New Paradigm of Process Control Solutions for Advanced Semiconductor Devices

Sang Hyun Han, Ph.D.
VP of Strategic Marketing

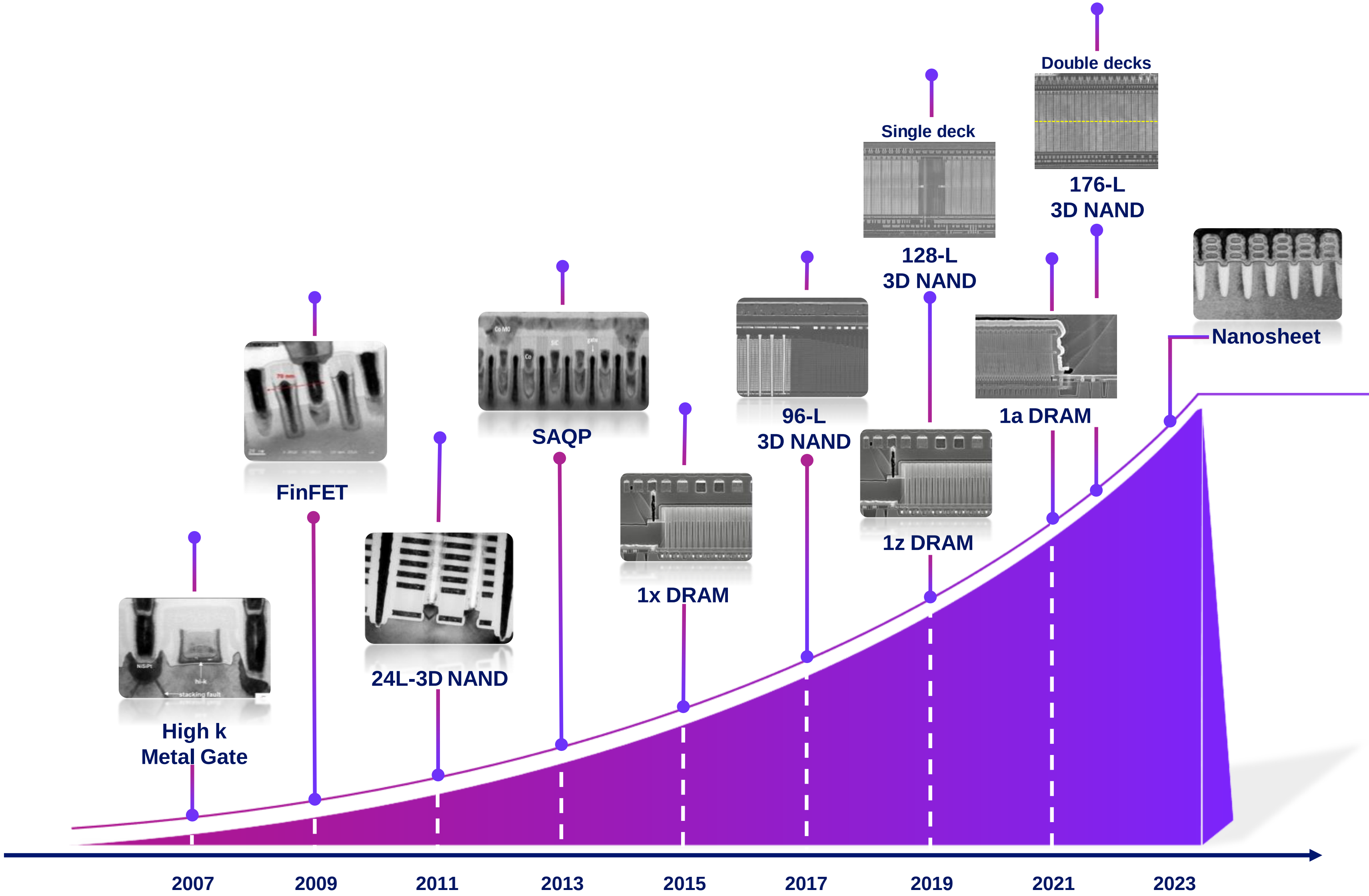
FCMN Conference, Monterey
June 2022

NOVA® PROCESS INSIGHT

What I will talk about today

- Semiconductor device trends
- Lab solutions to In-line solutions
- In-cell solutions
- Combined or hybrid solutions
- AI solutions
- Summary

Semiconductor Device Trend



Metrology Complexity

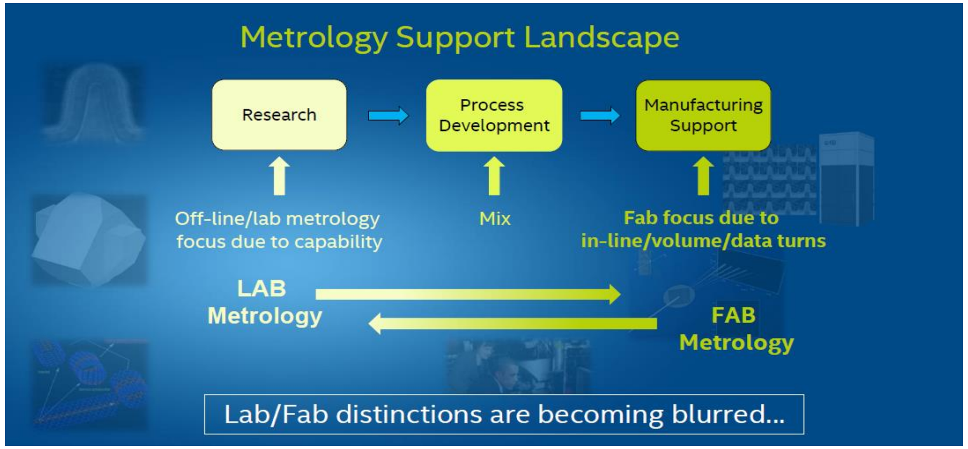
3D architectures

3D challenges

Lab Solutions to In-line Solutions

If you can not measure it, you can not improve it.

~ Lord Kelvin



Metrology Support Landscape

Research → Process Development → Manufacturing Support

Off-line/lab metrology focus due to capability

Mix

Fab focus due to in-line/volume/data turns

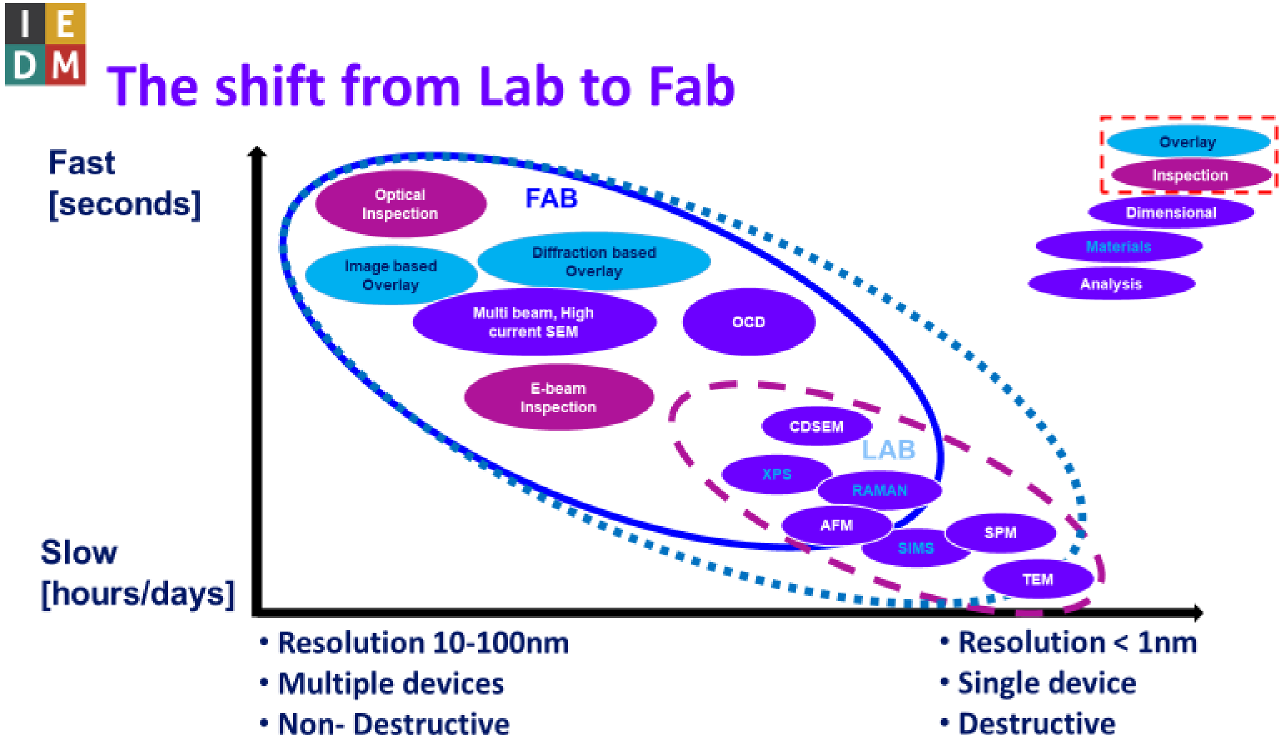
LAB Metrology ⇄ FAB Metrology

Lab/Fab distinctions are becoming blurred...

Kuhn M. et al., FCMN 2017

How fast do we measure process variation to improve yield at HVM Fab?

Lab Solutions to In-line Solutions



Roy Koret, IEDM 2021 short course:

Requirements for In-line metrology

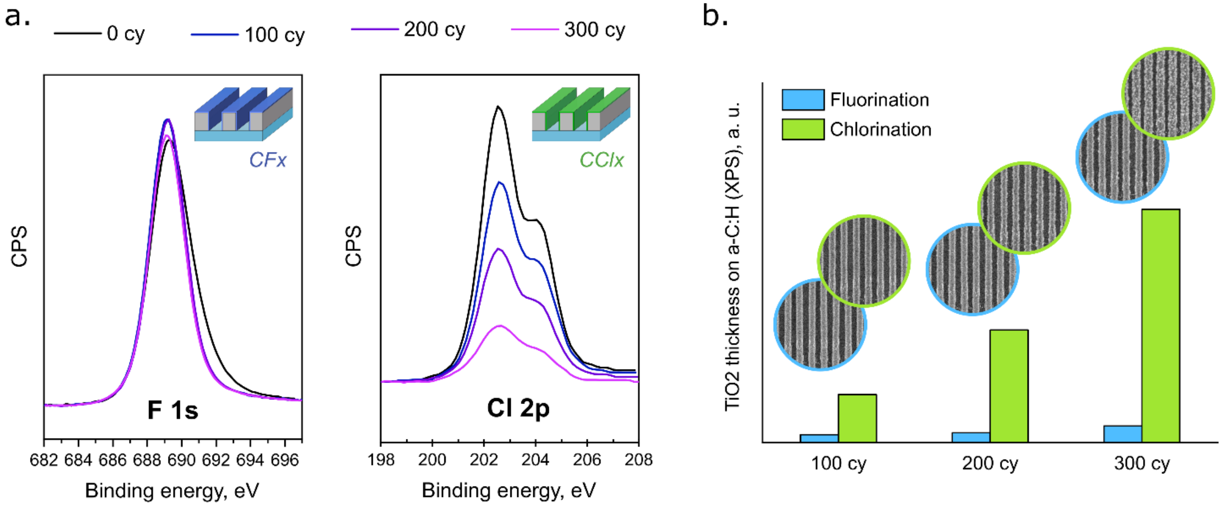
- Fully automated 300mm wafer capability
- Spot size
- Throughput
- Precision
- Long term stability
- Tool-to-tool matching

How can we transform the lab solutions to in-line solutions to fabs?

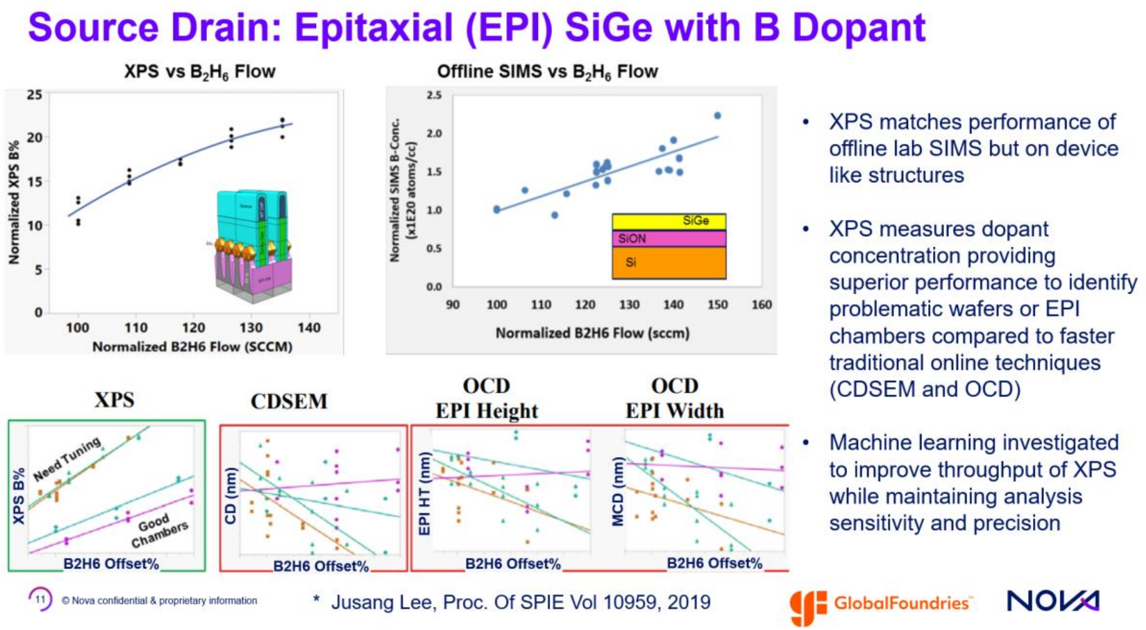
Lab XPS → *In-line XPS*

High throughput thickness + composition X-Ray metrology

XPS analysis on TiO2 ASD



Krishtab M. et al., SPIE 2020



Source Drain: Epitaxial (EPI) SiGe with B Dopant

- XPS matches performance of offline lab SIMS but on device like structures
- XPS measures dopant concentration providing superior performance to identify problematic wafers or EPI chambers compared to faster traditional online techniques (CDSEM and OCD)
- Machine learning investigated to improve throughput of XPS while maintaining analysis sensitivity and precision

11 © Nova confidential & proprietary information

* Jusang Lee, Proc. Of SPIE Vol 10959, 2019

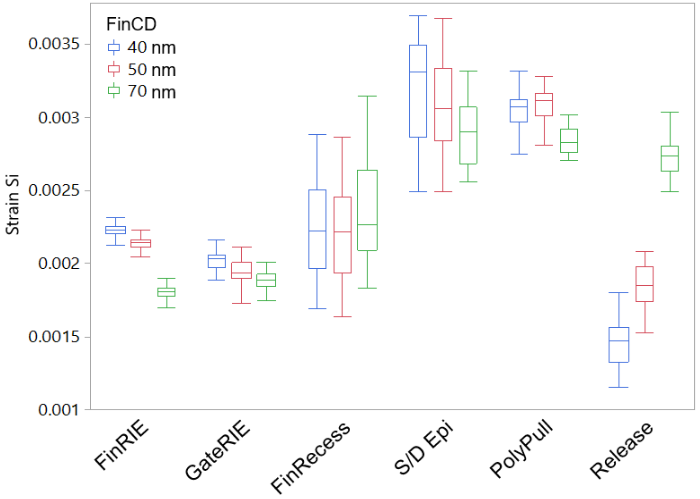
GlobalFoundries NOVA

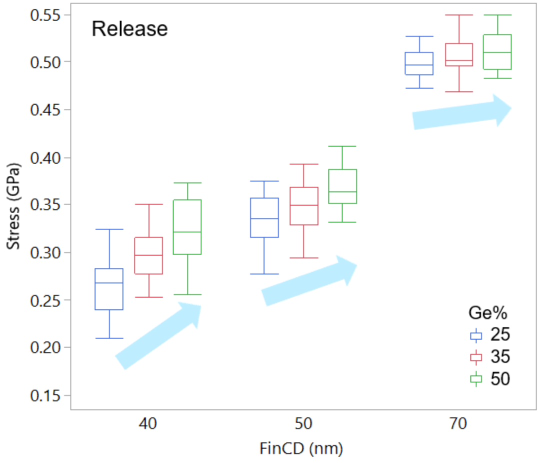
Lee J. et al., SPIE 2019

Lab Raman → *In-line Raman*

Features

- Direct measurements of strain, crystallinity & phases of **in-die structures**
- Sub-probe separation by polarization control
- Crystallinity properties and phases of complex 3D structures
- Advanced peak fitting and signal extraction algorithmic suite
- Fab level, yield related material metrology at high speed

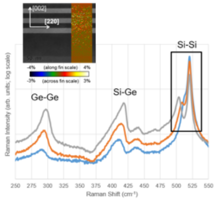




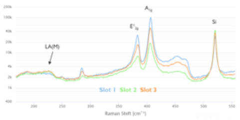
Schmidt D. et al., SPIE 2021

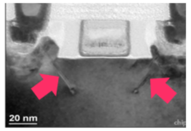
Logic application space

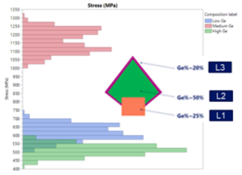
	FinFET	GAA	Power & III-V
Strain	EPI or channel strain	NS and EPI strain	SiC/GaN strain
EPI	EPI strain & Ge/P%	EPI strain, Ge/P%, volume	Cell/OVS crystallinity on structure
Doping	On structure B/F/As%	N/A	On structure - C & other
Phase	Silicide phases	Silicide phases	III/V alloys phases
Defectivity	Lattice defects – EPI/channel	Lattice defects, SiGe nodules, SiGe residues	Lattice defects



Direct measurements of Strain, EPI & Defectivity of in-die structures by utilizing optical, non-destructive metrology

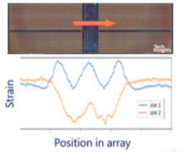




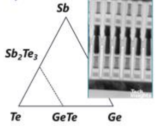


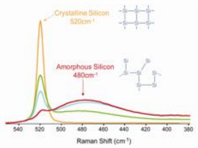
Memory application space

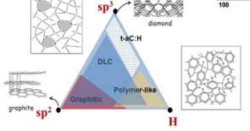
	3D-NAND	DRAM	PCM
Strain	Strain in-die	Cell to periphery strain mapping	*In development*
Crystallinity	Channel poly crystallinity gain size	Poly crystallization ratio & grain size	Cell/OVS crystallinity on structure
Phase	Salicide phases	Salicide phases	GST phases
Film properties	DLC/ACL	Poly Si area & volume	*Some doping*

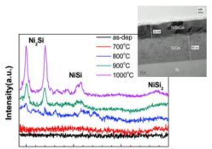


Direct measurements of strain, crystallinity & phases of in-die structures by utilizing optical, non-destructive metrology





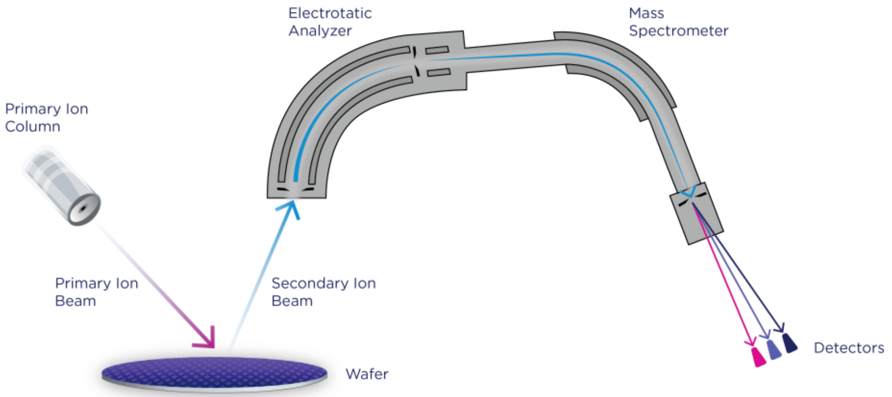




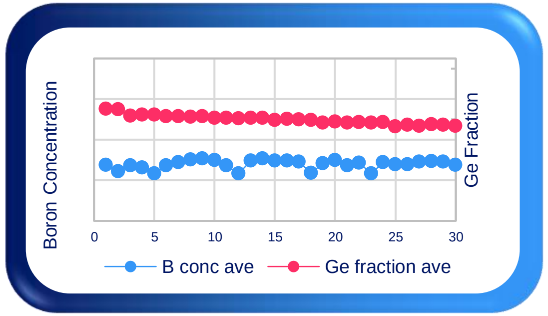
Lab SIMS → *In-line SIMS*

In-line Secondary-Ion Mass Spectrometer (SIMS)

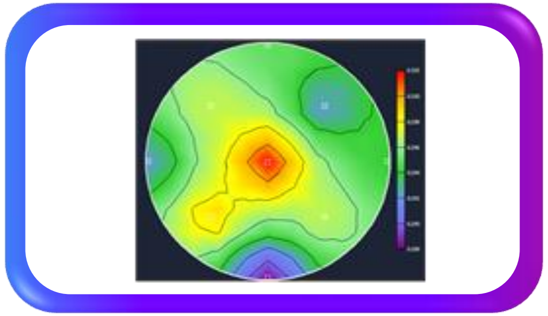
for statistical process control (SPC) of compositional profiles



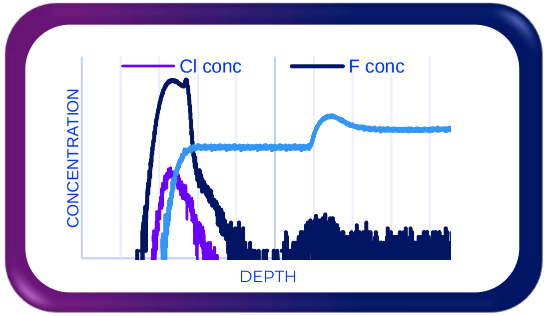
- Industry-first In-line SIMS
- Fully-automated, recipe-driven 300mm HVM-ready
- Recognized lab solution brought into the fab
- For complex logic & memory film stacks



Dopant concentration as a function of depth



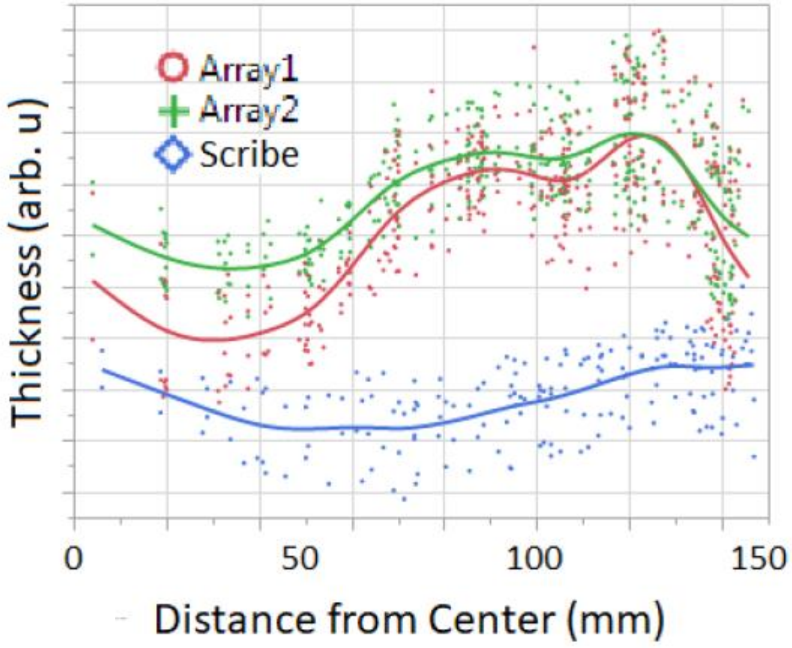
Full map uniformity monitoring

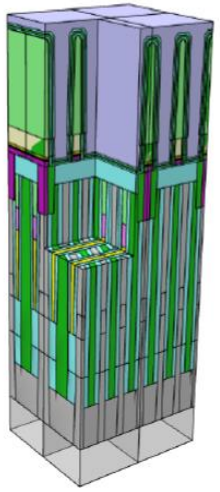


Contamination detection

In-cell Solutions

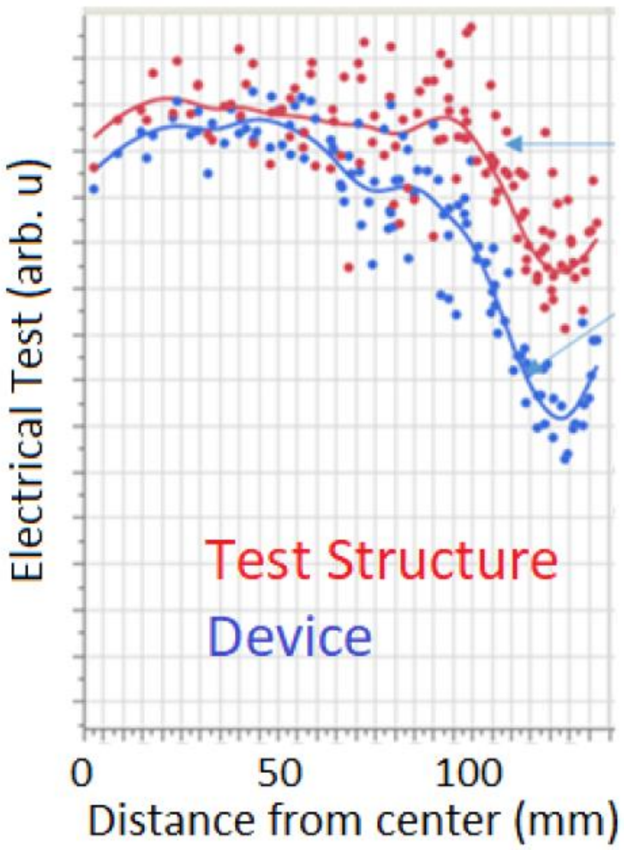
Profile



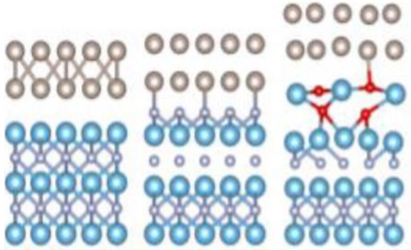


- Device complexity
- Local variability over average

Material



Chemistry



- Design sensitivity
- Detection sensitivity

Bozdog C., SPIE 2020

In-cell data better correlates with device performance than test structure data

In-cell Solutions: *Spectral Interferometry & VTS*

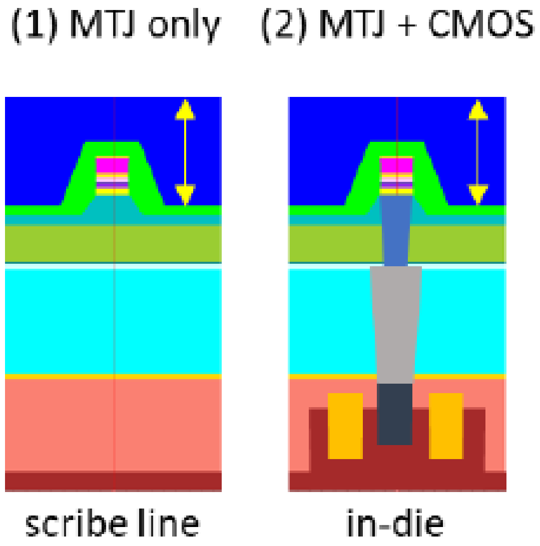
Spectral interferometry (SI)

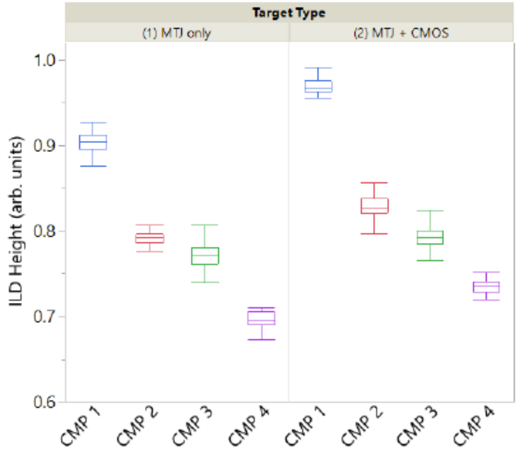
provides unique capabilities, beyond simply extending available information

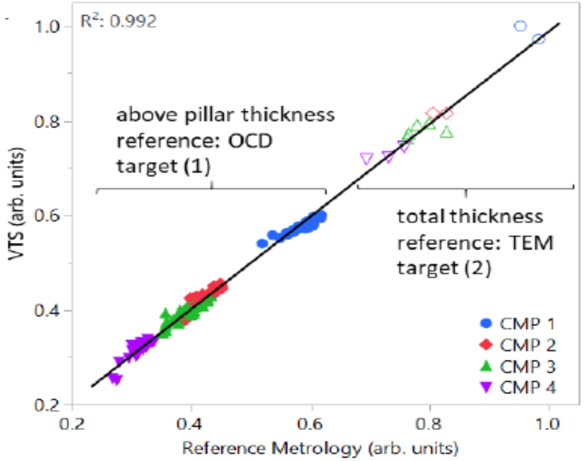
VTS technology*

- **Selectively filter-out signals from underlayer structures**
  - No need to even model these parts
  - Enabled by SI unique information space couple with an algorithmic suite
  - Supports both physical modeling and machine learning solutions

*VTS: *vertically traveling scatterometry*



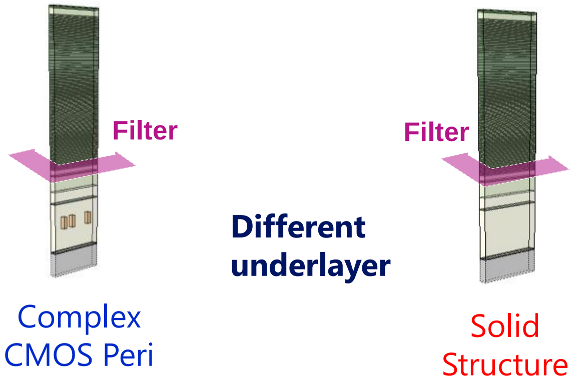




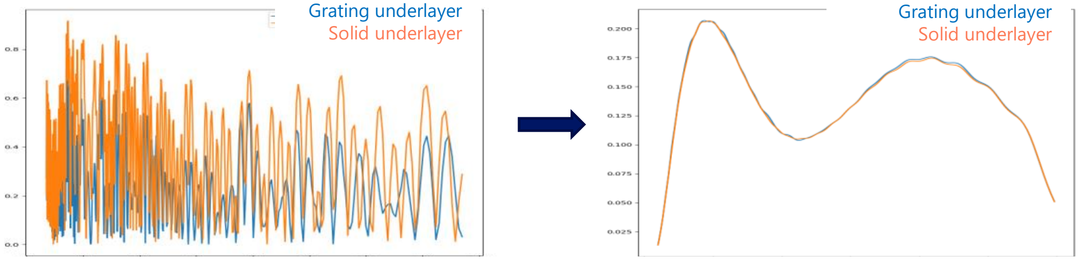
Schmidt D. et al., SPIE 2022

In-cell Solutions: *Spectral Interferometry & VTS*

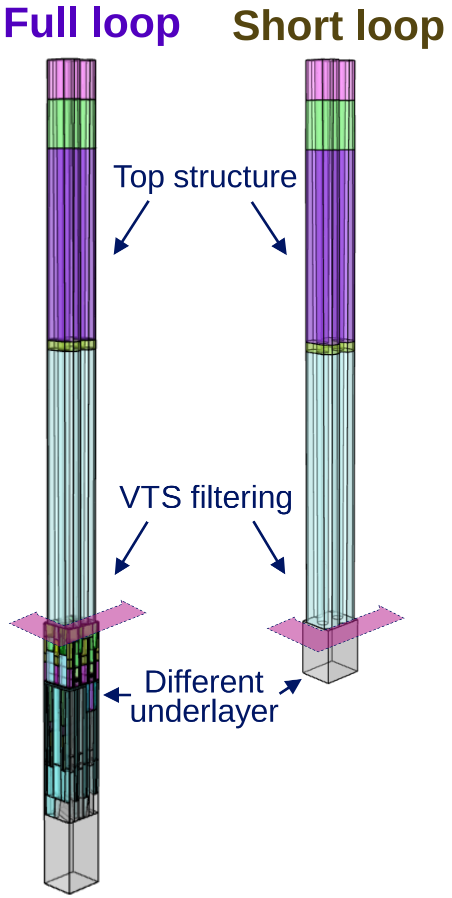
3D NAND



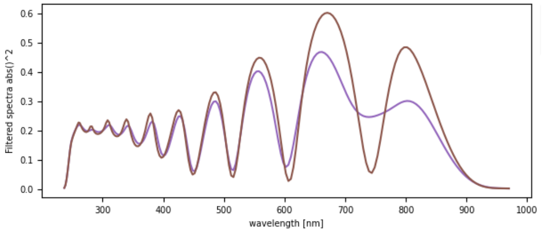
Spectra comparison



DRAM

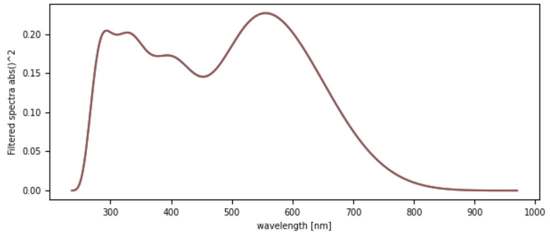


Pre-VTS



Large spectral difference between short & full loop

Post-VTS



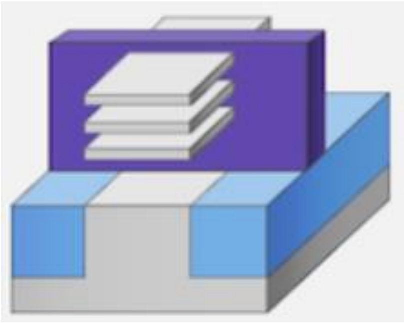
Identical spectra between short & full loop

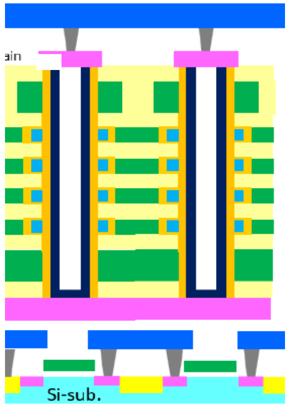
VTS unique values - Regardless of the underlayer (full & short loop)

Combined or Hybrid Solutions

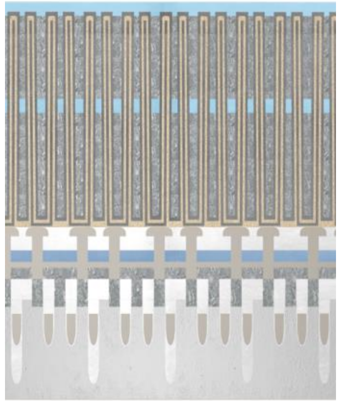
- Structural
- Chemical
- Material
- Surface
- Interface
- Stress/strain

3D architectures


Logic



3D NAND


DRAM

- Resolution
- Throughput
- Accuracy
- Precision
- Stability
- Traceability

Challenge: one metrology is not able to deliver all necessary data for 3D devices

Combined solution →


Dreamstime

← ***Hybrid solution***

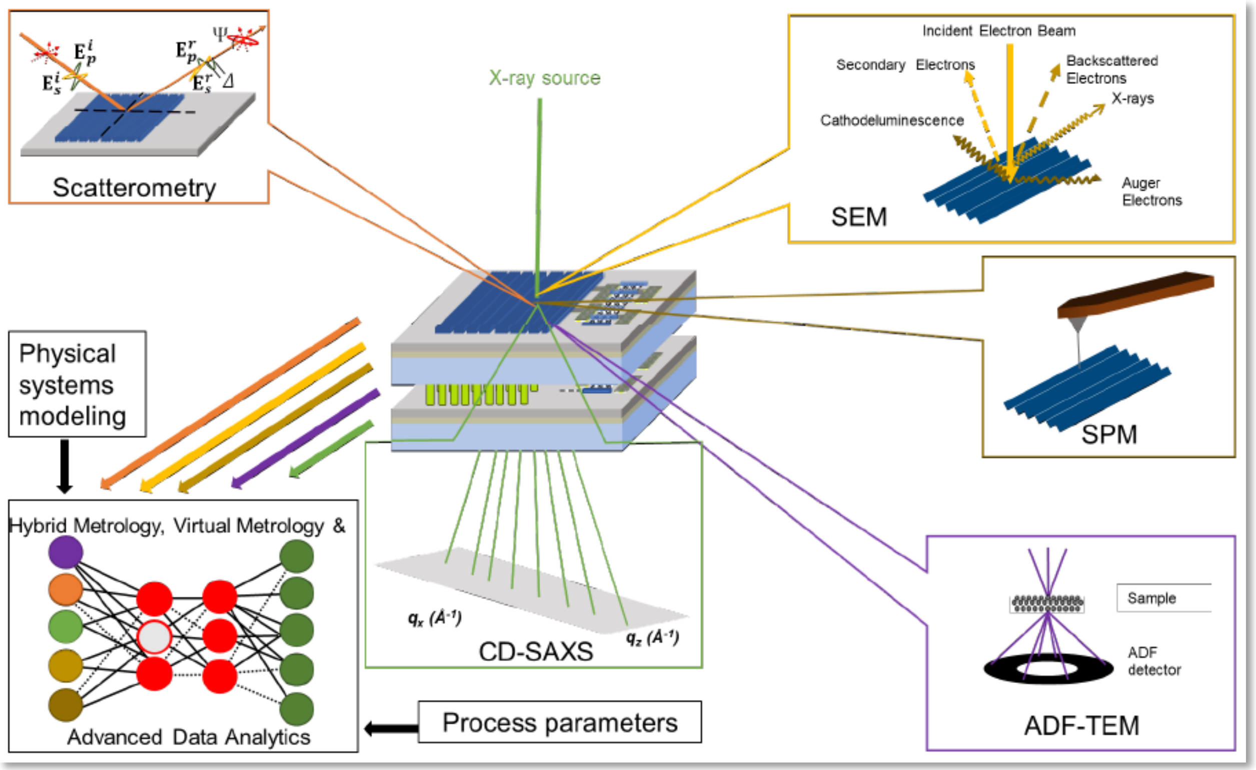
Combined Solutions

Data fusion of multiple metrology solutions

CD-AFM
Scatterometry CD

SEM
CD-SAXS

SEM
Scatterometry CD



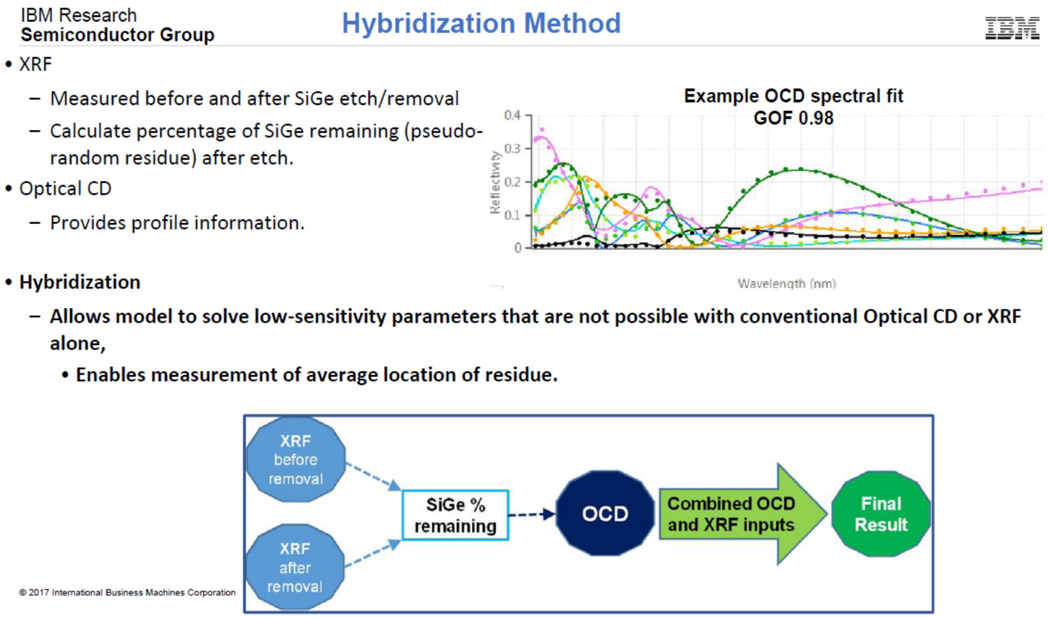
IRDS 2021

AFM
SEM , TEM

HA-ADF STEM
APT

Raman
Scatterometry CD

Combined Solutions: *Optical & X-ray*

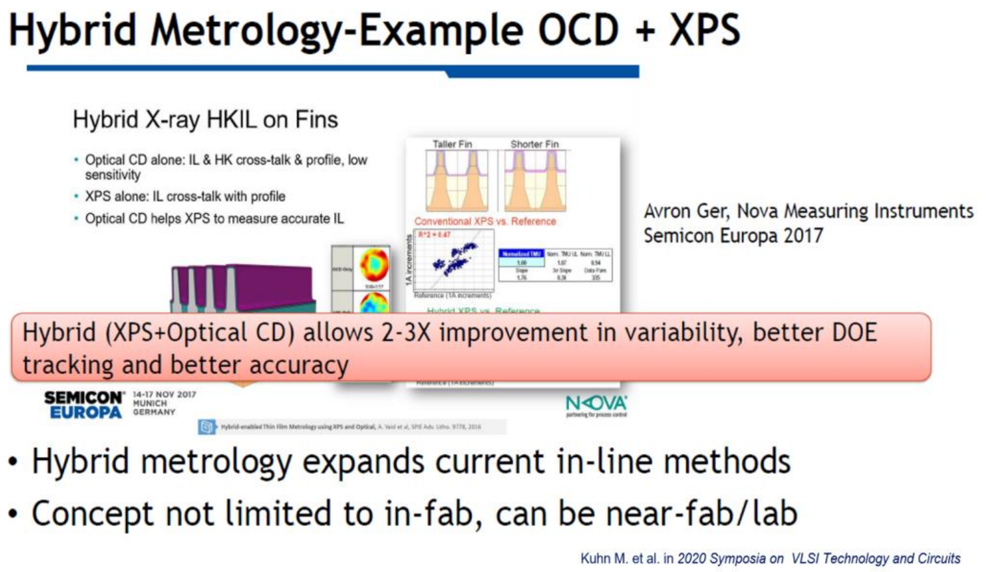


IBM Research
Semiconductor Group

Hybridization Method

- XRF
  - Measured before and after SiGe etch/removal
  - Calculate percentage of SiGe remaining (pseudo-random residue) after etch.
- Optical CD
  - Provides profile information.
- **Hybridization**
  - **Allows model to solve low-sensitivity parameters that are not possible with conventional Optical CD or XRF alone,**
    - **Enables measurement of average location of residue.**

Muthinti R. et al., SPIE 2018



Hybrid Metrology-Example OCD + XPS

Hybrid X-ray HKIL on Fins

- Optical CD alone: IL & HK cross-talk & profile, low sensitivity
- XPS alone: IL cross-talk with profile
- Optical CD helps XPS to measure accurate IL

Hybrid (XPS+Optical CD) allows 2-3X improvement in variability, better DOE tracking and better accuracy

Hybrid-enabled Thin Film Metrology using XPS and Optical, A. Vaid et al, SPIE Adv. Litho. 9778, 2016

Avron Ger, Nova Measuring Instruments
Semicon Europa 2017

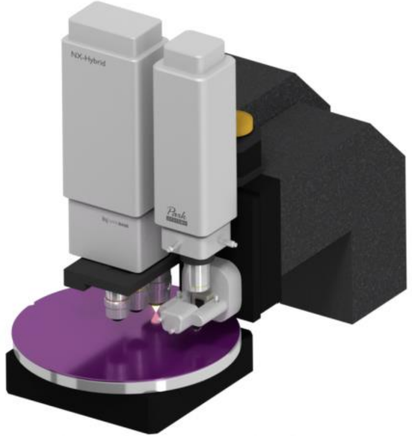
- Hybrid metrology expands current in-line methods
- Concept not limited to in-fab, can be near-fab/lab

Kuhn M. et al. in *2020 Symposia on VLSI Technology and Circuits*

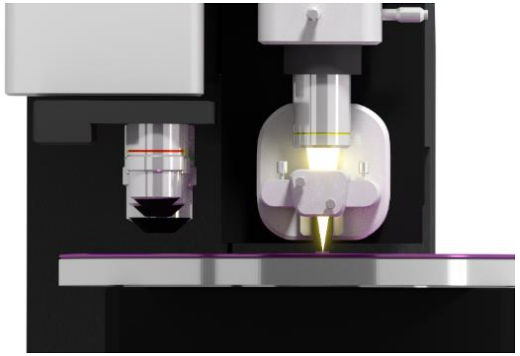
How can we fully optimize existing metrology solutions to deliver critical messages?

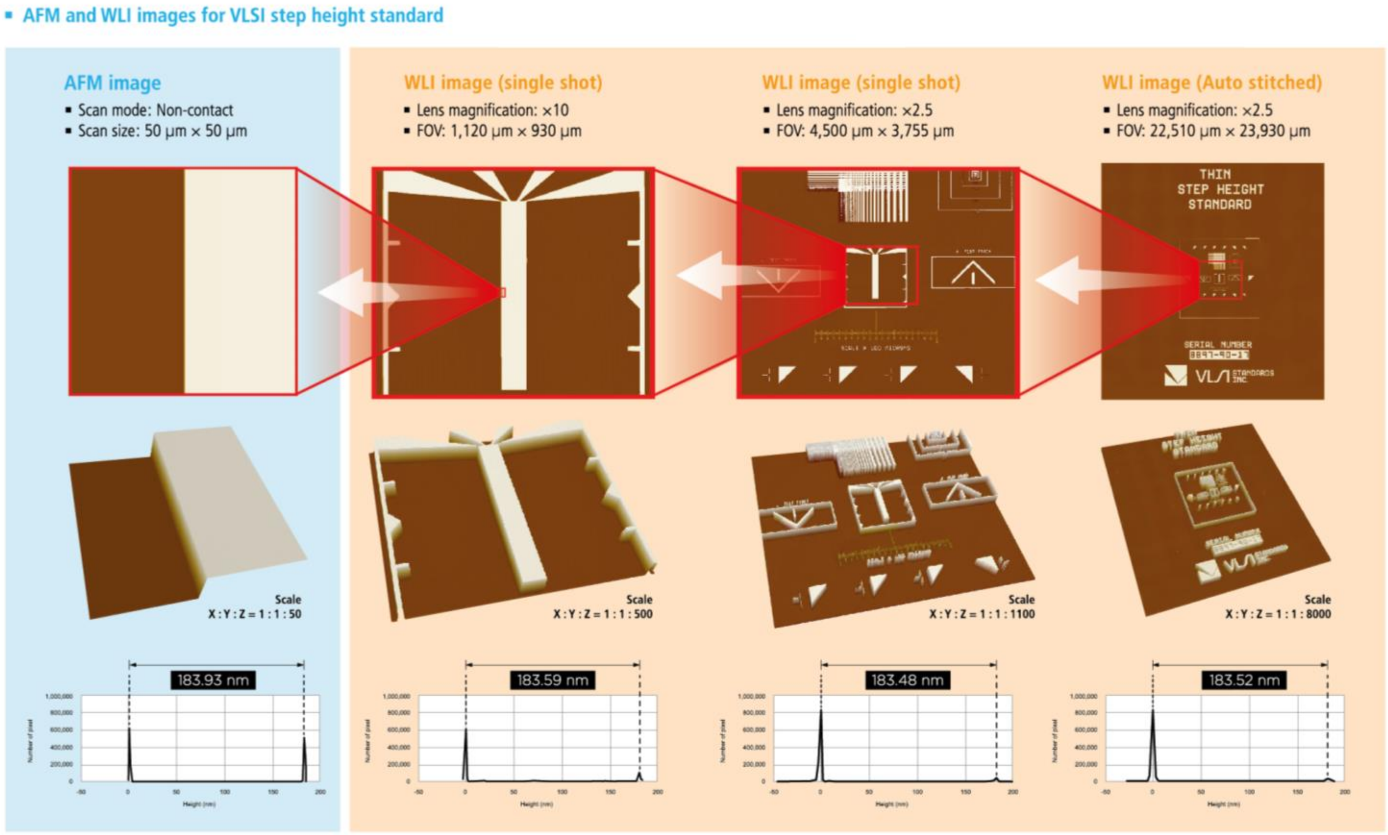
Hybrid Solutions: *Hybrid AFM (AFM + WLI)*

- 3D Concept image



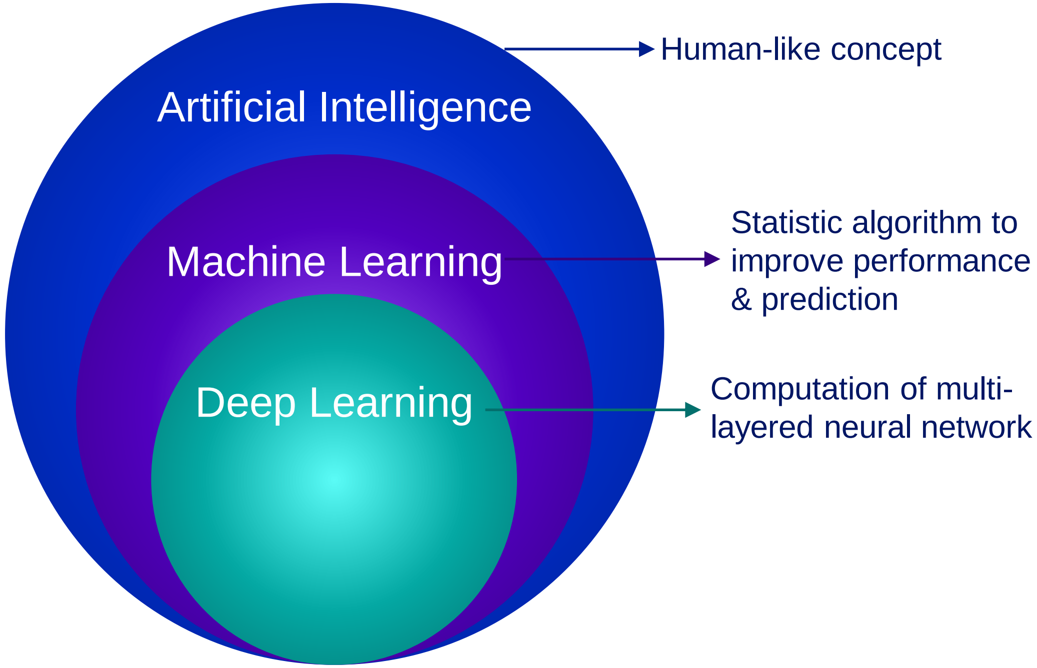
- Fast survey scan & High-resolution scan





Courtesy of Park systems

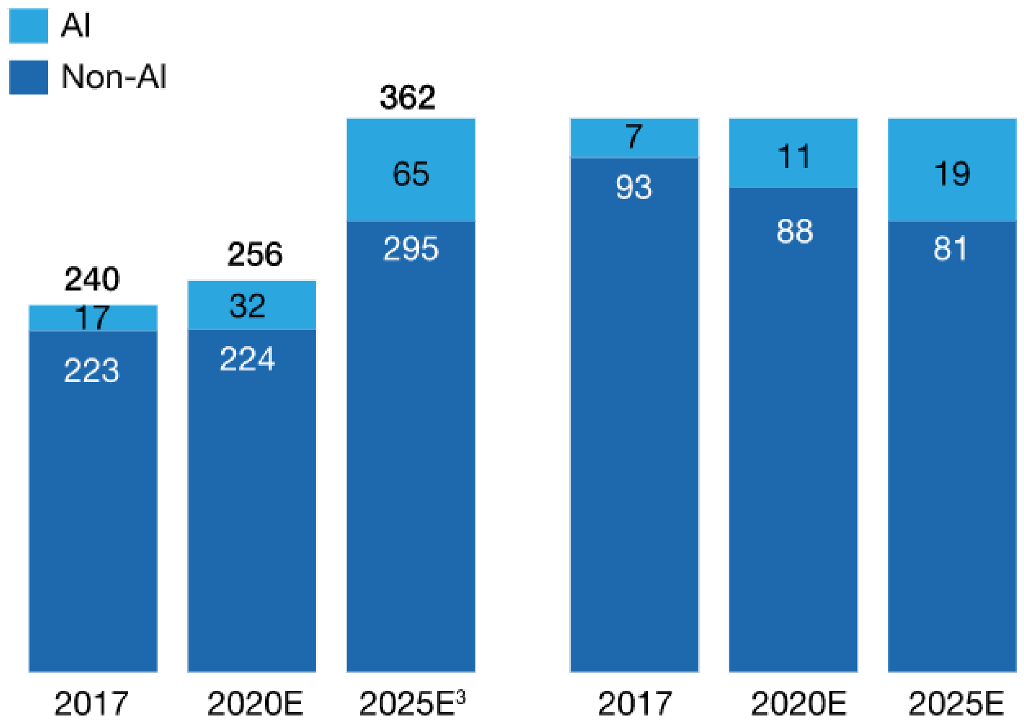
AI in Semiconductor Industry



Artificial Intelligence → Human-like concept

Machine Learning → Statistic algorithm to improve performance & prediction

Deep Learning → Computation of multi-layered neural network



AI semiconductor total available market,[1] $ billion

AI semiconductor total available market, %

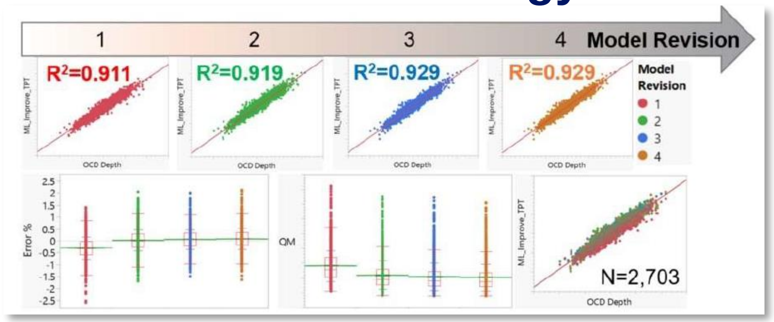
[1] Total available market includes processors, memory, and storage; excludes discretes, optical, and micro-electrical-mechanical systems.
[2] Compound annual growth rate.
[3] E = estimated.
Source: Bernstein; Cisco Systems; Gartner; IC Insights; IHS Markit; Machina Research; McKinsey analysis

What are our Ultimate Goals?

by Machine Learning & Deep Learning

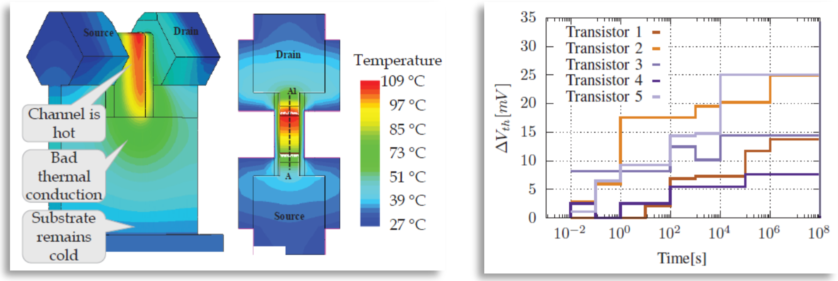
How we provide optimized ML & DL solutions to fabs?

ML for Metrology



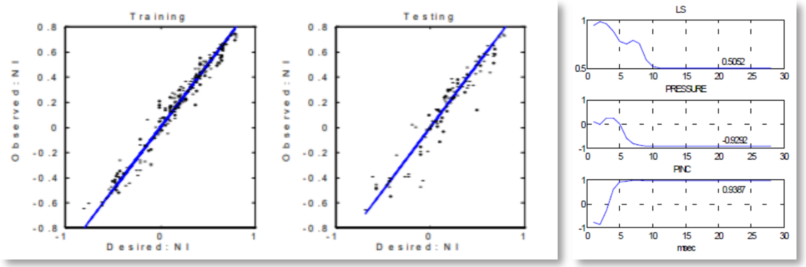
Timoney P. et al., SPIE 2020

DL for Reliability



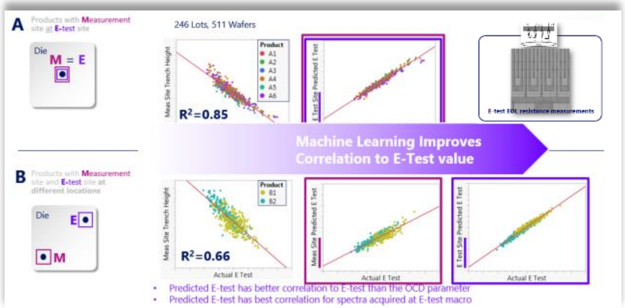
Amrouch H. et al., VTS 2021

ML for Process



Erten G. et al., ICNN 1996

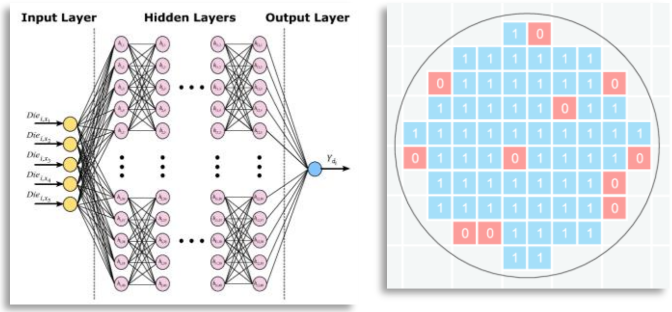
ML for e-Test



- Predicted E-test has better correlation to E-test than the OCD parameter
- Predicted E-test has best correlation for spectra acquired at E-test macro

Timoney P. et al., SPIE 2018

DL for Yield



Jang S.-J. et al., IEEE TSM., Nov. 2019

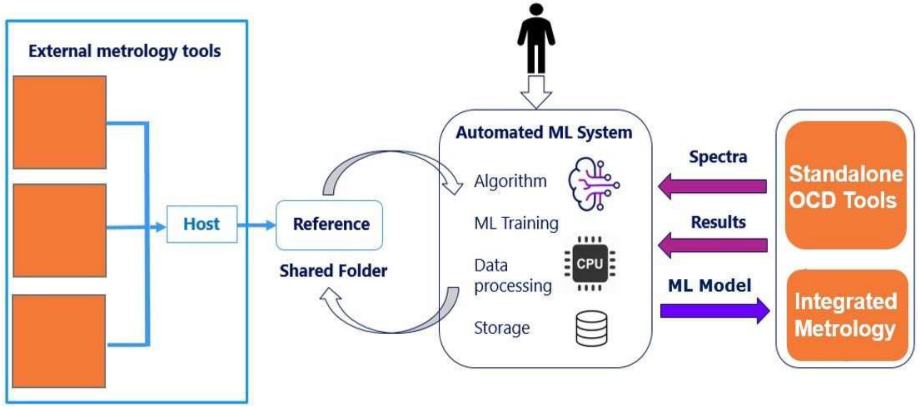
Machine Learning Solution

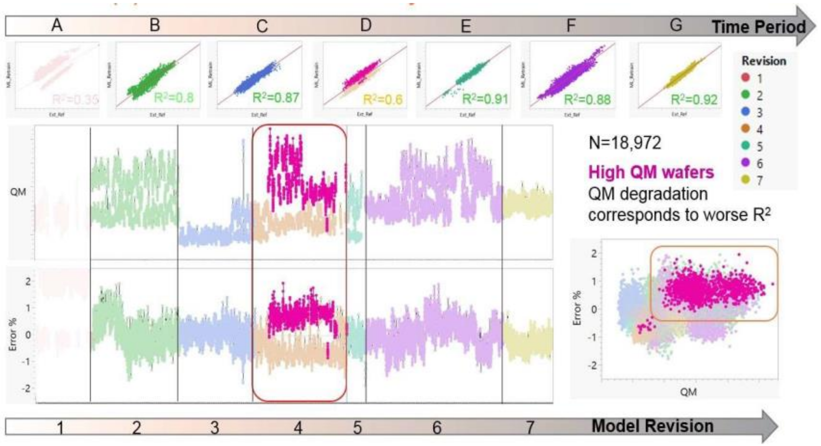
Algorithms
Advanced Machine Learning algorithms for accuracy and robustness

Software
State of the art SW for fast recipe creation and control

Connectivity
Seamless Connectivity with Nova Fleet and Fab HOST

Control
Automatic recipe optimization thru “Continuous Active Learning”





Timoney P. et al., SPIE 2020

Is metrology industry moving to the right direction on predictability?

Summary

- 3D architecture devices are accelerating new paradigm of process control solutions.

- **Transition of lab solutions to In-line solutions** accelerate to optimize processes and yields.
  - *In-line XPS, In-line Raman, In-line SIMS, and more*
- **In-cell solutions** deliver better correlation of process variability with device performances.
  - *SI & VTS and more*
- **Combined or hybrid solutions** give more degrees of freedom to fabs for 3D platform devices.
  - *OCD & XPS, Hybrid AFM, and more*
- **AI integrated metrology systems** enhance diversity of data analysis with accurate predictability.
  - *Advanced machine learning engines*

Thank You

Q & A