Outline

- Technology Scaling and Metrology
- Off-line/Lab Metrology
- Future Metrology Requirements
Technology Scaling and Metrology
Past to Present: 
Geometric → Novel Materials and Architectures

- Limitations of geometric scaling → need for novel process/architectural solutions
- Increased and more varied metrology demands. Driven by dimensional scaling, new materials, complexity of interactions and architectural changes, increased process sensitivities
Future: More Novel Materials and Architectures

- **Metrology Challenges**
  - Scaled dimensional
  - Integrated imaging/chemical
  - Unique system properties

- Future devices involve ever increasing and complex novel materials/architectures
- Metrology solutions are lacking in this emerging diverse technology landscape

Courtesy of Mike Mayberry, Intel
Metrology Evolution

Pre 1990
- Dimensional
- Defect
- Variability

1990s-mid 2000s
- Dimensional
- Compositional
- Defect
- Variability

Mid 2000s-present
- Dimensional
- Compositional
- Property
- Strain
- Adhesion/E/H
- Chemical State
- Density/Porosity/K
- Defect
- Variability

Future
- Property
- Strain
- Compositional Adhesion/E/H
- Chemical State
- Density/Porosity/K
- Spin
- Variability
- Magnetic
- + Other

Resolution/scaling/sensitivity

Technology Node

Critical Metrology for Advanced CMOS Manufacturing
Critical Metrology for Advanced CMOS Manufacturing

- Capability needs are being driven towards manufacturing support
- Volume/data turns/process control are being driven upstream
Off-line/Lab Metrology
Lab Metrology

- Scaling and disruptive technologies drive increased lab demand:
  - Dimensional metrology
  - Complexity, multiple analyses
  - Nanostructured/ultrathin film characterization/strain
  - Increased process sensitivities; lab-based fab process control

- Lab support is rapidly expanding: research → process development → manufacturing
- Increased data turn requirements
Dimensional Metrology

- As complexity increases, the number of key dimensional parameters also increases.
- Scaling driving SEM → TEM, data turn demands are increasing.

New capabilities to enable critical 3D measurements.
Complexity → Multifaceted Analyses

Example: Where are the dopants in this model system of fins?

TEM EDX
2D projection dataset

1.5D SIMS
1.5D dataset on array structure

Atom Probe
3D dataset

2D slices of 3D As distribution
Introduction of HK/MG film stack increased need for accurate/precise measurement and control of ultrathin film composition and interactions; including <1nm films and interfaces.

- Added complexity with 3D structures with 22nm node
Critical Metrology for Advanced CMOS Manufacturing

Ultrathin Film - Device to Wafer Level

- Compositional/thickness metrology is required to drive process improvement by using data at device level, array/die level and across wafer.

Device Level Data
- EDX
- EELS
- STEM

Array Level Data
- Transistor Array

Wafer Level Data
- Contour Plot
- Variability Chart
Successful strain engineering requires fundamental understanding and control of thin film properties; composition/doping, epitaxy/defects, interface contamination and strain.

Need measurements on “real” integrated structures; individual and statistical arrays; blanket studies are becoming less relevant.

Extending existing capabilities with modeling provides statistical key insights to film behavior at nano-scale dimensions.
Device Level Strain Measurements

- Development of NanoED with TEM is critical for providing accurate and precise transistor-level strain data.

Improvements using drift correction, descan and analysis algorithms → 2D strain mapping on 3D FinFET structures.
Quick Turn Monitor- Die/Wafer Level Strain Mapping

- Raman strain measurements are being developed to provide rapid, within die and within wafer strain mapping capabilities

Raman and FinFETs

Geometrical FinFET-induced field enhancement enables transistor level measurements

Wafer Mapping Si Channel Strain

Process A

Process B

Increasing Strain
Process Sensitivities: Airborne Molecular Contamination

- AMC support has increased significantly and is coupled with increased process sensitivities due to lithography wavelength scaling and new material introduction.
Lab-based Process Control

- Novel materials/architectures introduced several new critical materials parameters that require monitoring/control, especially early in maturity cycle.

- This pushes normally capability-based tools to their limits to provide the necessary precision.

In this case, in-fab metrology not yet developed; in-lab process control is required.
Automation for Improved Time to Data

Technology options
- Complexity/Parameters
- Process control

Data

Time to data is critical
- Cost of measurement
- Minimize analytical variation

Ultrathin Film Composition

 Calculated Person Hours

<table>
<thead>
<tr>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>20</td>
</tr>
</tbody>
</table>

- Traditional Methodology - Single Load
- Batch Loading
- Actual Data (After Implementation)
- Automated Analysis (Target)
Future Metrology Requirements
Critical Metrology for Advanced CMOS Manufacturing

- Nanowires
- TFETs
- Spin-based
- Other Non-CMOS

ALD-based HK/MG materials
- Composition
- Electronic Structure
- Stability
- Reliability

New Materials/Architectures
- Spin-based measurements
- Magnetic measurements
- Sub 1nm 3D tomography

Source/Drain Engineering
- Composition, doping
- Strain
- Electronic Properties

Dimensional Scaling
- <0.5nm resolution
- Complete Fin morphology
- Variability (device, wafer)

Novel interconnects
- Ultra low k ILDs
- Contacts
- EUV
- etc

Alternative Channels/Substrates
- Composition, doping
- Defect levels
- Electronic Properties
Critical Metrology Requirements

- Sub 1nm 3D imaging/spectroscopy
  - Morphological and physical structure
  - Elemental and chemical state speciation
  - Electronic structure
- Scalable dimensional patterning metrology; array level, wafer capable
- Properties of atomically scaled and integrated films
  - Compositional/chemical
  - Electronic and mechanical
- Ability to measure key properties at device, die and wafer levels (including 450mm)

Requires hybrid tools capable of meeting diverse technology and aggressive data turn requirements for development/manufacturing support; through rapid, highly parallel automated measurements.
Critical Metrology for Advanced CMOS Manufacturing

Metrology Trends

- Continued technology scaling and the evaluation and introduction of disruptive process technologies are directly driving a rapid increase in metrology requirements

- In-line capabilities will not always be adequate and off-line/lab solutions are required → increased manufacturing support

- Lab tools need to adapt to this environment where data turns, tool reliability, etc. are as important as the analytical capability itself; automation is a key enabler
Critical Metrology for Advanced CMOS Manufacturing
Acknowledgements

- We would like to acknowledge the generous contributions from the Intel Oregon TD Thin Film Analysis, TEM and Analytical Chemistry Labs.