3D (in-line) metrology challenges and solutions

Dr. Igor Turovets

March 15, 2019

The Impact of Data on Semi Industry

> “Data to this century is what oil was to the last one, a driver for growth and change”

The Economist

Crunch time in France

Ten years on: banking after the crisis

South Korea's unfinished revolution

Biology, but without the cells

MAY 6TH–12TH 2017

The world's most valuable resource

Data and the new rules of competition

Drivers for AI/ML in Semi Manufacturing

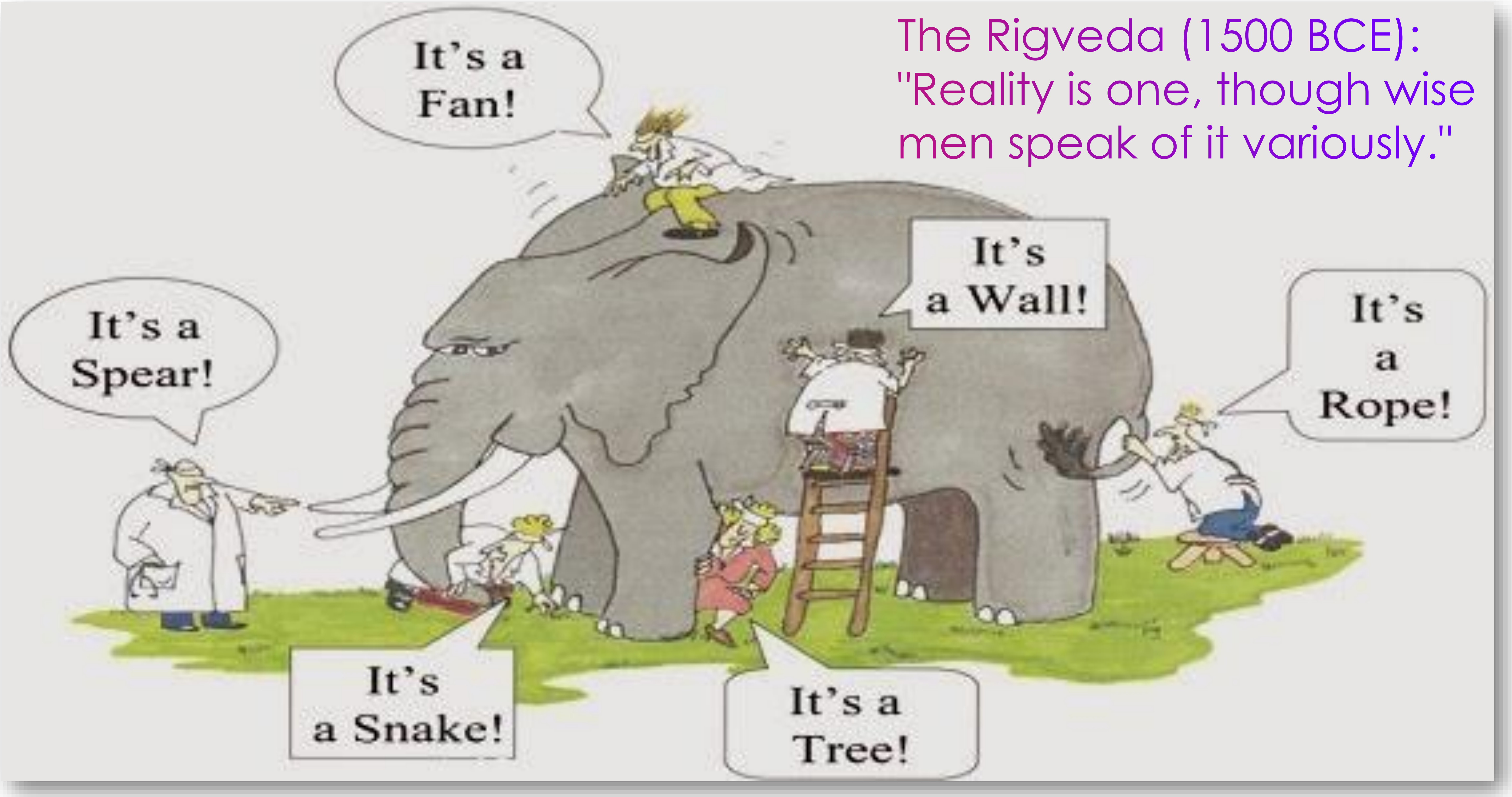
- Increase in Process **Complexity**
- Huge **amount** of data collected in the fab
- Only **small** part of the collected data is used
- Increasing challenges to achieve fast **Yield**
- Increasing need for high **Productivity**

Enabling New Capabilities for Metrology and Process Control

Agenda

- **Basics: Profile in-line metrology**
- **3D complexity and metrology challenges they create.**
- **Lab, FAB and In-line metrology (unique) solution for process control.**
  - Process development needs
  - Metrology trends:
    - LAB2FAB
    - FAB2LAB
- **Holistic metrology approach**
  - Hybrid and advanced modeling
  - Machine-Learning in HVM
- **Summary**

Profile metrology techniques at semiconductor industry



The Rigveda (1500 BCE): "Reality is one, though wise men speak of it variously."

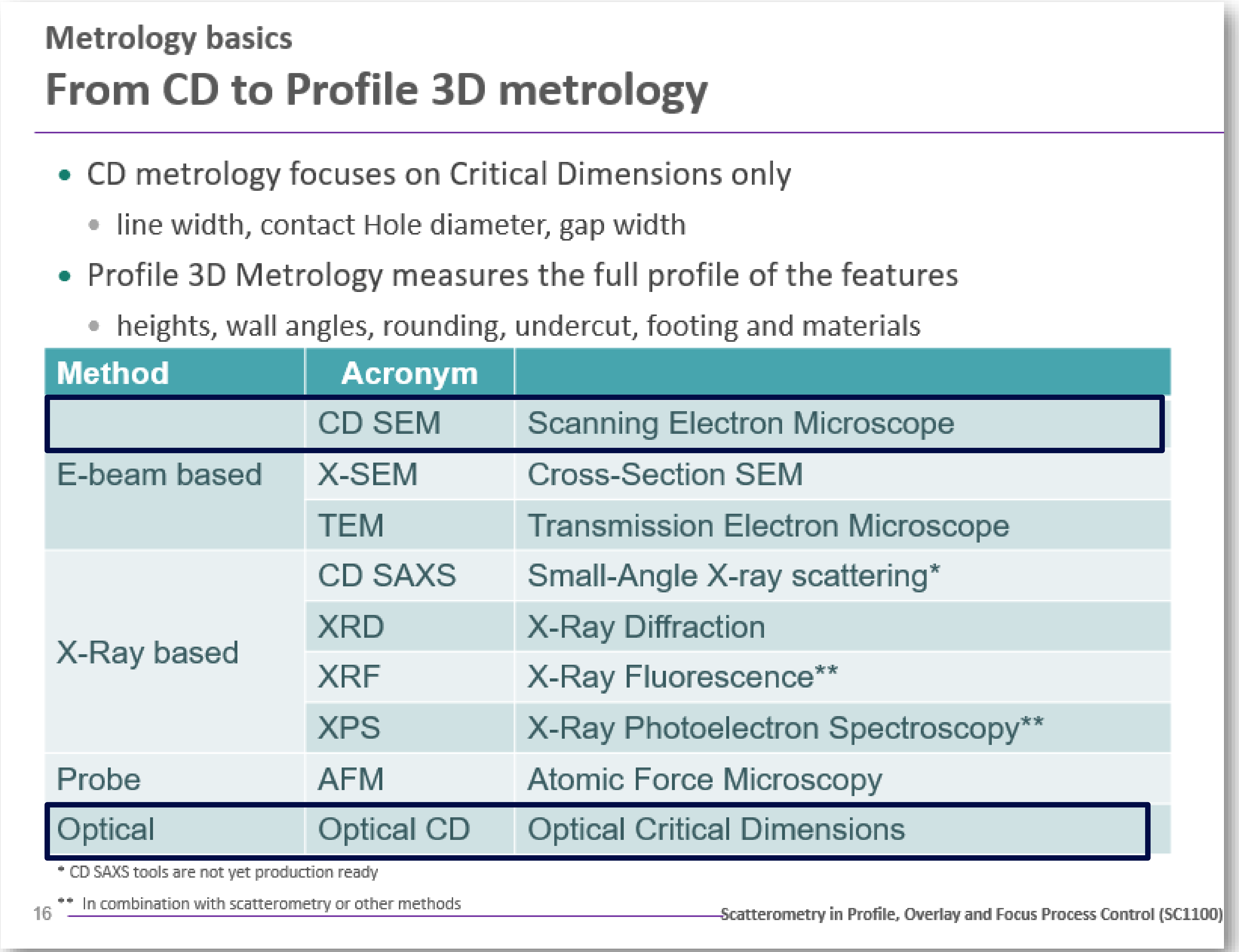
Partnership

People

Semiconductor technology development = Elephant become larger and larger and you need more "blind" people working together to understand what it is.

Basics

How many wise (blind) man are measuring now in-line in HVM of semiconductor devices?



Metrology basics

From CD to Profile 3D metrology

- CD metrology focuses on Critical Dimensions only
  - line width, contact Hole diameter, gap width
- Profile 3D Metrology measures the full profile of the features
  - heights, wall angles, rounding, undercut, footing and materials

Method	Acronym	
E-beam based	CD SEM	Scanning Electron Microscope
	X-SEM	Cross-Section SEM
	TEM	Transmission Electron Microscope
X-Ray based	CD SAXS	Small-Angle X-ray scattering*
	XRD	X-Ray Diffraction
	XRF	X-Ray Fluorescence**
	XPS	X-Ray Photoelectron Spectroscopy**
Probe	AFM	Atomic Force Microscopy
Optical	Optical CD	Optical Critical Dimensions

* CD SAXS tools are not yet production ready

** In combination with scatterometry or other methods

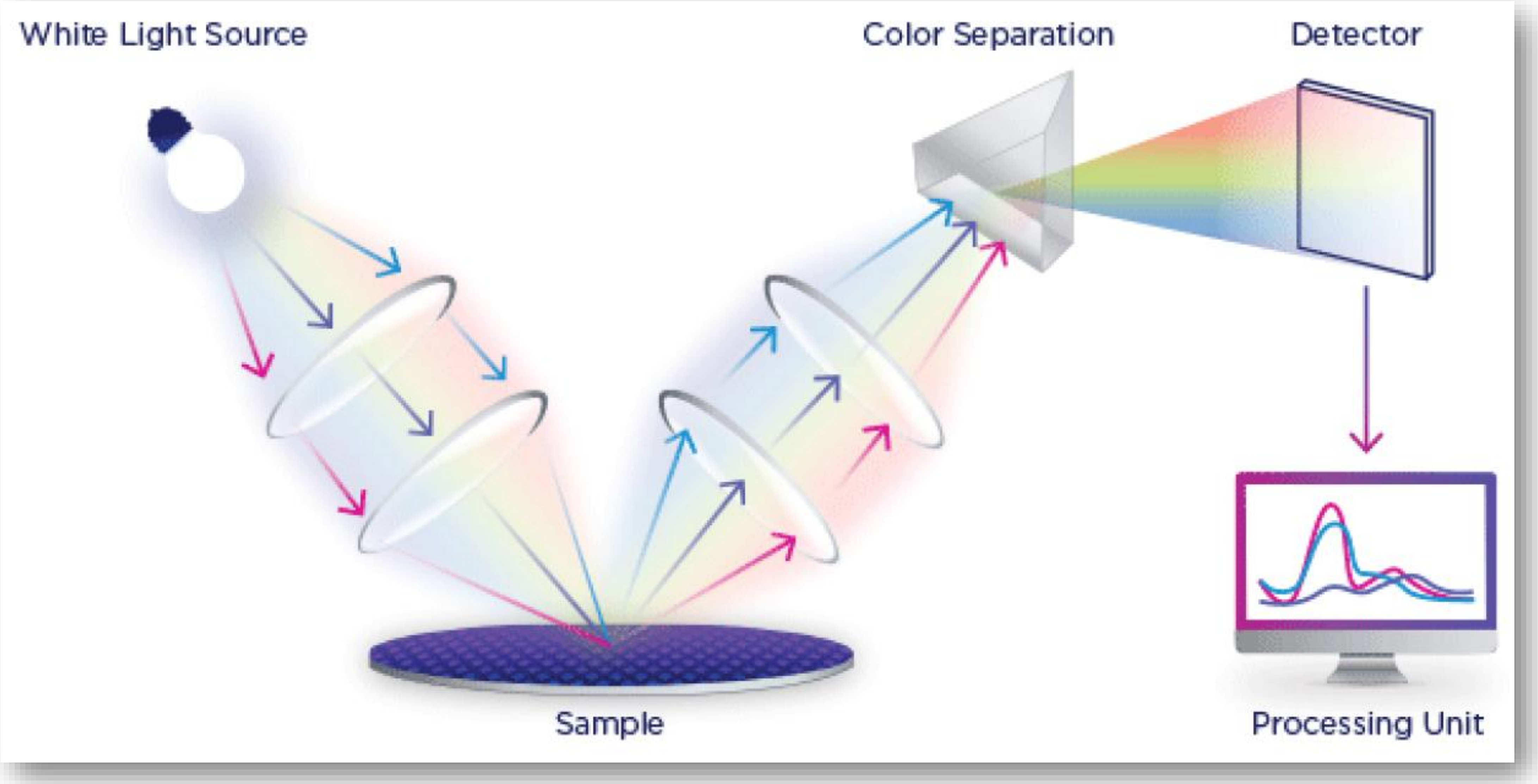
16 Scatterometry in Profile, Overlay and Focus Process Control (SC1100)

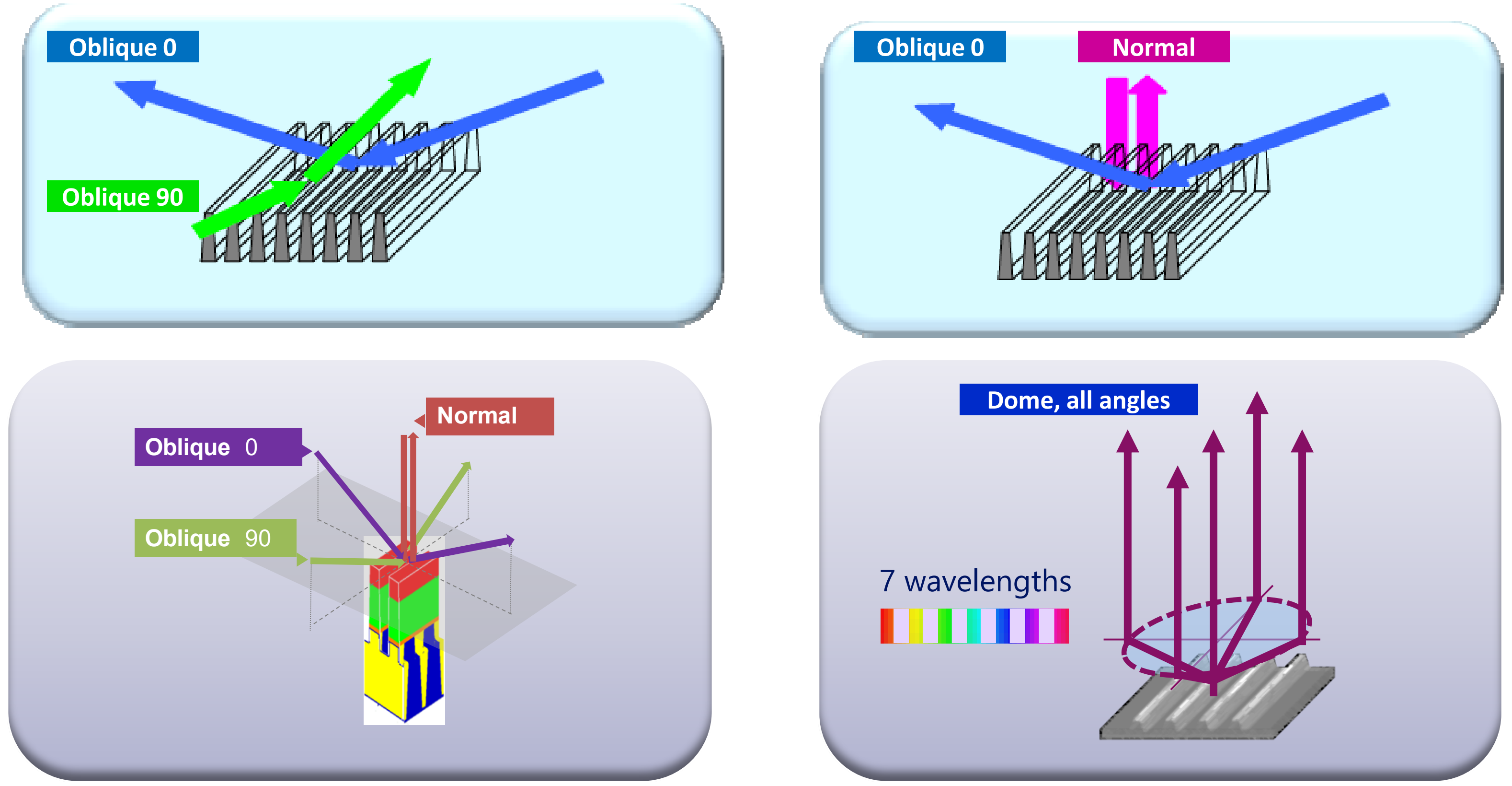
Traditional OCD

OCD measures light diffracted from **periodic structures** and reconstruct the geometry profile of measured patterns

Traditional OCD uses full geometrical model and rigorous calculations.

OCD tools can be stand alone and integrated (build into processing equipment - track, etcher, polisher, etc.)

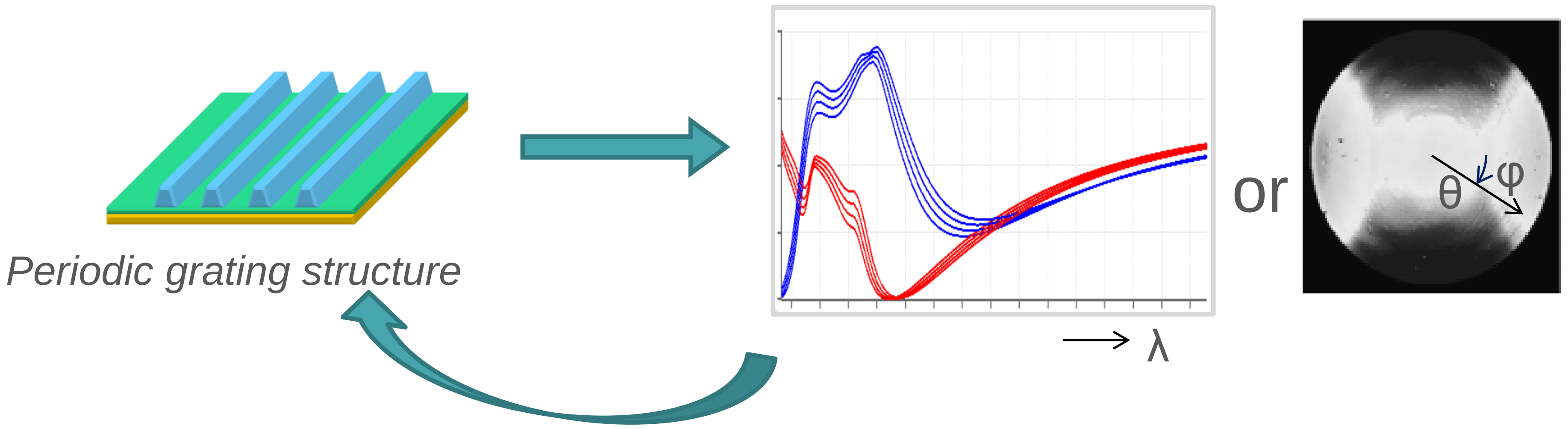


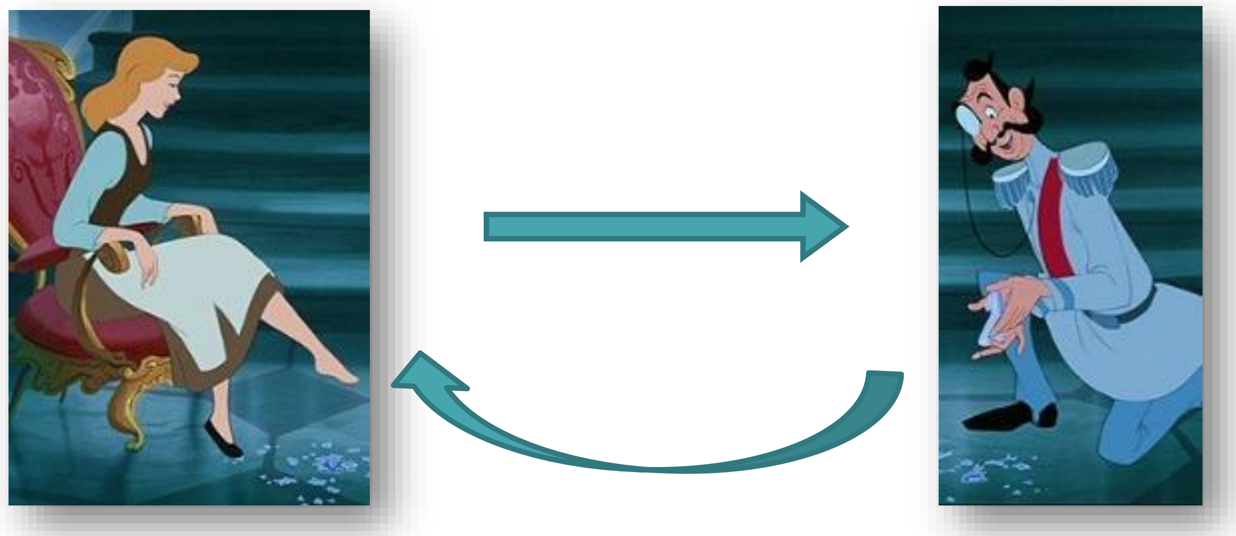


SA OCD tools (with multiple measurements channels and full polarization control)
are usually more complicated and expensive than in-line (in-process, in–situ) Integrated systems

Traditional OCD

Properties of the periodic structure (‘profile’) determine the signal





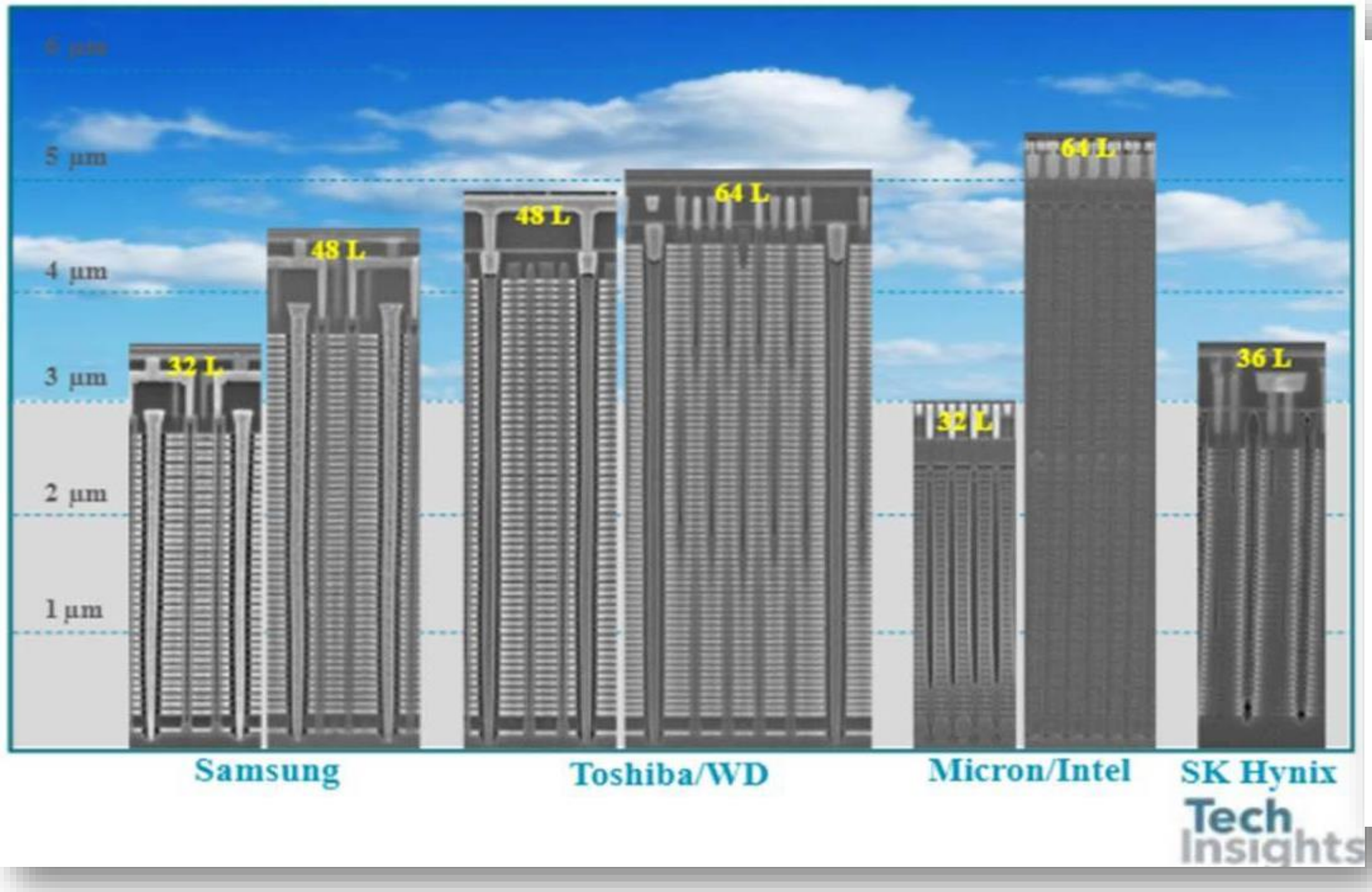
Our goal is to **solve** the **inverse problem**: from signal to profile

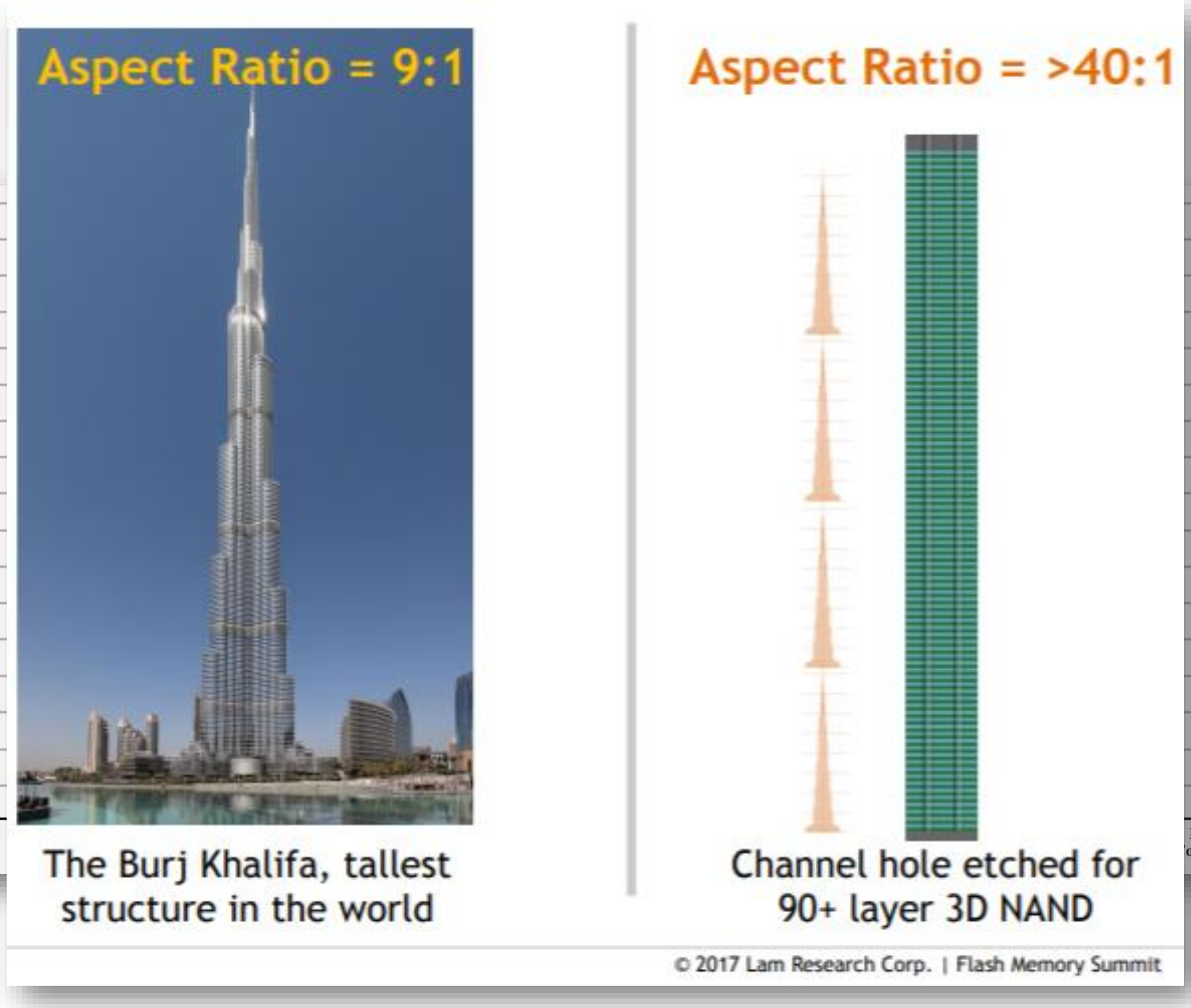
- There is no direct way to solve the inverse problem
- The approach
  - try ‘candidates’
  - determine the ‘best fit’

3D complexity

- In X-Y: from 2D layouts to 3D to in-die and non-periodic arrays
    - Blankets to “on-array”
    - Repetitive arrays to in-die memory (DRAM, SRAM)
    - Non-repetitive structures (Logic under Memory), E-test structures, etc.
- In Z: from simple gratings to complex overlapping arrays
- Multiplication of parameters of interest: multiple NW/NS, N and P transistors in SRAM, CD at different HAR depth, etc
- From Geometrical Profiles to Materials Profiles, including gradients, concentrations, stress

From 2D to 3D in Memory – 3D NAND



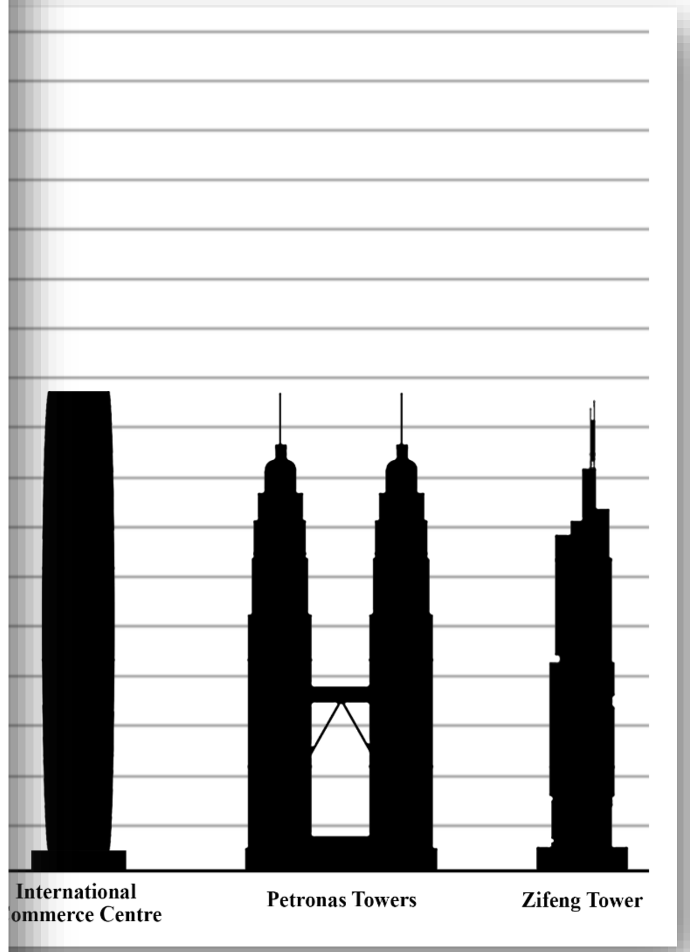

Aspect Ratio = 9:1

The Burj Khalifa, tallest structure in the world

Aspect Ratio = >40:1

Channel hole etched for 90+ layer 3D NAND

© 2017 Lam Research Corp. | Flash Memory Summit



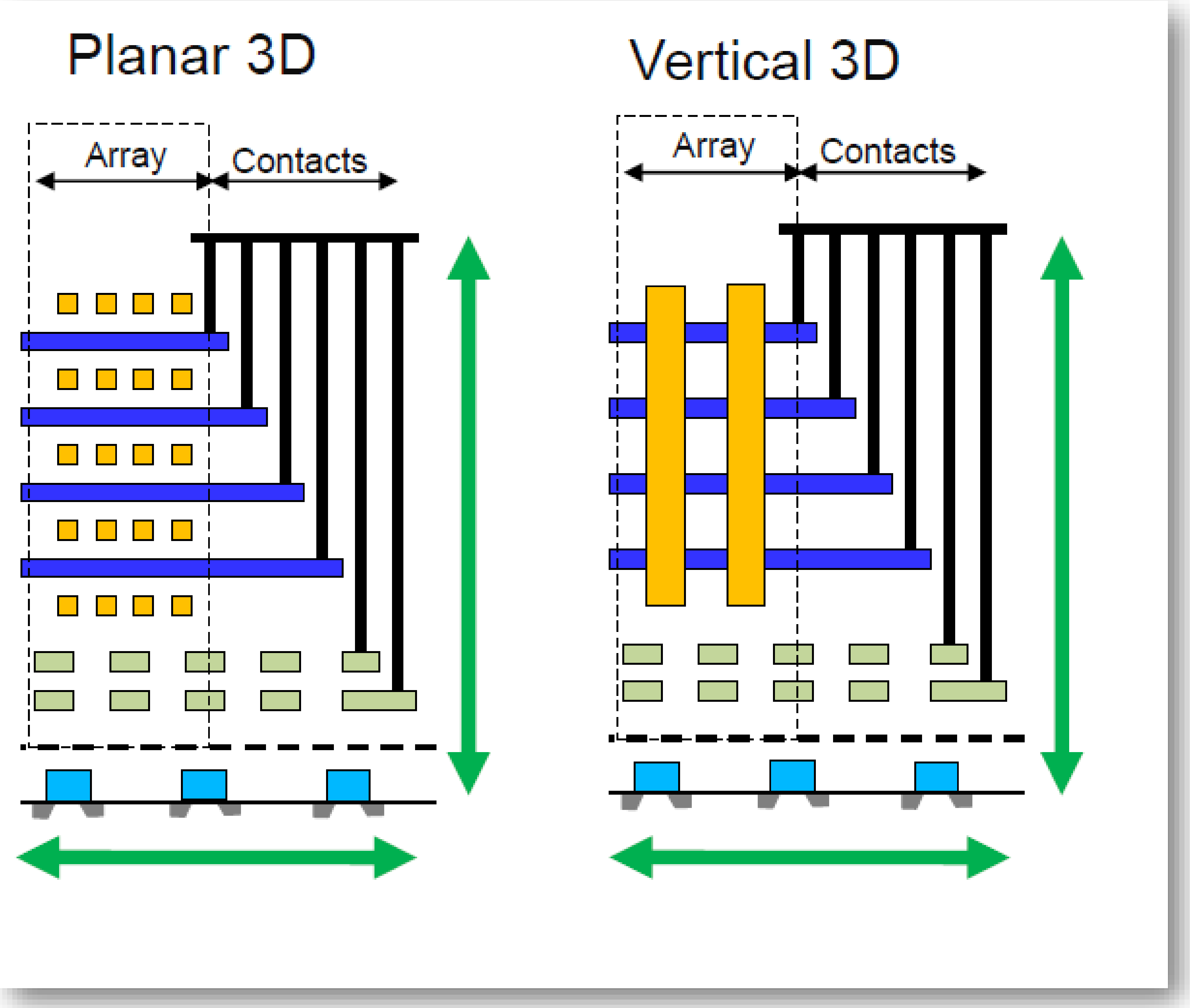
3D NAND now: 128+ layers, array over logic, multideck…
512 layers feasible

3D architecture types

- There are two distinct ways to continue “Moore” Law for increasing density of transistors on the chip:

- 3D stacking of the planar devices
  - Multideck emerging memories,
  - High density embedded memories,
  - 3D monolithic integration

- Real 3D Vertical structures
  - 3D Vertical NAND, ReRAM, etc
  - Vertical NW

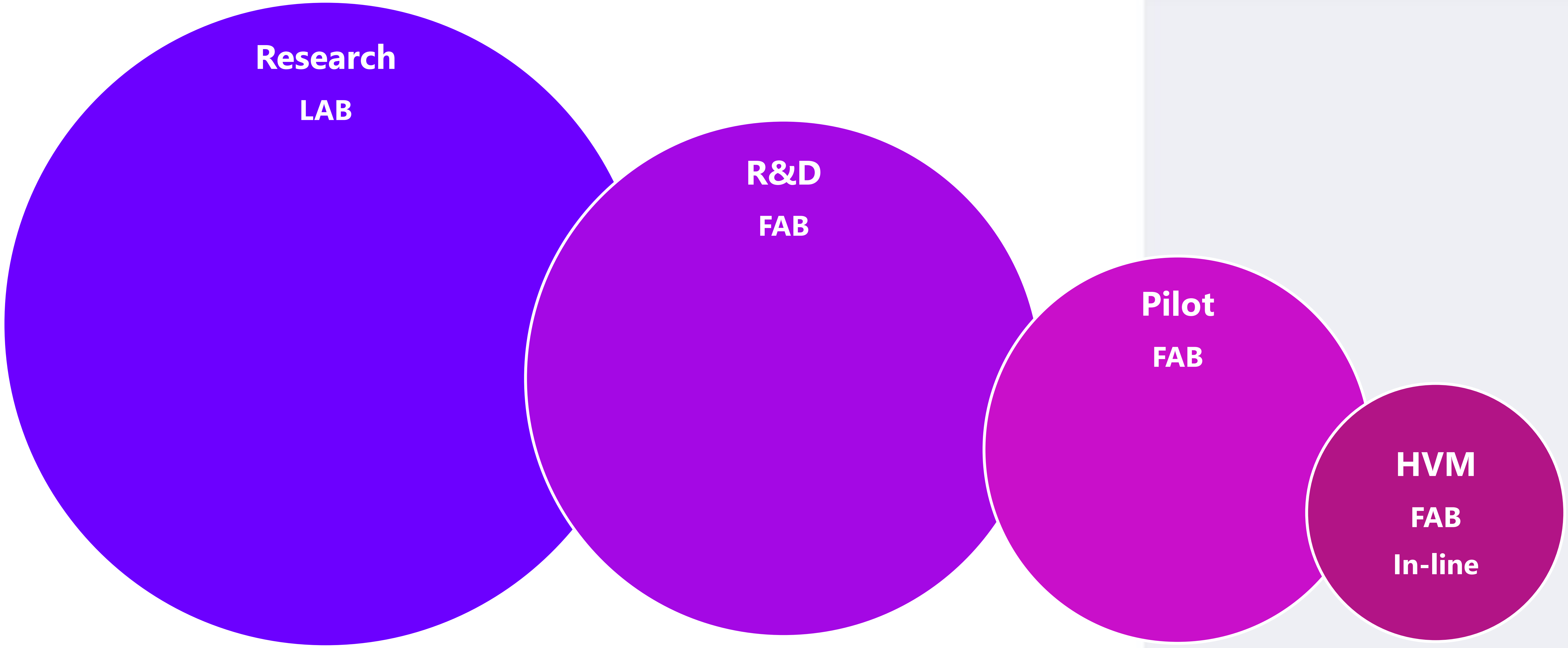


Both directions require to measure very complex 3D structures with multiple target parameters.

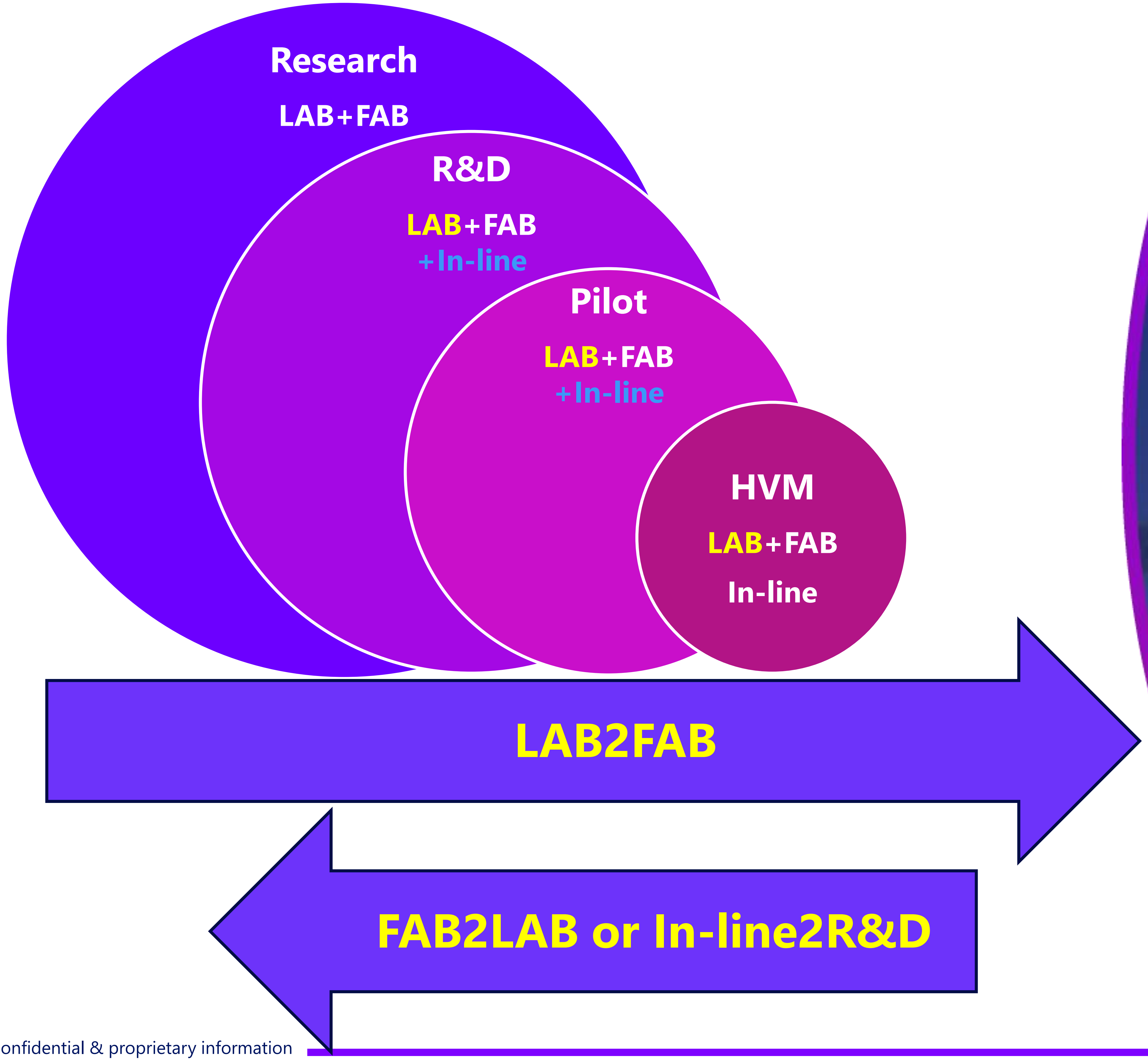
Lab, FAB and In-line metrology

Once:

For different process development steps - Deep Research, R&D, Pilot, HVM – different metrology tools were used for each step



Lab, FAB and In-line metrology


Research
LAB+FAB
R&D
LAB+FAB
+In-line
Pilot
LAB+FAB
+In-line
HVM
LAB+FAB
In-line
LAB2FAB
FAB2LAB or In-line2R&D

Now:

for shorter development cycles of Deep Research , R&D and Pilot requirements for metrology are changing:

- More directions and complexity to be tested both in R@D and in HVM
- More sampling to address variability at early R&D stages

New metrology is required: LAB2FAB trend

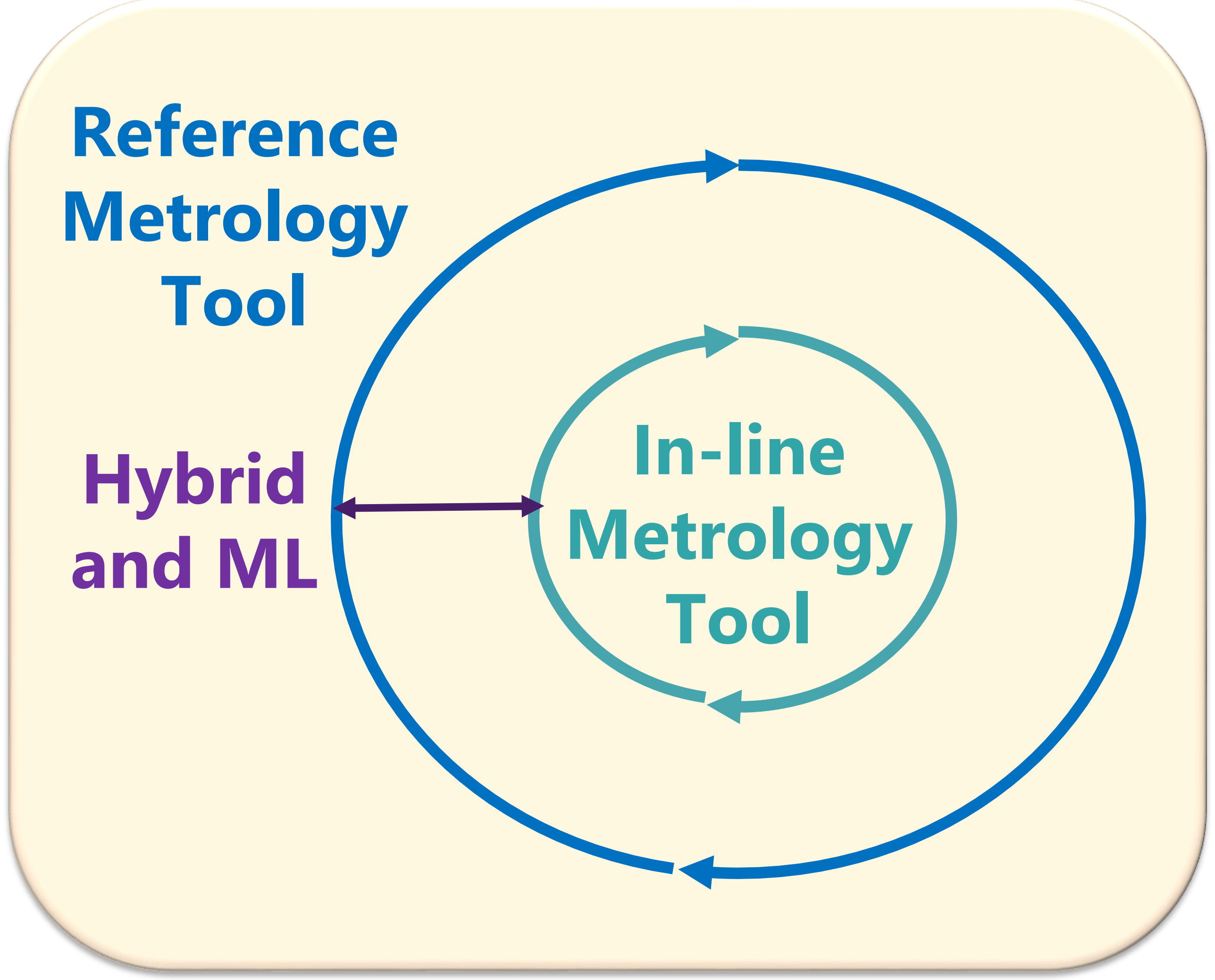
- More diverse metrology is required closer to the manufacturing process
- To allow wide FAB acceptance LAB metrology need to:
  - Add clean room compatibility and capability to measure wafers (test and production),
  - Reduce COO (faster throughput) and full automation
  - Ensure accuracy @ precision and non-destructiveness
- Examples of recently (being) introduced in-line techniques:
  - XPS/XRF
  - TEM


© 1999 Randy Glasbergen. www.glasbergen.com

"It's the latest innovation in office safety. When your computer crashes, an air bag is activated so you won't bang your head in frustration."

New metrology is required: FAB2LAB (In-line2R@D) trend

- Early usage of sensors/in-line metrology in R@D – to shorten R&D and streamline R@D – pilot –HVM transition.
- To allow wide R&D acceptance in-line metrology:
  - Fast recipe creation and validation for frequent process changes
  - Robustness for non-expected process changes and variations
- Examples includes wide usage of sensors, in-line and integrated metrology tools in R&D for advanced technology nodes:
  - Optical and electrical in-situ sensors
  - Integrated OCD metrology

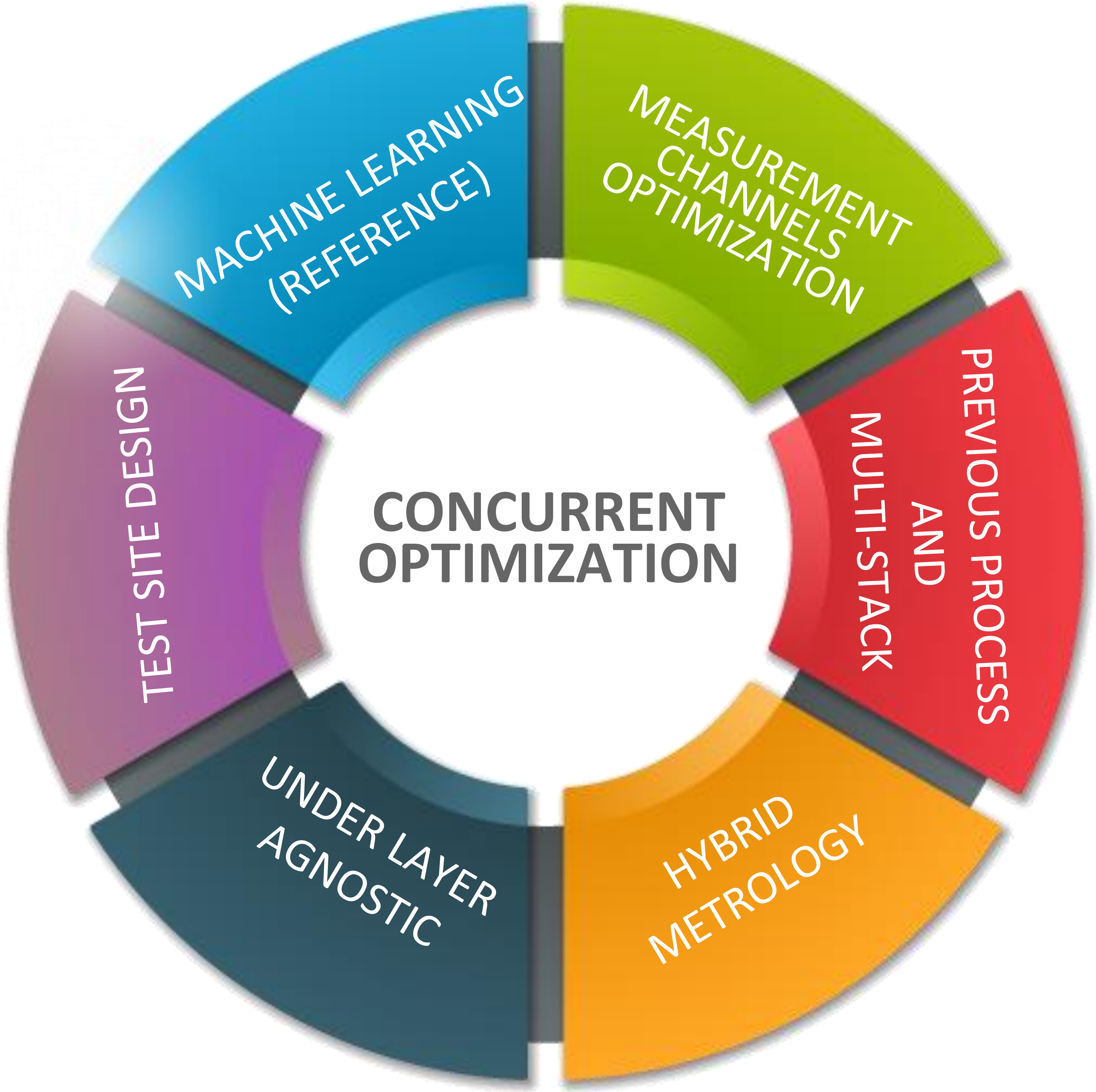


Enabling/enhancing metrology solution in terms of precision, accuracy and tool matching

Hybrid Metrology 2.0: From Metrology to Information Technology, A. Ger, Semicon Europe, 2017

Holistic Metrology Approach

- Holistic approach move focus from improvement of HW to more efficient use of all available information,
- Combining various sources of information from different metrology tools,
- Using more and differentiated information channels,
- Improvements of SW, including new calculation engines, improved calculation times and accuracy.



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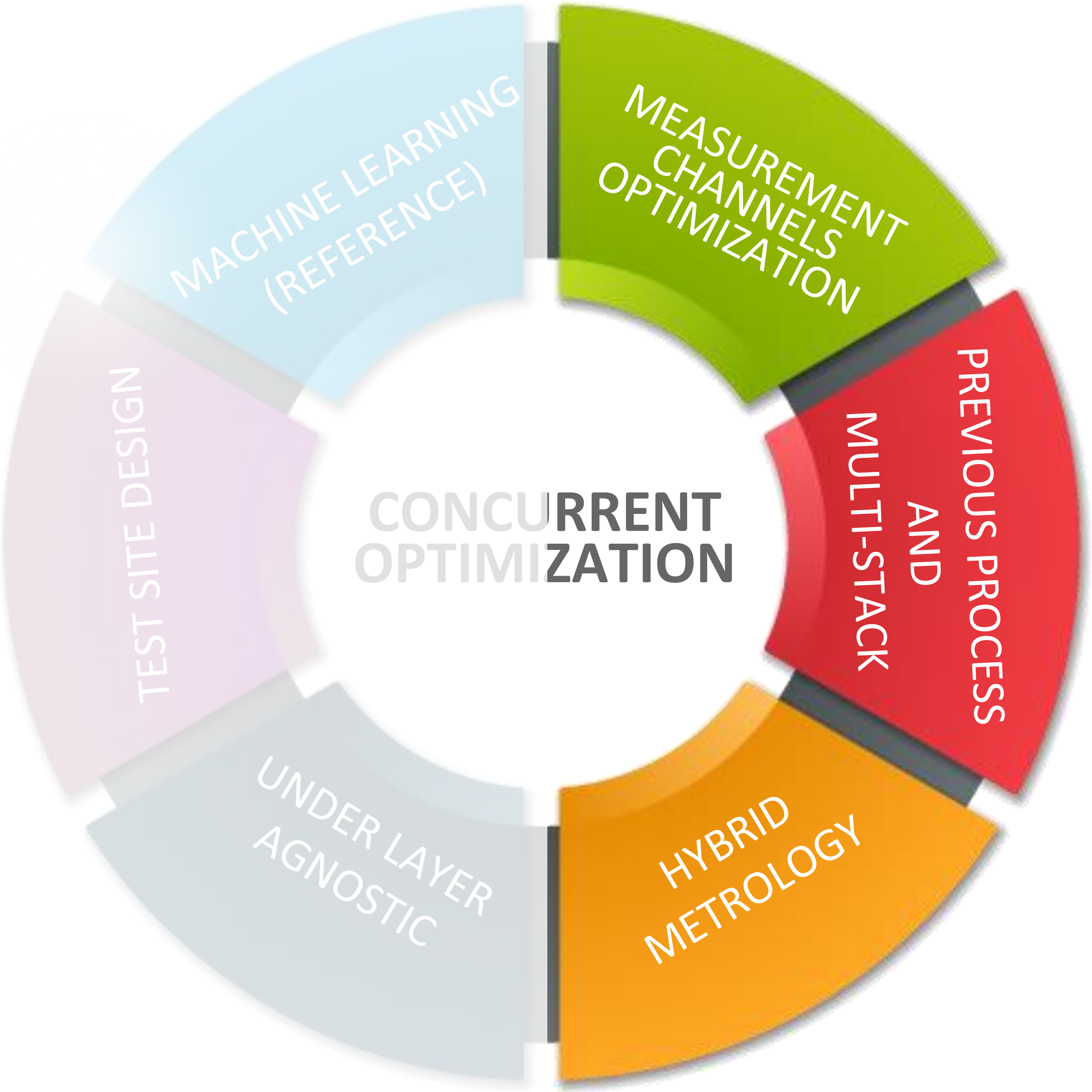
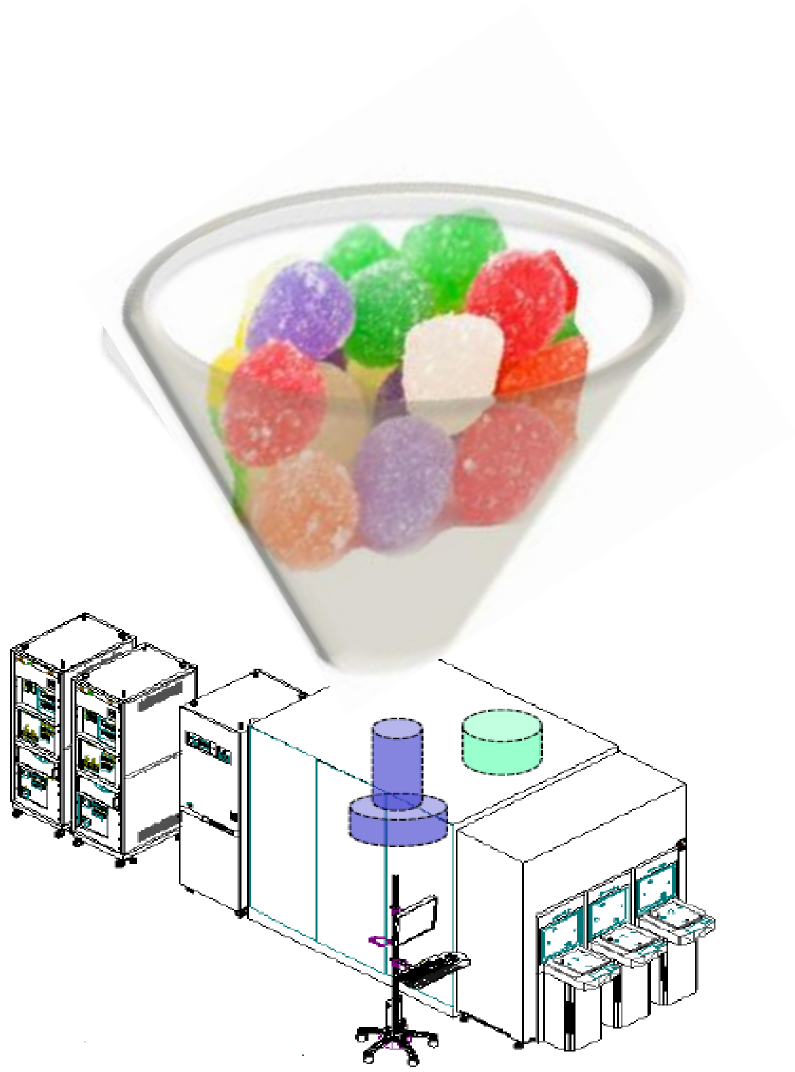


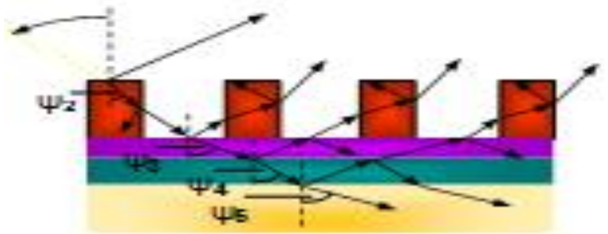
In current presentation we will focus on holistic solutions for 3D problems, supporting both: LAB2FAB
and In-line2R&D metrology trends.

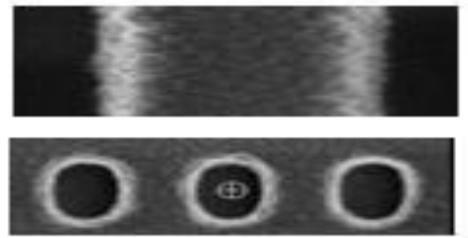
Hybrid Metrology

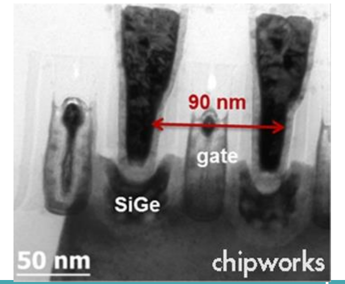


- Smart sampling for precise measurement
- Smart recipe for OCD measurement
- Fusion map of height and EPE

Current and Future Critical Dimension Metrology Perspective for Sub-10nm Process, M. Nozoe FCMN 2017



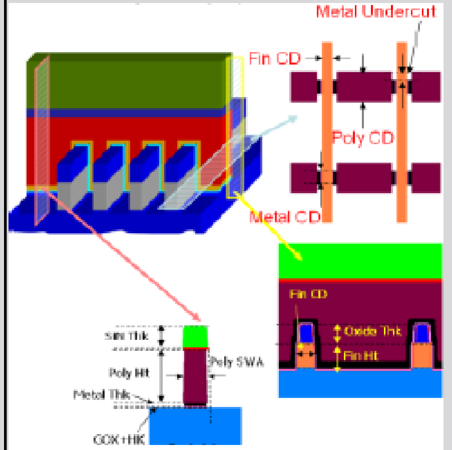
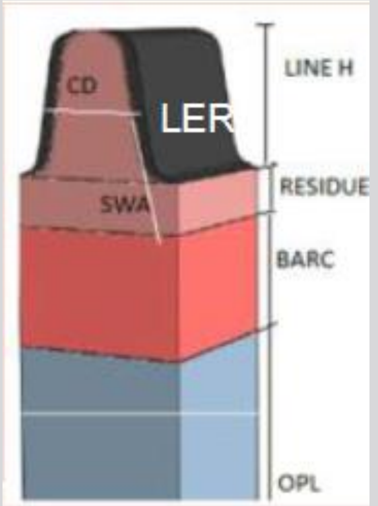
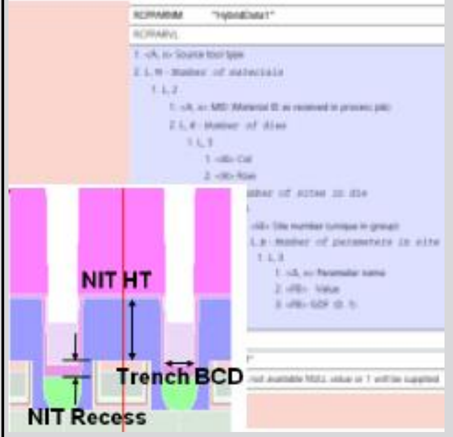
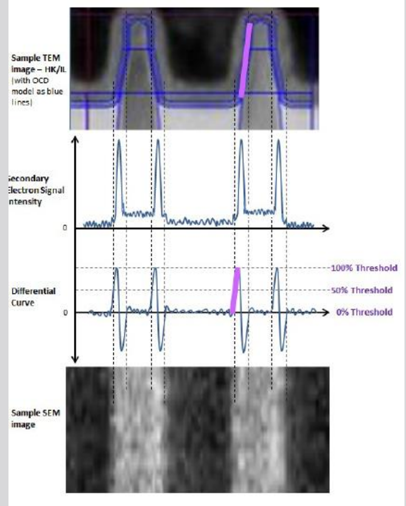
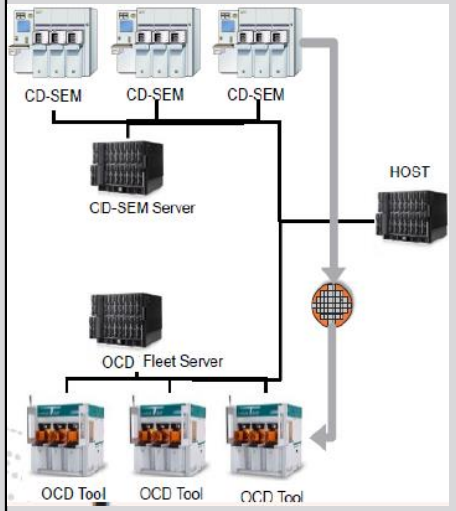
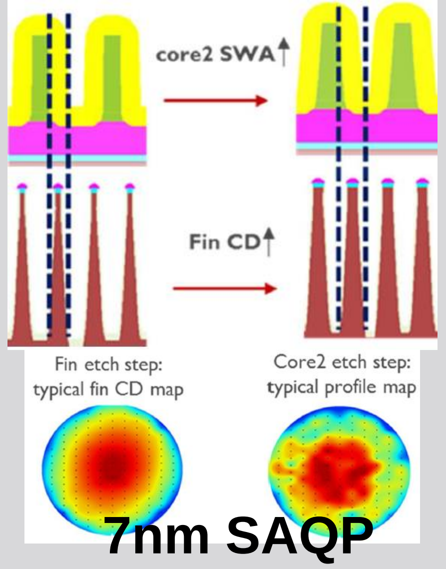
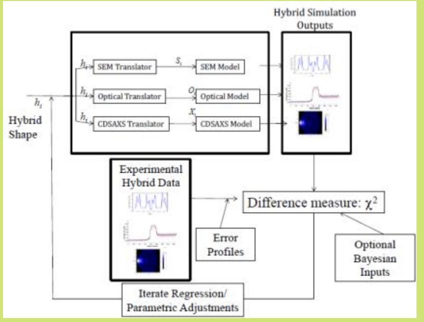
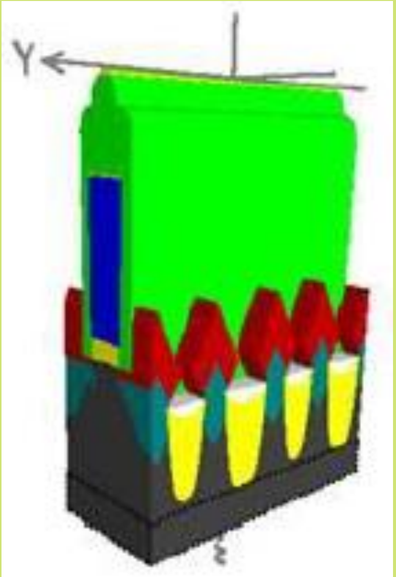
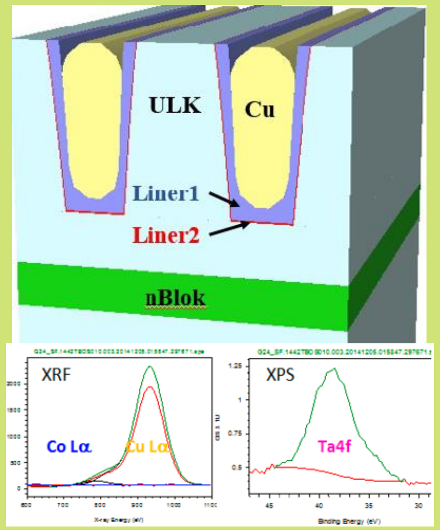
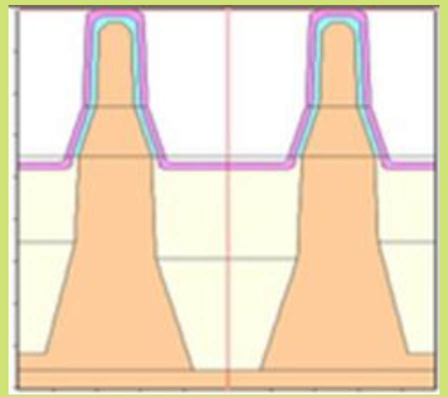




	Scatterometry	CDSEM	AFM	TEM/XSEM	XPS/XRF
What to measure	CD, profile, other	CD	CD, profile	CD, profile, other	Ultrathin films, composition
Where	Periodic grating	Anywhere	Anywhere*	Anywhere	Anywhere*
Time-to-solution	Days to weeks	Minutes	Hours	Hours to days	Minutes
Destructive	Negligible	Minor (resist)	No	Yes	None
Time to measure	Seconds	Seconds	Minutes	Days	Seconds/ Minutes
Summary: Strengths	Fast measure Most profile info	Quick setup & fast measure Measure anywhere	Most profile info High accuracy	Full profile info High accuracy	Ultrathin films Synergy to OCD
Assumptions & limitations	Model assumptions Tradeoff b/w Accuracy-Precision Requires grating	No profile info, assume uniform profile Diff. to measure true bottom	Tip wear & characterization Large space Low TPT	Resolution is process dependent Limited statistics	XPS – only top 10nm info XRF – only volume info
Typical Fab usage	"Workhorse" for CD & profile	"Workhorse" for CD	• Good RMS • Partial in-line	Absolute reference	Composition, ultrathin films
Issues alleviated via Hybrid Metrology	Correlation & sensitivity and long setup time	Measurement error due to profile variation	Restriction on structure (tight spaces)		Dependence on profile

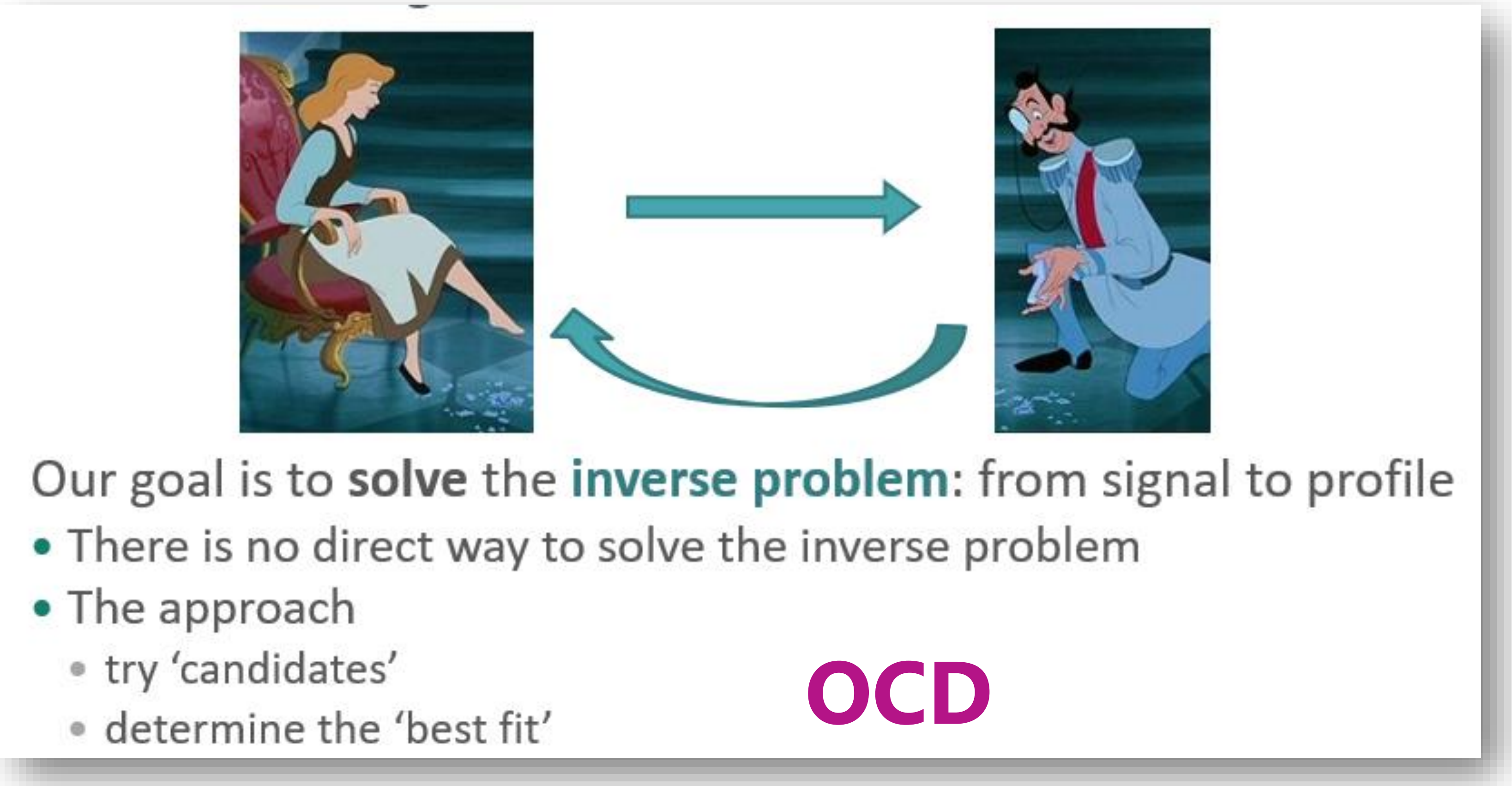
Optical metrology for advanced process control..., C. Bozdog et al, SPIE Adv. Litho., 9782-13, 2016

Hybridization of OCD with CDSEM/TEM/XPS/XRF/AFM…

	2011	2012	2013	2014	2015	2016
	Proof of concept	DFM, first algorithms	HVM host implemented	Co-optimization	Server use-case	SAQP control
CD – SEM (AFM)	 32nm FINFET, 22nm Gate DI	 14nm EUV litho, DSA holes	 20nm CA/CB profiles, 14nm Gate RIE	 14nm HK/IL		 7nm SAQP Core 2 etch
			+ CD SAXS	XRD hybrid	XRF/XPS hybrid	XPS: TF on pattern
X-Ray			 14nm Si lines	 14nm SiGe H, C	 10nm Cu CMP	 14nm HK/IL 10nm ultra-thin films

Hybrid Metrology 2.0: From Metrology to Information Technology,
A. Ger, Semicon Europe, 2017

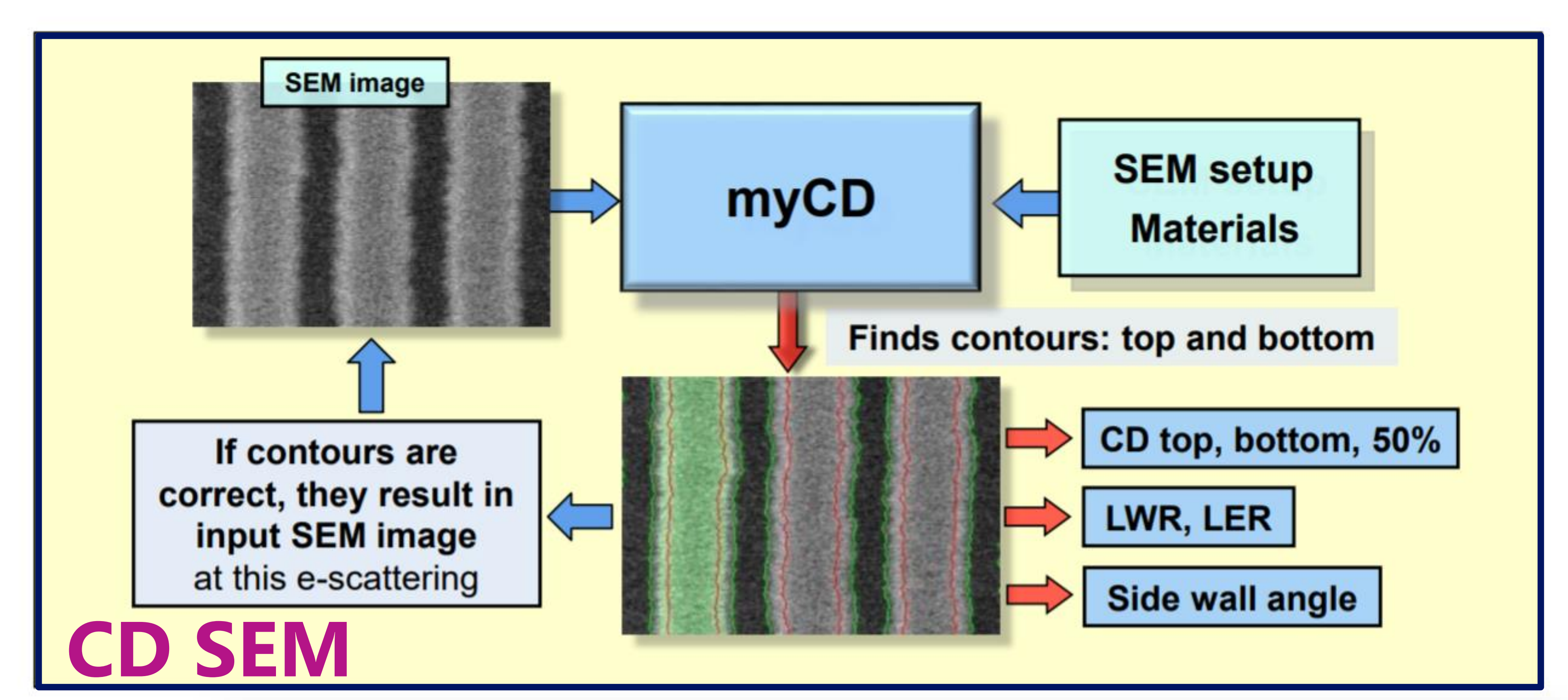
Modeling: from OCD to CDSEM (TEM, XPS, etc)



Our goal is to **solve** the **inverse problem**: from signal to profile

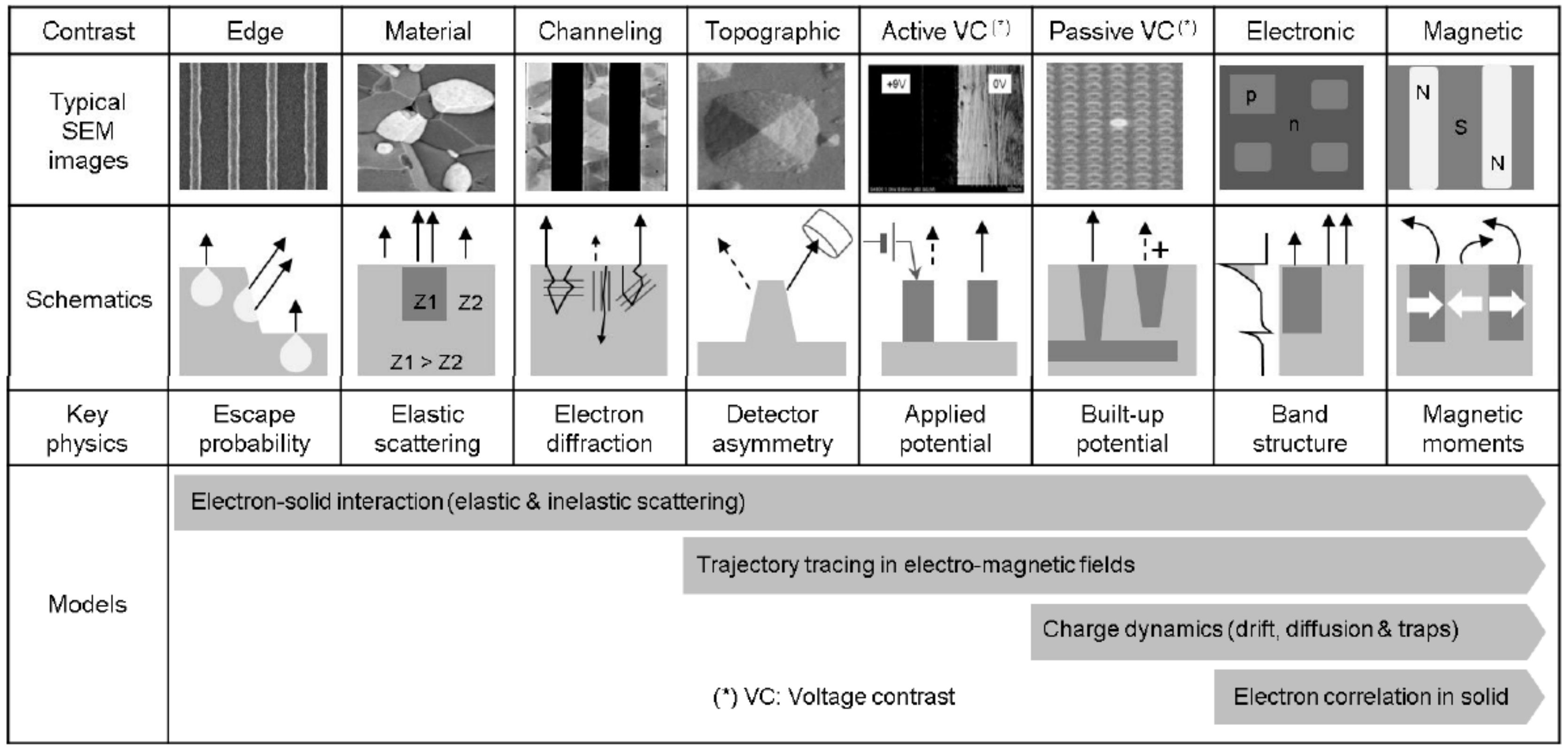
- There is no direct way to solve the inverse problem
- The approach
  - try ‘candidates’
  - determine the ‘best fit’

OCD



CD SEM Modeling

- improves accuracy
- allows automatic extraction of contours
- measures profile (CD, SWA and Height)
- enables better hybridization with other model based methods such as OCD.



Contrast	Edge	Material	Channeling	Topographic	Active VC (*)	Passive VC (*)	Electronic	Magnetic
Typical SEM images					+9V 0V		p n	N S N
Schematics		Z1 Z2 Z1 > Z2				+		
Key physics	Escape probability	Elastic scattering	Electron diffraction	Detector asymmetry	Applied potential	Built-up potential	Band structure	Magnetic moments
Models	Electron-solid interaction (elastic & inelastic scattering)							
				Trajectory tracing in electro-magnetic fields				
						Charge dynamics (drift, diffusion & traps)		
				(*) VC: Voltage contrast			Electron correlation in solid	

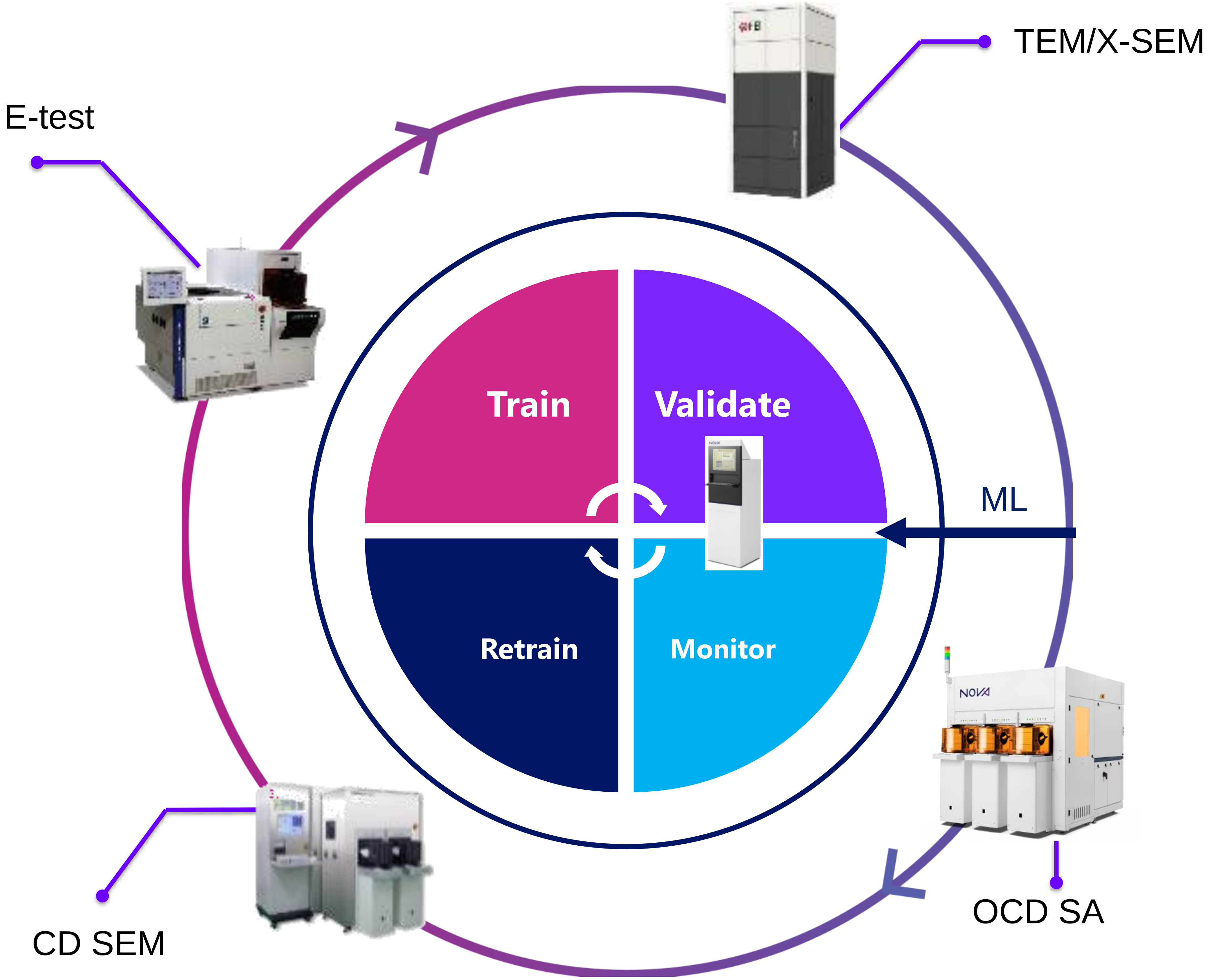
Frontiers in CD-SEM metrology, A. Babin, SPIE 2018

Modeling of electron-specimen interaction in scanning electron microscope for e-beam metrology and inspection: Challenges and perspectives, M. Suzuki, Proc. of SPIE 10585, 2018

In-line2R&D: OCD ML in HVM/Pilot/R&D

ML use cases:

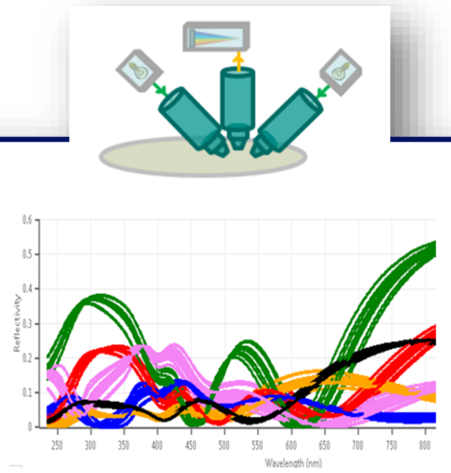
- To allow usage of high sampling in-line metrology, in-process and in-situ sensors - **close to the process or during the process:**
- To allow measurements on real complicated 3D structures **anywhere in the die:**
  - ❉Non-periodical or quasi-periodical structures
  - ❉Complex structures with unknown underlayers
- For **complimentary measurement of additional parameters** that have complex dependence on multiple factors, such as EOL electrical parameters (E-test)
- For measuring of **on product overlay** (POL) what is defined by multiple process steps



Implementation of Machine Learning in Metrology for Advanced Semiconductor Manufacturing M. Shifrin, Semicon Korea, 2019

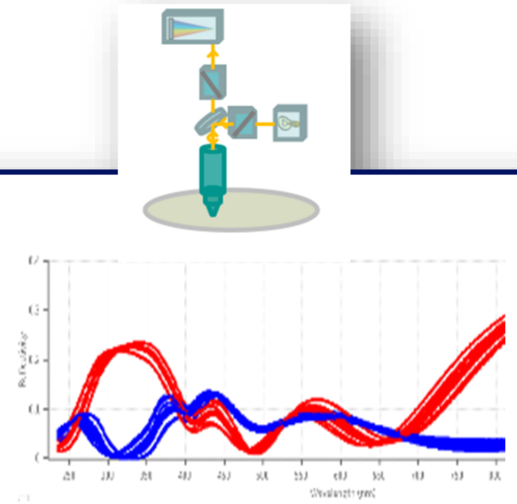
ML enabler for Integrated Metrology

ML



Multi Channel RCWA solution (Polarization and Azimuth)

- Model based solution
- Potentially reference-less technique
- Limited by model accuracy and computational resources



Reduced Channels Machine Learning Solution

- No limitation for computational resources
- No RCWA model errors
- System gain calibration errors reduced by "learn out"
- Require reference to run

OCD SA to IM

CHALLENGE

Scale Integrated Metrology (IM) benefits to complex applications

- SRAM sites in logic
- Advanced DRAM/3D NAND nodes

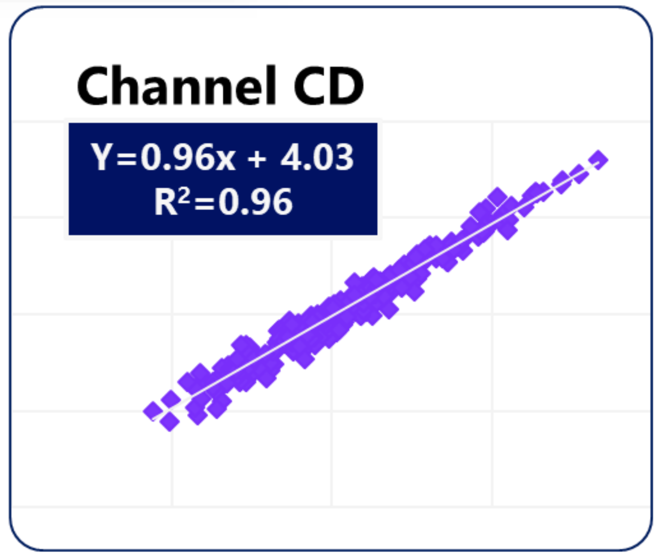
Meet accuracy and precision requirements to allow successful APC

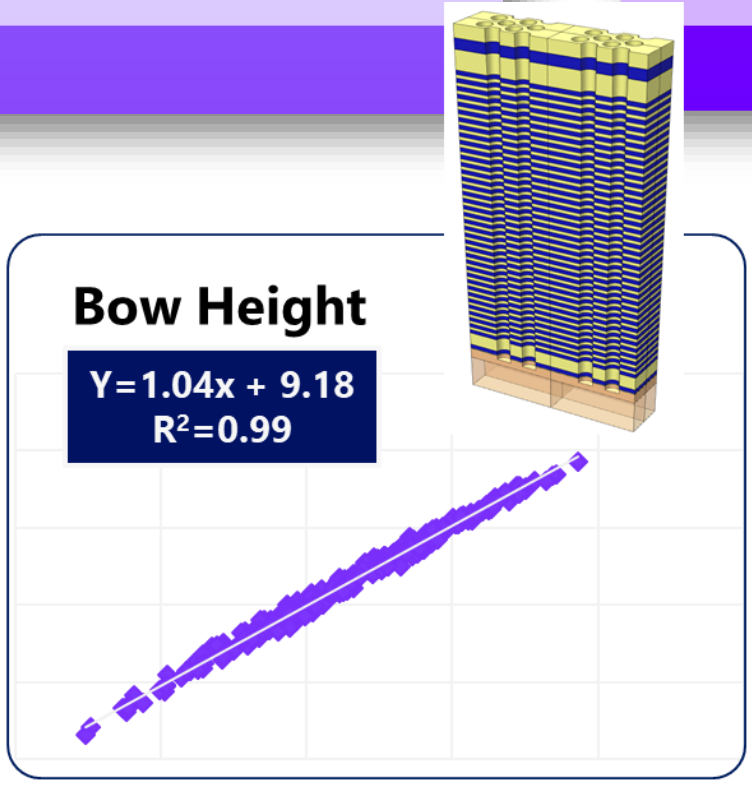
Extend Integrated Metrology Benefit to other areas of high W2W variability

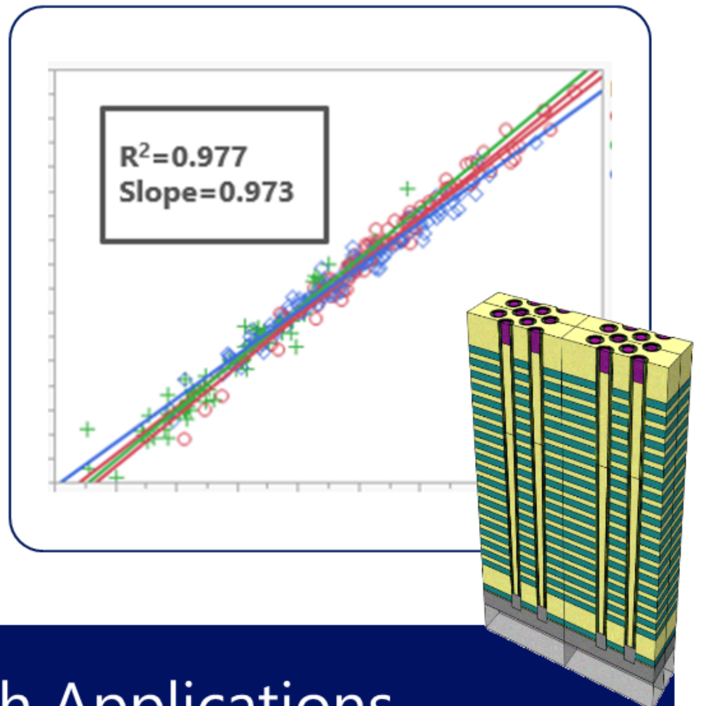
SOLUTION

Machine learning based on Integrated metrology spectra and Standalone (SA) OCD Metrology

- Achieve high accuracy solution with IM form factor
- Meet sampling and info turn requirement to allow W2W APC
- Reduce the total cycle time and cost by reducing SA sampling







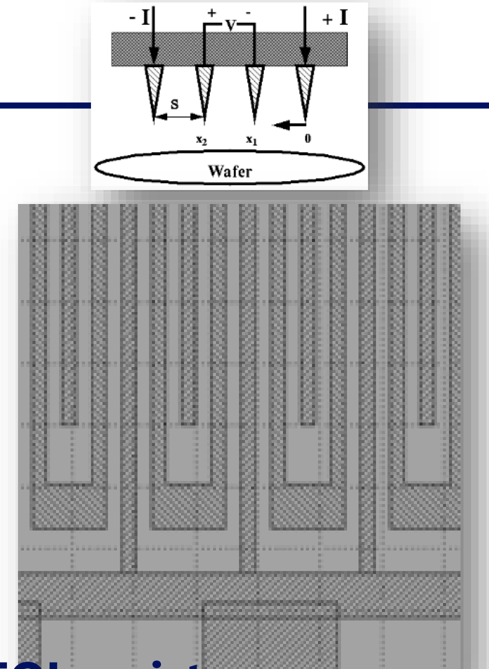
OCD SA to IM Machine learning brings precise metrology close to the process.

Implementation of Machine Learning in Metrology for Advanced Semiconductor Manufacturing M. Shifrin, Semicon Korea, 2019

Machine Learning is enabler for IM on Complex Etch Applications

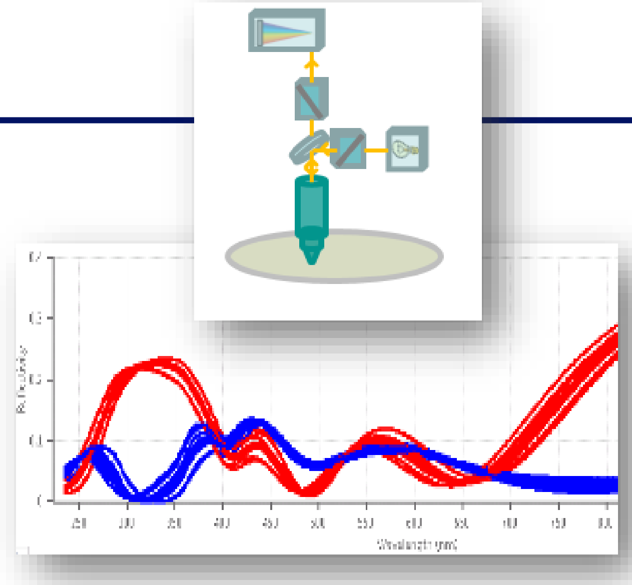
- W2W APC for etch process
- High sampling with fast info turn

OCD ML for E-test prediction (resistance)

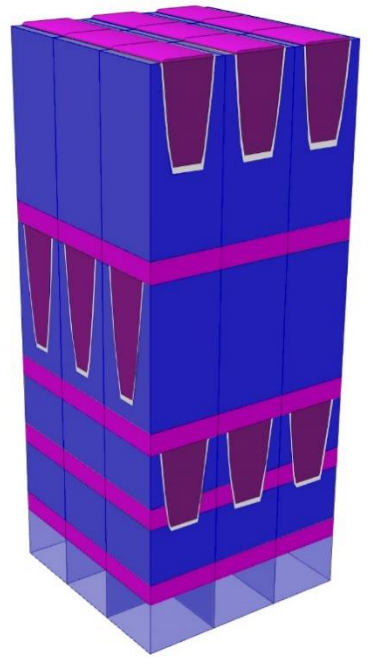


E-test EOL resistance measurements

ML



IM Spectral Measurements
ML based solution



$$Etest \sim \frac{1}{AREA_{Cu}}$$

IM provides to polisher all profile information required for APC.

Complimentary E-test ML is enabling early prediction of electrical performance

SPIE. ADVANCED LITHOGRAPHY

BEST PAPER AWARD 2018

GLOBALFOUNDRIES NOVA

Implementation of machine learning for high-volume manufacturing metrology challenges

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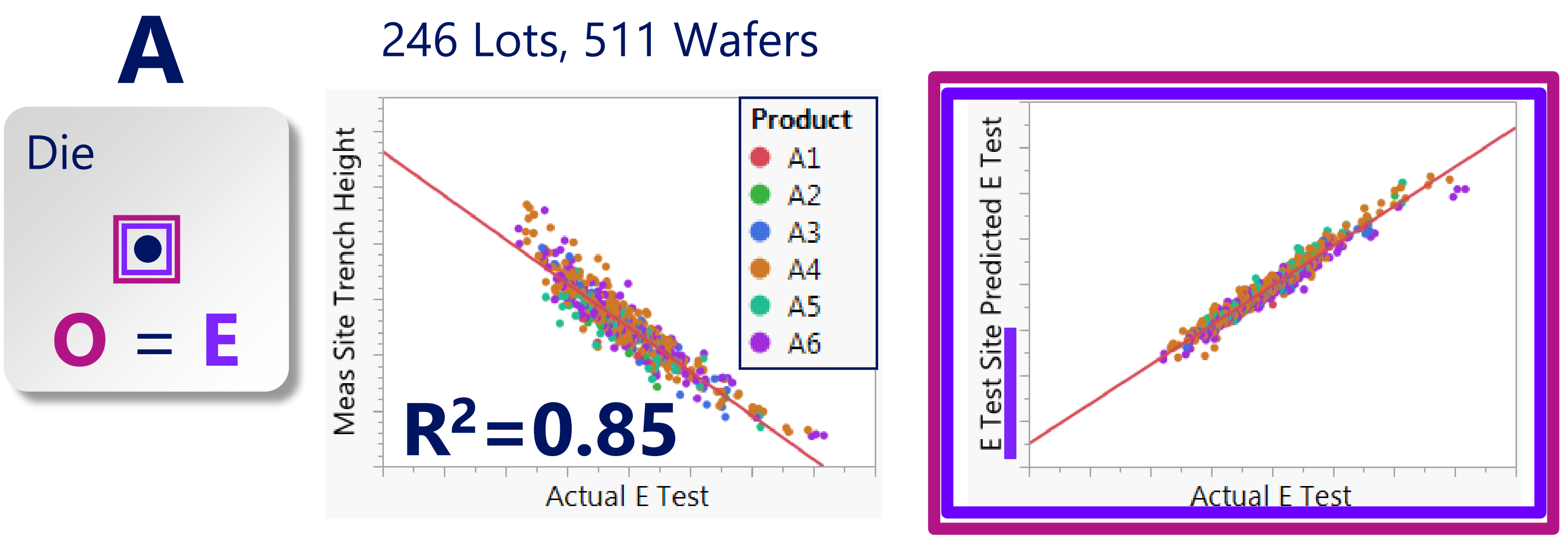
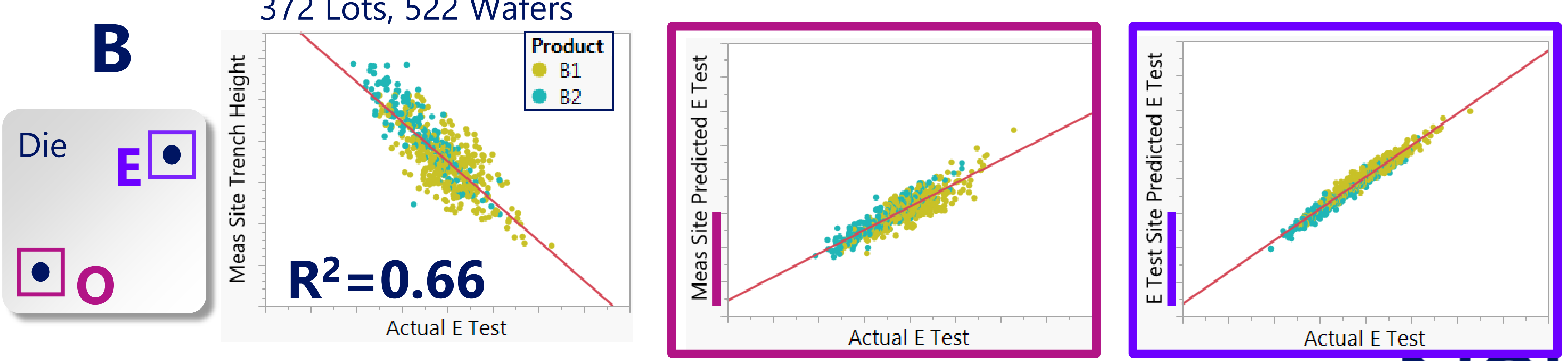
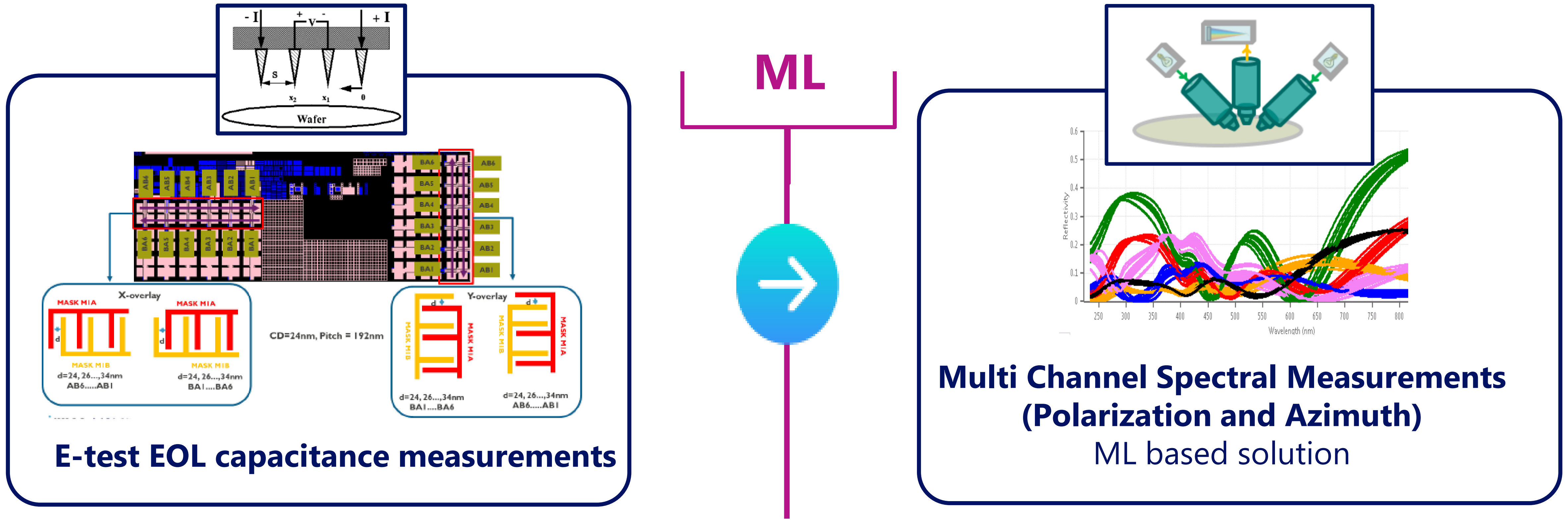


ML Predicted E-test better correlates to E-test than the model based OCD

Machine Learning Improves Correlation to E-Test



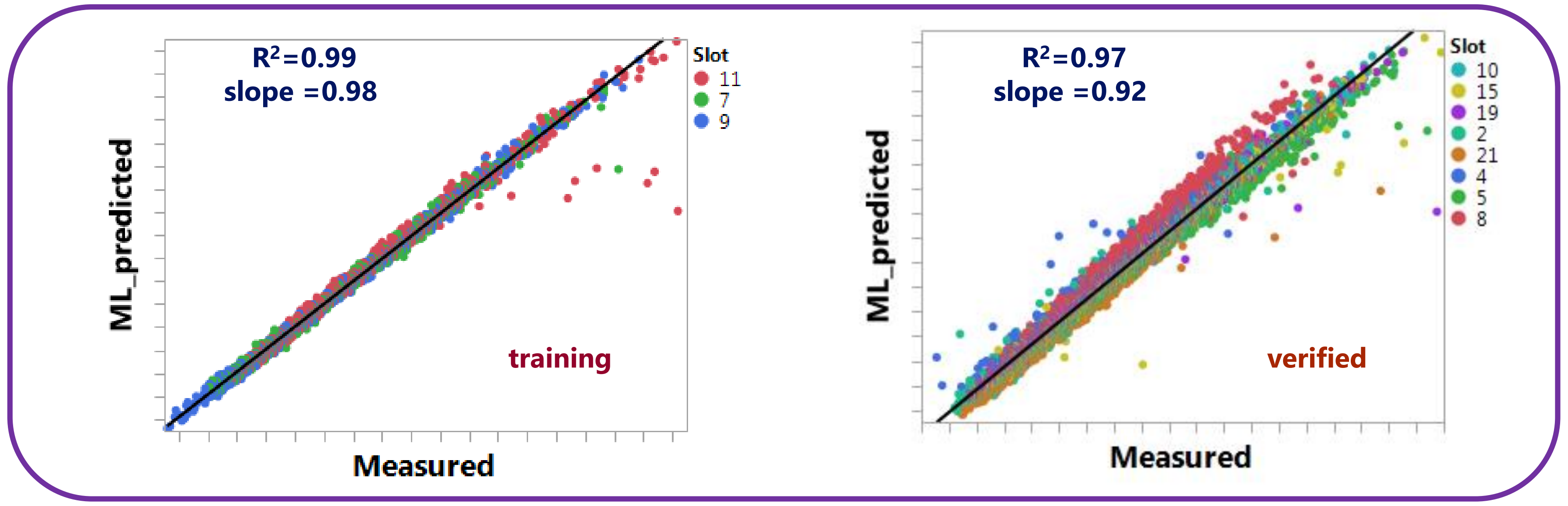
OCD ML for E-test prediction (capacitance)

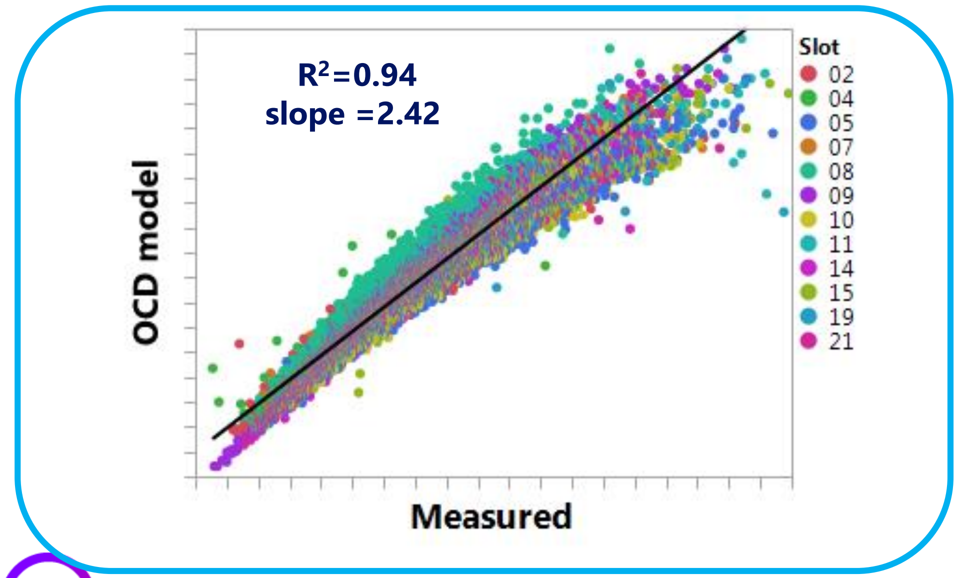


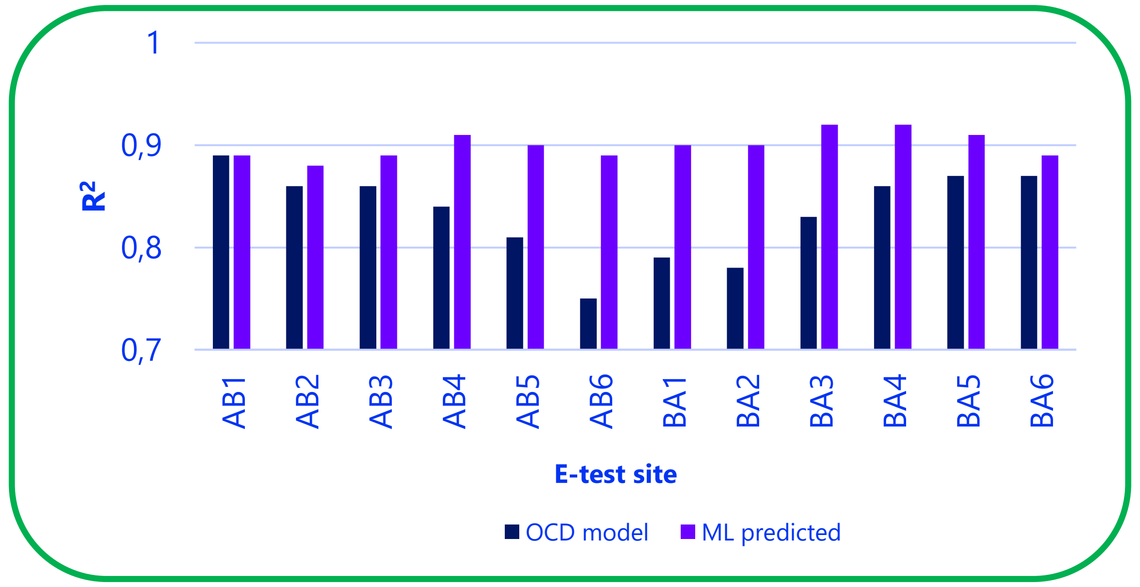
E-test EOL capacitance measurements

ML

Multi Channel Spectral Measurements (Polarization and Azimuth)
ML based solution



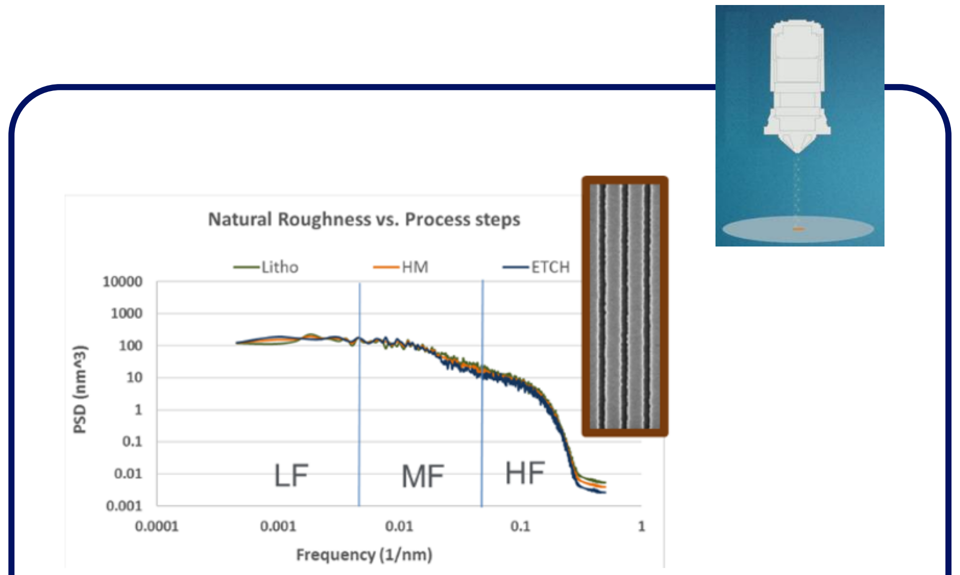




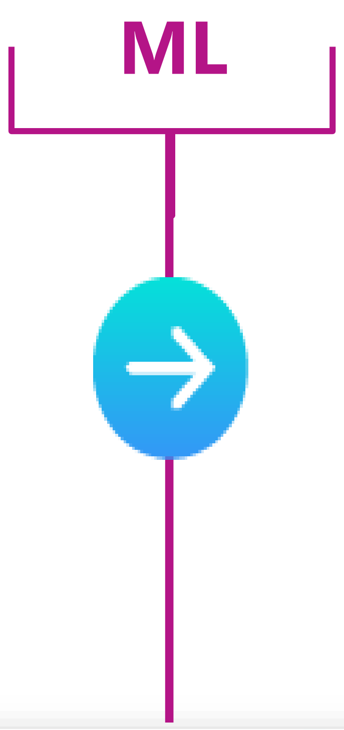
Complementary E-test machine learning solution to OCD spectra shows better R2 values compared to OCD models.

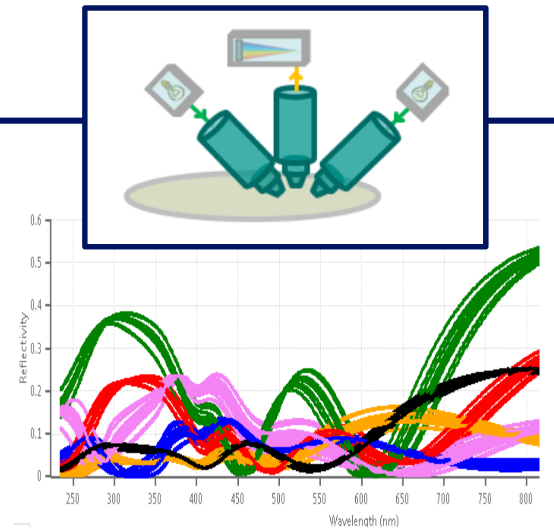
Machine learning for predictive electrical performance using OCD, S. Das et al, Proc. SPIE Adv. Litho, 2019

OCD ML for LER/LWR control



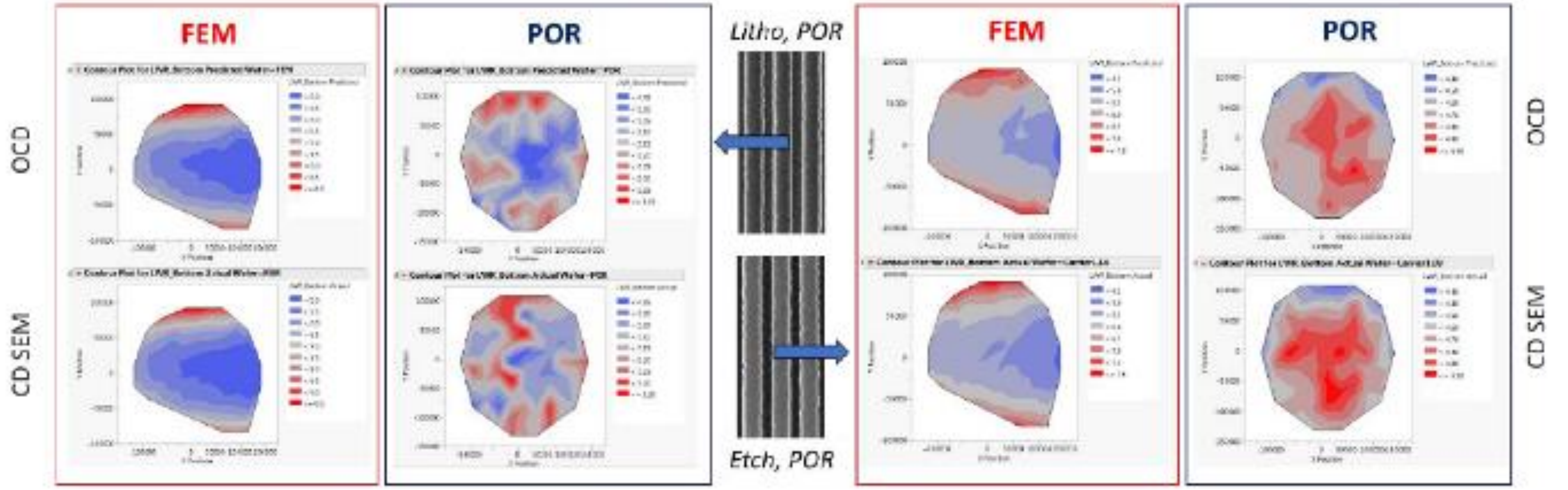
CD SEM Roughness measurements

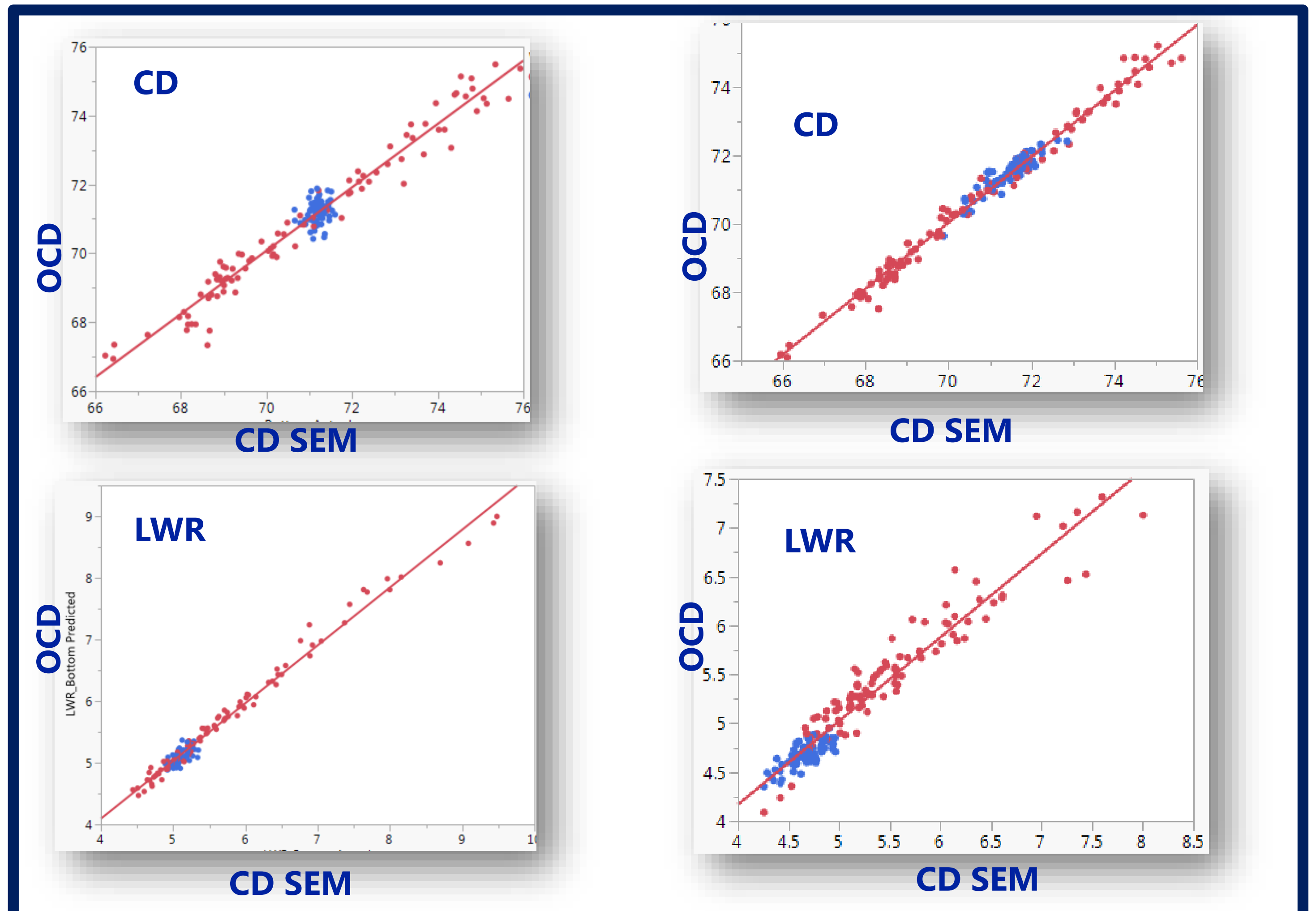




Multi Channel Spectral Measurements (Polarization and Azimuth)

ML based solution





Parameter, nm	R^2	Slope	STDEV, nm
CD	0.95	0.92	0.39
LWR	0.94	0.98	0.11

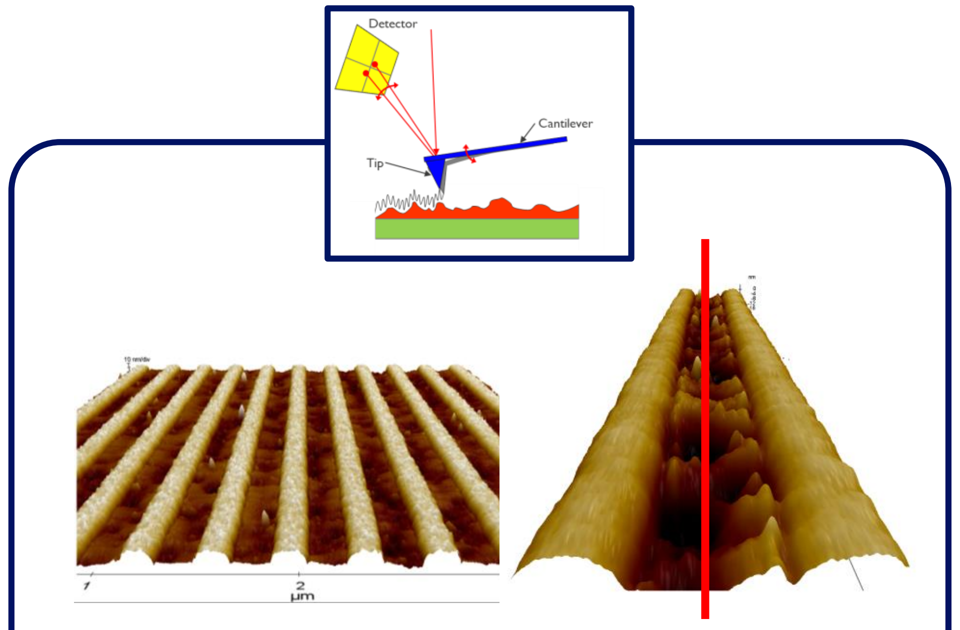
Parameter, nm	R^2	Slope	STDEV, nm
CD	0.98	0.96	0.26
LWR	0.93	0.86	0.2

OCD is capable to measure standard profile parameters, such as CD, SWA and Height.

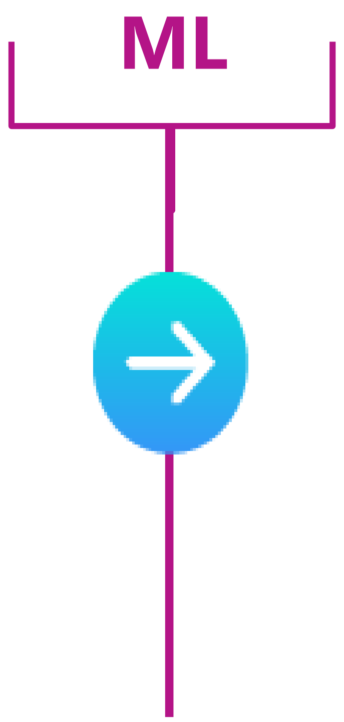
Complimentary CD SEM ML is enabling OCD to control roughness

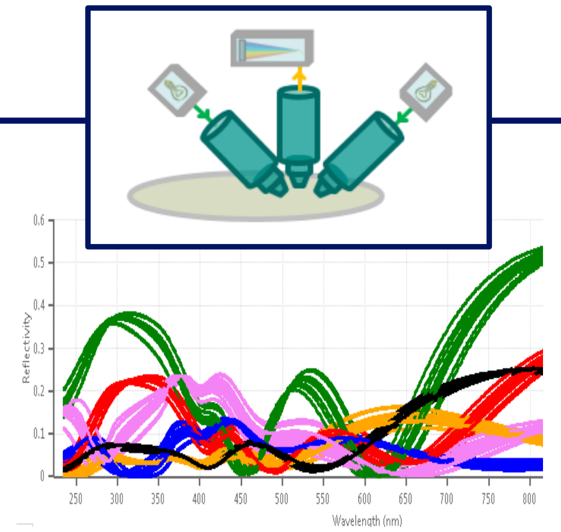
A holistic metrology sensitivity study for pattern roughness quantification on EUV patterned device structures with mask design induced roughness, S. Levi et al, Proc. SPIE Adv. Litho, 10585, 2018

OCD ML for selective deposition selectivity

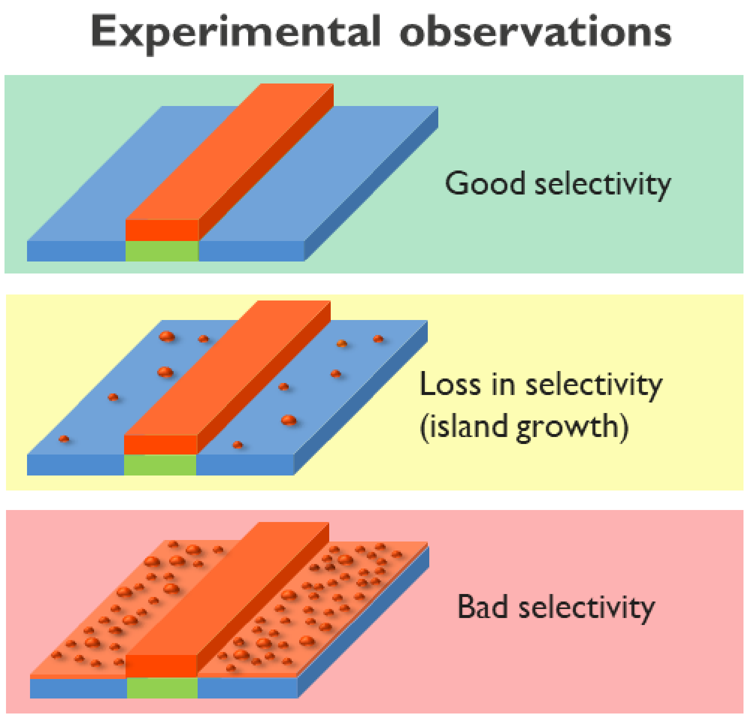


AFM nucleation measurements



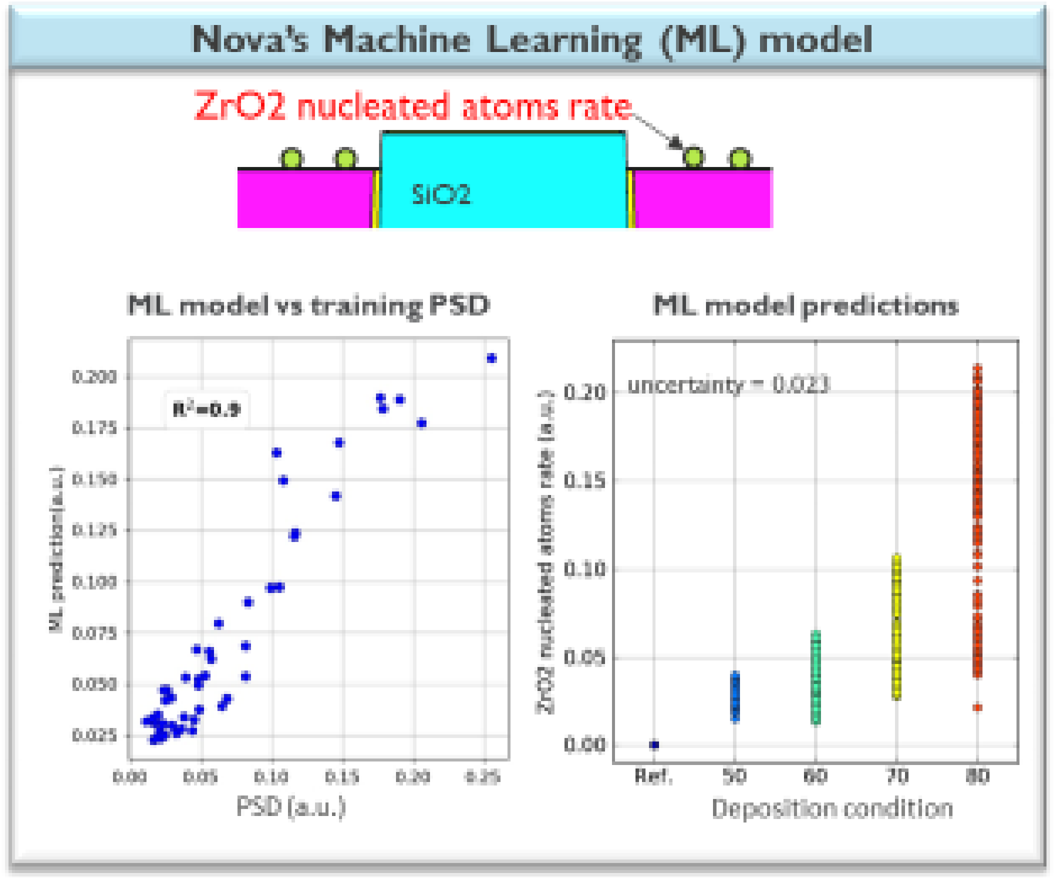


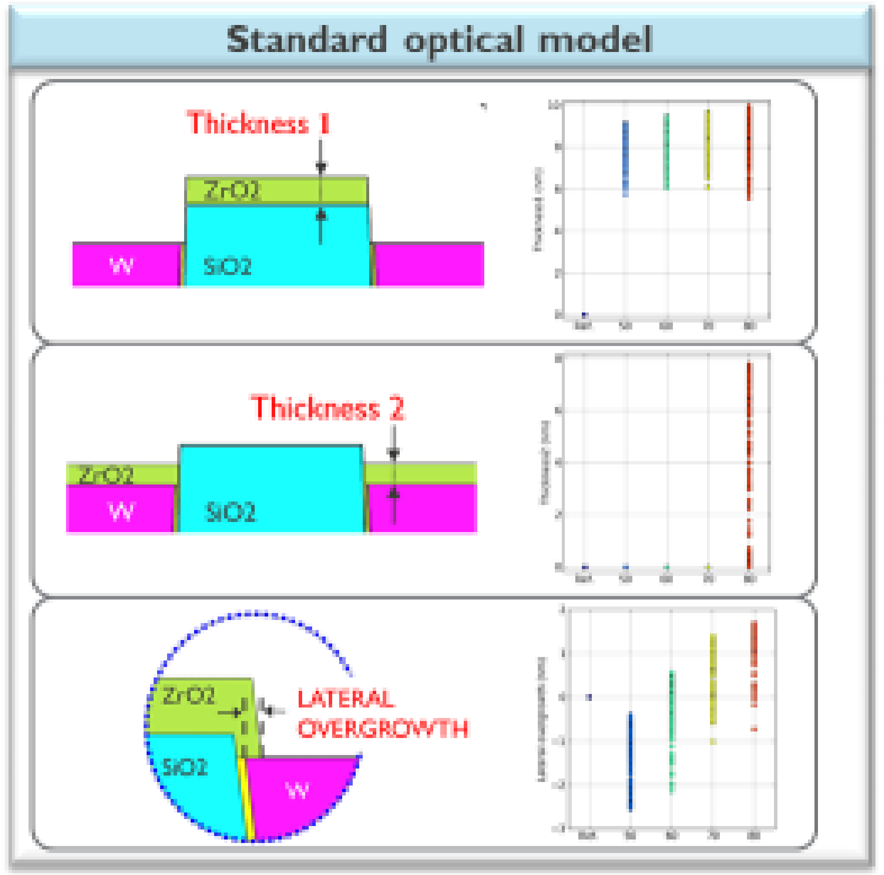
Multi Channel Spectral Measurements (Polarization and Azimuth)
ML based solution

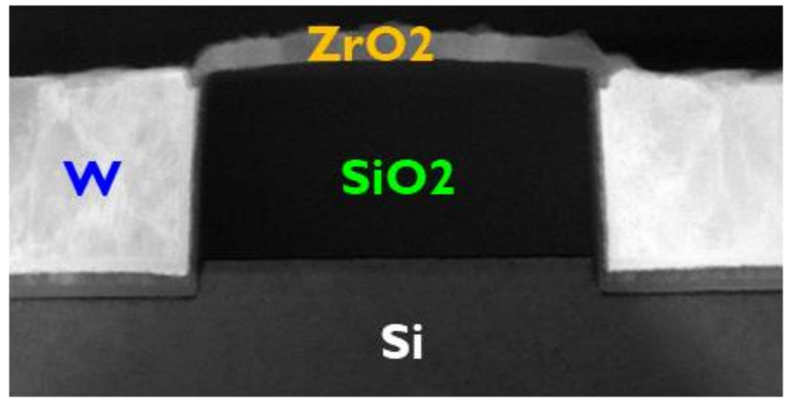


OCD is capable to measure standard profile parameters, such as deposition thickness and recess/overhang.

Complimentary AFM ML is enabling OCD to control deposition selectivity (nucleation)

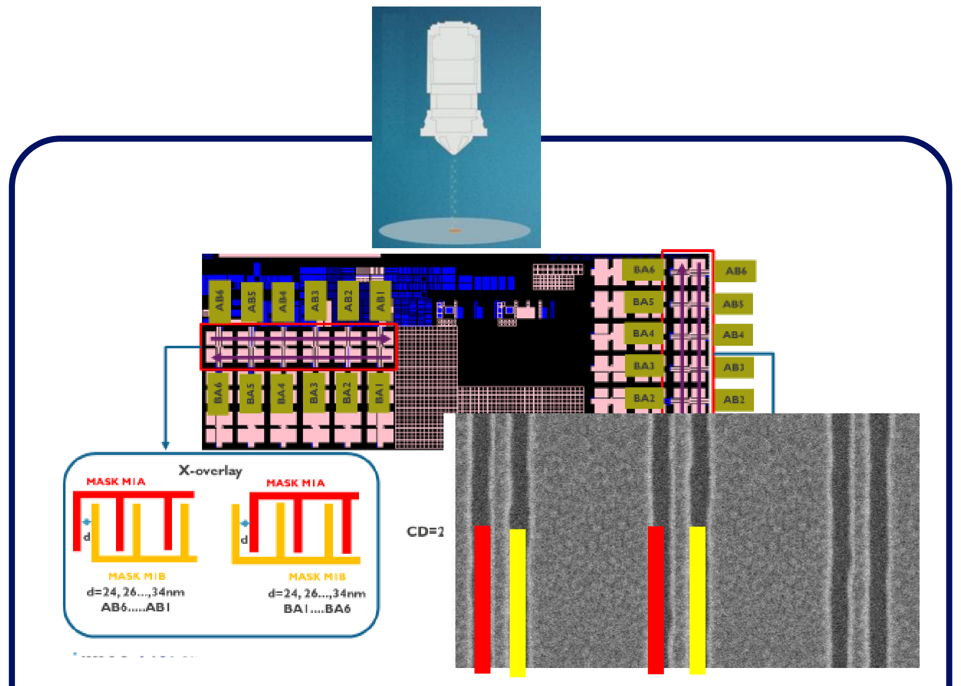




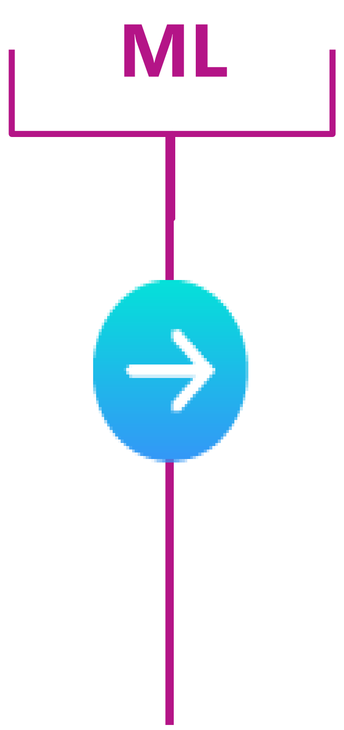


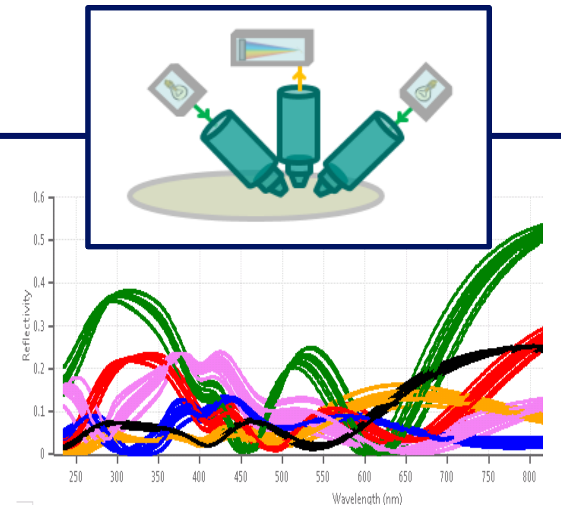
Scatterometry and AFM measurement combination for Area Selective Deposition process characterization, M. Saib et al, Proc. SPIE Adv. Litho, 2019

OCD ML for OL measurements



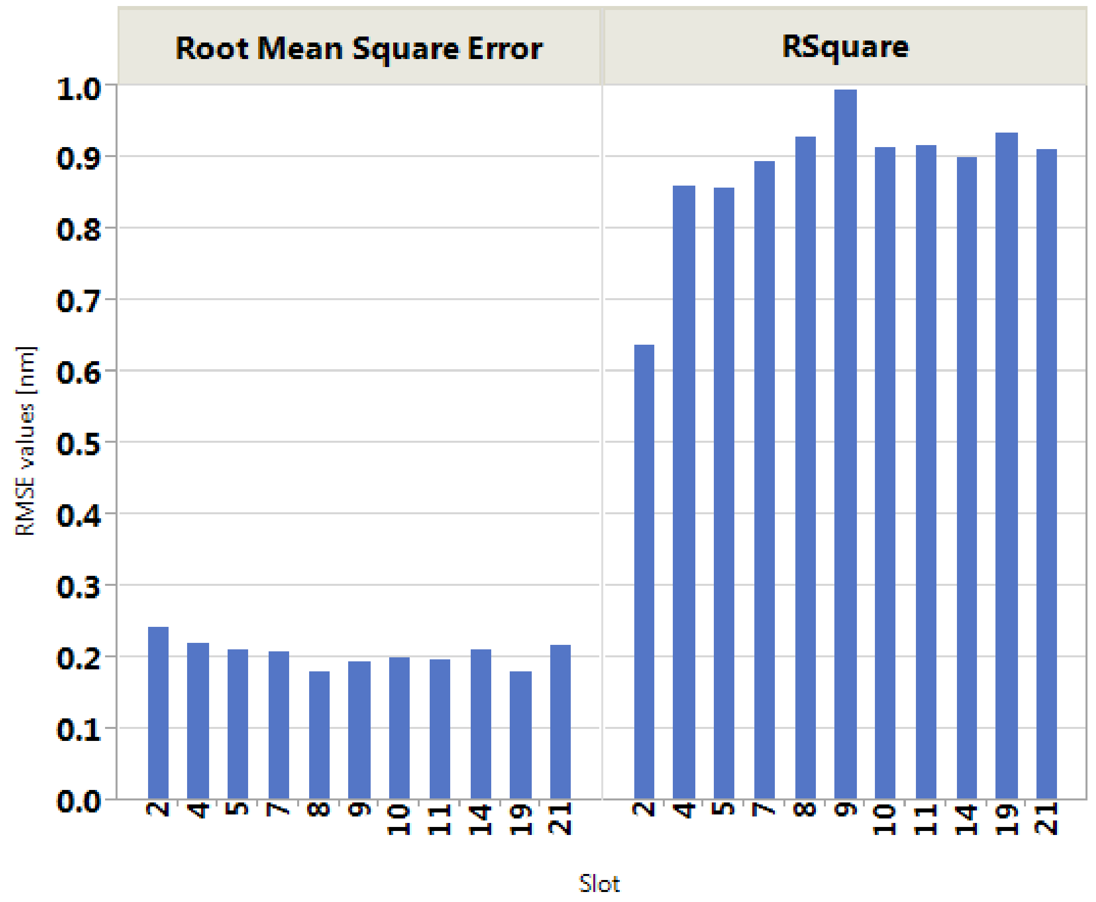
CD SEM POL measurements



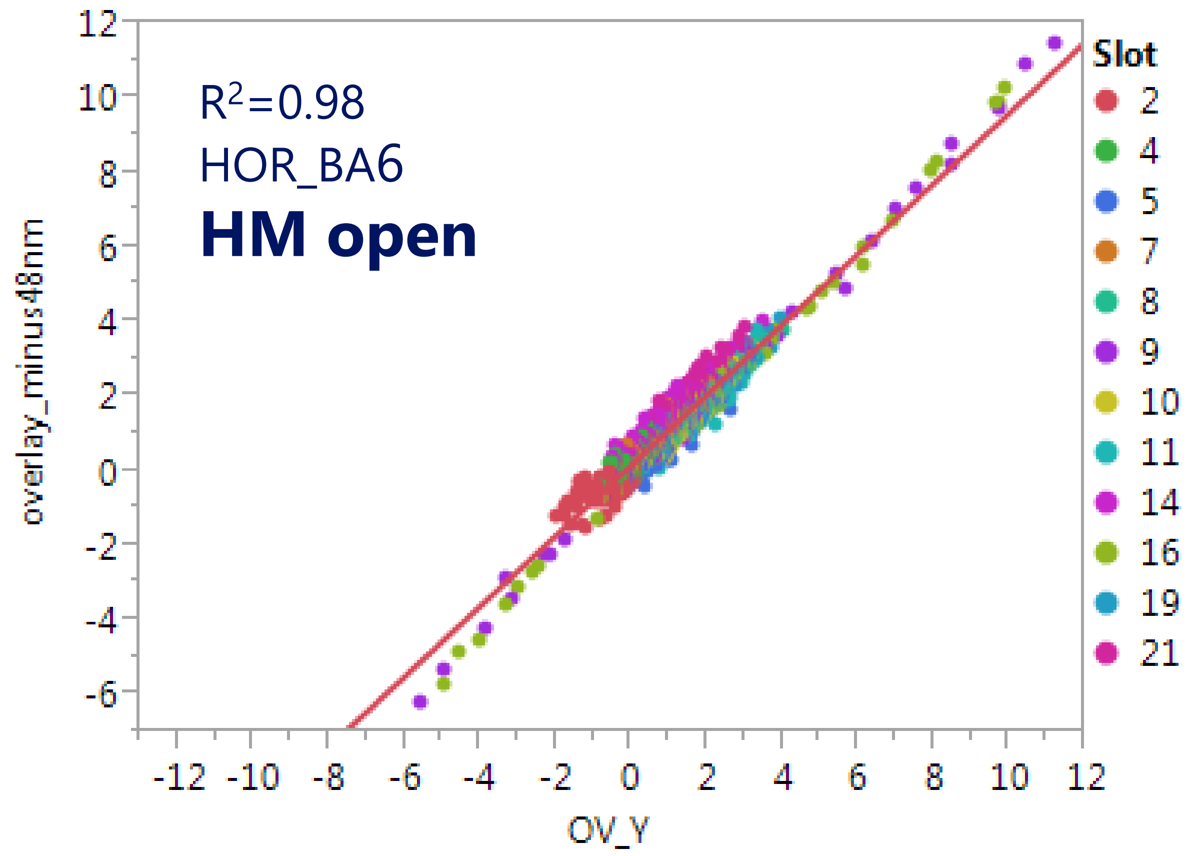


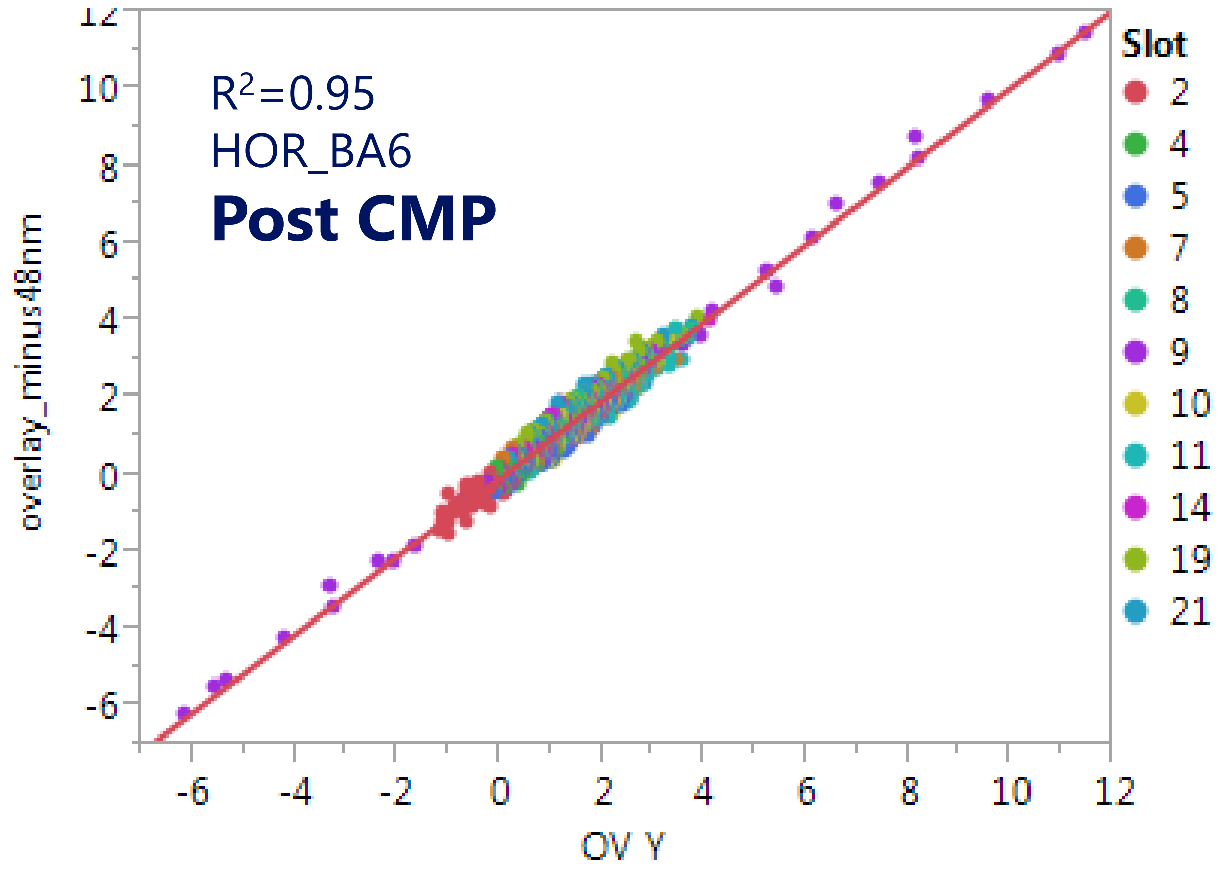
Multi Channel Spectral Measurements (Polarization and Azimuth)
ML based solution

Post CMP



Complementary CD SEM machine learning solution to OCD spectra allows OL measurements at design rule targets with good accuracy.





Machine learning for predictive electrical performance using OCD, S. Das et al, Proc. SPIE Adv. Litho, 2019

Summary

- Growing 3D complexity create new metrology challenges. Unique metrology solutions are required to deal with process control and development needs
- Two “opposite” metrology trends were discussed - LAB2FAB and In-line2R&D.
- Holistic metrology approach helps OCD to address future 3D challenges.
- Two most promising complimentary holistic directions are discussed in details:
  - Hybrid metrology and advanced modeling
  - Machine-Learning for HVM and R&D.

THANK YOU

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