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Sandia National Laboratories

Low-Energy Ion Implantation - Range Comparisons between Theory and Experiment

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U.S. DEPARTMENT OF ENERGY NNSA

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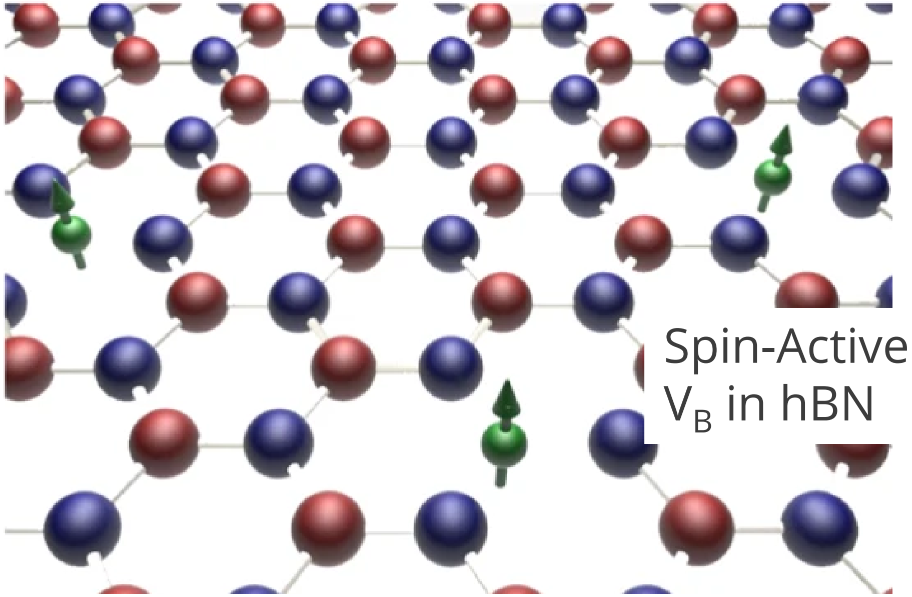
Motivation for 2D Material Emitters

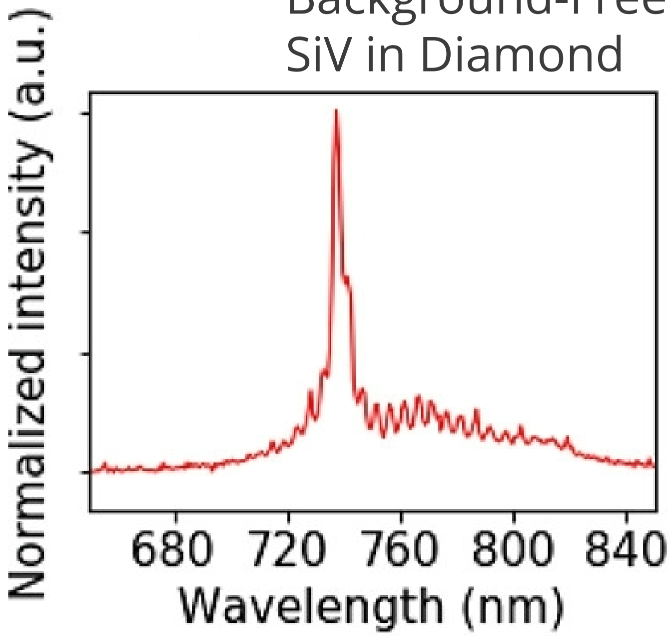
- 2D materials are attractive material class for CMOS-integrable quantum optics
- Deterministic placement of **impurity**-type emitters is challenging
  - Stopping in single atomic layer
  - Minimize damage to surrounding lattice
  - Introduce non-native atom



Spin-Active Defect V_B in hBN

A. Gottscholl et al., Nat. Mater., 19, 540 (2020)

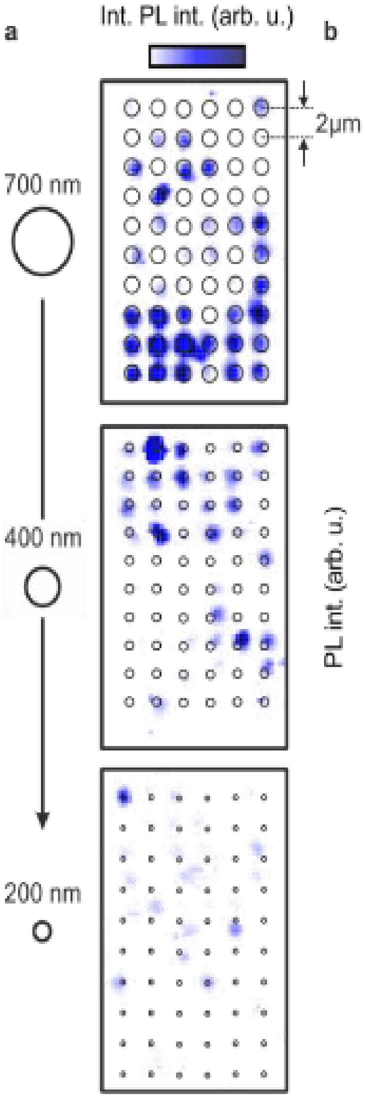
Background-Free Spin-Active SiV in Diamond



M. Titze et al., Nano Lett. (2022)

How to make Defect Emitters in 2D Materials

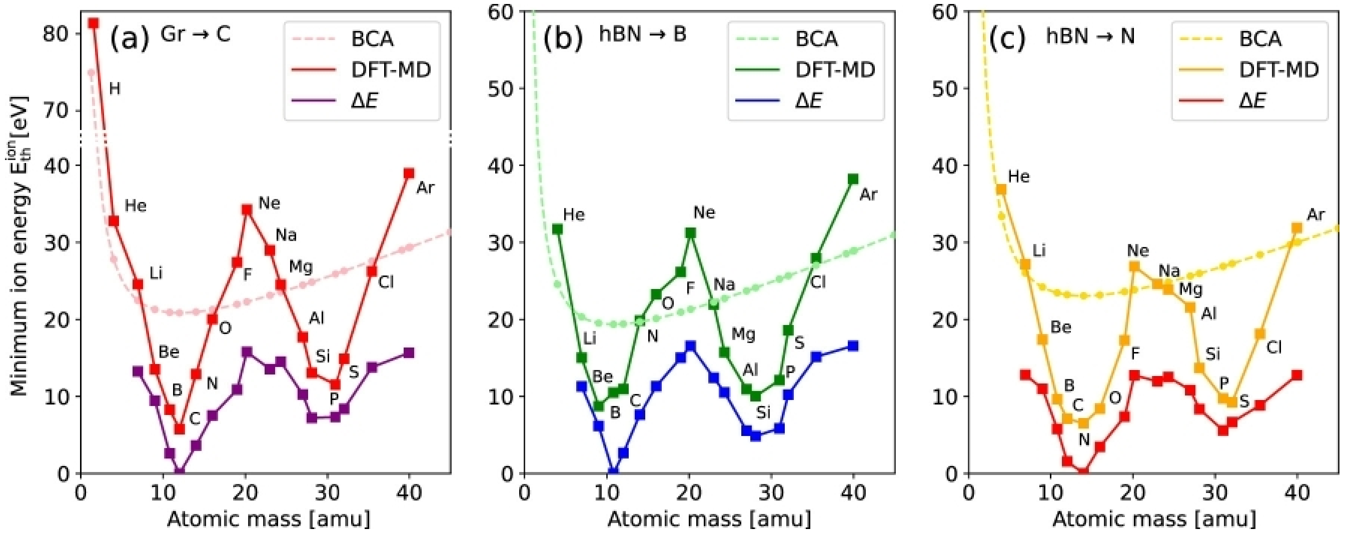
Vacancy Defects



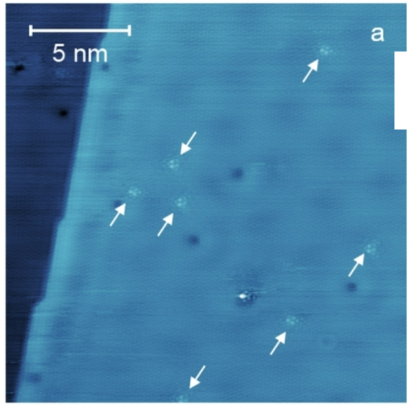
J. Klein et al., ACS Photonics, 8, 2, 669 (2021)

He Ion Microscope
35 keV He @ 5x10^{12} ions/cm^2

Impurity Defects (Background Free Emitters)



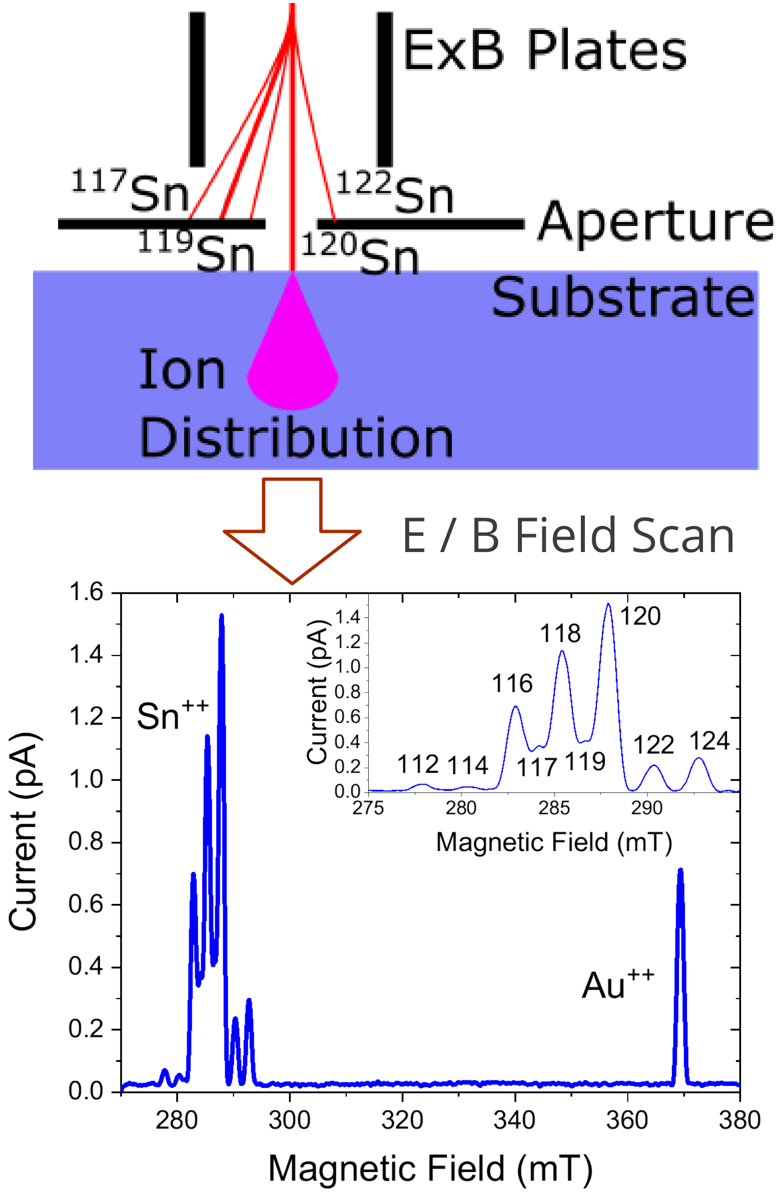
S. Kretschmer et al., J. Phys. Chem. Lett., 13, 2, 514 (2022)



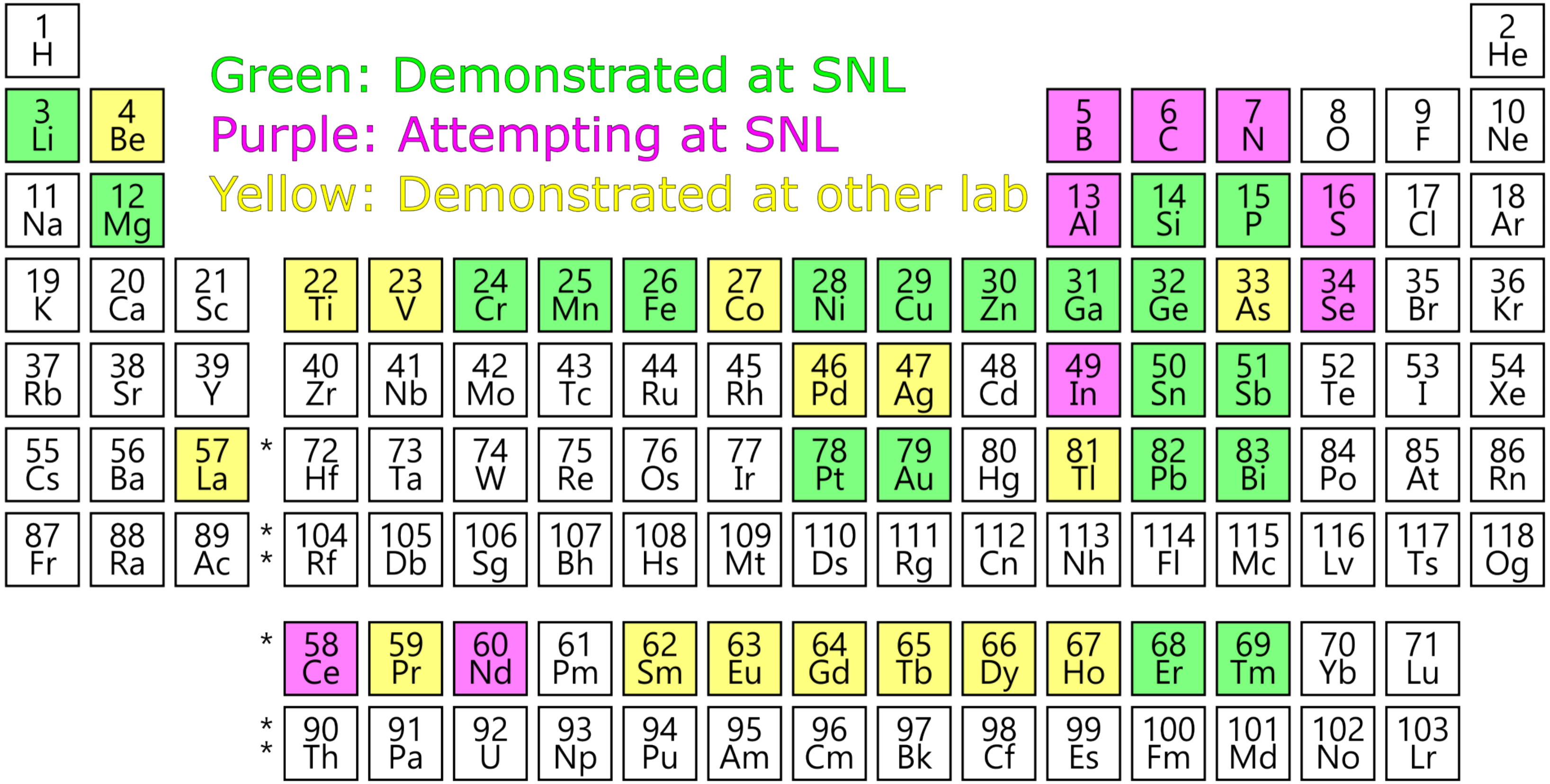
40 eV Mn in Graphene

P. C. Lin et al., ACS Nano, 15, 3, 5449 (2021)

Impurity Implantation using Liquid Metal Alloy Ion Sources

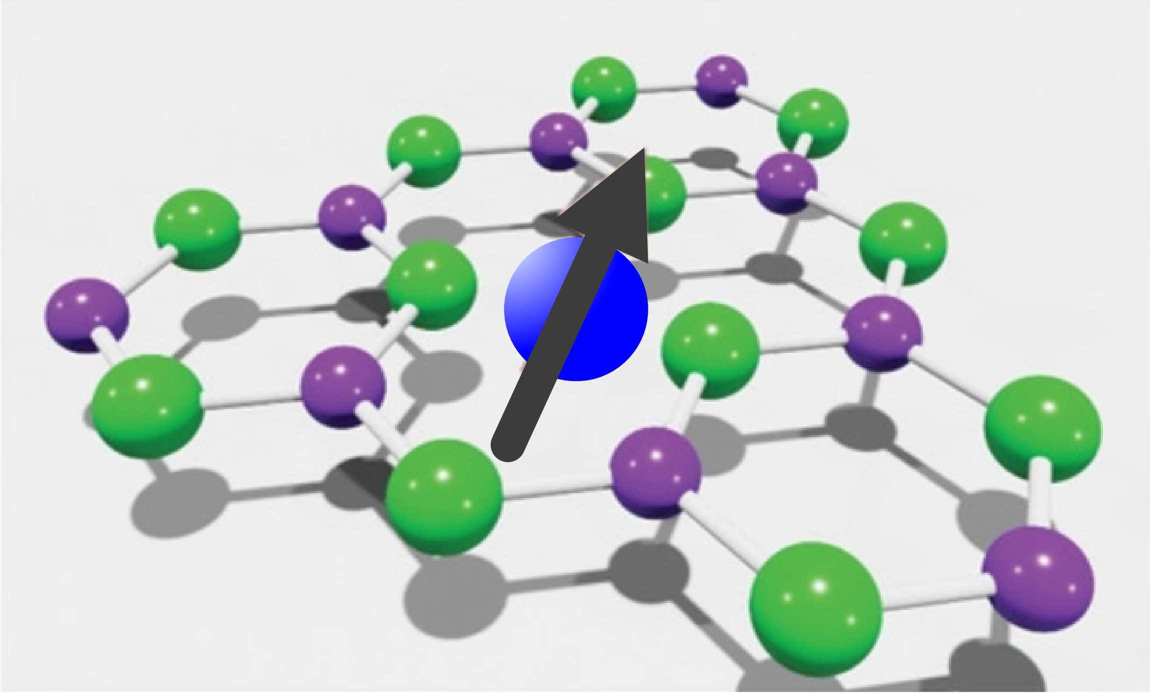


Added 8 new elements over past 3 years



Adapted from L. Bischoff et al., Appl. Phys. Rev., 3 (2016)

Challenges with FIB-Based Ultra-Low Energy Ion Implantation

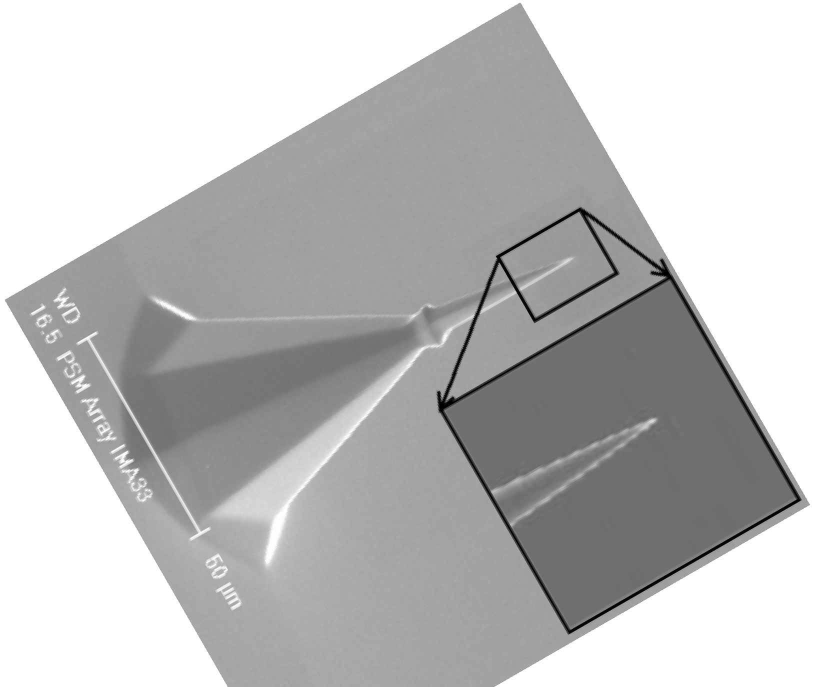


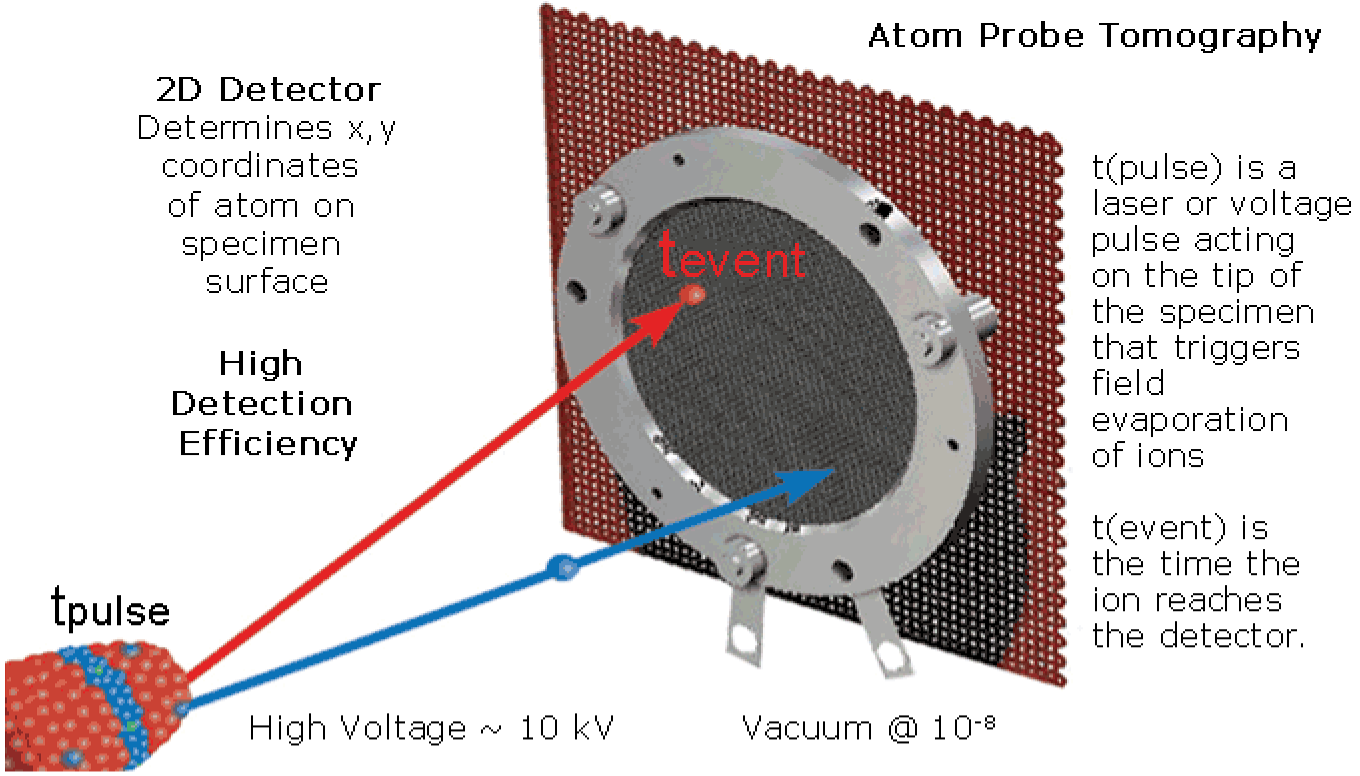
Adapted from N. Mendelson et al., Adv. Mater., 34, 2106046 (2022)

- Spot Size increase due to chromatic aberrations → targeting 100-300 nm spatial resolution
- Range Prediction vs Experiment → SRIM overestimates range by 30% at 10 keV
- Need to reduce the implantation Energy to stop in atomic monolayer → This Talk!

Atom-Probe Tomography as a probe for ultra-shallow implantation

- Field emission from a sharp Si tip
- TOF mass spectroscopy by applying short voltage pulses
- Atomic layer resolution from calibration to Si lattice planes

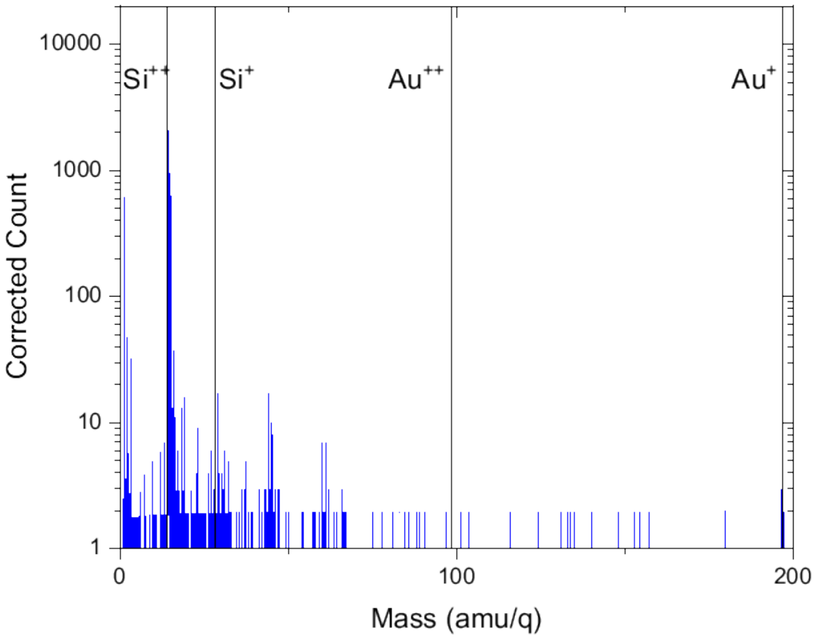


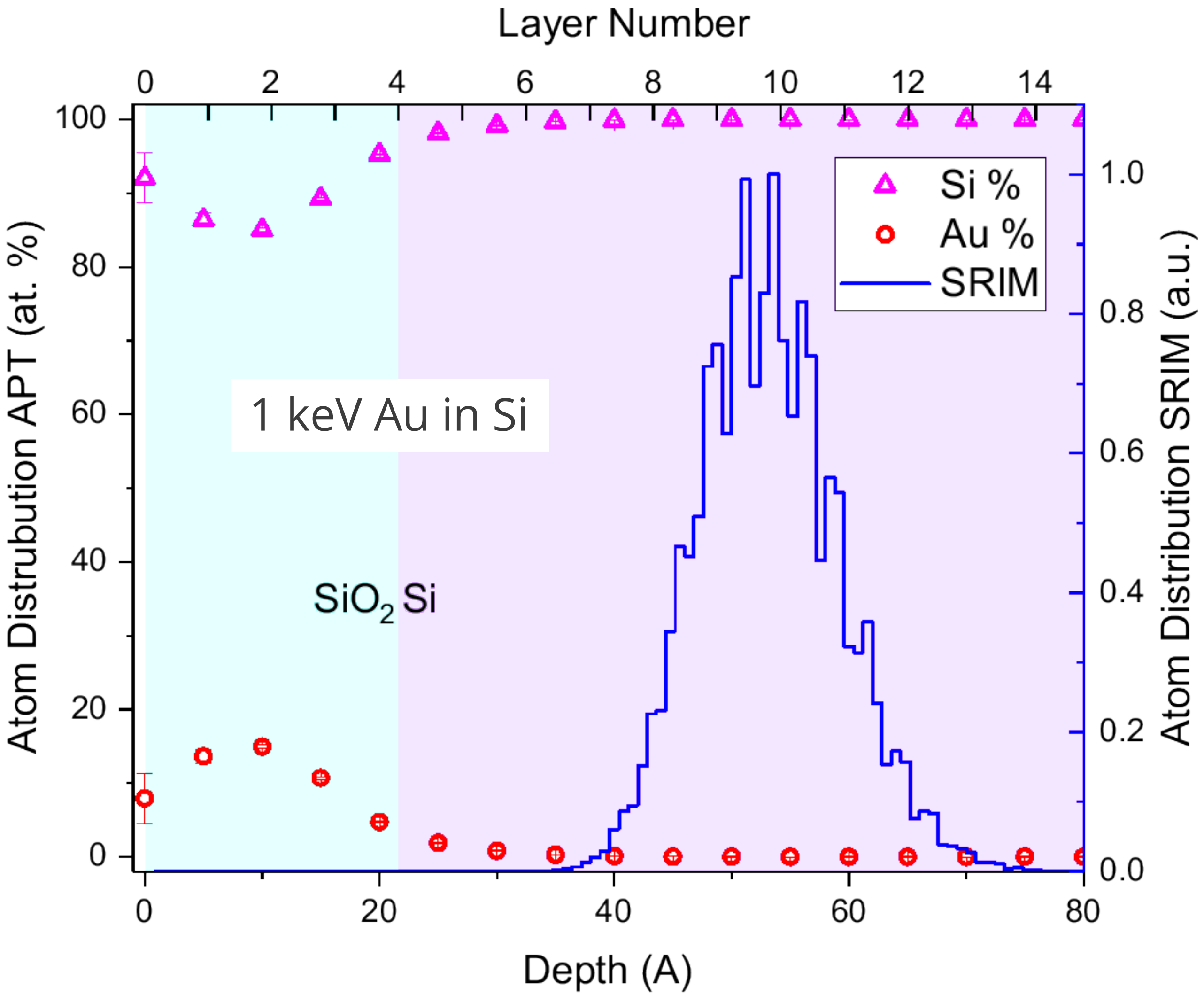


https://www.cameca.com/products/apt/technique

Atom-Probe Tomography on Low Energy Implanted Sample

- SRIM overestimates range by **6X**
  - SRIM is not made for such low energy
- Indicates that 100s of eV will be sufficient to target single atomic layers



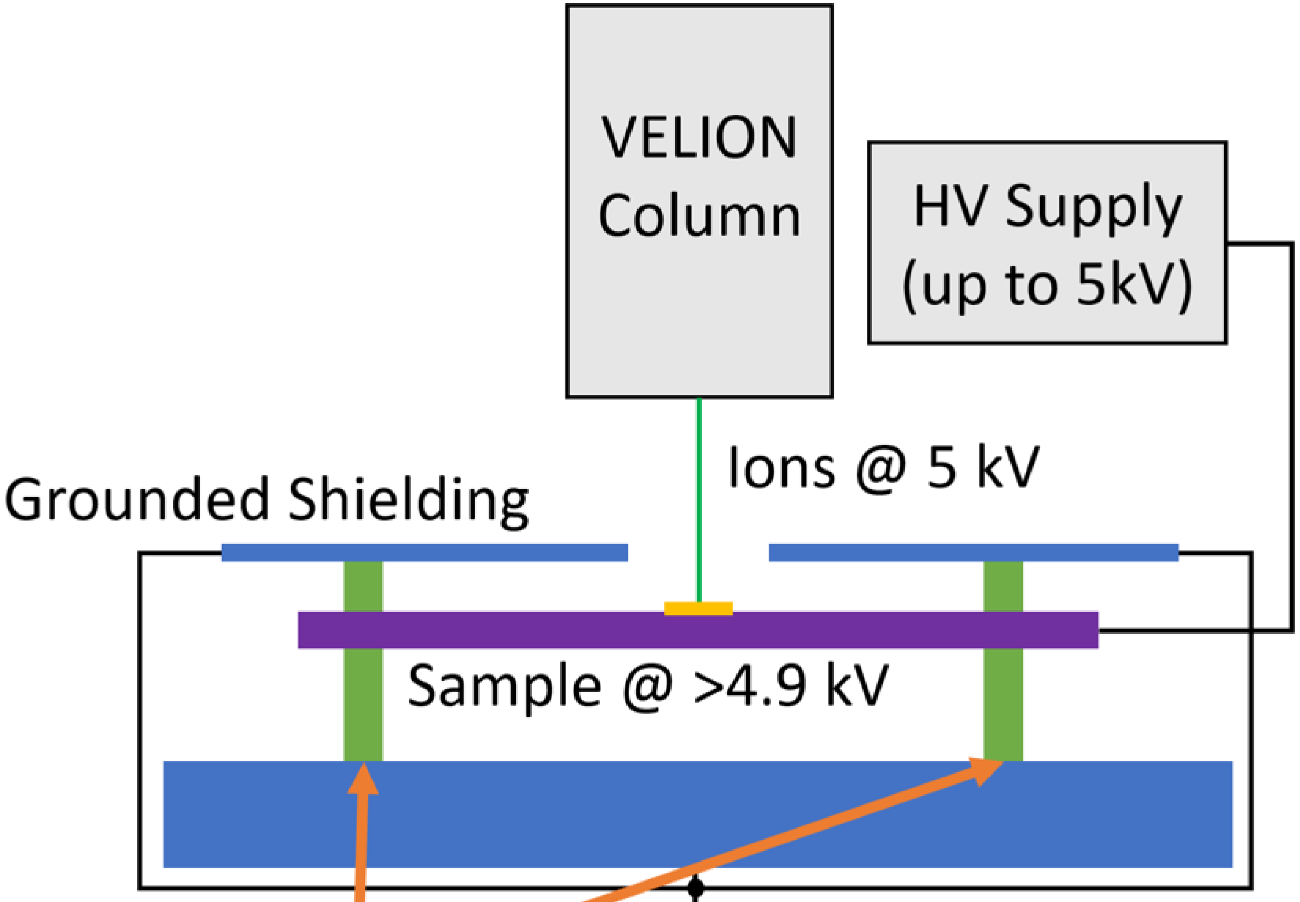


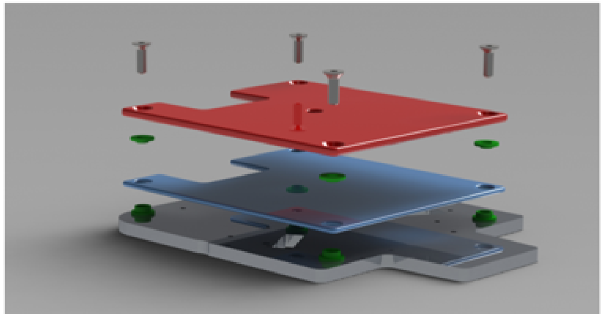
How to further reduce the implantation energy?

- 1 keV Au stops within 4 atomic layers of SiO_2
- To target atomic layers of 2D materials
  - Stopping in a single layer
  - Lower mass ions interesting for their optical properties

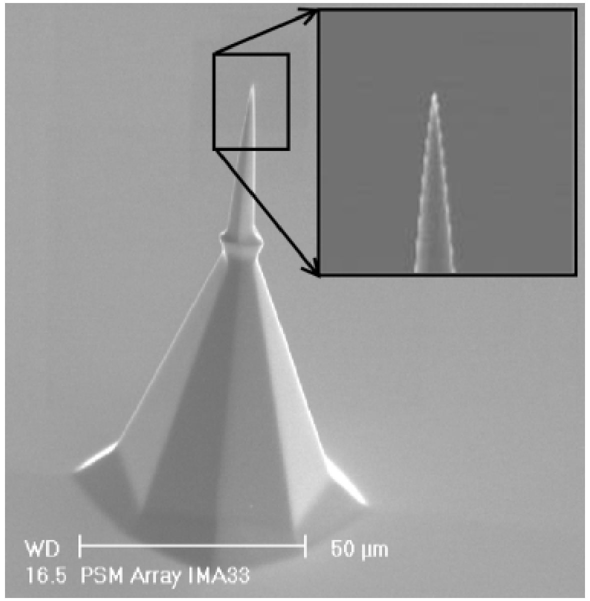
→ Need even lower energy

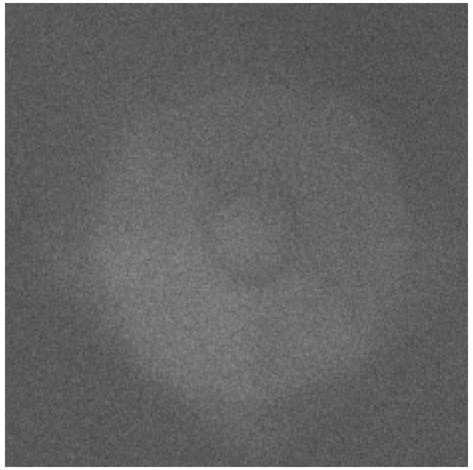
Biased sample holder to decelerate ions



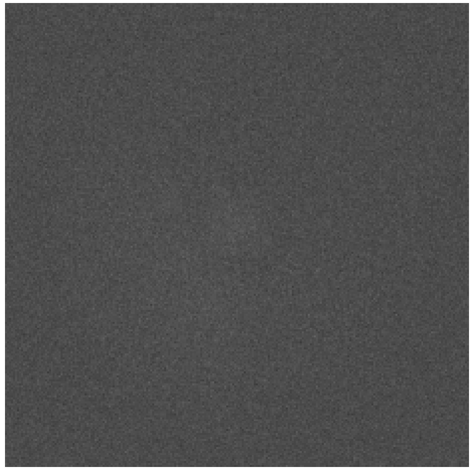


Stimulated Emission Observed at Low Energy

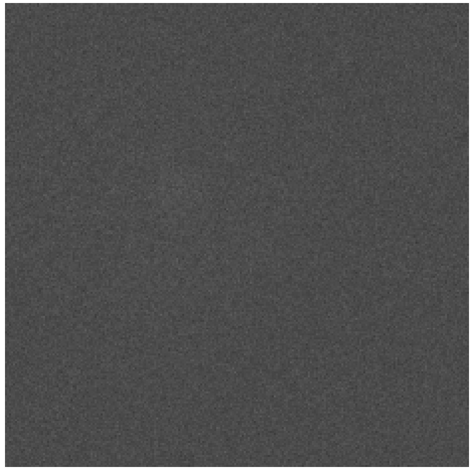




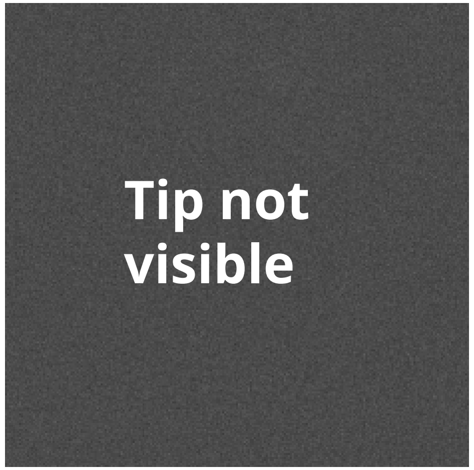
5 kV Au⁺ HVPS Off



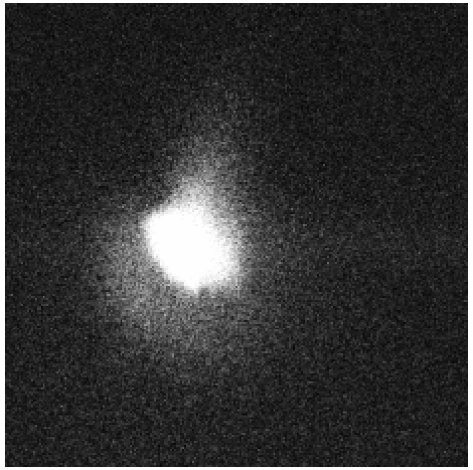
5 kV Au⁺ HVPS 1kV



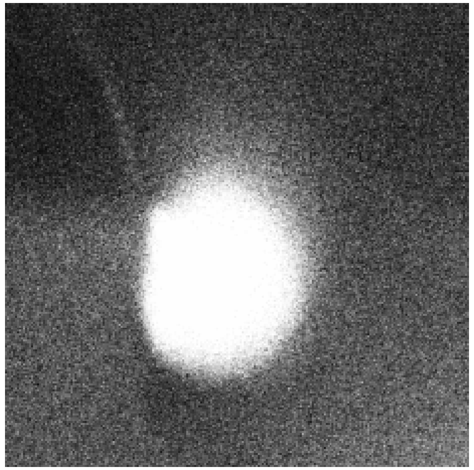
5 kV Au⁺ HVPS 2kV



5 kV Au⁺ HVPS 4 kV



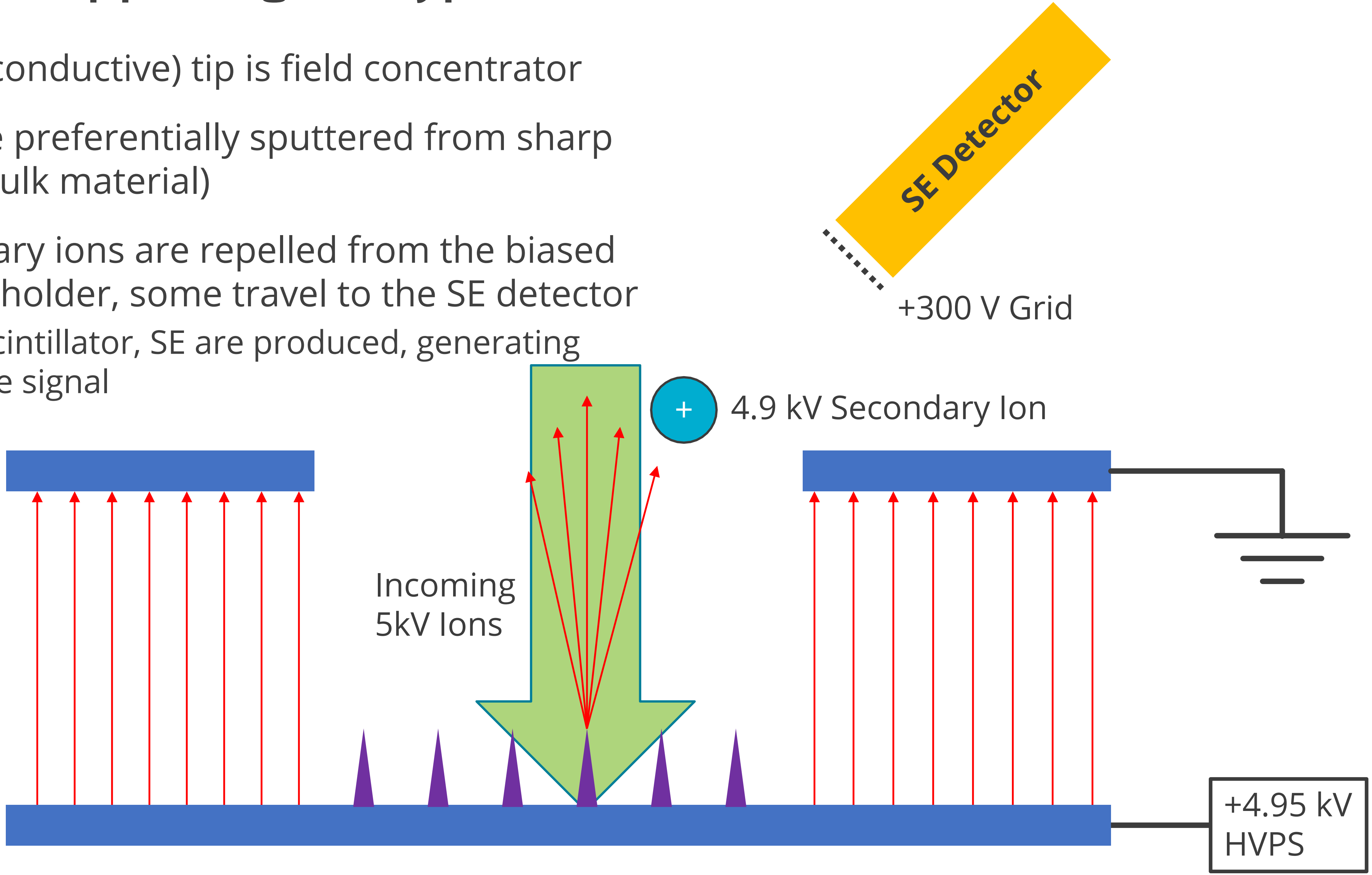
5 kV Au⁺ HVPS 4.9 kV



5 kV Au⁺ HVPS 4.95kV

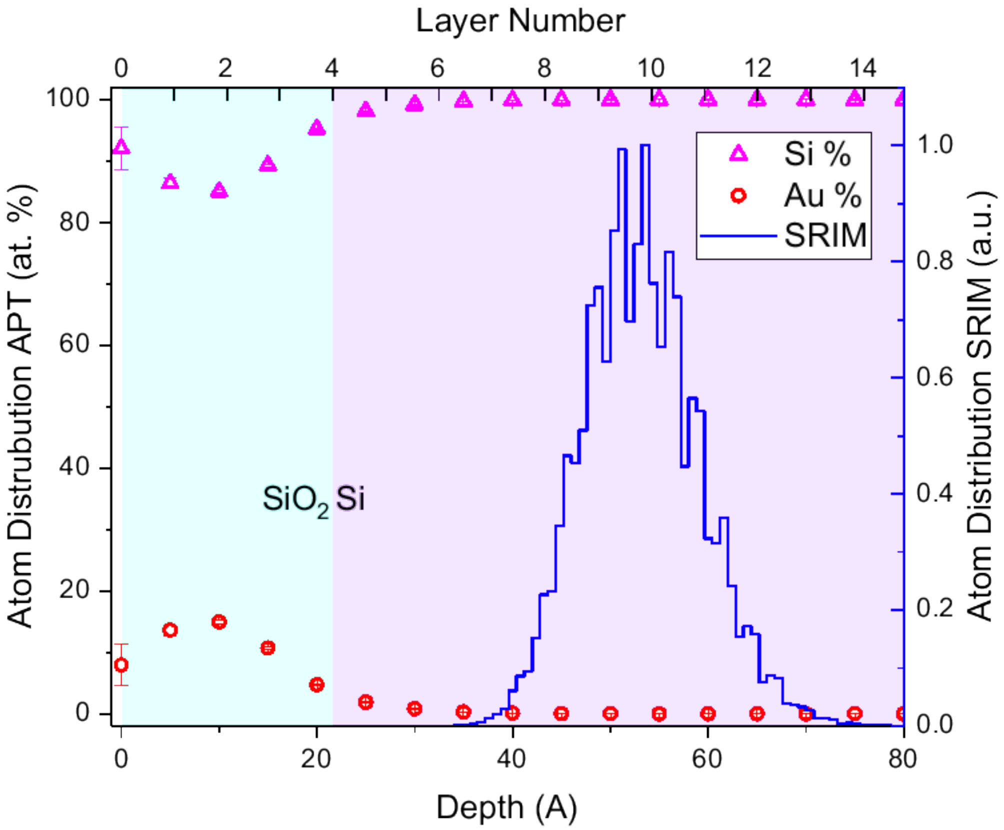
What is Happening? – Hypothesis of Emission Mechanism

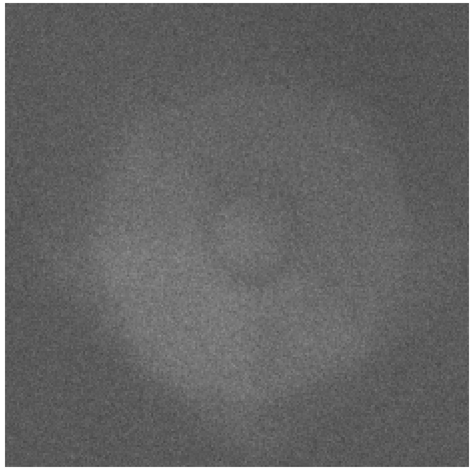
- Sharp (conductive) tip is field concentrator
- Ions are preferentially sputtered from sharp tip (vs bulk material)
- Secondary ions are repelled from the biased sample holder, some travel to the SE detector
  - In scintillator, SE are produced, generating large signal



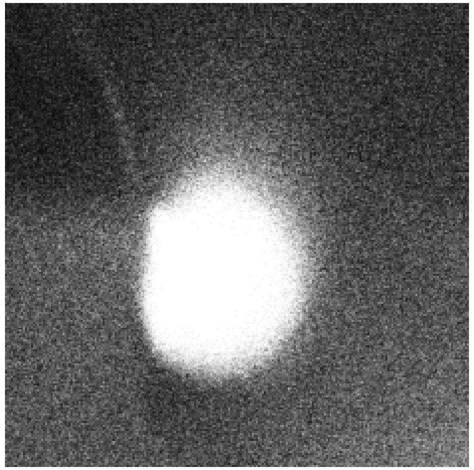
Conclusion

- Focused ion beam implantation down to 1 keV has been demonstrated
  - SRIM simulation does not work at low energies, need different modeling code
- Lower energy implantation has been done, sample is awaiting APT measurement
- At >4.8 kV sample bias stimulated emission is observed





5 kV Au^+ HVPS Off

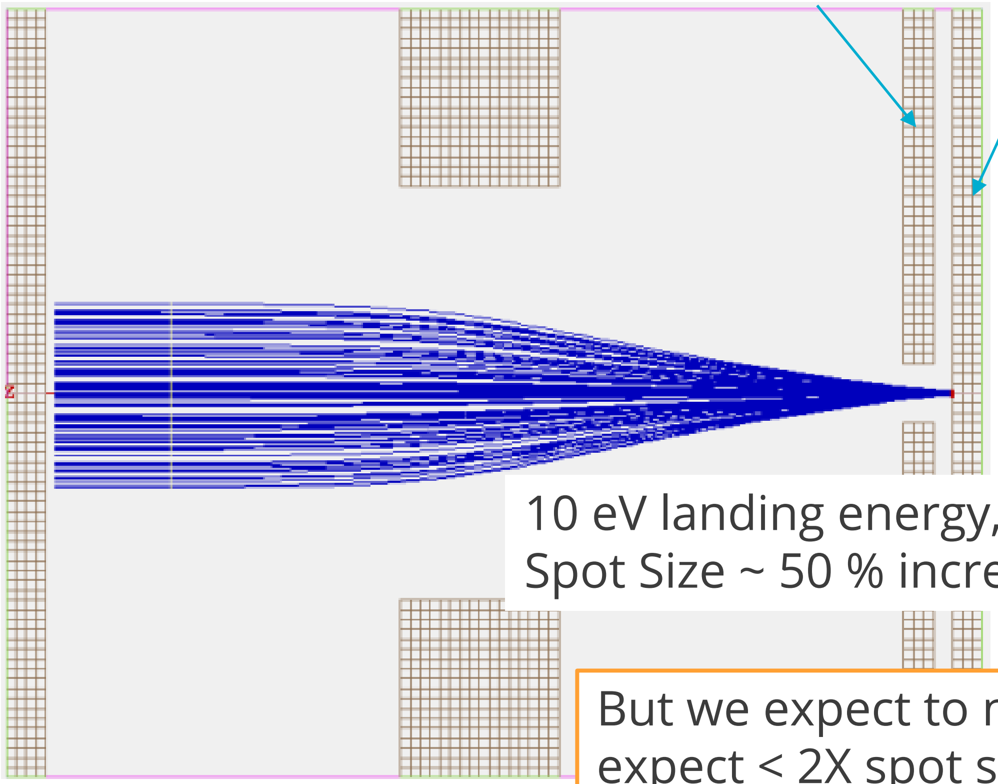


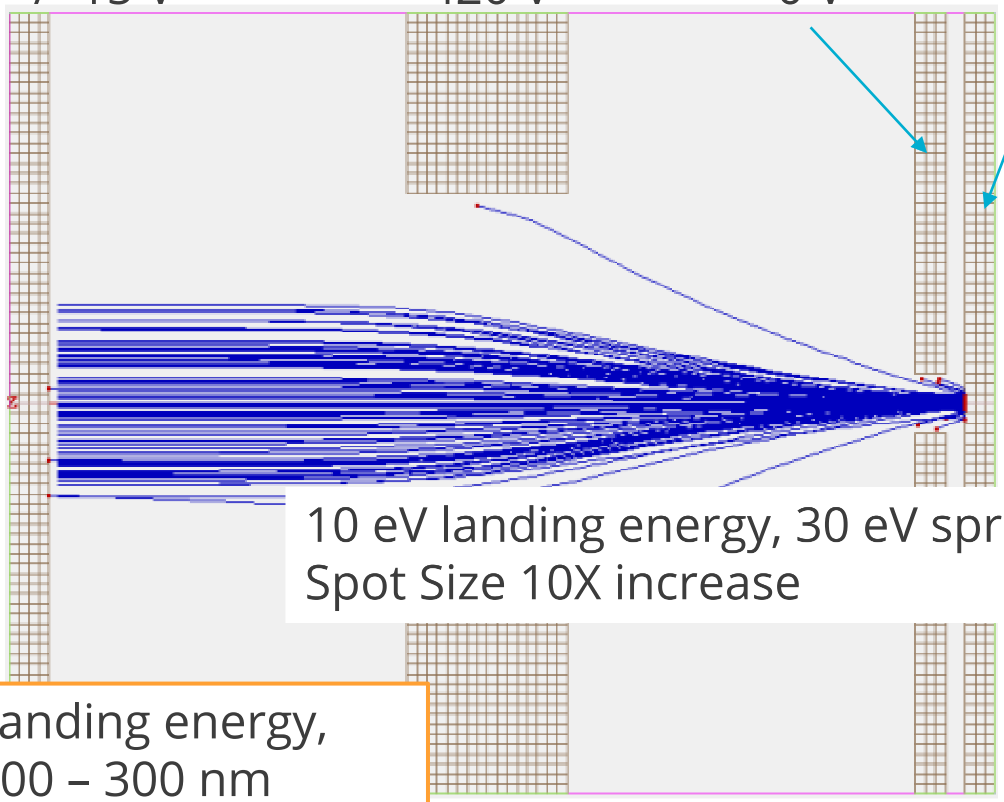
5 kV Au^+ HVPS 4.95kV

M. Titze et al., JVST A 39, 063222 (2021)

Ion Source Energy Spread Disallows Focusing

- SIMION Simulations show the ion deceleration leads to increased spot size
- When landing energy ~ energy spread ions get reflected + spot size increases

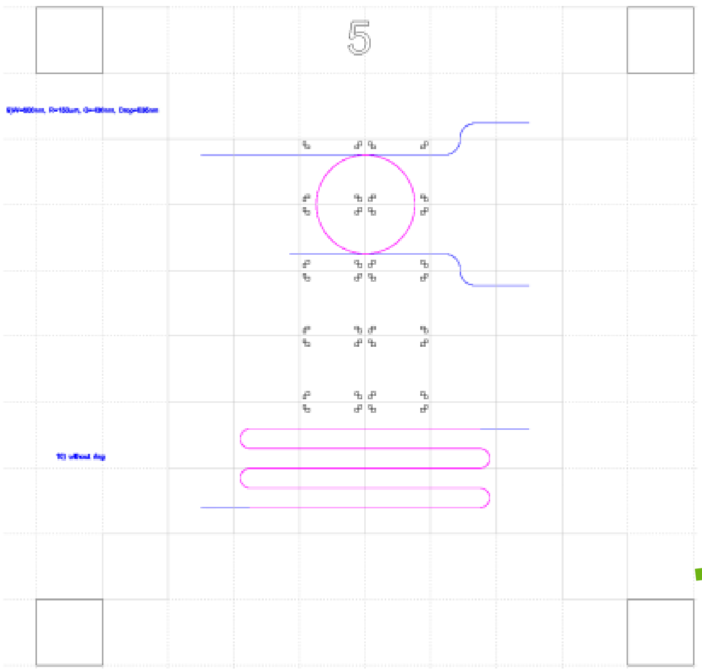




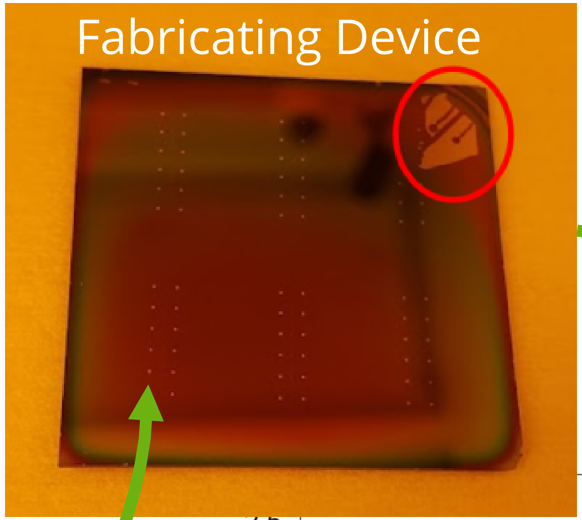
But we expect to need ~**100** eV landing energy, expect < 2X spot size increase, 100 – 300 nm

Interaction with CINT Users – Design to Manuscript

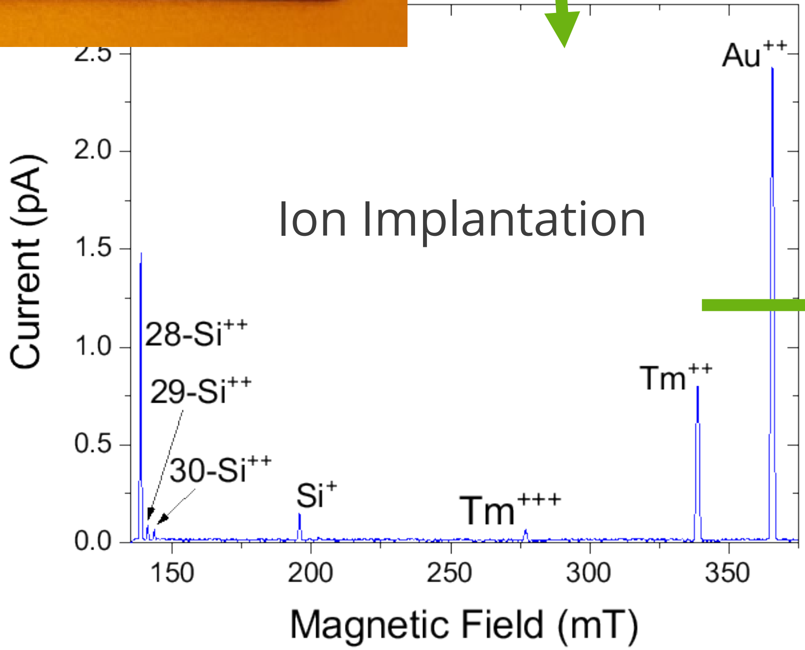
M. Hosseini @ Purdue



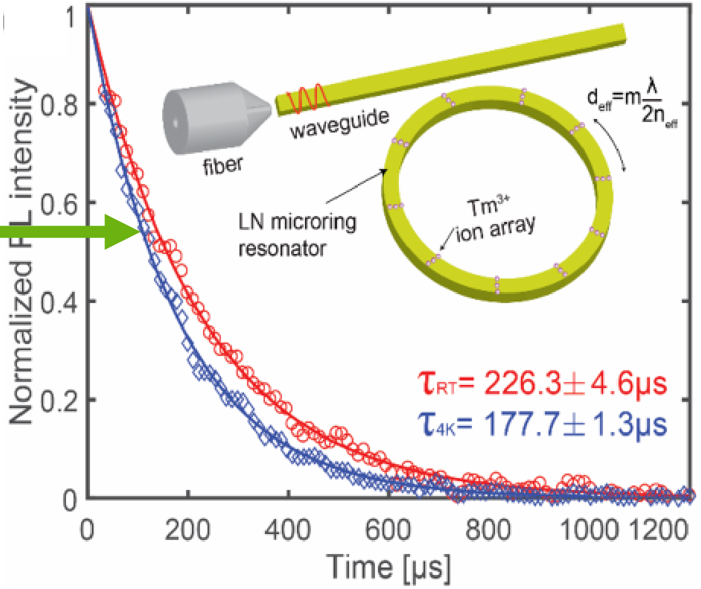
Discussion of design feasibility



Tm for $LiNbO_3$ Photonics



Post-Processing
+ Measurement



Dongmin Pak, ..., M. Titze et al. (in review)

How can YOU access these capabilities? CINT User Proposal

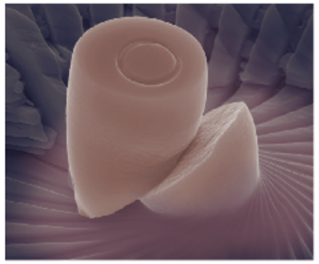
THE CENTER FOR INTEGRATED NANOTECHNOLOGIES

One Scientific Community Focused on Nanoscience Integration

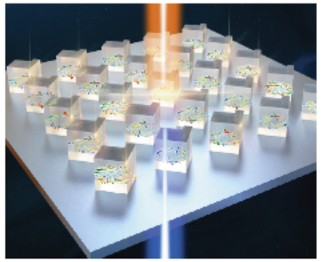
The Center for Integrated Nanotechnologies (CINT) is a Department of Energy Office of Science Nanoscale Science Research Center. CINT offers world-leading scientific expertise and specialized capabilities to create, characterize, and integrate nanostructured materials at a range of length scales, from the nano- to meso-scale. It is jointly operated by Los Alamos and Sandia national laboratories and leverages the unmatched scientific and engineering expertise of the host labs.

Science Thrusts

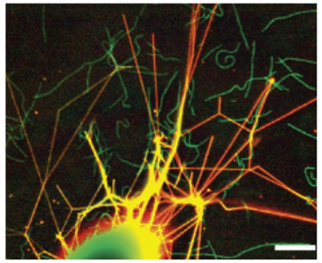
Integration is the key to exploiting the novel properties of nanoscale materials and creating new technologies. CINT's scientific staff and capabilities are organized around four interdisciplinary science thrusts which address different challenges in nanoscience integration.



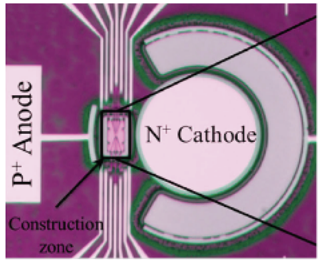
In-Situ Characterization and Nanomechanics
Developing and implementing world-leading capabilities to study the dynamic response of materials and nanosystems to mechanical, electrical, or other stimuli.



Nanophotonics & Optical Nanomaterials
Synthesis, excitation, and energy transformations of optically active nanomaterials and collective or emergent electromagnetic phenomena (plasmonics, metamaterials, photonic lattices).



Soft, Biological & Composite Nanomaterials
Synthesis, assembly, and characterization of soft, biomolecular, and composite nanomaterials that display emergent functionality.



Quantum Materials Systems
Understanding and controlling quantum effects of nanoscale materials and their integration into systems spanning multiple length scales.

User Program

CINT is an Office of Science national user facility. CINT helps the international research community perform cutting-edge research in the areas of nanoscience and nanotechnology, and is available free of charge for open science. As a user facility, CINT has the structure and mission to collaborate widely across academia, industry, and within DOE labs. Access is via peer-reviewed technical proposals. Proprietary research may be conducted in accordance with Federal regulations for full-cost recovery. CINT cannot provide funding to users.

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