New Advances in Mid-Infrared Critical Dimension Ellipsometry and Machine Learning

Addressing Complex Metrology Challenges in Semiconductor Manufacturing

MARCH 2021

Franklin Wong

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Speaker Biography

- Senior Applications Manager at Onto Innovation
- Based in Milpitas, CA, USA
- Experience in optical metrology solution development (physics- and machine learning-based) and new technology introduction
- Degrees in Materials Science

Acknowledgements and References

- **Collaborators**
  - Zhuan Liu (IRCD)
  - Andy Antonelli (IRCD)
  - Nick Keller (IRCD)
  - Zhuo Chen (IRCD)
  - Jie Li (ML)
  - Petar Žuvela (ML)
  - Wenmei Ming (ML)
  - Peifen Teh (ML)
  - Jingsheng Shi (ML)

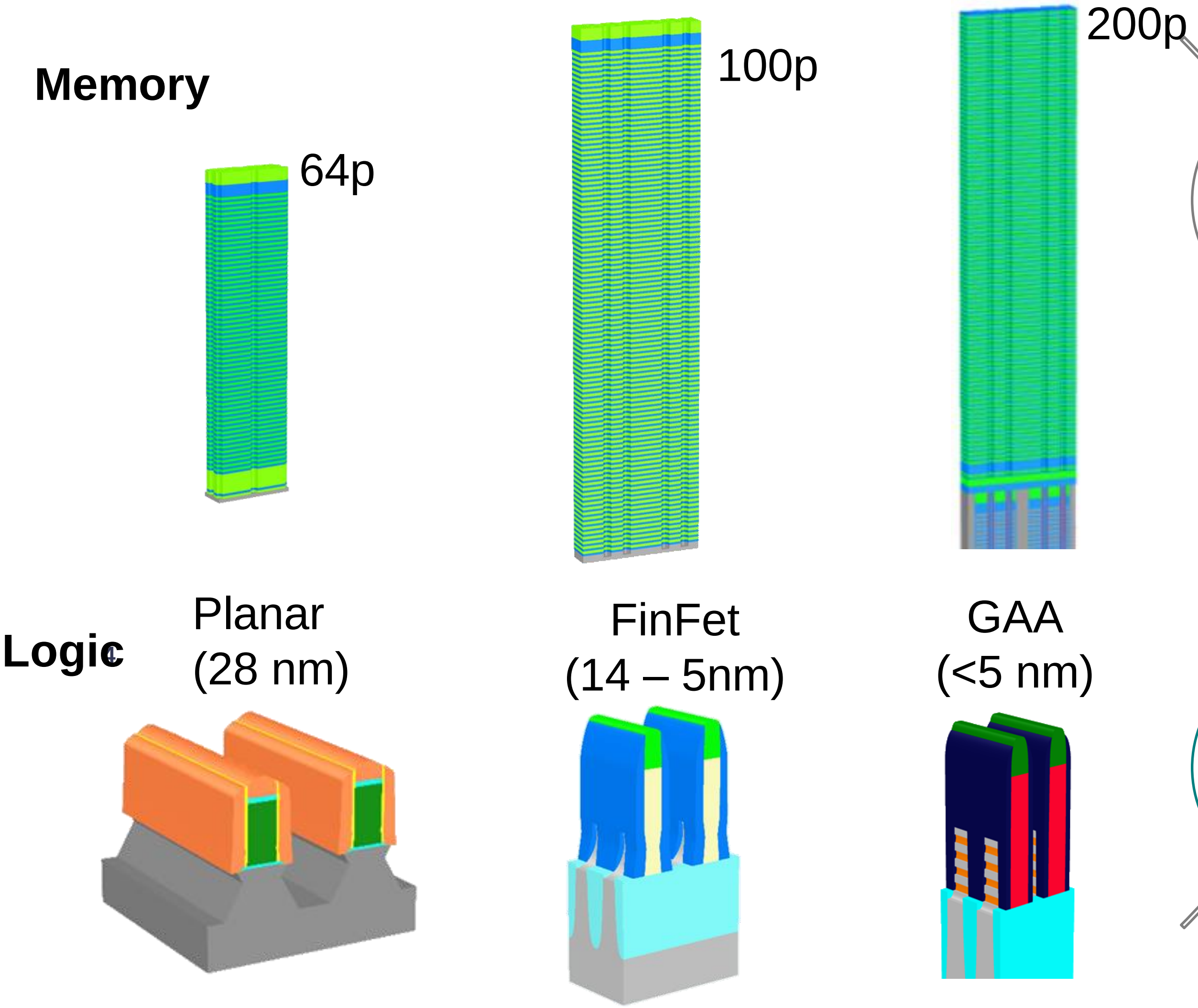
- **References**

  - G. Andrew Antonelli, et al. "Ellipsometric critical dimension metrology employing mid-infrared wavelengths for high-aspect-ratio channel hole module etch processes", Proc. SPIE 11611, Metrology, Inspection, and Process Control for Semiconductor Manufacturing XXXV, 116111O (22 February 2021); https://doi.org/10.1117/12.2583786

  - Franklin J. Wong, et al. "Methods to overcome limited labeled data sets in machine learning-based optical critical dimension metrology", Proc. SPIE 11611, Metrology, Inspection, and Process Control for Semiconductor Manufacturing XXXV, 116111P (22 February 2021); https://doi.org/10.1117/12.2583774

Semiconductor Device Scaling: A Metrology Perspective

Continuous scaling demands new technologies for accurate, fast, and robust 3D metrology



Stacks are higher

- High-aspect-ratio etch
- CD profile and uniformity, tilt, shift control

Structures are more complex

- Time to solution
- Process coverage
- Loading effect

Critical dimensions are smaller

- Error budget is tighter
- Local variation control
- Key parameters may be buried

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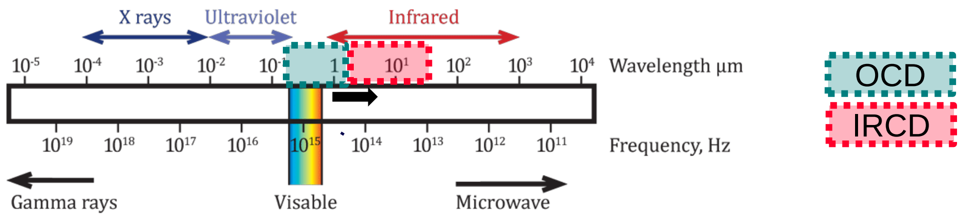
Metrology Requirements for Advanced Node Process Control

- **Capability:** Technology to measure physical dimensions of advanced node structures with high accuracy and precision
- **High-Volume Fab Sampling:** Nondestructive, fast, and inline with real-time feedback for excursion identification and enabling real-time process control
- **Time to Solution:** Metrology solution development to keep pace with (be faster than) process development

Semiconductor Device Scaling: Metrology Solutions

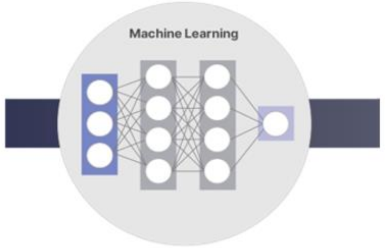
Continuous scaling demands new technologies for accurate, fast, and robust 3D metrology

Novel mid-IR ellipsometry system to augment traditional OCD



Electromagnetic wave spectrum

Innovative metrology-targeted machine learning with high accuracy and reduced time to solution



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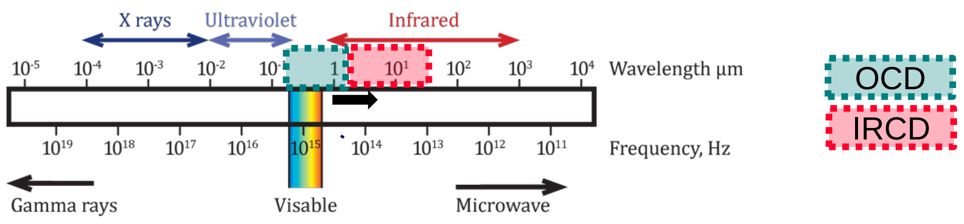

Electromagnetic wave spectrum

Innovative metrology-targeted machine learning with high accuracy and short time to solution

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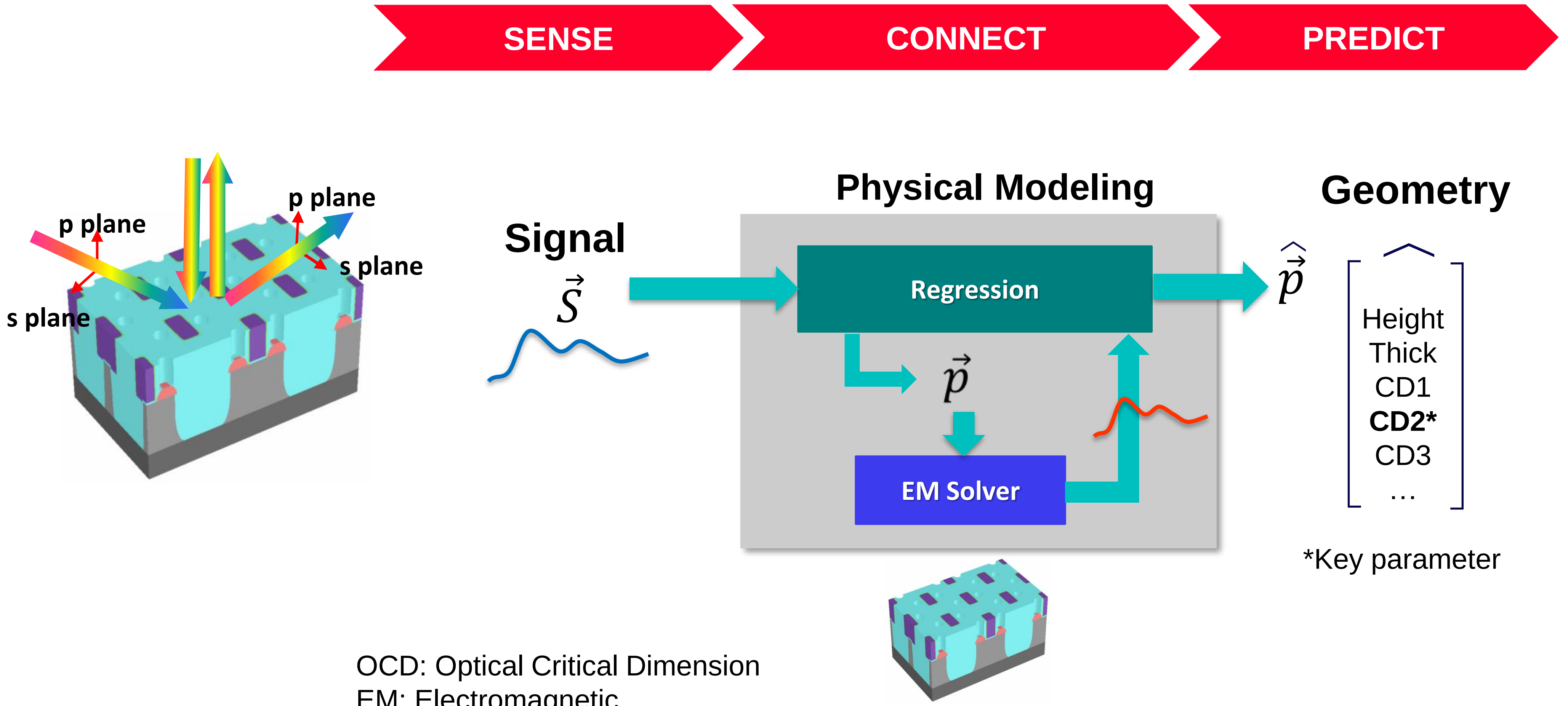
OCD Metrology: Workhorse for Semiconductor Process Control

Established baseline: Physics-based modeling of **UV/Vis/near-IR** signals



OCD: Optical Critical Dimension
EM: Electromagnetic

Mid-IR Offers Enhanced CD Profile Information for HAR Structures

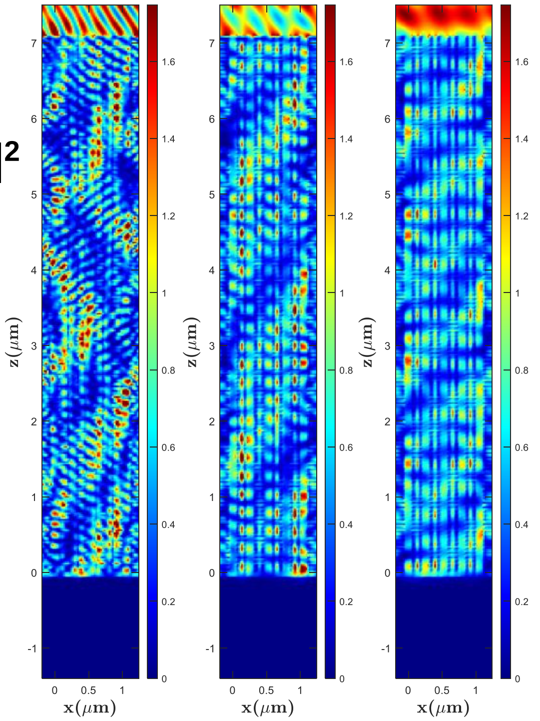
Near-field simulations of 3D NAND Channel Hole Profile

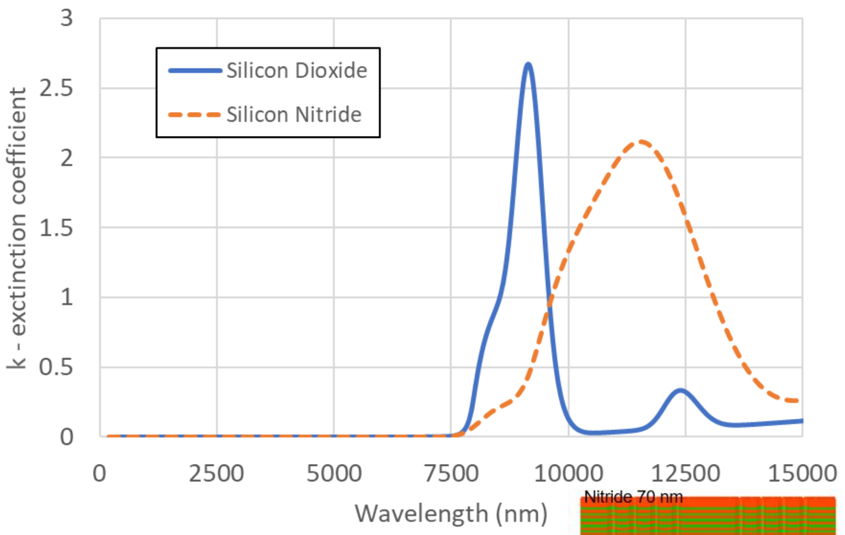
Limited profile sensitivity due to similar light-structure interaction at all λs (high parameter correlation)

OCD

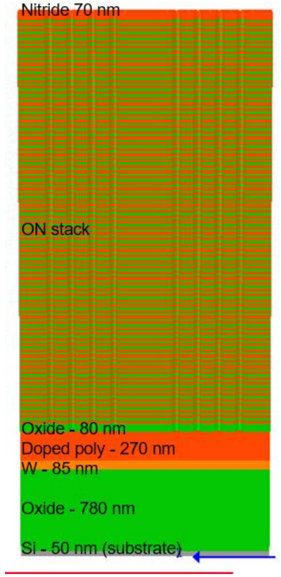
400 nm 600 nm 800 nm

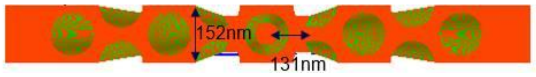
$|E|^2$





FDTD simulation of $|E|^2$ in 128L 3D NAND structure SiO_2/Si_3N_4 superlattice pair thickness 25 nm/30 nm and hole diameter of 120 nm with hexagonal lattice



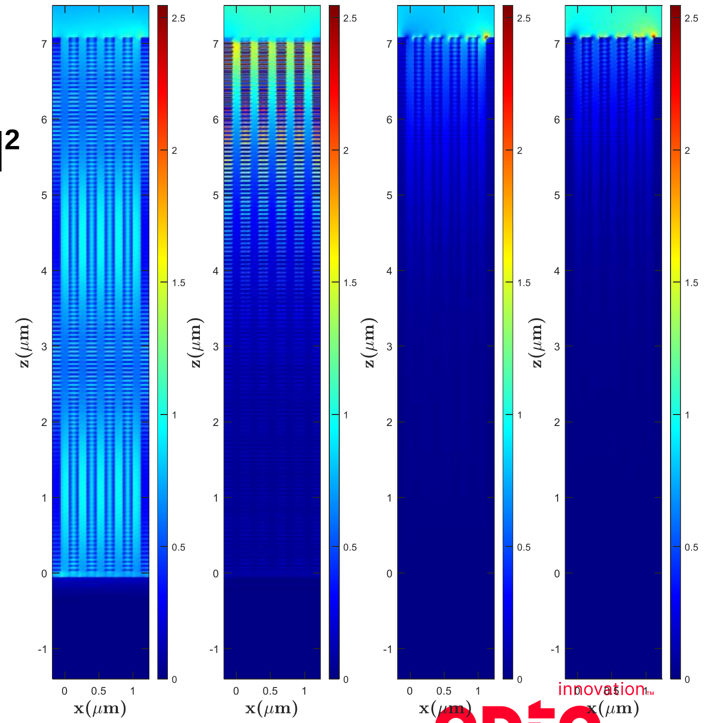


High-fidelity CD profile due to unique light-structure interaction at different λs (enhanced z-sensitivity)

IRCD

6000 nm 8000 nm 10000 nm 12000 nm

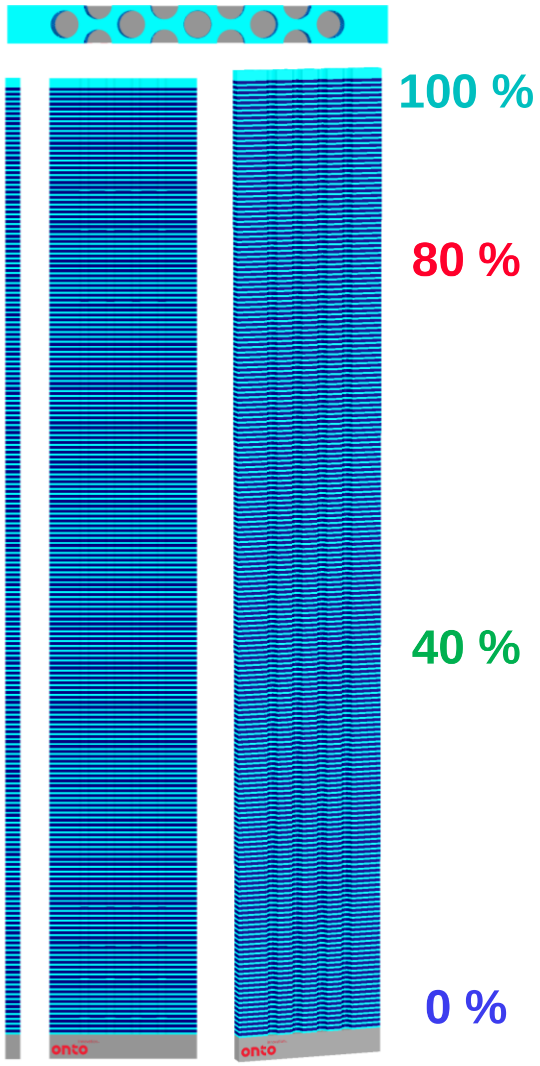
$|E|^2$



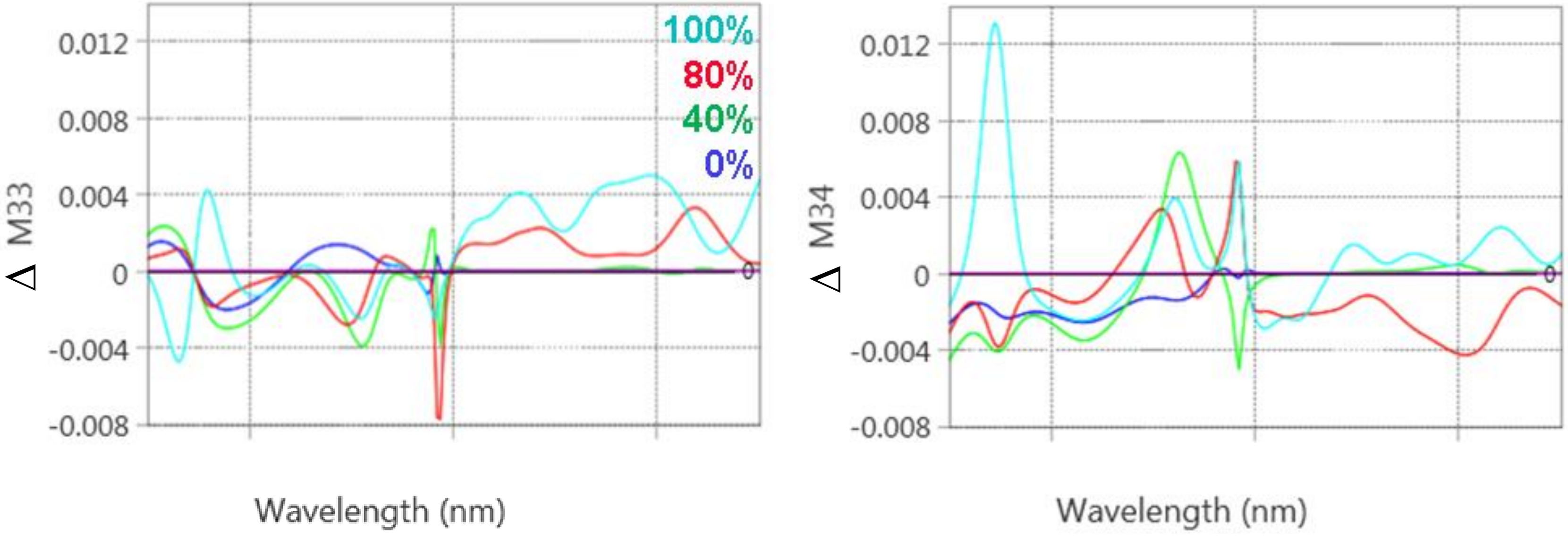
HAR: high aspect ratio

IRCD Simulations of Channel Hole Profile

Spectral sensitivity to changes in channel hole profile



Simulated mid-infrared spectral response of the M33 and M34 Mueller matrix elements

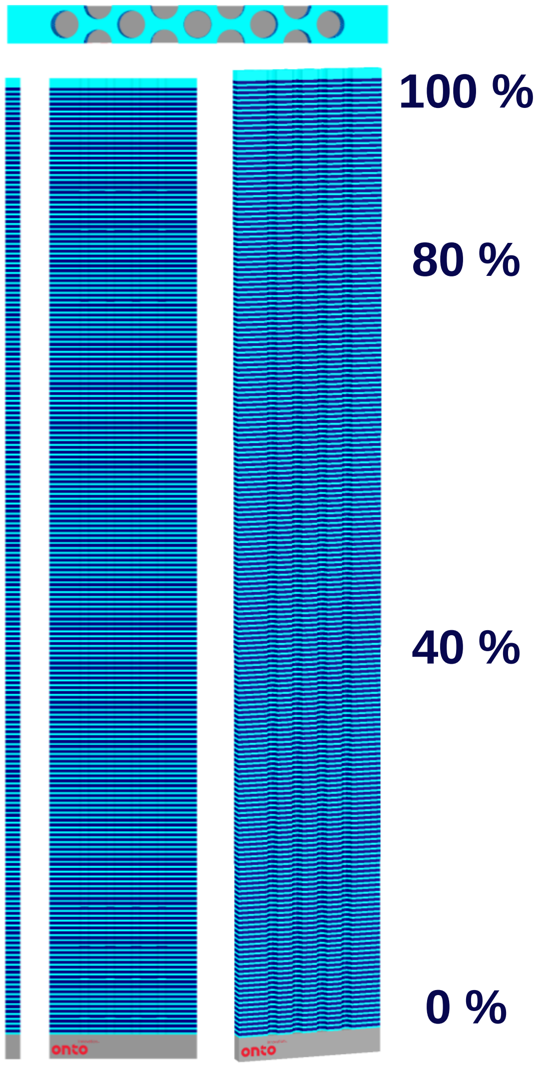


1 nm change in CD at different heights on the channel hole, where 0% indicates the bottom and 100% indicates the top

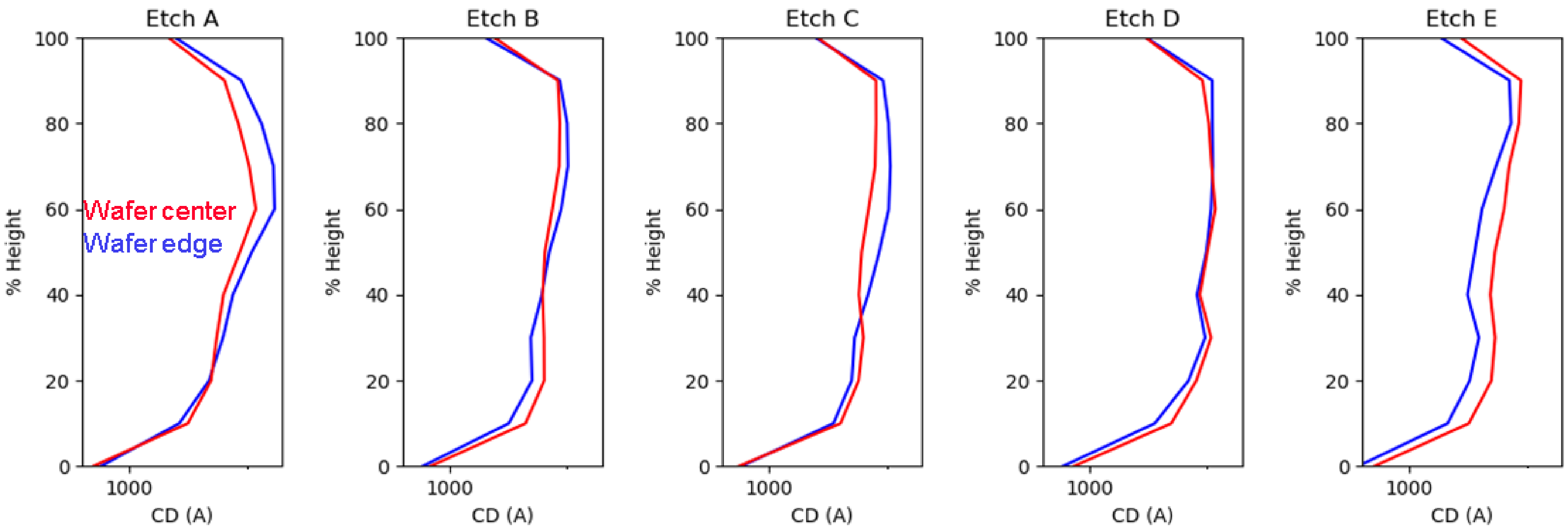
IRCD simulations indicate a high level of sensitivity to changes in profile

IRCD Measurements of Channel Hole Profile

Nondestructive metrology coverage across different etch packages and from center to edge



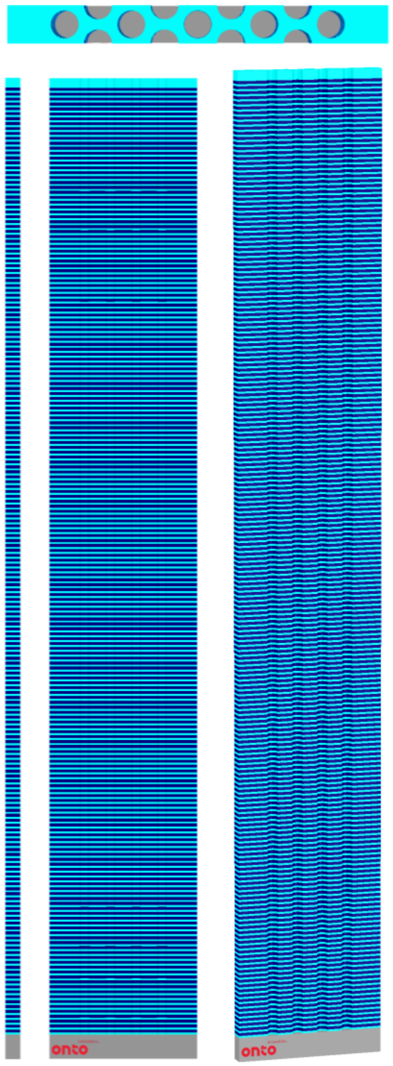
A, B, C, D, and E represent different etch process conditions

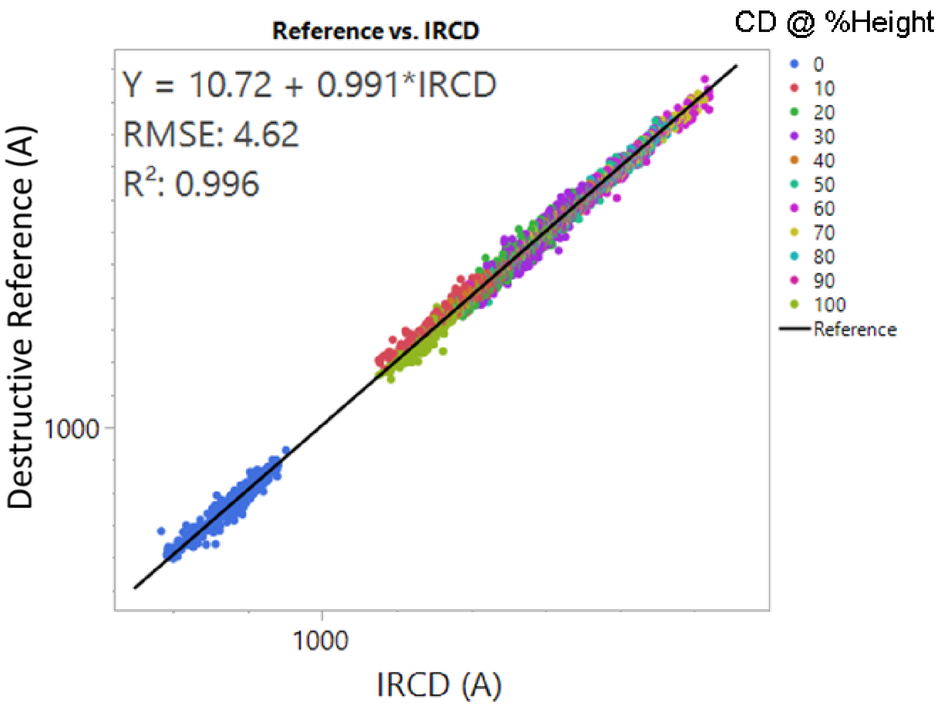


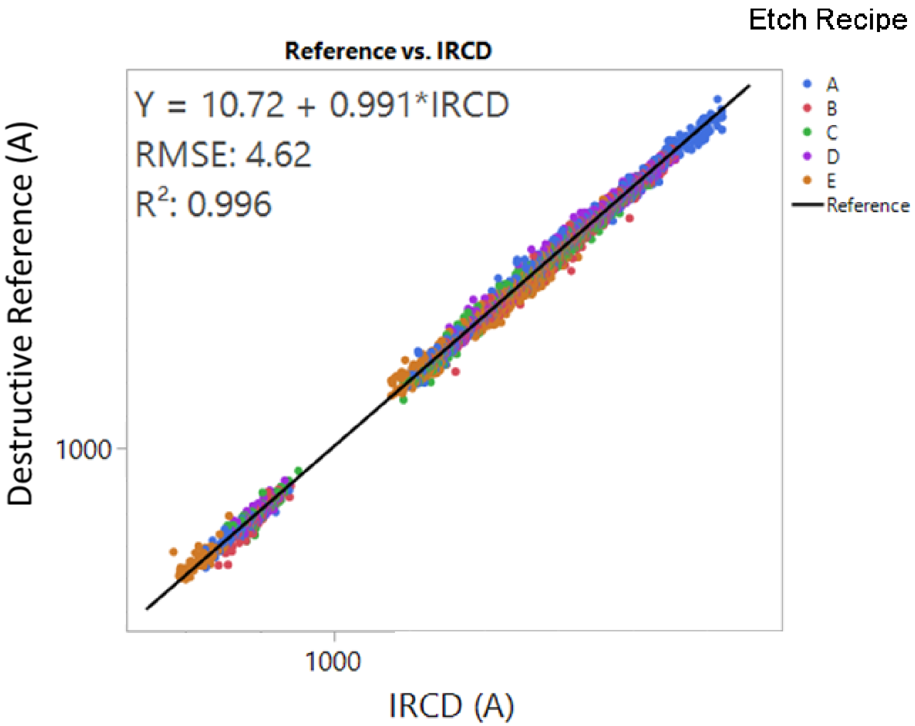
IRCD yields high-resolution CD profile

IRCD Measurements of Channel Hole Profile

High-accuracy channel hole profile by nondestructive IRCD







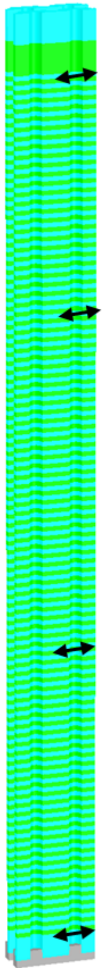
IRCD profile agrees well with reference profile for all etch process conditions

** Angstrom-level agreement to with destructive reference. Difference is a convolution of reference and IRCD error.*

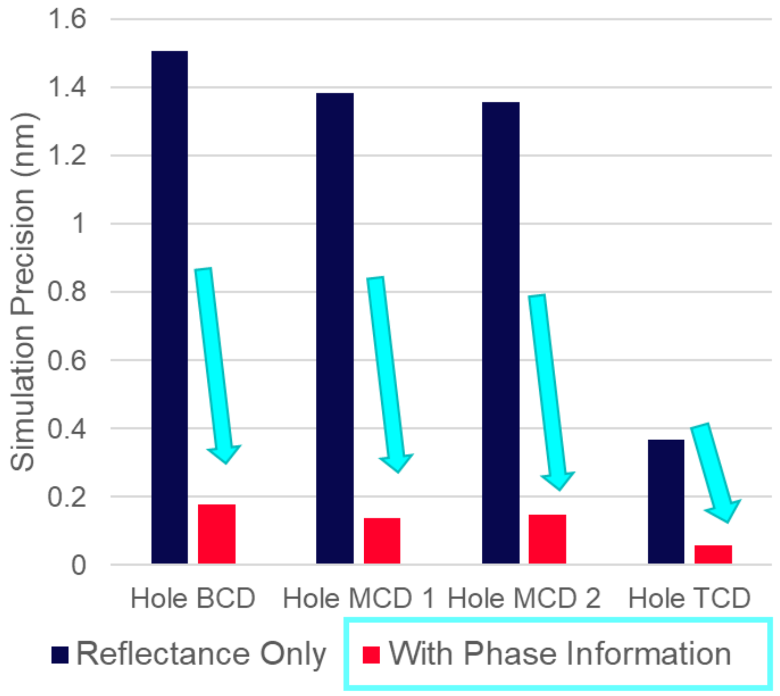
IRCD Technology on an Ellipsometric Platform

High-precision metrology for process control

- Mid-IR wavelength range is key to CD profile decorrelation
- Polarization and optical phase information needed for Å-level metrology
- Inline on-device measurements



~10x performance gain with phase information



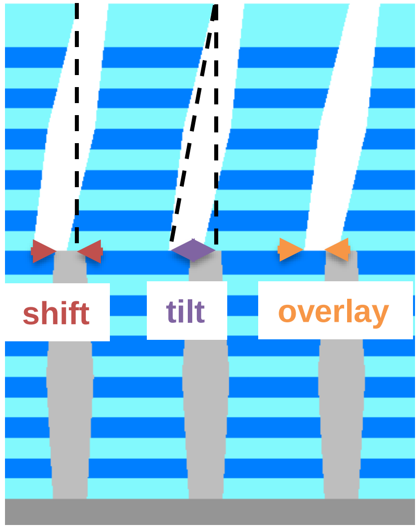
Simulation Details

- 200 pair channel hole structure
- Assume same noise level for both reflectance only and with phase information

Channel Hole Tilt and Shift: Full Mueller OCD (UV/Vis/near IR)

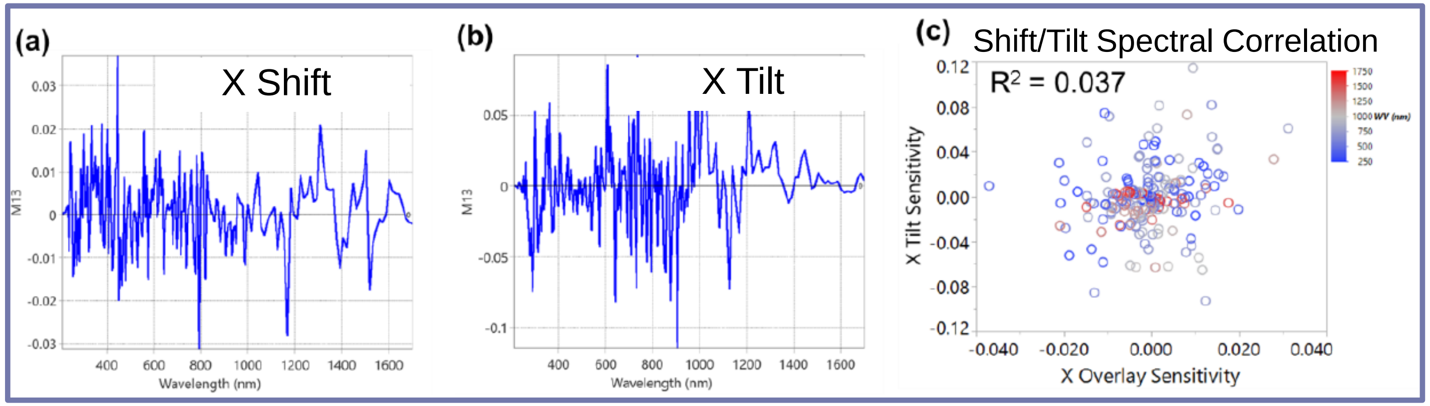
Traditional OCD provides high structural asymmetry sensitivity

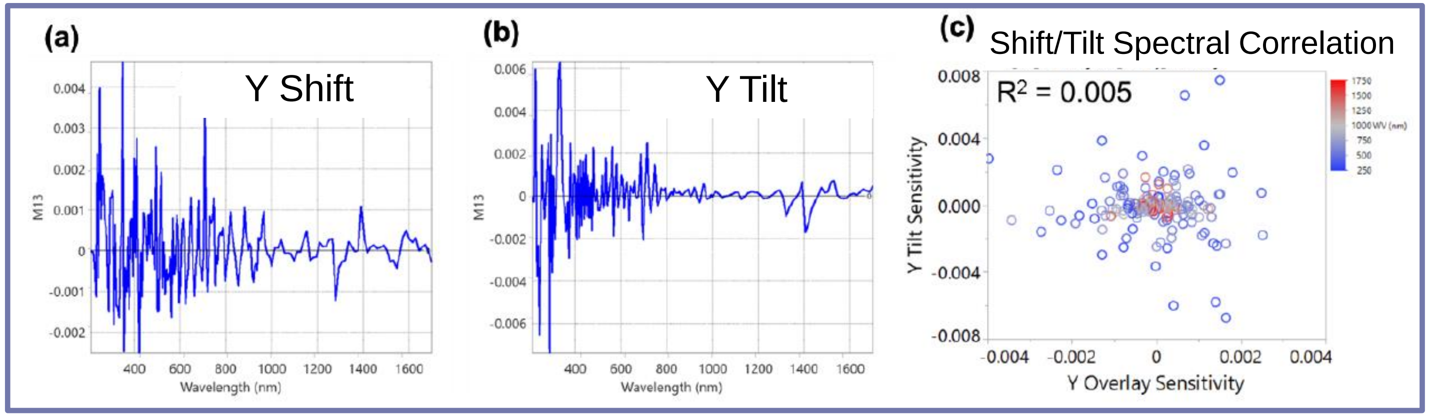
- Off-diagonal Mueller sensitive to asymmetry
- Overlay: shift and tilt components can be decoupled by OCD; x and y are independent as well



$$\begin{bmatrix} 1 & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix}$$

Sensitivity simulations @ 5nm change (no spectral correlation between shift and tilt)

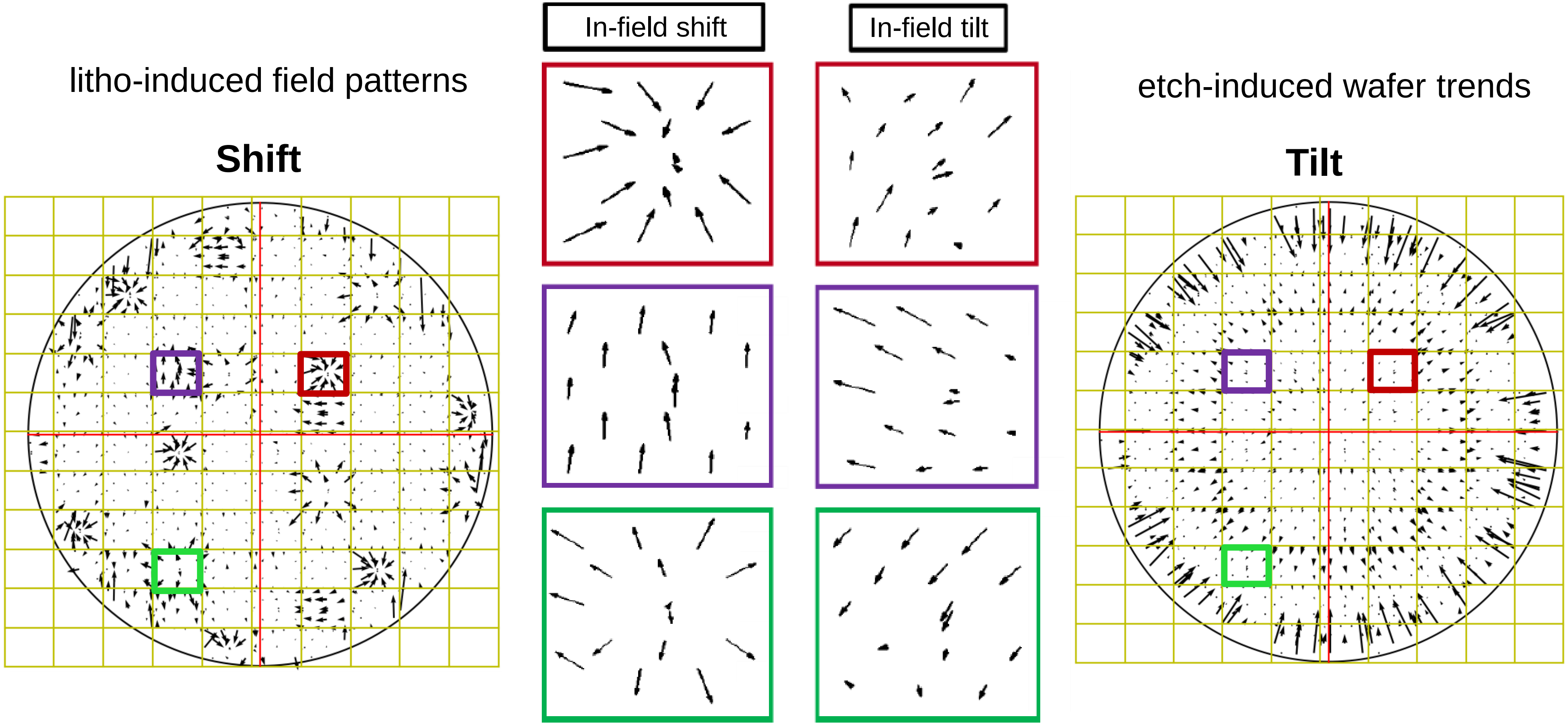




US Patent: US2011/0080585 A1. Scatterometry measurement of asymmetric structures.

Independent Measurement of Shift and Tilt by Full Mueller OCD

High point-level inline sampling required to identify shift and tilt features



Combined novel IRCD and established OCD address the key 3D NAND channel hole process control needs

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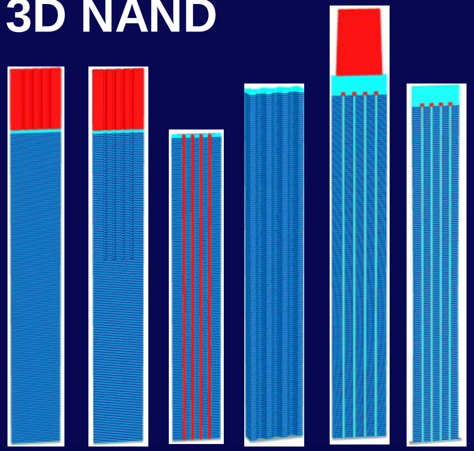
IRCD Metrology Space for Process Control

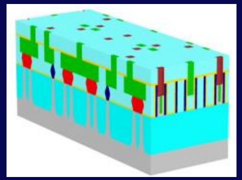
3D NAND

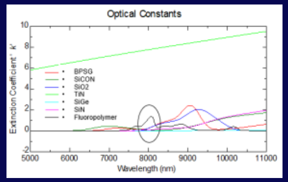
- Multiple HAR structures in process flow
- Thick carbon etch hardmasks opaque in visible

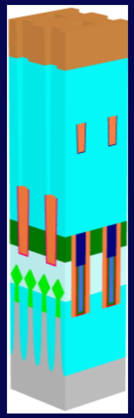


Advanced Logic

- HAR supervias
- IR-sensitive composition and residue detection





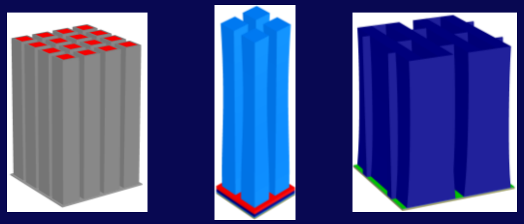


DRAM

- HAR capacitor
- IR-sensitive composition

CMOS Image Sensor

- Multiple HAR structures (Si, oxide, photoresist) in process flow



HAR: high aspect ratio

Semiconductor Device Scaling: Metrology Solutions

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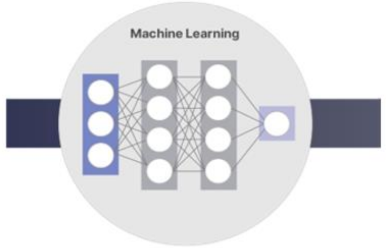

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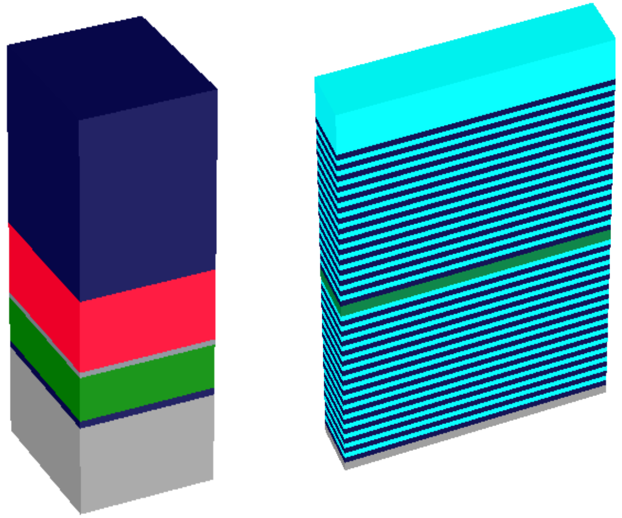
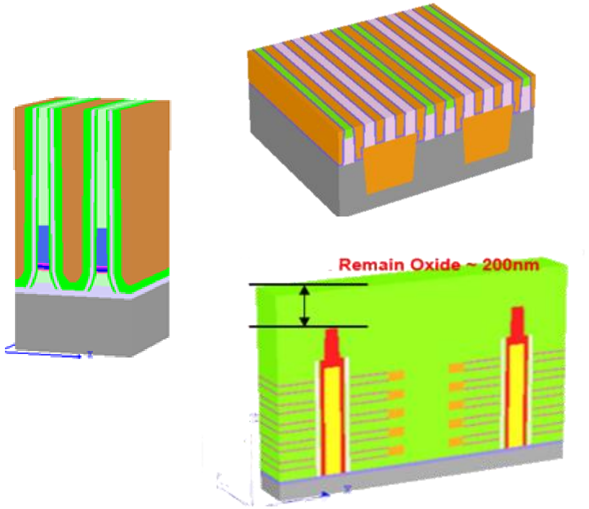
Optical Metrology Applications

CVD TF Applications



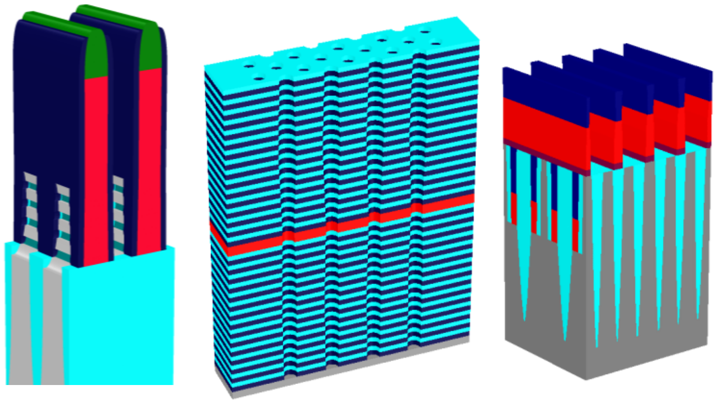
- Key parameters at top only
- Simple models

CMP Applications



- Key parameters at top only
- Medium complexity structures

Etch Applications



- Key parameters are subsurface, buried, and/or related to profile
- Complex structures

Modeling and Metrology Difficulty

Time to Physical Model Solution

Value Add of Machine Learning

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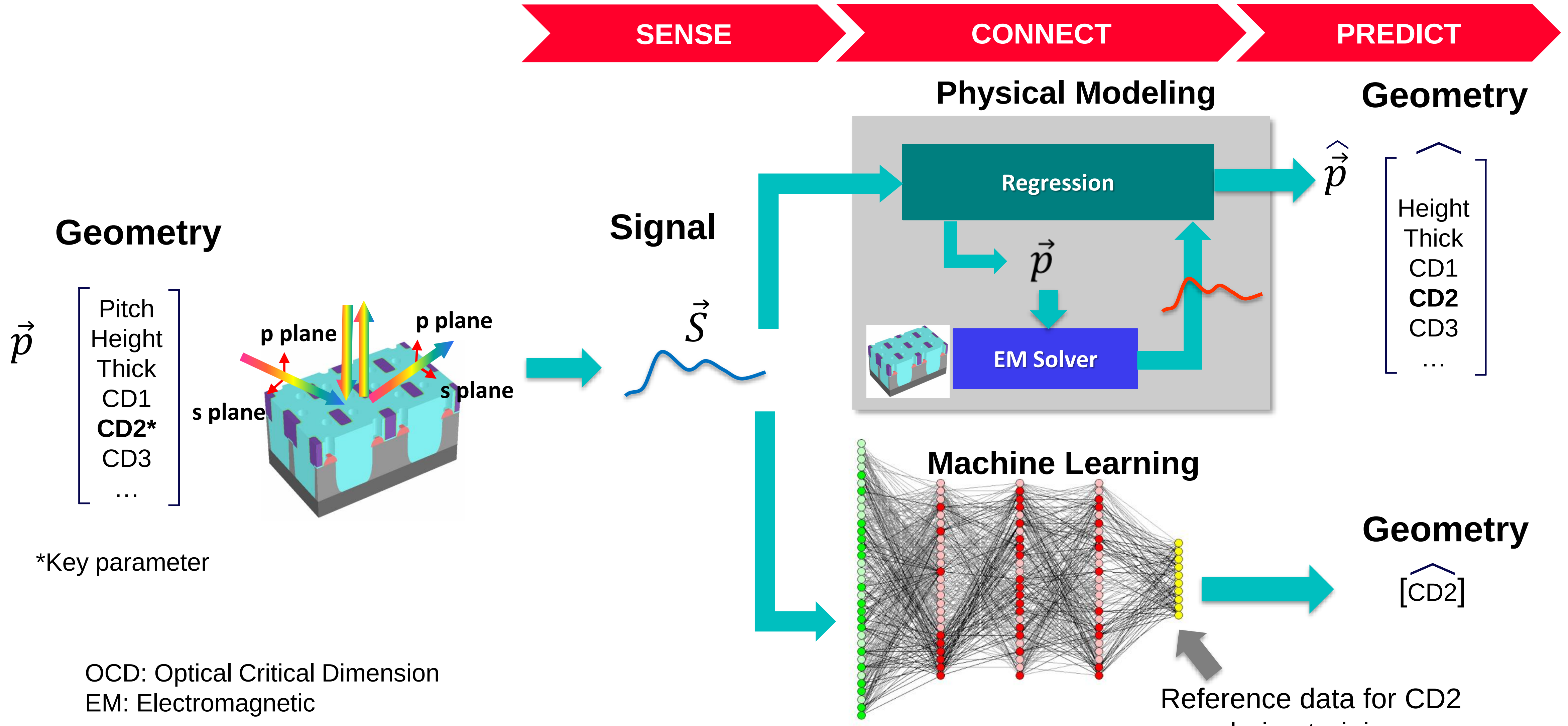
Machine Learning as an Alternative OCD Solution

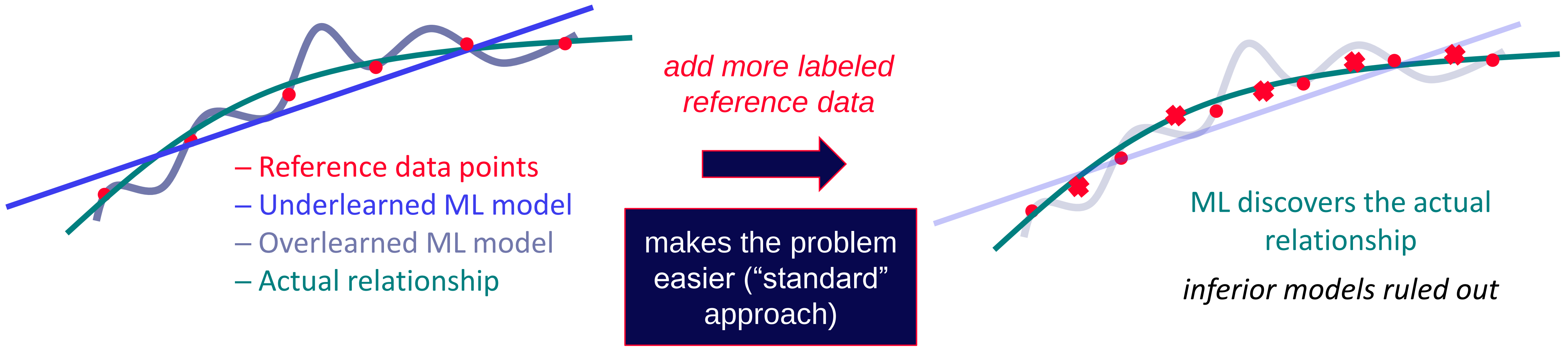


*Key parameter

OCD: Optical Critical Dimension
EM: Electromagnetic

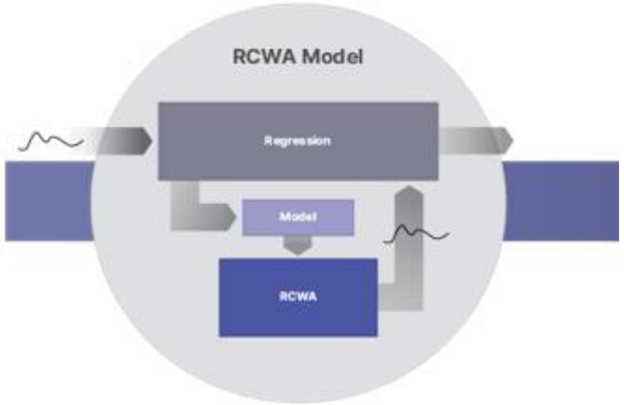
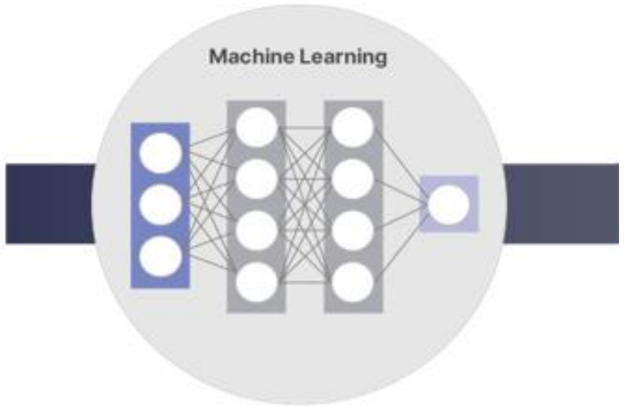
Challenges in Standard Machine Learning Solutions

- **Under-Learning (Accuracy Gap):** Limited labeled data insufficient to determine the complex relationship from signal to geometry, leading to model errors
- **Over-Learning (Robustness Gap):** Minimizing error with overly complex models results in poor predictive capability in production



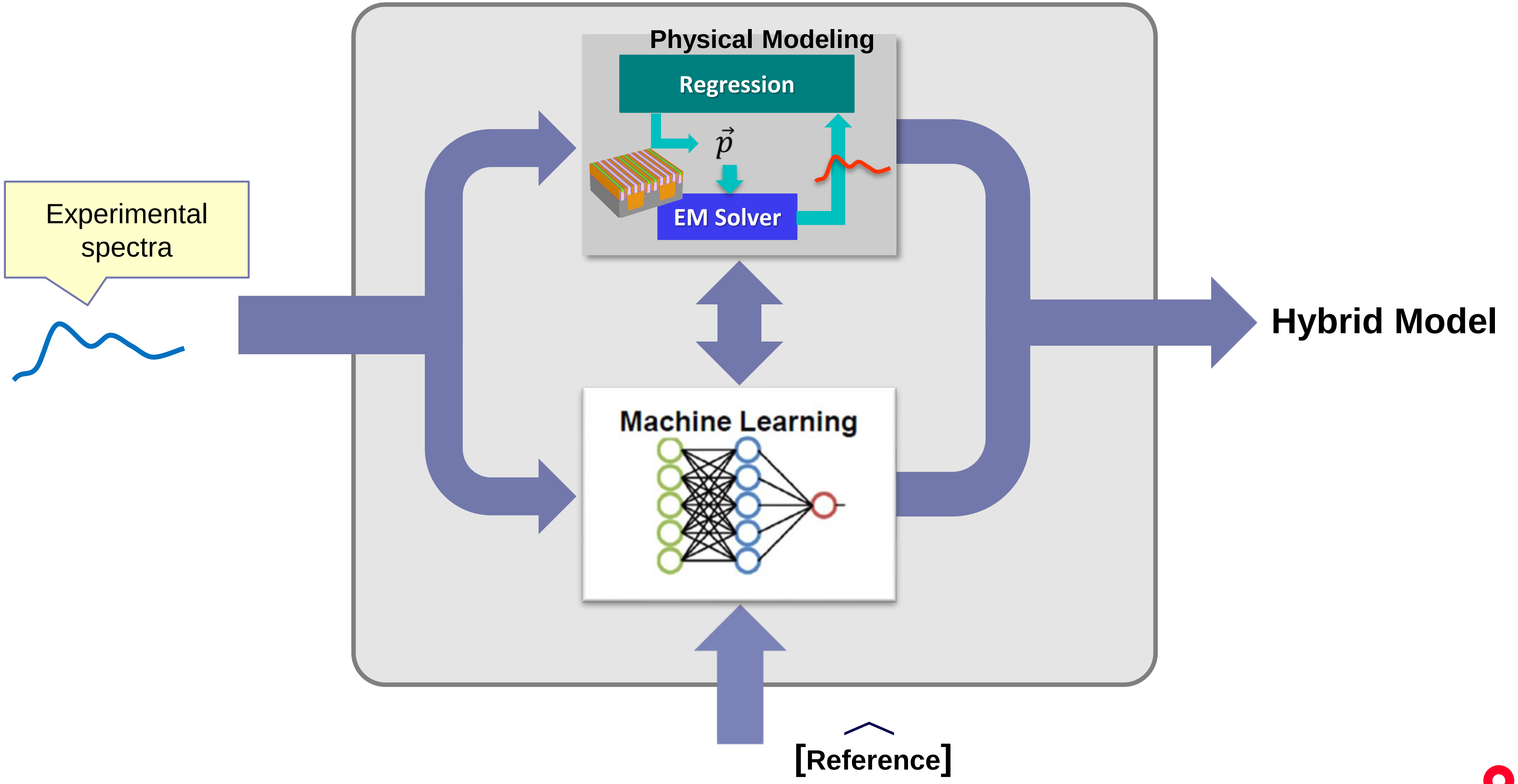
Hard (High-Value) Problem: How to rule out inferior models *without* the benefit of more (large quantity of) labeled reference?

Hybrid Approach: Robust Physics + Powerful ML

	STRENGTHS	WEAKNESSES
	✓ Physical sense / extrapolation capability / process coverage ✓ Requires few reference data	– Long time to solution
	✓ Fast time to solution ✓ Extracts small signals leading to high accuracy	– No physical constraints – Standard approaches prone to overtraining and/or require large quantities or reference

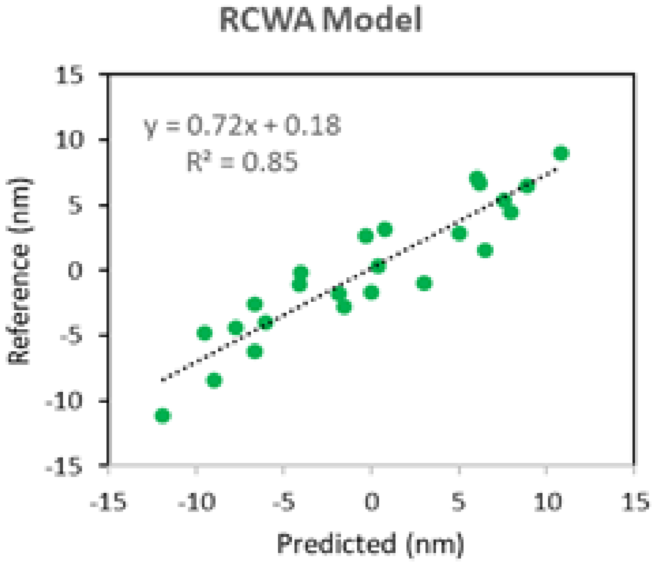
Synergized Physical Modeling / Machine Learning Hybrid

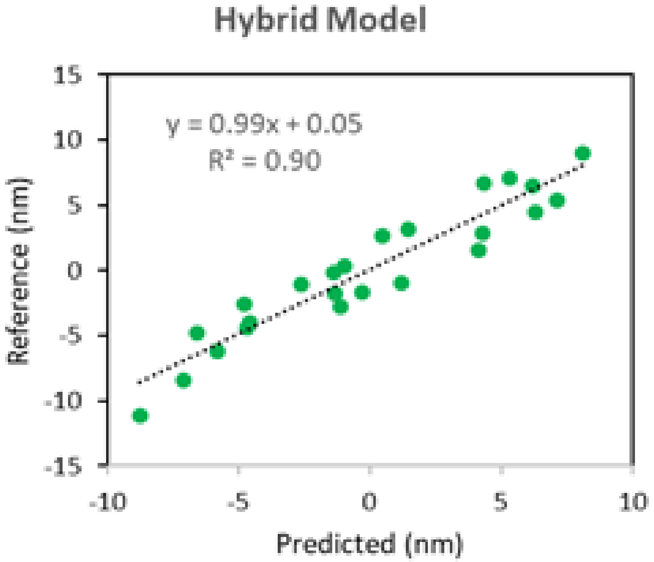
Merging the strengths of both approaches

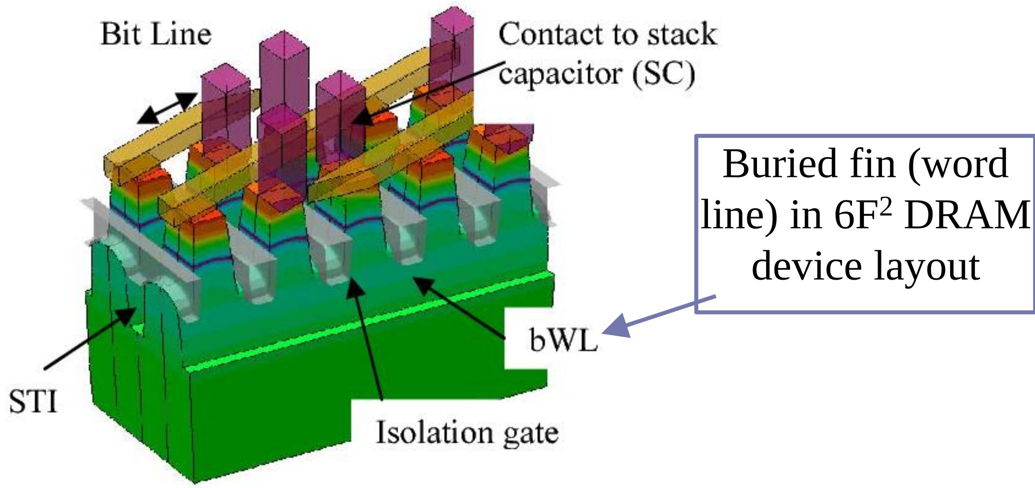


Hybrid Approach Reduces Error of a Physical Model

- ML enhances existing physical model performance
- Reference: destructive imaging

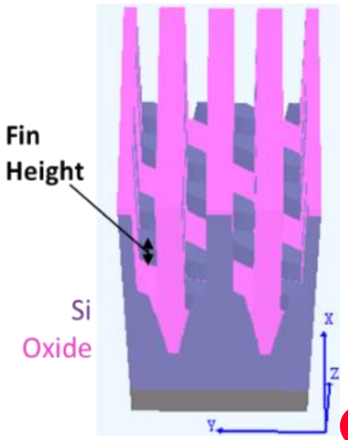






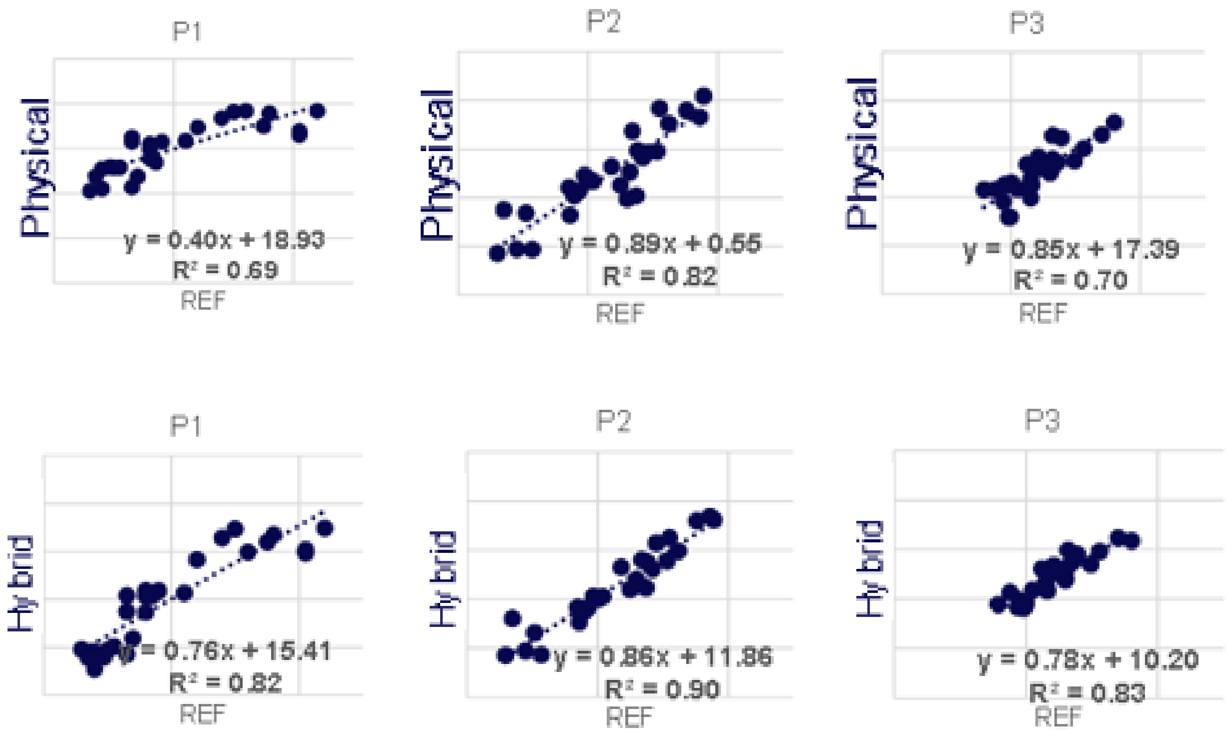
T. Schloesser, et al. 2008 IEEE Inter. Electron Dev. Mee

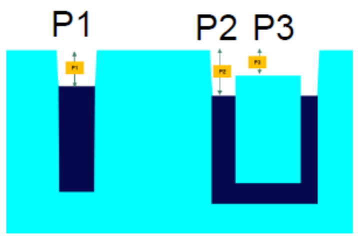
process step that creates the buried fin requiring metrology



Hybrid: Improved Accuracy on FEOL Logic Etch Application

- Multiple key parameters in single process step often pose challenges to standard ML
- Physical model backbone maintains recipe robustness against overtraining compared to standard ML
- Hybrid approach leads to improved performance for all parameters





Conclusions

- Novel IRCD in combination with traditional OCD provide high-aspect-ratio channel hole process control for advanced 3D NAND nodes
- Hybrid physics and machine learning innovations improve time to solution and boost accuracy
- Synergistic combinations in both hardware technology and data analysis innovation are key to pushing the frontiers of semiconductor metrology

Thank You

谢谢 | 謝謝

ありがとう

Obrigado

Danke

감사합니다

Merci

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