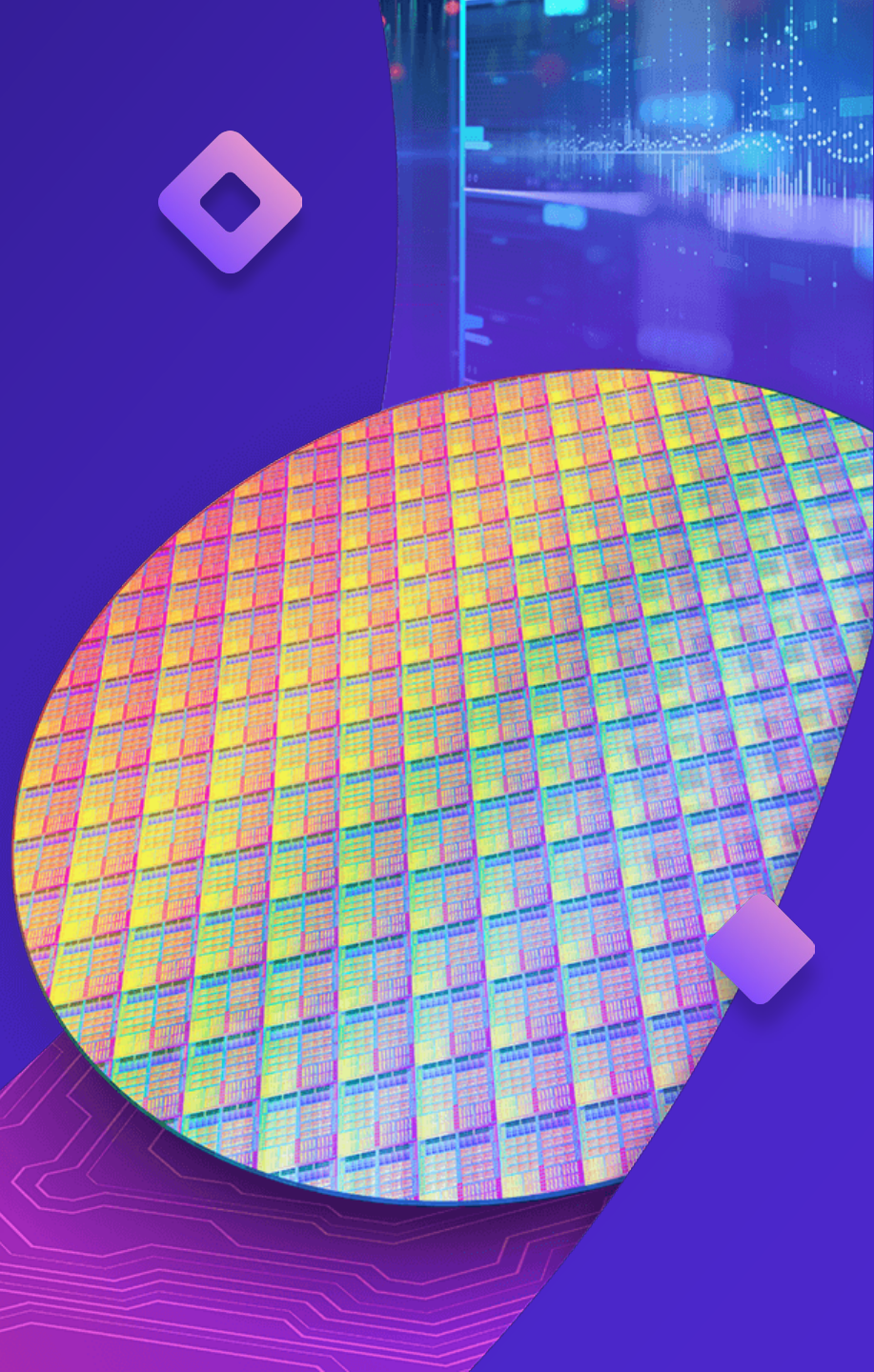
NOVA PROCESS INSIGHT

Advanced Logic Device Architectures: Challenges & Solutions in Materials Metrology



Dr. Shay Wolfling, CTO, Nova Ltd.

Agenda

Topic

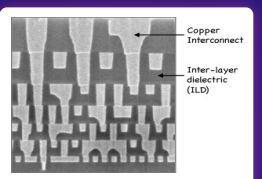
Background: Trends and Architectures

Building Blocks: Challenges & Technologies

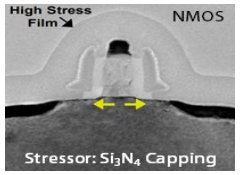
Solutions: Technology meets challenges

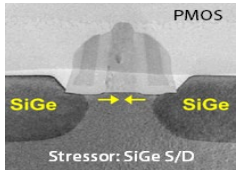
Summary

The Impact of Materials on Logic Scaling Roadmap

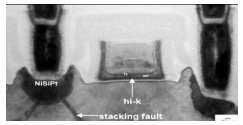


Cu DD BEOL

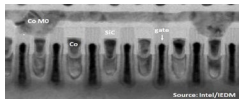




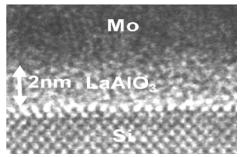
SiGe Source / Drain Strain



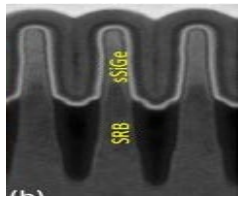
High k Gate



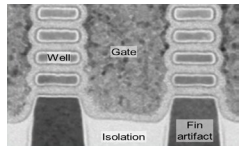
Co contacts



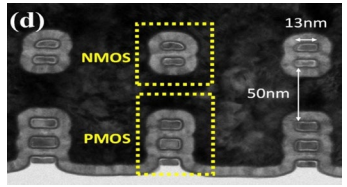
LaO in the Gate



SiGe FIN



Dipole materials in the GAA



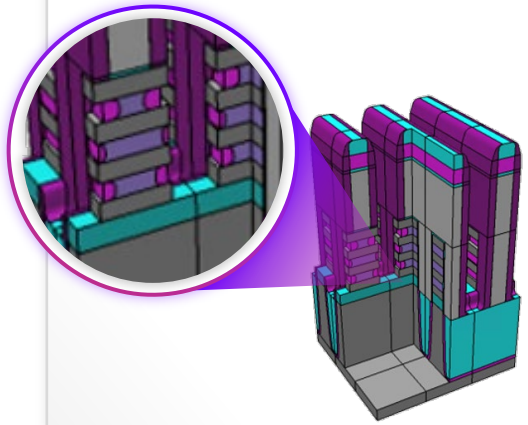
2D materials (MoS2, WS2, ...) in CFET

Future Materials Innovation

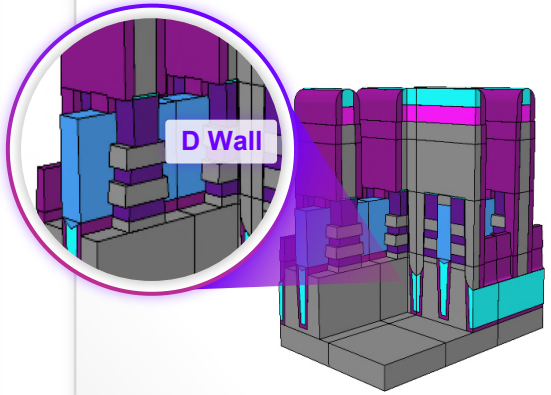
110 nm | 90 nm | 45 nm | 10 nm | 7 nm | 3 nm | 2 nm | Ax

Logic GAA Centric Roadmap

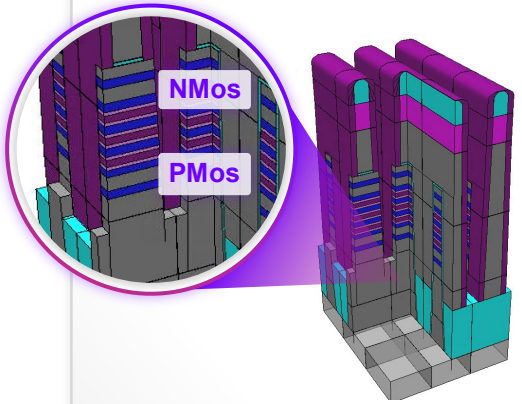
NanoSheet



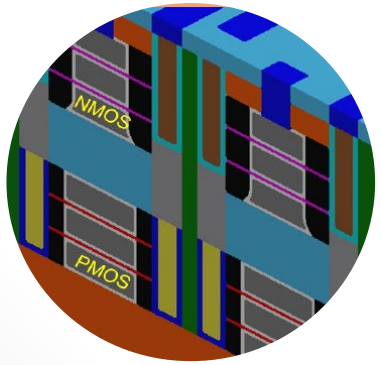
ForkSheet



CFET Complementary FET



CFET - 2D Materials

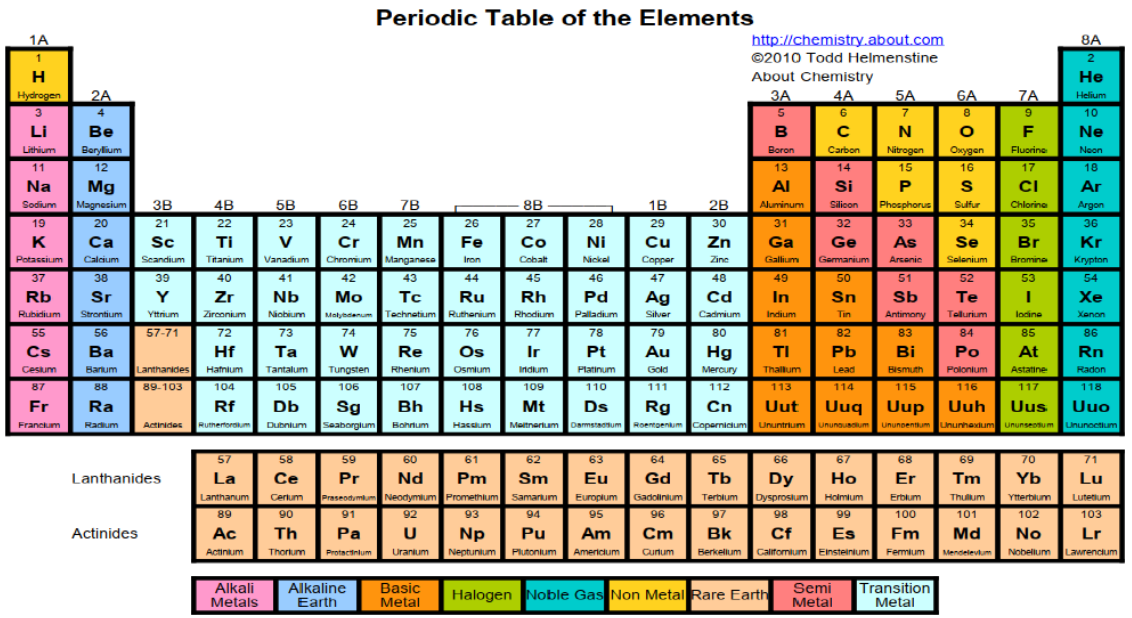


Tech node: From “2nm” — A Long Road Ahead — To “2A”

+ Backside Power Delivery with Nano-TSV, passive elements

+ Advanced packaging, W2W and D2W, Hybrid bonding, …

The Material Era



Source: Intel

Nearly the entire periodic table is used in IC Production:
photoresists, developers, cleaners and more

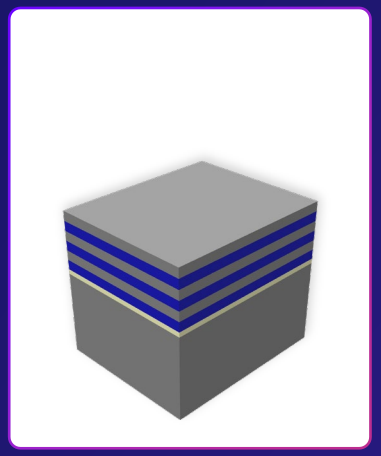
Material types

- Metals
- **Dielectrics**
- **Semiconductors**
- Ferroelectrics
- Magnets
- **Dipoles**
- **2D (TMD, Graphene)**
- Complex Perovskites
- GaN and III-V materials
- Binary and ternary alloys
- Photoresists
- …

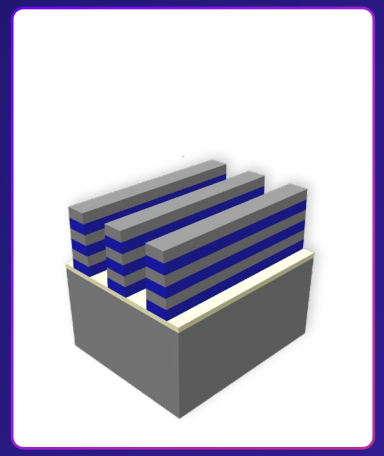
Material properties

- Composition
- **Strain**
- **Doping**
- Crystallinity
- Phase
- Grain size
- Lattice defectivity
- **Interfaces**
- Etch selectivity
- Electrical properties
- ….

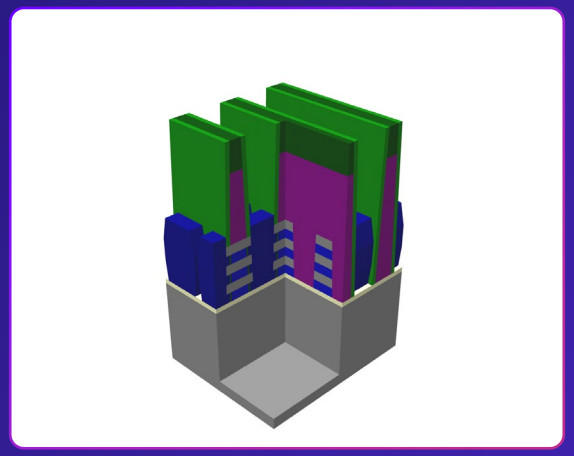
GAA (Partial) Flow: Material Challenges



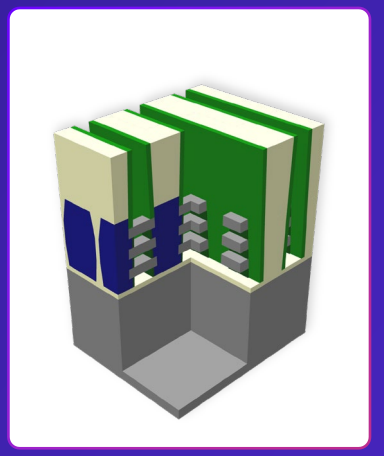
SiGe



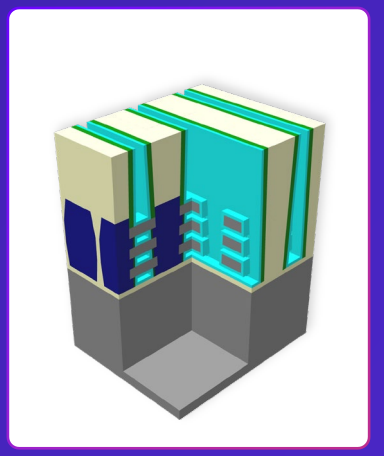
Fin



Source Drain EPI



Poly Pull



HK/MG

Measure Ge%, strain and uniformity

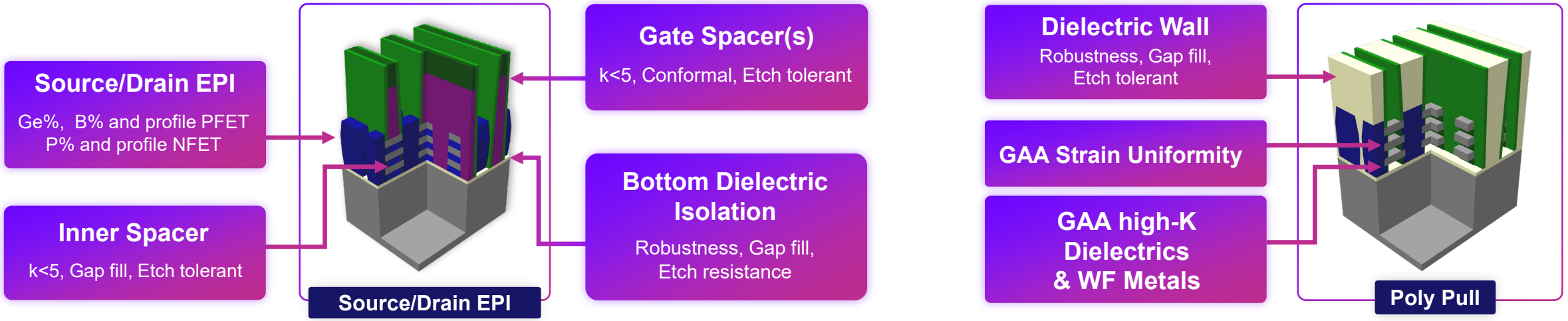
Monitor Ge & B% for PFET
P% for NFET

Detect Ge Residues

HK/MG Dipole Layer Tune

Measure Si/SiGe GAA Strain Evolution

Abundance of Materials Related Challenges

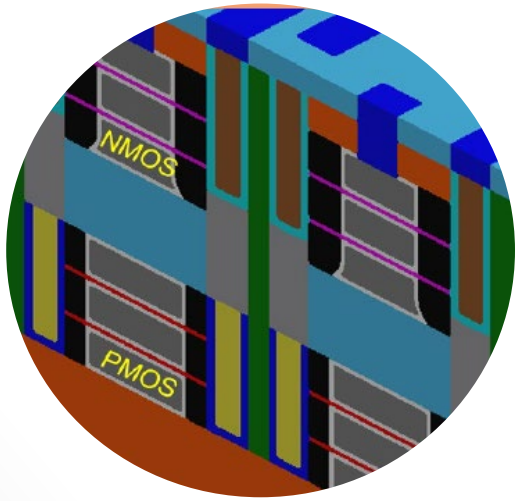


Additional material challenges in the advanced logic processing:

- Novel materials for high NA patterning
- Silicides with low contact resistance and good coverage
- Contact plugs and vias with low resistance and gap fill
- BEOL conductor materials with low resistance for narrow lines
- BEOL dielectric materials for capacitance control with low k
- Materials enabling pores & airgaps

Beyond GAA – 2D Materials

Similar Architecture – Completely Different Materials!



M. Metz, TUT1, IEDM 2023

- Integration challenges – adhesion, patterning, doping
- High quality 2D wafer-scale growth
- Contact materials and resistance
- Interfaces and gate dielectric quality
- Low defects in gate oxide and channel
- Uniform layer count
- Minimize impact of grain boundaries

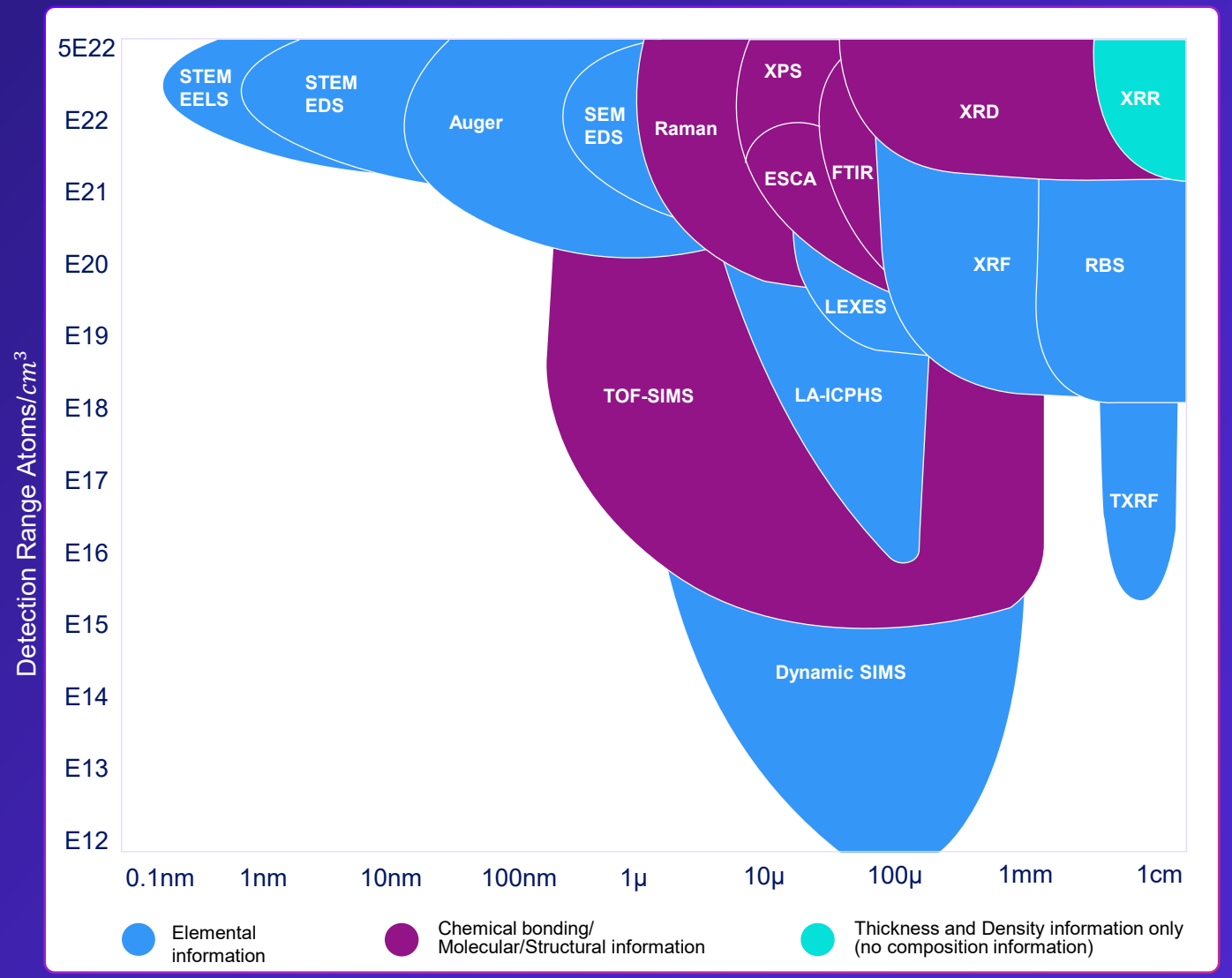
For 2D materials most challenges are materials related!

Materials Metrology Technologies

A Multitude of Technologies

With varying depths and capabilities

XRR	X-Ray Reflectometry	RBS	Rutherford Backscattering Spectrometry
XRD	X-Ray Diffraction	LEXES	Low energy Electron induced X-ray Emission Spectrometry
FTIR	Fourier Transform Infrared Spectroscopy	XRF	X-Ray Fluorescence Spectroscopy
XPS	X-Ray Photoelectron Spectroscopy	TOF- SIMS	Time-of-Flight Secondary-Ion Mass Spectrometer
ESCA	Electron Spectroscopy for Chemical Analysis	SIMS	Secondary-Ion Mass Spectrometer
SEM	Scanning Electron Microscopy	LA-ICPHS	Laser Ablation Inductively Coupled Plasma High-Resolution Mass Spectrometry
EDS	Energy-Dispersive X-Ray Spectroscopy	TXRF	X-Ray Total Reflection Fluorescence
STEM	Scanning Transmission Electron Microscopy	EELS	Electron Energy Loss Spectroscopy



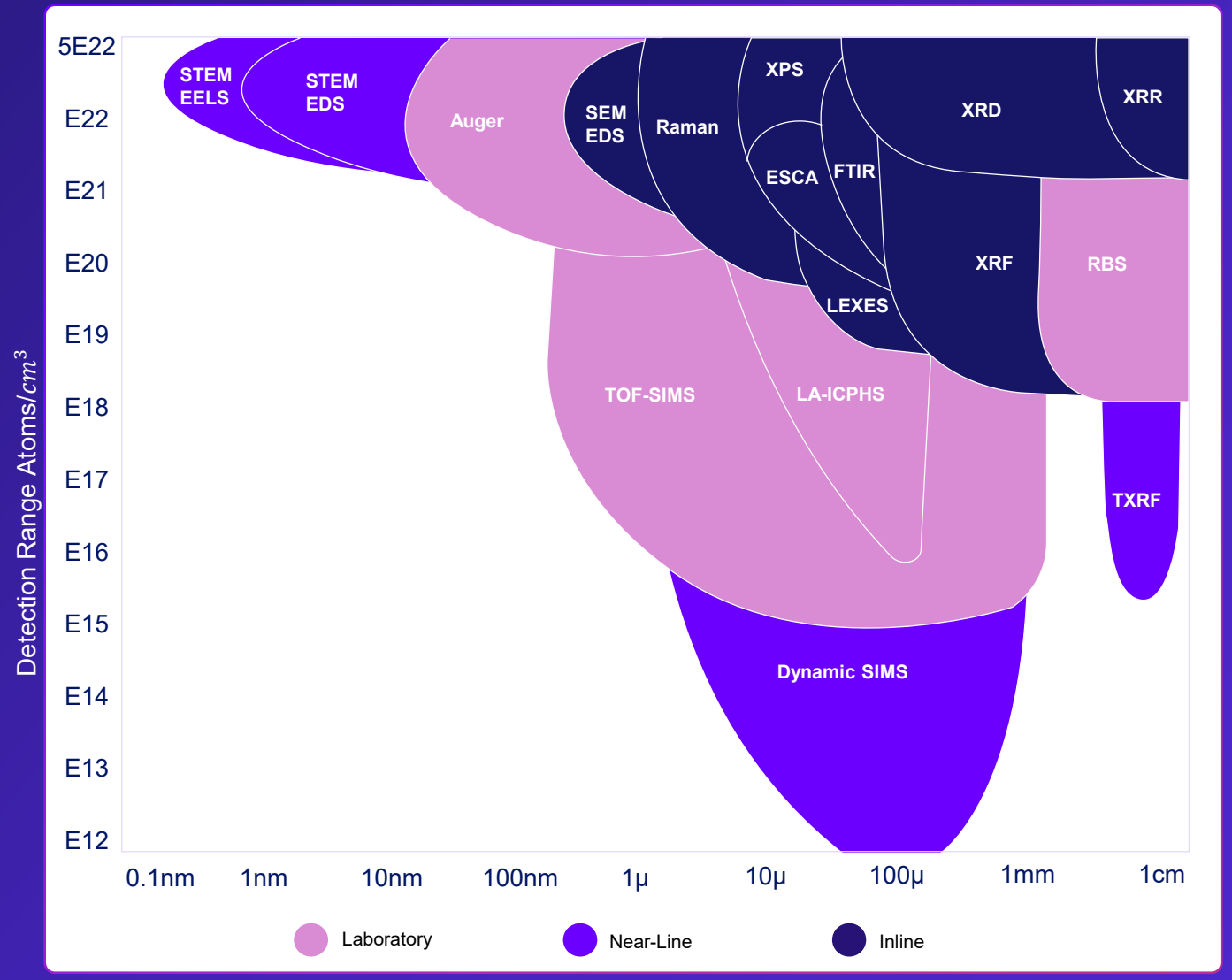
Adapted from Eurofins EAG Laboratories

Materials Metrology Technologies

A Multitude of Technologies

Laboratory, Near-line and Inline

XRR	X-Ray Reflectometry	RBS	Rutherford Backscattering Spectrometry
XRD	X-Ray Diffraction	LEXES	Low energy Electron induced X-ray Emission Spectrometry
FTIR	Fourier Transform Infrared Spectroscopy	XRF	X-Ray Fluorescence Spectroscopy
XPS	X-Ray Photoelectron Spectroscopy	TOF- SIMS	Time-of-Flight Secondary-Ion Mass Spectrometer
ESCA	Electron Spectroscopy for Chemical Analysis	SIMS	Secondary-Ion Mass Spectrometer
SEM	Scanning Electron Microscopy	LA-ICPHS	Laser Ablation Inductively Coupled Plasma High-Resolution Mass Spectrometry
EDS	Energy-Dispersive X-Ray Spectroscopy	TXRF	X-Ray Total Reflection Fluorescence
STEM	Scanning Transmission Electron Microscopy	EELS	Electron Energy Loss Spectroscopy



Adapted from Eurofins EAG Laboratories

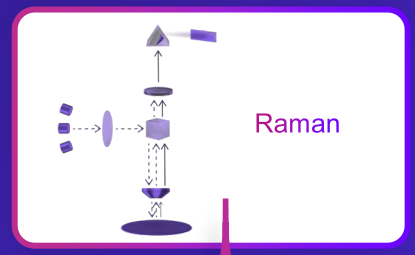
A Complex Journey from Lab to Fab

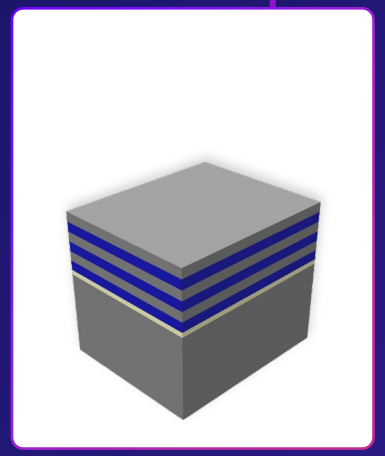
The Multiple Hurdles in Transitioning a Technology to HVM

Laboratory → Near-Line → In-Line

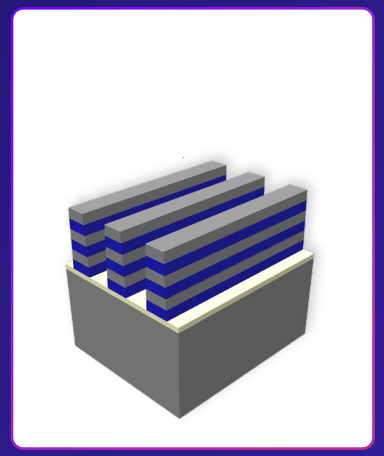
- Automation
- Measure on product wafers
- HVM Worthy
- Performance & Productivity

GAA (Partial) Flow: Challenges & Solutions





SiGe



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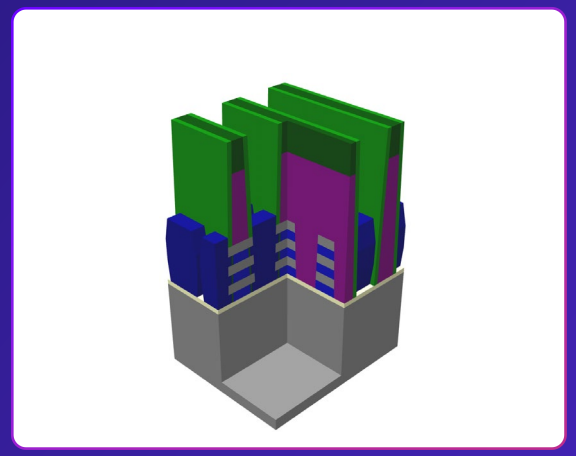
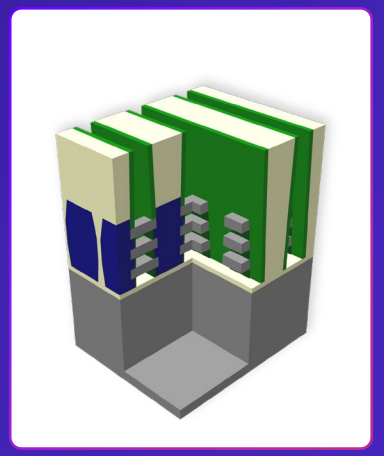
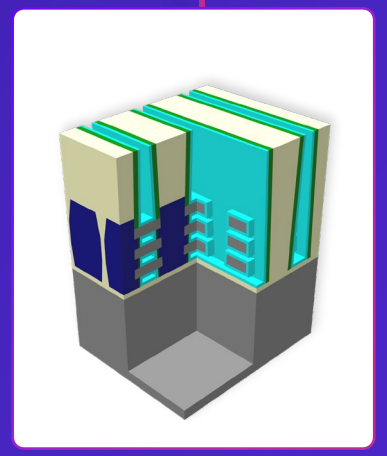


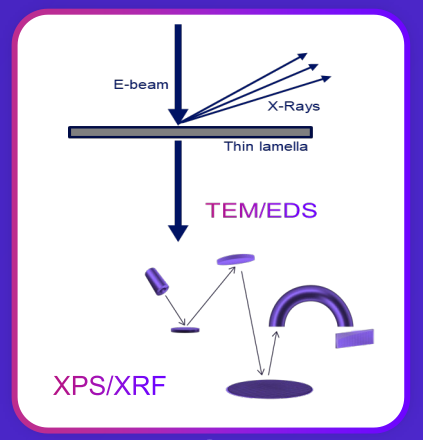
Source Drain EPI



Poly Pull



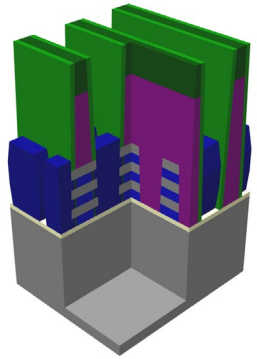
HK/MG

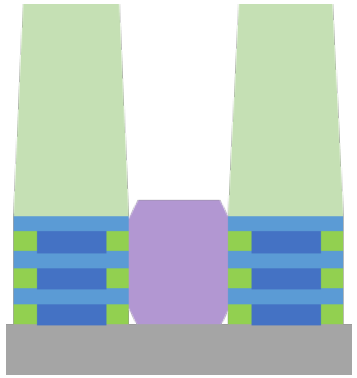


Dopant Concentration – SIMS on GAA Structure

Challenge

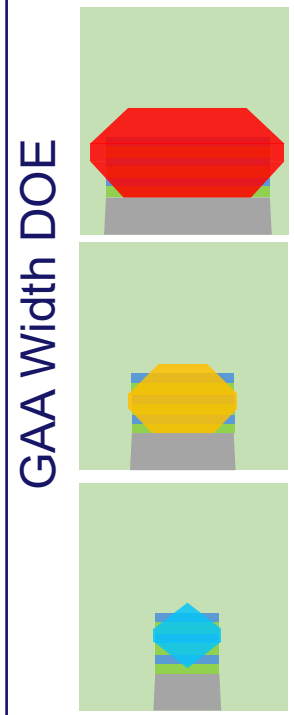
Small variations of dopant concentration in S/D impact device performance

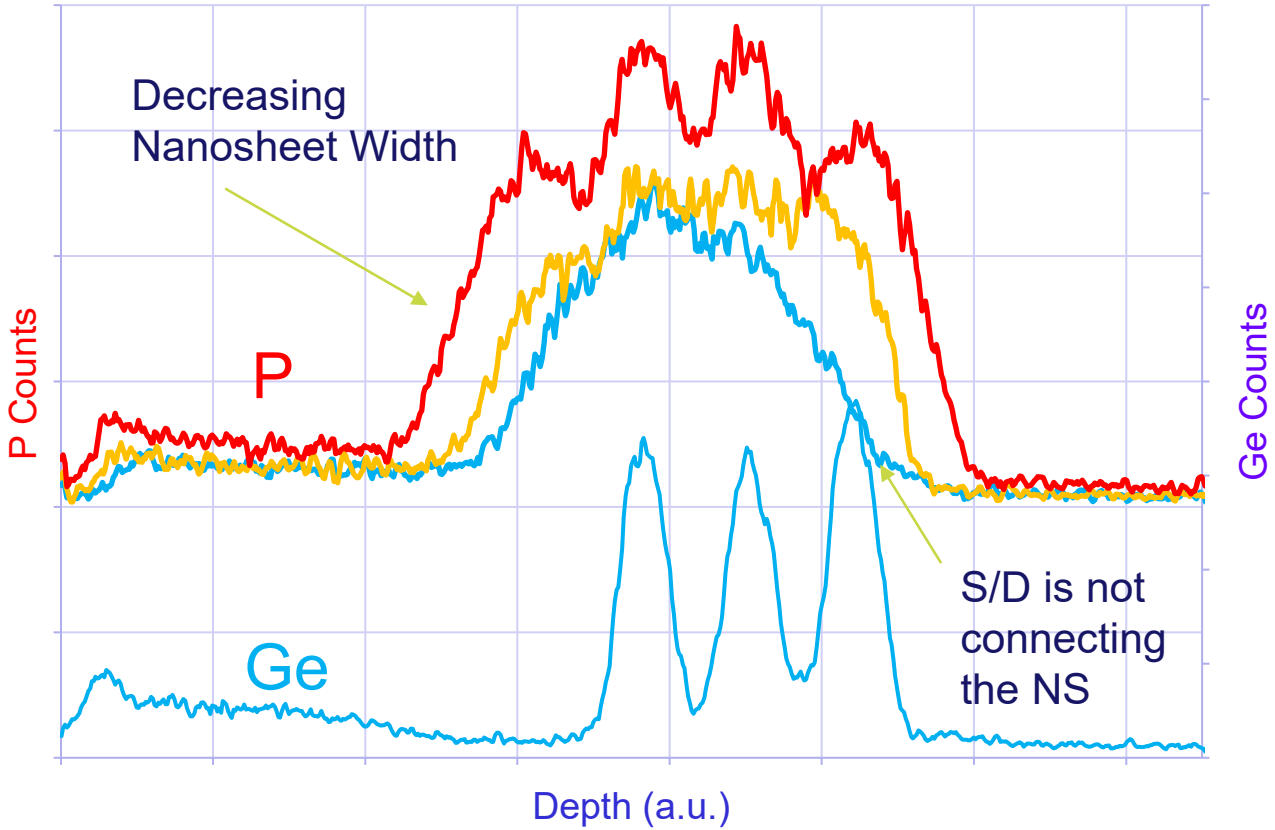




SiGe Epitaxy

SIMS Dopant Concentration After S/D of SiP is Grown Around the Fins





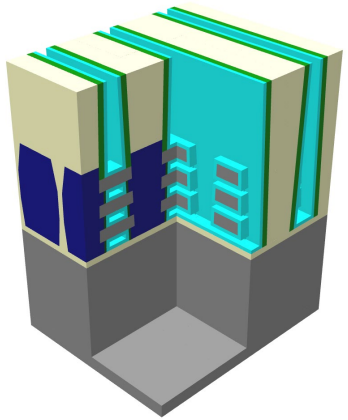
Quantitative P results enabled by Hybrid OCD-SIMS metrology

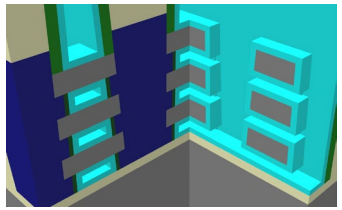
S. Schoeche et al., Proc. SPIE 12955, 2024

Dipole Thickness – XPS in HK/MG

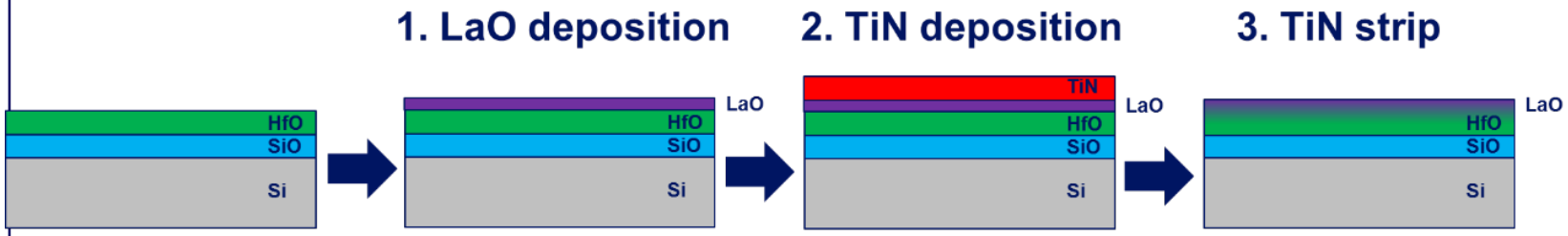
Challenge

LaOx dose & sub 5A thickness during the dipole process





XPS & XRF Thickness & Composition to Fine-Tune WF Metals

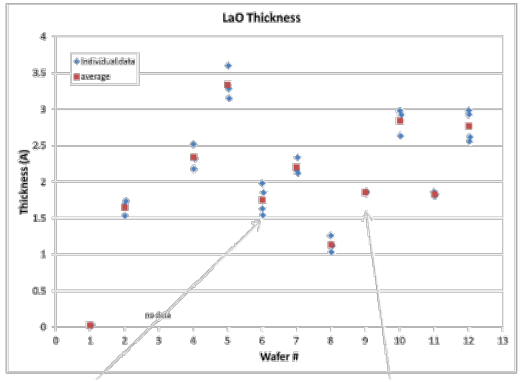


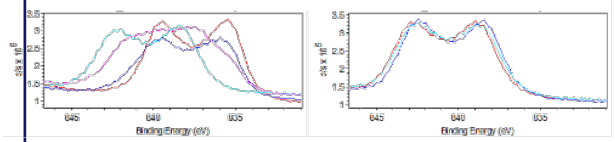
Measurements:
- LaO Thickness
- La Dose

Measurements:
- La Dose

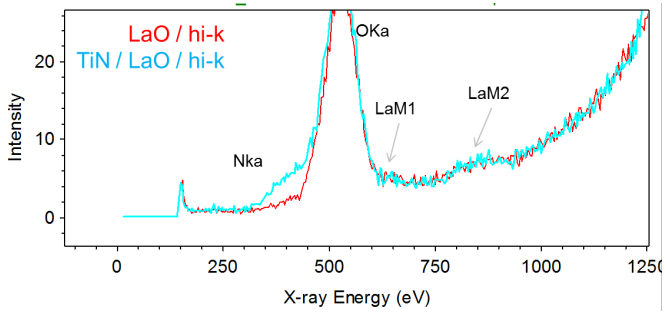
Measurements:
- La Dose
- La Centroid

XPS LaO thickness range ~ 0 - 3.5Å

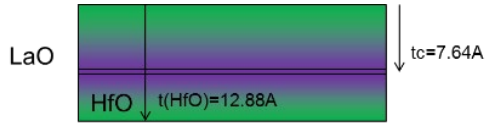




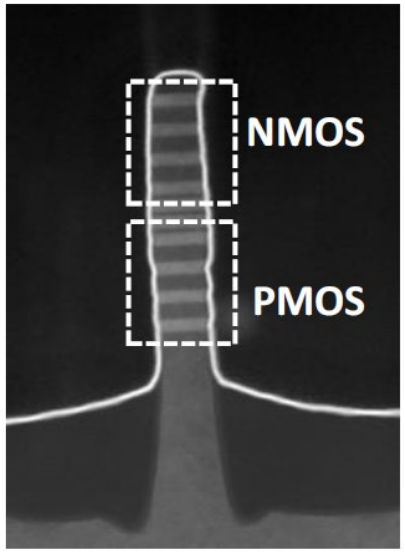
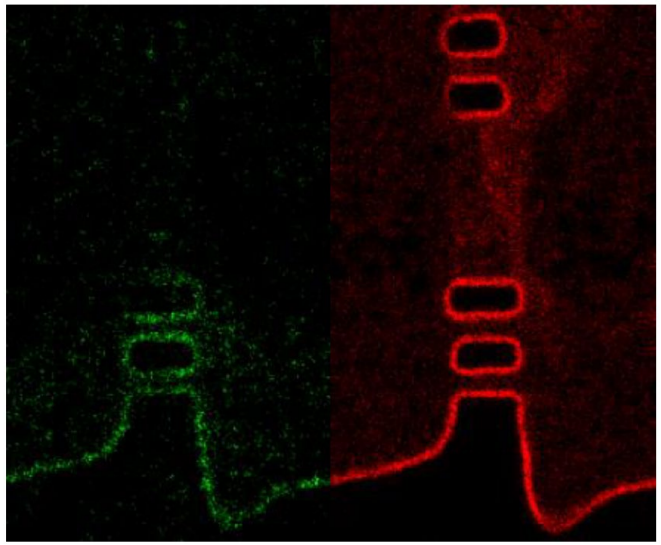
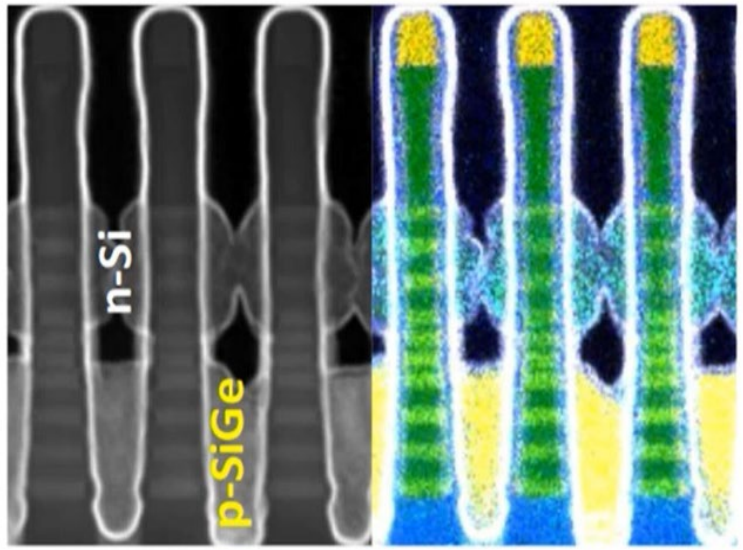
Consistent LaM1 and LaM2 XRF signal from with and without TiN cap layer



Mathematical model of La centroid thickness



In-line TEM with EDS in CFET Process Flow

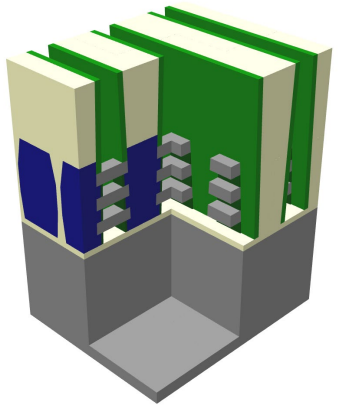
Challenge	EDS Visualization for CFET
Visualize the exact locations of the different material (elements) in the 3D structures	EDS shows that WF metals removed from the top of the CFET
	
	Different HK/MG films to enable independent Vt for each MOS
	Full Material separation
	
	Dual 3x3 CFET S/D

M. Radosavljevic et al., IEDM, 29-2, 2023

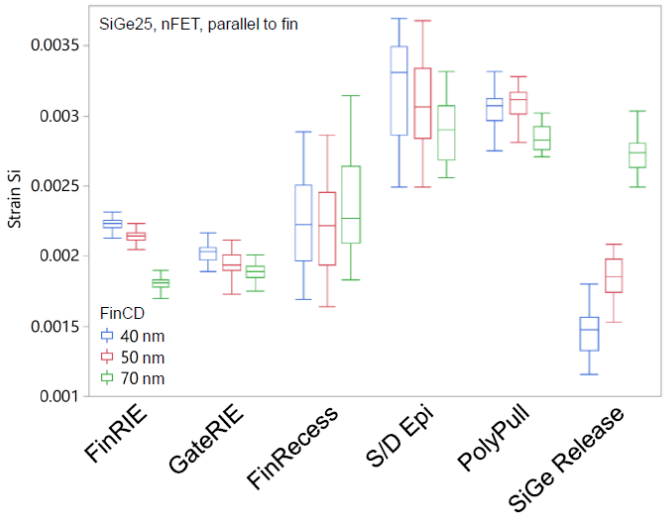
Strain Evolution – Raman Spectroscopy in GAA Process Flow

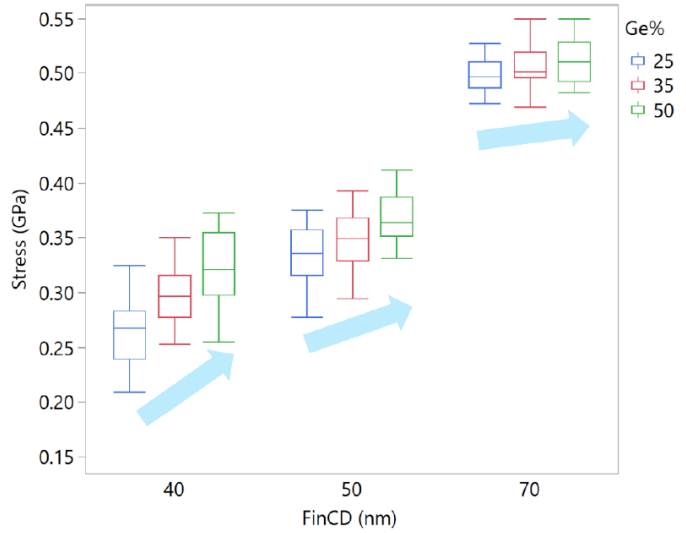
Challenge

GAA Si strain defines transistor performance



Monitor Stain Using Raman for nFET GAA





Si Channel strain evolution:

- Increases at Fin Recess & post S/D EPI
- Relaxation post SiGe release for small FinCDs

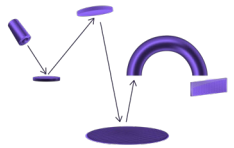
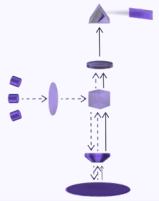
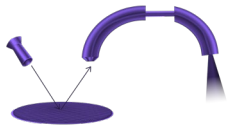
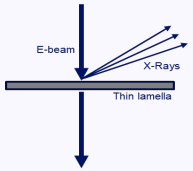
SiGe release step:

- Si channel tensile strain tuned by Ge% of sacrificial SiGe layers

D. Schmidt et al., Proc. SPIE 11611, 2021

Material Metrology Solutions

GAA Process Control

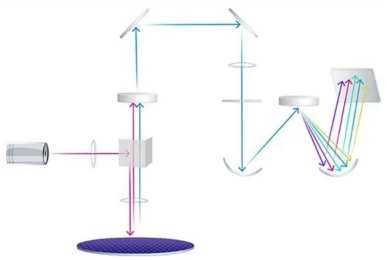
Used in High-Volume-Manufacturing Process Control		Main uses	Thickness	Composition	Stress & Strain	Dopant Concentration	SiGe Residue	Ge Diffusion	Depth Profiling
	**Inline XPS and XRF**	Surface sensitivity	●	●	○	○	●	○	○
	**Inline Raman Spectroscopy**	Strain, Phase, Crystallinity	○	●	●	●	●	○	○
	**Inline SIMS**	Depth profiling	●	●	○	●	○	●	●
	**TEM/EDS**	Full 3D dimensional and materials visualization	●	●	○	●	○	●	○

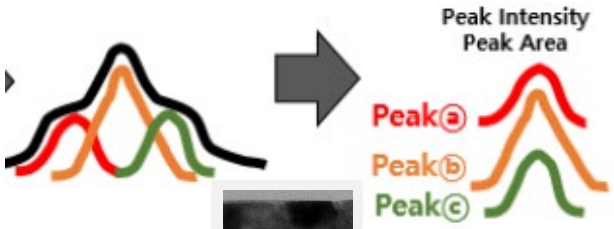
AI - Merge of Material Properties and Dimensions

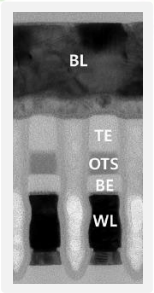
In the complex 3D GAA architecture dimensions and materials properties are closely connected.

AI helps to solve both challenges together. Two examples of using hybrid metrology with AI are presented.

TEM calibrated Raman peak intensity to train OCD for thickness measurements



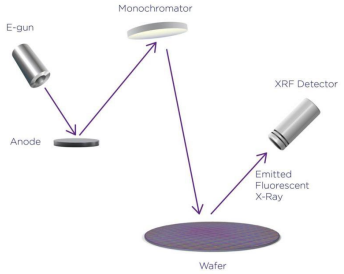


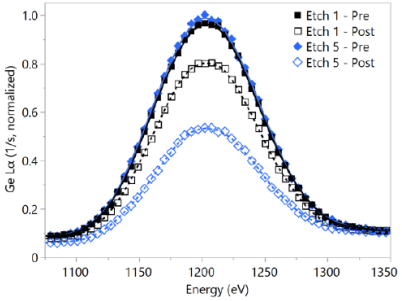


Raman Measurement
TEM calibrated

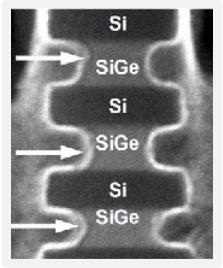
H. Ryoo et al., Proc SPIE 12955, 2024

TEM calibrated XRF delta (pre and post) for average SiGe GAA recess measurements by OCD





XRF Pre-Post Measurement
TEM calibrated



D. Schmidt et al., IEEE TSM, 2022

Summary & Conclusions

Materials play a pivotal role in the path forward for logic

Multiple challenges addressed by a variety of techniques

Lab to Fab: a spectrum of technologies and a complex transition

Raman, SIMS, XPS, EDS and others provide solutions to critical challenges in GAA and future architectures

Material & dimensional solution can be merged using AI & modeling

Materials metrology solutions are critical for the future

Acknowledgments

IBM

- In-line Raman spectroscopy for stacked nanosheet device manufacturing, SPIE, 2021
- From Lab to Fab: In-line SIMS for Process Control in Semiconductor Manufacturing, SPIE, 2024

Samsung

- On-Cell Thickness Monitoring of Chalcogenide Alloy Layer using Spectral Interferometry, Raman spectroscopy, and Hybrid Machine Learning, SPIE, 2024

Intel

- New Materials Systems for Moore's Law Continuation, IEDM, 2023
- Demonstration of a Stacked CMOS Inverter at 60nm Gate Pitch with Power Via and Direct Backside Device Contacts, IEDM, 2023

TEL

- Process Technology toward 1nm and beyond, IEDM, 2023

imec

- Based discussion and papers by Dr. Paul van der Heide

Nova

- Avron Ger, Dr. Igor Turovets

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Thank You

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