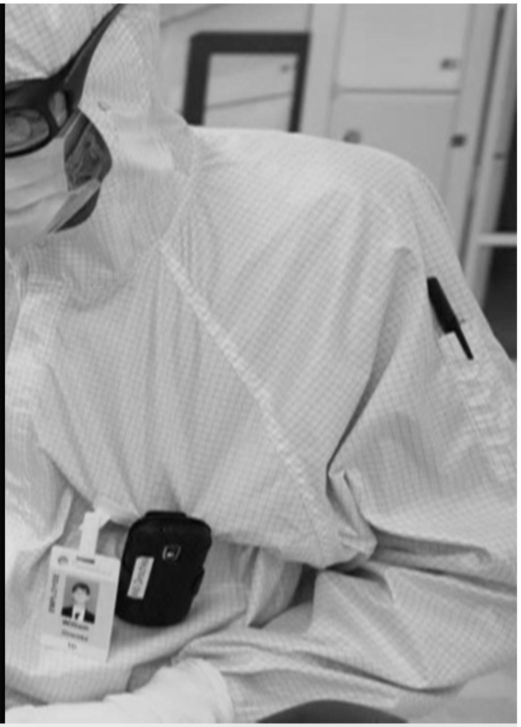


CMOS characterization/metrology challenges for the lab to the fab

Paul van der Heide, Michael Gribelyuk, Jeremy Russell

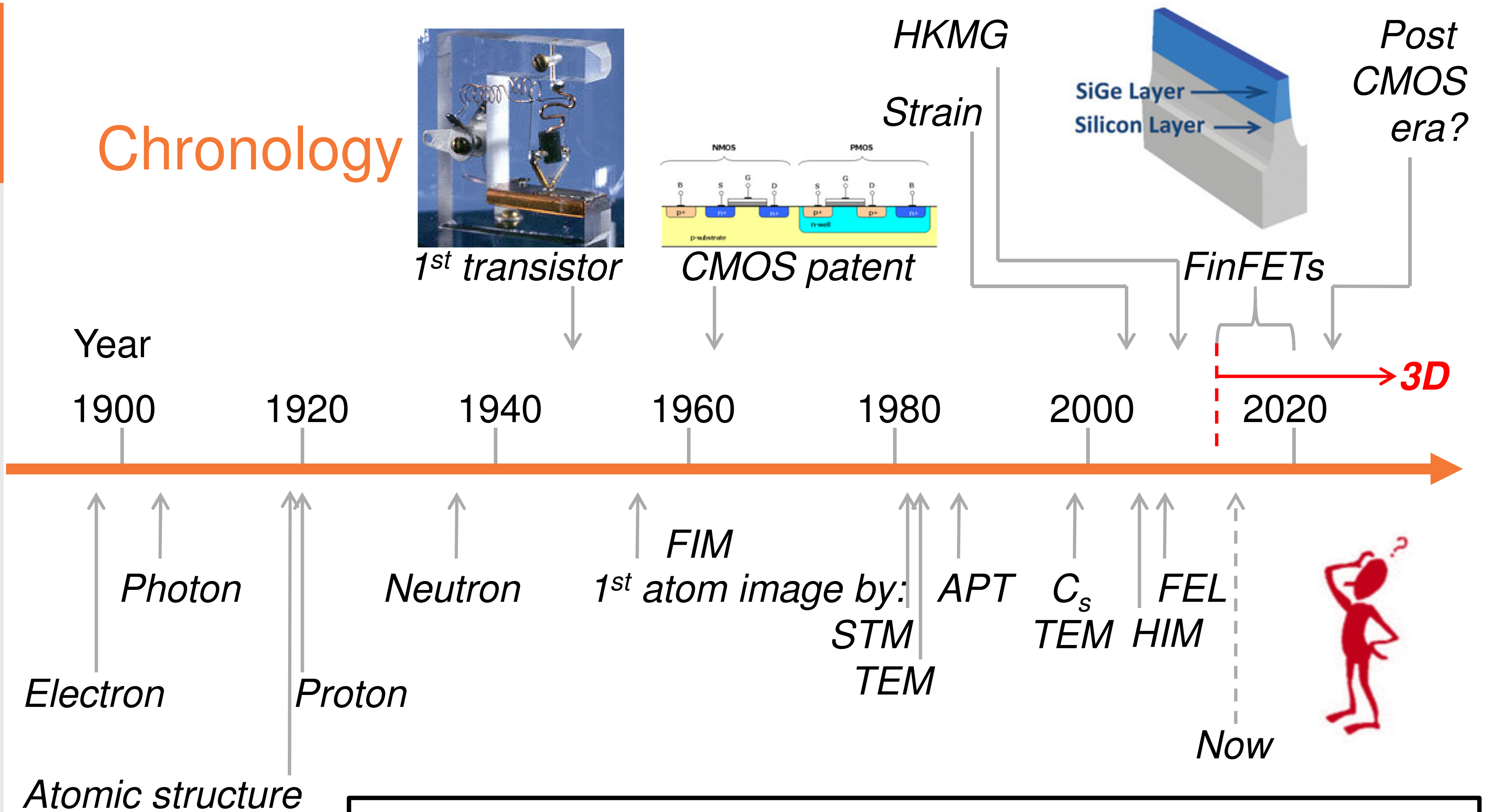
GLOBALFOUNDRIES®

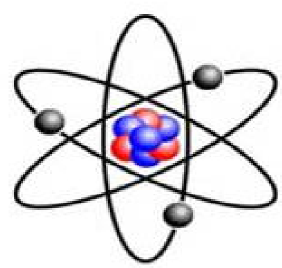
Agenda

1. Where we are and where we need to go
   - i. Individual approaches
   - ii. Hybrid approaches, etc.
2. Recognized issues/possible solutions
3. Summary/conclusions

Can we see into the future: No
Can we make educated guesses: We can attempt to

Chronology



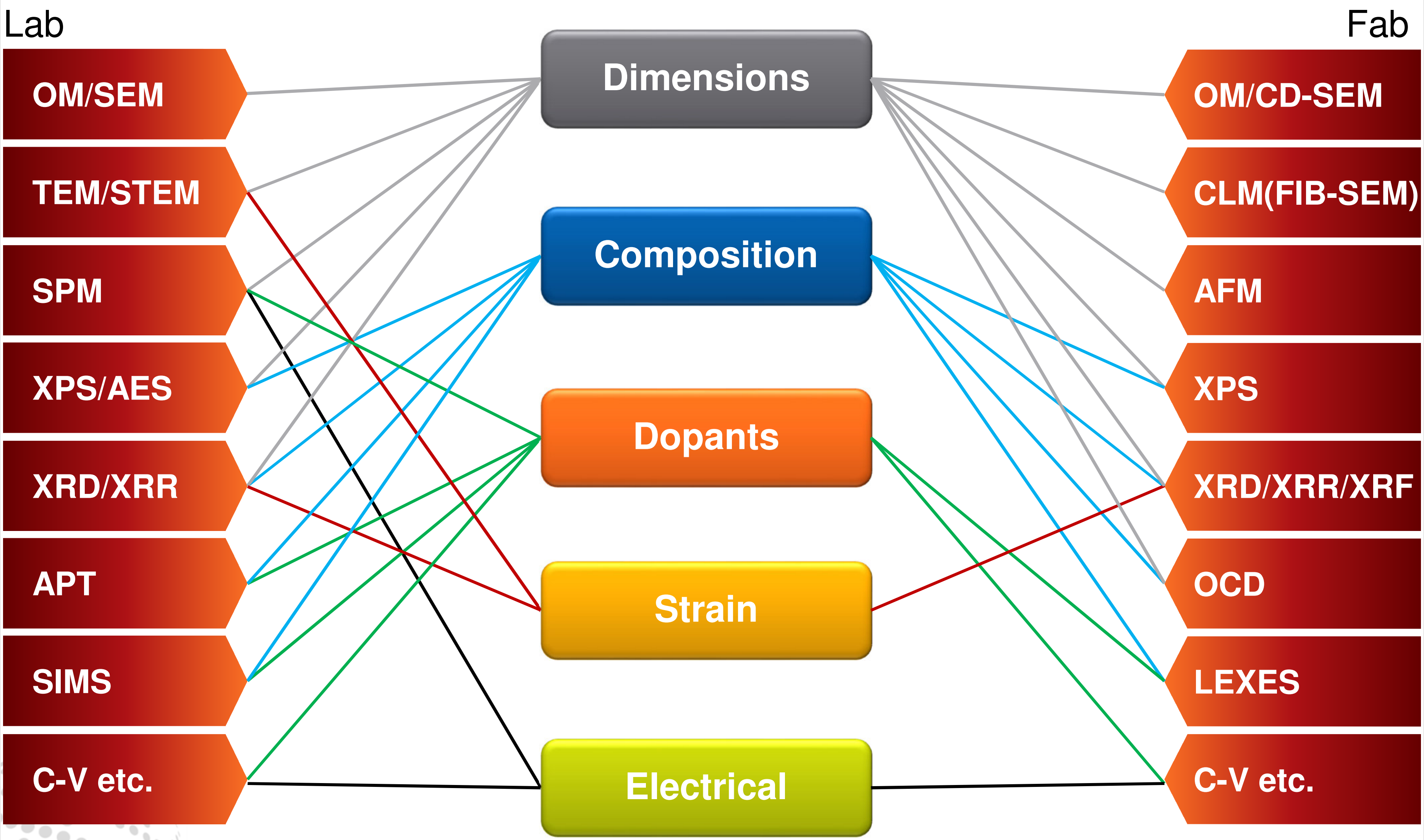


What next ?

1st step is to look at where we are

Why: If we can't measure it, we can't control it

Primary techniques presently used in the lab & fab



SPM includes: AFM, SSRM, STM, nanoprobe, etc
C-V includes: Hg-Probe, Faast, Thermowave, 4pt probe, etc

Primary techniques presently used in the lab

	Status	Used for
OM/SEM	Approaching physical limits	Topography, CDs, Defect analysis
TEM/STEM	Approaching physical limits*	2D sub atomic resolution imaging, Dopant distributions (BF), Strain (DF)
SPM	Approaching physical limits	AFM for Topography, CDs, SCM, SSRM for carrier distributions, etc.
XPS/AES	Approaching physical limits	Composition, sub 6nm film thickness
XRD/XRR	Developments ongoing	Composition, Phase, Strain, Orientation
SIMS	Approaching physical limits	Dopant distributions (all elements detectable), Pattern recognition
APT	Approaching physical limits	3D atomic scale reconstruction (all elements detectable)
C-V etc.	Developments ongoing	Band parameters, Trap sites and densities, Dielectric constants, carrier concentrations

* Meets needs since wavelength/capability<than atomic dimensions

Primary techniques presently used in the fab

Status	Used for	
Approaching physical limits	Topography, CDs, Defect analysis	OM/CD-SEM
Approaching physical limits	2D nm scale resolution imaging	CLM(FIB-SEM)
Approaching physical limits	AFM for Topography, CDs,	AFM
Approaching physical limits	Composition, sub 6nm film thickness	XPS
Developments ongoing	Composition, Phase, Strain	XRD/XRR/XRF
Approaching physical limits?	Composition, thickness, Pattern recognition	OCD*
Approaching physical limits	Dosimetry	LEXES
Developments ongoing	Band parameters, Trap sites and densities, carrier concentrations, SPV	C-V etc.

* Covers Ellipsometry/Scatterometry applications

Dimensions

Expectation. Method provides:
1) Information needed
2) Fast turn around
3) Good uptime

Data collection rate

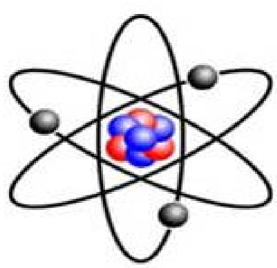
Slower ← → *Faster*

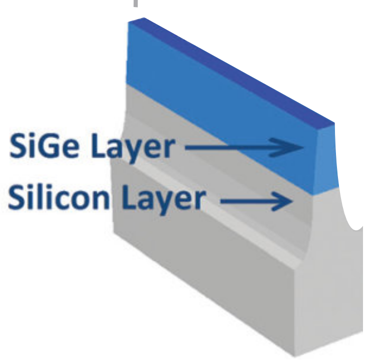
Dimension scale

1 Å | 1 nm | 10 nm | 100 nm | 1 μm | 10 μm | 100 μm

TEM *APT* *SEM* *SPM* *SNOM* *micro-Raman* *SIMS, XPS, XRD, OCD, …*

Atom





Future possibilities?

1) Collect data over periodic structure

2) Compare output with simulated data based off 3D structural model

Sound familiar? Basis of scatterometry

Personal opinion: Many possibilities still to unfold

Expectation. Method provides:
1) Information needed
2) Fast turn around
3) Good uptime

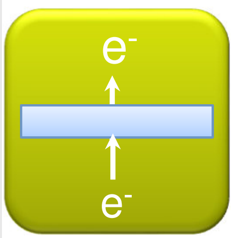
Individual technique approaches

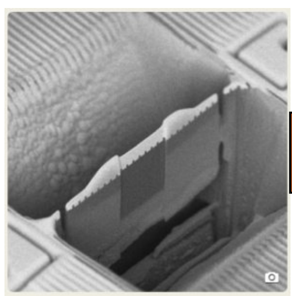
More Dimensions (2D→3D)

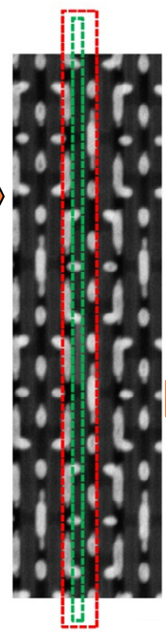
-TEM and STEM are intrinsically 2D projection techniques,

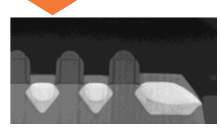
-But … ***Other options available***

FIB→TEM



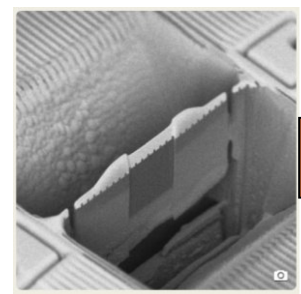


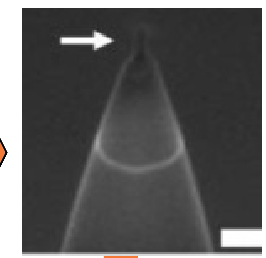


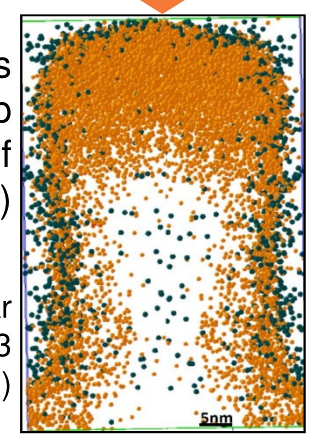


ROI (Green region) smaller than standard lamellae thickness (red region)

FIB→APT







Arsenic atoms (orange) at top and side wall of fin (S/D region)

From: Ajay Kumar PhD thesis 2013 (IMEC)

TEM/STEM: Smaller volume solutions needed
APT: Reconstruction improvements required

Expectation. Method provides:
1) Information needed
2) Fast turn around
3) Good uptime

Individual technique approaches

More Dimensions (2D→3D)

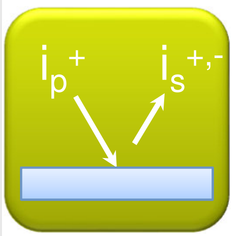
-SIMS is not a 3D technique,

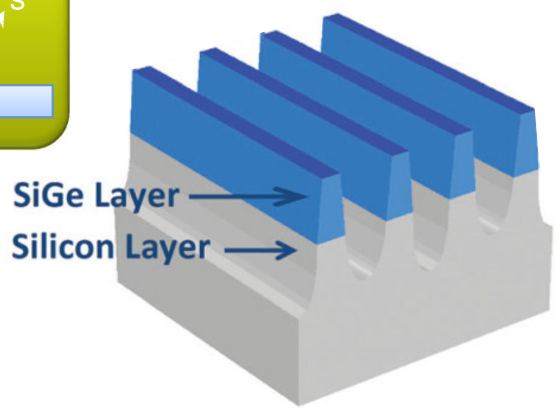
-But … ***More information available***

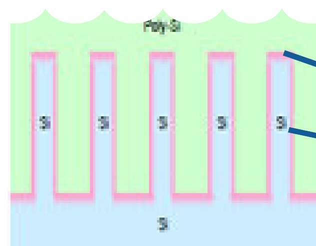
SIMS can provide:

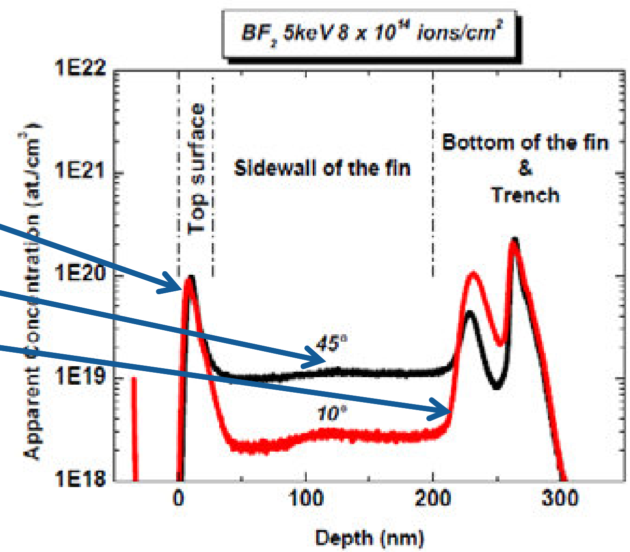
a) Dopant distribution
b) Fin walk
c) Fin geometry

SIMS example from periodic structure









Dopant/carrier profiling
for 3D-structures

Wilfried Vandervorst[*,1,2], Andreas Schulze[1,2], Ajay Kumar Kambham[1,2], Jay Mody[1,2], Matthieu Gilbert[2], and Pierre Eyben[2]

More development work needed

Expectation. Method provides:
1) Information needed
2) Fast turn around
3) Good uptime

Individual technique approaches

<u>More Dimensions (2D→3D)</u>

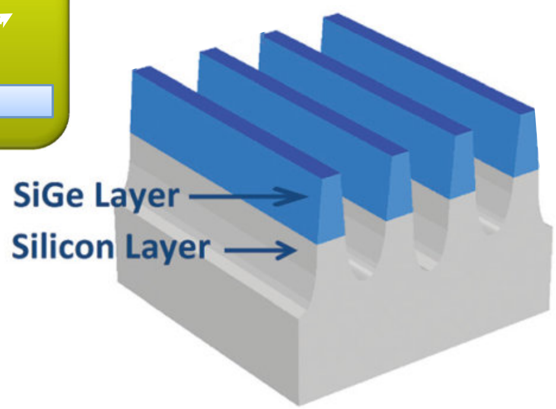
-XRD is not a 3D technique,

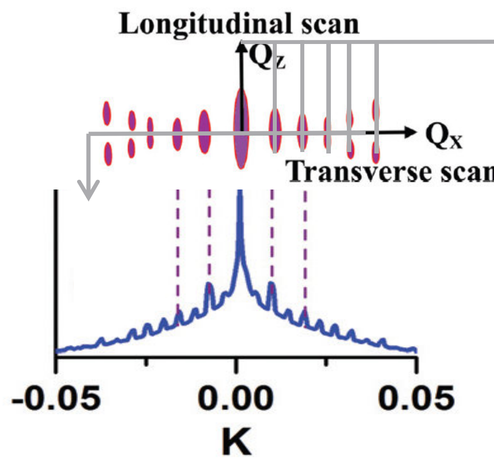
-But … ***More information available***

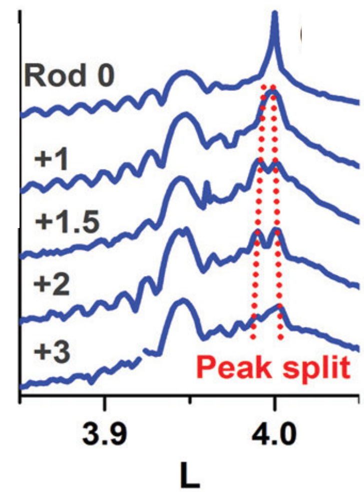
XRD can provide:

a) Fin pitch (K)
b) Fin walk (K)
c) Fin geometry (K+L)

XRD example from periodic structure







Spectra from:
M. Medikonda, et al, J. Vac. Sci. Technol. B 32(2), Mar/Apr 2014

Higher brightness (synchrotron like) sources needed

Expectation. Method provides:
1) Information needed
2) Fast turn around
3) Good uptime

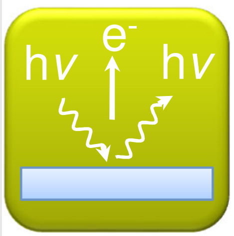
Hybrid approaches

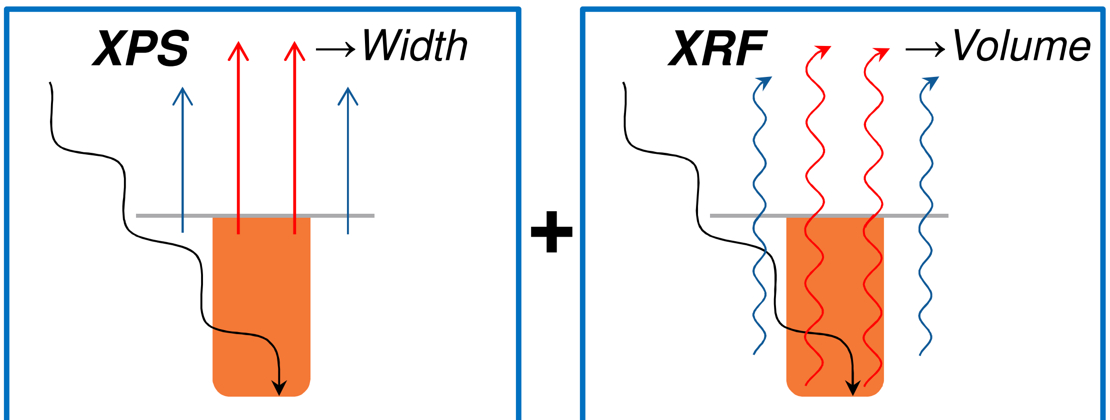
More Dimensions (2D→3D)

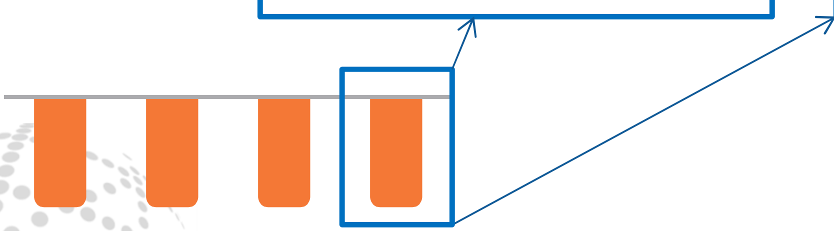
-Simultaneous collection of more than one data set

-Introduces capability to extract more information than from individual techniques (1+1=3 as opposed to 1+1=2)

XPS-XRF example from periodic structure







B. Lherron, et al, AVS-61 Technical & Exhibitor Program, Page 101, 2014

= *Depth = $\frac{\text{Volume}}{\text{Width}}$*

Many other possibilities i.e.: Raman IR, PL, XRD, CD-SAXS, etc.

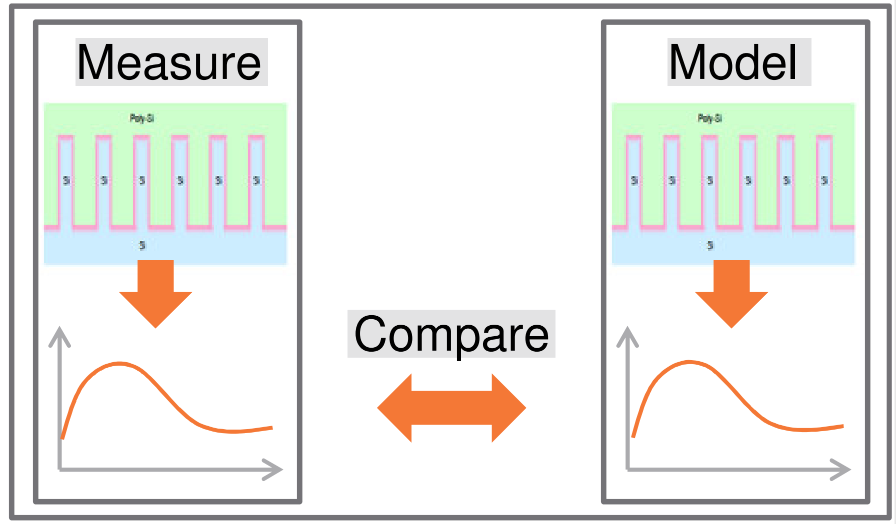
Specific test structures needed

Expectation. Method provides:
1) Information needed
2) Fast turn around
3) Good uptime

Simulation/Emulation

Simulation

-Develop library of possible analytical outcomes based on structure differences (much work to do, but same concept as used in scatterometry)



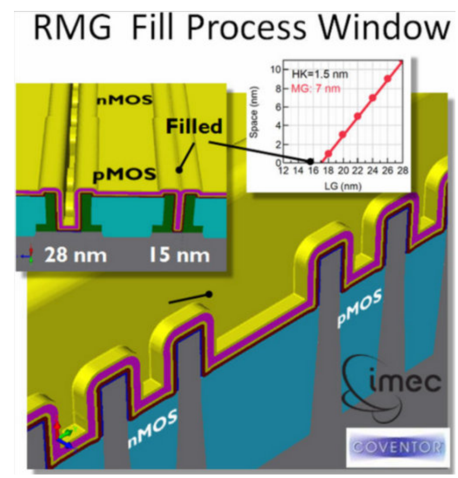
Emulation

-Use of nm scale building blocks (voxels) to

-Model (emulate) entire device flow

-Adjusting parameters allows one to answer questions such as: How does adjusting one parameter affect downstream CDs?

-Provides a form of virtual metrology



Example from:
http://www.coventor.com

Will take macro-scale techniques to the next level

Recognized issues/possible solutions for the lab

Primary issues of concern

1) *Movement from 2D→3D structures*
   - *More elaborate modeling required (XRD, ellipsometry, etc.)*
     - *Many existing methods do not translate well to 3D*

2) *Region of interest will encompass smaller volume*
   - *Damage/modification becomes a greater concern*
     - *Most existing methods are approaching physical limits*

3) *Movement to more chemically complex systems*
   - *More elaborate modeling required (XRD, ellipsometry, etc.)*
     - *More characterization demands expected*

Possible solutions

1) *Technological innovations/breakthroughs (hardware)* **?**
2) *Novel test structure designs mimicking nanoscale structures* ✓
3) *Hybrid approaches (multiple techniques feeding into each other)* ✓ ✓
4) *Software inclusive of simulation/emulation* ✓ ✓ ✓

From the Lab to the Fab

Areas of concern	Expectations
1) Particles/contamination	Clean room spec'd
2) Large samples	300/450 mm wafer capability
3) Damage	Use of sufficiently low doses
4) Speed	Examination of highly specific signals
5) Uptime	Robust design/implementation/support
6) Cost	Market need must support cost of entry

Note I: Requirement of speed limits number of applicable techniques and confines data collection to narrow windows

Possible solutions

1) *Technological innovations/breakthroughs (hardware)* **?**
2) *Novel test structure designs mimicking nanoscale structures* ✓
3) *Hybrid approaches (multiple techniques feeding into each other)* ✓ ✓
4) *Software inclusive of simulation/emulation* ✓ ✓ ✓

Summary/Conclusions

Characterization needs (number and type) will continue to increase

And with many presently applied analytical techniques at, or close to, their physical limits, how do we contend with this

Lab:
- *New/improved analytical capabilities/strategies*
- *Better sample preparation methodologies*
- *Incorporation of simulation/emulation approaches*

Fab:
- *More analytical capabilities to examine*
- *Greater development of hybrid approaches*
- *Improved use of simulation/emulation (need to retain confidence in results for increasingly complex approaches)*

Software will open up possibilities not previously imagined