CAMECA®
SCIENCE & METROLOGY SOLUTIONS

LEAP® 5000

EIKOS™

Toward Correlative Analysis & Enhanced Productivity for the Semiconductor Industry

D. J. Larson et al.

April 2019

www.cameca.com

AMETEK®
MATERIALS ANALYSIS DIVISION

SCIENCE & METROLOGY SOLUTIONS

Correlative Analysis in III-V Fins

Co-Authors

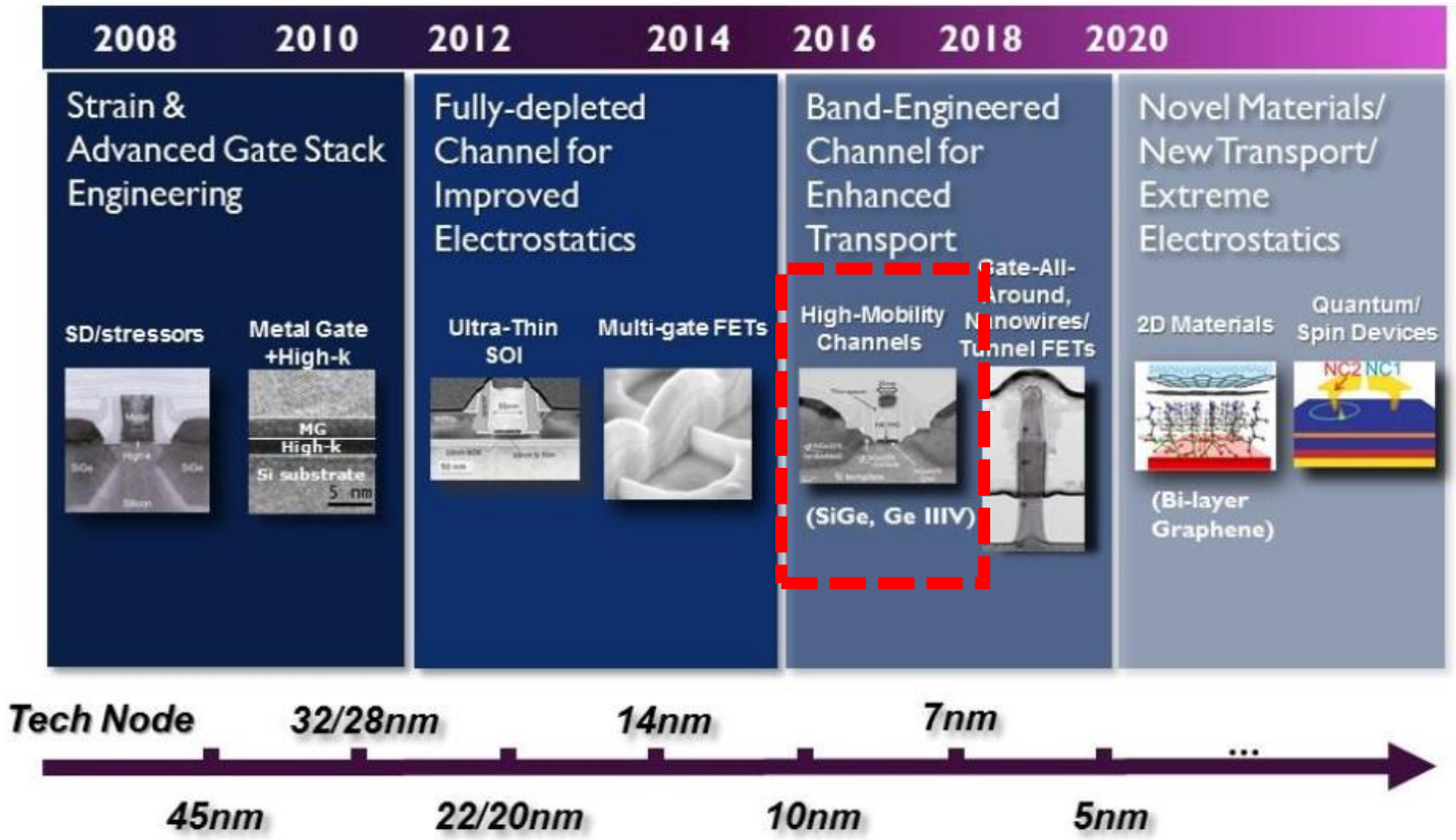
- SIMS: P. van der Heide. A. Franquet, V. Spampinato, W. Vandervorst, and (formerly) A. Schulze (IMEC)
- STEM: V. Delaye, Z. Saghi, N. Bernier (CEA-LETI)
- APT+LEXES: I. Martin, A.-S. Robbes, A. Merkulov, K. Rice, O. Dulac, D. Reinhard, D. Lenz, J. Bunton, G. Geiser, T. Prosa (Cameca)
- L. Kwakman and A. F. de Jong (Thermo Fischer)

This project received funding from the Electronic Component Systems for European Leadership Joint Undertaking under agreement No 692527. It receives support from the European Union's Horizon 2020 research and innovation programme and Netherlands, Belgium, France, Hungary, Ireland, Denmark, Israel. Work done on the PlatForm for NanoCharacterisation (PFNC) was additionally supported by the "Recherches Technologiques de Base" Program of the French Ministry of Research.

ECSEL JU

Motivation: 3DAM Project

Technology Challenges Toward 5nm Node



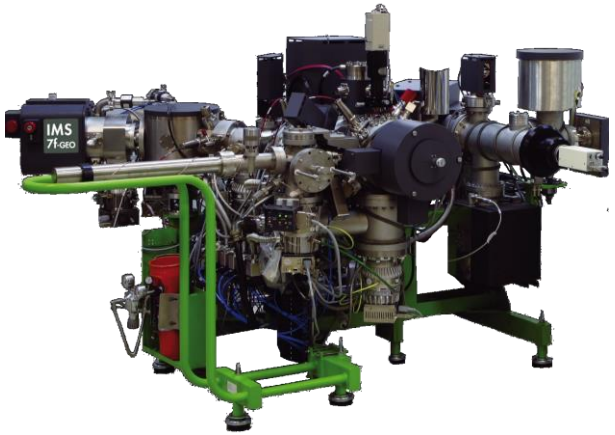
Participant organisation name
FEI Electron Optics BV
Applied Materials Israel LTD
Interuniversitair Micro-Electronica Centrum IMEC VZW
Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek TNO
NOVA MEASURING INSTRUMENTS LTD
Jordan Valley Semiconductors, LTD.
COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES; LETI
Attolight Sarl
SEMILAB FFLS
CAMECA
ADAMA INNOVATIONS LTD
FEI SAS
ST MICROELECTRONICS CROLLES 2 SAS
TECHNISCHE UNIVERSITEIT EINDHOVEN
CAPRES A/S
DANMARKS TEKNISKE UNIVERSITET
APPLIED MATERIALS FRANCE

- 3DAM: "3D Advanced Metrology for Advanced Devices & Materials"
- More than 15 EU partners funded from the Electronic Component Systems for European Leadership Joint Undertaking
- This presentation focuses on correlation of electron microscopy, SIMS, and APT methods to measure III-V layers formed into fins contained in oxide

The Characterisation Methods

Low Energy Electron induced X-ray Emission Spectroscopy (LEXES)

SIMS

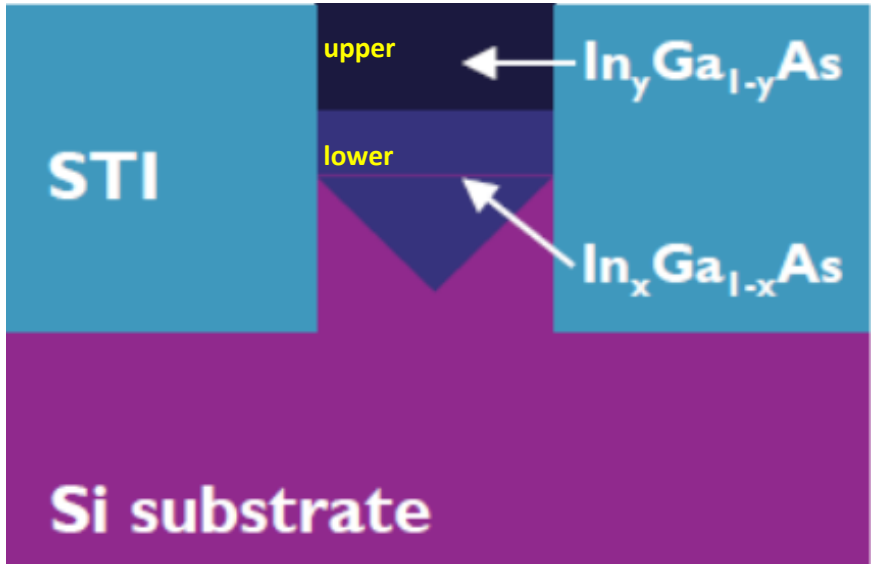


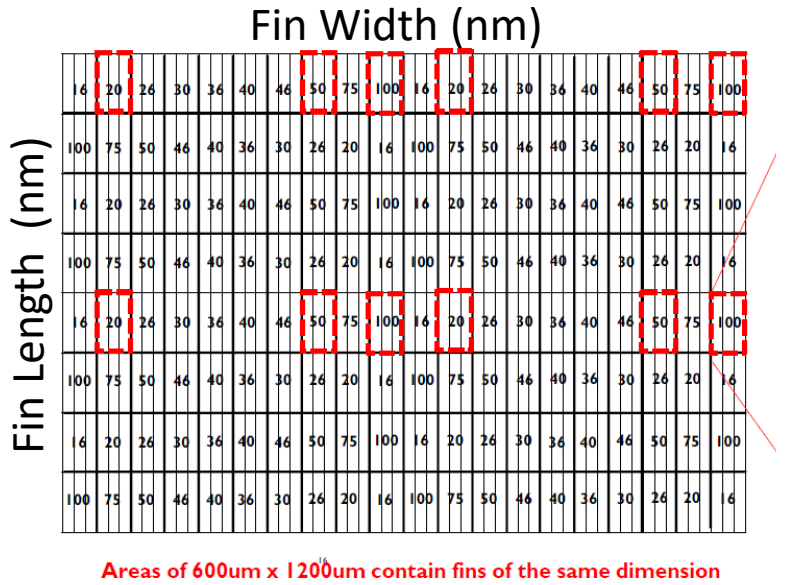
STEM / EDX

Atom Probe Tomography

- LEXES uses a low energy, high current electron column designed to optimize surface analysis. Probe energy can vary from a few hundreds eV to 10keV and the electron beam current can be adjusted from 0.1 to 100µA. Resulting probing volume depth is typically down to 700 nm. The beam size can be adjusted from 5 to 60µm. Nominally nondestructive technique for wafer analysis.
- SIMS analyzes the composition of solid surfaces by sputtering the specimen with a primary ion beam and collecting and analyzing the mass/charge ratios of the secondary ions.
- STEM/EDX using a scanned focused beam of electrons passing through a thin specimen to form an image, and can be combined with energy dispersive spectroscopy to compositional imaging.
- APT uses a high electric field to remove ions from a sharp specimen and collected the ions using time of flight mass spectrometry. Spatial information is obtained from using a position sensitive detection system.

The Sample



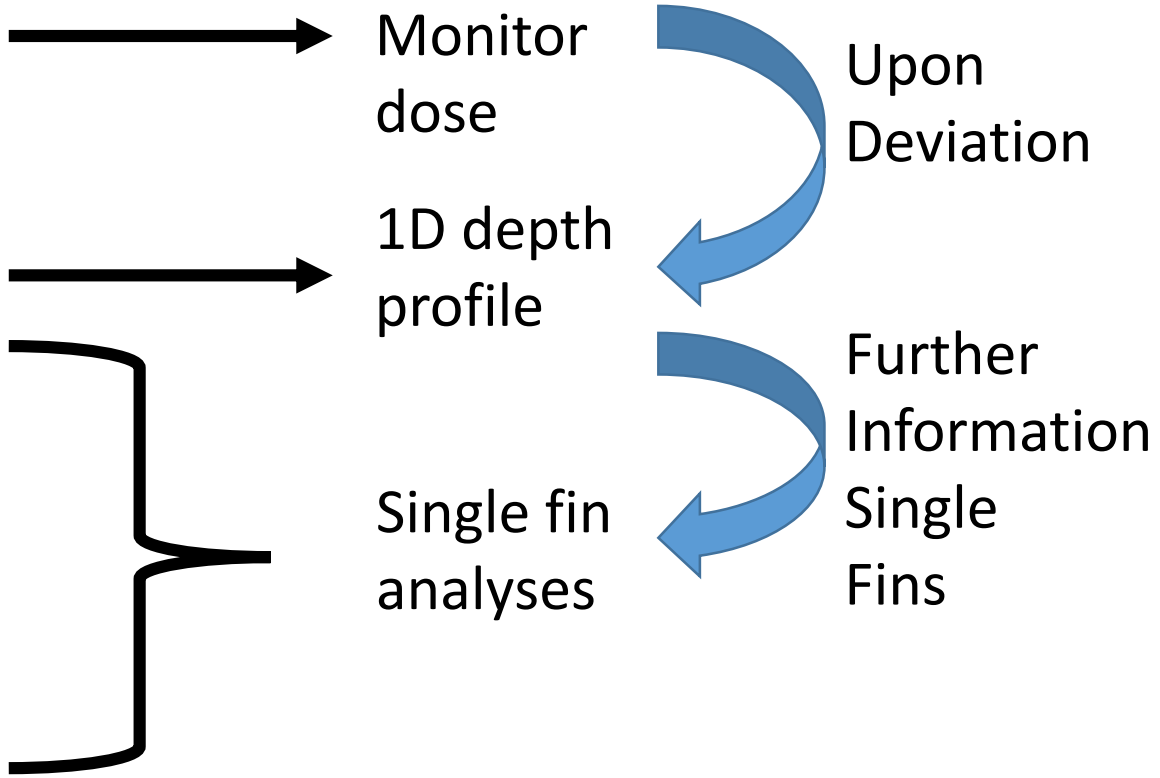


- LETI and IMEC scientists identified metrology and characterization challenges for semiconductor devices and materials to be addressed in the 3DAM project – III-V based fin structures is one of those challenges
- The sample shown above was fabricated at IMEC and contains arrays of different fin widths and lengths with each array pad ~600x1200 μm – fin widths of 20nm, 50nm, and 100nm will be focus on current work
- The nominal Indium content in the sample is ~15 at.% indium in the lower layer with slightly higher content for wider fins, and ~25-30 at.% in the upper layer with similar variation depending on fin width

The Monitoring and Characterisation Plan

Time Consuming

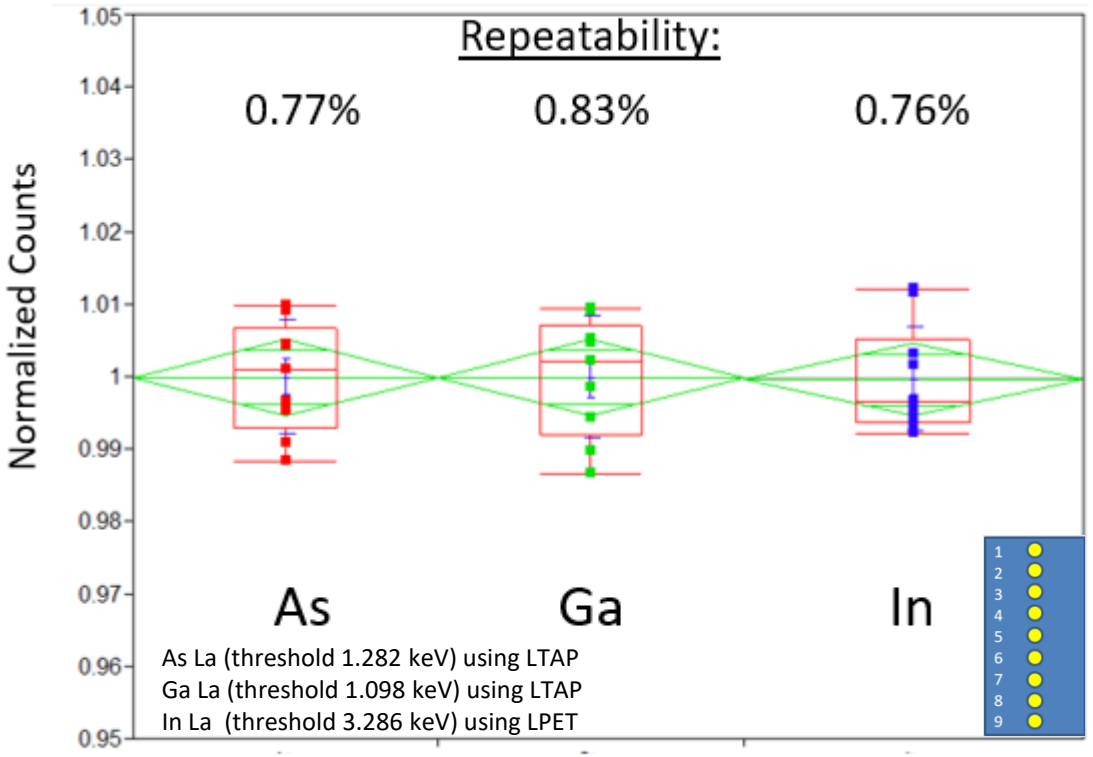
- LEXES is nondestructive, measures many fins with one spot (~60μm), provides fast knowledge of potential within wafer variation, but has no spatial information
- SIMS is destructive in most cases, measure many fins with one spot, provides spatial information in depth (sputtering) direction
- STEM/EDX is destructive (requires liftout), provides compositional information about a single fin, adds second (at least) spatial dimension capability
- APT is destructive (requires liftout), provides compositional information about a single fin, adds third spatial dimension capability

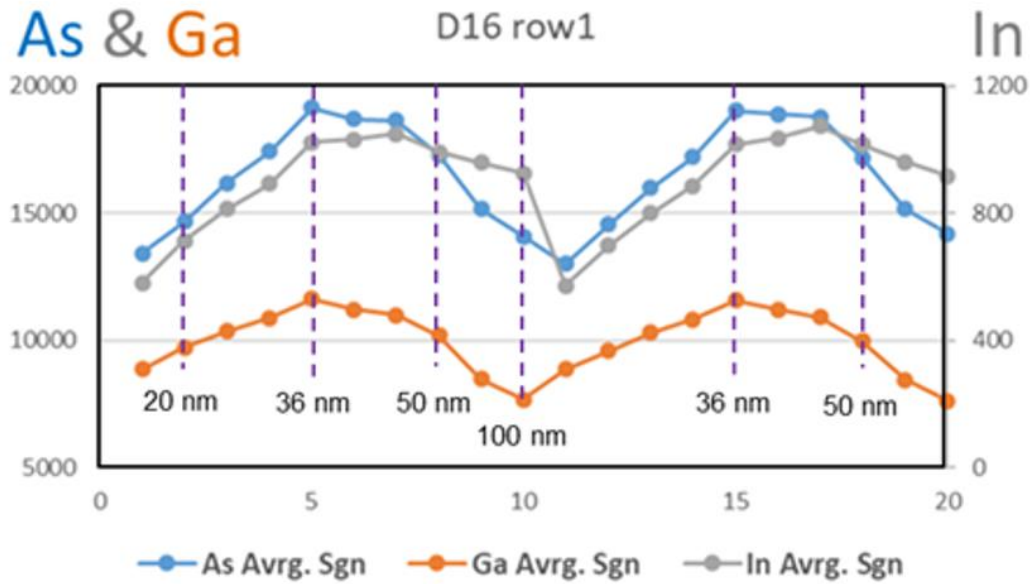


<u>So what do we need to do to believe in this plan</u>

- Show LEXES repeatability and correlate to SIMS dose
- Correlate EDS and APT (single fin) with SIMS (average) concentration

LEXES





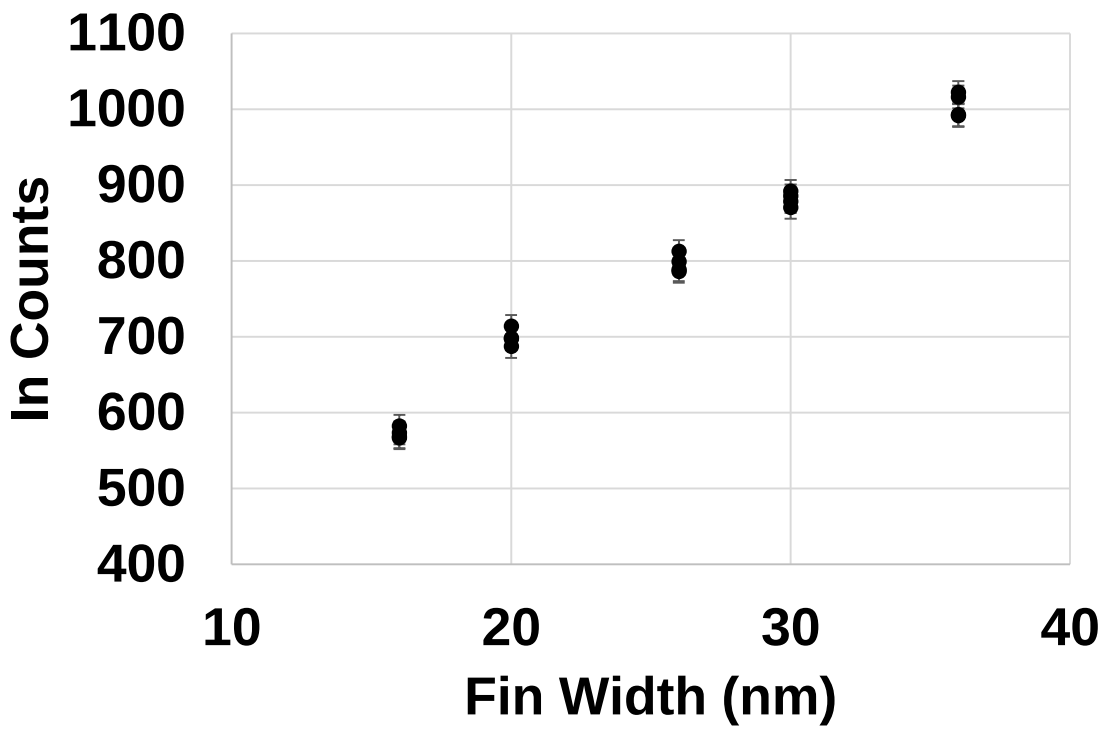
LEXES data – A.-S. Robbes (Cameca)

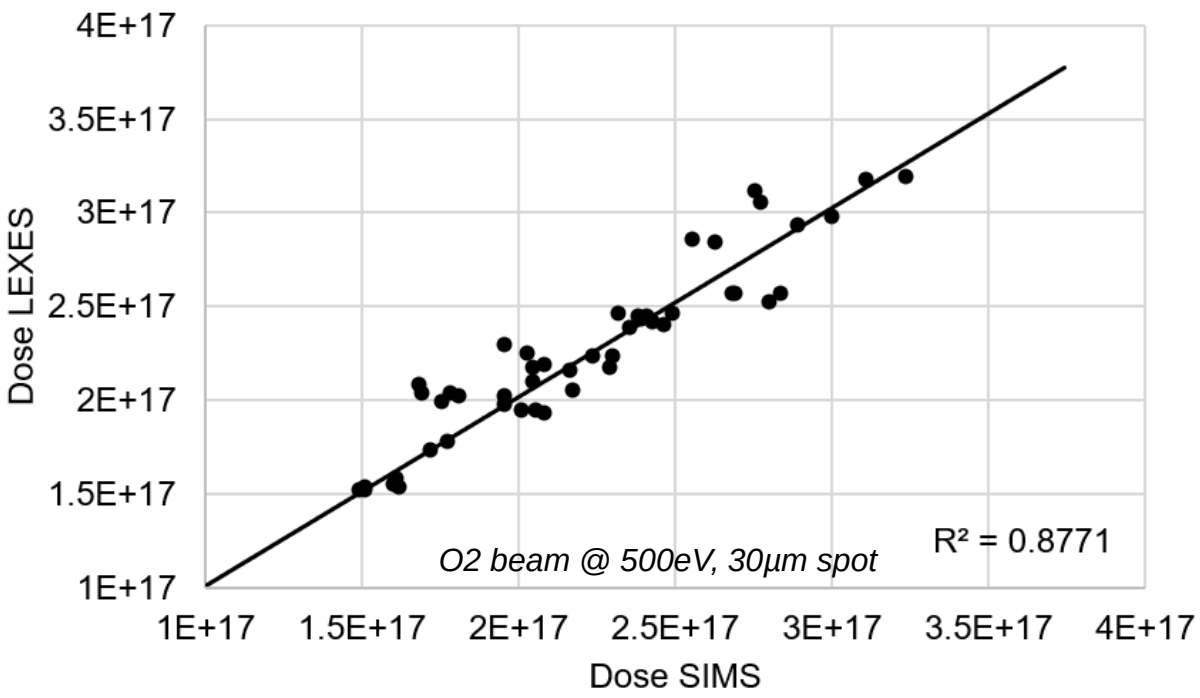
- 5kV, 2 or 10μA, 80 μm spot size
- Counting time
  - 3s on peak
  - 1.5s for each background measurement
- Std/mean for each element <1%

- Fin widths 16,20,26,30,36,40,46,50,75,100 were measured and repeated
- For fins >40nm there are currently issues with normalization for open area, so we will consider only widths less than this

LEXES vs SIMS

LEXES data – A.-S. Robbes (Cameca), SIMS data – A. Merkulov (Cameca)

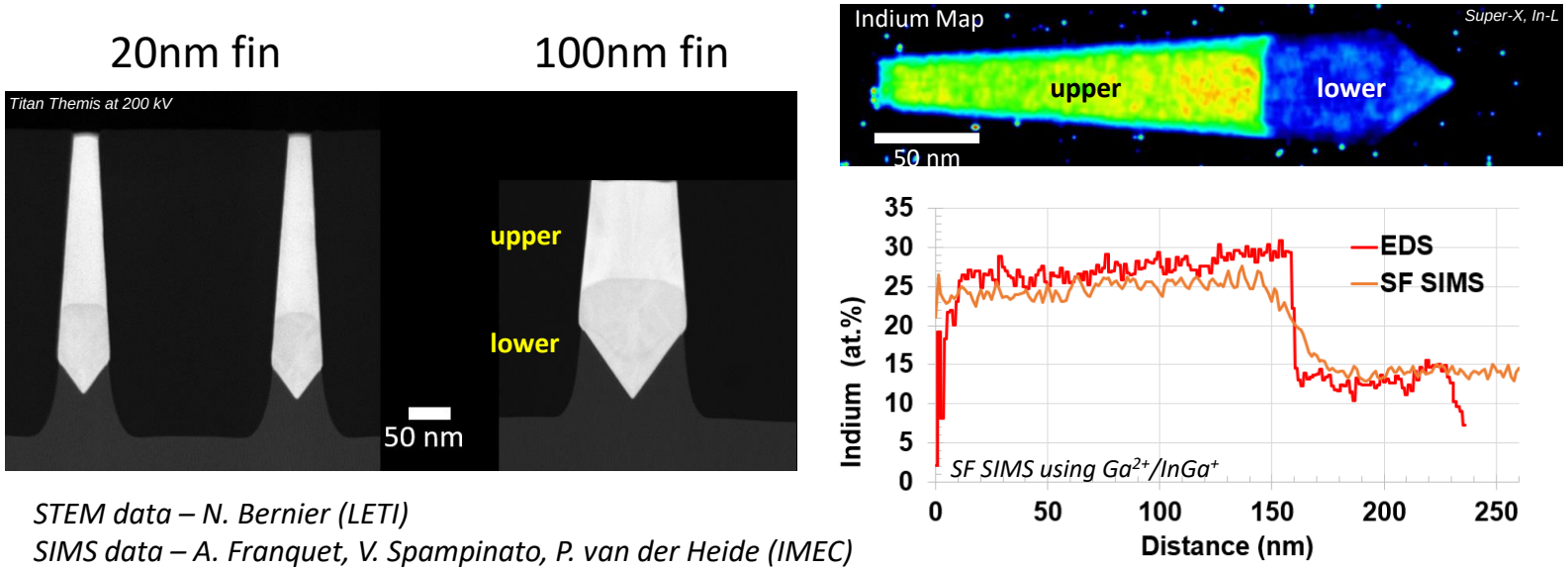




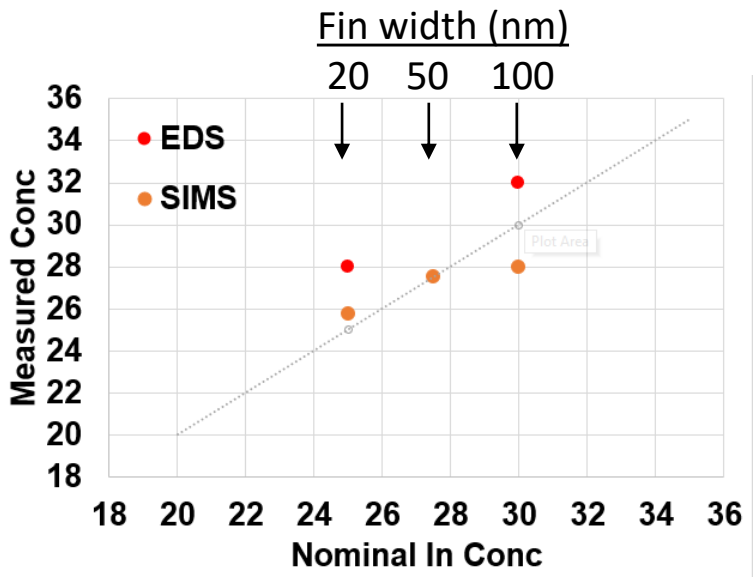
- Fin widths 16,20,26,30,36 were used to compare to SIMS measurements

- Exact same pads were measured (with several fin width repeats) with LEXES and SIMS
- Reasonable initial correlation of LEXES data to SIMS

STEM/EDS vs SIMS



STEM data – N. Bernier (LETI)
SIMS data – A. Franquet, V. Spampinato, P. van der Heide (IMEC)

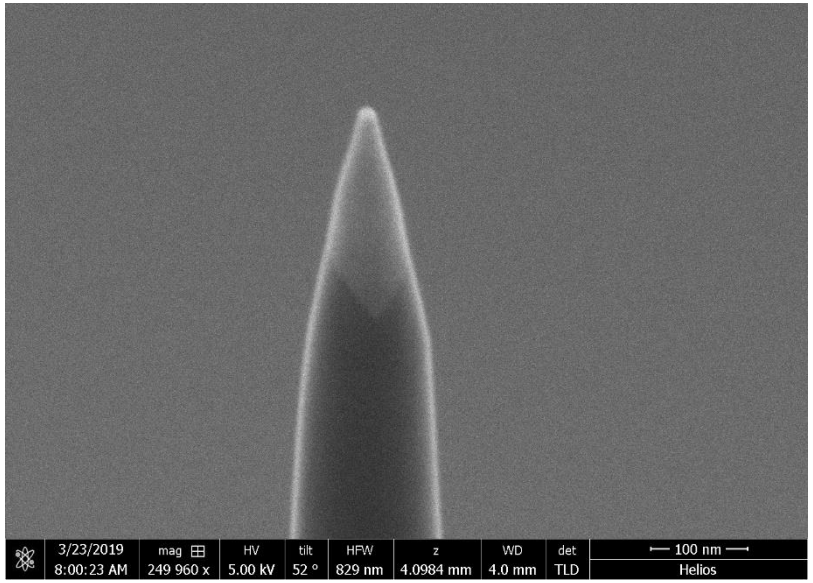


- HAADF STEM images of 20 and 100nm fin widths
- Some contrast variation seen within the STEM images and within the EDS maps
- Reasonable matching over for EDS (single 20nm fin) and SF-SIMS

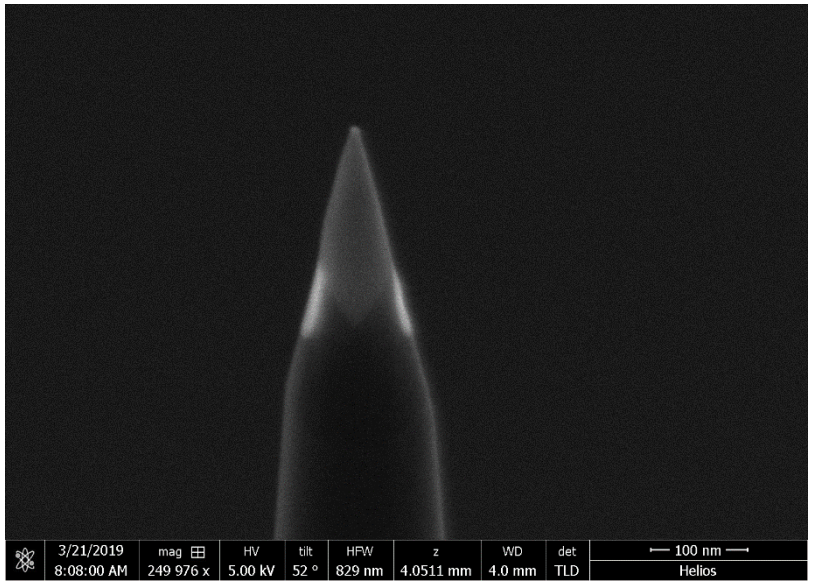
- EDS and SF-SIMS data vs nominal concentration over range of fin widths for upper region only
- The trend is good, although we do not have EDS data for the 50nm fin width

Atom Probe Tomography – Specimen Preparation

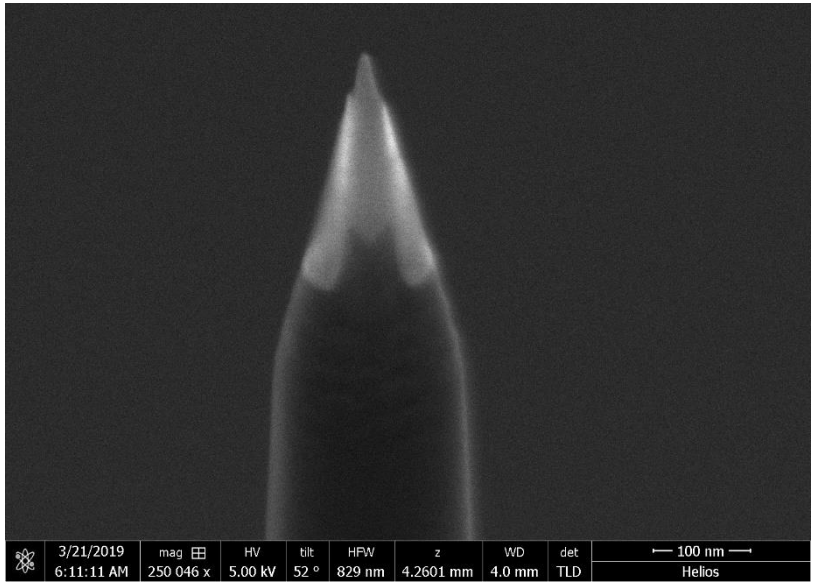
100nm fin



50nm fin



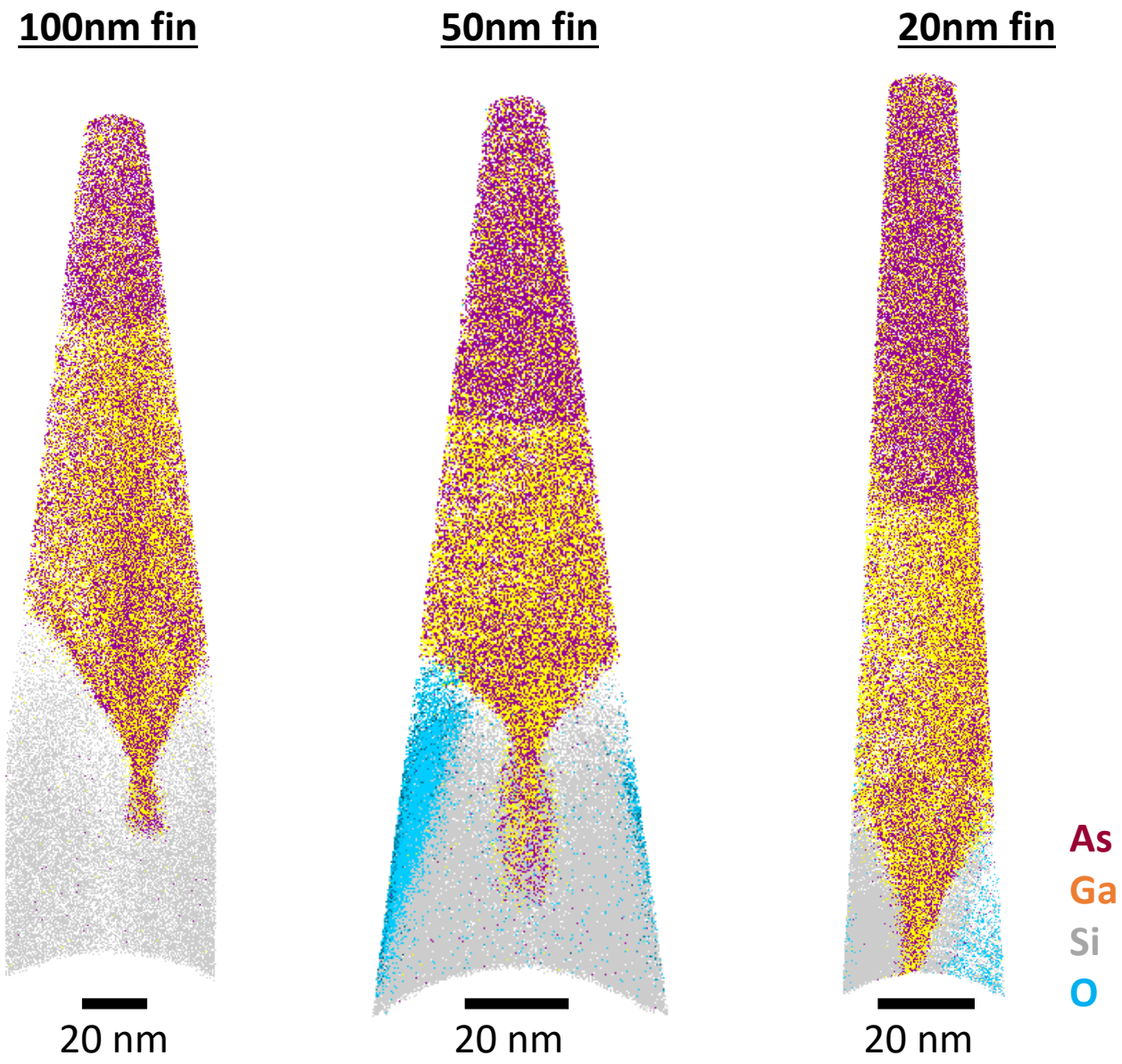
20nm fin



- For APT, the specimen IS the optic of the instrument, so it is a crucial part of the performance – asymmetric / poorly shaped specimens can lead to distortions in the spatial reconstruction
- For the narrower fins it can be challenging to remove all oxide from the specimen, which also can lead to distortions in the spatial reconstruction and well as (potentially) change the laser absorption behavior
- Preparation by FIB takes about 2h for a single liftout (~10 individual specimens) and microtip propagation and then ~15min per specimen for sharpening
- Specific conditions: 30kv 0.18nA first pass (inner 1um, 0.5um), 30kV 18pA (inner 0.25 then adapt time to remove oxide), final cleaning step at 5kV 32 pA

Atom Probe Tomography – Datasets from All Fin Widths

- Can we get data from these samples? Difficult initially, especially for the narrower fins, but yes…as the specimen preparation learning improved, yield eventually became ~100% for the 100nm fins
- Acquisition conditions: T=30K, Detection rate = 0.4-1%, variable laser energy
- Do we get the correct concentration…need exploration of laser energy to answer that question…



Low Field – High Field Materials Can Be A Challenge

Field evaporated endform

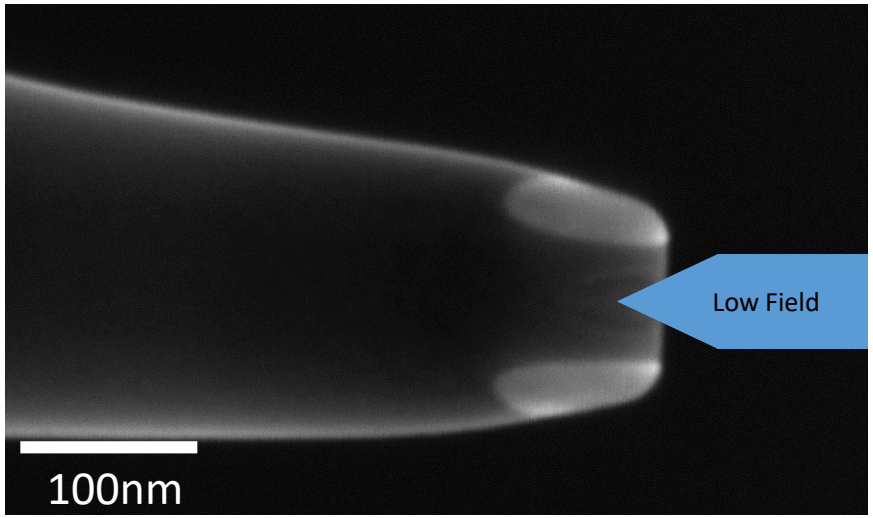
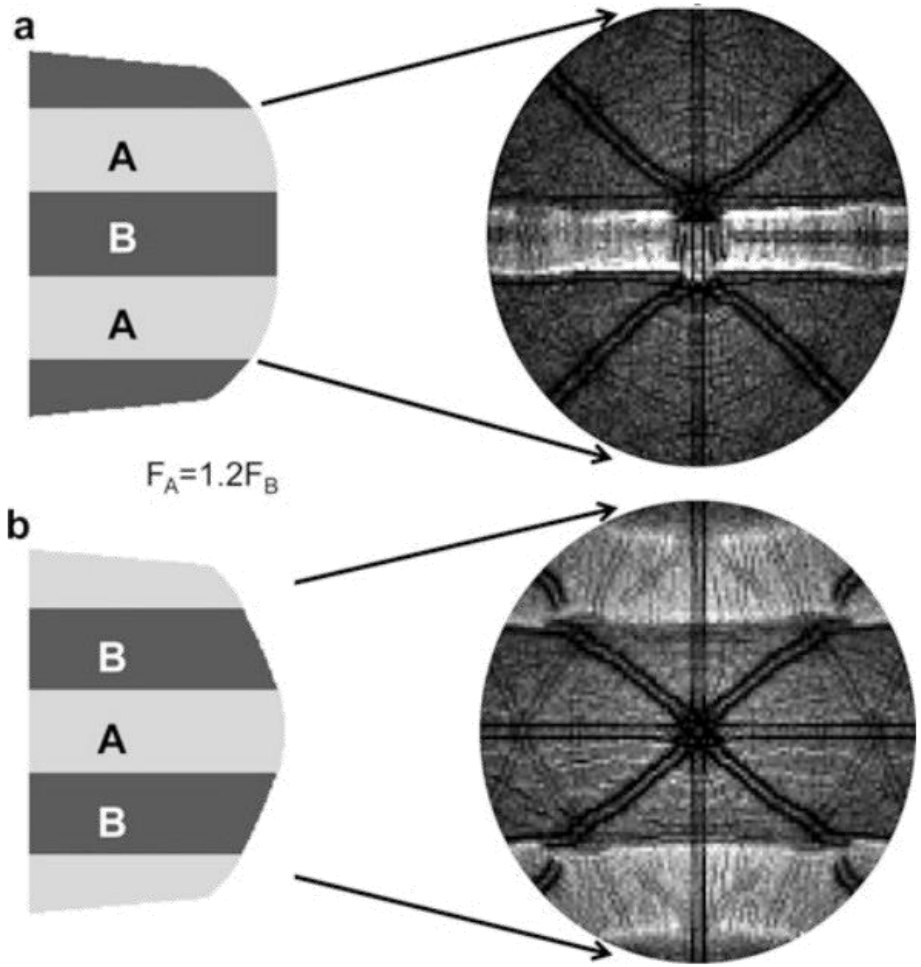


Fig. 5.17 Simulated evaporated shape and corresponding detector hit-maps for (**a**) ABA and (**b**) BAB configurations where the evaporation field for material A is to be 20 % higher than that of material B and the initial shape of the specimen was a hemisphere for each case

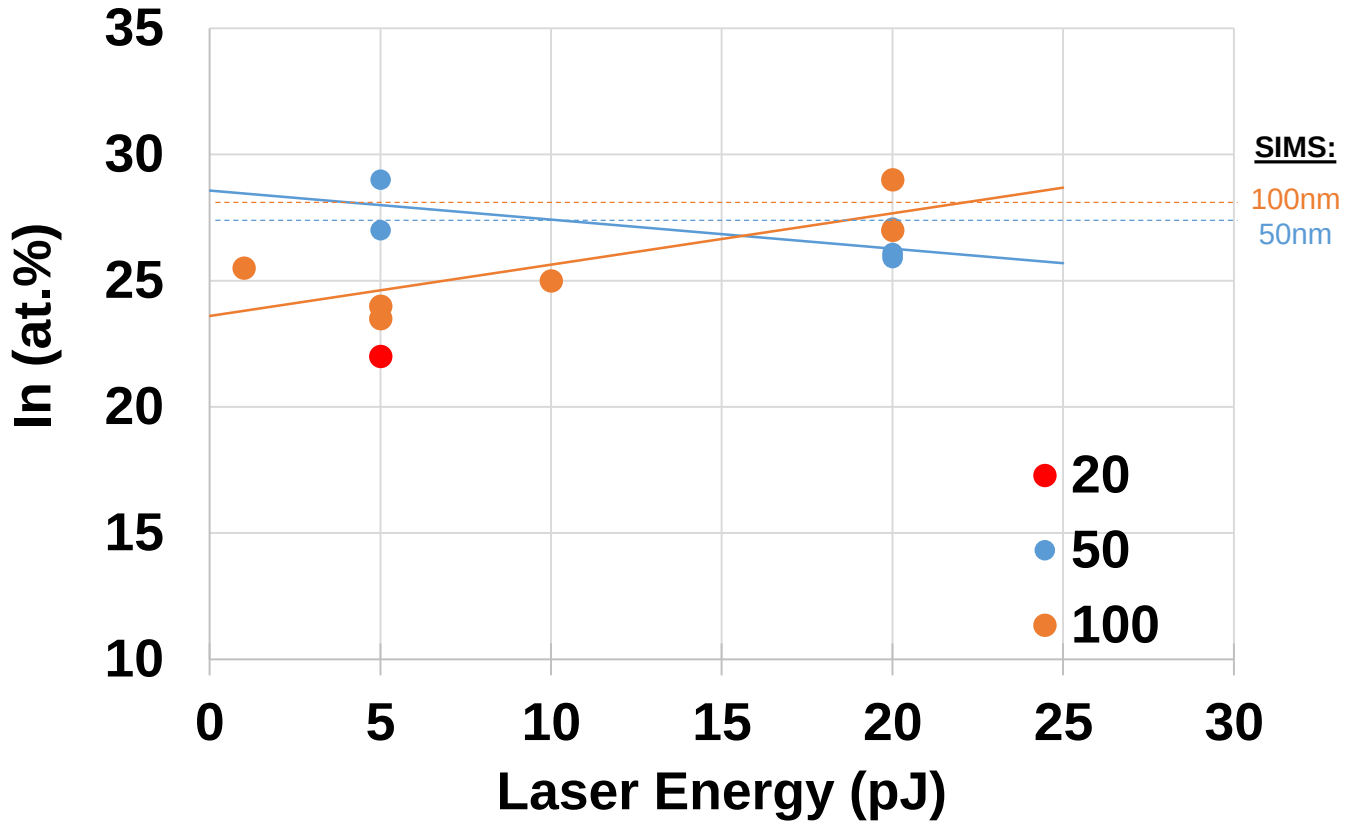


"Local Electrode Atom Probe Tomography" (Springer Publishing, 2013). D. J. Larson, T. J. Prosa, R. M. Ulfig, B. P. Geiser and T. F. Kelly

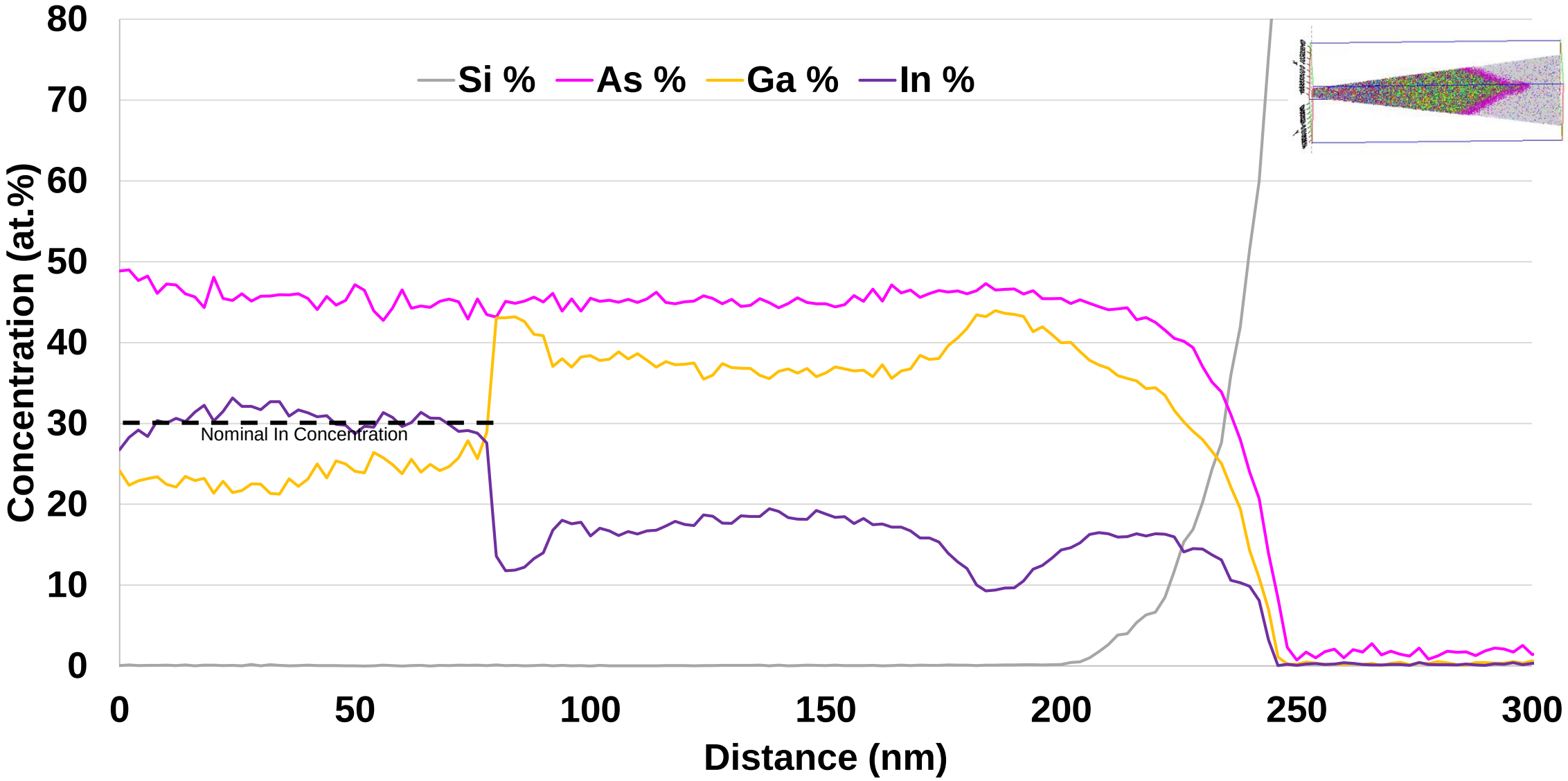
- The shape change that occurs due to the evaporation field difference between materials A and B leads to a variable projection over the "evaporated shape" surfaces shown at right
- This results in compression of the B material (fin) and expansion of the A material (oxide) in the hitmap shown at right and explains the thin B layer reconstruction

Atom Probe Tomography – In% Dependence on Laser Energy

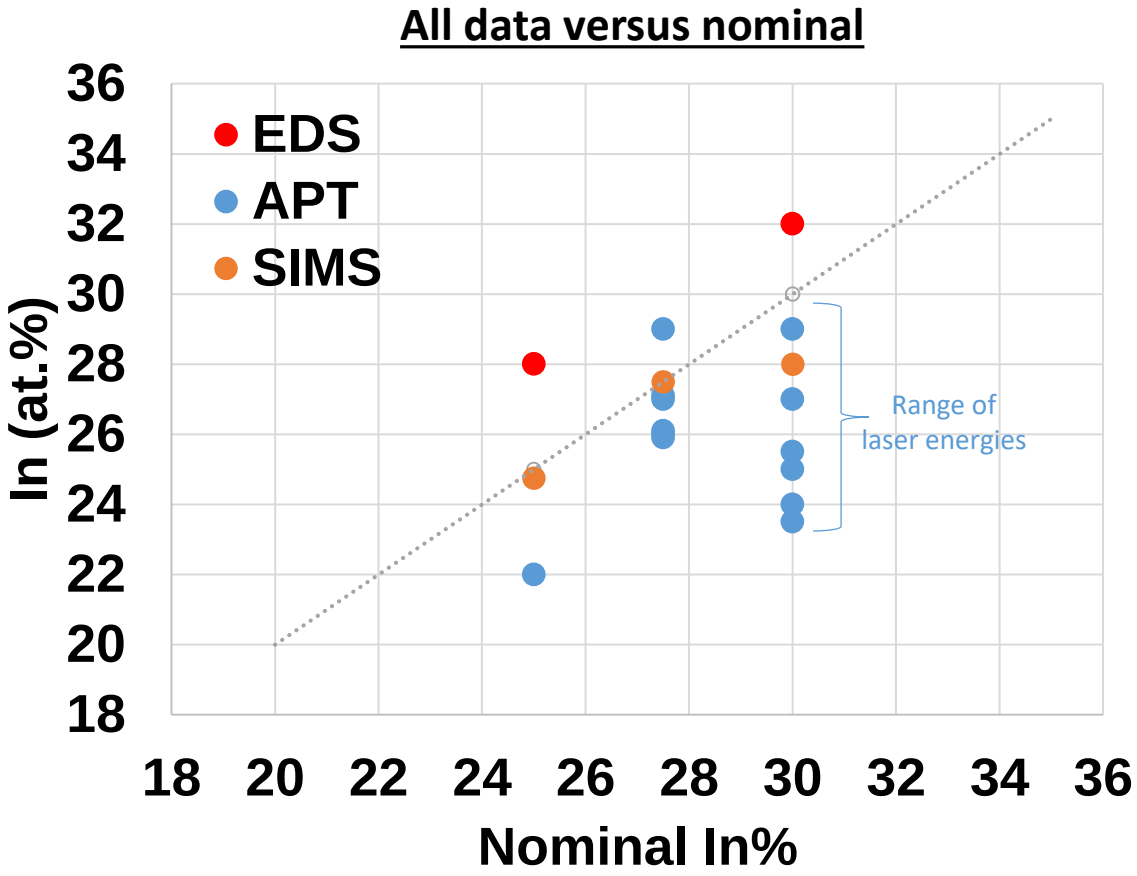
- Trends with laser energy
- If we take the SF-SIMS (dashed lines) as the correct concentration (upper layer only) we have
  - 25% for 20nm fin
  - 27% for 50nm fin
  - 28% for 100nm fin
- Currently working on this curve for the 20nm fins

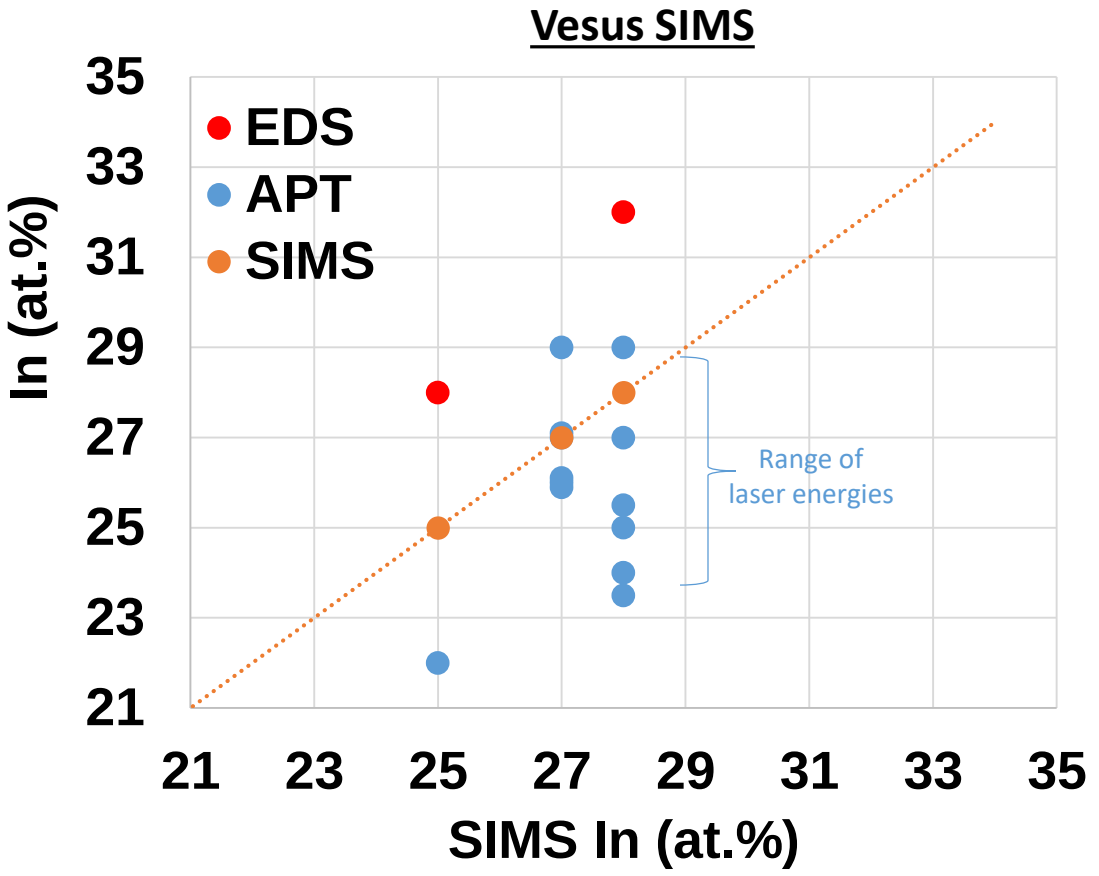


Example APT Profile from 100nm fin at 20pJ



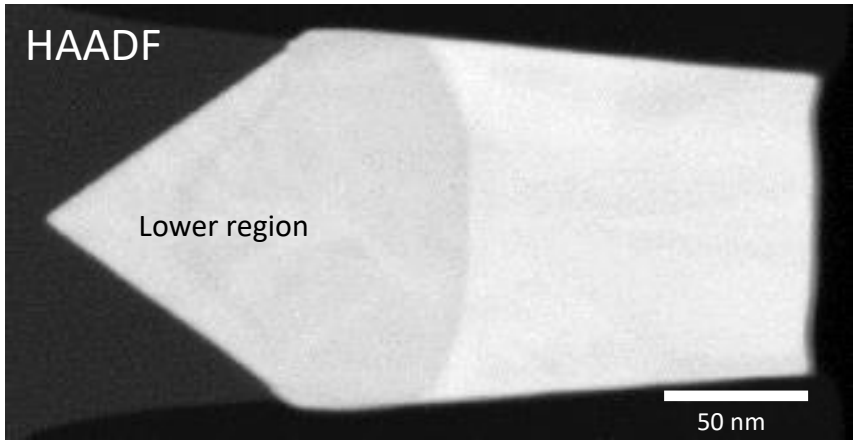
APT and EDS vs SIMS

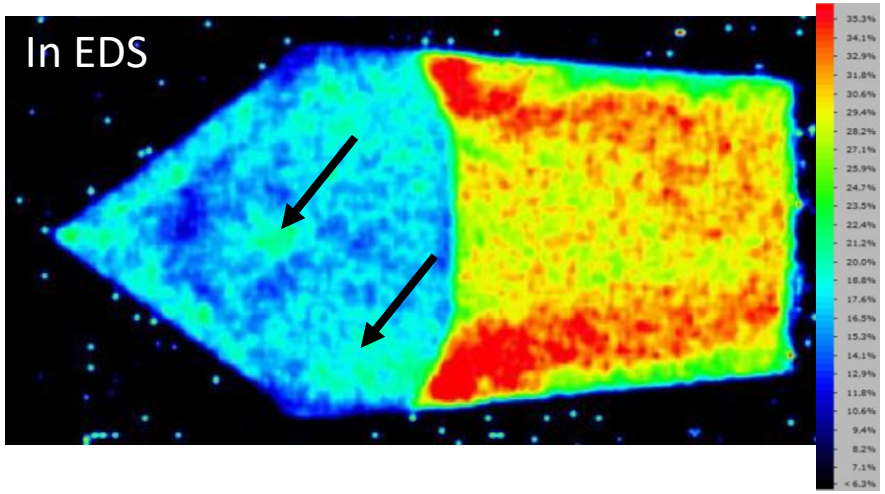


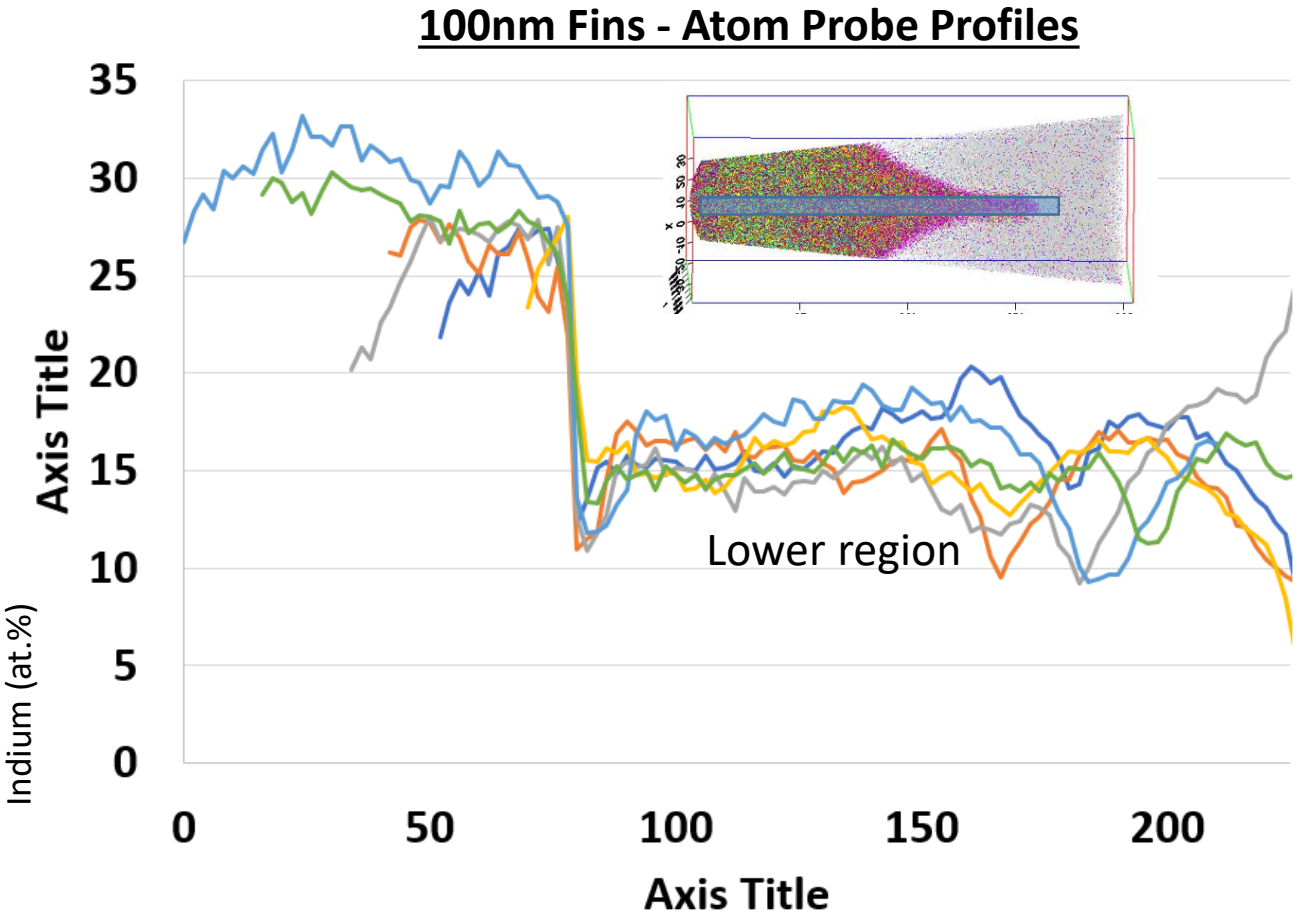


- Left side shows range of laser energies, right side shows data plotted vs. SIMS values
- APT data seem to be more in agreement with SIMS data rather than EDS data

Within-Fin Indium Variation

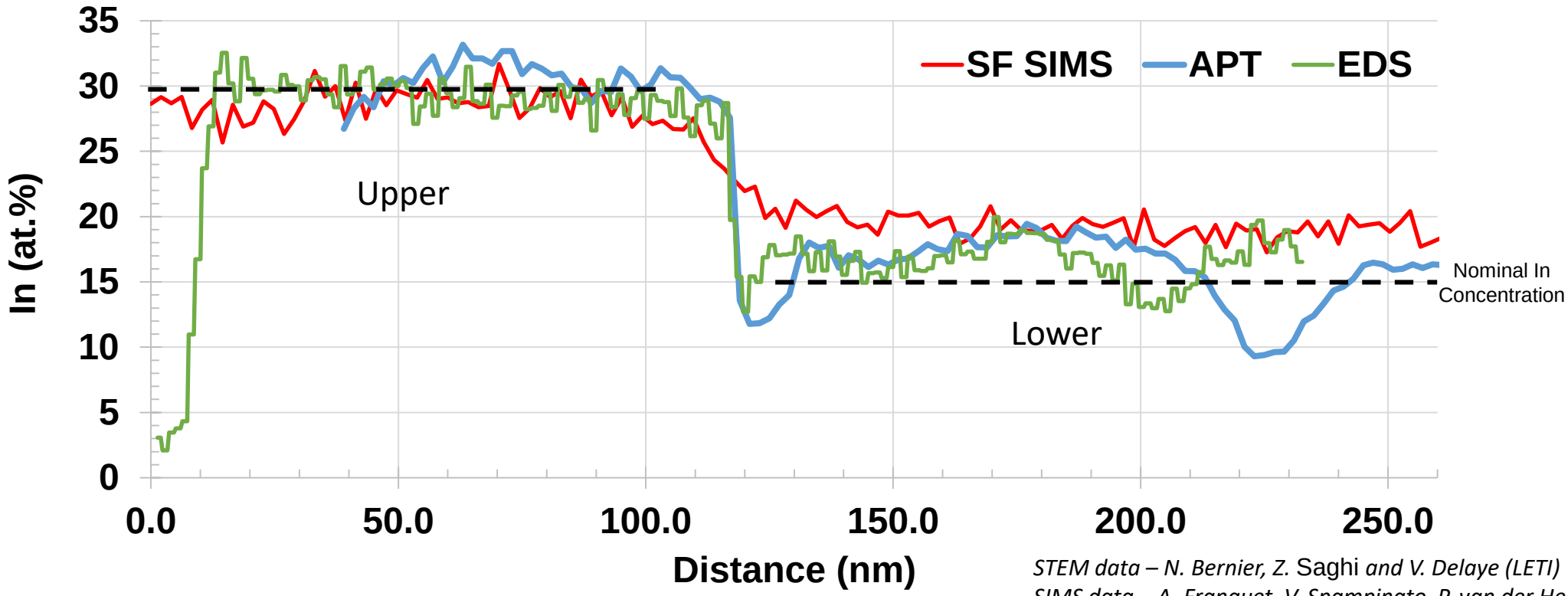






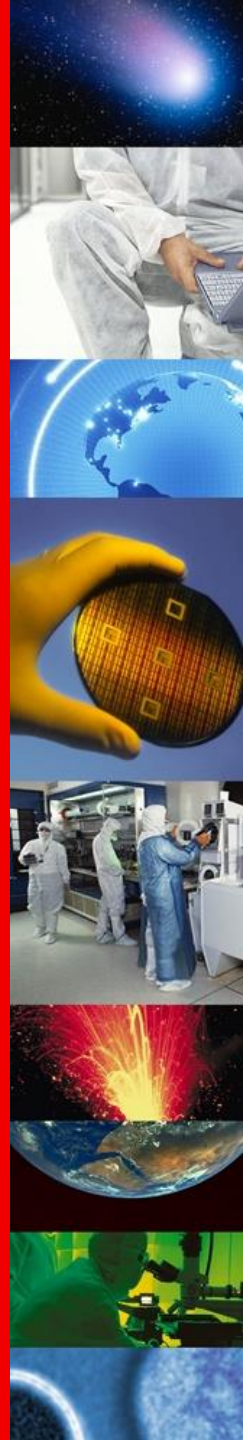
- Both STEM and APT data suggest variations in indium content within individual single fins – both techniques show variations of ~10%
- Repeatable, not spatially correlated, variations show up in the APT data

100nm fin: EDS, SIMS and APT



STEM data – N. Bernier, Z. Saghi *and V. Delaye (LETI)*
SIMS data – A. Franquet, V. Spampinato, P. van der Heide (IMEC)

- SIMS average over many devices but has the potential to be fast
- STEM/EDS and APT can measure a single device and have good spatial resolution, but are slower
- APT has the advantage of having three-dimensional information and also good detection sensitivity for light elements
- If these methods (and LEXES) correlate, then they can form the basis for a range of required metrology



CAMECA®
SCIENCE & METROLOGY SOLUTIONS

LEAP® 5000

LEAP Productivity Enhancement

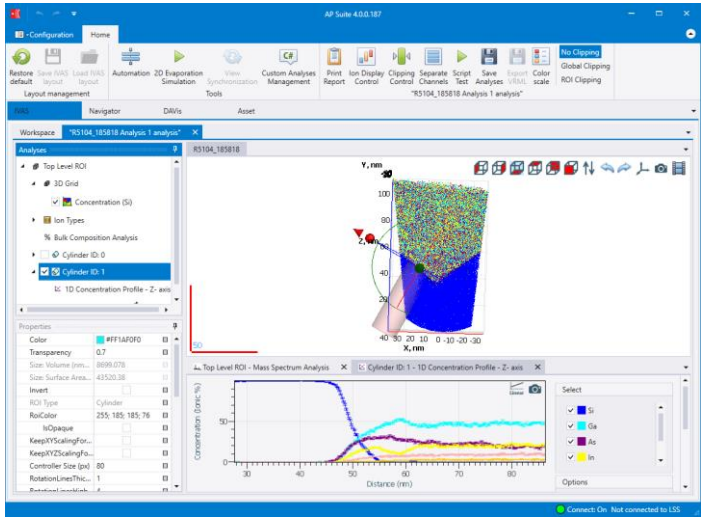
EIKOS™

www.cameca.com

AMETEK®
MATERIALS ANALYSIS DIVISION

SCIENCE & METROLOGY SOLUTIONS

Current Model



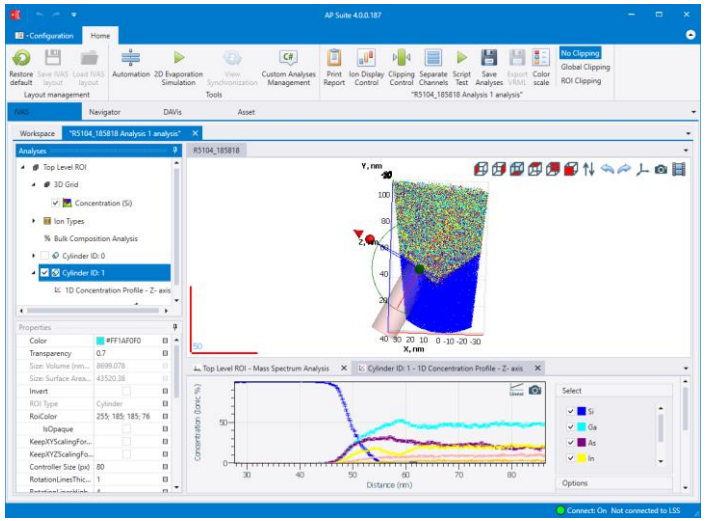
- Specimen preparation: Lift out and mount to a microtip array via a dual beam FIB
- Data Acquisition: LEAP 5000 platform
- Data Analysis: CAMECA's IVAS software package

Each of these requires a skilled user and is idle when not staffed

Goal

- Specimen preparation: Lift out and mount to a microtip array via a dual beam FIB

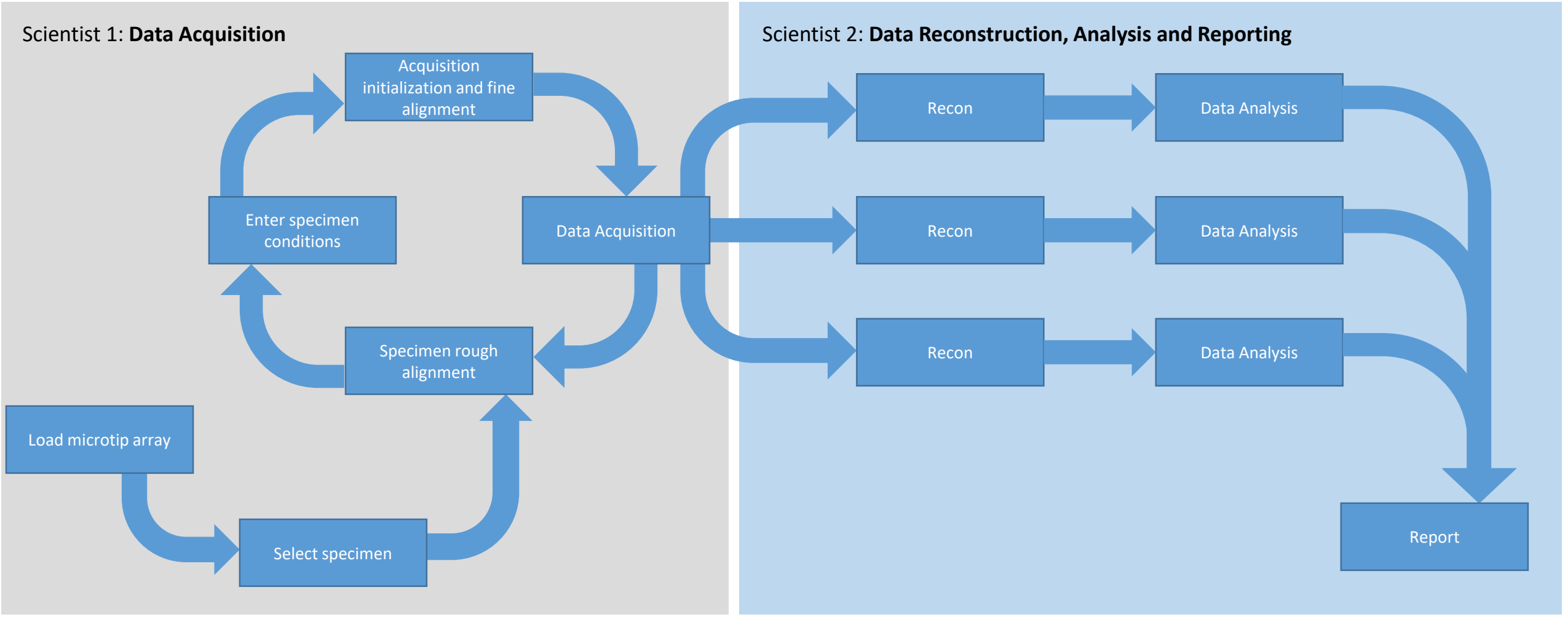
- Data Acquisition: LEAP 5000 platform



- Data Analysis: CAMECA's IVAS software package

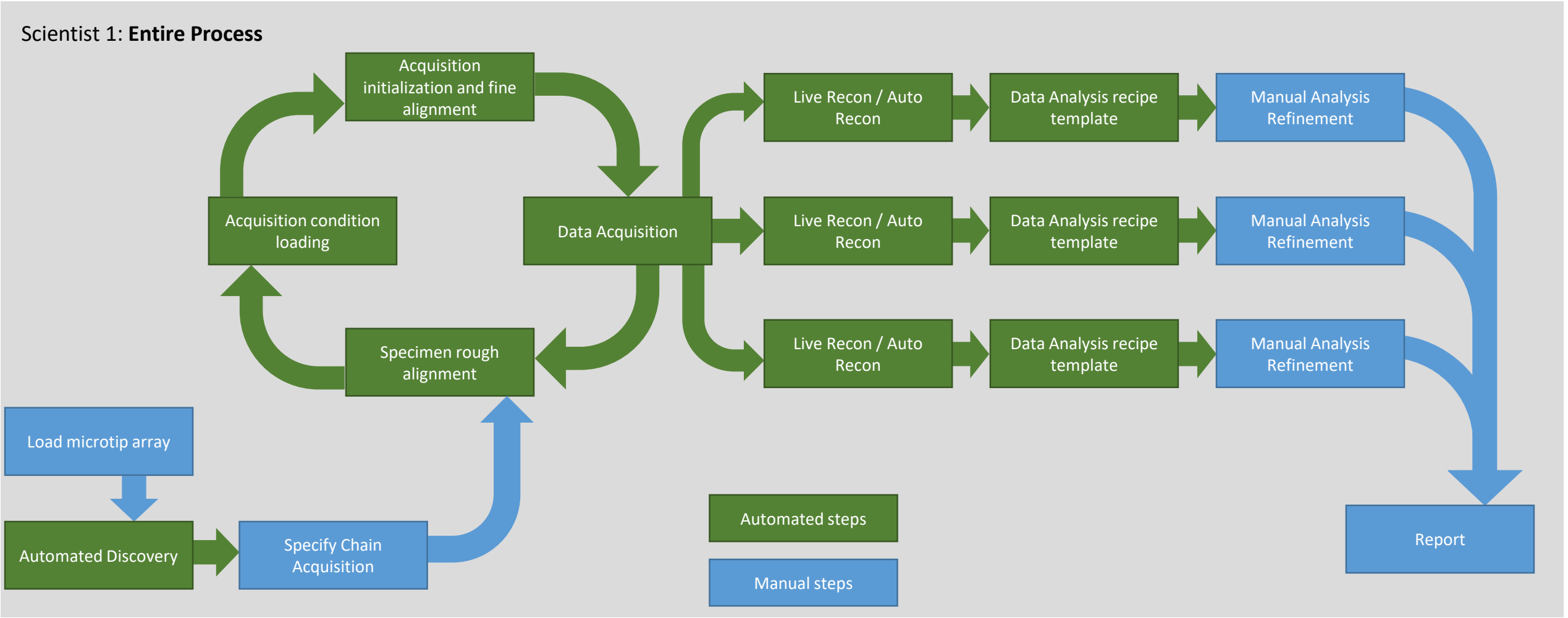
CAMECA is working towards automation of the data acquisition, reconstruction, and analysis of atom probe data to increase throughput and resource utilization

Acquisition, Reconstruction & Analysis: Present



To maintain maximum utilization of the LEAP required (ideally) multiple individuals dedicated to its operation around the clock

Acquisition, Reconstruction & Analysis: Future



With enhanced automation the operation is more efficient, and utilization can be realized during off-hours

Summary & Conclusion

- InGaAs fin structures: Electron microscopy, SIMS, and APT correlation
- Further work ongoing on 20nm fins and to understand variation of In concentration with laser energy in APT
- CAMECA is making progress towards automation of the data acquisition, reconstruction, and analysis of atom probe data to increase throughput and resource utilization

Acknowledgements

- P. van der Heide. A. Franquet, V. Spampinato, W. Vandervorst (IMEC)
- V. Delaye, Z. Saghi, N. Bernier (LETI)
- I. Martin, A.-S. Robbes, A. Merkulov, O. Dulac, D. Reinhard, T. Prosa (Cameca)
- L. Kwakman and A. F. de Jong (Thermo Fischer)

3DAM

This project received funding from the Electronic Component Systems for European Leadership Joint Undertaking under agreement No 692527. It receives support from the European Union's Horizon 2020 research and innovation programme and Netherlands, Belgium, France, Hungary, Ireland, Denmark, Israel. Work done on the PlatForm for NanoCharacterisation (PFNC) was additionally supported by the "Recherches Technologiques de Base" Program of the French Ministry of Research.