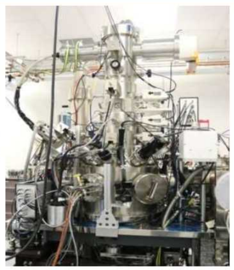
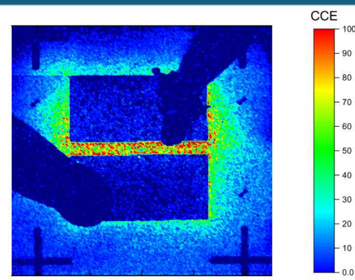
SAND2020-5405C

Sandia National Laboratories

Ion Beam Implantation for Nanofabrication and Modification





Edward Bielejec

Sandia National Laboratories, Albuquerque, NM 87185

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Sandia's Ion Beam Laboratory (IBL)

- 6 accelerators + 1 installing
- 25 end-stations
- Six focused ion beamlines with implantation (nm to μm)

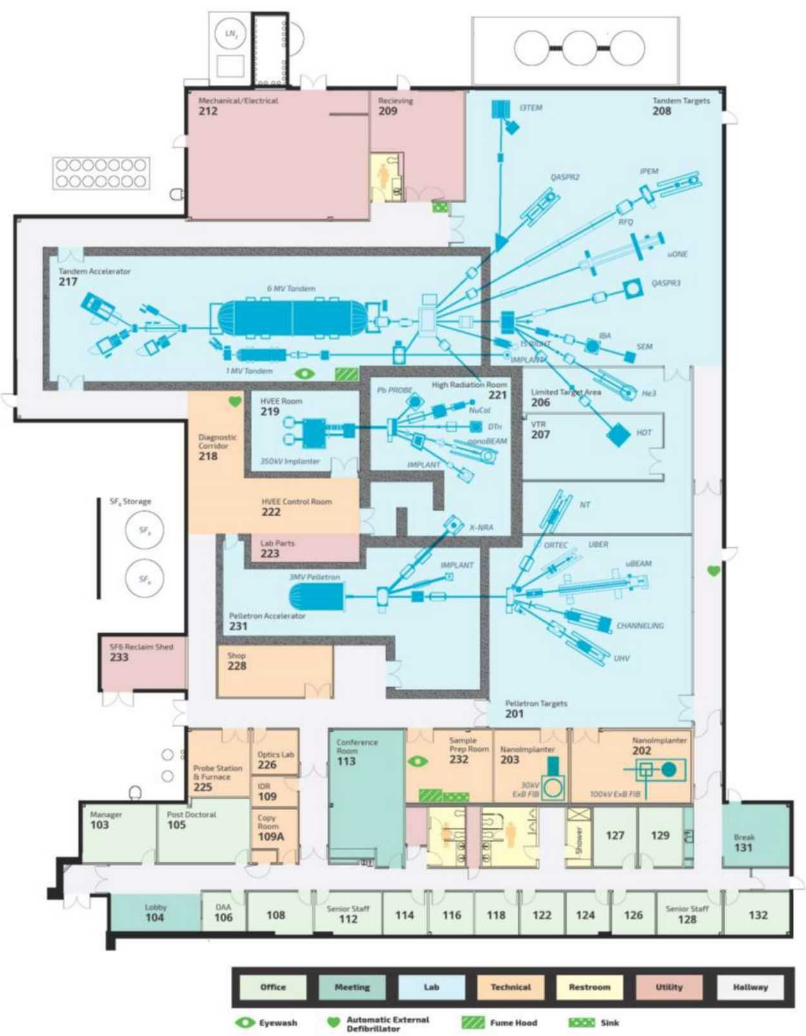
Outline

- Introduction to Sandia's Ion Beam Laboratory (IBL)
- Multi-species Focused Ion Beam
  - Sandia's nanoImplanter and Raith Velion
- Single Atom Devices and Nanofabrication
  - Case 1: Ion Beam of Seeding Memristors

    Demonstration of focused ion beam implantation (millions of ions)
  - Case 2: Defect center formation in Diamond

    Localized implantation and single ion detection (down to single ion implantation)
- Summary

building 720
ION BEAM LABORATORY



Operational

(1) 6 MV Tandem Accelerator

Average usage 5 days a week, 50 week/yr.

(2) 3 MV Pelletron Accelerator

Ion beam analysis and displacement damage

(3) 350 kV HVEE Implanter

>90% usage for mono-energetic neutrons

High energy focused micobeams 1 μm to mm's

(4) 100 kV ExB FIB nanoImplanter

High spatial resolution implantation

(5) 35 kV ExB FIB Raith Velion

Higher spatial resolution at lower energies

(6) 35 kV Zeiss HeIM

<0.5 nm beam spot, high resolution imaging

Low energy focused nanobeams <1 to 20 nm

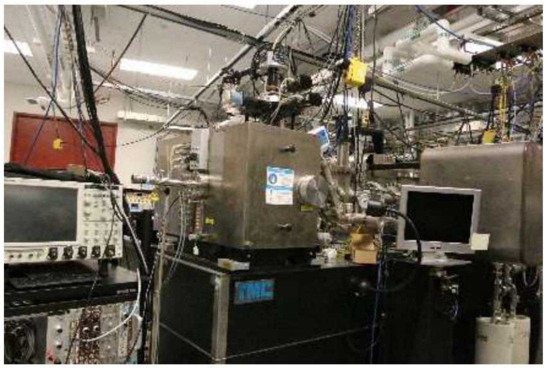
Installing

(7) 1 MV Tandem Accelerator

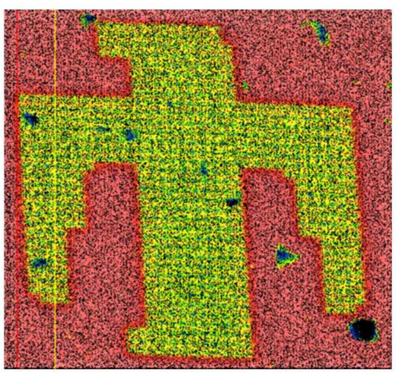
Support in-situ (I3TEM) and "replace" HVEE for ions

High Energy Microbeams ~1 μm to mm's

- 6 MV Tandem microbeam (microONE)

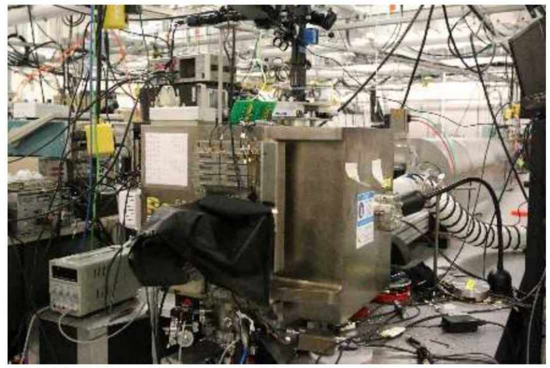


- High resolution laser stage
- Spot size <1 μm
- Energy 800 – 70 MeV
- H to Au

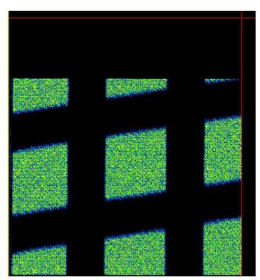


IBIC on PIN diode

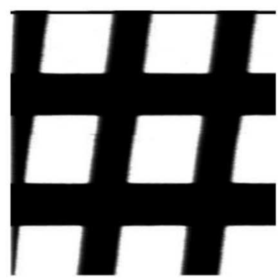
- 3 MV Pelletron microbeam (Light Ion Microbeam)



- High resolution laser stage
- Spot size <600 nm
- Energy 250 – 3 MeV
- H, He, N, Ar, Xe, …

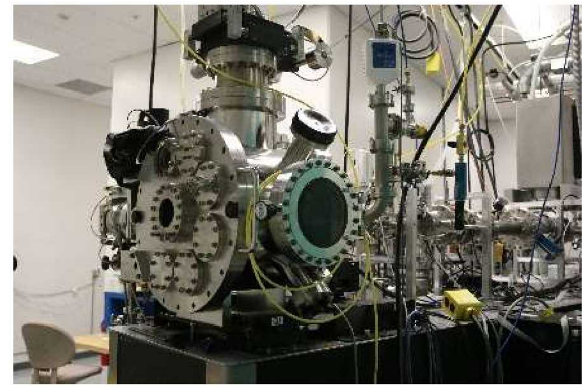


IBIC on PIN diode

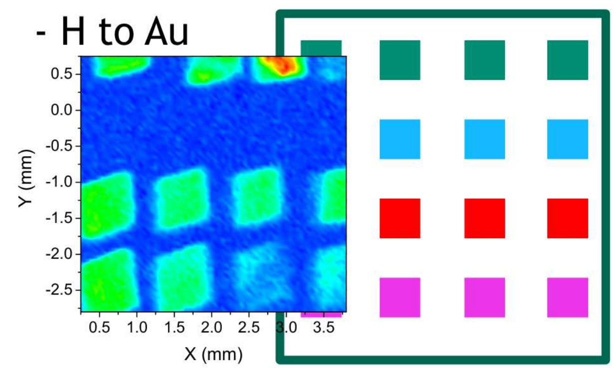


SED on PIN diode

- 350 kV HVEE microbeam (NanoBeamLine)

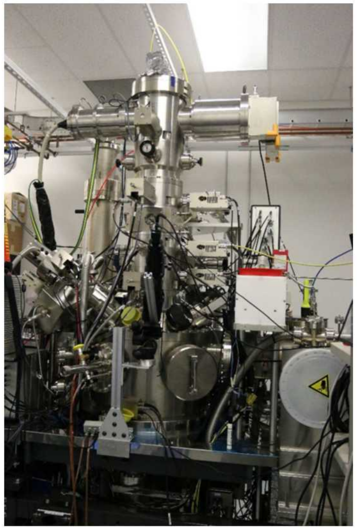


- Piezo stage
- Spot size <1 μm
- Energy 20 – 350 keV
- H to Au



Low Energy Nanobeams <1 to 20 nm

- 100 kV A&D FIB100NI (nanoImplanter)

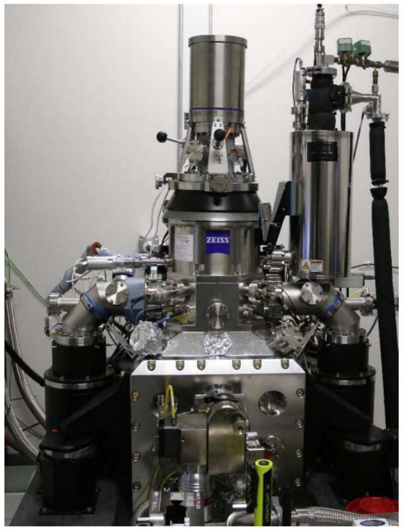


- High resolution laser stage
- Spot size <10 nm (Ga)
- Energy 10 – 200 keV
- 1/3 periodic table

- 35 kV Raith Velion (Velion)

- High resolution laser stage
- Spot size <6 nm (Ga)
- Energy 5 – 70 keV
- 1/3 periodic table

- 35 kV Zeiss Orion Plus (HeIM)



- Piezo stage
- Spot size <1 nm
- Energy 10 – 35 keV
- He

All equipped with Lithography Software for Patterning

Overview of High Resolution Implantation

Resolution

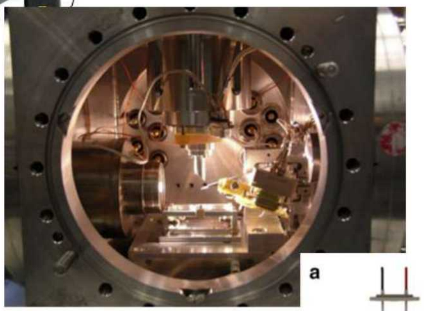
(1) Hydrogen Lithography

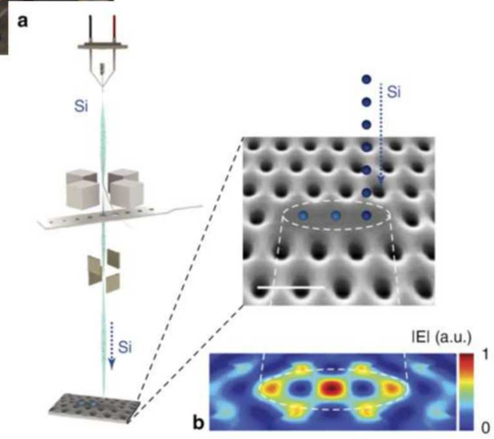
(2) Probe Based Implantation

(3) Focused Ion Beam Implantation

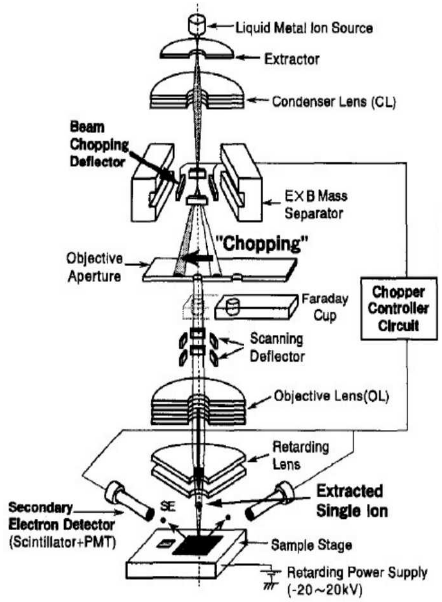
(4) Masked Implantation

Speed

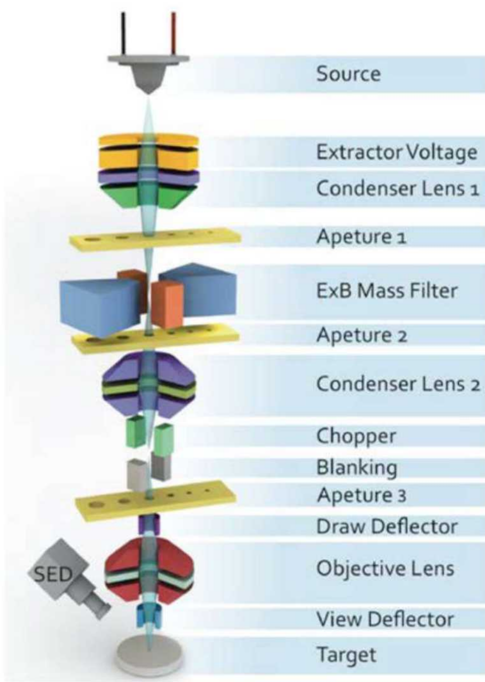




Focused Ion Beam Implantation



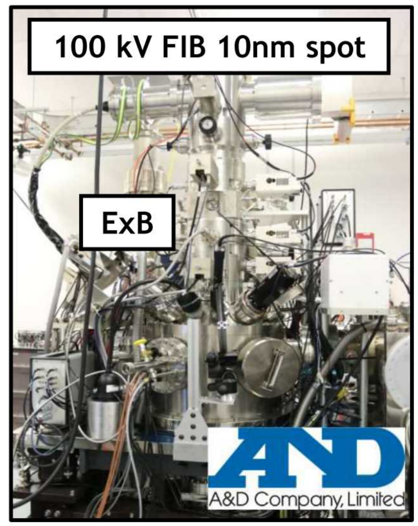
M. Hori, *et al.*, Applied Physics Express **4**, 046501 (2011)



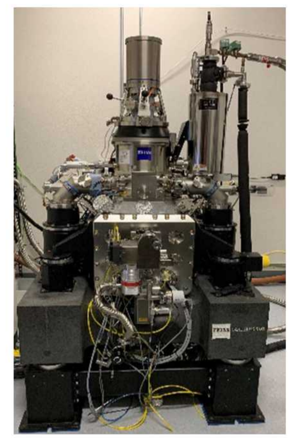
J. Pacheco, *et al.*, Review of Scientific Instruments **88**, 123301 (2017)

Like a standard FIB + ExB Filter + LMAIS

SNL is developing three machines for nano-scale focused ion beam implantation and modification



A&D FIB100NI



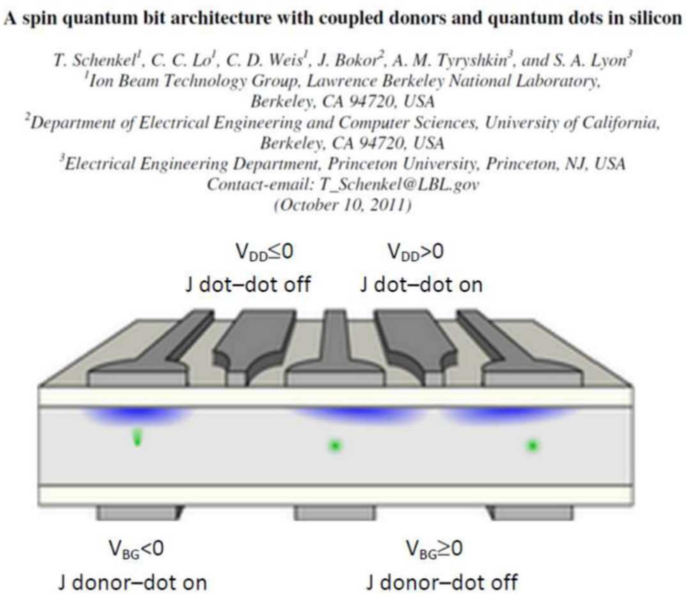
Zeiss Helium Ion Microscope

Installed Aug'19

Raith Velion

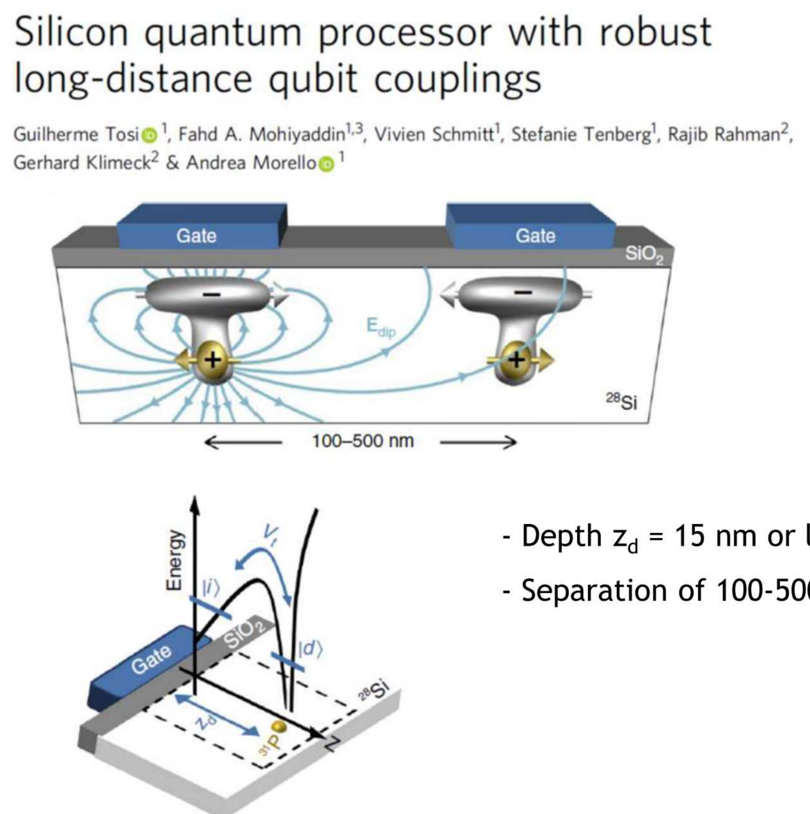
Installed Jan-Feb'20

Example of Needed Resolution – Si Qubit



T. Schenkel et al., US 8,816,325 B2 (2014)

- Depth ~20-50 nm
- Donor separation ~100 nm



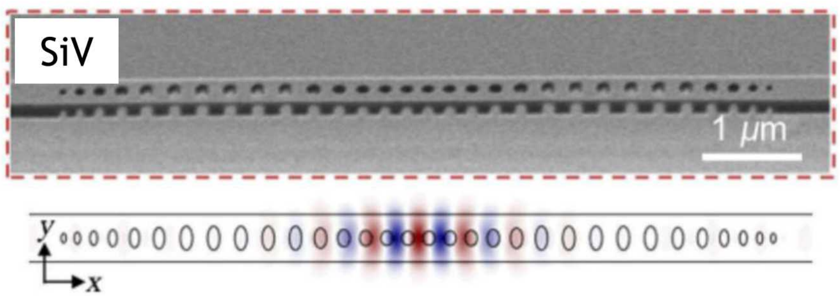
- Depth z_d = 15 nm or larger
- Separation of 100-500 nm

G. Tosi et al., Nat. Comm. ***8****, 450 (2017)*

Lateral Resolution – OK, but Depth Resolution requires low energies!

Example of Needed Resolution - Nanophotonics

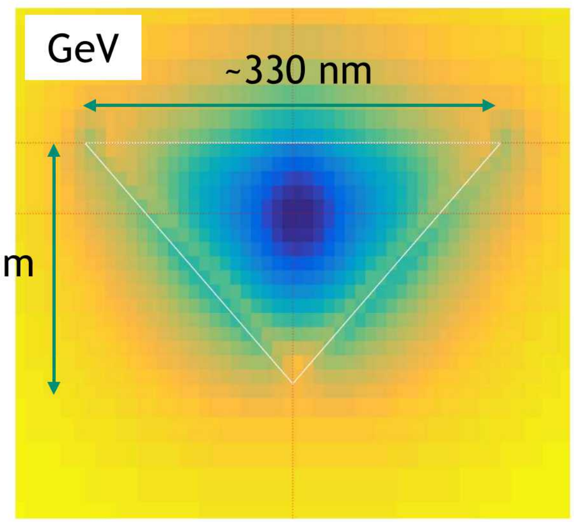
Coupling Diamond defect center to cavity



M. J. Burek et al., Phys. Rev. Applied ***8****, 024026 (2017)*

- Design the cavity around ion straggle
- Typically linear fall off in coupling strength

Cross-sectional energy profile of cavity mode

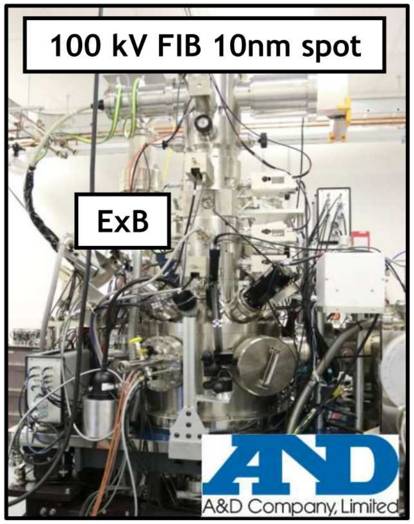


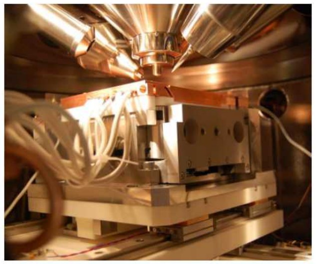
Center of mode is ~ 55 nm below the surface of the waveguide

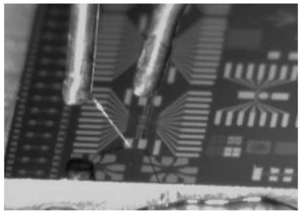
M. Bhasker et al.,

Lateral Resolution – OK, Depth Resolution – OK!

SNL nanoImplanter (nI) and Velion







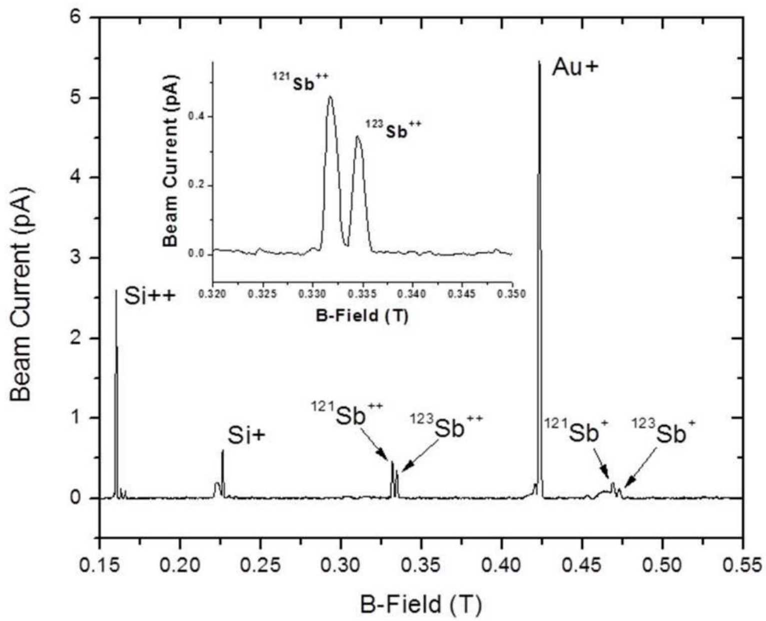
- Focused ion beam system (FIB)
  → nm beam spot size on target
- ExB Filter (Wien Filter)
  → Multiple ion species
  e.g., Li, Si, P, Sb, etc… (separating out ^{28}Si, ^{29}Si, etc…)
- Fast blanking and chopping
  → Single ion implantation
- Direct-write lithography
  → nm targeting accuracy

RAITH NANOFABRICATION

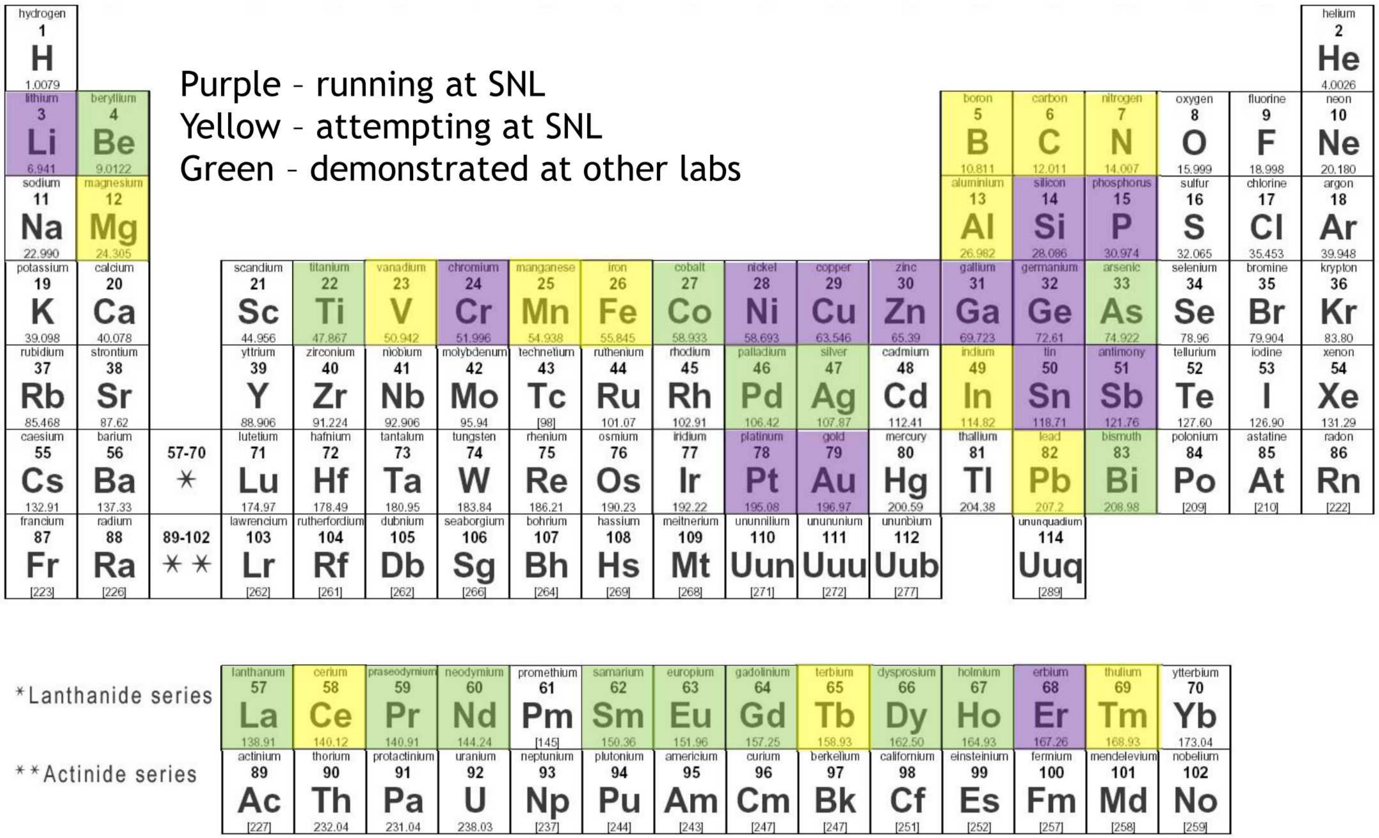
- Low temperature stage
- In-situ electrical probes

kleindiek nanotechnik

Sb Source: Mass Spectrum



SNL nanoImplanter (nI) and Velion - Sources



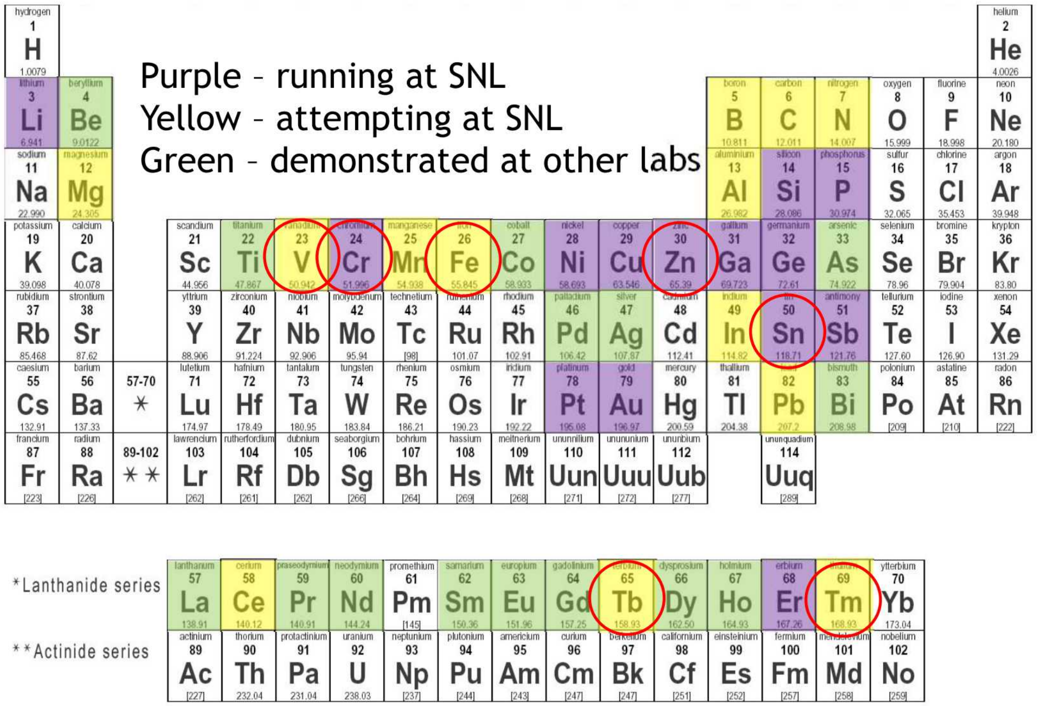
L. Bischoff, *et al*., Applied Physics Reviews **3**, 021101 (2016)

After A. Weick University of Bochum

Wide Variety of Ion Species Available

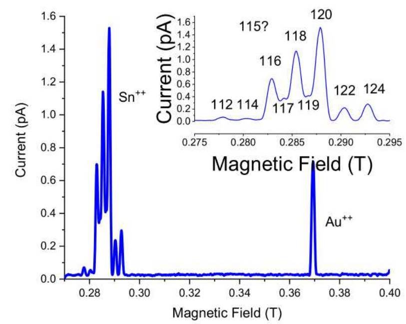
New Sources – V, Cr, Fe, Zn, Sn, Tb, Tm (easy-ish)

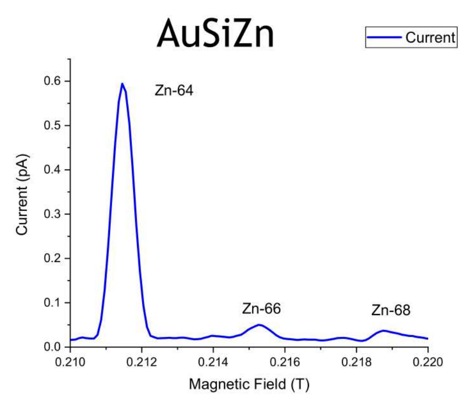
Purple – running at SNL
Yellow – attempting at SNL
Green – demonstrated at other labs

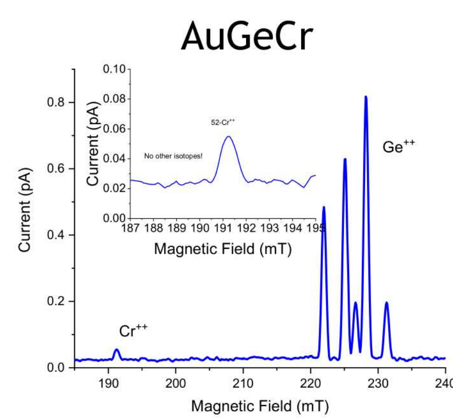


- Based on AuSiX or AuGeX alloys
- Easy to wet the tip and easy to run

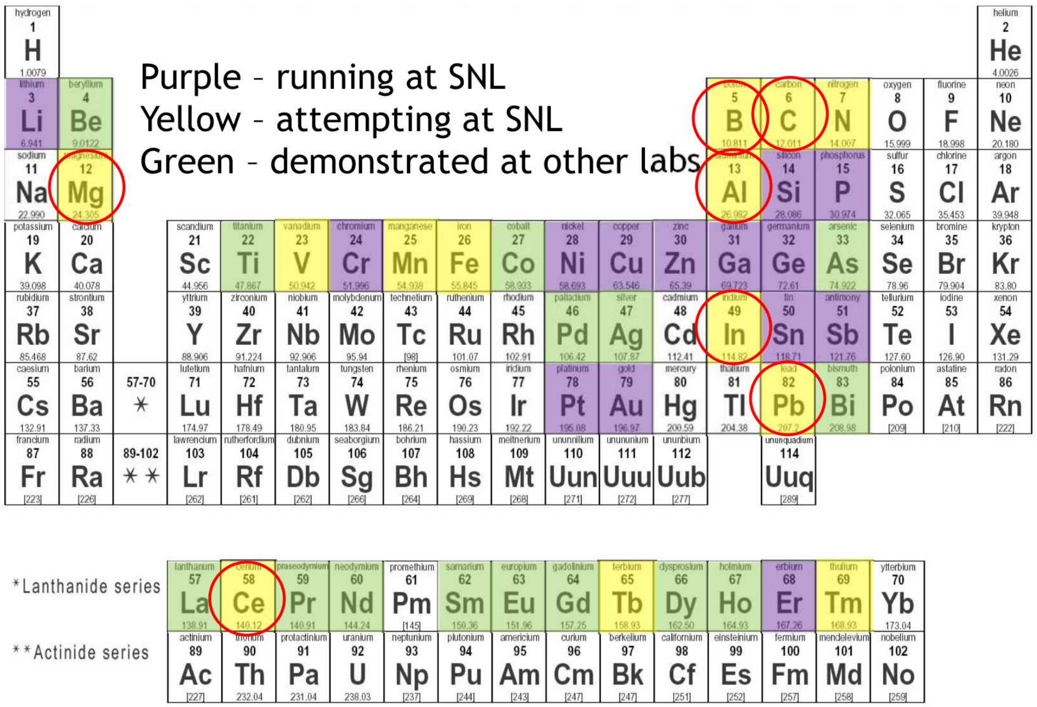
AuSn





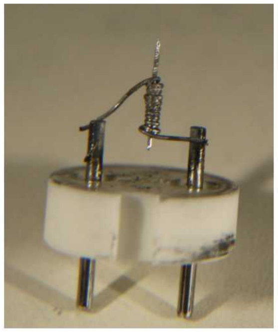


New Sources – B, C, Al, Ce, Mg, In, Pb (Hard)

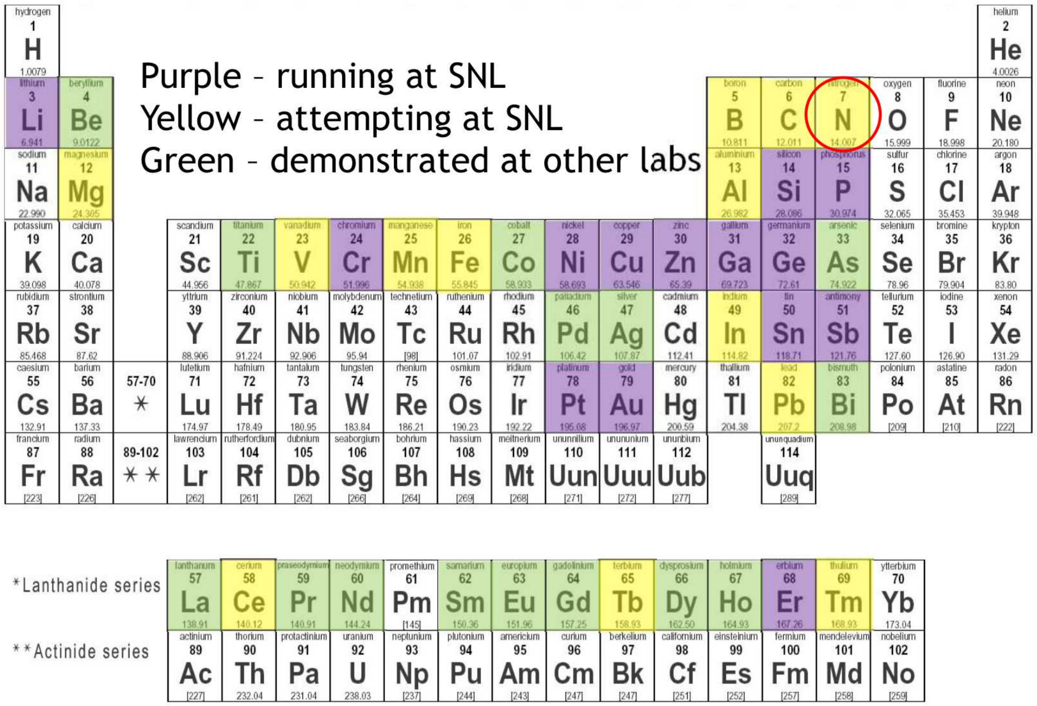


- B
  - → Hard to load into the alloy BNiPd
- C, Al, Ce
  - → AlCeC alloy oxides while running, killing beam
- Mg
  - → GaMg alloy oxides in the boat
- Pb
  - → PbSn alloys with W tip, working on new materials

SNL SnPb tip
on Kovar wire

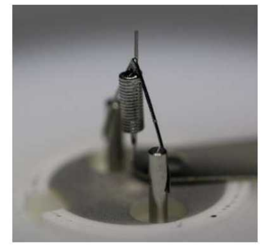


New Sources – N (How to do???)



(1) Liquid metal alloys with implanted N

i.e., AuSn+N, In+N

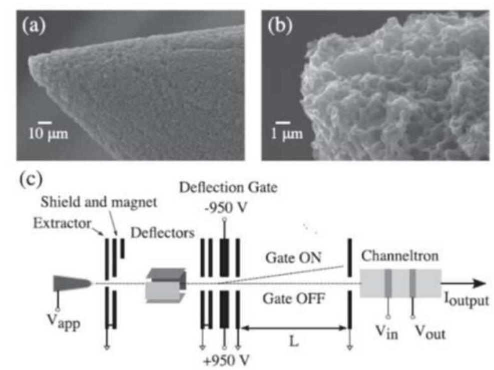


- Have N loaded alloys
  → Checked with IBA
- In the process of attempting tips

(2) Ionic Liquid Ion Source (with MIT)

(At SNL for testing)

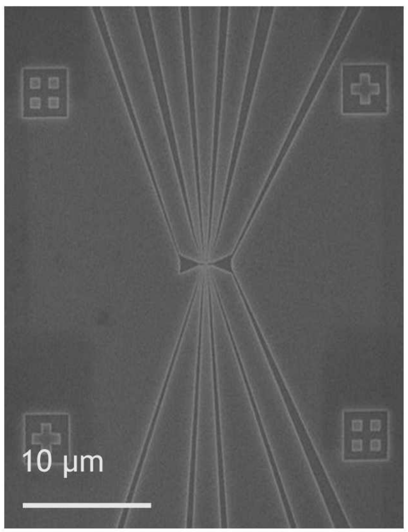
Carbon Xerogel Microtip with ILIS



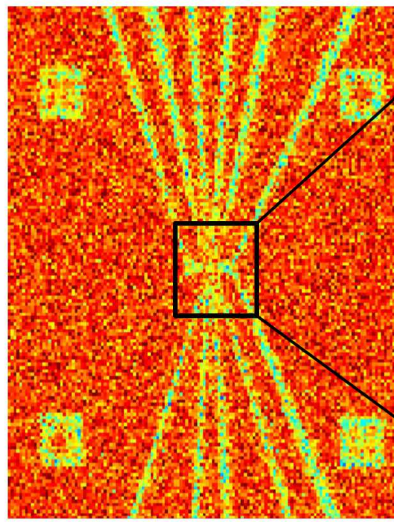
C. S. Perez-Martinez, *et al.*, *Appl. Phys. Lett.* **107**, 043501 (2015)

SNL nanoImplanter (nI) – Targeting Resolution

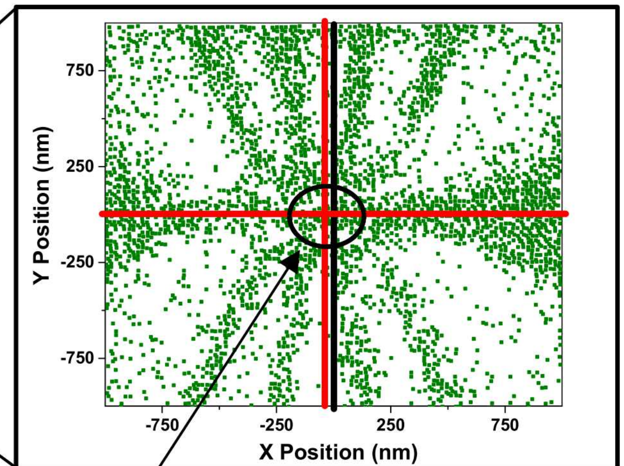
SEM of nanostructure



Ion Beam Induced Charge Collection (IBIC) of nanostructure

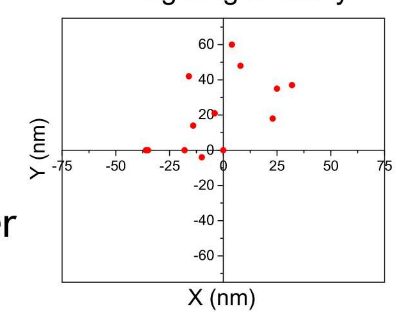


High resolution IBIC for targeting



Δx ~35 nm
Δy ~0 nm

Targeting Acuracy



Targeting resolution <40 nm, new Velion should improve this number

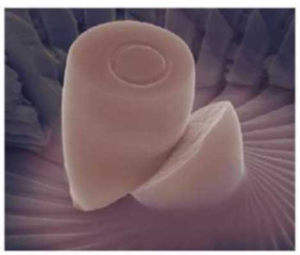
THE CENTER FOR INTEGRATED NANOTECHNOLOGIES

One Scientific Community Focused on Nanoscience Integration

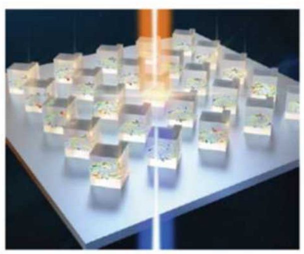
The Center for Integrated Nanotechnologies (CINT) is a Department of Energy Office of Science Nanoscale Science Research Center. CINT offers world-leading scientific expertise and specialized capabilities to create, characterize, and integrate nanostructured materials at a range of length scales, from 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

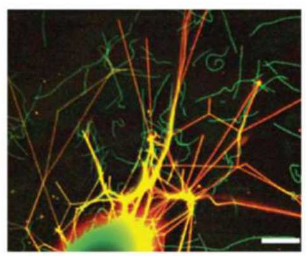
Integration is the key to exploiting the novel properties of nanoscale materials and creating new technologies. CINT's scientific staff and capabilities are organized around four interdisciplinary science thrusts which address different challenges in nanoscience integration.



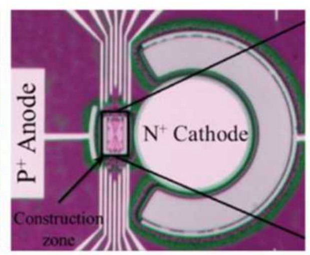
In-Situ Characterization and Nanomechanics
Developing and implementing world-leading capabilities to study the dynamic response of materials and nanosystems to mechanical, electrical, or other stimuli.



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

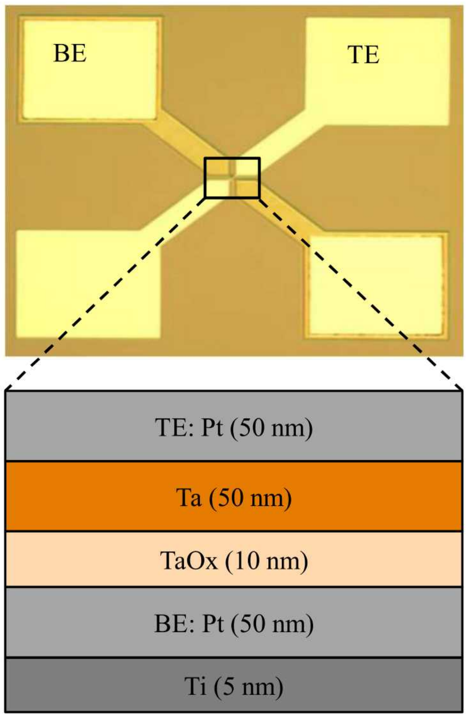
CINT is an Office of Science national user facility. CINT helps the international research community perform cutting-edge research in the areas of nanoscience and nanotechnology, and is available free of charge for open science. As a user facility, CINT has the structure and mission to collaborate widely 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.

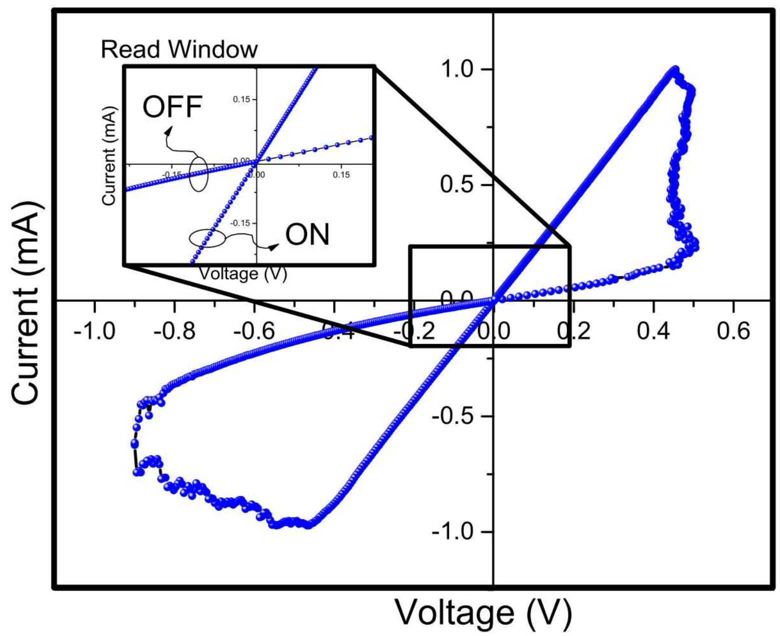
Opened the SNL nanoImplanter as a user accessible facility in 2019

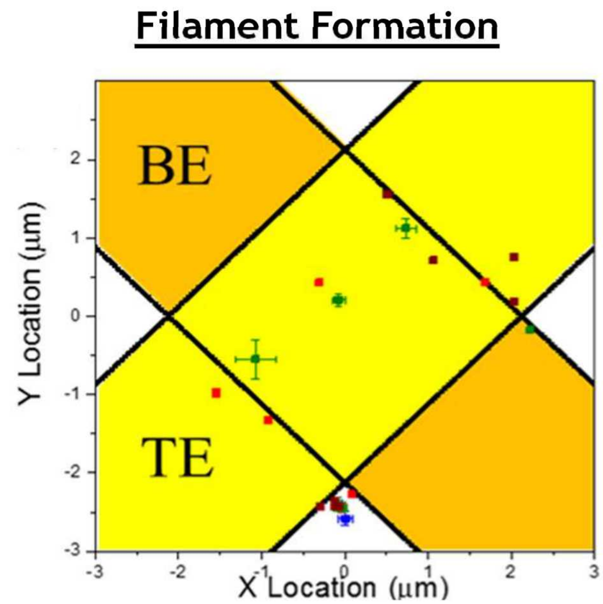
https://cint.lanl.gov/

Case 1 – Ion Beam Seeding of Memristors

- Memristor based memories are promising solid-state memories with high speed, low power, high density and are naturally radiation hardened



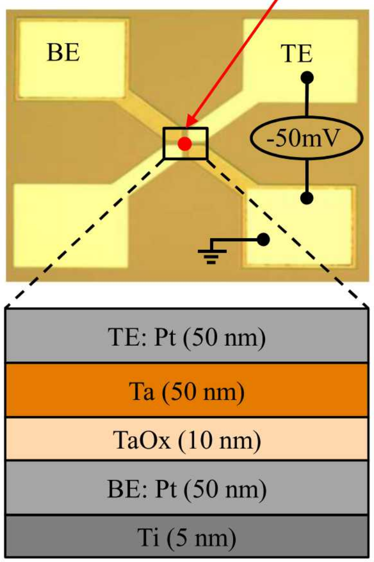


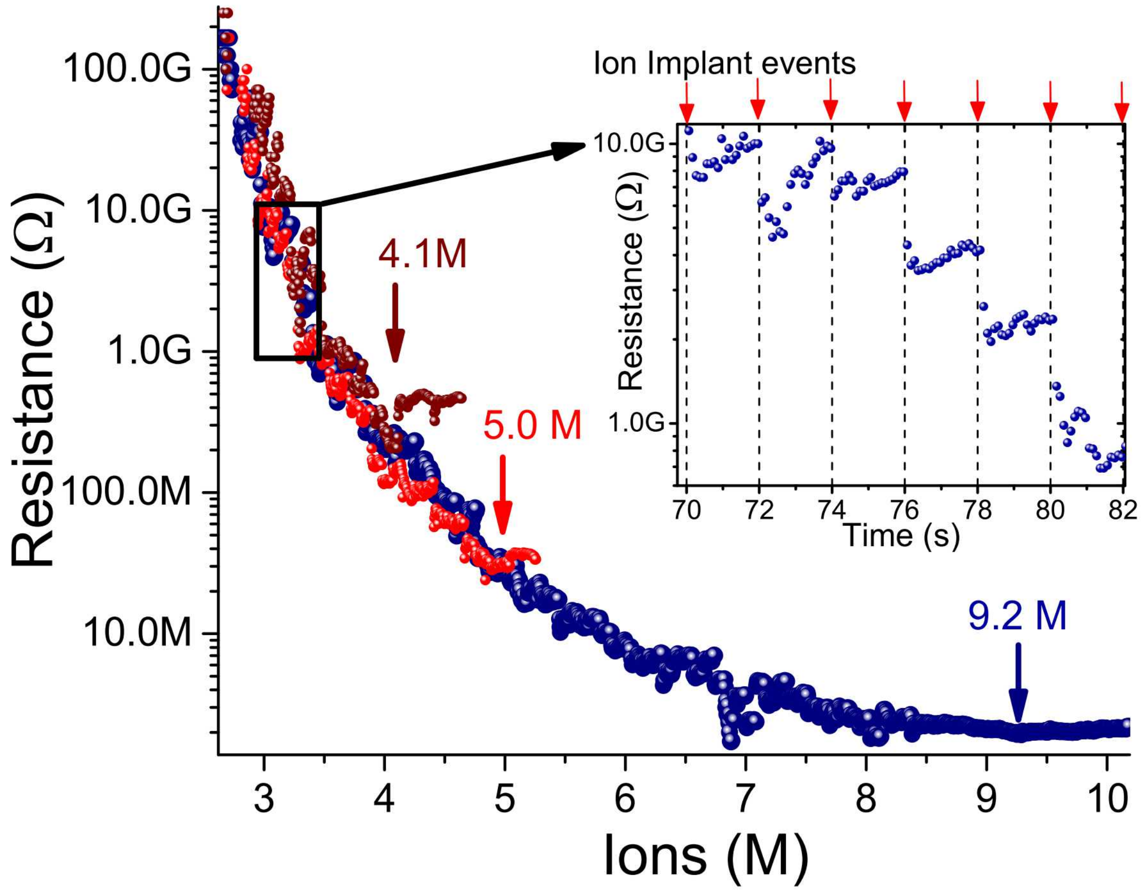


- Can we use focused ion beam implantation to act as seeding sites for the conductive filament formation bypassing electroformation?

Modification of the TaOx Film Resistance using Ion Irradiation

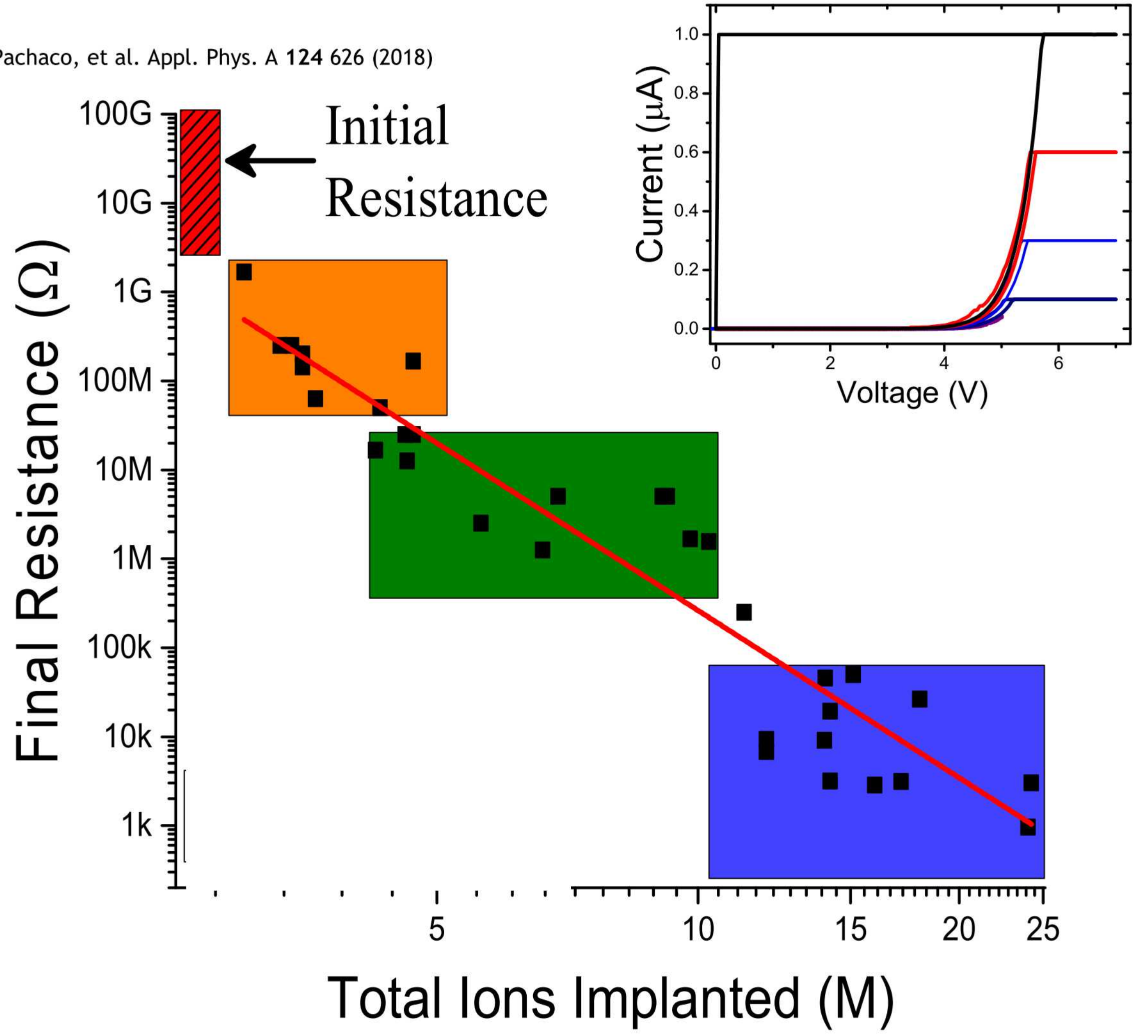
200 keV Si Implantation

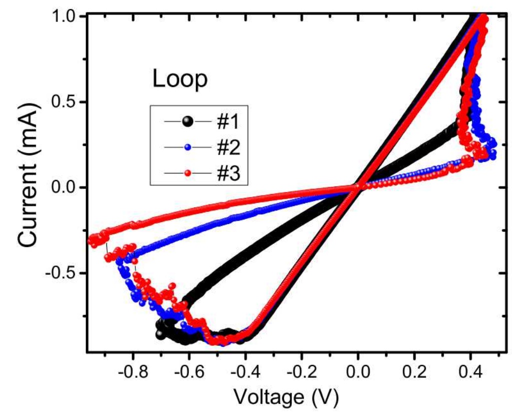


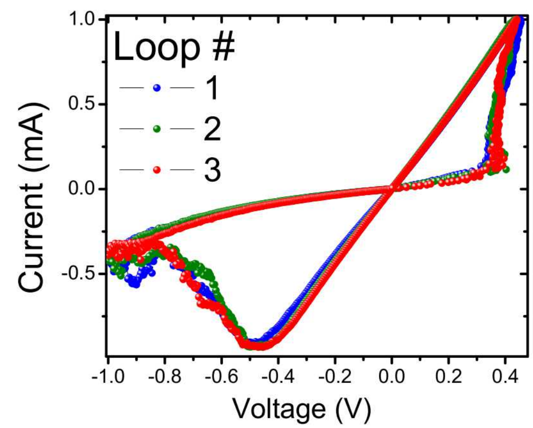


Ion Beam Seeding of Memristor Filament

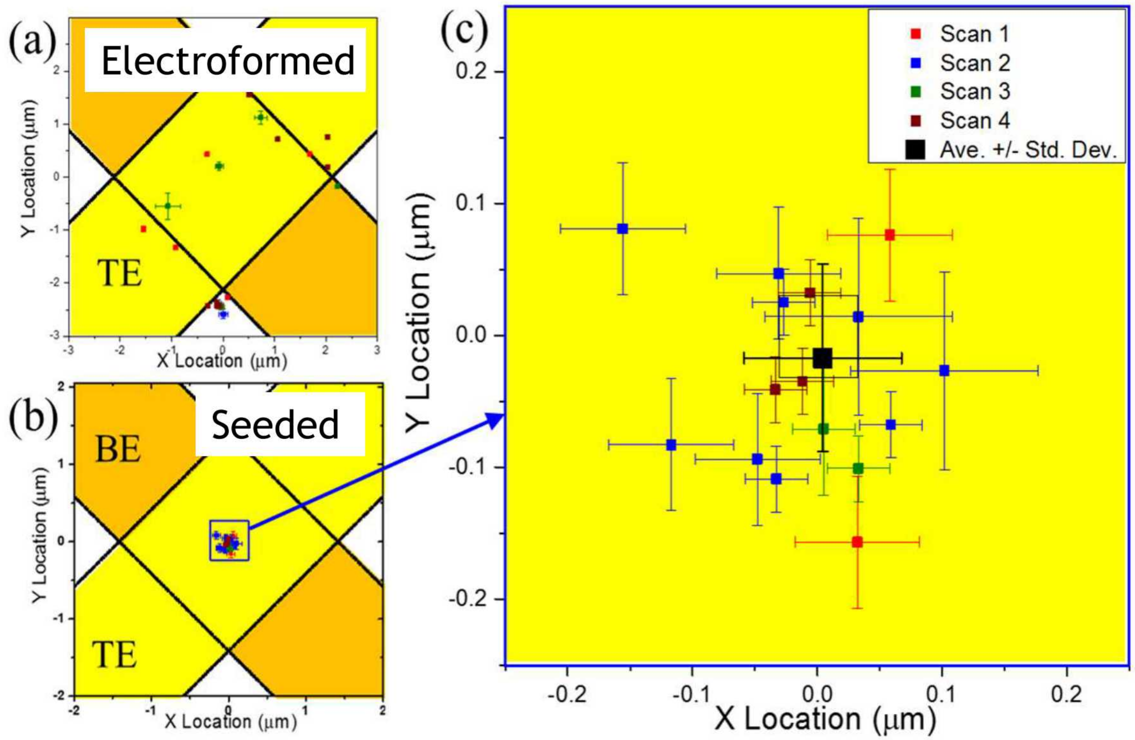
J. Pachaco, et al. Appl. Phys. A **124** 626 (2018)







Control over Filament Location



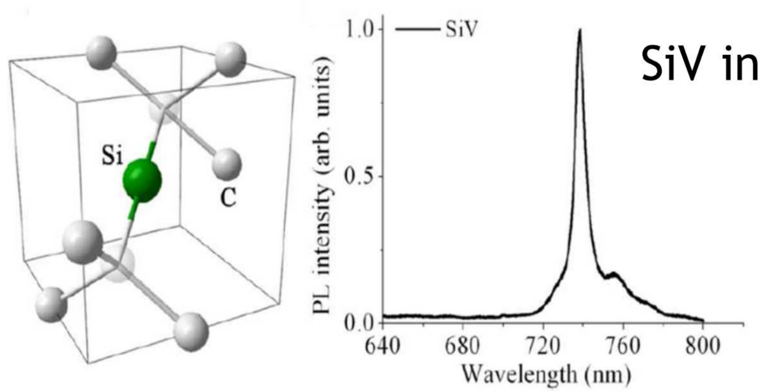
Results:

- Control over filament location and resistivity
- No Electroforming is necessary

J. Pachaco, et al. Appl. Phys. A **124** 626 (2018)

Case 2 – Color Centers in Diamond

- Color centers (defect complex) in diamond include NV, GeV, SiV plus many more… for applications from metrology to quantum computation



SiV in diamond

I. Aharonovich *et al.*, Rep. Prog. Phys. **74**,076501 (2011)

- What is the problem?

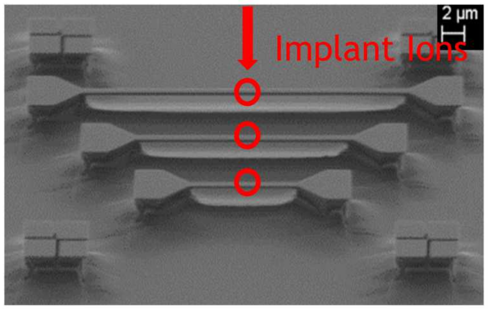
How to produce a ***single*** color center ***where*** you want it?

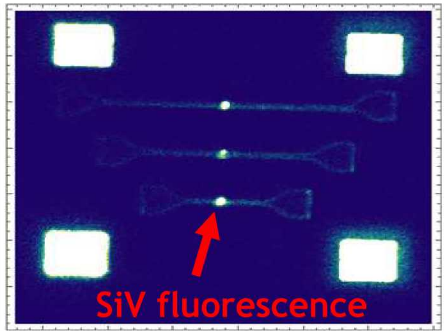
1.) Location

2.) Yield

Location Problem is Solved

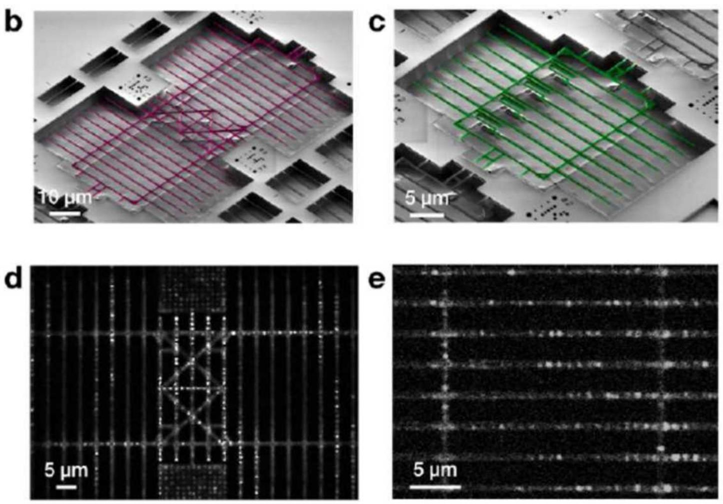
Diamond Nanobeams (with Harvard)





A. Sipahigil, *et al.*, *Science* (2016)

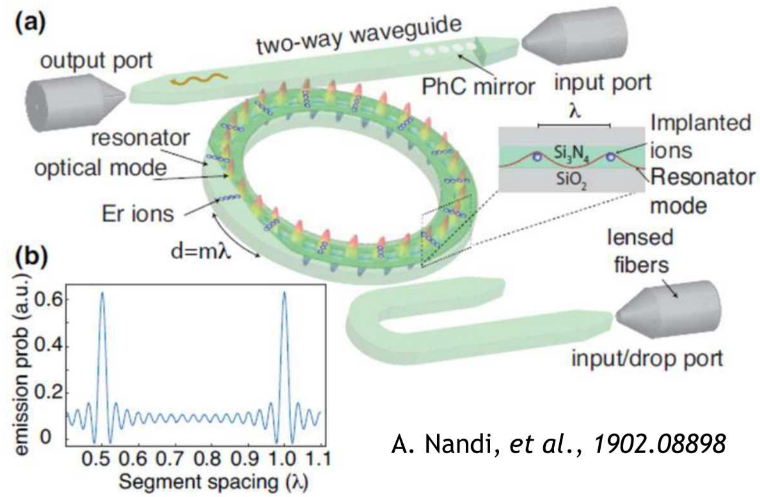
Diamond waveguides with AlN photonics (with MIT)



16 and 8 channel "quantum micro-chiplets"

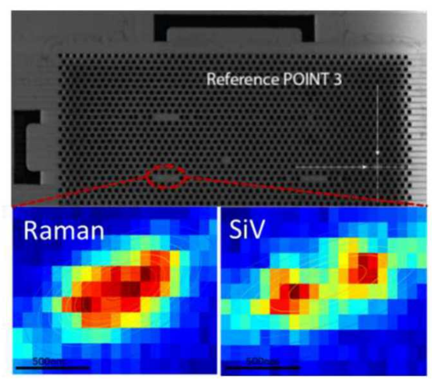
N. Wan, *et al.*, *1911.05265*

Silicon Photonics (with Purdue)



A. Nandi, *et al.*, *1902.08898*

2D photonic Crystals (with MIT)



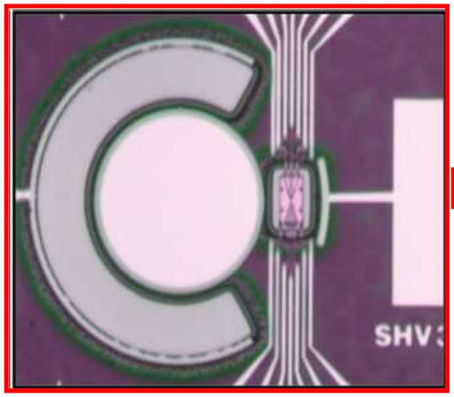
Accuracy is <50 nm

T. Schroder, *et al.*, Nature Communications (2017)

SNL Approach to Activation Yield

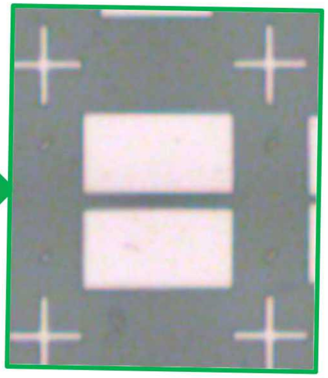
Single Ion Detectors to Understand Yield

Silicon



Translating single ion detection to diamond

Diamond



J. Seamons, *et. al*. Appl. Phys. Lett, 93, 043124 (2008)

E. Bielejec, *et. al*. Nanotechnology 21, 085201 (2010)

J. Abraham *et al*, APL 109, 063502 (2016)

→ Improve yield understanding by directly counting the number of implanted ions

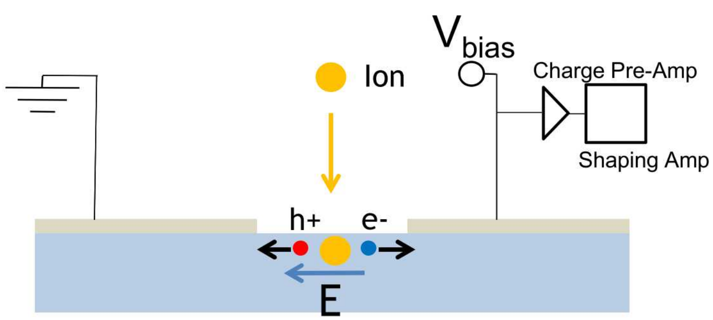
Using Diamond Detectors to Understand Yield

Yield = # measured SiV / # implanted Si

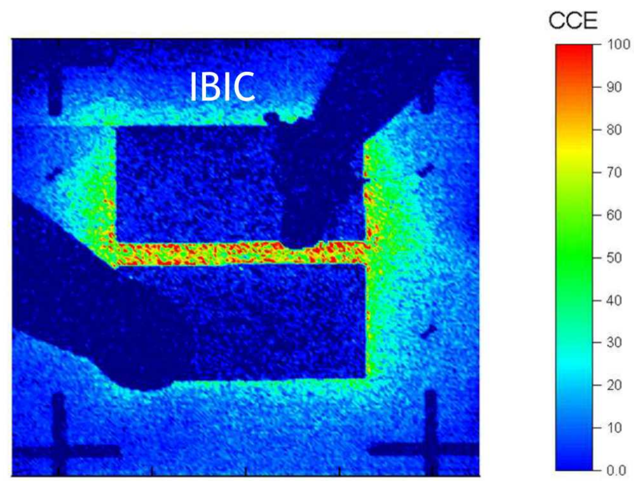
Poisson Statistics

(Uncertainty in number of centers is $\sqrt{N}$)

Ion Beam Induced Charge (IBIC)



Side View



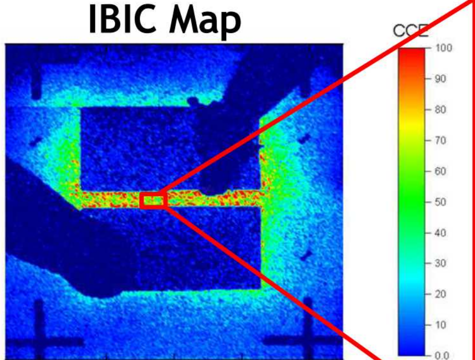
$$\text{CCE} = \frac{\textit{Charge Collected}}{\textit{Charge Depositied}}\, x\ 100$$

IBIC/detection demonstrated for low energy heavy ions

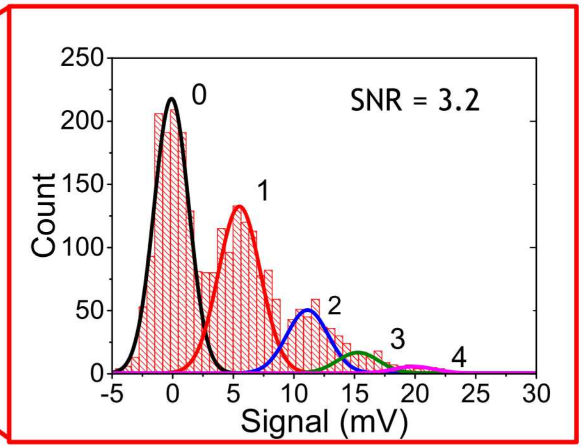
Abraham *et al*, APL **109**, 063502 (2016)

Single Ion Diamond Detectors

IBIC Map



Quantized Detection <0.65> ion

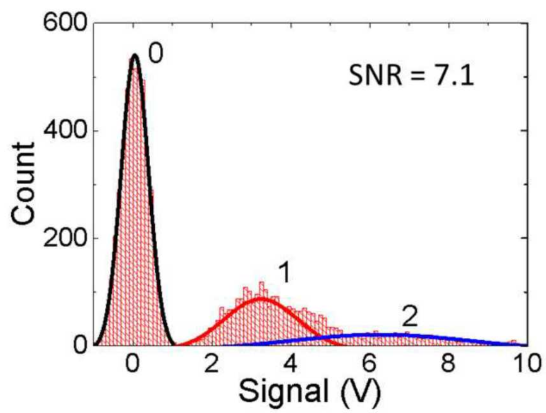


$$SNR = \frac{\mu_{signal}}{\mu_{noise} + \sigma_{noise}}$$

Signal amplitudes match Poisson statistics to 4%

Optimizing gain for single ion detection

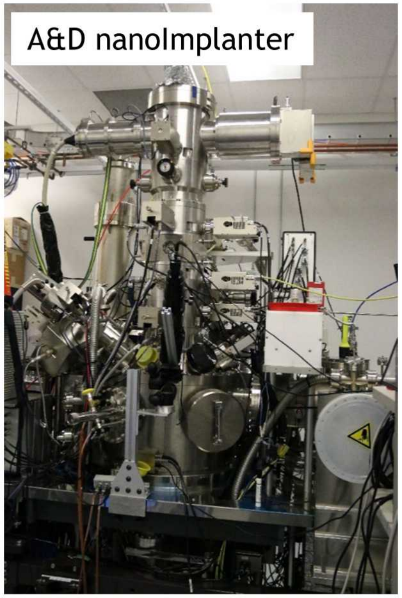
Single Ion Counting <0.2> ion



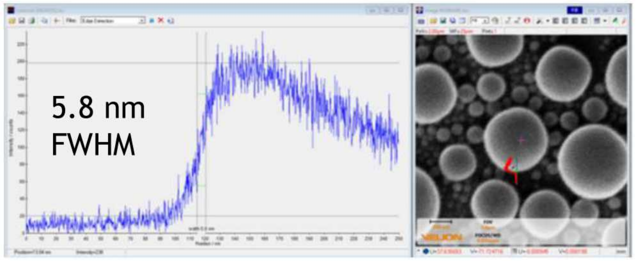
Single Ion Detection in Diamond with high SNR

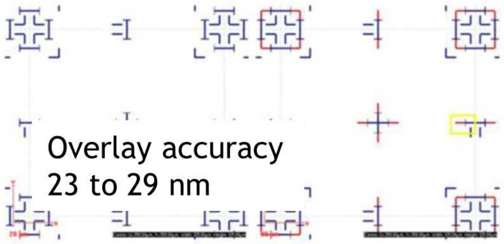
Abraham *et al*, APL **109**, 063502 (2016)

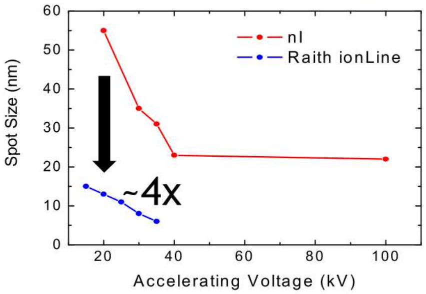
What's Next…… Raith Velion



- 100 kV accelerating potential
- LMAIS with 10 nm spot
- Spot blows up at low energy (100-150 nm)
- Implantation resolution 40-50 nm



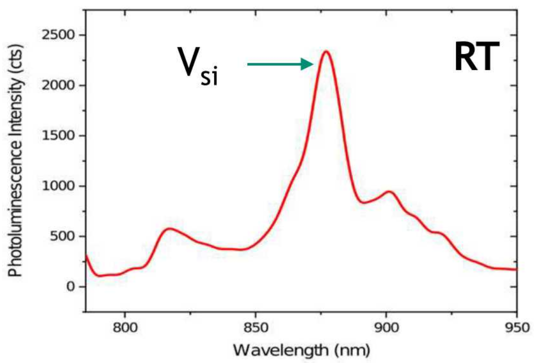




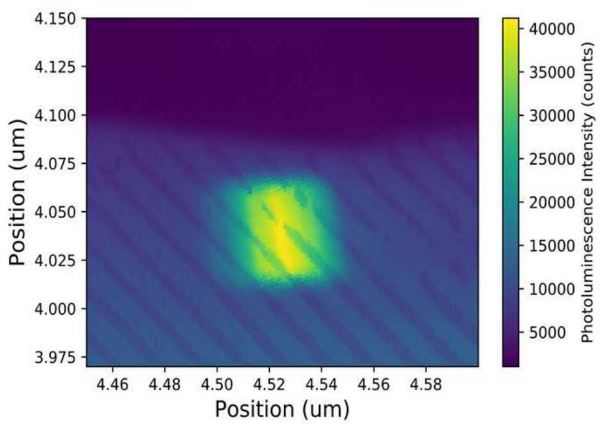
- 35 kV accelerating potential
- LMAIS with <6 nm spot
- Improved low energy resolution
- Improved implantation resolution

What's Next…… In-situ Photoluminescence

Ex-situ V_{si} Photoluminescence

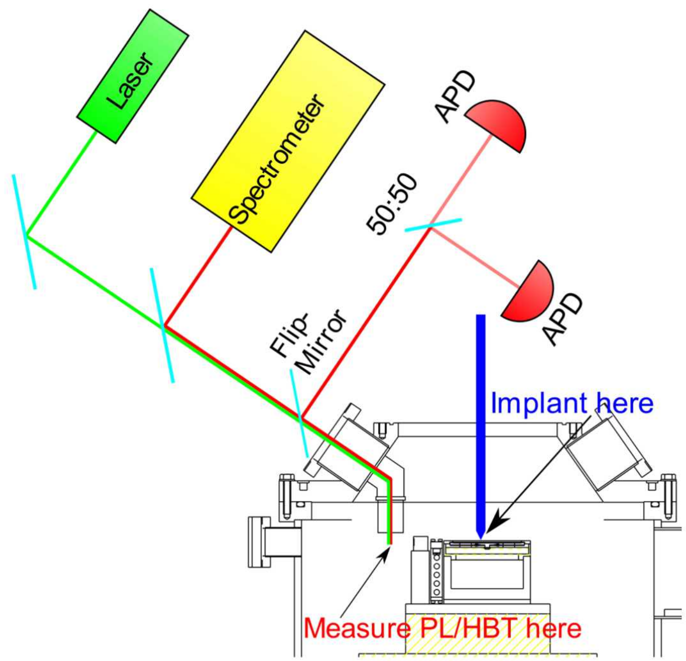


- SiC FIB implanted with 300 keV He (3 MV Pelletron)
- RT Emission from V_{si} w/o annealing



Fluence ~10^{12} ions/cm^2

In-situ V_{si} Photoluminescence



- Two-step process enabled by high resolution implantation:

(1) Aligned implantation, <40 nm

(2) Detect PL with objective

Acknowledgements

Sandia has developed a strong internal ion beam implantation and optical group

M. Titze, **W. Hardy**, **J. L. Pacheco**, **J. B. S. Abraham**, G. Burns, A. Flores, G. Vizkelethy (SNL)

M. Zaibari, **Jacoby Henshaw**, A. Mounce, P. Keyayias, M. Lilly (SNL)

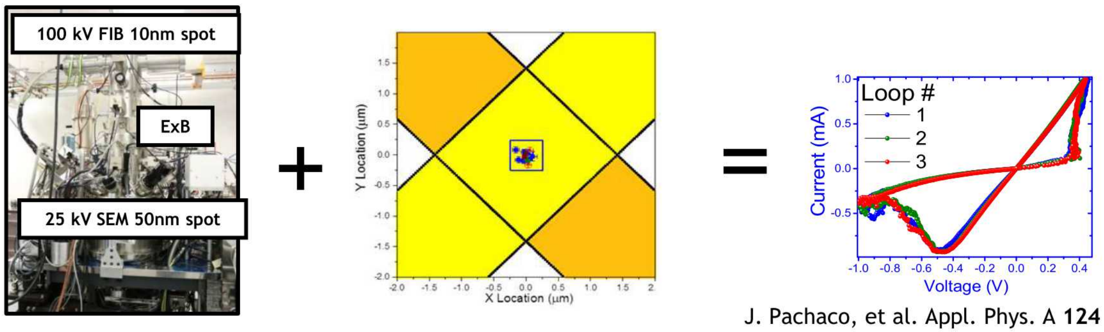
Han Htoon (LANL)

V. Costa (UNM)

And we have continued to support a wide range of user groups through CINT

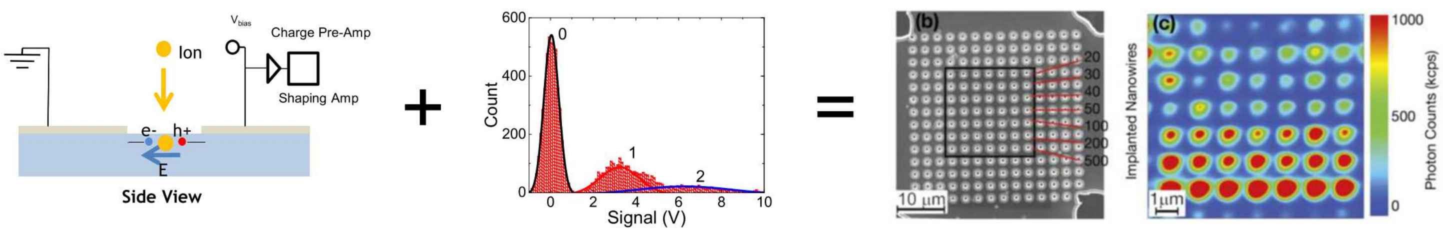
Summary

- Ion Beam Seeding of Memristor Devices



J. Pachaco, et al. Appl. Phys. A **124** 626 (2018)

- Towards Deterministic Color Centers in Diamond



Abraham *et al*, APL **109**, 063502 (2016) L. Marseglia, *et al.*, *Optics Express* (2018)

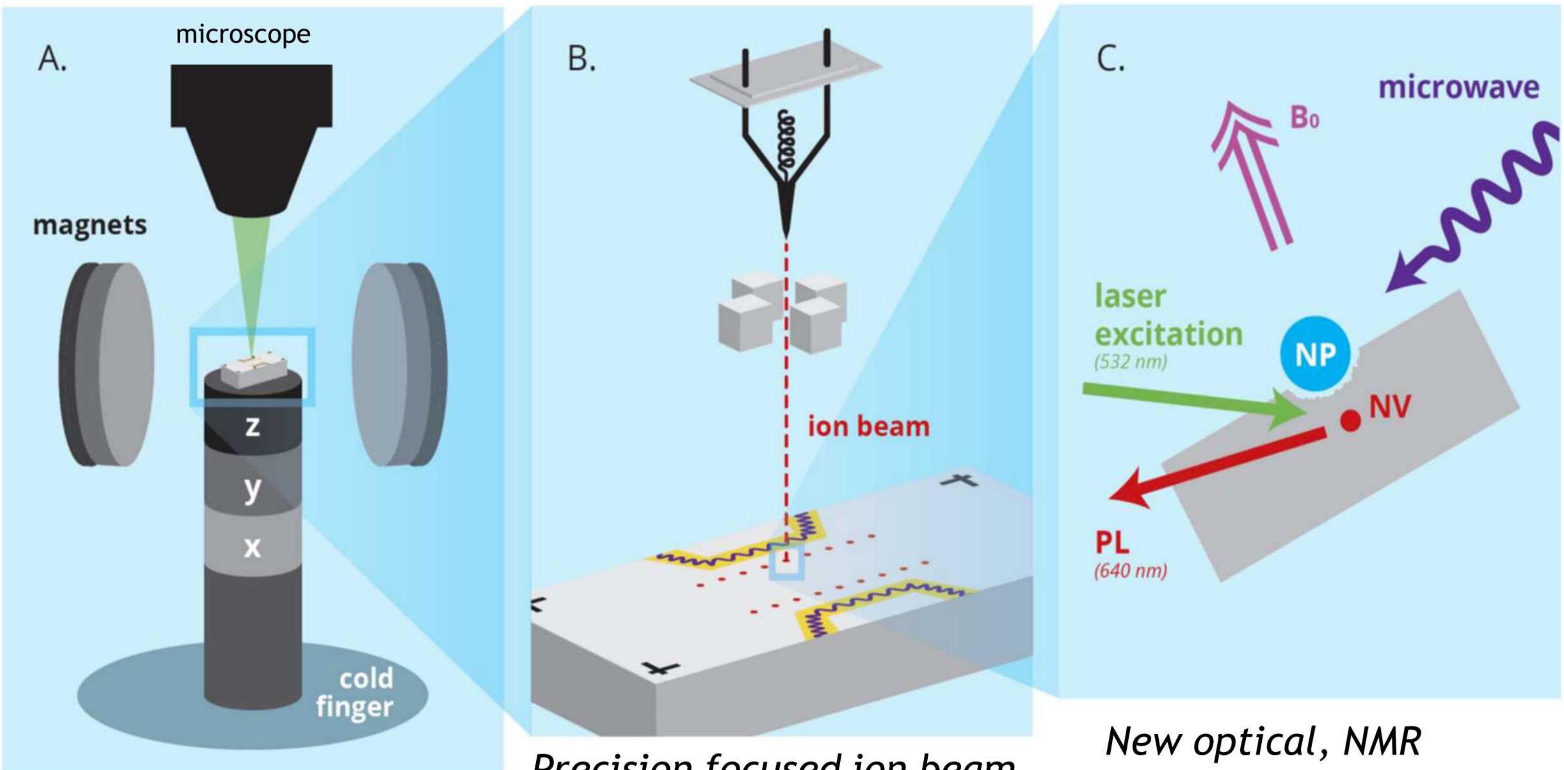
- Focused ion implantation is a direct pathway to fabrication of single atom devices and small scale nanofabrication

On-going work in diamond, SiN, SiC, hBN, GaN, etc…

Extra Slides

Quantum Sensed NMR CINT Discovery Platform - CINT

Nanoscale NMR experiments using Nitrogen-vacancy (NV) centers in diamond



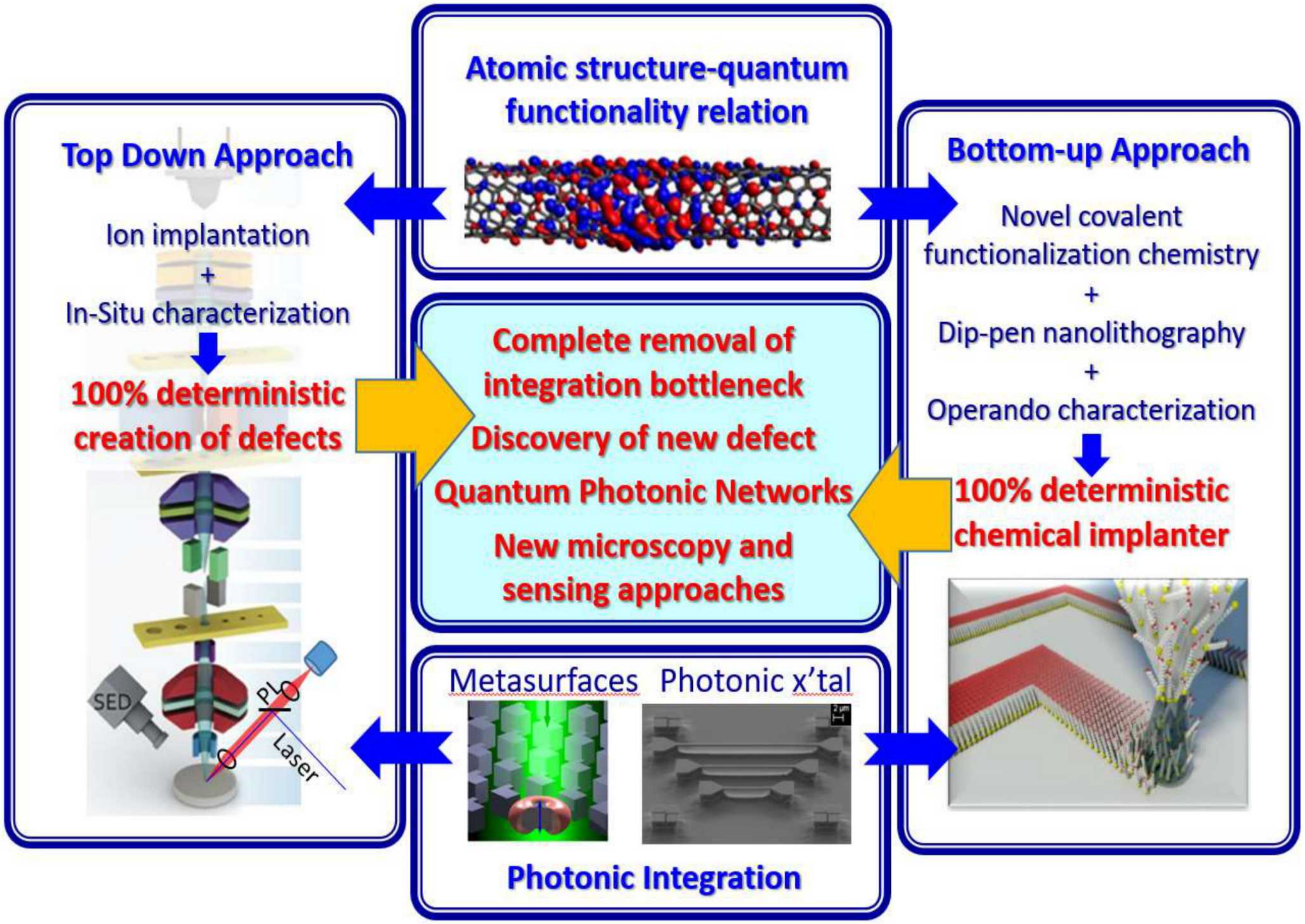
New optical cryostat with 1T magnetic field

Precision focused ion beam implantation capability

New optical, NMR setup for NV readout

Deterministic Placement and Integration of Quantum Defect Centers - CINT

Creating defect centers in a range of material systems – wide bandgap to 2D

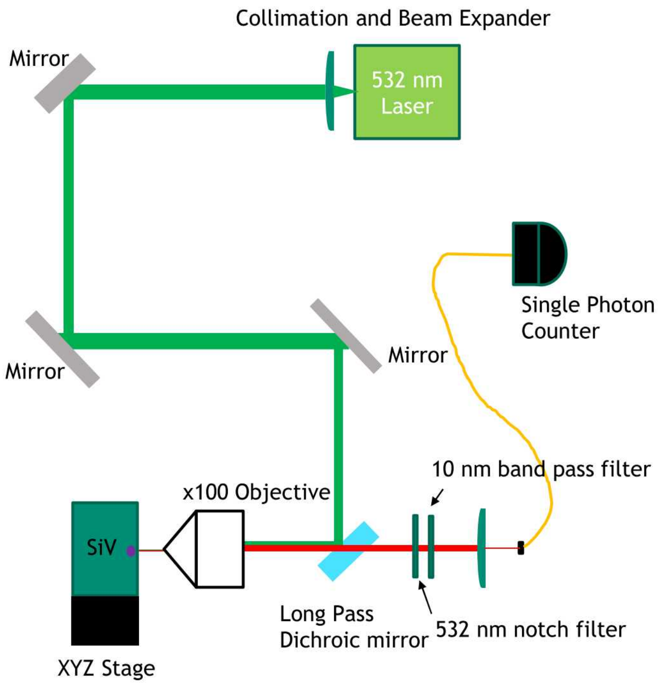


From the ion beam side of the house

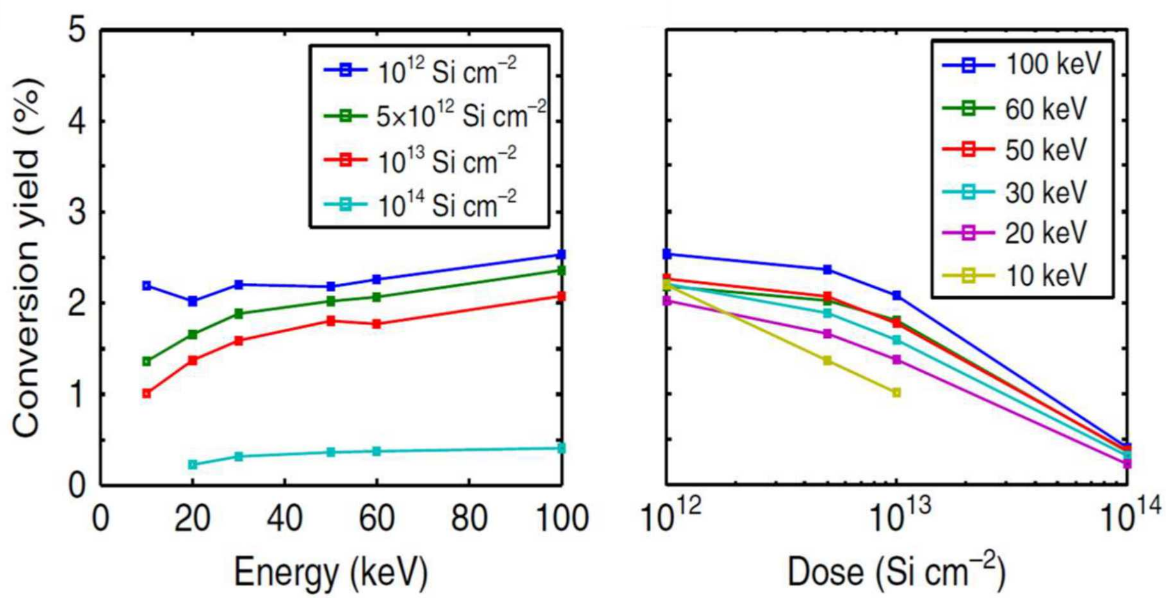
(1) FIB for high spatial resolution with in-situ PL

(2) Colutron for hyper-thermal implantation

Yield: Mapping SiV Photoluminescence



Yield = # measured SiV / # implanted Si



T. Schroder, *et al.*, Nature Communications (2017)

Similar yield to

S. Sangtawesin et. al. Appl. Phys. Lett. 105, 063107 (2014)

S. Tamura et. al. Appl. Phys. Express 7, 115201 (2014)

Yield is low and dominated by Poisson Statistics!

Yield Improvements Efforts

(1) Post electron irradiation
(2) Post ion irradiation
(3) Sequential ion irradiation
→ Create excess vacancies

(4) Hot ion irradiation — Enable vacancy migration

B. Diller *et al.*, arXiv:1909.08778

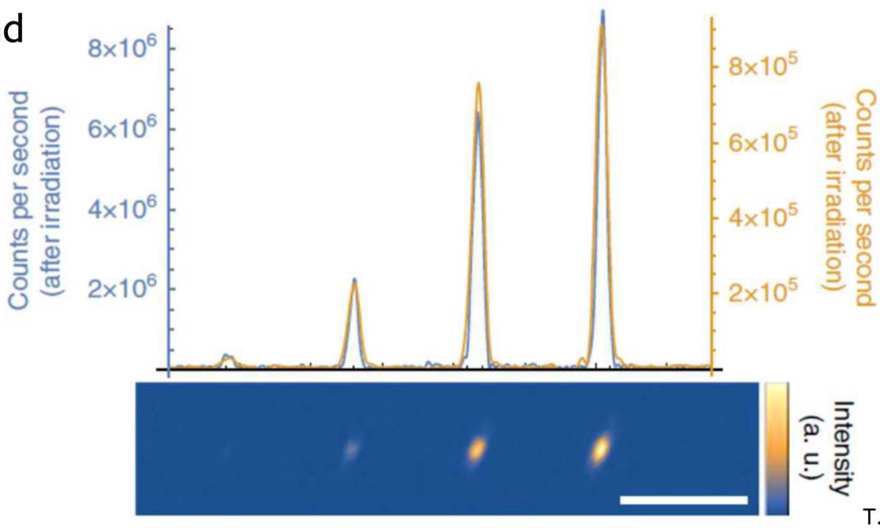
(5) Substrate doping — Enable preferential defect formation?

B. Rose *et al.*, Science **361**, 60-63 (2018)

T. Luhmann *et al.*, Nature Comm. **10**, 4956 (2019)

After electron irradiation and anneal

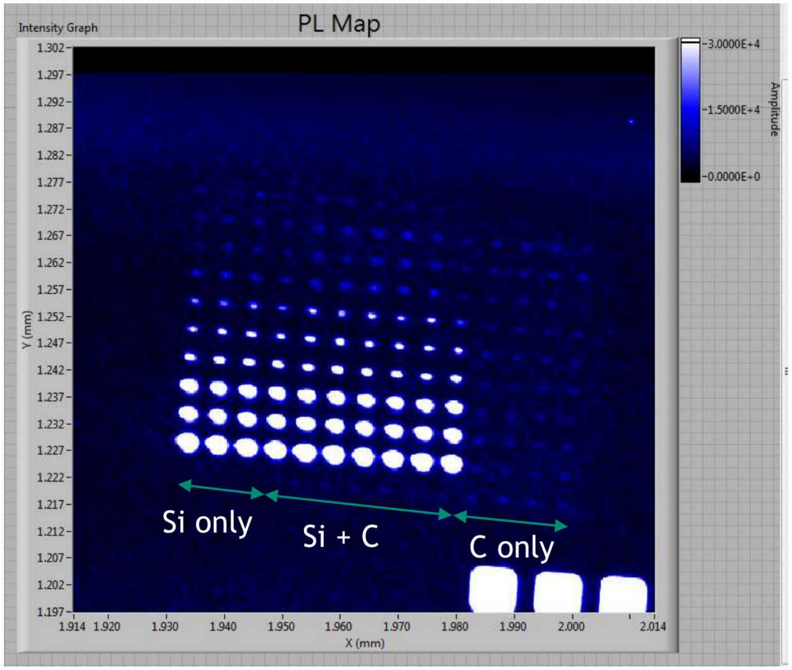
10x improvement

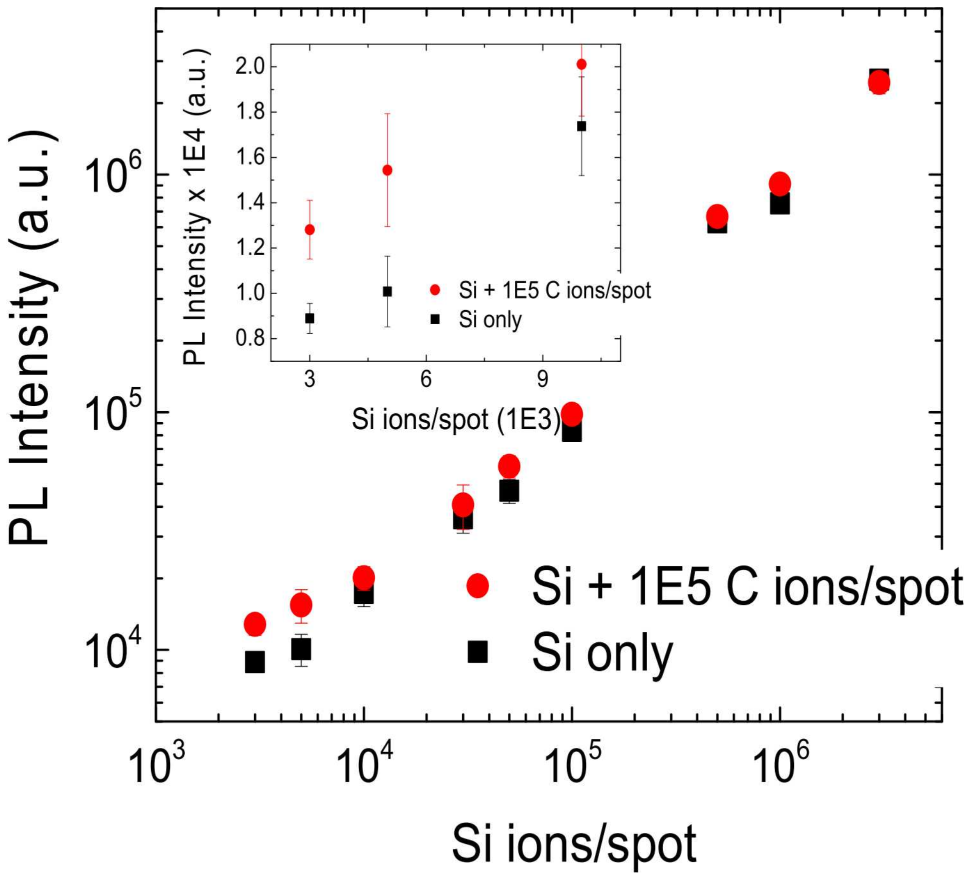


After ion implant and anneal

T. Schroder *et al.*, Nature Communications **8**, 15376 (2017)

Sequential Implantation – μm sized areas





Units

1E5 C ions/spot → ~1E13 ions/cm²

3E3 Si ions/spot → ~4E11 ions/cm²

→ Below the damage threshold

Si+C PL is ~1.4x larger than Si PL → Yield improvement observed in μm spots

Progress on Nitrogen Source Development

Approaches for building a nitrogen source for the nanoImplanter:

(1) Implant N into a known working source

(2) Use ionic liquid sources as demonstrated in the literature

Start with a working LMAIS – AuSn, In, AiSi, etc… and implant N

(1) Can we implant N into the LMAIS?

- N implanted into AuSn and In alloys at 200 keV N^{+} to fluences of 5E17 ion/cm^2

(2) Does N stay in the alloy?

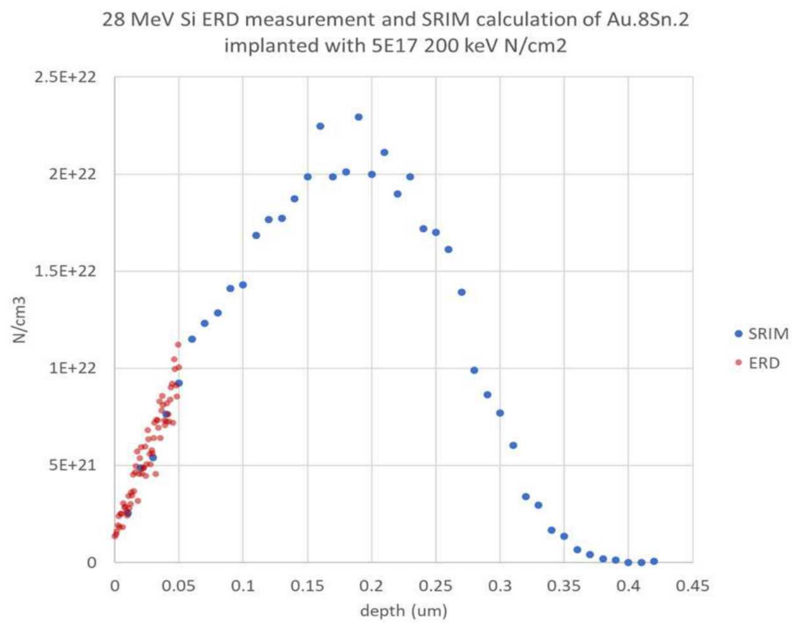
- N concentration measured by 28 MeV Si^{+5} ERD

- AuSn+N → N stays in place at least in the very near surface (figure on right)

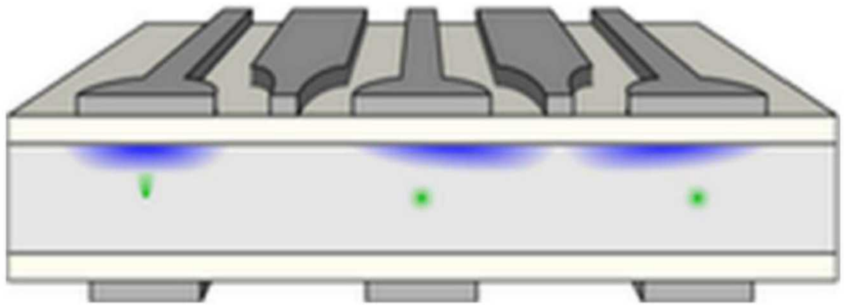
- In+N → N concentration is less than calculated:
  - N diffused deeper into the In
  - Or it may have left the sample

(3) Can we form a N containing tip?

- On-going! But, at most we expect ~4e3 N/s



Case 1 – Donor Based Qubit using ^{31}P in Silicon



T. Schenkel et al., US 8,816,325 B2 (2014)

T. Schenkel et al., arXiv:1110.2228

A spin quantum bit architecture with coupled donors and quantum dots in silicon

T. Schenkel[1], C. C. Lo[1], C. D. Weis[1], J. Bokor[2], A. M. Tyryshkin[3], and S. A. Lyon[3]
[1]Ion Beam Technology Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[2]Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA
[3]Electrical Engineering Department, Princeton University, Princeton, NJ, USA
Contact-email: T_Schenkel@LBL.gov

(October 10, 2011)

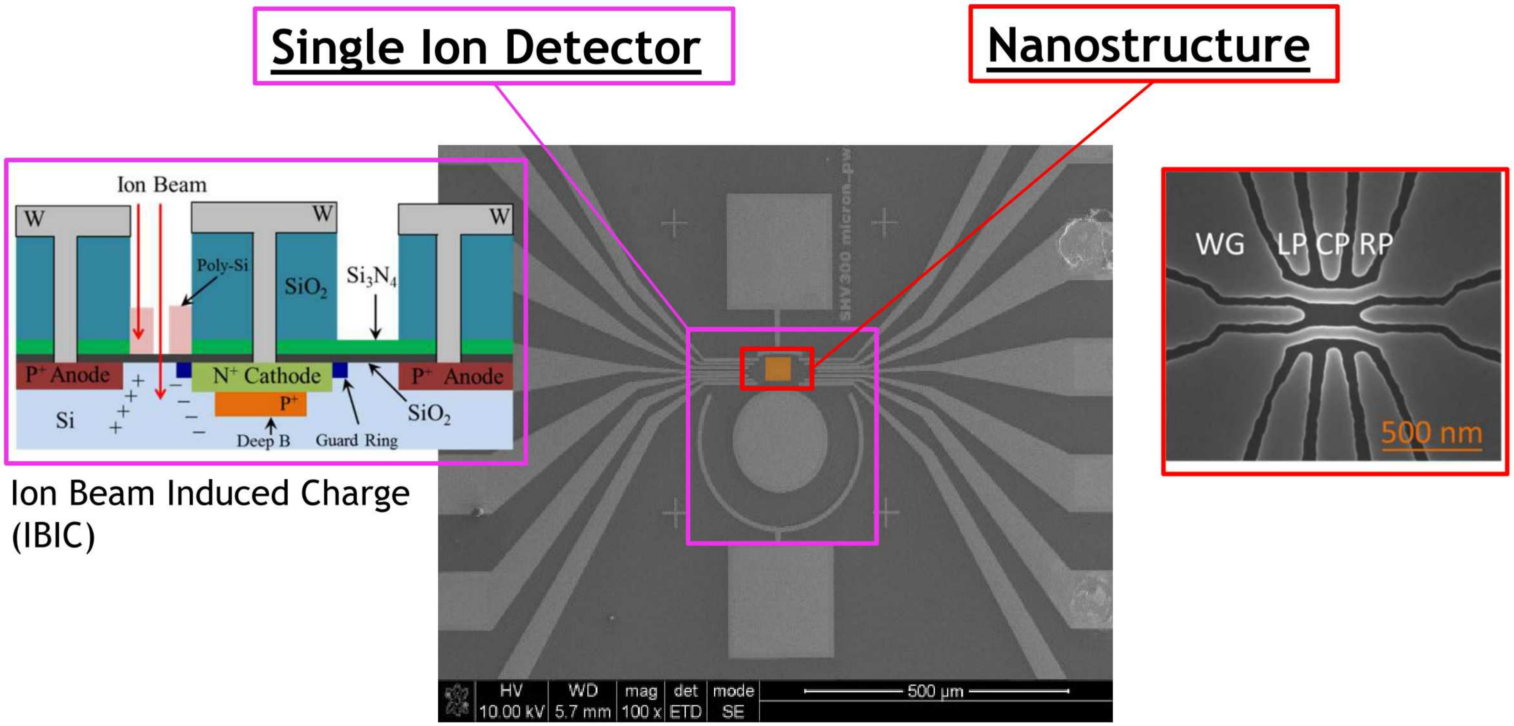
(1) Single Donor control

(2) Donor to QD coupling

(3) QD to QD coupling

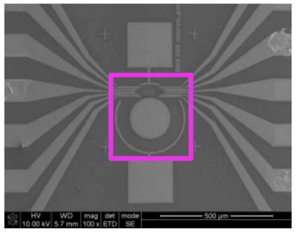
Single Donor Devices for Si Qubits

Si-MOS platform integrated with:
- Single Ion Detector
- Nanostructure for Qubit operation



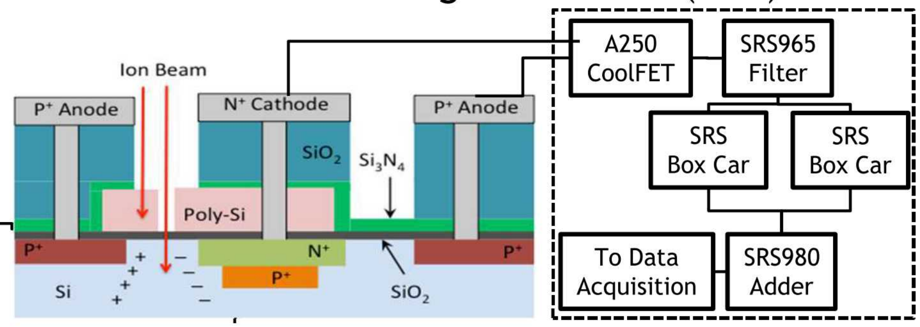
Ion Beam Induced Charge (IBIC)

Combined Single Ion Detector and Nanostructures Demonstrated

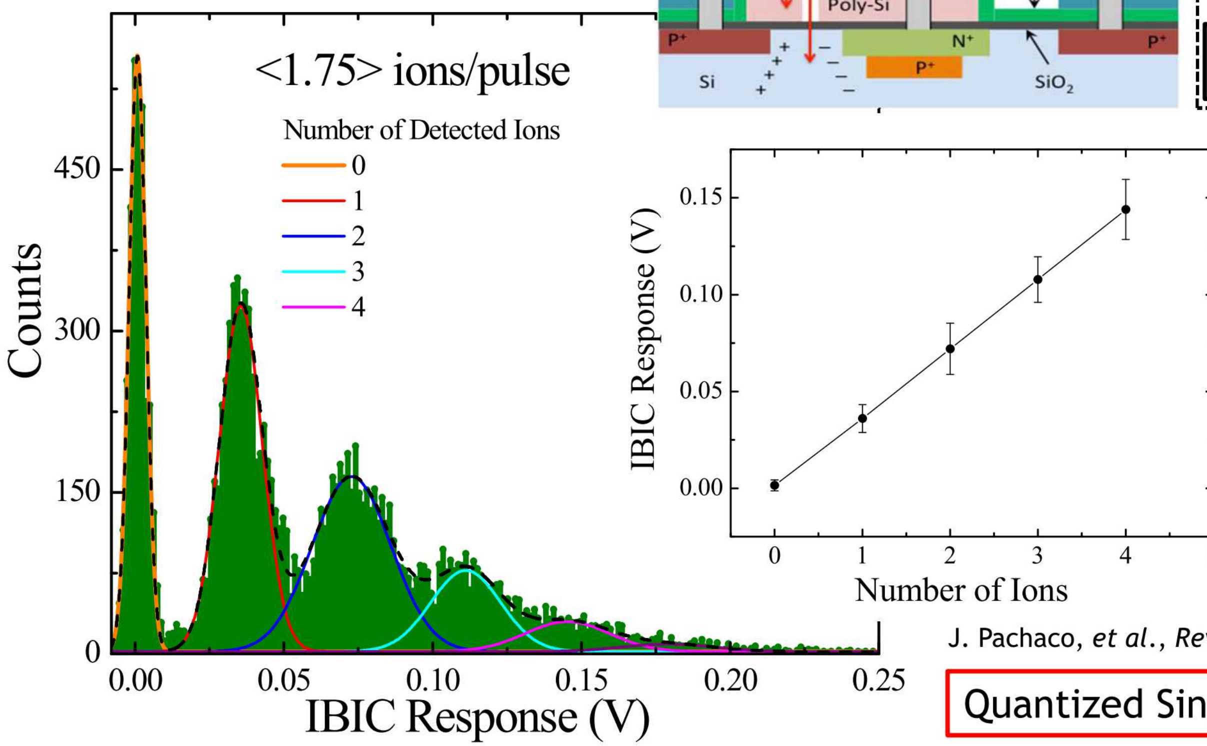


Integrated Single Ion Detectors

Ion Beam Induced Charge Collection (IBIC)

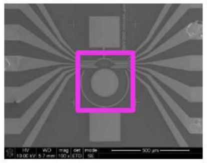


200 keV Si Detection



J. Pachaco, *et al.*, *Rev. of Sci. Instr.* (2017)

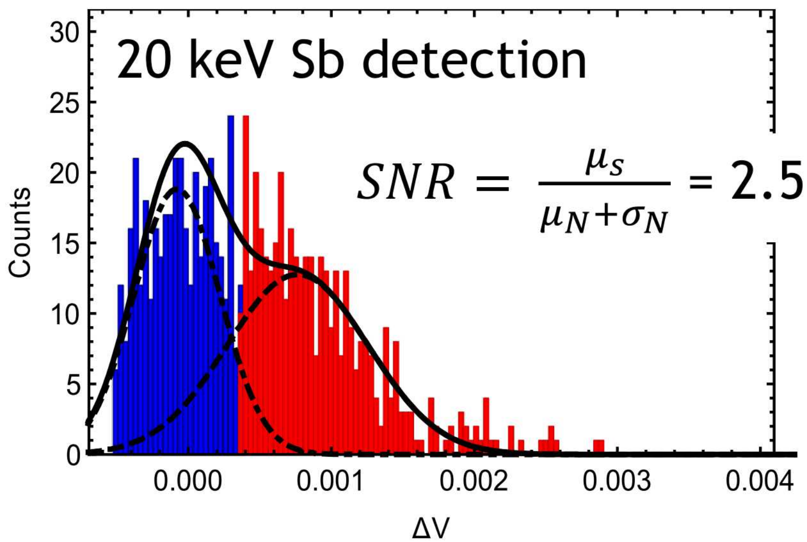
Quantized Single Ion Detection



Lowest SNL Detected Single Ion Implantation

Ion	Energy (keV)	SiO_2 thickness (nm)	Range[a] (±straggle) (nm)	e-h pairs (k)[a]	SNR	Error rate (%)	Detection efficiency (%)
Si	200	7	273 (±76)	39	21.2	≪1	100
Sb	120	35	25 (±17.5)	8.5	5.2	…	…
Sb	50	7	25 (±9)	5.0	4.4	…	…
Sb	20	7	11 (±5)	1.4	2.5	15	87.6

[a]Range and e-h pairs calculated from the SiO_2/Si interface into the Si substrate.



How to further improve SNR?

- In-vacuum preamp ☑
- Cool detector and FET ☑

Path forward to low energy <10 nm implantation and detector