AI and Machine Learning for Advanced Semiconductor Metrology and Process Control

Shay Wolfing, PhD, Chief Technology Officer

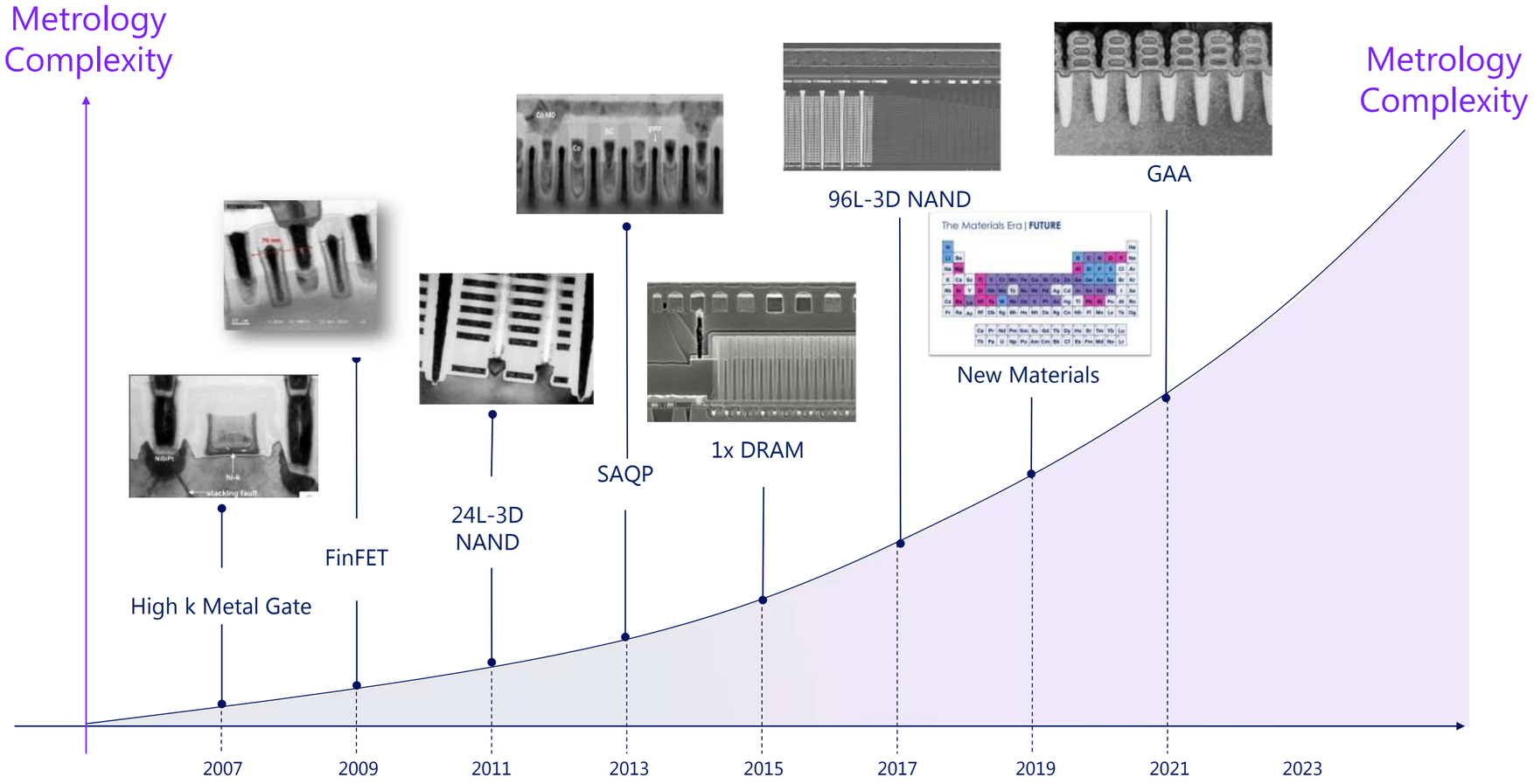
FCMN Conference, Monterey, April 2019

NOVA® PROCESS INSIGHT

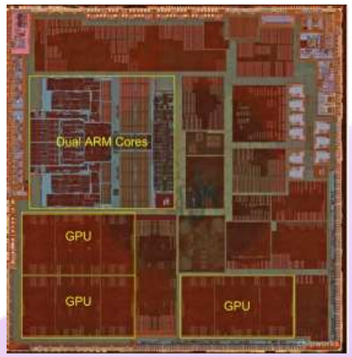
Agenda

- Introduction
- Machine Learning Use Cases in Metrology
- Improvements Required for Sustainable HVM
- Future Directions
- Summary

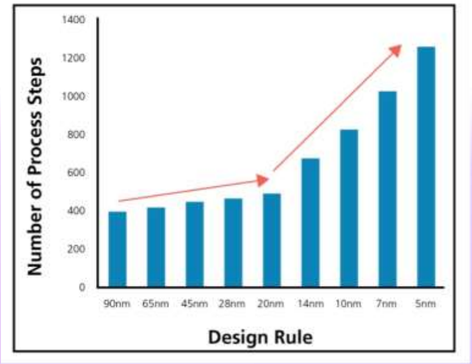
OCD Challenges from Past to Future



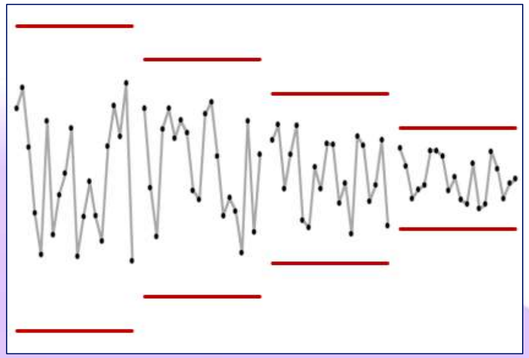
Rising OCD Challenges



In-Die Measurement

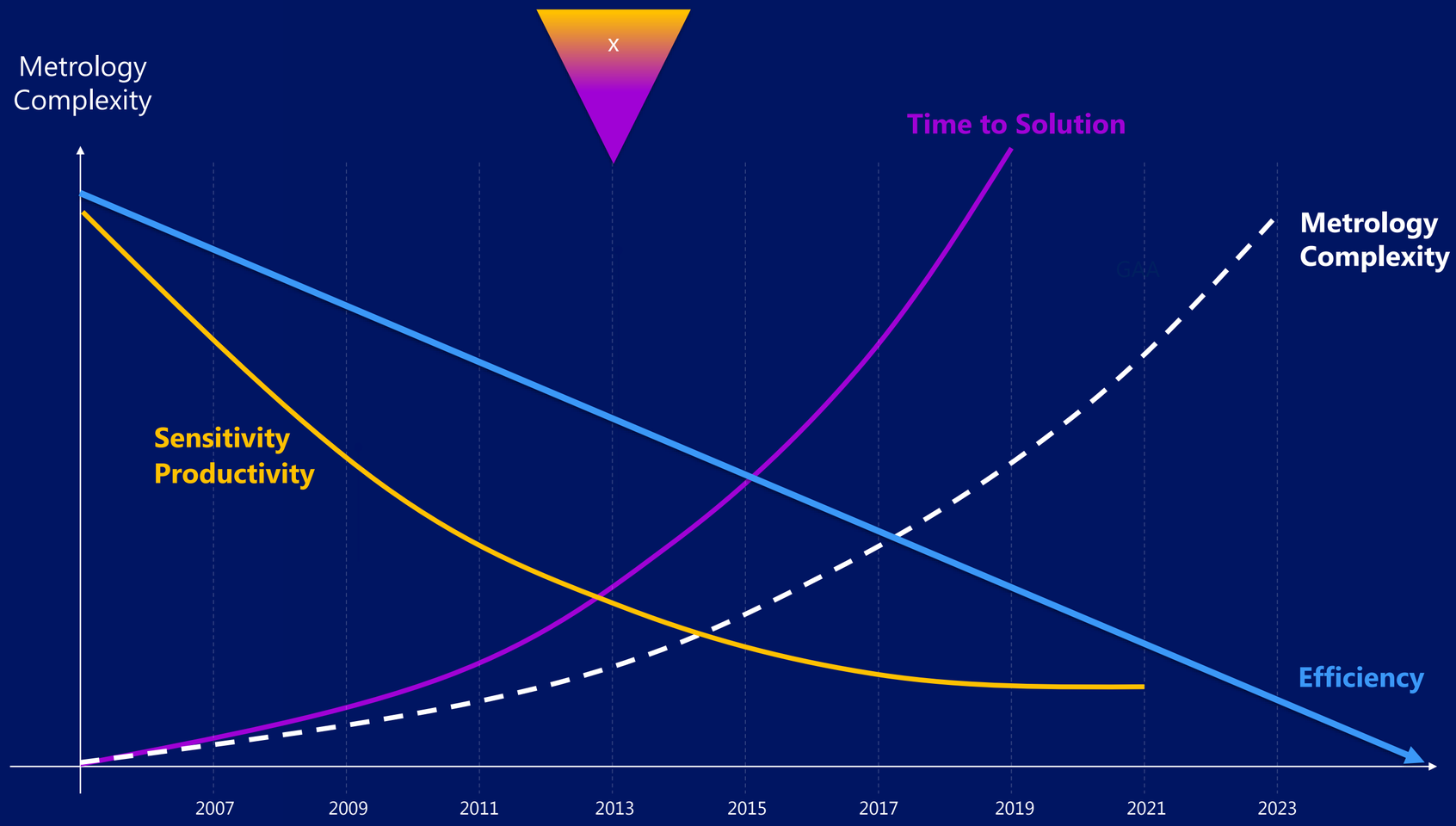


More Steps & Higher Sampling

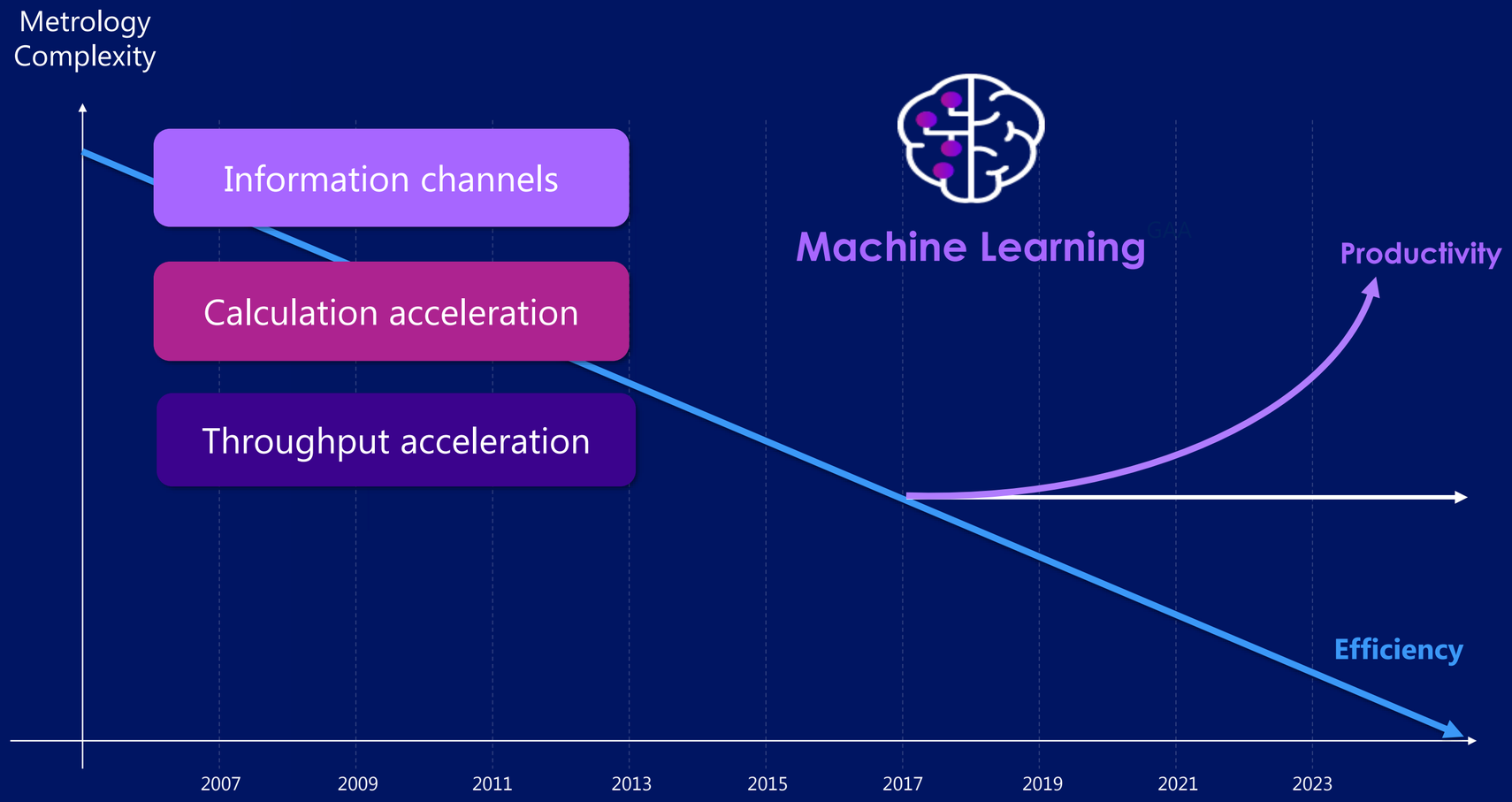


Tighter Specs & Faster Development

From OCD Challenges to Efficiency



How Do We Fix the Trend?

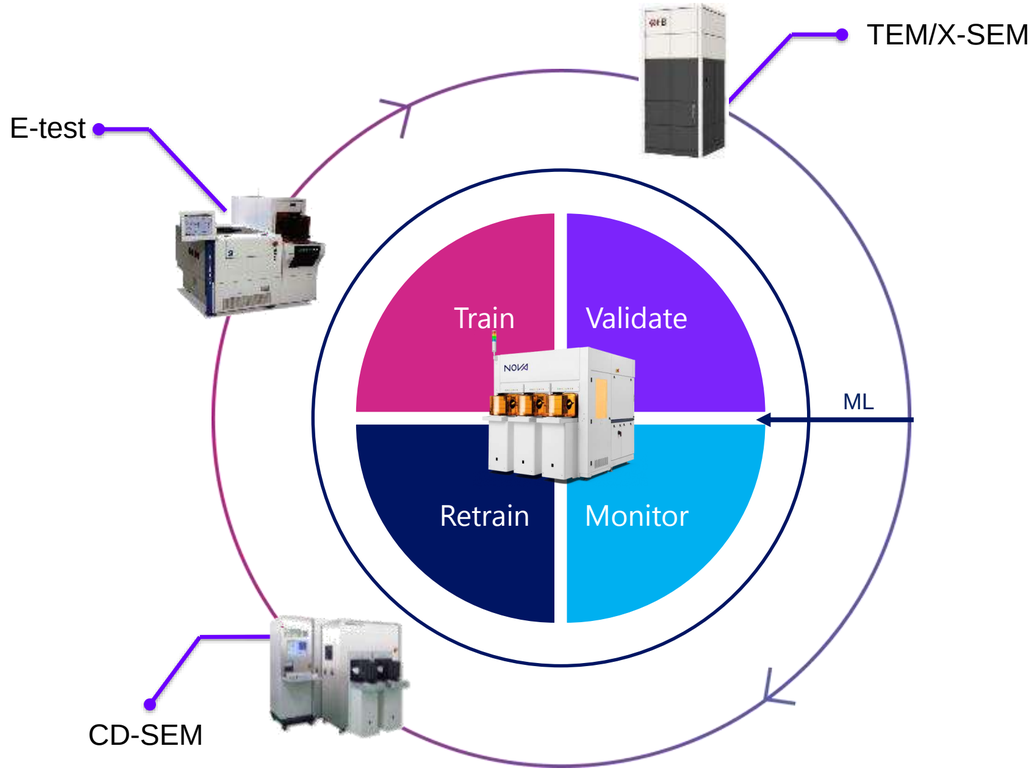


Data Driven and Machine Learning Metrology

Machine Learning enables metrology solution transfer from High Accuracy Metrology to High Efficiency Optical Metrology

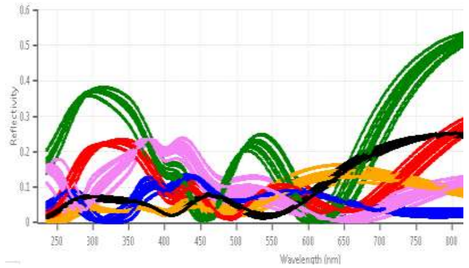
- Gain both accuracy and productivity
- Short time-to-solution
- Automated process

Increased Metrology Efficiency

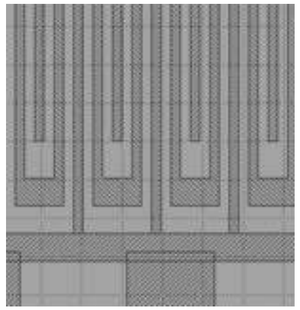


Machine Learning in Optical Metrology

In-line optical measurement



Device under test



Electrical test

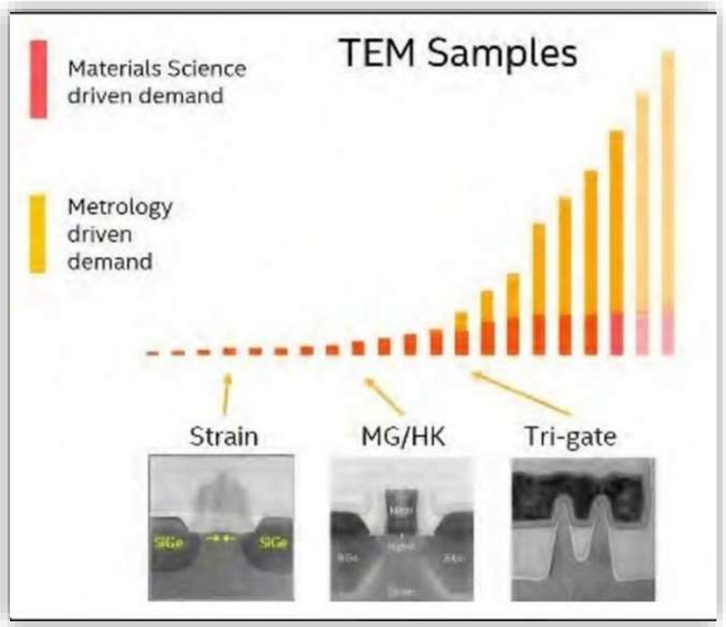
TEM/SEM image

Reference metrology

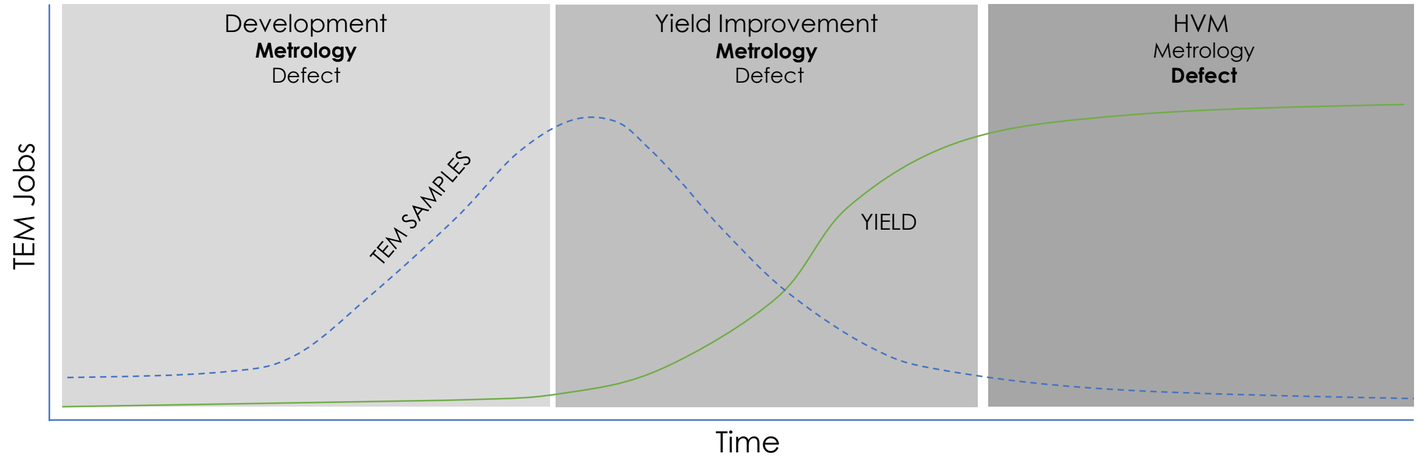
Machine Learning Model

Metrology Needs are Driving TEM Demand

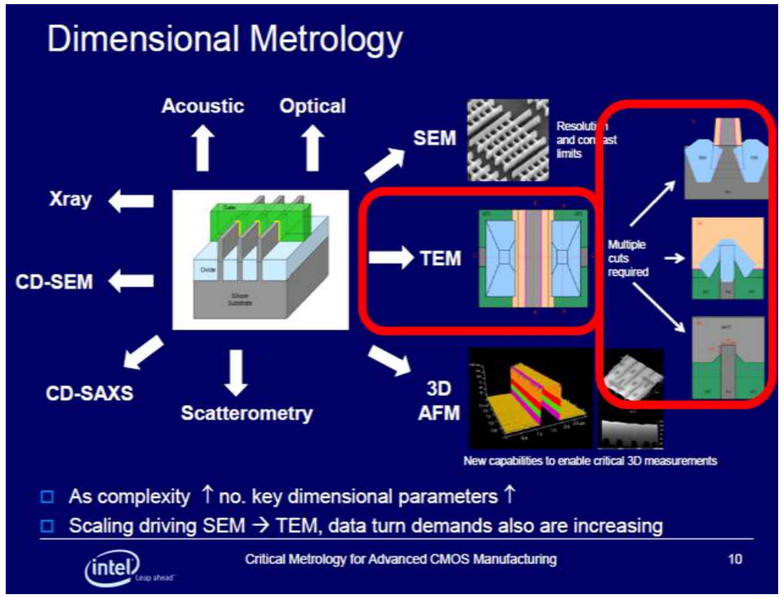
- Process and device complexity drive increasing demand for TEM resources
- TEM needs are increasing in HVM node over node
- Multiple cuts required to retrieve 3D information



Source: Intel SPIE 2016



Challenge:
Increasing TEM Demand



Need multiple cuts to get all 3D information

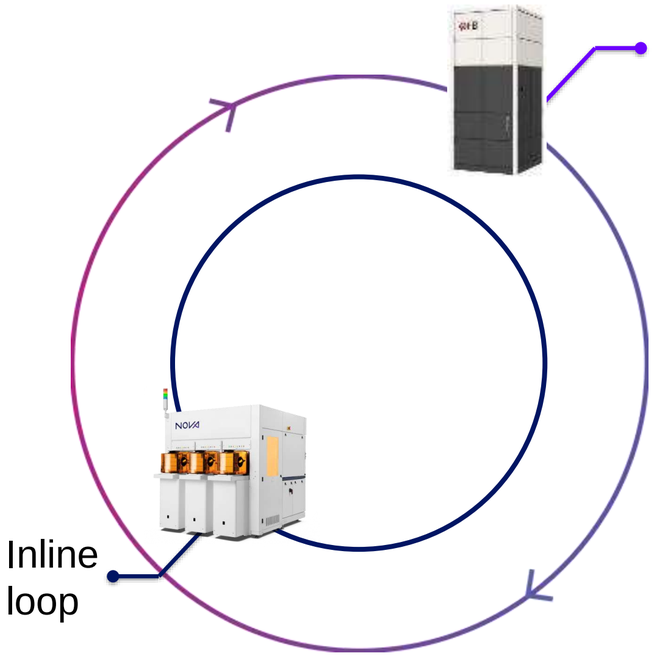
* Source: Intel Markus Kuhn @ FCMN Conference 2017

CHALLENGE

Process complexity causes productivity hit with TEM increase

- Time to data
- Destructive sampling
- High CoO
- Limited statistics and WiW characterization

Challenge:
Increasing TEM Demand



CHALLENGE

Process complexity causes productivity hit with TEM increase

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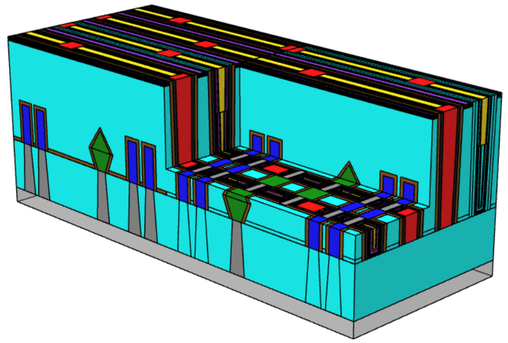
SOLUTION

Complement TEM with optical technique combined with machine learning

- Train optical spectra by TEM reference
- Reduce wafer scrap and time to data
- Optimal CoO & productivity
- High statistical sampling by non-destructive method

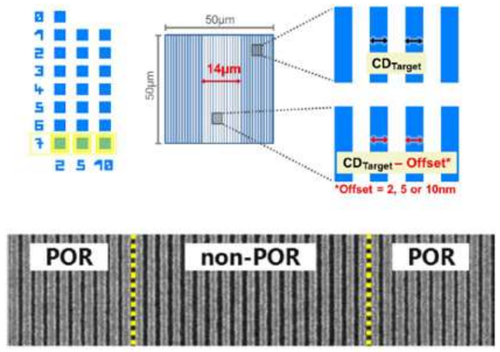
Reference Matching by OCD with Machine Learning

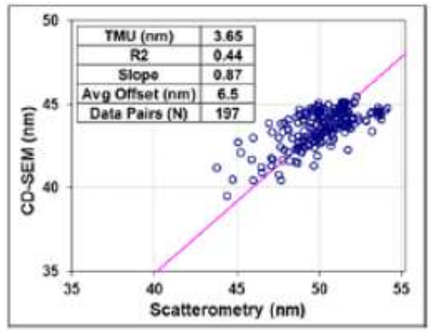
SRAM cell measurement by TEM Reference



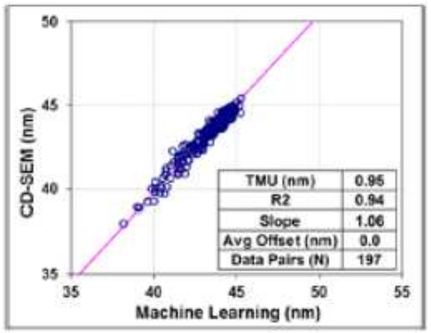
Application	Accuracy to TEM (Std)
App 1	10 A
App 2	7 A
App 3	16 A

Non-periodic CD measurement by CD-SEM Reference





(a)

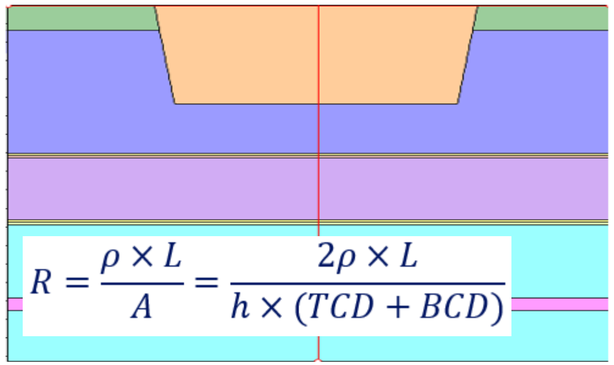


(b)

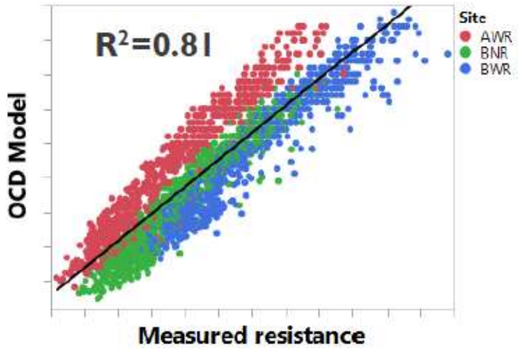
Application of Scatterometry Based Machine Learning to Control Multiple e-beam Lithography
Blancquaert, et al, ASMC 2018

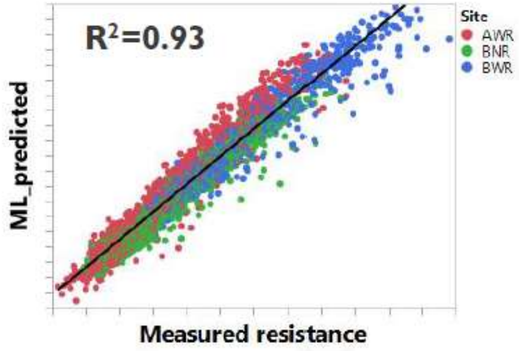
ML as Enabler for New Process Control Capabilities

E-test resistance

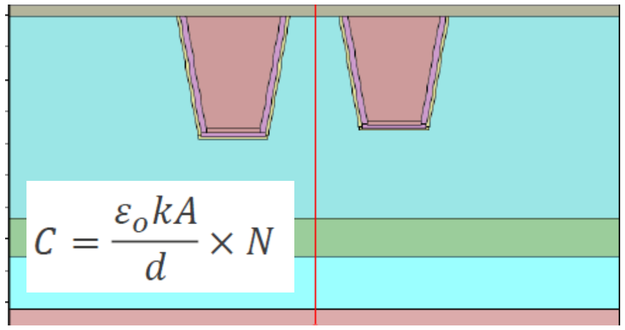


$$R = \frac{\rho \times L}{A} = \frac{2\rho \times L}{h \times (TCD + BCD)}$$

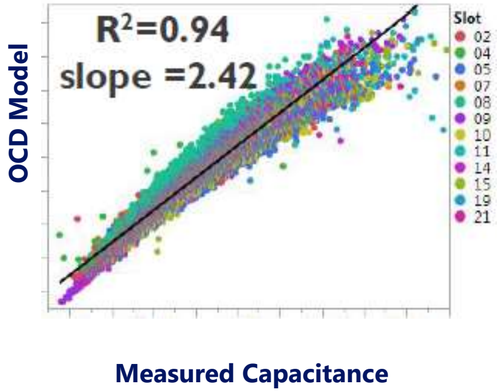


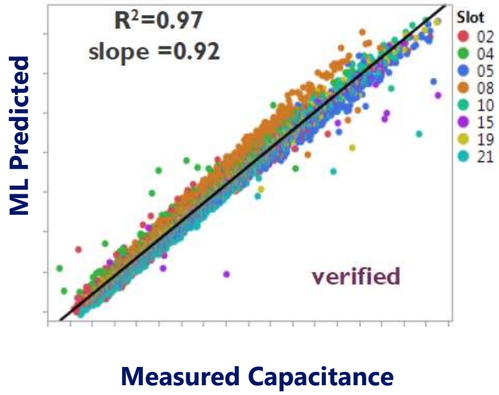


E-test capacitance



$$C = \frac{\varepsilon_o k A}{d} \times N$$





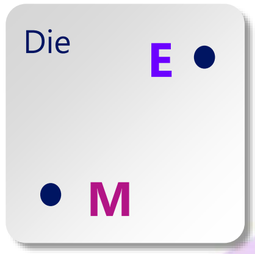
Combination of machine learning with OCD spectra enables in-line electrical test prediction with unprecedented accuracy

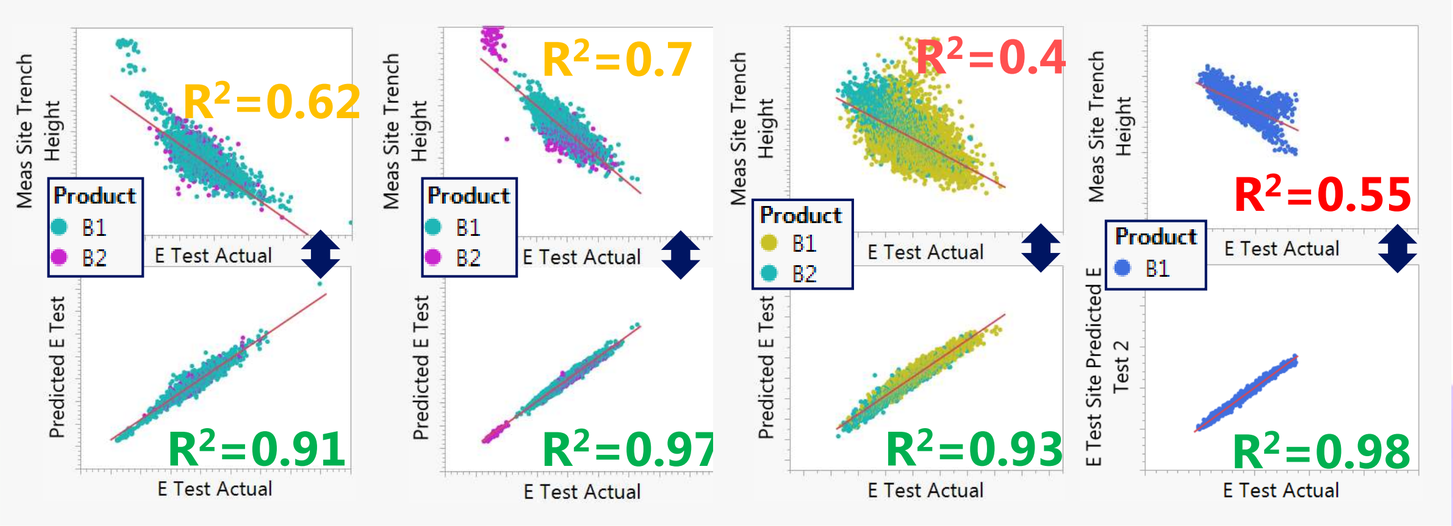
Machine Learning for Predictive Electrical Performance Using OCD
Das et. al, SPIE Advanced Lithography 2019

ML based In-line E-test in HVM Environment

Products with **M**easurement site and **E**-test site **at different locations**

B






SPIE. ADVANCED LITHOGRAPHY

2018 DIANA NYYSSONEN MEMORIAL BEST METROLOGY PAPER AWARD

Padraig R. Timoney
Taher Kagalwala, Edward Reis
Houssam Lazkani
Jonathan Hurley
GLOBALFOUNDRIES Inc. (USA)

Charles Kang
Paul Isbester, Haibo Liu
Naren Yellai
Michael Shifrin
Yoav Etzioni
Nova Measuring Instruments Ltd. (Israel)

On behalf of SPIE and the organizers of the Metrology, Inspection, and Process Control for Microlithography Conference

For their paper:
Implementation of machine learning for high-volume manufacturing metrology challenges (10585-32)

Presented by:
Vladimir A. Ukraintsev, Qorvo Corp. (United States)
Ofer Adan, Applied Materials (Israel)
2019 Metrology, Inspection, and Process Control for Microlithography Conference Chairs

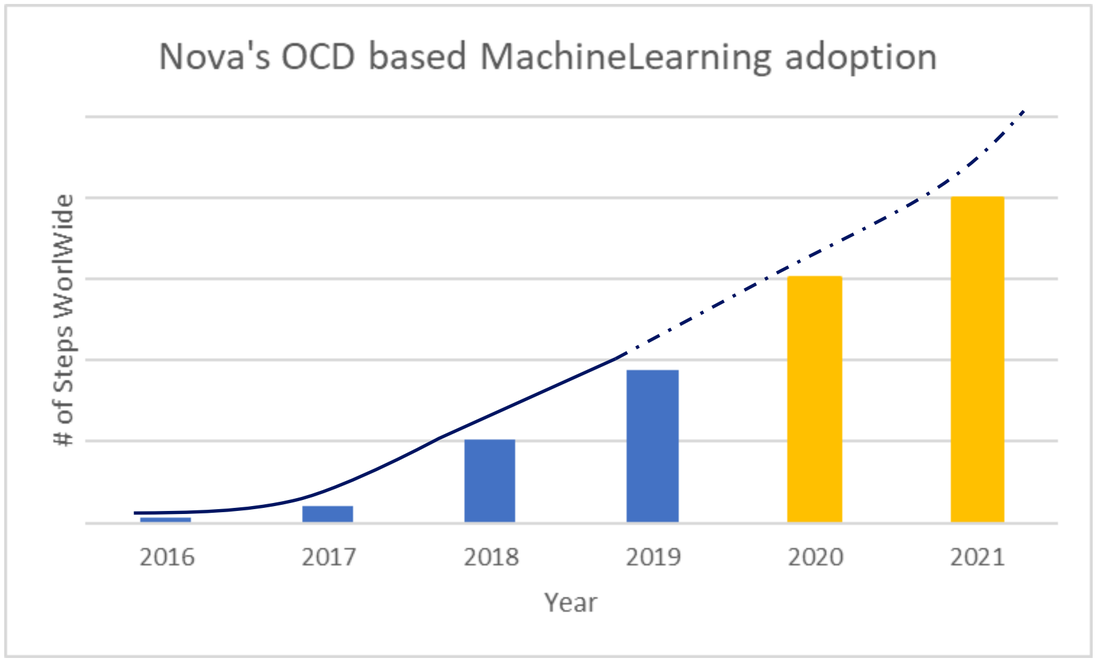
Award Sponsored by:
Hitachi High-Tech

- Proven HVM method with more than 1 year of production data
- Covering 4 critical BEOL steps in multiple products
- Verified robustness vs. initial training setup

Nova's OCD-Based Machine-Learning Adoption

Multiple Publications

1. Implementation of machine learning for HVM metrology challenges
2. In-array Tungsten protrusion measurement by scatterometry during post CMP
3. In-line characterization of non-selective SiGe nodule defects with scatterometry enabled by machine learning
4. Machine learning for predictive electrical performance using OCD spectra
5. Application of scatterometry-based machine learning to control multiple electron beam lithography
6. Scatterometry and AFM measurement combination for area-selective deposition process characterization
7. Electrical test prediction using hybrid metrology and machine learning
8. Advanced in-line metrology strategy for self-aligned quadruple patterning
9. Scatterometry-based metrology for SAQP pitch walking using virtual reference



Given projected proliferation of machine learning based solutions - What does it take to make it scalable?

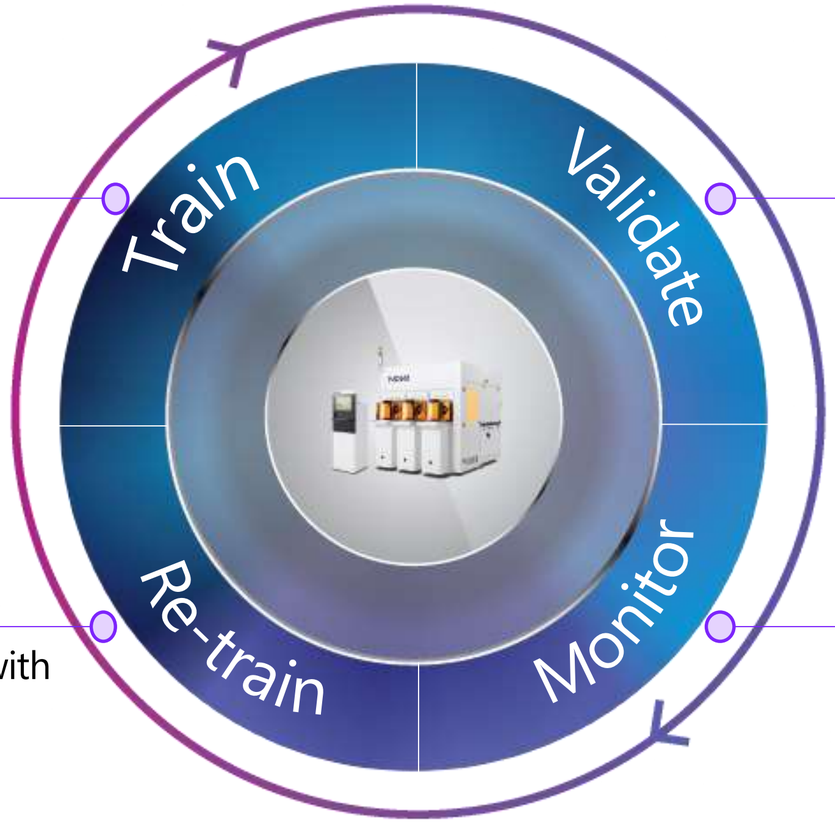
OCD Spectra-Based Machine-Learning Engine

Train

- OCD tailored Algorithms
- Automatic training

Validate

- Automatic validation
- Establish OCD trust



Re-train

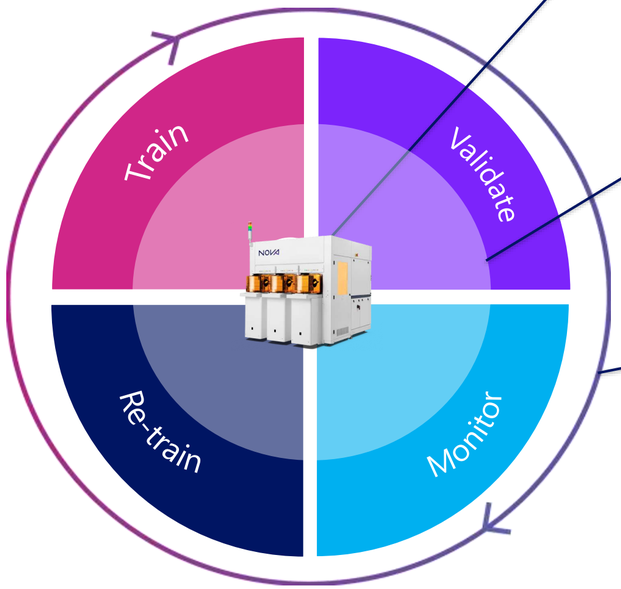
- Easily retrained with new training set

Monitor

- Merit for production monitoring

- Lower dependency on structural complexity
- Stronger direct link to reference e.g. e-test
- Same cycle time as conventional OCD
- Faster time to solution
- Can work in tandem with physical OCD model

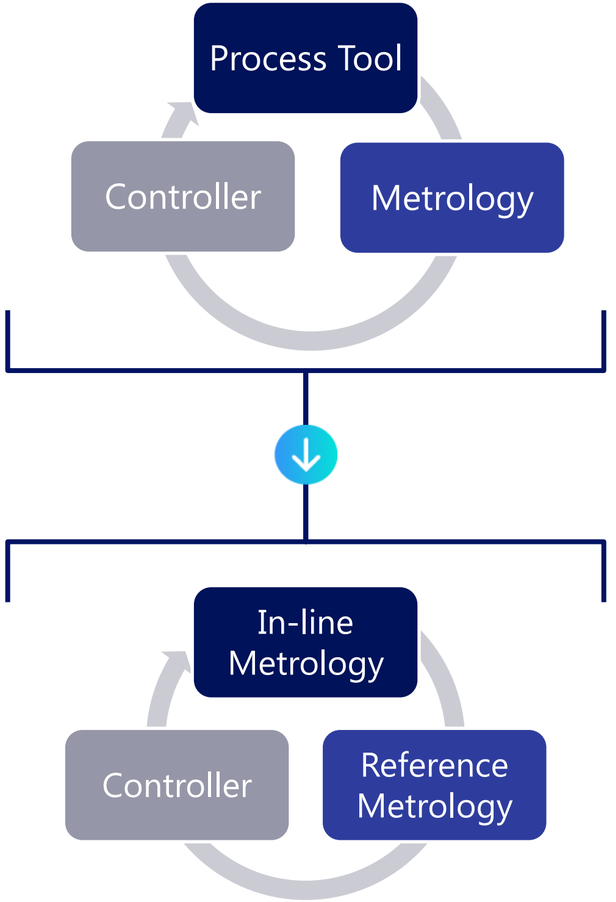
Extending Metrology Capability with APC Methodology



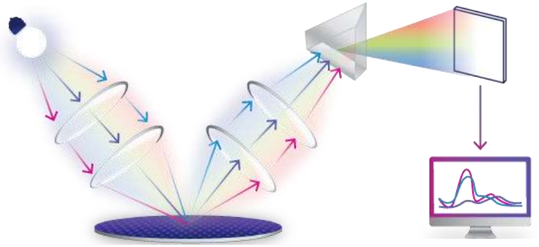
Inline Metrology

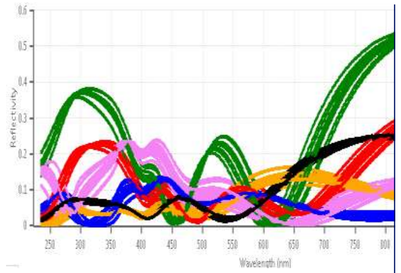
Data connectivity and computational infrastructure **Controller**

Reference Metrology



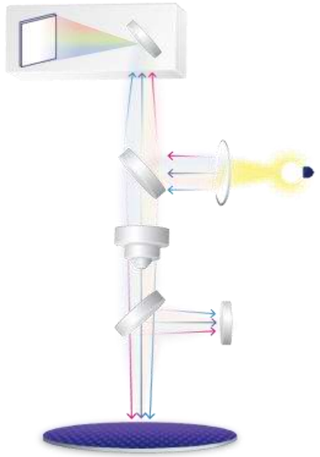
Machine Learning and OCD Modeling Fusion

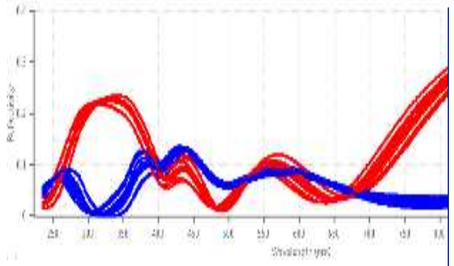




Multi Channel RCWA solution (Polarization and Azimuth)

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



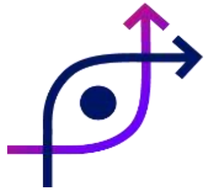


Normal Incidence Machine Learning Solution

- No limitation for computational resources
- No RCWA model errors
- Requires reference to run

Future Directions

Interpretability – Can we gain insights from “Black Box”?
Fusion with OCD knowledge can provide better insights!

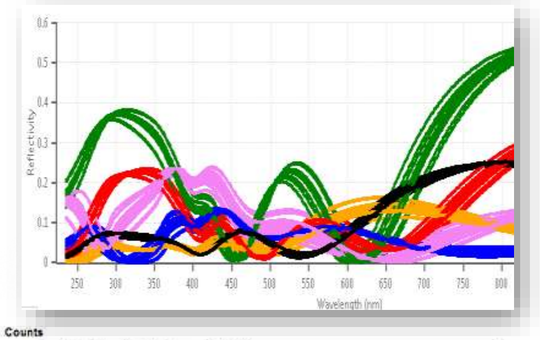


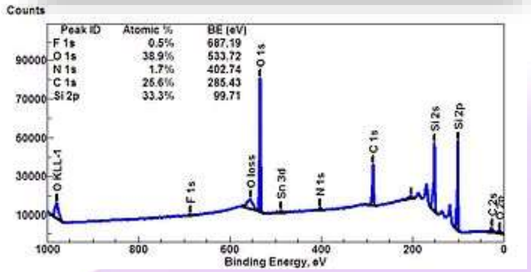
Connecting Multiple Technologies, by smart and adaptive sampling based on ML prediction

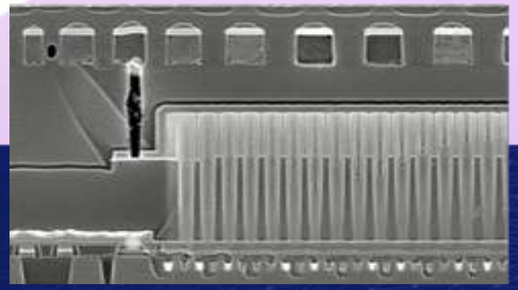
Enhance In-Line Materials Metrology Capabilities -
New signal richness beyond direct measurement valuable to in-line measurement

New **Hybrid** capabilities

Future Directions

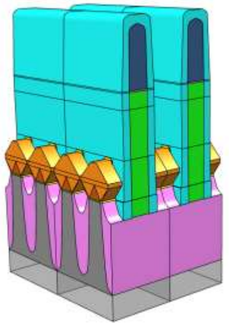






Machine Leaning

Full profile and composition



New Capabilities of Hybrid Metrology

AI and Machine Learning for Advanced Semiconductor Metrology and Process Control

Summary

Machine Learning is HVM proven
Extending OCD and allowing direct correlation to reference:

- TEM, SEM, AFM
- In-line E-test

Complementary technique for **accuracy to productivity balance** for most complex applications, while keeping OCD benefits

Combination of **big data connectivity** and cutting edge Machine Learning algorithms enables new applications for highly productive optical-metrology

Future directions allow **APC extension to metrology** control by autonomous metrology correction

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