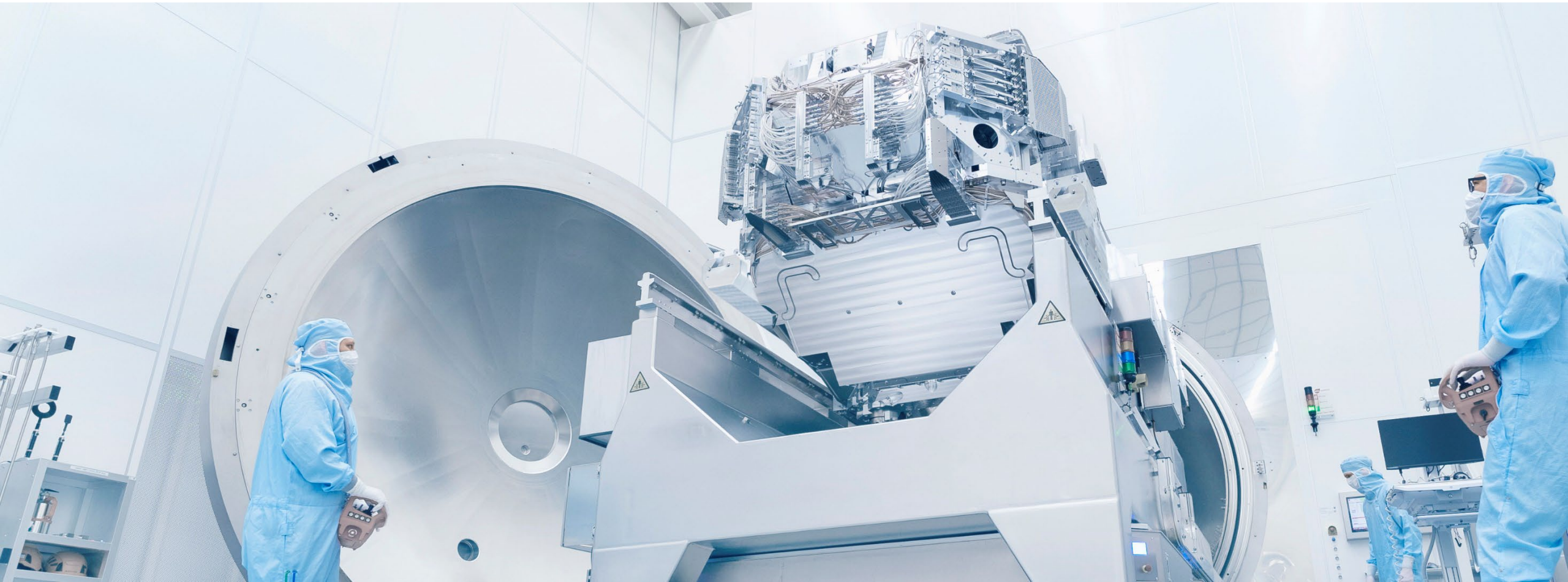
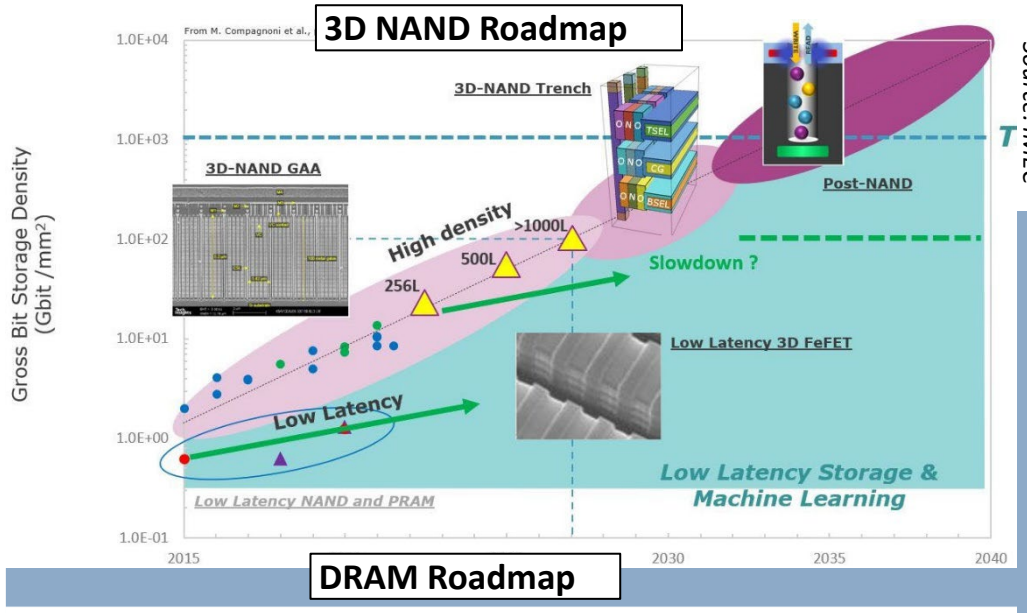
3D Metrology And Inspection Of Advanced NAND And DRAM Devices Via Full 3D Characterization With FIB-SEM Tomography

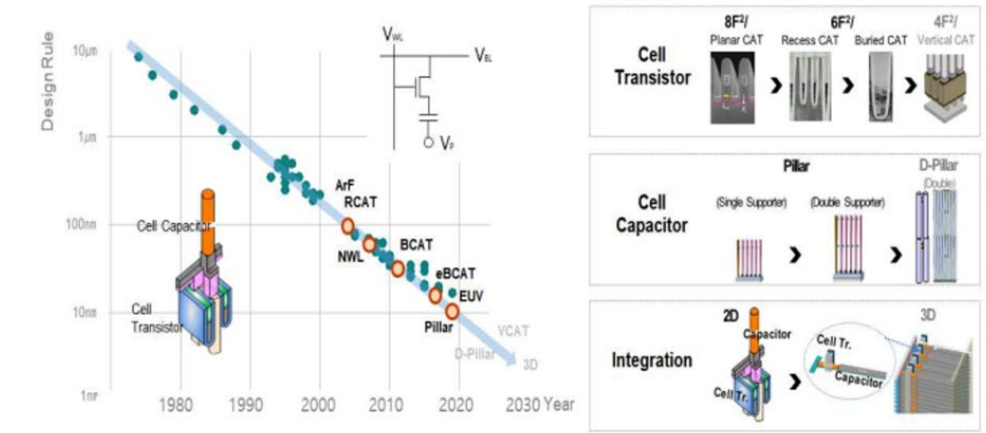
D. Klochkov, T. Korb,
K. Lee, H. Kim,
R. Pichumani, L. Mantha,
P. Hüthwohl, and E.Foca



3D scaling is a major trend in semiconductor manufacturing that will continue to proliferate over the next decade



Source: IMEC



Source: SAMSUNG

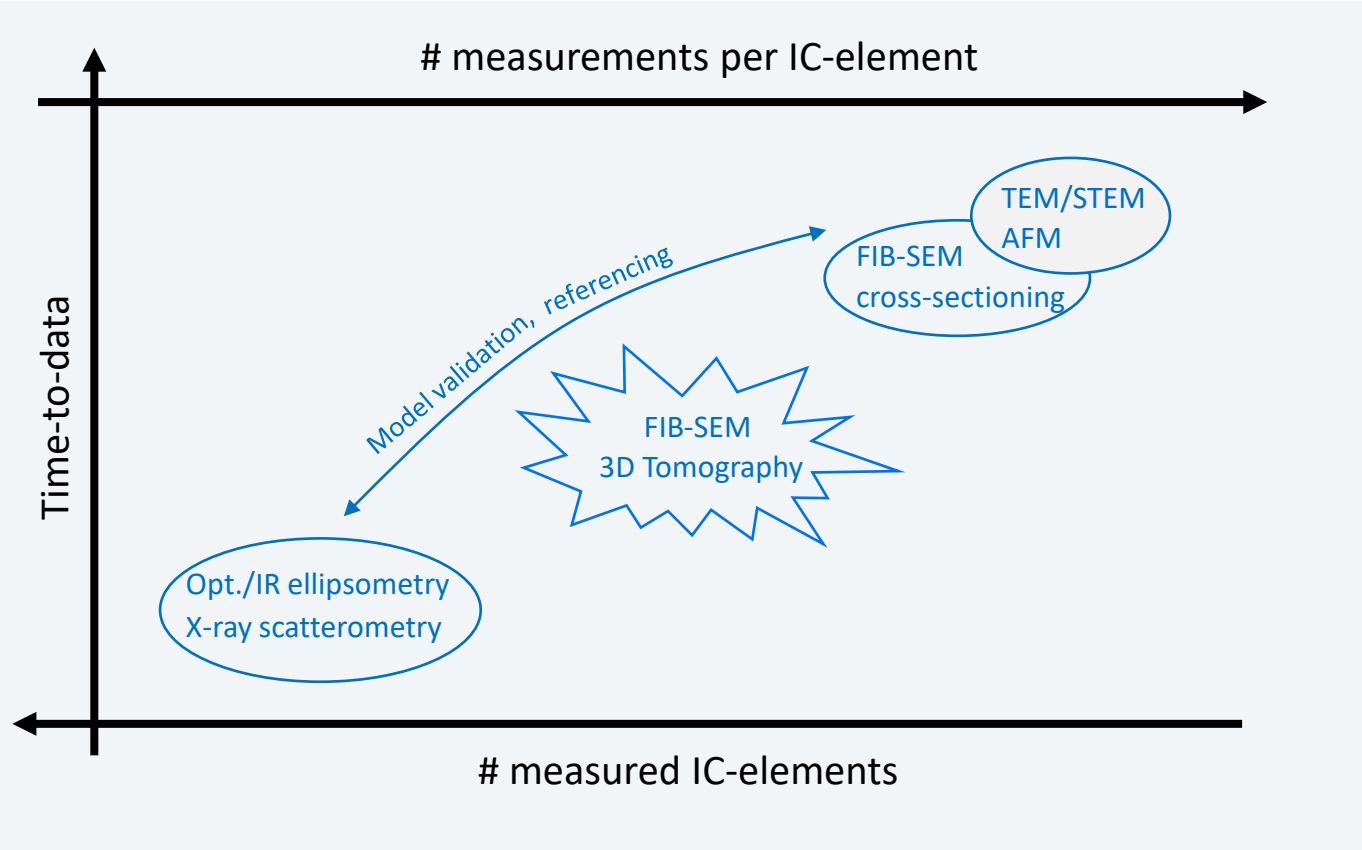
3D architectures and scaling became ubiquitous on nearly all semiconductor devices roadmaps

These trends demand new process control solutions with the focus in 3D metrology & inspection

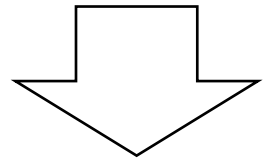
ZEISS' primary focus is to provide novel M&I solutions for in-line and fabs to support these trends

3D metrology & inspection tools for semiconductor devices

“Landscape” of 3D MI tools adopted in semi fabs



- Opt./IR/X-ray ellipsometry/scatterometry tools (OCD, CD-SAXS) are fast and cover millions of IC-elements per “shot”; the measurements are model-based and are averaged over the entire field of view
- (S)TEM, AFM, and FIB-SEM X-sectioning are slow but provide independent measurements of **each** of (much fewer) IC-elements in FoV

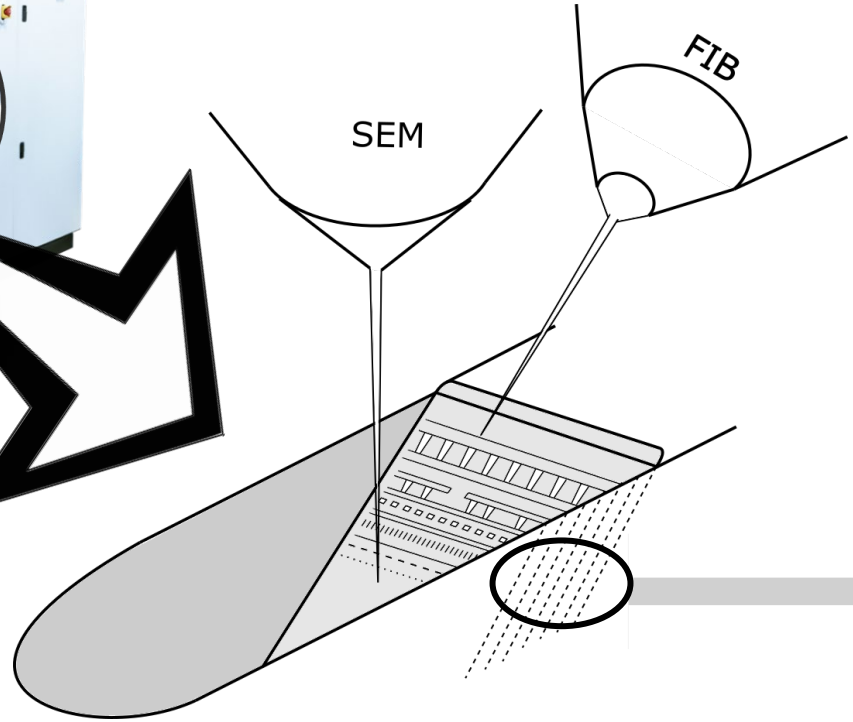


- A large gap has to be closed by referencing the opt./IR/X-ray methods to the ground truth from (S)TEM/AFM/FIB-SEM. **FIB-SEM based 3D tomography tools are intended to fill this gap**

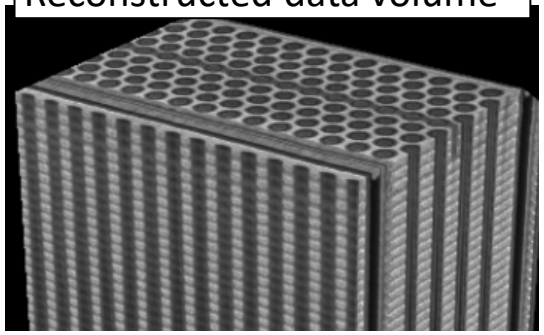
Thanks to extremely precise and stable delayering in ZEISS systems, unparalleled precision of 3D reconstruction is possible

300mm wafer tool (fab 3D-tomography solution)

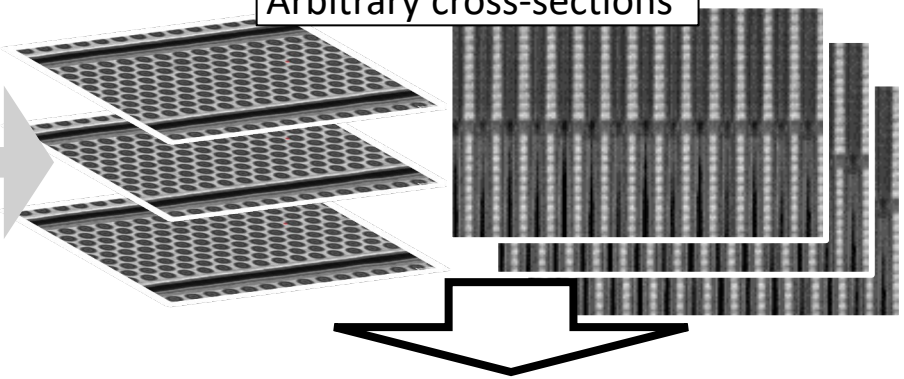
High-precision slicing & imaging to acquire precise 3D volume with high spatial resolution



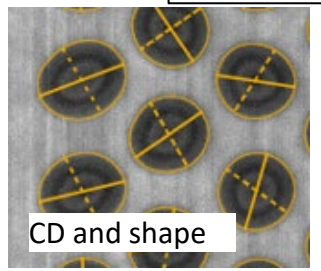
Reconstructed data volume

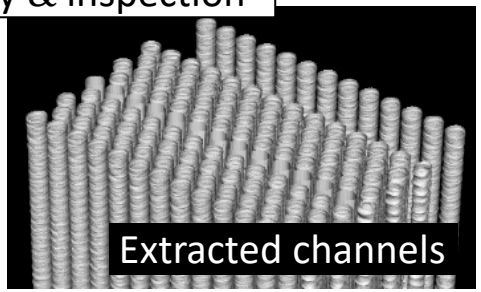


Arbitrary cross-sections



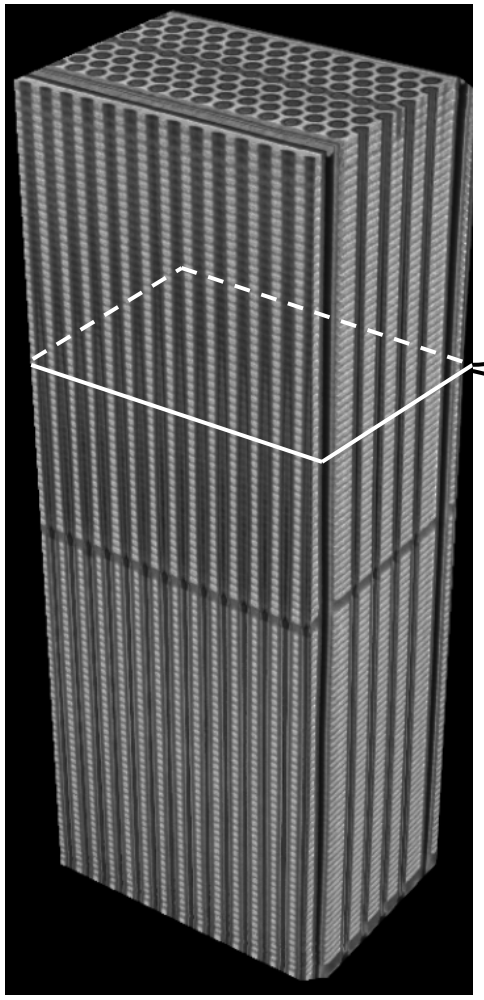
Metrology & inspection



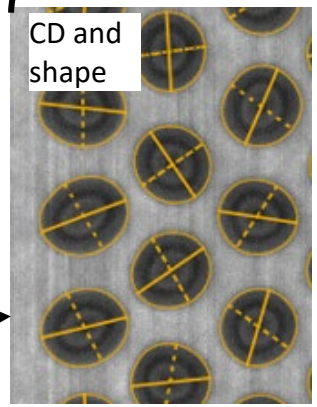


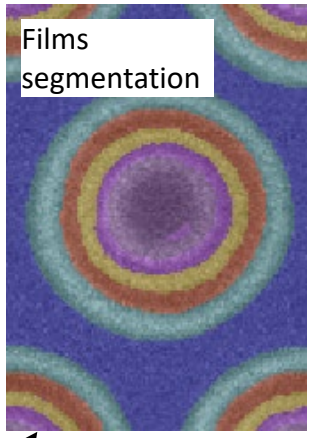
Measurement types for the storage area of 3D-NAND and DRAM (I): 2D-measurements in lateral cross-sections

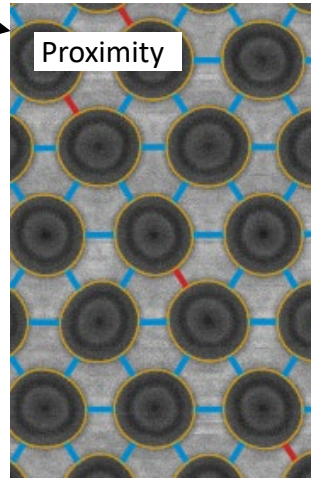
Reconstructed volume (3D-NAND)

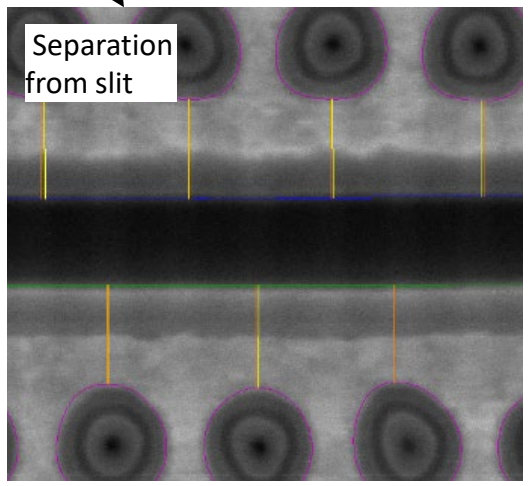


Measurements in lateral planes

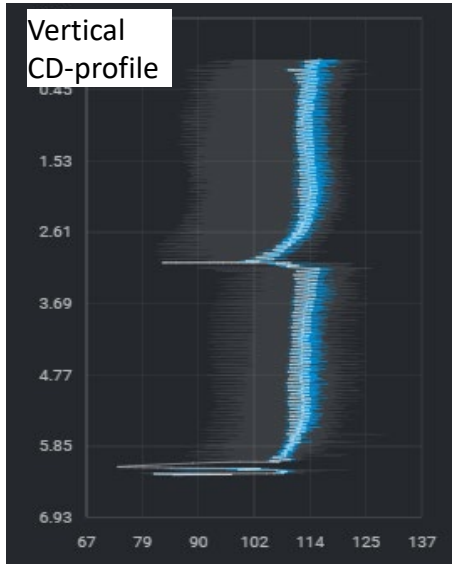


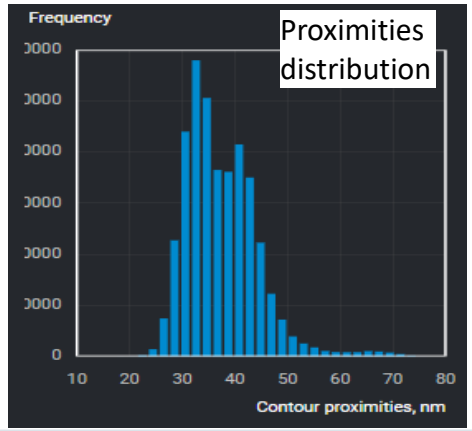






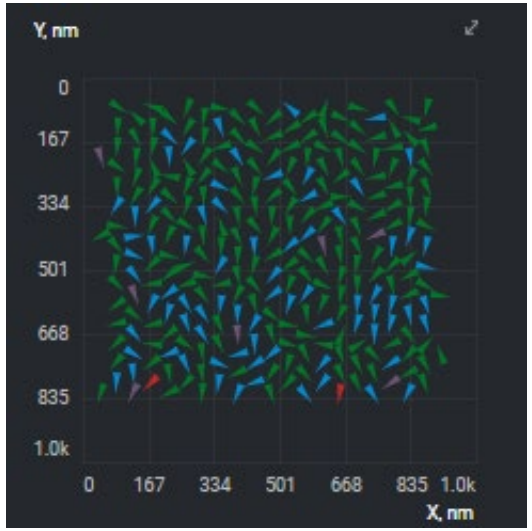
Vertical profiles and histograms



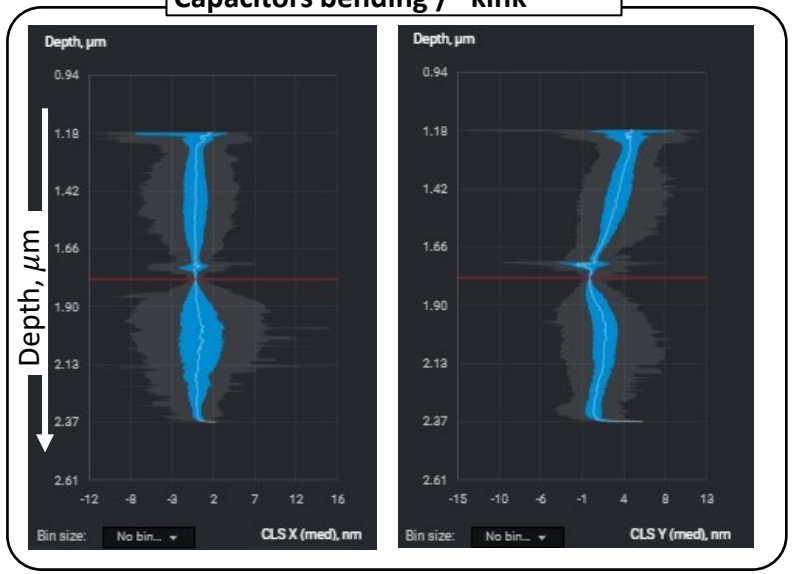


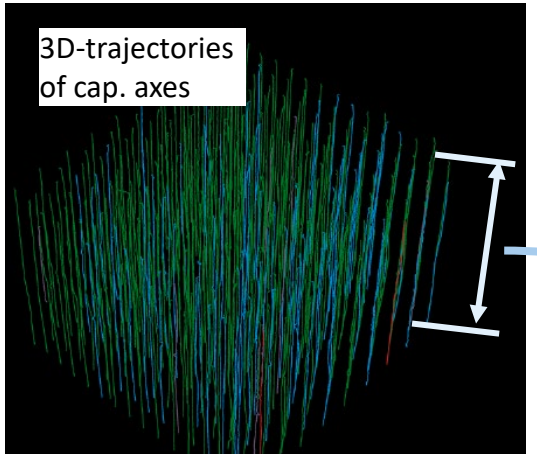
Measurement types for the storage area of 3D-NAND and DRAM (II): “Integral” 3D-measurements of the HAR structures

´DRAM Capacitor tilts (direction and amplitude)

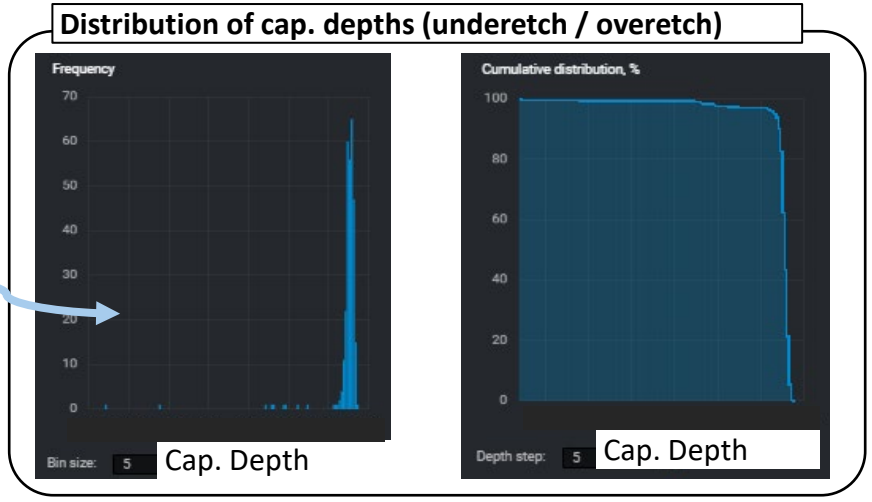


Capacitors bending / “kink”

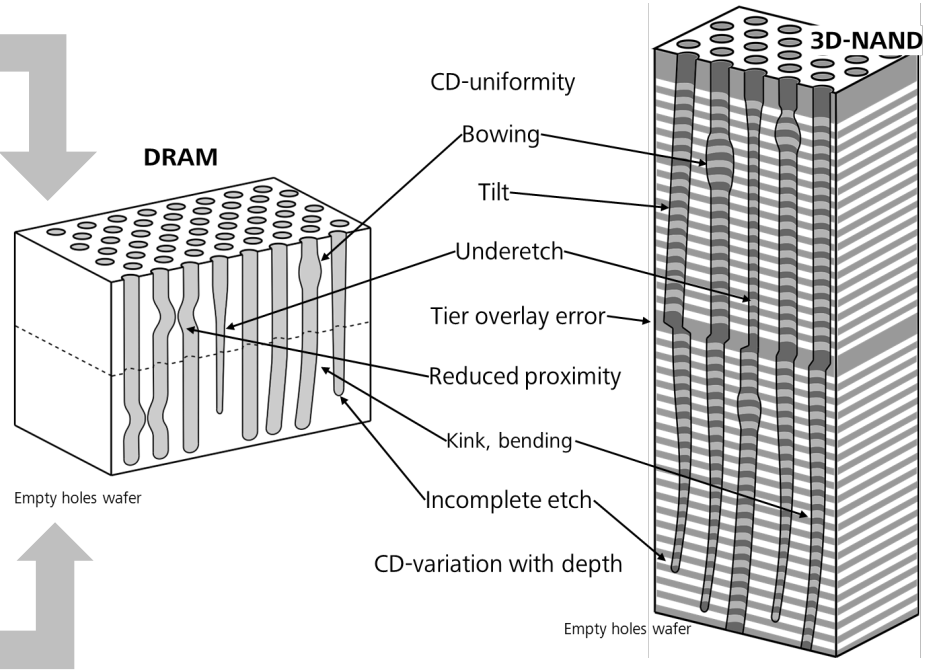




Distribution of cap. depths (underetch / overetch)



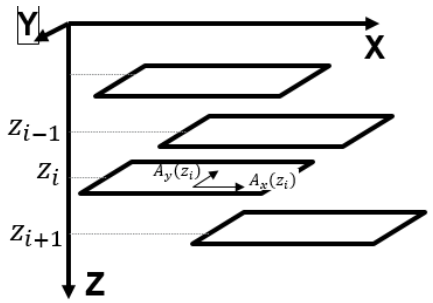
MANUFACTURING CHALLENGES IN DRAM AND NAND



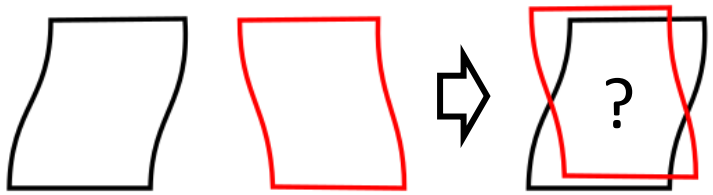
Challenges to be addressed for error-free 3D reconstruction (I): Variable image distortion caused by ROI drift and sample charging

Lateral alignment

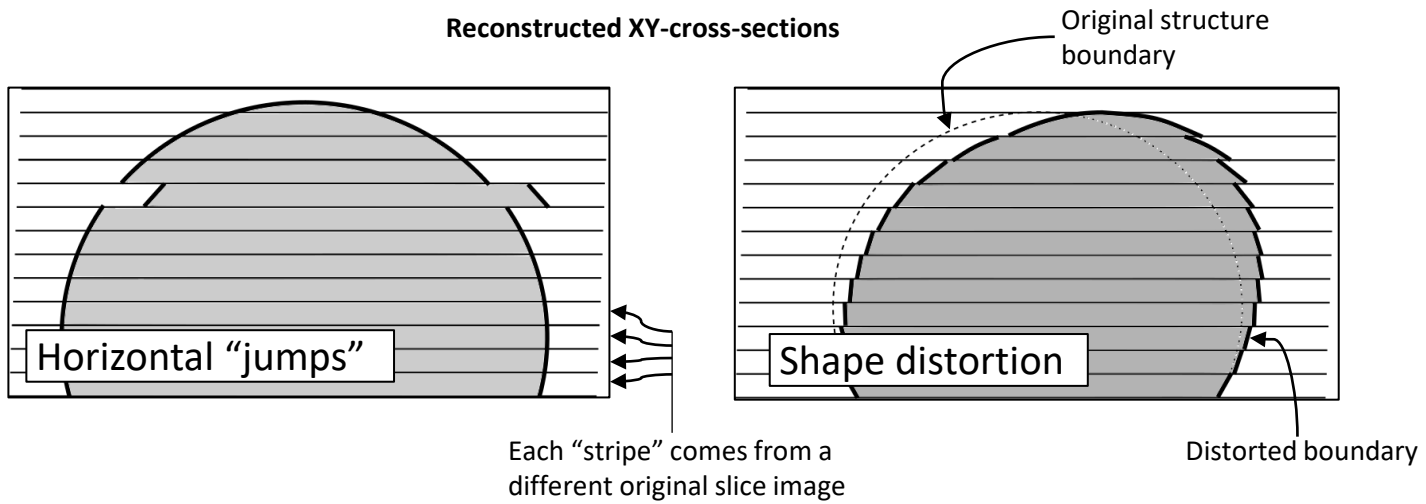
Lateral image offsets are removed by a multistep-step alignment procedure:



Distorted images cannot be easily aligned



Effects of drift-driven distortions on a reconstructed image if not properly addressed

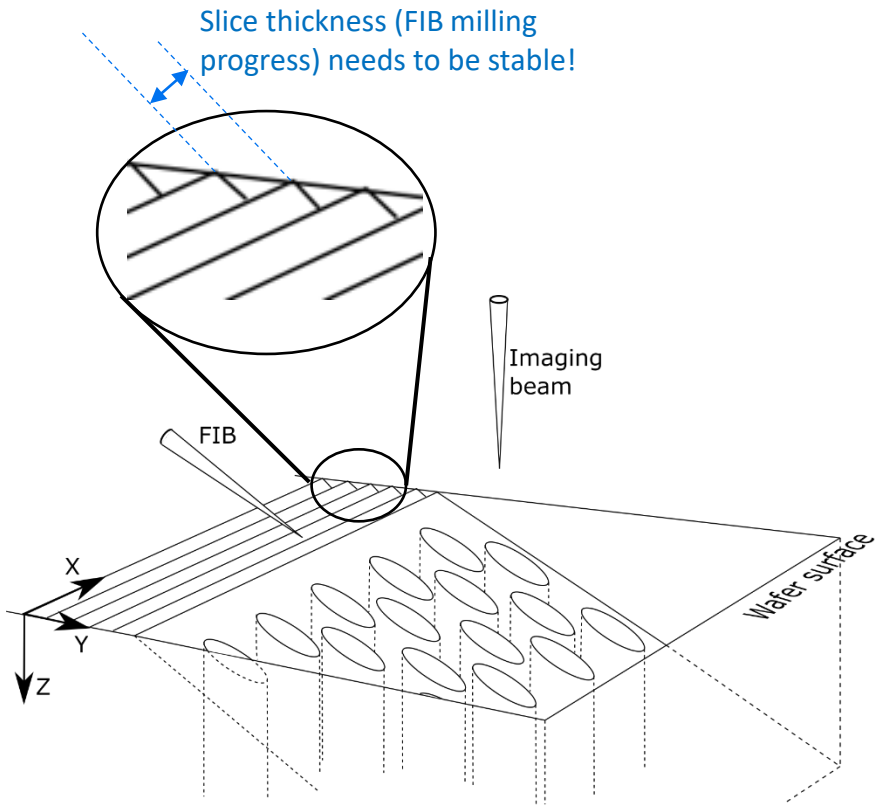


Implemented 3D MI overcomes the alignment problems through:

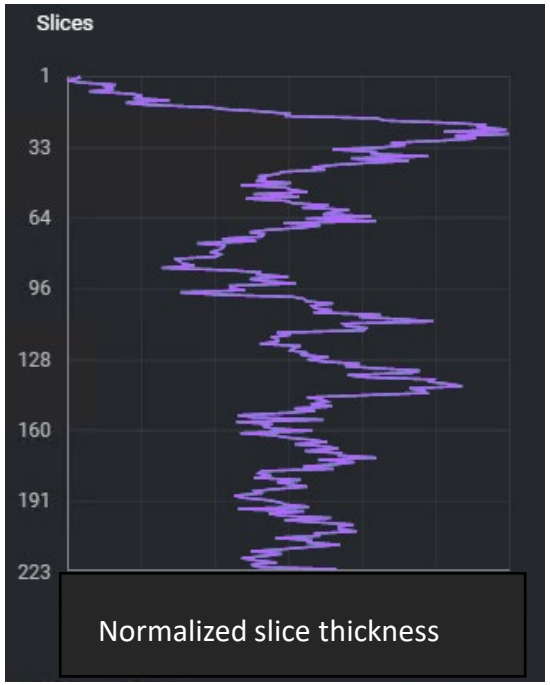
- smart frame averaging algorithms
- optimized acquisition modes
- advanced quantification and active monitoring of distortion modes

Challenges to be addressed for error-free 3D reconstruction (II): Slicing precision and stability

Precise milling (slicing) accuracy

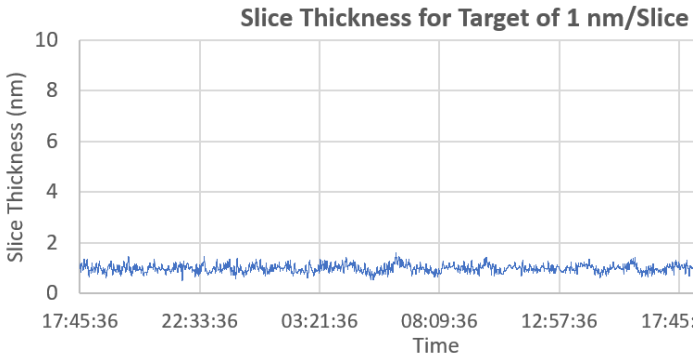


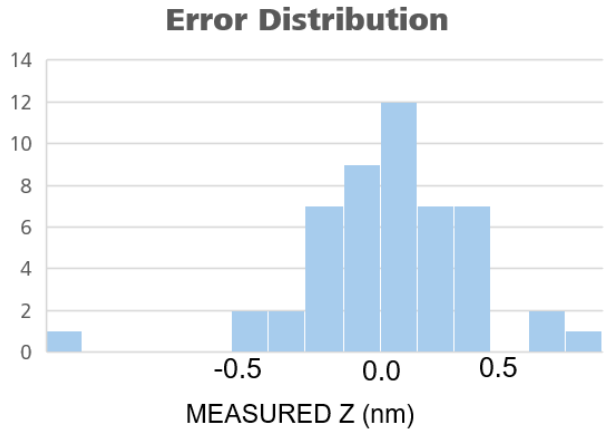
Example of unstable slicing



In presented approach, sub-nm slicing precision and stability are achieved using continuous slice thickness measurements supplied

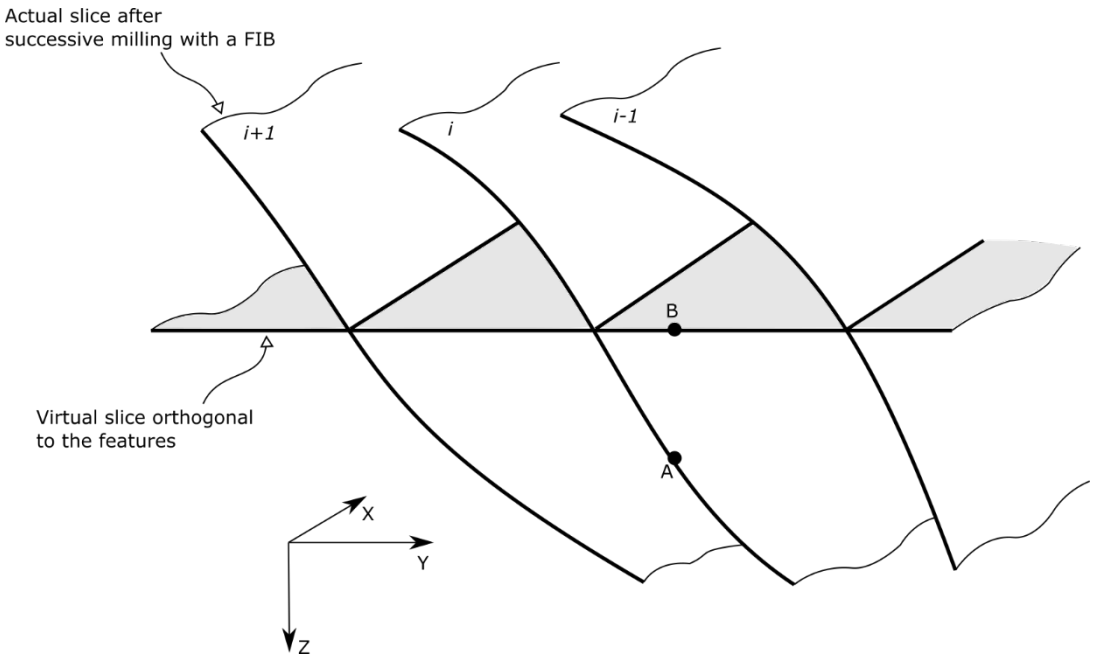
1. **to the acquisition feedback loop**
2. **to subsequent postprocessing**





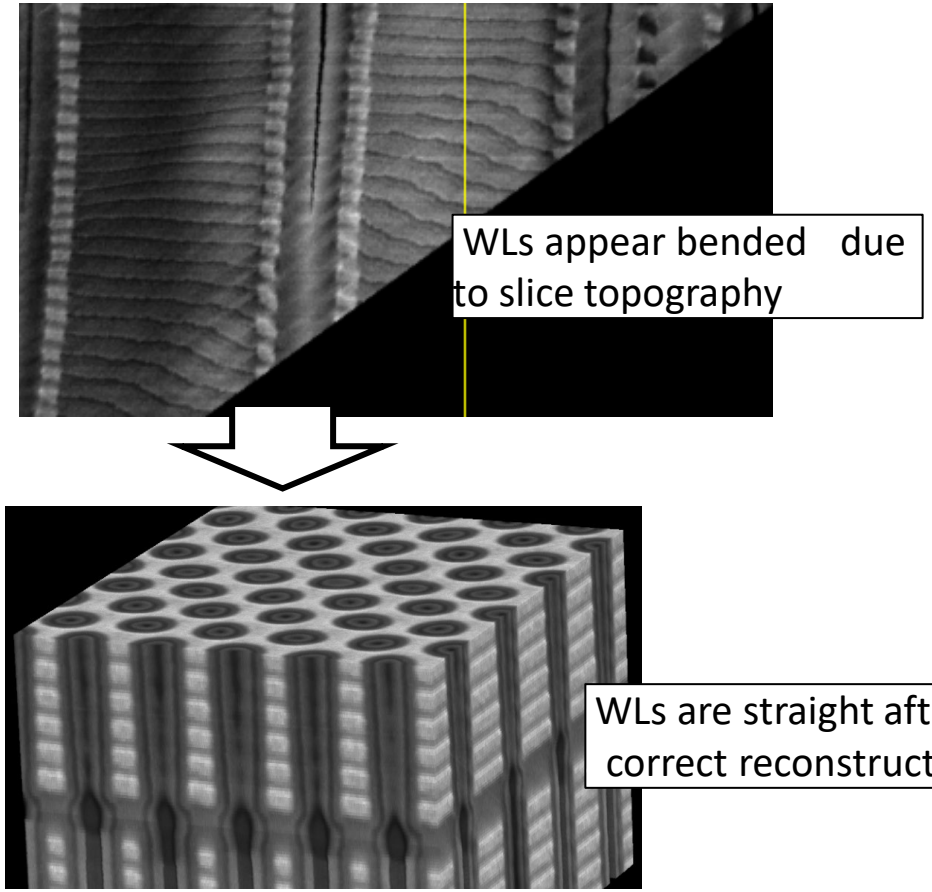
Challenges to be addressed for error-free 3D reconstruction (III): Non-planarity and topography of slices

Topography of milled slices needs to be taken into account properly while reconstructing virtual cross-sections as illustrated below!

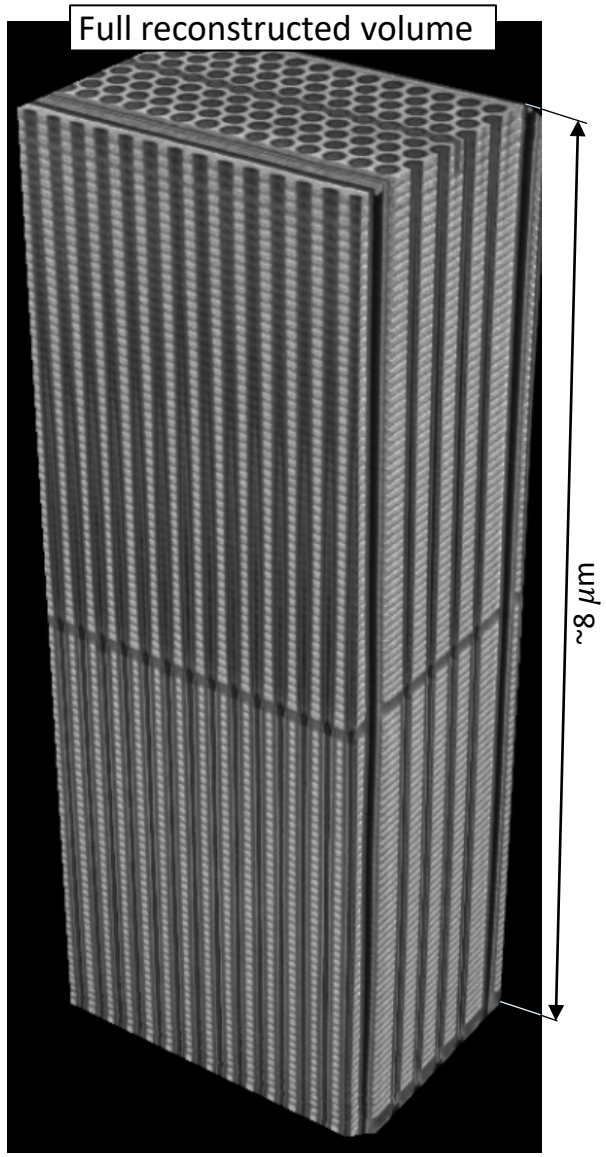


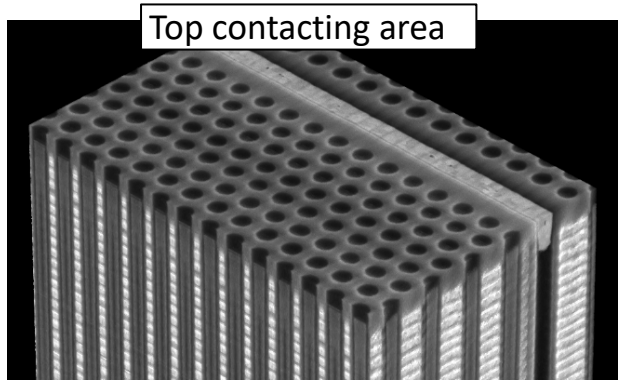
Slice topography / non-planarity is exaggerated in the graph to make the effect visible

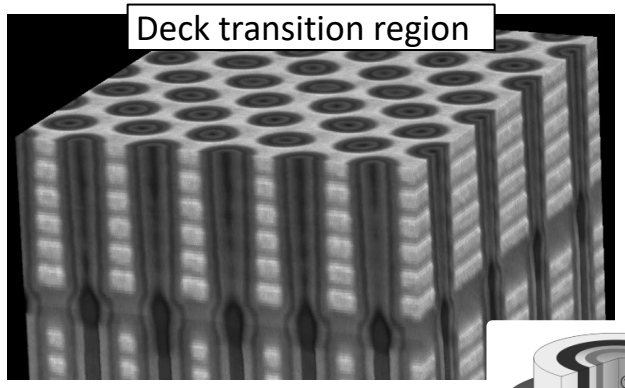
In presented solution, the slice topography is properly accounted for as demonstrated below on a challenging NAND periphery sample

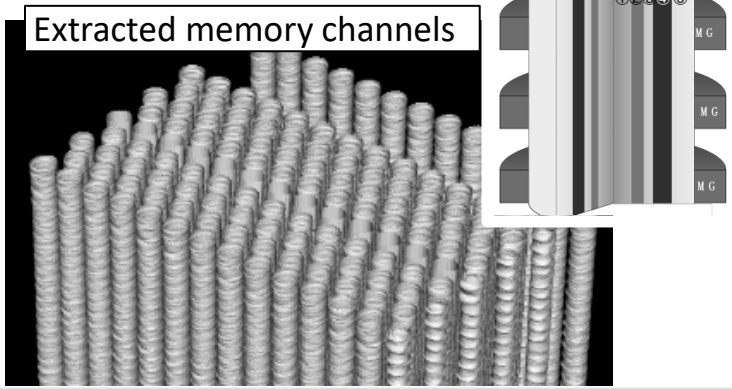


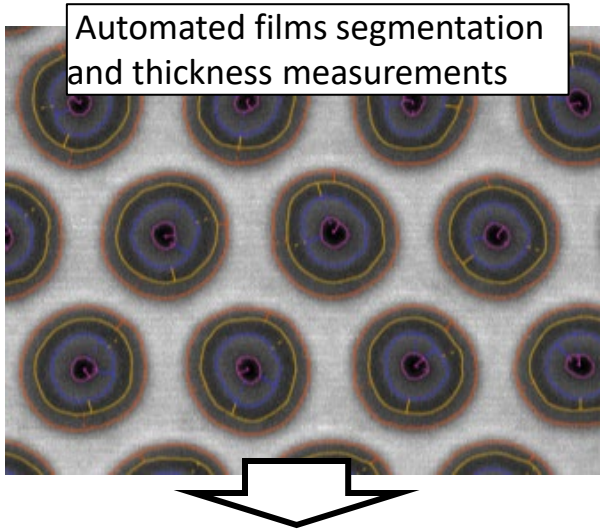
Examples of successful reconstruction and metrology (I)
3D NAND



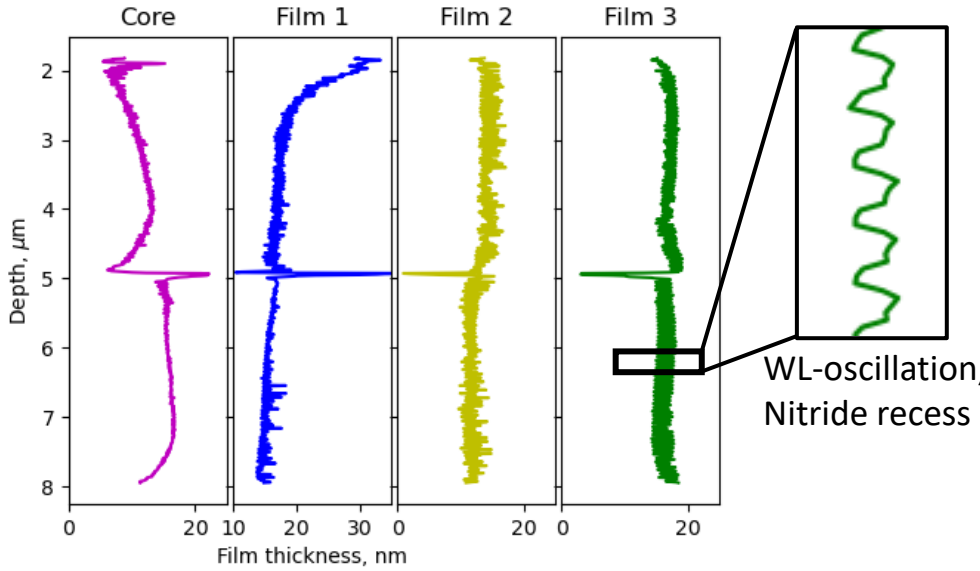






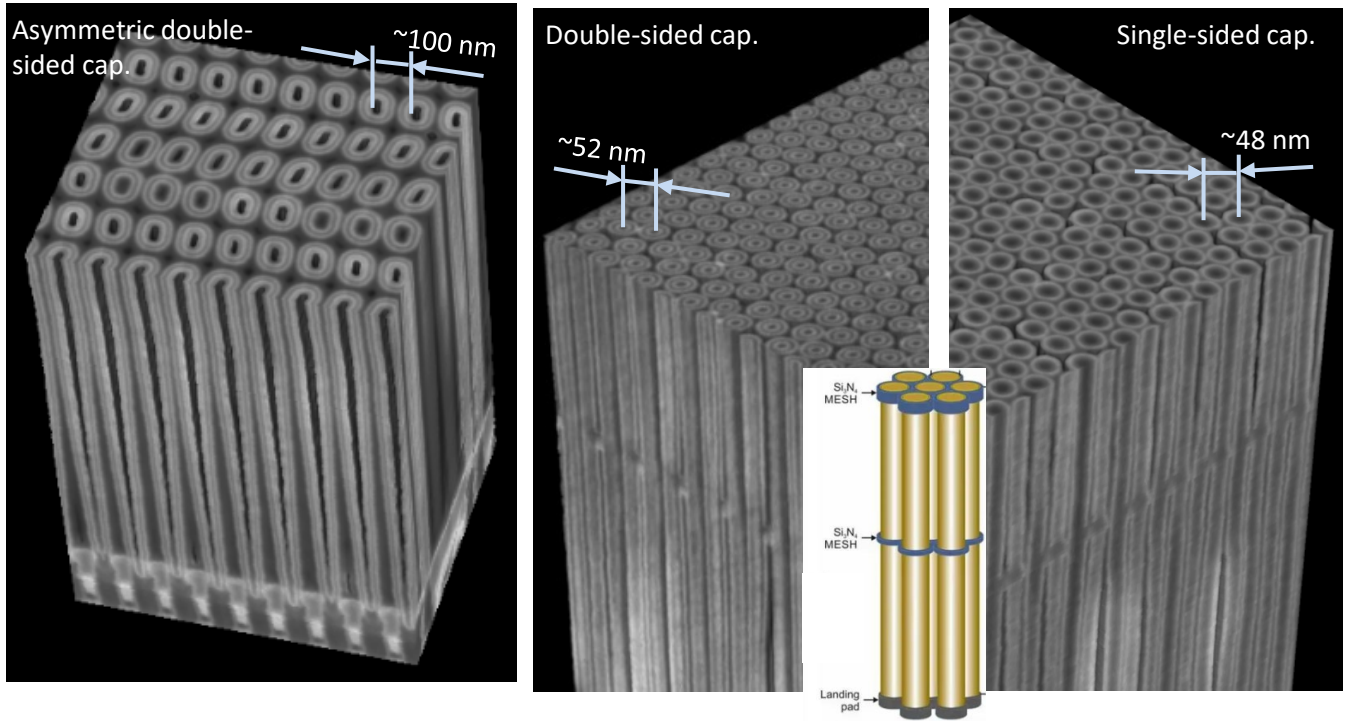


Measured films thickness profiles



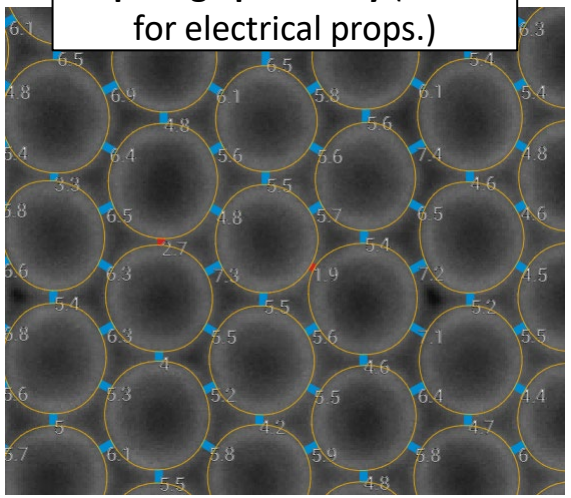
Examples of successful reconstruction and metrology (II)
DRAM capacitors

Reconstructed commercial DRAM samples with different capacitor architectures and lateral pitches

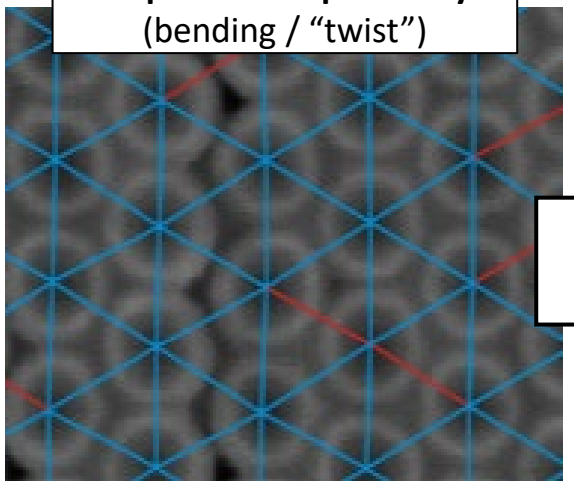


Full 3D characterization of several thousands of **individual** DRAM capacitors is achieved during a typical 3D tomography acquisition run

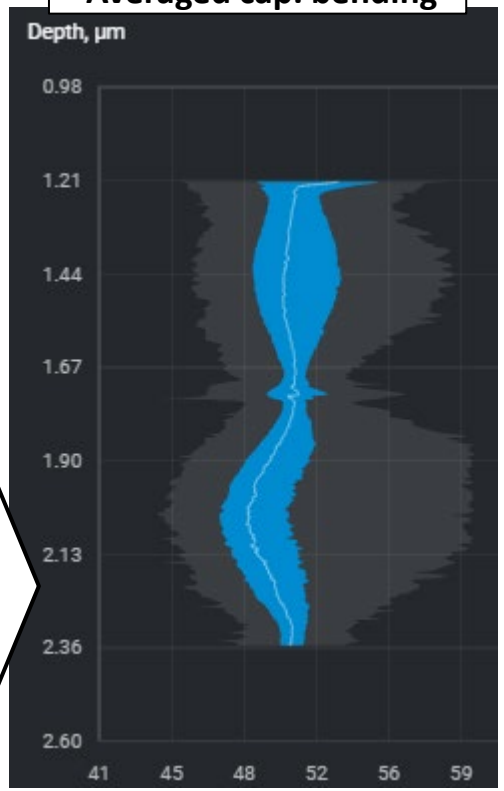
Cap. edge proximity (critical for electrical props.)



Cap. centroid proximity (bending / "twist")



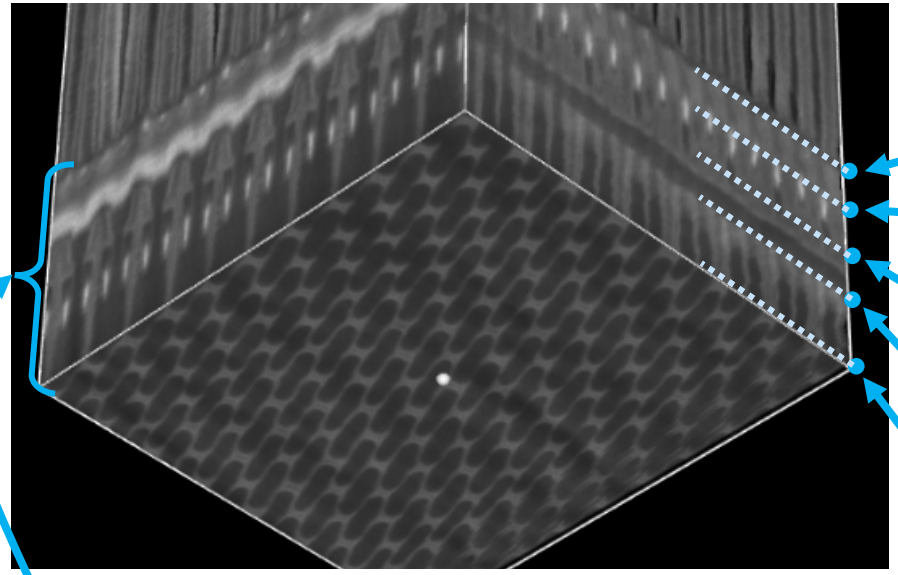
Averaged cap. bending

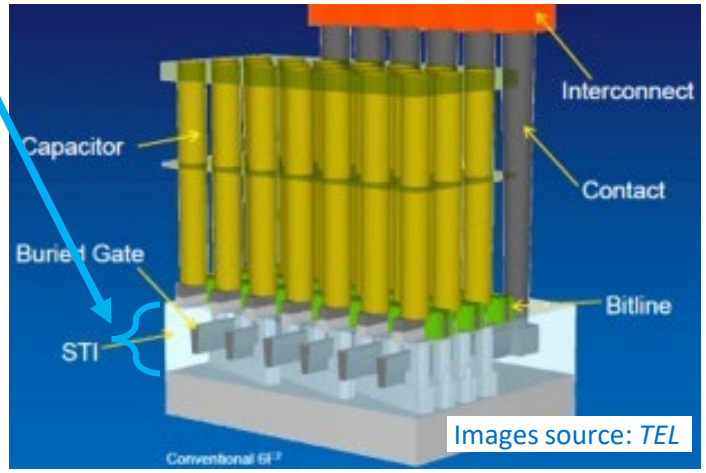


Centroid proximities, nm

Examples of successful reconstruction and metrology (III)
DRAM bottom transistor region

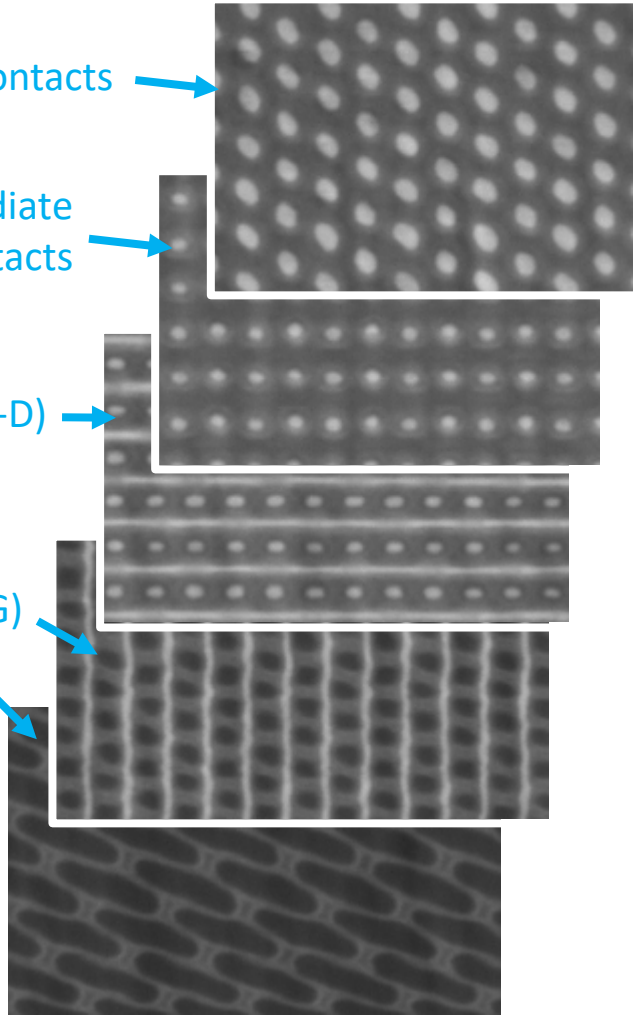
Reconstruction of the DRAM bottom tr. Region

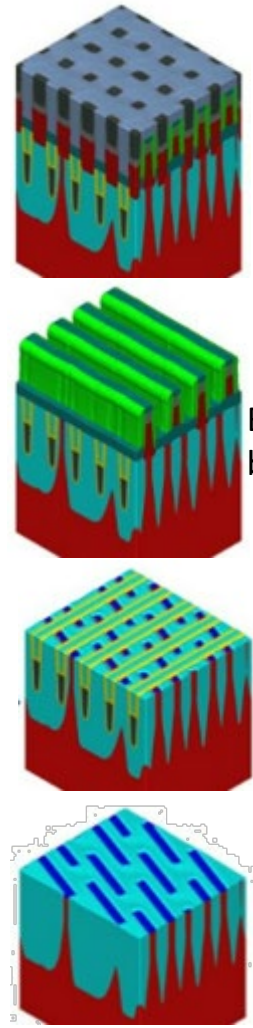




Images source: *TEL*

Reconstructed lateral cross-sections

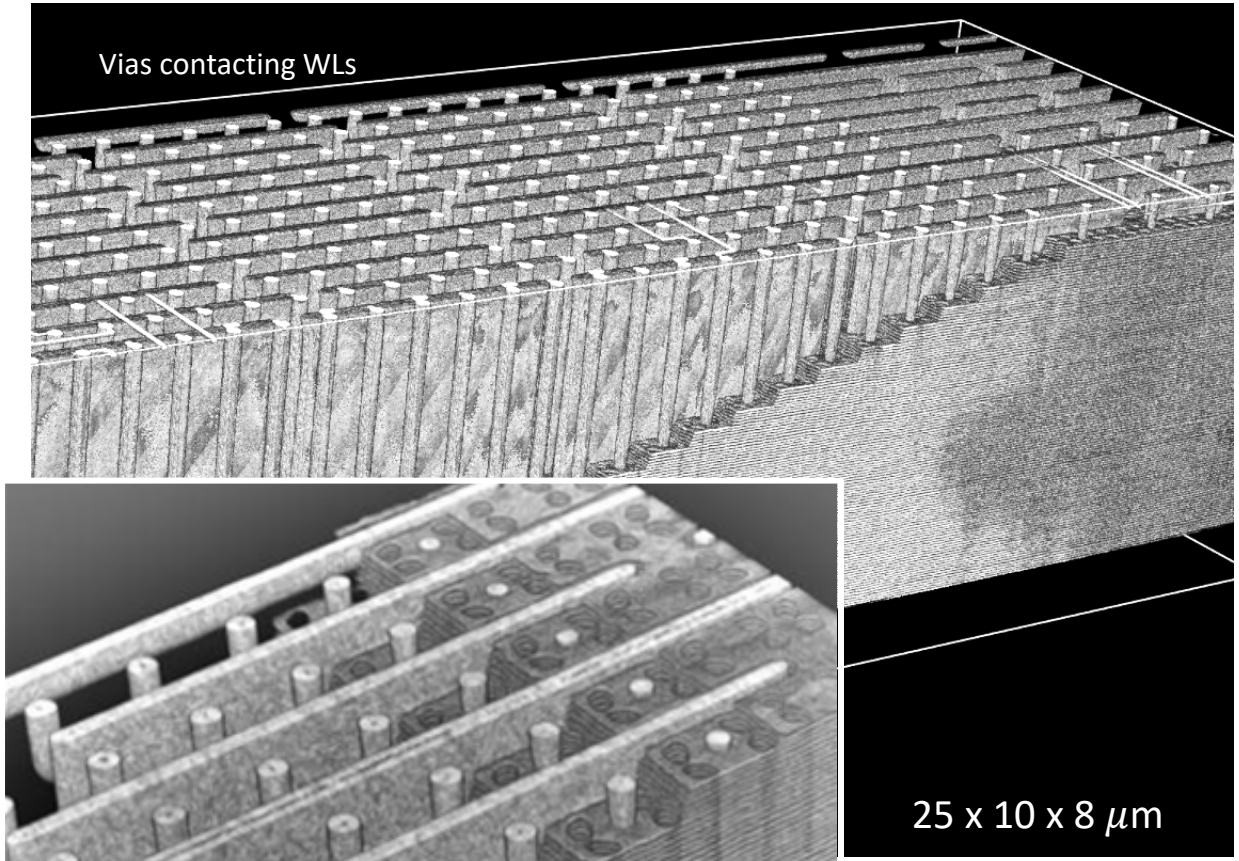




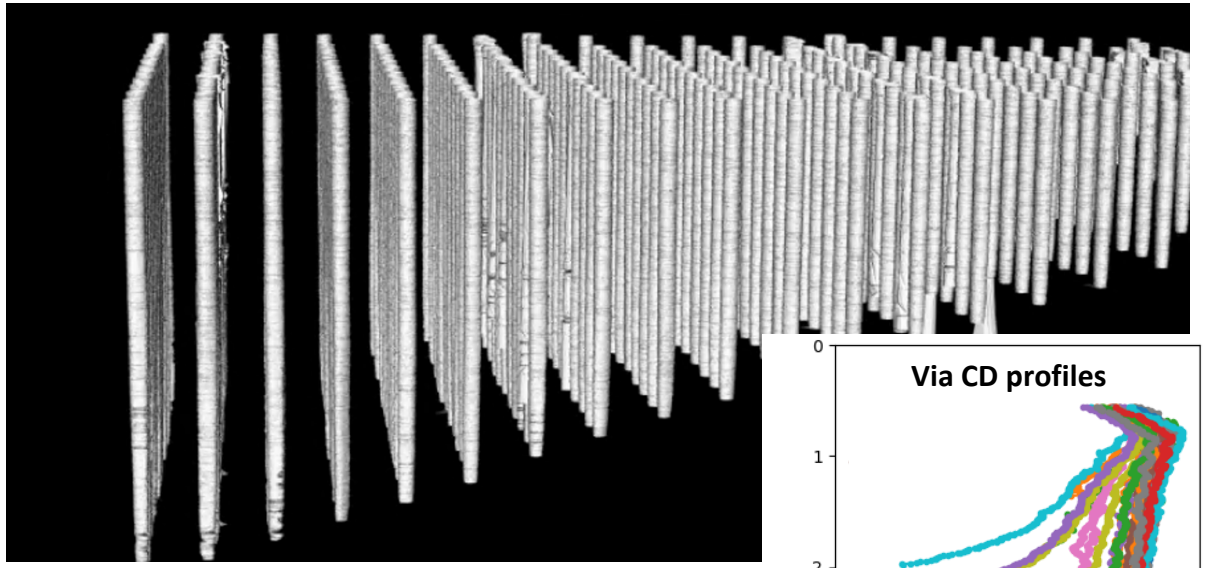
Images source: *Daebin Yim (2020)*
https://semiengineering.com/process-window-optimization-of-dram-by-virtual-fabrication/

Examples of successful reconstruction and metrology (IV)
3D-NAND periphery / “Staircase”

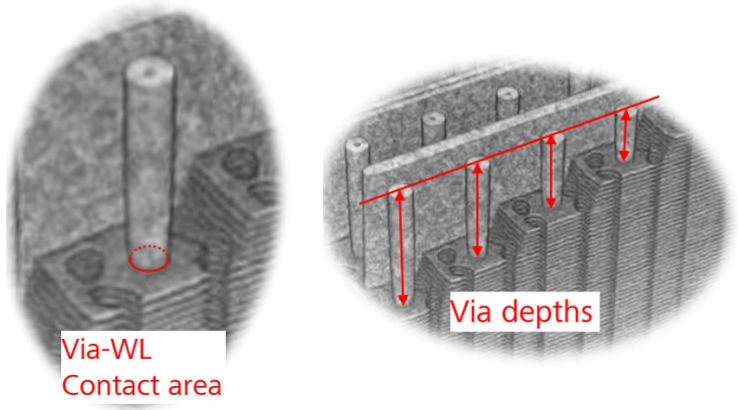
Reconstructed NAND periphery

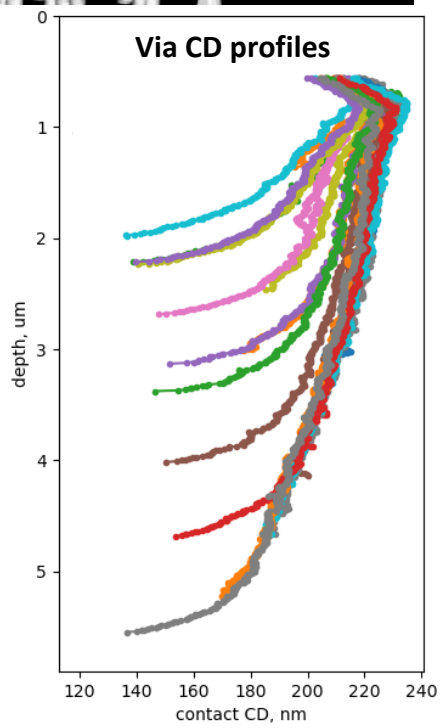


Extracted via/contacts



Examples of measurements



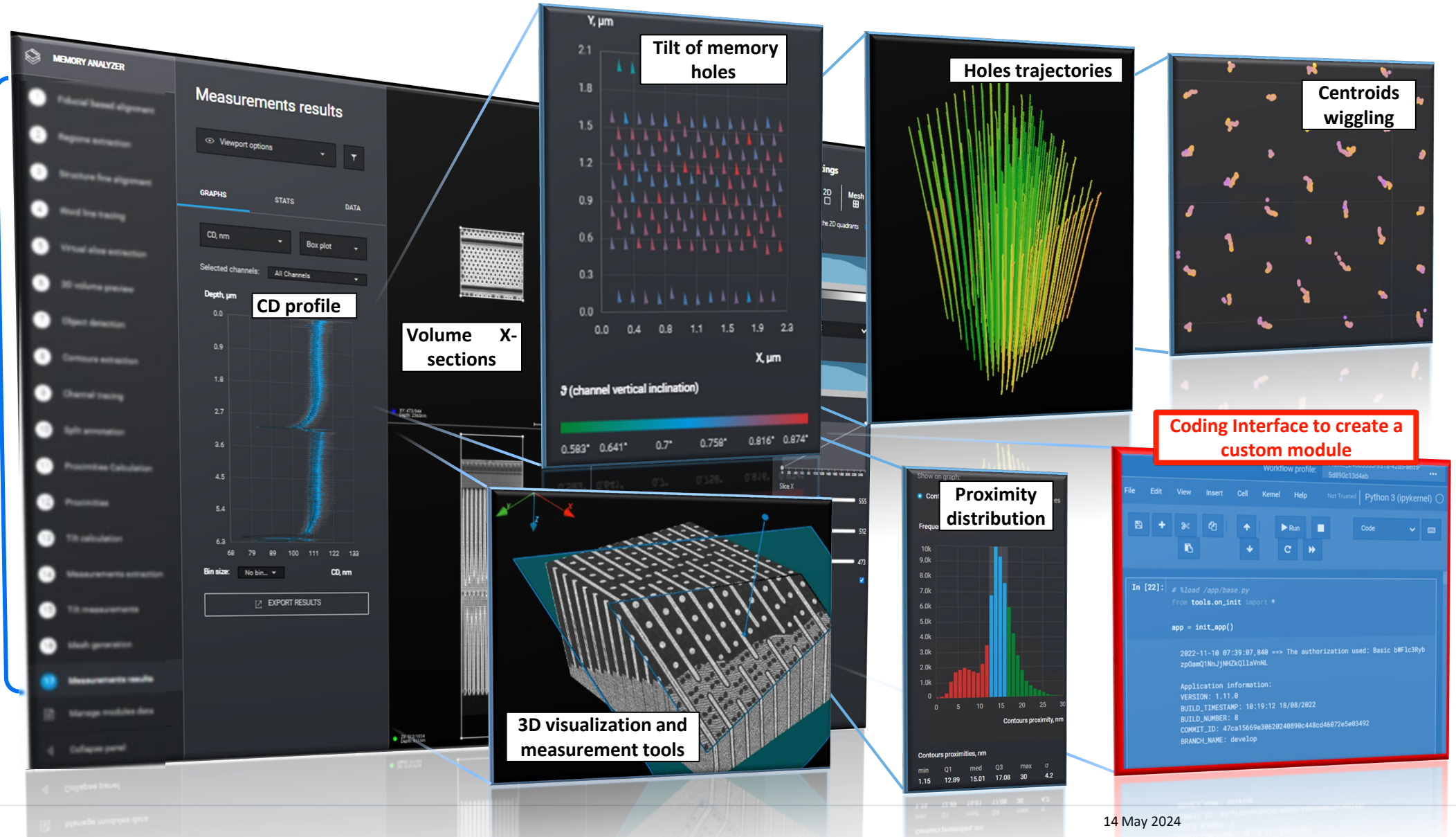


Dedicated data analytics platform for 3D tomography data

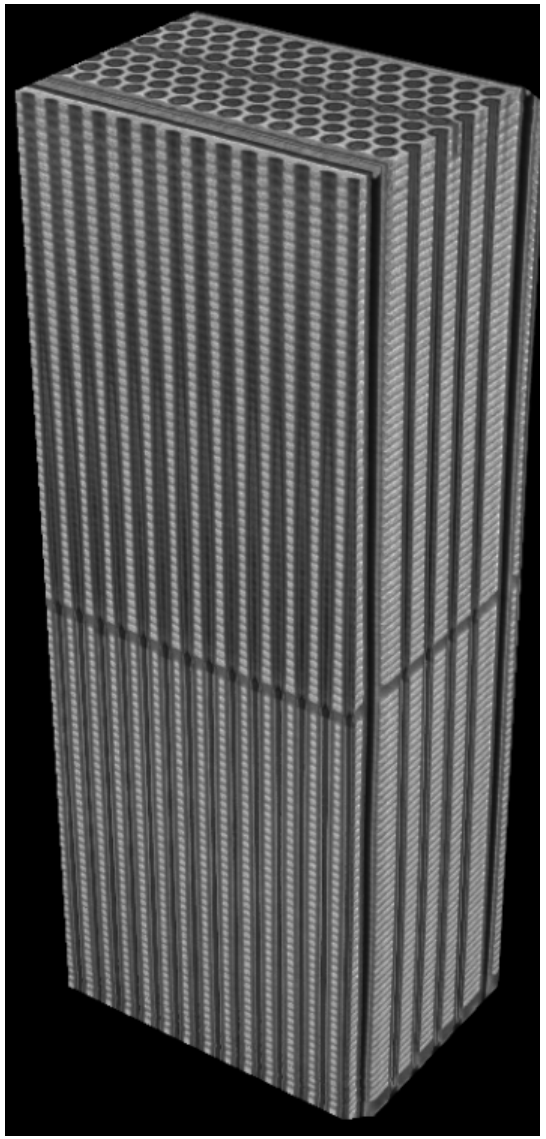
Workflow/recipe formed by a <u>configurable</u> sequence of modules

Main features of our analytics platform:

- Collection of pre-defined workflows for most common use cases
- Workflow constructor for customized analysis recipes using a large library of available modules
- *Coding Interface* module allowing the user to create and test completely new analysis step using *Python*



Conclusions



- Beyond the classical shrink, 3D architectures became the main technological trend on roadmaps for logic, 3D NAND and DRAM devices
- To continue 3D scaling, M&I techniques need to deliver accurate 3D characterization of the structures to be built
- TEM and optical characterization methods (OCD and CD-SAXS) will continue to deliver key process information albeit with limitations regarding statistical relevance or specificity
- At the same time, FIB-SEM techniques remain an essential pillar for the characterization of 3D structures. They can be used in in-line / near-line or in analytical labs
- To enable precise and error-free 3D imaging of complex architectures with FIB-SEM systems, the presented technology address essential impediments such as:
  - effects of drift- and charging-induced distortions
  - slicing imperfections
  - milling instability
- The presented approach offers a fully automated process of 3D image generation and extraction of all relevant geometrical parameters

A team effort of brilliant scientists and engineers

Dmitry Klochkov

Thomas Korb

Keumsil Lee

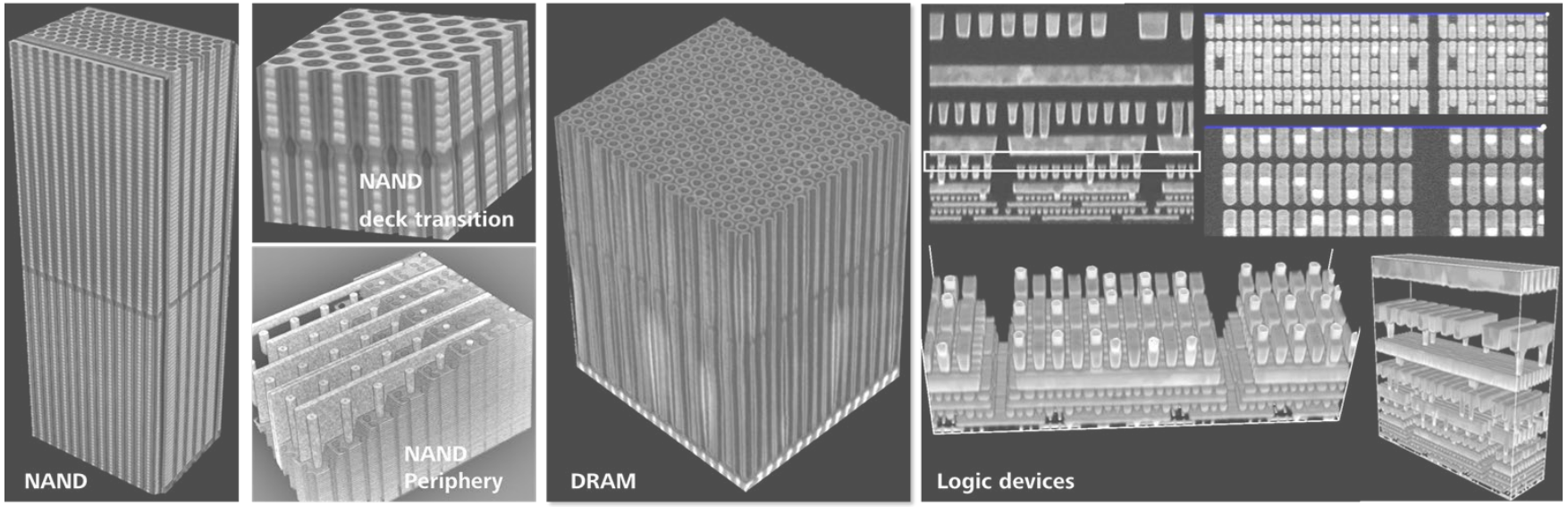
Hyunhwa Kim

R. Pichumani

Lakshmi Mantha

Philipp Hüthwohl

Eugen Foca



Seeing beyond