3D (in-line) metrology challenges and solutions

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The Impact of Data on Semi Industry

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

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

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

<table>
<thead>
<tr>
<th>Method</th>
<th>Acronym</th>
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<tbody>
<tr>
<td>E-beam based</td>
<td>X-SEM Cross-Section SEM</td>
</tr>
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<td></td>
<td>TEM Transmission Electron Microscope</td>
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<tr>
<td>X-Ray based</td>
<td>CD SAXS Small-Angle X-ray scattering*</td>
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<tr>
<td></td>
<td>XRD X-Ray Diffraction</td>
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<tr>
<td></td>
<td>XRF X-Ray Fluorescence**</td>
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<tr>
<td></td>
<td>XPS X-Ray Photoelectron Spectroscopy**</td>
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<tr>
<td>Probe</td>
<td>AFM Atomic Force Microscopy</td>
</tr>
<tr>
<td>Optical</td>
<td>Optical CD Optical Critical Dimensions</td>
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* CD SAXS tools are not yet production ready
** In combination with scatterometry or other methods
**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

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

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
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

Reference Metrology Tool

Hybrid and ML

In-line Metrology Tool

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.
Holistic Metrology Approach

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

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

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<tbody>
<tr>
<td></td>
<td>Proof of concept</td>
<td>DFM, first algorithms</td>
<td>HVM host implemented</td>
<td>Co-optimization</td>
<td>Server use-case</td>
<td>SAQP control</td>
</tr>
<tr>
<td>CD – SEM (AFM)</td>
<td>32nm FINFET, 22nm Gate DI</td>
<td>14nm EUV litho, DSA holes</td>
<td>20nm CA/CB profiles, 14nm Gate RIE</td>
<td>14nm HK/IL</td>
<td>7nm SAQP Core 2 etch</td>
<td></td>
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<tr>
<td>X-Ray</td>
<td>+ CD SAXS</td>
<td>XRD hybrid</td>
<td>XRF/XPS hybrid</td>
<td>XPS: TF on pattern</td>
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<tr>
<td></td>
<td>14nm Si lines</td>
<td>14nm SiGe H, C</td>
<td>10nm Cu CMP</td>
<td>14nm HK/IL 10nm ultra-thin films</td>
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Hybrid Metrology 2.0: From Metrology to Information Technology, A. Ger, Semicon Europe, 2017
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.


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

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

Machine Learning is enabler for IM on Complex Etch Applications
- W2W APC for etch process
- High sampling with fast info turn

Implementation of Machine Learning in Metrology for Advanced Semiconductor Manufacturing M. Shifrin, Semicon Korea, 2019
OCD ML for E-test prediction (resistance)

IM provides to polisher all profile information required for APC. Complimentary E-test ML is enabling early prediction of electrical performance.

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

Machine Learning Improves Correlation to E-Test

246 Lots, 511 Wafers

$R^2 = 0.85$

372 Lots, 522 Wafers

$R^2 = 0.66$
OCD ML for E-test prediction (capacitance)

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.

OCD ML for LER/LWR control

OCD is capable to measure standard profile parameters, such as CD, SWA and Height. Complimentary CD SEM ML is enabling OCD to control roughness.
OCD ML for selective deposition selectivity

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).

OCD ML for OL measurements

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

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