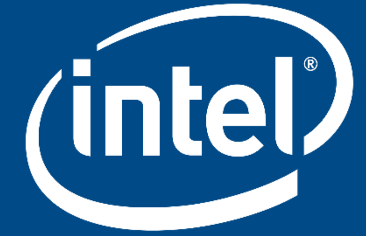
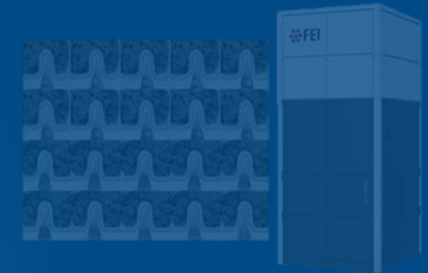
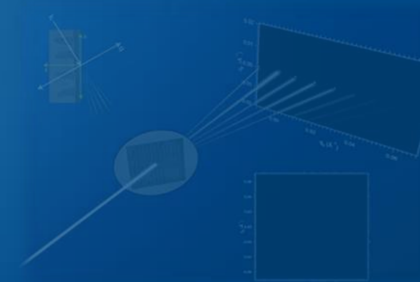


Opportunities and Challenges for Lab-based Hybrid Metrology for Emerging Technologies

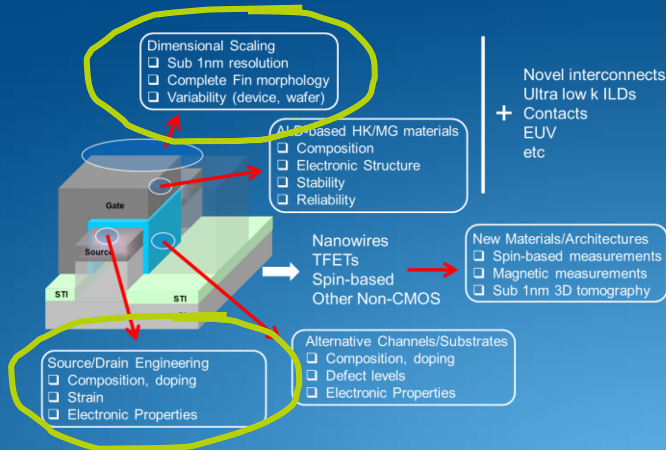


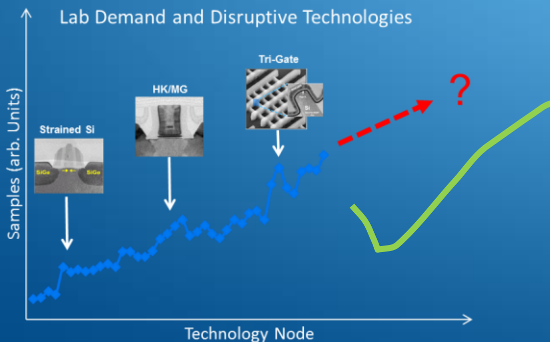


Markus Kuhn, Ying Zhou and Kevin Johnson

Intel Corporation

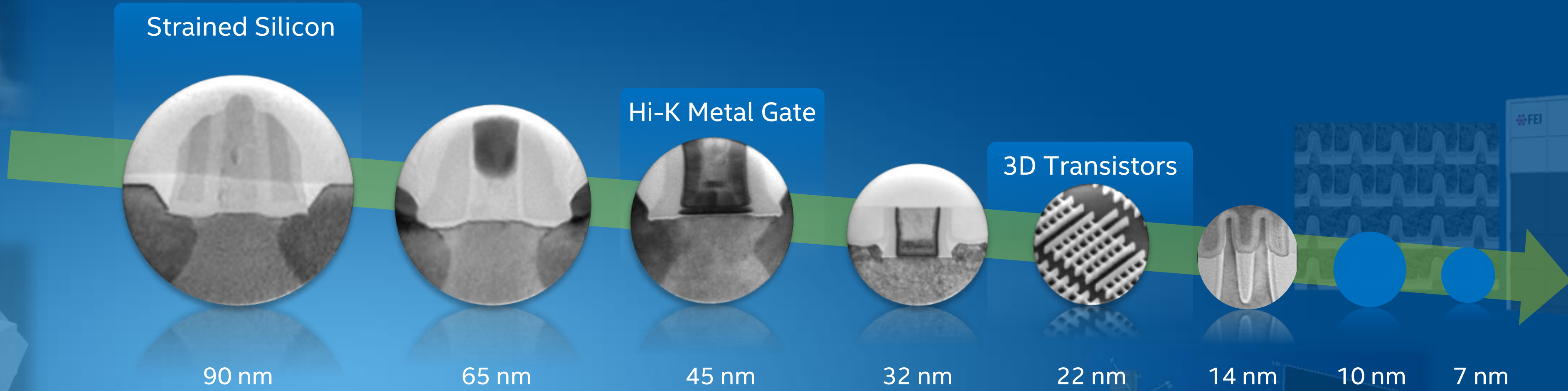
- Materials Characterization and Metrology Challenges- update
  - → Emerging nano- and atomic-scale characterization methods
  - → The business of metrology → velocity and “smart” or “hybrid” metrology

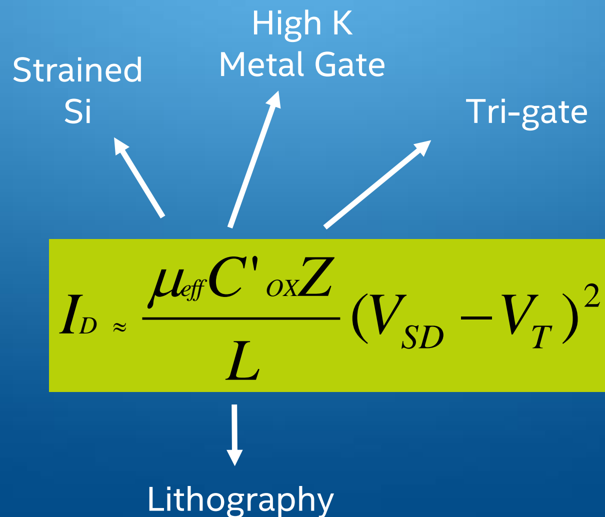


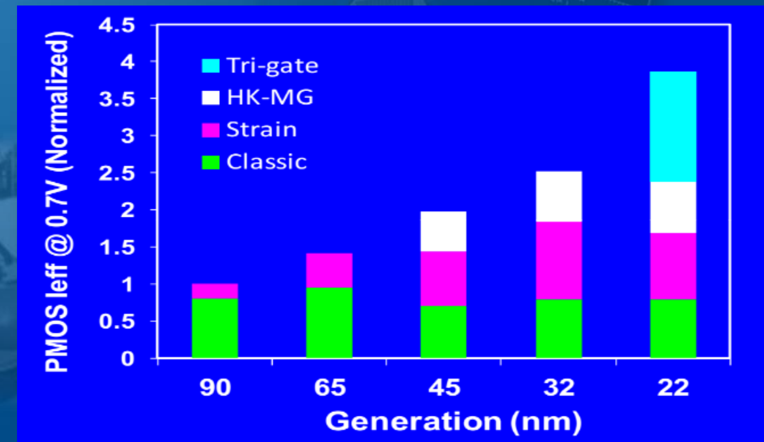


M. Kuhn FCMN 2013

Performance is increasingly driven through novel materials and architectures…

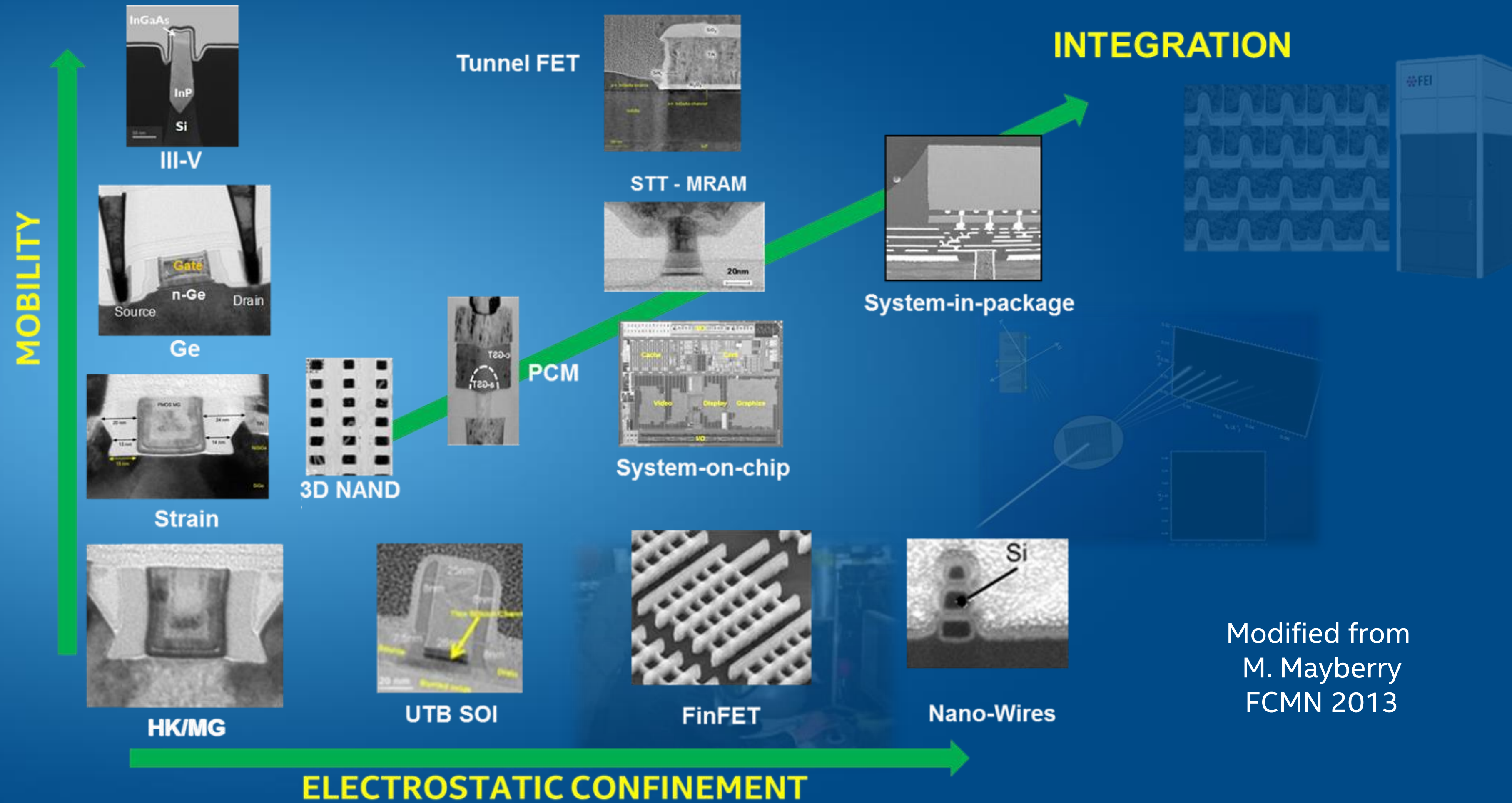






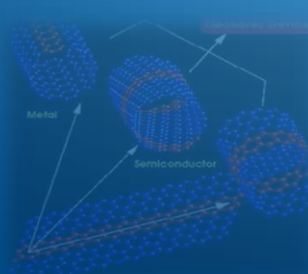
Kuhn et al.
ECS 2010
IEDM 2012

Future has an abundance of possibilities but increasingly smaller and more complex…

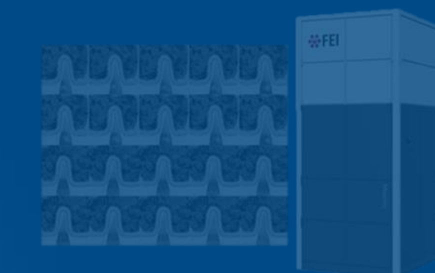


Modified from
M. Mayberry
FCMN 2013

intel



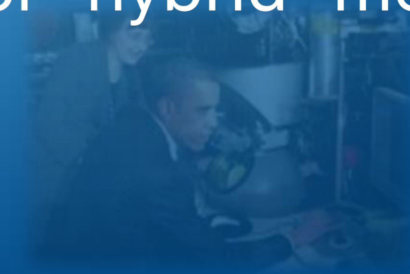
Outline



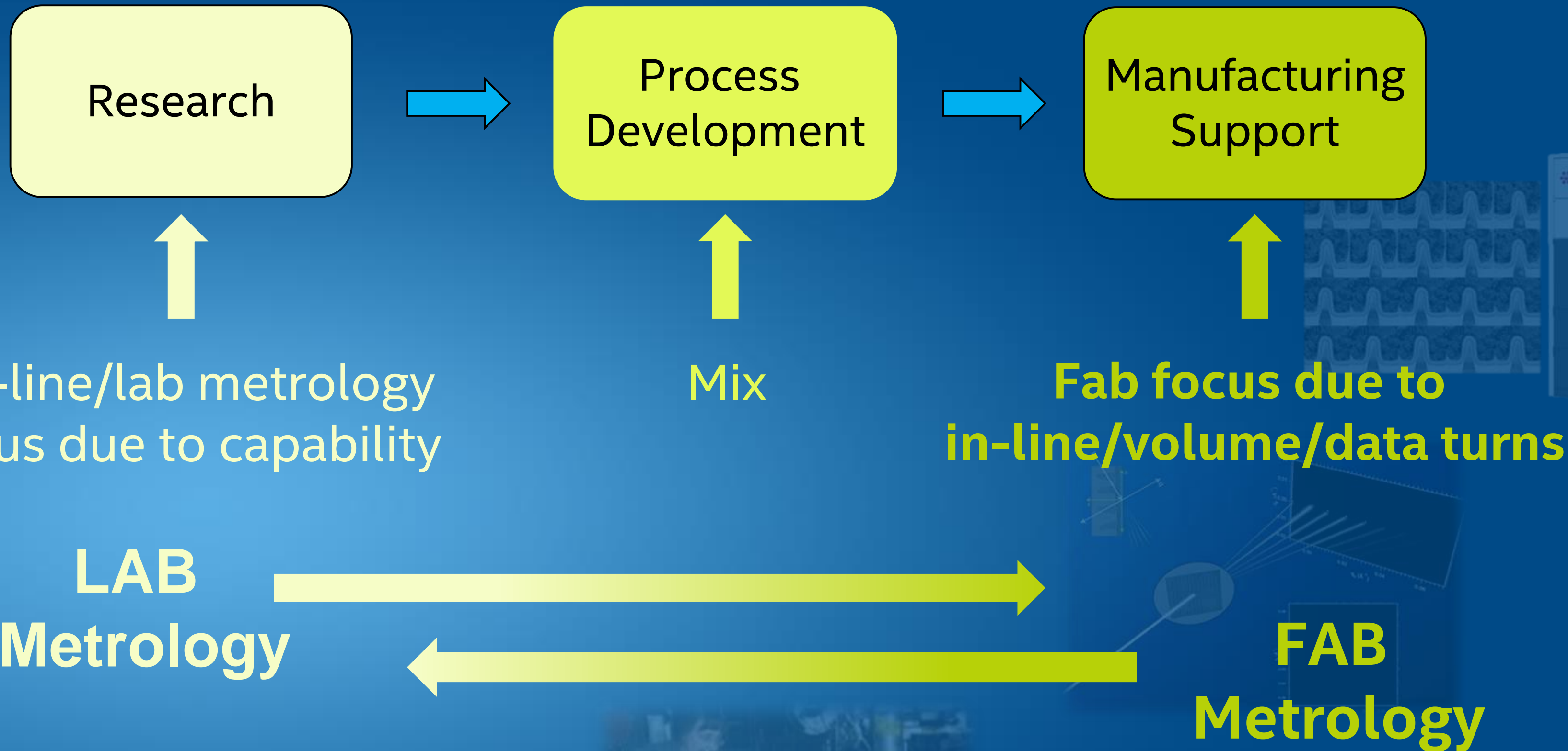
- Materials Characterization and Metrology Challenges-update

→ Emerging nano- and atomic-scale characterization methods

→ The business of metrology → velocity and "smart" or "hybrid" metrology

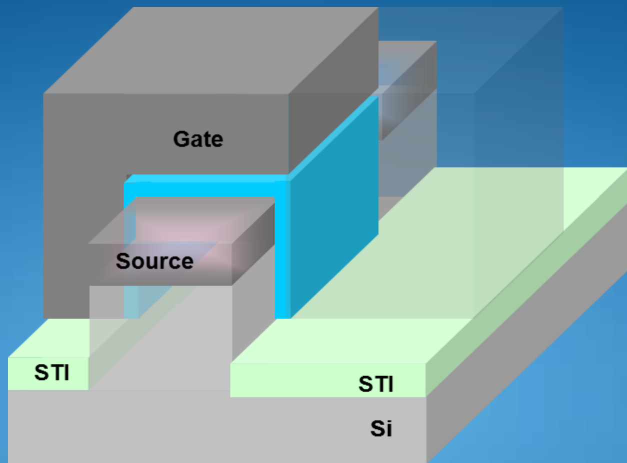


Metrology Support Landscape



Lab/Fab distinctions are becoming blurred…

Characterization Needs and Gaps?



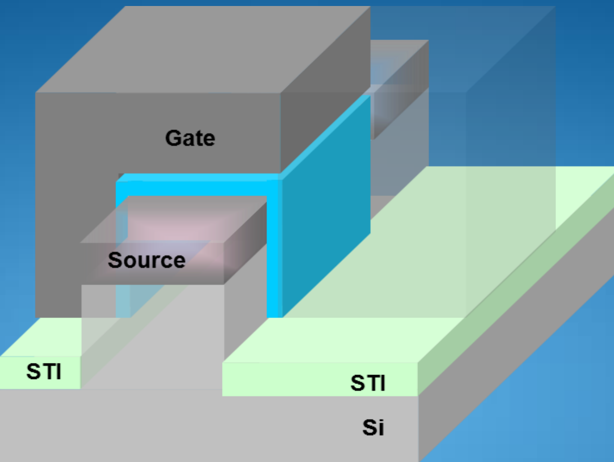
- Atomic-scale full 3D dimensional and compositional characterization
- Critical and novel properties → strain, electronic, magnetic, spin, thermal mechanical…

+ Device → array → wafer

+ Rapid time to data → even for characterization

+ “Hybrid” metrology → holistic

Characterization Needs and Gaps?



- Atomic-scale full 3D dimensional and compositional characterization

Through the development of Transmission Electron Microscopy and Atom Probe Tomography methods

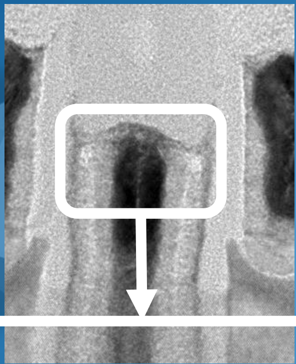
+ Device → array → wafer

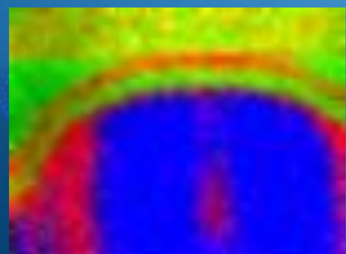
+ Rapid time to data → even for characterization

+ “Hybrid” metrology → holistic

Atomic-scale 3D Characterization- Transmission Electron Microscopy

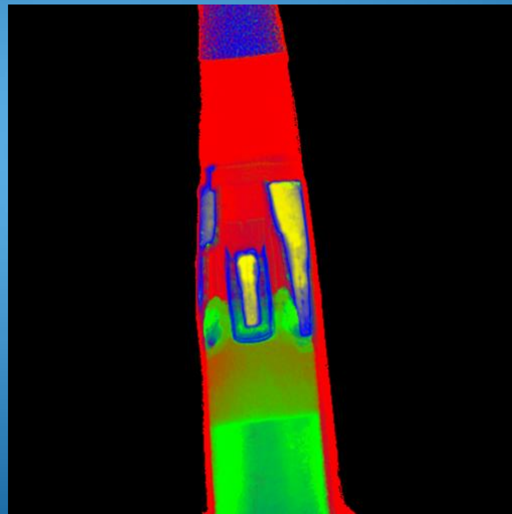
2D TEM Projection





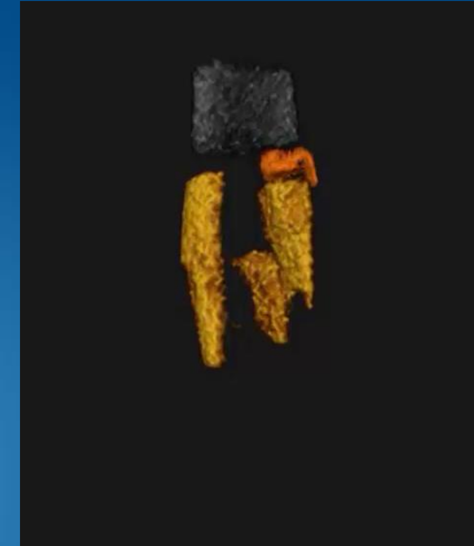
2D TEM EELS

Multi-component Tomography

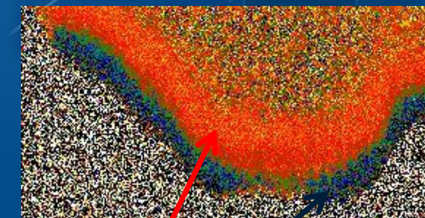


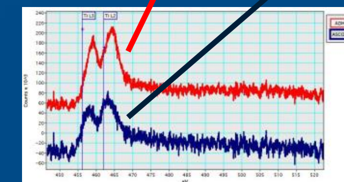
Jiong Zhang, Intel and Andrew Herzing, NIST

EELS Elemental Tomography



EELS Chemical State Tomography





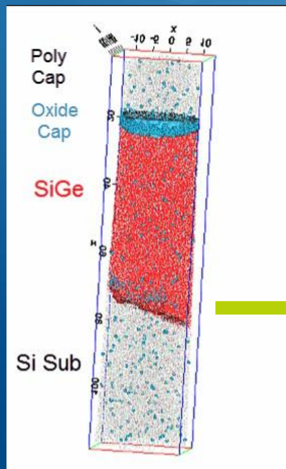
In Progress

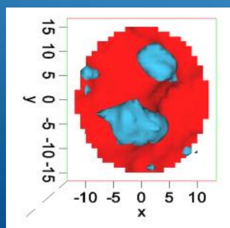
Atomic-scale 3D Characterization- Atom Probe Tomography

Transistor Strain Engineering

TEM

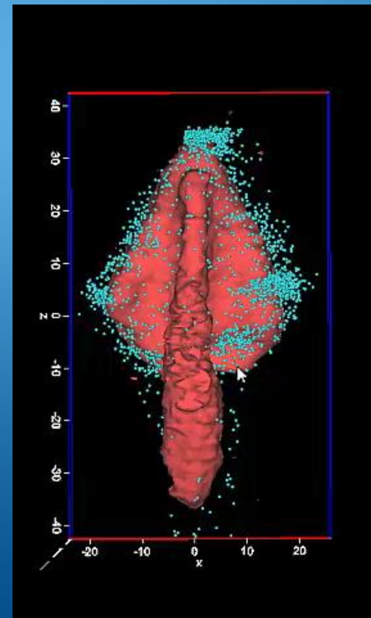
APT: interface contamination





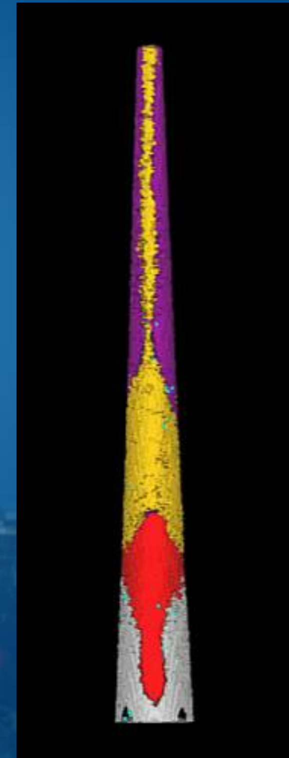
With Karen Henry, Intel

APT: doping

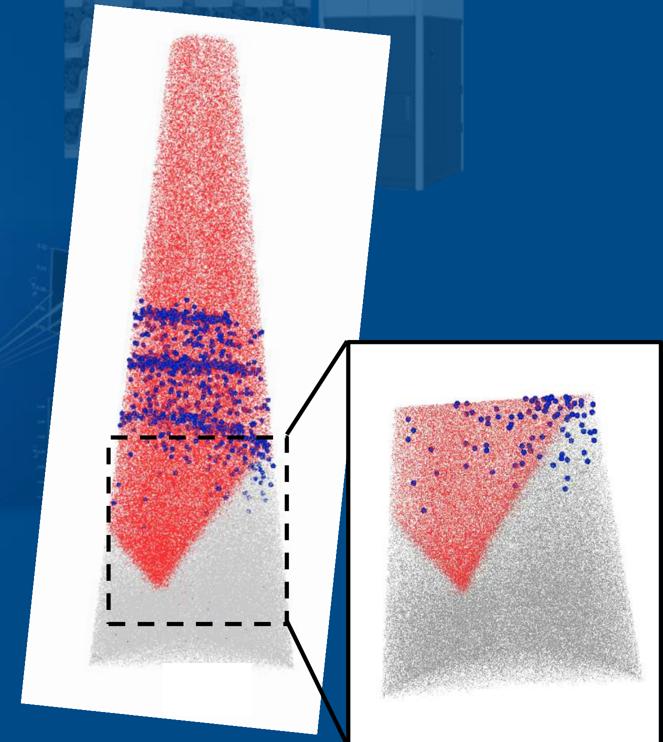


High Mobility Channels

APT: III-V



APT: doping/contamination



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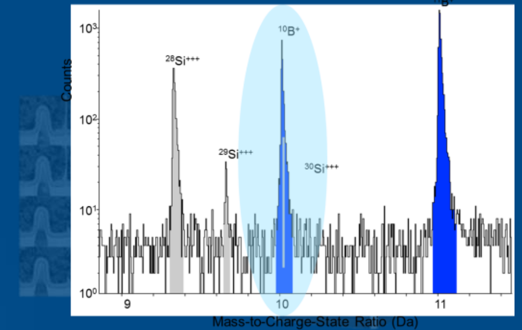
Atomic-scale 3D Characterization- Atom Probe Tomography

Hardware

- Mass interferences limit compositional accuracy
- Detection efficiency (~80%) limits sensitivity and true atomic-scale tomography

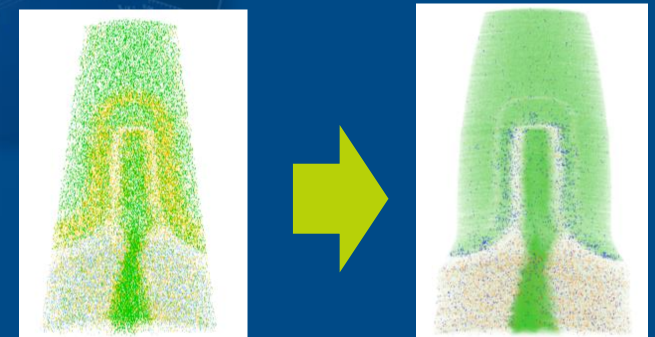
+ New detector technology needed



Software

- Trajectory aberrations limit spatial resolution

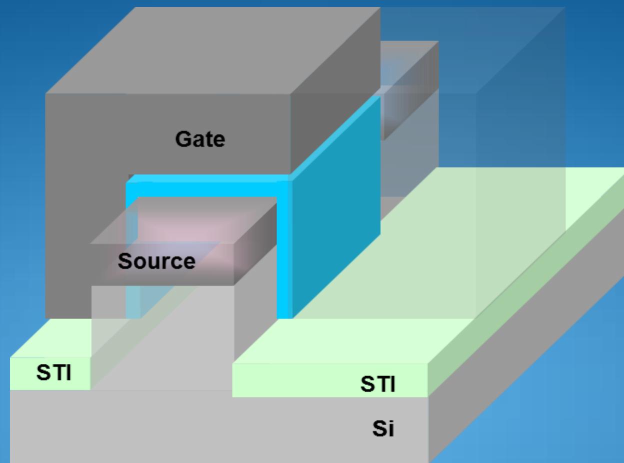
+ New reconstruction protocols
+ Simulate specimen evolution
+ Incorporate correlative microscopy



F. Vurpillot, U. of Rouen

intel

Characterization Needs and Gaps?



- Atomic-scale full 3D dimensional and compositional characterization
- Critical and novel properties → **strain**, electronic, magnetic, spin, thermal mechanical...

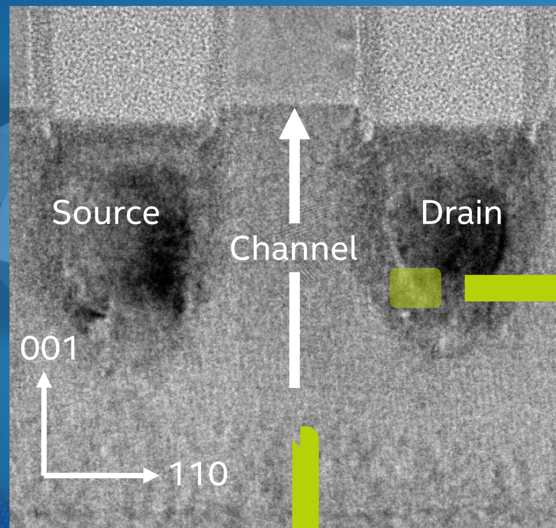
+ Device → array → wafer

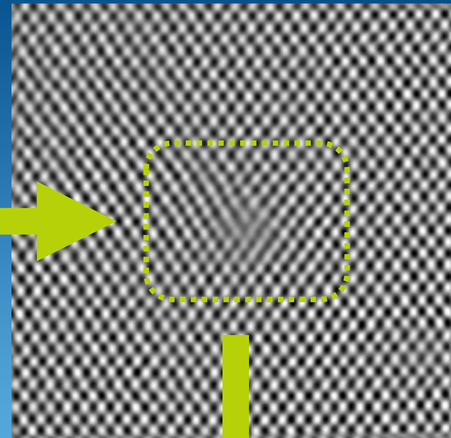
+ Rapid time to data → even for characterization

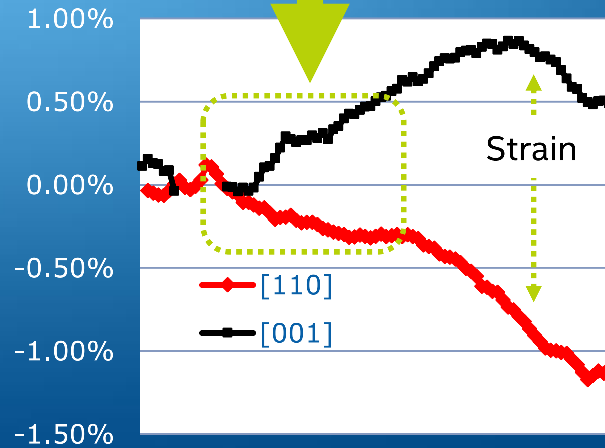
+ "Hybrid" metrology → holistic

Device Strain Characterization- NanoED

Line Scan

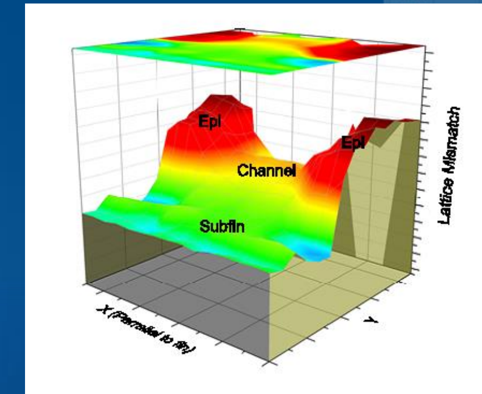






Mapping

[001]



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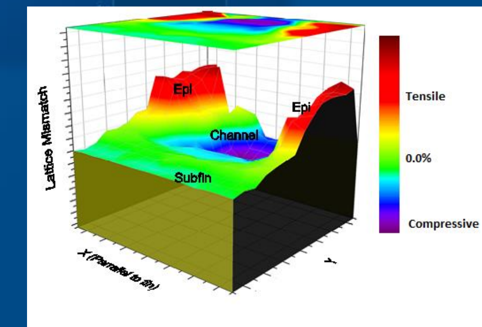
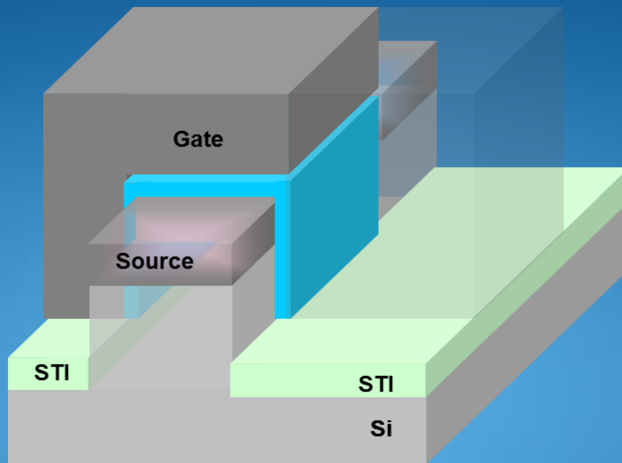


Characterization Needs and Gaps?



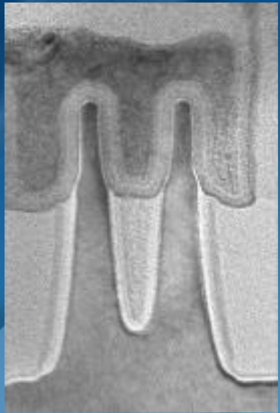
- Atomic-scale full 3D dimensional and compositional characterization
- Critical and novel properties → strain, electronic, magnetic, spin, thermal mechanical…

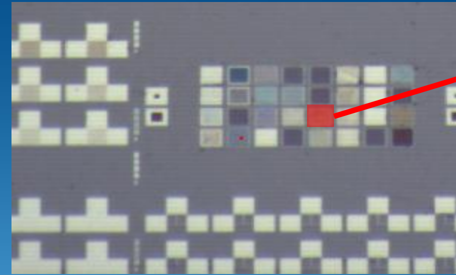
+ Device → array → wafer (eg. strain and doping)

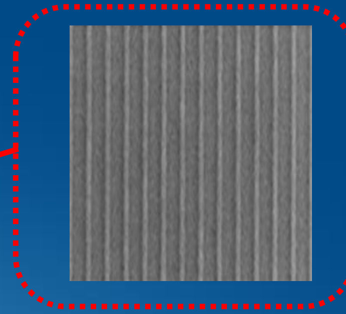
+ Rapid time to data → even for characterization

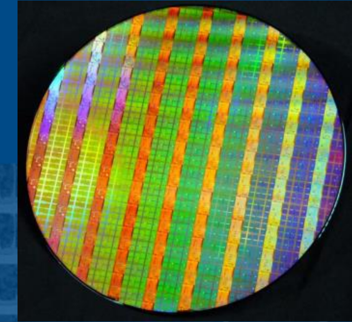
+ “Hybrid” metrology → holistic

Strain Measurements- design for metrology

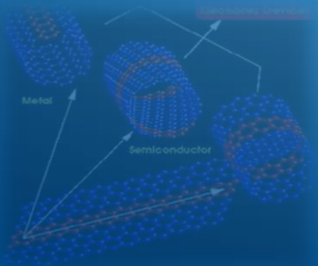




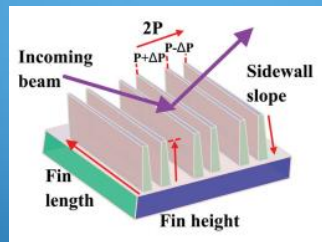


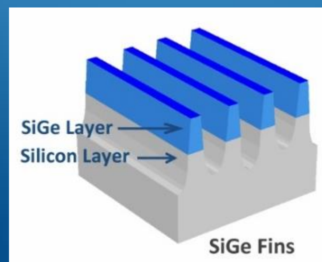


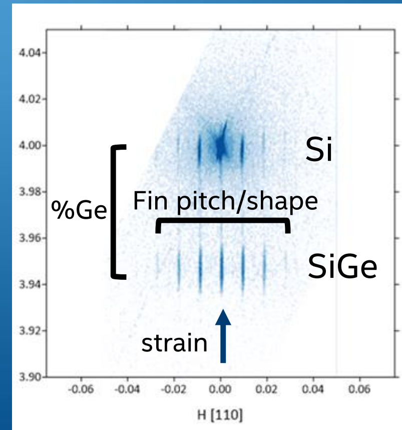
TEM NanoED



uHRXRD

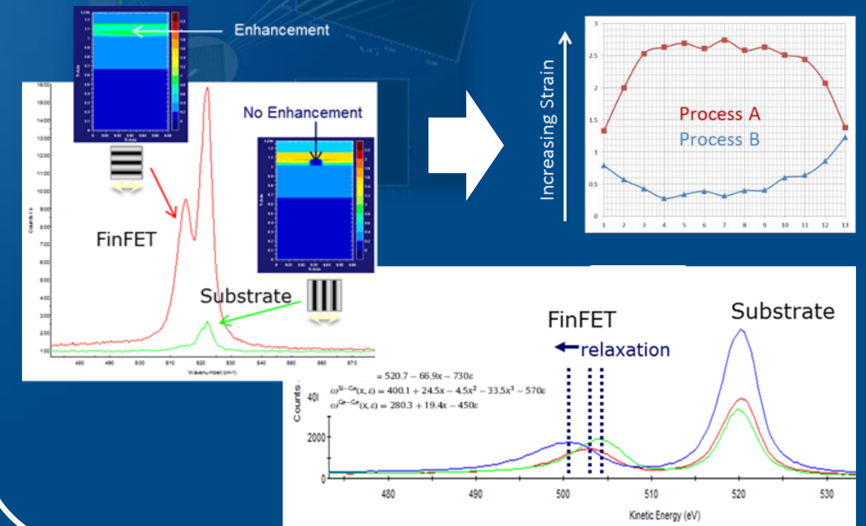






Matthew Wormington, Bruker

uRaman



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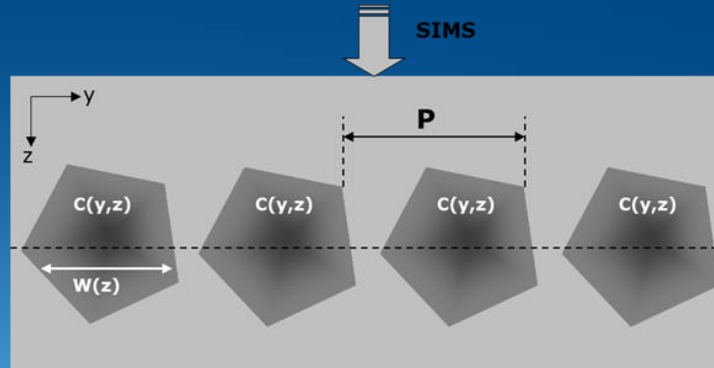
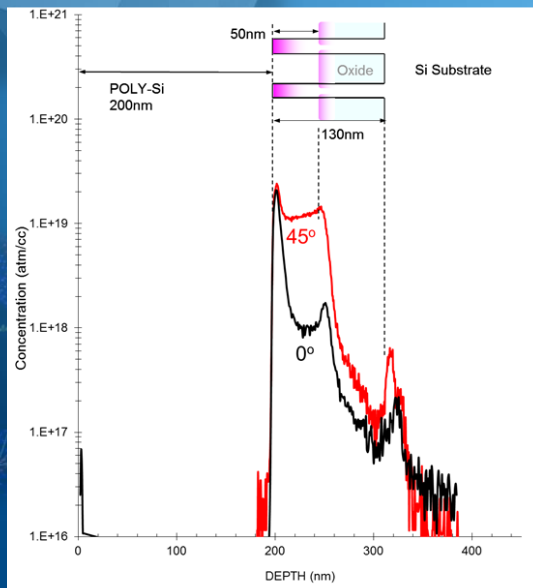
SIMS Dopant Measurements- design for metrology

Standard 1.5D SIMS

$$I \sim c(z)\frac{w(z)}{P}$$



Repeated nanostructure of known shape required

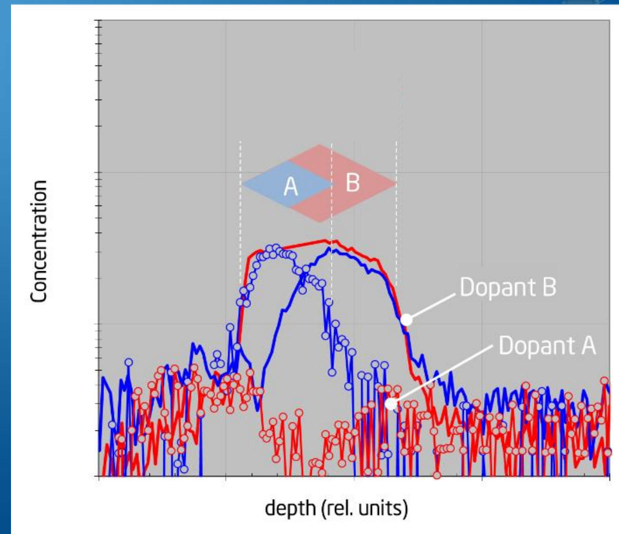


Wilfried Vandervorst, imec
Andre Budrevich, Intel

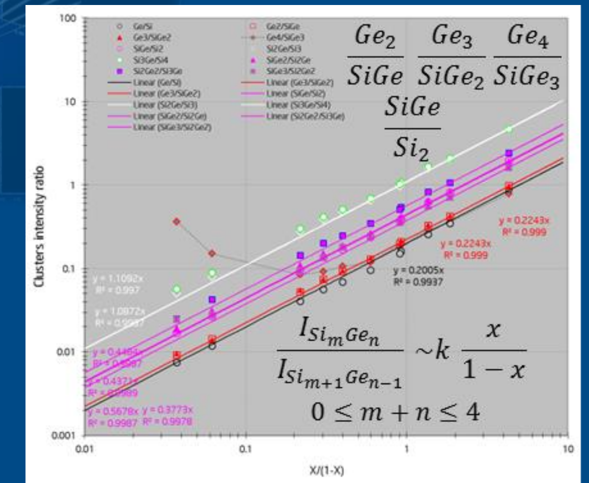
Self-focusing or cluster-confined volume analysis

$$\frac{I_m}{I_n} \sim \frac{c(z)^m w(z)}{c(z)^n w(z)} = c(z)^{m-n}$$

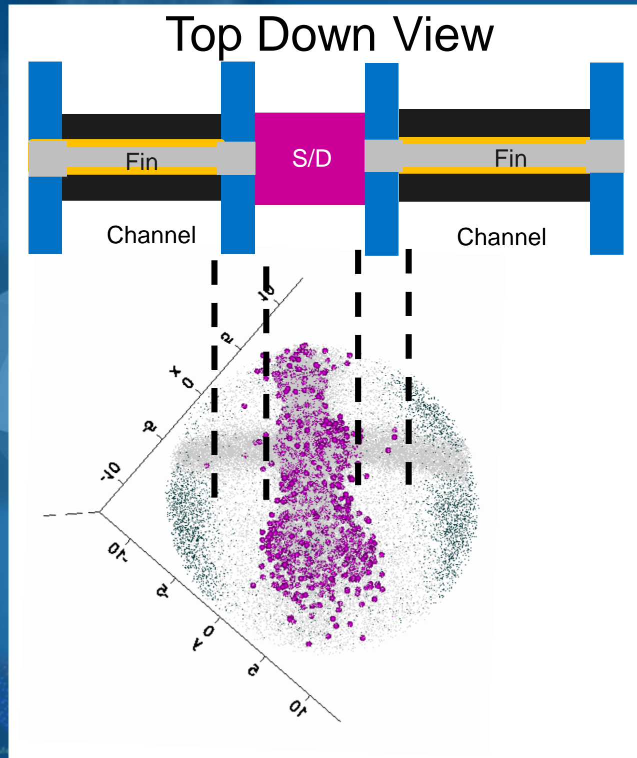
Repeated nanostructure or known shape not required

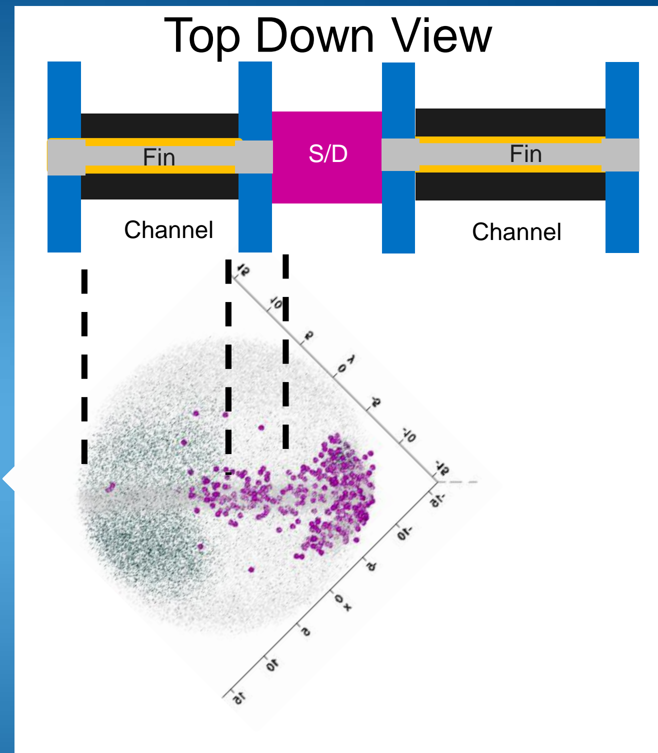


Calibration curves



APT Dopant Measurements- design for metrology





- APT provides site-specific 3D compositional analysis of electrically tested devices
- Complementary to DSIMS quantification on device array

DSIMS provides statistics allowing for process targeting, APT allows for device-level electrical understanding

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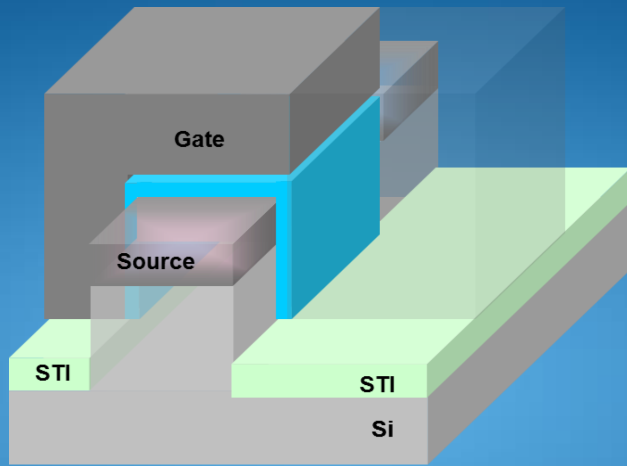
Characterization Needs and Gaps?



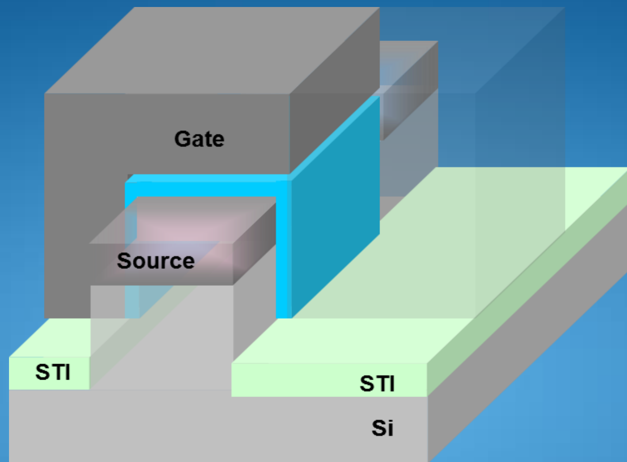
- Atomic-scale full 3D dimensional and compositional characterization
- Critical and novel properties → strain, electronic, magnetic, spin, thermal mechanical…

+ Device → array → wafer

+ Rapid time to data → even for characterization

+ “Hybrid” metrology → holistic

Characterization Needs and Gaps?



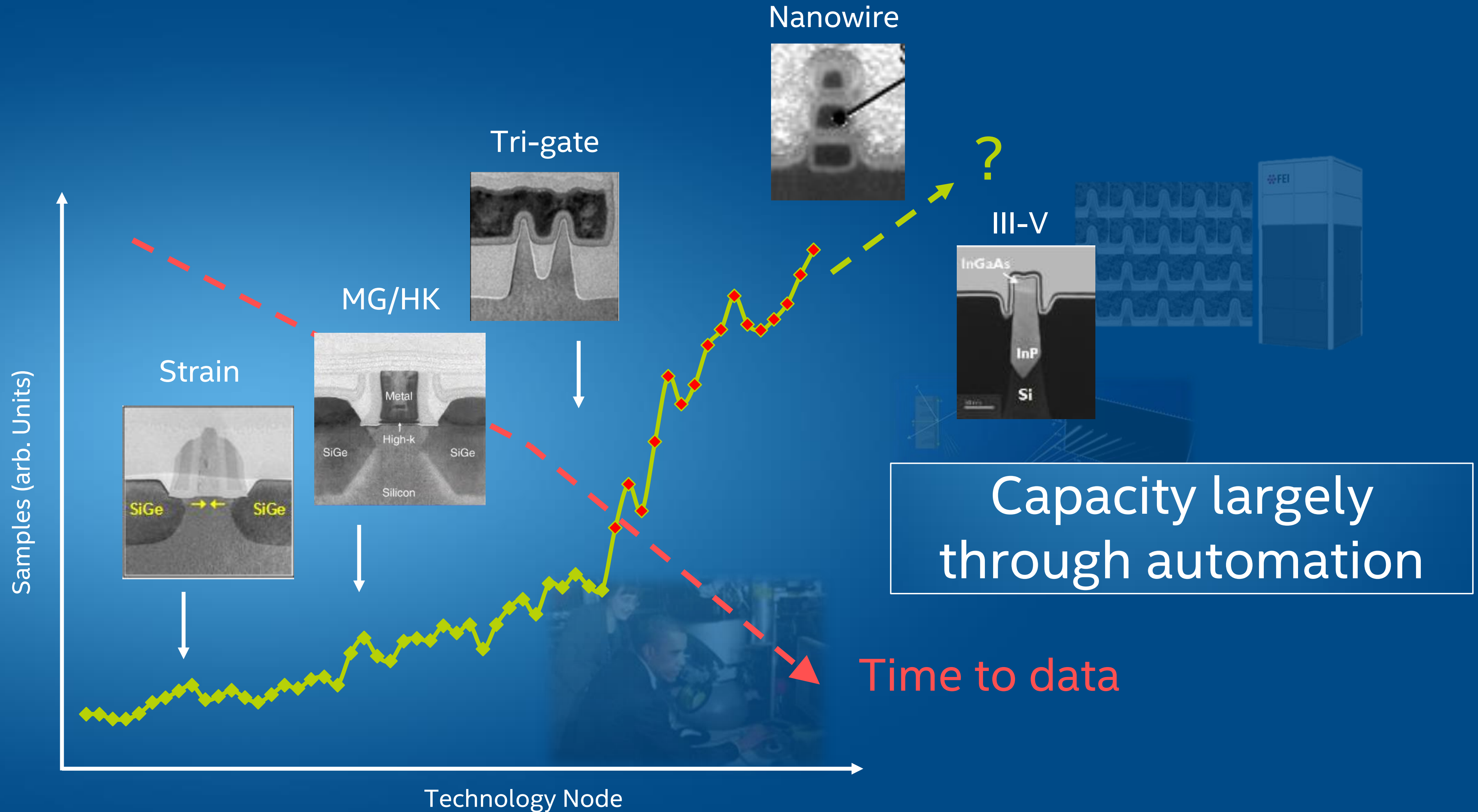
The Business of Metrology/Characterization: Velocity and "Hybrid" Metrology

+ Device → array → wafer

+ Rapid time to data → even for characterization

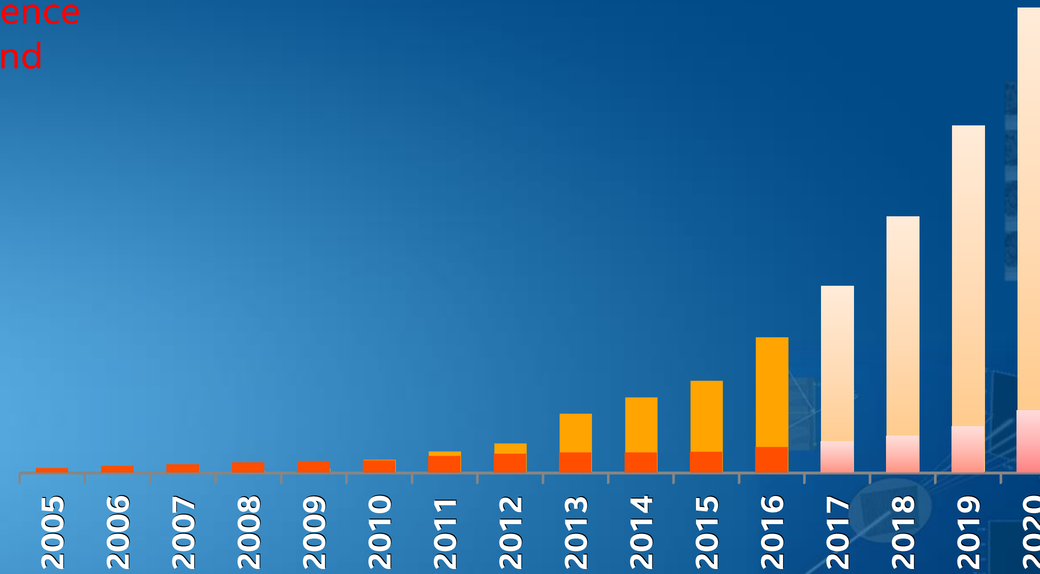
+ "Hybrid" metrology → holistic

Disruptive technologies driving lab demand



Capacity largely through automation

Dimensional metrology lab demand



Strain   MG/HK   Tri-gate

TEM demand explodes to meet 3D transistor and pitch division challenges

Automated TEM Flow = Prep tools + Imaging Tools + Metrology Software

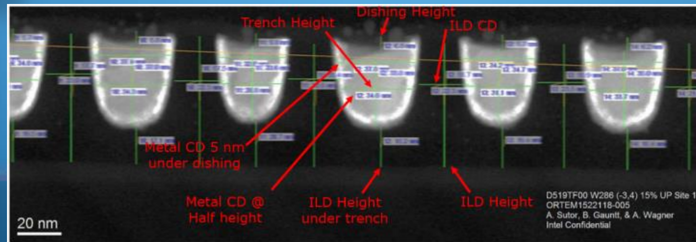
FAB

Exsolve Auto-Prep

TEMLink Liftout

Metrios Auto-Image/Auto-EDX

Off-line Workstation Auto-Metrology



High volume, fast, reproducible

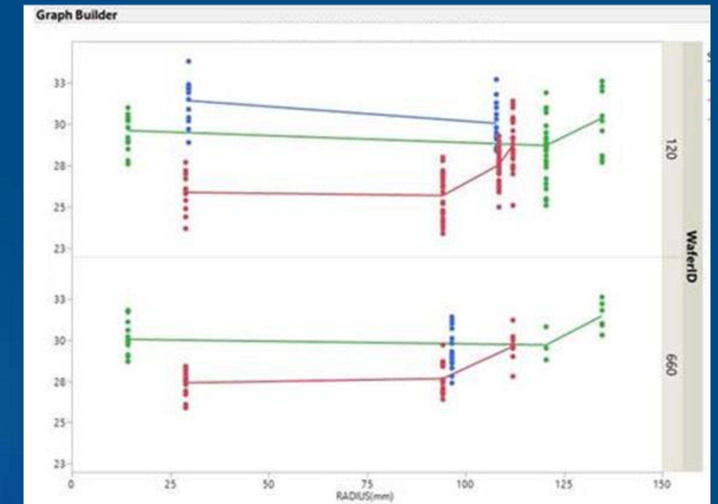
Dimensional metrology lab demand- AutoTEM

- AutoTEM flow has progressed significantly
  - hardware/automation for prep and imaging
  - autometrology remains a challenge

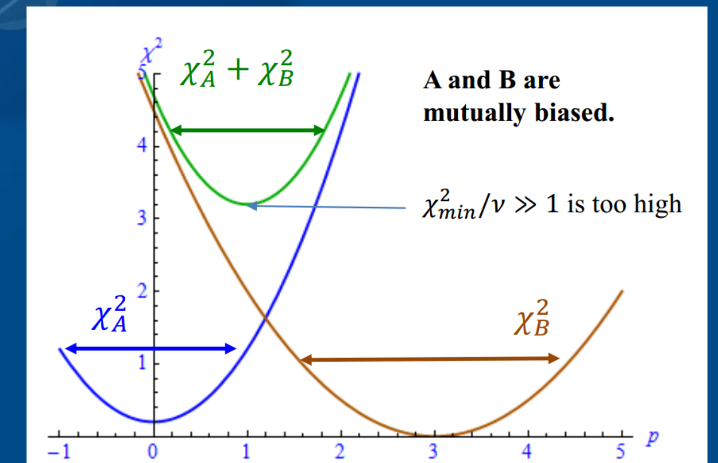
- Velocity enables more data, including some statistics within die, across wafer

- For well-defined use case, can be used in hybrid approach,
  → enabling in-fab high TPT measurements for process targeting and monitoring
  → data fusion required

AutoTEM: In-fab Process Evaluation



J. Villarrubia: SPIE Adv. Lithography 2016



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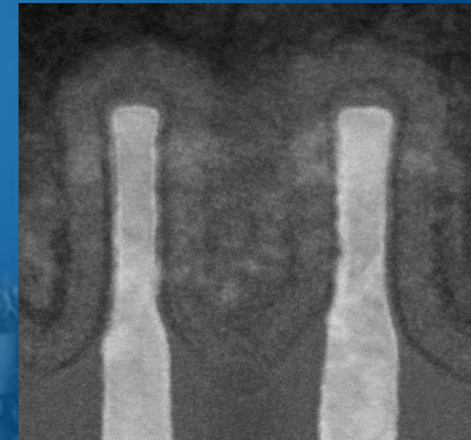
Dimensional metrology lab demand- AutoTEM

- Challenges include flexibility in handling of non pre-defined sample types/data into flow
- Most significant for process development use cases

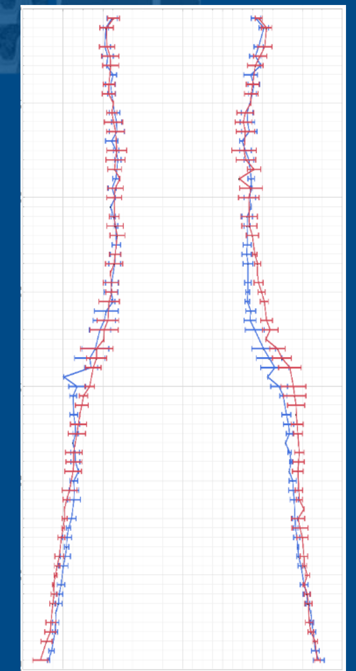
Strain, EDS, EELS, etc

- However, unique high-volume yet localized data opens up new avenues for process understanding and control

AutoTEM: Local Variation



Automated Profile Analysis

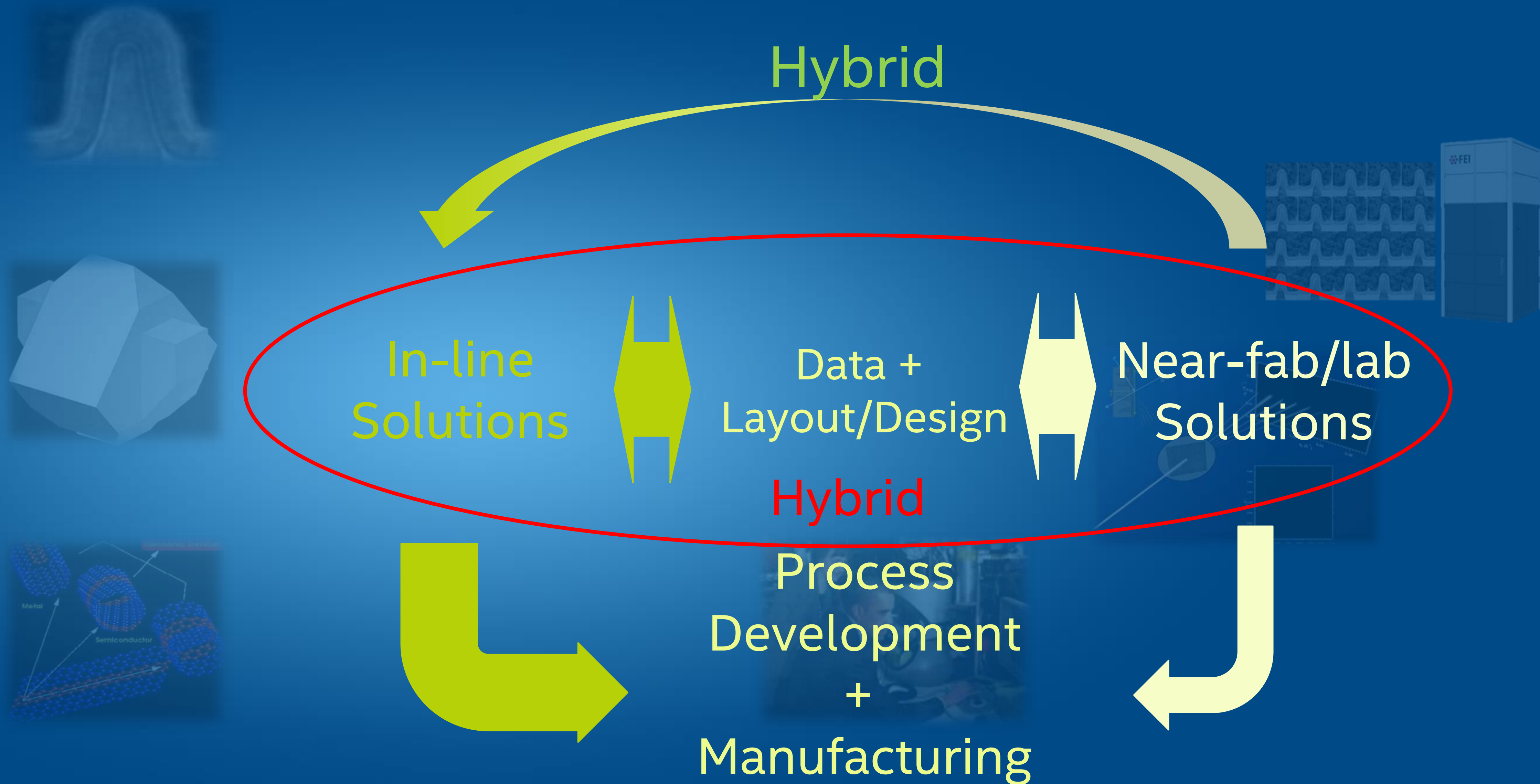


“Smart” Metrology requirements?

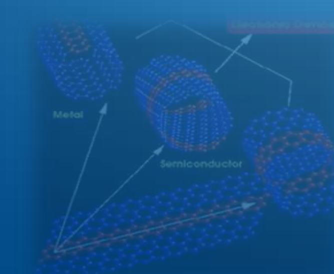
- Development of hybrid metrologies
- Transfer of near-fab/lab technologies and/or data to the fab
- Integration of manufacturing-worthy and cost effective near-fab capabilities
- Product/layout awareness

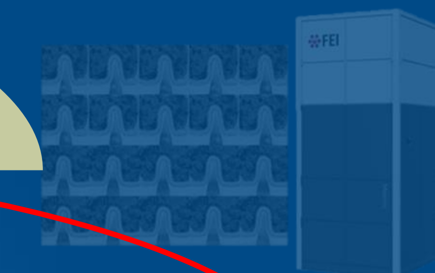
A manufacturing flow that seamlessly incorporates all of these elements

What can “Smart” Metrology look like?



3D FinFET dimensional metrology?





CDSAXS, AFM, SEM, uHRXRD

OCD + ?

Data +
Layout/Design

TEM

Hybrid

Process
Development
+
Manufacturing

Summary

- Continuing challenges for lab-based metrology to provide needed capabilities for emerging technologies
- Velocity, time to data matter → automation is key
- Hybrid metrologies need to be developed → can incorporate lab/near-fab capabilities

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Thank You!