Applications of Electron Microscopy in Semiconductor Memory Industry

Presentation on ASCI (Advanced Structural and Chemical Imaging), 5/18 – 5/20, 2016, Boise, Idaho, USA.

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Overview

- Introduction of Electron Microscopy (EM) - SEM/FIB & TEM in the semiconductor industry.
  - Process geometries beyond optical capabilities drove initial SEM requirements. Became crucial in the 1990s (especially in late 90s).
  - Establish separate paths for metrology and nano-probe analysis in year 2000.
- Evolution of Metrology
- Failure Analysis
- Evolution of analytical TEM
- Future challenges

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General Flow from R&D to Market

R&D → Manufacture → Testing (QA)

R&D

- Design
- Layout
- New Materials
- Process Module development
- Integration
- Transfer

Manufacture

- Process control
- Equipment Qualifications
- Failure analysis

Testing (QA)

- Failure analysis

EM supports are involved in steps marked in red.

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Evolution of Metrology

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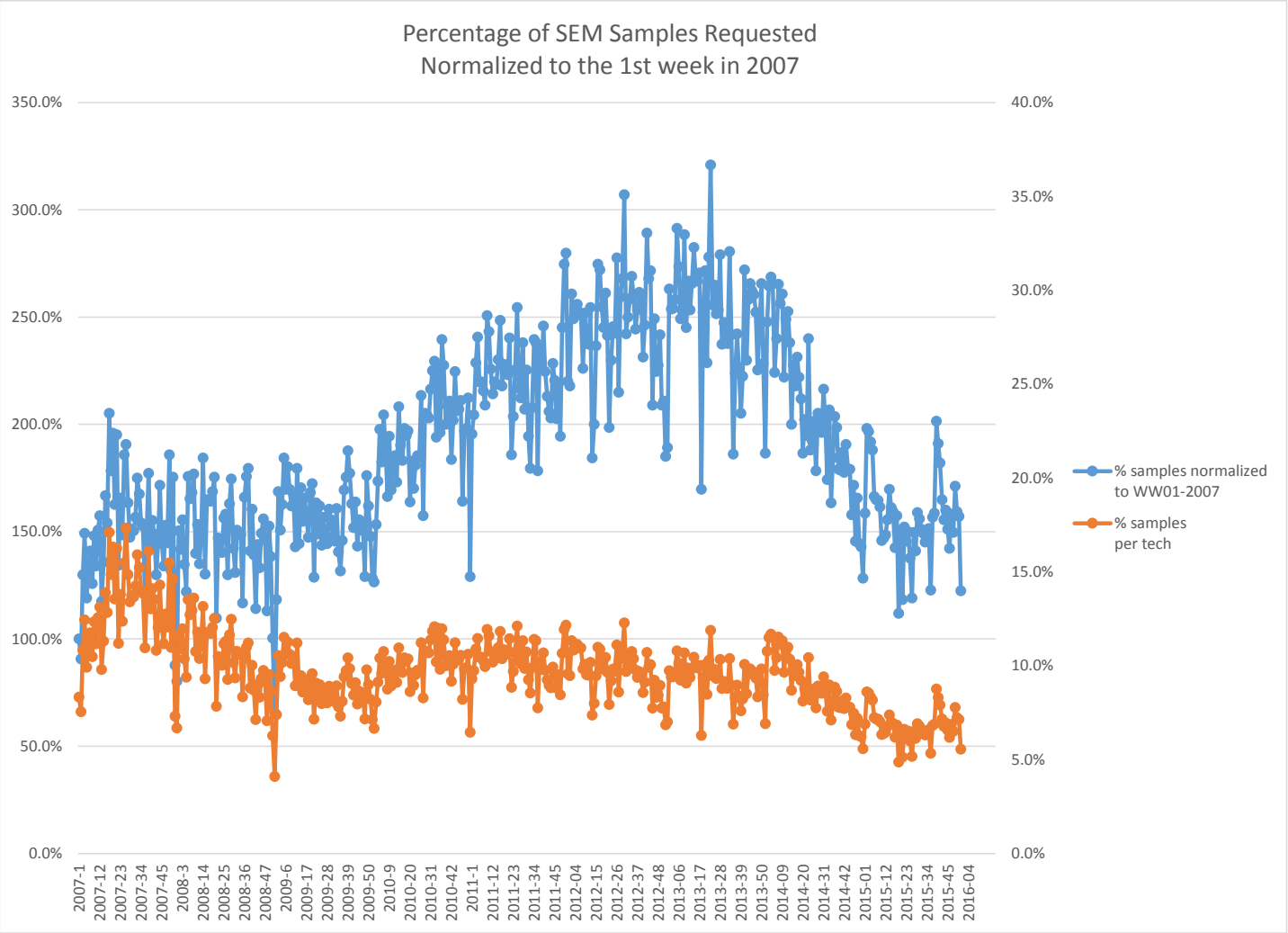
Micron SEM Lab Sample Demand Evolution



- Blue line represents the change in number of samples as normalized to the first week in 2007 at 100%.
  - One observes a dramatic rise in the amount of requested work through 2013 (~250%).
  - Starting in 2014 SEM demand drops, until the beginning of 2015, then it flattens out at ~150%.
  - The drop in demand is due to adoption of other metrology techniques in the Fab, as well as better process control.
- The amount of SEM work completed by each SEM tech is portrayed via the orange signal.
  - One observes that the orange line trends down, indicating that the complexity or amount of time for each request is on the rise.

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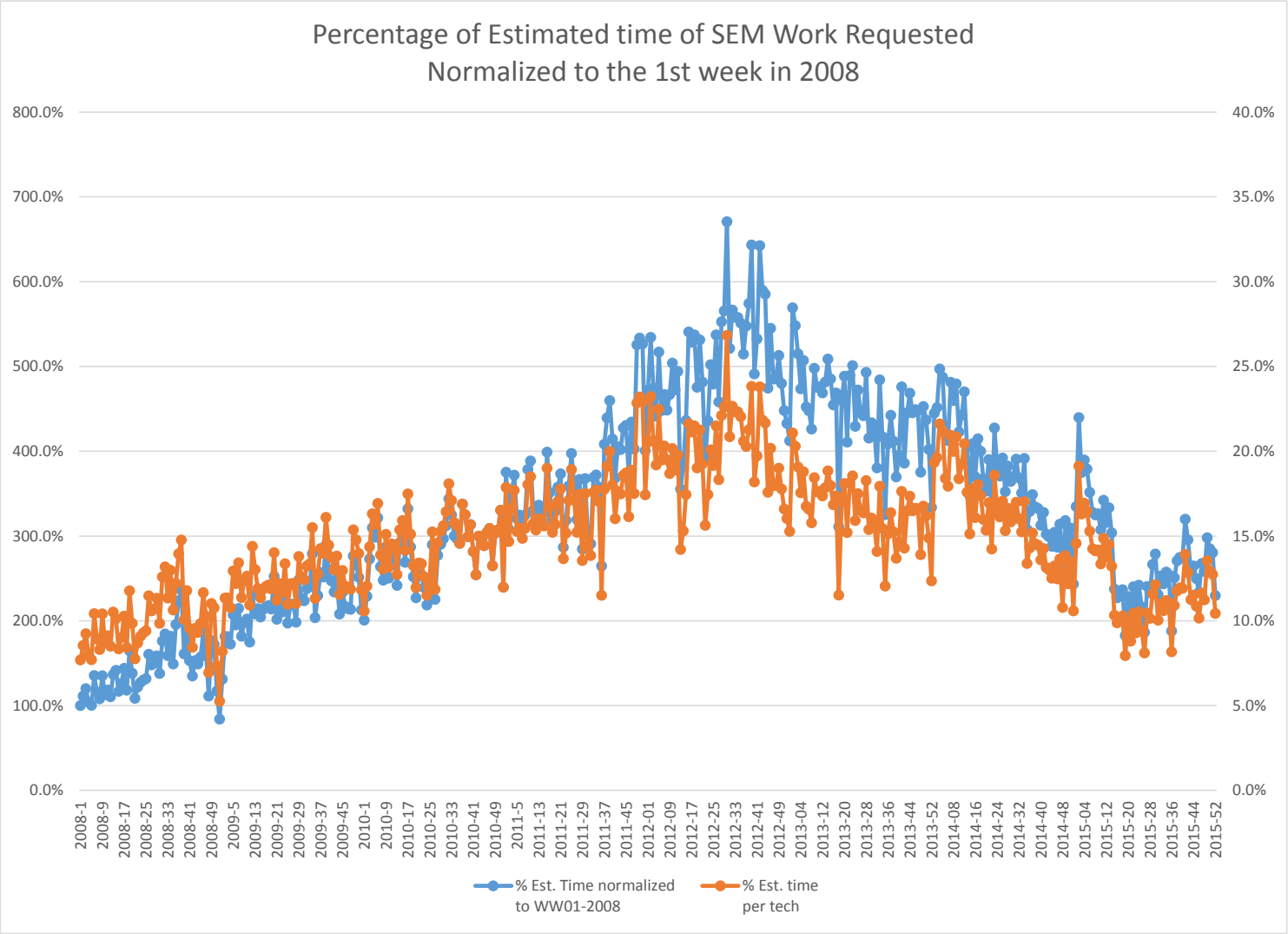
Micron SEM Lab Estimated Time Evolution



- Blue line shows the change of the estimated time normalized to the first week in 2007 at 100%.
  - One observes a dramatic rise in the amount of time to complete the requested work through 2012 (~500-600%).
  - Starting in 2013 the estimated time drops, until the middle of 2015 where it is now trending back up to 2010 levels (~300%).
- The orange line depicts the amount of estimated time completed by each SEM technician.
  - This correlates better to the amount of work each SEM tech completes, which fluctuates between 10-20%.

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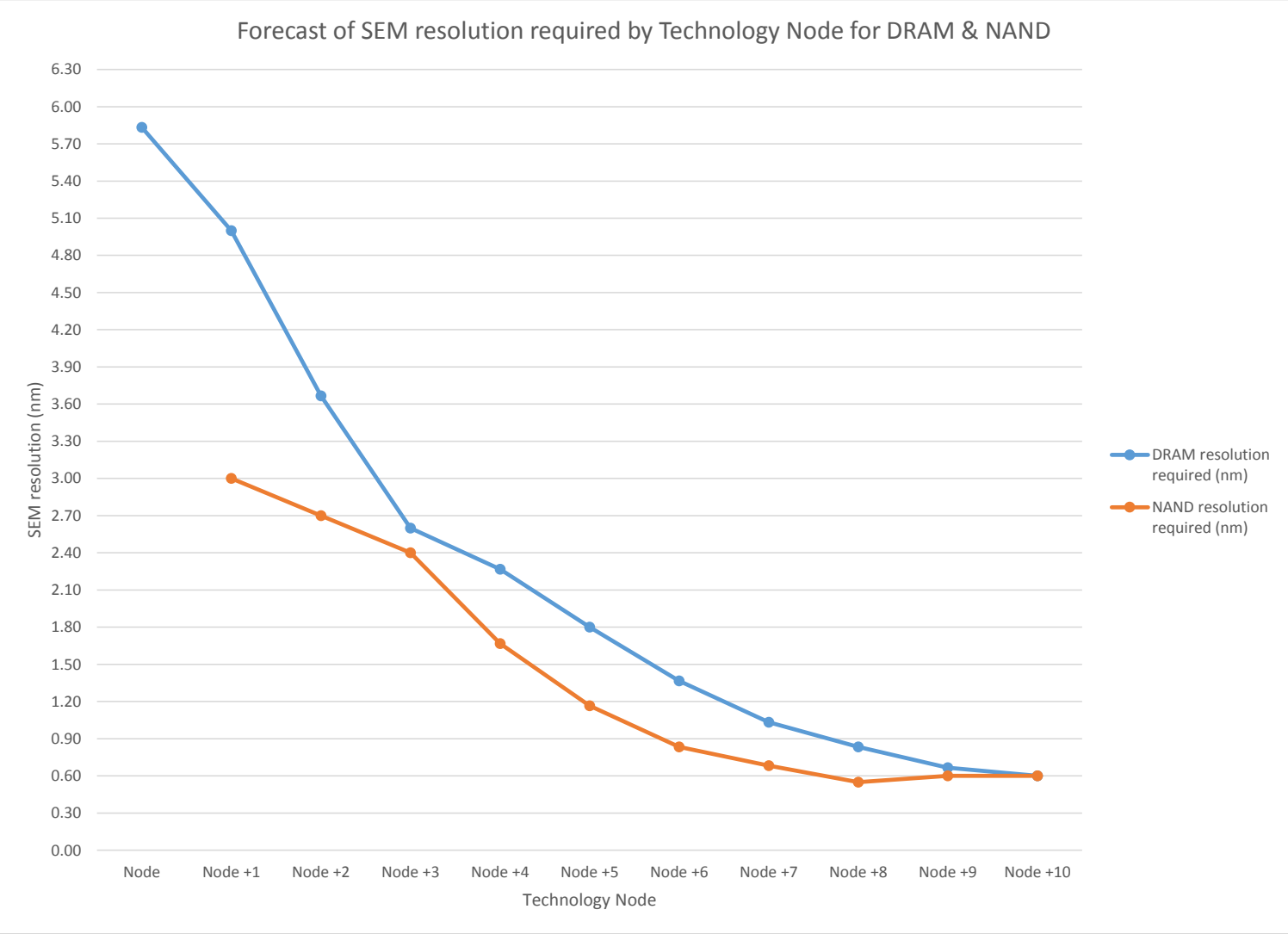
Micron SEM Resolution Roadmap



- In 2006 it was empirically determined that the minimum performance needed for SEM to support the memory development was 1/30 of the half pitch of the technology.
  - To illustrate this point, a memory technology with a half pitch of 30 nm would need a SEM with e-beam resolution of 1 nm (using the gold/carbon standard reference).
  - This empirical dimensional relation has held for nearly 10 years.
- Unfortunately the need for better materials contrast coupled with the continued drop in feature size is limiting the accuracy and precision of SEM metrology.

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Transition of SEM Metrology to TEM Metrology

- Through innovative advances in SEM hardware and software, the memory industry was able to delay significant TEM metrology levels.
- Today, some of the metrology work can still be monitored through SEM, while the remaining work requires STEM or TEM based metrology to meet the needs of the memory industry.
- Fortunately advances in Fast TEM Prep (FTP) has been somewhat overcome through new hardware and software advances, allowing TEM metrology to be pursued with a more reasonable ROI.

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ROI Consideration for SEM and TEM Metrology

- Historically, the small dual beam preparation and then TEM imaging had a traditional fully loaded cost for TEM metrology in the memory industry more than 10X per image in comparison with that from SEM.

- With the enablement of the Fast TEM preparation (FTP) solution, the cost of TEM metrology in the memory industry has dropped to less than half the traditional full-loaded cost for TEM metrology.

- The cost structure continues to improve as system efficiencies and business processes are further optimized.

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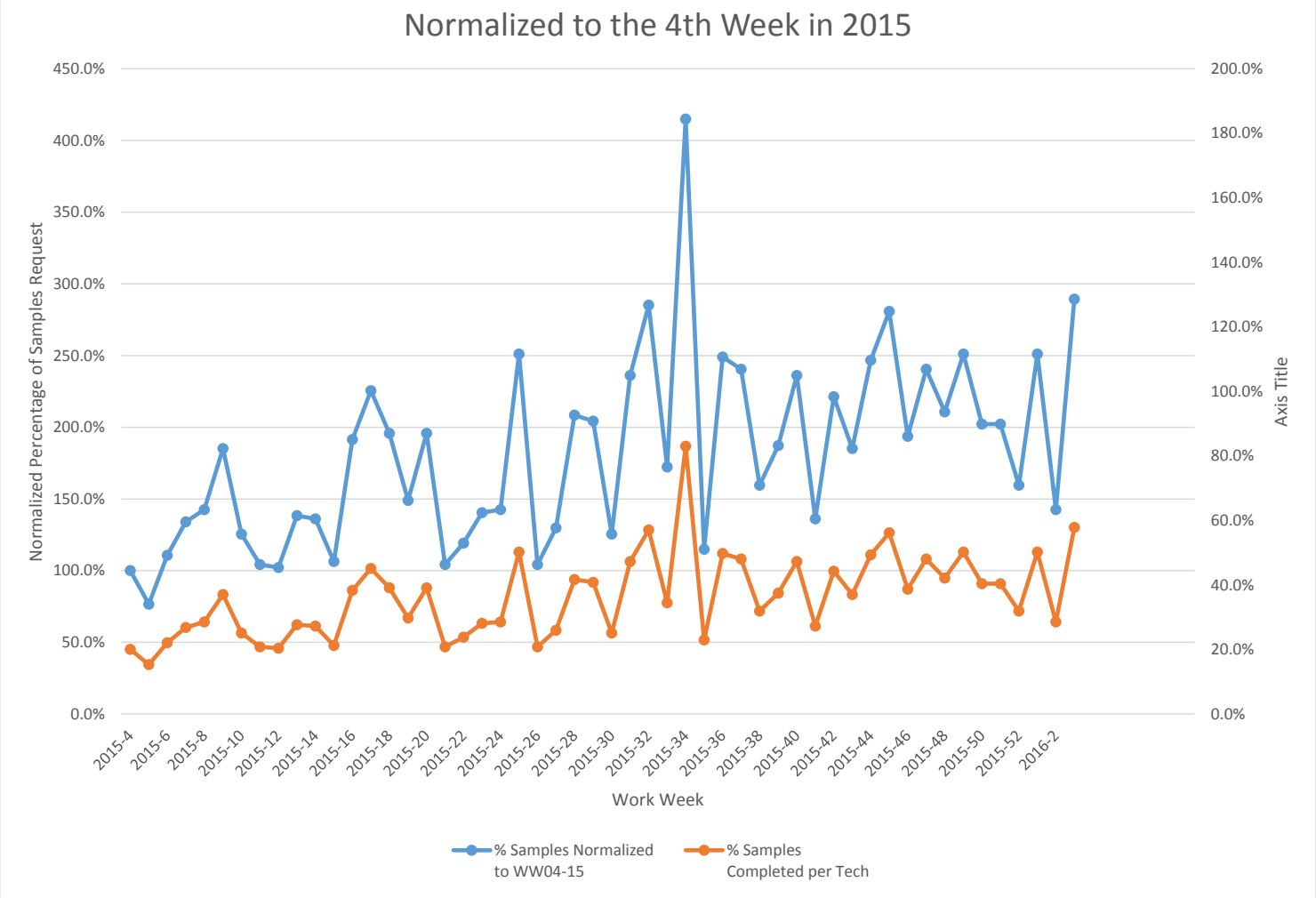
Micron FTP Lab Sample Demand Evolution



- Blue line: Demand over time
  - 150% growth in automated TEM business since the initiation of tracking.
  - Handling of the demand growth by efficiency improvements and batch loading of jobs through the system.
- Orange line: Contribution of each technician towards completion of the requested work.

Note: Similar trends between blue and orange lines indicates efficiency improvements as the process is getting mature.

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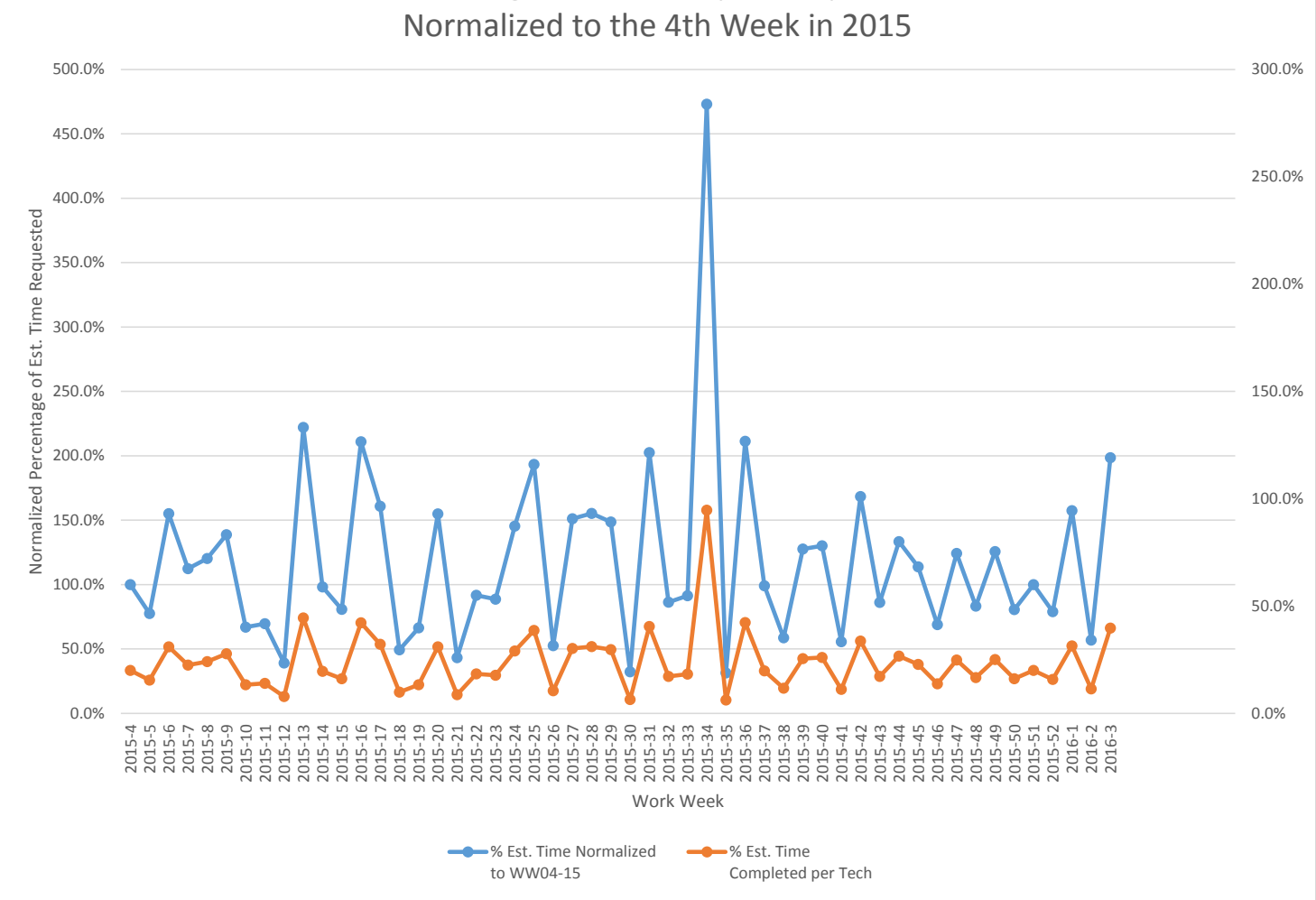
Micron FTP Lab Estimated Time Evolution



- Blue line:
  - A fair amount of volatility in the estimated time, indicating that there isn't a consistent relationship between the number of samples and the amount of estimated time it will take to complete the work.
- Orange line:
  - Once again tracking with the blue line, indicating that the existing team is able to handle these drastic swings in submission level.
  - The volatility of the orange line dampened in WW 37, suggesting that the business process in place has the capability of accommodating these large swings in estimate time.

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Failure Analysis

– where EM metrology and analysis merge together

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Failure Analysis Overview

LOT REVIEW ANALYSIS:

Wafer test results are reviewed.

Wafers are selected and scrapped for further analysis.

ELECTRICAL FAILURE ANALYSIS

Selected wafers are first electrically characterized through bench testing or through emission analysis.

Once electrical analysis is complete it is sent forward for physical failure analysis.

PHYSICAL FAILURE ANALSIS

Selected devices are de-processed.

Depending on failure type, the physical observation is completed in one of three general approaches.

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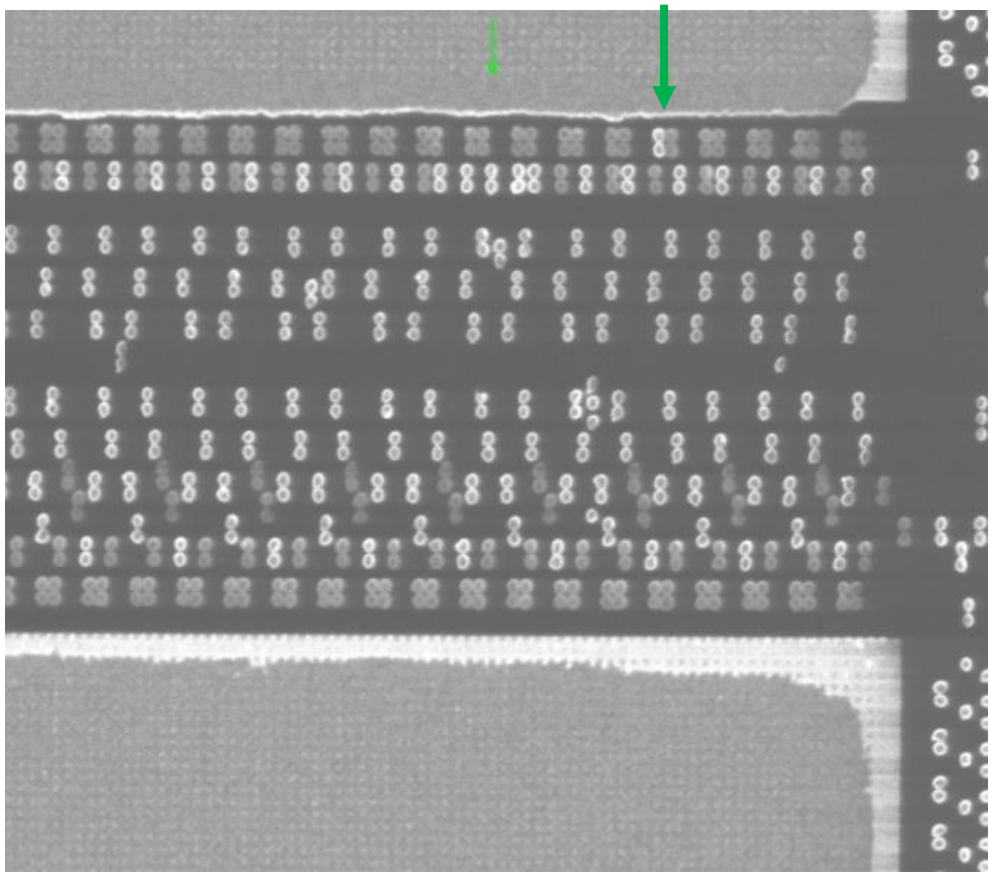
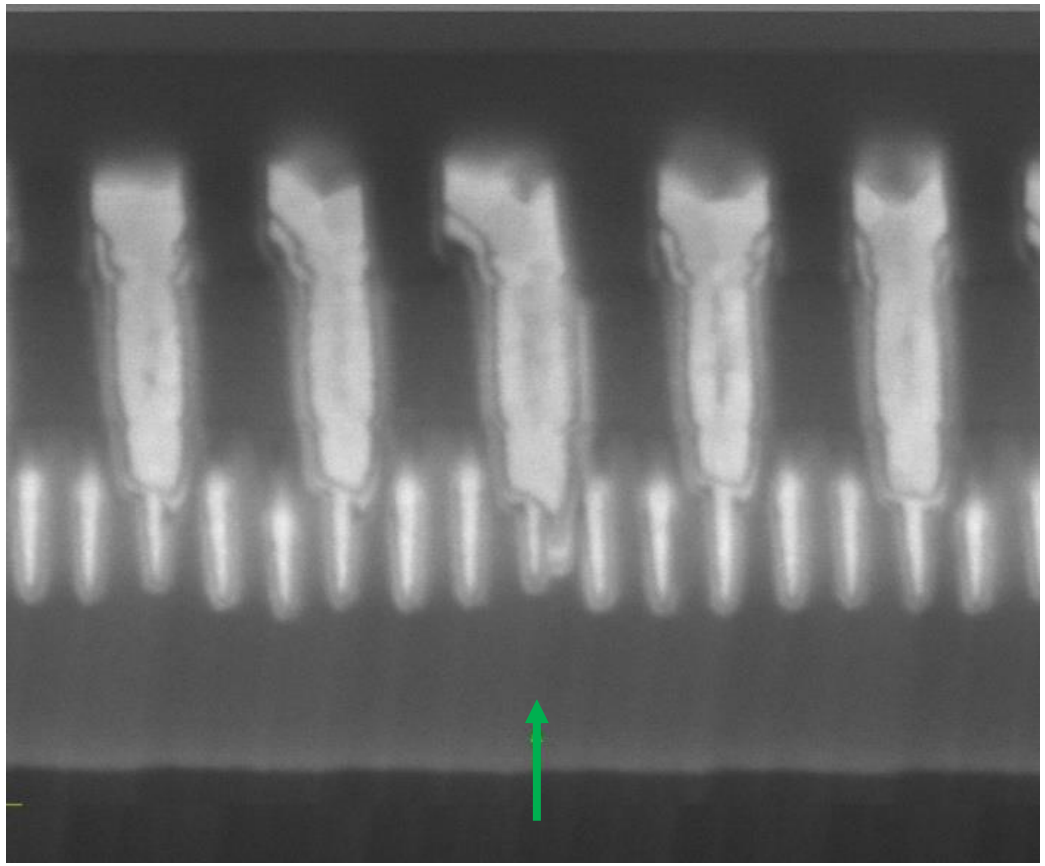
Failure Analysis-Top down or Cross Section observation in SEM





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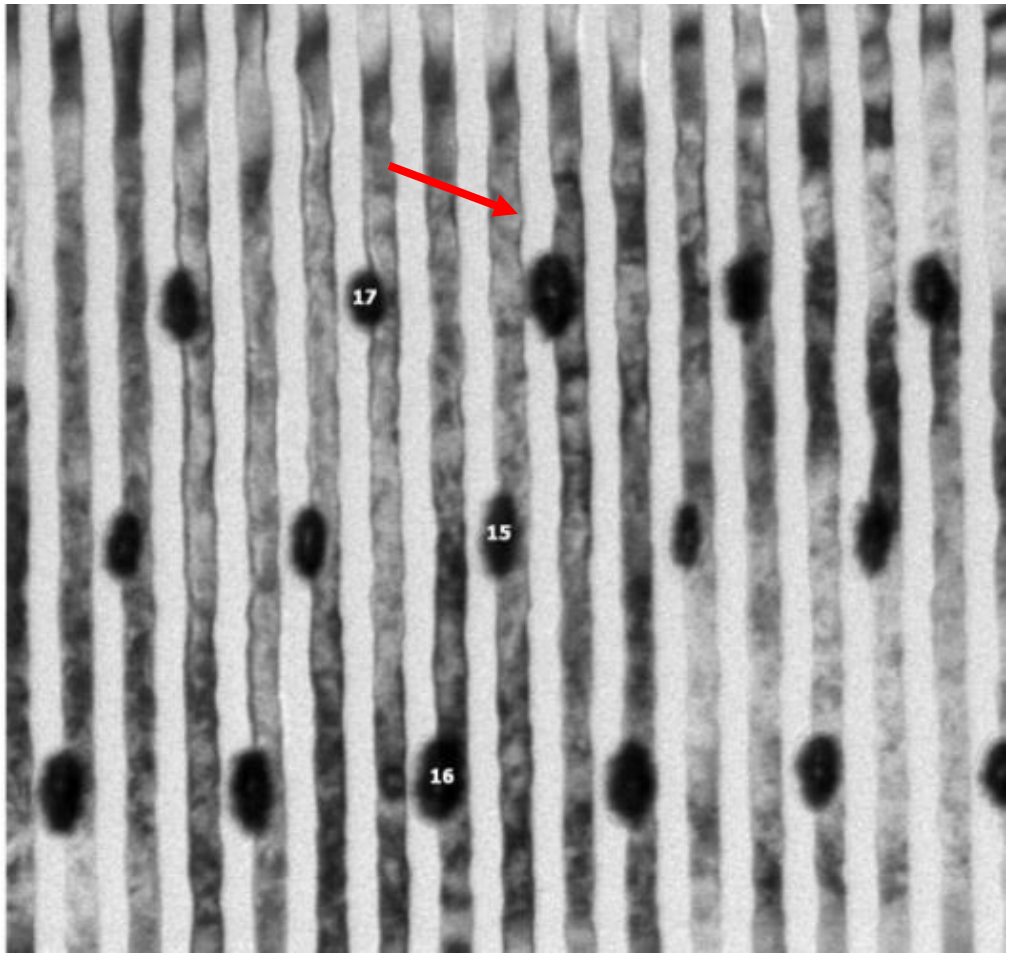
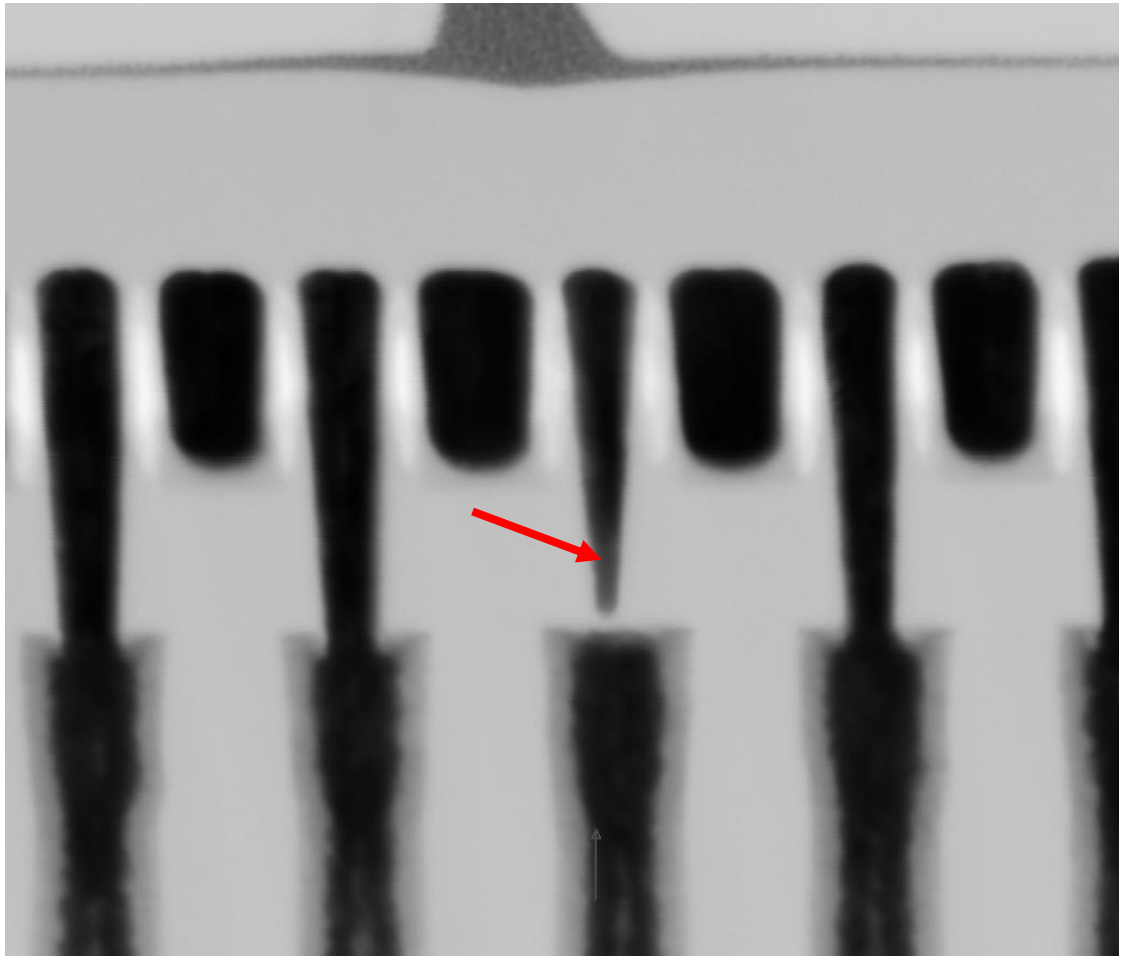
Failure Analysis-Top down or Cross Section observation in TEM





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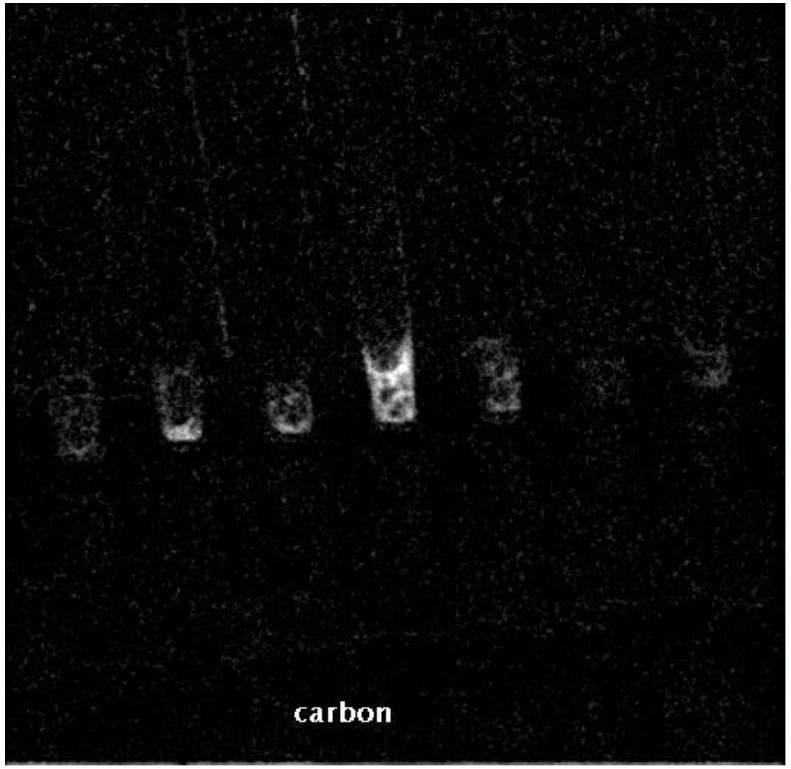
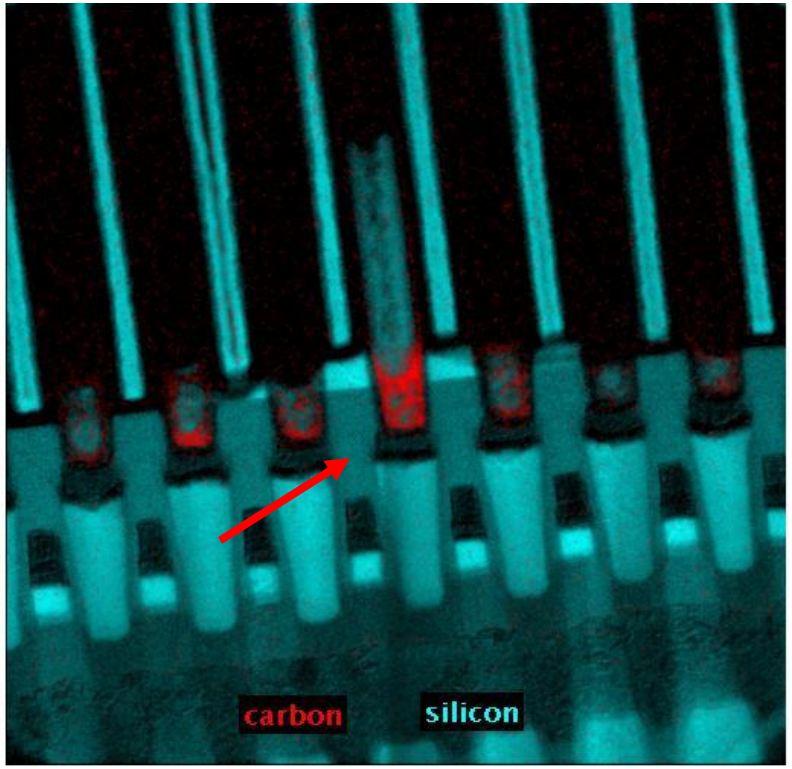
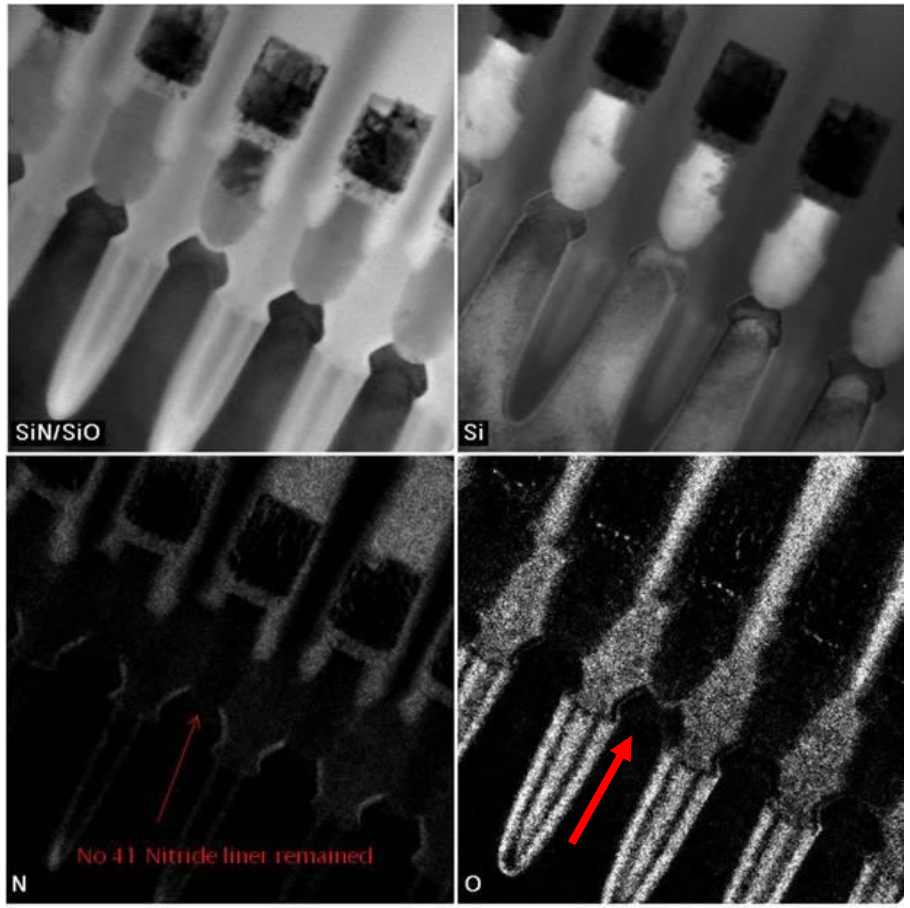
Failure Analysis-Detailed Analytical work in TEM





elemental maps by EELS



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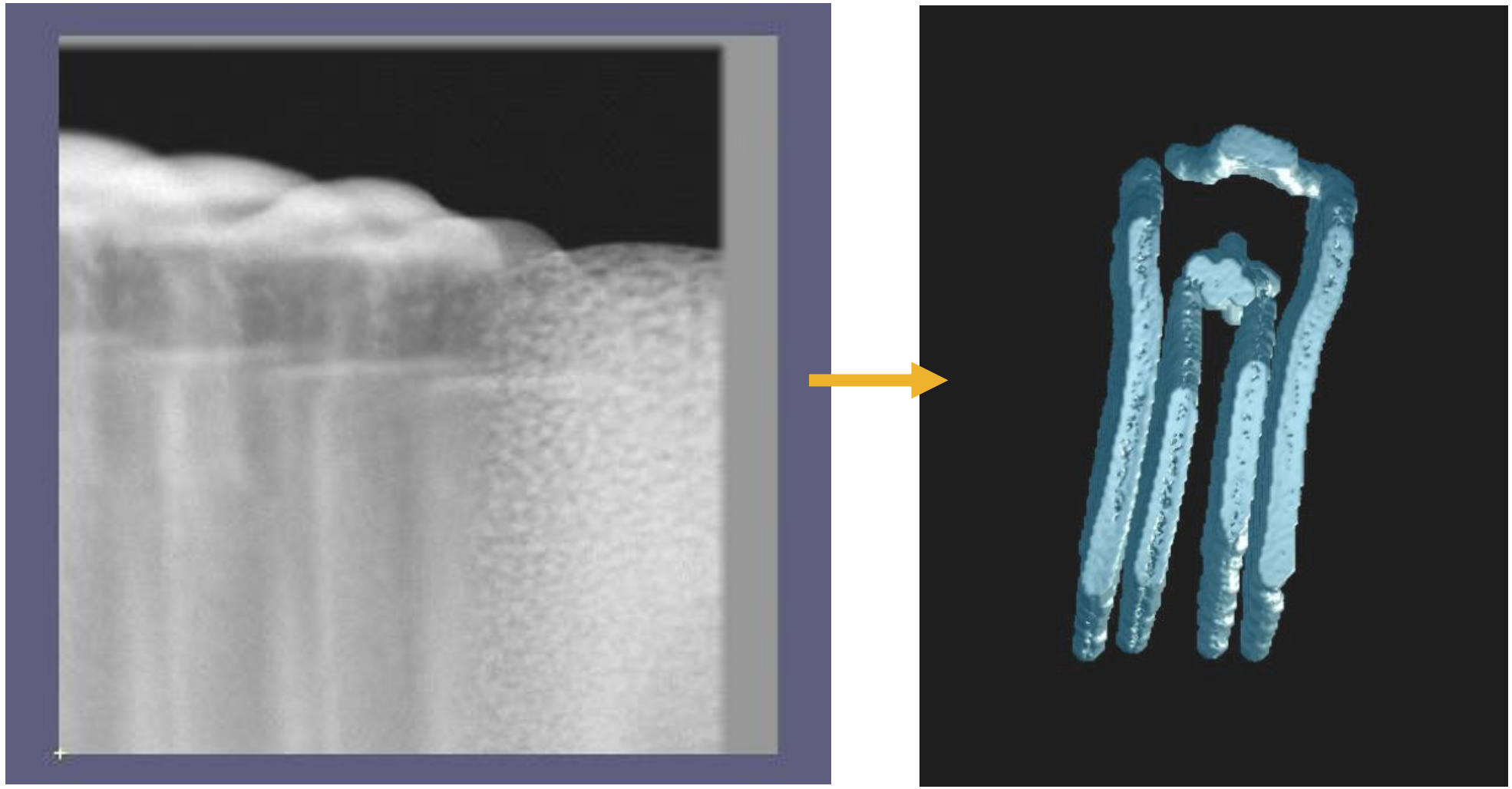
Z-Contrast STEM Tomography to Show Cell Dielectric Structure



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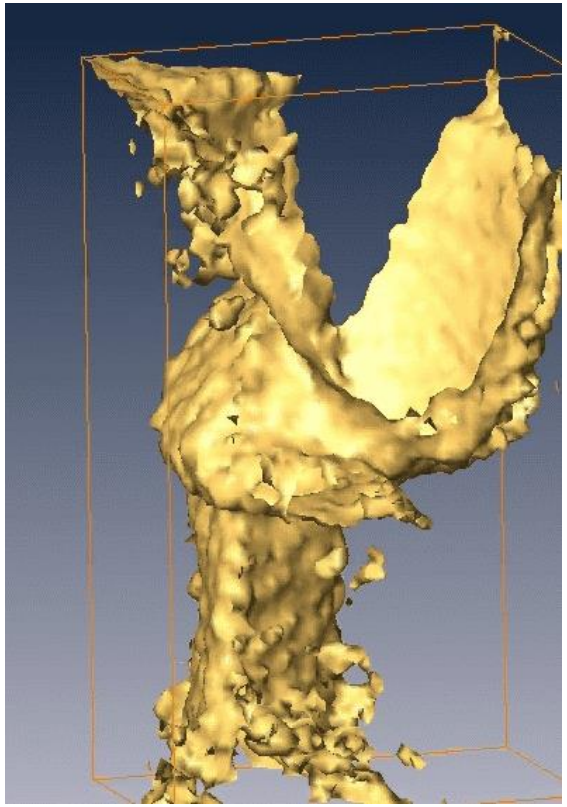
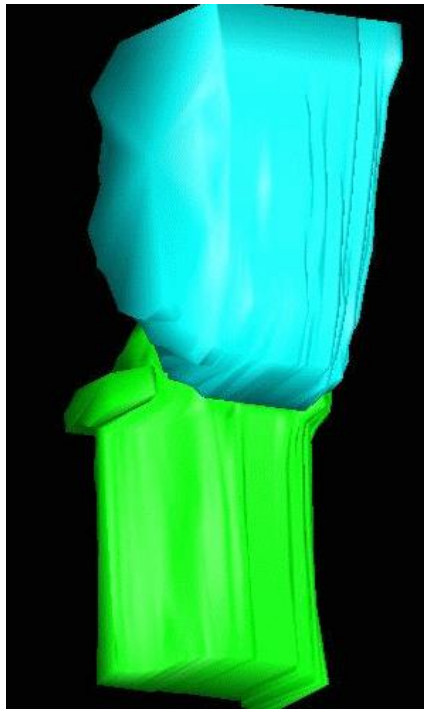
EFTEM Tomography to Show Si Contact

A fine-step slicing movie



Iso-surface model



3D model

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Evolution of analytical TEM

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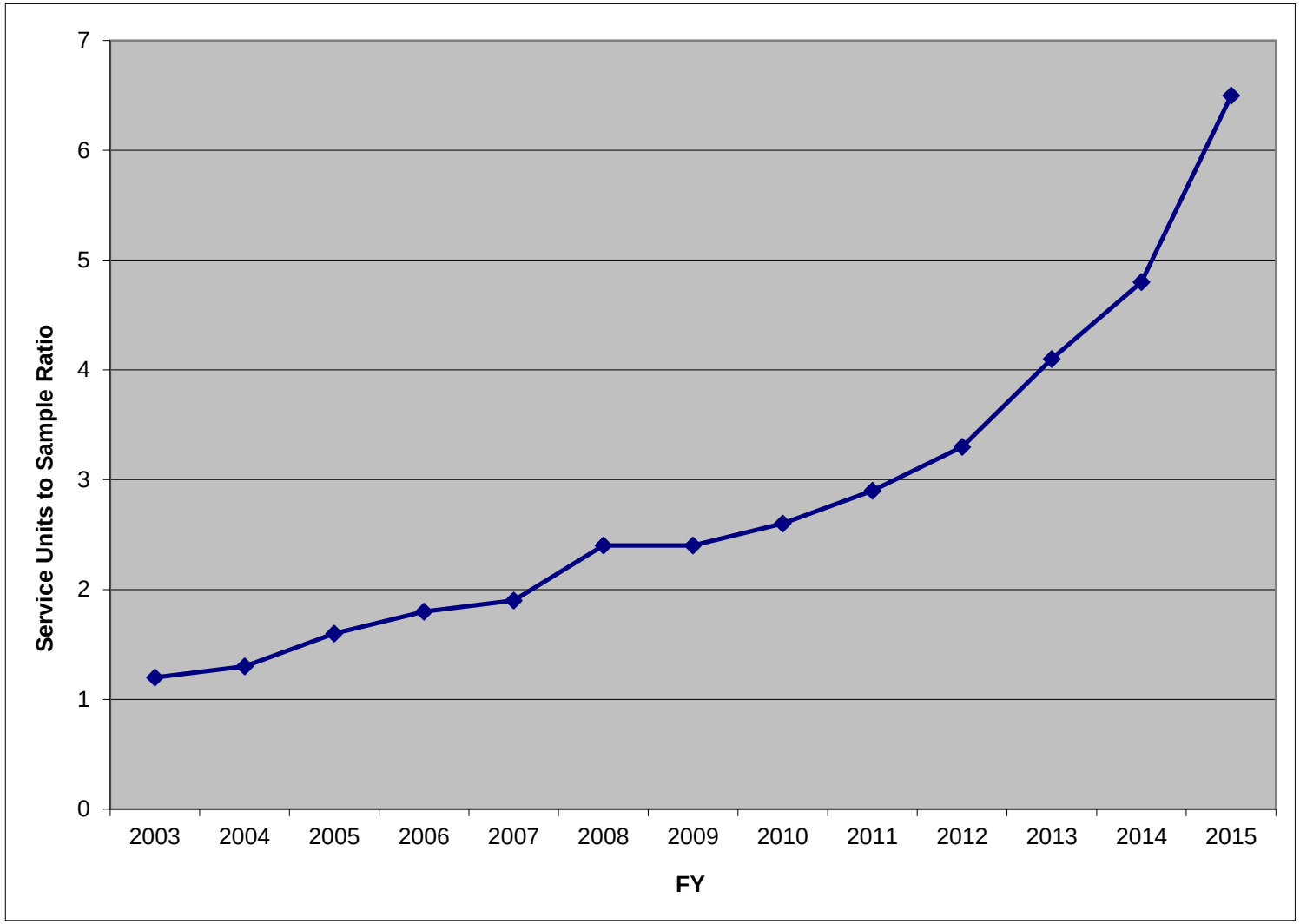
Evolution of Service Unit to Sample Ratio



- Service Unit (SU): BF/DF imaging, STEM analysis, EDS or EELS analysis, etc.
- Plot is based on the average of last 13 weeks' data for each fiscal year

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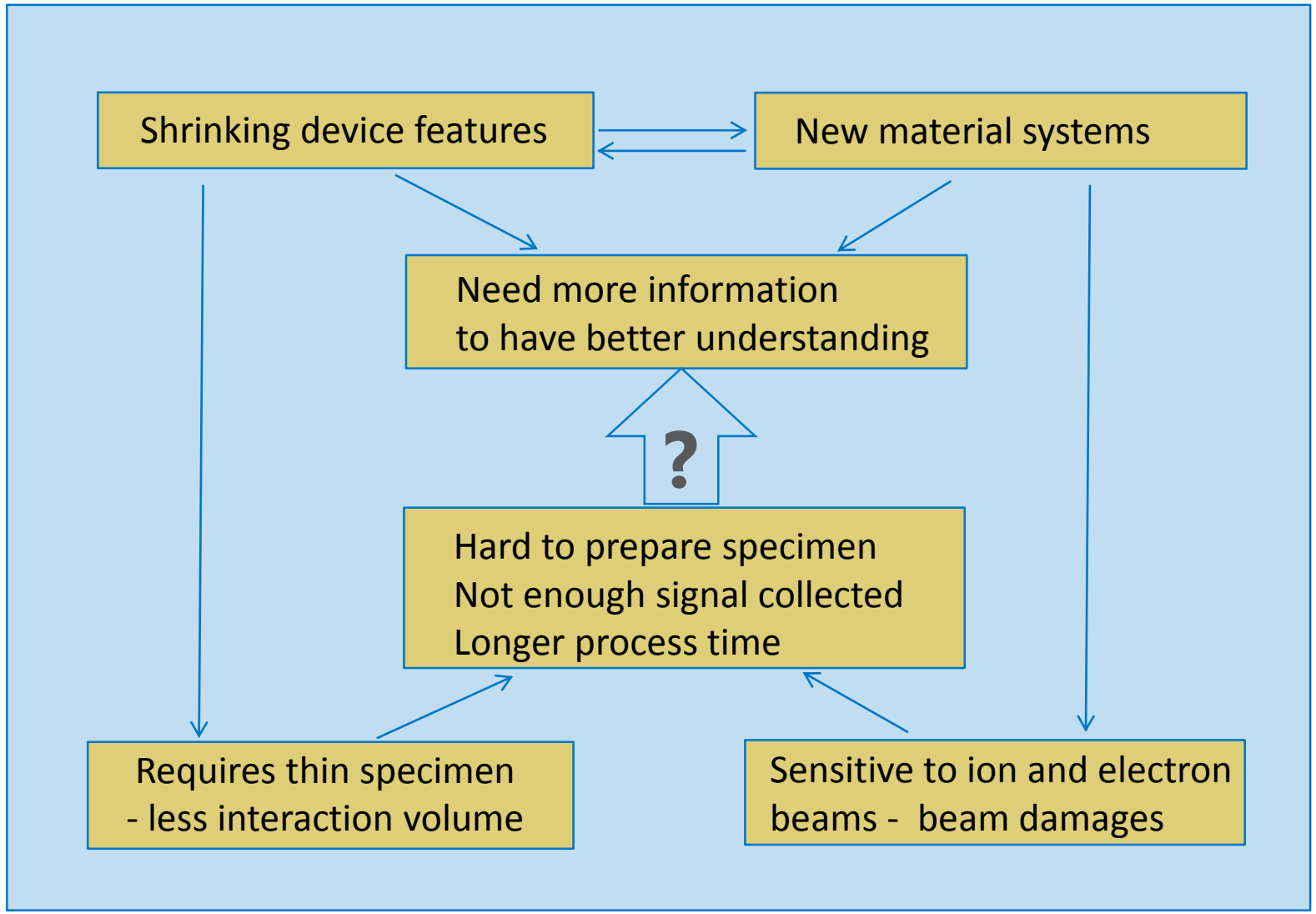
Challenges due to the Shrink in Process Geometry and the Utilization of New Material Systems



Difficulties in two aspects;

- Metrology
  - Quick and reliable.
- Composition analysis
  - Enough signal for quantification without substantial beam damage.

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Advancements in TEM Technologies

- Optimization in hardware and analysis conditions.

- Computerized electron microscopy.

  Advanced computer data acquisition and processing has enabled phenomenal improvements in analysis capabilities (covered in Shixing Wang's presentation).

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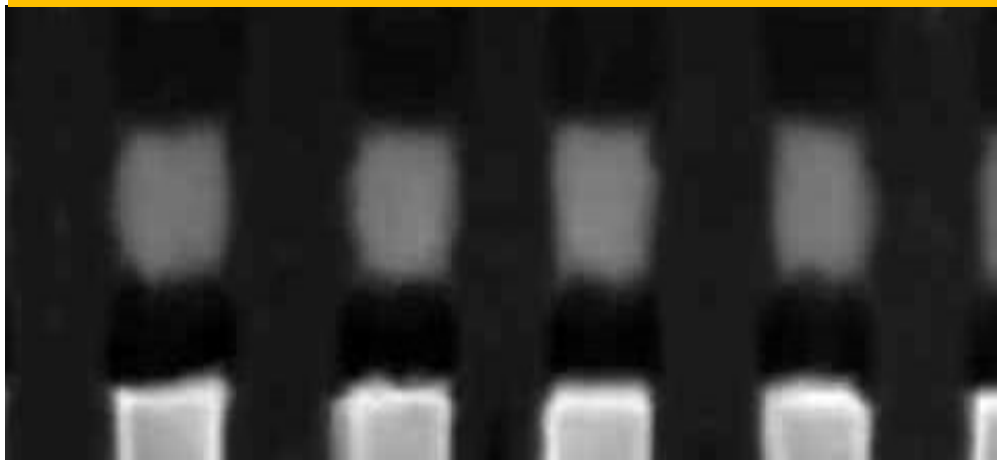
E-Beam Sensitive Materials

Before EDS mapping



After EDS mapping

e-Beam causes physical deformation and elemental redistribution, which limits much of what we can do in TEM. Yet CD measurements and elemental distribution information are so critical to device characterization that additional improvements over what we have today.

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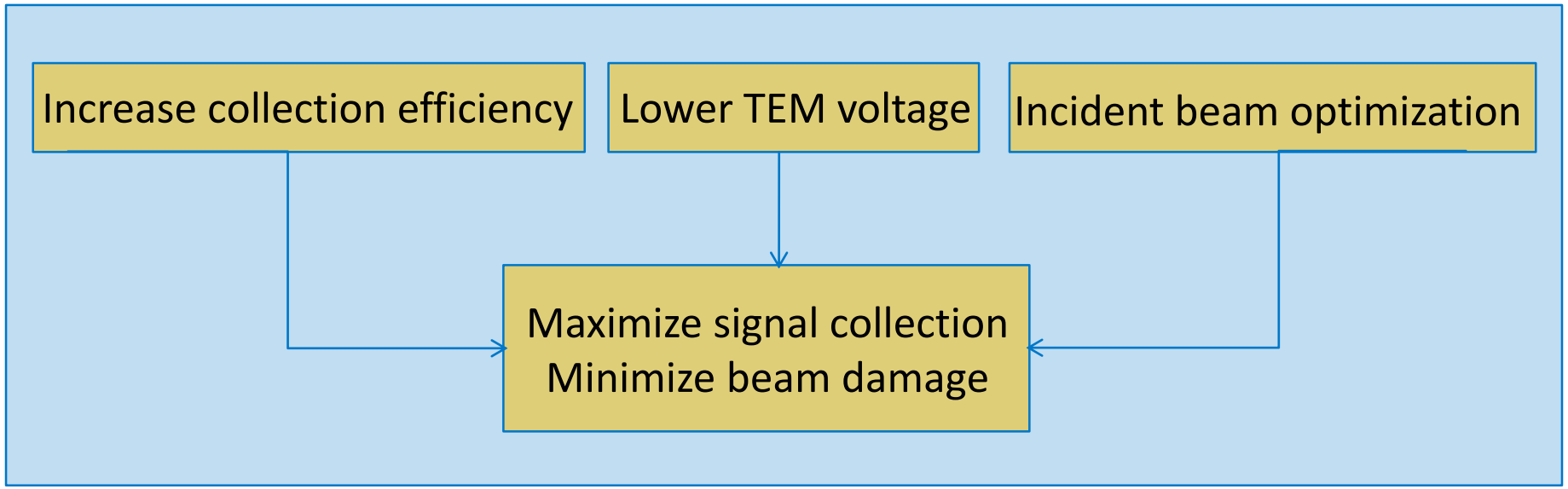
Optimization in Hardware and Operations



- The ultimate goal is to get enough X-ray signal before the specimen is damaged by electron beam.

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Lower TEM Operating Voltage to Increase X-ray Generation

- Low acceleration voltage increases interaction between incident electrons and the specimen, generating more X-ray signal for a given specimen and e-beam dose.
  - TEM operated at 80 kV can increase X-ray generation levels by 2x as compared to 200 kV operations.
- Lowering the operating voltage can also reduce the knock-on damage on the specimen.

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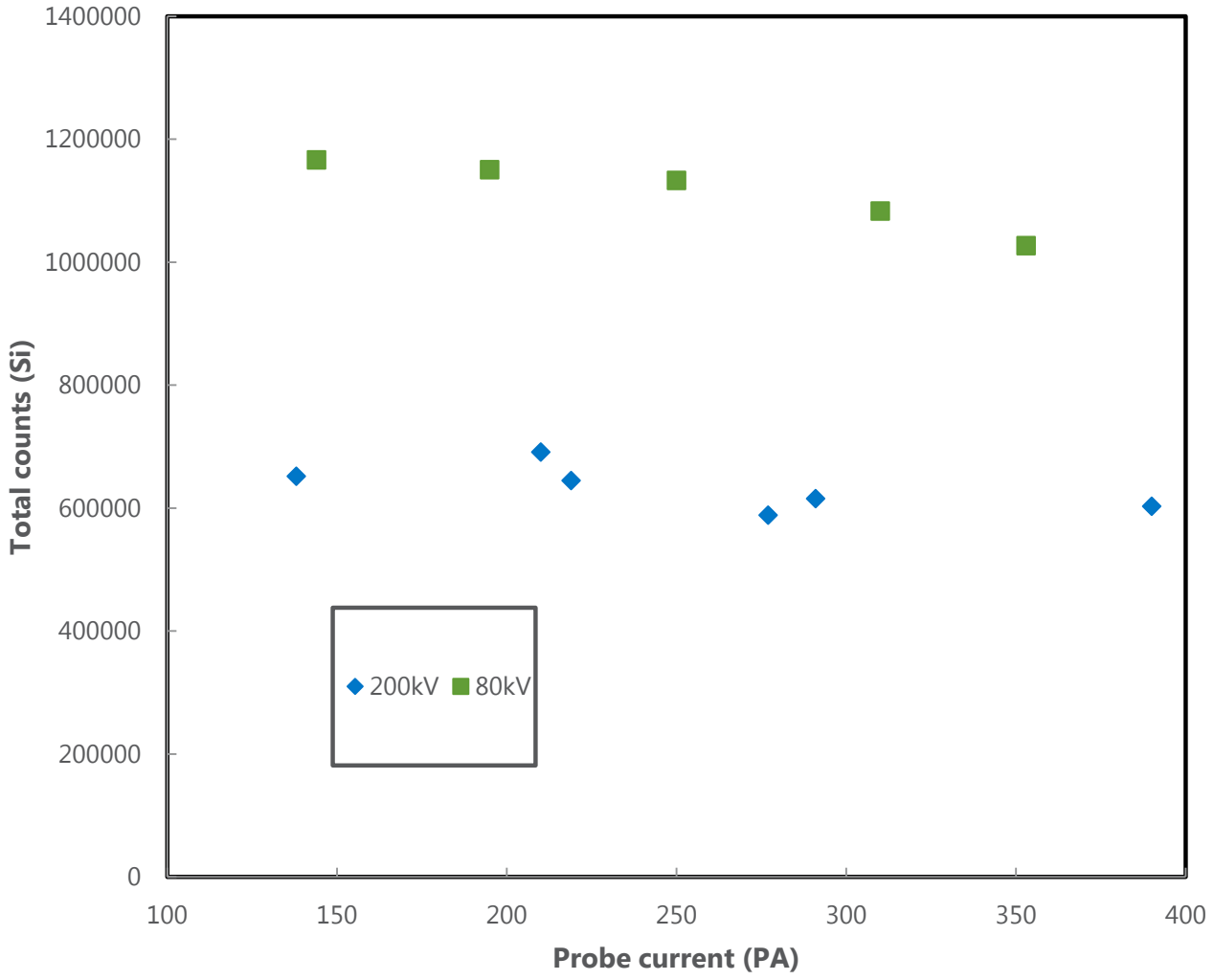
Experimental Confirmation



- Similar areas of a pure Si sample (~40 nm thick) were used to collect Si-K series X-rays at both 80 kV and 200 kV with the same electron dose. The total X-ray counts collected at 80 kV is roughly twice of that of the 200 kV operations.

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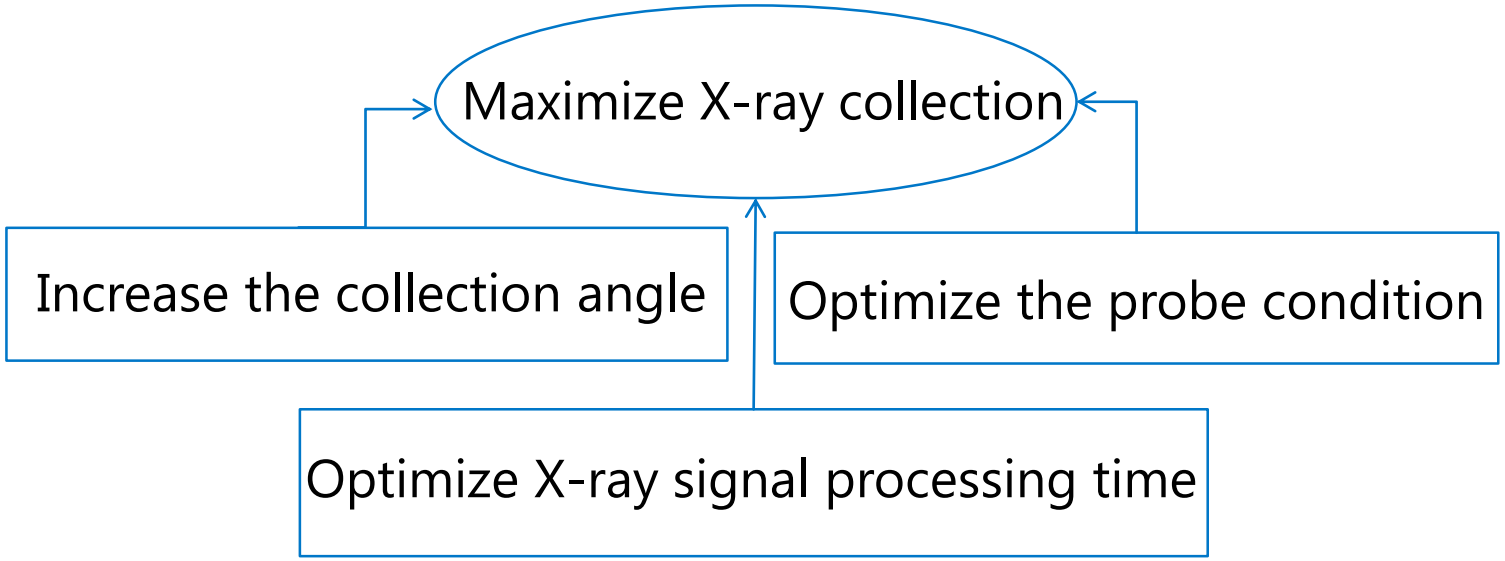
Maximize X-ray Collection



- Increase the collection angle. Two 100 mm^2 Silicon Drift Detectors (SDD) provide solid angle of 1.72 sr.
- Optimize the microscope operating parameters, looking for the best probe condition that maximize X-ray generation/collection efficiencies for a given electron dose.
- Optimize the signal processing time to achieve higher counts without sacrificing the energy resolution.

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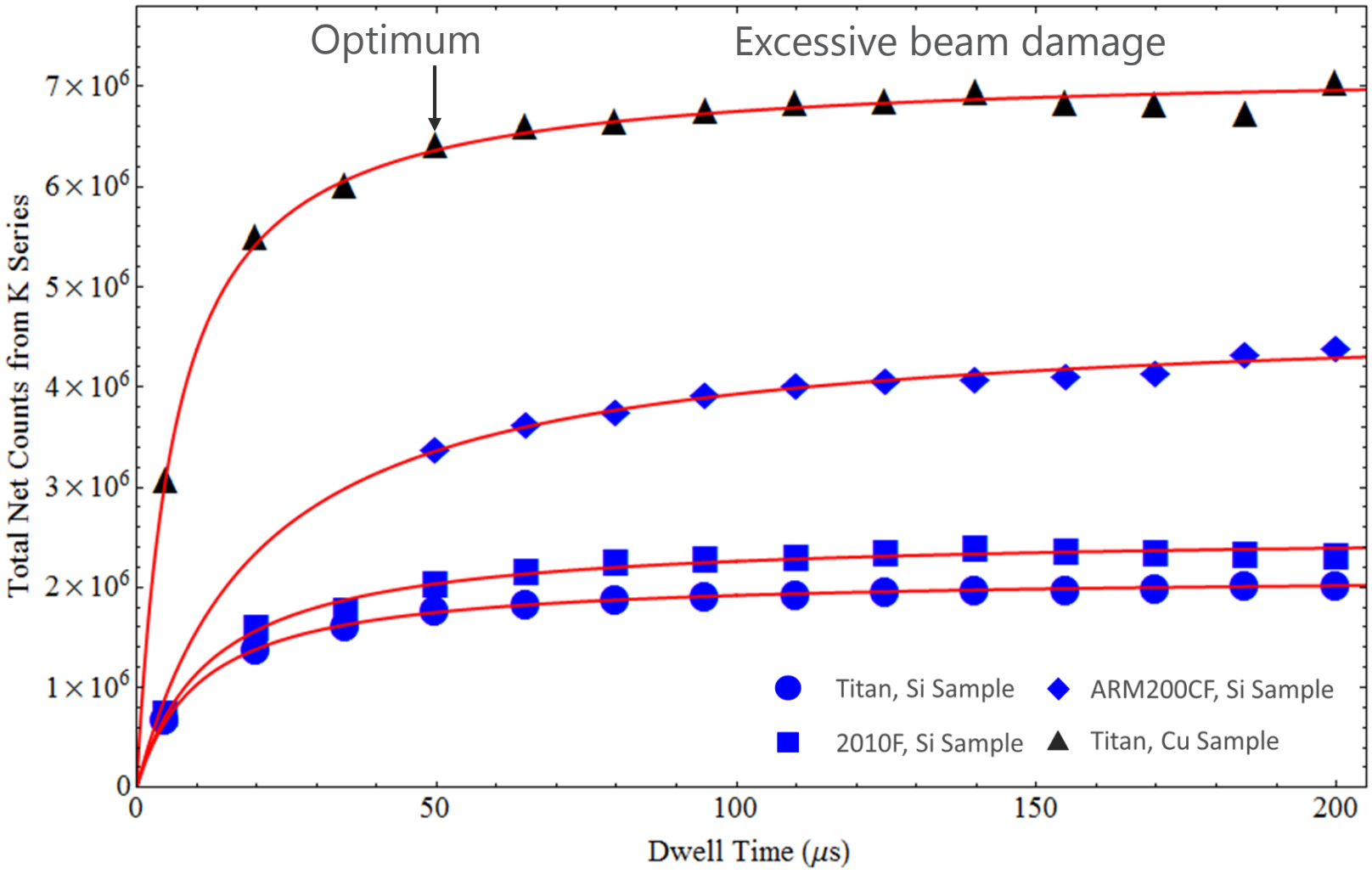
Optimizing Dwell Time



- Operation at 200 kV.
- Probe current: 2 nA.
- Specimen thickness: ~30nm.
- Total collection time: 10 min.
- EDS solid angle
  - ARM200-CF: 0.82 sr.
  - Titan: 0.18 sr.
  - 2010F: 0.18 sr.

<u>Note</u>

80 kV trend will be similar, showing small increases in Net Counts beyond a given dwell time. Frame count used to match collection times.

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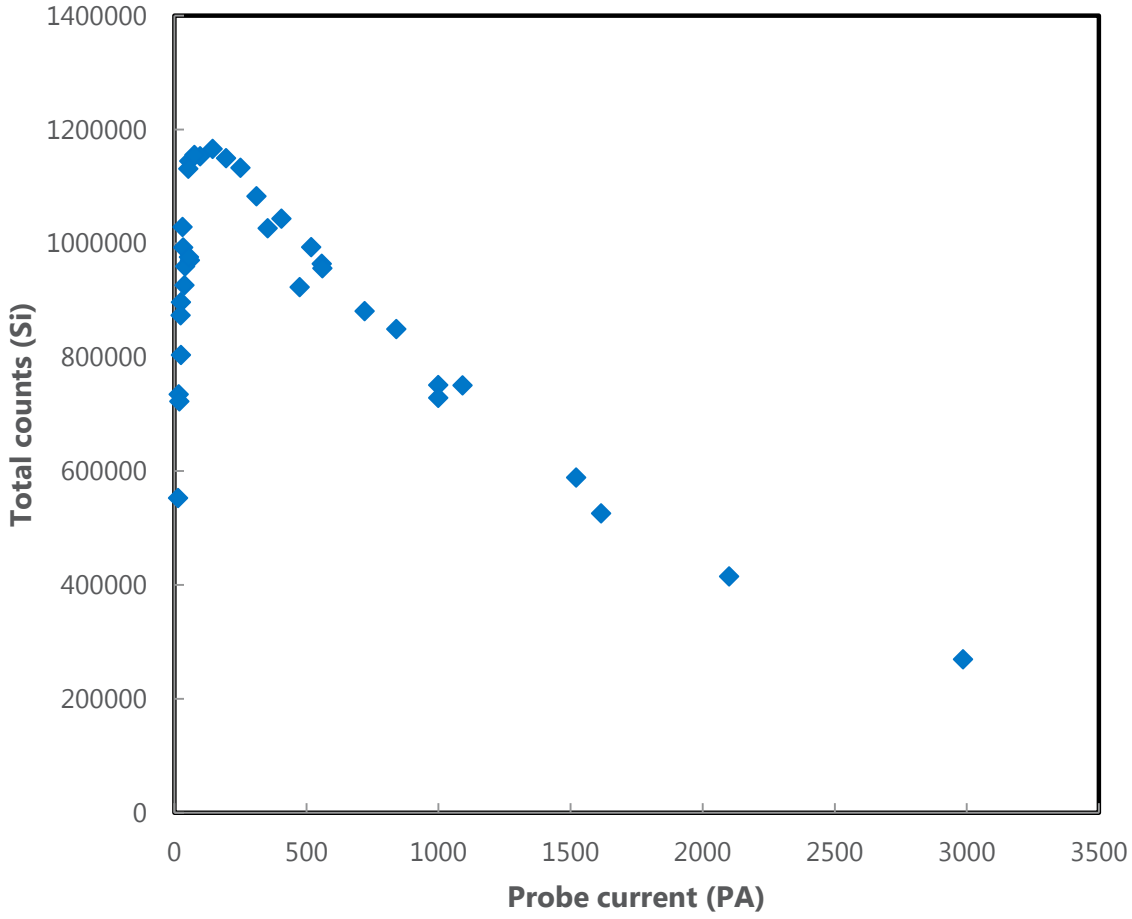
Optimizing Probe Conditions



- Similar area is used to evaluate the effect of various probe currents on total X-ray counts collected over the same electron dose.
- There exist optimum values for probe currents (100 – 250 pA), which generate maximum X-ray counts for the same electron dose.

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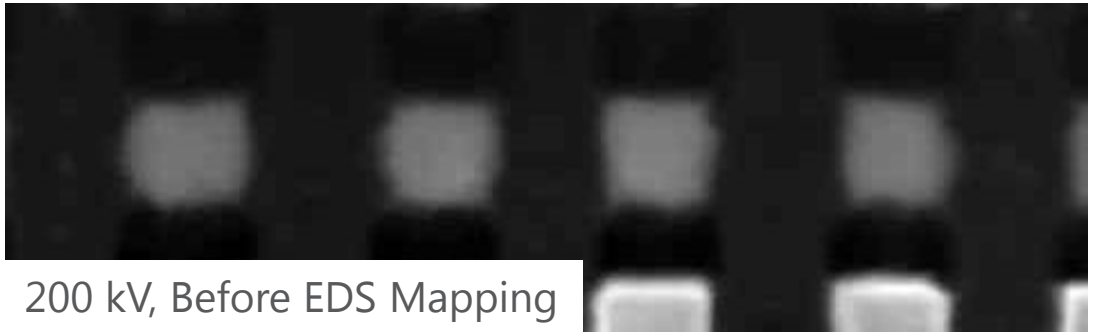
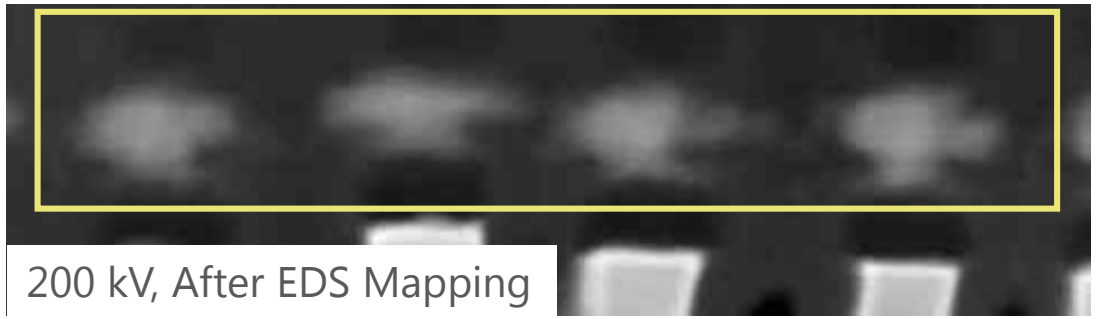
Comparison of E-Beam Damage before/after Optimization

Single 100 mm^2 SDD detector

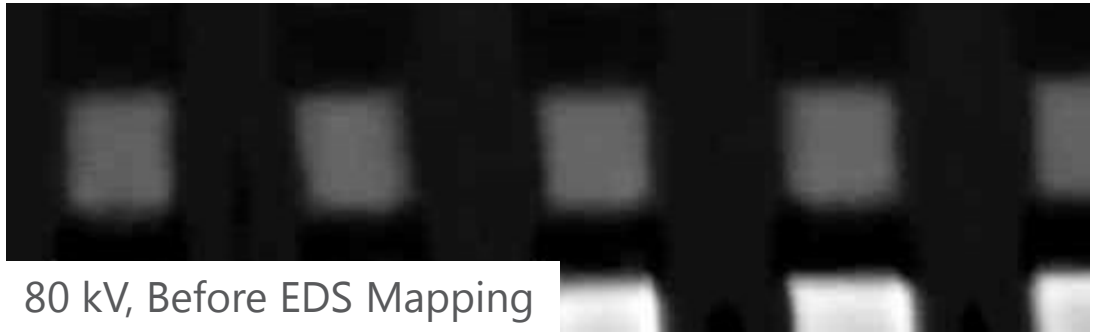


200 kV, Before EDS Mapping

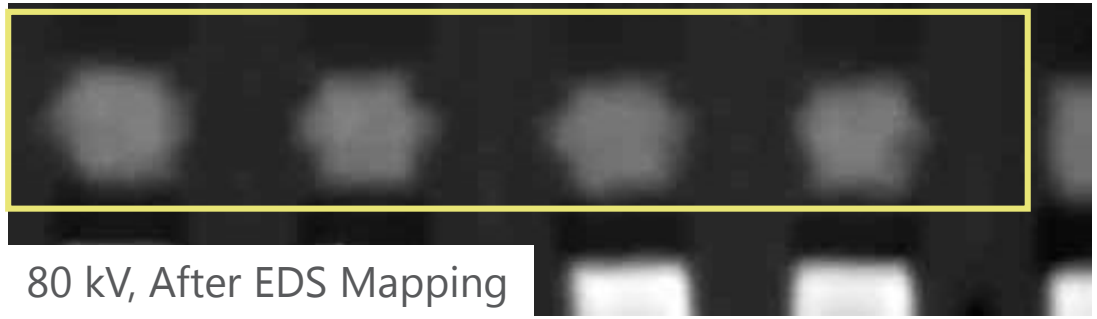


200 kV, After EDS Mapping

Dual 100 mm^2 SDD detectors



80 kV, Before EDS Mapping



80 kV, After EDS Mapping

Further improvements still needed

Note: Total net X-ray counts collected within the yellow box are about the same with the same elemental setting.

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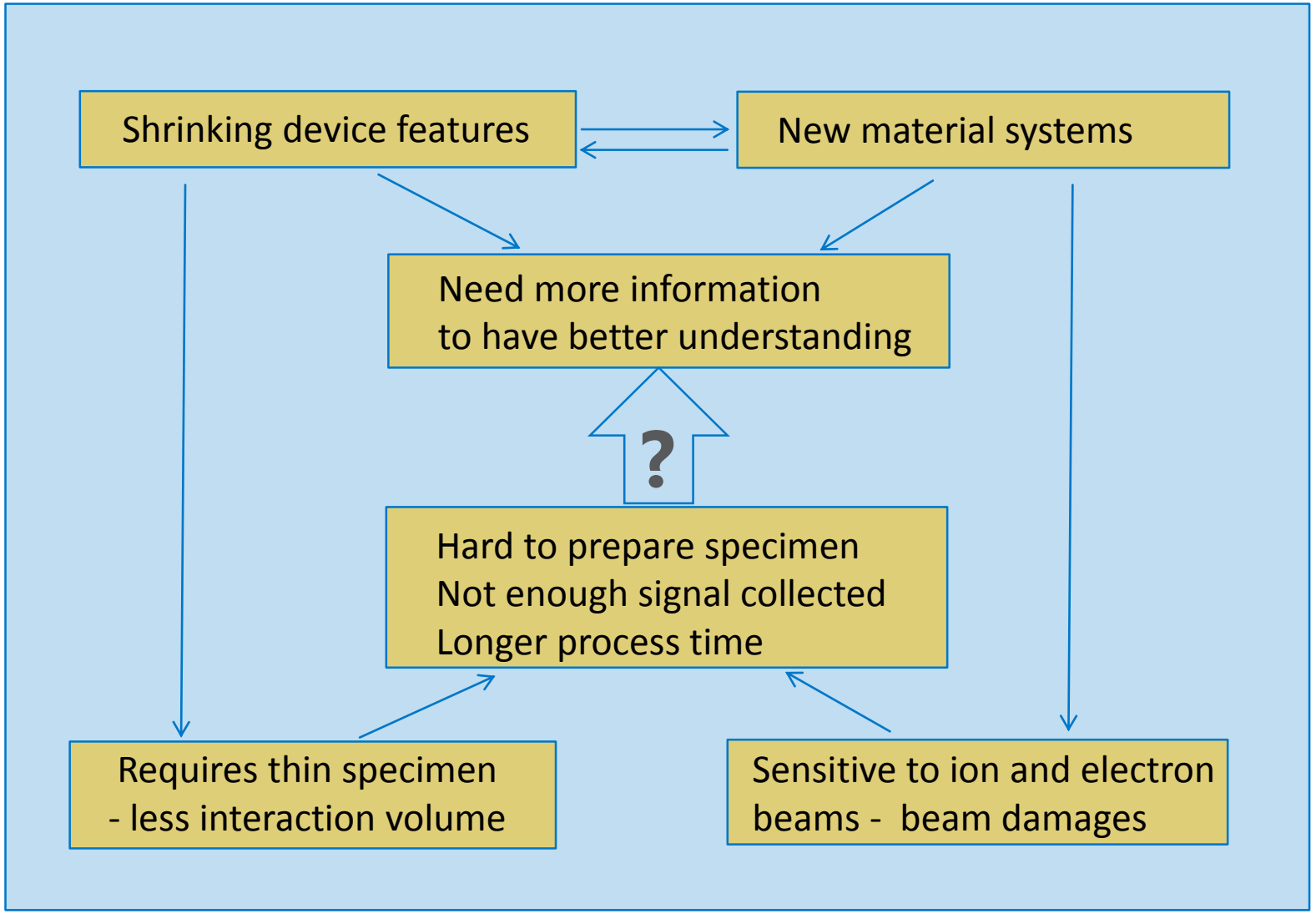
Summary of on-going Challenges



- SEM resolution insufficient.
- 1/3 Feature size requirements.
  - Ultra-thin specimen.
  - edge electron density interpretations (software).
  - Tomography (Both Metrology & analysis).
- Sufficient signal.
  generation/detection from Ultra thin specimen.
  - Low kV TEM.
  - More sensitive detectors.
- Less Beam Damages.

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Acknowledgements

- Organizational and financial support from Micron Technology, Inc.
- YE and TEM Labs team members providing data and materials.
- Organization committee providing the opportunity for us to present our on-going challenges.

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