# Advanced Manufacturing using Virtual Metrology and Equipment Intelligence®

*New techniques to solve difficult metrology and process optimization challenges*

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# Cautionary statement regarding forward-looking statements

This presentation and the accompanying discussion contain “forward-looking statements” under U.S. securities laws. Forward-looking statements include any statements that are not statements of historical fact. Examples of forward-looking statements include, but are not limited to: (1) anticipated business, balance sheet, cash flow and financial measures and results, including guidance, whether on a GAAP or non-GAAP basis; (2) economic, market, industry and industry segment expectations; (3) product performance and changes in market share or customer demands; (4) our ability to successfully execute business, capital allocation, product and growth plans or strategies, or otherwise deliver value for customers and stockholders; (5) the impact of the COVID-19 pandemic on our operations and financial results, and our ability to mitigate operational and business impacts caused by it; and (6) the impact of trade regulations, export controls and trade disputes. Forward-looking statements speak only as of the date they are made and are subject to risks and uncertainties that could cause actual results to differ materially from those expressed, including: the severity, magnitude and duration of the COVID–19 pandemic (and the related governmental, public health, business and community responses to it), and their impacts on our business, results of operations and financial condition, are evolving and are highly uncertain and unpredictable; business, political and/or regulatory conditions in the consumer electronics industry, the semiconductor industry and the overall economy may deteriorate or change; the actions of our customers and competitors may be inconsistent with our expectations; trade regulations, export controls, and trade disputes may inhibit our ability to sell our products; and widespread outbreaks of illness may impact our operations and revenue in affected areas; as well as the other factors discussed in our filings with the Securities and Exchange Commission (“SEC”), including specifically the Risk Factors described in our annual report on Form 10–K for the fiscal year ended June 28, 2020 and our quarterly report on Form 10-Q for quarter ended September 27, 2020. You should not place undue reliance on forward-looking statements. Lam undertakes no obligation to update any forward-looking statements.

# Agenda

# Next Node Technologies and Metrology Challenges

*Challenges to Process Integration and Metrology*

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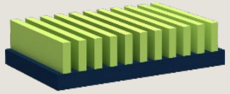
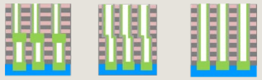
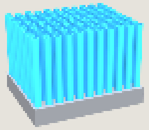
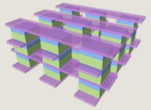
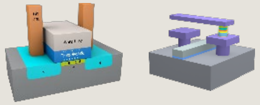
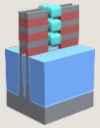
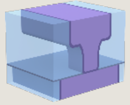
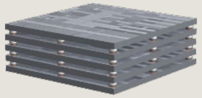
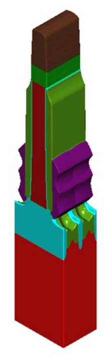
# Critical Technology Inflections

| | | | | |
|---|---|---|---|---|
| **Patterning** | **Patterning** | EUV<br>Additive Patterning |  | **Variability, Cost** |
| **Memory** | **3D NAND** | Stacked 3D NAND |  | **Density** |
| | **DRAM** | New Materials & Architectures<br>Non Volatile Fast Memory |  | **Density, Power** |
| | **Storage Class Memory** | 3D Vertical Architecture<br>New Materials |  | **Density, Cost** |
| | **Embedded Memory** | Magnetic, Phase Change &<br>Ferroelectric Memory |  | **Speed, Power, Density** |
| **Logic** | **Transistor** | Gate All Around<br>Negative Capacitance FET |  | **Power, Speed** |
| | **RC Management** | New Materials<br>Barrierless |  | **Power, Speed** |
| **Packaging** | **Chip Integration** | Heterogeneous Integration |  | **Footprint, Speed** |

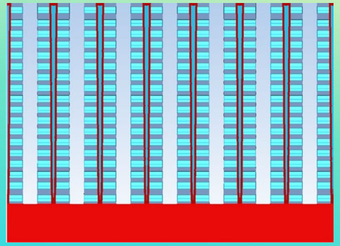
# Metrology Challenges

*Next Node Technologies*



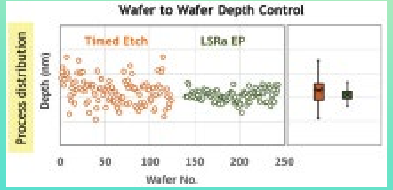
## Smaller Dimensions

Requires metrology with greater sensitivity and precision



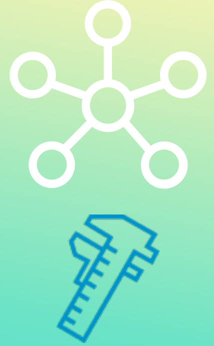
## 3D Device Geometry

Difficult to measure inside HAR structures, opaque thick films, other “hidden” structures




## Measurement Frequency

Lack of low-cost, high-quality measurements can lead to process excursions



## Hybrid Metrology

Need to combine fragmented metrology data from different sources

# Process Modeling & Virtual Metrology

*Using Unit Process Models, Virtual Fabrication, Virtual Metrology and Domain Expertise to Optimize Processes and Pathfinding*

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# Virtual Fabrication Platform

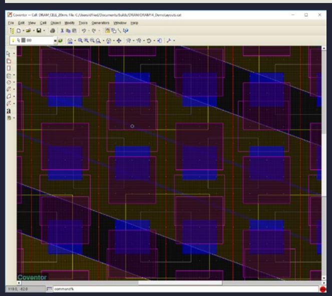
*Virtualize the entire fabrication process flow (or a subset, patterning sequence, etc.)*

**Process Flow ⇔ Step-by-Step Process, Behavioral description, process library**

| Number | Lock | Name |
|---|---|---|
| 1 | | Wafer Start |
| 2 | | AA |
| 2.1 | | AA_SAQP |
| 2.1.1 | | DEP PadOx |
| 2.1.2 | | ION Well B |
| 2.1.3 | | DEP PadNit |
| 2.1.4 | | DEP Mandrel1 Silicon |
| 2.1.5 | | DEP TransOx |
| 2.1.6 | | DEP Mandrel2 Silicon |
| 2.1.7 | | DEP ODL |
| 2.1.8 | | DEP SiARC |
| 2.1.9 | | DEP MandrelResist |
| 2.1.10 | | LTH Mandrel |
| 2.1.11 | | RIE Mandrel2 |
| 2.1.11.1 | | RIE SiARC |
| 2.1.11.2 | | RIE ODL |
| 2.1.11.3 | | RIE SiARC |
| 2.1.11.4 | | RIE MandrelSi |

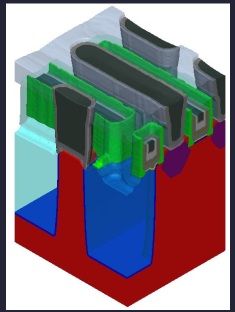
- …
- Hard mask dep.
- Lithography
- Mask open etch
- Mem. hole etch
- …

**Design ⇔ Editor and Viewer to support GDS layout and other input types**

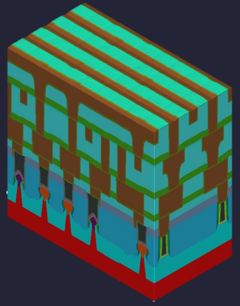


- Design
- GDS
- OPC
- Contours
- …

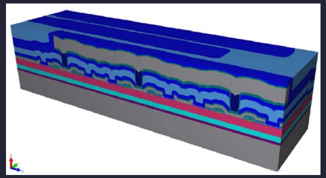
**3D Model ⇔ SEMulator3D Virtual Fab Modeling Engine**



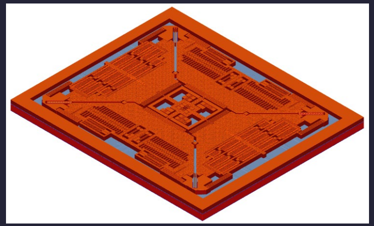
Front End Logic



BEOL



Power



MEMS

**Applications**

**PATHFINDING**

- Process integration validation
- Big Branch decisions
- Process assumptions

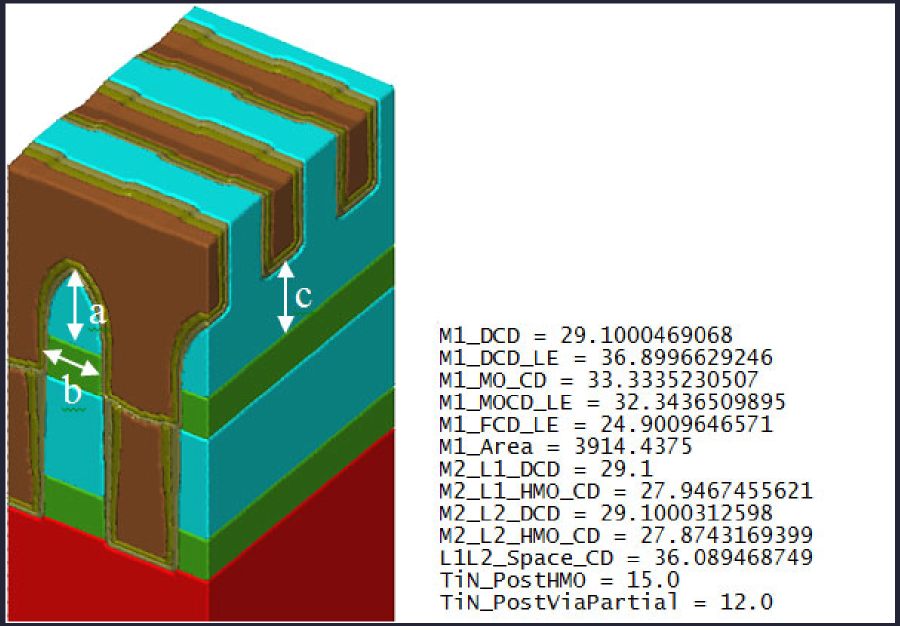
**DEFECT ANALYSIS**

- 3D Failure Checks
- Defect Kill Ratio
- R/C, Leakage, Device, IV, CV, etc.

**YIELD: RAMP AND HVM**

- Design Process Optimization
- Process Window Optimization
- Cross-Wafer Uniformity

# Virtual Metrology




## Measure Critical Structural Attributes during Simulation

Similar to in-line metrology in the fab

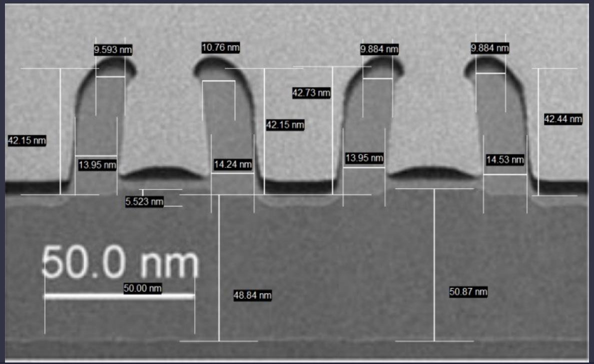
Can measure items such as film thickness, critical dimension (width), step height, sidewall angle, contact area and more

### Advantages

- Measure parameters that could only be determined destructively in the fab
- Applicable to any device type - no special metrology structures or equipment required
- Useful in validating process assumptions and effect of process changes on design rules.
- Validate process model by comparing wafer-based metrology data to virtual metrology

# Process Model Calibration: Virtual & Physical Metrology

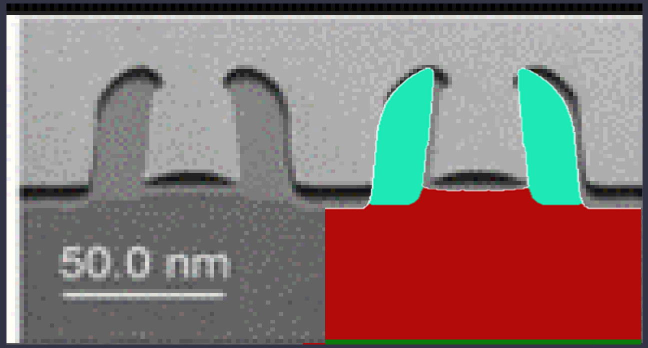
## SPACER 1 OXIDE FIN CD STEP – XSEM IMAGE FROM IMEC




## COMPARISON OF XSEM WITH VIRTUAL METROLOGY

| Measurement | XSEM Image (nm) | Before PMC (nm) | Virtual Metrology PMC Trial-0 (nm) |
|---|---|---|---|
| Spacer 1 Oxide Fin TCD | 9.5 | 11.87 | 9.84 |
| Spacer 1 Oxide Fin BCD | 13.8 | 12.85 | 13.84 |
| Spacer 1 Oxide Height | 42.5 | 45.7 | 43 |
| Spacer 1 Oxide OE | 5.75 | 5.33 | 5.76 |

## CALIBRATION RESULTS




## GATHER TARGET MEASUREMENTS

Enter target measurements from an actual semiconductor

- Critical dimensions from XSEM or TEM

## PROCESS MODEL CALIBRATION AFTER MULTIPLE AUTOMATED TRIALS

Actual XSEM values and predicted target values converge after process model calibration optimization study

## COMPARISON OF ACTUAL VS. CALIBRATED MODEL RESULTS

Comparison of actual device and SEMulator3D model built from optimized parameters

# Mass Metrology

*Angstrom-Level Measurements for Advanced Process Monitoring and Control of 3D Device Structures*

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# Metryx® Mass Metrology

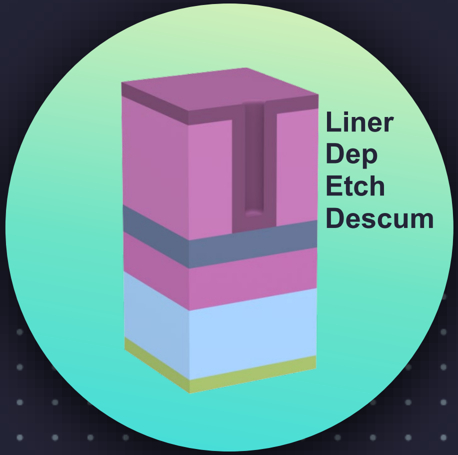
*Monitoring HAR/Hidden Processes with Å-Level precision*

## High Precision

Mass metrology enables Å-level precision process monitoring with direct measurement at high TPUT

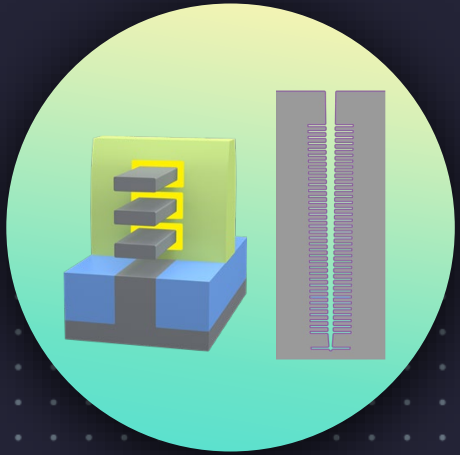
## Accurate & Non-Destructive

Delta-mass is non-destructive & accurately represents wafer state/ process (incl. oxidation)




## Application Flexibility

Measure etch, dep, bevel, clean, curing & all wafer-processes, from R&D through to HVM



## 3D/ Hidden

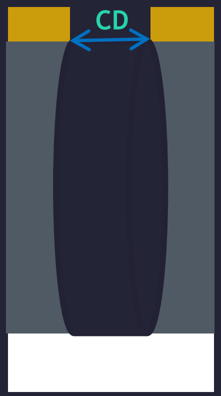
Enables quantification of HAR, hidden/buried processes where conventional metrology fails

# Metryx® Metior®

## Challenges in DRAM and 3D-NAND HVM

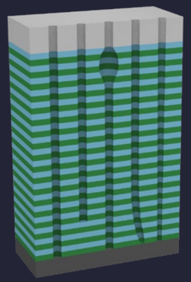
Monitoring and control of ultra-thin films, thick films or stacks, and complex 3D geometries (HAR structures) is difficult with traditional optical metrology.

**DRAM**

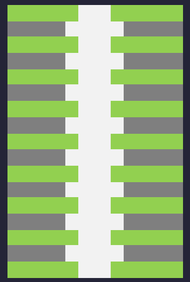



Capacitor Etch

**3D-NAND**

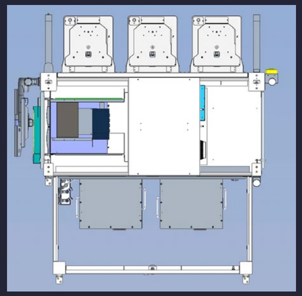


Memory Hole & Conformal Deposition



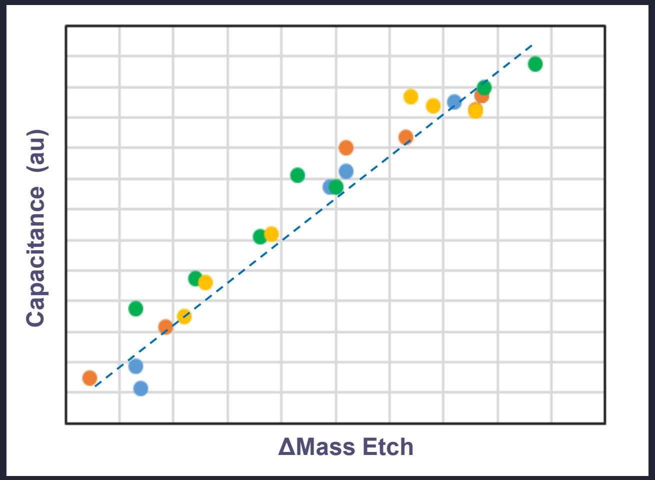
Sidewall Process & Fill

## Detect Process Excursions not possible with Optical Metrology

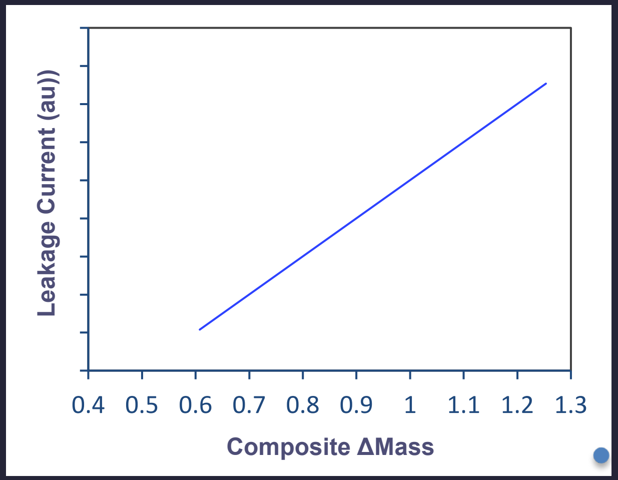


- Sensitive & Non-Destructive
- Direct Measurement
- Correlation to Electrical performance
- Independent of Device Patterning
- Low Cost of Ownership

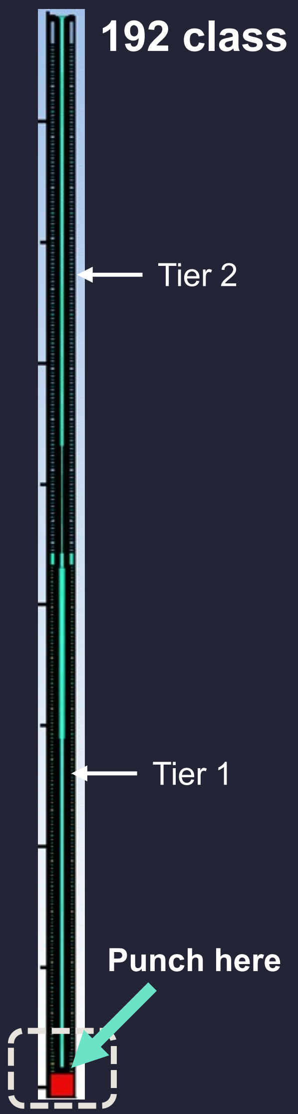
**Direct correlation to Capacitance**

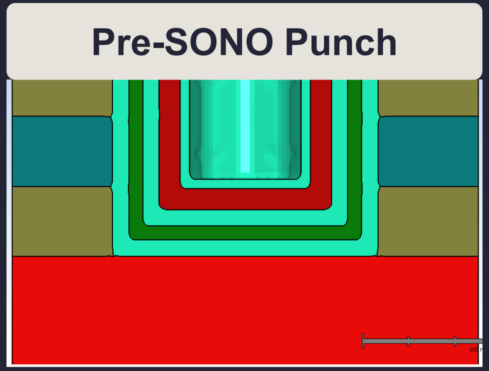


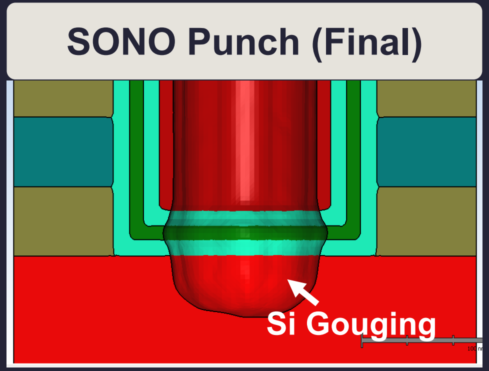

**High-k Predictive of Leakage**

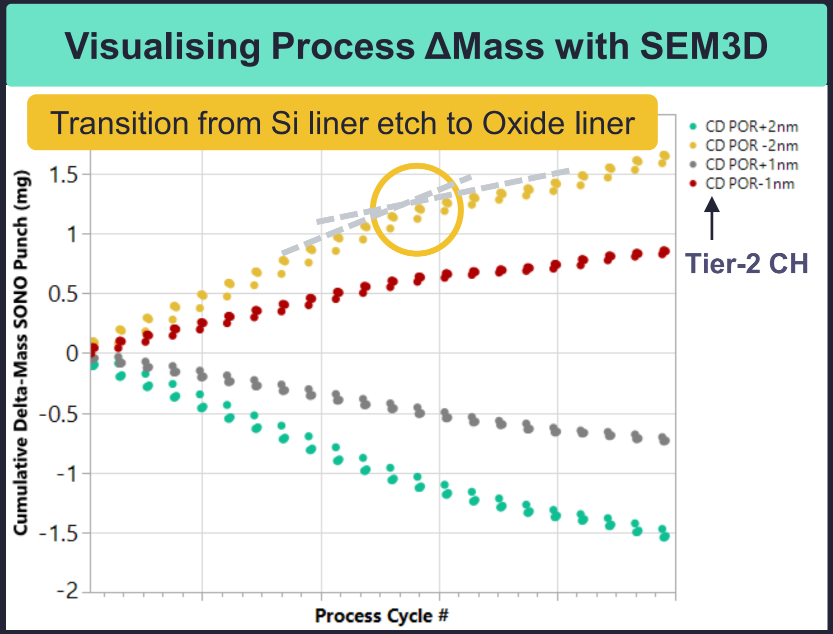


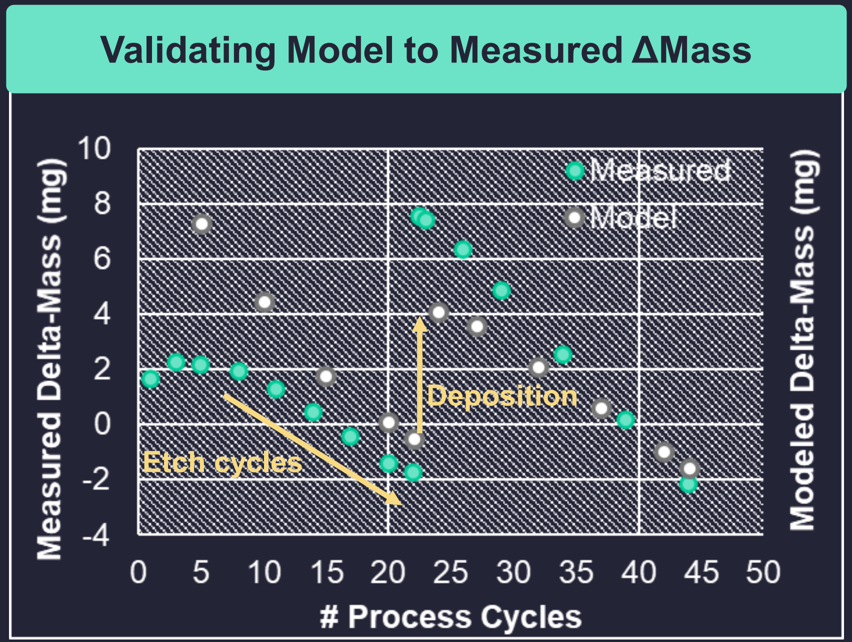
# 3D-NAND SONO Punch: Metryx with SEM3D process model



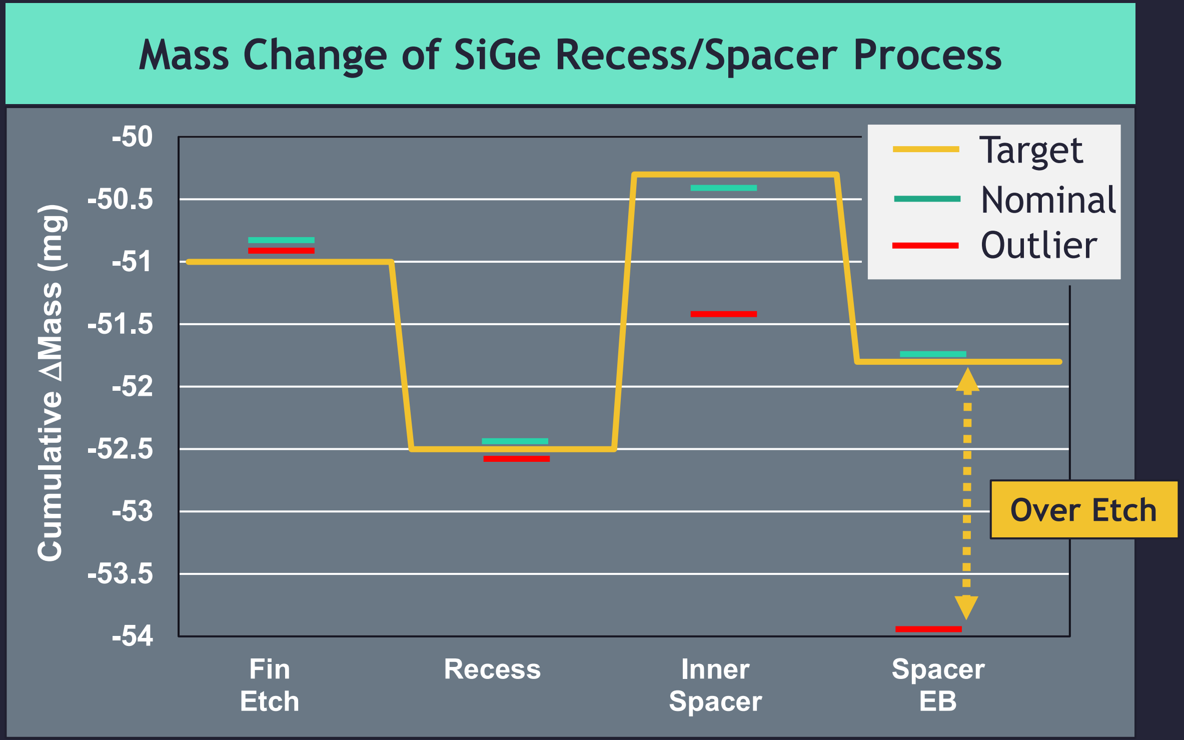



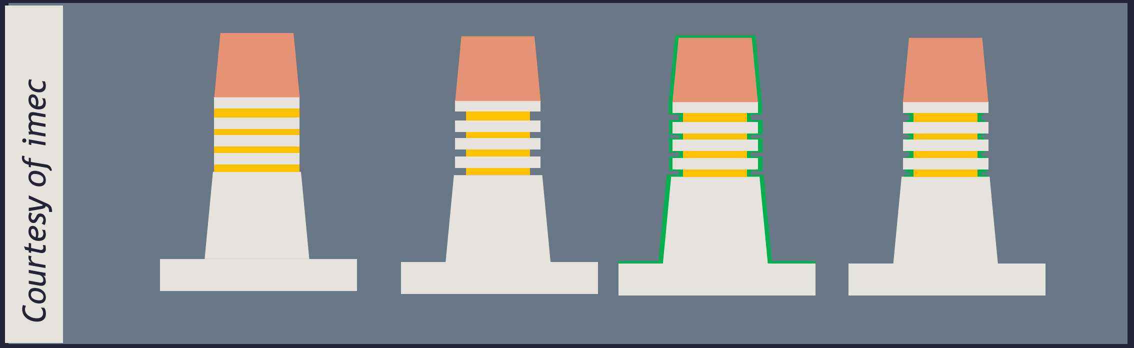



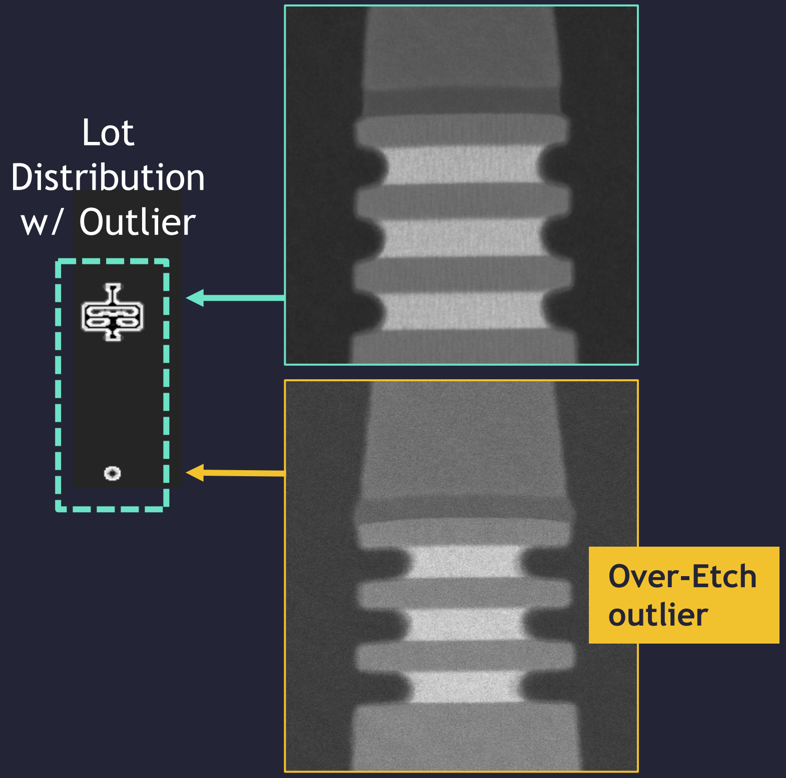




- Delta-Mass enables monitoring of SONO Punch process (optical alternatives are limited due to low signal response)
- ΔMass response to Tier-2 Channel Hole CD (left), aligns well with process model expectation
- SEM3D model and measured ΔMass results (above) show good correlation & trend rate with process cycles

# Mass Measurement of Gate-All-Around Fin Etch/Spacer



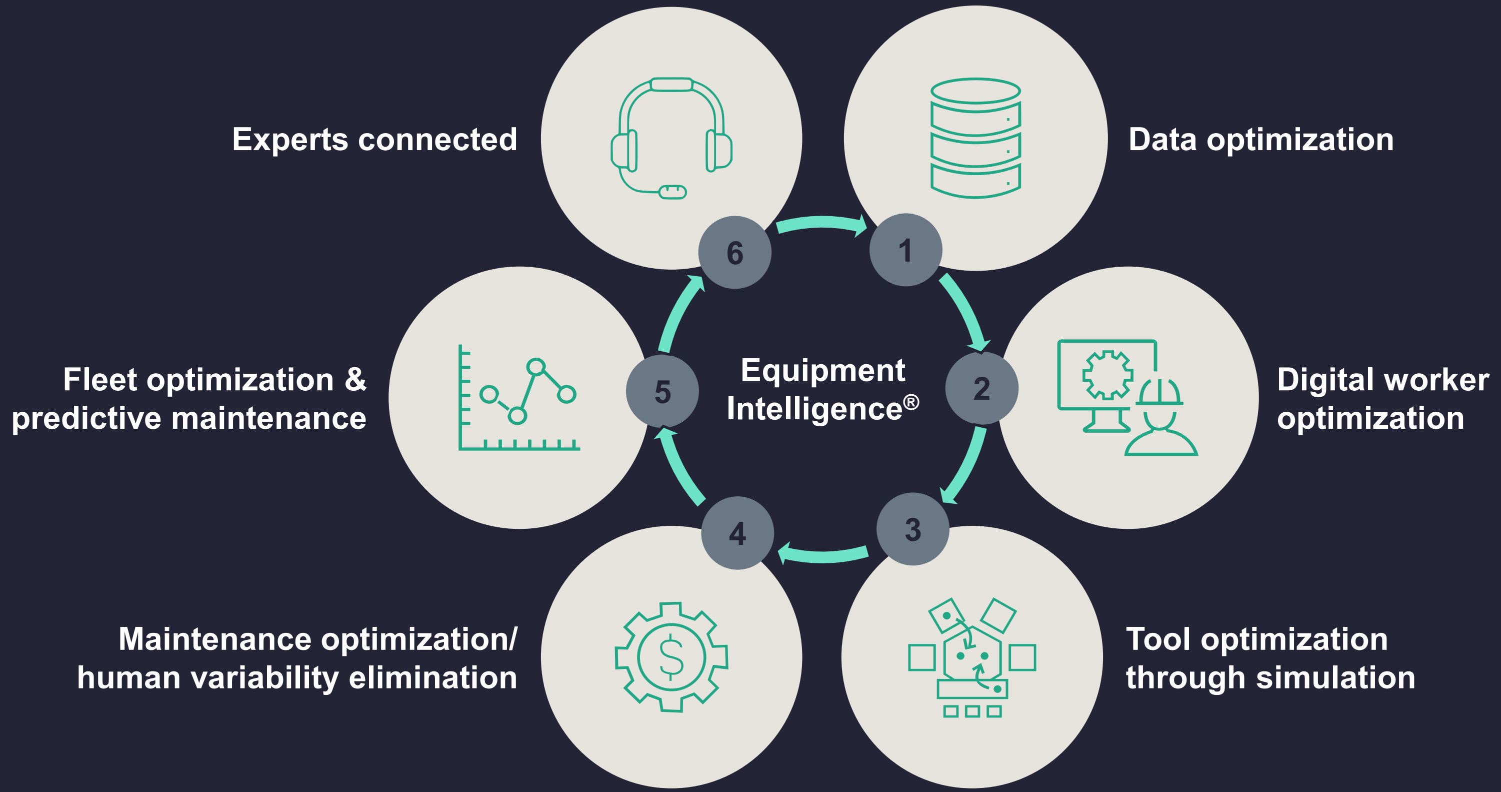




- Mass Metrology enables quick & accurate targeted development for process monitoring in R&D & HVM
- Excellent ability to monitor isotropic-etch and ALD conformality in trench/recess

# Equipment Intelligence®

*Enables advanced adaptive modeling using tool and sensor data*

# Lam Equipment Intelligence® is focused on addressing customer needs

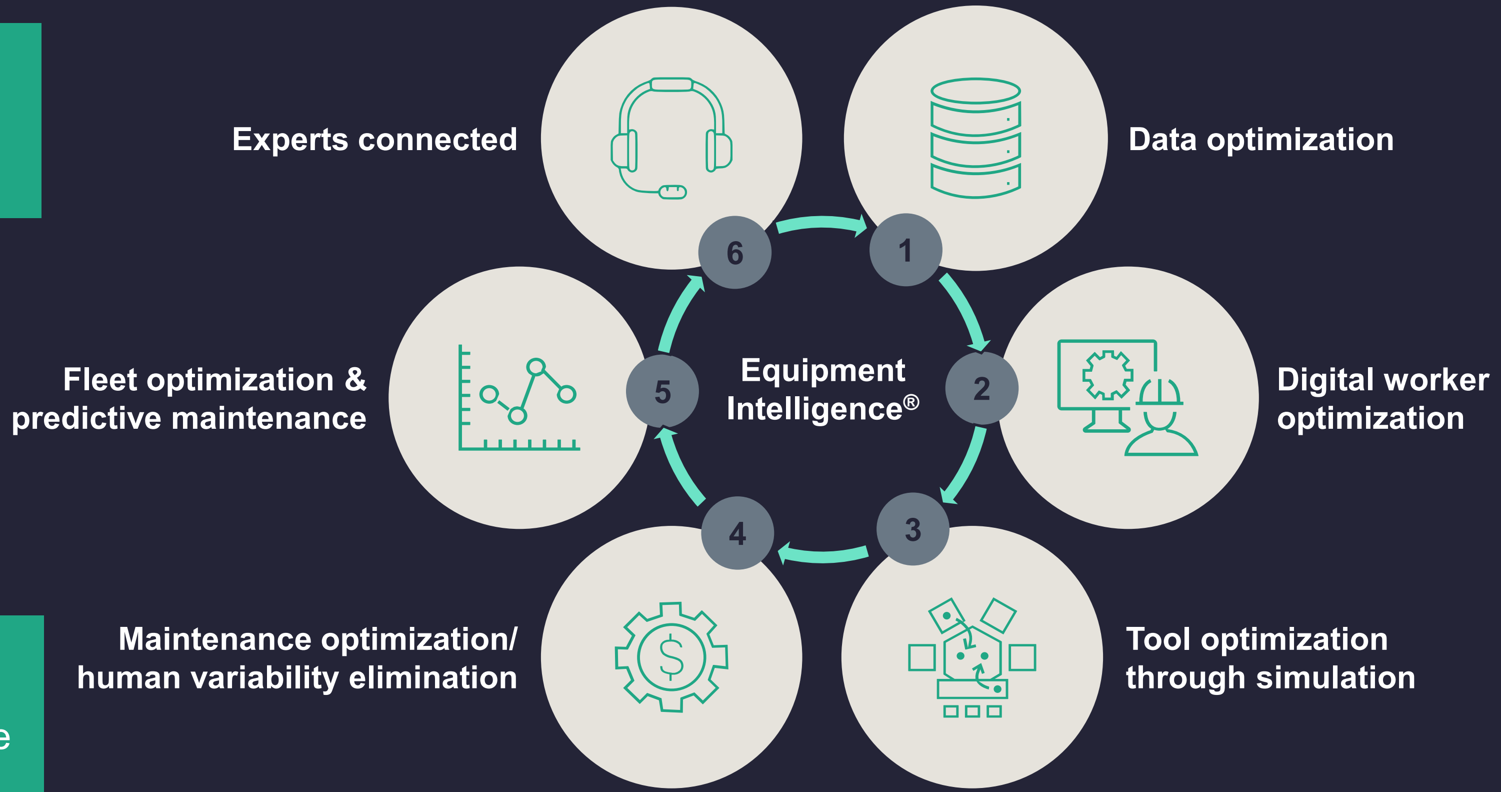



Smart tools for early learning to HVM productivity

# Lam Equipment Intelligence® is focused on addressing customer needs

Leverage the best experts available

Bringing value out of data



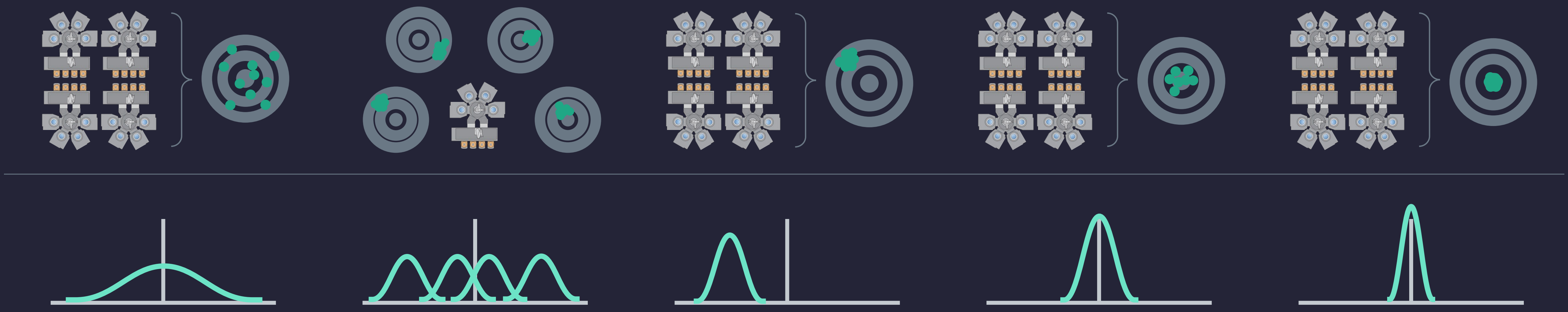

Transitioning from reactive to predictive

Improving productivity and quality

Smart tools for early learning to HVM productivity

# Lam Equipment Intelligence® - Enables Tool-to-Tool (Fleet) Matching & Process Performance Improvements

| INITIAL FLEET | FLEET MAINTENANCE OPTIMIZATION | FLEET OPTIMIZATION (EI-DA) | EI-DA + ON-WAFER RESULTS FEEDBACK | PREDICTIVE CAPABILITY FOR APC TUNING |
|---|---|---|---|---|
| Broad distribution within the process window | Reduce chamber variability due to human variability | Reduce fleet variability using machine learning | Center the process window using on-wafer results to tune the fleet | Improve process Cpk using predictive capability for APC |

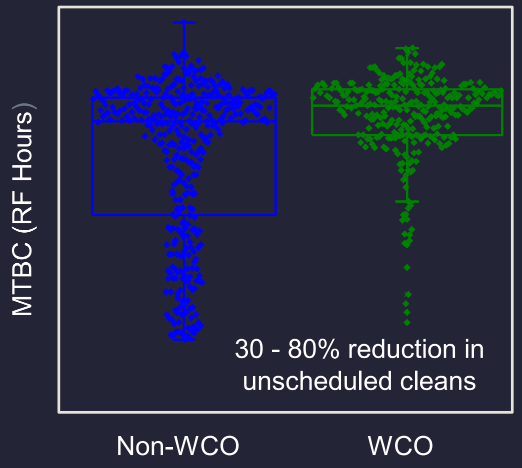


## Improved fleetwide process control

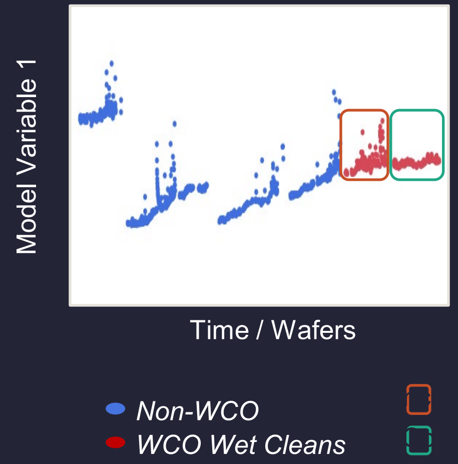
# Illustration of how maintenance and fleet optimization combined enables higher level of control

**MAINTENANCE OPTIMIZATION (ELIMINATION OF HUMAN ERROR) + FLEET OPTIMIZATION BASED ON TOOL SENSOR DATA**

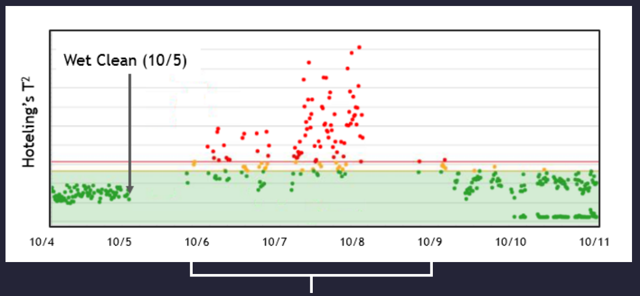
Improved MTBC (and availability) by eliminating unscheduled cleans due to poor clean quality




Reduced variability in sensor signal output increases signal to noise for tool health monitoring models




Reduced yield risk due to higher sensitivity models with low false alarms




Wet Clean procedure issue (no on-wafer shift detected):

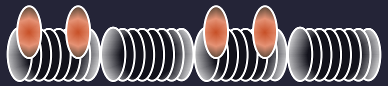
Top heater screw was found to be loose (10/8)
After tightening, the trend returned to normal

Reducing chamber to chamber variation enables useful detection & prediction models
= higher equipment availability, higher yield

# Equipment Intelligence® Data Analyzer prediction: monitor chamber shift & drift by Y-data regression

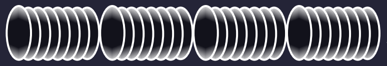
## Advanced adaptive modeling system using tool and sensor data to monitor and control on-wafer performance

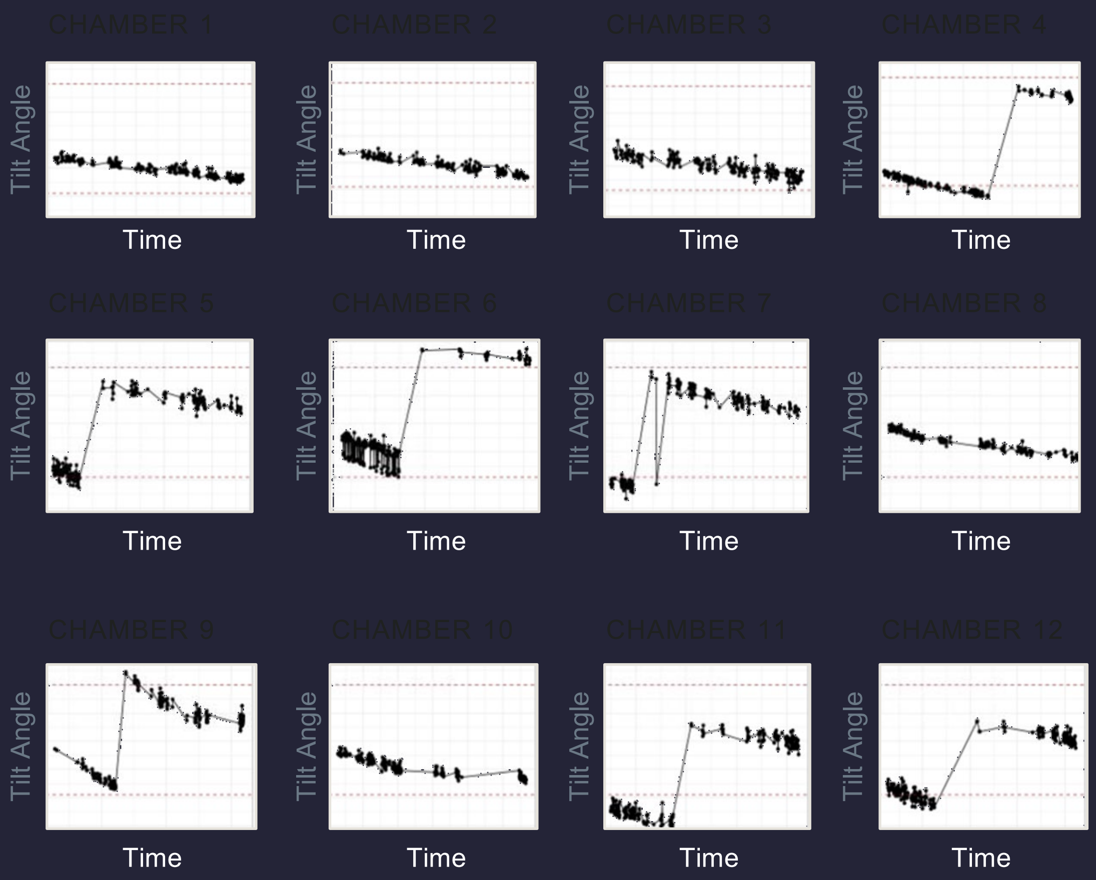
Low frequency Measurement



- Tool data
- Sensor data


Every Wafer Measurement






*Regression is based on:*

Tool and sensor parameter data to Measurement data (CD, Angle, Thickness …)

## Ability to monitor every lot and flag out-of-control wafers

- Reduce scrap and excursion events
- Flag OOC wafers for additional disposition

## *Using sensors for Equipment Intelligence®*

Lam's latest generation etch product, Sense.i®, is powered by Equipment Intelligence® which includes almost 400 more sensors than previous-generation tools. It autonomously self-calibrates, has self-maintenance capabilities and uses machine learning to adapt to process variations.

# In-Situ Metrology: Etch Depth Control Solutions

*Broadband Spectral Reflectometry to Achieve Repeatable and Accurate EndPoint Control without Stop Layers*

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# Traditional *in situ* Metrology Inadequate for Endpoint at NM Scale

**Standalone metrology**

- Pre or post measurement
- Lot-to-lot (L2L) Control
- High Accuracy
- Flexible sampling

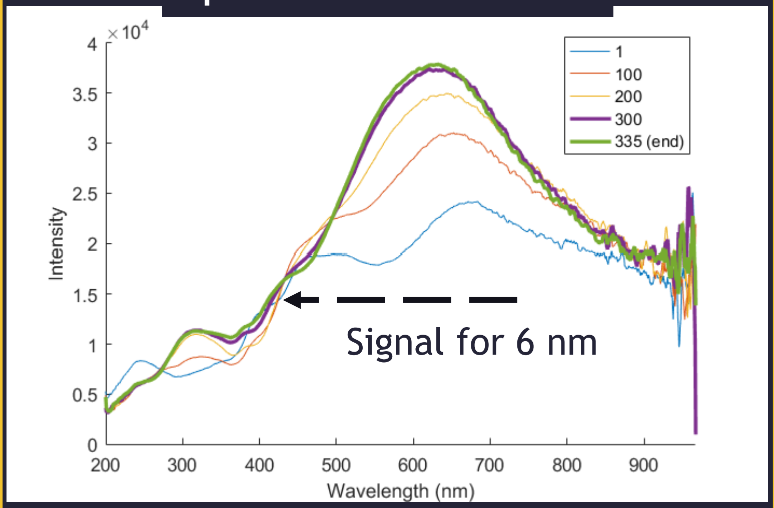
**Integrated metrology**

- Pre or post measurement
- Wafer-to-wafer (W2W) or within wafer advanced process control
- Process tool integration

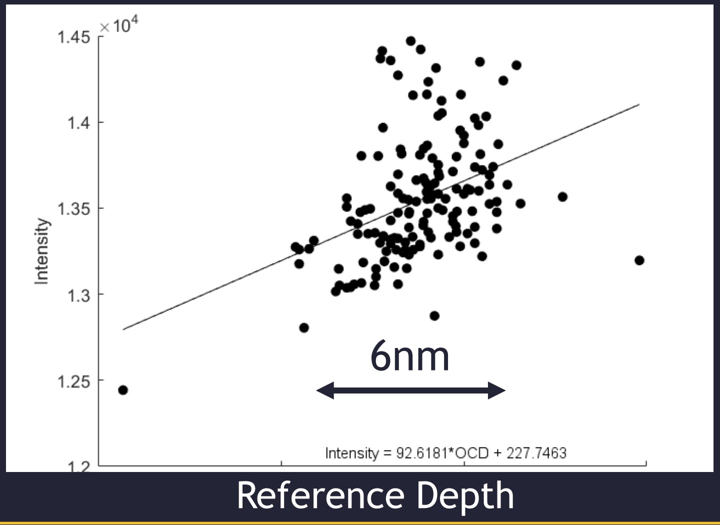
***In situ* metrology**

- **Realtime continuous measurement**
- ***In situ* active control**
- **Multi-step**
- **Poor sensitivity & accuracy with conventional endpoint methods**

**Spectra of Si1 vs Frame**




**Intensity at 400nm vs OCD $R^2$=0.16484**

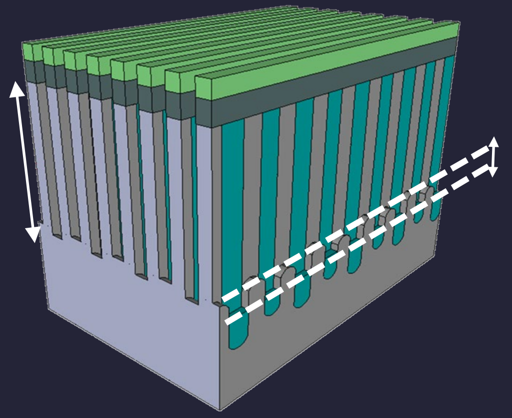


# *In Situ* Etch Depth Metrology with Machine Learning

*Feature monitoring & endpoint detection*

## Challenges

- Repeatable etch end point for etch-to-depth application without stop layers
- Etch compensation for wafer to variability due to incoming variations

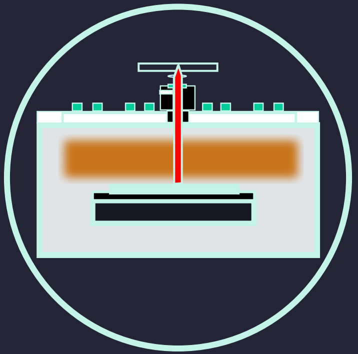


Example: endpoint detection of buried gate etch

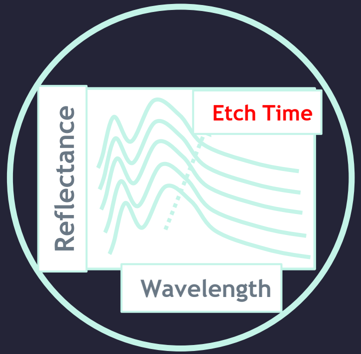
## Differentiated Solution: Lam Spectroscopic Reflectometry (LSRa)

### LSRa: Stable *in situ* reflectometry with advanced signal analysis

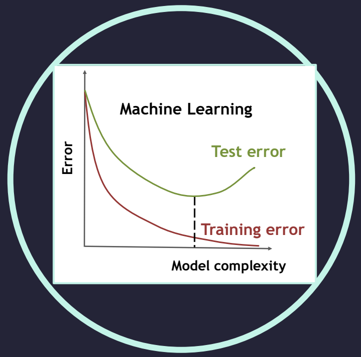
*In situ* signal collection



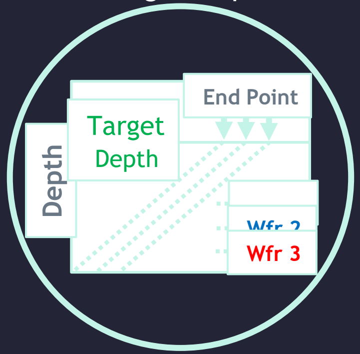
Advanced reflectometry




Signal processed with machine learning algorithm



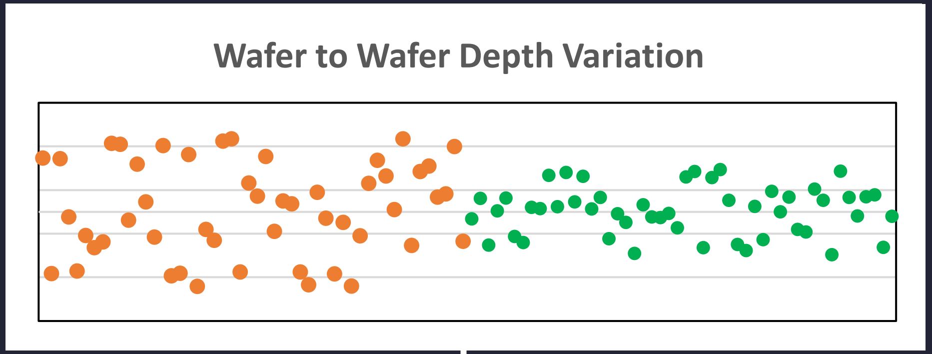

Repeatable endpoint control for target depth




### Repeatable metrology enables precision etch depth matching

**Metrology quality data designed for HVM**

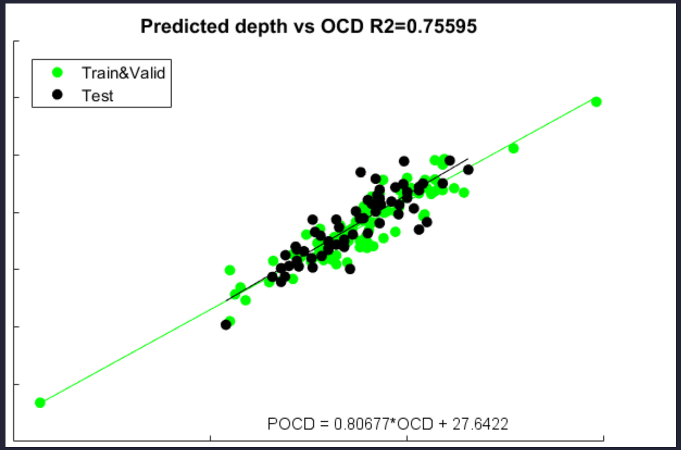
- High SNR Sensor
- Long term stability
- Reliable ML Algorithm




***Without*** In-situ Control | ***With*** In-situ Control

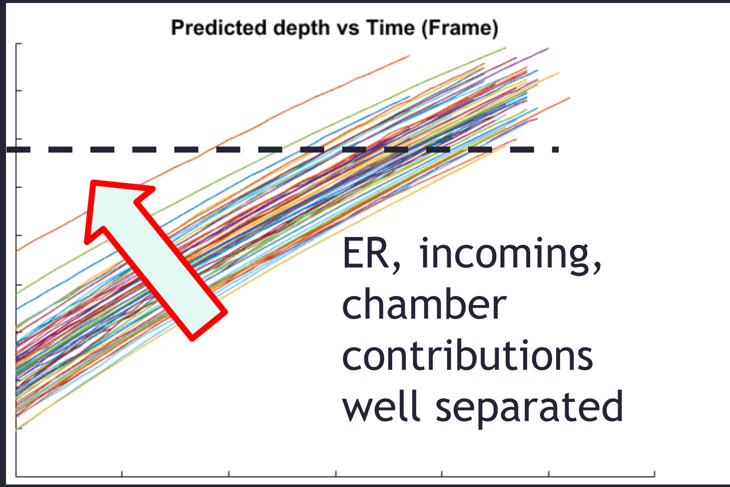
# Machine Learning of *in situ* Spectra

Predicted Depth

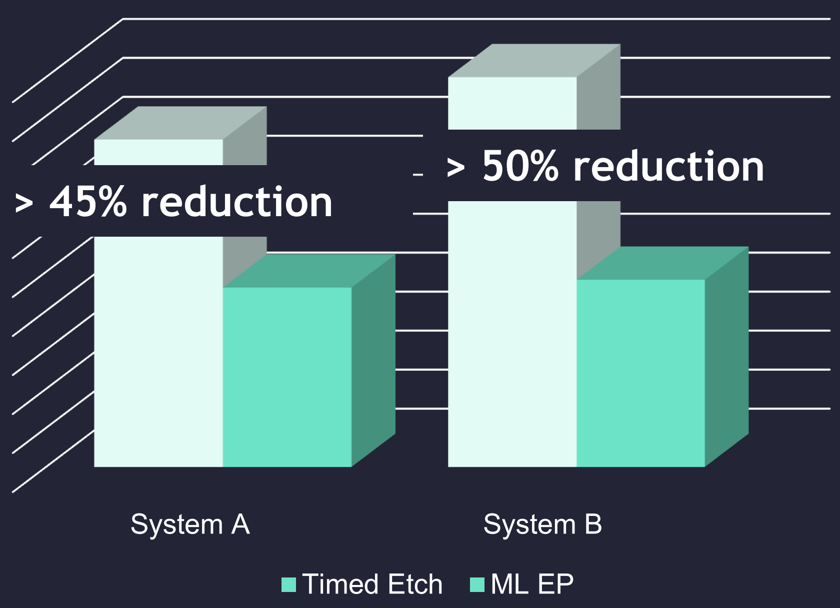



Reference Depth

Predicted Depth




Etch Time

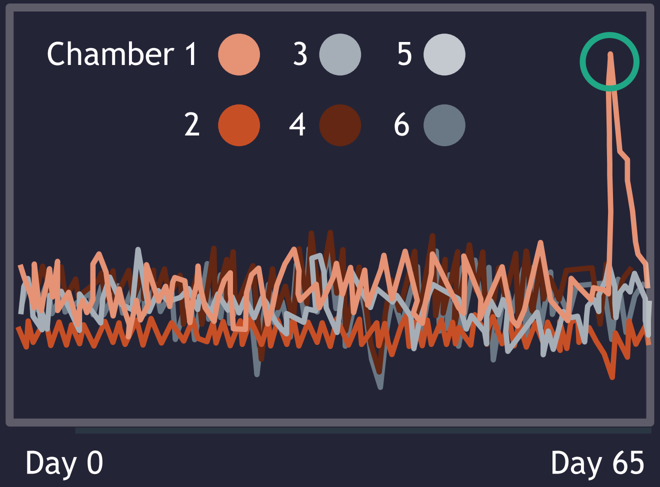


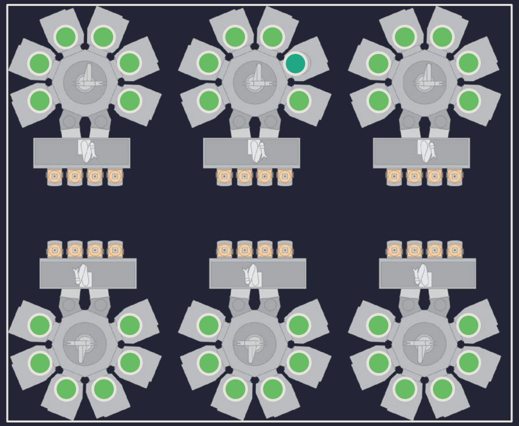

**In situ spectral endpoint provides significant improvements to W2W control compared to timed endpoint**

# Ramp to Yield Faster

## Virtual Metrology and Fleet Matching:

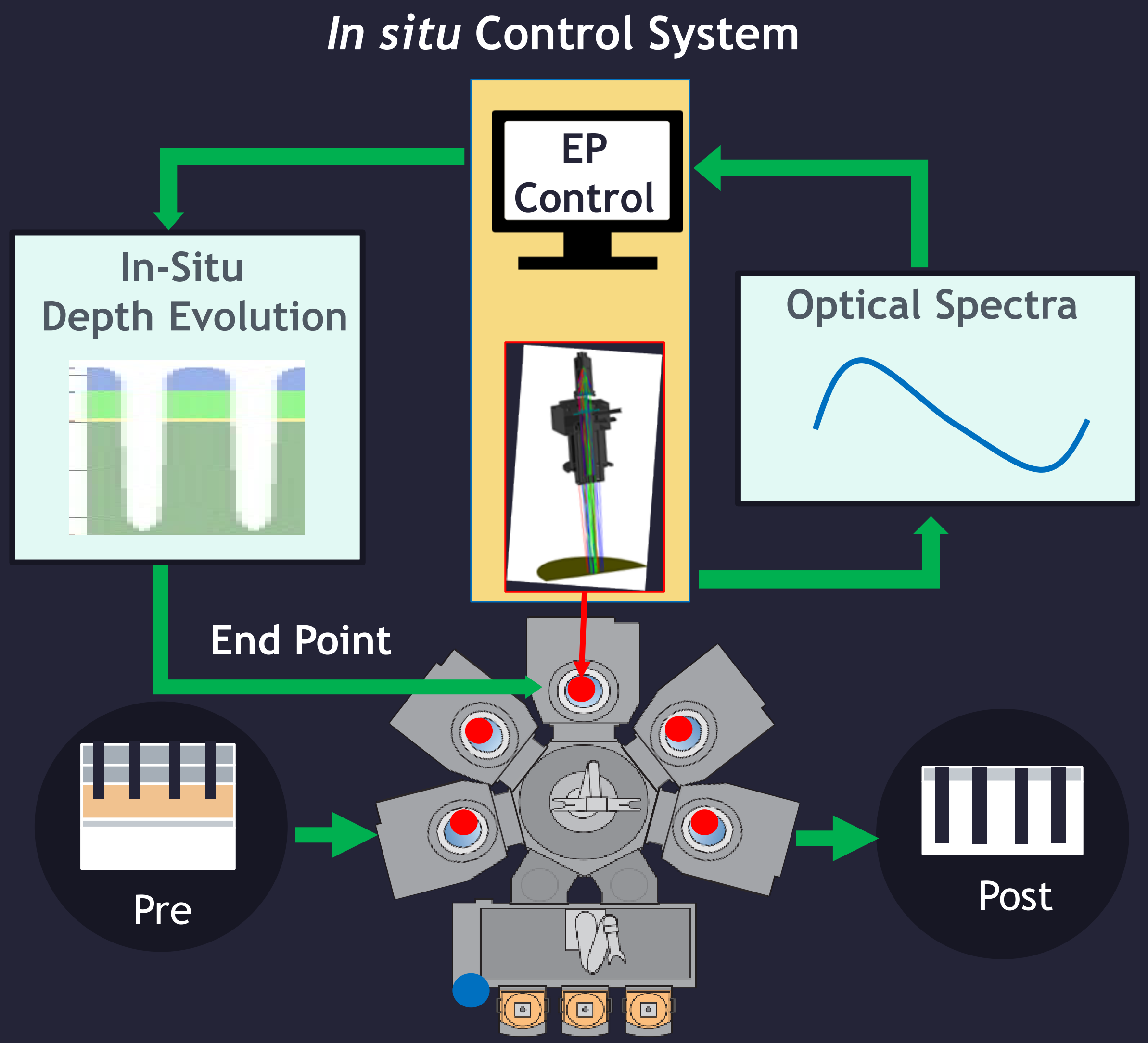
**Machine learning to correlate system behavior to end of line performance to enable the rapid identification of chamber mismatch and process variability**



# Summary

- Machine learning enables *in situ* metrology where
  - No clear endpoint signal (no etch stop layer)
  - Low signal to noise ratio; tight control spec
  - Complex incoming variations & patterning
- Lam has successfully demonstrated *In situ* endpoint control on etch systems in HVM
- High-quality sensor data, process expertise, and intelligent control opens up new APC possibilities



# Conclusion

# Conclusions

Smaller dimensions, 3D structures, and measurement & integration requirements will create metrology challenges for next node architectures.

Data from in-situ and standalone metrology , using ML/AI, calibrated models and advanced analytics, will drive real-time feed-forward and feedback optimization.

Process domain expertise is required to meet these challenges. The Equipment Intelligence® product uses Lam's domain expertise, unit process excellence and advanced analytics to add value to data.

Result: Better process and integration decision making and results.

*Call to Action: Fabs, metrology vendors and tool vendors need to share data and expertise to solve these issues, with secure data sharing solutions needed.*

# Q&A

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