Hybrid Metrology for Hot Spot Prediction in Post-Etch Patterning

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SandBox Semiconductor

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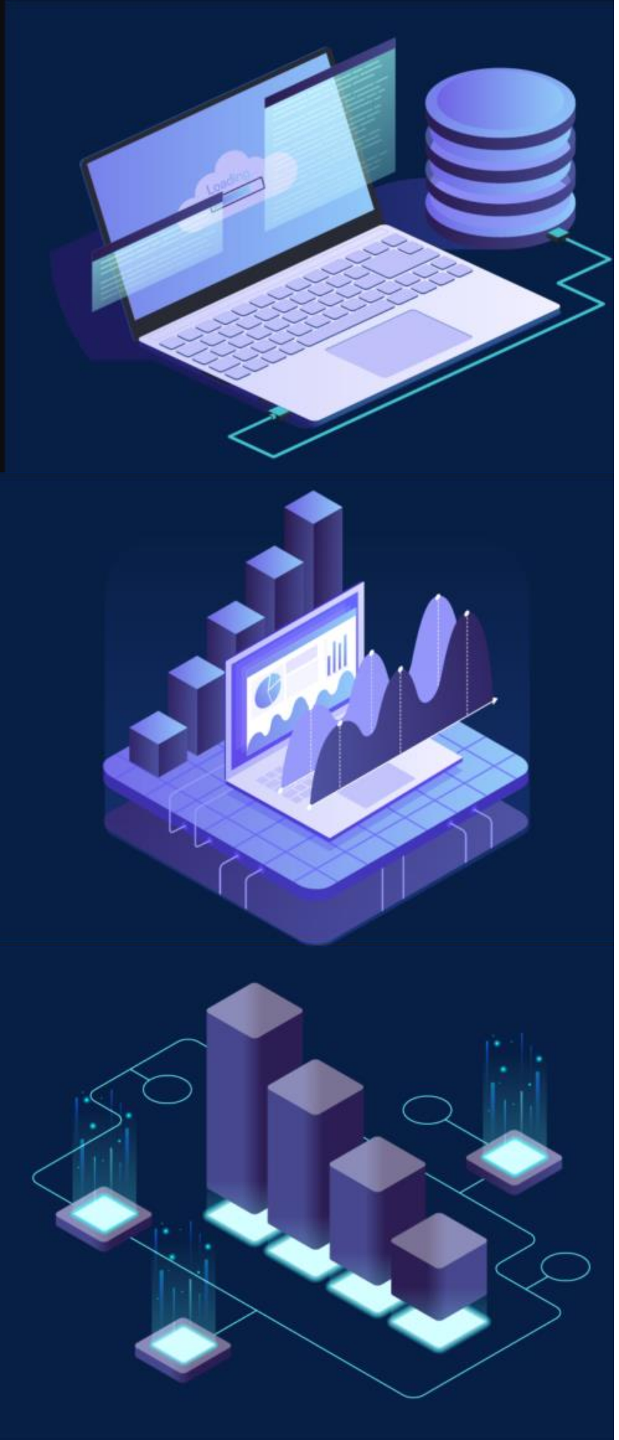

Contents

PROCESS INTEGRATION CHALLENGES

Industry trends

- Process nodes shrink
- Processing steps grow in number and complexity
- The error budget shrinks in every step.
- Processing steps must be co-optimized
- Yield losses and defects must be considered across the entire process.

Modeling will play a key role

Pattern Complexities Impact Etch Hot Spots

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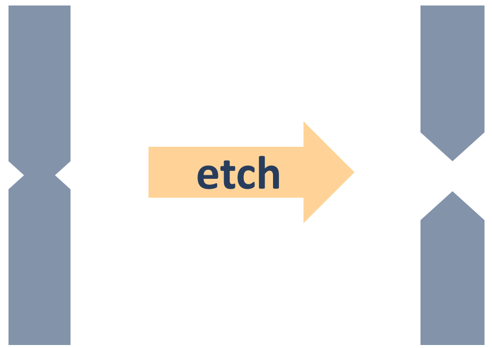
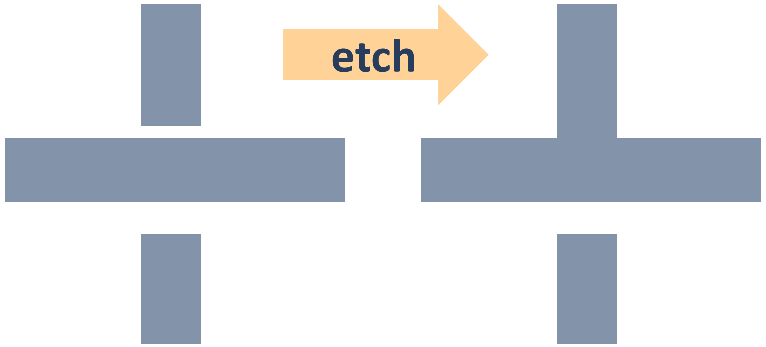
Marginal patterns with higher chance of defects

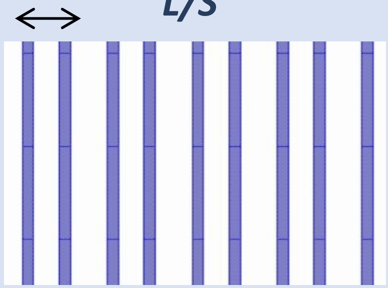
Pinching



Bridging

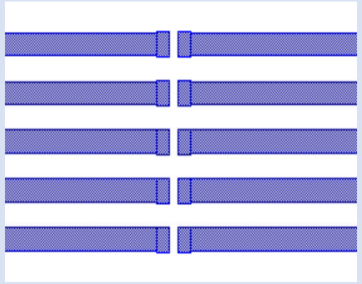


L/S



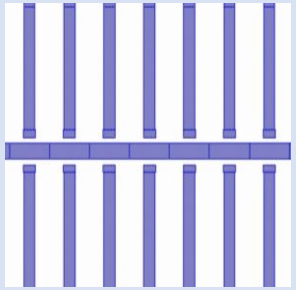
Line spacing variation,
LER, LWR, …

T2T



Tip placement variation

T2L



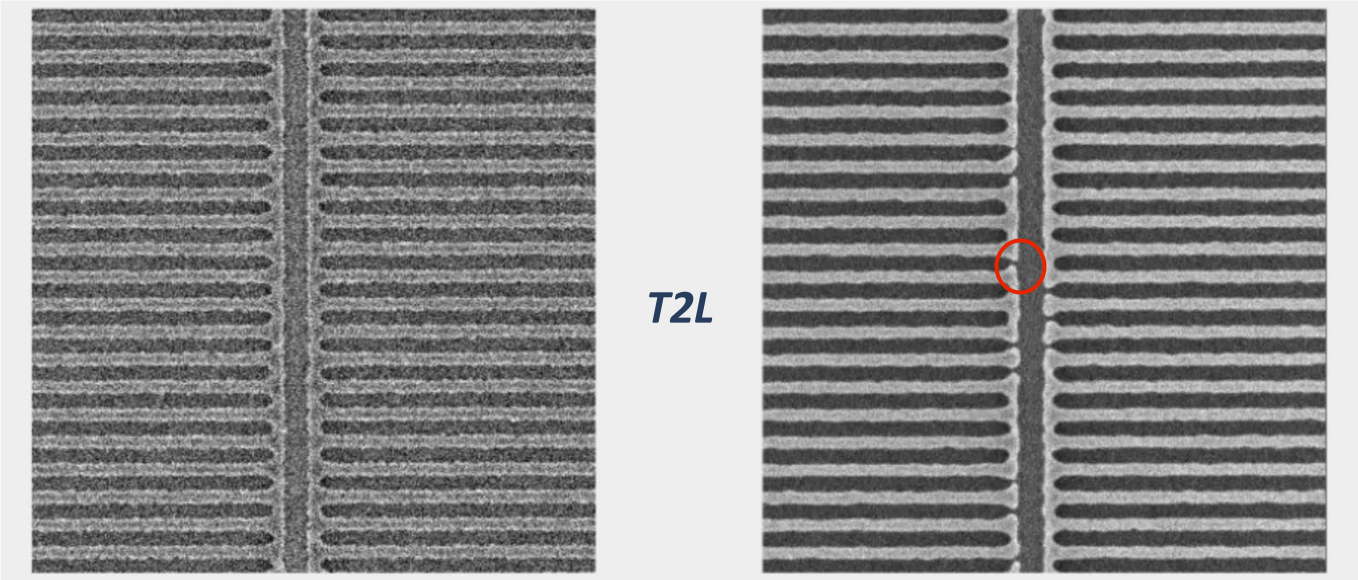
Line and/or tip
placement variation

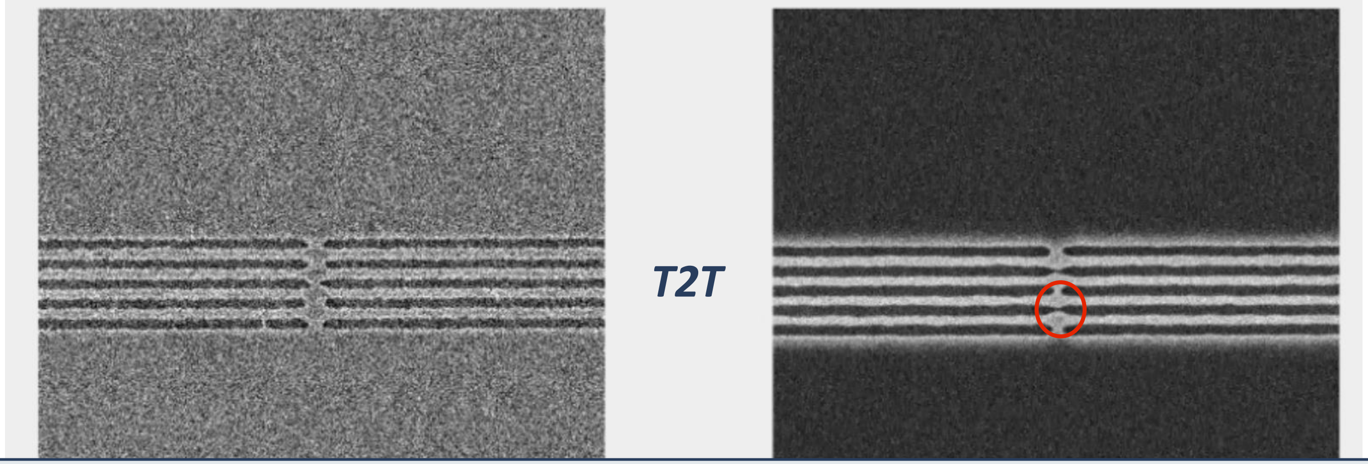
Random Logic

All the above

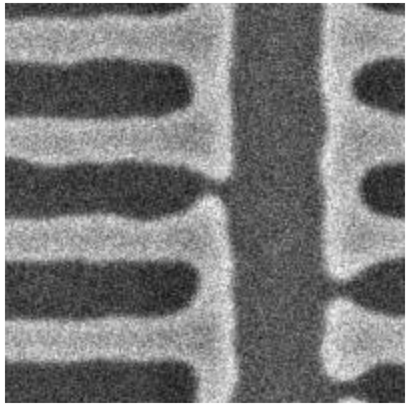
Pattern Complexities Impact Etch Hot Spots

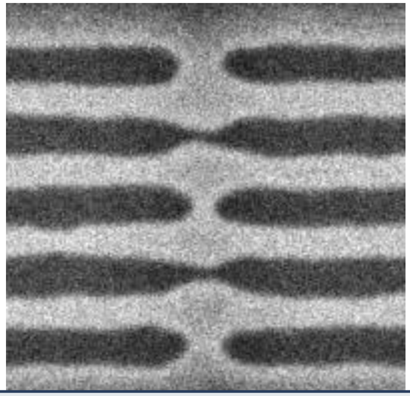
Post-development





Post-etch

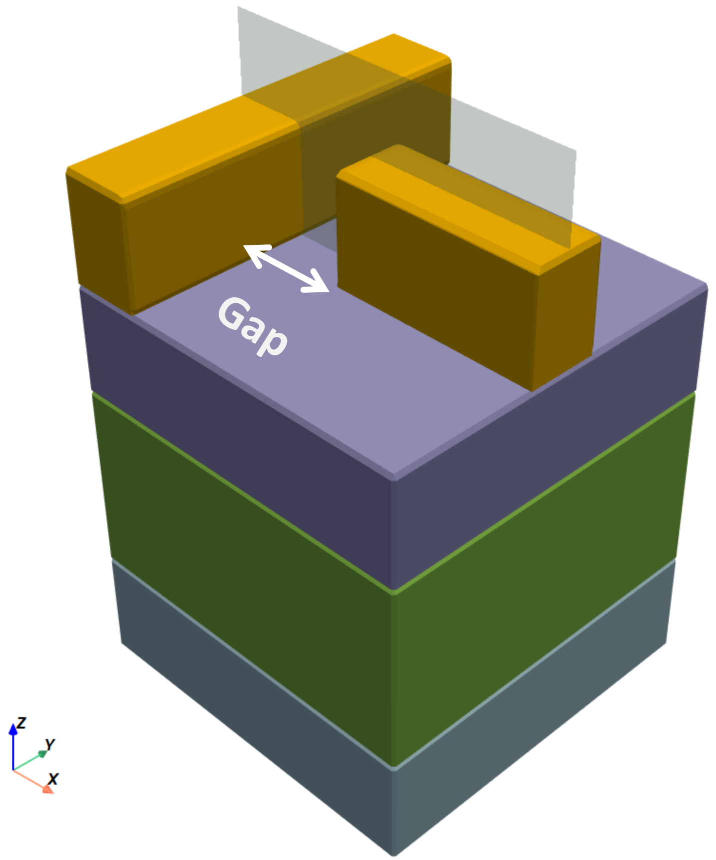




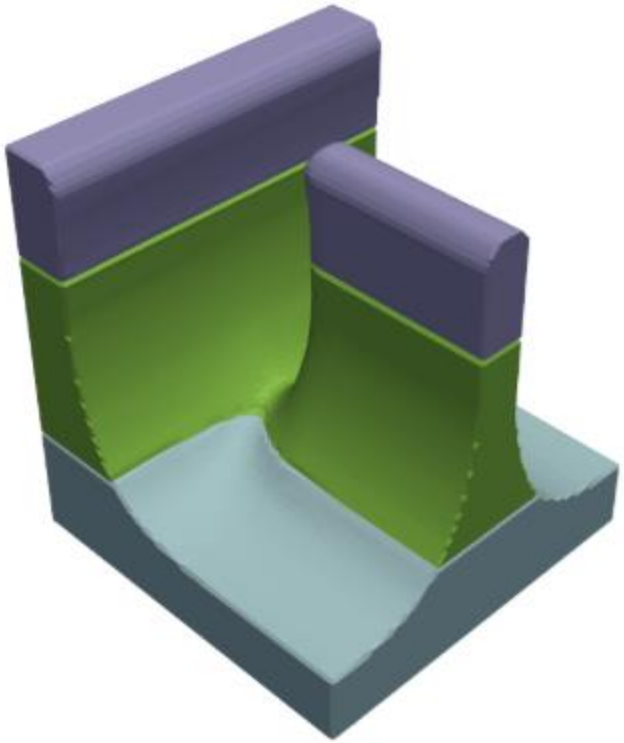
Litho-etch interactions present significant co-optimization challenges

Edge Placement Sensitivity

Post Development



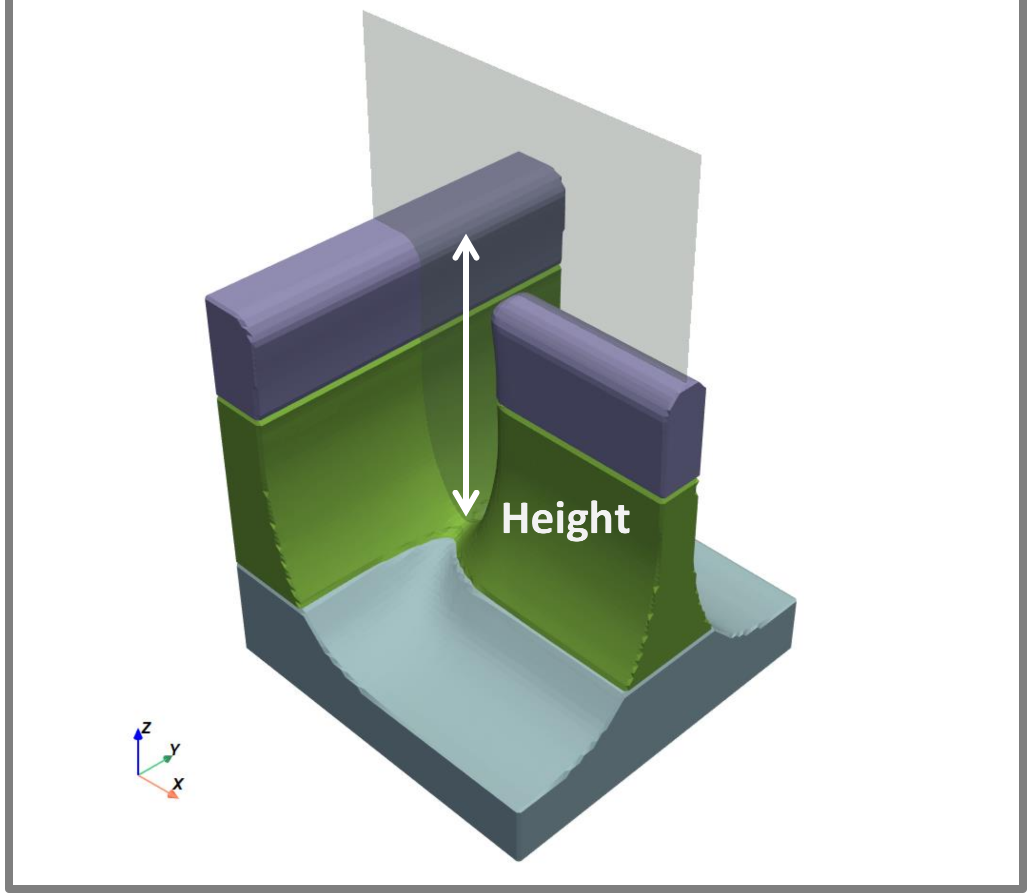
Post Etch

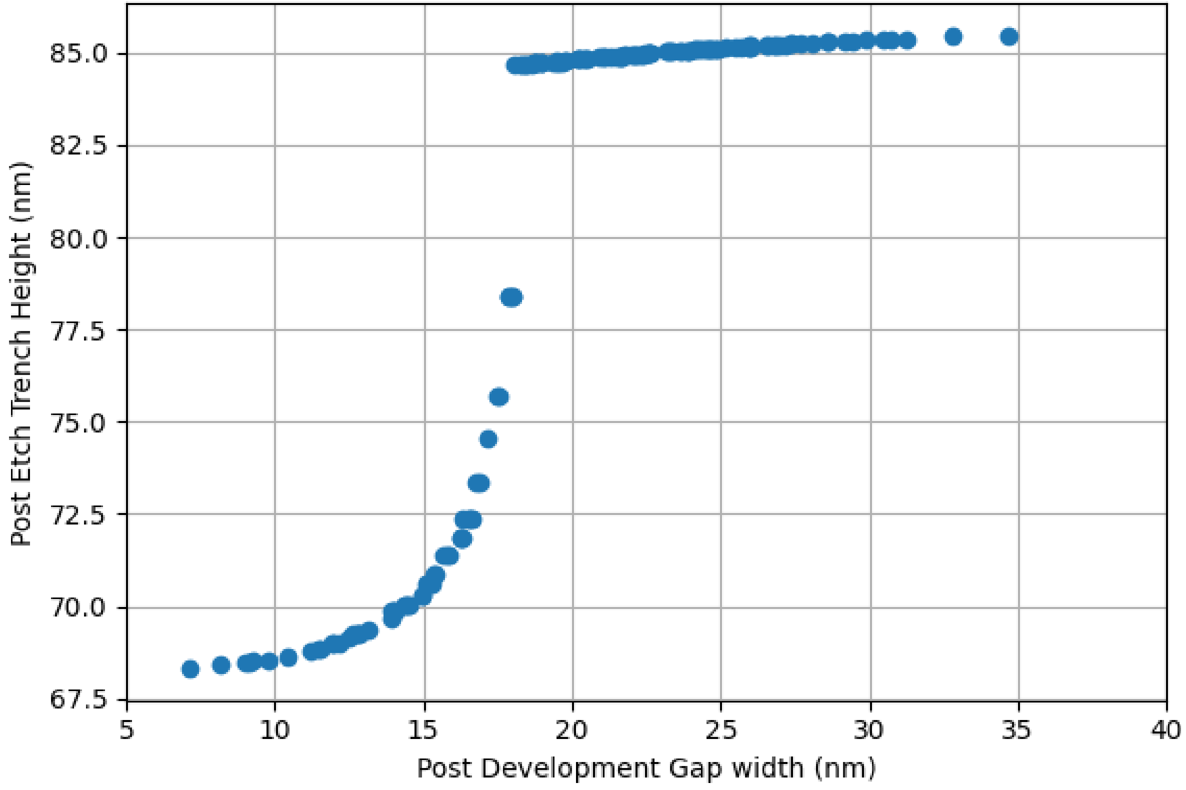


Edge Placement Impacts Local Etch Rate

EDGE PLACEMENT SENSITIVITY

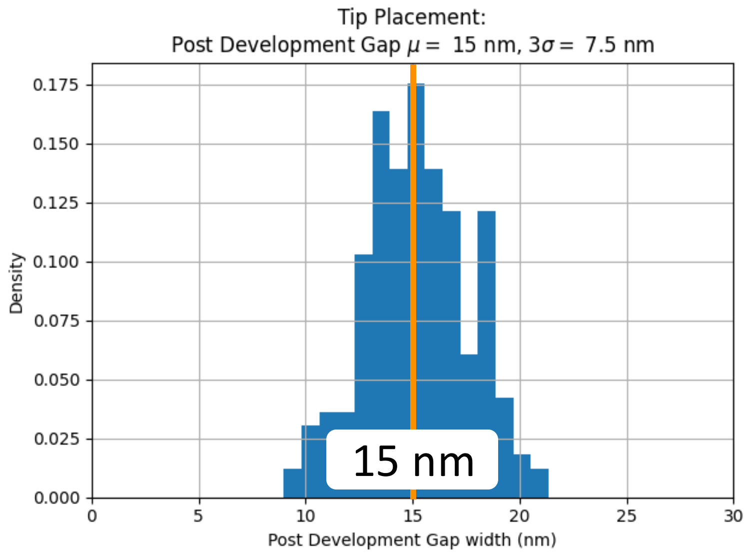
Post Etch

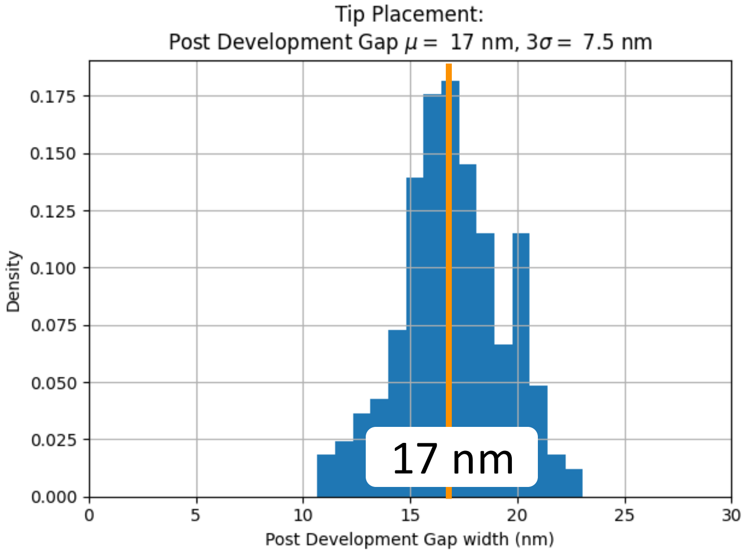




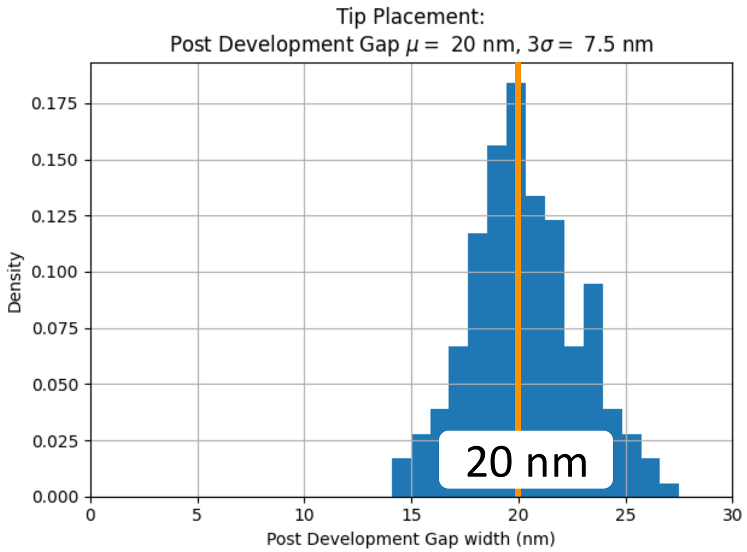
Gap width has clear impact on post-etch trench height. Trench height falls off a cliff when gap width ~18 nm.

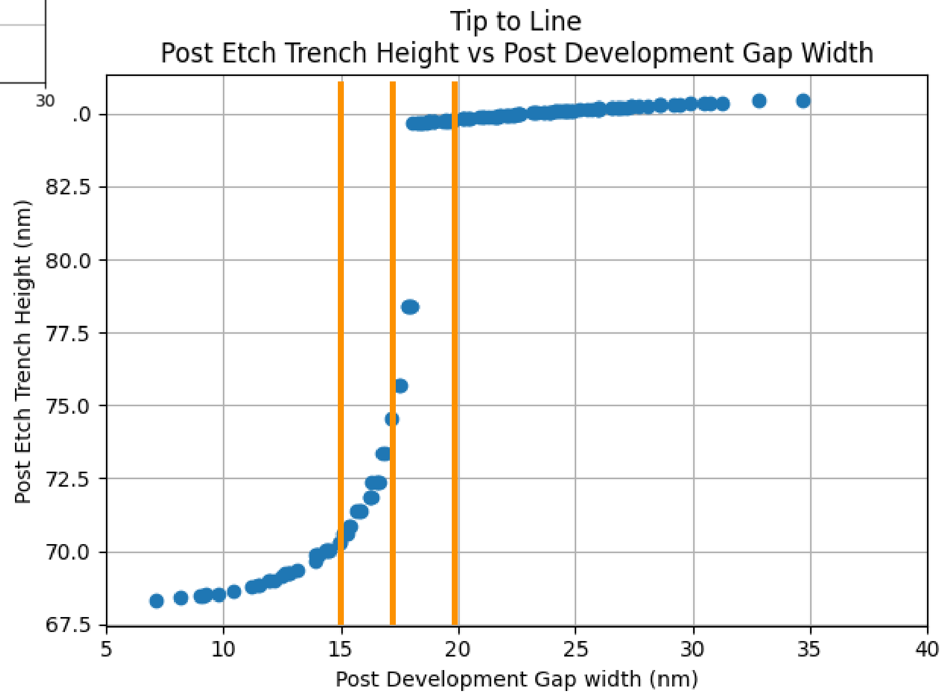
Tip to Line Edge Placement Sensitivity





Cliff for process variation at ~18 nm





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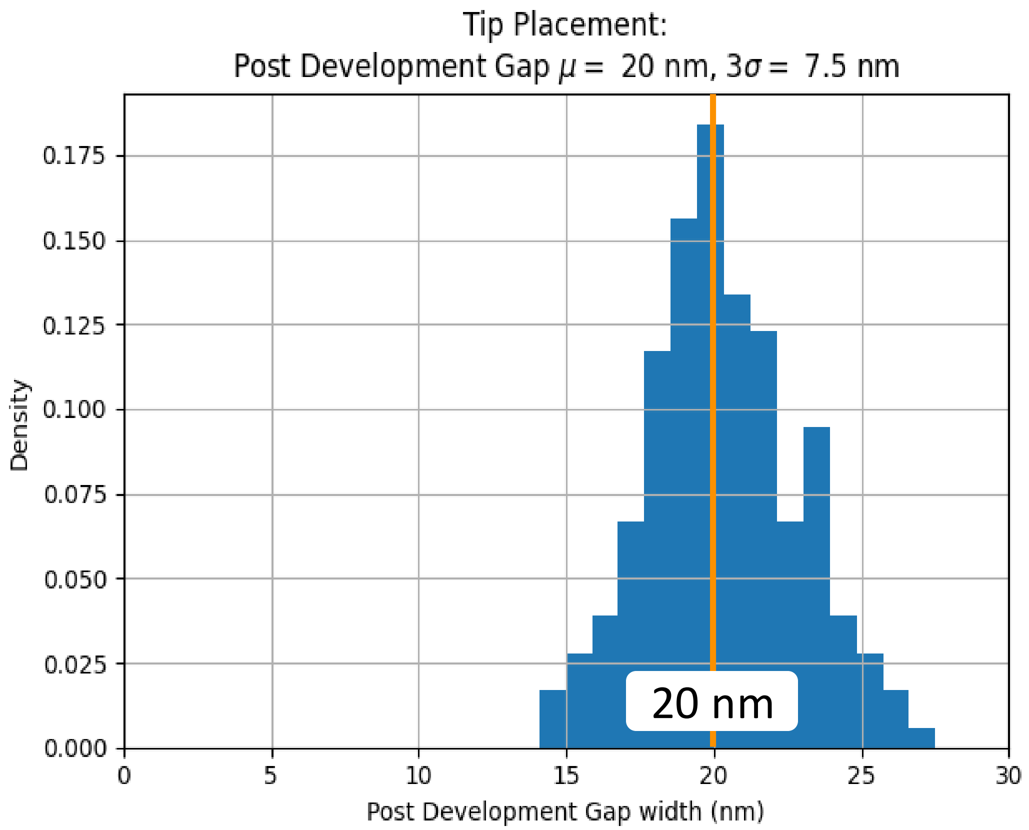
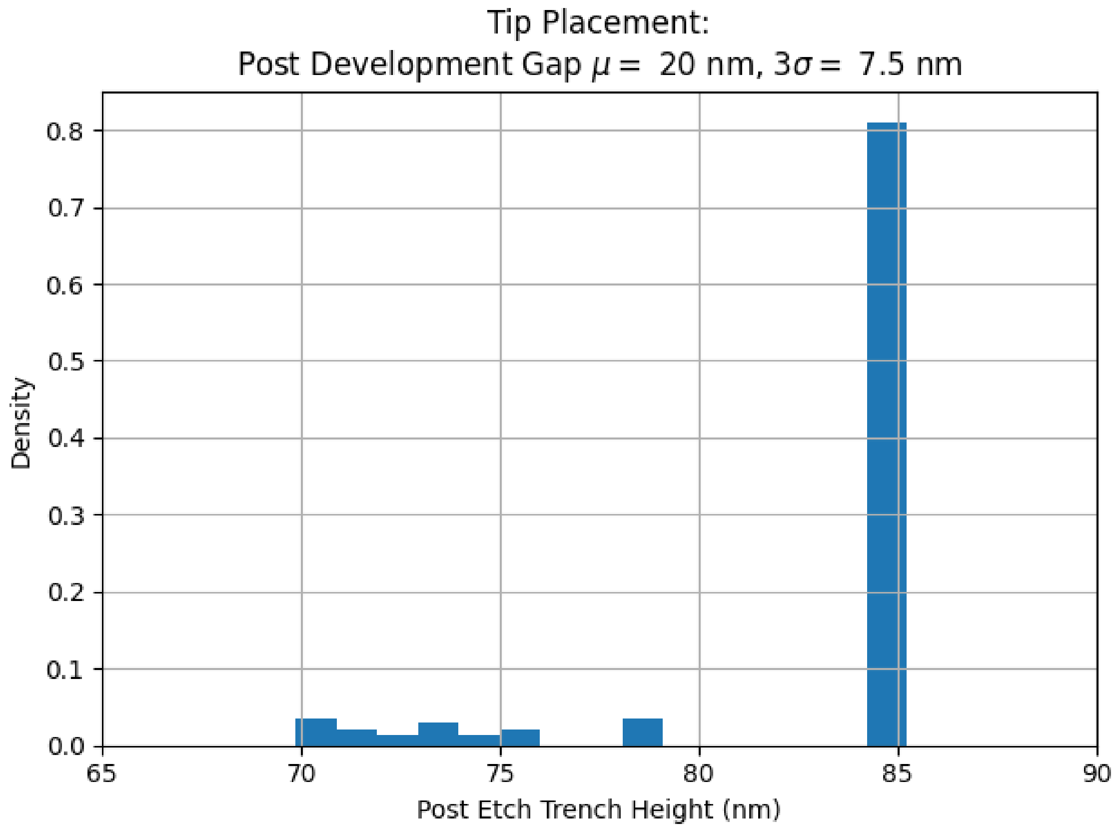
Post Development



Post Etch

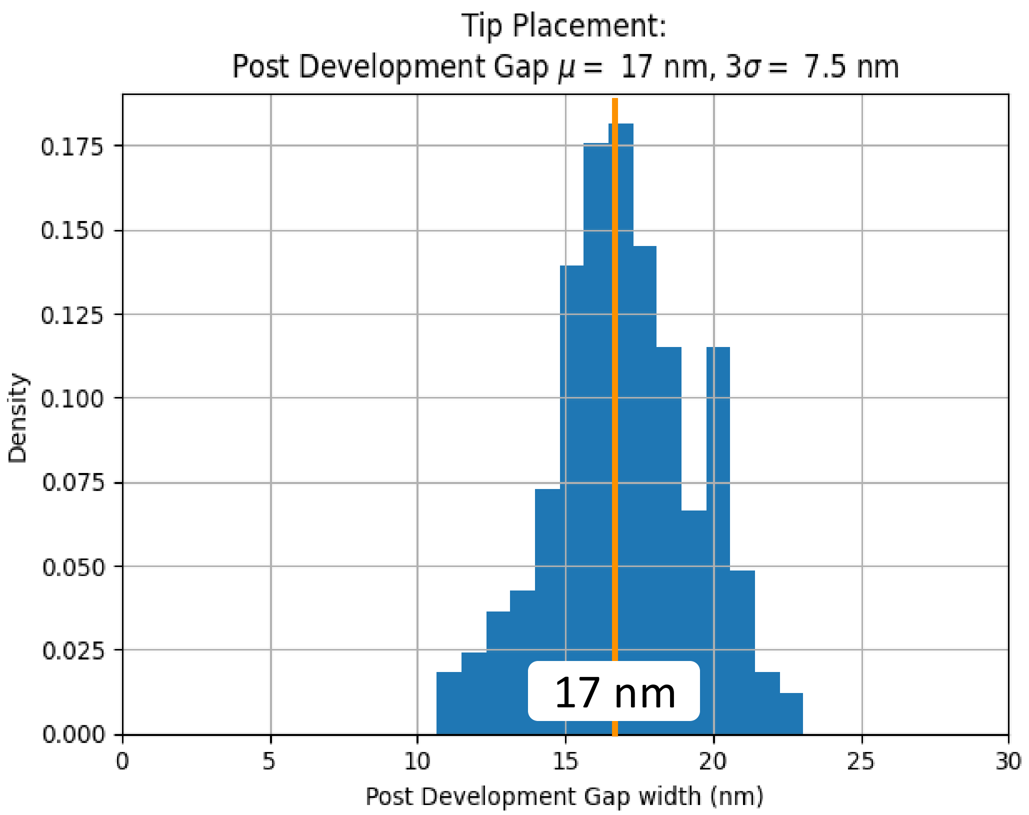


Total 200 Samples

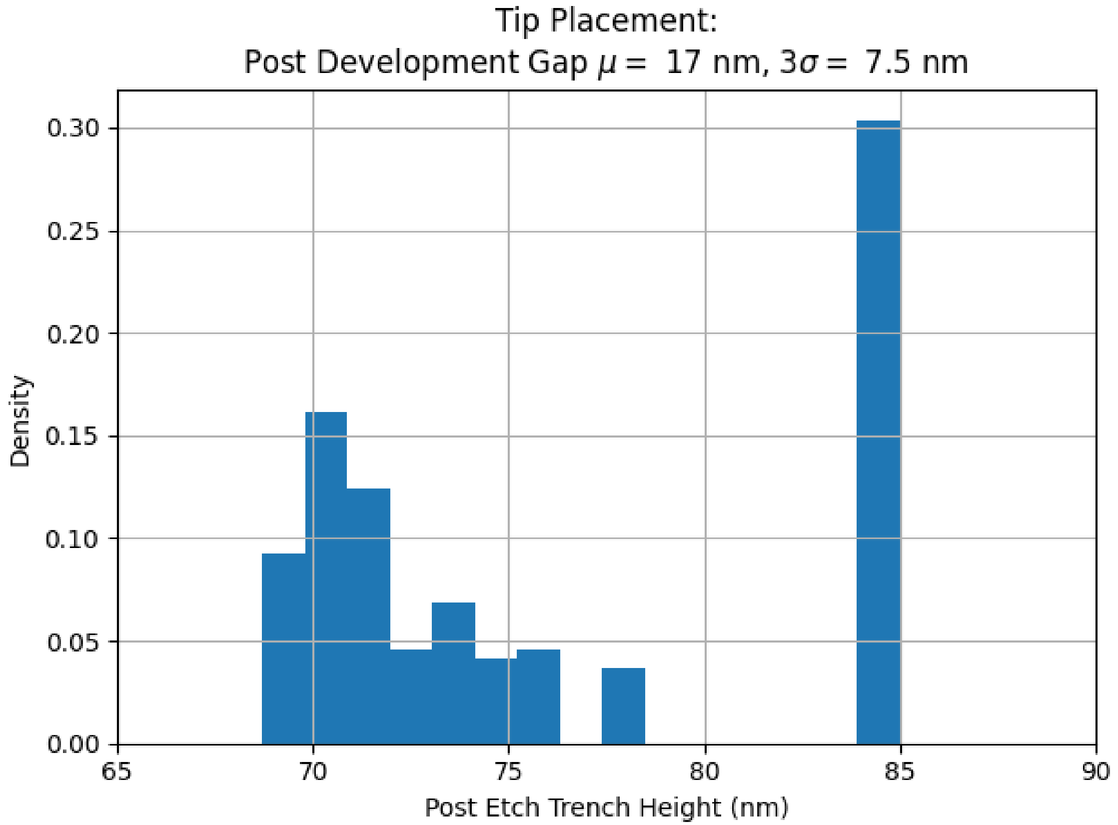
20 nm gap is minimally impacted by process variations

Tip to Line Edge Placement Sensitivity

Post Development



Post Etch

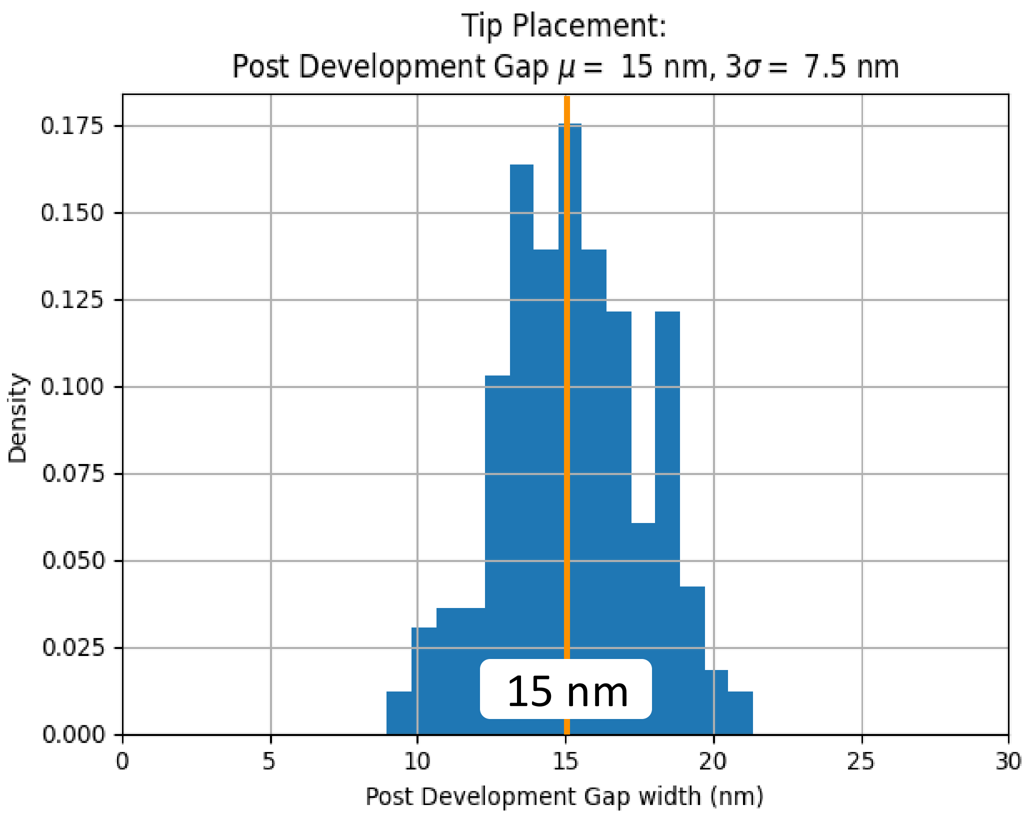


Total 200 Samples

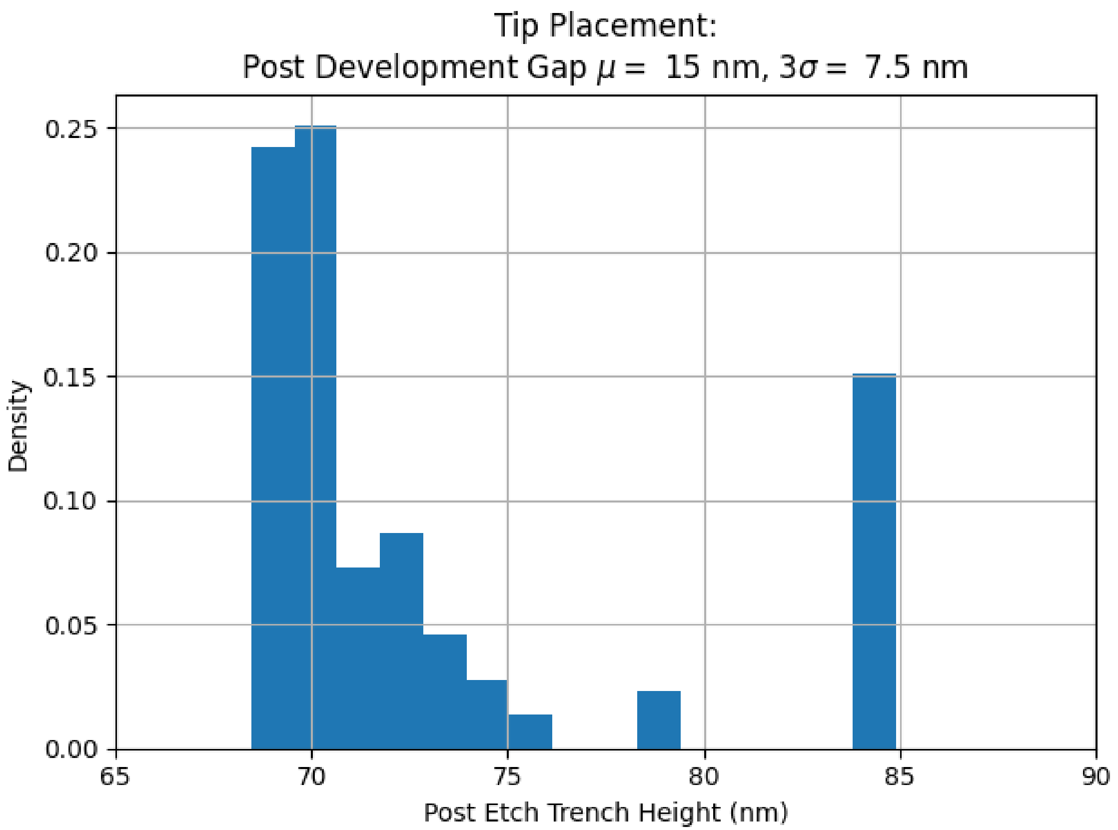
17nm gap is more sensitive to process variation and shows reduced yield.

Tip to Line Edge Placement Sensitivity

Post Development



Post Etch



Total 200 Samples

15 nm gap is highly sensitive to process variations and shows poor yield.

CHALLENGES OF METROLOGY

Defect characterization requires robust, reliable, scalable metrology

Traditional metrology	Solution
▪ Slow (XSEM, TEM) ▪ Low-res (XSEM, CD-SEM) ▪ Dedicated design (XSEM, OCD) ▪ Single 2D plane (XSEM, TEM, CD-SEM) ▪ Destructive (XSEM, TEM, delamination, CD-SEM)	?

Different techniques must be combined to mitigate weaknesses

What do you mean "model"?

Critical components for model-assisted recipe development

Adaptive Experimental Design

- Traditional experimental designs are static
- When stack geometries change, materials are adjusted, and/or tools drift, designs typically need to be repeated

→ *Models must tolerate change*

Holistic Metrology

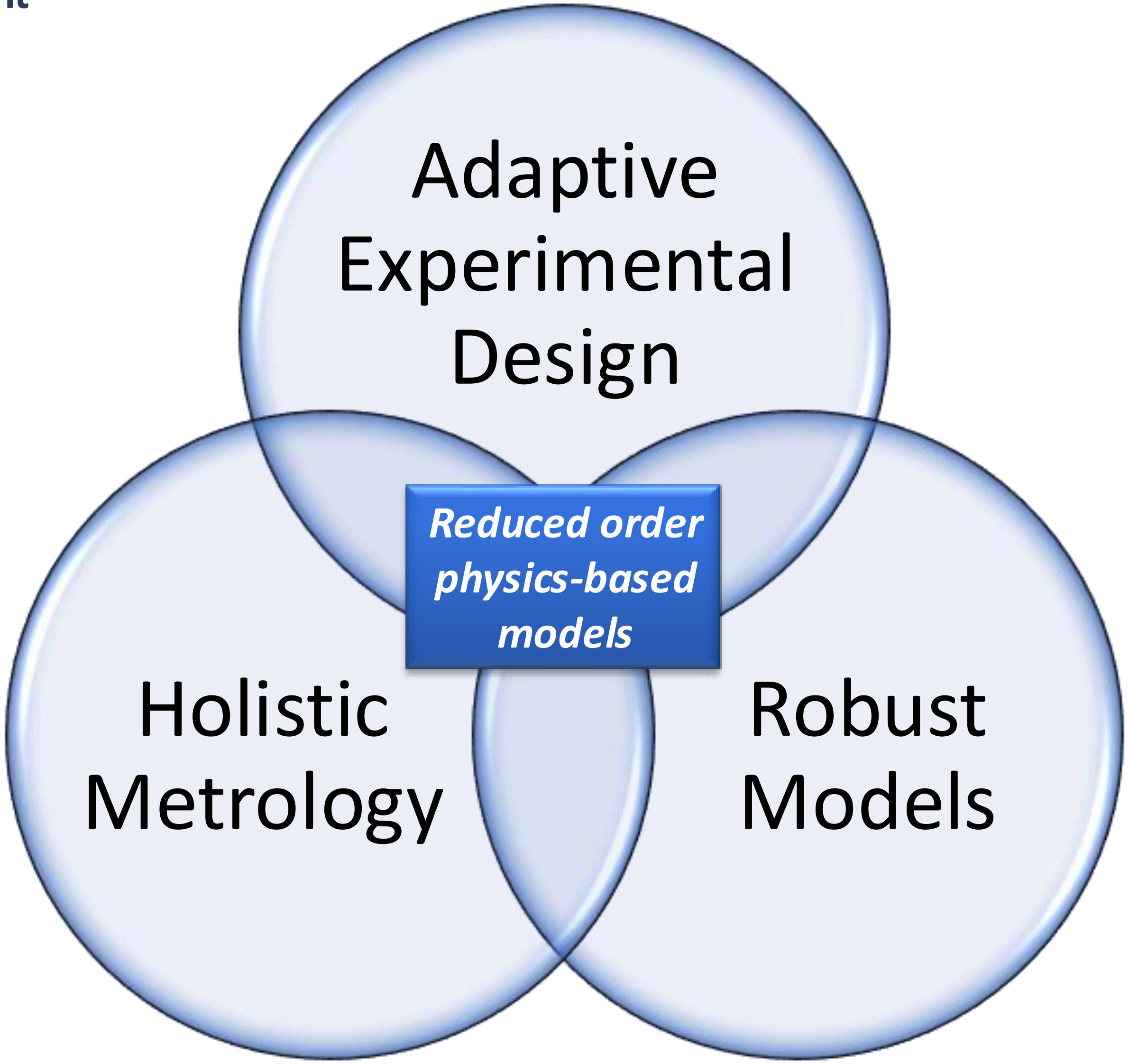
- Models need a lot of measurements
- Many metrology tools are conflicting

→ *Models must make sense of conflicting measurements*

Robust models

- Models need to make predictions with accuracy
- Models must be economically feasible to build
  - Models should be tolerant of IP concerns

→ *Models must balance accuracy and data/compute availability*



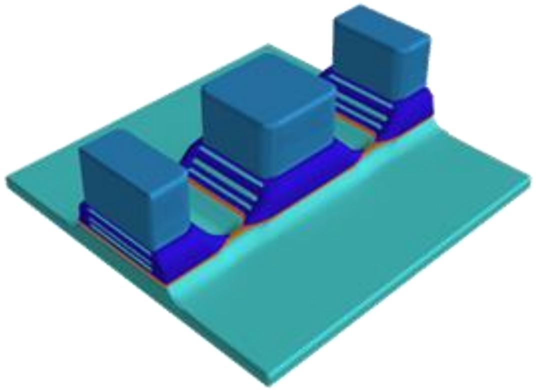
Physics-enhanced AI Hybrid Metrology

Inputs

- Initial Geometry
- Process Behavior
- Metrology:
  - CD-SEM
  - X-SEM
  - AFM
  - …

SANDBOX STUDIO AI

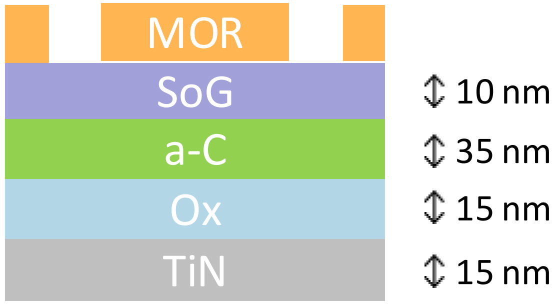
3D Profile Reconstruction = f(Metrology, Physics)



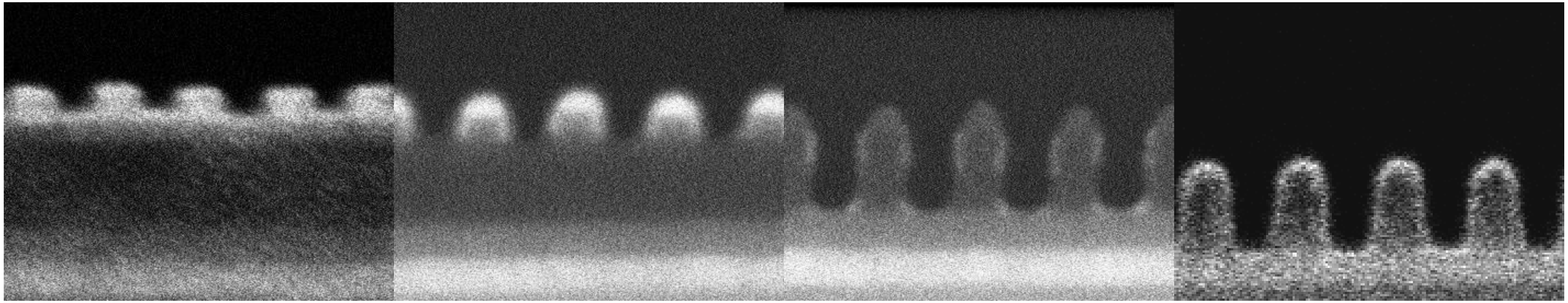
- *Physics AI model is calibrated based on given metrology input*
- *Calibrated model can be used to make predictions on new geometries (given the same etch or deposition process)*

EXPERIMENTAL CASE STUDY

Predicting Profile Evolution Across a Multi-step Etch Process



Post Litho → Post SOG Etch → Post a-C Etch → Post Ox Etch

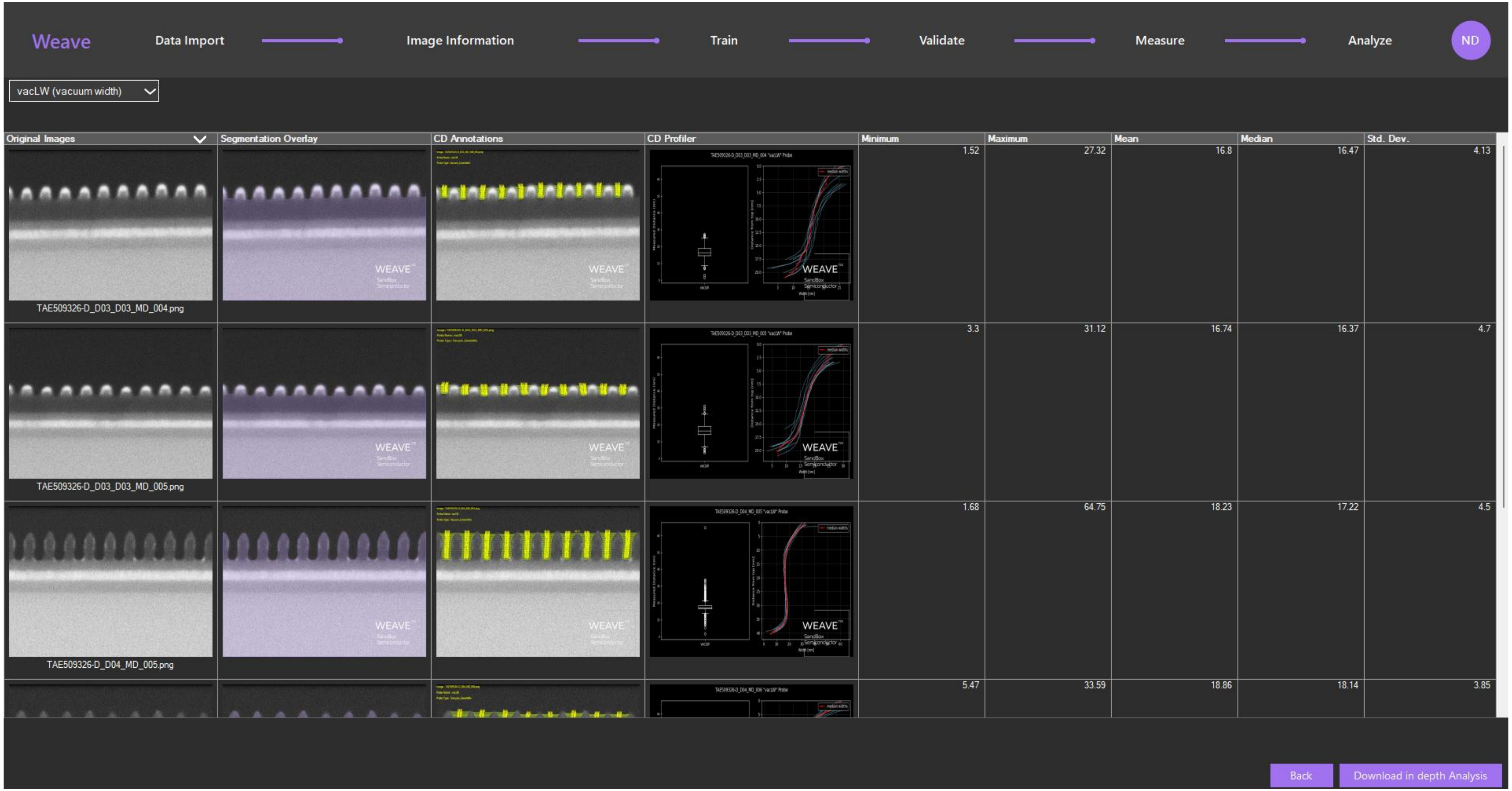


Target application includes as multi-step etch process over an SoG, a-C, and Ox.

X-SEMs after each etch step were provided by imec.

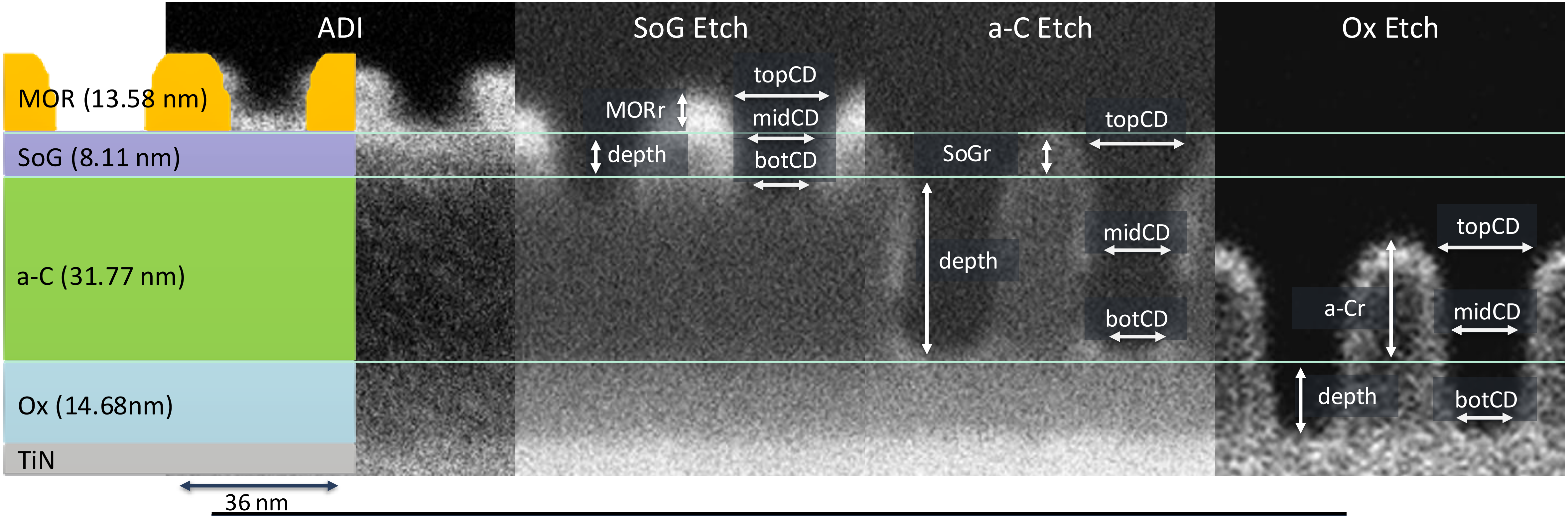
AUTOMATED MEASUREMENT EXTRACTION WITH WEAVE™

Using AI-enabled Image Segmentation Weave™ can extract hundreds of measurements instantaneously



EXPERIMENTAL CASE STUDY

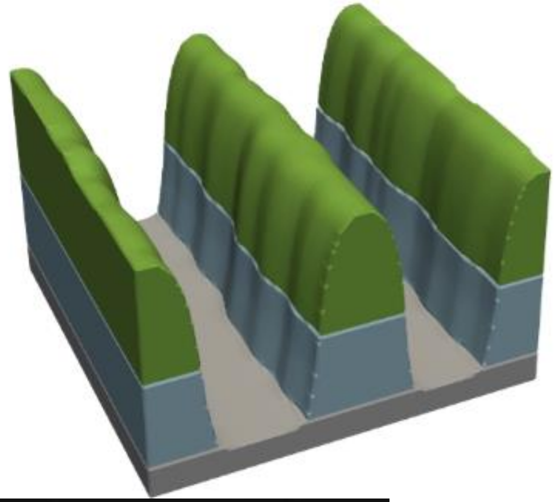
Model was calibrated using a single series of X-SEMs from a linespace pattern

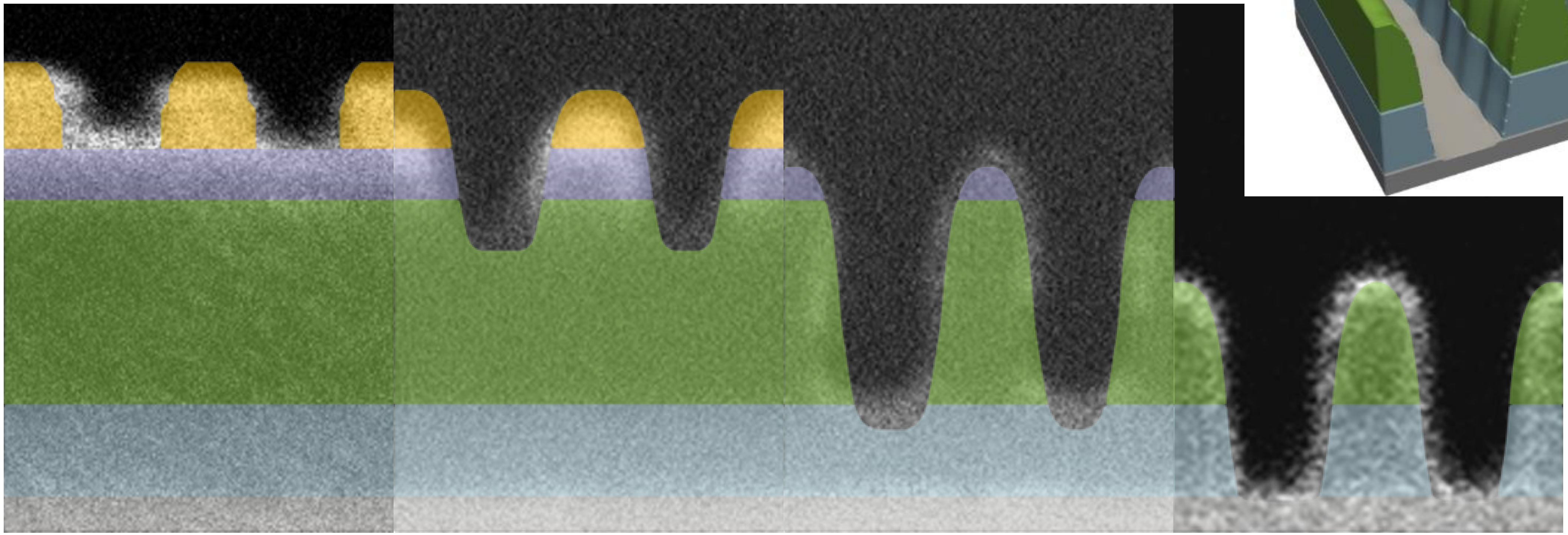


Step	Etch Time	topCD	midCD	botCD	depth	MORr	SoGr	a-Cr
SoG	115	20.0	12.75	10.0	15.5	5.3	8.1	31.7
a-C	115	24.01	16.56	13.42	28.4	0	4.8	31.7
Ox	115	22.44	16.72	12.88	14.0	0	0	19.1

Physics AI model constructed using metrology from line-space pattern X-SEMs.

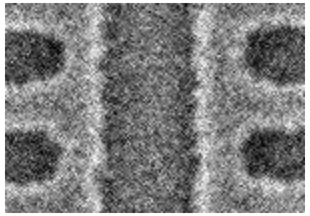
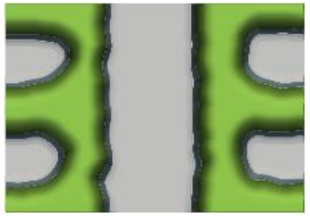
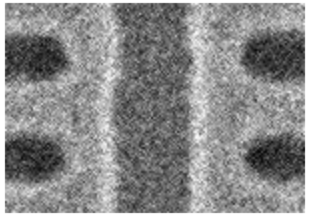
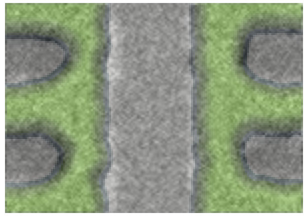
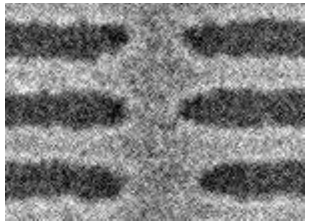
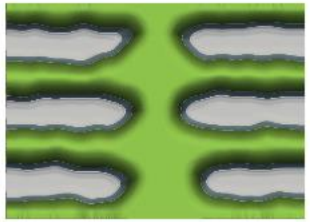
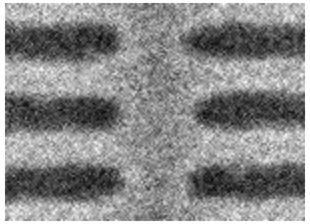
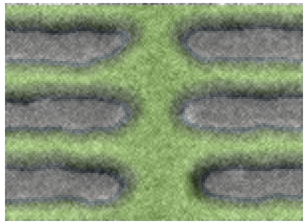
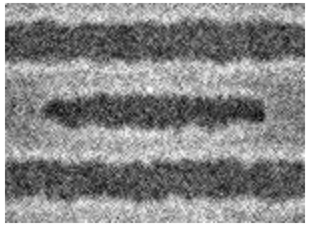
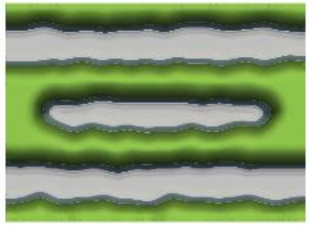
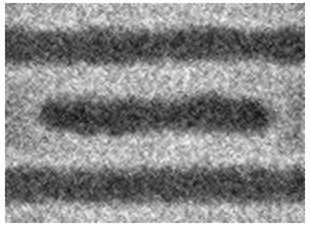
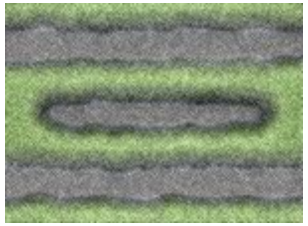
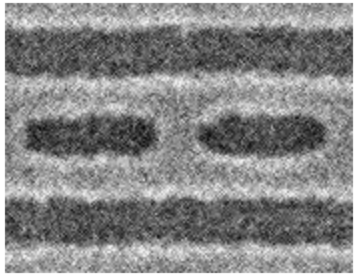
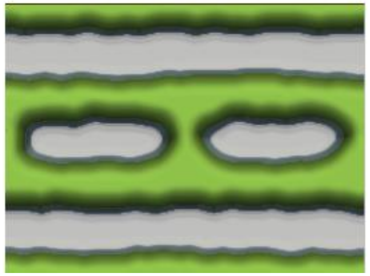
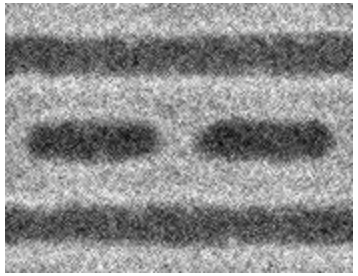
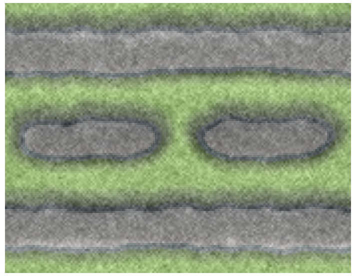
- *Calibrated model has high accuracy with a mean error of 2.4 nm*
- *Calibration time: ~7 hours on i7-14700F / GeForce RTX 4070*





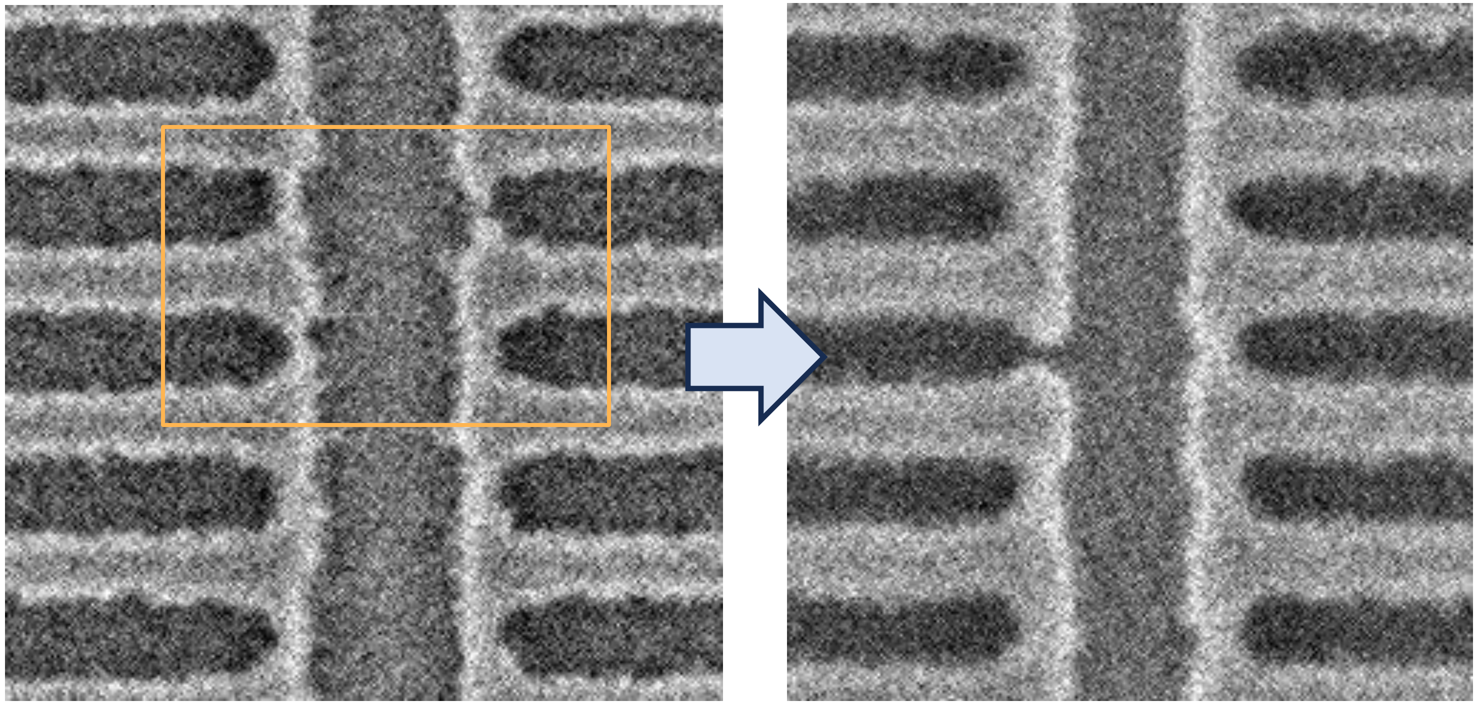
Leveraging Physics-Based AI for Scalable, Accurate, and Cost-Efficient Simulations

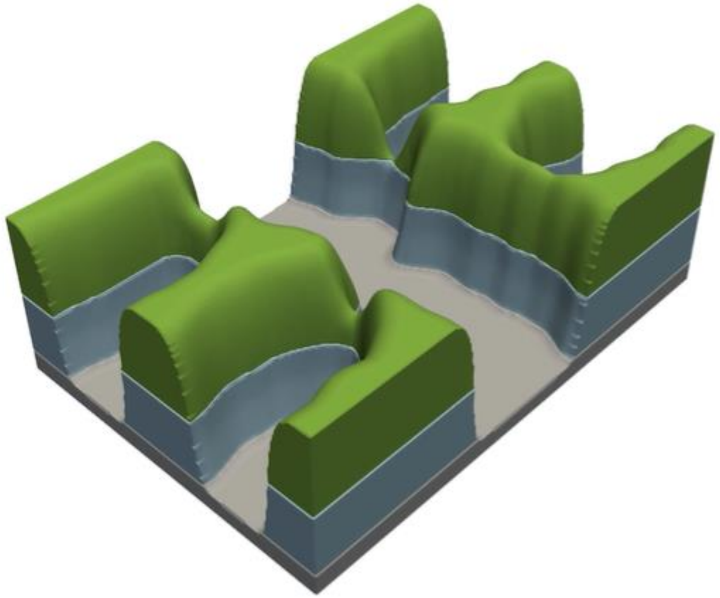
Physics AI model is able to predict key post-etch profile behavior on complex geometries

ADI SEM	Etch simulation	AED SEM	Sim overlayed on exp
			
			
			
			

HOT SPOT DETECTION

Physics AI model can predict probability and location for defects

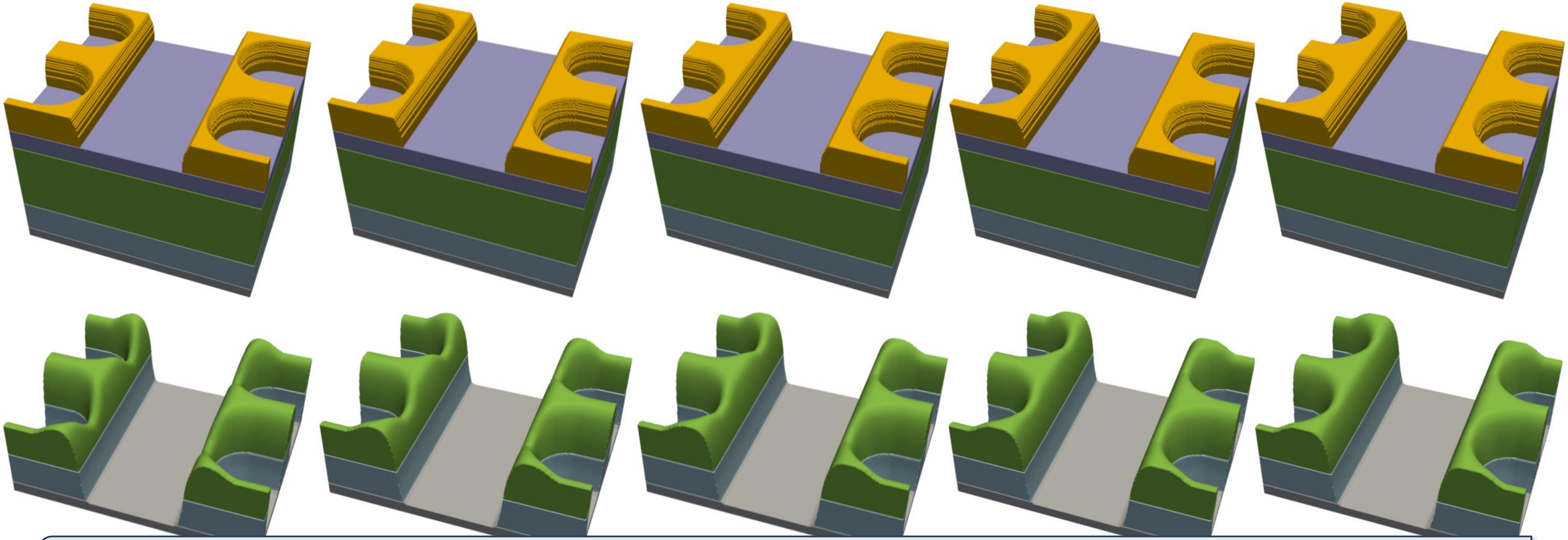




Initially marginal pattern results in defects after etch processing

VARIATIONS ON COMPLEX GEOMETRIES

-3σ	-2σ	-1σ	0σ	$+1\sigma$
13.1 nm	15.6 nm	18.1 nm	20.6 nm	23.1 nm



Note CD loss on a-C material, particularly for -3σ and -2σ

Hybrid Metrology Mitigates Weaknesses

Defect characterization requires robust, reliable, scalable metrology

Traditional metrology	SandBox Studio AI Physics-Enhanced Metrology
Slow (XSEM, TEM)	Fast
Low-res (XSEM, CD-SEM)	High resolution
Dedicated design (XSEM, OCD)	Real design
Single 2D plane (XSEM, TEM, CD-SEM)	Full 3D geometry
Destructive (XSEM, TEM, delamination, CD-SEM)	Non-destructive*
	Insights on etch/deposition behavior at every step
	Massive sampling and statistical cross-section analysis
	Significantly reduces TAT for physical analysis.

SandBox Studio AI overcomes many of the limitations in traditional metrologies

1. Physics-Enhanced AI reconstructs profile from **limited** CD data; predicts post-etch metrology for a wide range of patterns.
2. Model determines design rule for controlled impact on etch outcome. Defect detection achieved **before** wafer processing.
3. Future work will include large area simulations with automated defect prediction and extraction.

Physics-Enhanced Hybrid Metrology meets critical metrology challenges for next-generation semiconductor devices during process pathfinding and ramp-up.

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