Soft X-Ray Scatterometry:

At-Resolution, 3D Metrology for the EUV Era

Presenter: Christina Porter[1]

Co-Authors: Teis Coenen[1], Niels Geypen[1], Sander Roobol[1], Sandy Scholz[1], Loes van Rijswijk[1], Han-Kwang Nienhuys[1], Johan Reinink[1], Jeroen Ploegmakers[1], Omar el Gawhary[1], Patrick Helfenstein[1], Janusz Bogdanowicz[2], Hans Mertens[2], Amier-Hossein Tamaddon[2], Anne-Laure Charley[2]

[1]ASML Research, Veldhoven, The Netherlands; [2] Imec, Leuven, Belgium

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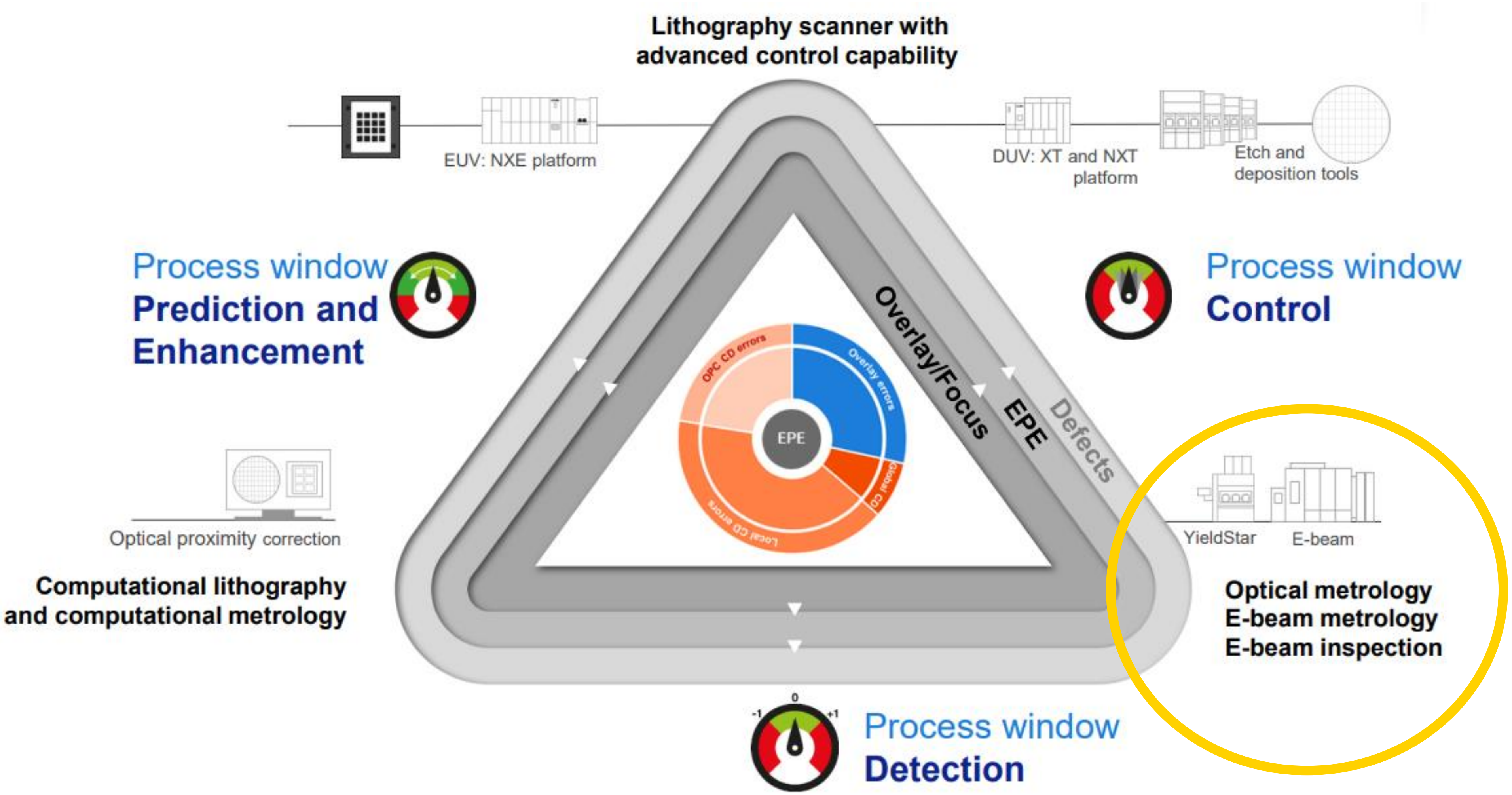
FCMN Conference 2022

ASML holistic lithography approach seeks to maximize patterning process performance and control



Lithography scanner with advanced control capability

Process window
Prediction and Enhancement

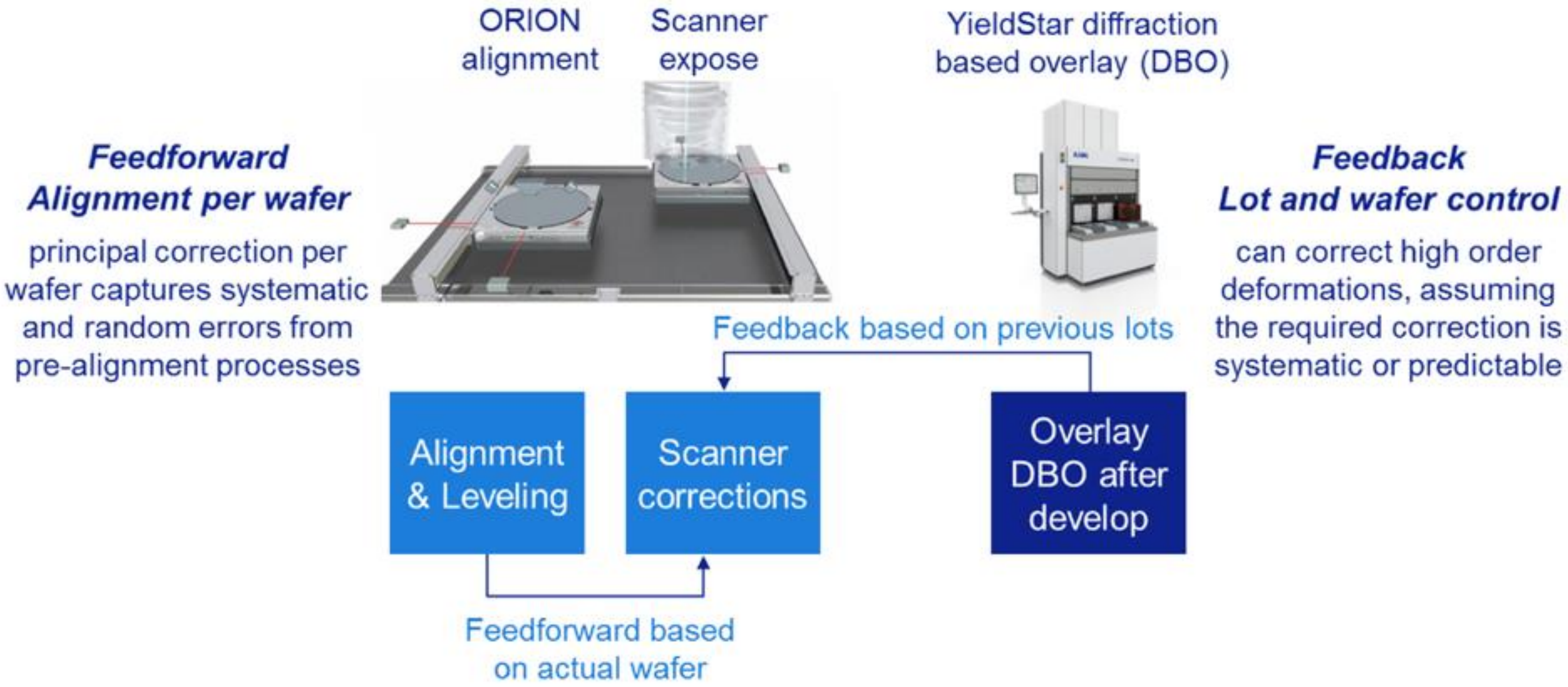
Process window
Control

Process window
Detection

Computational lithography and computational metrology

Optical metrology
E-beam metrology
E-beam inspection

Overlay Control: Measure & feedback ASAP after exposing



ORION alignment

Scanner expose

YieldStar diffraction based overlay (DBO)

Feedforward
Alignment per wafer

principal correction per wafer captures systematic and random errors from pre-alignment processes

Feedback
Lot and wafer control

can correct high order deformations, assuming the required correction is systematic or predictable

Feedback based on previous lots

Alignment & Leveling

Scanner corrections

Overlay DBO after develop

Feedforward based on actual wafer

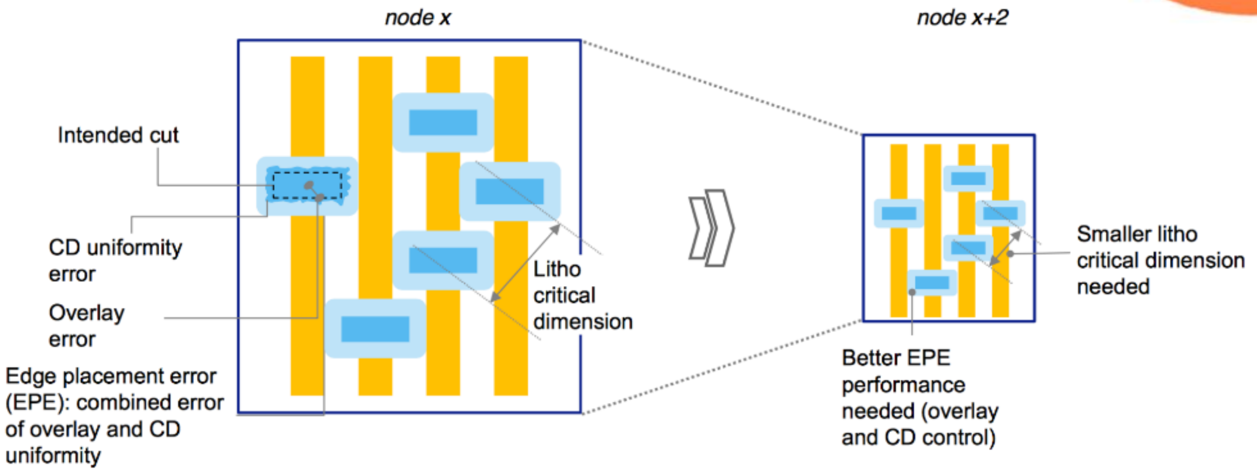
H. Megens et al., “Holistic feedforward control for the 5 nm logic node and beyond,” Proc. SPIE 10961, Optical Microlithography XXXII, 109610K (20 March 2019).

Metrology: All problems are becoming more 3D

Edge placement error: For a device to work, all layers must land on each other as designed!

Typical Logic EPE budget

2D View



Intended cut

CD uniformity error

Overlay error

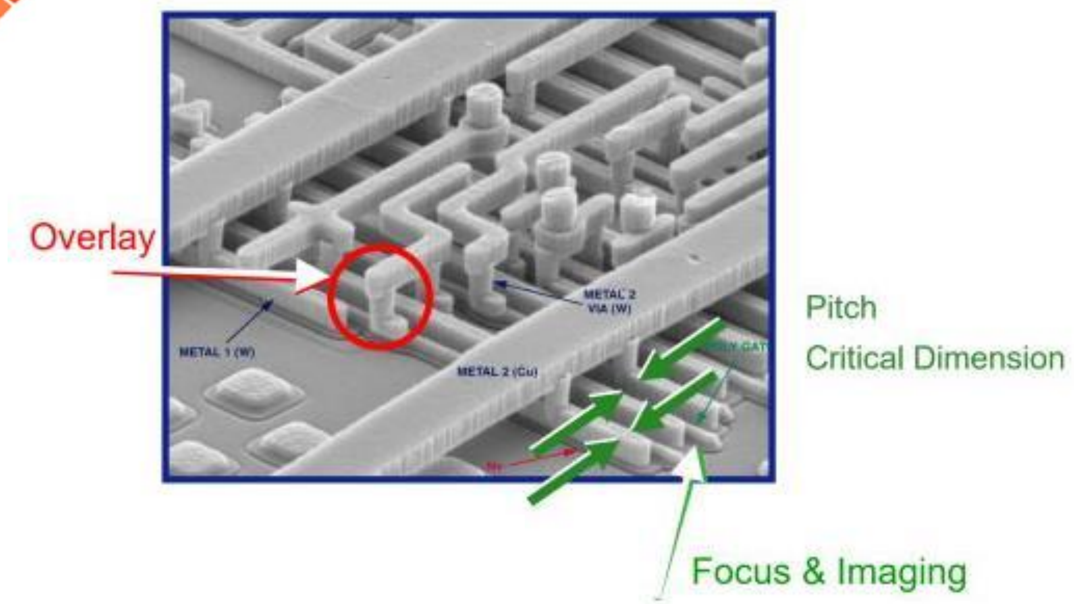
Edge placement error (EPE): combined error of overlay and CD uniformity

Litho critical dimension

Smaller litho critical dimension needed

Better EPE performance needed (overlay and CD control)

3D View



Overlay

Pitch

Critical Dimension

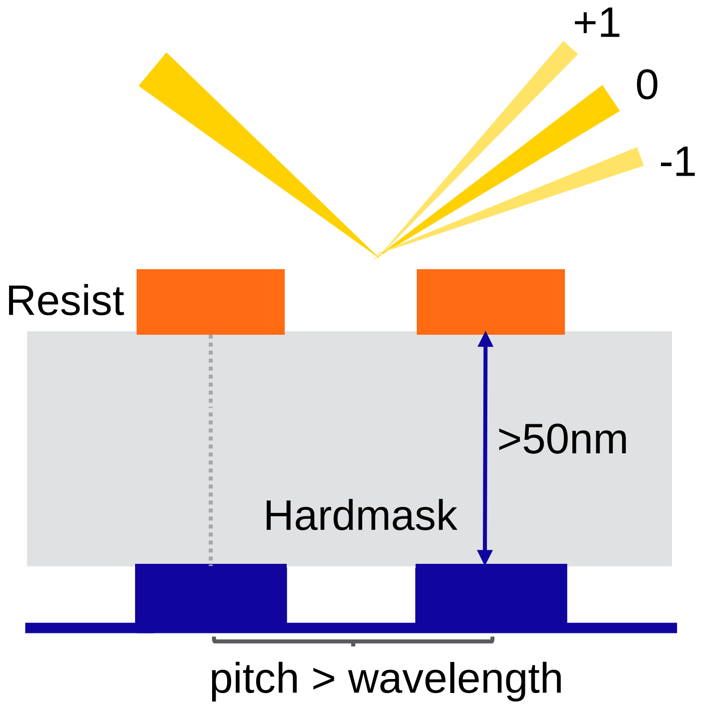
Focus & Imaging

Kaustuve Bhattacharyya, "Tough road ahead for device overlay and edge placement error," Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII, 1095902 (26 March 2019);

Overlay (OVL): What can visible light (400-700nm) measure?

After Develop Inspection (ADI) = measure OVL @ large grating separation

+ Enables fast feedback to scanner!



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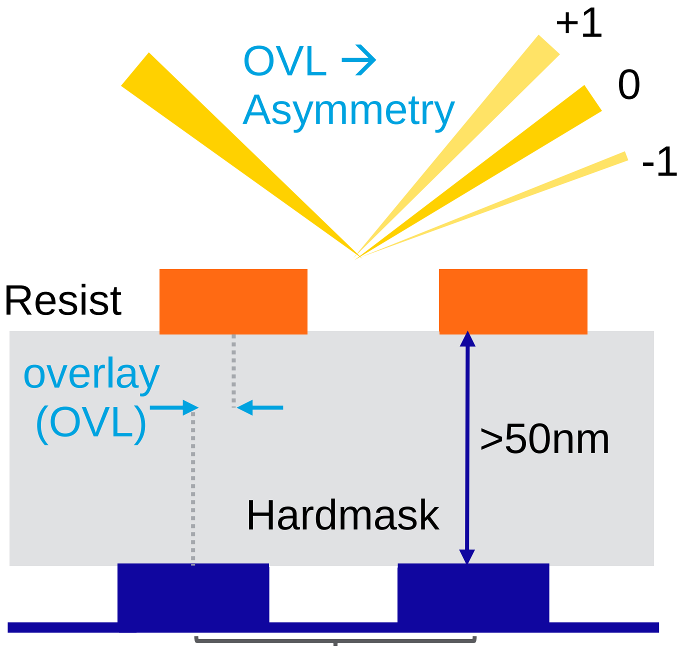


pitch > wavelength

Generate overlay signal via asymmetry in intensity of ±1 diffraction order.

Issue: Process is optimized for device pitch.

Example: CD imbalance-induced mark to device offset

Triggered by local density variations in large pitch targets

Sub-segmented, optical Diffraction Based Overlay (DBO) target, ideal case → Symmetric Signal

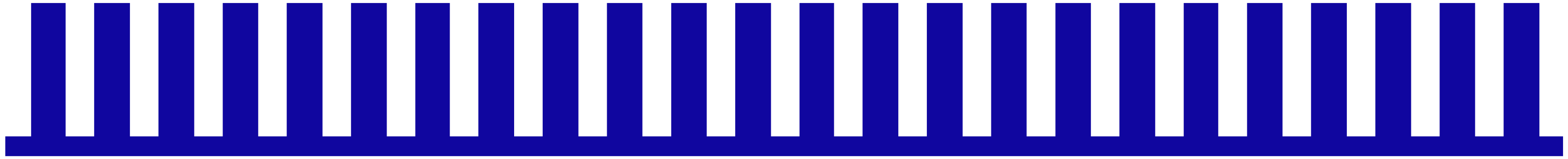
CD

pitch ok for visible light (i.e. 600nm)

critical pitch for which
process is optimized
(i.e. <50nm)

Sub-segmented optical DBO target, real case: CD Imbalance → Asymmetric Signal

CD



Device pitch targets will not suffer from this issue!

K. Bhattacharyya,, "Characterization of metrology to device overlay offset and novel methods to minimize it," Proc. SPIE 11611, Metrology, Inspection, and Process Control for Semiconductor Manufacturing XXXV, 116110C (22 February 2021);

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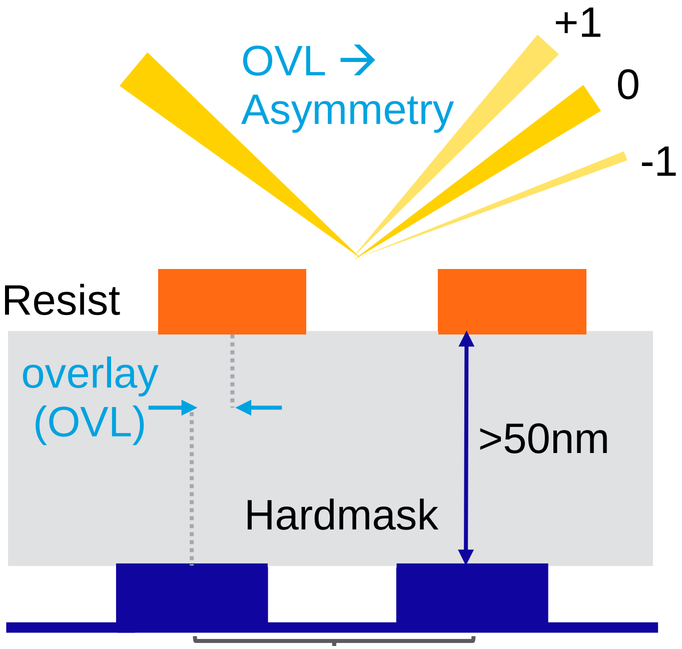


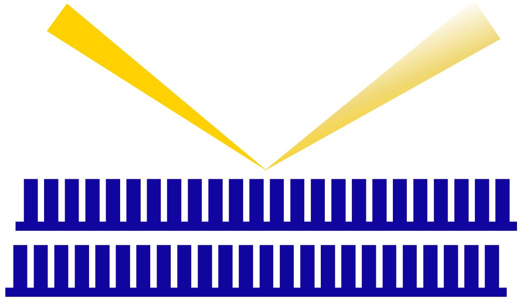
pitch > wavelength

Generate overlay signal via asymmetry in intensity of ±1 diffraction order.

Issue: Process is optimized for device pitch.

After Etch Inspection (AEI) → measure OVL @ small grating separation

\+This is where OVL has to be right, measure here!



Coupling between top and bottom grating generate overlay signal in reflected beam.

→ **device pitch measurable!**

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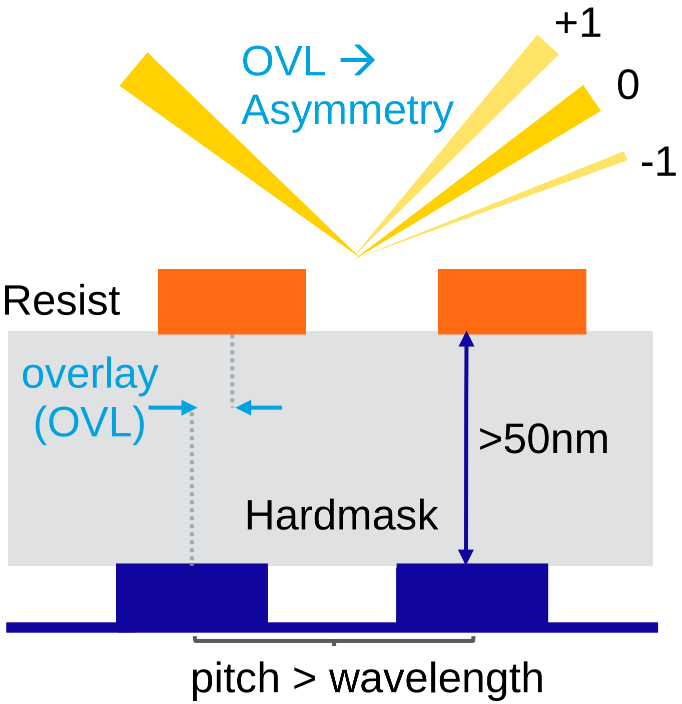
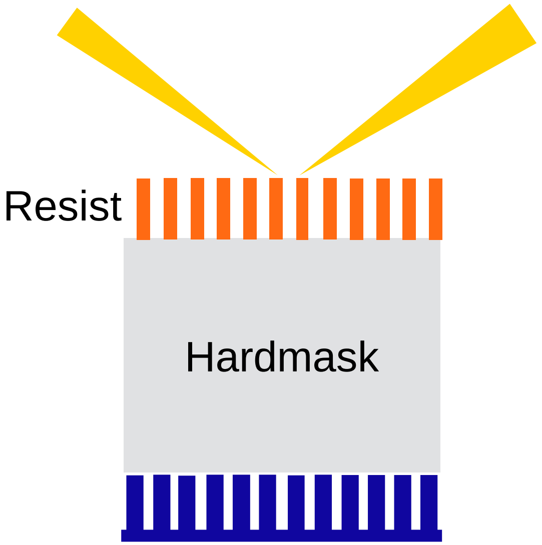


Generate overlay signal via asymmetry in intensity of ±1 diffraction order.

Issue: Process is optimized for device pitch.

No Solution!



No propagating diffraction orders if pitch < wavelength!

No evanescent signal in 0th order if layer separation >50nm!

→ ASML research investigating solutions

After Etch Inspection (AEI) → measure OVL @ small grating separation

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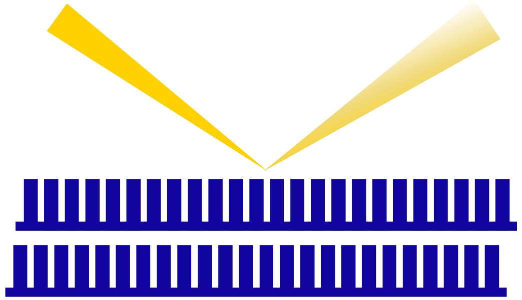

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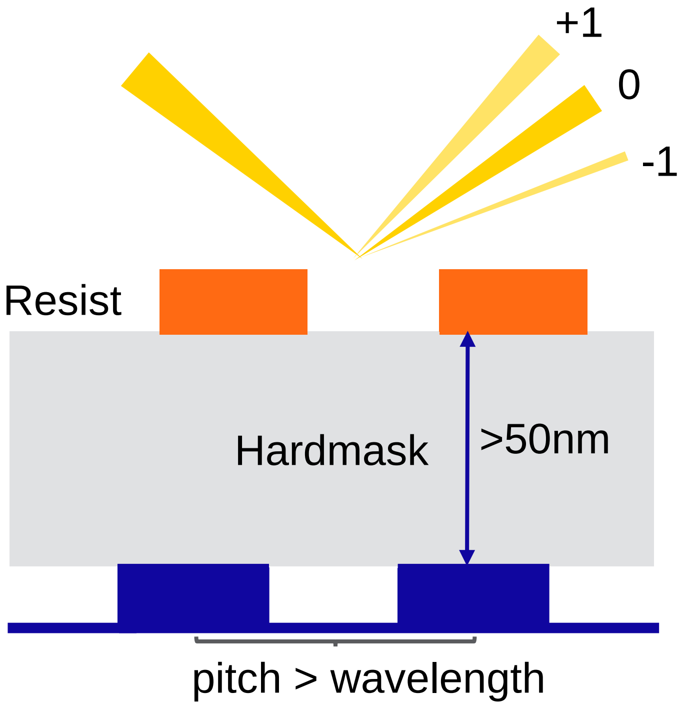

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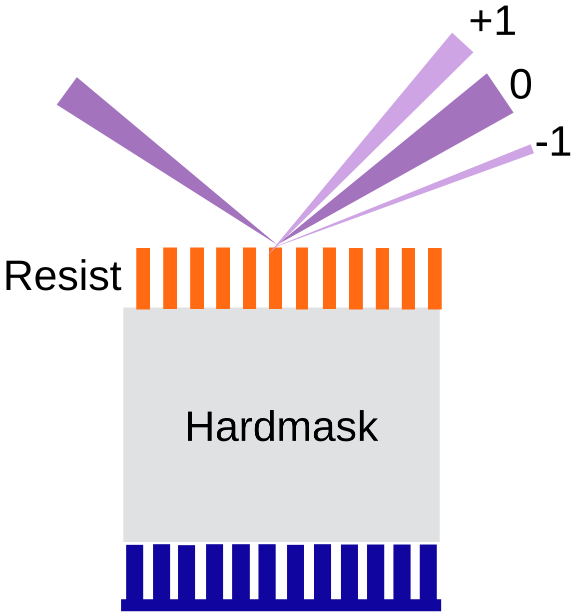

Possible Solution: Decrease wavelength so that diffraction orders re-appear!

After Etch Inspection (AEI) → measure OVL @ small grating separation

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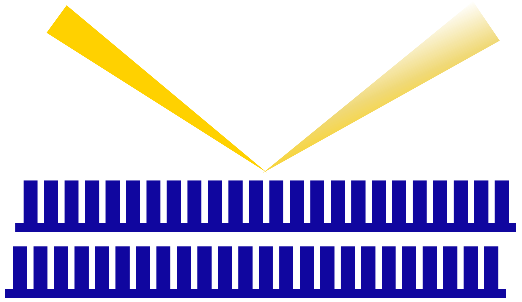
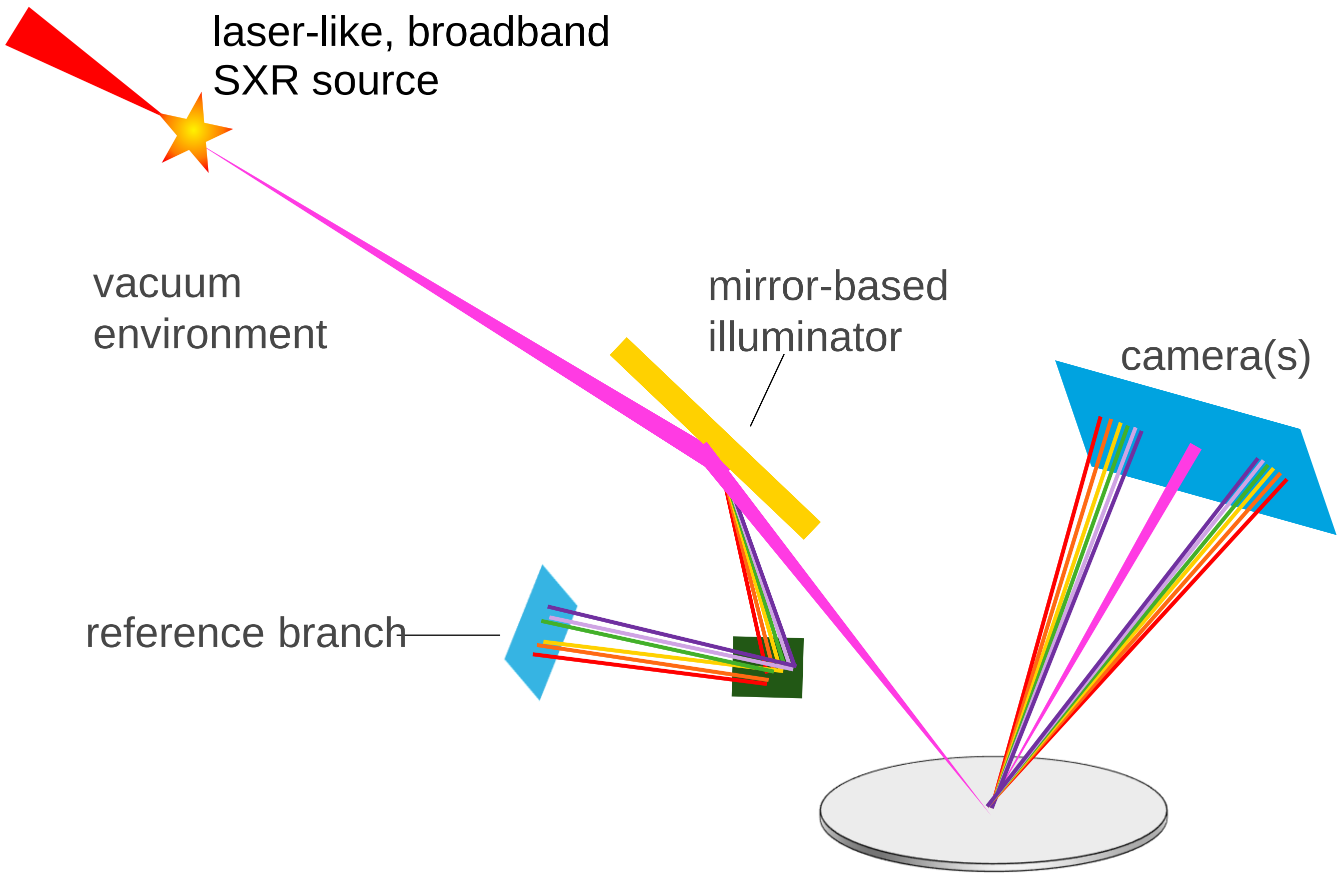


Coupling between top and bottom grating generate overlay signal in reflected beam.
→ **device pitch measurable!**

Soft X-Ray (SXR) Metrology Concept

Broadband, high-brightness, short-wavelength scatterometry for **overlay** and **3D profile metrology**.

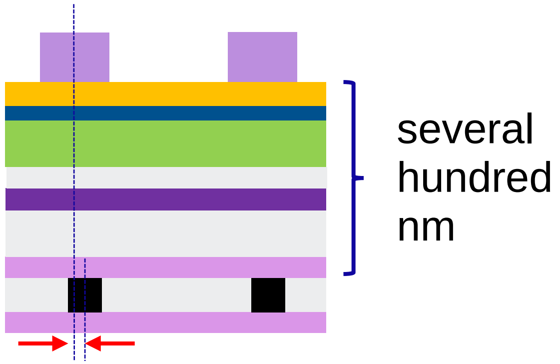


Key Technology Advantages

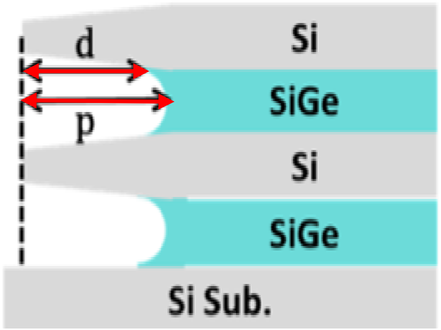
- Wavelength range **matching device scale** leads to strong scatterometry signals.
- Broadband source gives **depth information** in a single shot, with optimal material **contrast**.
- Strong **decorrelation** between parameters of interest.
- **Single, versatile, high-throughput** tool supports many applications.

SXR Supported Applications

At-resolution **OVERLAY** after develop & after etch



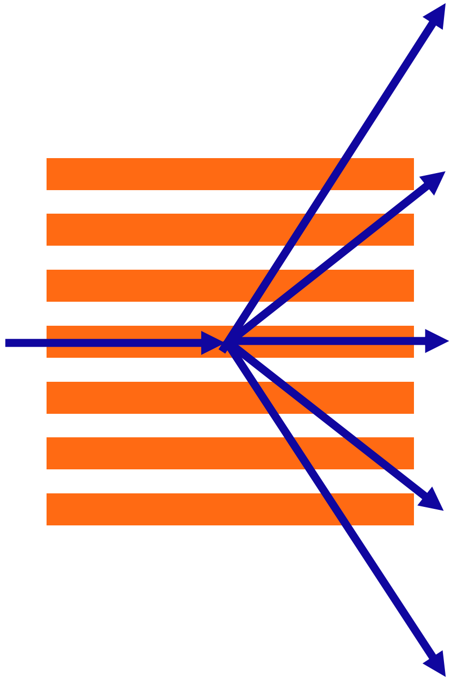
3D PROFILE metrology



Signal formation in Soft X-Ray

Propagation from sample to camera → a spatial **Fourier Transform**

Top view of grating target



diffracted +2

diffracted +1

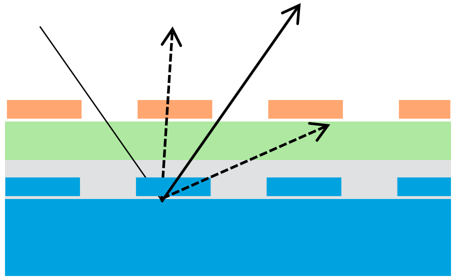
incoming

reflected

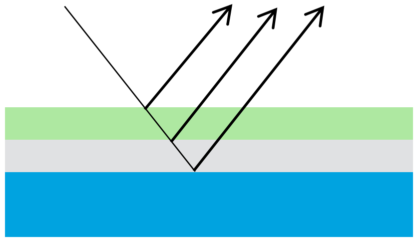
diffracted –1

diffracted –2

Propagating diffraction orders
separate lateral length scales
and carry asymmetry information



Interferometric effects
scale with 1/λ



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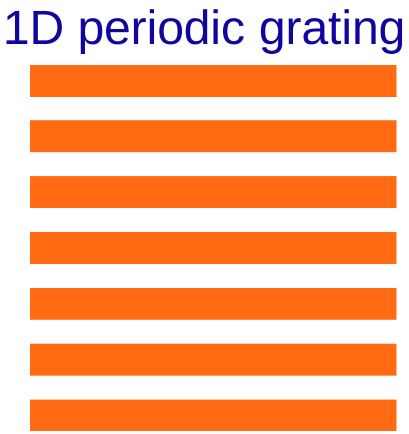
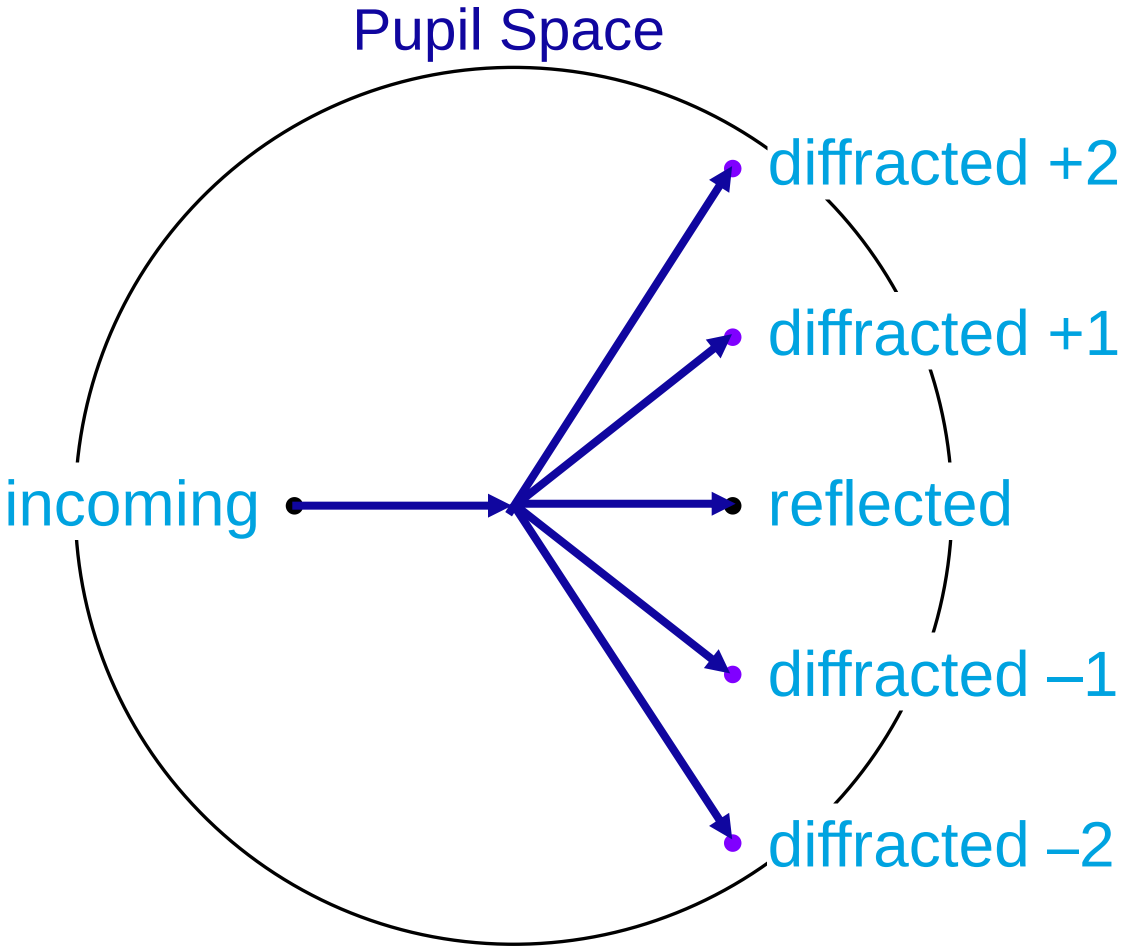
Propagation from sample to camera → a spatial **Fourier Transform**

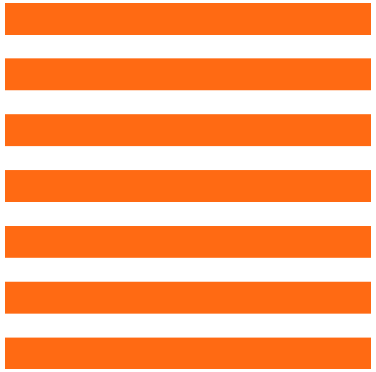




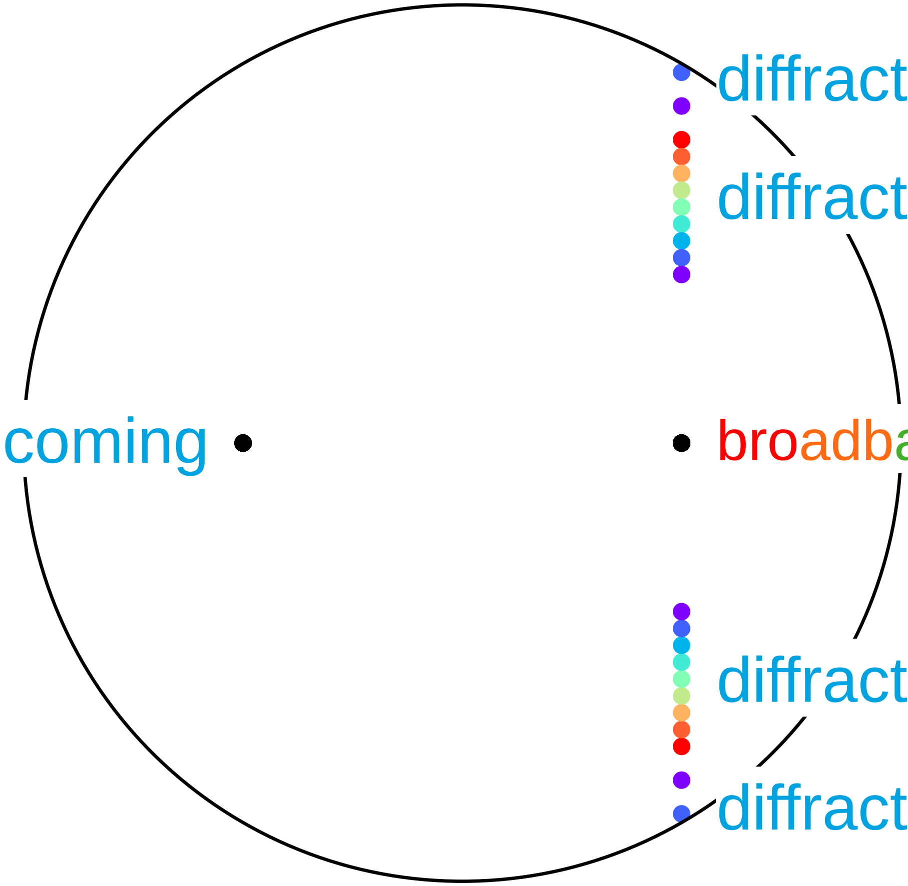
Signal formation in Soft X-Ray

Propagation from sample to camera → a spatial **Fourier Transform**

1D periodic grating



Pupil Space



diffracted +2

diffracted +1

broadband incoming

broadband reflected

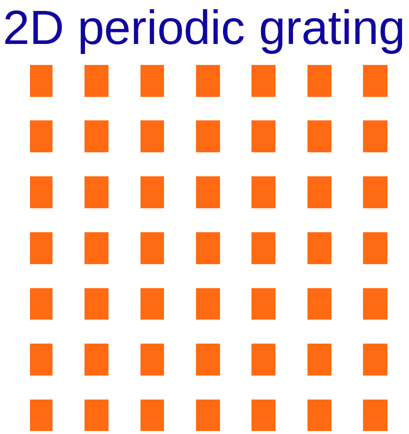
diffracted –1

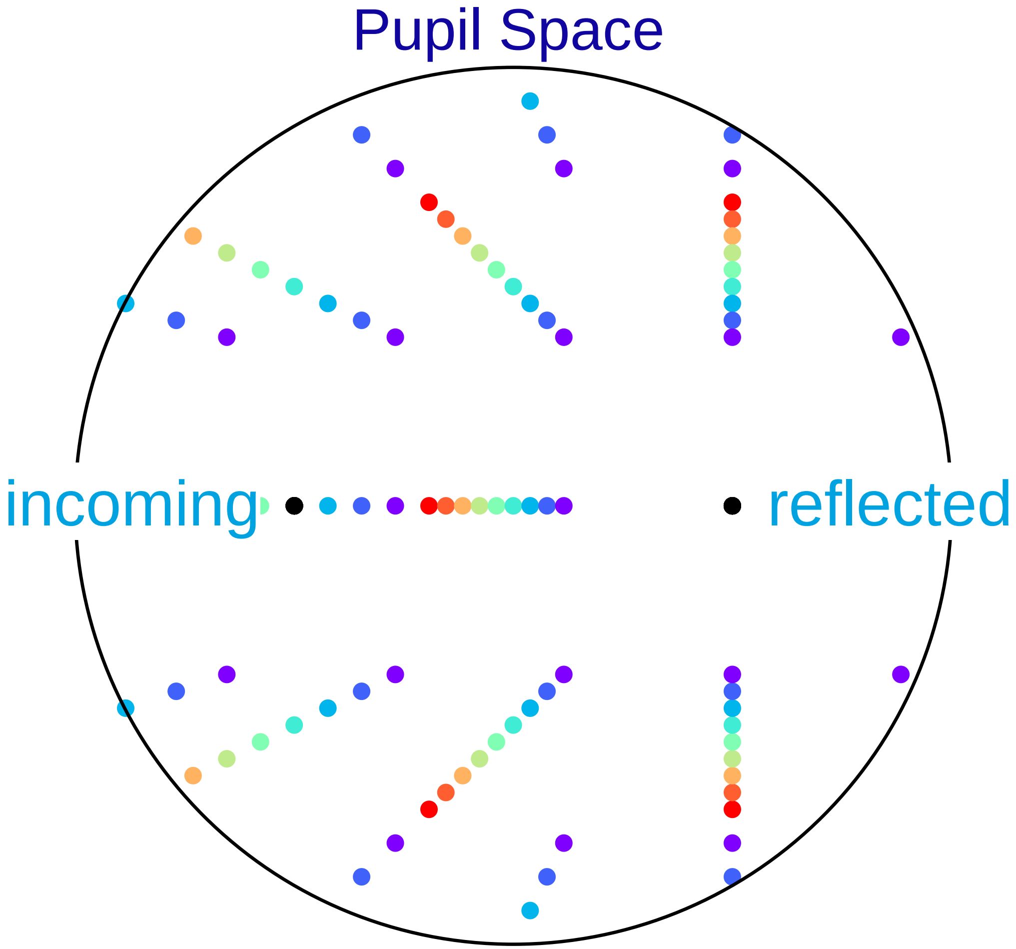
diffracted –2

broadband light carries
depth information

Signal formation in Soft X-Ray

Propagation from sample to camera → a spatial **Fourier Transform**

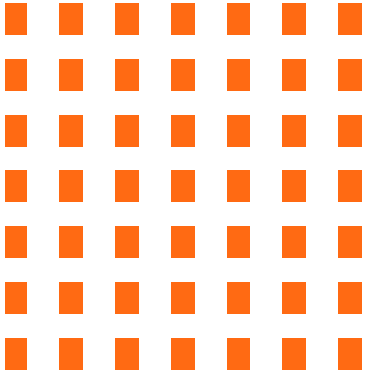




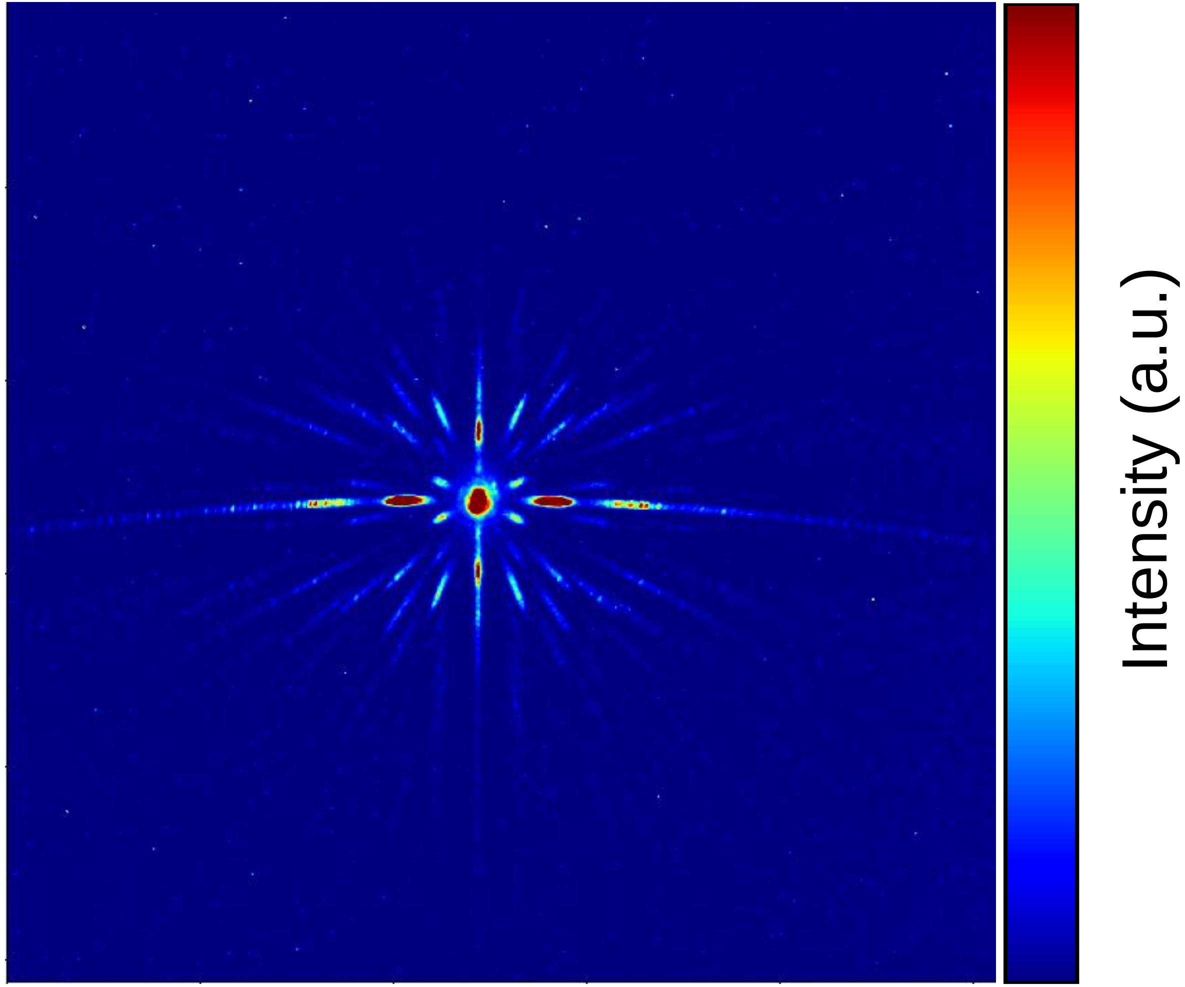
Signal formation in Soft X-Ray

Propagation from sample to camera → a spatial **Fourier Transform**

2D periodic grating



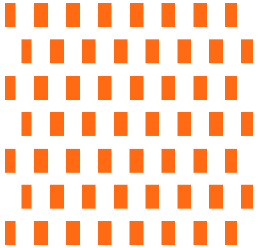
Experimental data in detector space
from SXR metrology test bench



Signal formation in Soft X-Ray

Propagation from sample to camera → a spatial **Fourier Transform**

2D periodic grating
smaller pitch



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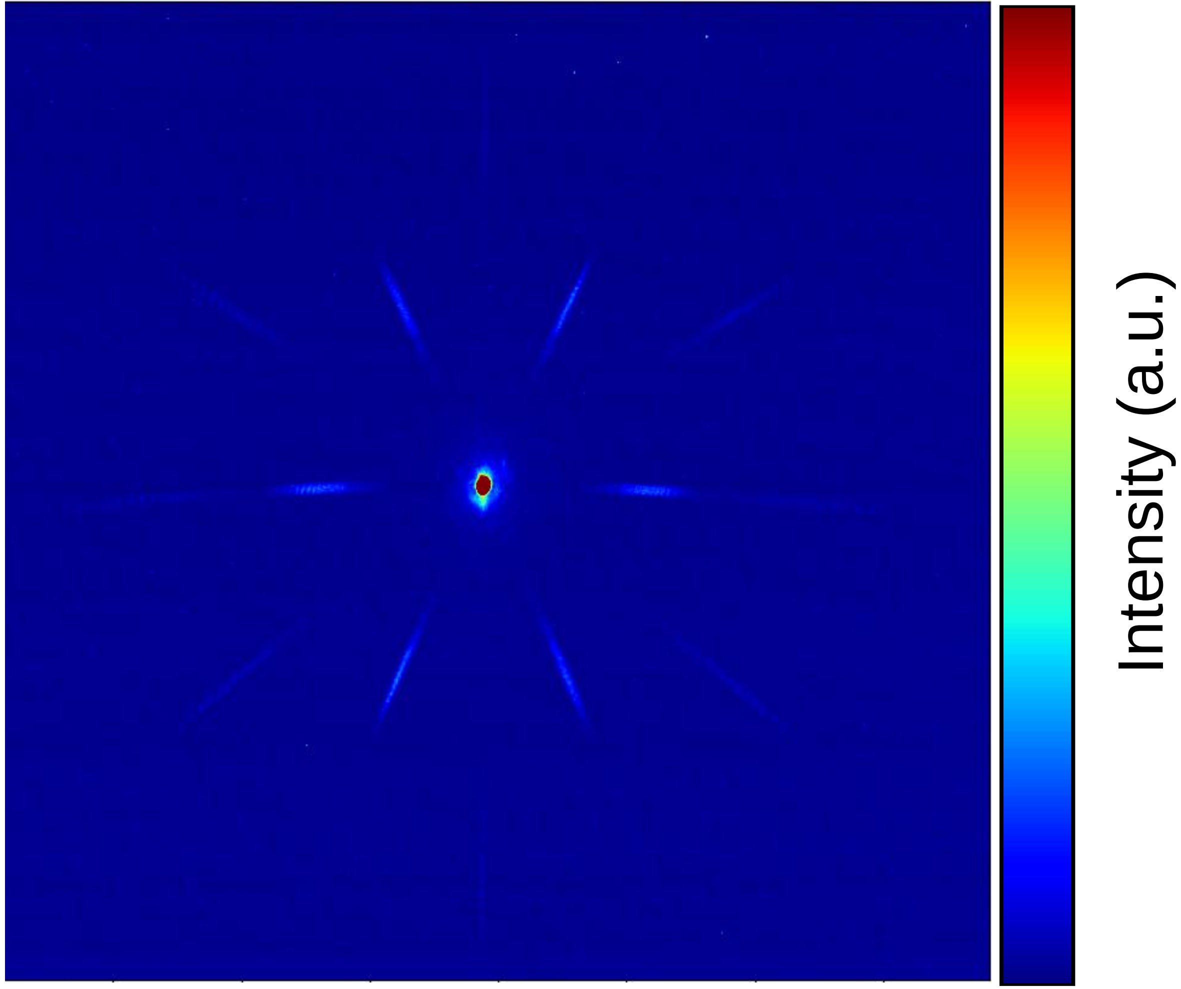
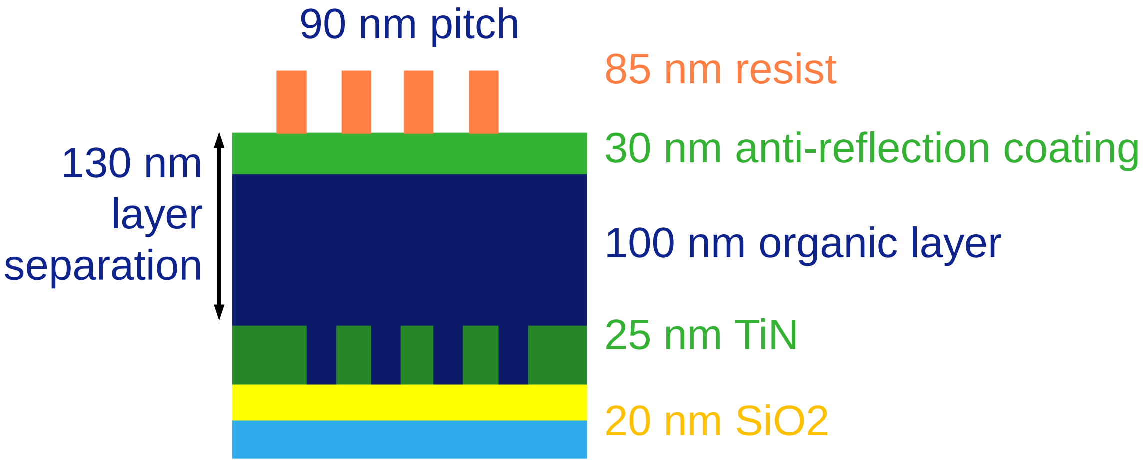


Device Pitch After Develop Overlay

Device Pitch, After Develop (ADI) Overlay Sample for Benchmarking

Stack not measurable with visible light due to device pitch & layer separation!

IMEC litho-etch-litho-etch stack
grating on grating, 90 nm pitch



90 nm pitch

130 nm layer separation

85 nm resist

30 nm anti-reflection coating

100 nm organic layer

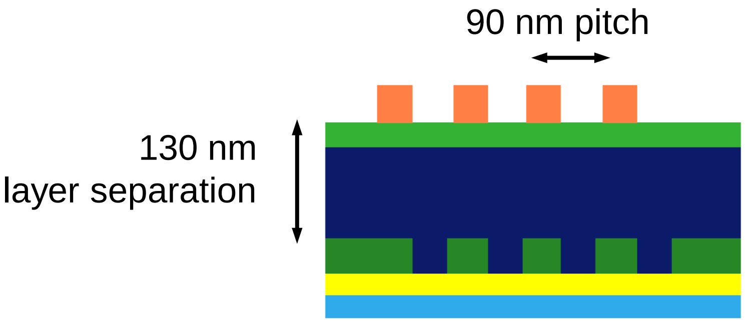
25 nm TiN

20 nm SiO2

overlay targets (overlay bias -45 to 45 nm)

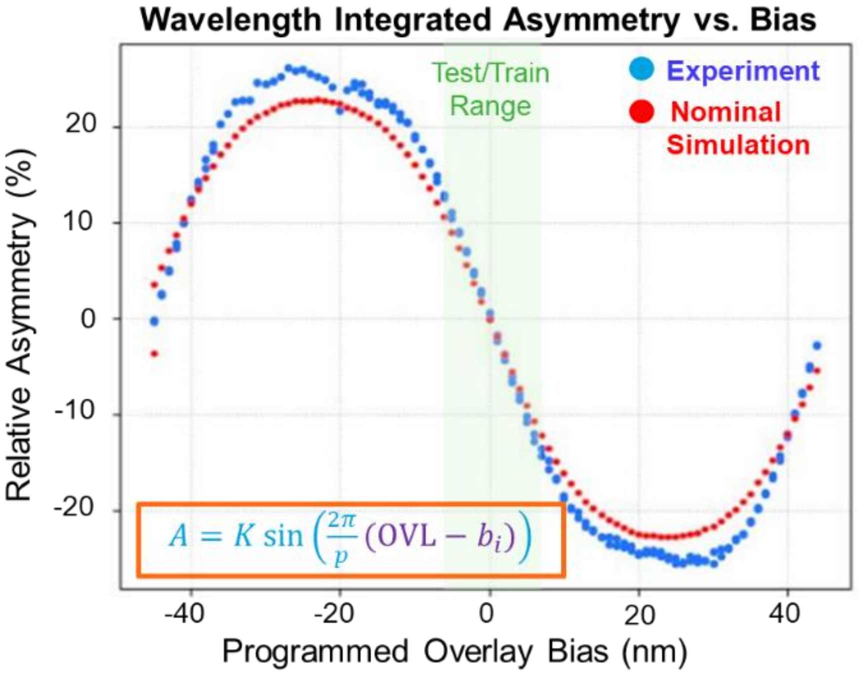
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
-41	-40	-38	-37	-36	-35	-34	-33	-32	-31	-30	-29	-28	-27	-26	-25	-24	45
42	-22	-21	-20	-19	-18	-17	-16	-15	-14	-13	-12	-11	-10	-9	-8	23	-44
-42	22	21	20	19	18	17	16	15	14	[illegible]	12	11	10	9	8	-23	44
43	-23	6	5	4	3	2	1	0	[illegible]	-2	-3	-4	-5	-6	-7	22	-43
-43	23	-6	-5	-4	-3	-2	[illegible]	0	1	2	3	4	5	6	7	-22	43
44	-24	7	8	9	10	[illegible]	12	13	14	15	16	17	18	19	20	21	-42
-44	24	-7	-8	[illegible]	-10	-11	-12	-13	-14	-15	-16	-17	-18	-19	-20	-21	42
45	-25	-26	-27	-28	-29	-30	-31	-32	-33	-34	-35	-36	-37	-38	-39	-40	-41
-45	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Device Pitch, After Develop Overlay: Signal and Performance

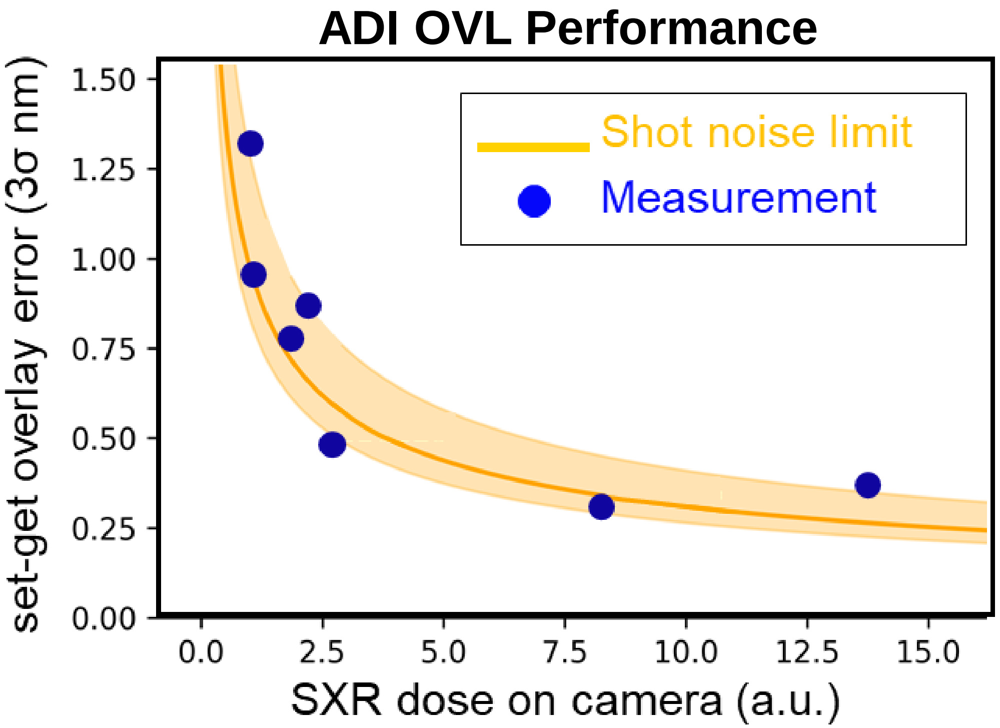


‘Error’ sources:

- Target variations (e.g. **real OVL variation**)
- Shot noise
- Light outside target
- System/sample drift



$$A = K \sin\left(\frac{2\pi}{p}(\mathrm{OVL} - b_i)\right)$$

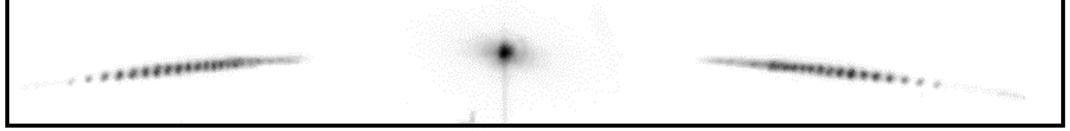


Testbench dynamic reproducibility (including source restarts, sample unload/reload): 0.2nm

Fourier Visualization:

Rich Signals → Model free geometry estimate for simple stacks

SXR diffraction pattern (intensity)



**Broadband Source →
Depth Axis**

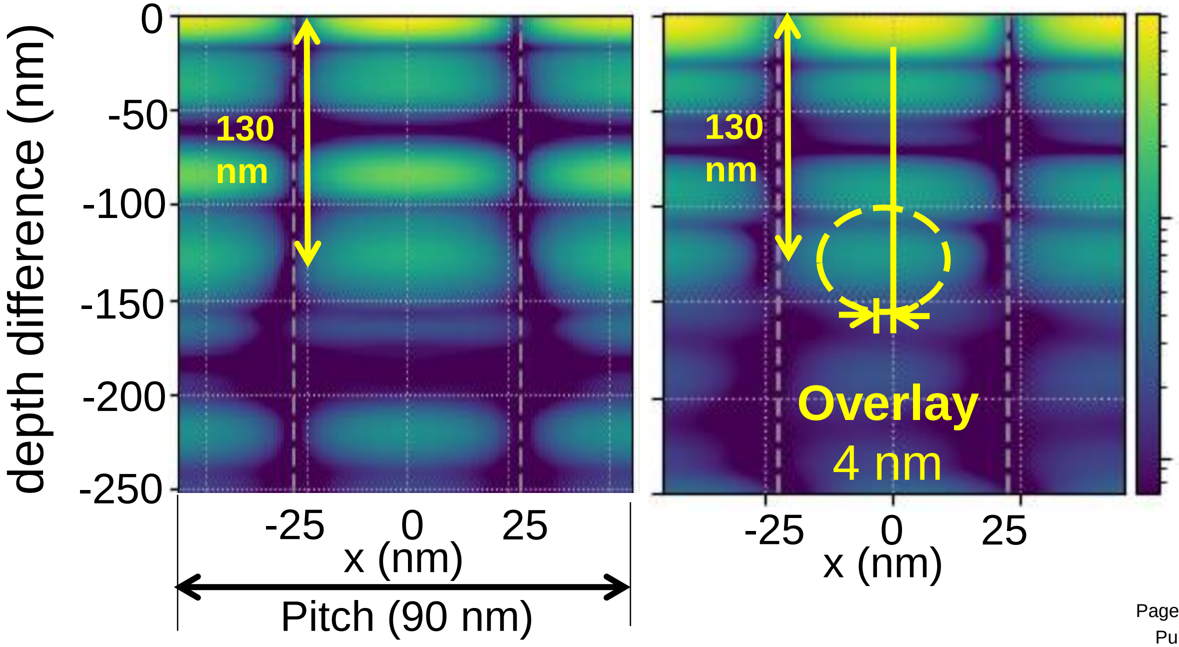
Fourier transform

Fourier transform

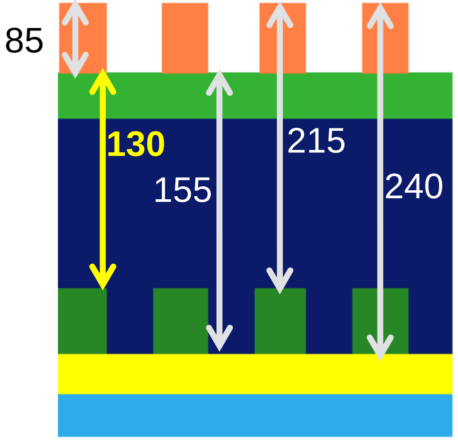
**Autocorrelation space (amplitude):
Well-behaved for geometry perturbations**

Simulation, 0 OVL:

Experiment:



compare

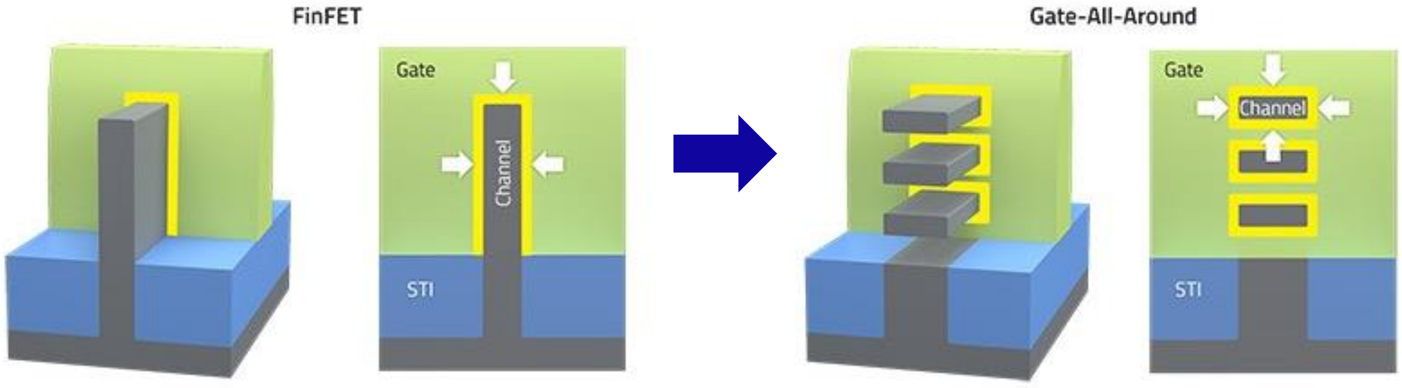


Overlay Unit Cell

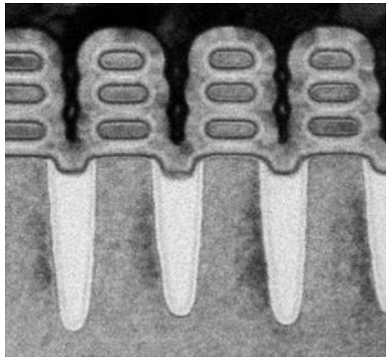
GAA Profilometry

Gate all around (GAA), “nanosheet” transistors

New 3D devices pose significant metrology challenges



FinFETs Give Way to Gate-All-Around | Lam Research

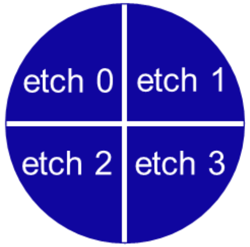


The Nanosheet Transistor Is the Next (and Maybe Last) Step in Moore’s Law IEEE Spectrum

Customers request metrology solutions enabling monitoring/control of **individual** nanosheets, and report that most traditional techniques only give **average** properties.

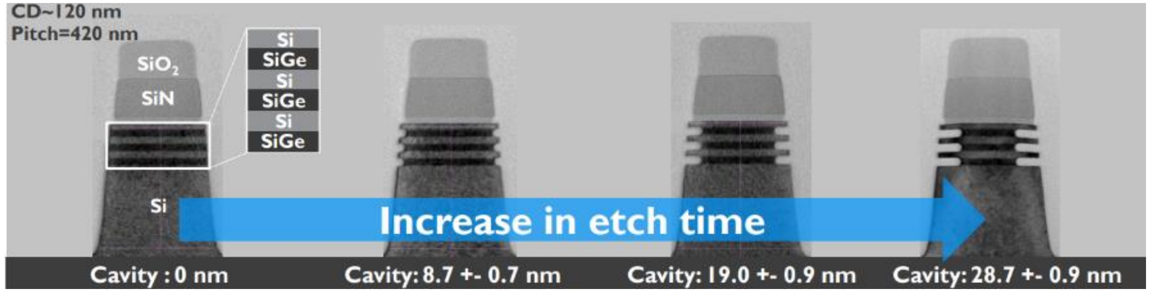
IMEC Nanosheet Measurements

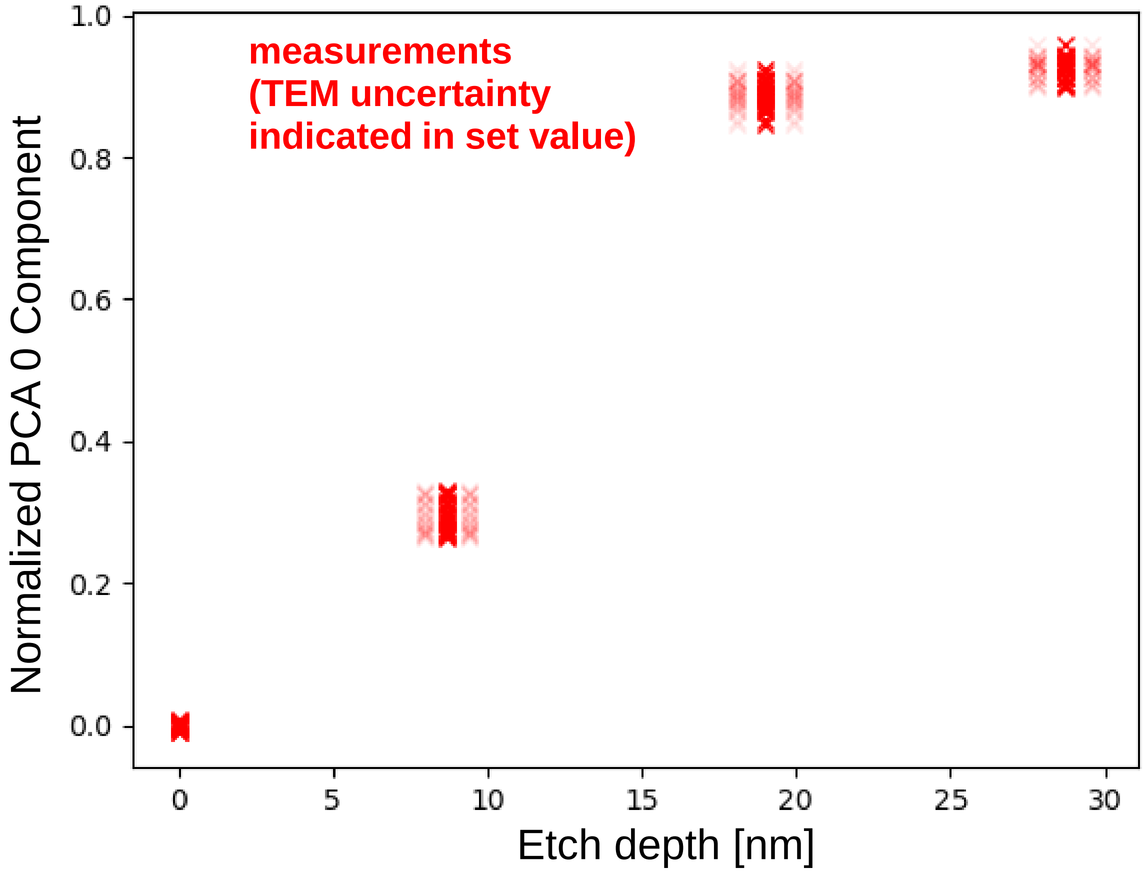
Sensitivity to average recess etch depth & agreement with model confirmed.



Measured: 1 wafer with 4 etch conditions

1D nanosheet lines, 420nm pitch





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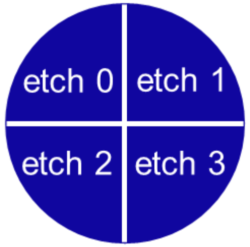

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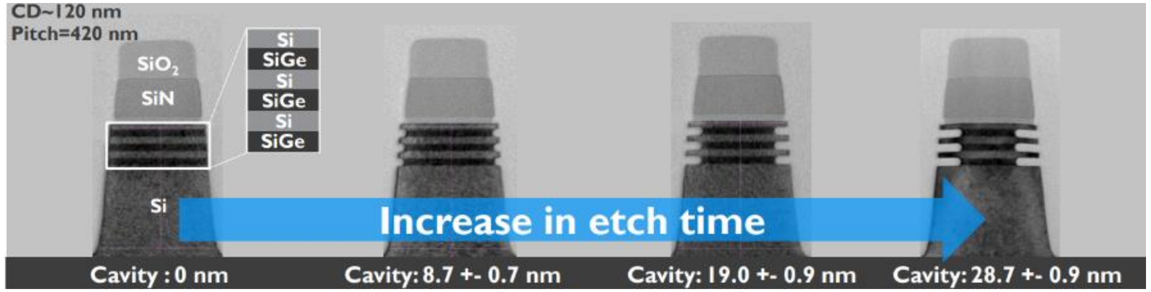
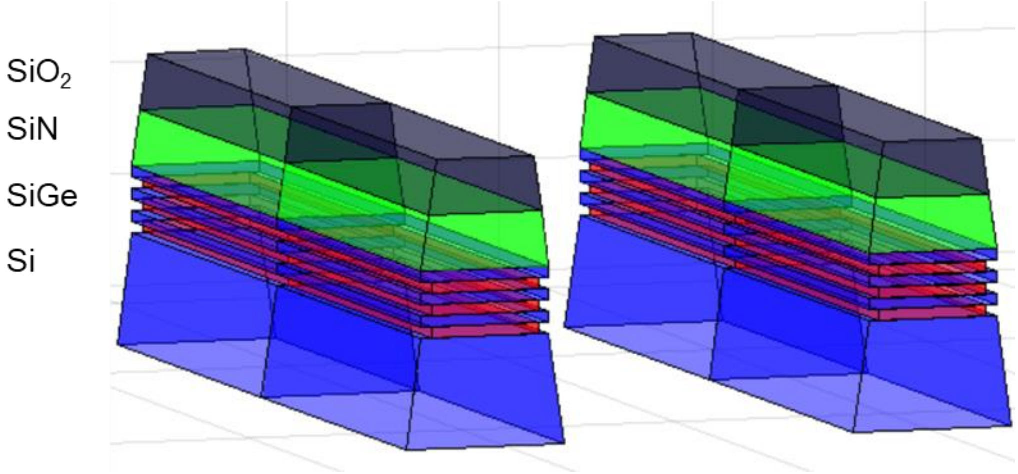
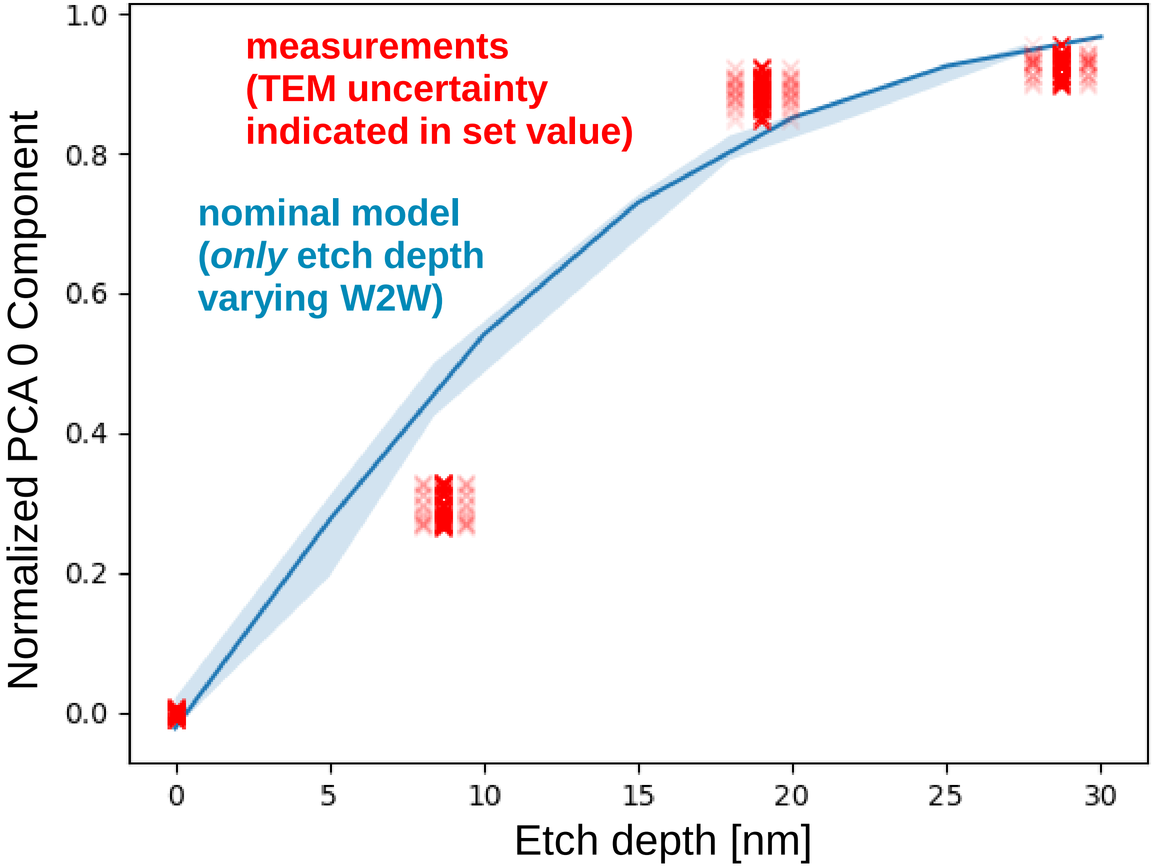




Do PCA on measured data and compare to rigorous models → similar trend as for simulations

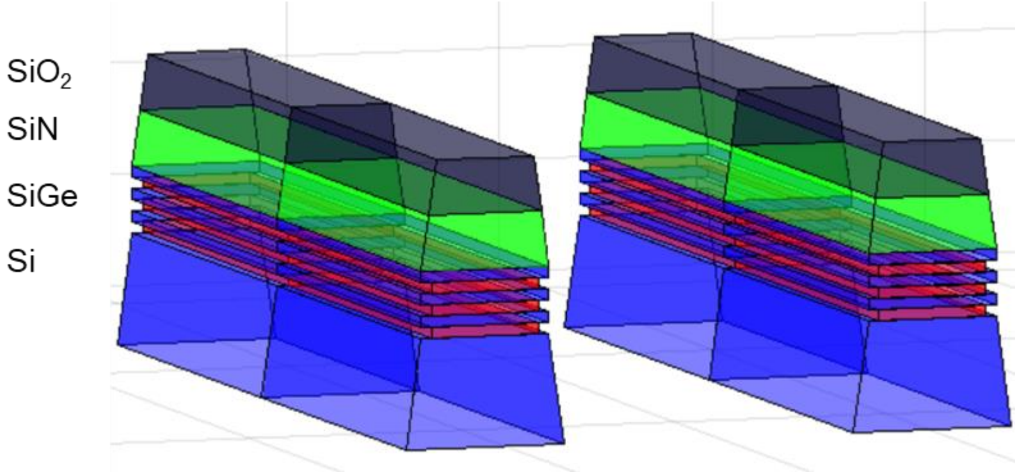


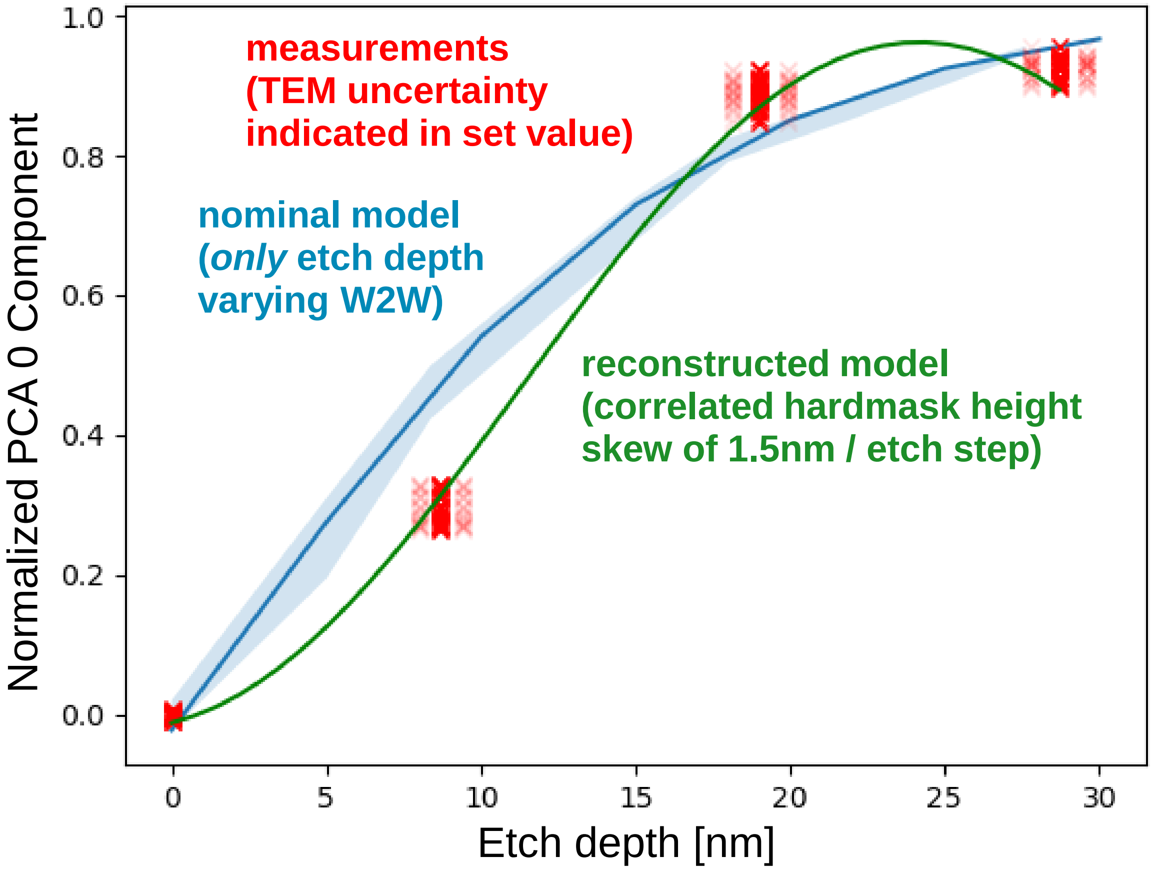
IMEC Nanosheet Measurements

Sensitivity to average recess etch depth & agreement with model confirmed.

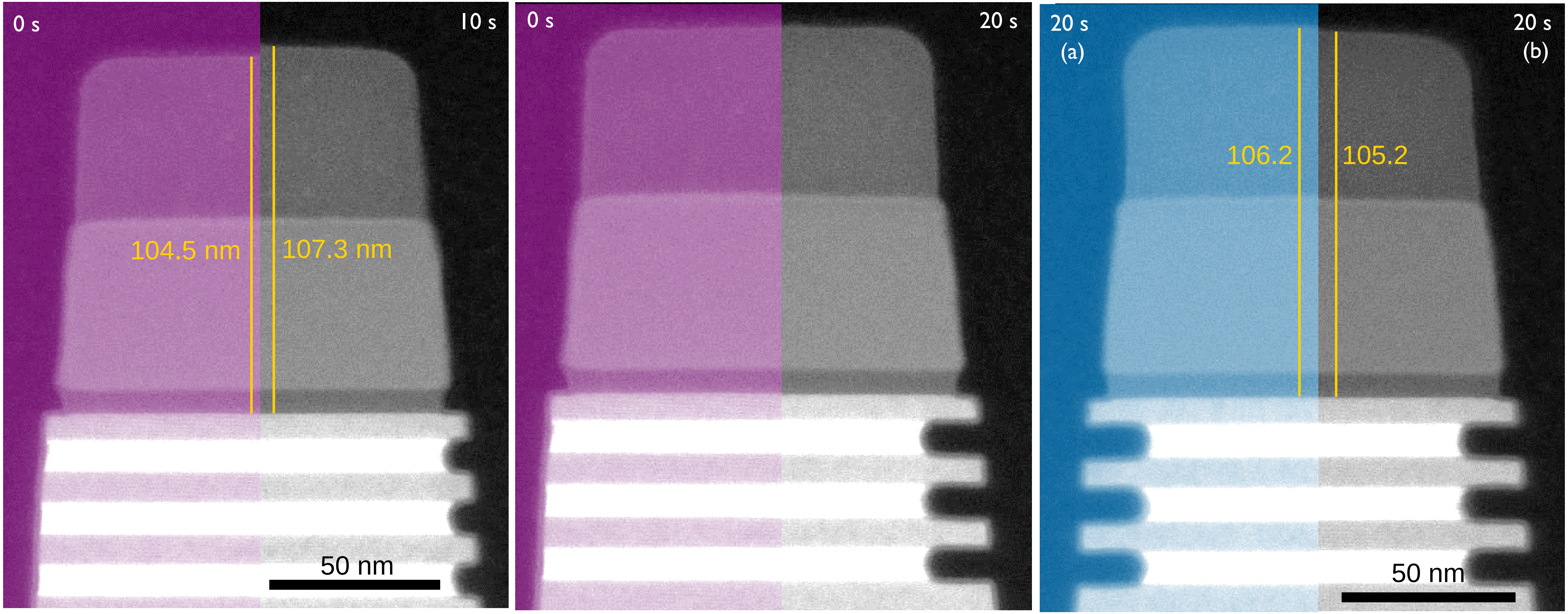
Model based reconstruction via PCA trend fitting enables use of coarse model and minimal sensor calibration.

	Energy in PCA 0	Energy in PCA 1
Measured	**77.8%**	**18.7%**
Nominal simulation, only etch depth varied per wafer	**94.2%**	**5.2%**
Reconstructed model with correlated height skew	**79.2%**	**19.2%**



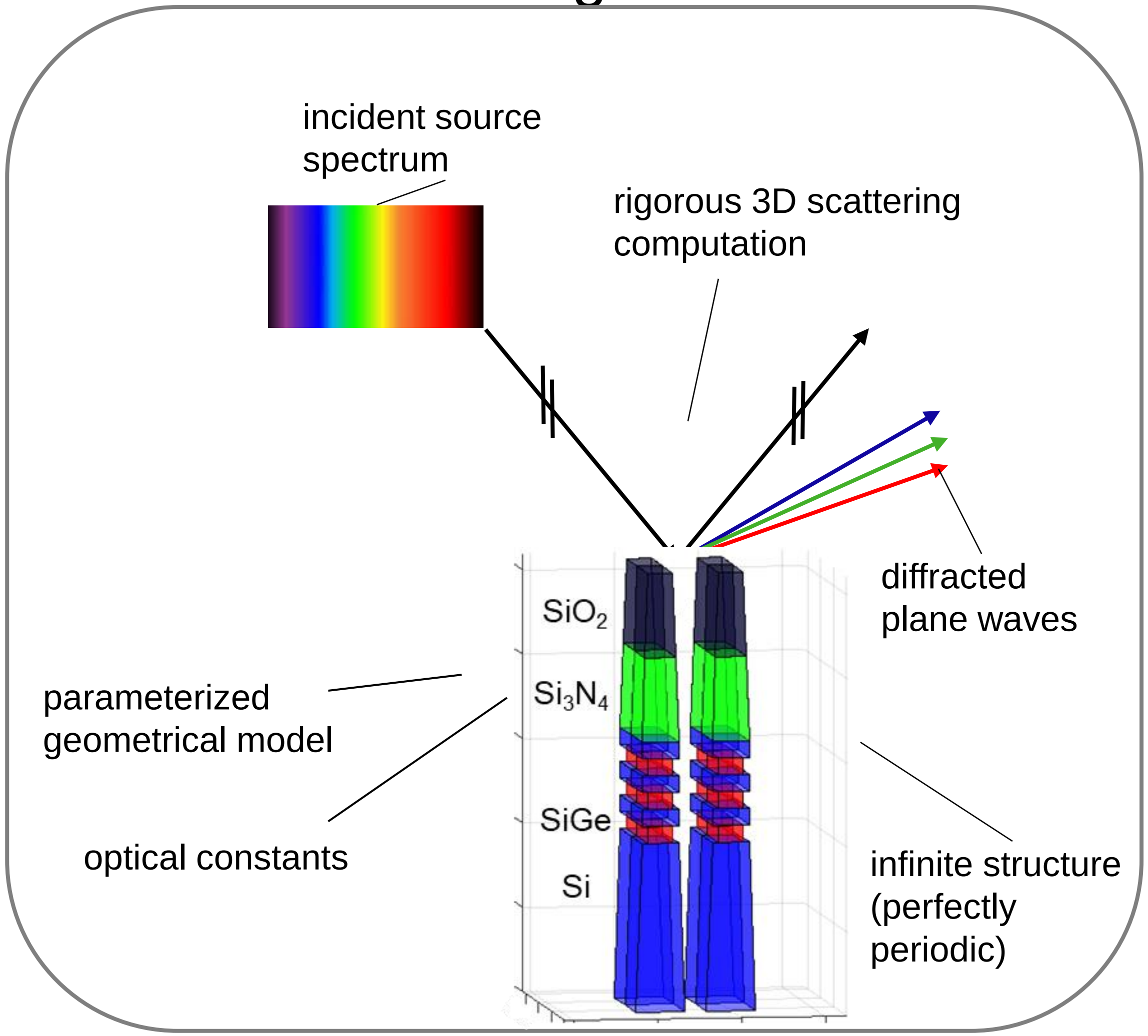


TEMs: Hardmask height appears to vary



Is SXR sensitive to individual layer etch depths at device pitch?

scattering model



incident source spectrum

rigorous 3D scattering computation

diffracted plane waves

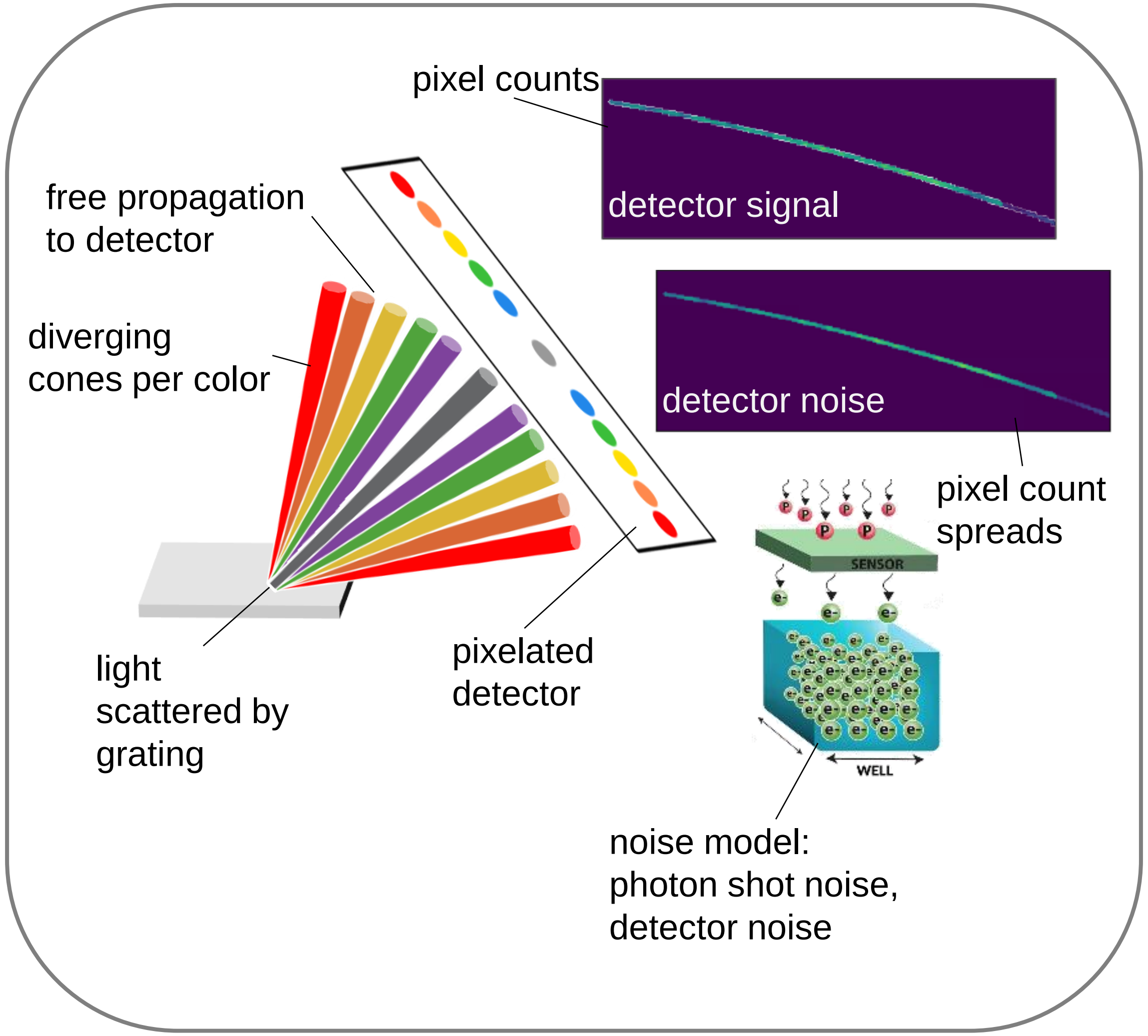
parameterized geometrical model

optical constants

infinite structure (perfectly periodic)

42 nm pitch case

sensor model



pixel counts

free propagation to detector

diverging cones per color

light scattered by grating

pixelated detector

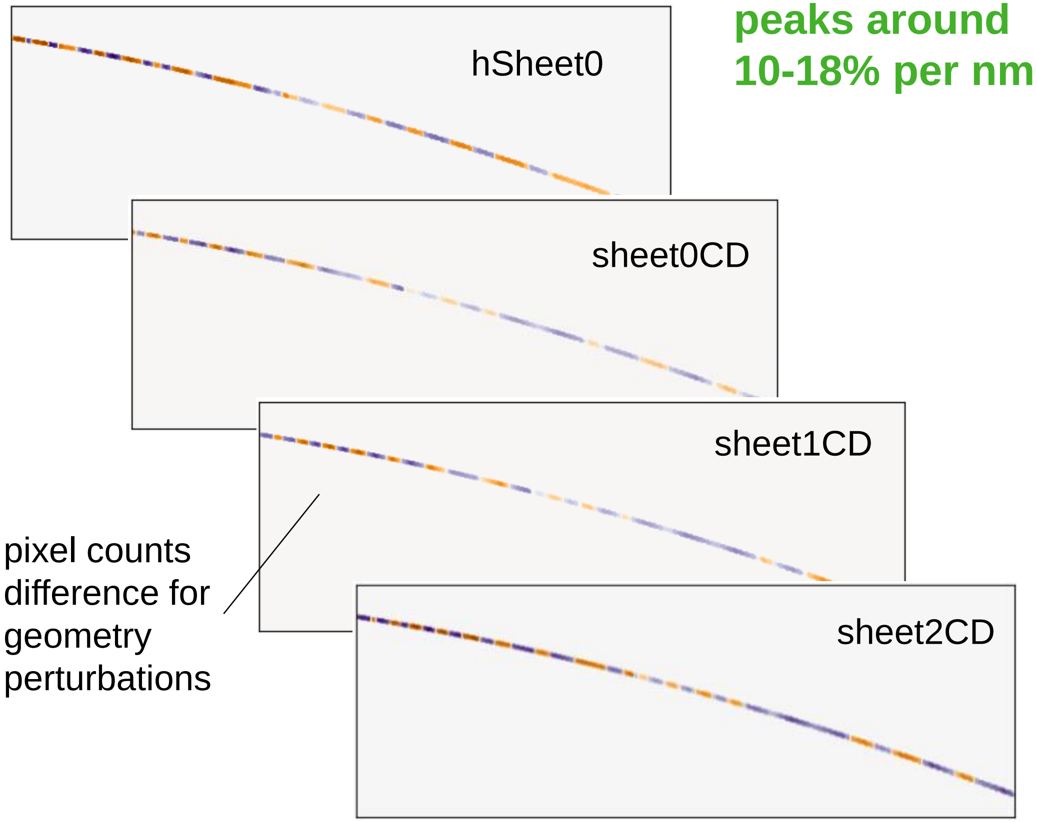
pixel count spreads

noise model:
photon shot noise,
detector noise

Simulation: Individual layer etch depths have unique fingerprints and low repro.

Good sensitivity and parameter decorrelation on nanosheets

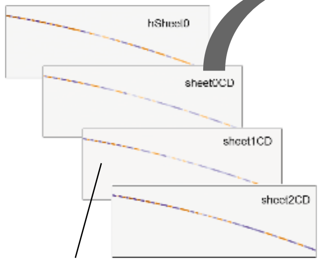
parameter perturbations



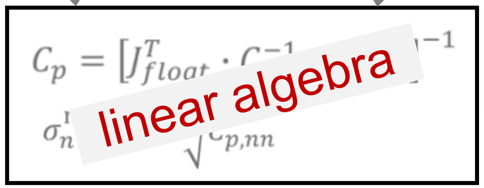
peaks around 10-18% per nm

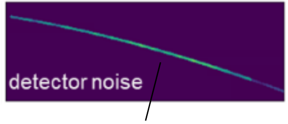
pixel counts difference for geometry perturbations

performance estimate



parameter sensitivities on detector



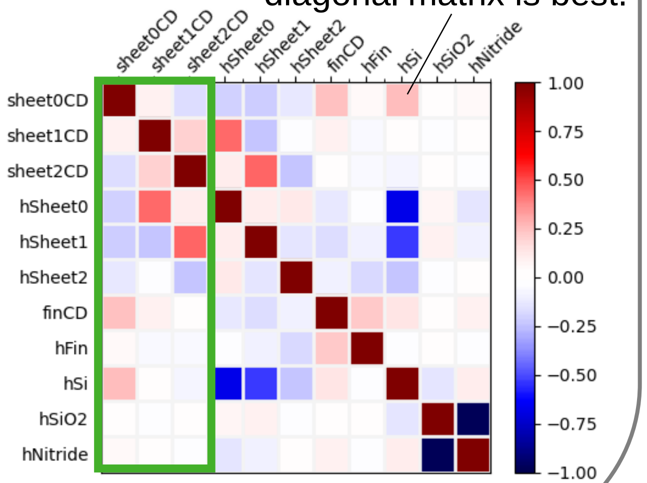


noise on detector

	3σ
sheet0CD (nm)	0.087
sheet1CD (nm)	0.113
sheet2CD (nm)	0.138
hSheet0 (nm)	0.014
hSheet1 (nm)	0.013
hSheet2 (nm)	0.014
finCD (nm)	0.027
hFin (nm)	0.052
hSi (nm)	0.007
hSiO2 (nm)	0.023
hNitride (nm)	0.023

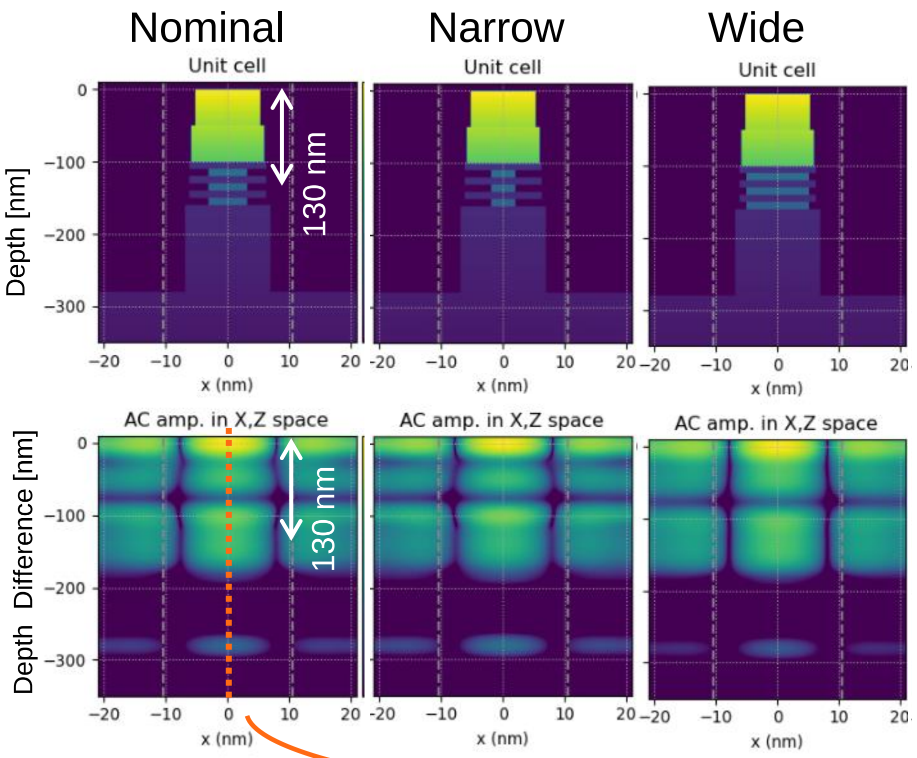
parameter static repro

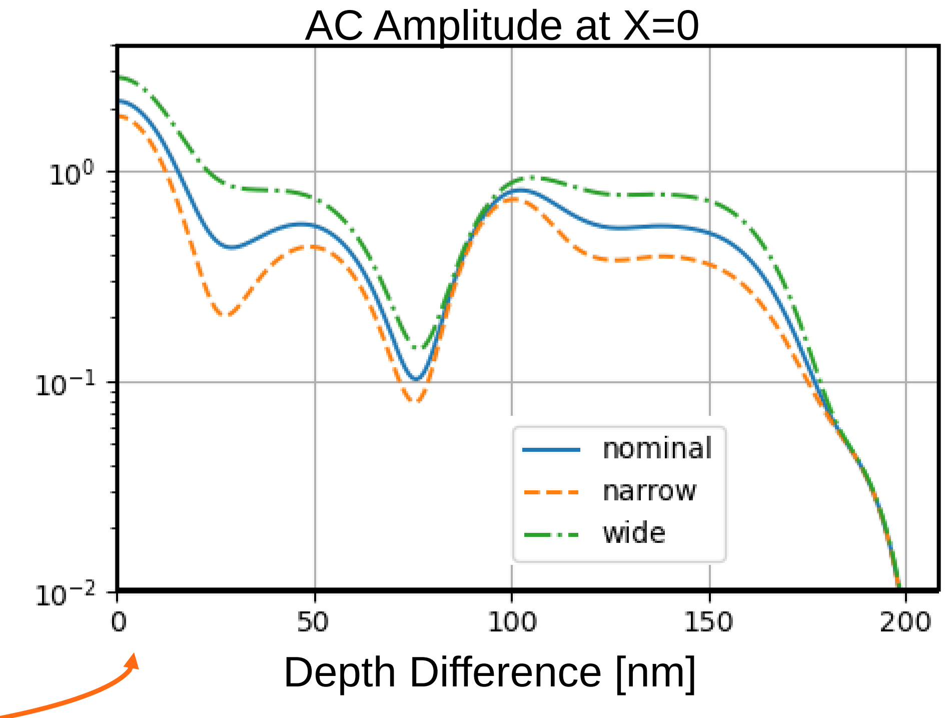
parameter correlations: diagonal matrix is best.



Autocorrelation Simulation: Individual etch depths can be observed

AC space has promise as a well-behaved domain for model-based reconstruction!





- Pitch 42nm.
- Detection NA realistic.
- Realistic n, k for nanosheet materials used (at central wavelength).
- DISCLAIMER: Not a rigorous (Maxwell Solver) analysis. “Toy model” → Born approximation.

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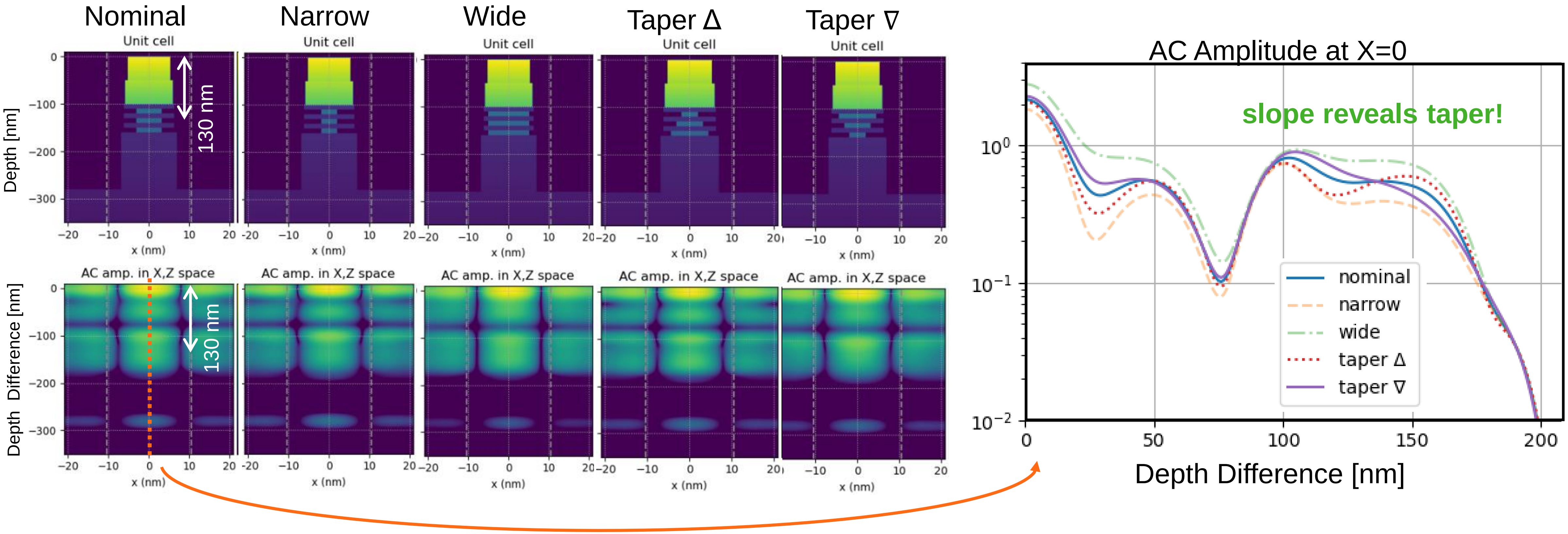

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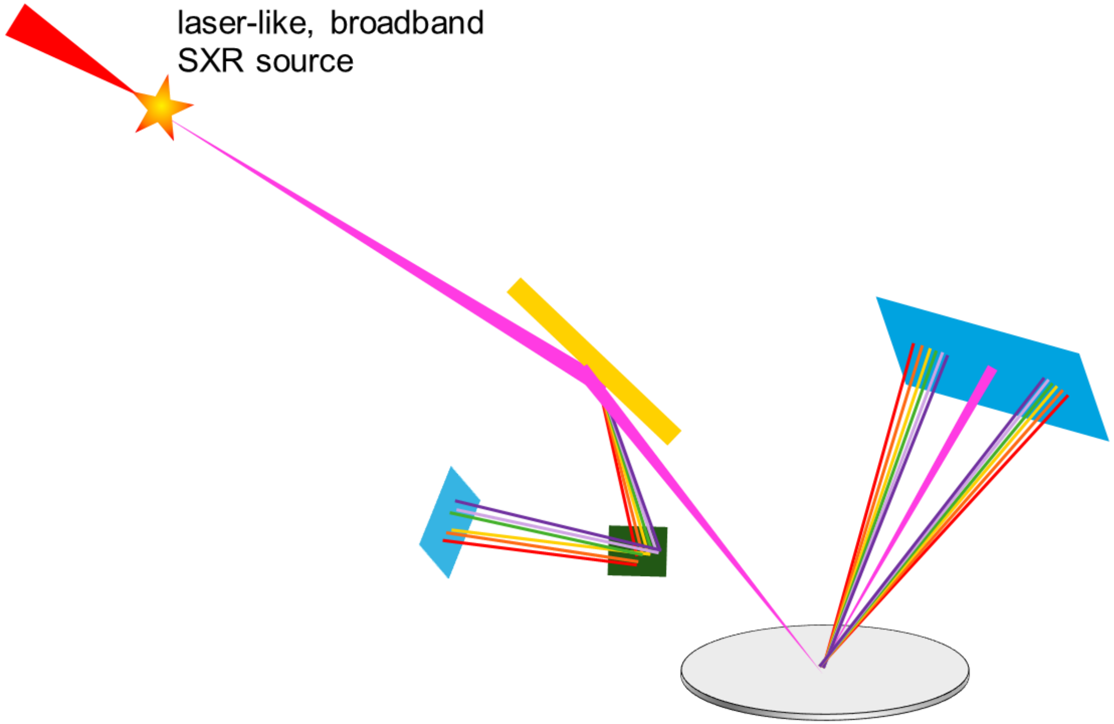
Conclusion

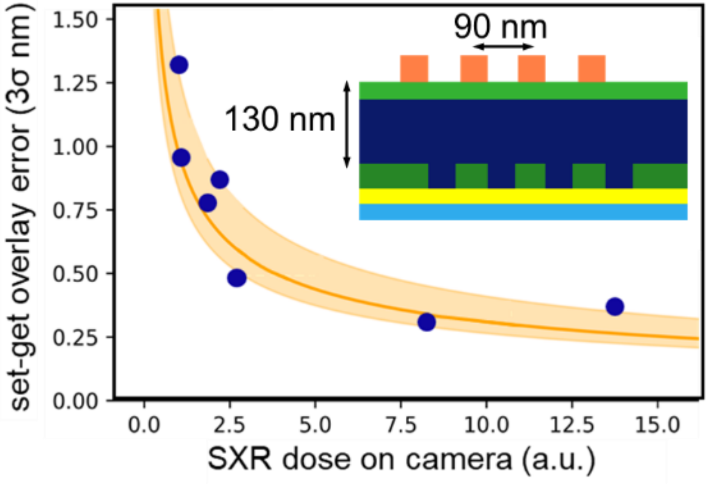
- **Most metrology problems are becoming more 3D**
  - OVL → EPE → 3D EPE
  - FinFETs → Gate All Around

- Soft X-ray metrology shows promise for **device pitch overlay** and **3D profile metrology** on advanced devices, with potential applicability in HVM control settings.

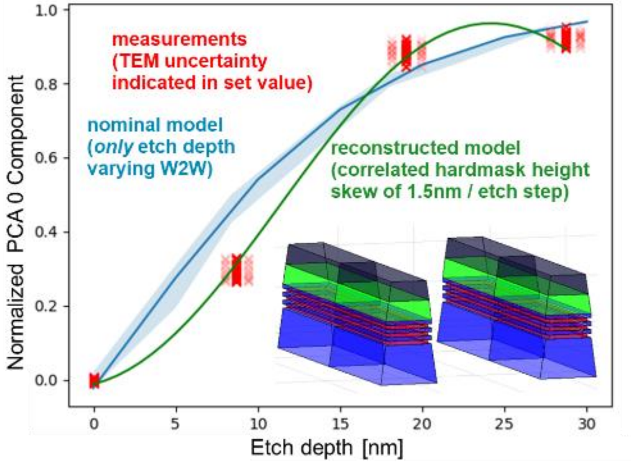
- Contact us if interested in exploring together!



ADI OVL Performance



GAA Recess Etch Depth Inference



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