Advances in 4D-STEM for Applications in Phase Analysis and Strain Engineering

Daniel Nemecek

TESCAN Group

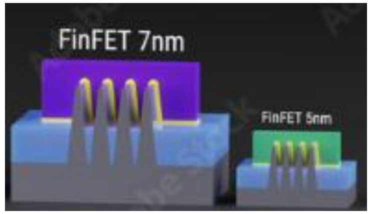
Agenda

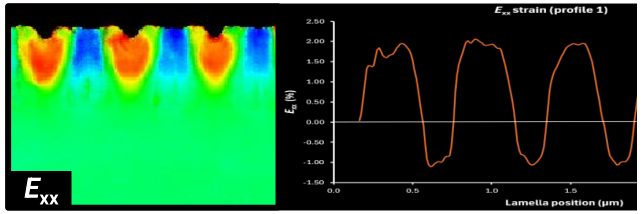
01	Analytical 4D-STEM Applications in Semiconductors
02	Quantitative Phase Analysis of Polymorphic Thin Films
03	Characterization of Crystallinity in Device Failure Analysis
04	Strain Analysis in Advanced Nodes (FinFET, C-FET)
05	Summary and Q&A

01 Analytical STEM and 4D-STEM Applications

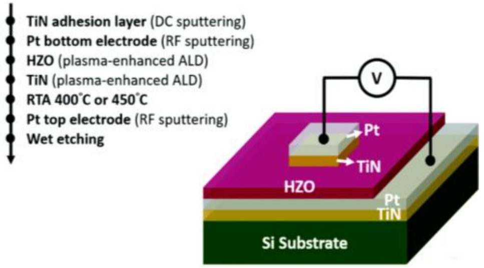
Needs for Analytical STEM in Semiconductors

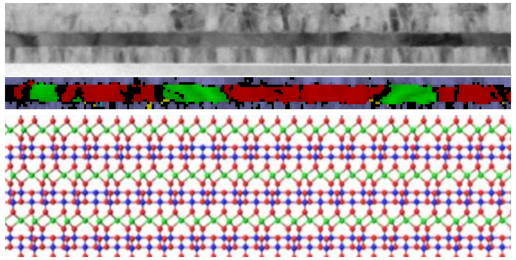
- ***Research & Development***
  Development of new and improved devices comprises both modelling and experimental validation, such as the case of strain engineering or electric field distribution at PN junctions. Analytical STEM plays an essential role as the experimental technique in these R&D projects.



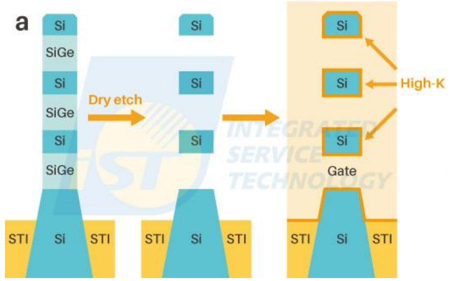


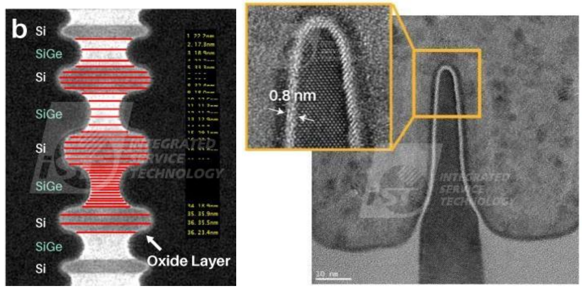
- ***Process Development & Failure Analysis***
  Efficient development and scaling of a new device production requires both functional and structural feedback, the latter provided by analytical STEM. The structure and composition of these samples can be variable, requiring flexible, robust methods. Most cases are addressed by STEM metrology, complemented by EDX elemental mapping. New technologies and materials require 4D-STEM for the characterization of crystallinity.





- ***Near-line Production Monitoring***
  Production of devices is monitored at individual processing steps to minimize waste and scrap downstream in the production. The samples are well known and defects identified as deviations. STEM metrology is sufficient in most cases, complemented by EDS and EELS analysis when needed.





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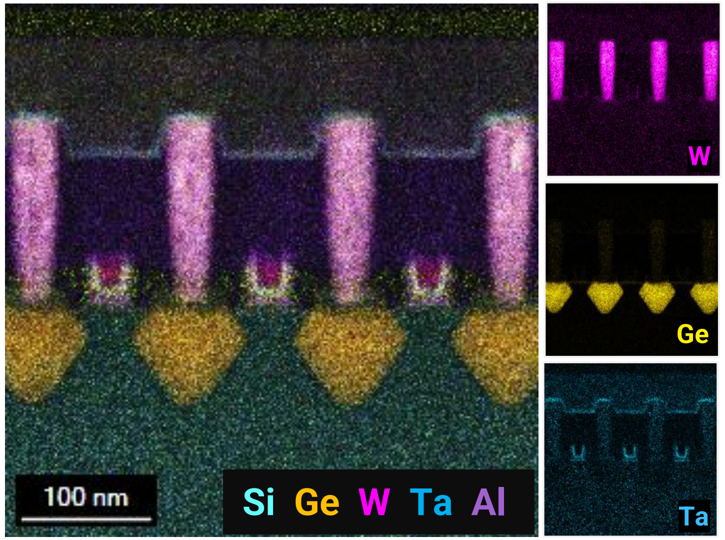
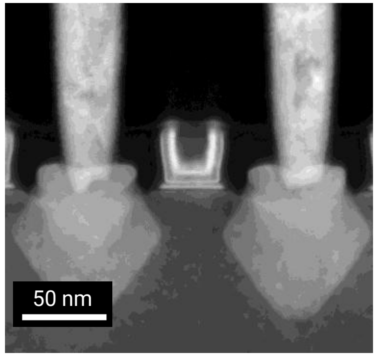
Analytical Scanning Transmission Electron Microscopy

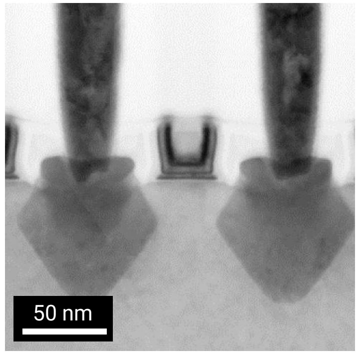
EDX elemental mapping

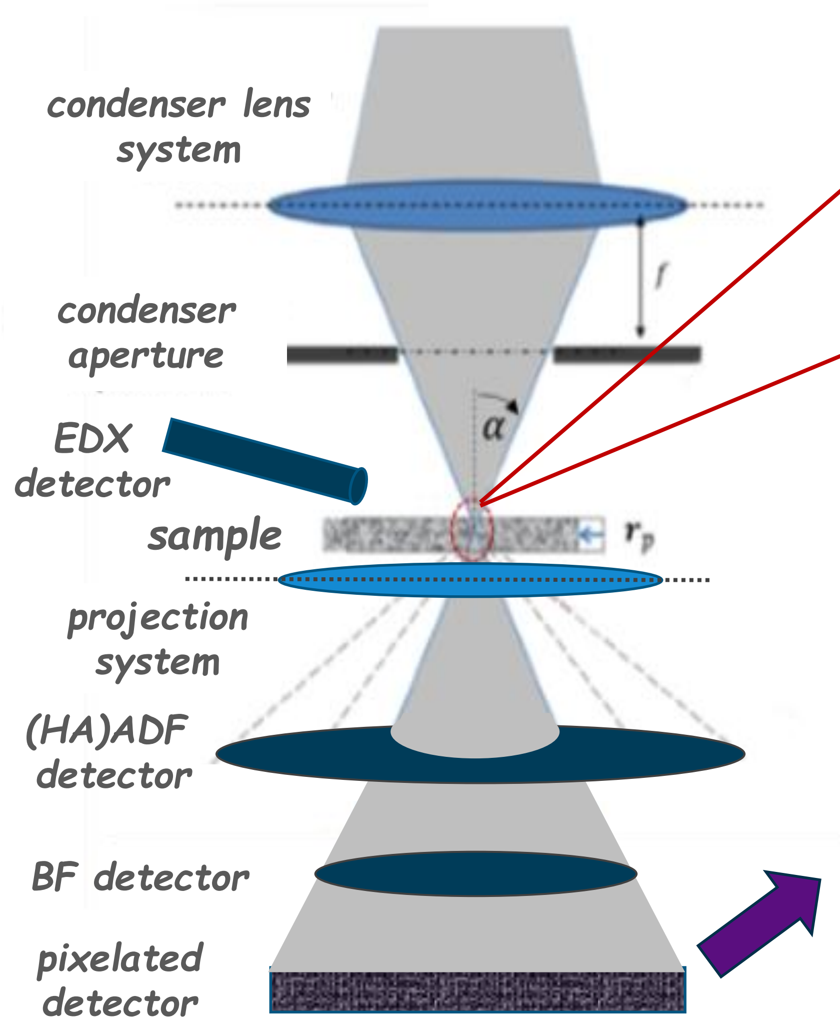


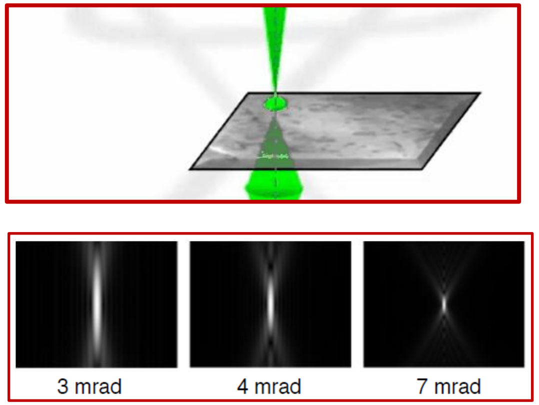
DF STEM



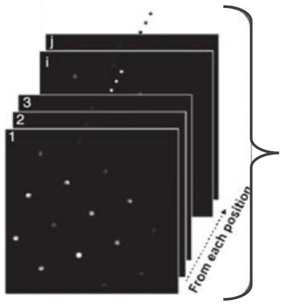
BF STEM







Structural information



diffraction patterns

- Phase mapping
- Orientation mapping
- Strain measurements
- Electric field measurements
- 3D structure determination

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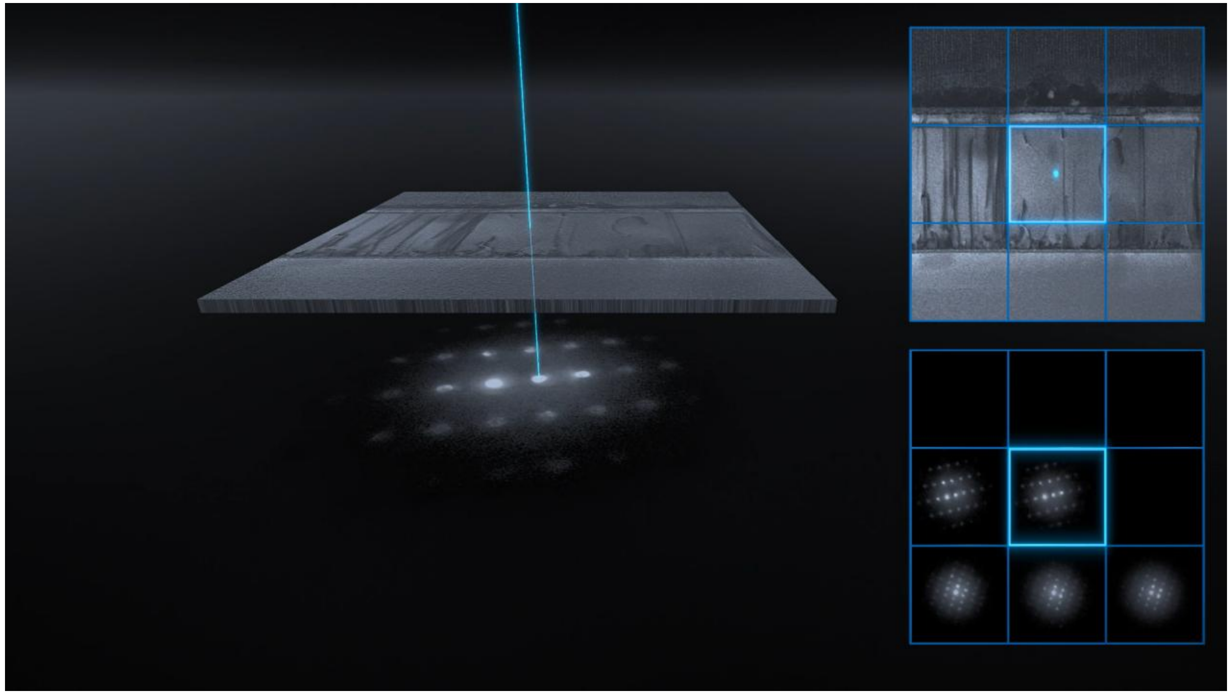
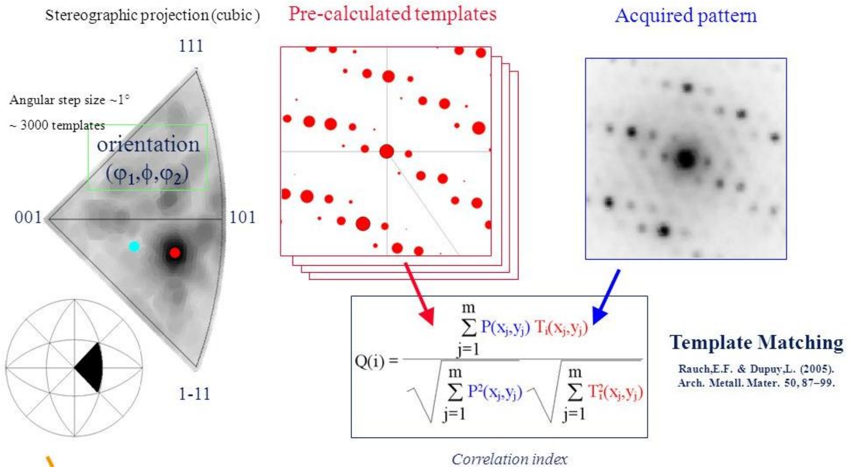
4D-STEM Measurements

- Collection of diffraction patterns at every pixel
- Nanobeam diffraction of transmitted electrons
- Spatial resolution of 1-2 nm (using FEG STEM)
- Fast analysis of large sample areas (< 30x30µm^2)



Automated crystallographic orientation mapping

- Template matching of acquired diffraction patterns
- Requires known structural file(s) for templates
- High angular resolution and large FOV possible
- Specimen is not specifically tilted
- Edgar Rauch and Muriel Veron (2005)



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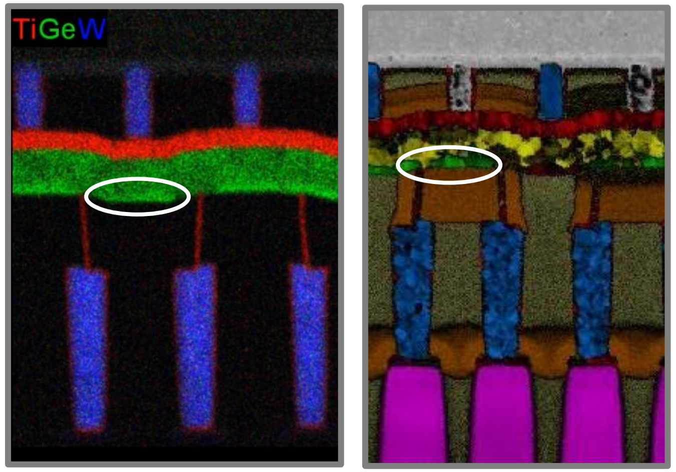
Challenges in Analytical STEM Characterization

❖ Failure Analysis

Defects not revealed by STEM

Defects not revealed by EDS

Fast feedback for production

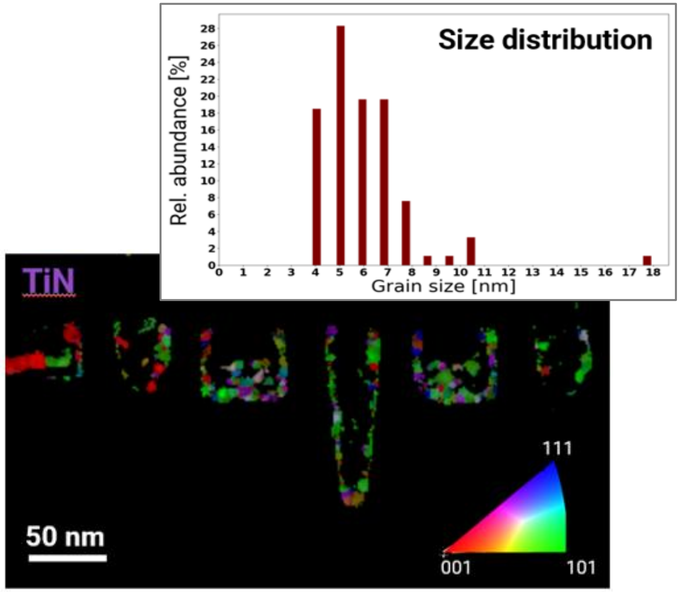


❖ Process Development

Quantification of amorphization

Quantification of minor phases

Crystalline grain size distribution



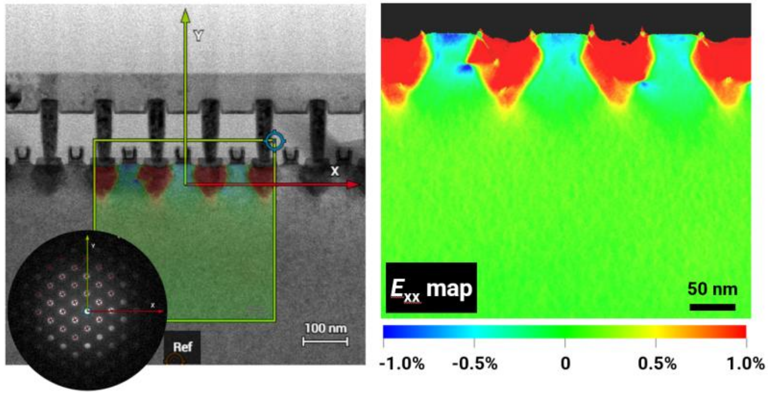
❖ Strain engineering

Validation of strain simulations

Accuracy, precision, reproducibility

Sufficiently fast time to results

Sufficiently high spatial resolution



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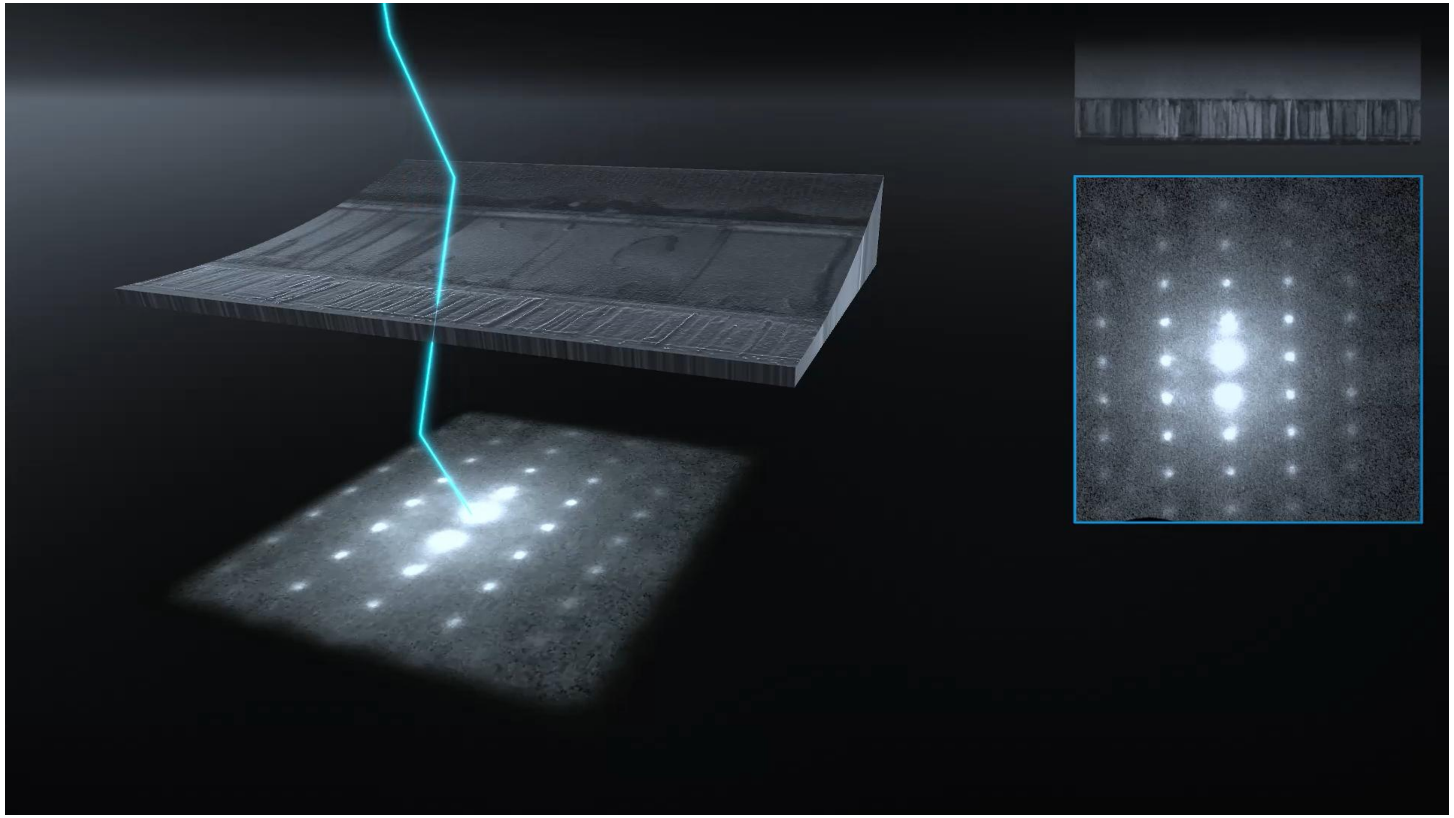
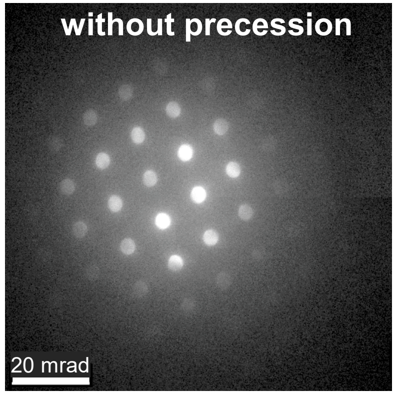
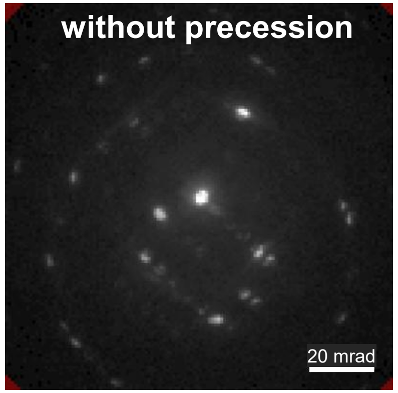
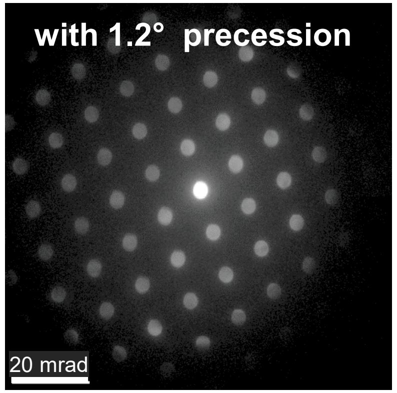
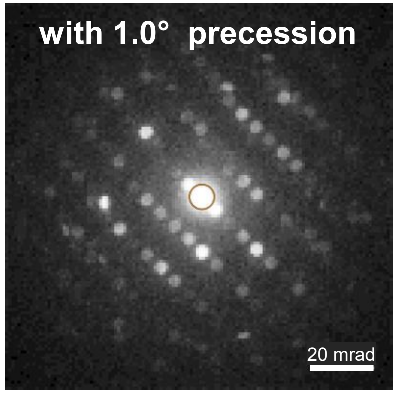
Enhancing Diffraction Data Quality by Beam Precession











- Intensity within spots is more homogeneous and Kikuchi lines are averaged out
- Higher order Bragg spots are excited and observed in diffraction patterns
- Observed spot intensities correspond better to kinematical intensities

R. Vincent and P. A. Midgley (1994)

TENSOR: Streamlined Analytical STEM Platform for Sample Analysis

Fully automated workflows

Guided, application-driven workflows deliver consistent and repeatable outcomes by any operator anytime as no manual alignments or parameter tuning are required.

Unified control environment

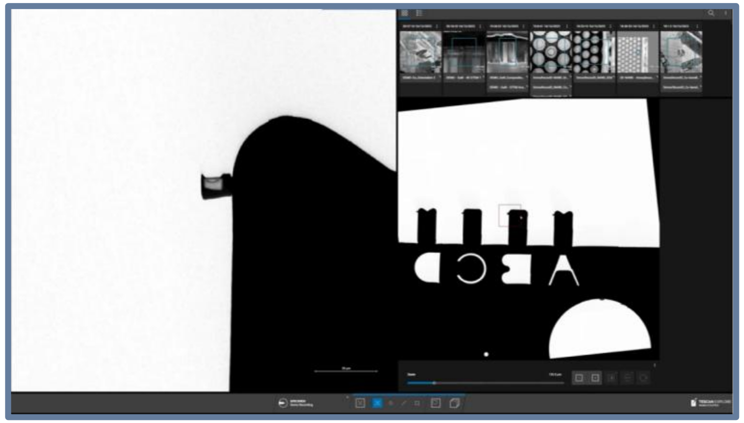
All hardware integrated into a single and intuitive software interface with data processing and analysis.

Click-to-result simplicity

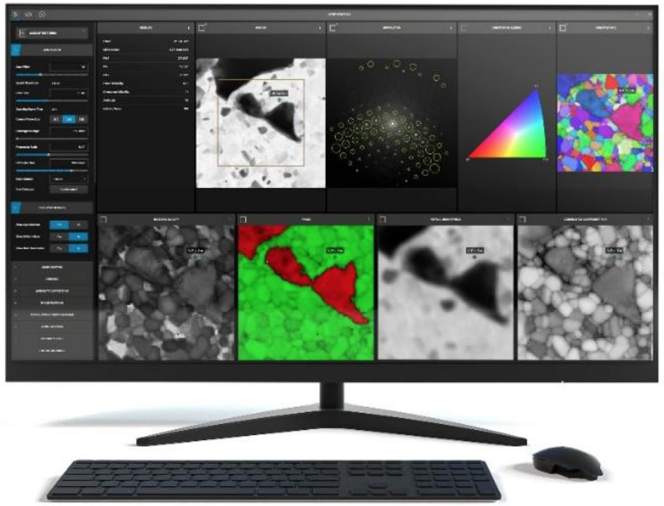
Fast data collection enables on-the-fly data processing and interactive sample analysis in just few minutes.

Select a Region of Interest (ROI) → Choose measurement → Set acquisition parameters → Acquire and analyze data

Sample overview for ROI navigation



Data collection and processing



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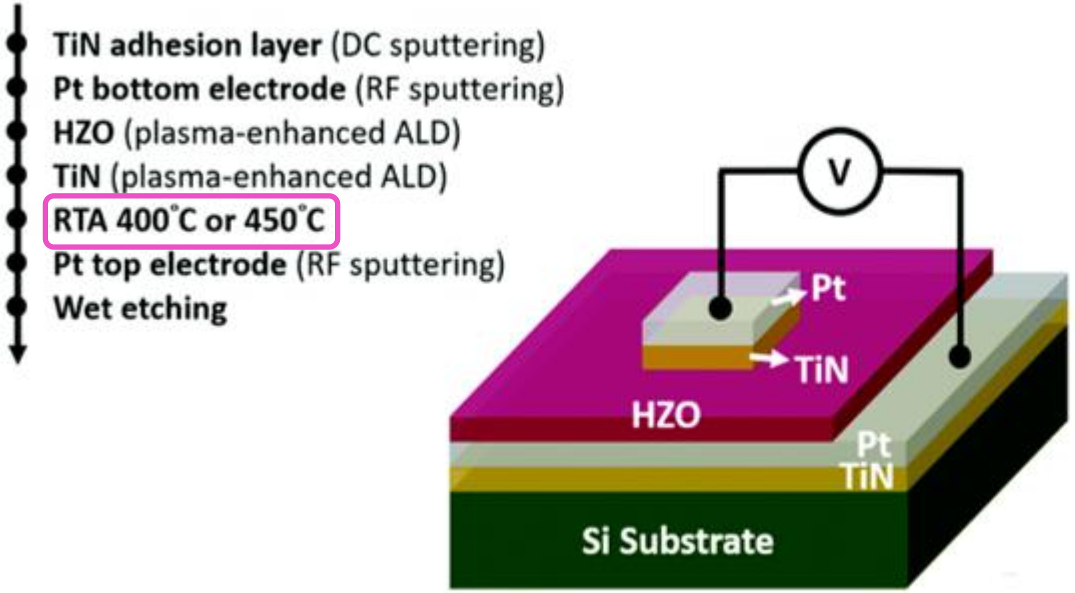
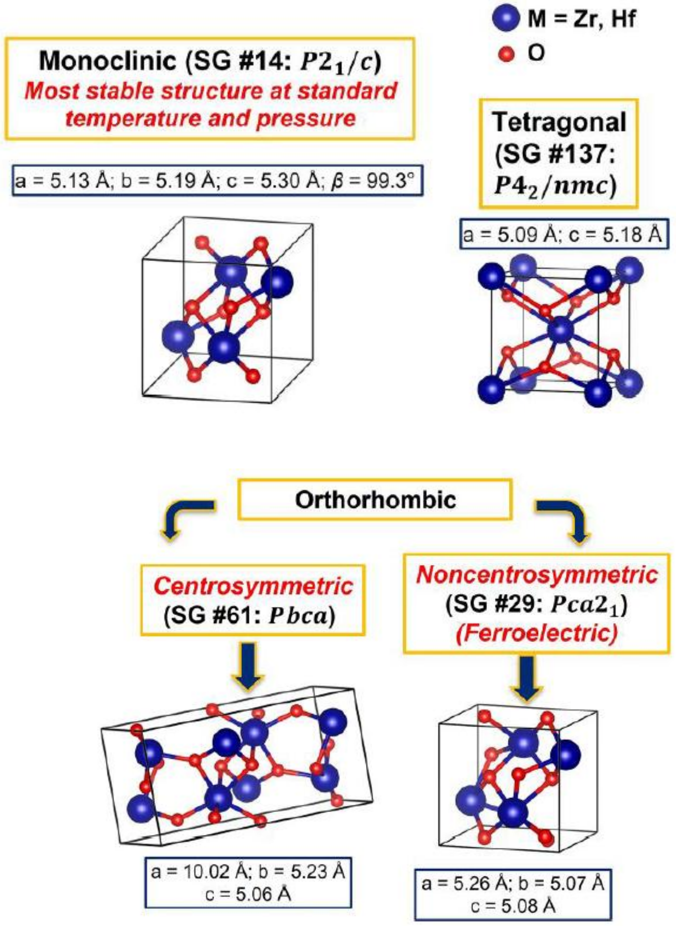
02

Phase Analysis: A Case Study of HZO

Quantitative Analysis of HZO Phase and Grain Distribution

Preparation process of HZO-based FE-FETs





- Low-temperature anneal may fail to produce ferroelectric behavior.
- Higher anneal temperatures increase polarization.
- Mechanical stress from electrodes or seeding layers may alter the formed HZO phase, favoring the desirable orthorhombic phase.

A.C. Diebold, et al., *Microsc. Microanal.*, 2025, **31**, ozaf019

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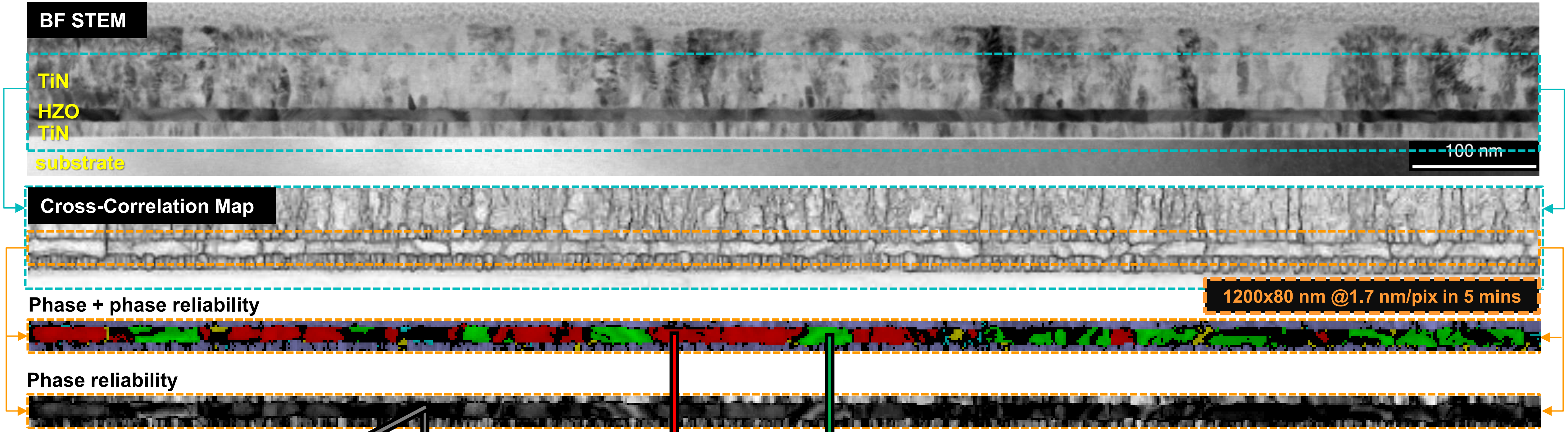
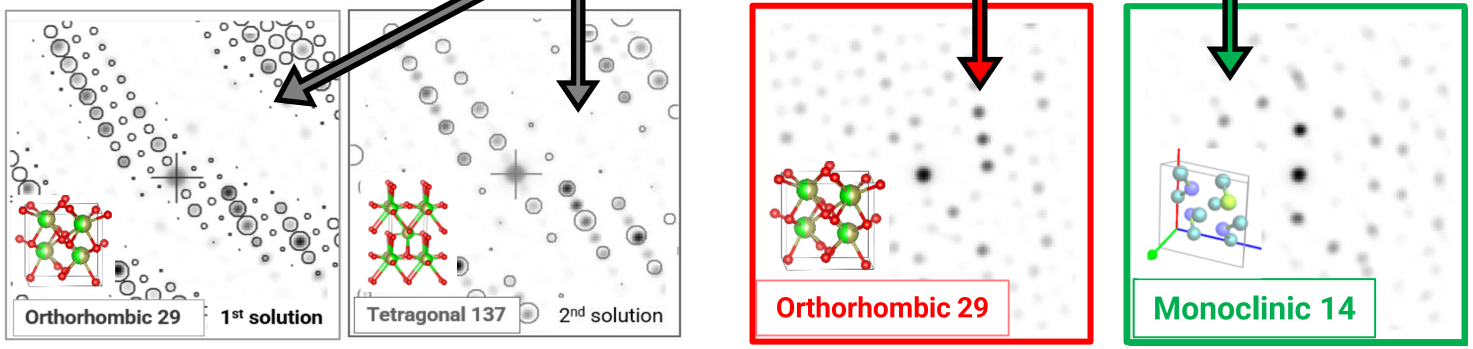
Quantitative Analysis of HZO Phases in an Annealed Thin Film





Phases	Fraction
HZO – monoclinic 14	51%
HZO – tetragonal 137	2%
HZO – orthorhombic 29	40%
HZO – orthorhombic 61	7%

A.C. Diebold, et al., *Microsc. Microanal.*, 2025, **31**, ozaf019

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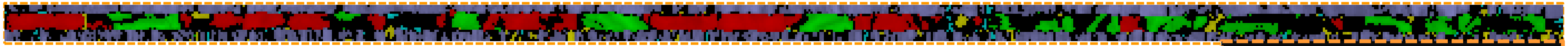
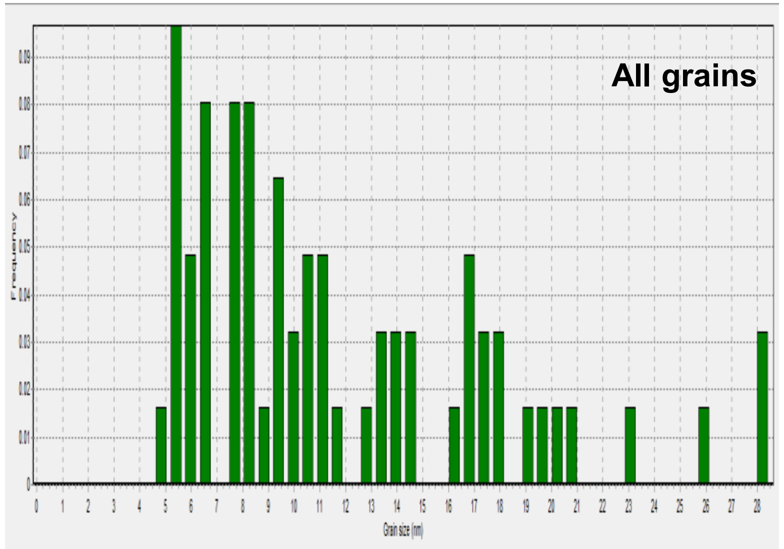
Quantitative Analysis of HZO Phase and Grain Distribution

Phase + phase reliability

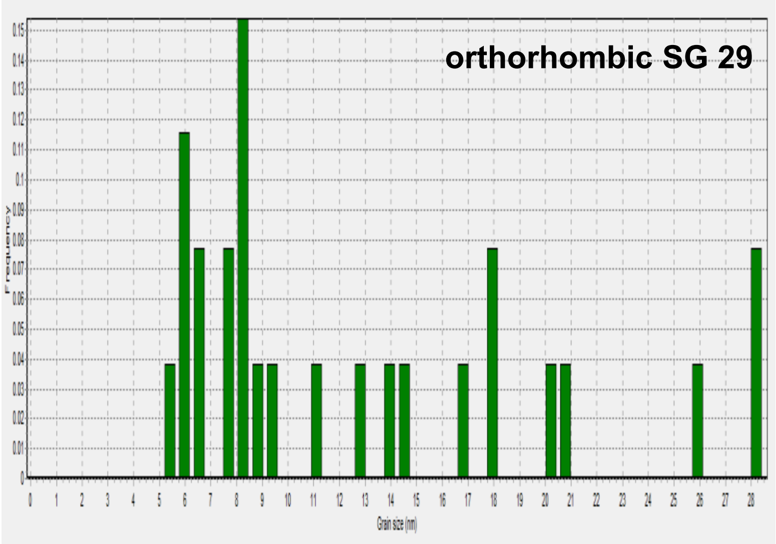


1200x80 nm @1.7 nm/pix in 5 mins

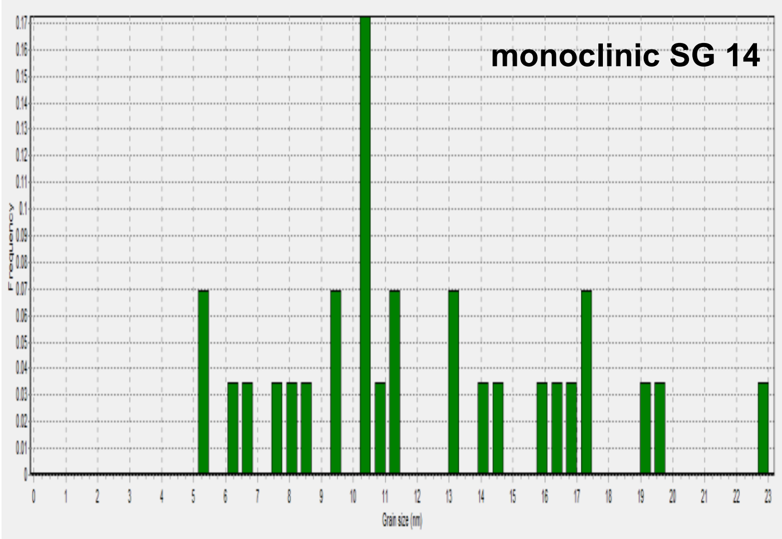
Grain boundary map



Average grain size: 11.8 nm



Average grain size: 12.8 nm



Average grain size: 12.2 nm

Min grain size set as 3*step size = 5nm
Truncated grains disregarded to keep only HZO phases

A.C. Diebold, et al., *Microsc. Microanal.*, 2025, **31**, ozaf019

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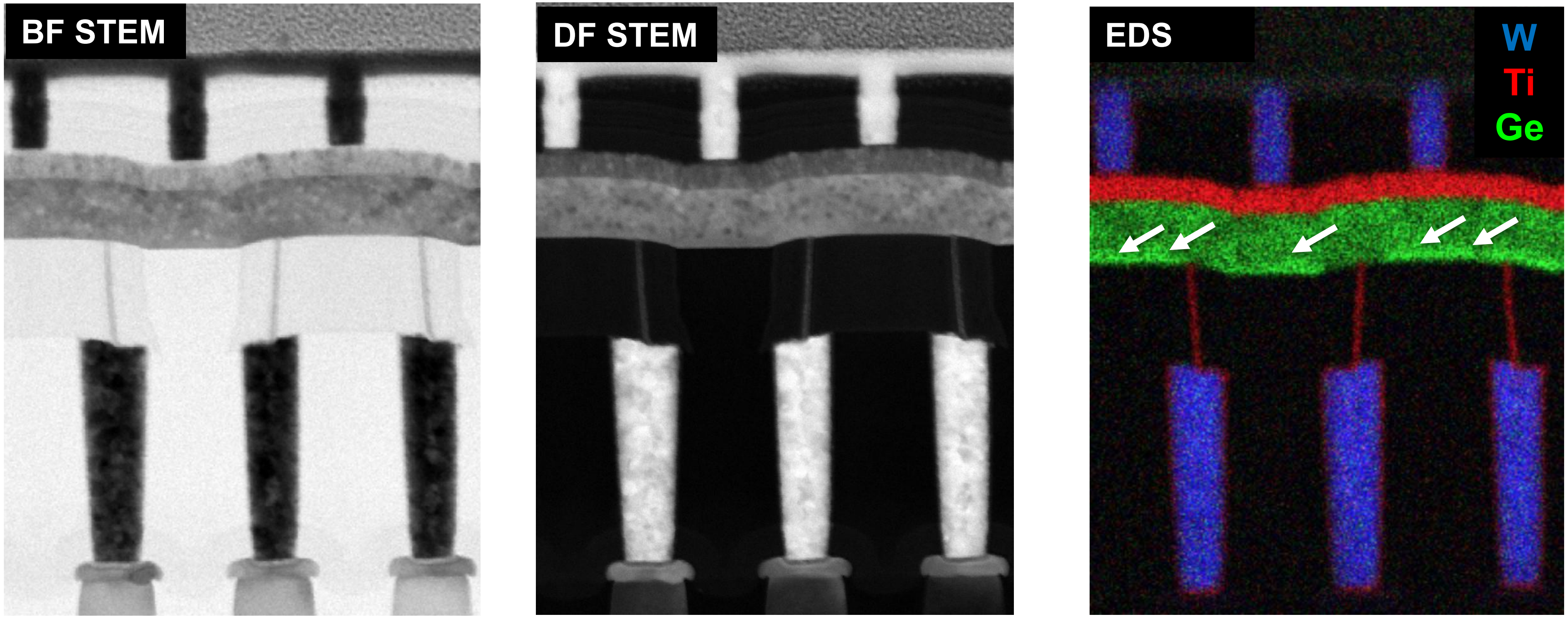
03 Crystallinity in FA: A Case Study of PCM

Assessing Composition and Crystallinity in Failure Analysis



Conventional characterization using BF/DF STEM imaging and EDS mapping

(PCM device, courtesy of STMicroelectronics)

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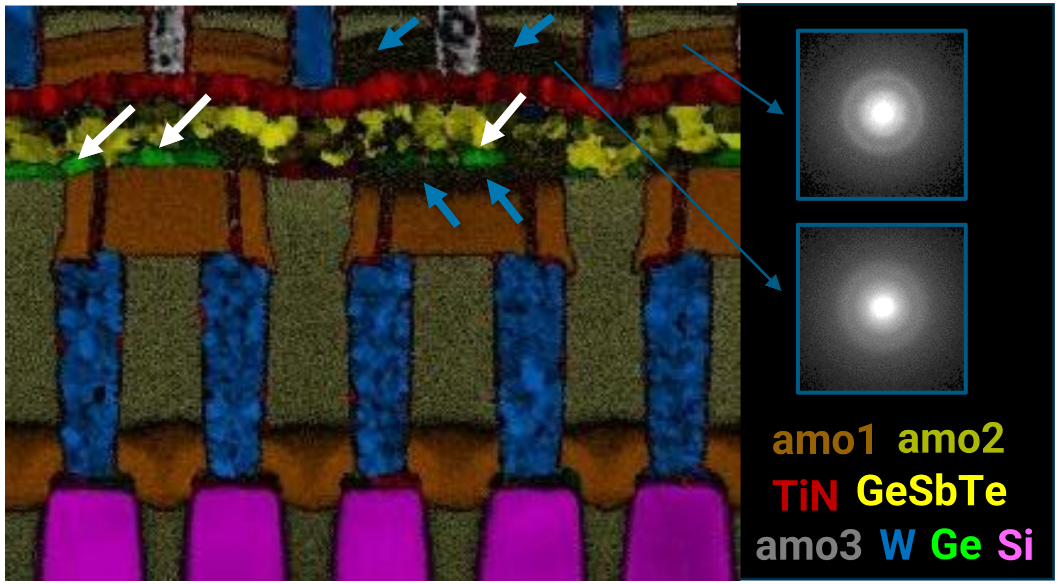
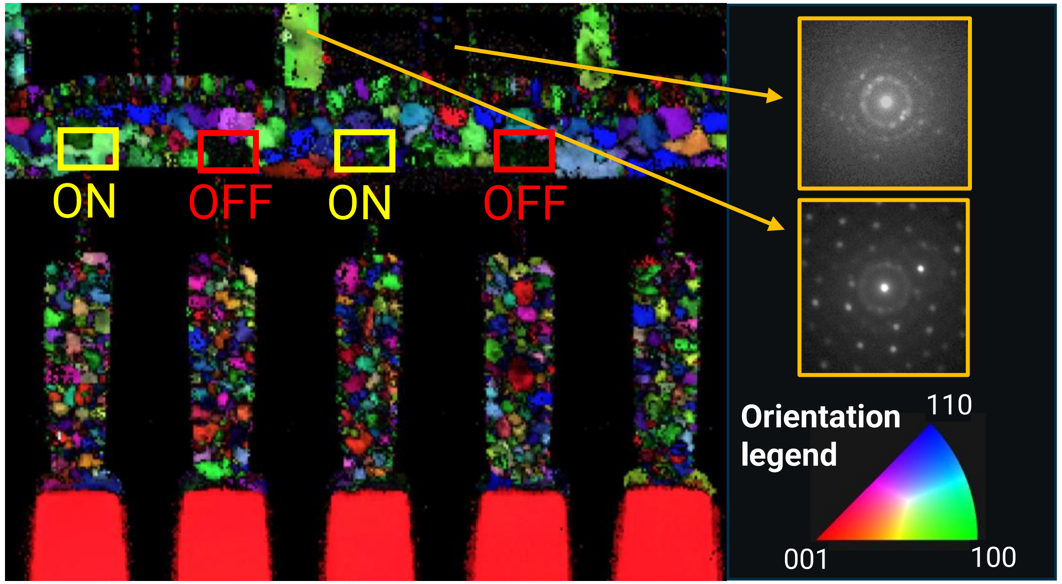
Assessing Composition and Crystallinity in Failure Analysis

4D-STEM Phase Map (total 12 mins)



4D-STEM Orientation Map (total 12 mins)



- Separation of germanium from the GST layer
- Amorphization of layers in one PCM element

- Alternating crystallinity in the tungsten vias
- ON and OFF states of the PCM memory cells

Advanced characterization using precession-assisted 4D-STEM phase-orientation mapping

(PCM device, courtesy of STMicroelectronics)

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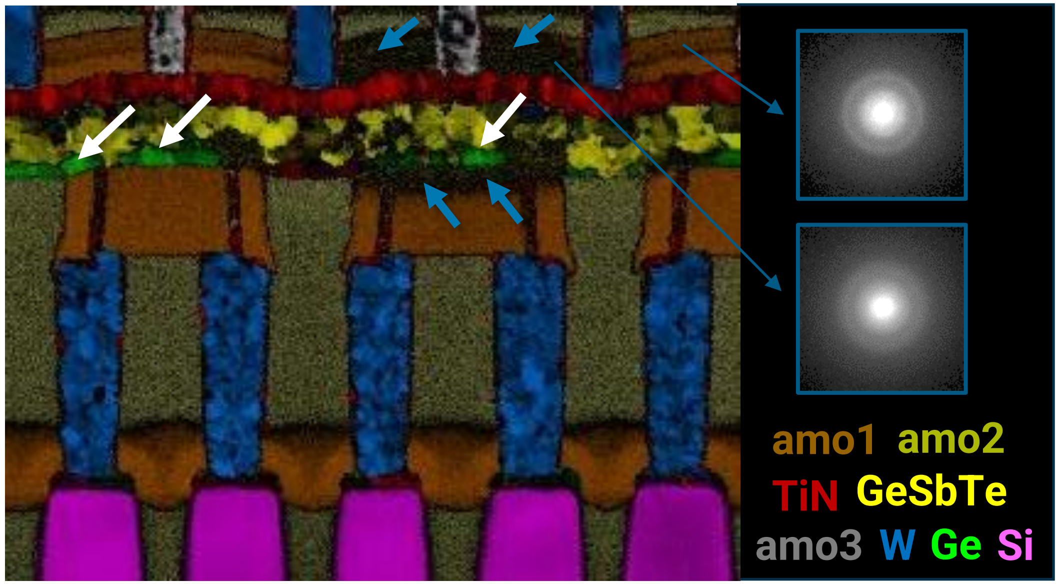
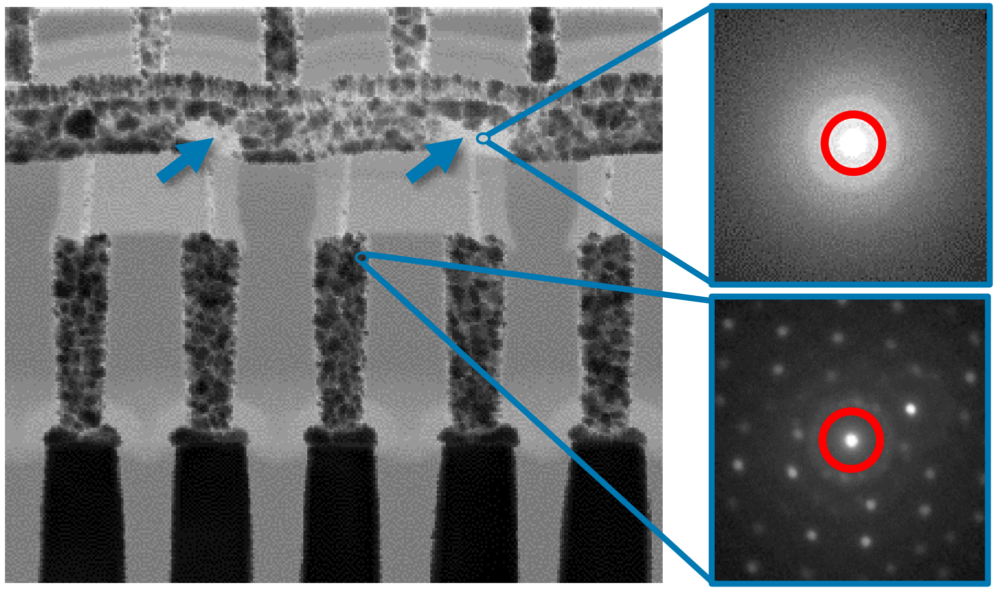
Assessing Composition and Crystallinity in Failure Analysis

4D-STEM Phase Map (total 12 mins)



Virtual ADF-STEM Map (total 5 mins)



- Separation of germanium from the GST layer
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- ON and OFF states of the PCM memory cells

Advanced characterization using precession-assisted 4D-STEM phase-orientation mapping

(PCM device, courtesy of STMicroelectronics)

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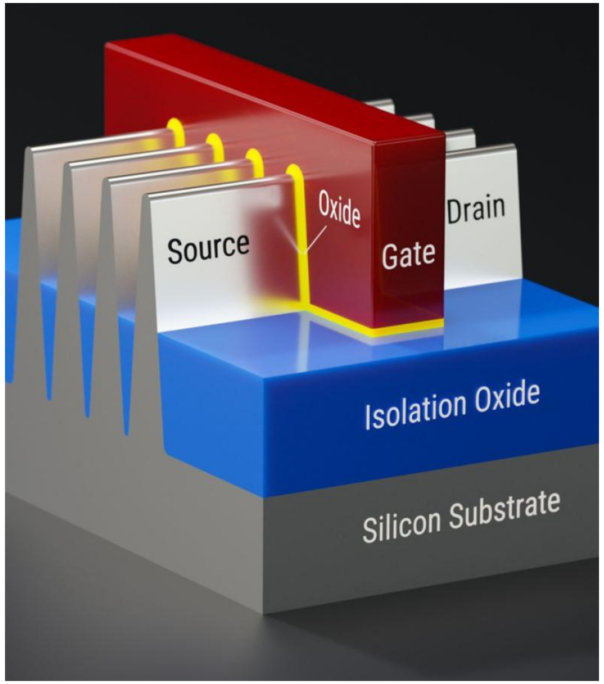
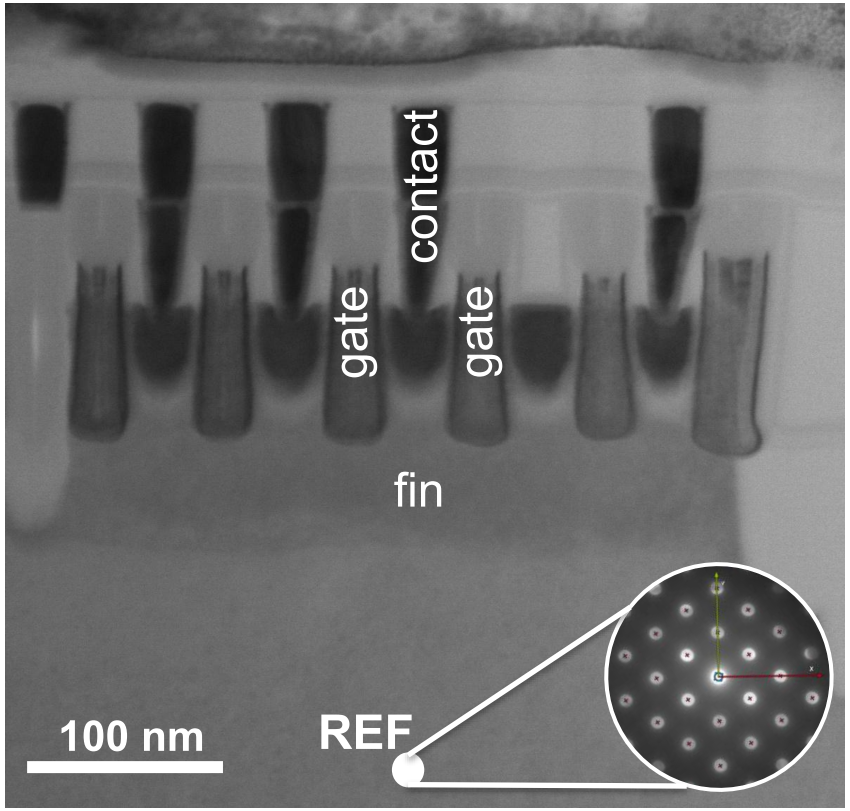
04 Strain Analysis: A Case Study of a 5-nm FinFET circuit

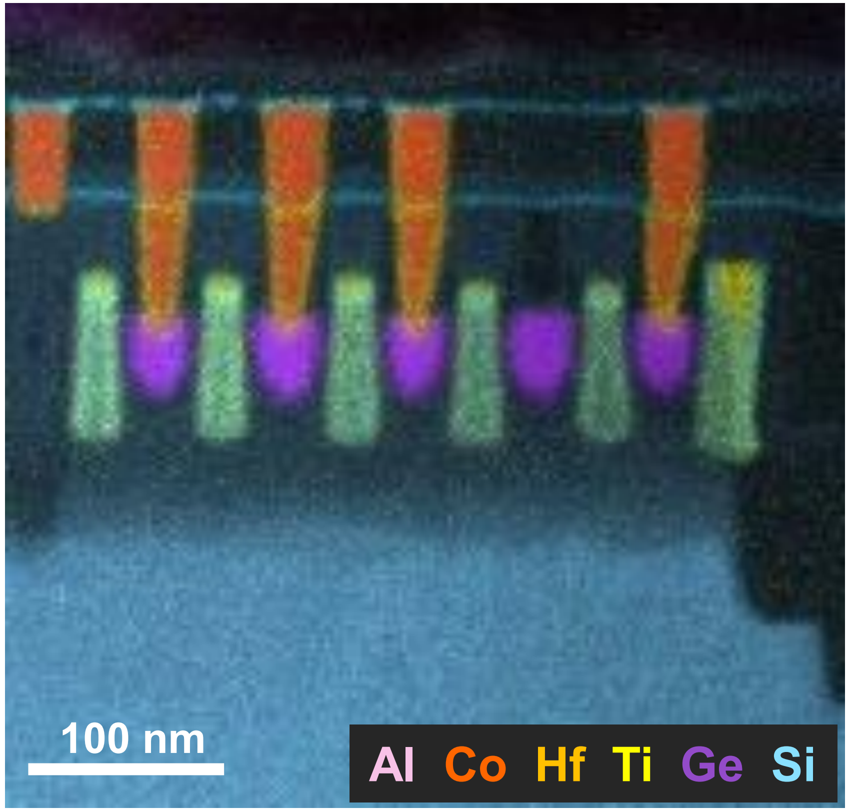
Fast and Intuitive Strain Analysis of a FinFET Circuit



FinFET Architecture



Bright Field STEM image



EDX multi-elemental map

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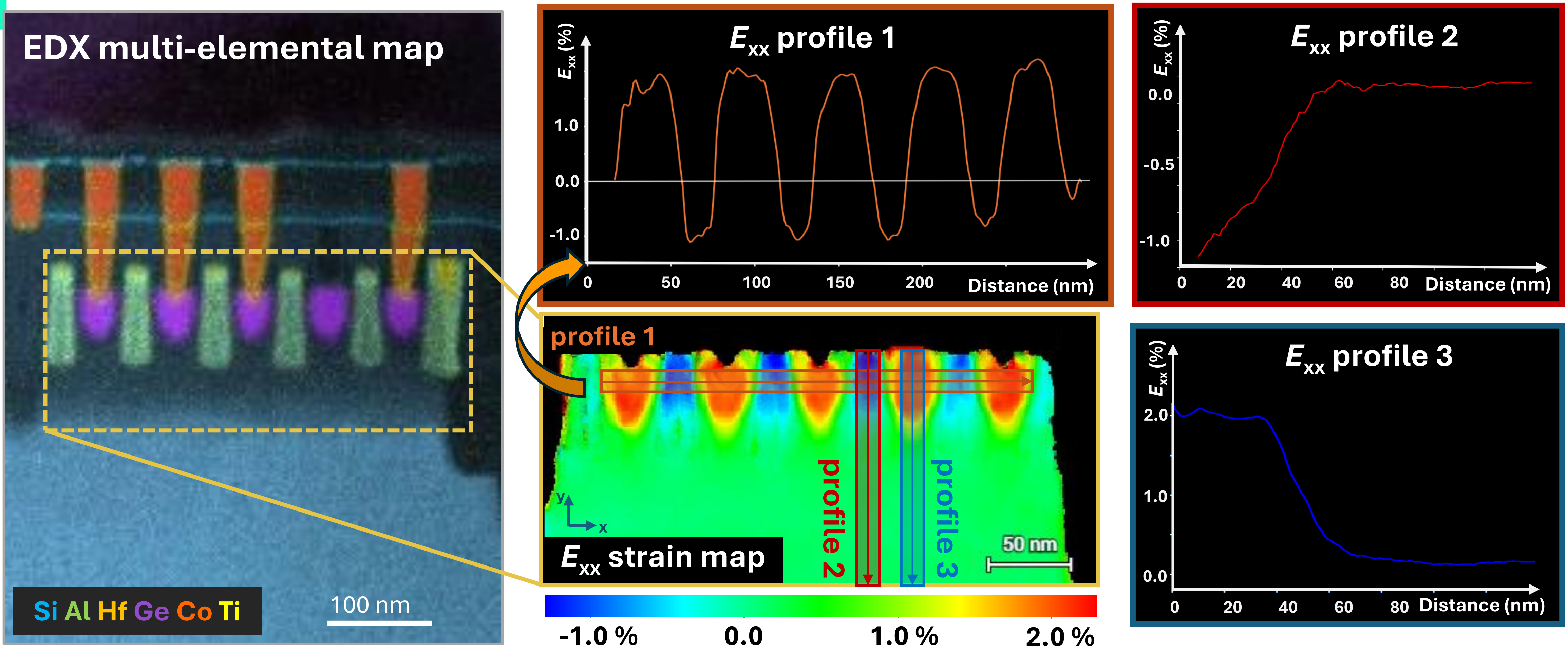
Fast and Intuitive Strain Analysis of a FinFET Circuit



Tescan TENSOR

- Accurate strain results even at regions with more phases
- High precision results due to precession-assisted diffraction
- Fast time to results (300x150nm map @1.1 nm/pix in 3 mins)

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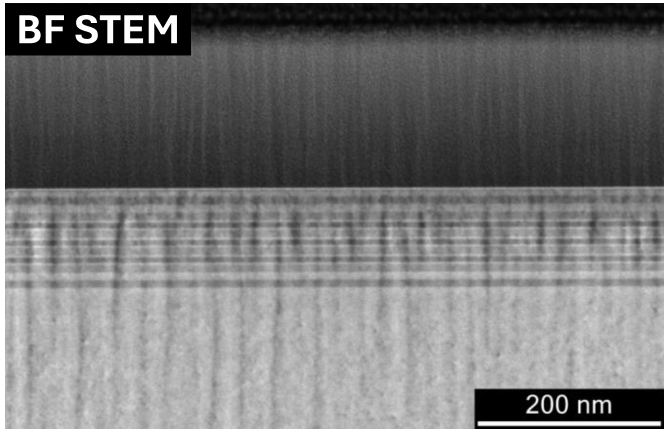
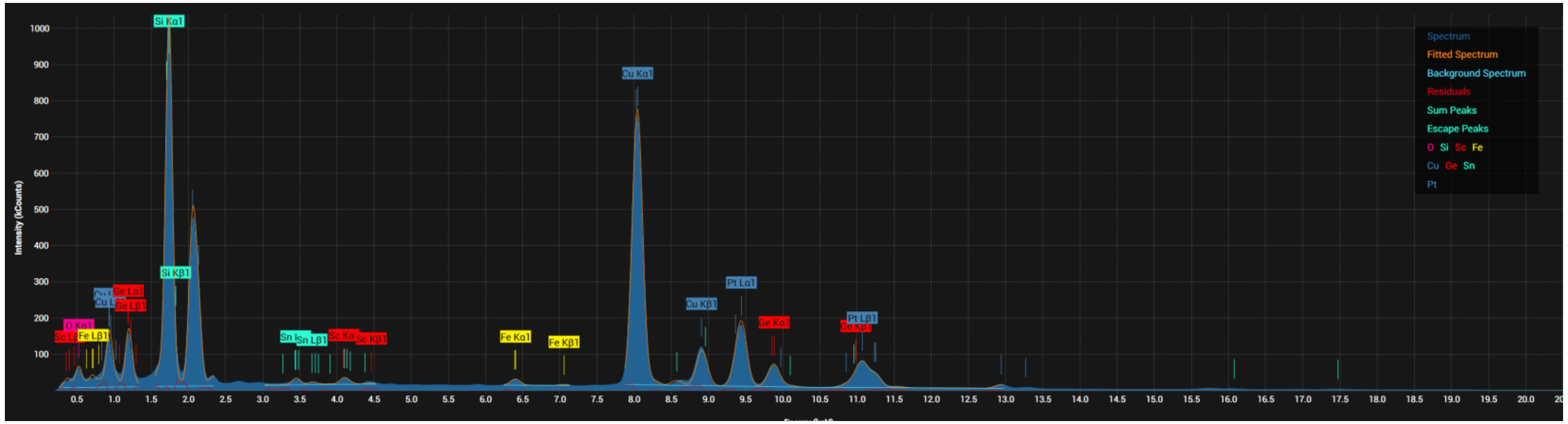
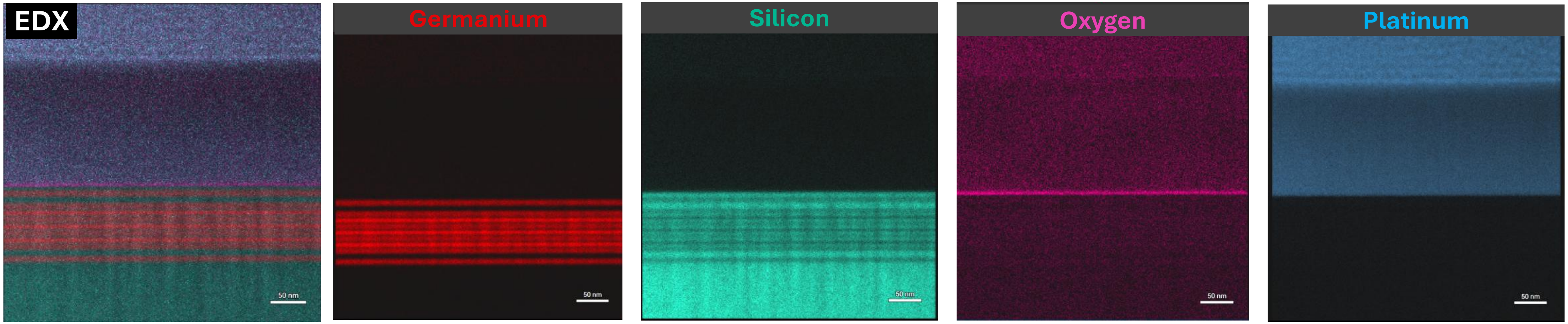
05 Strain Analysis: A Case Study of Si-Ge Multilayers

Benchmark NBED Strain Analysis with Precise Alignments







Epitaxial Si-Ge multistack as used for CFET devices (courtesy of imec)

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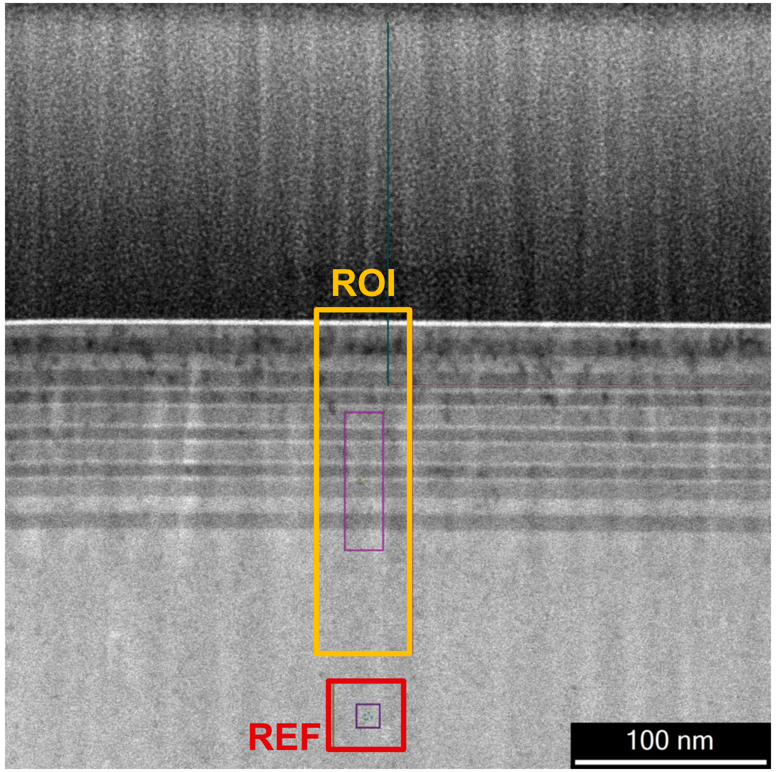
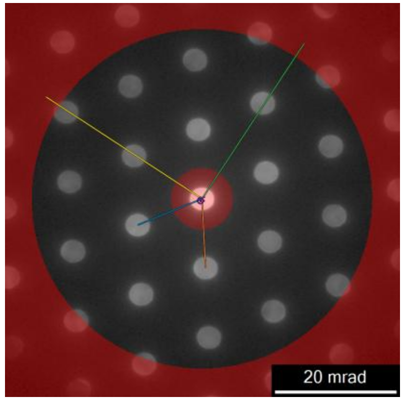
Benchmark NBED Strain Analysis with Precise Alignments

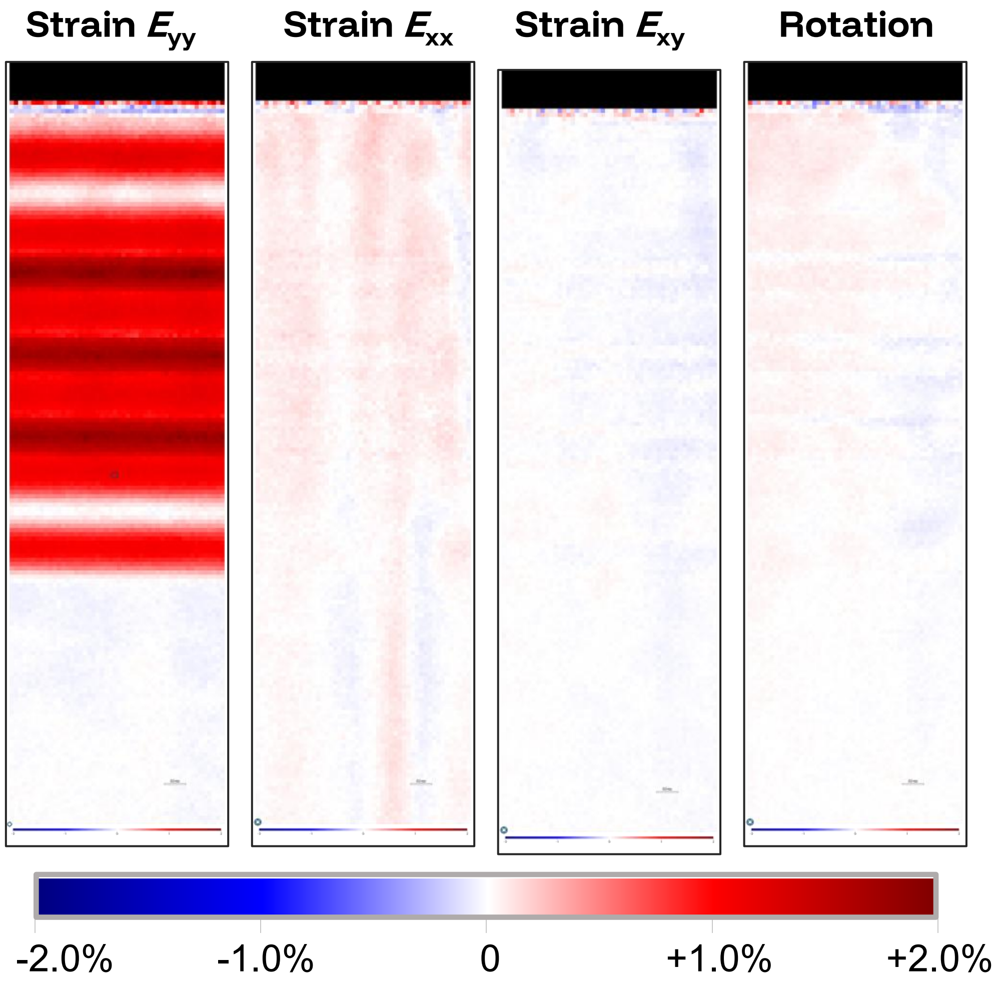
BF STEM overview



Reference Diff. pattern



Epitaxial Si-Ge multistack as used for CFET devices (courtesy of imec)



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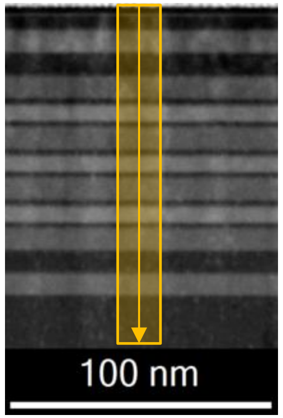
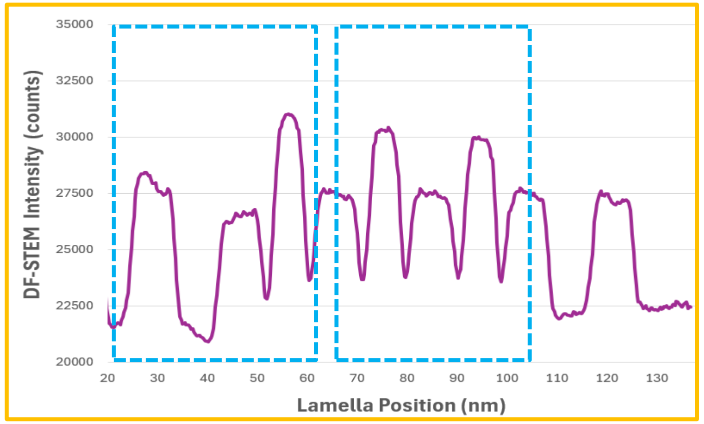
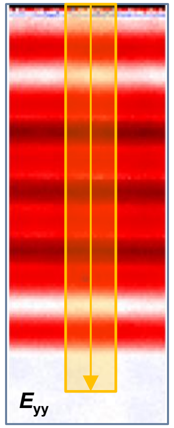
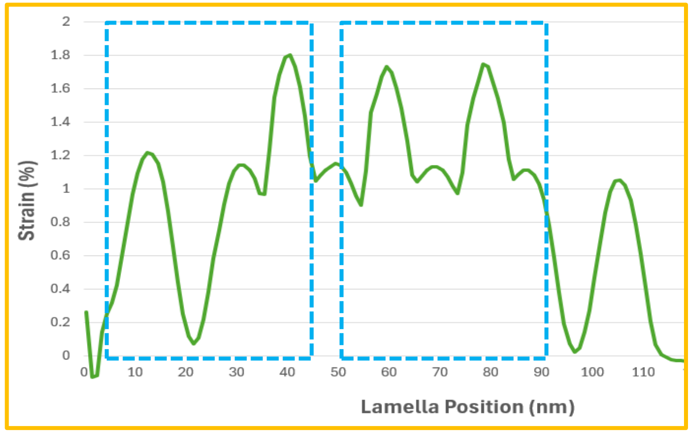
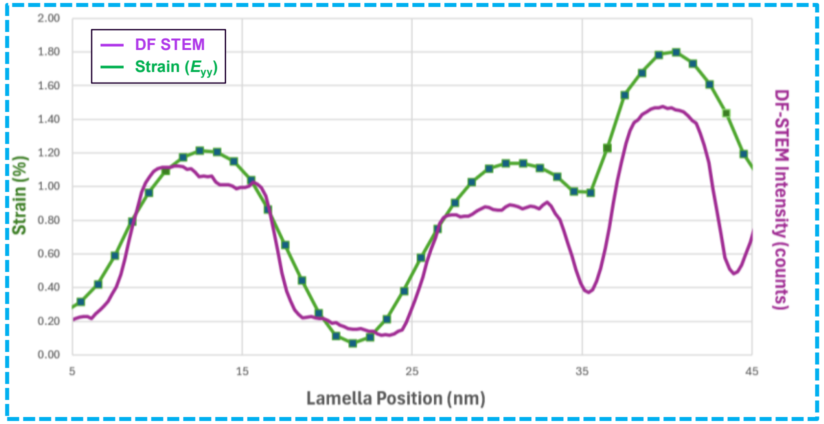
Benchmark NBED Strain Analysis with Precise Alignments

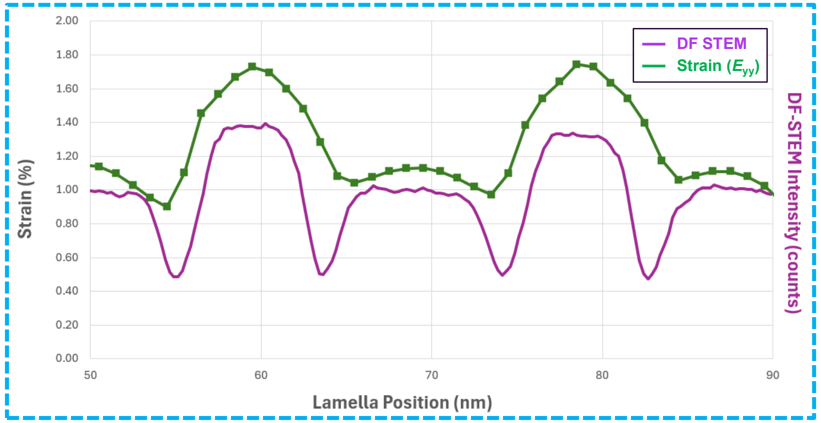












Epitaxial Si-Ge multistack as used for CFET devices (courtesy of imec)

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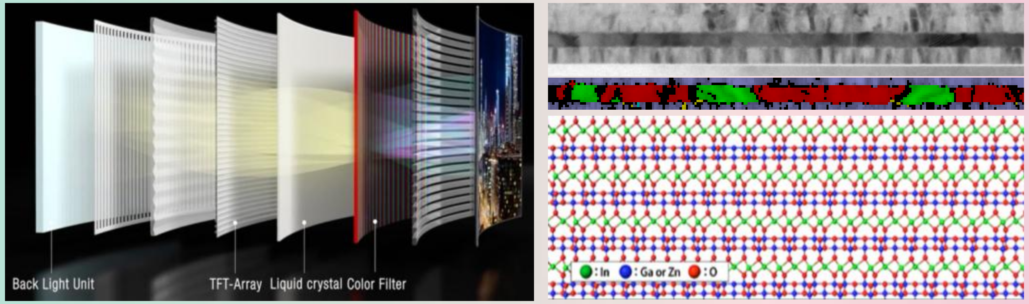
Summary: Enabling Fast and Precise Analytical 4D-STEM

- **Beam Precession is essential for robust 4D-STEM:**
  Tescan TENSOR enables analytical 4D-STEM for rutine use in semiconductor labs by any operator with fast time to results.

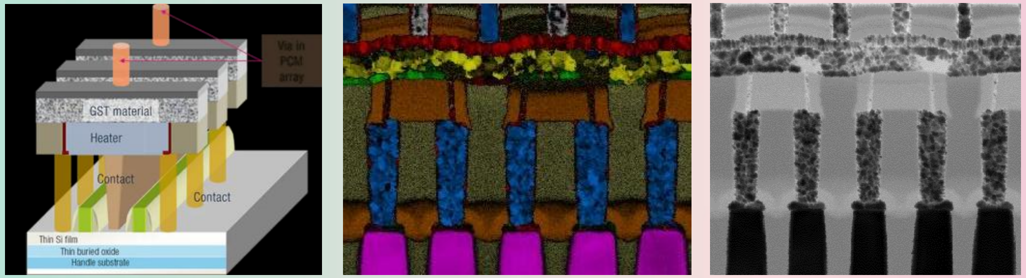
- **Reliable phase analysis of ferroelectric thin films:**
  Quantitative phase and grain orientation analysis of polymorphic HZO thin film from large ROI for efficient process development.

- **Fast phase and crystallinity mapping in FA:**
  Interactive 4D-STEM analysis revealed the structural basis of a single device failure in a PCM stack by phase analysis.

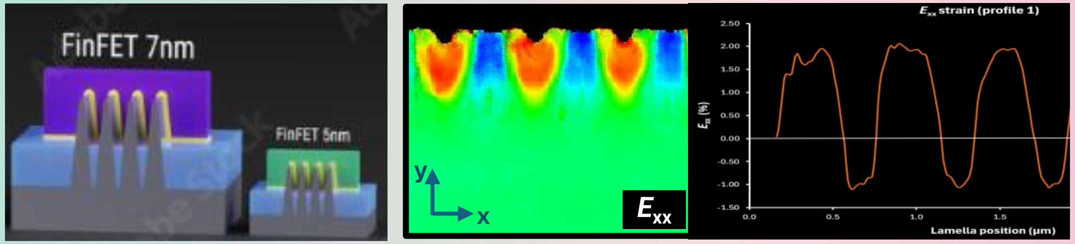
- **Precise strain analysis at spatial resolution <2 nm:**
  NBED strain analysis from large ROIs can be achieved in minutes and at sufficiently high resolution to resolve thin Si interlayers.



FE-FET: Process development of polymorphic thin films



Non-Volatile Memory: Crystallinity and Failure Analysis



FinFET / C-FET : Strain engineering and validation

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Tescan

Accelerating The Art Of Discovery

Thank you