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

Addressing Complex Metrology Challenges in Semiconductor Manufacturing

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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)
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• References
Semiconductor Device Scaling: A Metrology Perspective

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

Memory

Logic

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

Planar (28 nm)

FinFet (14 – 5nm)

GAA (<5 nm)
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

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Novel mid-IR ellipsometry system to augment traditional OCD

Innovative metrology-targeted machine learning with high accuracy and reduced 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

![Diagram showing SENSE, CONNECT, PREDICT processes with Signal, Physical Modeling, and Geometry blocks.](image)
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)

400 nm  600 nm  800 nm

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

6000 nm  8000 nm  10000 nm  12000 nm

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

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 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

Simulation Details

• 200 pair channel hole structure

• Assume same noise level for both reflectance only and with phase information

~10x performance gain 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

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

14 shift
tilt overlay

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
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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Novel mid-IR ellipsometry system to augment traditional OCD
### Optical Metrology Applications

<table>
<thead>
<tr>
<th>CVD TF Applications</th>
<th>CMP Applications</th>
<th>Etch Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Key parameters at top only</td>
<td>• Key parameters at top only</td>
<td>• Key parameters are subsurface, buried, and/or related to profile</td>
</tr>
<tr>
<td>• Simple models</td>
<td>• Medium complexity structures</td>
<td>• Complex structures</td>
</tr>
</tbody>
</table>

#### Modeling and Metrology Difficulty

#### Time to Physical Model Solution

#### Value Add of Machine Learning
Machine Learning as an Alternative OCD Solution

Geometry

\[ \hat{p} \]

Pitch
Height
CD1
CD2*
CD3
...

*Key parameter

OCD: Optical Critical Dimension
EM: Electromagnetic

SENSE

CONNECT

Physical Modeling

Regression

EM Solver

PREDICT

Geometry

\[ \hat{p} \]

Height
Thick
CD1
CD2
CD3
...

Machine Learning

Reference data for CD2 during training

SENSE > CONNECT > PREDICT

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CSTIC 2021 SYMPOSIUM VI: METROLOGY, RELIABILITY AND TESTING
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

- Physical sense / extrapolation capability / process coverage
- Requires few reference data
- Fast time to solution
- Extracts small signals leading to high accuracy

## WEAKNESSES

- Long time to solution
- 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

[Diagram showing the integration of Physical Modeling and Machine Learning with Experimental spectra and Hybrid Model]
Hybrid Approach Reduces Error of a Physical Model

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


Buried fin (word line) in 6F² DRAM device layout

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
• 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

谢谢你 | 謝謝 | ありがとう
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Merci

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