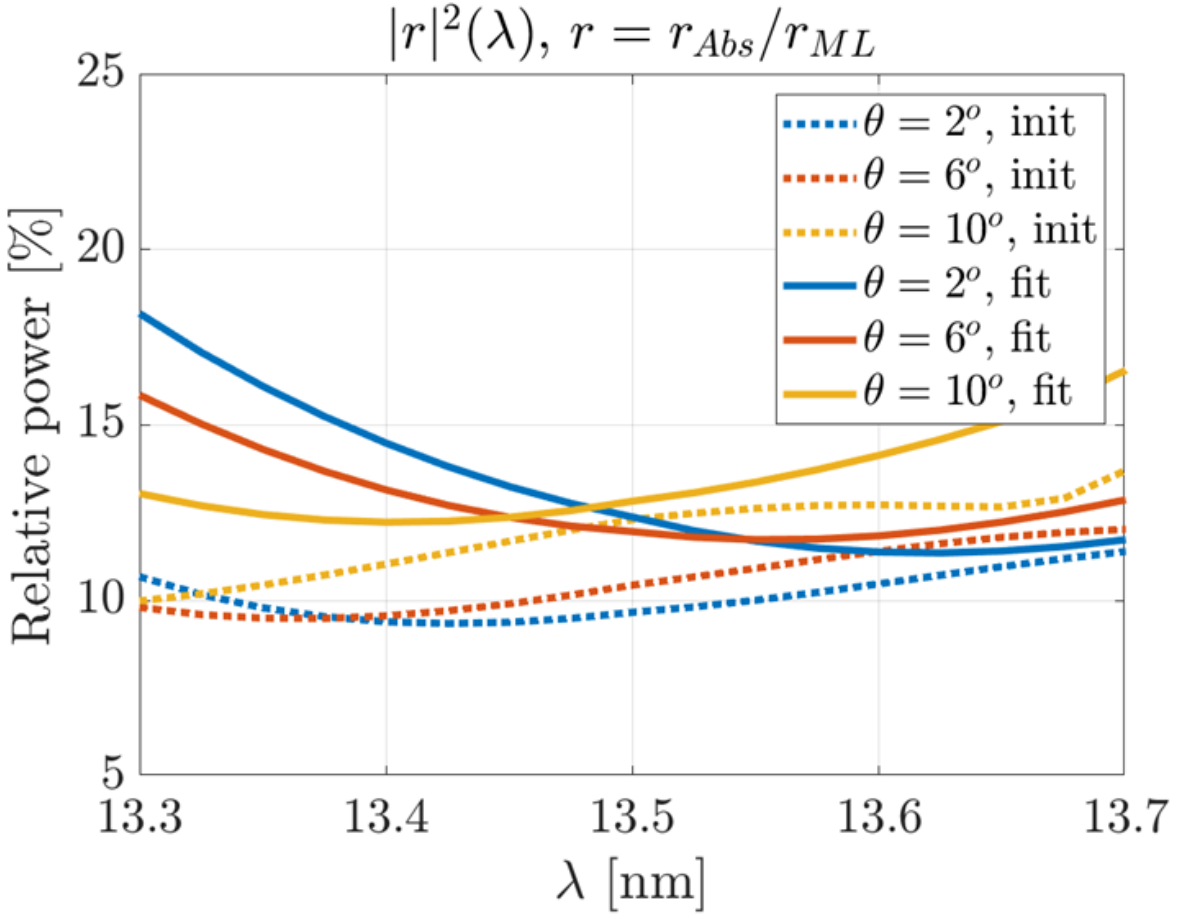


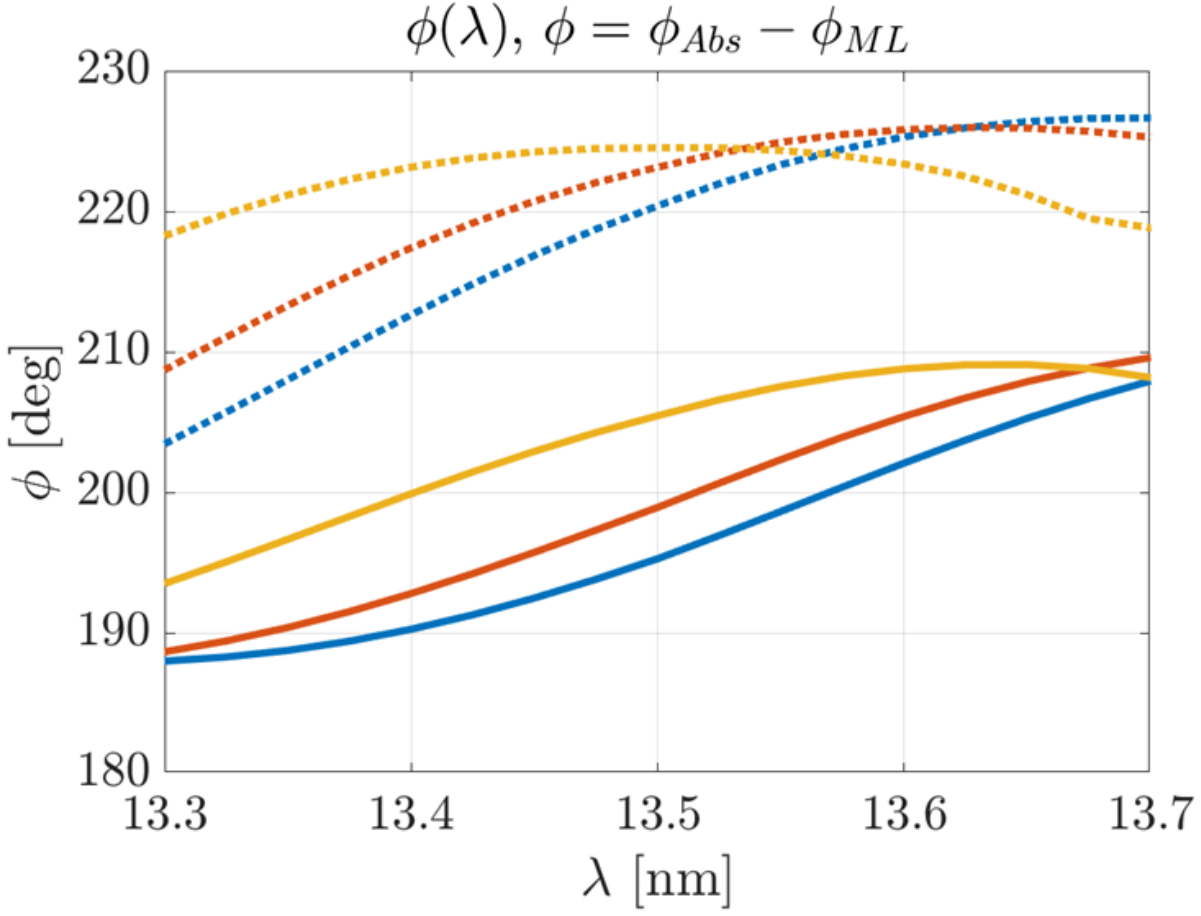


Measured using EUV Tech ENK tool

euvtech

Phase highly sensitive to subtle changes in as-deposited characteristics

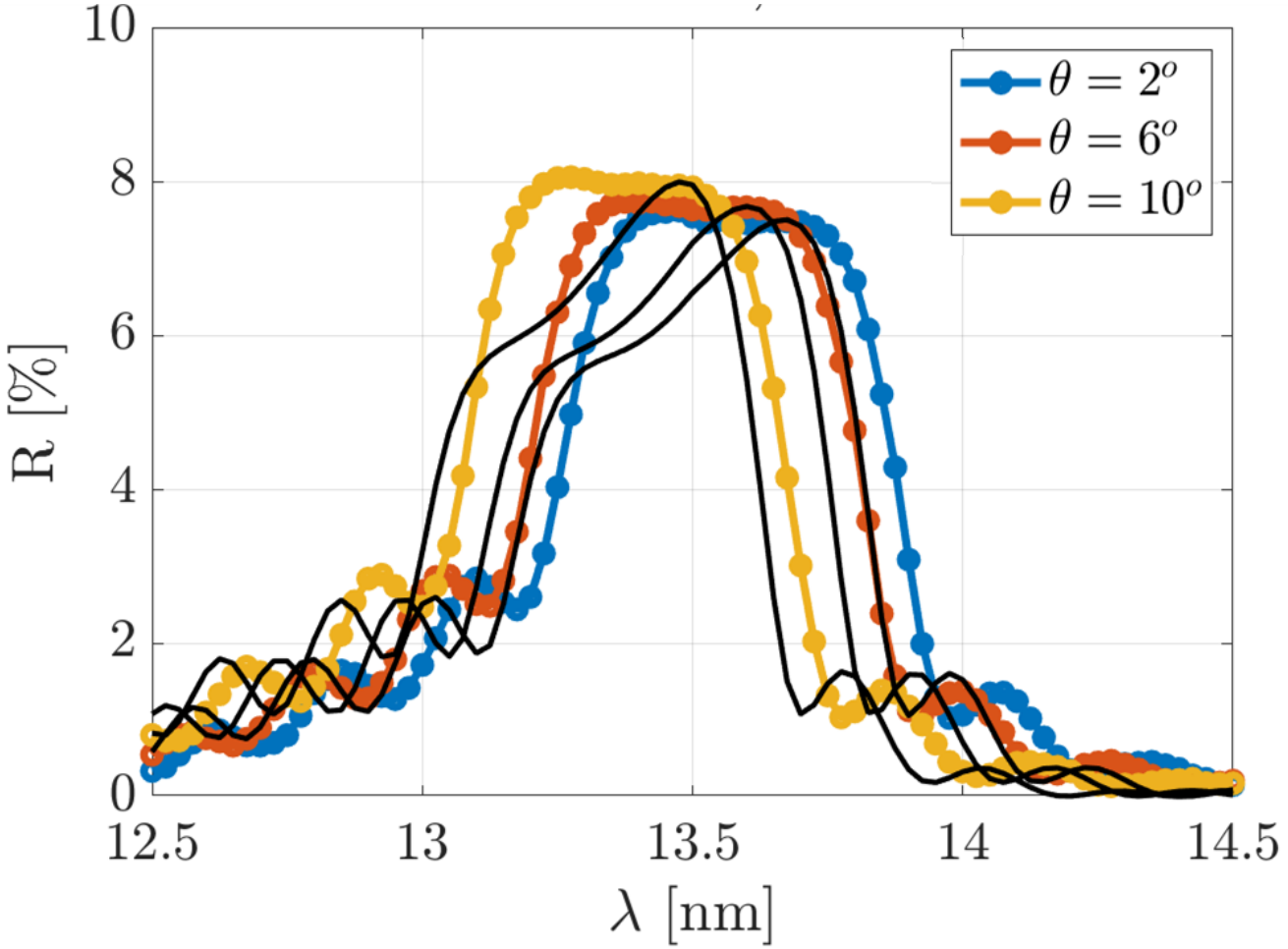




Measured using EUV Tech ENK tool

euv tech

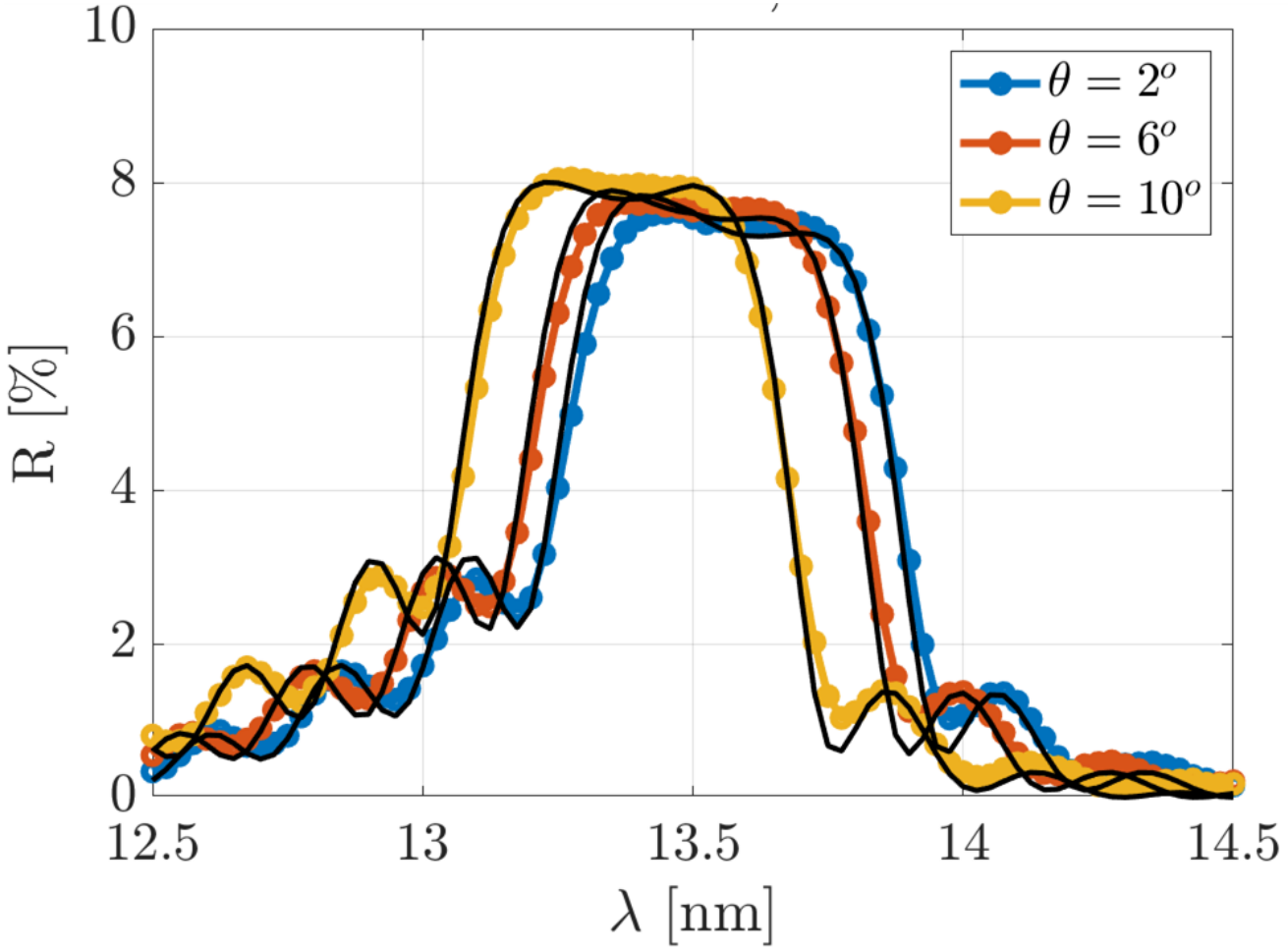
Errors clearly manifest in reflectance behavior



Measured using EUV Tech ENK tool

euv tech

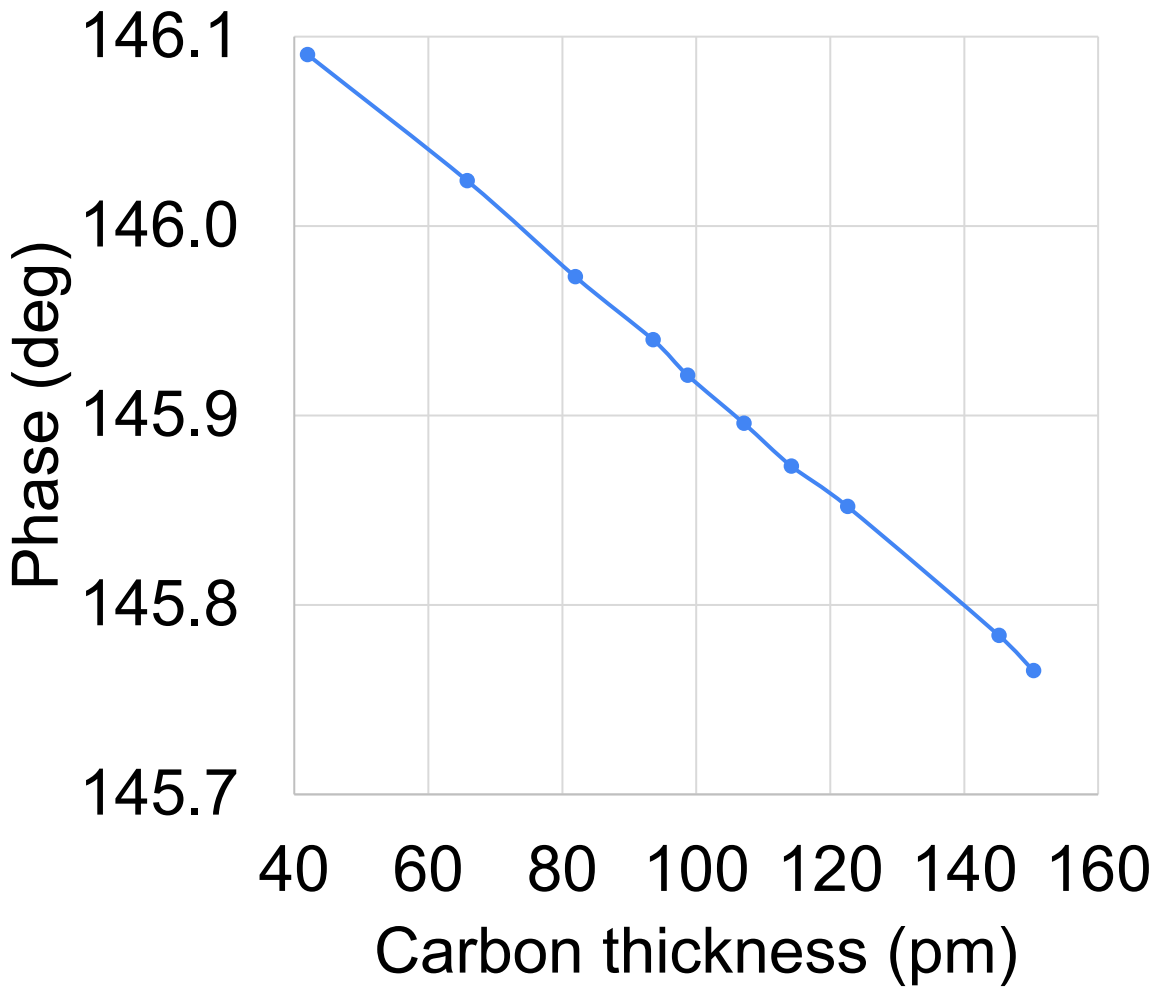
Errors clearly manifest in reflectance behavior



Measured using EUV Tech ENK tool

euv tech

Phase also dependent on contamination



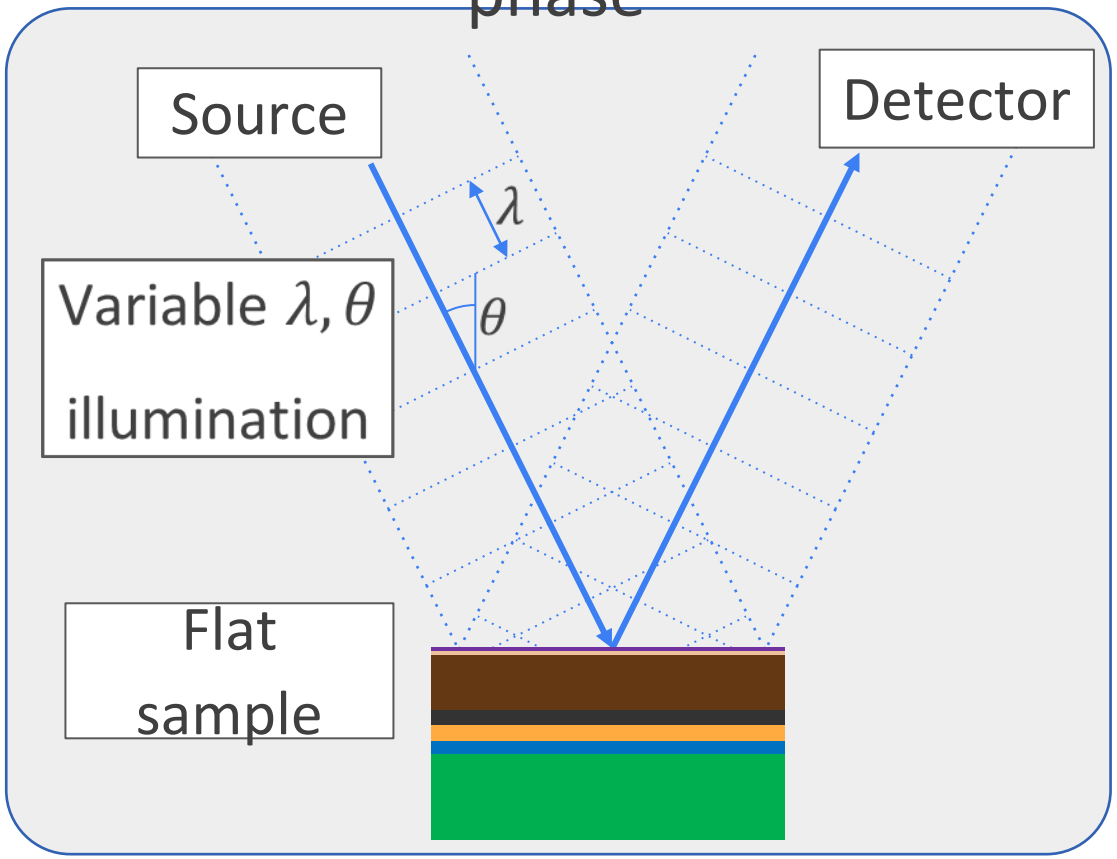
- Phase measurably dependent on pm level contamination
- 0.3-degrees per 100-pm of carbon

Measured using EUV Tech ENK tool

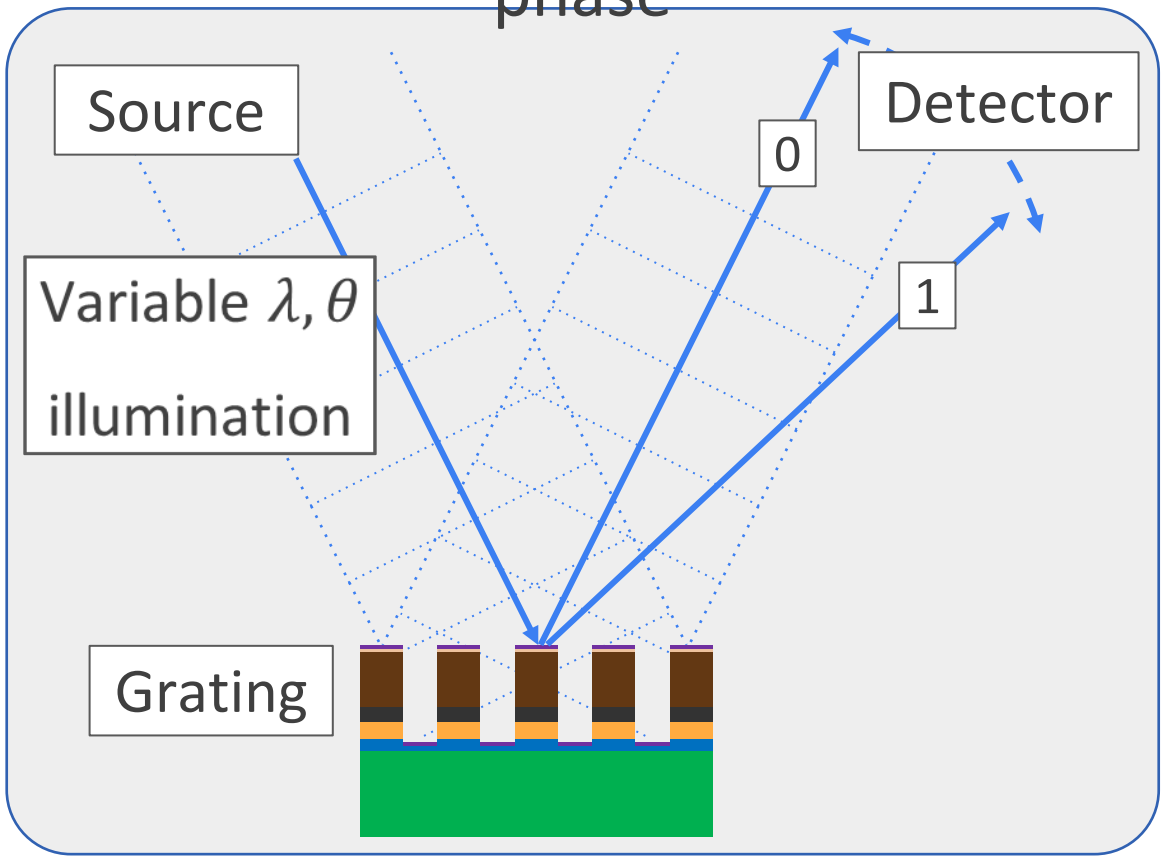
euvtech

Film phase versus pattern phase

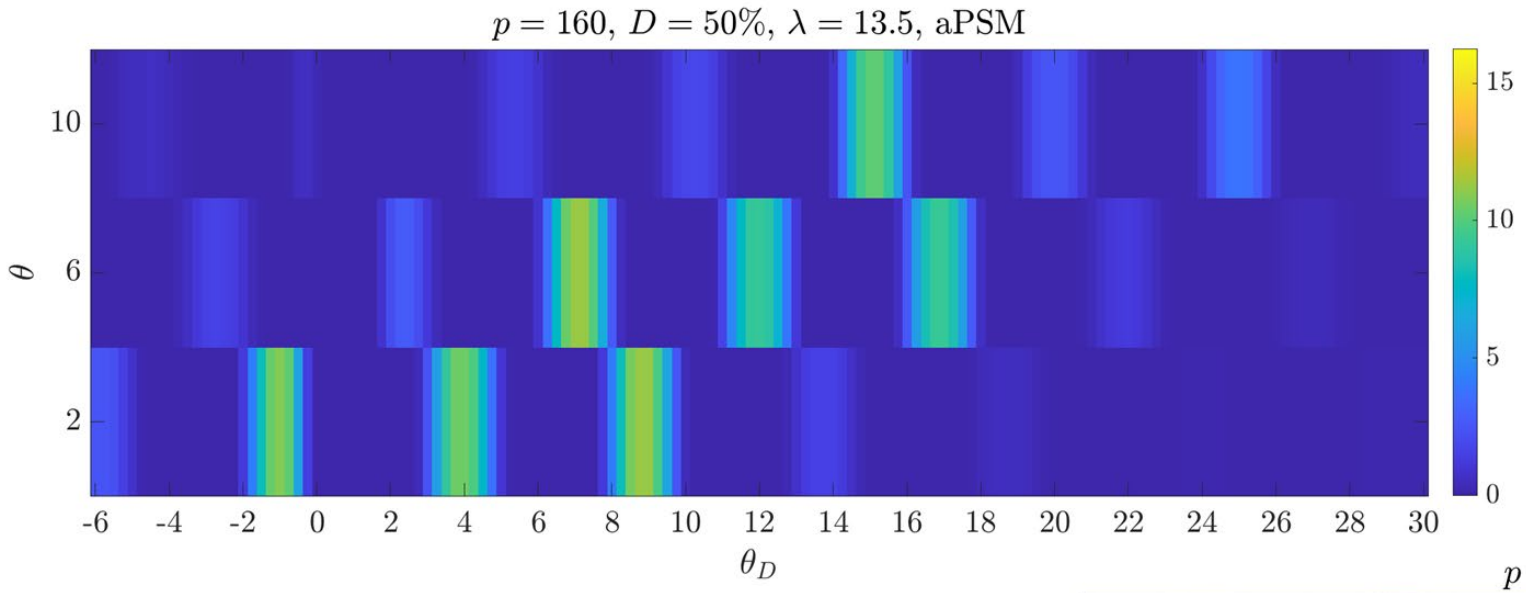
Reflectometry: Measure film phase

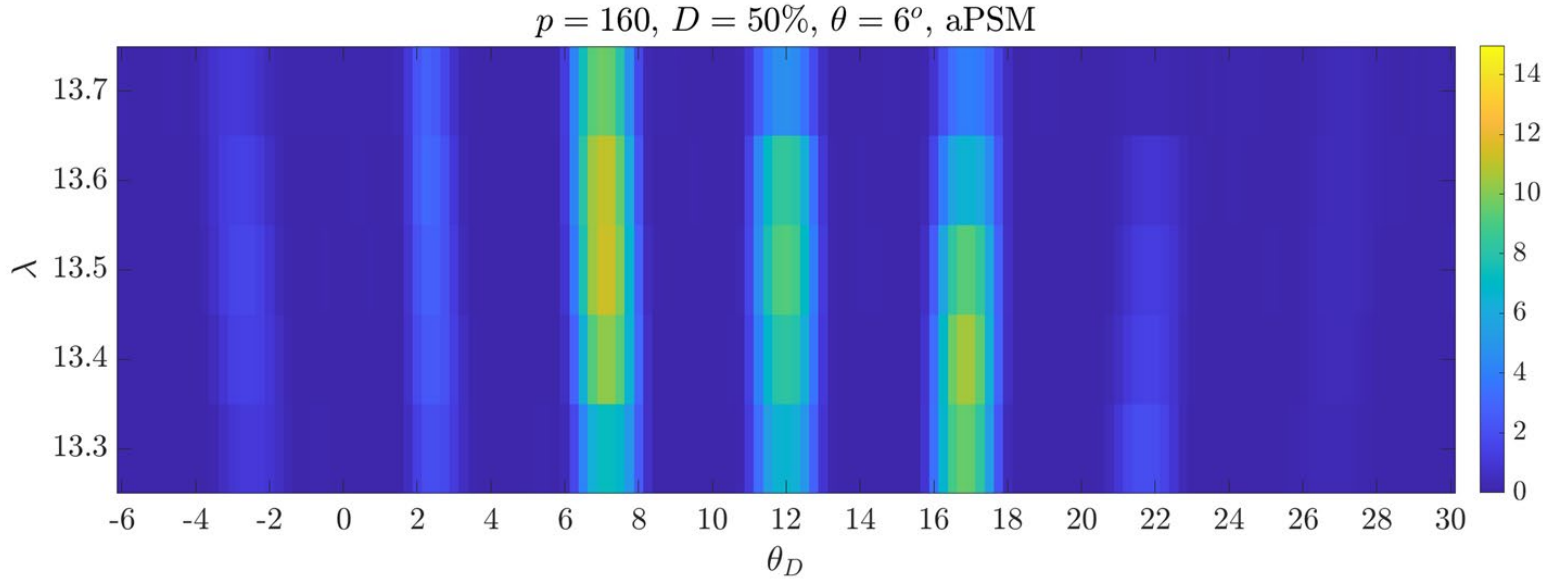


Scatterometry: Measure pattern phase



Scatterometry: pattern phase measurement

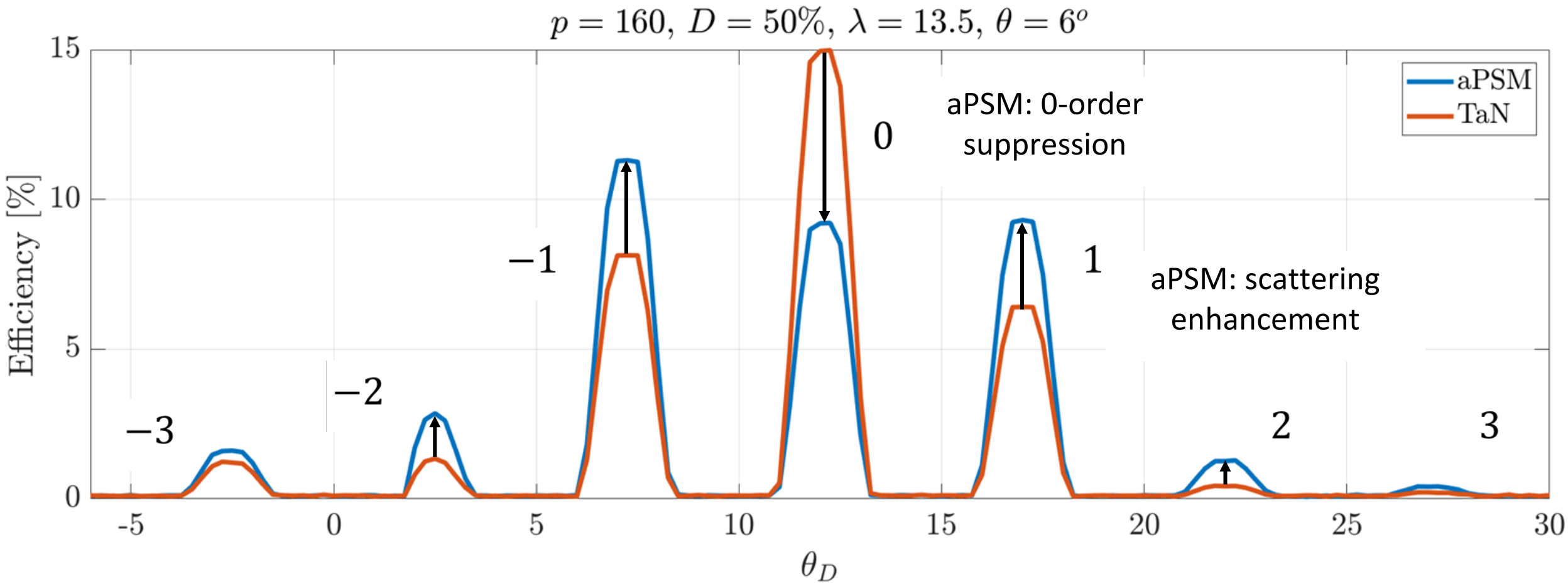




Measured using EUV Tech ENK tool

euv tech

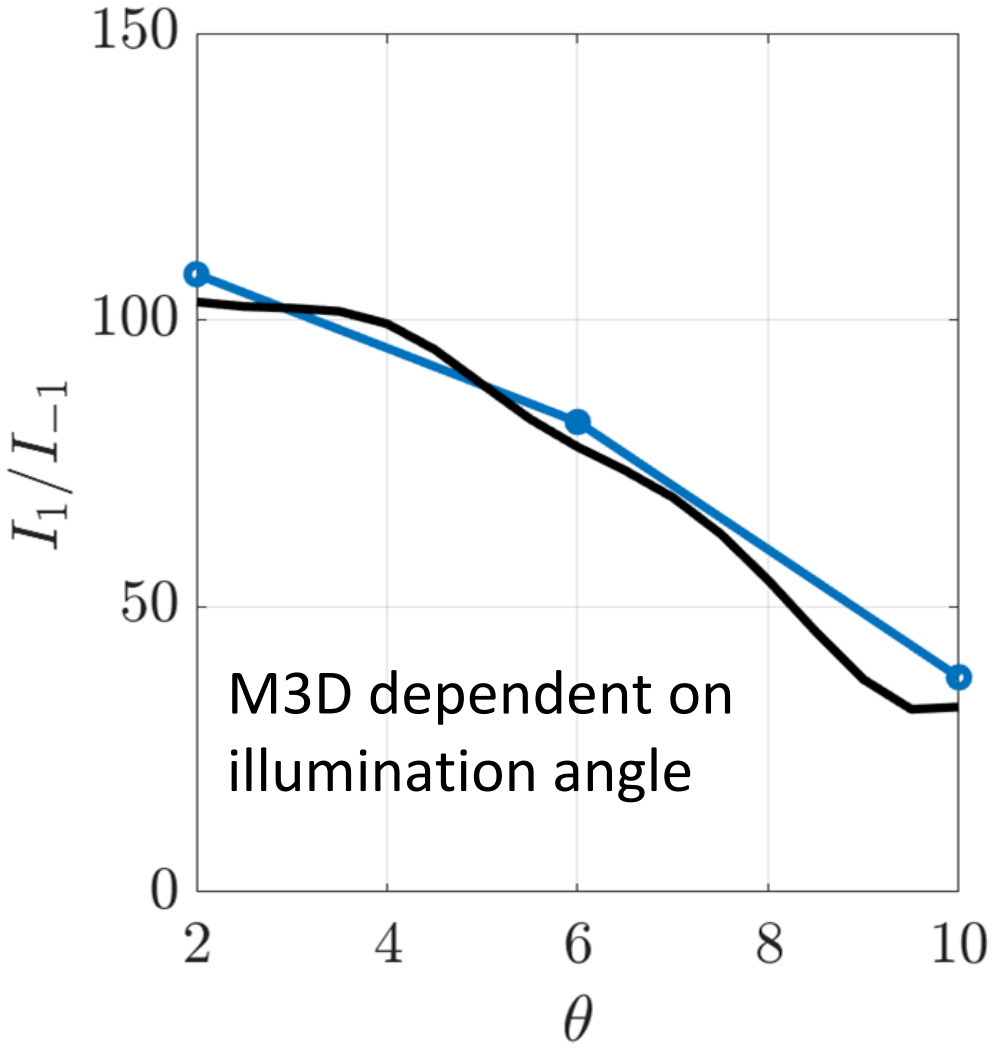
Scatterometry: pattern phase measurement

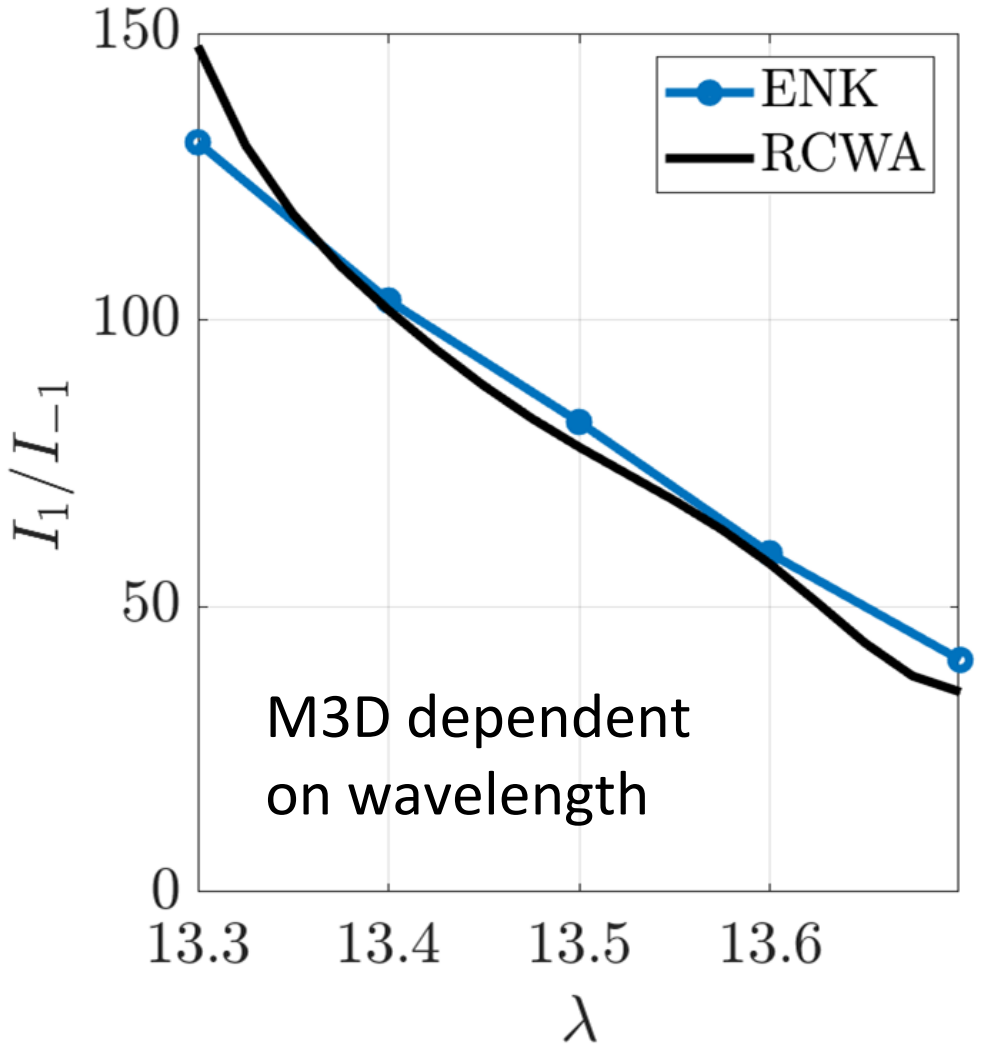


Measured using EUV Tech ENK tool

euv tech

M3D effects highly dependent on wavelength

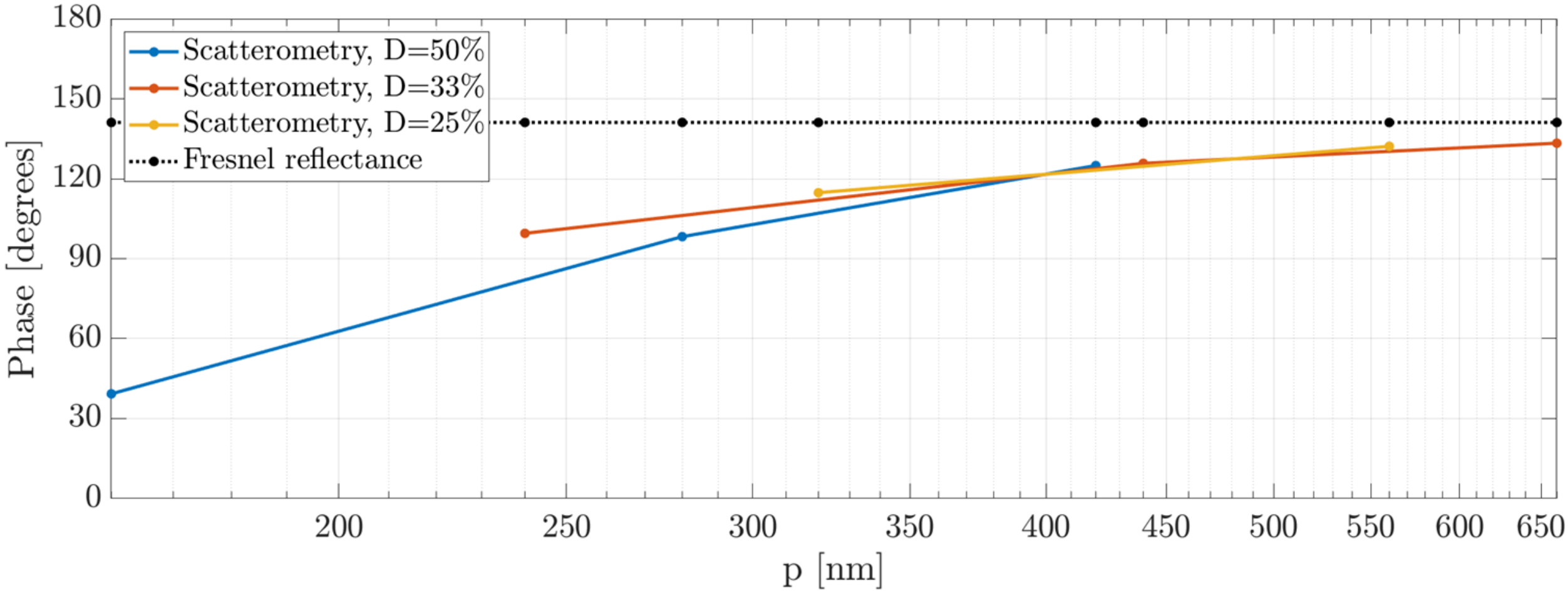




Measured using EUV Tech ENK tool

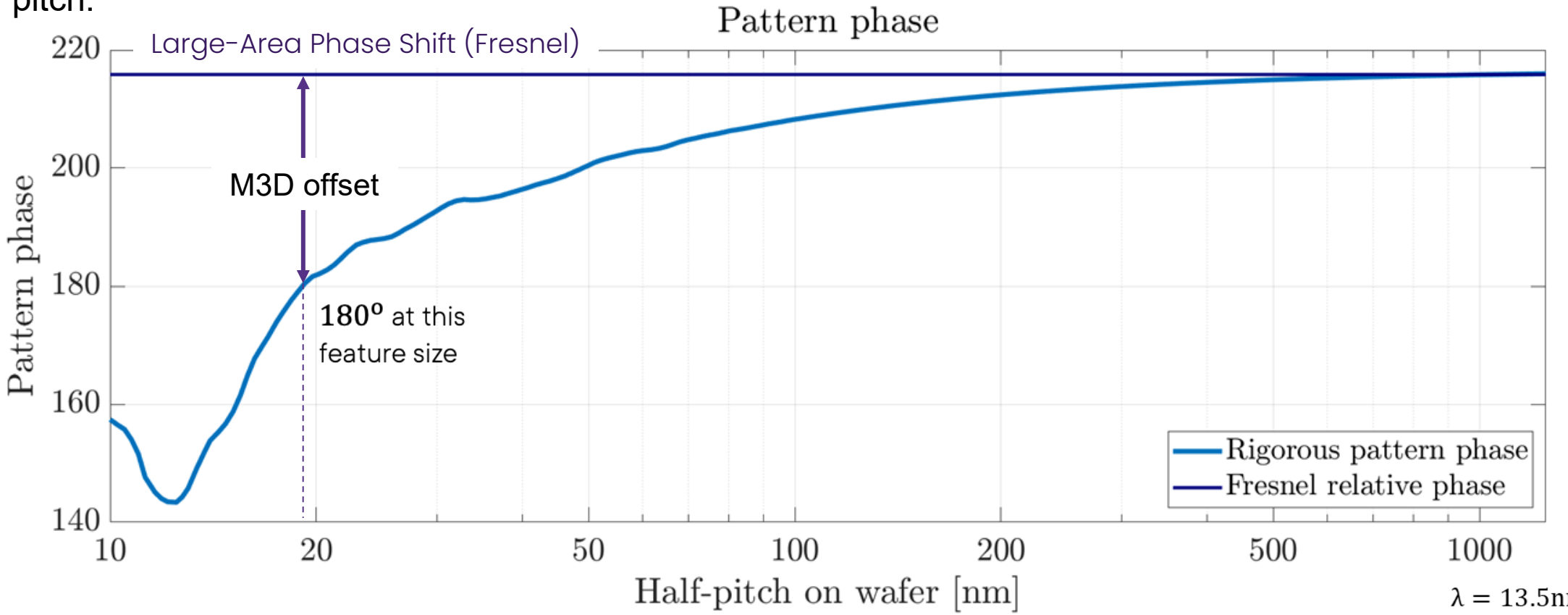
euvtech

Pattern phase deviates from film phase due to edge effects: converges to film phase at large pitch



Pattern Phase vs Pitch: M3D Phase Shift

Due to 3D absorber + multilayer structure, design must account for phase shift through pitch.

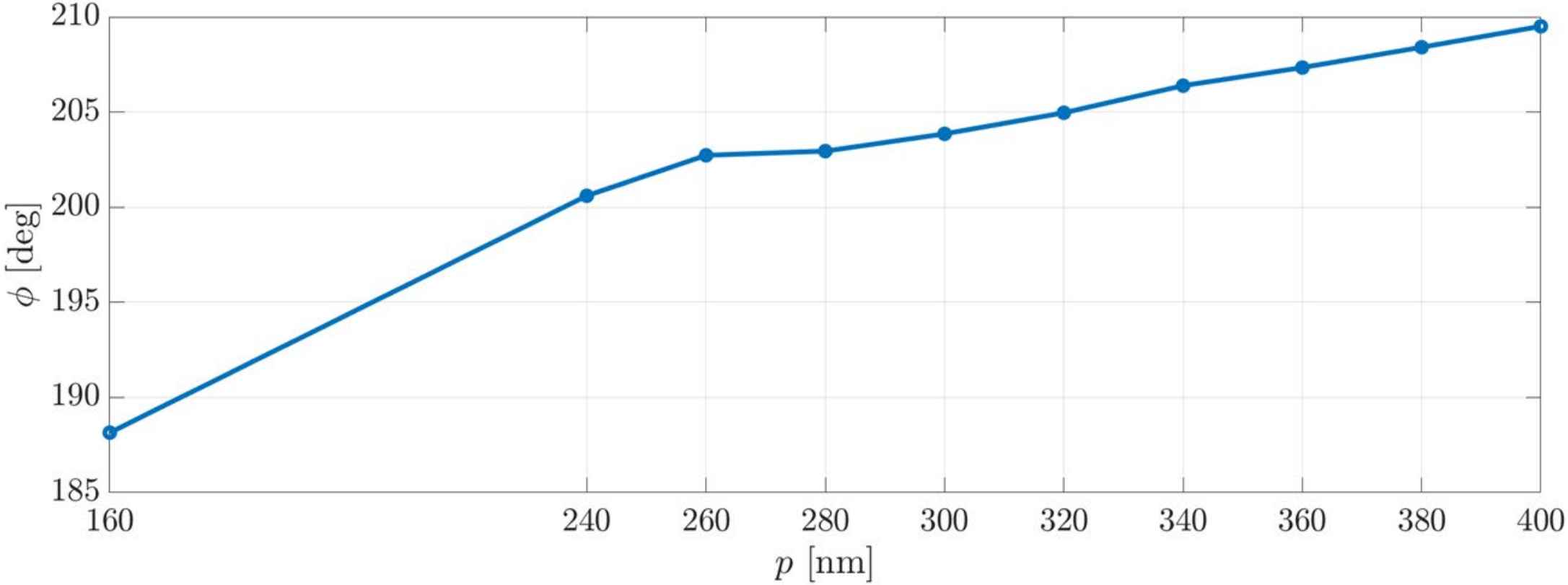


EUV Actinic Scatterometry for In-Pattern Phase Metrology
BACUS, Monterey 2023

$\lambda = 13.5\text{nm}, \theta = 6^\circ$
Horizontal L=S
aPSM Absorber
Standard Multilayer

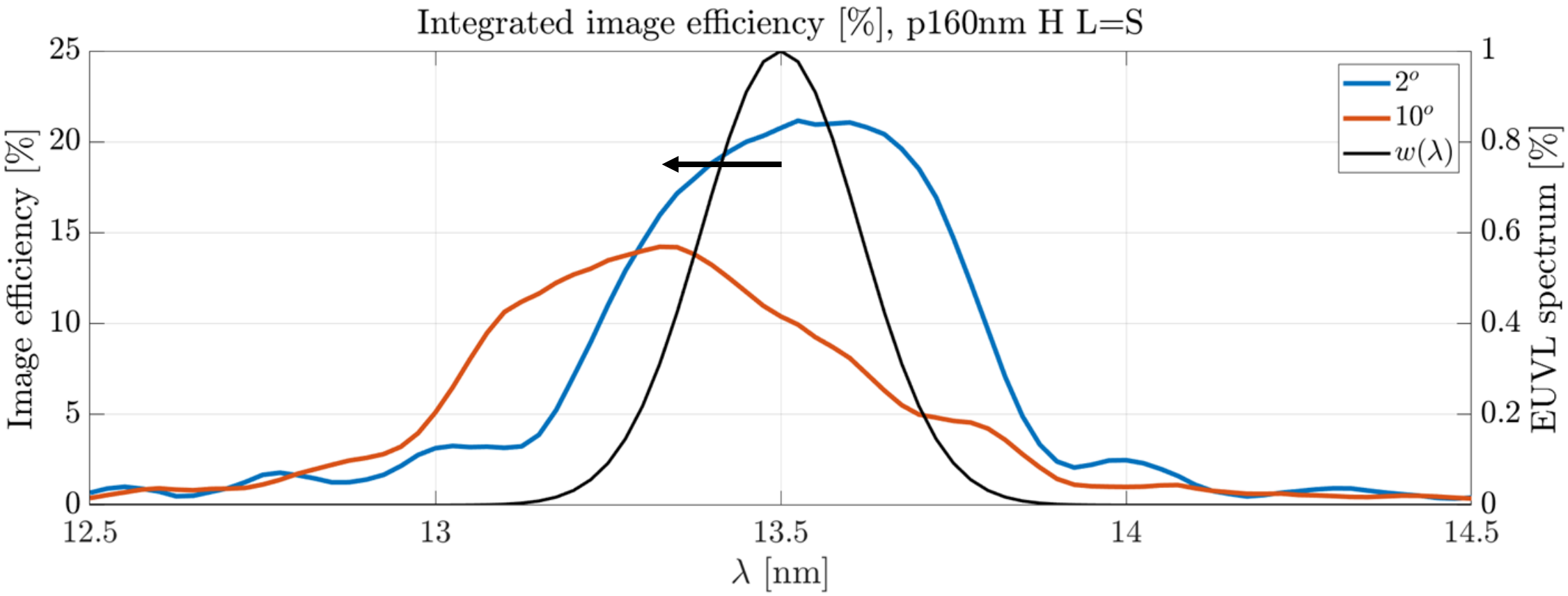
Pattern Phase on ENK: Phase Trend vs Pitch

ENK measured phase shift vs pitch on aPSM → ENK can measure phase, including M3D effects.



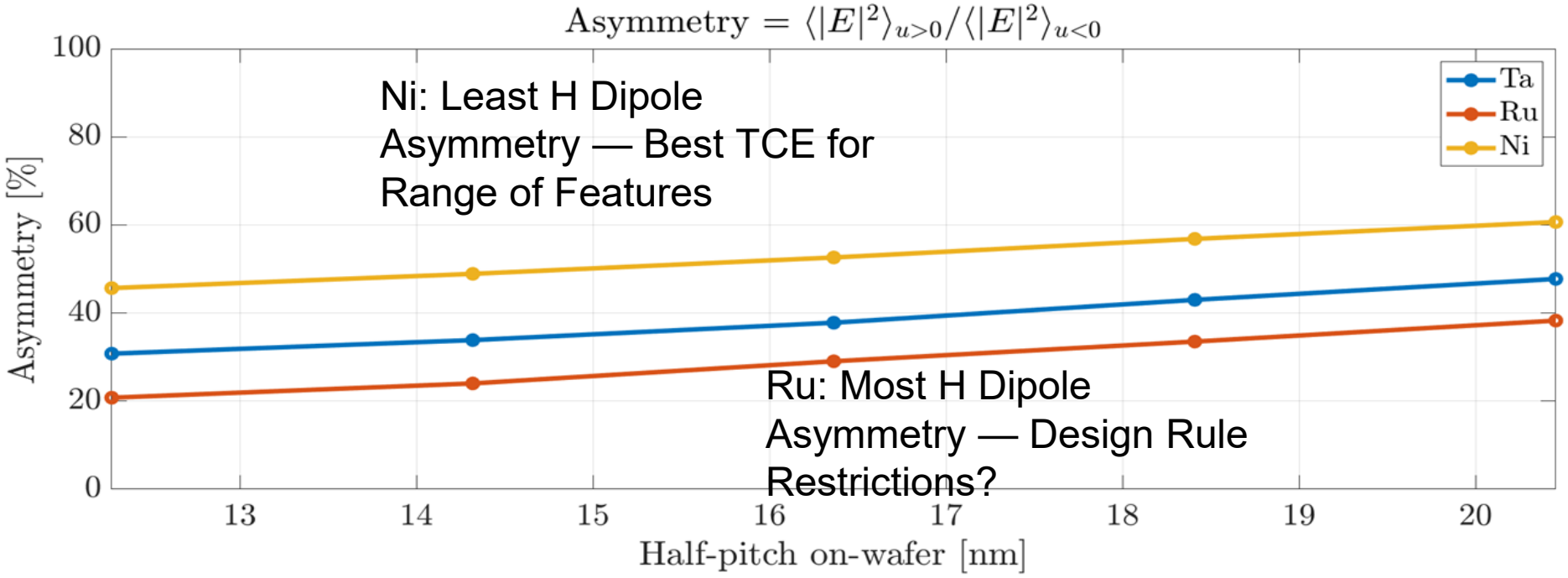
Spectral Efficiency of H Dipole on ENK

ENK measured image efficiency spectra at 2^o vs 10^o → ENK can measure M3D spectral shifts.



H Dipole Asymmetry [0.33 NA, Standard Multilayer]

Ni high-k absorber symmetric H dipole efficiency—minimum TCE, less design restrictions.

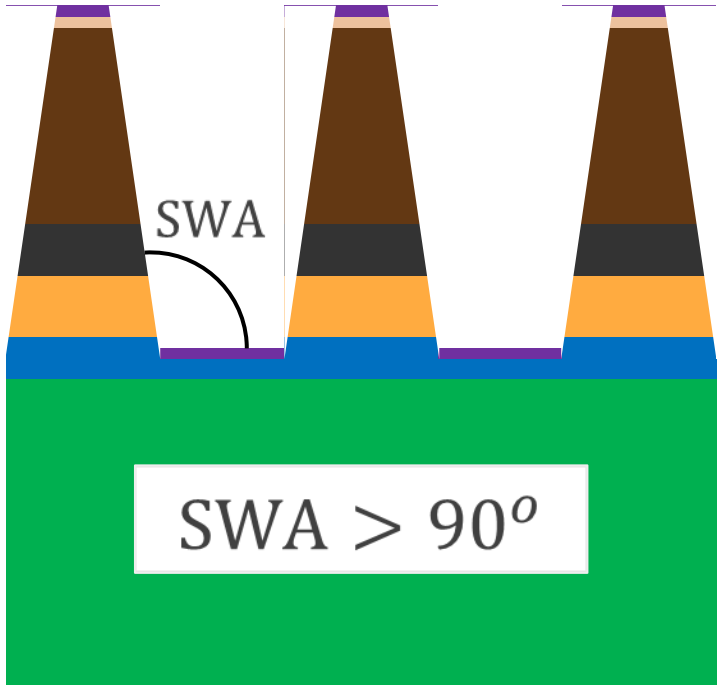


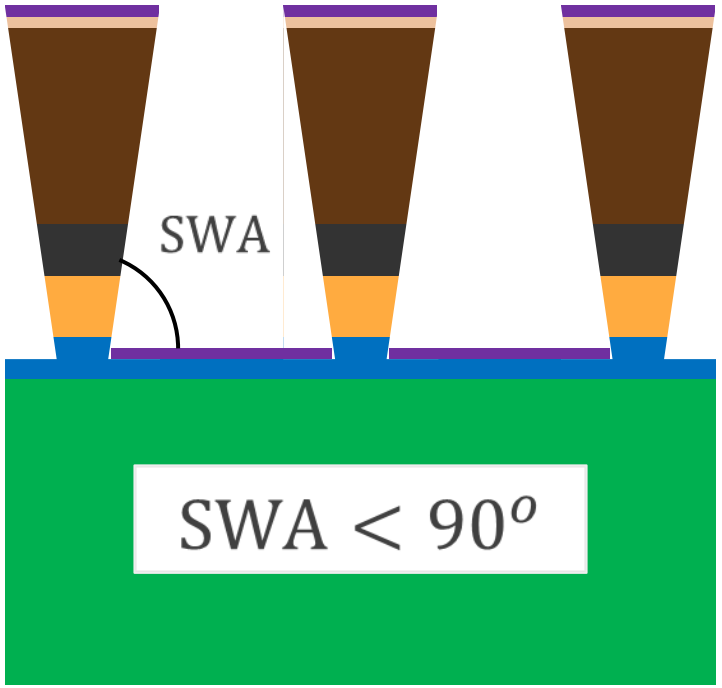
H Dipole, 12.5% PFR
0.33 NA, 0.3 to 0.5 k1
2% Spectral Bandwidth
3 Absorbers
Standard Multilayer

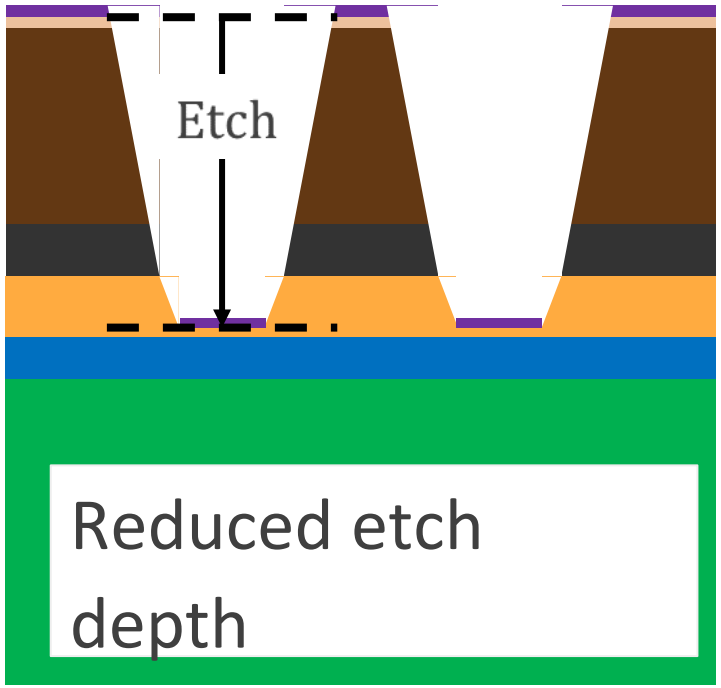
Scatterometry still necessary after reflectometry

All these gratings could come from same multilayer/absorber blank

Reflectometry sensitive to 1D, scatterometry sensitive to 3D

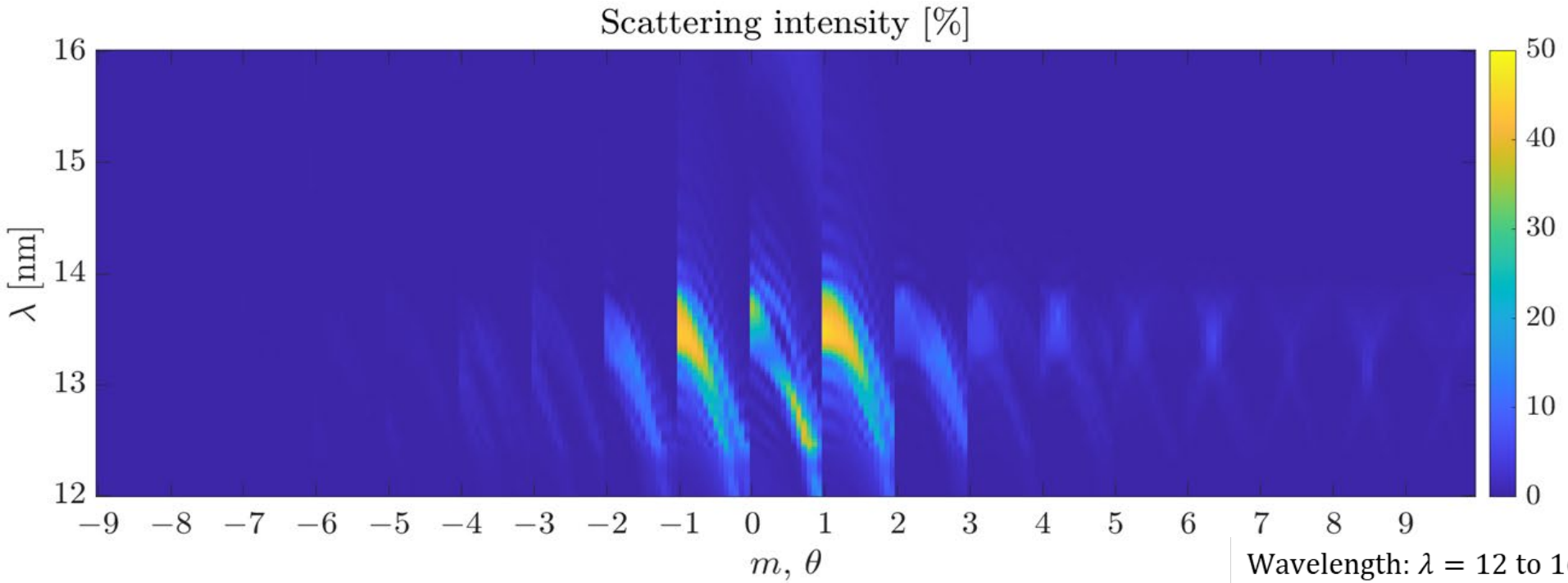






Scattering intensity for measuring 3D geometry on mask

Simulation of Ru aPSM, p200nm, L=S, H orientation over wide range of ENK measurement conditions
Approximate detection limits: CD—0.07nm; SWA—0.6deg; Absorber thickness—0.01nm



Wavelength: $\lambda = 12$ to 16nm, $\Delta\lambda = 0.025$nm
Angle: $\theta = 2$ to 30^o, $\Delta\theta = 2^o$
Diffraction order: $m = -9$ to 9

Internal tool available at EUV Tech R&D facility for partner/customer measurements

- EUV n and k measurements of both mask and patterning materials
- Film thickness and roughness measurements
- Angle and wavelength dependent phase measurements
- Scatterometry measurements of pattern phase

Summary

- Phase shift masks provide important benefits
- Phase is not adequately captured by a single value, wavelength and angle dependence also critical
  - EUV phase rapidly evolves through angle and wavelength
- EUV phase highly sensitive to thin film effects
  - As deposited film properties are critical
- Pattern phase can deviate significantly from film phase
- EUV reflectometry and scatterometry uniquely suited to measuring all these effects

References

1. Stuart Sherwin, Matt Hettermann, Dave Houser, Patrick Naulleau “Understanding and Measuring EUV Mask 3D Effects”, SPIE Advanced Litho 2024
2. Stuart Sherwin, Eric Gullikson, Matt Hettermann, Dave Houser, Chami Perera, Patrick Naulleau, “EUV phase monitoring applications with actinic reflectometry,” Proc. SPIE PC12494, Optical and EUV Nanolithography XXXVI, (30 April 2023)
3. Stuart Sherwin "Actinic EUV reflectometry and scatterometry: from national lab to commercial applications", Proc. SPIE PC12292, International Conference on Extreme Ultraviolet Lithography 2022, PC122920P (11 November 2022)
4. Stuart Sherwin, Ryan Miyakawa, Eric Gullikson, Laura Waller, Andrew Neureuther, Patrick Naulleau, “EUV phase scatterometry with linearized rigorous scattering,” SPIE Advanced Lithography + Patterning, San Jose, CA, April 24-28, 2022
5. Stuart Sherwin, Isvar Cordova, Ryan Miyakawa, Markus Benk, Laura Waller, Andrew Neureuther, Patrick Naulleau, “Picometer sensitivity metrology for EUV absorber phase,” J. of Micro/Nanopatterning, Materials, and Metrology, 20(3), 031011 (2021).
6. Stuart Sherwin, Laura Waller, Andrew Neureuther, Patrick Naulleau, “Linearized scatterometry for detecting EUV phase deviations,” 2021 EUVL Workshop, online, Leuven, Belgium, June 5-10, 2021.
7. Stuart Sherwin, Isvar Cordova, Ryan Miyakawa, Laura Waller, Andrew Neureuther, Patrick Naulleau, “Picometer sensitivity metrology for EUV absorber phase,” Proc. SPIE 11517, 1151707 (2020).
8. S. Sherwin, I. Cordova, L. Waller, A. Neureuther, P. Naulleau, “Measuring the phase of euv photomasks,” Proc. SPIE 11147, 111471F (2019).

Thank You

euvtech

2830 Howe Road, Suite A, Martinez, CA 94553
+1 (925) 229-4388 | euvtech.com