CHARACTERIZATION REQUIREMENTS OF THE CMOS INDUSTRY

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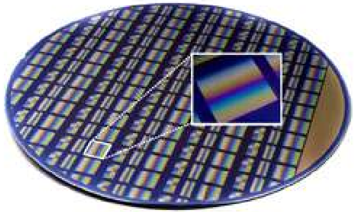
Agenda

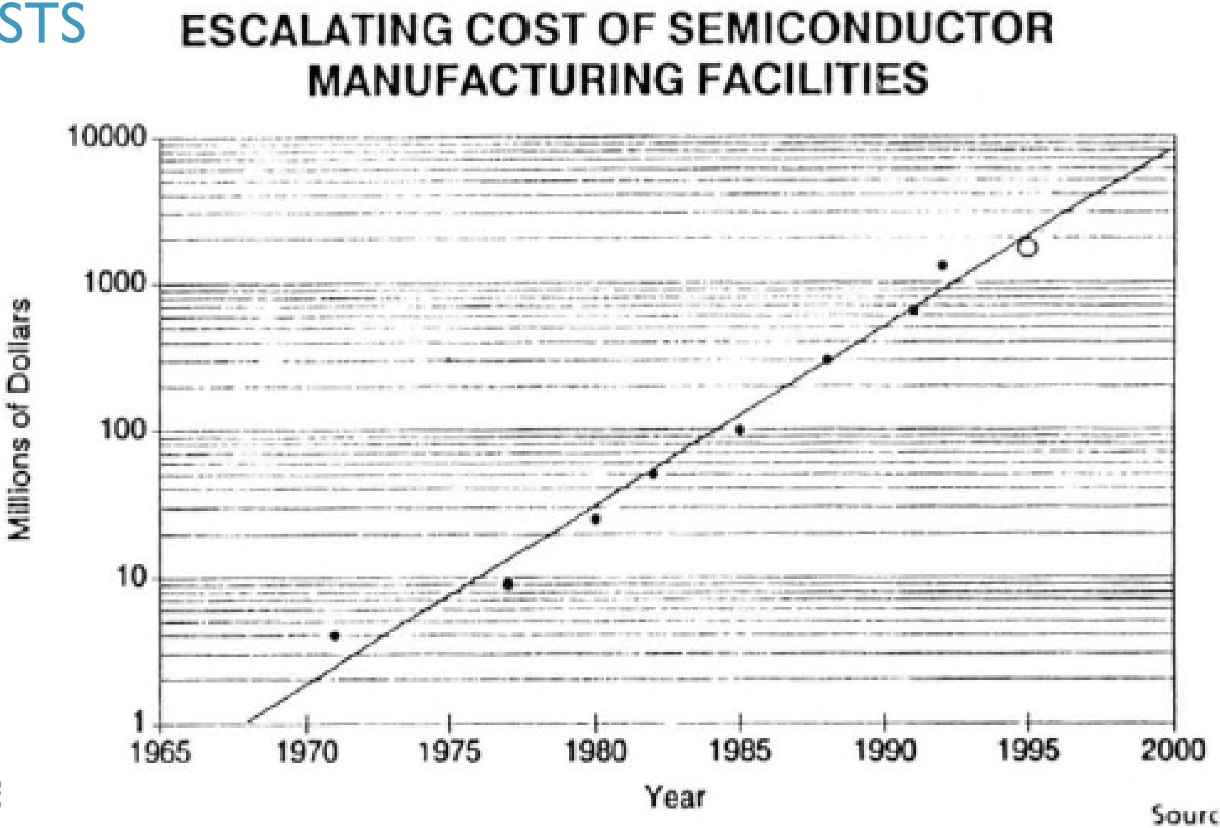
- **Why**
  - **Financial drivers**
- **How**
  - **Requirements/Expectations**
- **What’s next**
  - **Tomorrow solutions**

Todays logic fab (USD)

INDUSTRY & COSTS

- Manufacturing
  - >1 month
  - >1000 steps





Source. VLSI Research

- Application are
  - -Logic, memory and interconnects
  - -IoT, virtual reality, self driving cars, human-electronics interface, etc.

INDUSTRY COSTS & ROI

2nd law of thermodynamics:

In all spontaneous processes, the total entropy always increases, i.e. systems move towards disorder

- Return On Investment (ROI) is driven by
  - -1st to market (new products)
  - -Wafer yields (fastest, most effective and most efficient system)

- Yesterdays manufacturing philosophy's
  - -1980s: Japan pushed for "the prefect process"
    - A perfect process does not require inspection
  - -1990s: The Tiger's pushed for "reducing the imperfections"
    - Inspection needed to understand the defectivity

- Todays philosophy: Inspection to drive to near perfect process
  - -Yields prior to 1980s <20%, Yields following 2000 >90%

MATERIALS CHARACTERIZATION & COSTS

Todays logic fab (USD)
-Fab construction
~10-15 ($Bn)
-1 cycle of learning
~100 ($M)
-1 fab down event
>1 ($M)/day

- Inline/nearline: Automated analysis for process control, defect inspection, and issue resolution
  -Capex (total): >500 ($M)
  -Time (CMOS mfg process steps=$)
- Offline/nearline: Primarily manual based analysis for R&D, process step qualification/refinement, and issue resolution
  -Capex (total): >50 ($M)
  -Time (CMOS mfg process steps and 1st to market=$)

Must provide the fastest possible "time to solution"

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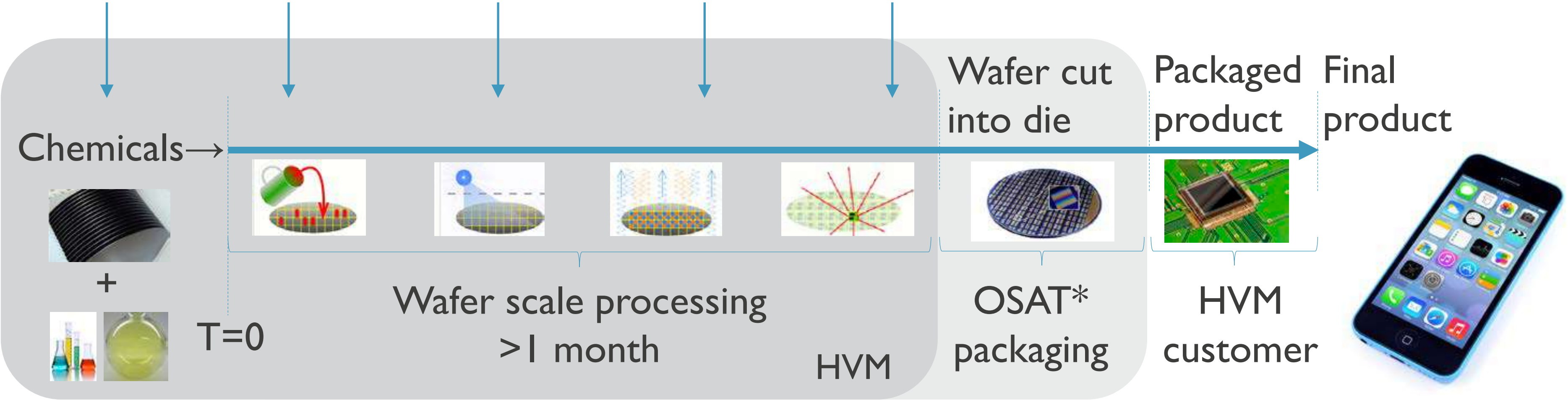
TODAYS END TO END HVM SUPPORT (1 OF 2)

HVM=High Volume Manufacturing
*Outsourced Semiconductor Assembly and Test
(done inhouse in some cases)

- Requirement: Extreme control of input materials and process recipes
  -Precision is paramount → Best insight into process variations



Process tool verification, Recipe verification
Incoming chemical verification, Electrical verification

Electrical test

Chemicals→

+

T=0

Wafer scale processing
>1 month

HVM

Wafer cut into die

OSAT* packaging

Packaged product

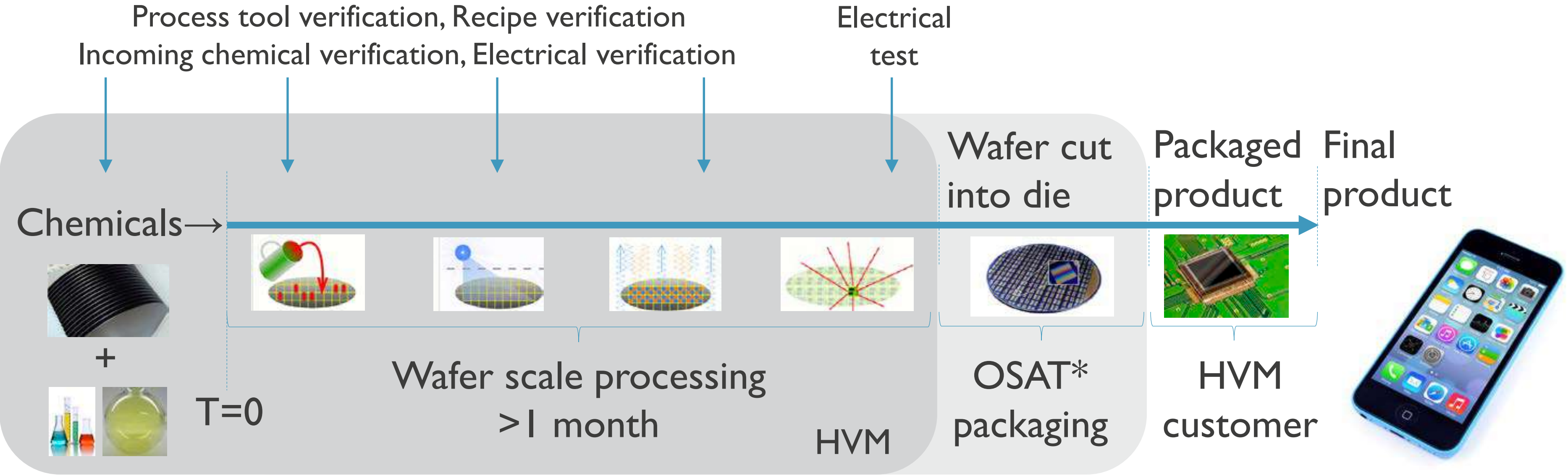
HVM customer

Final product

HVM=High Volume Manufacturing
*Outsourced Semiconductor Assembly and Test
(done inhouse in some cases)

TODAYS END TO END HVM SUPPORT (2 OF 2)

- Requirement: Identify steps/recipes that have greatest device yield impact
  -Analysis is costly → Only do where needed, i.e. at critical steps



PROPERTIES/ANALYTICAL TOOLBOX

*And there are others for supporting R&D+HVM

Incoming chemicals

VP UV-
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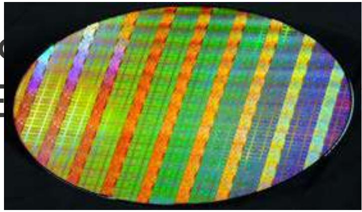

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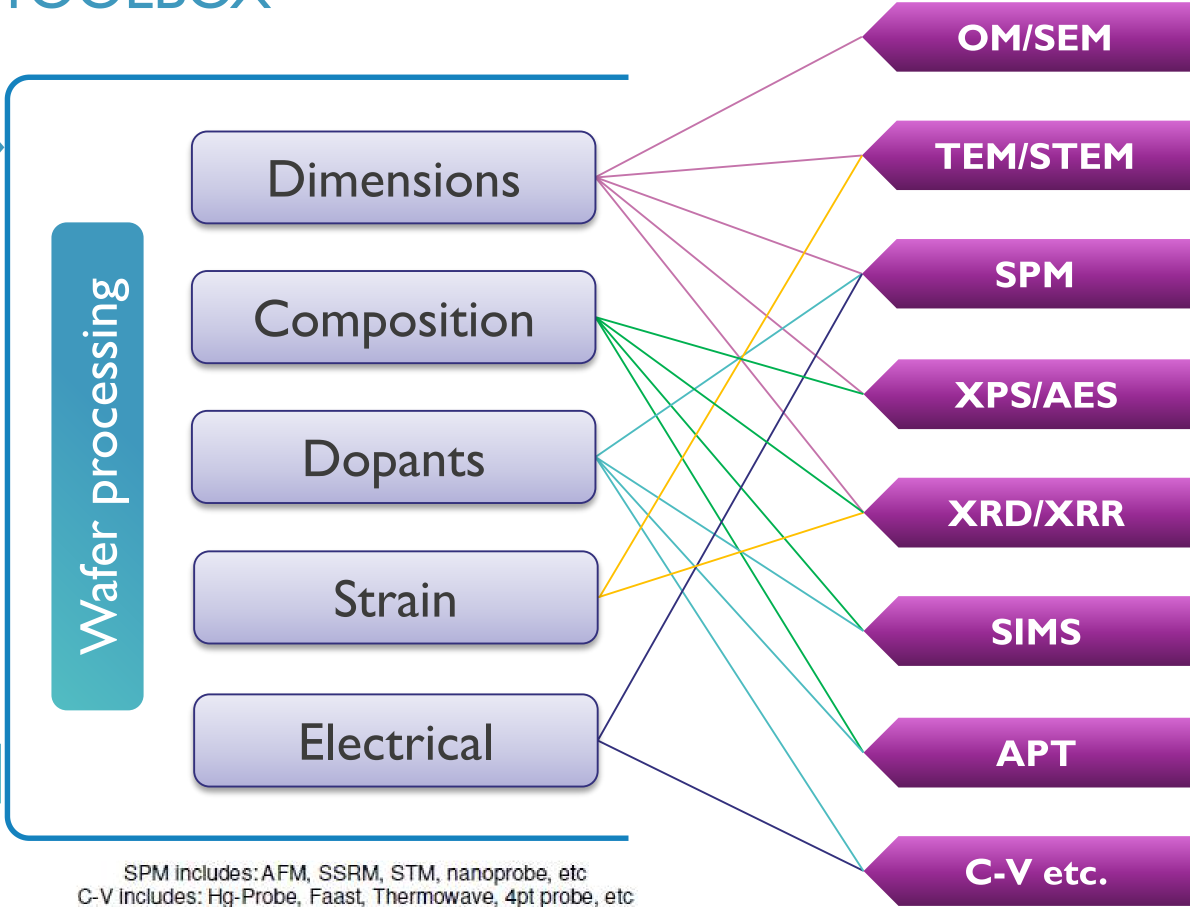
Failure Analysis



Wafer processing

- Dimensions
- Composition
- Dopants
- Strain
- Electrical

- OM/SEM
- TEM/STEM
- SPM
- XPS/AES
- XRD/XRR
- SIMS
- APT
- C-V etc.

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

ANALYTICAL TOOLBOX: REQUIREMENTS

FOR MATERIALS CHARACTERIZATION

- Must provide the needed information
  - -High precision
  - -High throughput

Repeatability (same platforms-same lab)
Reproducibility (same platforms-different labs)

- Must be sufficiently robust
  - -95% or better uptime
  - -Predictable and routine maintenance cycles (PMs)

- Must be cost effective and must not be overly complex (no “one of a kind”)
  - -Transferable “recipe driven” analysis is the optimal end goal

Must be operational 24/7 with supporting infrastructure

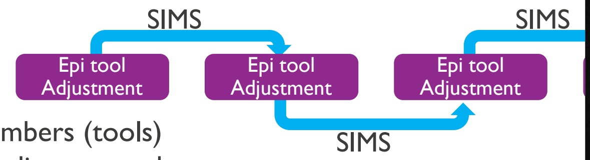
ANALYTICAL EXPECTATIONS: SIMS

FOR MATERIALS CHARACTERIZATION

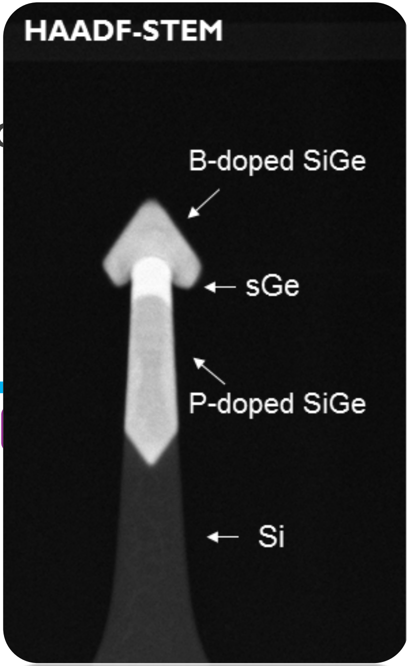
- As fast as possible “time to solution”
  -Includes 24/7 coverage & backup plans

- SIMS for dopant concentration validation
  -For epi chamber validation, shortest TAT ensure
  a) Job prioritization (1st in queue)
  b) Data processing automation

Example: $Si_{1-x}Ge_x$ dopant concentrations are tuned in a serial manner



$Si_{1-x}Ge_x$ is epitaxially grown in “epi” chambers (tools) with or without dopants depending on need



ANALYTICAL EXPECTATIONS: TEM/STEM

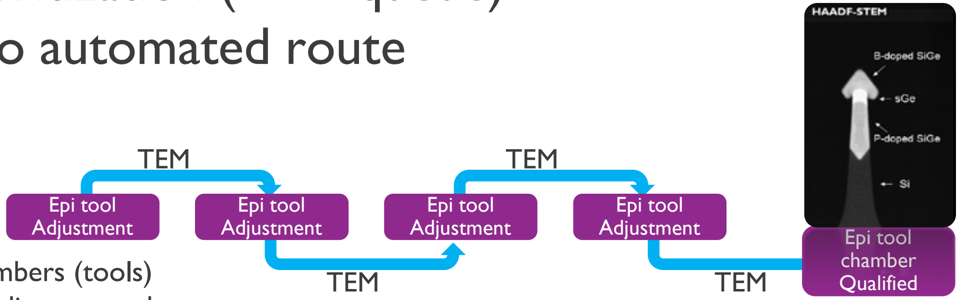
FOR MATERIALS CHARACTERIZATION

- As fast as possible “time to solution”
  -Includes 24/7 coverage & backup plans

TEM/STEM

- TEM for structure validation
  -For epi chamber validation, shortest TAT ensured via
    a) Job prioritization (1st in queue)
    b) Move to automated route

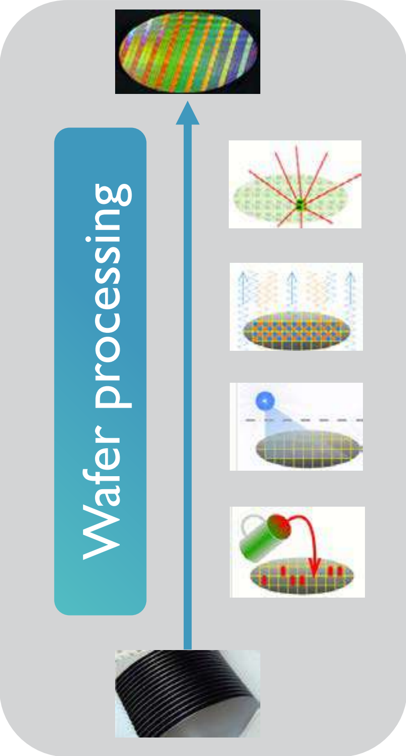
Example: $Si_{1-x}Ge_x$ structure is tuned in a serial manner

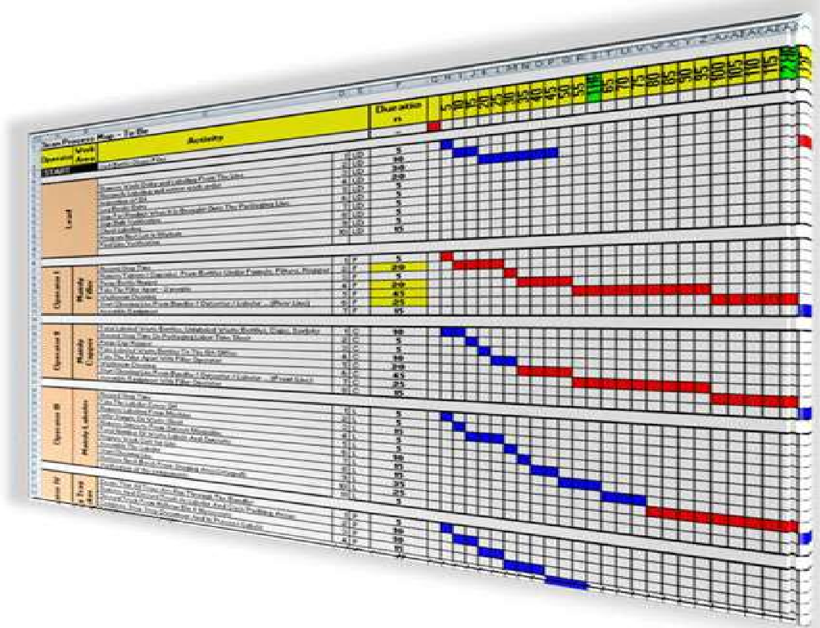


$Si_{1-x}Ge_x$ is epitaxially grown in “epi” chambers (tools) with or without dopants depending on need

SUPPORT TO COMMITMENTS

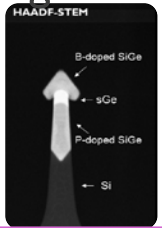
LIMS=Laboratory Information Management System
UDT=Unplanned Down Time
TAT=Turn Around Time





Resource mgmt

Uptime
-PMs
-Training



TEM/STEM

Coverage
-24/7 on site
-Vendors for UDT

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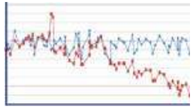

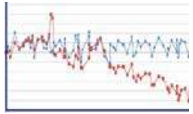

submit → QI | H1 | Q2 | H2 | CAP | Q3 | H3 | FIB | Q4 | H4 | TEM | Q5 | Report

🟪 queue
▭ hold
▭ execute

imec

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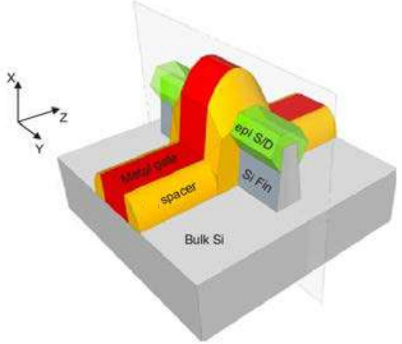
WHAT'S NEXT

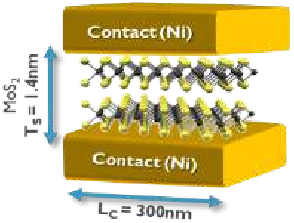
Two step to process
- 1) Development where accuracy is more important (R&D)
- 2) Implementation where precision becomes paramount (HVM)

FASTER TIME TO SOLUTION

- More complicated analysis needed faster

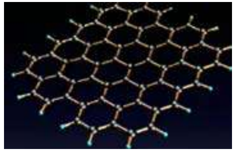
  3D structures, 2D materials, …





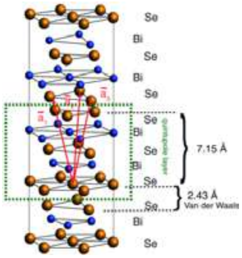
- Big data analytics

  Hybrid approaches, using what you can't perceive, …



- Lab (off-line) to fab (near-line or in-line)

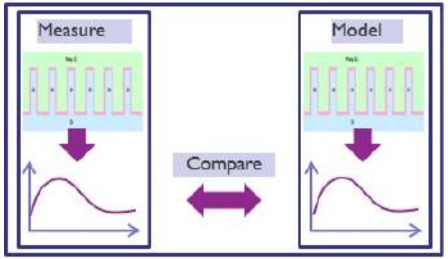
  Faster time to solution, highly automated approaches, …



BIG DATA ANALYTICS

GIGABITS → TERABITS AND BEYOND

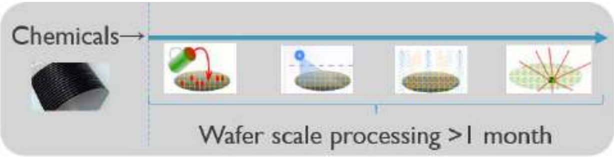
- Data sets will get larger and feedback is expected faster
  - Greater fidelity (detail)
  - Hybrid approaches (combining data sets)
  - Calculations (imaging, simulations, machine learning, etc.)



- Understanding the data is nice, but not absolutely necessary
  - Only need to know how the data compares to library datasets (good vs bad)

If profile compares to good structure
→High speed verification →release flow

If profile compares to bad structure
→High speed verification →stop flow
Optimize process flow conditions and re-examine, and do again as needed

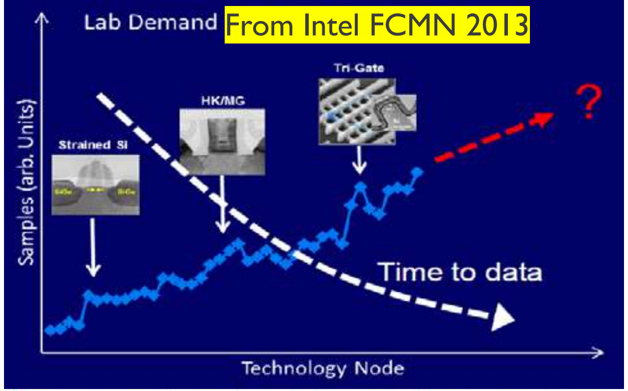


LAB → FAB CHARACTERIZATION SYNERGY

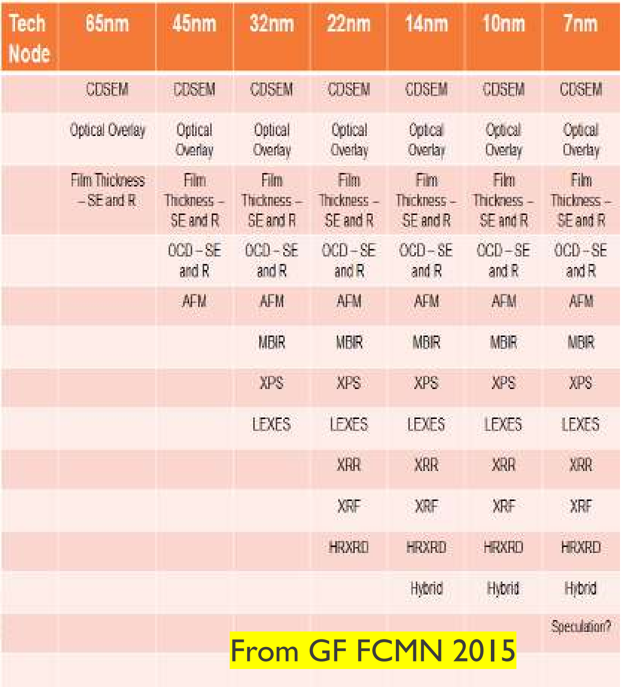
FOR FASTER TIME TO SOLUTION

- Only occurs in highly specific cases:
  - -Fast and fully automatable analysis (recipes)
  - -Zero contamination risk to wafers (in-line)

Analysis	Offline	Nearline	Inline	✱ Comment
Optical	✓	✓	✓ ✱	Combined wit
SEM	✓ ✱	✓ ✱	✓ ✱	Multi-beam sys
AFM	✓	✓ ✱	✓ ✱	Analysis is still
XPS	✓	✓ ✱	✓ ✱	3rd generation
TEM	✓	✓	✗	Destroys ROI,
SIMS	✓	✗ ✱	✗	Destroys ROI,
APT	✓ ✱	✗ ✱	✗ ✱	Destroys ROI,



From Intel FCMN 2013

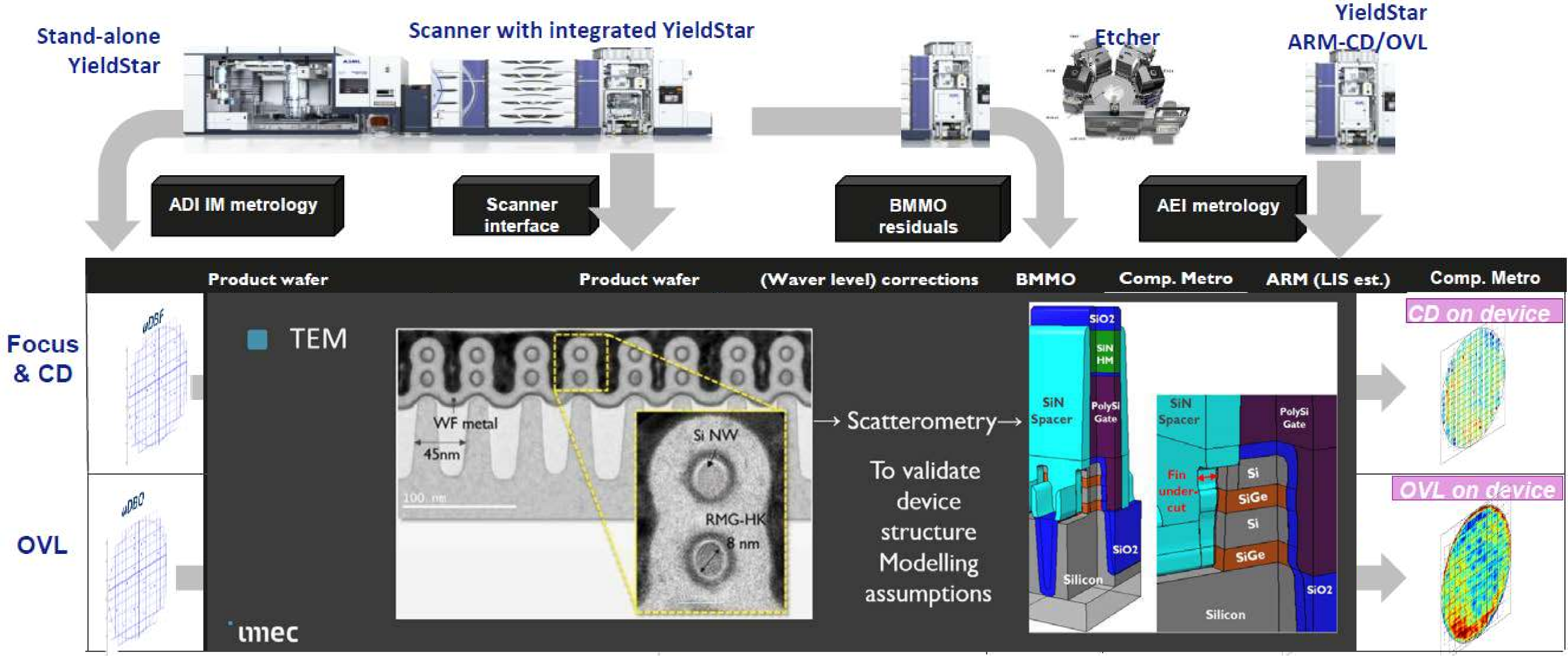


Tech Node	65nm	45nm	32nm	22nm	14nm	10nm	7nm
	CDSEM	CDSEM	CDSEM	CDSEM	CDSEM	CDSEM	CDSEM
	Optical Overlay	Optical Overlay	Optical Overlay	Optical Overlay	Optical Overlay	Optical Overlay	Optical Overlay
	Film Thickness – SE and R	Film Thickness – SE and R	Film Thickness – SE and R	Film Thickness – SE and R	Film Thickness – SE and R	Film Thickness – SE and R	Film Thickness – SE and R
		OCD – SE and R	OCD – SE and R	OCD – SE and R	OCD – SE and R	OCD – SE and R	OCD – SE and R
		AFM	AFM	AFM	AFM	AFM	AFM
			MBIR	MBIR	MBIR	MBIR	MBIR
			XPS	XPS	XPS	XPS	XPS
			LEXES	LEXES	LEXES	LEXES	LEXES
				XRR	XRR	XRR	XRR
				XRF	XRF	XRF	XRF
				HRXRD	HRXRD	HRXRD	HRXRD
					Hybrid	Hybrid	Hybrid
							Speculation?

From GF FCMN 2015

IN-LINE METROLOGY: HIGHLY AUTOMATED ENVIRONMENT

FOR FASTER TIME TO SOLUTION



Stand-alone YieldStar

Scanner with integrated YieldStar

Etcher

YieldStar ARM-CD/OVL

ADI IM metrology

Scanner interface

BMMO residuals

AEI metrology

Product wafer

Product wafer

(Waver level) corrections

BMMO

Comp. Metro

ARM (LIS est.)

Comp. Metro

Focus & CD

OVL

TEM

→ Scatterometry→

To validate device structure Modelling assumptions

CD on device

OVL on device

Yieldstar image from ASML

SUMMARY

- Todays demand/costs

  Device yields critically dependent on analytical solutions whether outside or inside of the fab (→lab-fab synergy)

- Tomorrows demand/costs

  Escalation in costs and device complexity amplifies dilemma:
  “more complex analysis needed faster”

- Tomorrows materials characterization?

  What is needed
  How to implement

- -Big data analytics
  -Complex computational approaches
  To provide additional morphological insight
- -Coherence patterns
  -Coherent sources and novel processing algorithms
  To provide information beyond that immediately visible
- -Hybrid characterization
  -Feeding data from different techniques
  -Feeding data from different process steps
  To provide an output equal to more than the sum of the data

embracing a better life