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International Conference on Frontiers of Characterization and Metrology for Nanoelectronics

BRUKER

Latest Developments in X-ray Metrology for Semiconductor Structures

Dr. Juliette van der Meer

Overview

1 X-ray Metrology

2 Advanced Logic: Gate-All-Around Metrology

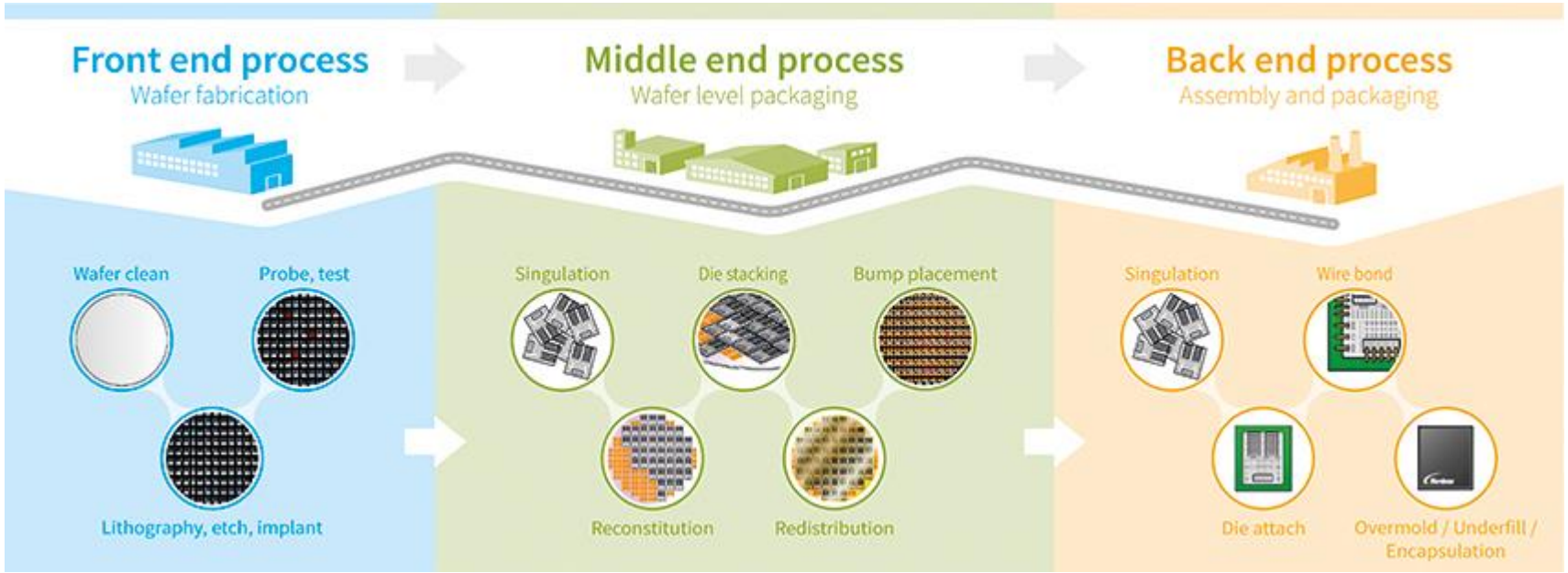
3 Advanced Memory: Profiling of HAR Memory Structures

4 High-Value Substrates: Crystalline Fault Detection

5 Advanced Packaging: Imaging of Complex Stacks

6 Summary

Semiconductor X-ray Metrology and Inspection Techniques



X-ray solutions

HRXRD XRR µXRF XCD XRDI TXRF

µXRF XRI

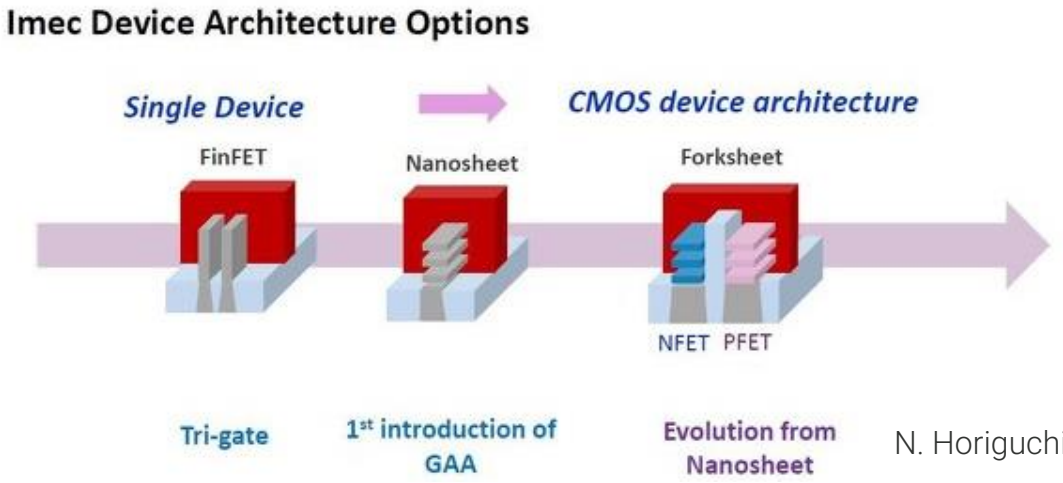
XRI

ADVANCED LOGIC

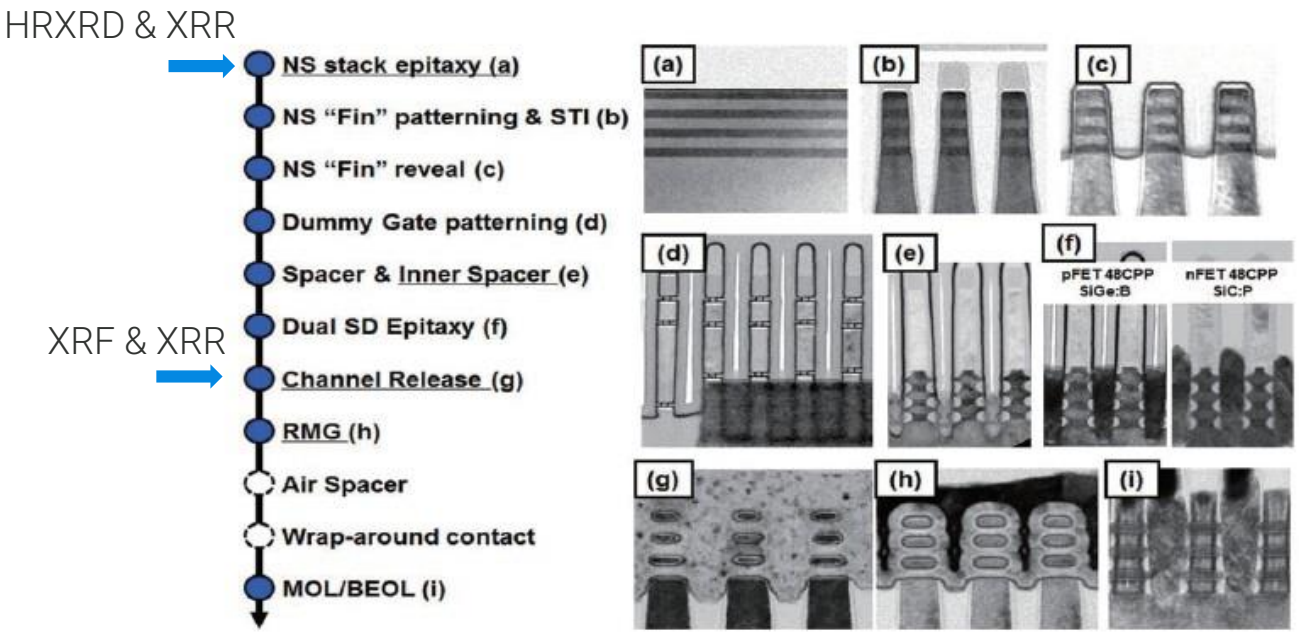
Gate-All-Around (GAA-FET) Metrology

Gate-All-Around Logic Process Flow

- Non-destructive X-ray metrology adds to the suite of tools needed to measure and control critical steps in advanced logic process flows
- In this section, we'll see how High-Resolution XRD, X-ray Reflectivity and X-ray Fluorescence provide vital information for R&D and process monitoring



N. Horiguchi, EETimes (2021)



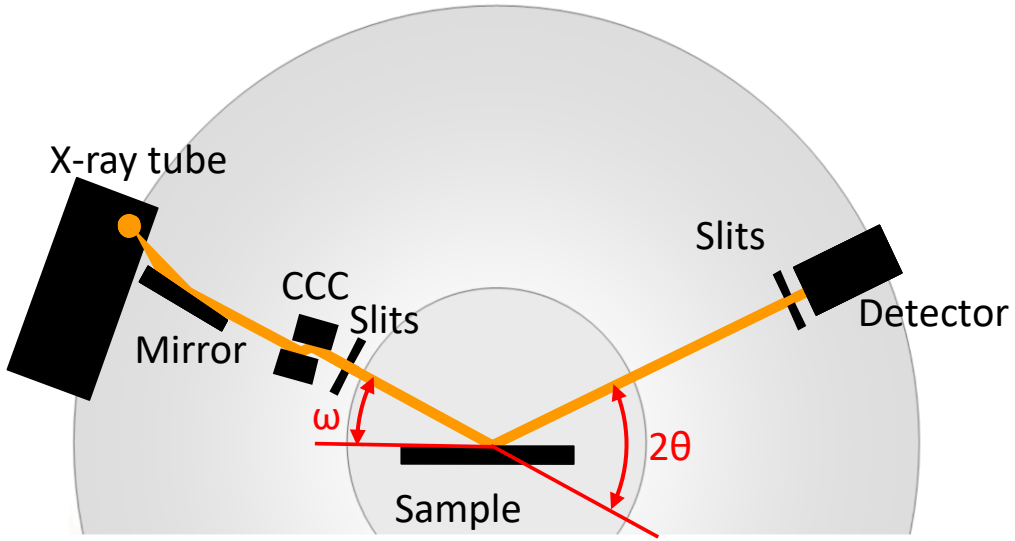
M. Lapedus, «What's after FinFETs», (2017)
https://semiengineering.com/whats-after-finfets/

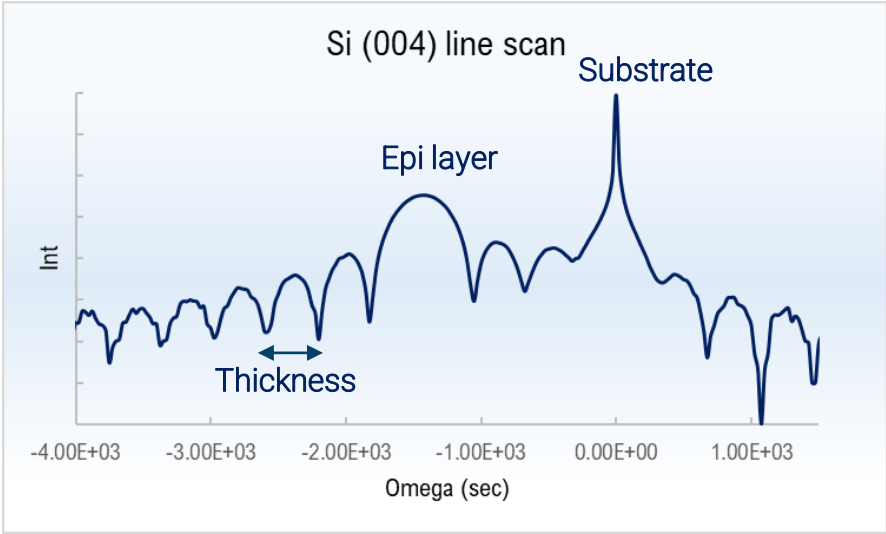
Engineered Substrates

- SiGe/Si multi-pair stack on Si is the base for Gate-All-Around transistors
  - SiGe nanowires/forksheets are formed by selective etching of the stack
  - Ge content affects the etch rate
- Metrology challenge: to monitor and control thickness and concentration
- Two X-ray methods are applied
  - High Resolution X-ray Diffraction (HRXRD) for Ge content and thickness (and relaxation)
  - X-ray Reflectivity (XRR) for extra accurate and precise layer thickness (and roughness and density)

High-Resolution X-ray Diffraction

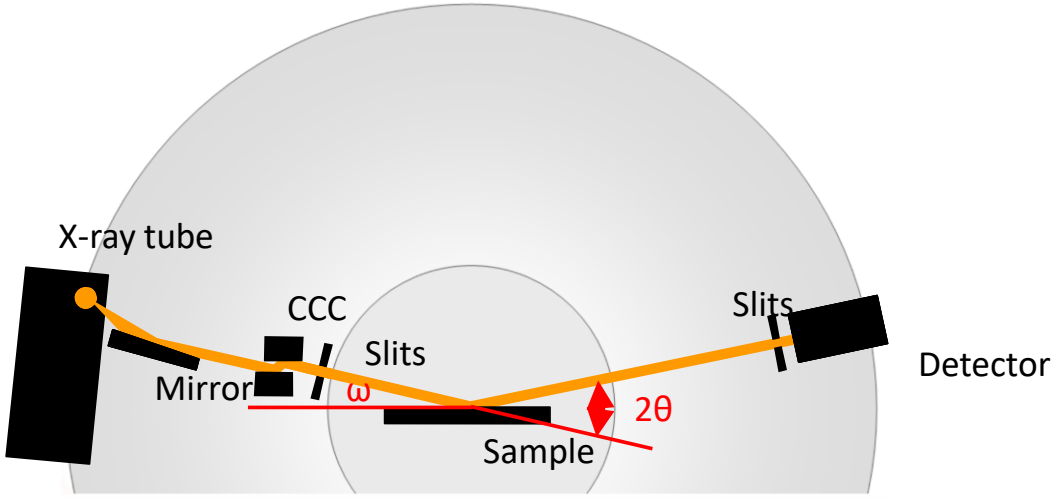
- High-resolution = high resolution in angle and wavelength
- Cu-Kα_1 beam used to probe the crystalline lattice
  - Diffraction scan over Bragg condition of the substrate
- Peaks and interference fringes
  - Diffraction peak shifted due to small change in crystalline lattice, e.g. by Ge incorporation
  - Peak positions: translate to Ge concentration
  - Fringes: thickness can be deduced

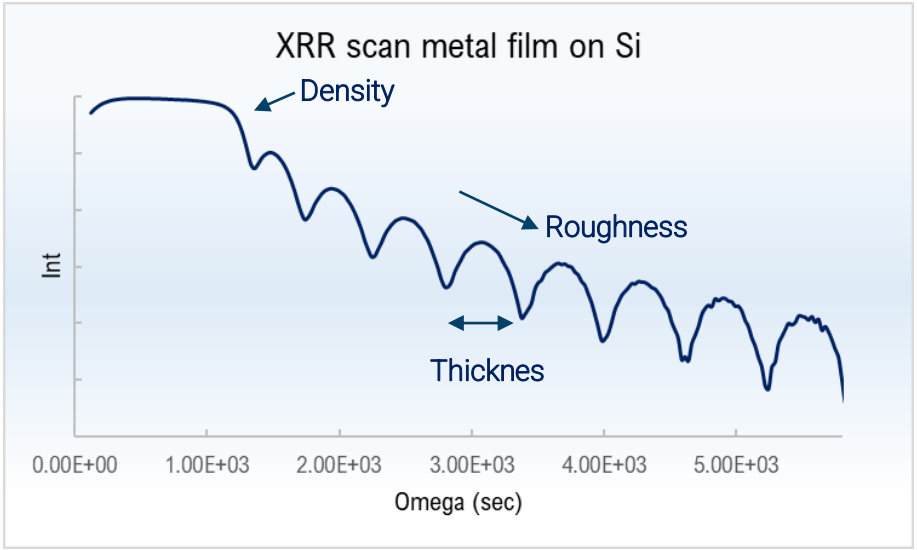




X-ray Reflectivity

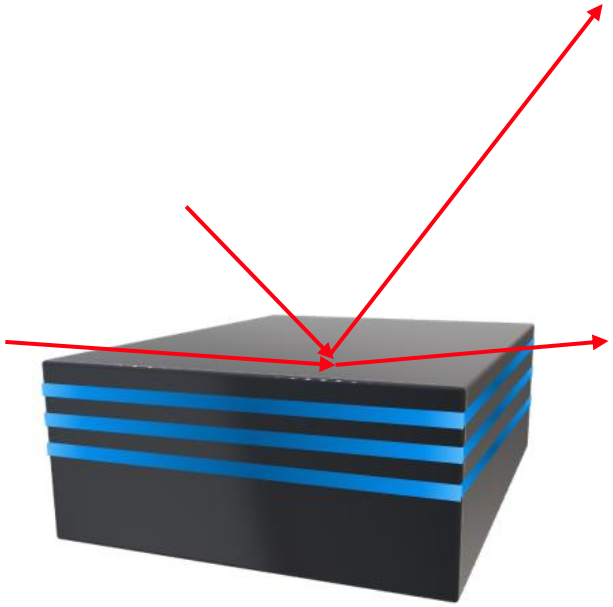
- Specular reflection on smooth surfaces
- XRR probes the electron density with depth
  - Interference fringes give information on thickness
  - Critical angle: density
  - Slope: roughness

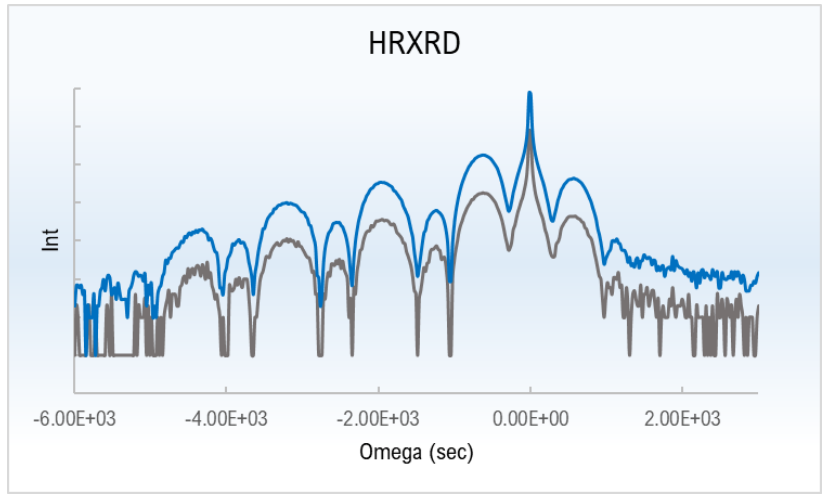


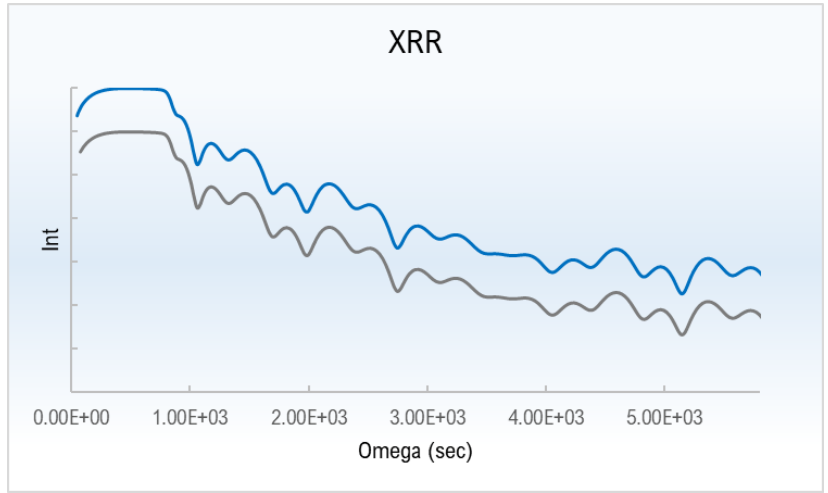


Boosted Performance on SiGe/Si Nanosheet Stacks with Novel Hardware and Analysis

- New high flux rotating anode X-ray sources
- New large area, high dynamic range detectors to capture maximum flux (8-10x of previous generation tool)
- Compared to systems with sealed tubes and 0D detectors
  - Better accuracy and precision
  - Higher productivity
  - Enables cross-wafer variation measurement (wafer maps)
- Complimentary analysis
  - HRXRD for concentration & thickness
  - XRR thickness

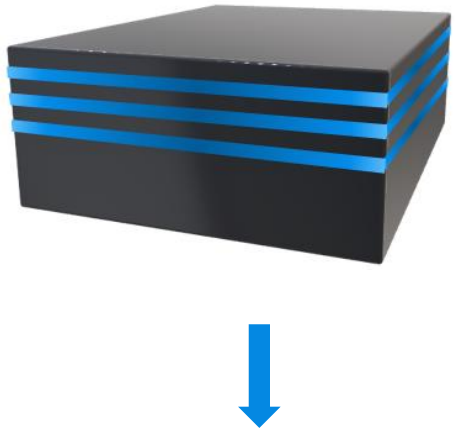


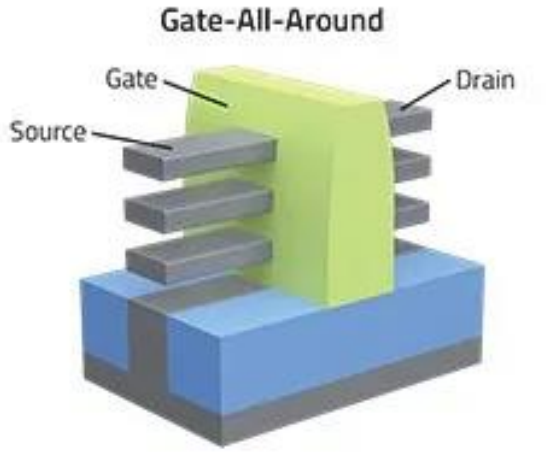


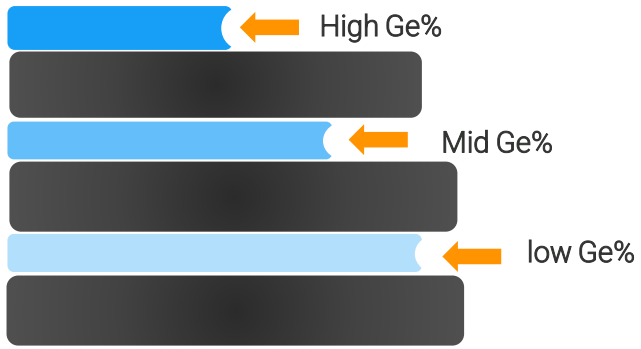


SiGe Recess Metrology

- The SiGe/Si multistack is etched to form Gate-All-Around transistors
- Metrology challenge: to monitor and control the depth of the selective etch of the SiGe
- µXRF offers a fast, simple and non-destructive method for average recess depth metrology on product wafers
- Techniques may be combined in hybrid metrology schemes



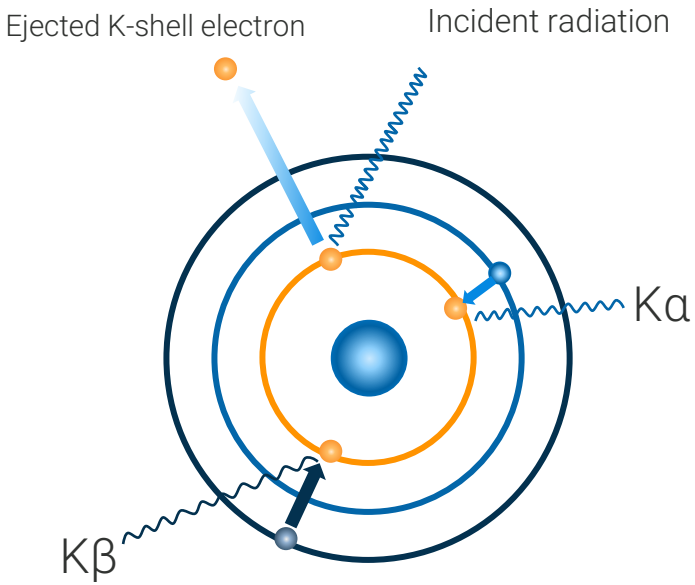




N. Draeger, Semiengineering, Nov'20

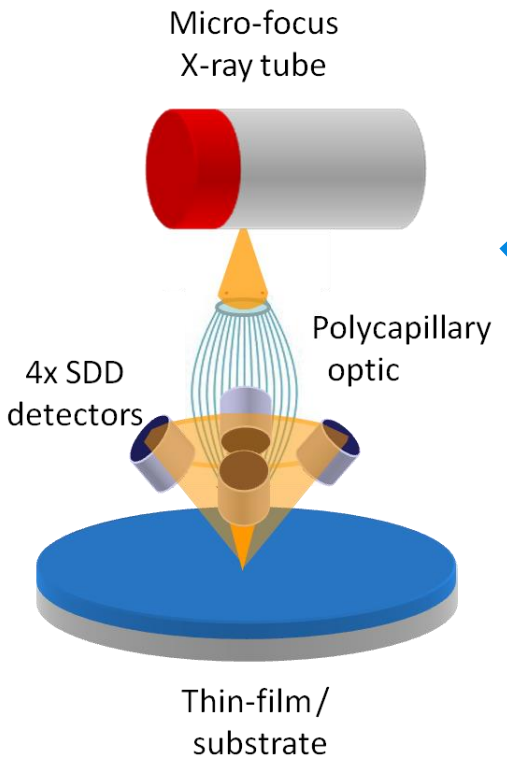
X-ray Fluorescence Principle

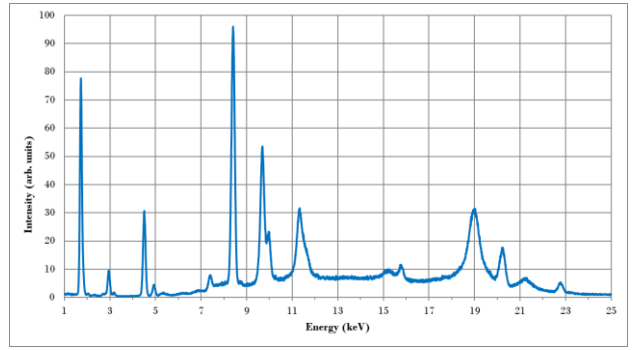
- Radiative transitions between different atomic shells result in a discrete series of X-ray energies (lines)
  - K or L lines are commonly used for XRF analysis of metals in air
  - Energies in 3-20 keV range, e.g. Ge-Ka 9.9 keV
- Each element has a unique series of lines, and the intensity is proportional to the number of atoms within the incident X-ray beam
  - Qualitative analysis
  - Quantitative analysis after calibration
    - Thickness
    - Concentrations

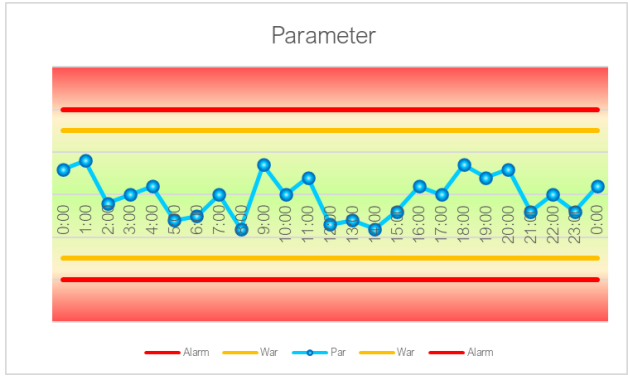


µXRF Metrology Channel for Inline Process Monitoring

- Multiple microfocus X-ray sources
  - Mo, Cu, Rh, W are common (depends on application)
- Detection
  - Up to four SDD detectors for efficient photon collection
- Product wafer metrology
  - Small spot / edge-exclusion
  - Vertical geometry: Low sensitivity to Z-errors
- Benefits
  - Fast
  - Non-destructive
  - Simple analysis

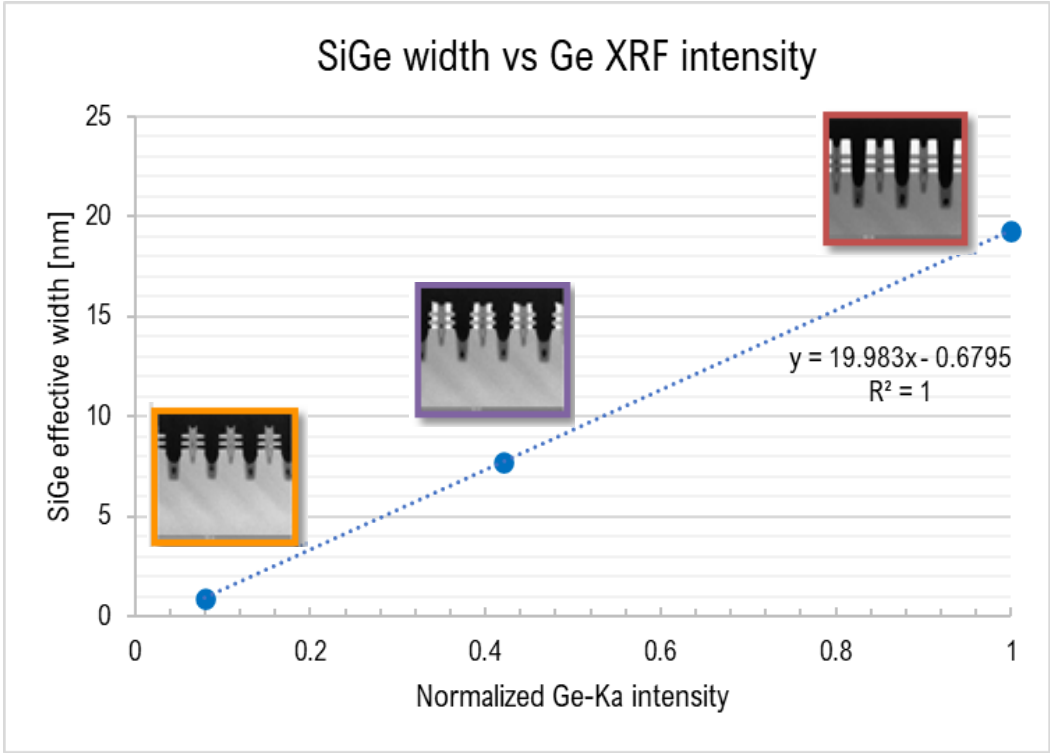






XRF Results on Etched Forksheet GAA FET Fins

- Ge-K intensity was measured on etched fins
- Perfect linear relationship between intensity and nominal SiGe width (Ge etch rate)
- The exciting X-rays and fluorescent signal Ge-K are “hard” X-rays, so there are no absorption effects
- Therefore, no complex model needed
- Fast, non-destructive
- Measurement on product wafers with gate structure



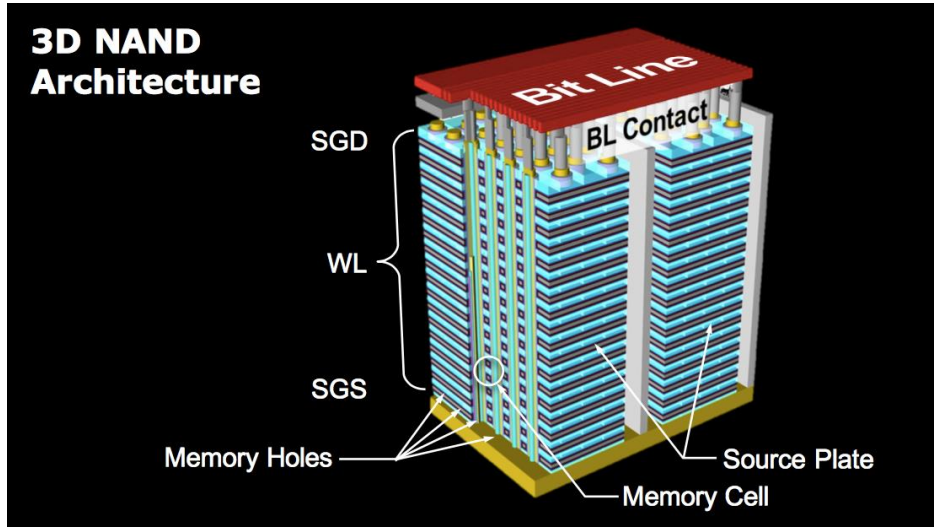
J. Bogdanowicz (imec) et al. „A See-Through Metrology Toolbox For Fast Gate-All-Around Device Characterization”, FCMN 2022

ADVANCED MEMORY

Profile and Tilt of HAR Structures with Small Angle X-ray Scattering

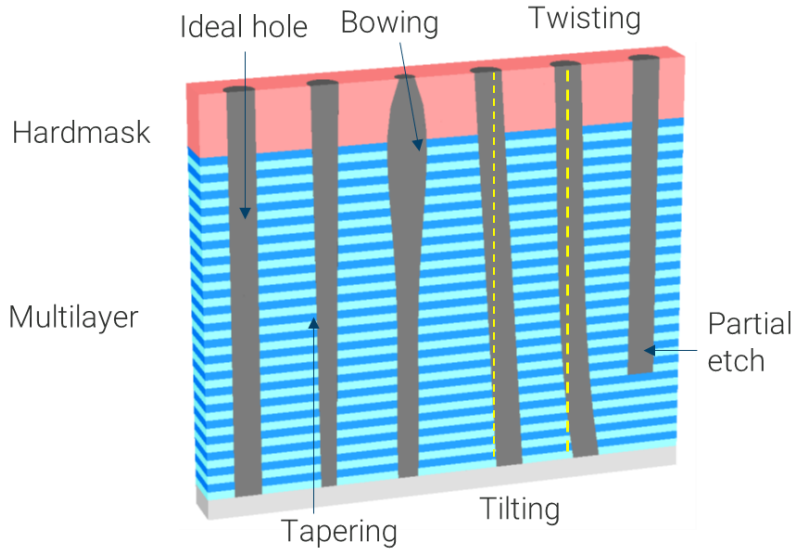
High-Aspect Ratio Structures for Memory

- High Aspect Ratio (HAR) etched structures are critical for 3D NAND and DRAM memory to increase storage density through vertical scaling
- Aspect ratio of 3D NAND channel holes > 50:1



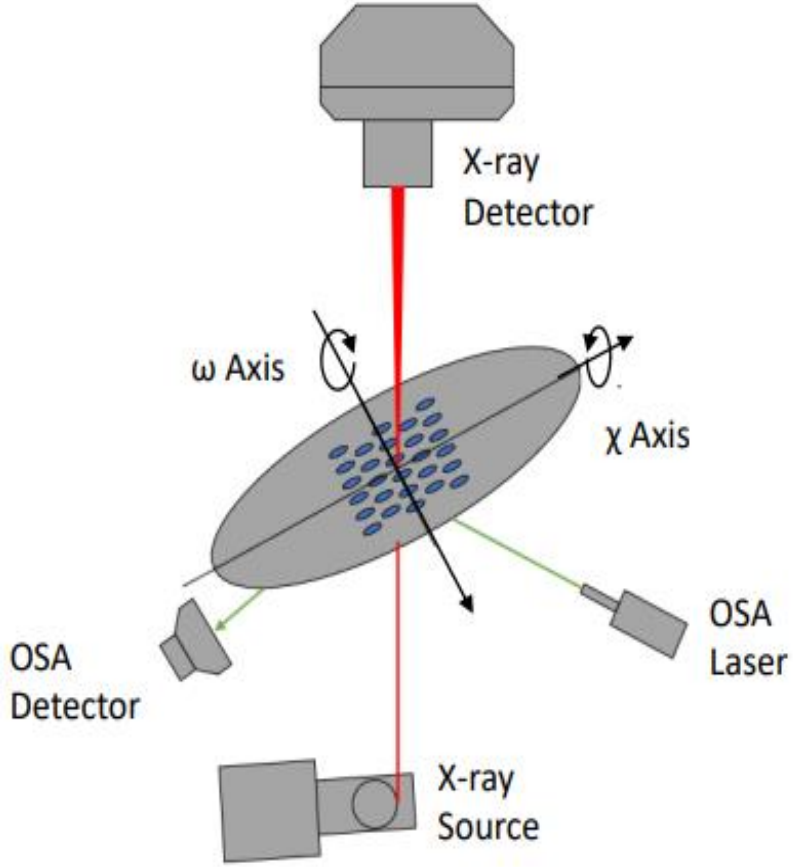
M. Lapedus, «3D NAND Fash Wars Begin» (2018),
3D NAND Flash Wars Begin (semiengineering.com), source: Western Digital

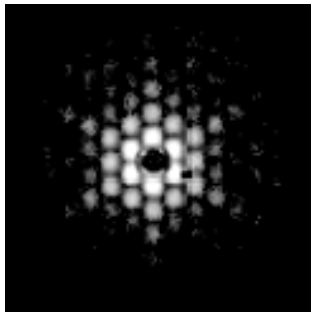
- Metrology challenges: profile and tilt of the etched HAR holes in hardmask and multilayer film-stacks
  - Non-destructive
  - Accurate and precise
  - On-die measurements



X-ray Critical Dimension (XCD™) Metrology

- Also known as CD Small Angle X-ray Scattering (CD-SAXS)
- High-brightness rotating anode X-ray source
- Vertical beam path for small tool footprint
  - Wafer stays in horizontal position
- High performance 2D detector
- Wafer angle accurately measured by optical surface alignment system
- High sensitivity to HAR structures
  - Scattered X-ray intensity increases with taller structures

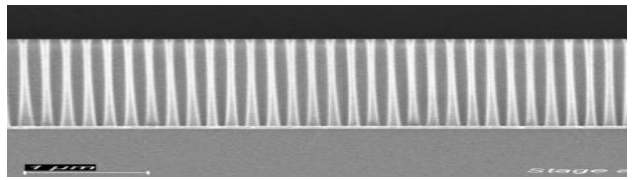




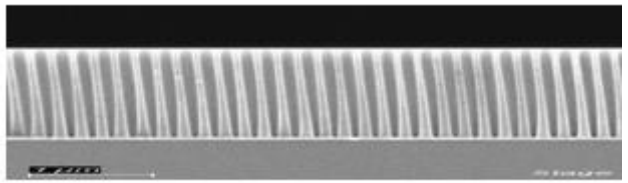
XCD Fast Tilt Analysis

- Developed a direct measurement of the angular tilt components of single-tier HAR holes with respect to the surface of wafers that is fast, accurate and precise
  - Scattered X-ray intensity can be collected in just a few seconds per rotation angle
  - Model-free analysis
  - Tilt precision for Memory Hole (MH) structure is 3σ < 0.01 deg

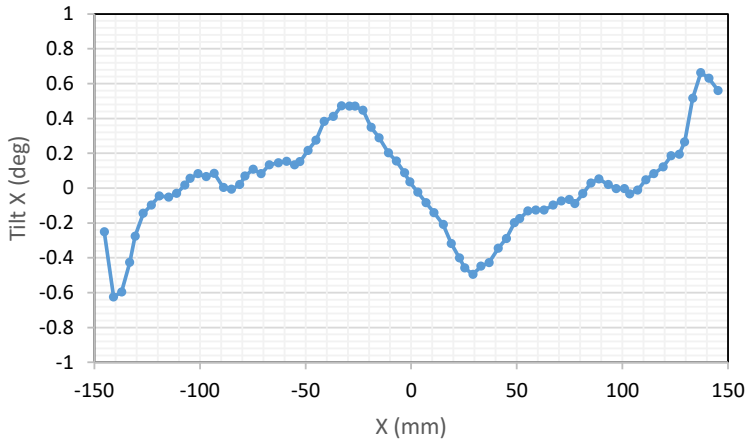
Feature	XCD	HVSEM	XSEM	FIB+SEM (delayering)	OCD
Beam	X-ray	electron	electron	electron	UV/Vis
Lateral sampling	~100 µm	~10 µm	~10 µm	~10 µm	~25 µm
Array/device sampling	Device	Device	Device	Device	Array
MAM time	1-2 min	~15 s	~days (to results)	~days (to results)	~5 s
Non contact / non-destructive	Y	N	N	N	Y
Model-free	Y	Y	Y	Y	Y
Calibration-free	Y	Y	Y	Y	N
Precision [3σ]	<0.01°	<0.02°	10-20 nm	10-20 nm	0.1°
Depth limit	>10 µm	~5 µm	>10 µm	>10 µm	~5 µm



XSEM image: Tilt ~0°

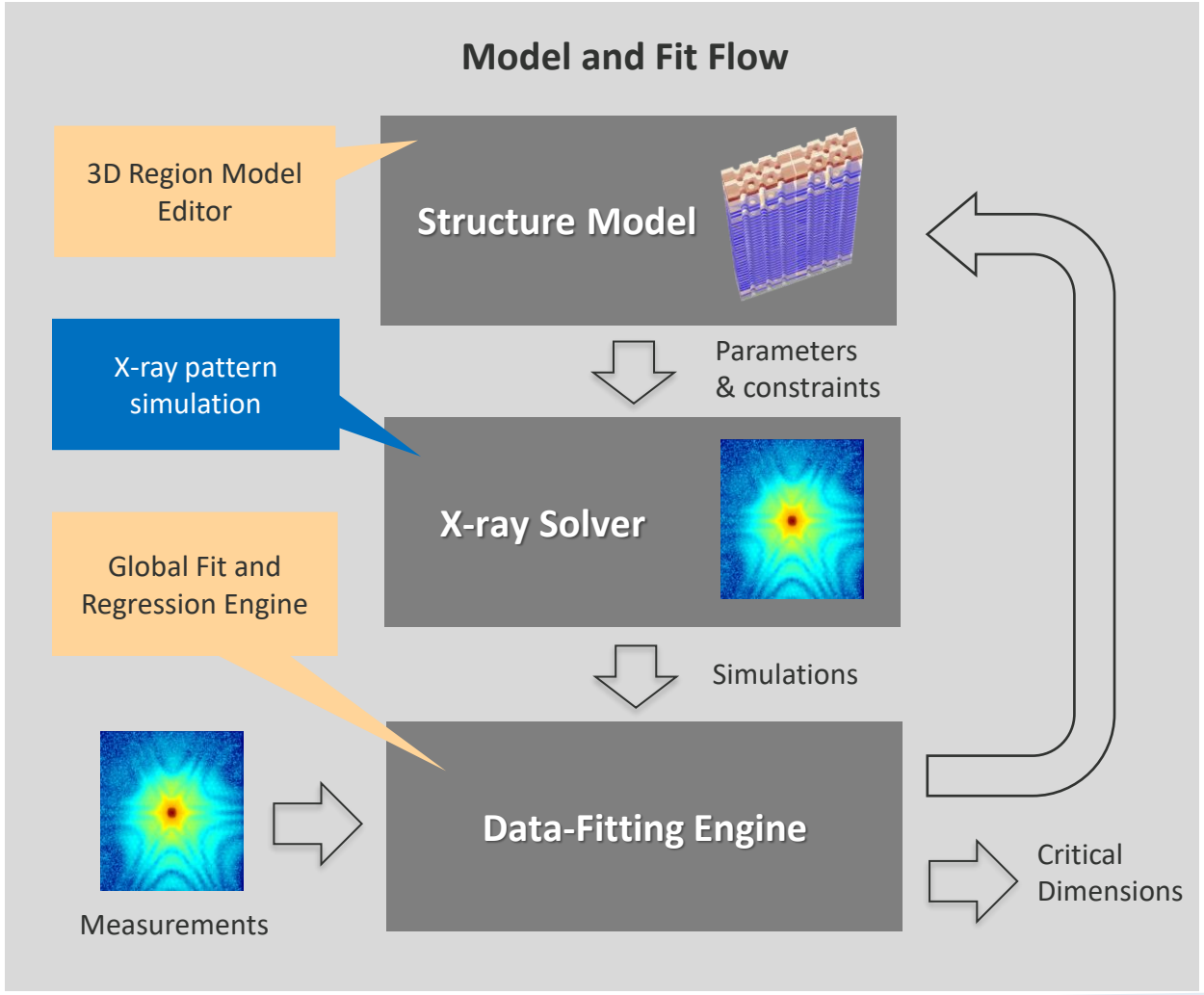


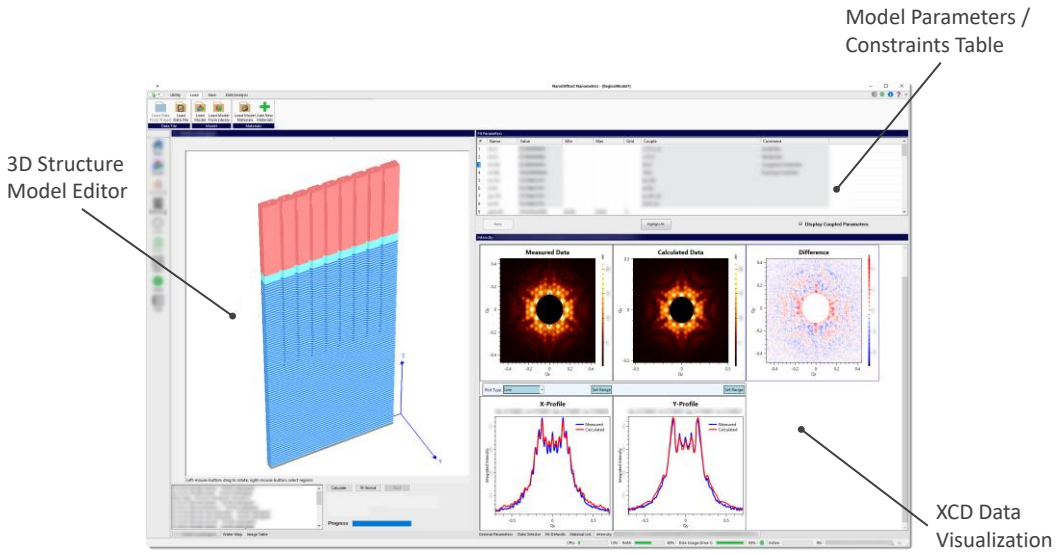
XSEM image: Tilt ~0.8°



TiltX measured at Y = 0 mm along the X-axis

XCD Shape Analysis

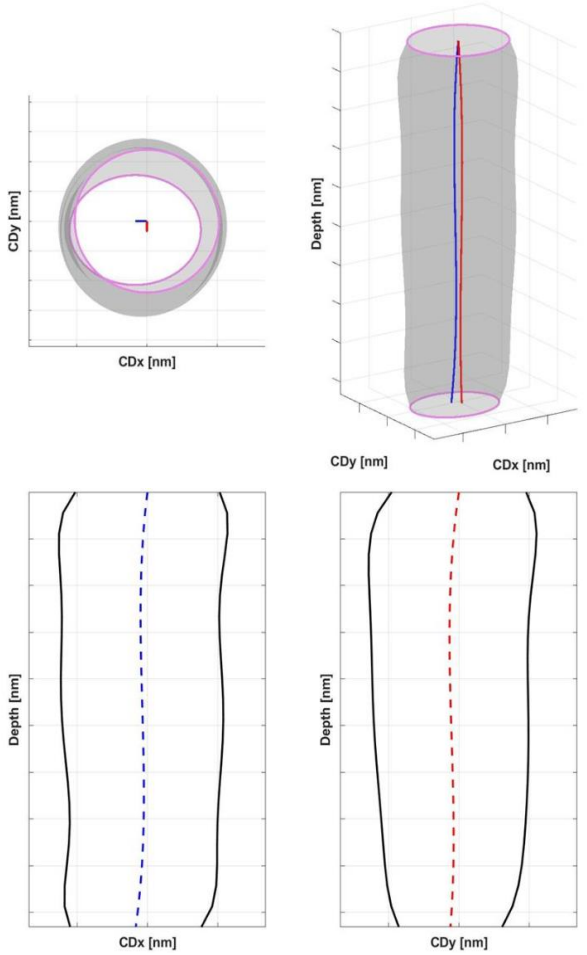




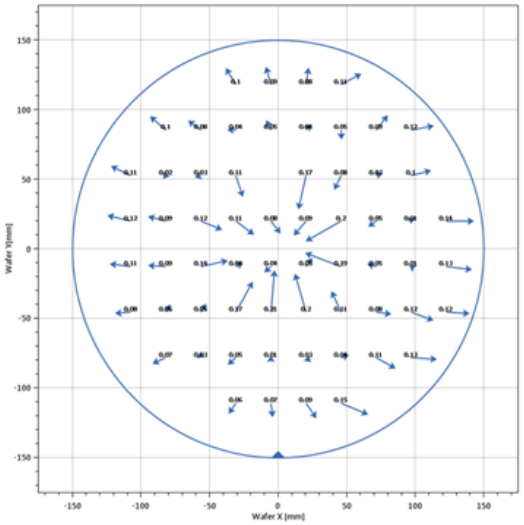
- Model based analysis for shape determination
  - XCD much less sensitive to chemical composition
- Advanced analysis software and hardware for complex structure analysis
  - Flexible CAD-based structure model builder
  - Easy input of fit parameters
  - Clear graphical comparison of measured and simulated data
  - Real-time regression using cluster computing

XCD Shape Results

- XCD fit results include critical parameters for HAR hole etch process control and development
  - Max CD magnitude and depth
  - CDx , CDy, ellipticity
  - Center line shift (CLS) in x and y-directions
  - Average hole tilt
  - Depth
  - Dual-tier overlay / joint shift
- Results can also be visualized graphically at each site
- Plots of parameters to show cross wafer trends (average CD, tilt, depth, etc.)
- Generally good correlation to reference techniques (CD-SEM)



Profile and tilt of 3D-NAND channel holes as volume render and in x- and y-projections



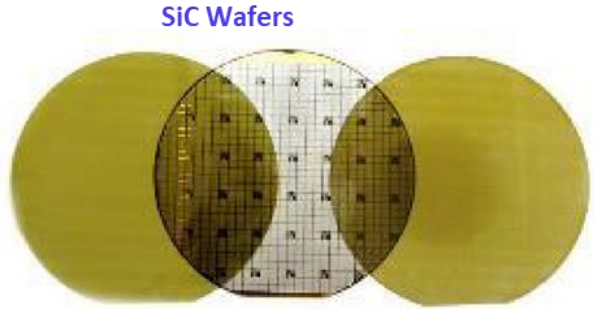
Average tilt of 3D-NAND channel holes as cross wafer vector plot

HIGH-VALUE SUBSTRATES

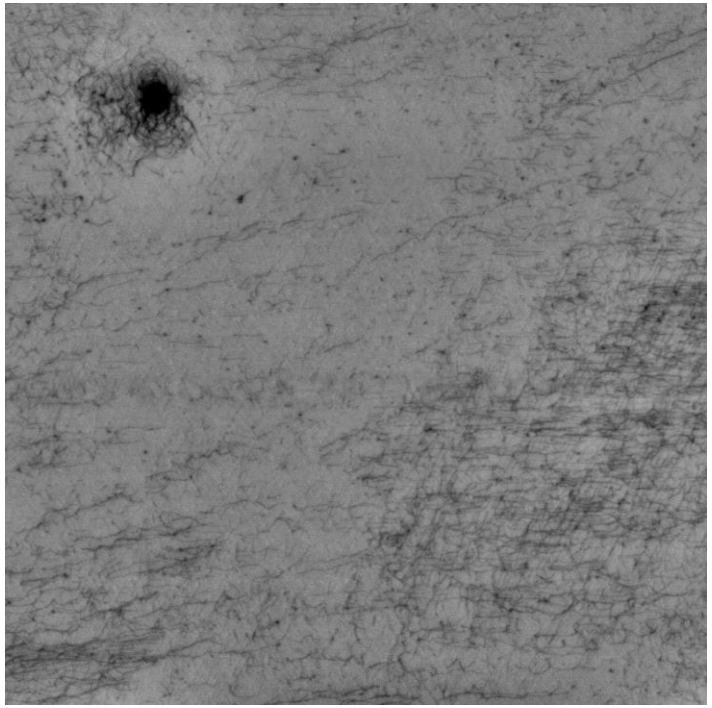
High Resolution, High Speed Crystalline Defect Characterization

Substrate Inspection

- SiC is used for high voltage power electronics / opto devices
- Defects in Silicon carbide are detrimental to device performance and long-term reliability
  - Increased leakage current
  - Reduced carrier lifetime
- Understanding defects in detail helps to improve growth, reduce defect densities
- Light Scattering and Photoluminescence have limited penetration depth on polished surfaces and n^+ substrates used for most SiC devices
- X-ray Diffraction Imaging offers a fast and non-destructive method

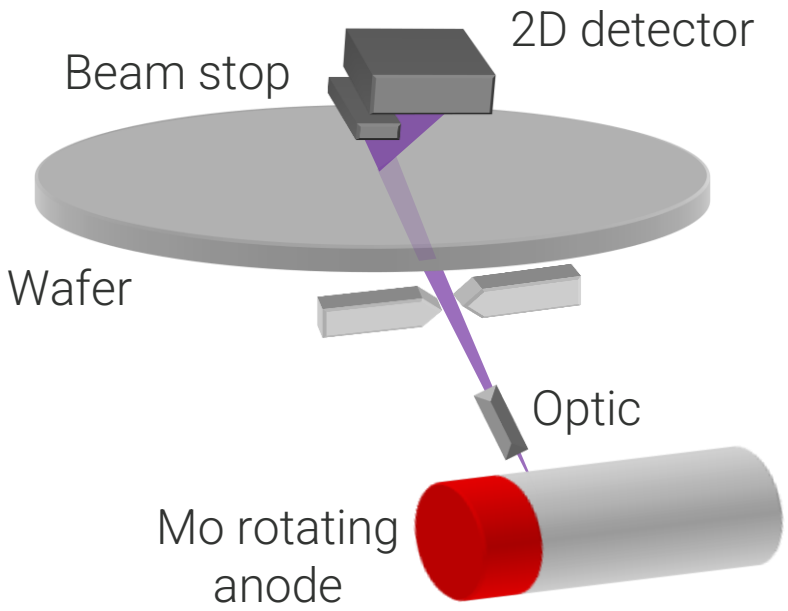


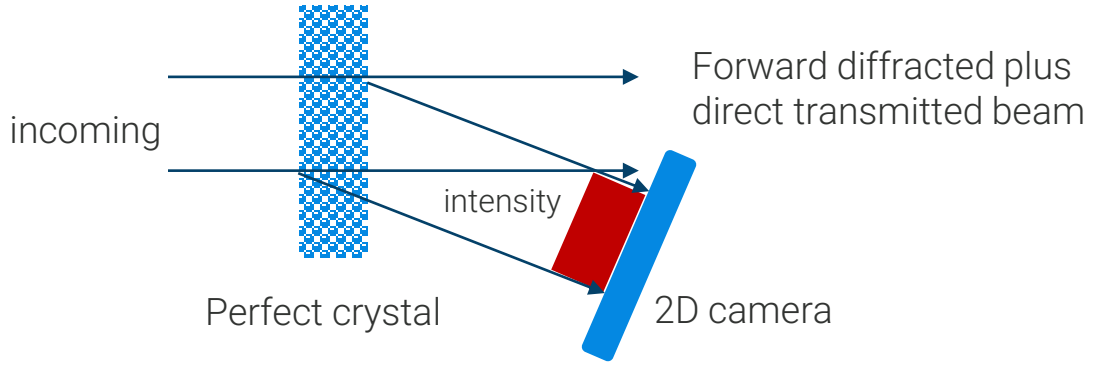
STM Catania

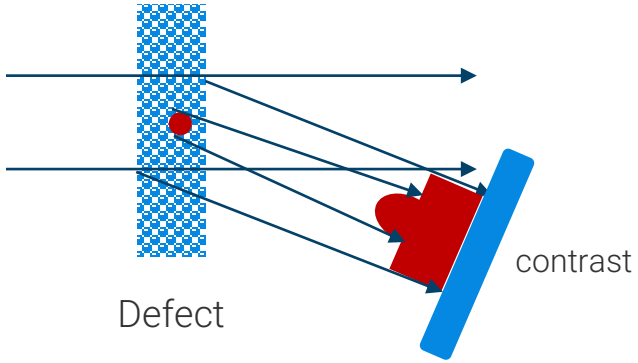


X-ray Diffraction Imaging (X-ray Topography)

- Multiple high power X-ray sources for enhanced flux
- High resolution detectors

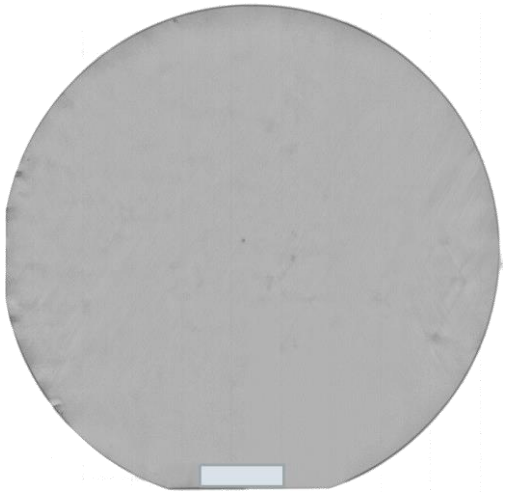




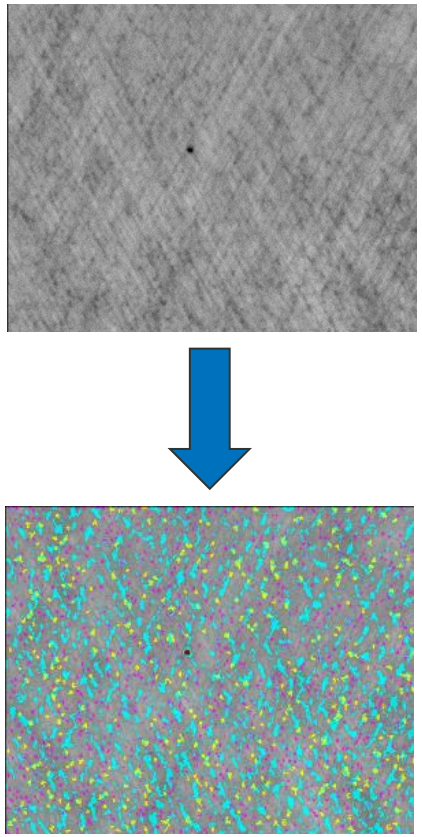


Automated Defect Detection in SiC

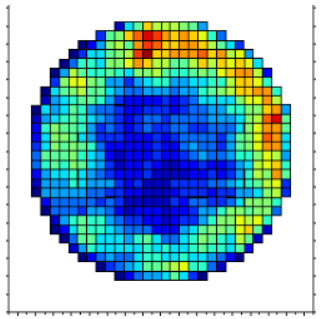
- Automated classification and quantification of defects
  - Threading screw dislocation (TSD)
  - Threading edge dislocation (TED)
  - Micropipes (MP)
  - Basal plane dislocation (BPD)
- Analysis developed for cases where defects overlap in wafers with high defect density
  - Densities for each defect type can be extracted and automatically reported via SECS/GEM



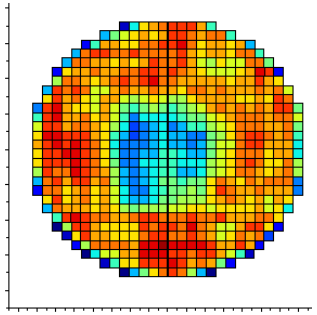
Full 6” SiC wafer map in high resolution at 2 wph throughput



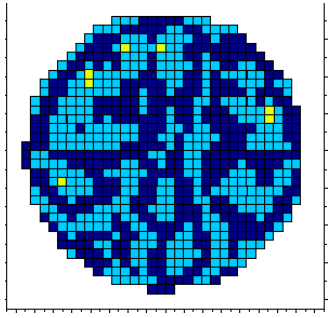
Defect classification and KLARF-formatted text output of defects densities



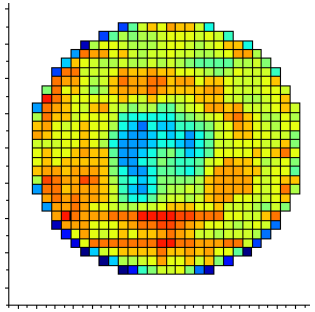
TSD Density Map



TED Density Map



MP Map



BPD Density Map

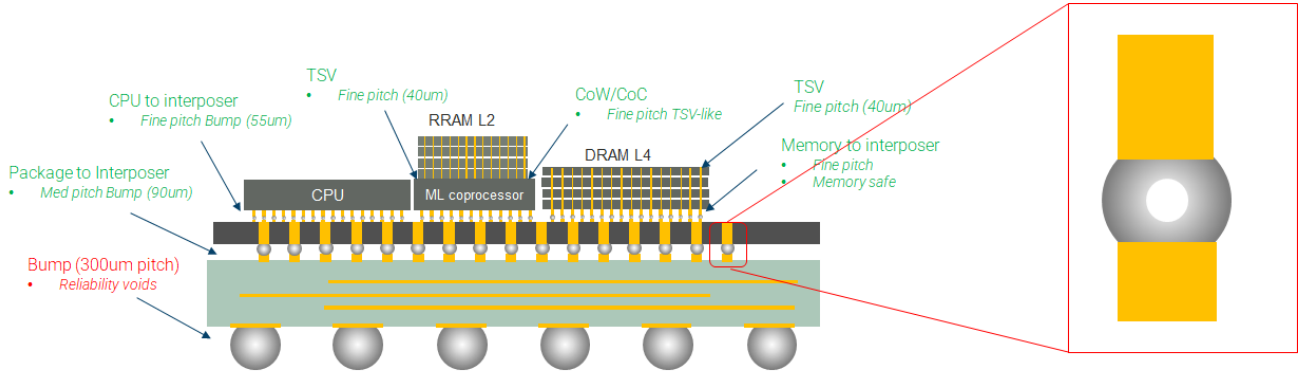
ADVANCED PACKAGING

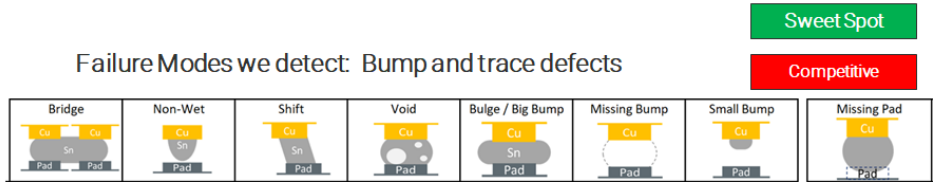
High Speed Inspection for Advanced Packaging

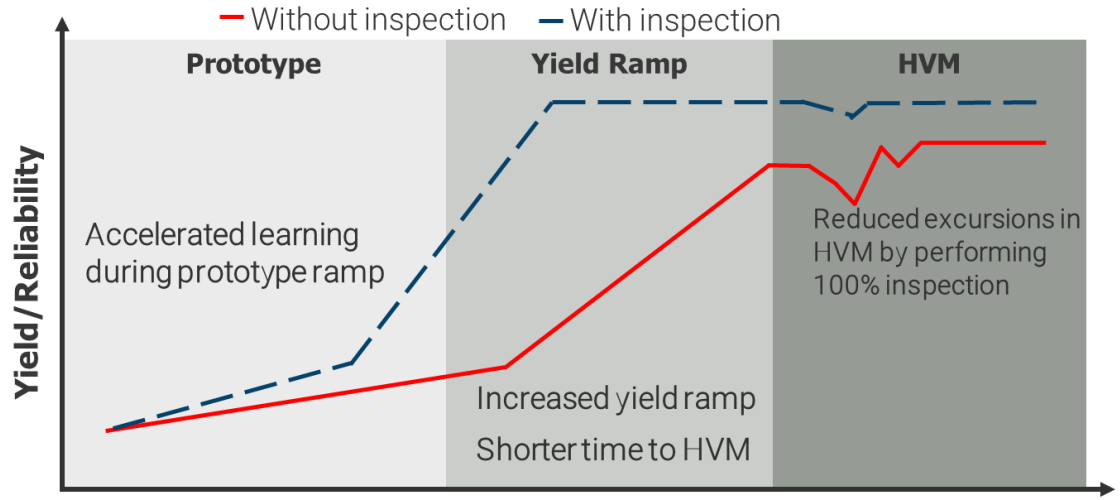
Inspection of Bonded Structures

- Advanced Packaging technologies are key enabler for heterogeneous, multiple chip architectures
- Problem: bridges, voids, and non-wets resulting in yield and reliability issues
- Challenge: fast and accurate inspection of buried structures

- X-ray Imaging
  - Offers a fully-automated in-line inspection and metrology solution
  - Prevents costly excursions
  - Gives shorter R&D cycles

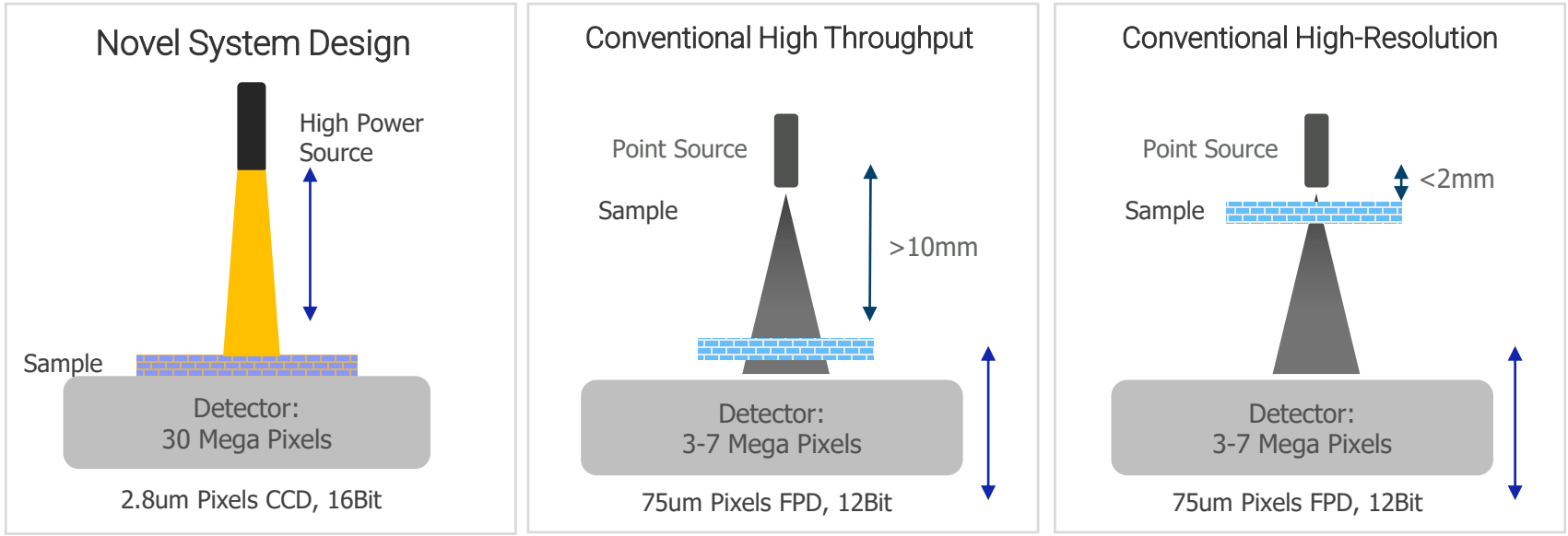






X-ray Imaging with a Novel Setup

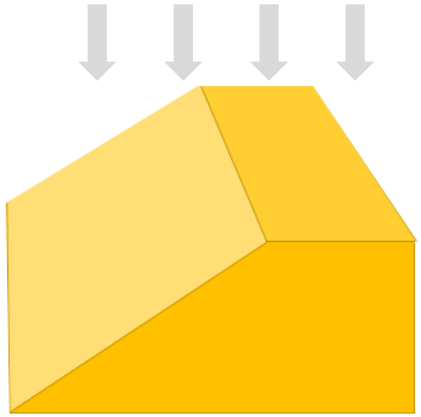
- High power X-ray source for increased flux
- Large field-of-view and high-resolution detector
- Continuous performance enhancements with machine learning



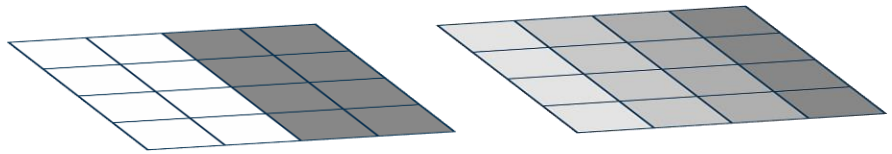
	Novel System	High Throughput System	High Resolution System
Wafers Per Hour*	1-2	7-10	< 0.10
FOV	12mm x 18mm	50mm x 50 mm	3mm x 3mm
Resolution	2.8 um / pixel	10um / pixel	< 1um / pixel

High Bit Depth Detector Enables Sensitivity to Defects

Metal Feature

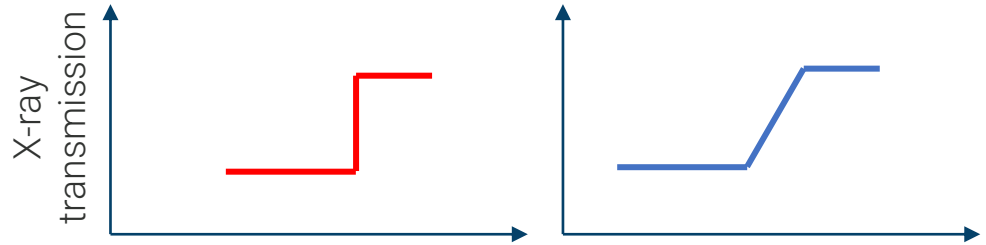


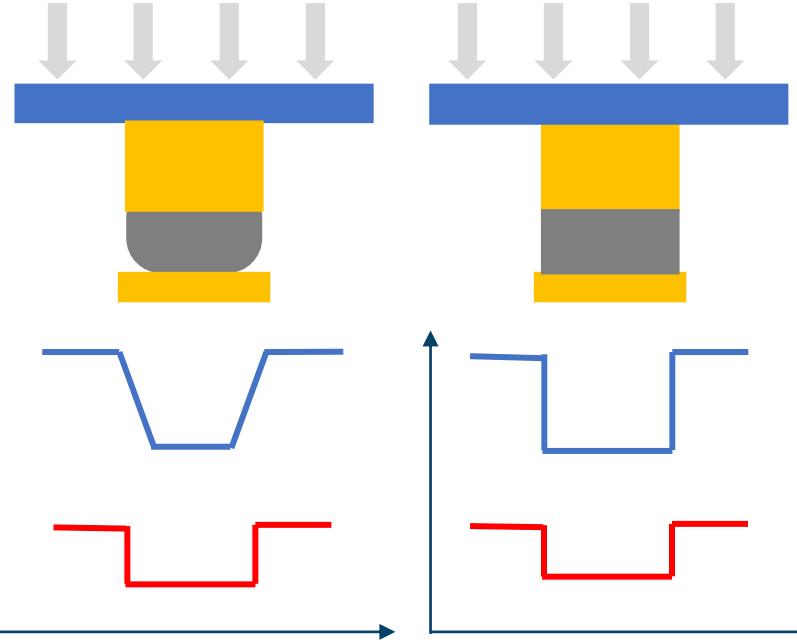
'X-ray Image' pixels

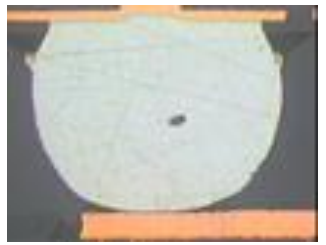


Low dynamic range

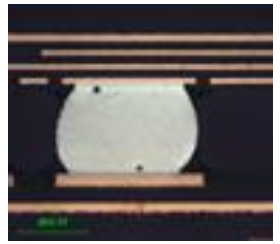
High dynamic range







Contact Non-wet



Good Joint

Summary

Summary and Outlook

- A variety of X-ray techniques characterize physical, chemical and structural parameters of semiconductor structures in a non-destructive way
- Advances in X-ray source and detector technology offer a significant performance gain and enable latest generation X-ray metrology and inspection tools to meet high volume manufacturing (HVM) demands
- Innovative software is the key driver for data analysis and user experience
- Future improvements are expected by the extended use of AI/ML supported algorithms and integration of novel high-brightness X-ray sources

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BRUKER

Thank you!

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