Understanding and measuring deterministic and stochastic phase in the realm of EUV patterning

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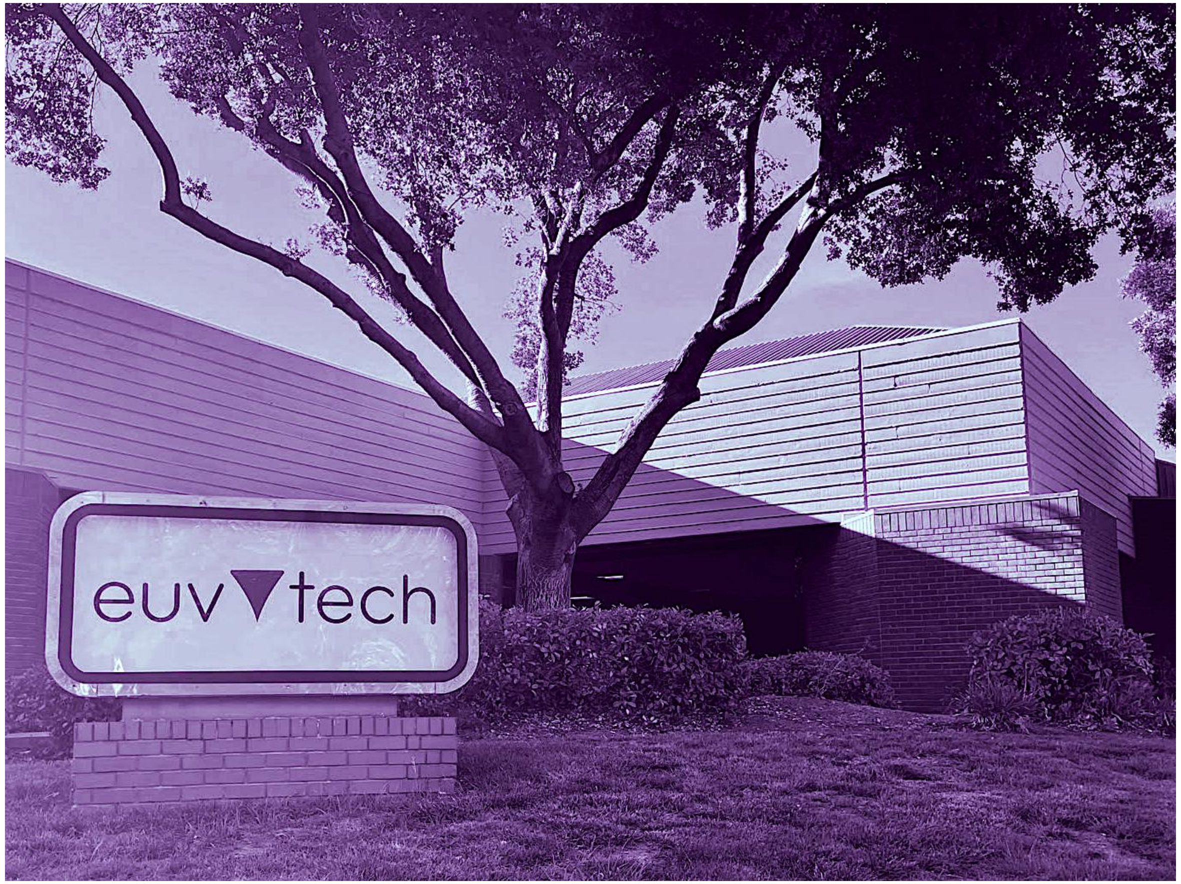
Agenda

Section 1: Why actinic metrology

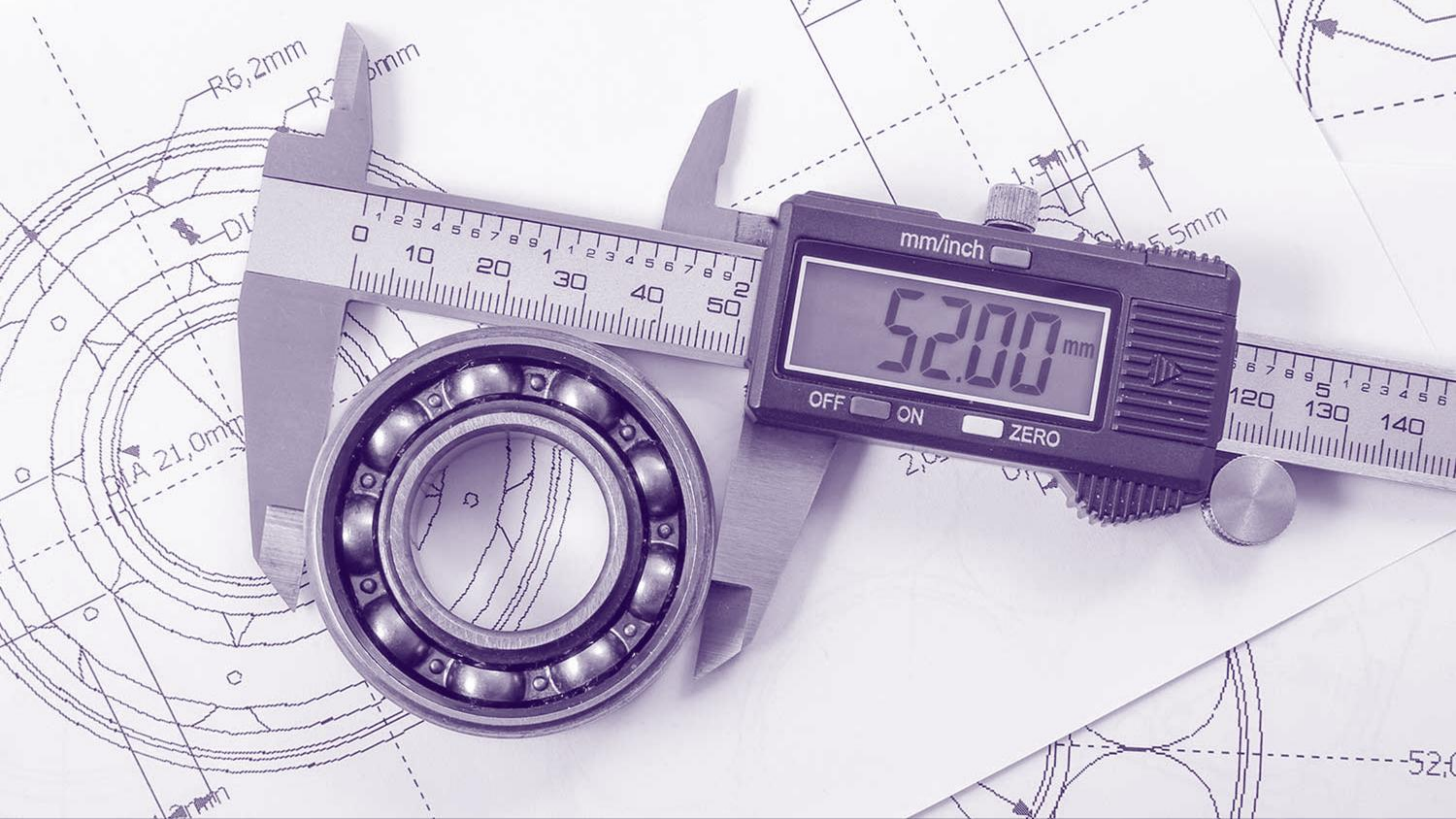
Section 2: Controlling phase in the EUV regime

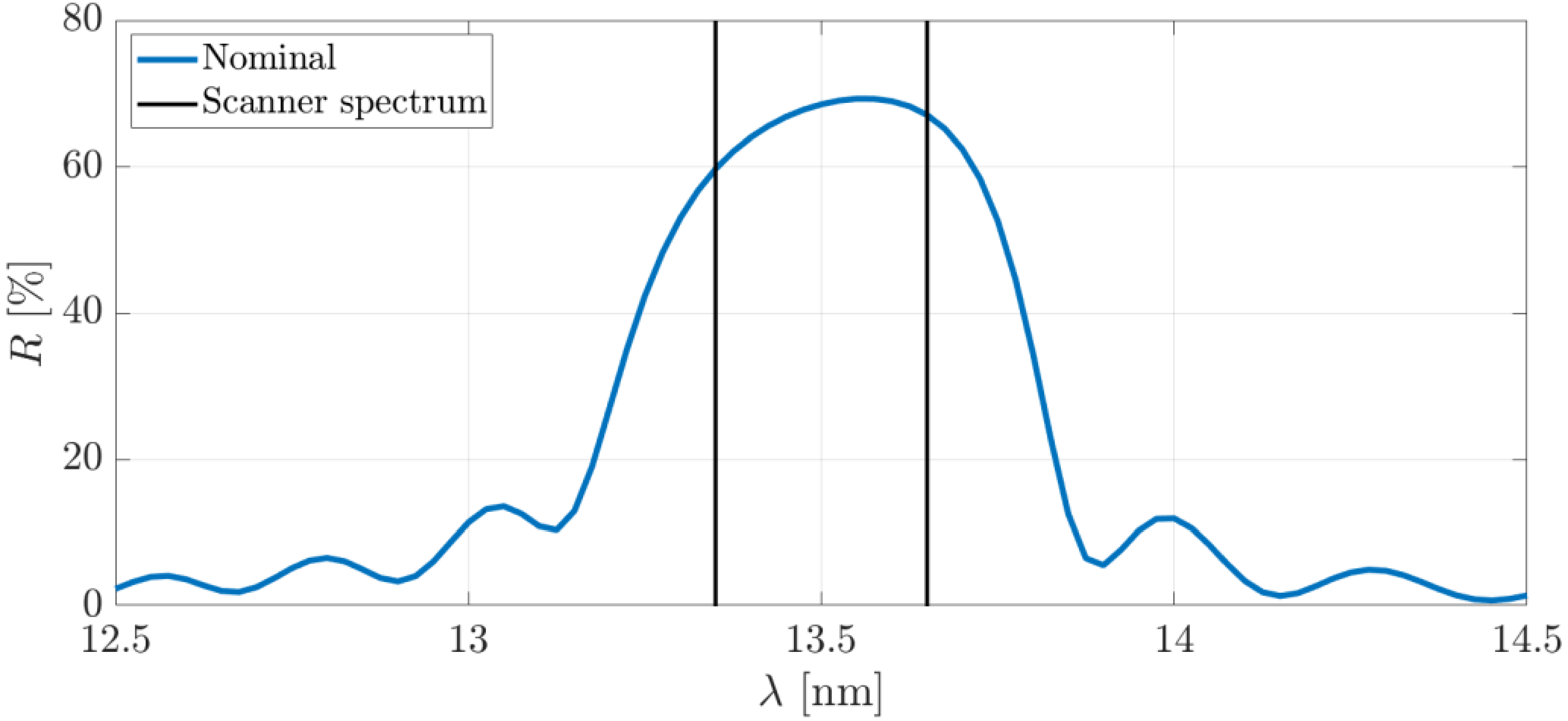
Section 3: EUV mask phase stochastics

EUV Tech: Proven Leader in Actinic Metrology

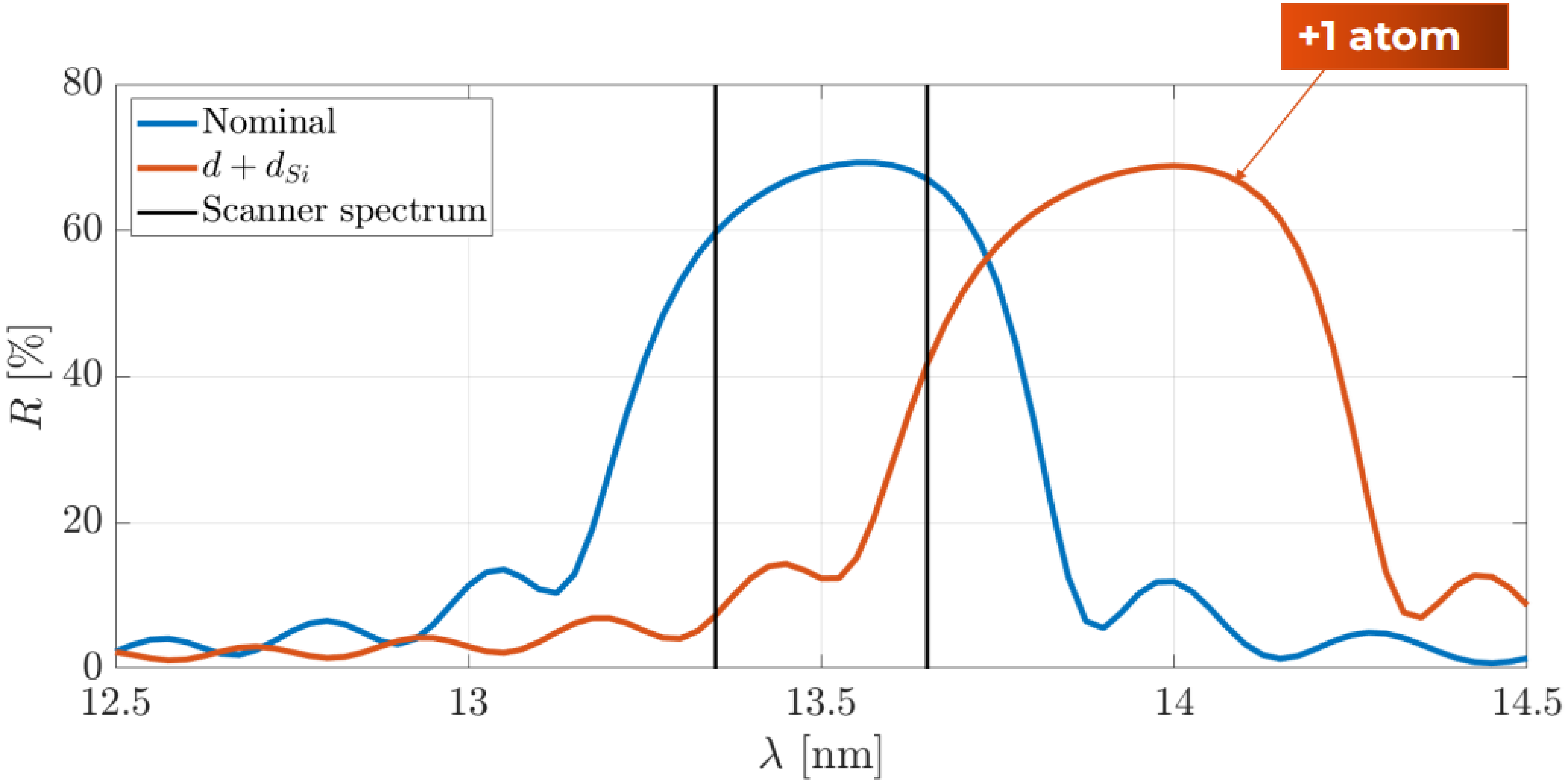


- Founded in 1997
- Headquartered in San Francisco Bay Area, California
- Technology driven organization born from Lawrence Berkeley National Laboratory
- Global leader in the development and production of at-wavelength EUV metrology tools
- Critical tool supplier in EUV mask space and process of record for all EUV mask blanks

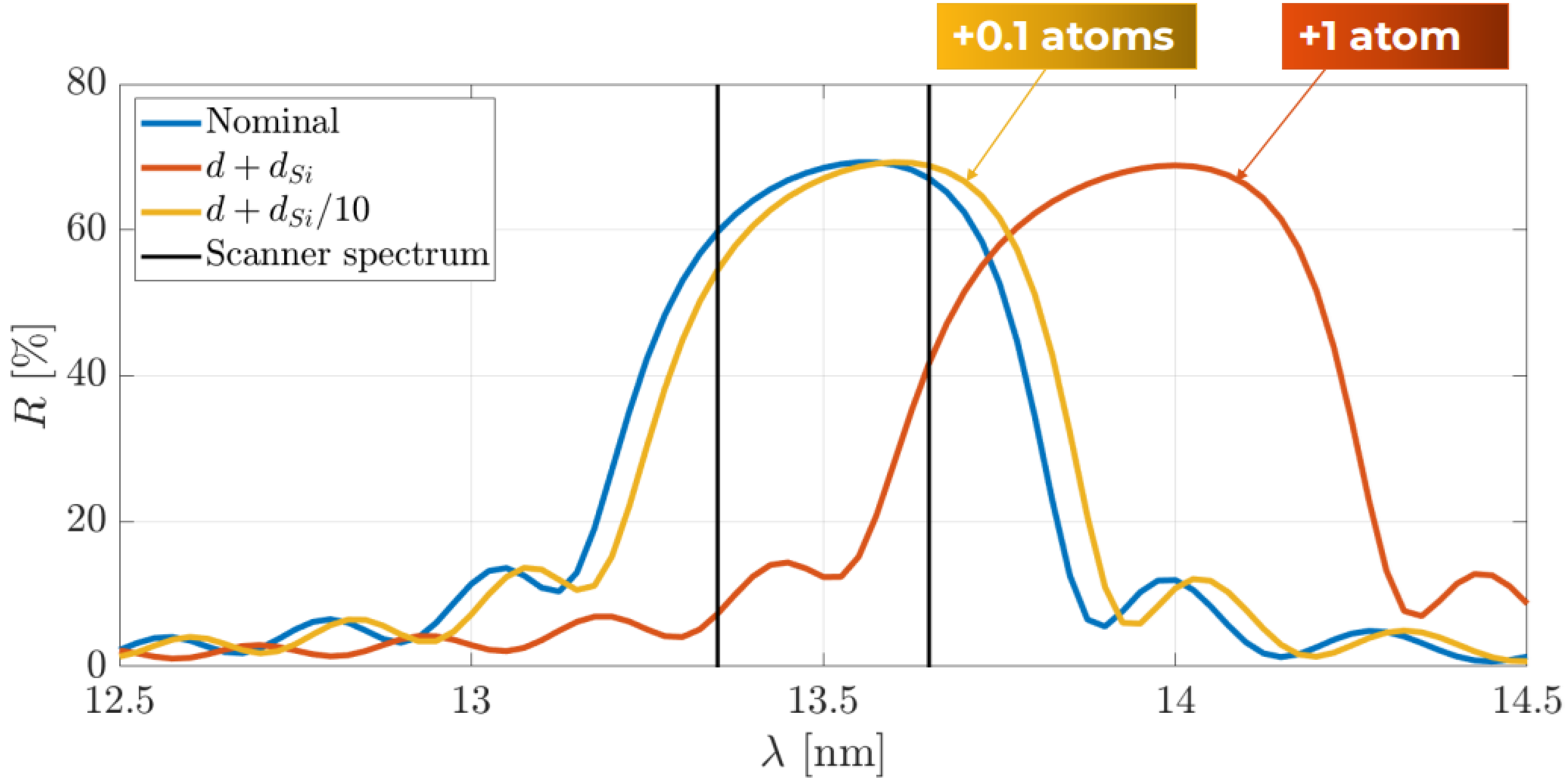

R6,2mm
mm/inch
52.00 mm
OFF
ON
ZERO
5.5mm



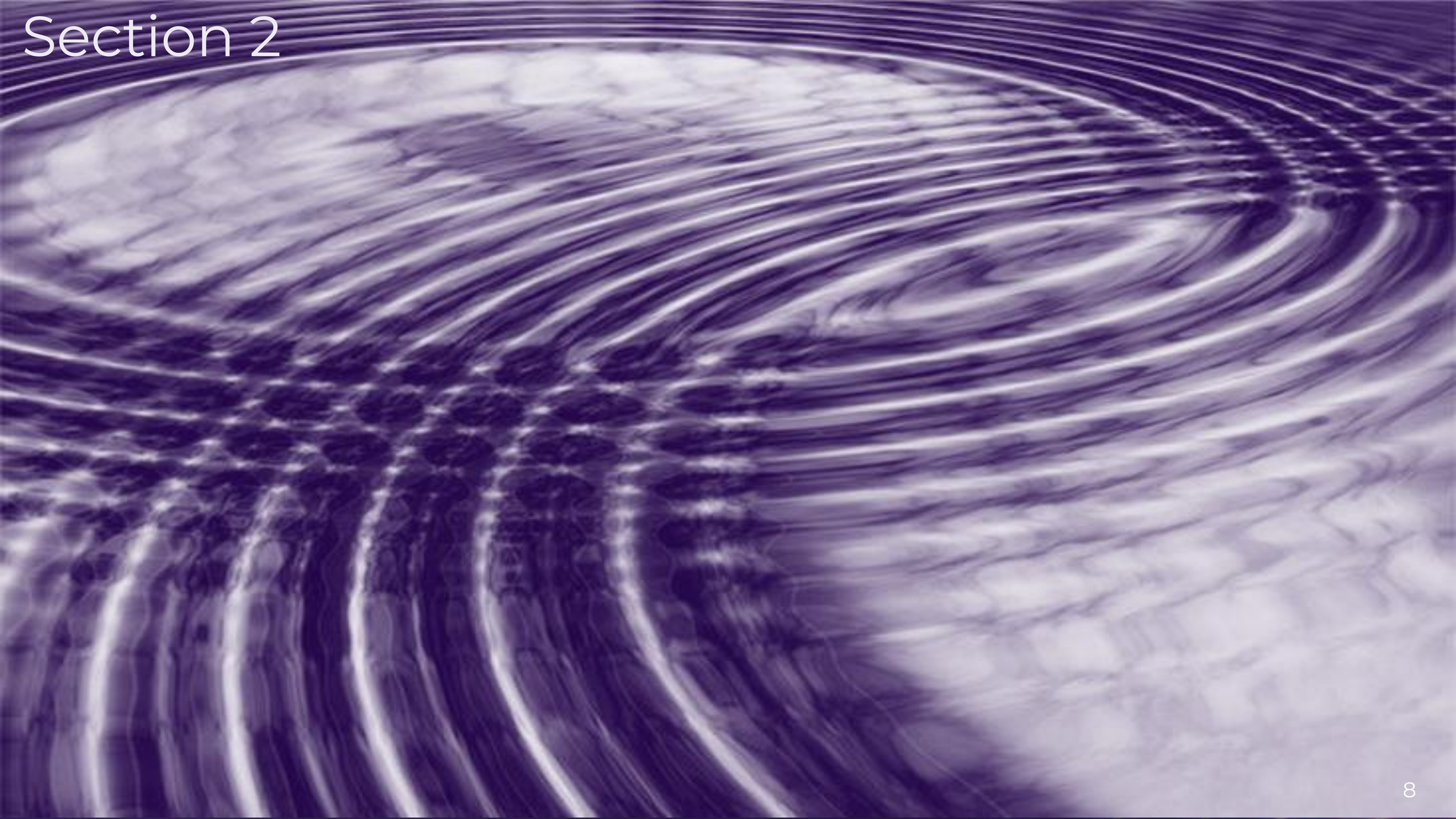
80
60
40
20
0
R [%]
Nominal
Scanner spectrum
12.5
13
13.5
14
14.5
λ [nm]



+1 atom
Nominal
$d + d_{Si}$
Scanner spectrum
80
60
40
20
0
R [%]
12.5
13
13.5
14
14.5
λ [nm]

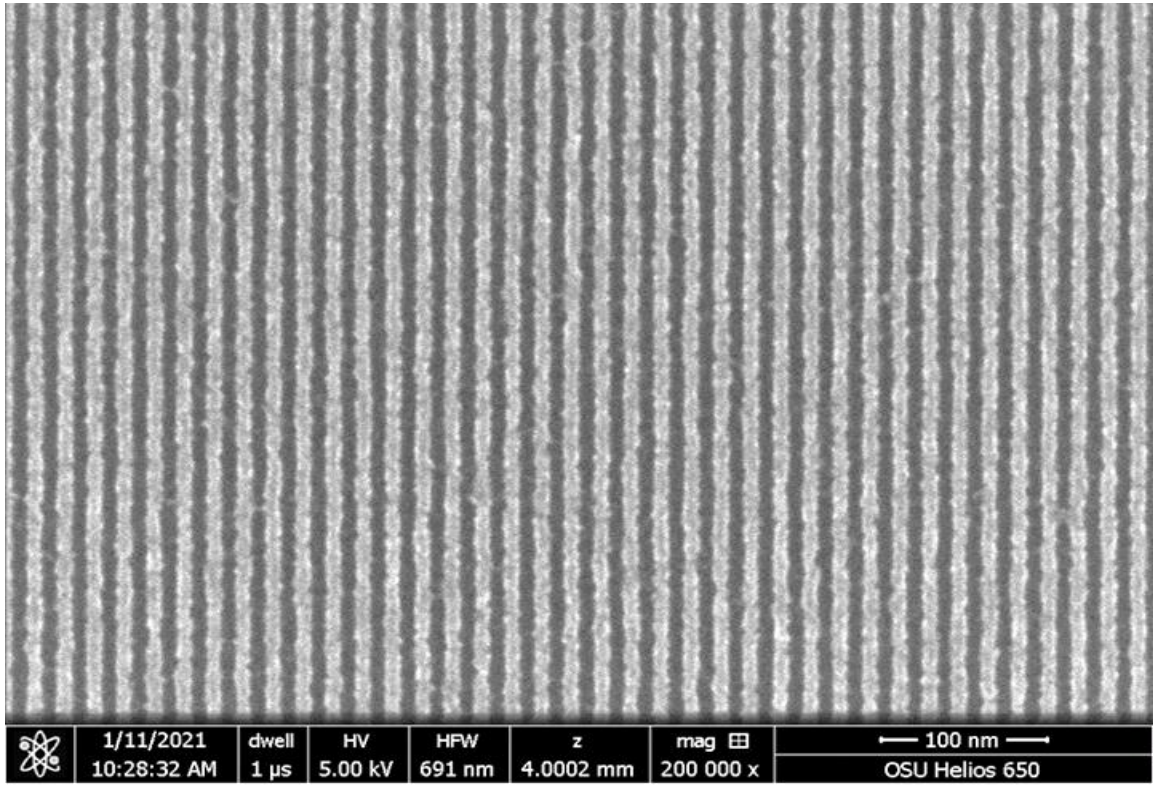

+0.1 atoms
+1 atom
Nominal
$d + d_{Si}$
$d + d_{Si}/10$
Scanner spectrum
R [%]
λ [nm]
80
60
40
20
0
12.5
13
13.5
14
14.5

Section 2

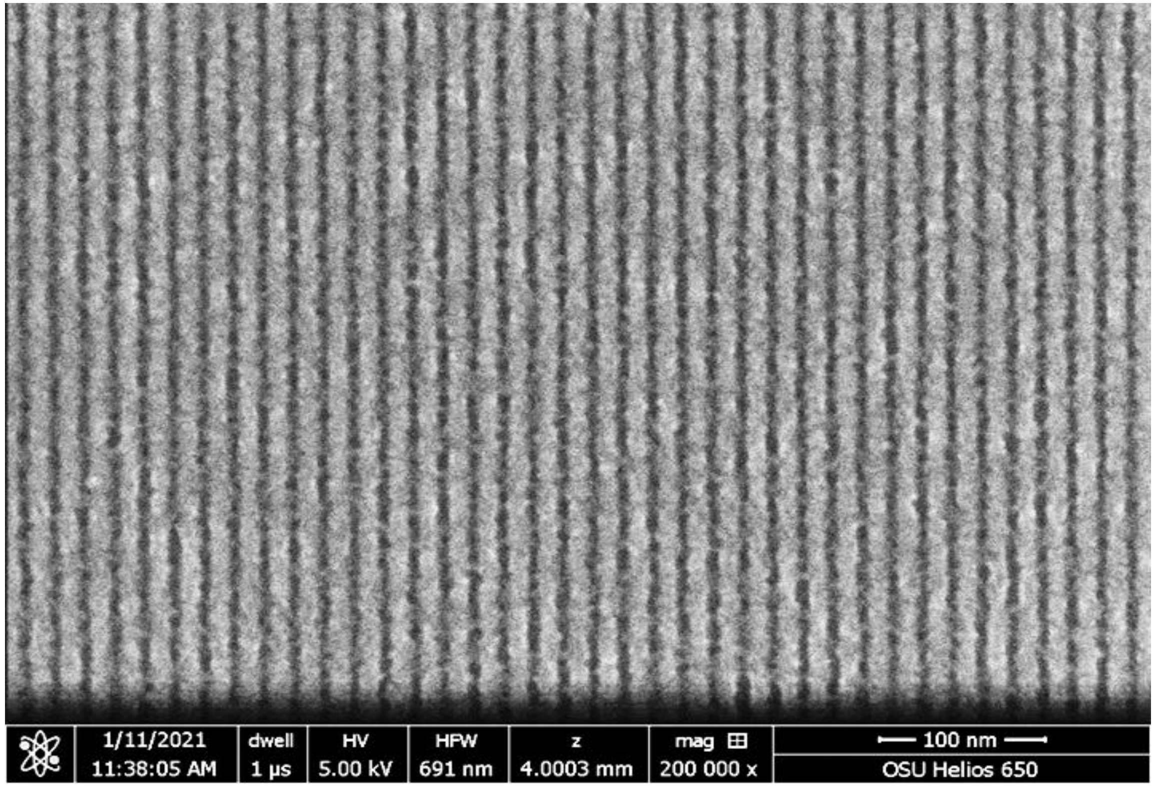


EUV resists set high bar for contrast/NILS

Optical contrast = 94%
NILS = 2.95



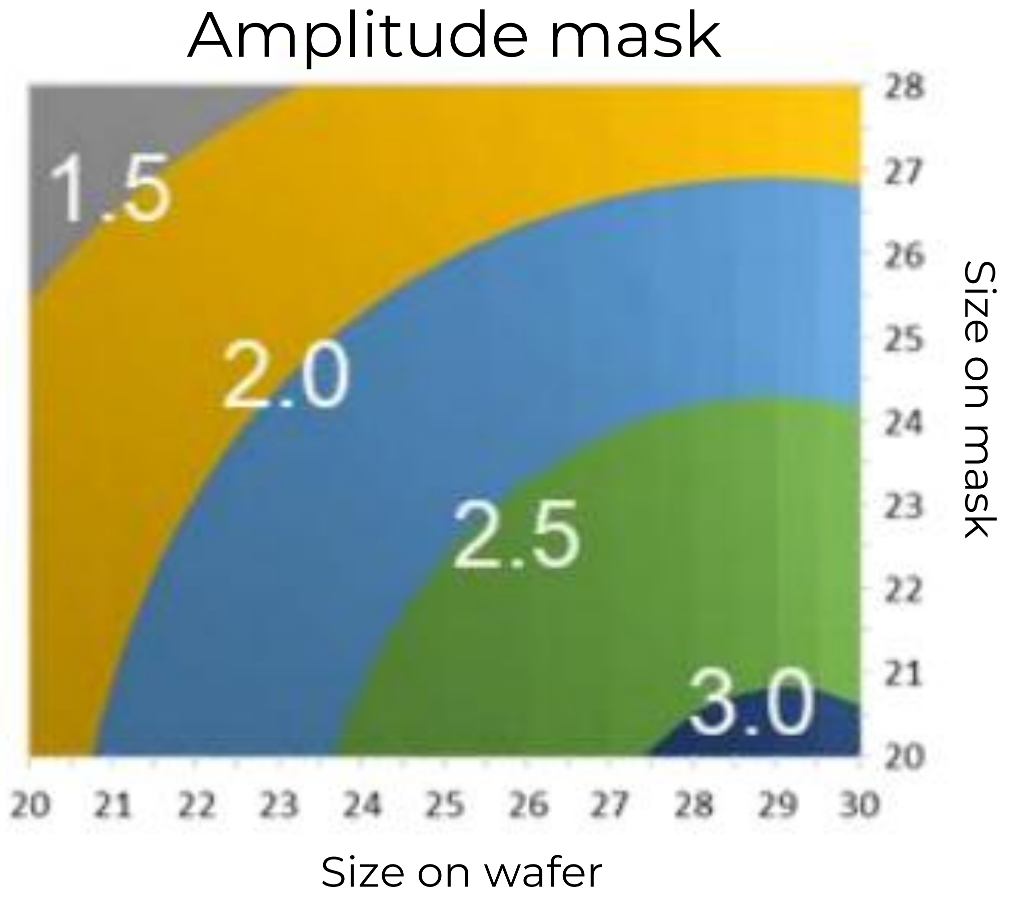
Optical contrast = 67%
NILS = 2.10

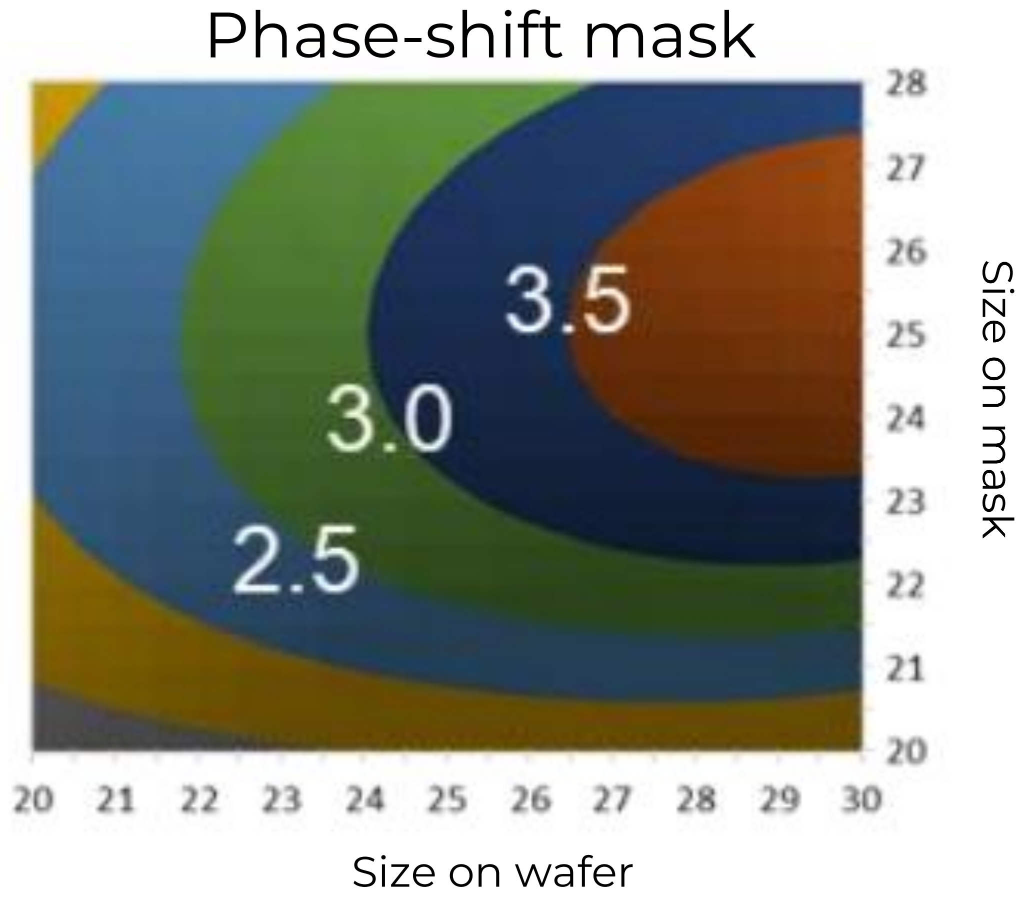


9-nm HP features in NCA resist printed on 0.5-NA tool

Phase-shift masks: proven method to optimize contrast

Phase shift provides 40% NILS (contrast) boost on 20-nm HP contacts





Chang-Nam Ahn, Dong-Seok Nam, Nakgeuon Seong, Anthony Yen, Proc. SPIE **11609**, 116090D (2021)

Phase-shift masks: proven method to optimize contrast

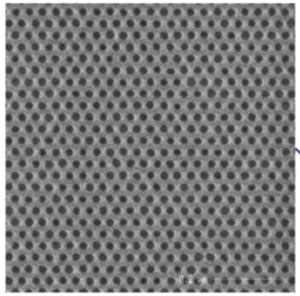
Initial experimental LCDU results: 15% reduction with low-n mask

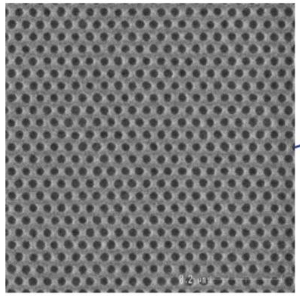
ASML

Public

HOYA

Hexagonal contact holes





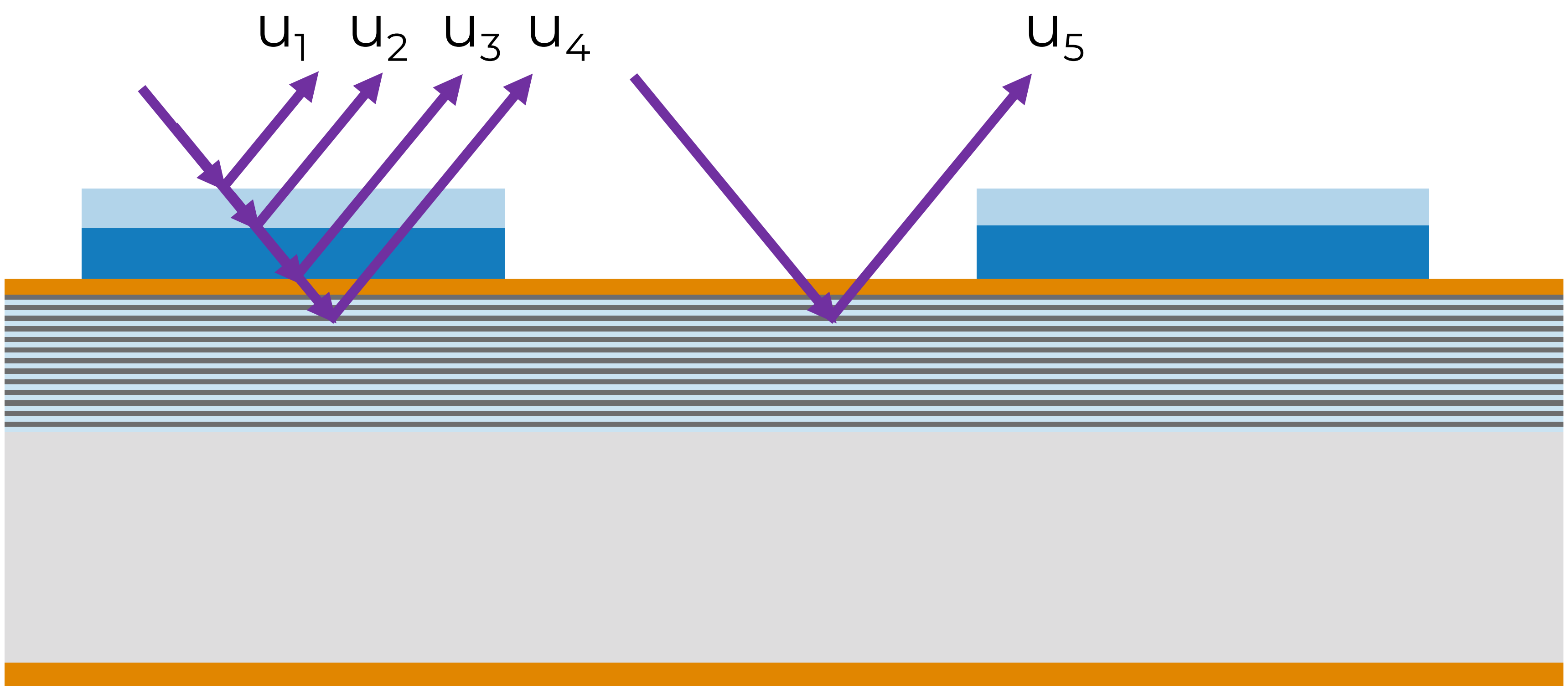
Pitch (nm)	Design mask bias (nm)	Dose (mJ/cm²)	LCDU (nm)	
			Ta mask	Low-n mask
38	3	48	3.41	2.89
40	3	48	3.09	2.63

LCDU numbers include mask contribution

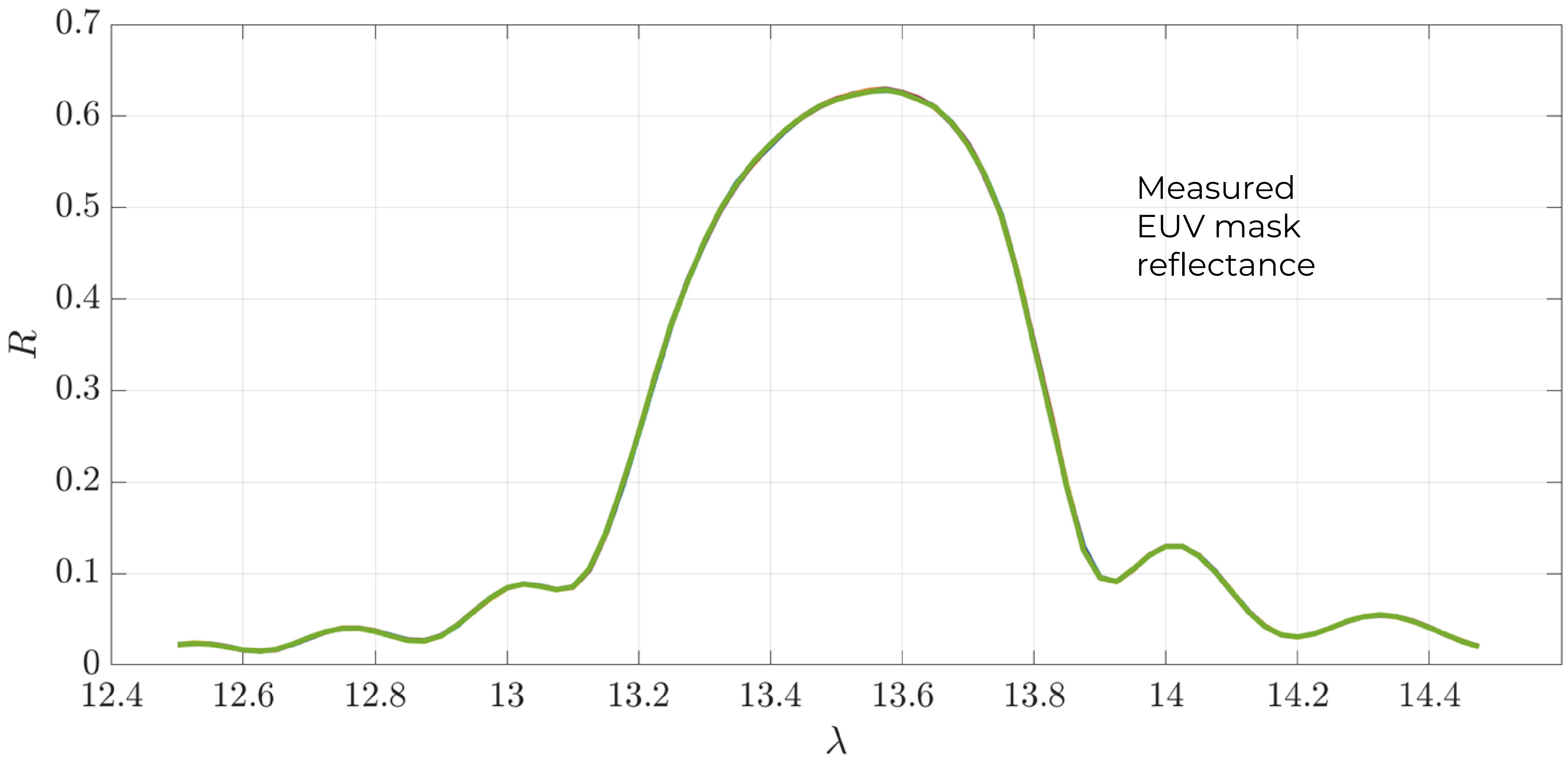
Claire van Lare, et al., Proc. SPIE 11609, 116090A (2021); https://doi.org/10.1117/12.2584725

EUV phase highly complex and dependent on wavelength and angle

$$\Delta\Psi(\theta,\lambda) = \text{phase}\{u_1(\theta,\lambda) + u_2(\theta,\lambda) + u_3(\theta,\lambda) + u_4(\theta,\lambda)\} - \text{phase}\{u_5(\theta,\lambda)\}$$

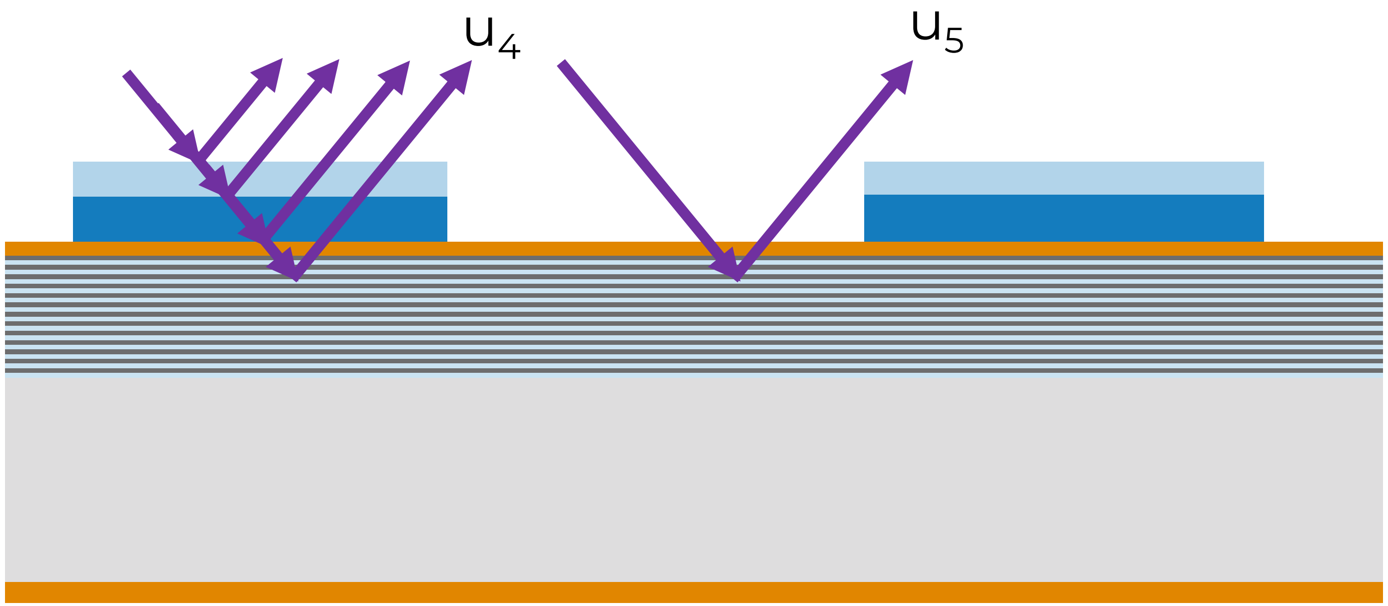


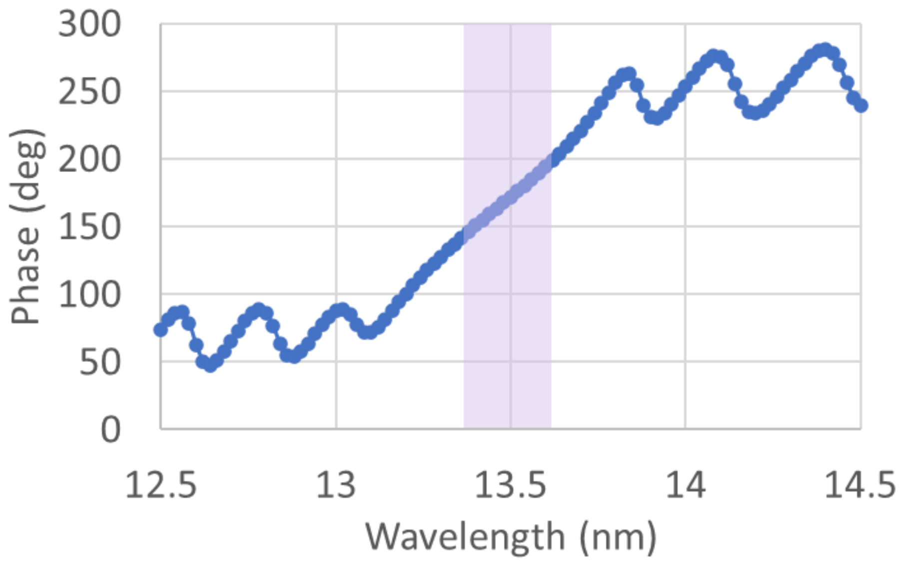
EUV is not strictly monochromatic

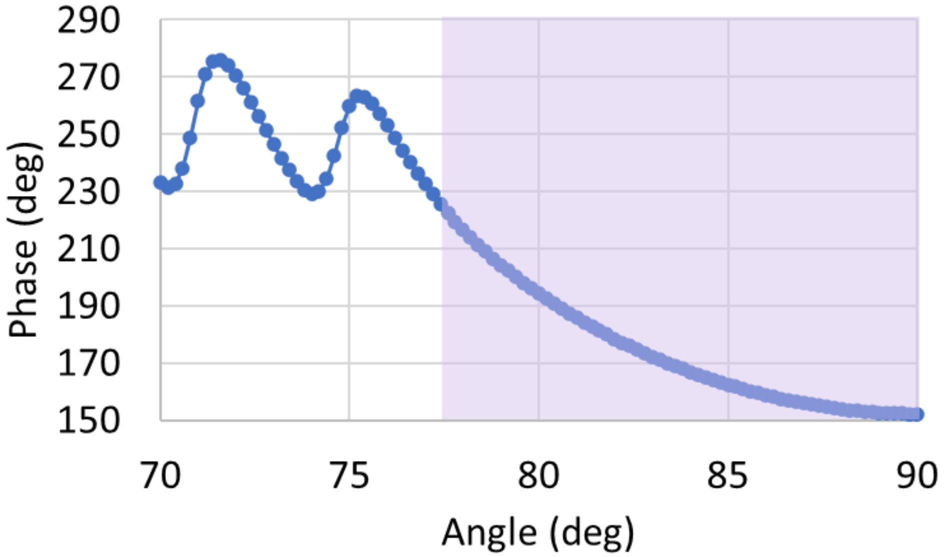


Consider the multilayer contribution

Multilayer coatings exhibit rapid phase change across Bragg peak

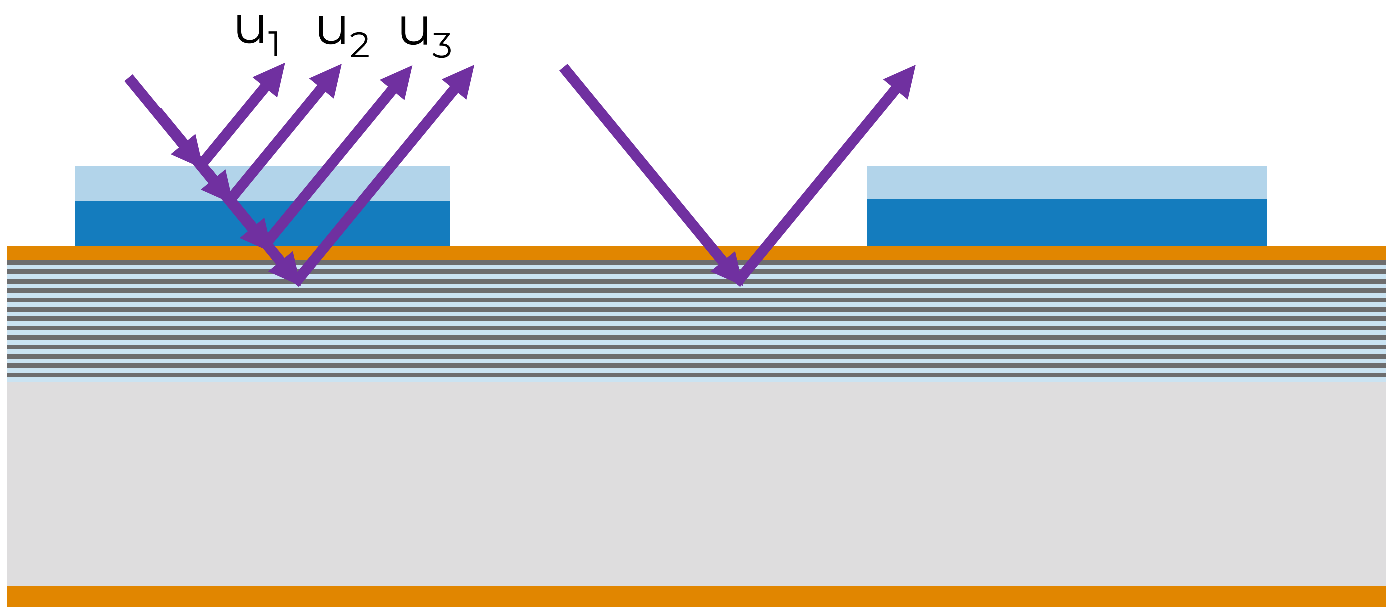


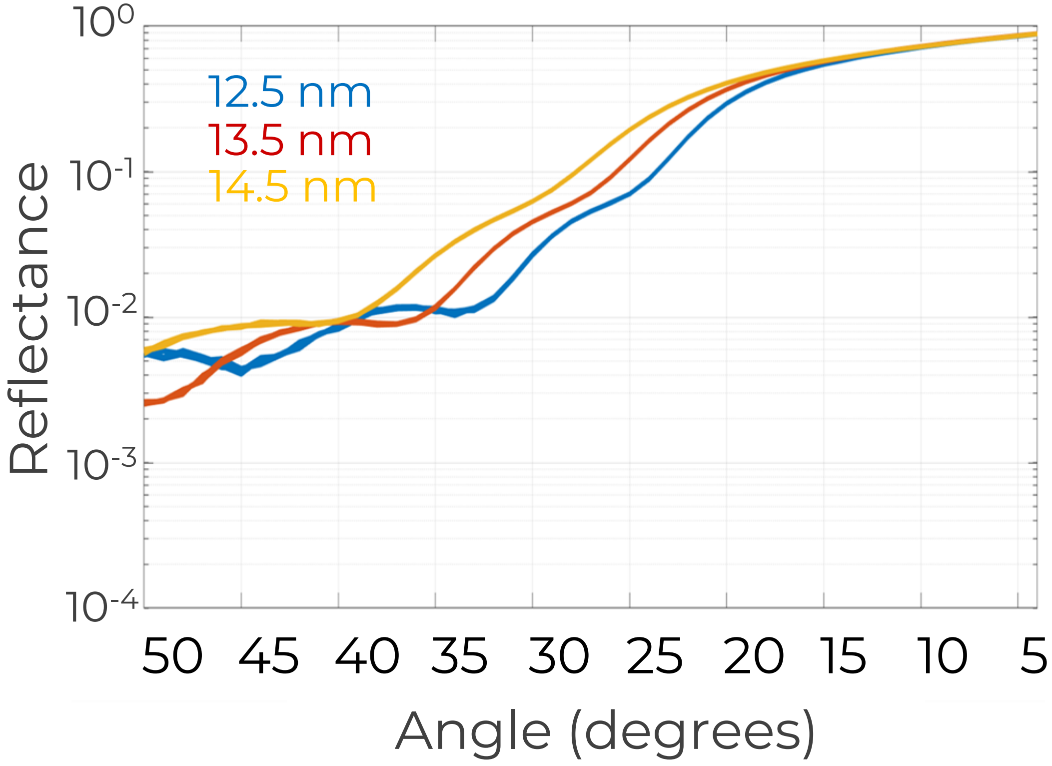




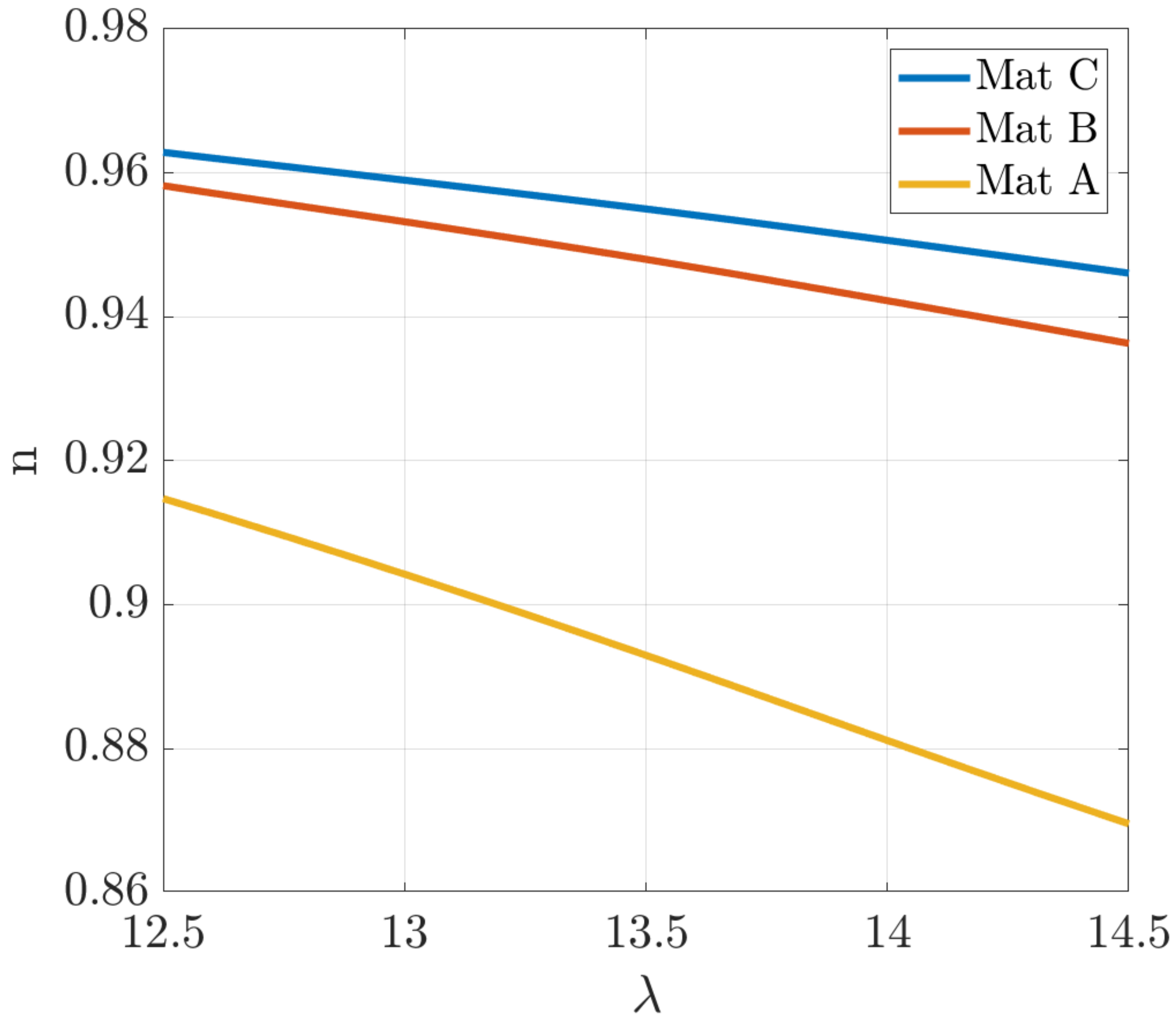
Consider the absorber contributions

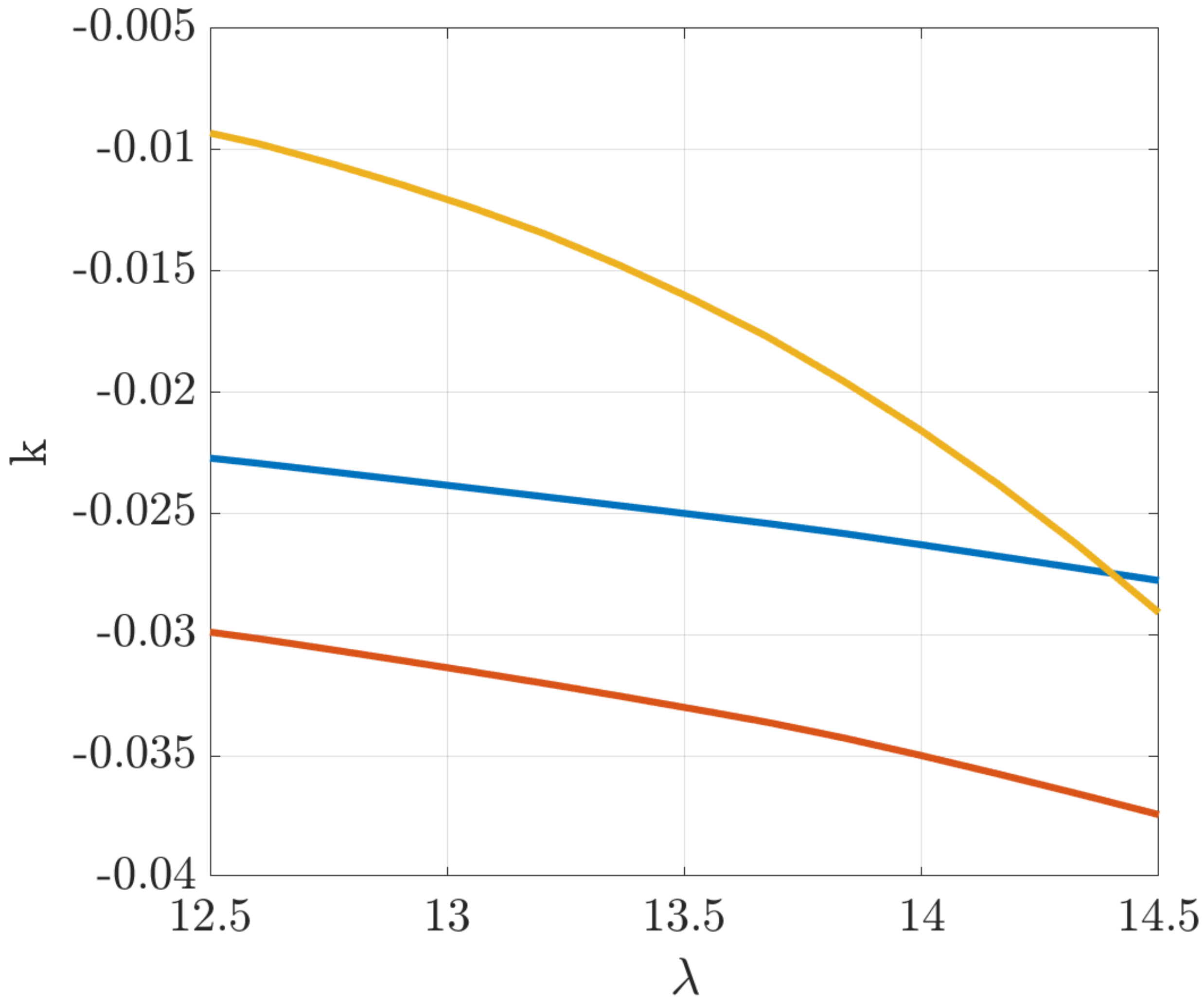
Strength of thin film terms also highly dependent on wavelength and angle





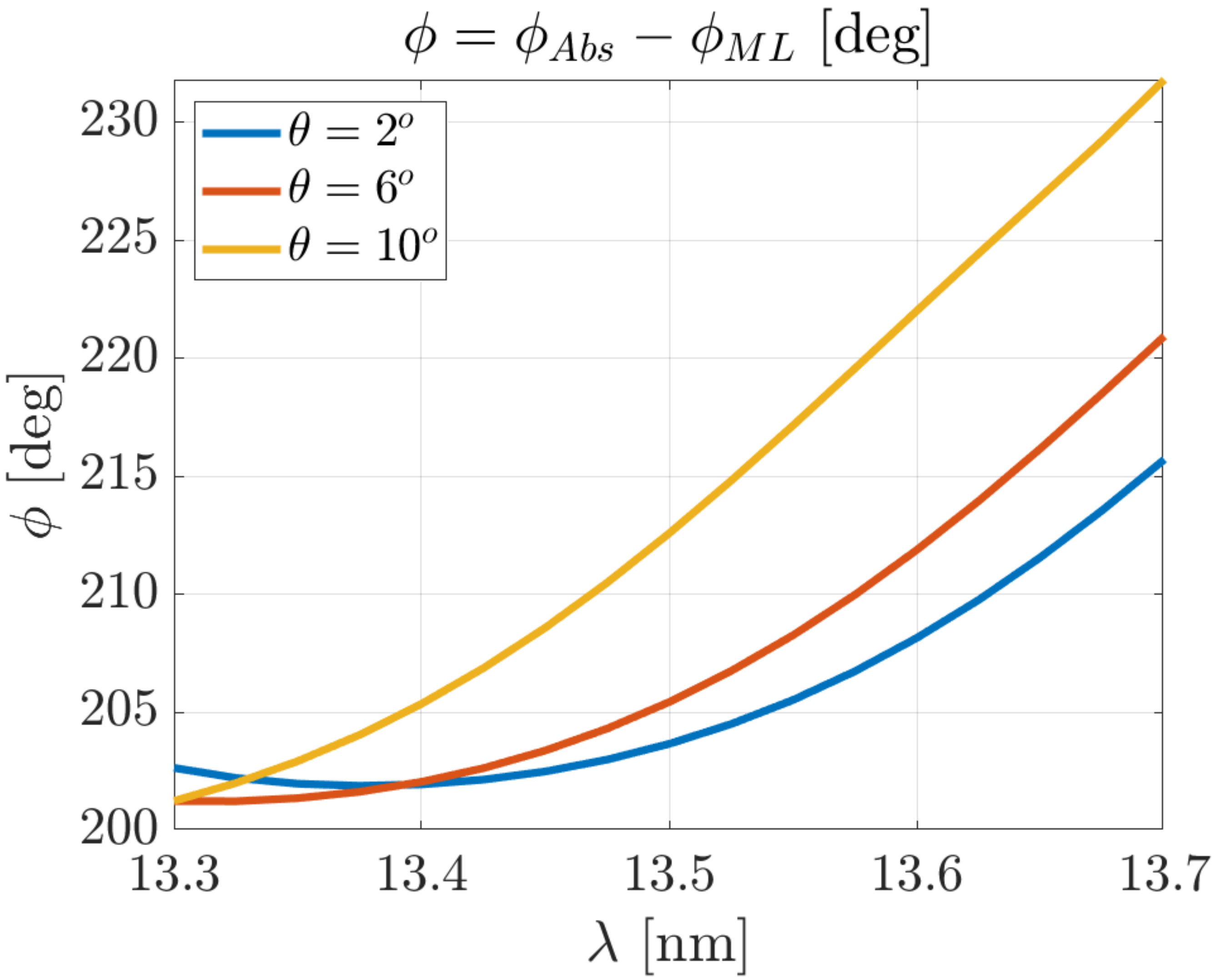
Materials dispersive in the EUV regime





Measured with EUV Tech ENK Tool

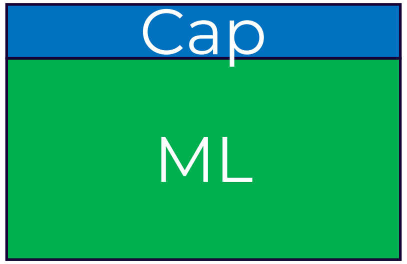
Relative phase rapidly evolving

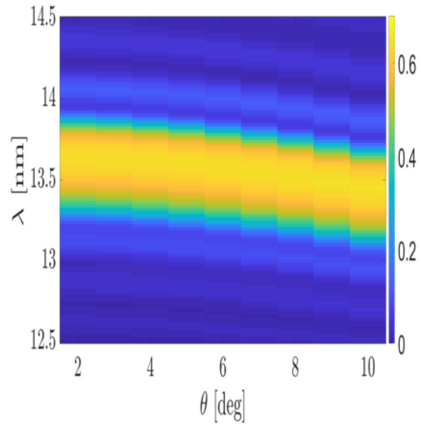


- Up to 30 degrees across passband
- Up to 15 degrees across illumination angle range

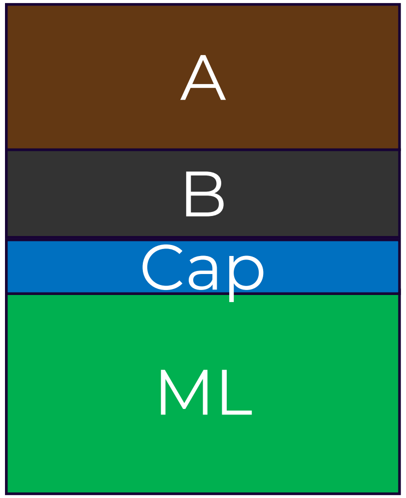
Phase measurement procedure overview

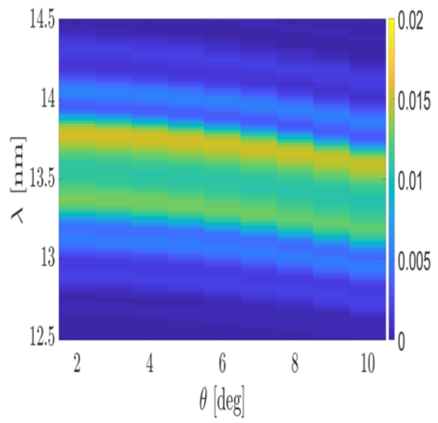
Measure λ and θ response in multilayer area



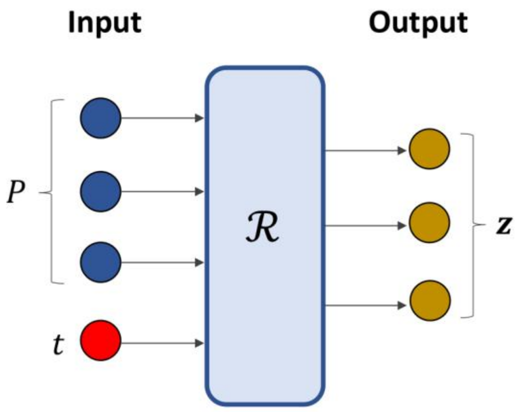


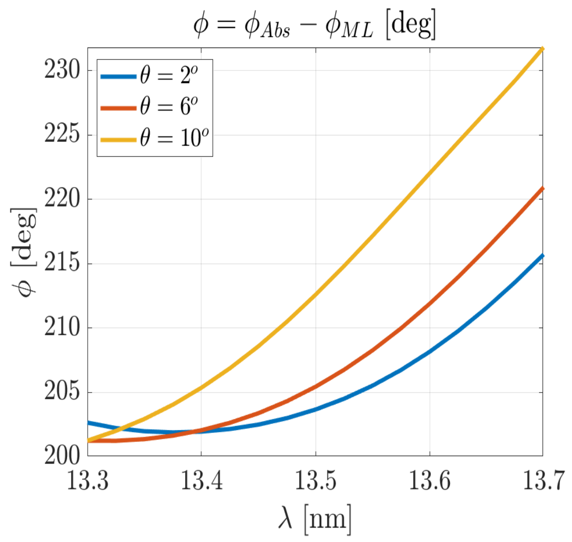
Measure λ and θ response in absorber stack area





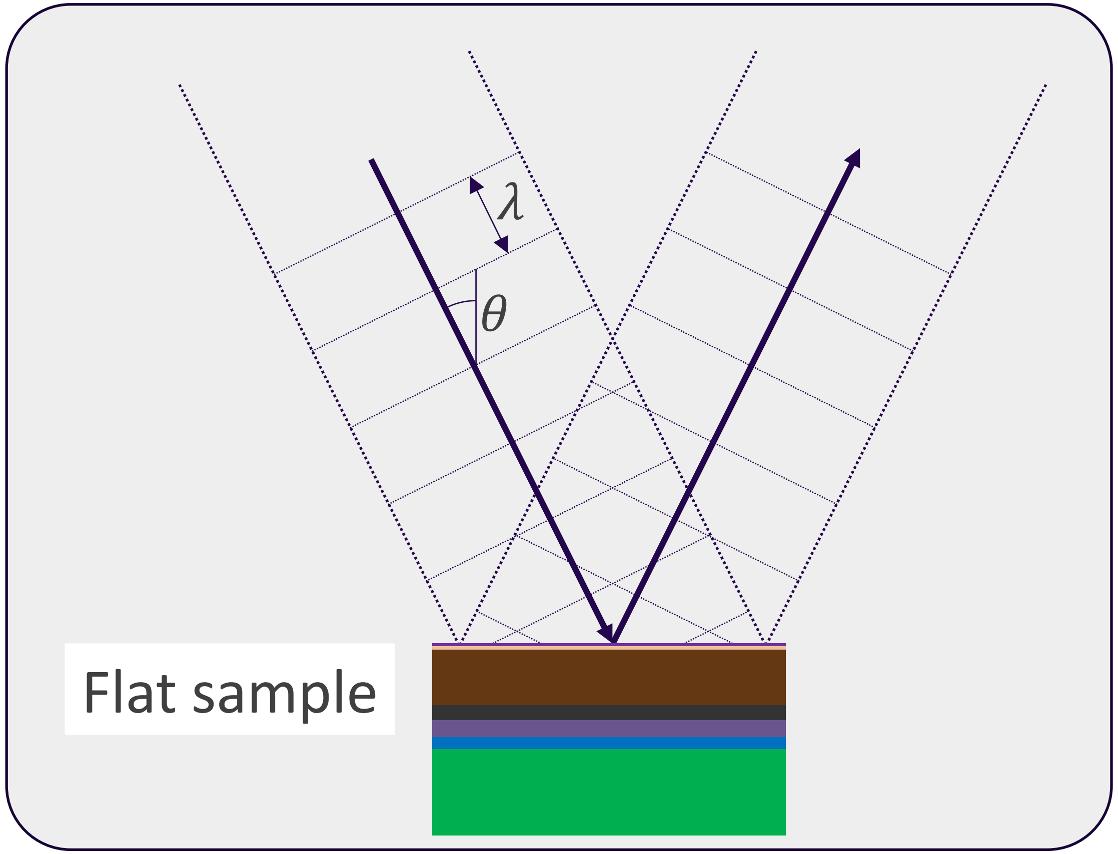
Regression determining phase from broad spectrum amplitude (angle and wavelength)



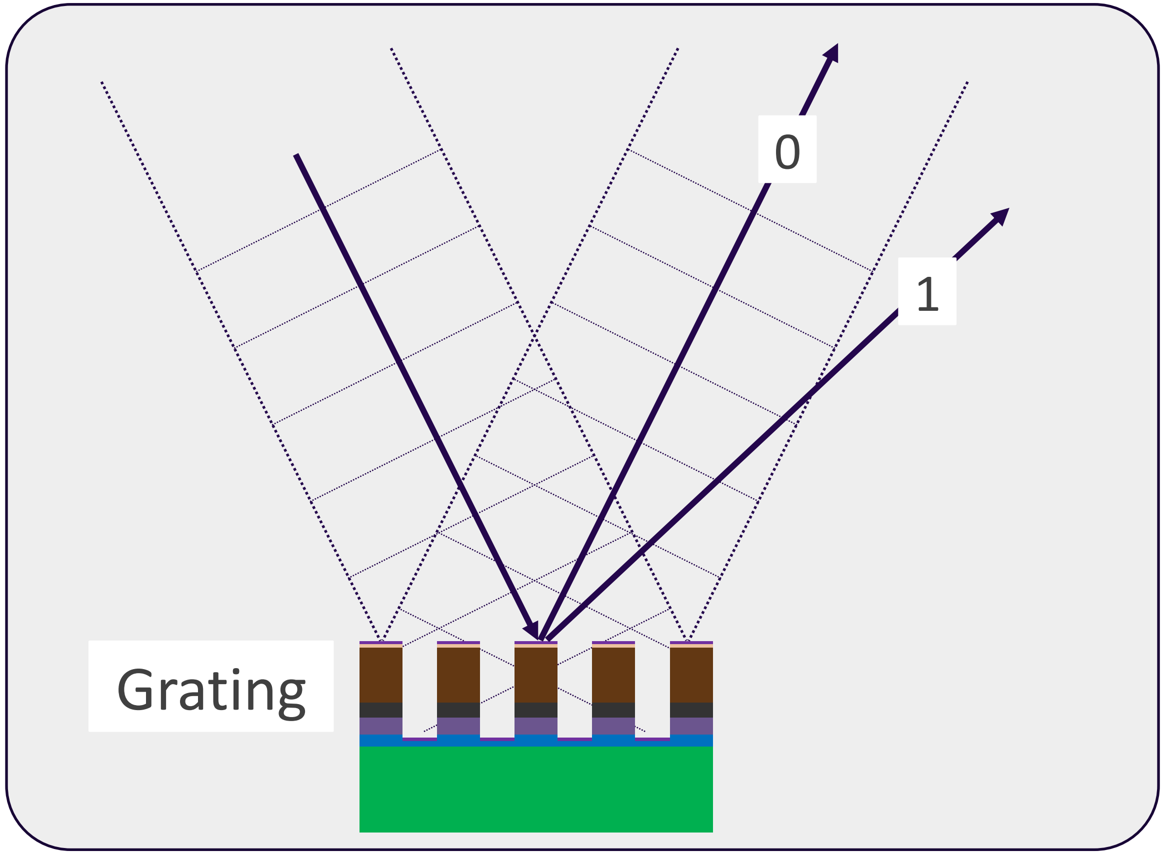


Film phase versus pattern phase

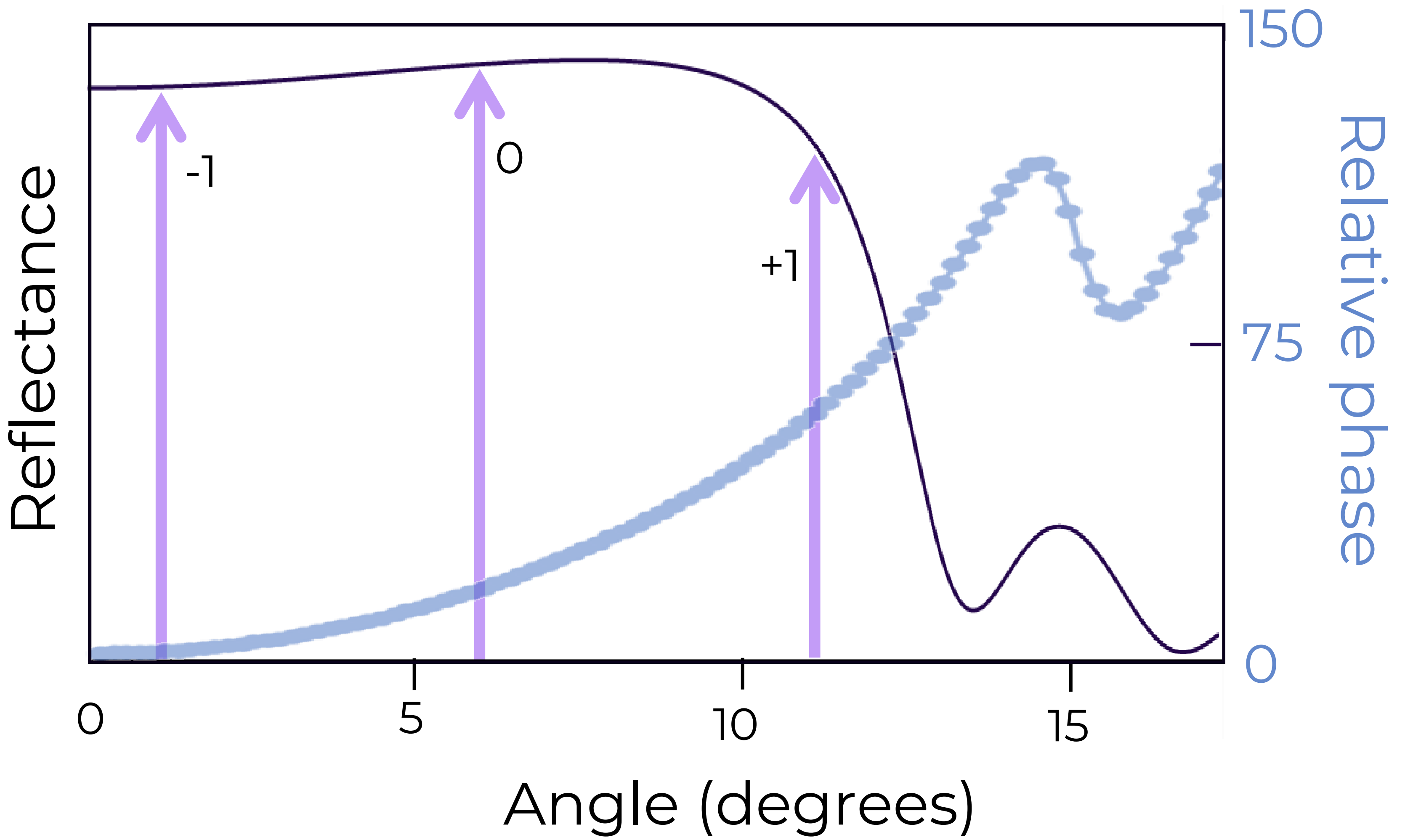
Film (Fresnel) phase

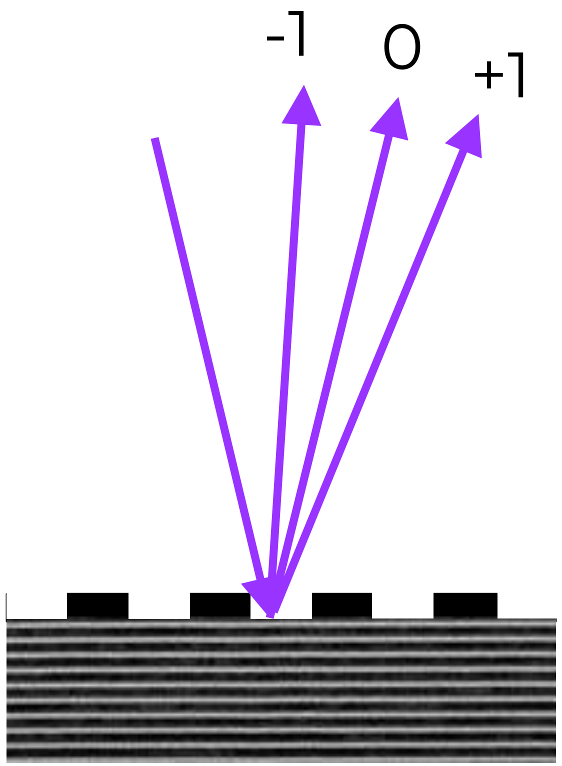


Pattern phase

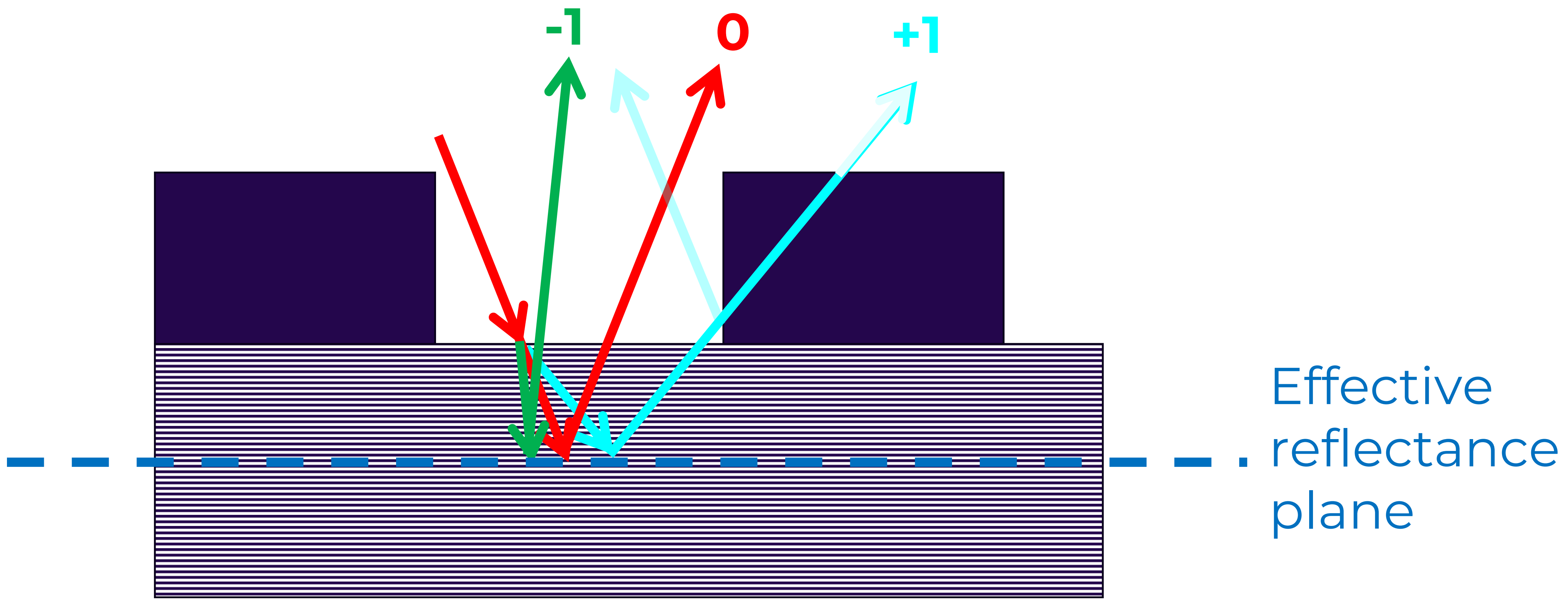


Multilayer M3D effects impact on scattering

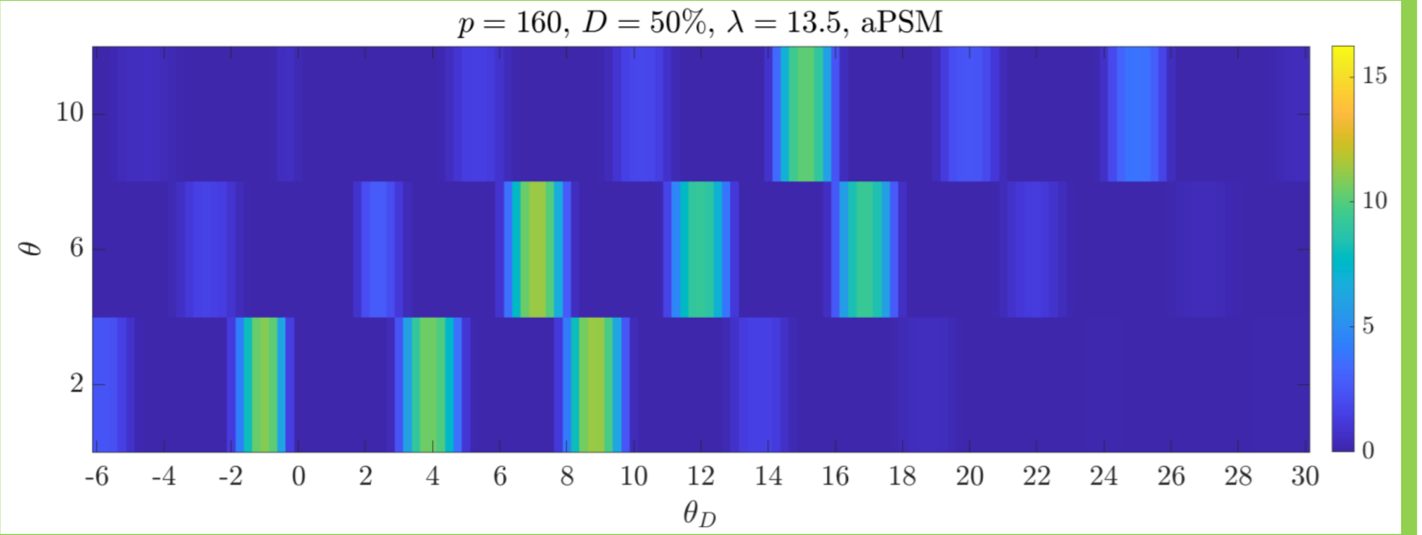


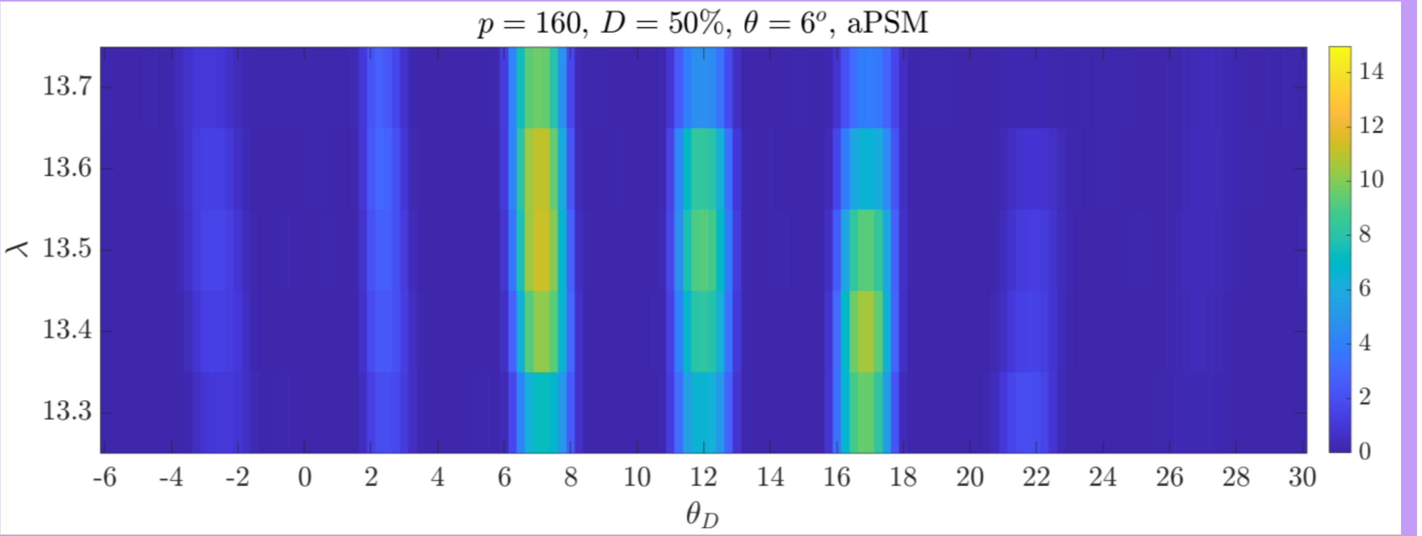


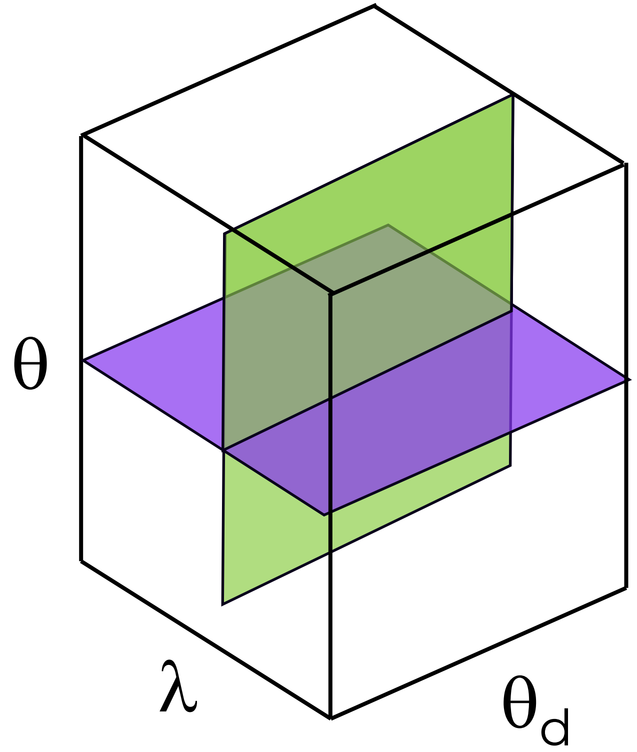
Absorber M3D effects impact on scattering



Scatterometry: pattern phase measurement

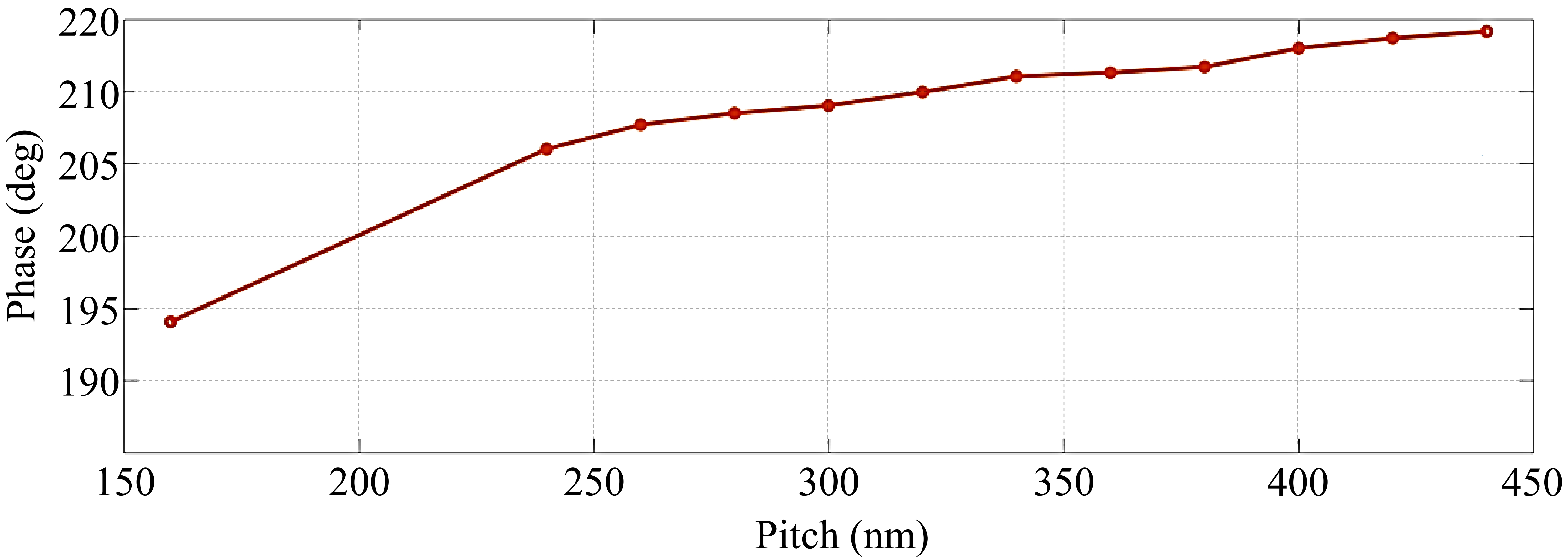






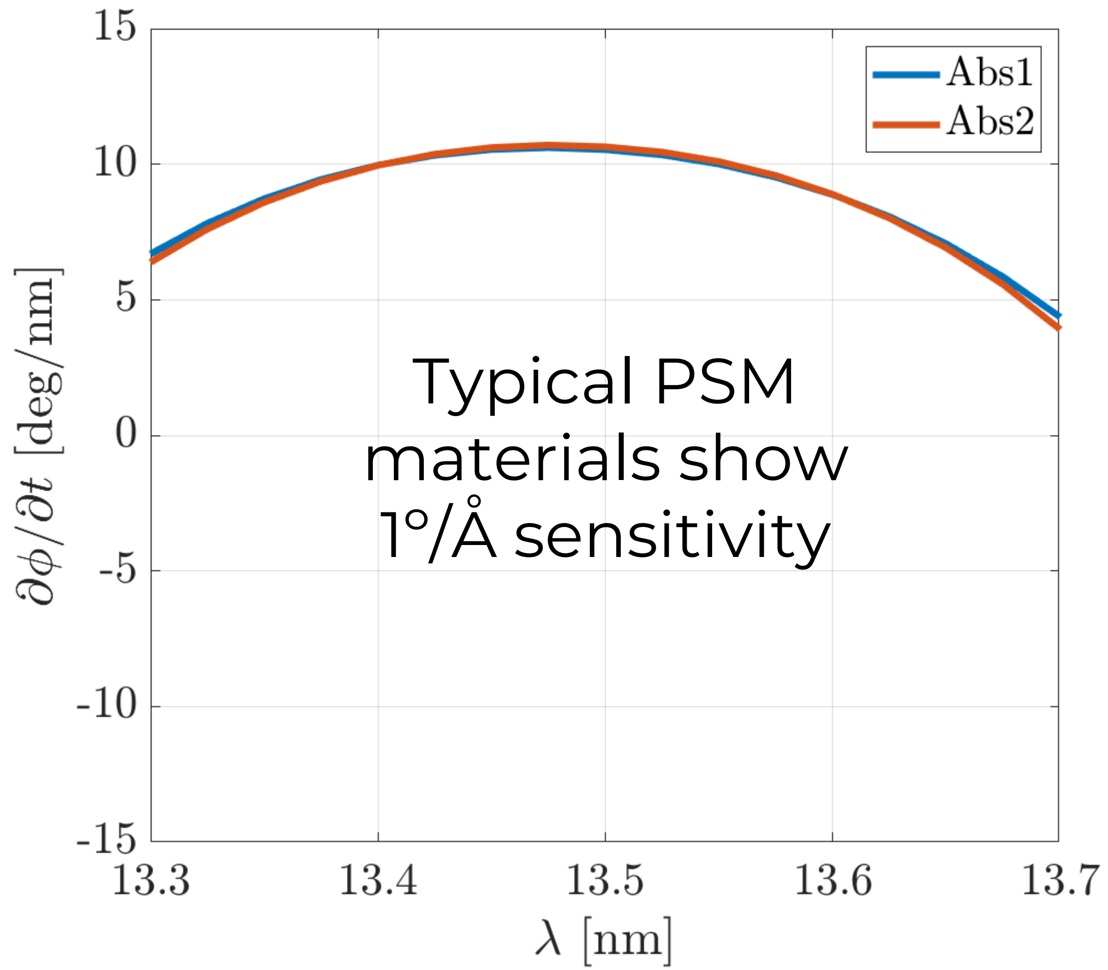
Orthogonal slices through full $\theta - \theta_d - \lambda$ volumetric space

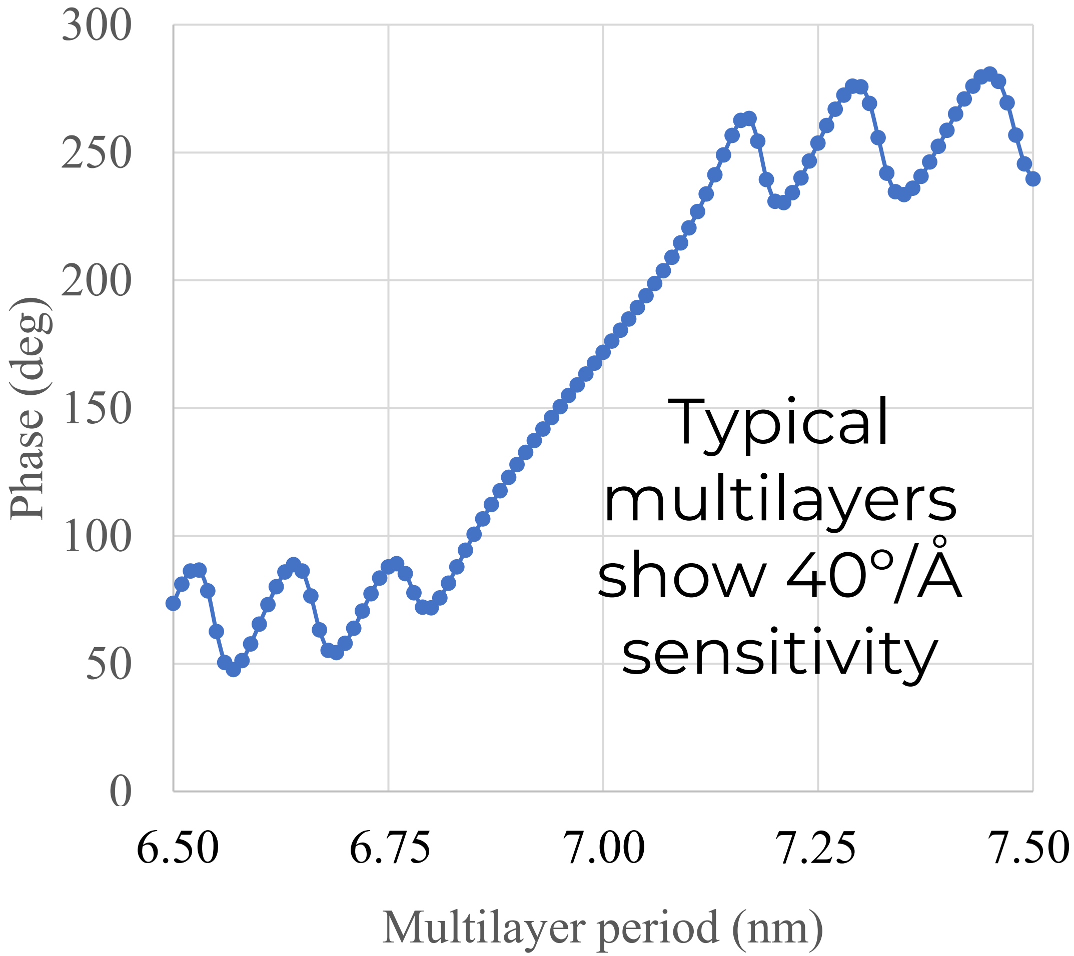
Pattern phase deviates from film phase due to edge effects: converges to film phase at large pitch



Section 3

EUV phase sensitive to angstrom level materials effects/roughness

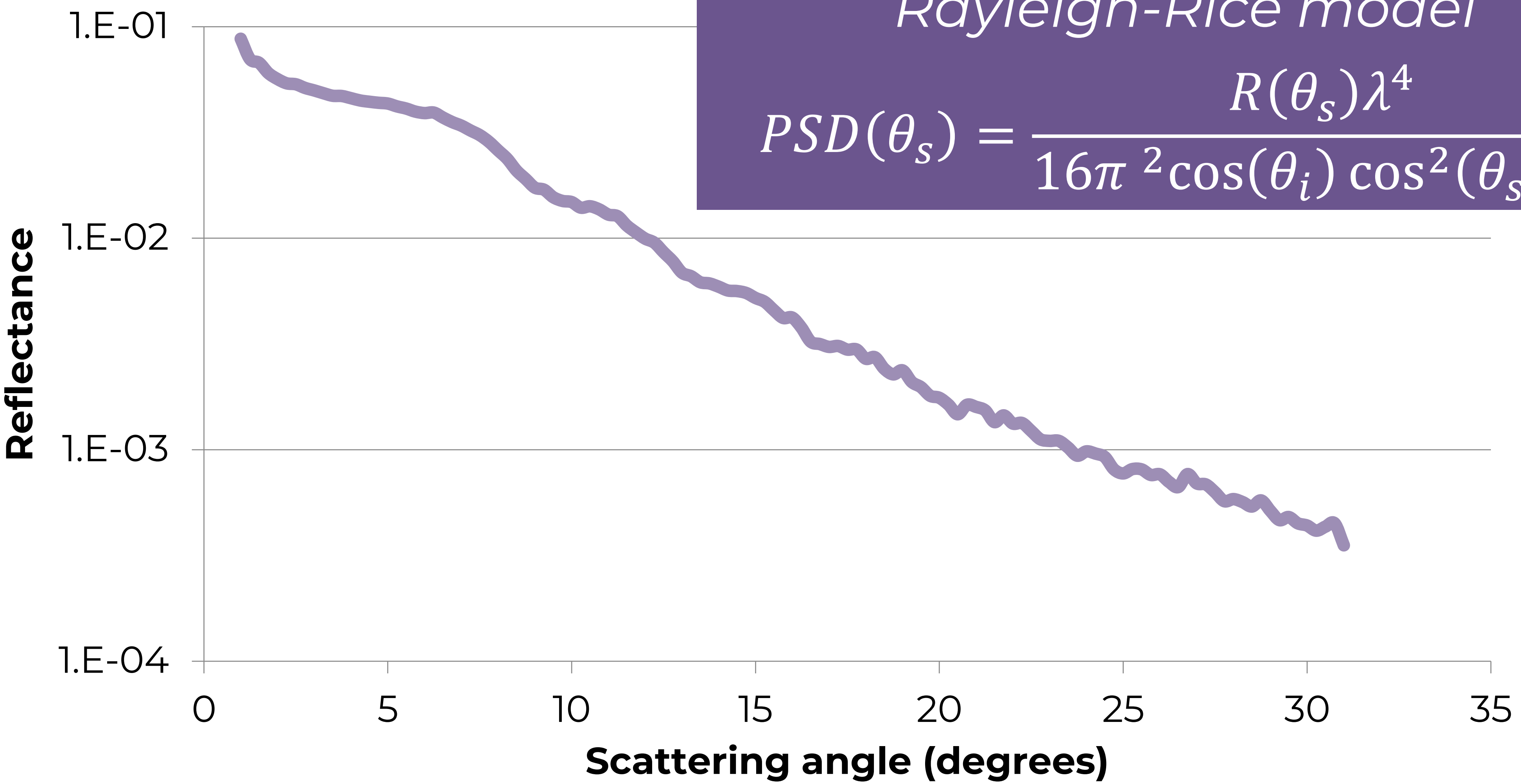




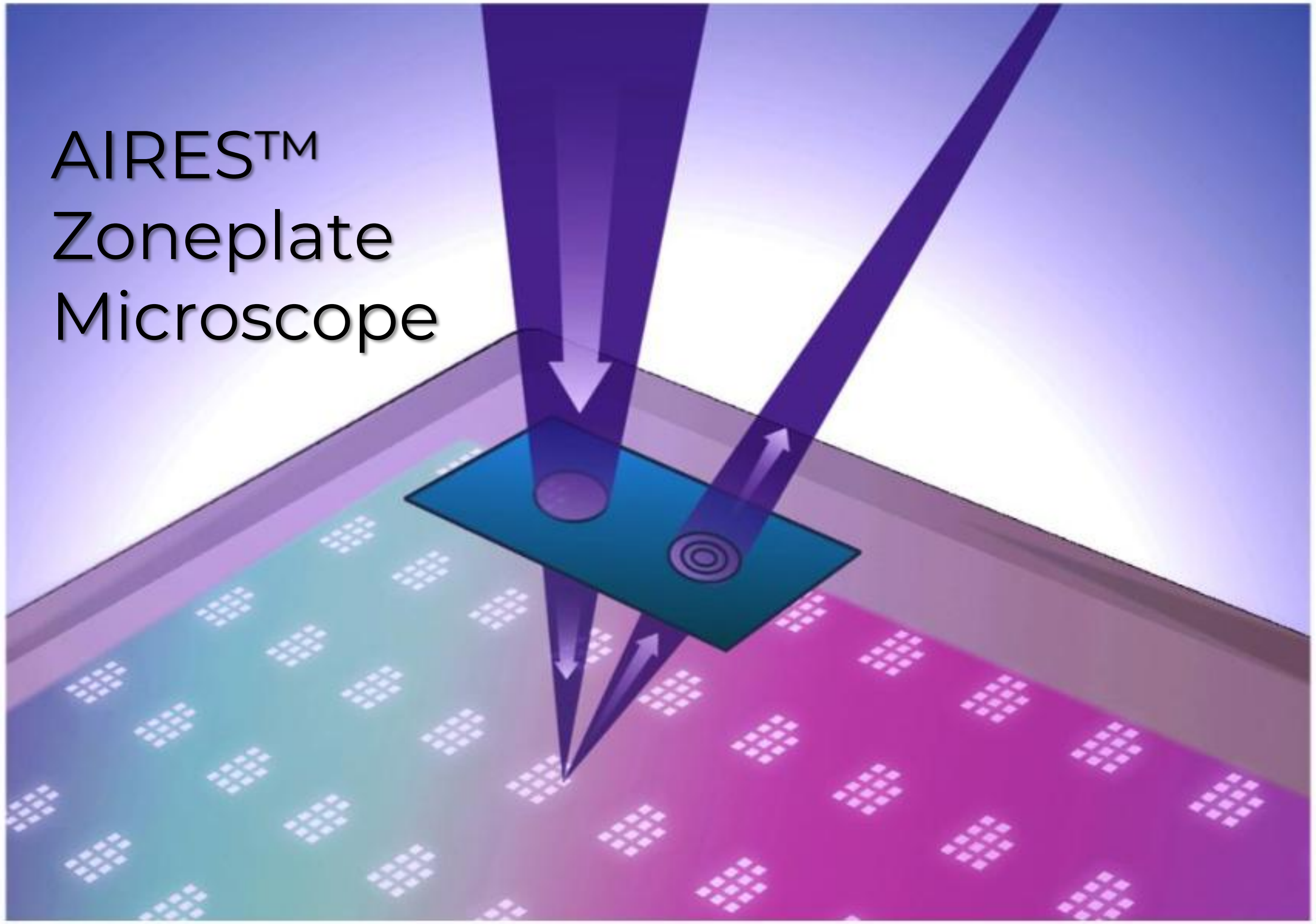
Actinic scattering measures true EUV phase roughness

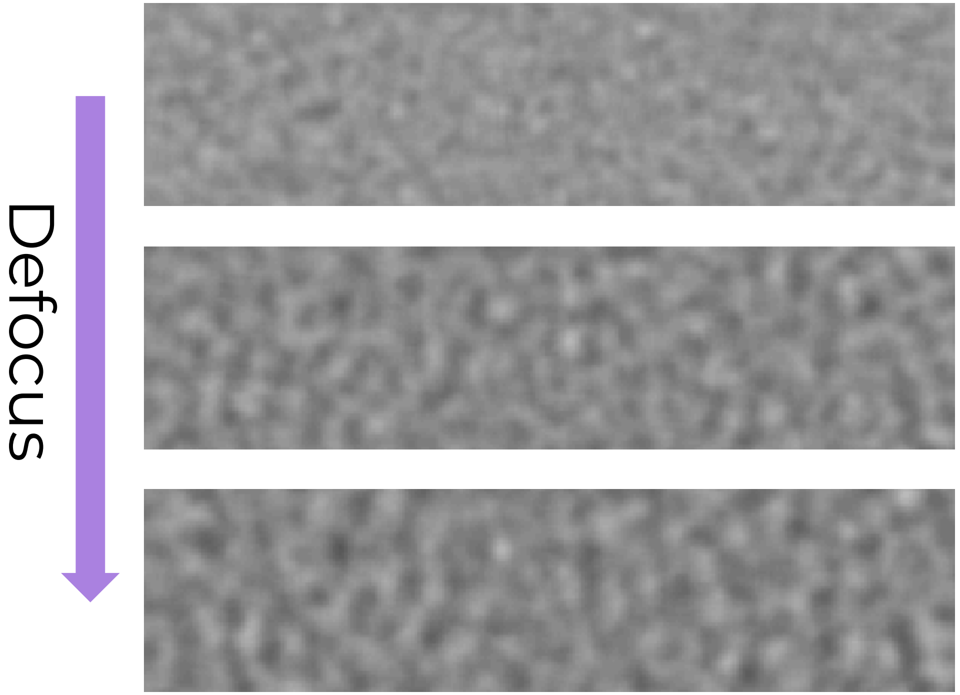
Rayleigh-Rice model

$$PSD(\theta_s) = \frac{R(\theta_s)\lambda^4}{16\pi^2 \cos(\theta_i)\cos^2(\theta_s) R_o}$$

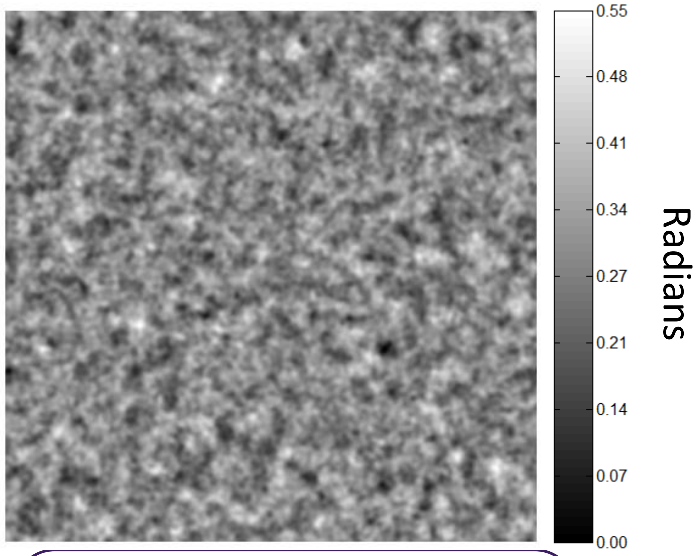


Mask phase roughness leads to image speckle as clearly observed using actinic microscopy

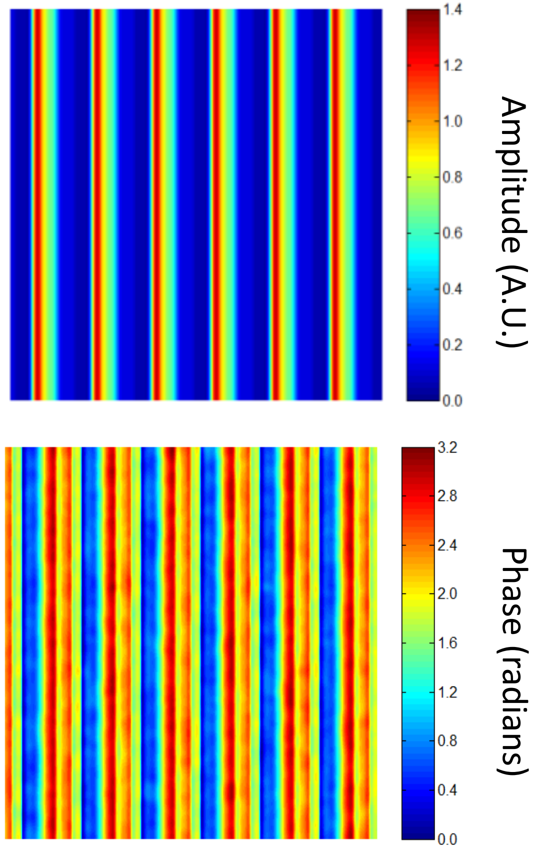




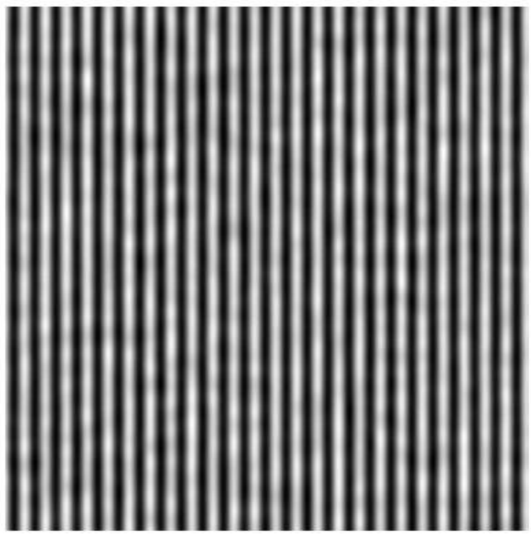
Pseudo-rigorous speckle impact modeling



Synthesize a phase roughness map based on measured EUV scattering



Add phase roughness to rigorous near field



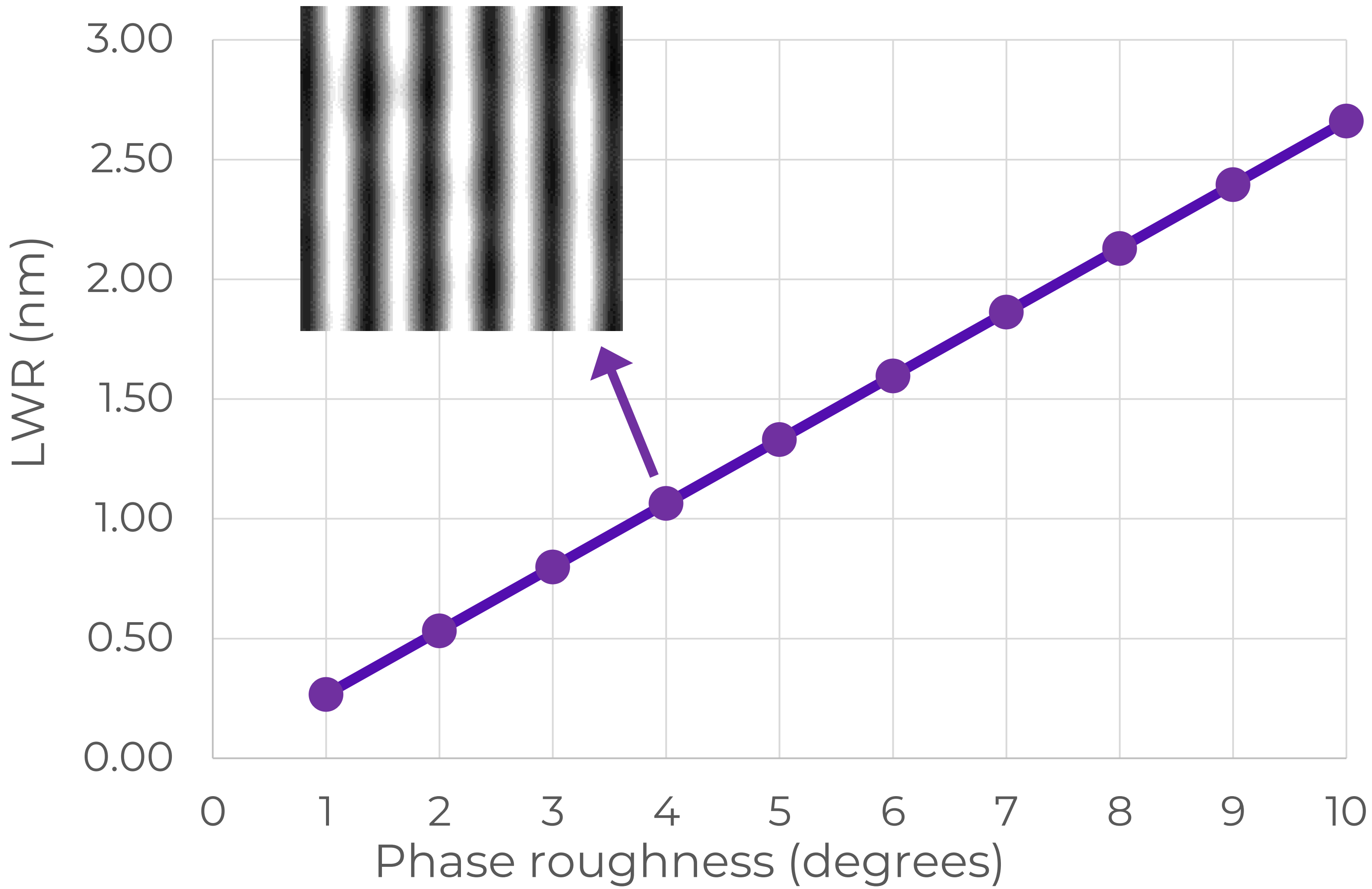
Compute aerial image and extract aerial image stochastics

Panoramic Technology

P. Naulleau, et al., Appl. Opt. 57, 1724-1730 (2018)

75-pm of roughness generates 1-nm LWR

10-nm HP
High NA
Dipole illumination
0.75 relative defocus



Statistical defects (and hotspots) per mask

10-nm HP
High NA
Dipole illumination
0.6 relative defocus
Defect = 10% ΔCD

		Resist MEEF					
Roughness (pm)	LWR (nm)	1.0	1.1	1.2	1.3	1.4	1.5
30	0.35	1.2E-22	6.2E-17	1.4E-12	3.3E-09	1.6E-06	2.5E-04
35	0.40	6.5E-14	1.0E-09	1.6E-06	5.1E-04	5.0E-02	2.0E+00
40	0.46	3.1E-08	5.2E-05	1.5E-02	1.2E+00	4.1E+01	7.1E+02
45	0.52	2.5E-04	8.8E-02	7.9E+00	2.6E+02	4.3E+03	4.1E+04
50	0.58	1.5E-01	1.8E+01	7.1E+02	1.2E+04	1.2E+05	7.6E+05
55	0.63	1.8E+01	9.8E+02	2.0E+04	2.2E+05	1.4E+06	6.7E+06
60	0.69	7.1E+02	2.0E+04	2.6E+05	1.9E+06	9.6E+06	3.5E+07
65	0.75	1.2E+04	2.2E+05	1.9E+06	1.1E+07	4.3E+07	1.3E+08
70	0.81	1.2E+05	1.4E+06	9.6E+06	4.3E+07	1.4E+08	3.7E+08
75	0.87	7.6E+05	6.7E+06	3.5E+07	1.3E+08	3.7E+08	8.7E+08

Summary

Only actinic metrology is adequately sensitive to litho-relevant mask effects

Phase in EUV is sensitive to a broad range of parameters and evolves significantly across scanner spectral and angular BW

EUV phase highly subject to stochastic materials constraints leading to stochastic phase

Stochastic phase leads to intrinsic mask defects as well as stochastic hot spots

Stochastic phase implications on mask inspection should also be considered

Thank you

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