# Applications of the Cesium Low Temperature Ion Source (LoTIS)

*High Resolution FIB and SIMS*

Adam V Steele, zeroK
Brenton Knuffman, zeroK
AD Schwarzkopf, zeroK

adam@zeroK.com

FIBSEM 2021

# Technology Highlights

ZER0K

## LoTIS is a new $Cs^+$ ion source

AV Steele, et al., Nano Futures, Volume 1, Number 1 (2017)

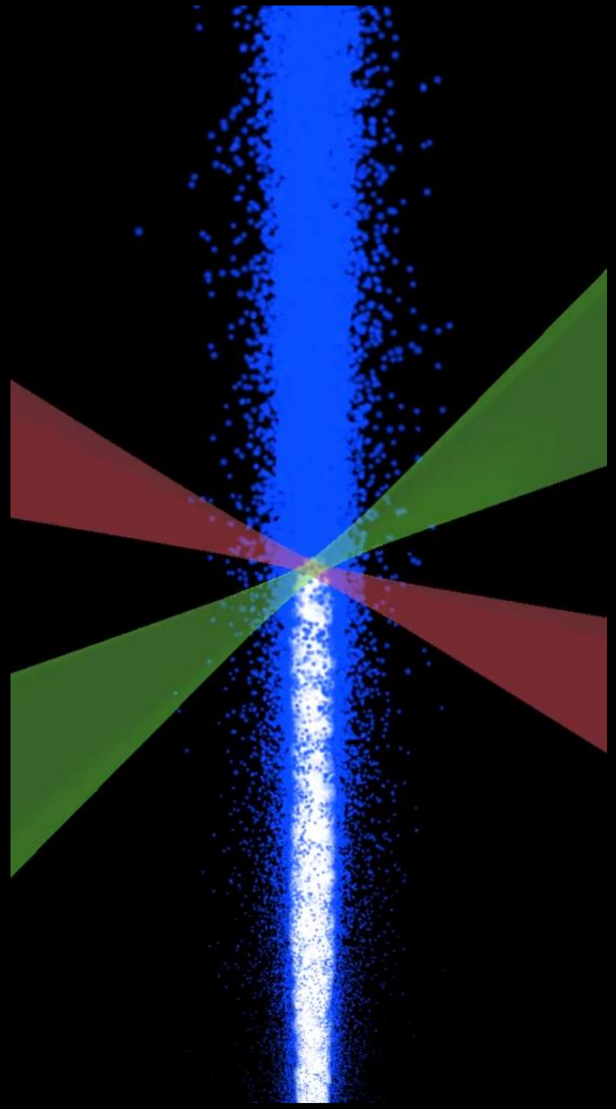
## A LoTIS FIB instrument has been built and tested

- Successful circuit edits on 10 nm node chips
- Imaging and milling demonstrations

## LoTIS Beam Performance

- Demonstrated 2 nm spots with 1 pA, at 10 kV beam
- Provides currents >10 nA (so far)
- 1 kV to 18 keV
  - Performs very well at low-energy relative to $Ga^+$
- Yields large numbers of secondary ions

## Available in FIB and SIMS variants



# $Cs^+$ LoTIS Pros/Cons

ZER0K

## Strengths

- Small Spot Sizes
- Low-Energy Performance
- High Sputter Yields
- Reduced Range, Straggle
- Versatile range of currents (pA-nA)
- High Secondary-**Ion** Yields (Cs)

## Weaknesses

- Cost*
- Cs is 'new'
- Unknown-Unknowns

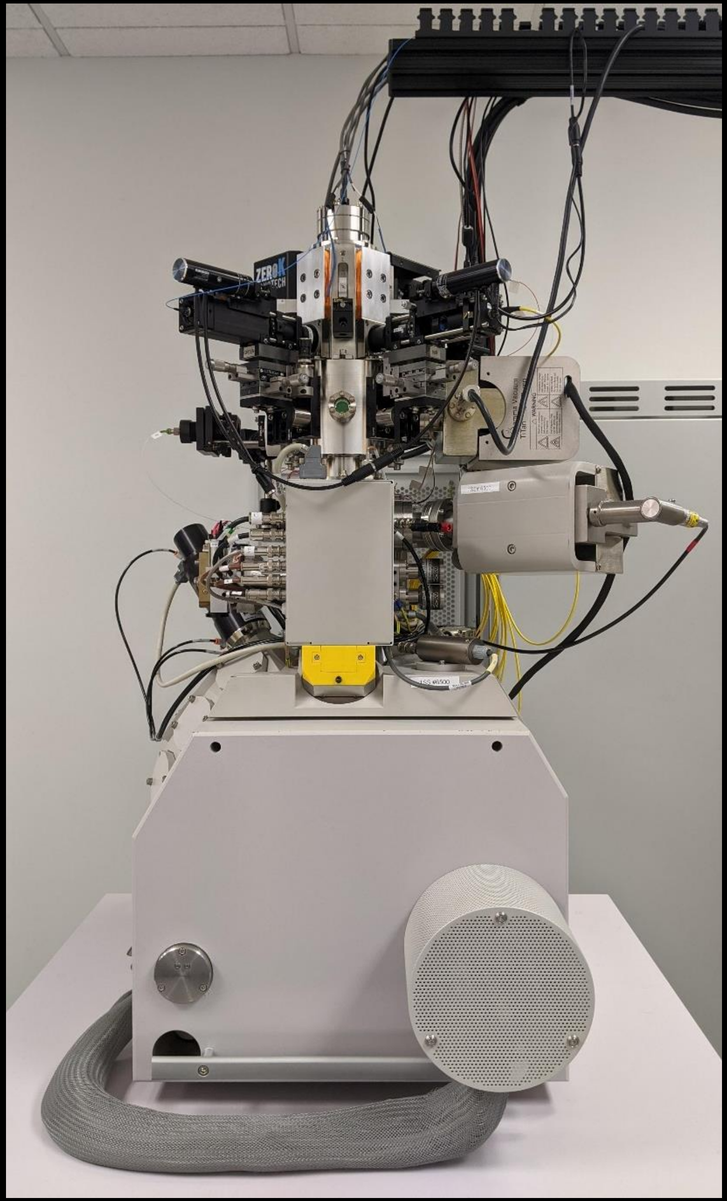
## Ideal Applications

- General FIB Milling
- Nanomachining
- SIMS Elemental Analysis

*Relative to Ga LMIS, Plasma **But** Reasonable compared with platform overall

# FIB:ZERO

- Modified Thermo-Fischer v600 platform
- 2 nm resolution at 1 pA, 10 keV
  (2-3x better spot sizes and at 3x lower beam energy than LMIS)
- <1 pA to 10+ nA
- Platinum GIS (others available)
- Generates secondary ion images as well
- Demonstrations available



# Spot Sizes
# Selected Beam Energies and Currents

Results from Normal FEI FIBs (FIB200, v600)

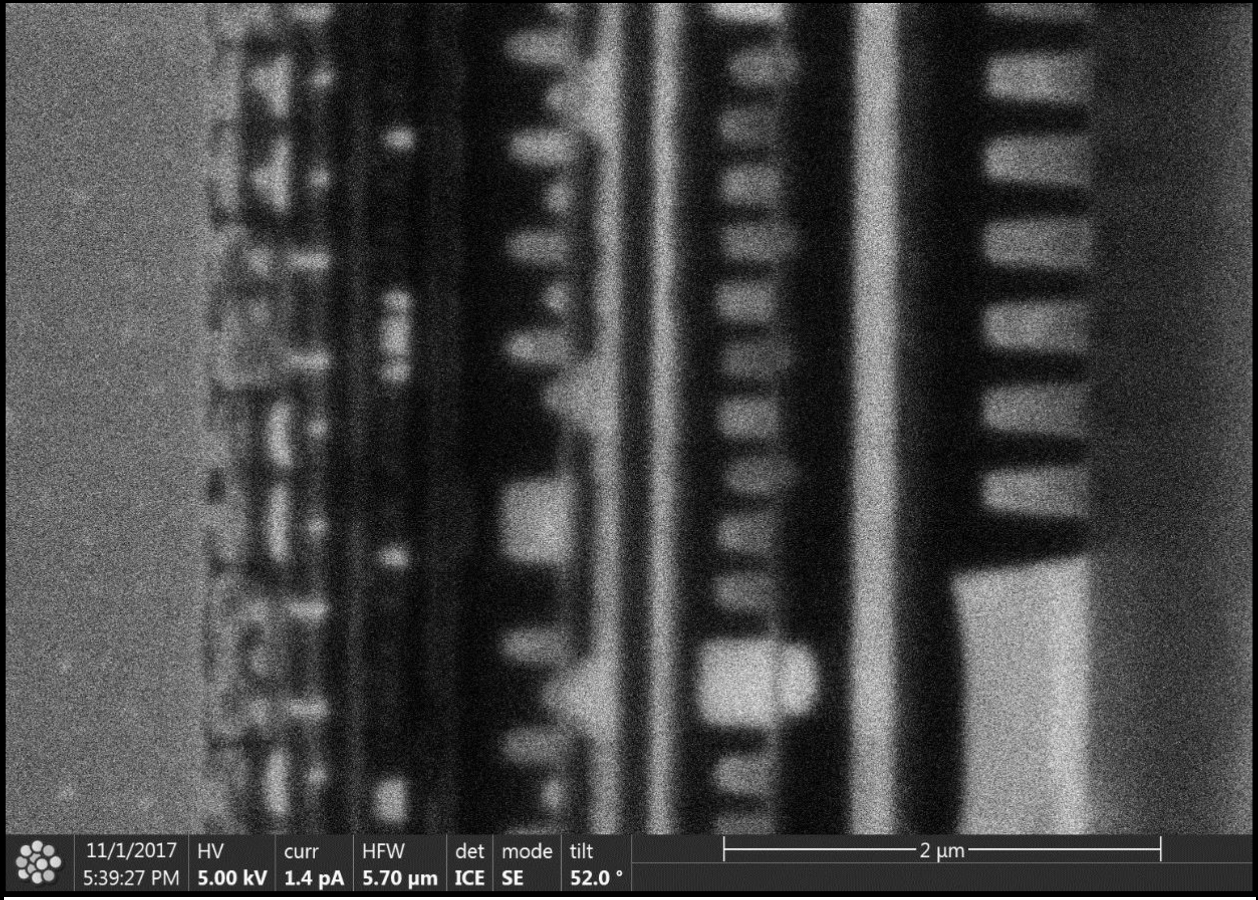
No apertures used

Note: Results given as a $\sigma$

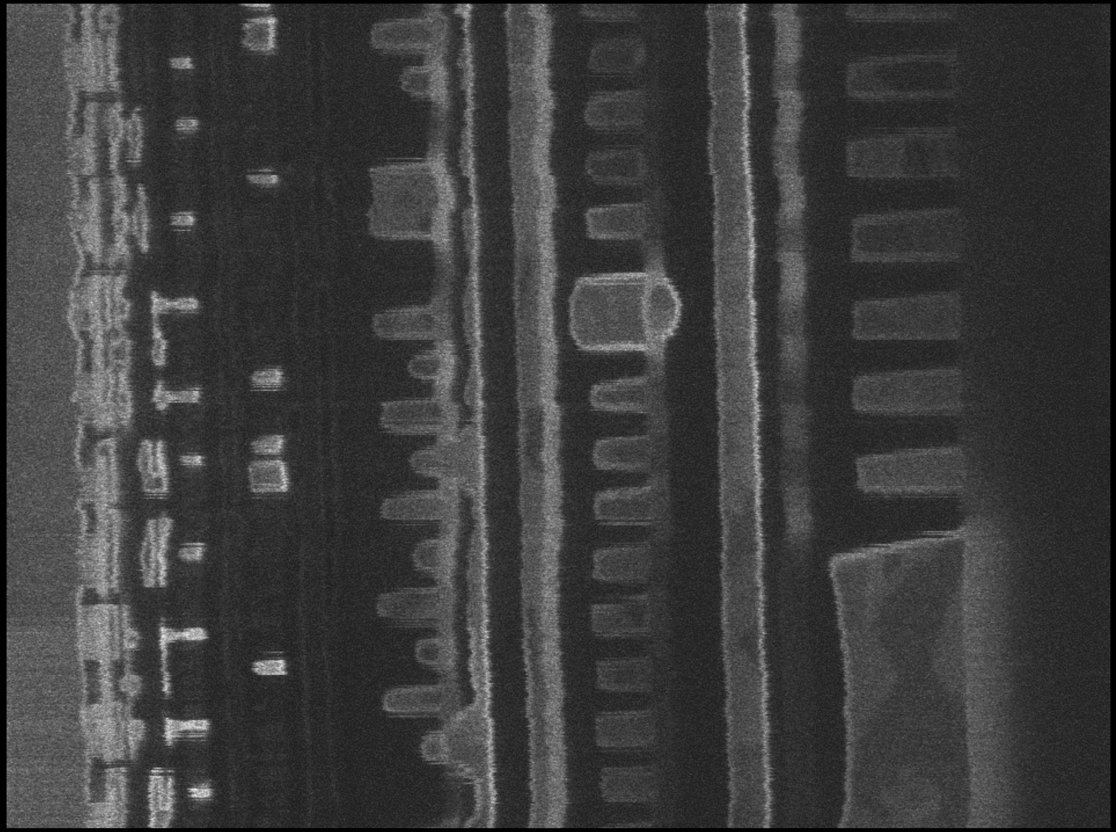
- $R_{35-65} = \frac{\sigma}{1.3}$,
- $R_{16-84} = \sigma * 2$

| Energy (keV) | Current (pA) | Spot Size (1-$\sigma$ nm) |
|---|---|---|
| 18 | 1.5 | <2 |
| 18 | 1,000 | 150 |
| 10 | 2 | <2 |
| 8 | 80 | 46 |
| 8 | 1,200 | 343 |
| 8 | 10,000 | 700 |
| 4 | 1.2 | 11 |
| 2 | 1.5 | 32 |
| 1 | 2.0 | 36 |
| 1 | 50 | 660 |
| 1 | 1,000 | 2900 |
| 1 | 10,000 | 4000 |

# 5kV FIB imaging: LoTIS vs LMIS




**Ga+ LMIS:** 1 pA 5 kV



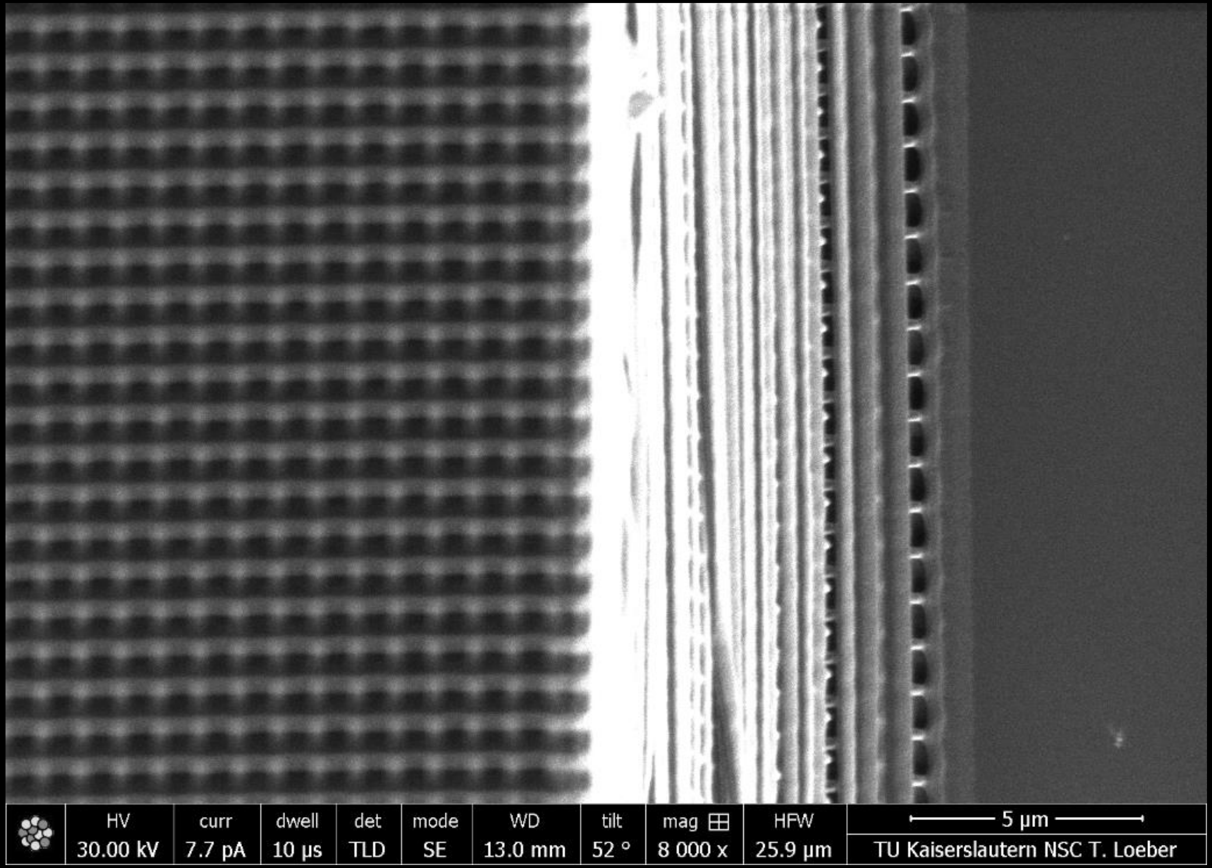
**Cs+ LoTIS:** 1 pA 5 kV

Easily seen channeling contrast in LoTIS image.
Improved resolution at low energy (LoTIS: ~3-4 nm)

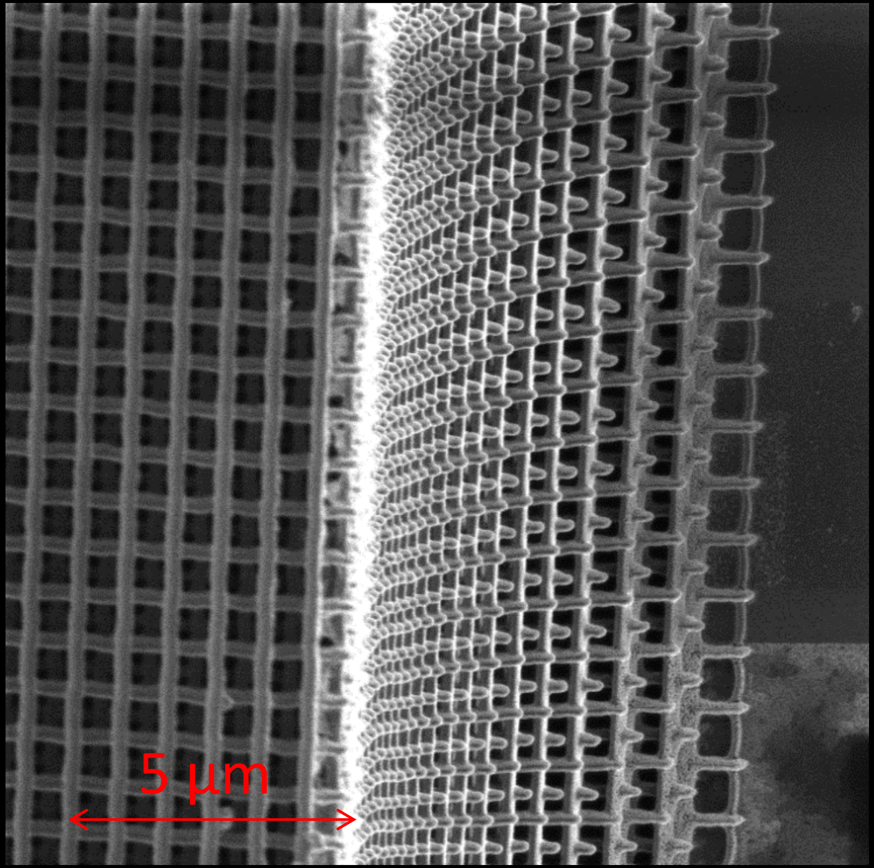
# Depth of Focus Comparison

→LoTIS depth of focus substantially better than Ga

Ga⁺ LMIS (30 kV)



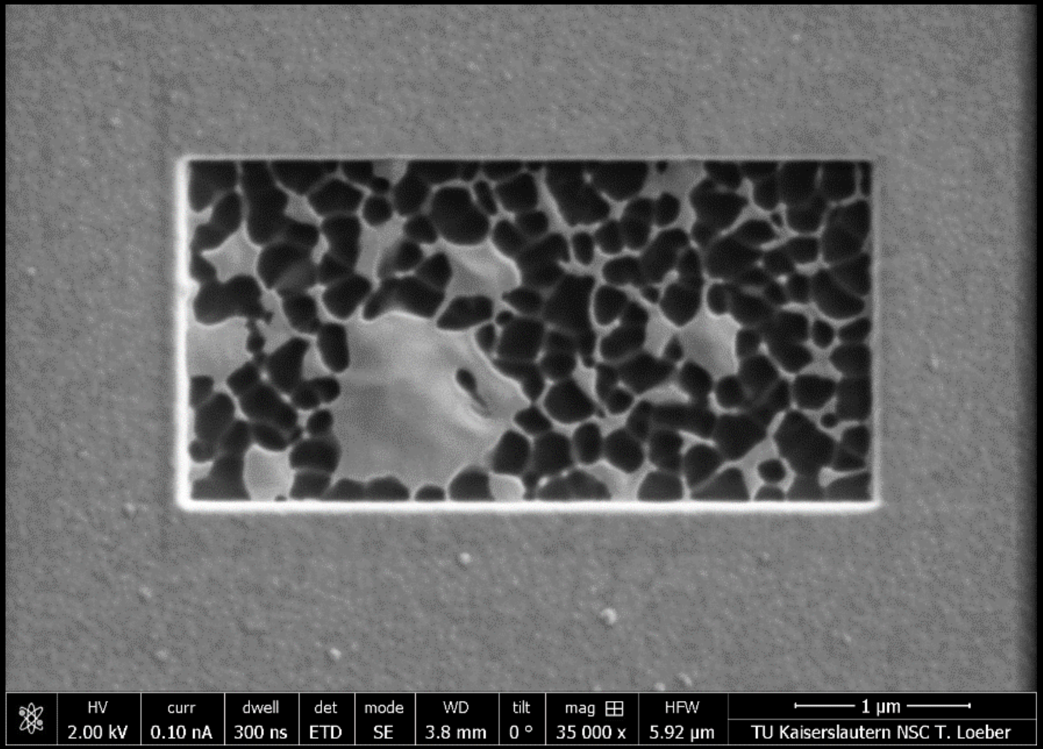

Cs⁺ LoTIS (10 kV)



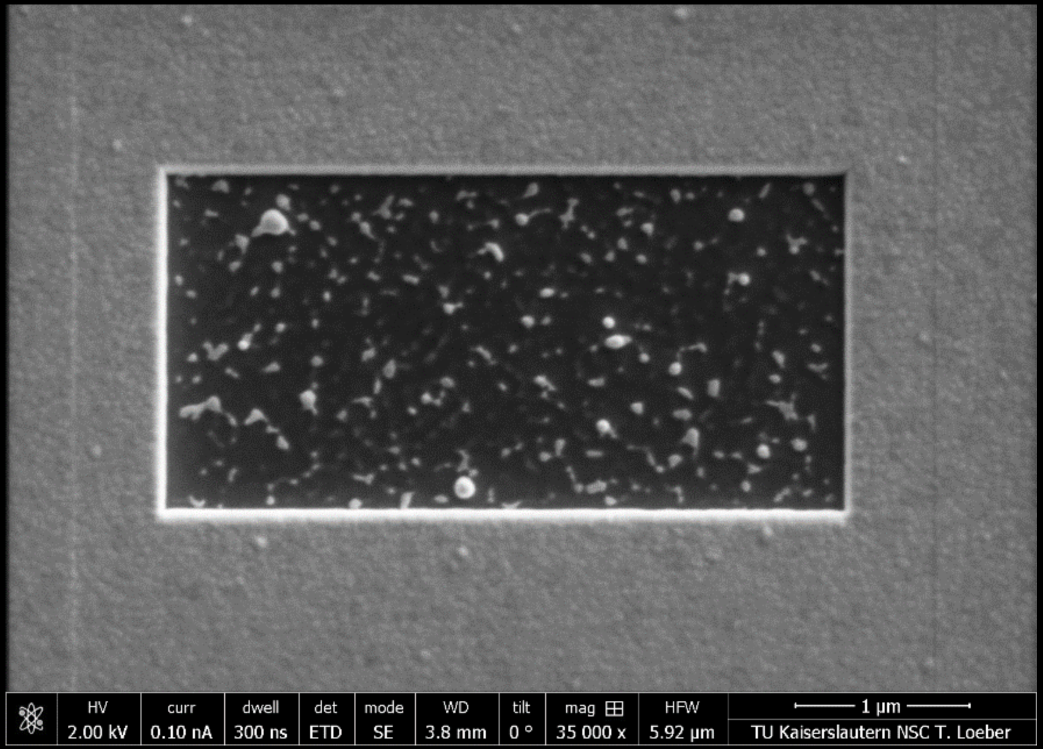

"Wood Pile" Height 120 µm

# Milling Homogeneity: 150 nm Au on Si
→$Cs^+$ LoTIS proves even touchdown

Milled with $Ga^+$ LMIS




Milled with $Cs^+$ LoTIS

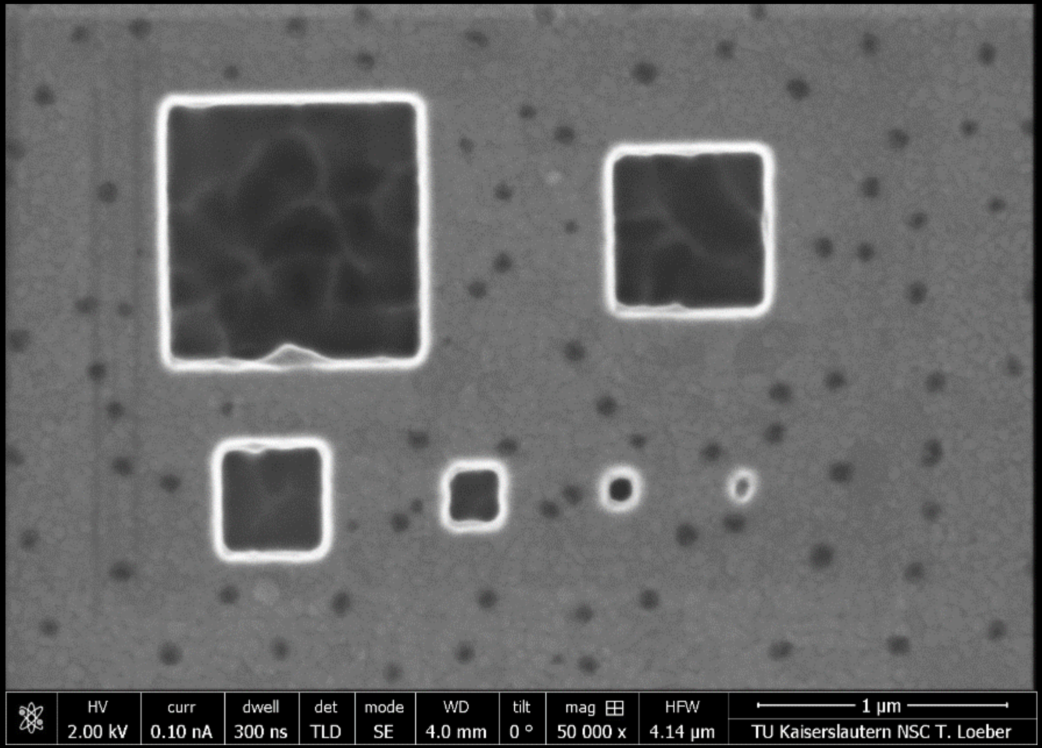



- milled rectangle 'almost through' the Au layer
- milling time Ga and Cs almost the same

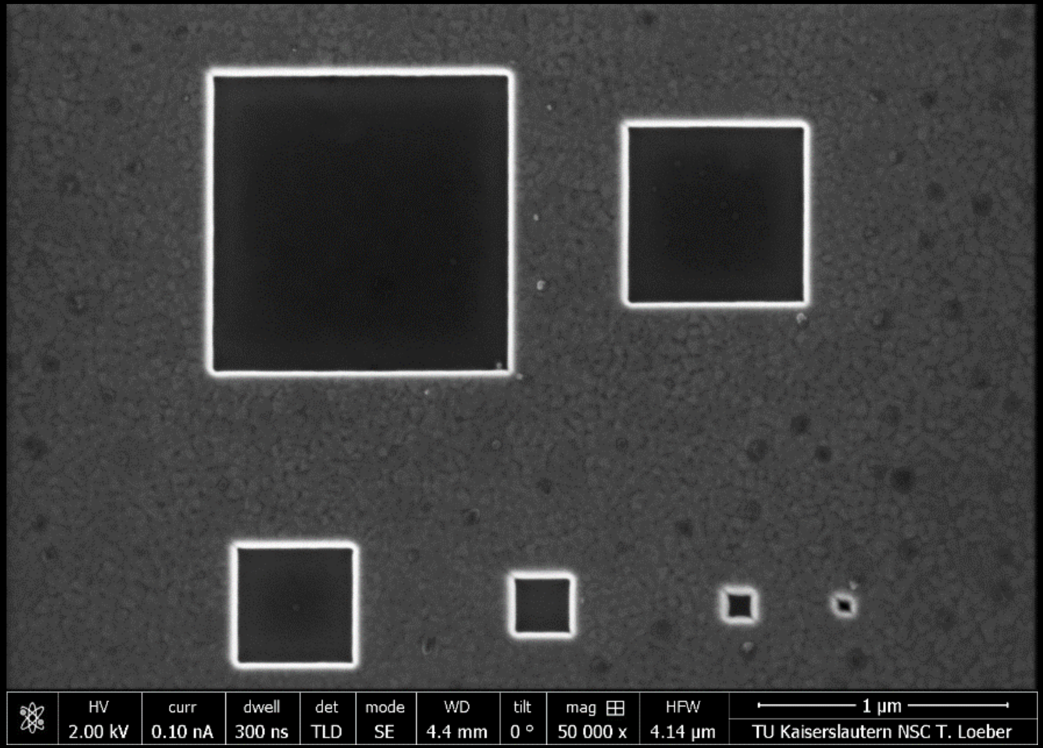
# Milling Accuracy: 110 nm Au on Si

→ LoTIS provides clean mill boxes with sharp corners

Milled with $Ga^{+}$ LMIS

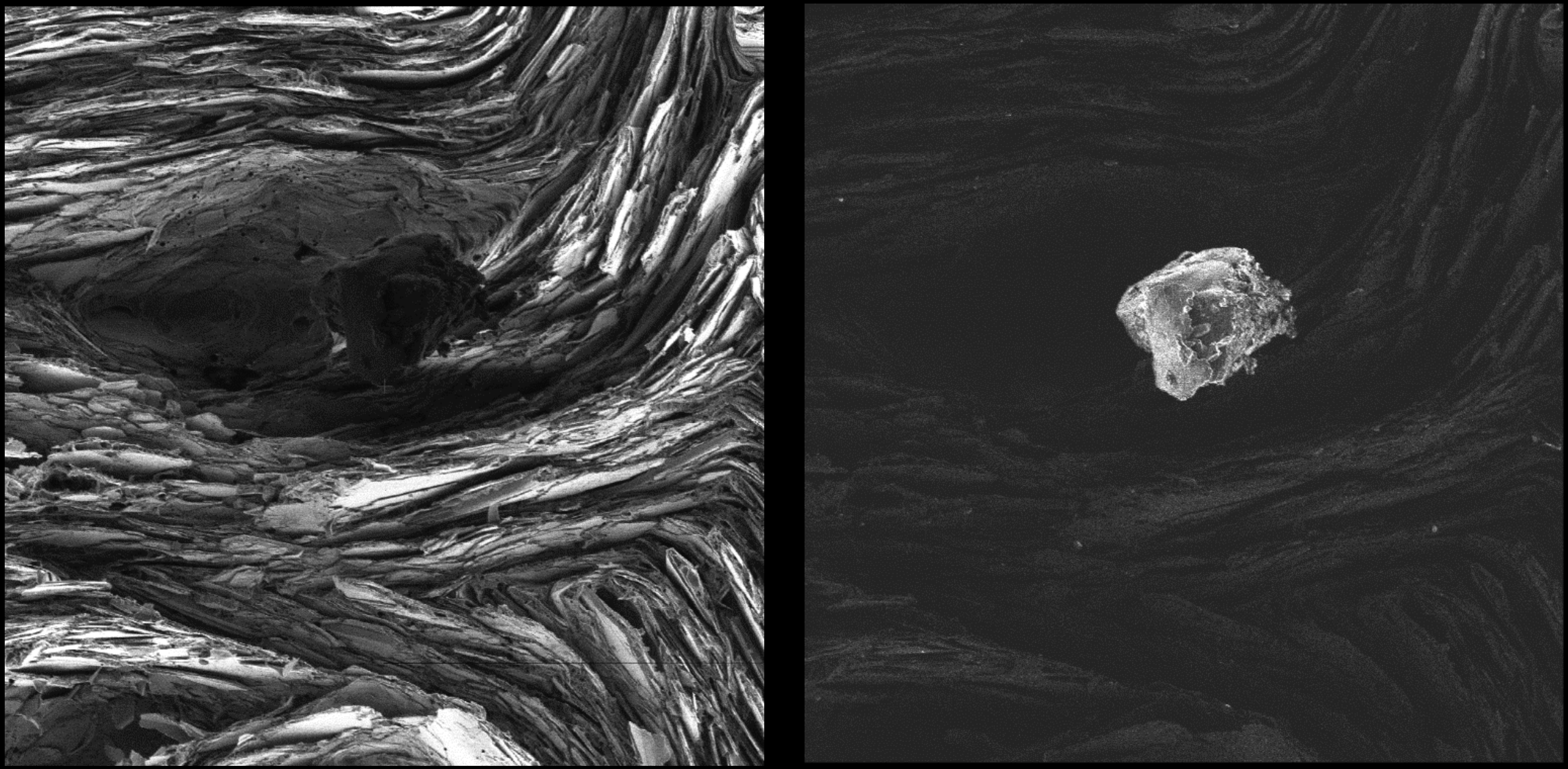



Milled with $Cs^{+}$ LoTIS




- squares with 1, 0.6, 0.4, 0.2, 0.1 and 0.05 µm length
- milled through the Au layer
- milling time Ga and Cs almost the same

# Secondary Electron, Ion Images



Pencil lead, 20 um FOV.  Comparison of secondary electron (left) and secondary ion modalities (right).

Graphite has a low sputter rate, while the dust particle has a high sputter rate and/or high yield of positive ions.

# Pain Points of Elemental Analysis Techniques

ZER0K

## EDX/EELS

- Long Sample Prep Times
- 3D analysis infeasible
- Low-Z elements Challenging

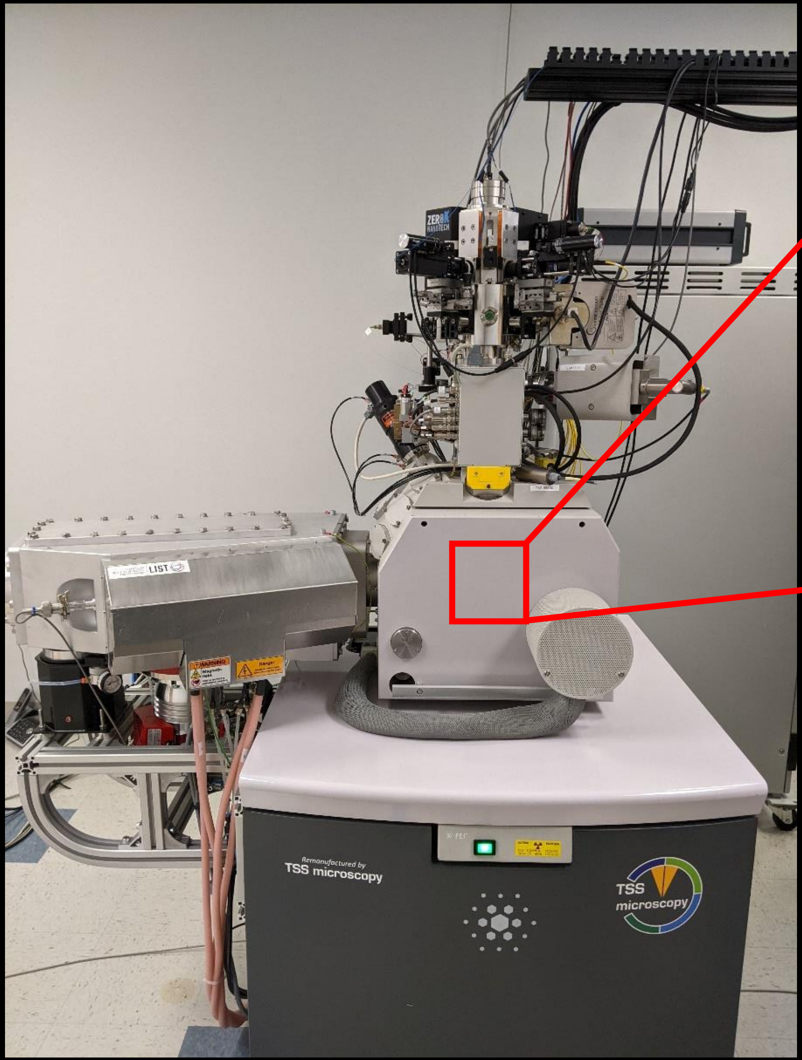
## Site-Spec. SIMS

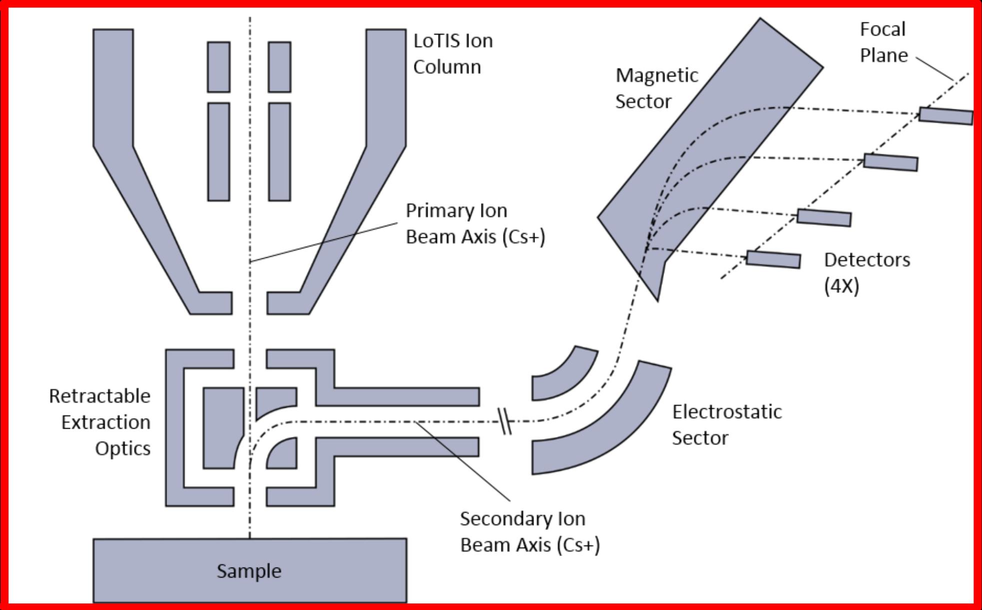
- Resolution >50 nm (eg NanoSIMS)
- Low yields with high-resolution beams (eg Ga, He, Ne)
- Long acquisition times
- Can't view all elements at once
  - (Loss of information)

These points are addressable
By LoTIS:

- Nanometer resolution
- High Secondary Ion Yield
- Integrated Sample Prep and Analysis capability

# SIMS:ZERO Overview




## Single-Beam FIB with high-efficiency collection of secondary ions

## Multiple imaging modalities:

- Electrons, +Ions, -Ions

## Performance compared with industry standard Cs focused beam SIMS

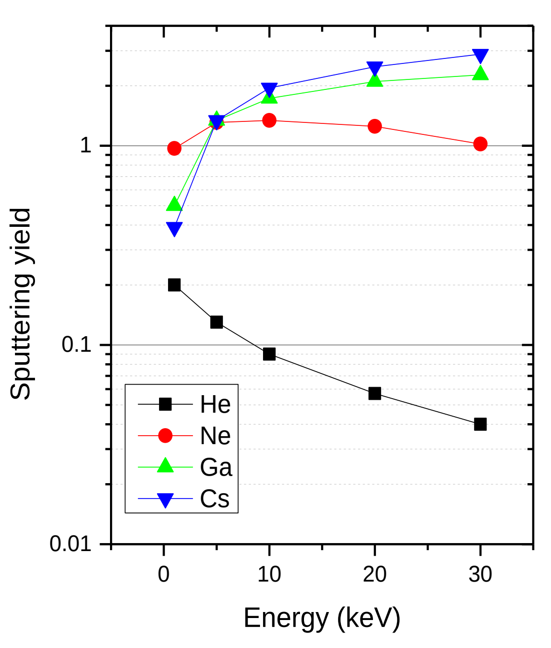
- 100x more current/area
- 10x better resolution (down to ~5 nm in non-abundance limited cases)

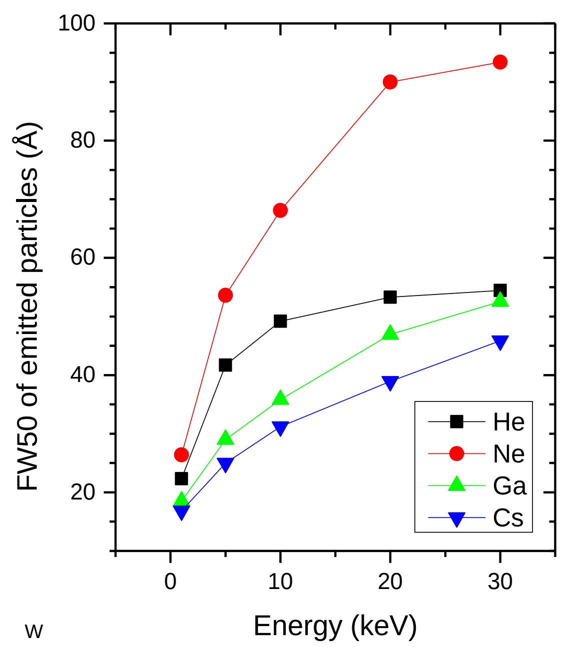
# Primary Ion Species Matters

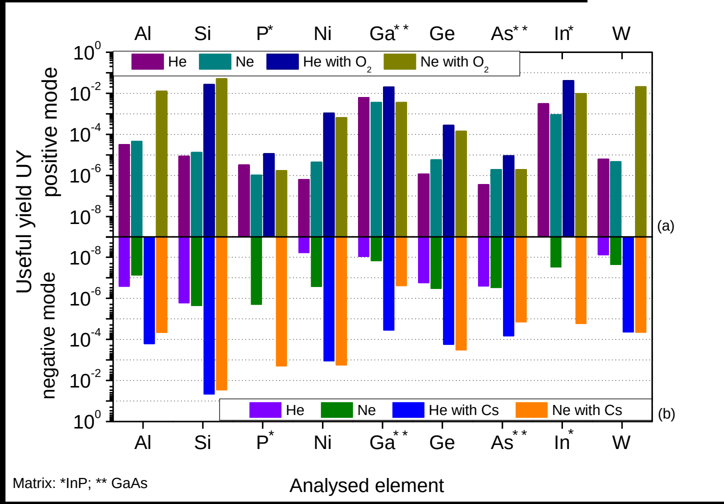
Differing Sputter Rates
→ Analysis Time

Differing interaction Volumes
→ Resolution

Differing Yields
→ Sensitivity Floor

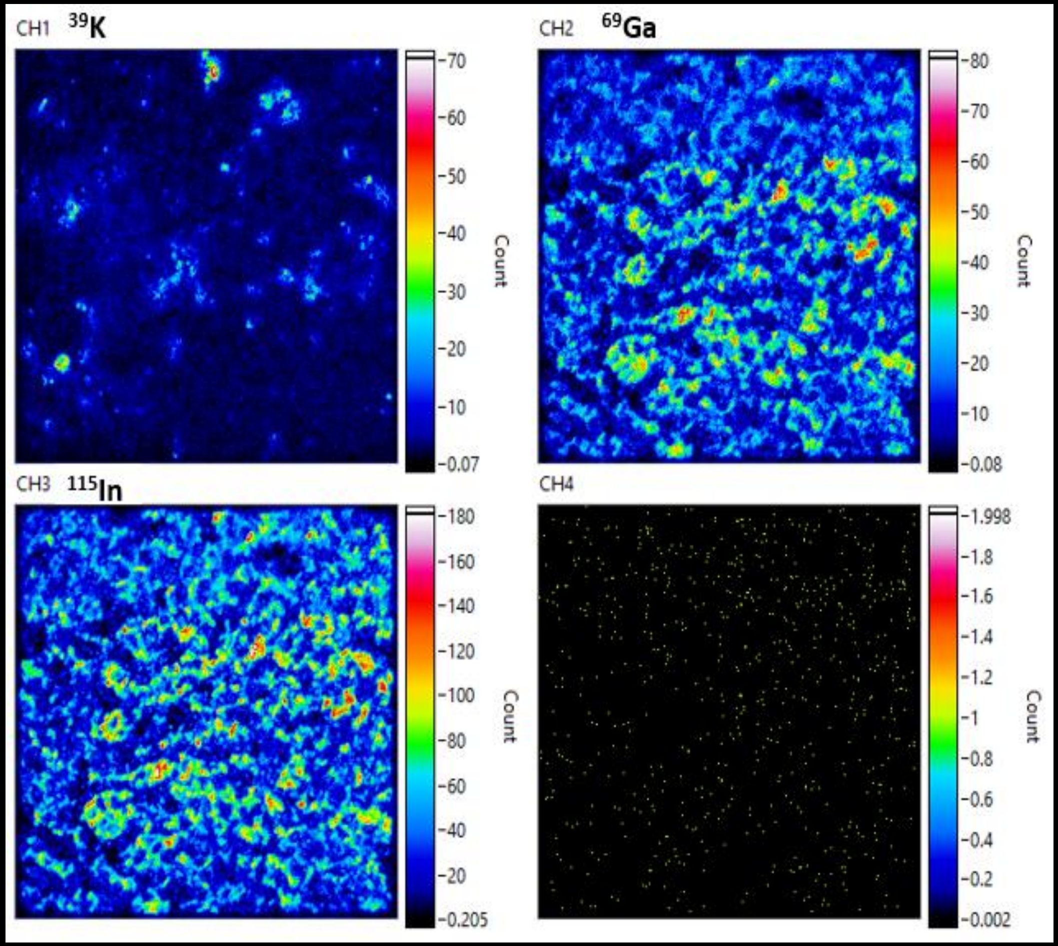


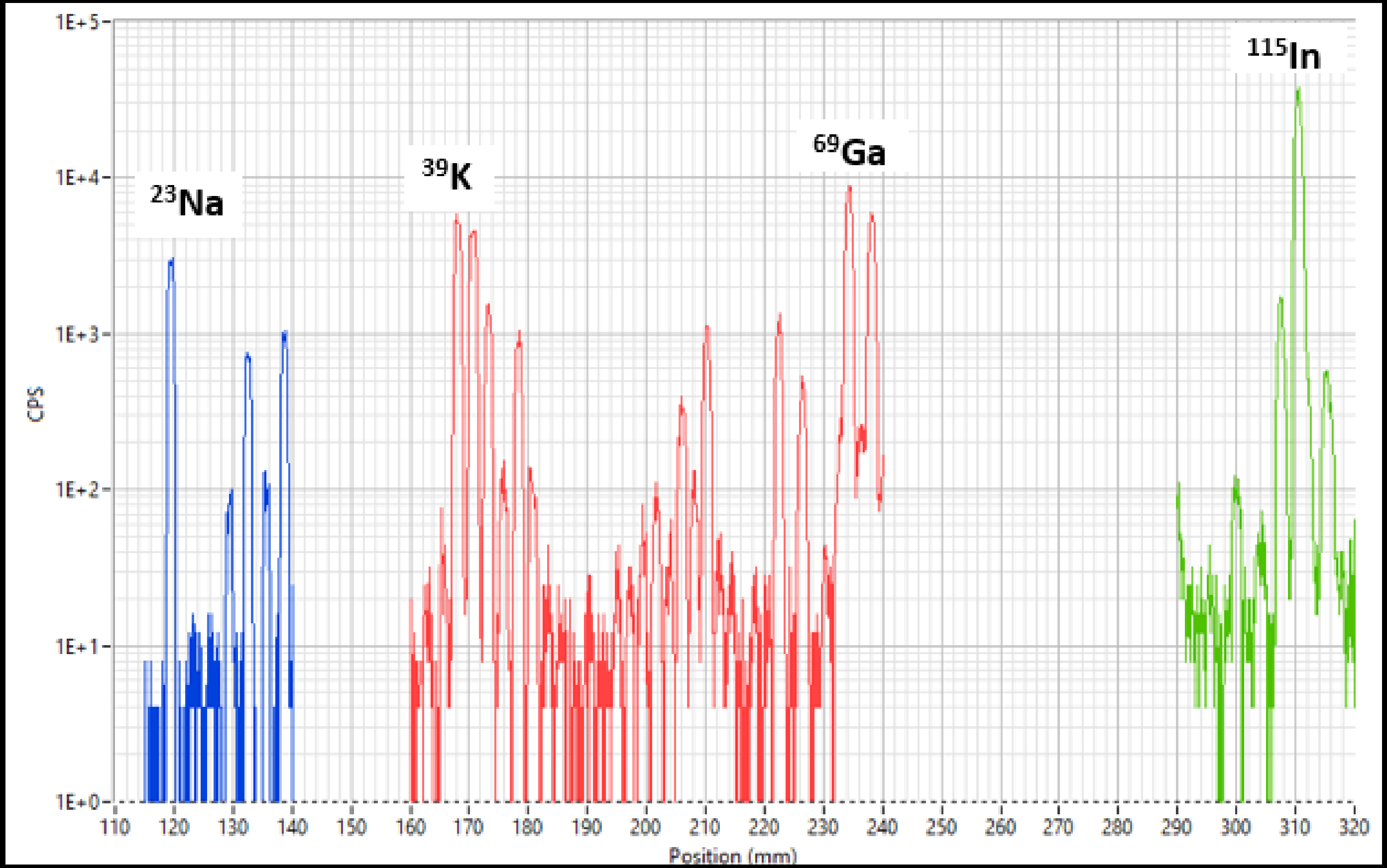



# SIMS:ZERO
# Preliminary First Data

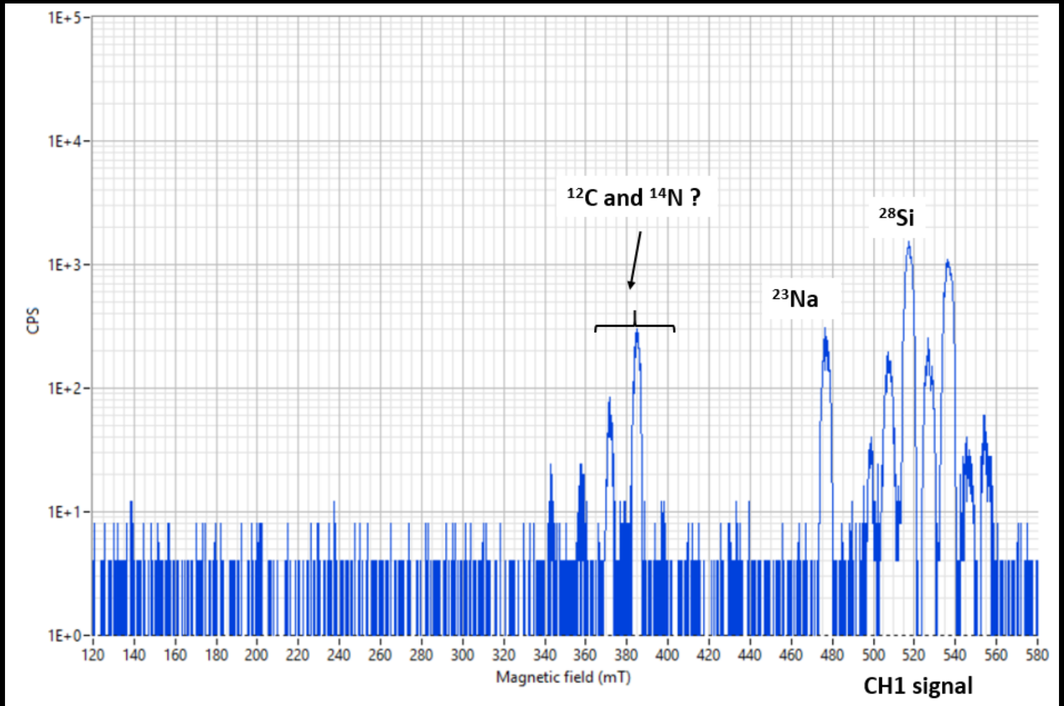
***CIGS (CuInGaSe) solar cell, ~90 um FOV***



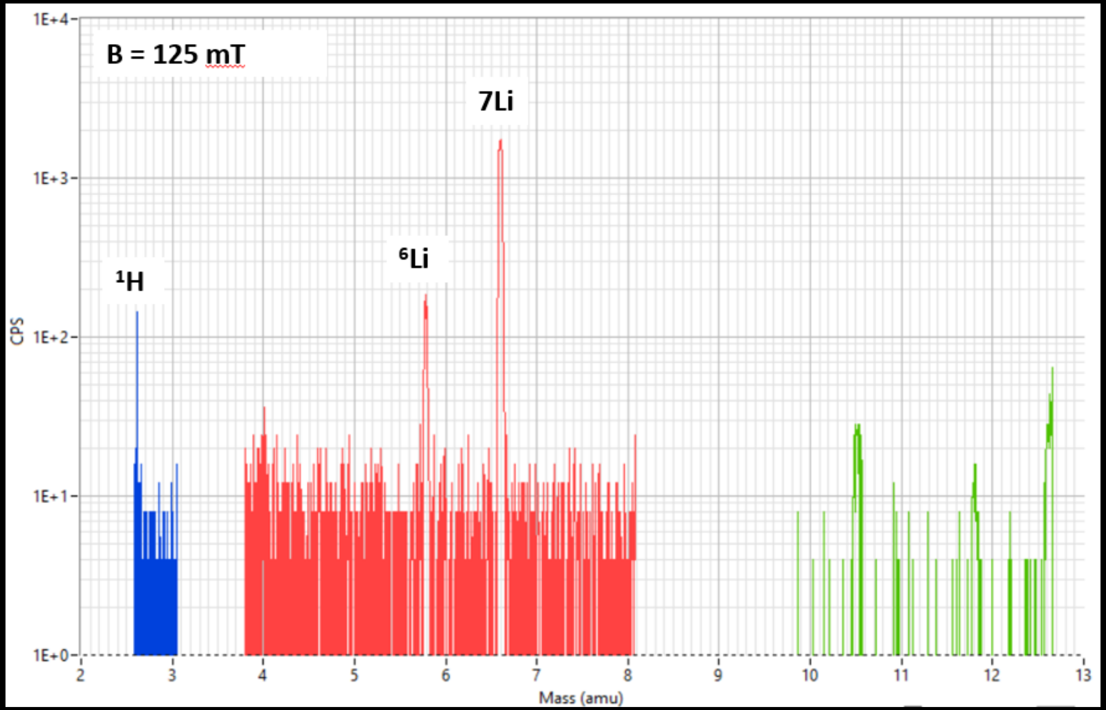



# SIMS:ZERO readily sees low-Z elements

*TiO2 anatase nanoparticles on Si wafer*




*LiTiO particles on InP wafer*



# Application Example:
## SIMS:ZERO as EDX Alternative

EDX elemental analysis is capable of few-nm resolution and can image the majority of elements well, but sensitivity is limited to a few tenths of a percent and sample prep is time consuming

Historically, SIMS has offered excellent (ppm) sensitivity but limited lateral resolution

Now, SIMS:ZERO enables creation of elemental maps with both few-nm resolution and excellent sensitivity without lamella preparation

These capabilities also make possible the creation of 3D elemental maps

**Existing** Workflow - Thin Sample EDX

Load Sample in FIB/SEM → Locate ROI → Prepare Lamella → Transfer to TEM with EDX → Locate ROI → EDX Analysis

Only one shot : analysis limited to a single depth

**Optimized** Workflow - SIMS:ZERO

Load Sample in SIMS:ZERO → Locate ROI → Prepare Cross Section → SIMS Analysis → SIMS Analysis on Deeper Plane → SIMS Analysis on Deeper Plane → SIMS Analysis on Deeper Plane

# SIMS:ZERO Impacts

## Features

- $Cs^+$ beam with nanometer resolution
- Full-featured FIB system
- Highest-Resolution SIMS
- Parallel readout of all masses (future upgrade)

## Benefits

- Obtain EDX-like spectra… without lamella Prep
- Gather SIMS data 100x faster
- Machine with higher precision
- Endpoint using mass spectra
- SIMS process control during nanofabrication