Critical Metrology for Advanced CMOS Manufacturing

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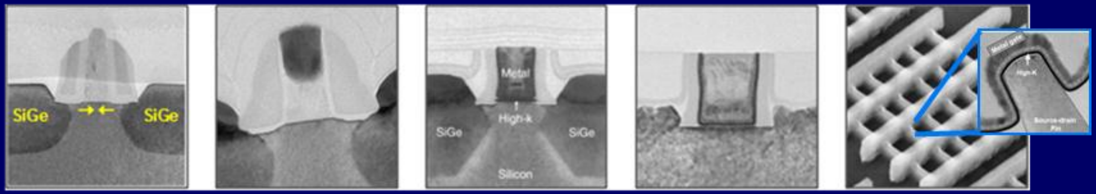
Outline

- Technology Scaling and Metrology
- Off-line/Lab Metrology
- Future Metrology Requirements

Technology Scaling and Metrology

Past to Present: Geometric →Novel Materials and Architectures

2003	2005	2007	2009	2011
90 nm	65 nm	45 nm	32 nm	22 nm

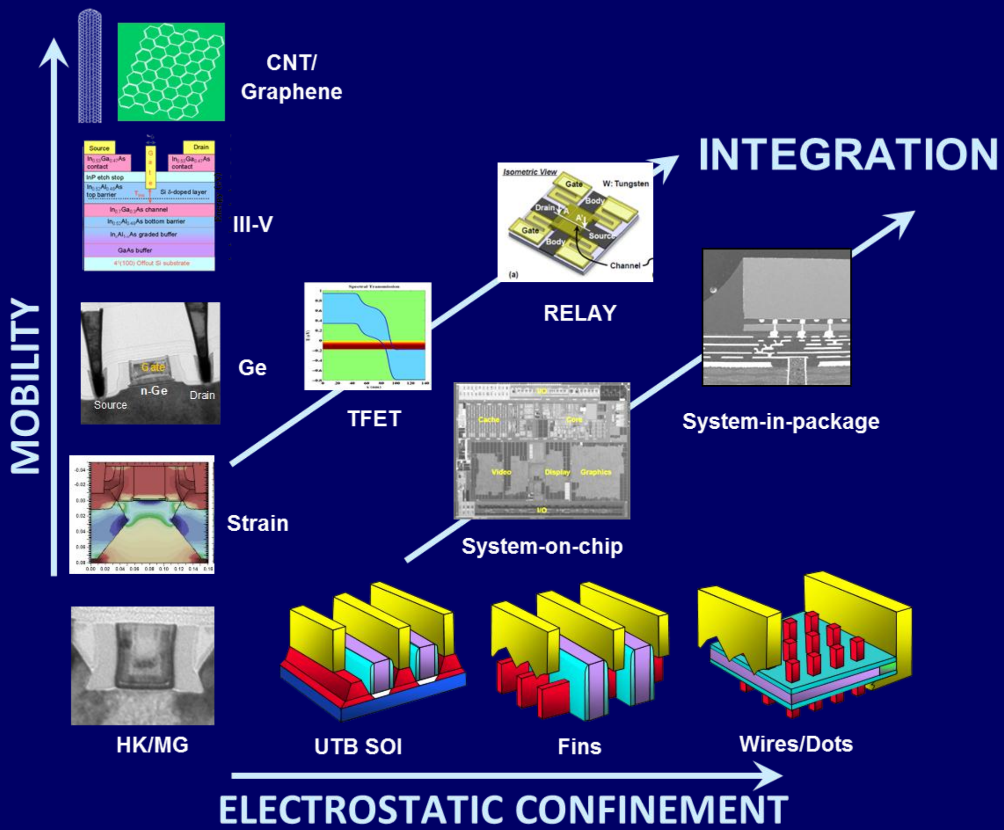


Strained Silicon	2nd Gen. Strained Silicon	High-k Metal Gate	2nd Gen. High-k Metal Gate	Tri-Gate

- 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



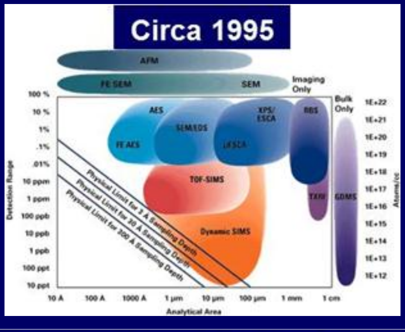
- Future devices involve ever increasing and complex novel materials/architectures
- Metrology solutions are lacking in this emerging diverse technology landscape

Courtesy of Mike Mayberry, Intel

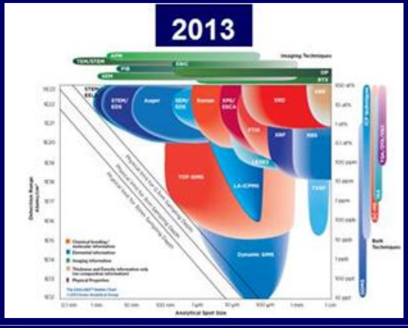
Metrology Evolution

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
- Magnetic
- + Other

Resolution/scaling/sensitivity

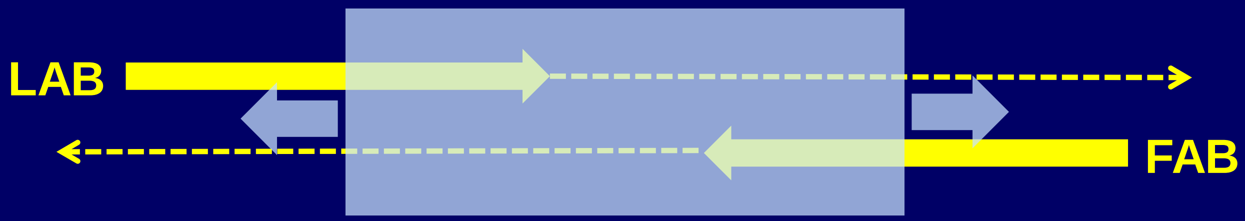
Technology Node

Metrology Support Landscape

Off-line/lab metrology focus due to capability

Mix

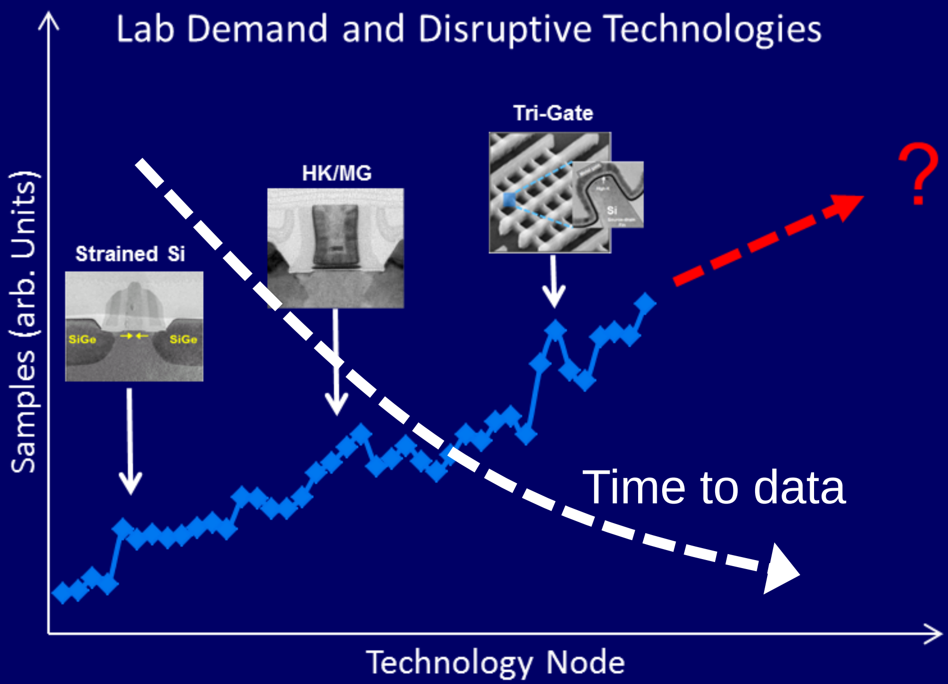
Fab focus due to in-line/volume/data turns



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

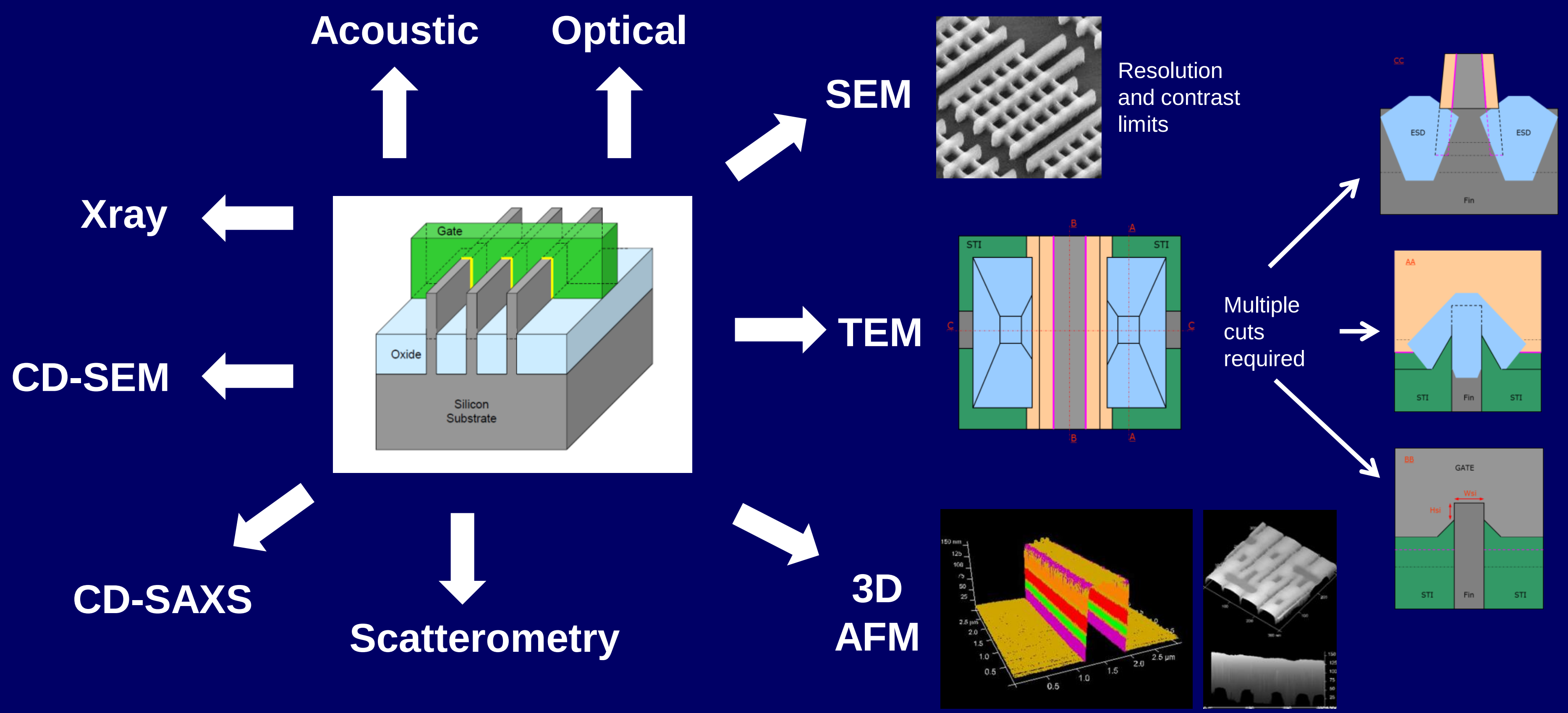
Off-line/Lab Metrology

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

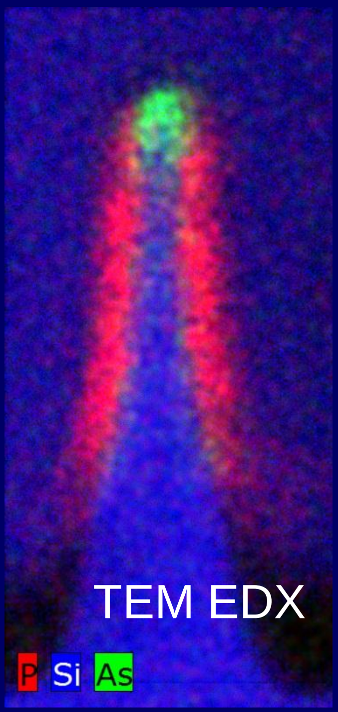


New capabilities to enable critical 3D measurements

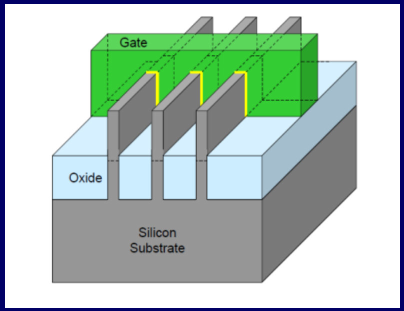
- As complexity ↑ no. key dimensional parameters ↑
- Scaling driving SEM → TEM, data turn demands also are increasing

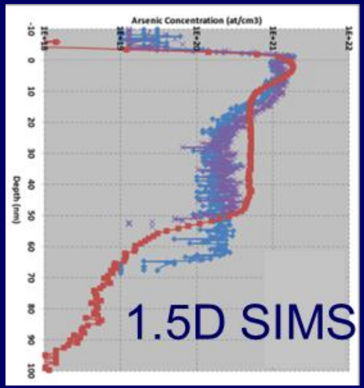
Complexity → Multifaceted Analyses

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

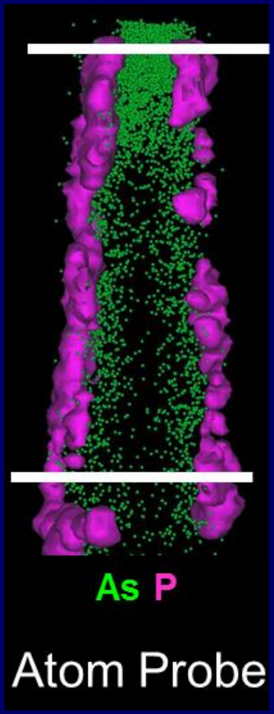


2D projection dataset

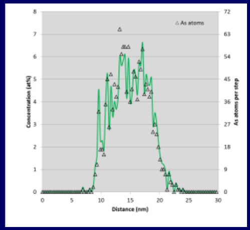


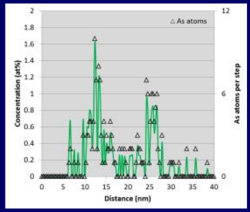


1.5D dataset on array structure



3D dataset

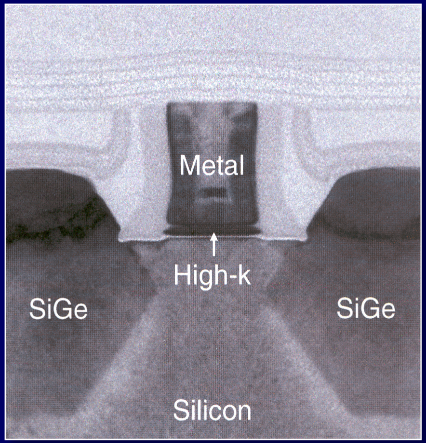


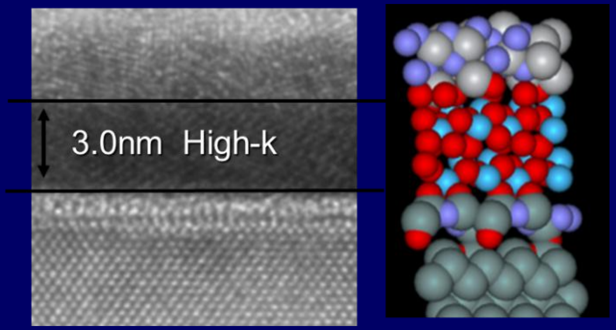


2D slices of 3D As distribution

Ultrathin Film Stack Composition

45nm Device





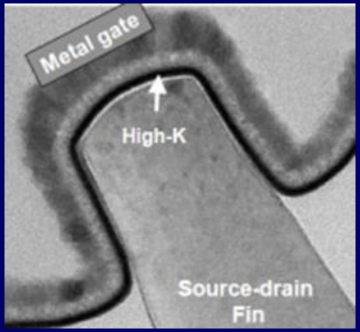
Gate stack metrology critical for determining performance and reliability metrics

- 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

Ultrathin Film- Device to Wafer Level

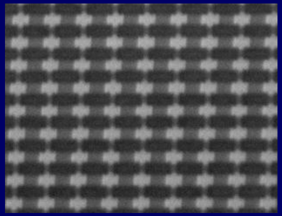
- Compositional/thickness metrology is required to drive process improvement by using data at device level, array/die level and across wafer

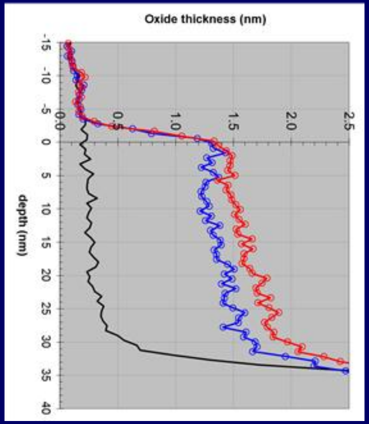
Device Level Data
EDX
EELS
STEM



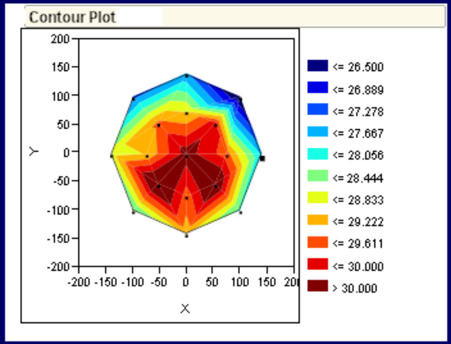
Array Level Data

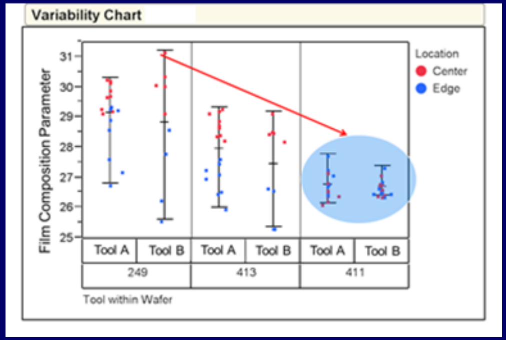
Transistor Array





Wafer Level Data

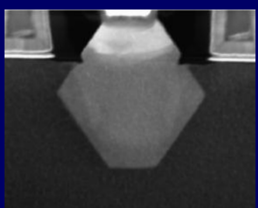




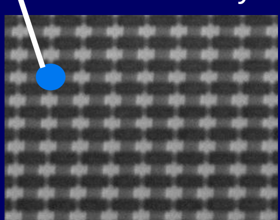
Thin Films for Strain Engineering

- 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

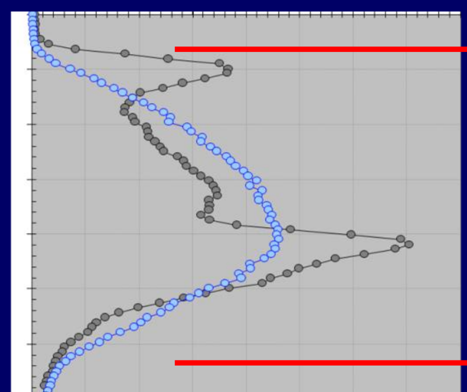
TEM



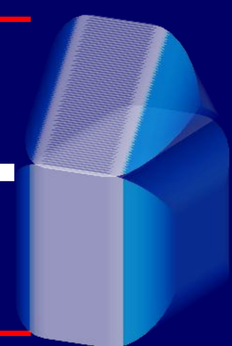
Transistor Array



1.5D SIMS



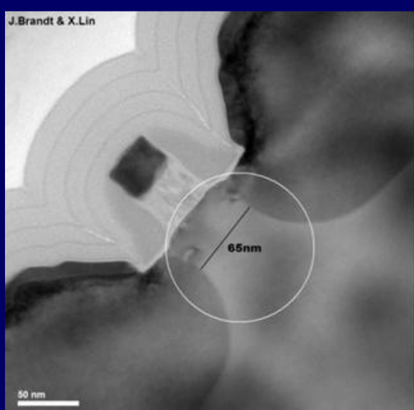
Model Structure



Extending existing capabilities with modeling provides statistical key insights to film behavior at nano-scale dimensions

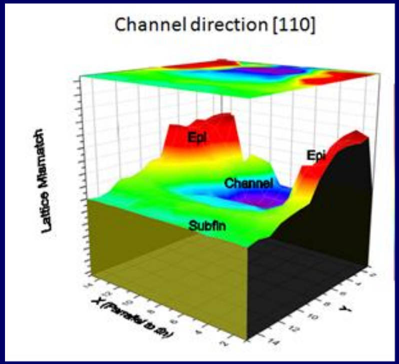
Device Level Strain Measurements

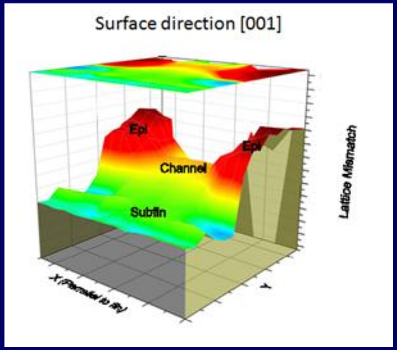
- Development of NanoED with TEM is critical for providing accurate and precise transistor-level strain data



Improvements using drift correction, descan and analysis algorithms

→ 2D strain mapping on 3D FinFET structures

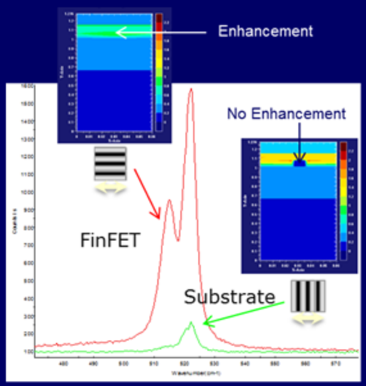




Quick Turn Monitor- Die/Wafer Level Strain Mapping

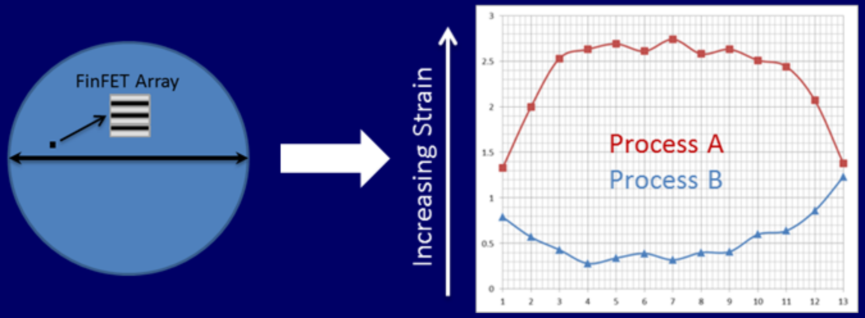
- Raman strain measurements are being developed to provide rapid, within die and within wafer strain mapping capabilities

Raman and FinFETs



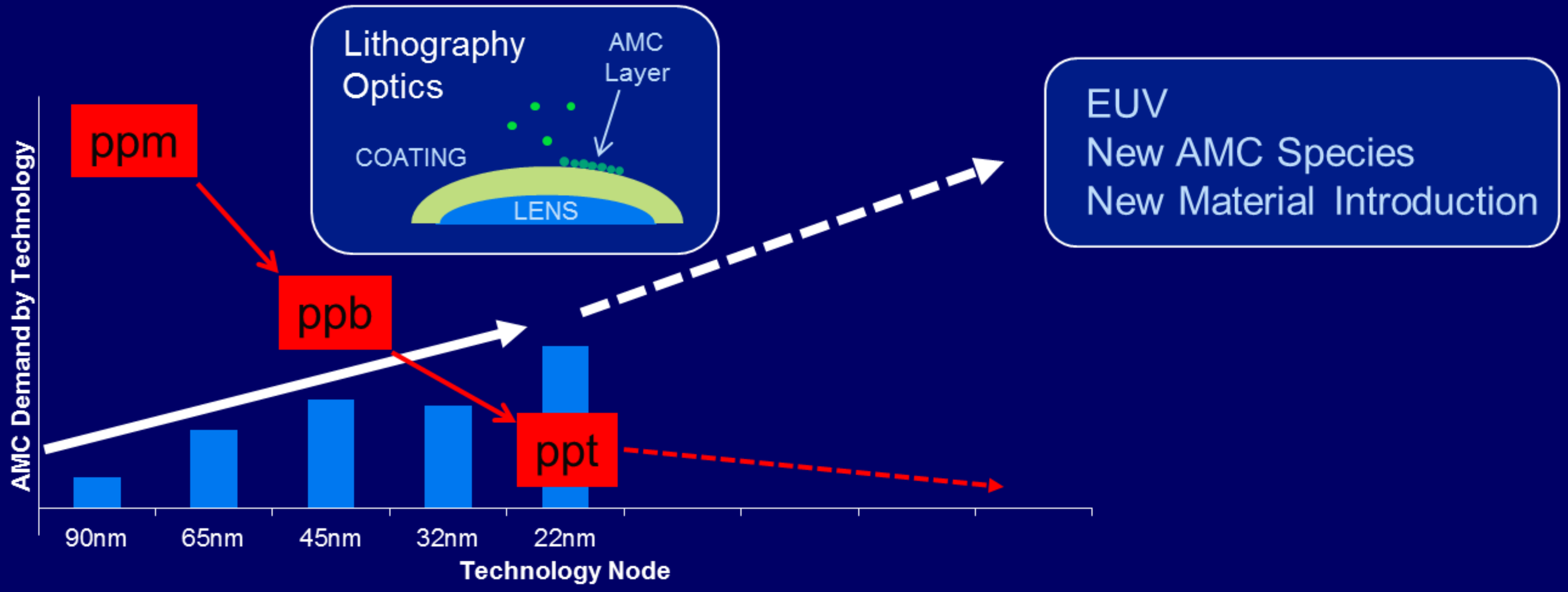
Geometrical FinFET-induced field enhancement enables transistor level measurements

Wafer Mapping Si Channel Strain



Process Sensitivities: Airborne Molecular Contamination

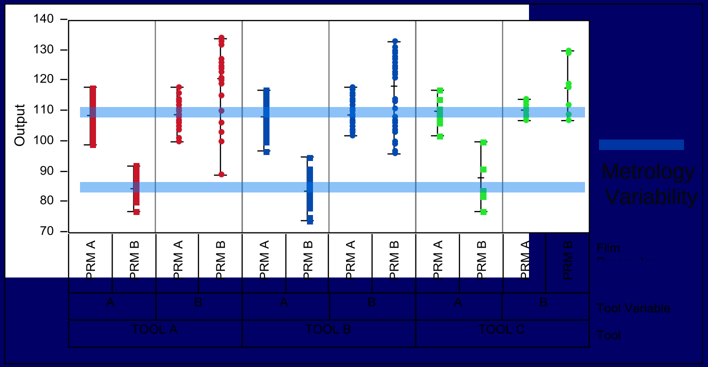
- AMC support has increased significantly and is coupled with increased process sensitivities due to lithography wavelength scaling and new material introduction

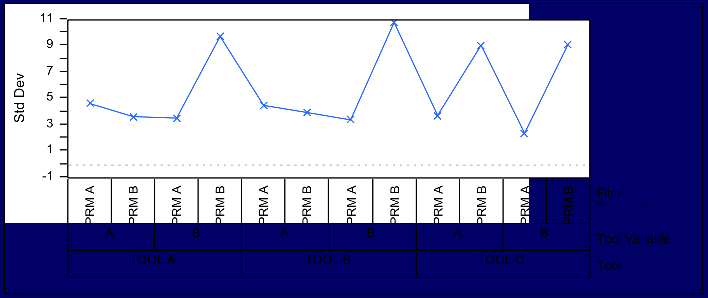


Lab-based Process Control

- 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

Ultrathin Film Composition





In this case, in-fab metrology not yet developed; in-lab process control is required

Automation for Improved Time to Data

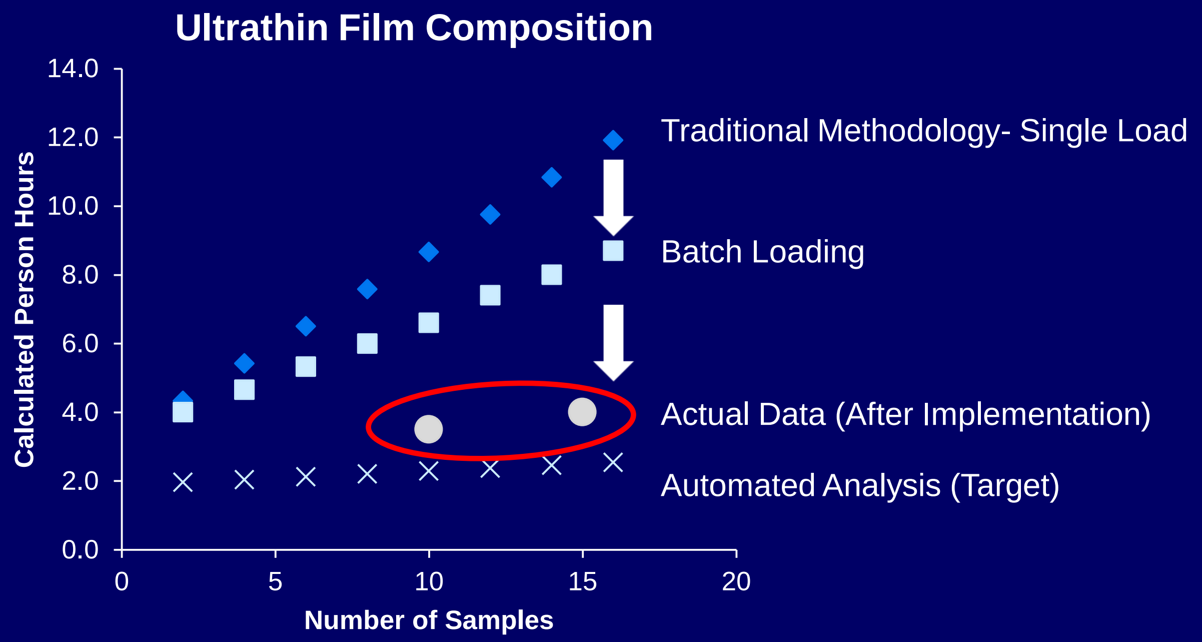
Technology options
Complexity/Parameters
Process control

⟷ Data

Time to data is critical
Cost of measurement
Minimize analytical variation

↓

AUTOMATION

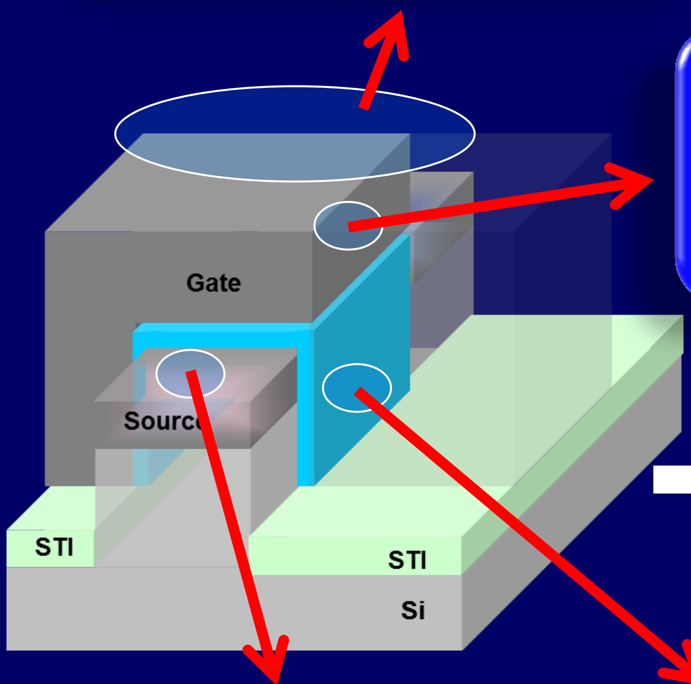


Future Metrology Requirements

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

\+ Novel interconnects
Ultra low k ILDs
Contacts
EUV
etc

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



Nanowires
TFETs
Spin-based
Other Non-CMOS

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

Alternative Channels/Substrates
- ❑ Composition, doping
- ❑ Defect levels
- ❑ Electronic Properties

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

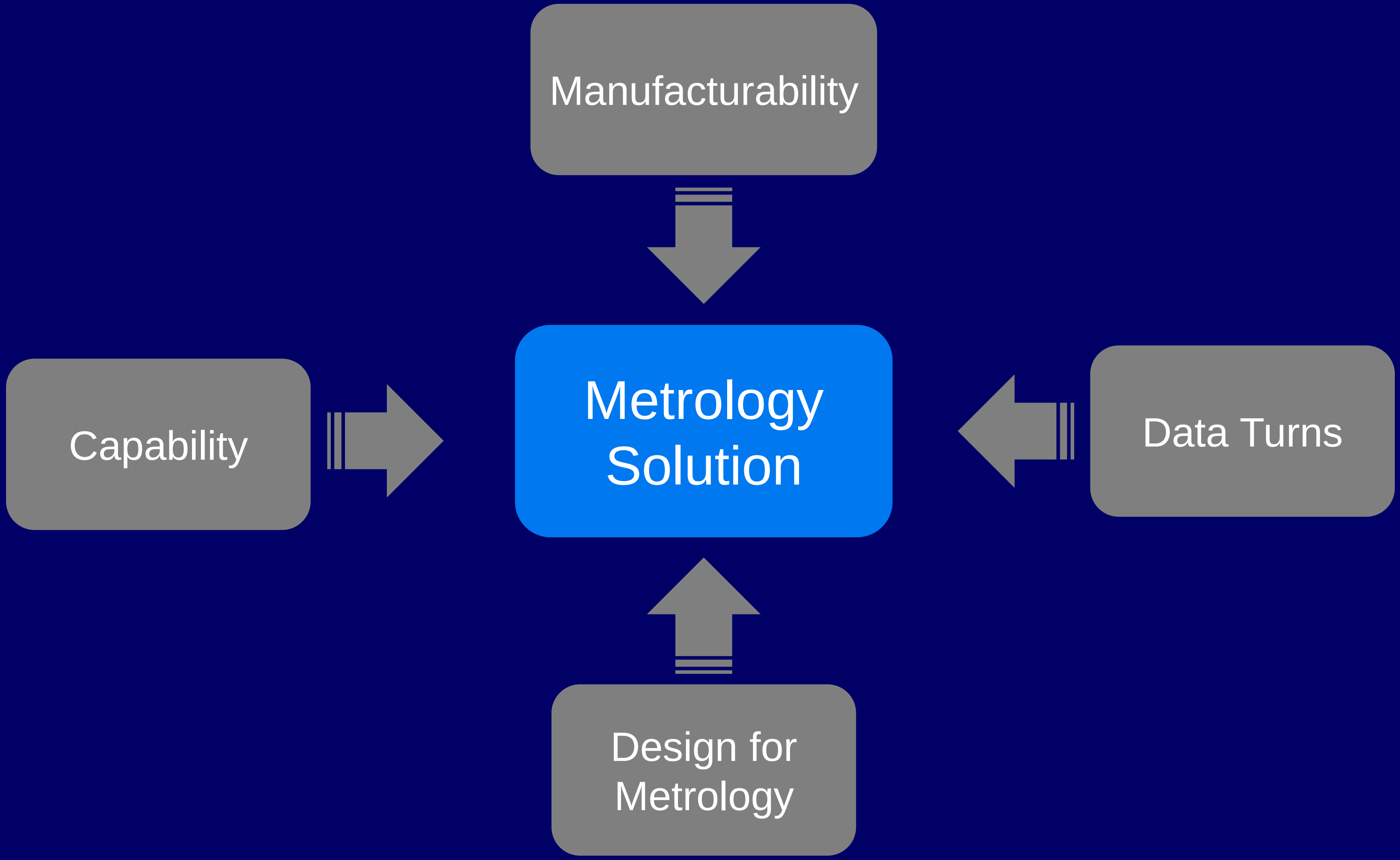
Critical Metrology Requirements

- 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 <u>meeting diverse technology and aggressive data turn requirements</u> for development/manufacturing support; through rapid, highly parallel automated measurements.

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 $\rightarrow$ 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


Manufacturability
Capability
Metrology Solution
Data Turns
Design for Metrology

Acknowledgements

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