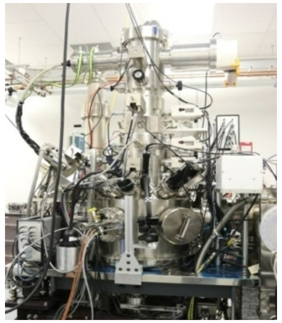
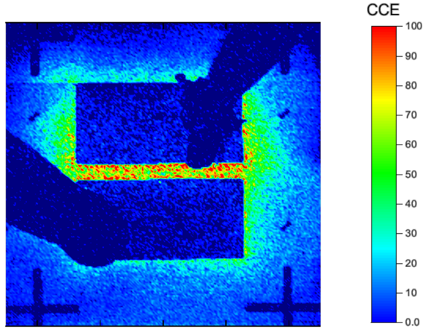
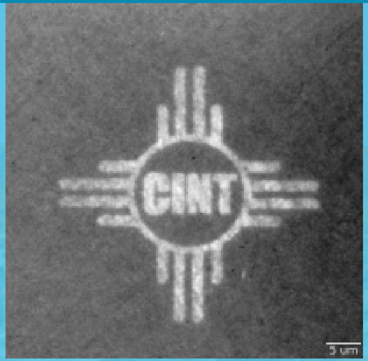
Sandia National Laboratories

SAND2021-3326C

Deterministic Positioning of Defect Based Qubits using Ion Beam Implantation for Nanofabrication and Modification







Edward Bielejec

Sandia National Laboratories, Albuquerque, NM 87185

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

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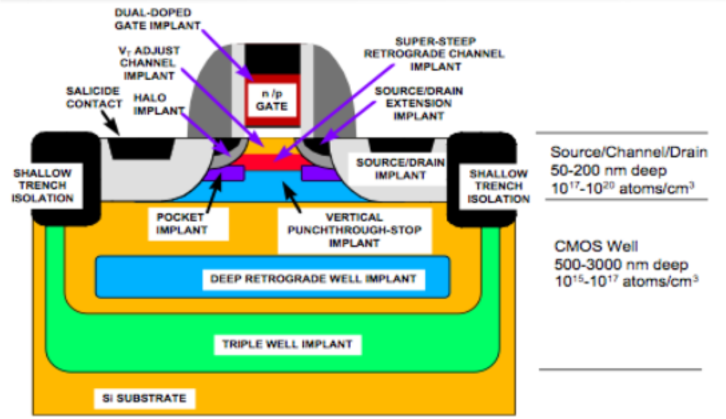
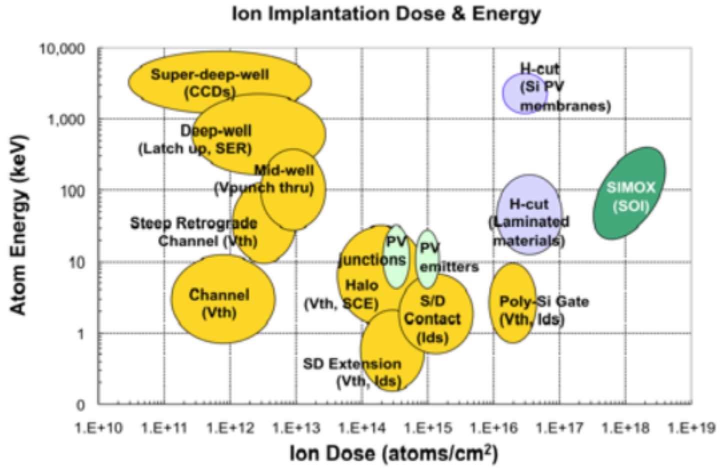
Ion Implantation and Irradiation for Device Fab

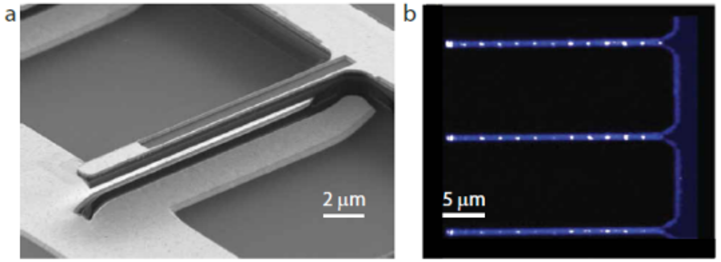
Ion Implantation has been a work-horse for the semiconductor industry



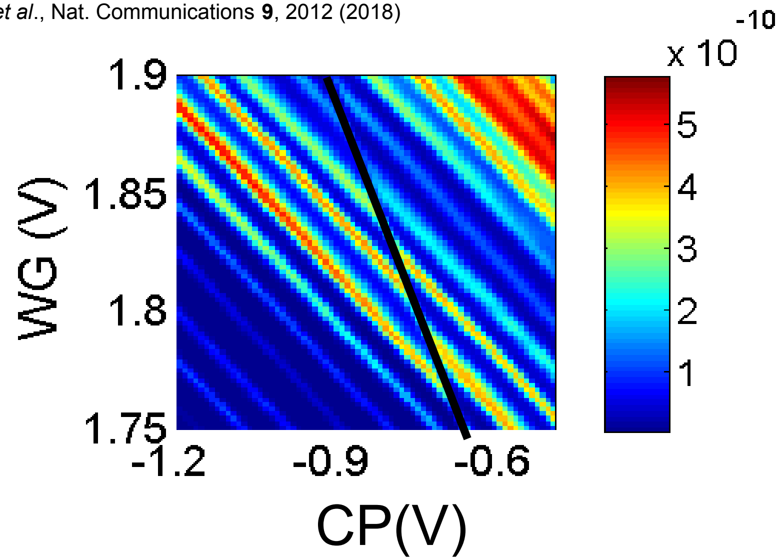


S. B. Felch, *et al.*, Proceedings of PAC2013, Pasadena, CA (2013)

Our work is centered on localized implantation and fabrication based on a deterministic number of ions



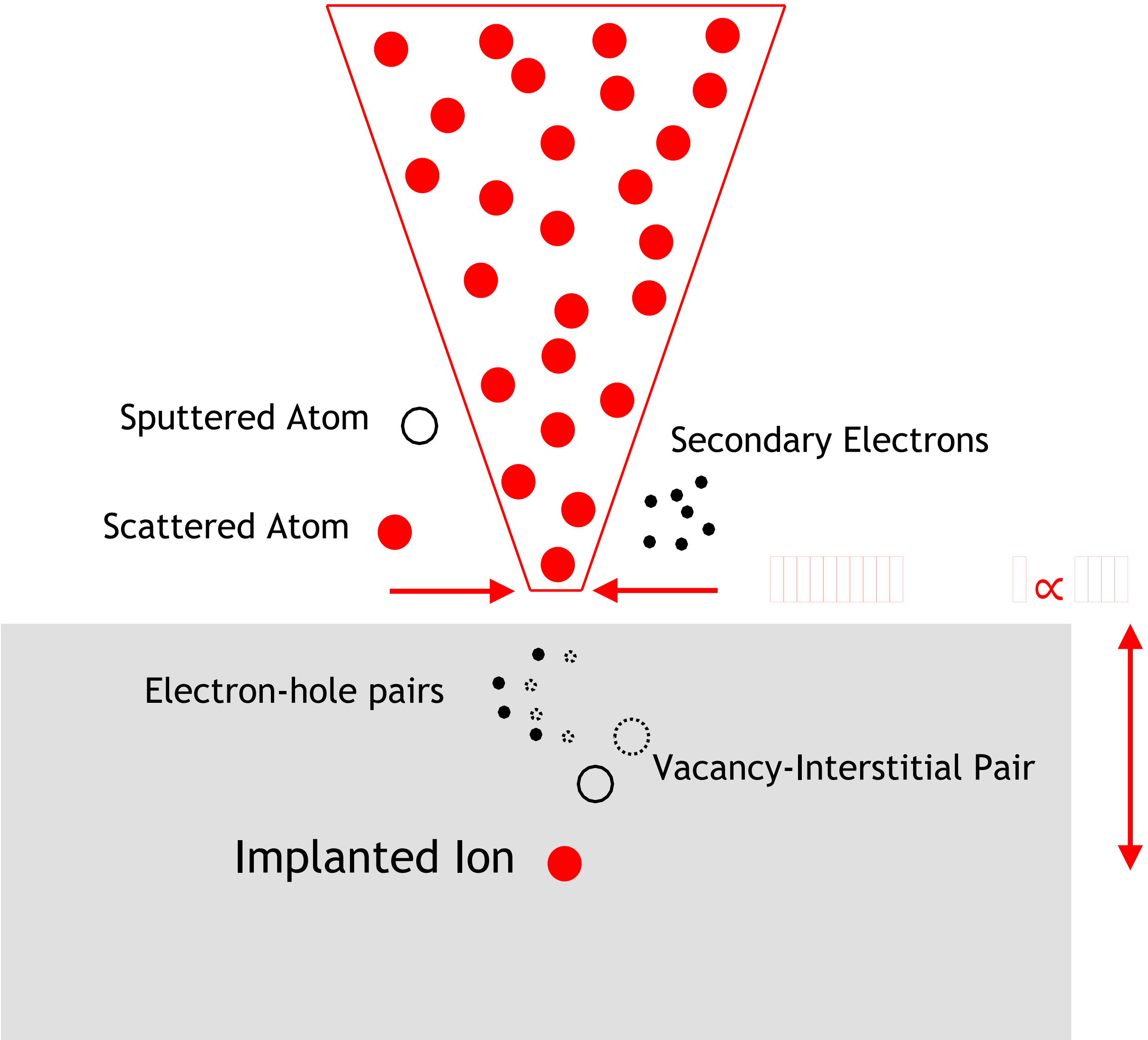
Y. Sohn, *et al.*, Nat. Communications **9**, 2012 (2018)

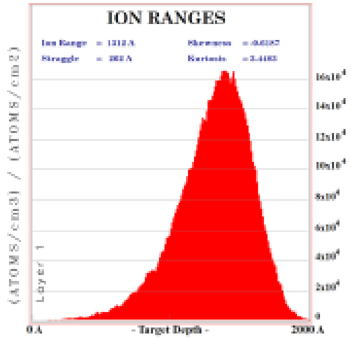


Singh et al. Appl. Phys. Lett. ***108****, 062101 (2016)*

Focused Ion Beam implantation for fabrication of single atom devices and nanofabrication

Overview of the Focused Ion Beam (FIB) Implantation





SRIM simulation

200 keV Si into diamond

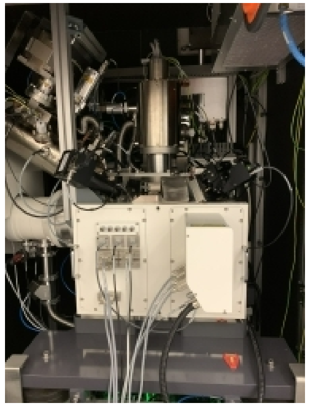
131 ± 26 nm

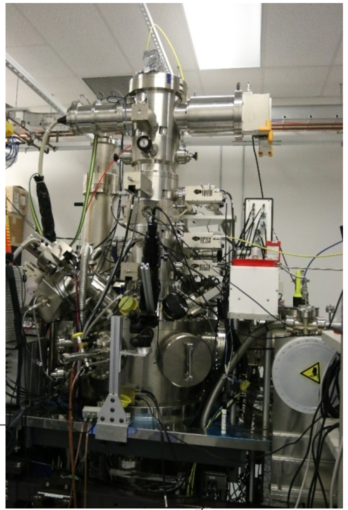
Outline

- Introduction to Sandia's Ion Beam Laboratory (IBL)

- Multi-species Focused Ion Beam (FIB)

  - Sandia's nanoImplanter and Raith Velion



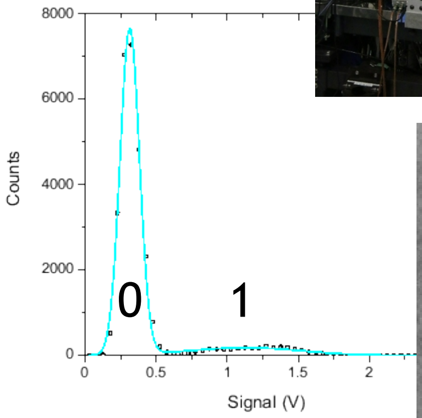


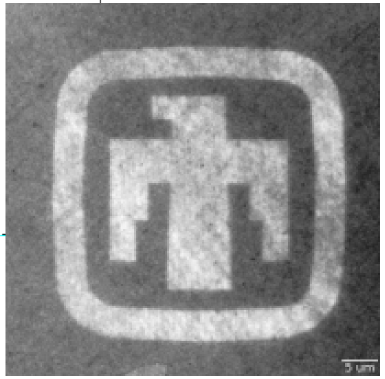
- Single Atom Devices and Nanofabrication

  - Example: Defect center formation in Diamond

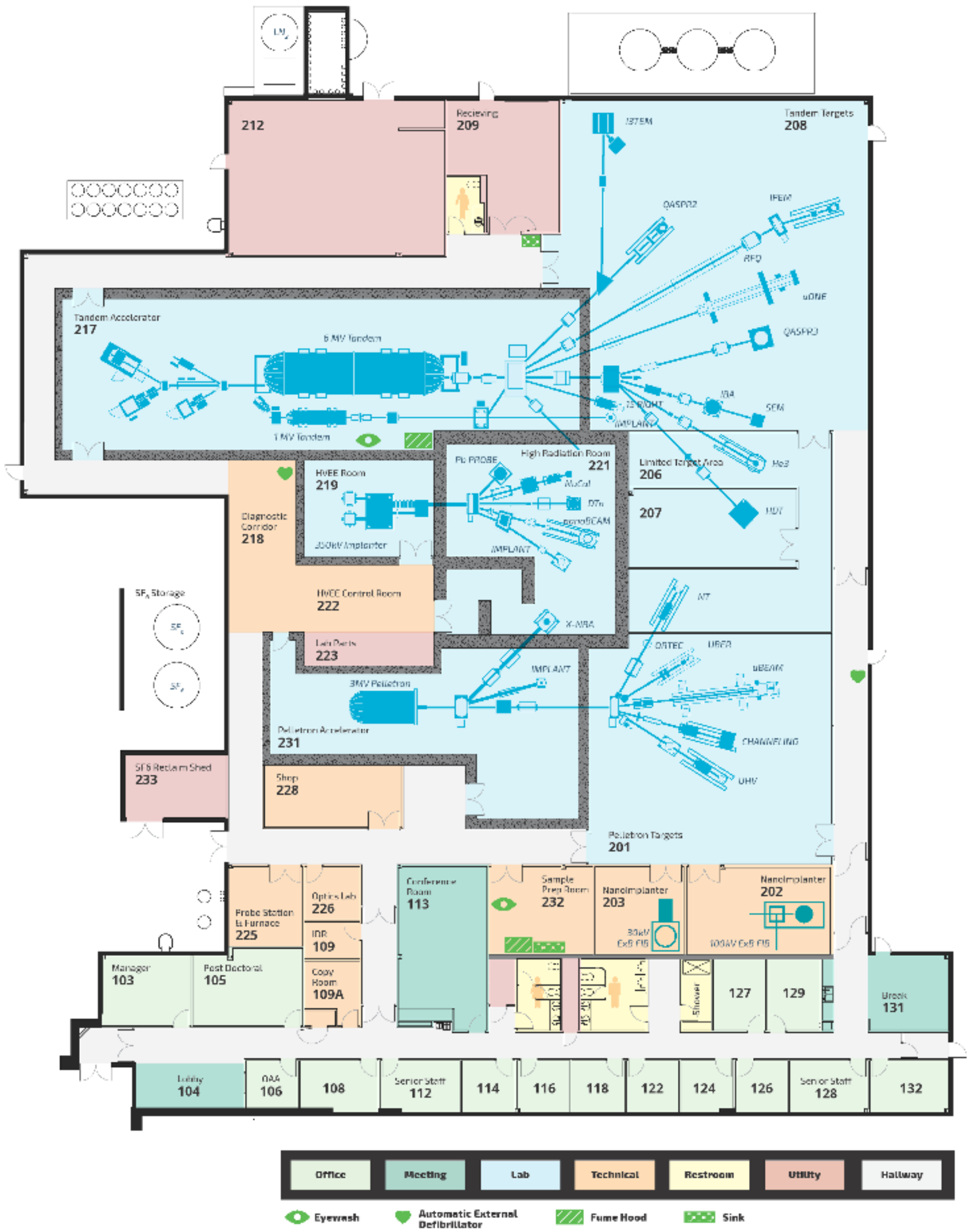
    →Localized implantation and single ion detection

- Summary





building 720
ION BEAM LABORATORY



Sandia's Ion Beam Laboratory (IBL)

7 Operational Accelerators and >25 end-stations

(including *in-situ* DLTS, PL, TEM, SEM, 1200°C heating, etc…)

Operational

(1) 6 MV Tandem Accelerator

(2) 3 MV Pelletron Accelerator

(3) 1 MV Tandem Accelerator

(4) 350 kV HVEE Implanter

High energy focused micobeams 1 μm to mm's

(5) 100 kV ExB FIB nanoImplanter

(6) 35 kV ExB FIB Raith Velion

(7) 35 kV Zeiss HeIM

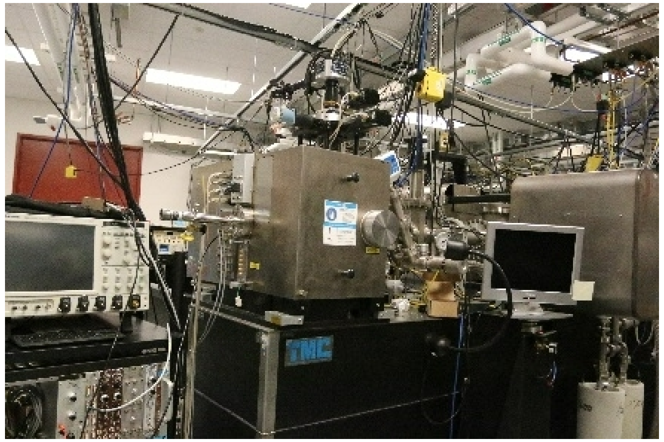
Installing

(8) 35 kV Plasma FIB

Low energy focused nanobeams <1 to 20 nm

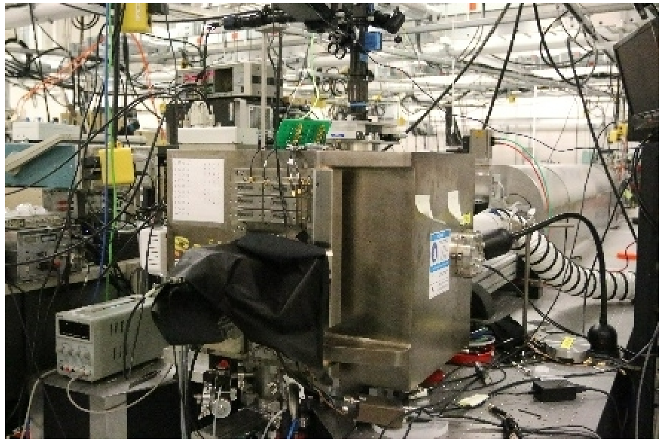
High Energy Focused Ion Beams ~1 μm to mm's

- 6 MV Tandem microbeam (microONE)



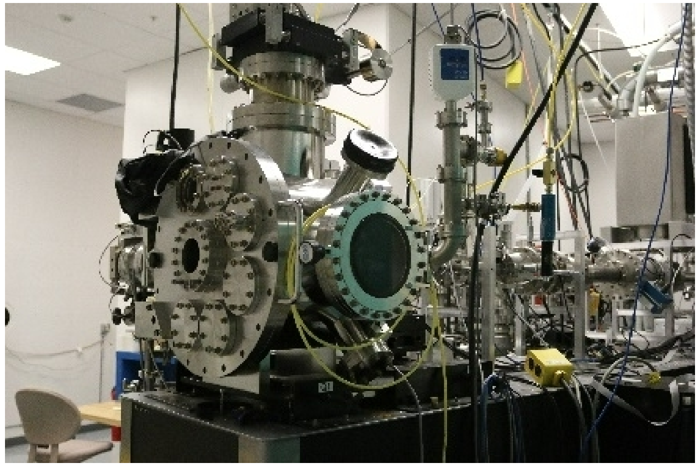
- High resolution laser stage
- Spot size <1 μm
- Energy 0.8 – 70 MeV
- H to Au

- 3 MV Pelletron microbeam (Light Ion Microbeam)

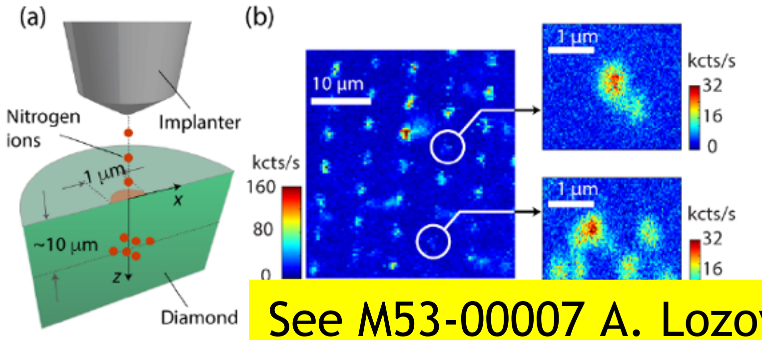


- High resolution laser stage
- Spot size <600 nm
- Energy 0.25 – 3 MeV
- H, He, N, Ar, Xe, …

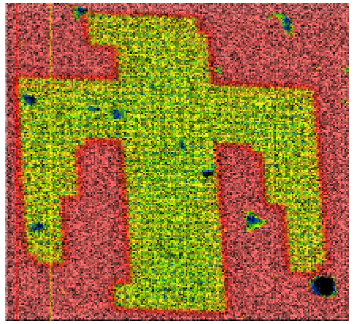
- 350 kV HVEE microbeam (NanoBeamLine)



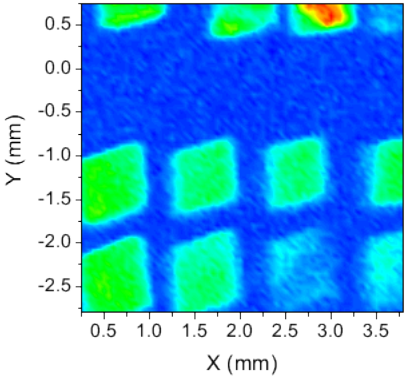
- Piezo stage
- Spot size <1 μm
- Energy 20 – 350 keV
- H to Au

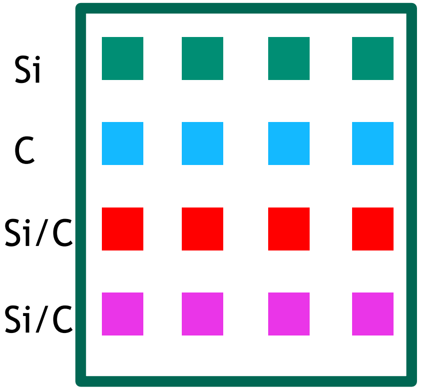


See M53-00007 A. Lozovoi



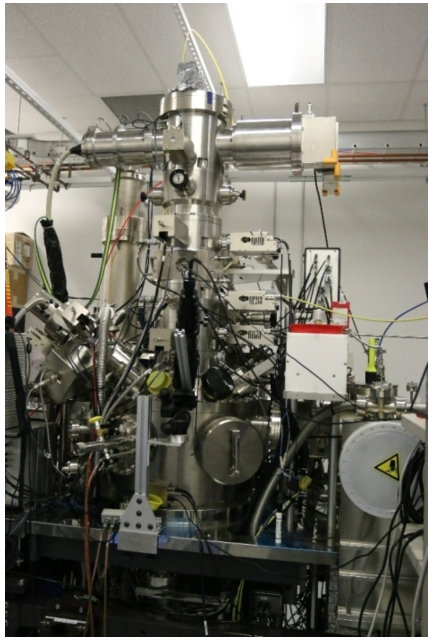
IBIC on PIN diode





Low Energy Focused Ion Beams <1 to 20 nm

- 100 kV A&D FIB100NI (nanoImplanter)

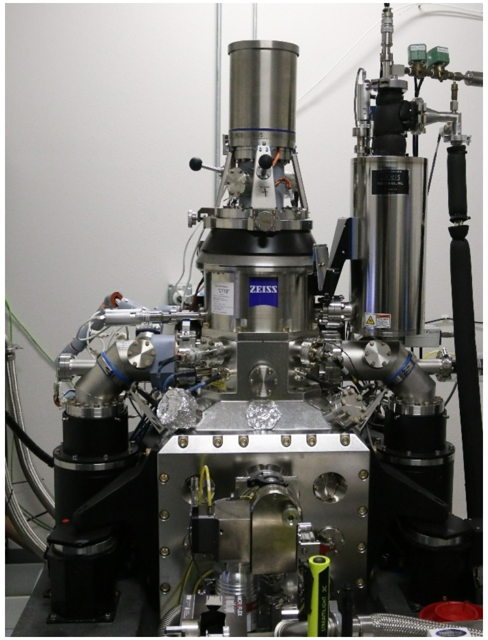


- High resolution laser stage
- Spot size <10 nm (Ga)
- Energy 10 – 200 keV
- 1/3 periodic table

- 35 kV Raith Velion (Velion)

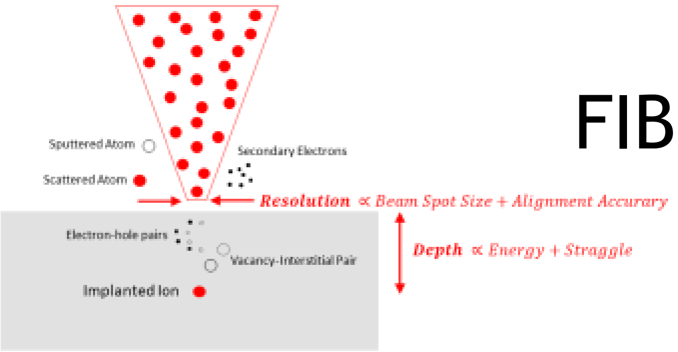
- High resolution laser stage
- Spot size <6 nm (Ga)
- Energy 5 – 70 keV
- 1/3 periodic table

- 35 kV Zeiss Orion Plus (HeIM)



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

All equipped with Lithography Software for Patterning



FIB Implantation Resolution

What our resolution?

What is the needed resolution?

High Energy FIB

Spot Size ~ 1 μm

Alignment accuracy ~ 1 μm

Overall resolution ~ 1-2 μm

Low Energy FIB

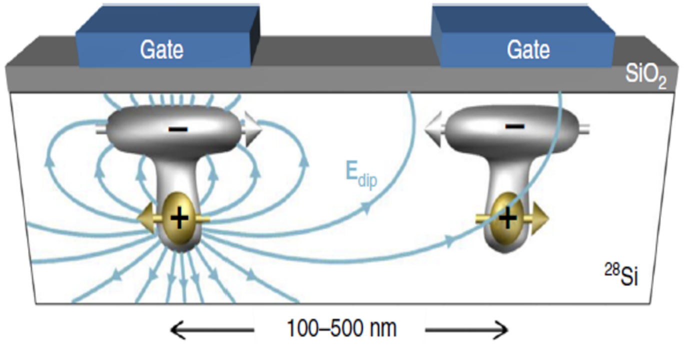
Spot Size ~ few nm

Alignment accuracy ~ 10’s nm

Overall resolution ~ 20-50 nm

Silicon quantum processor with robust long-distance qubit couplings

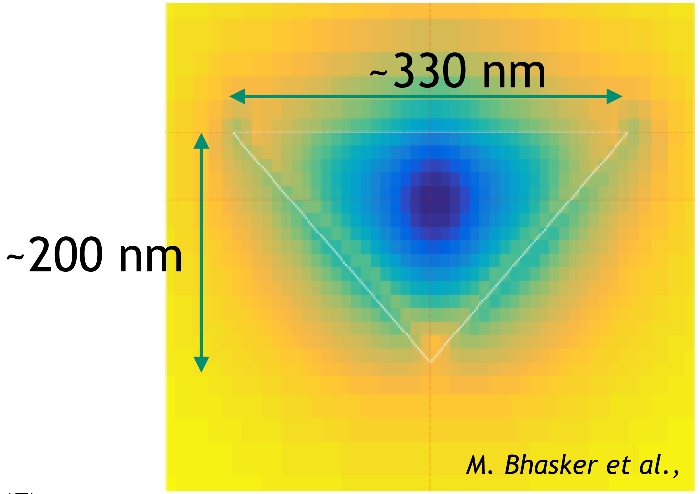
Guilherme Tosi[1], Fahd A. Mohiyaddin[1,3], Vivien Schmitt[1], Stefanie Tenberg[1], Rajib Rahman[2], Gerhard Klimeck[2] & Andrea Morello[1]



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

- Depth z_d = 15-20 nm ☑
- Separation of 100-500 nm ☑

Nanophotonic Applications



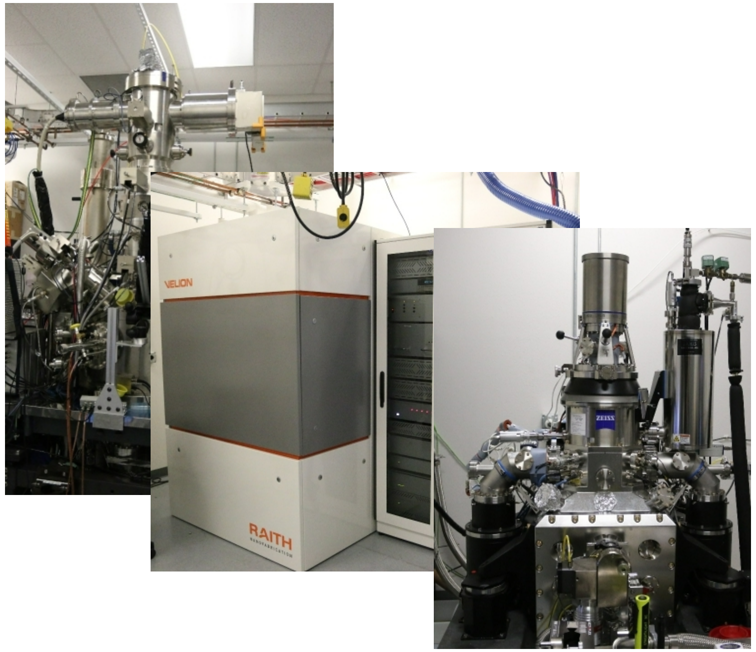
Center of mode is ~ 55 nm below the surface of the waveguide ☑

Low Energy Implantation? Lateral Positioning – OK, Target Depth – OK!

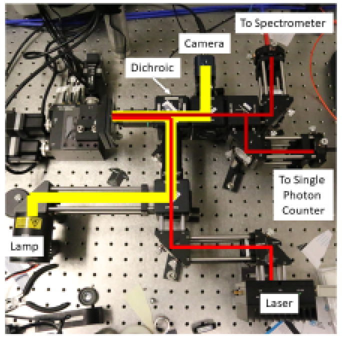
Practical Example of FIB Implantation

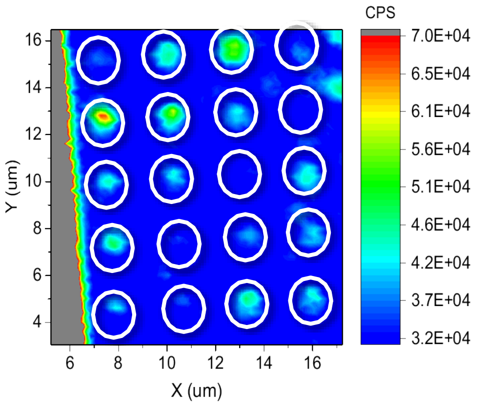
Conversation of what is needed?

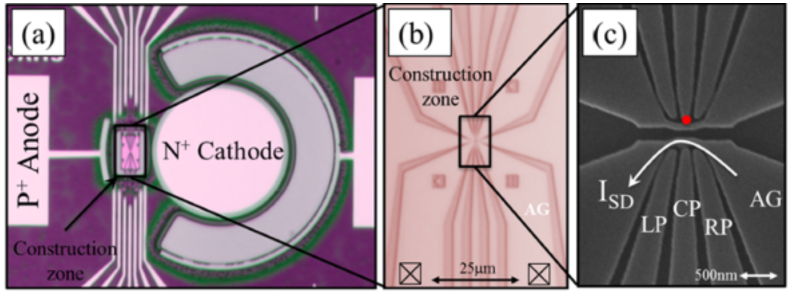
FIB Implantation/Irradiation



Post Implantation Characterization

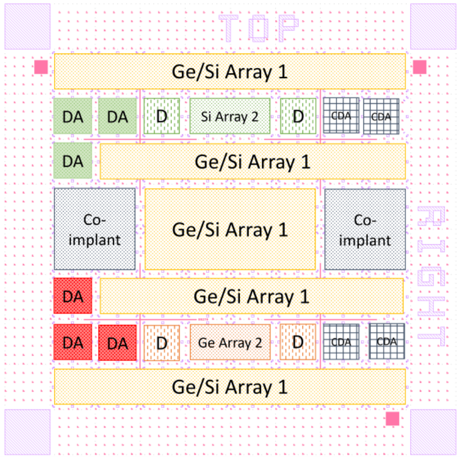


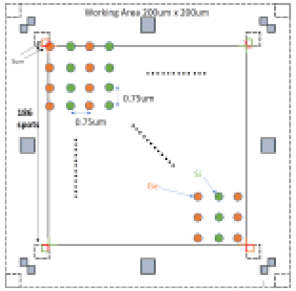




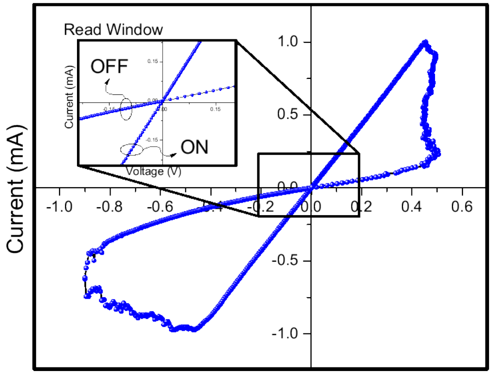
J. Pachaco, *et al*., *Rev. of Sci. Instr.* (2017)

Design and layout of sample





Post Implantation Sample Prep



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

How can you access these capabilities? CINT User Proposals

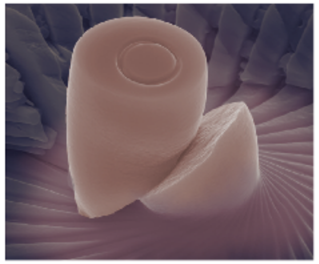
THE CENTER FOR INTEGRATED NANOTECHNOLOGIES

One Scientific Community Focused on Nanoscience Integration

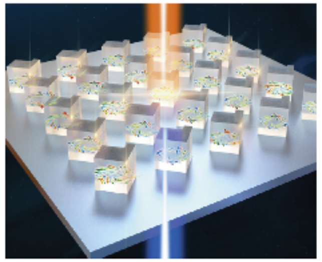
The Center for Integrated Nanotechnologies (CINT) is a Department of Energy Office of Science Nanoscale Science Research Center. CINT offers world-leading scientific expertise and specialized capabilities to create, characterize, and integrate nanostructured materials at a range of length scales, from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

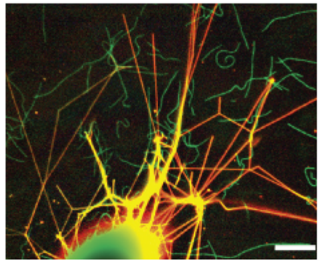
Integration is the key to exploiting the novel properties of nanoscale materials and creating new technologies. CINT's scientific staff and capabilities are organized around four interdisciplinary science thrusts which address different challenges in nanoscience integration.



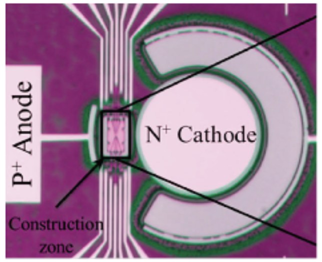
In-Situ Characterization and Nanomechanics
Developing and implementing world-leading capabilities to study the dynamic response of materials and nanosystems to mechanical, electrical, or other stimuli.



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.



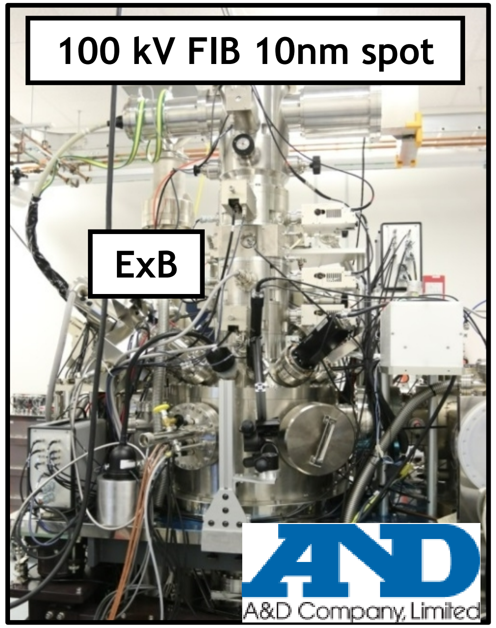
Quantum Materials Systems
Understanding and controlling quantum effects of nanoscale materials and their integration into systems spanning multiple length scales.

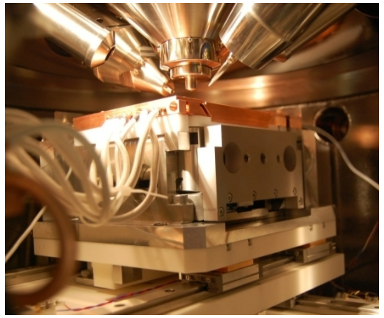
User Program

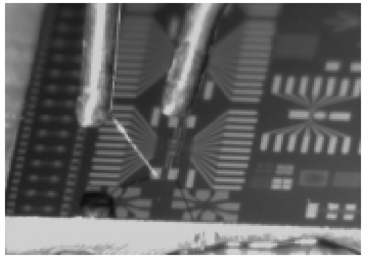
CINT is an Office of Science national user facility. CINT helps the international research community perform cutting-edge research in the areas of nanoscience and nanotechnology, and is available free of charge for open science. As a user facility, CINT has the structure and mission to collaborate widely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

https://cint.lanl.gov/

Focused Ion Beam Implantation - nanoImplanter (nI) and Velion







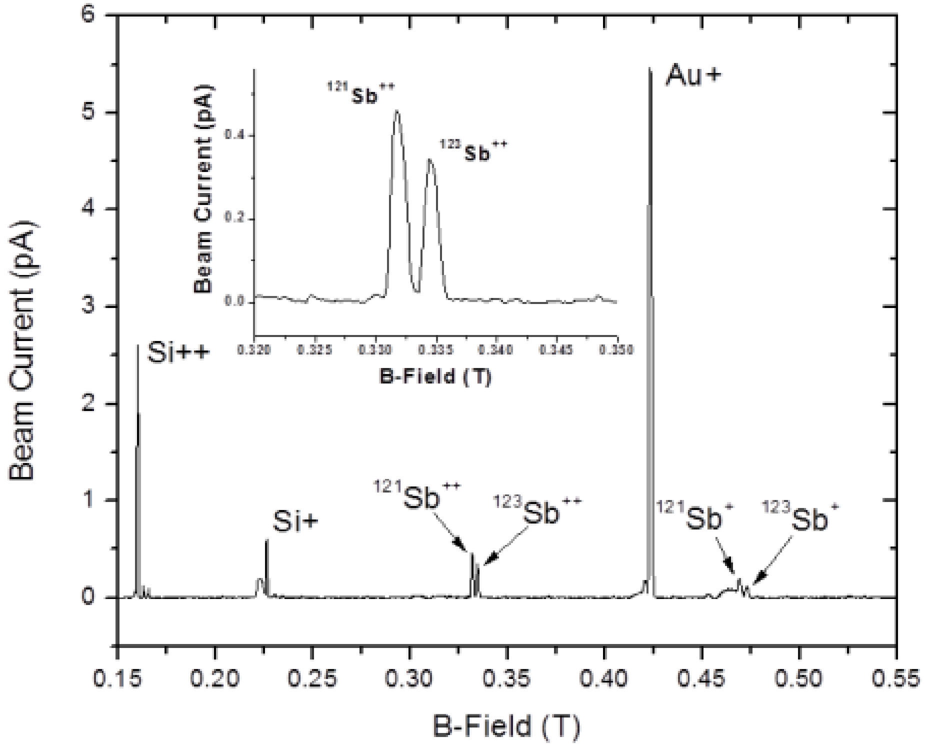
- Focused ion beam system (FIB)
  → nm beam spot size on target
- ExB Filter (Wien Filter)
  → Multiple ion species
  e.g., Li, Si, P, Sb, etc… (separating out ^{28}Si, ^{29}Si, etc…)
- Fast blanking and chopping
  → Single ion implantation
- Direct-write lithography
  → nm targeting accuracy

RAITH NANOFABRICATION

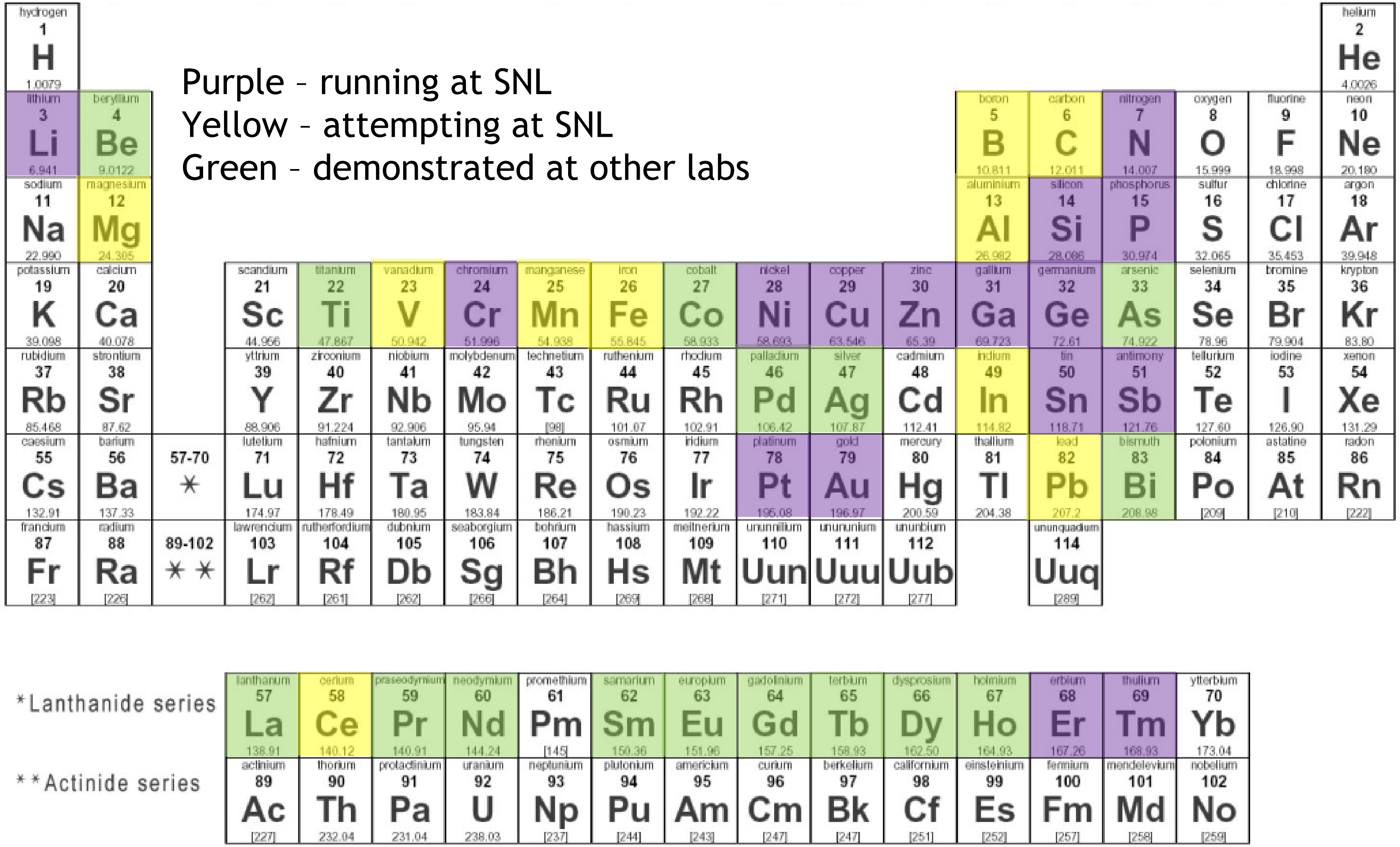
- Low temperature stage
- In-situ electrical probes

kleindiek nanotechnik

Sb Source: Mass Spectrum



Liquid Metal Alloy Ion Sources (LMAIS) for FIB Implantation



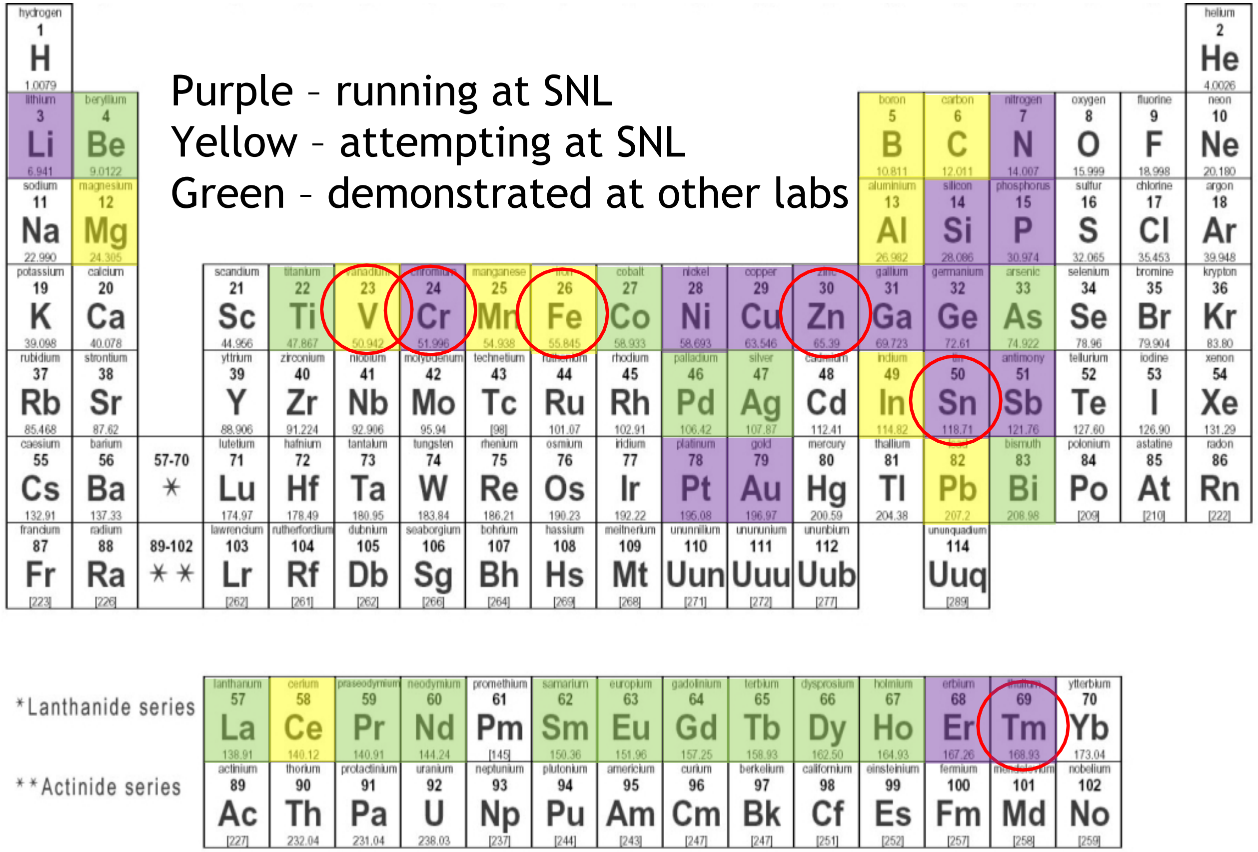
L. Bischoff, *et al.*, Applied Physics Reviews **3**, 021101 (2016)

After A. Weick University of Bochum

Wide Variety of Ion Species Available

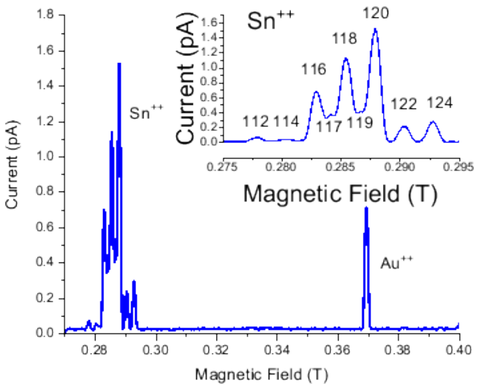
New Sources – V, Cr, Fe, Zn, Sn, Tm (easy-ish)

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

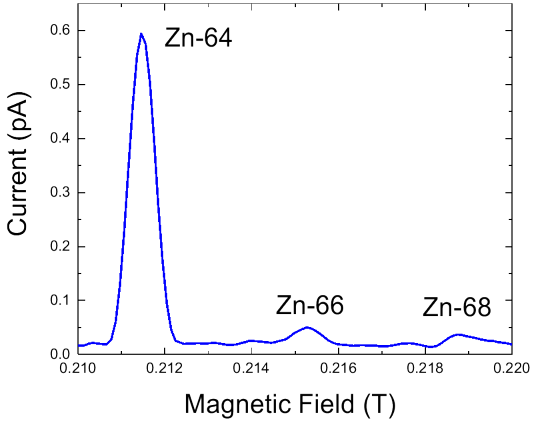


- Based on AuSiX or AuGeX alloys
- Easy to wet the tip and easy to run

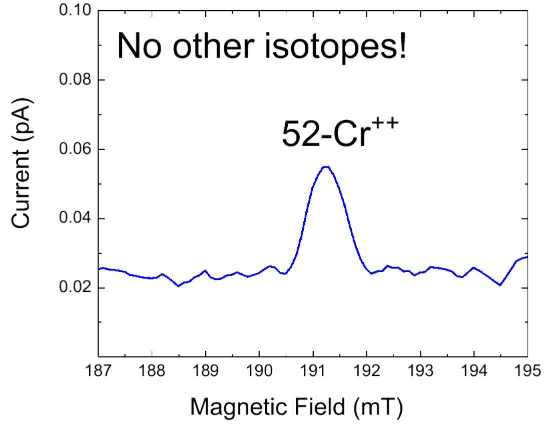
AuSn



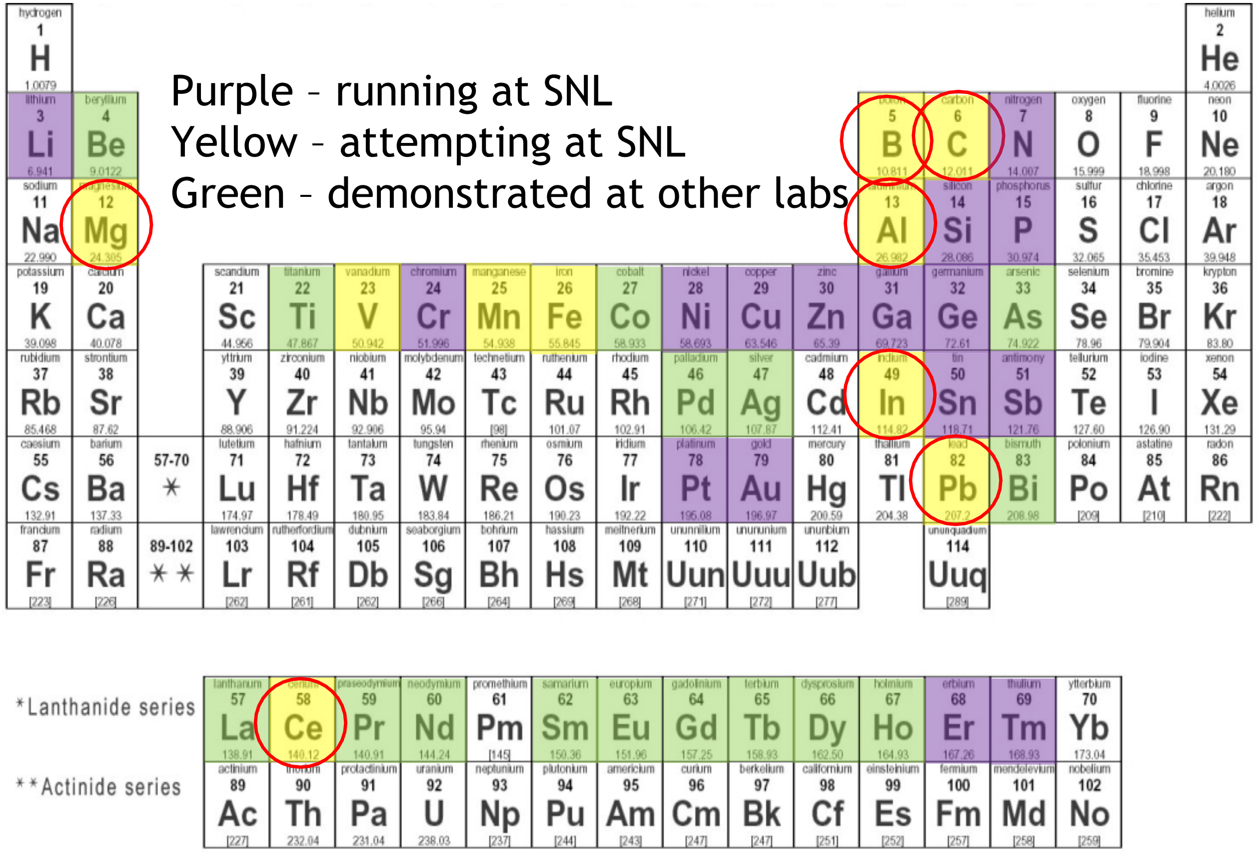
AuSiZn



AuGeCr

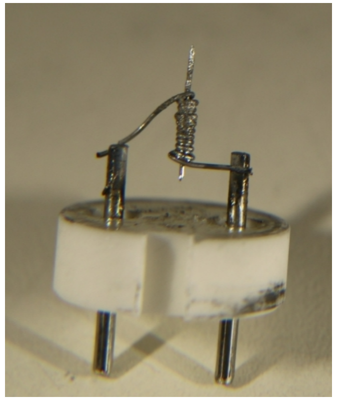


New Sources – B, C, Al, Ce, Mg, In, Pb (Hard)



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

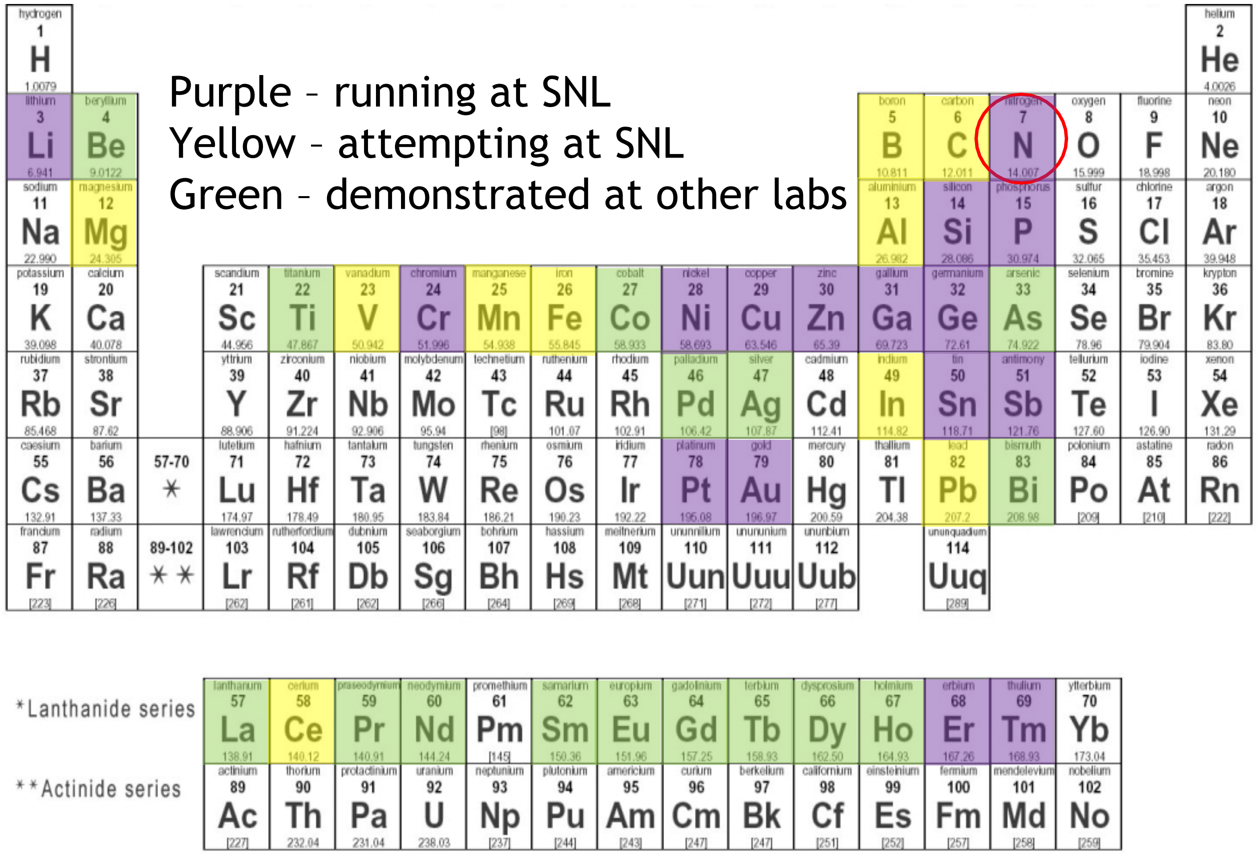
- B
  → Hard to load into the alloy BAuGeNi
- C, Al, Ce
  → AlCeC alloy oxides while running, killing beam
- Mg
  → GaMg alloy oxides in the boat
- Pb
  → PbSn alloys with W tip, working on new materials



SNL SnPb tip on Kovar wire

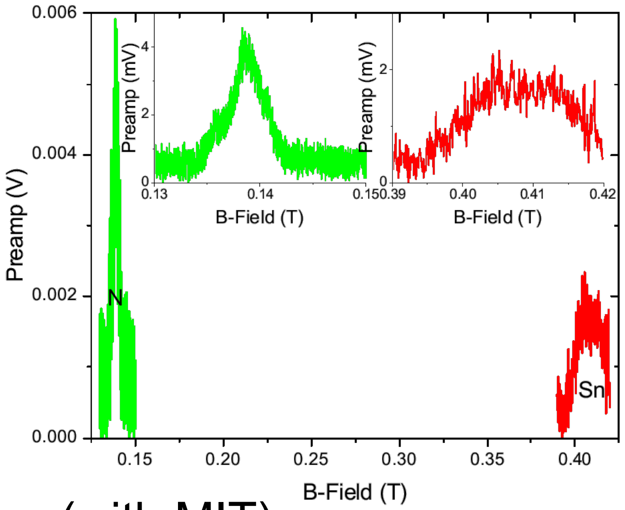
New Sources – N (How to do???)

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

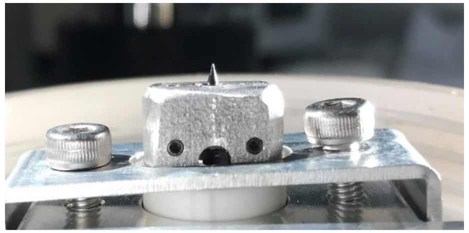


(1) Liquid metal alloys with implanted N

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

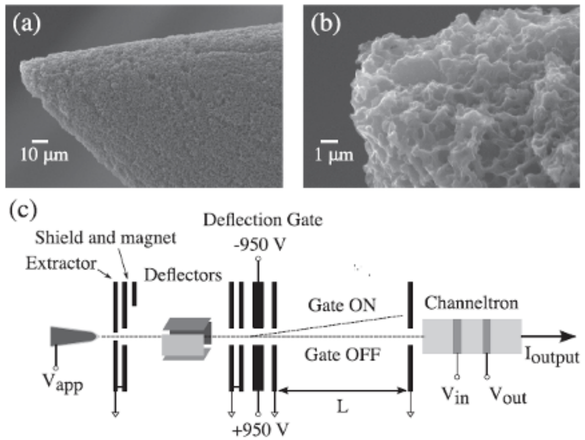


(2) Ionic Liquid Ion Source (with MIT)



(At SNL for testing)

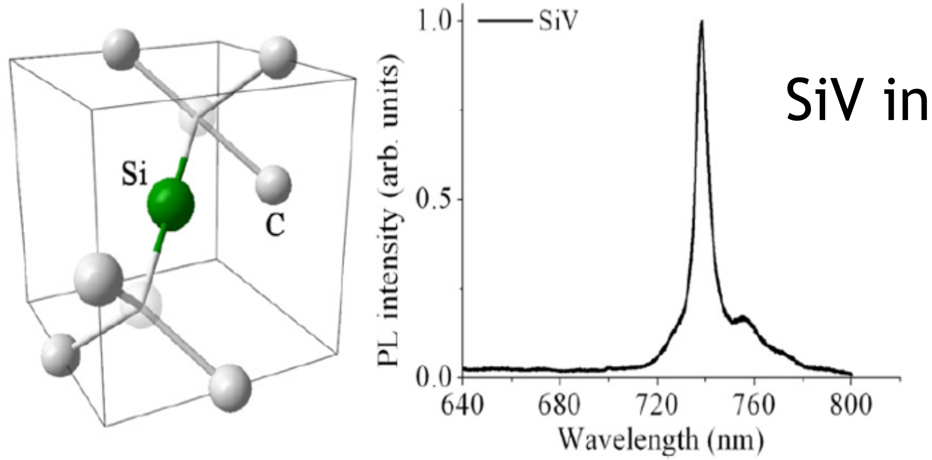
Carbon Xerogel Microtip with ILIS



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

Example: Color Center formation 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?

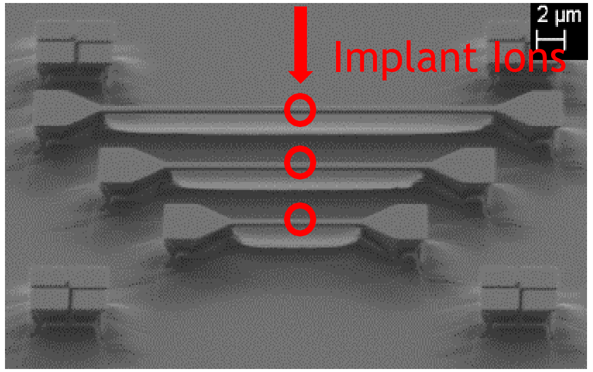
How to produce a ***single*** color center ***where*** you want it?

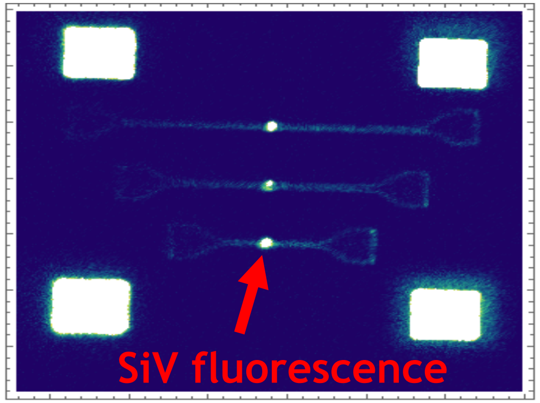
1.) Location – use focused ion beam implantation

2.) Yield – use counted implantation with single ion detection

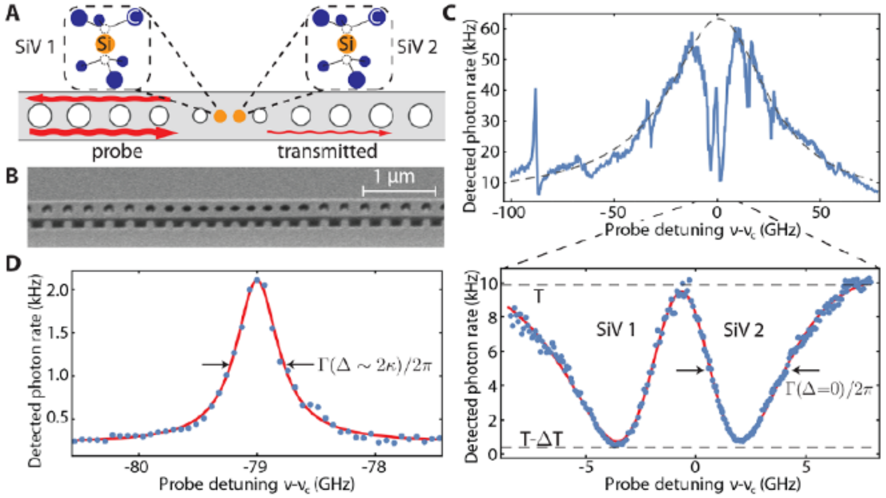
Location Problem is Solved using FIB Implantation

Diamond Nanobeams (with Harvard)



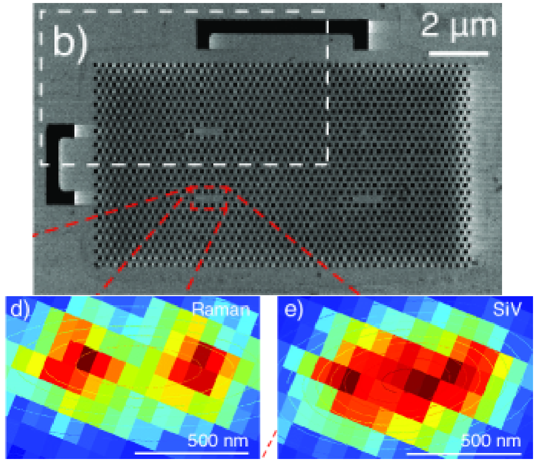


A. Sipahigil, *et al.*, *Science* (2016)



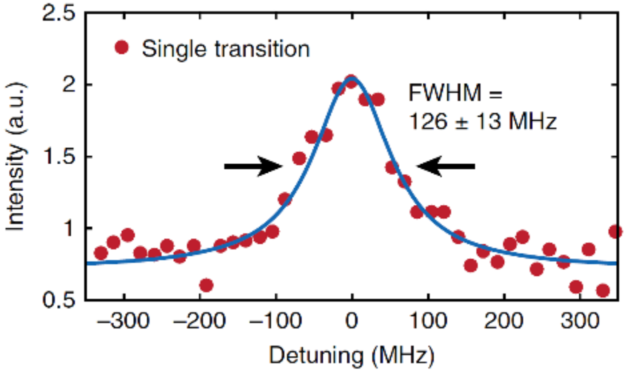
R. E. Evans, *et al.*, *Science* (2018)

2D photonic Crystals (with MIT)



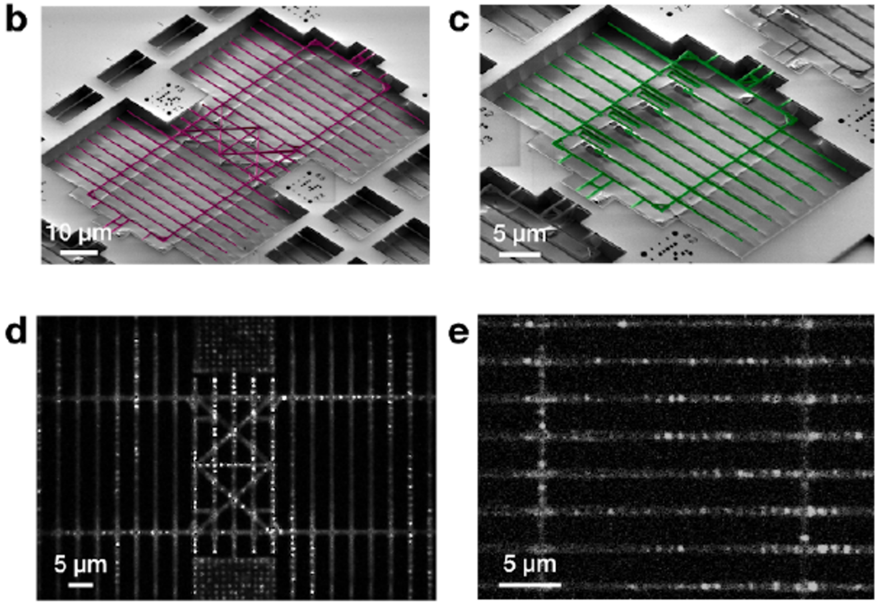
Accuracy is <50 nm

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



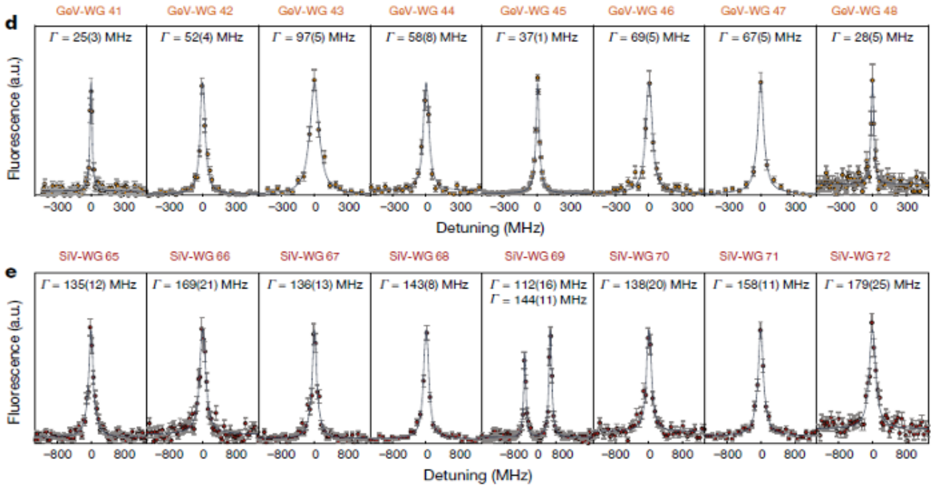
Location Problem is Solved using FIB Implantation

Diamond waveguides with AlN photonics (with MIT)

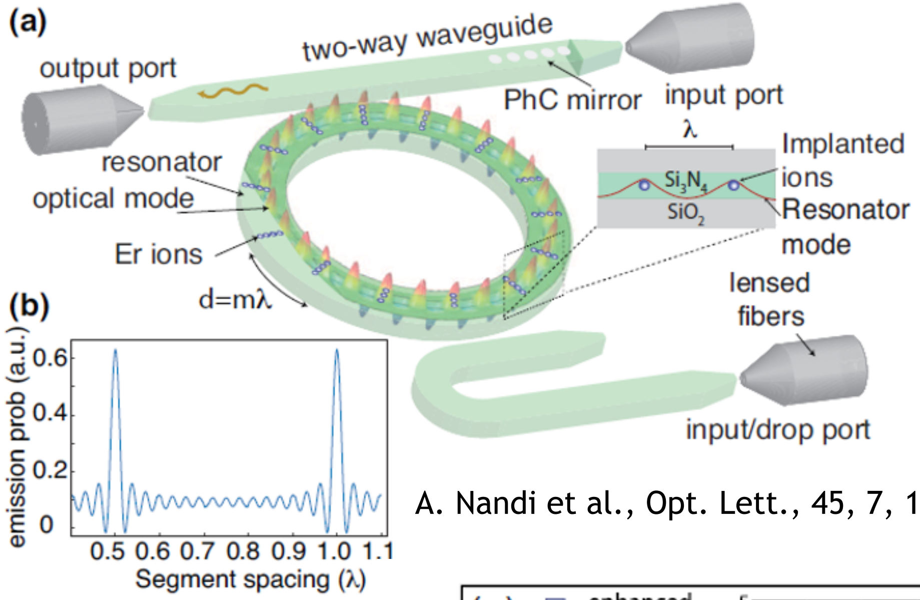


16 and 8 channel "quantum micro-chiplets"

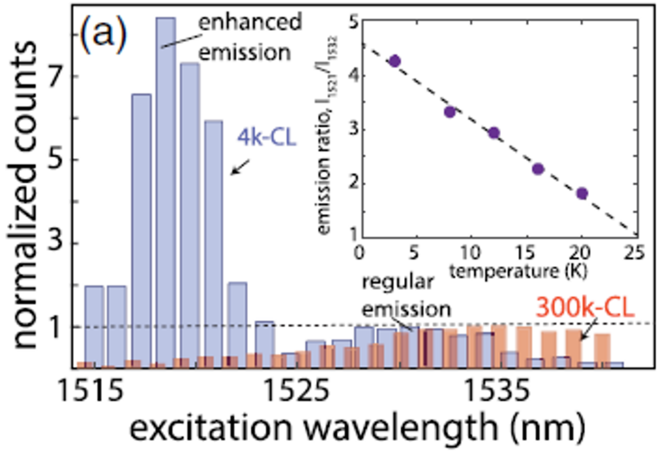
Noel H. Wan et al., Nature, 583, 226–231(2020)



Silicon Photonics (with Purdue)



A. Nandi et al., Opt. Lett., 45, 7, 1631 (2020)



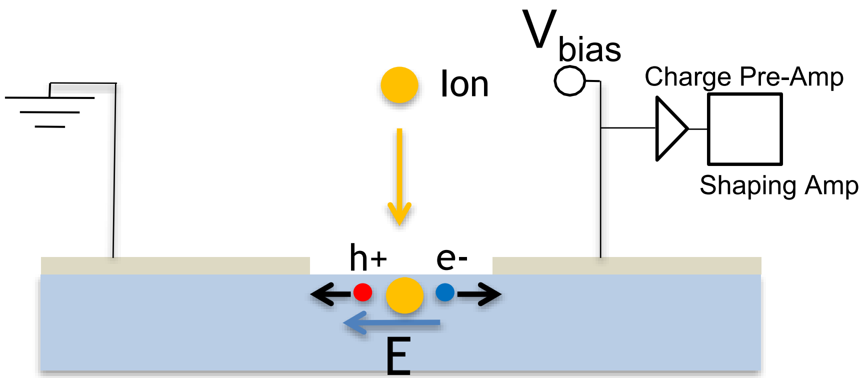
Use Counted Implantation to Better Understand Yield

Yield = # measured SiV / # implanted Si

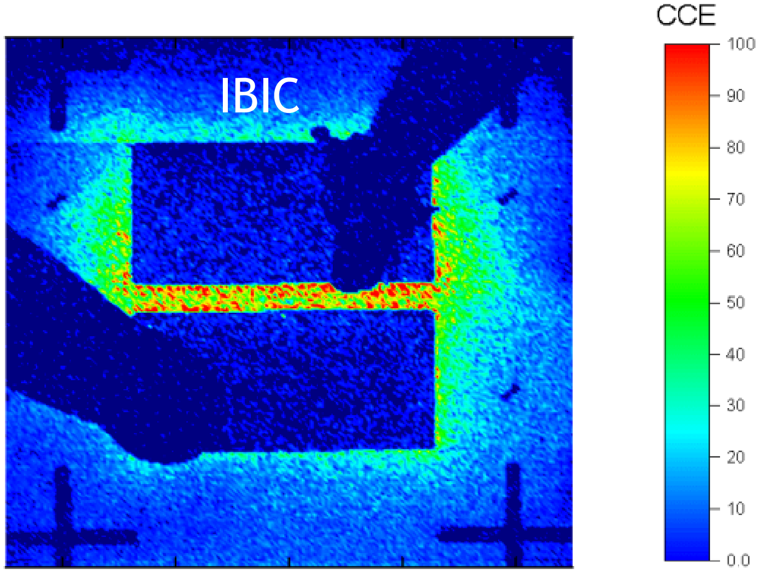
Poisson Statistics

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

Ion Beam Induced Charge (IBIC)



Side View

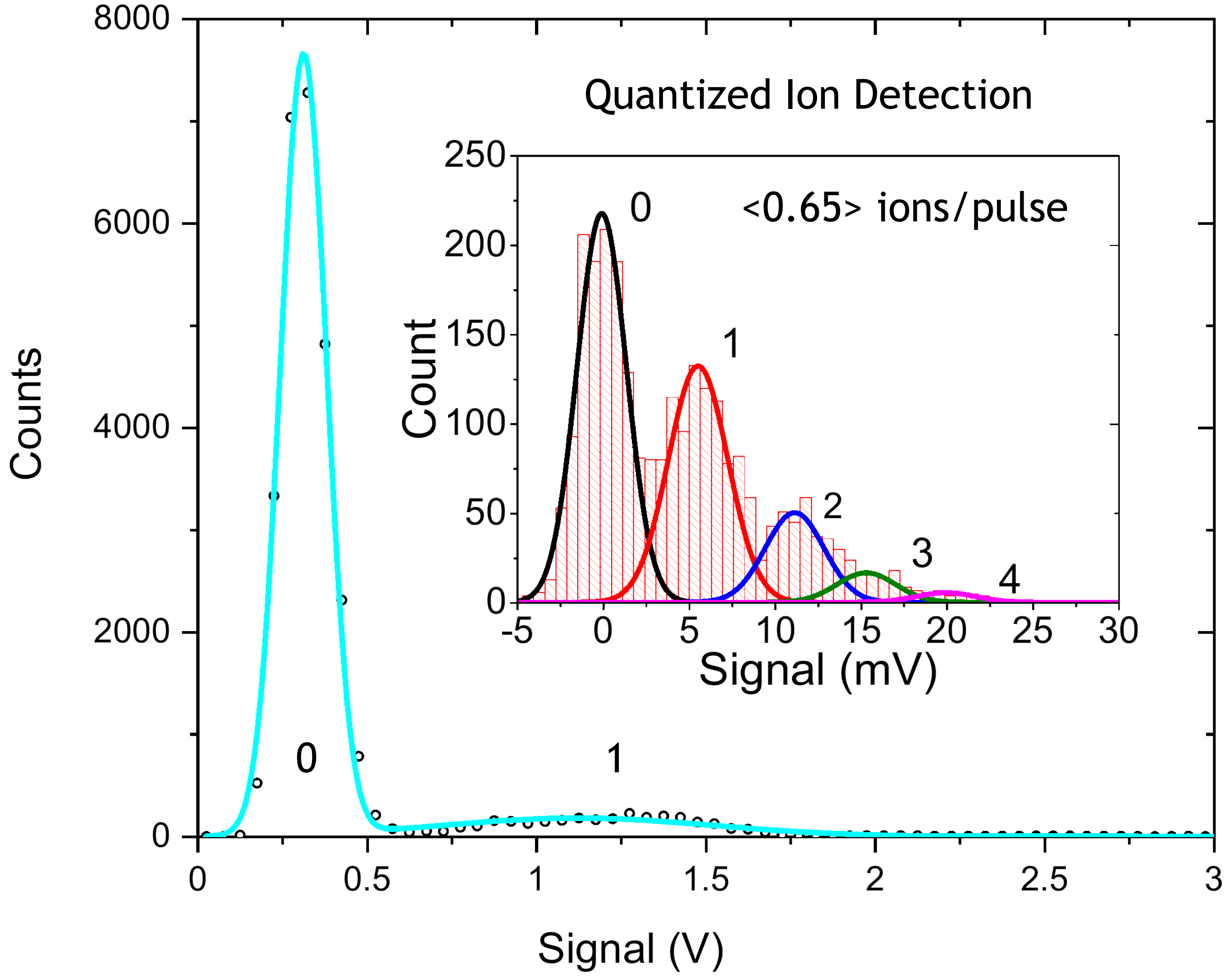


$$CCE = \frac{\text{Charge Collected}}{\text{Charge Depositied}} \times 100$$

IBIC/detection demonstrated for low energy heavy ions

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

Single Ion Diamond Detection at <0.1> ions/pulse



Signal-to-noise ratio

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

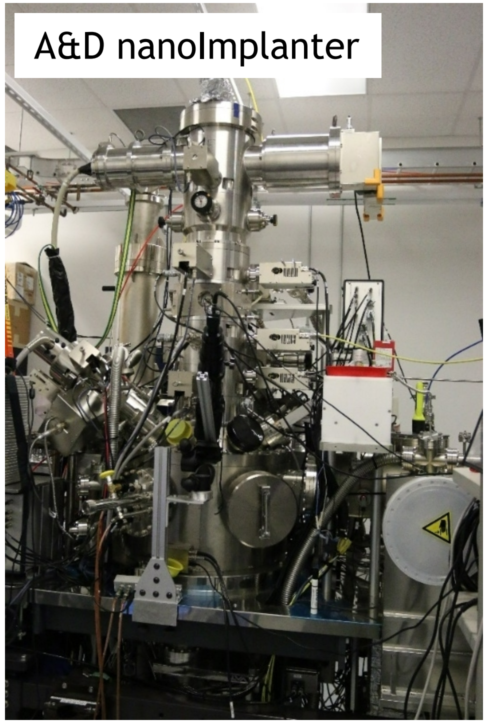
SNR = 4.7

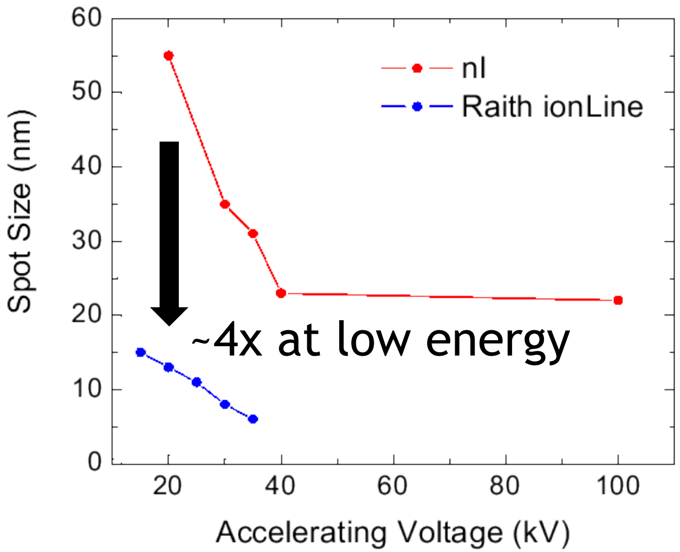
Good distinction between 0 and ≥1 ion

See S51-00008 M. Titze at 1:18-1:30 pm for more details

What's Next…… Raith Velion

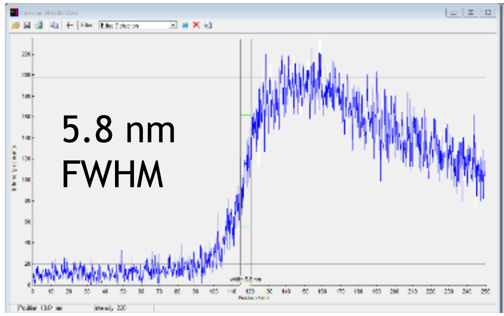
Work-horse Installed Jan'11 → New capability Installed Feb'20

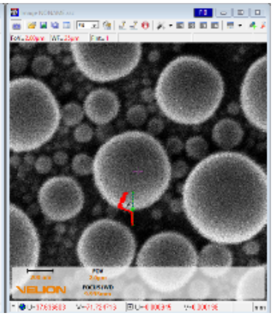


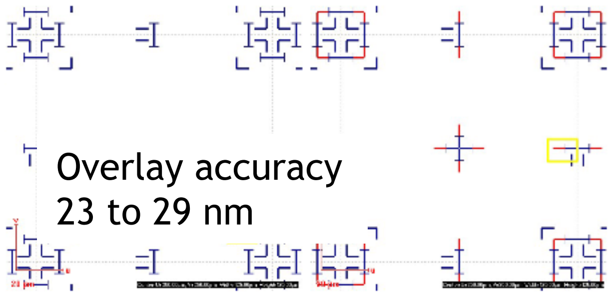


- 100 kV accelerating potential
- LMAIS with 10 nm spot
- Spot blows up at low energy (~50-60 nm)
- Implantation resolution 40-50 nm

- 35 kV accelerating potential
- LMAIS with <6 nm spot



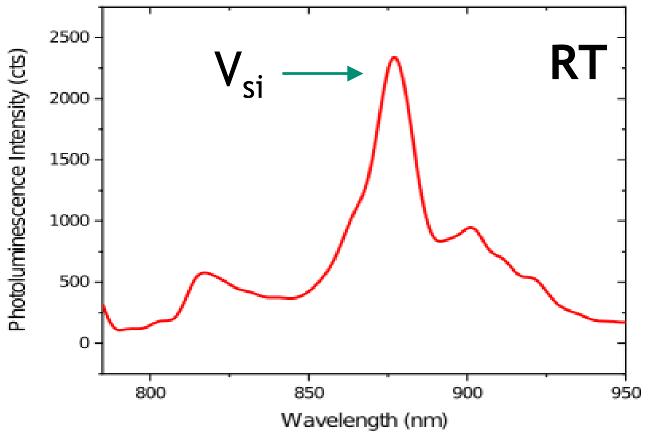




Allows for higher resolution, lower energy implantation

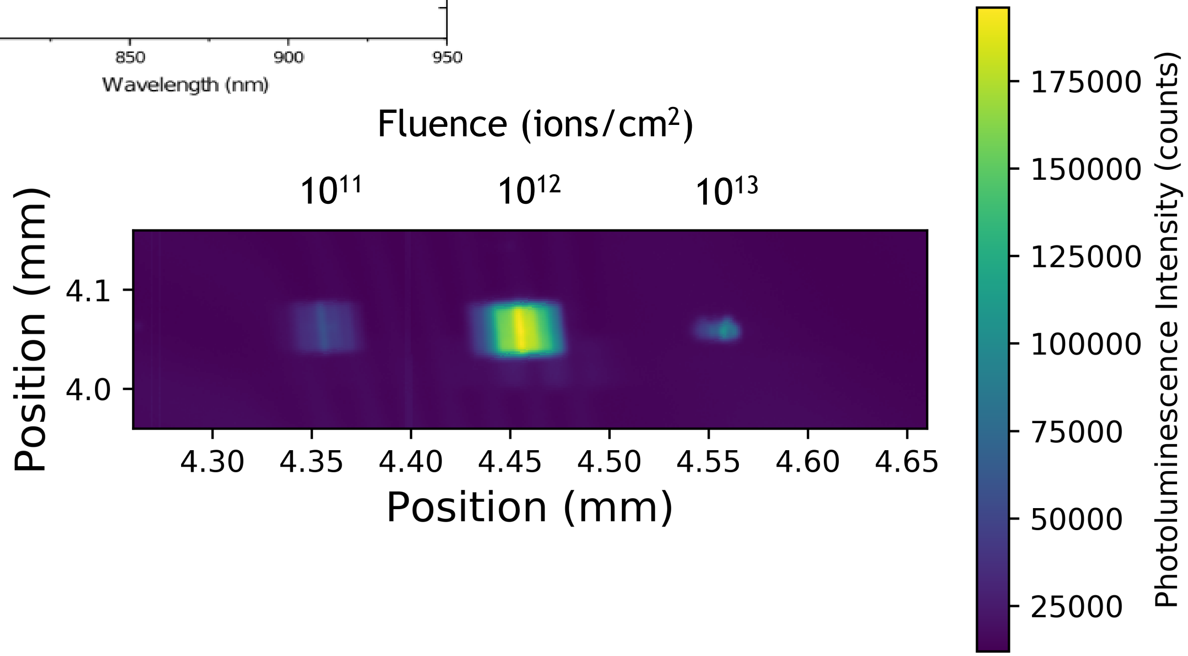
What's Next…… In-situ Photoluminescence in SiC

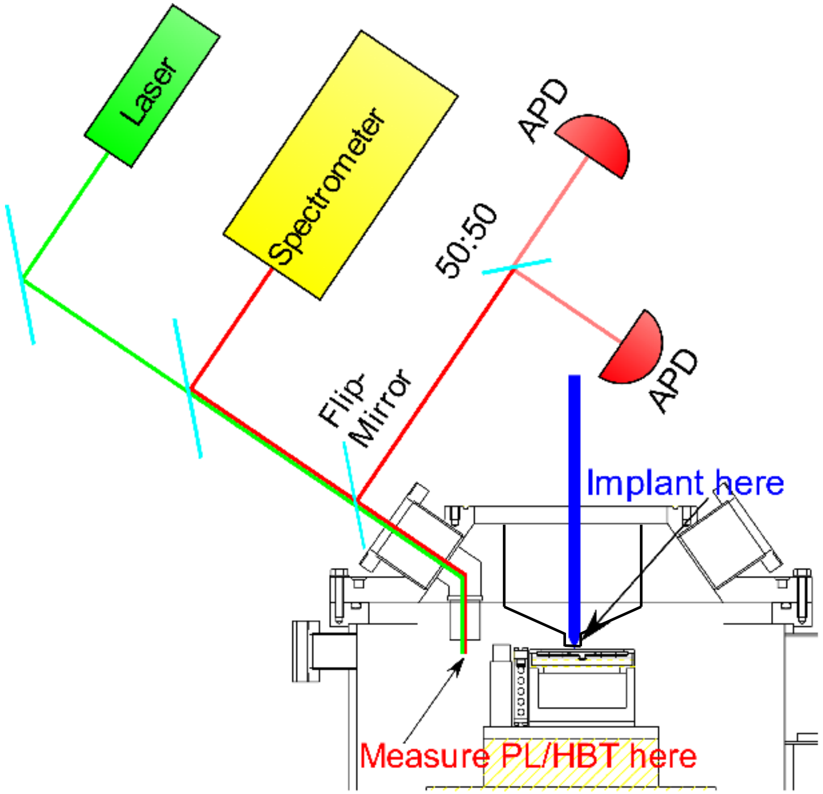
Ex-situ V_{si} Photoluminescence → **In-situ V_{si} Photoluminescence**



- SiC FIB implanted with 300 keV He (3 MV Pelletron)

- RT Emission from V_{si} w/o annealing





- Two-step process enabled by high resolution implantation:

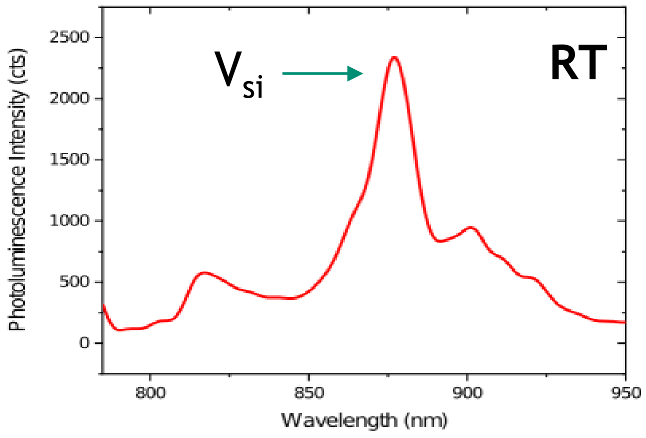
  (1) Aligned implantation, <40 nm

  (2) Detect PL

Will allows for fully ***deterministic*** defect center formation

What's Next…… In-situ Photoluminescence

Ex-situ V_{si} Photoluminescence → **In-situ V_{si} Photoluminescence**



- SiC FIB implanted with 300 keV He (3 MV Pelletron)
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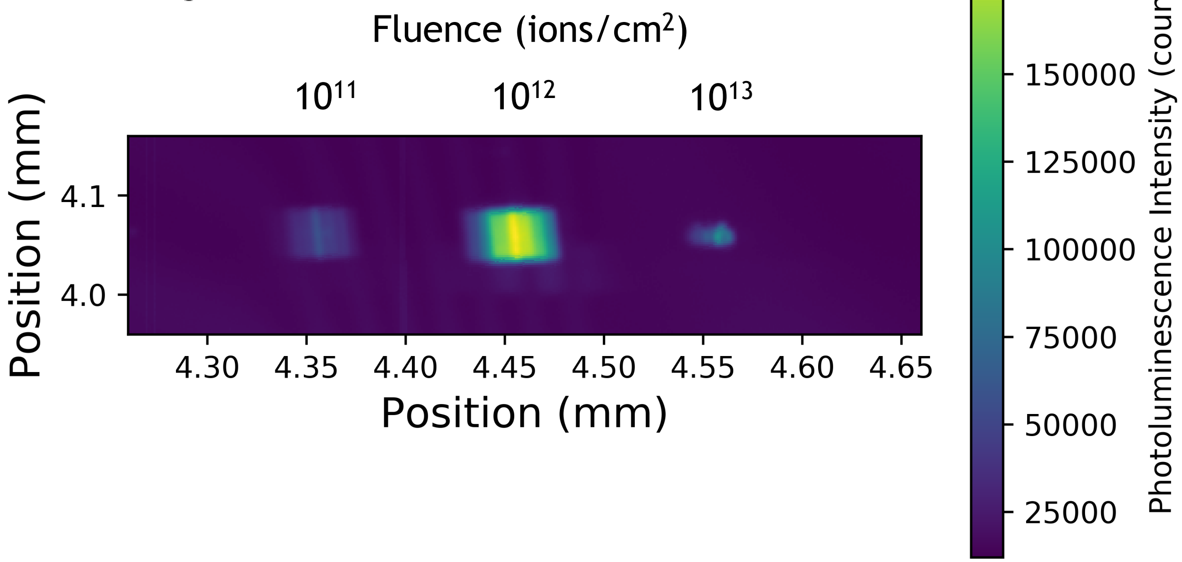
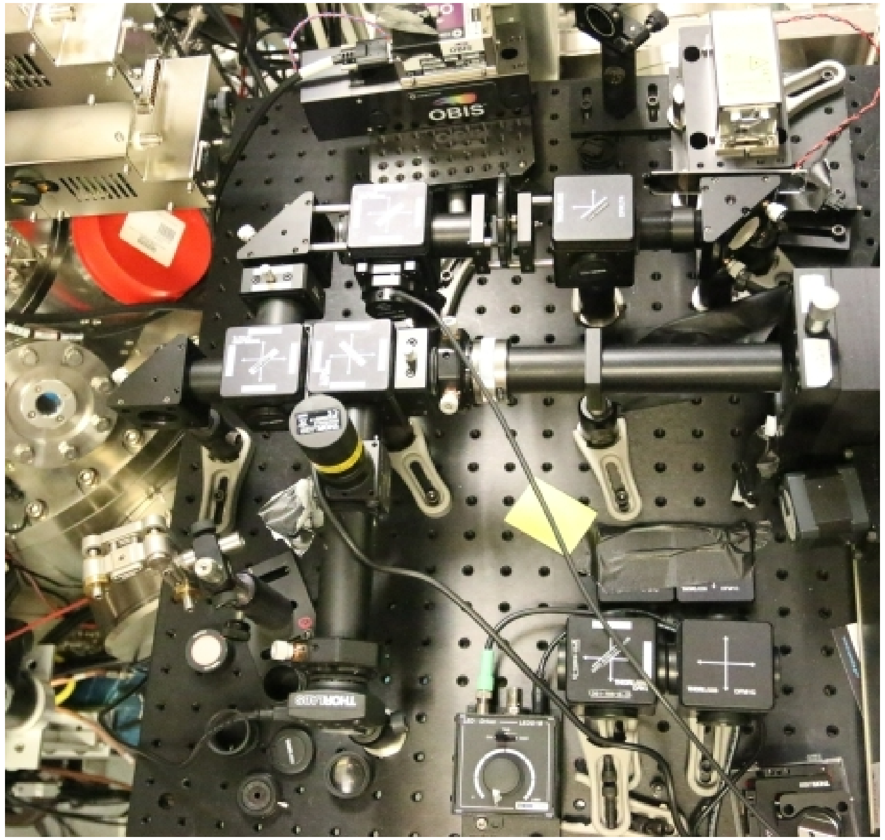




See S51-00008 M. Titze at 1:18-1:30 pm for more details

Will allows for fully ***deterministic*** defect center formation

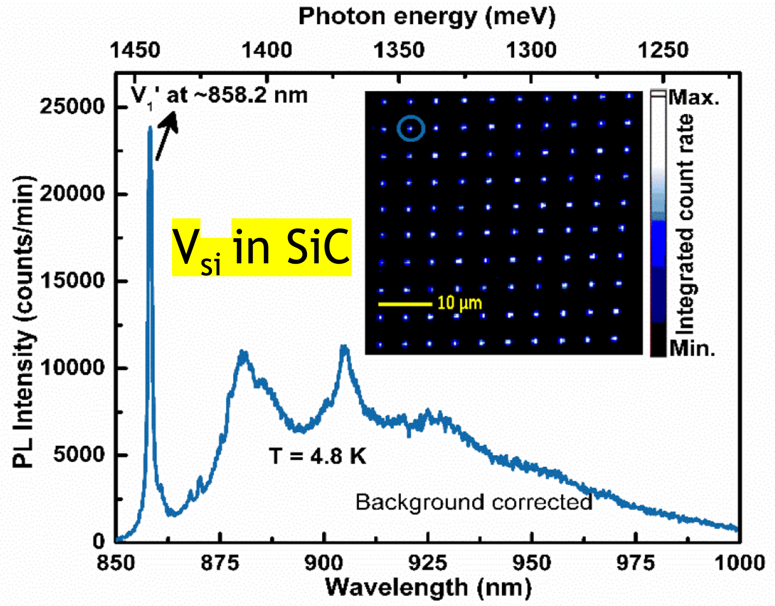
Acknowledgements

Sandia has developed strong internal ion beam implantation and optical groups

- M. Titze, W. Hardy, J. L. Pacheco, J. B. S. Abraham, G. Burns, A. Flores, G. Vizkelethy (SNL)
- M. Zaibari, Jacoby Henshaw, L. Basso, H. Byeon, A. Mounce, P. Keyayias, M. Lilly (SNL)
- V. Chandrasekaran, Han Htoon (LANL)
- V. Costa (UNM)

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

Summary



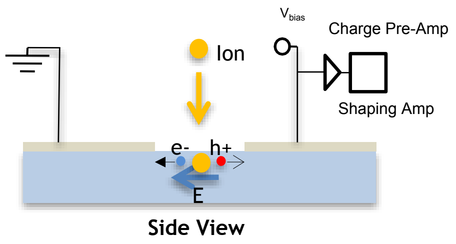
S. Pavunny et al., Scientific Report **11**, 3561 (2021)

- We have demonstrated focused ion implantation for fabrication of single atom devices and nanofabrication

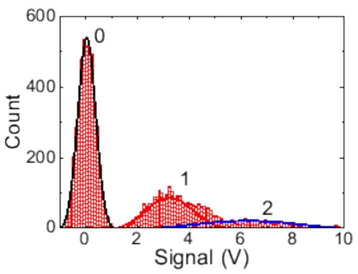
→ Viable solution for prototyping – fast and easy!

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

- Path Towards Deterministic Defect Centers in Wide Bandgap Materials



+



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

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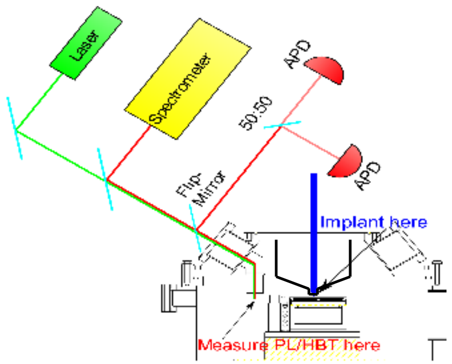

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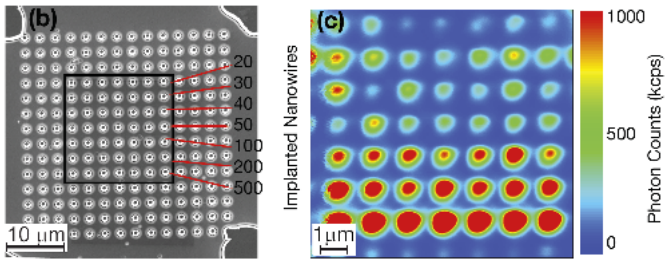


L. Marseglia, *et al.*, *Optics Express* (2018)

https://cint.lanl.gov/

Control the number of ions

Measure number of single photon emitters

Extra Slides

Overview of High Resolution Implantation Techniques

Resolution

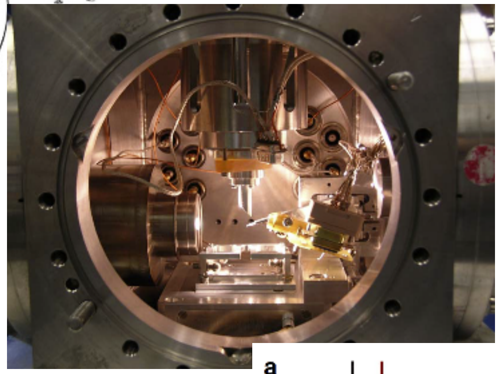
(1) Hydrogen Lithography

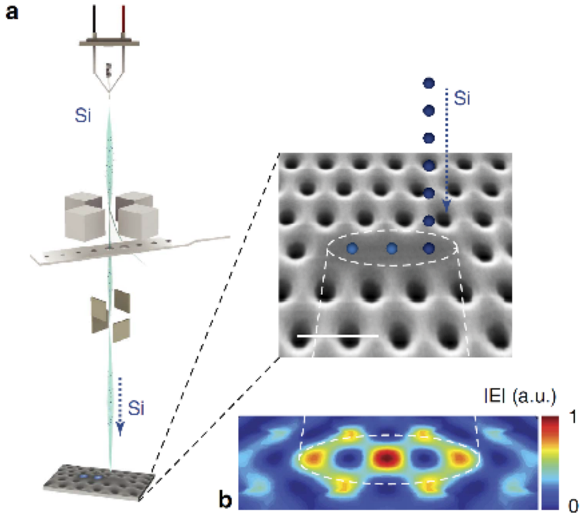
(2) Probe Based Implantation

(3) Focused Ion Beam (FIB) Implantation

(4) Masked Implantation

Speed

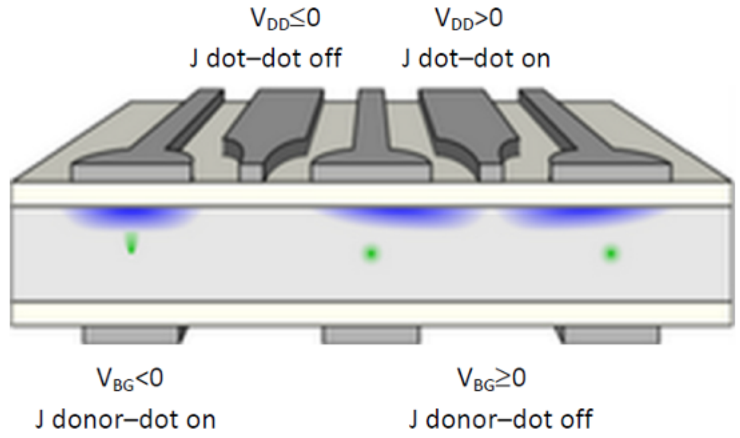




Needed Resolution for Si Qubit Applications

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)

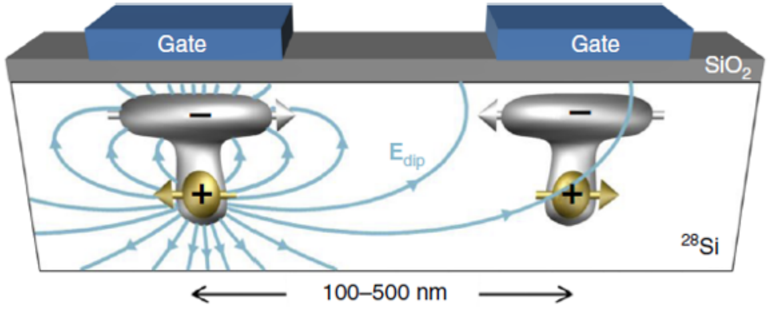


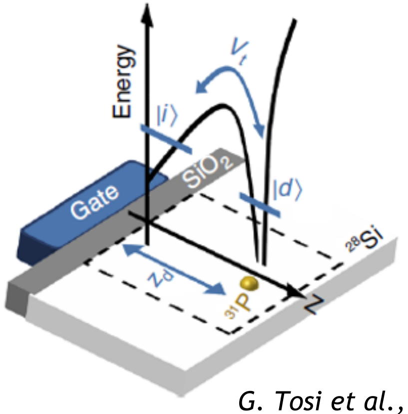
T. Schenkel et al., US 8,816,325 B2 (2014)

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

Silicon quantum processor with robust long-distance qubit couplings

Guilherme Tosi[1], Fahd A. Mohiyaddin[1,3], Vivien Schmitt[1], Stefanie Tenberg[1], Rajib Rahman[2], Gerhard Klimeck[2] & Andrea Morello[1]





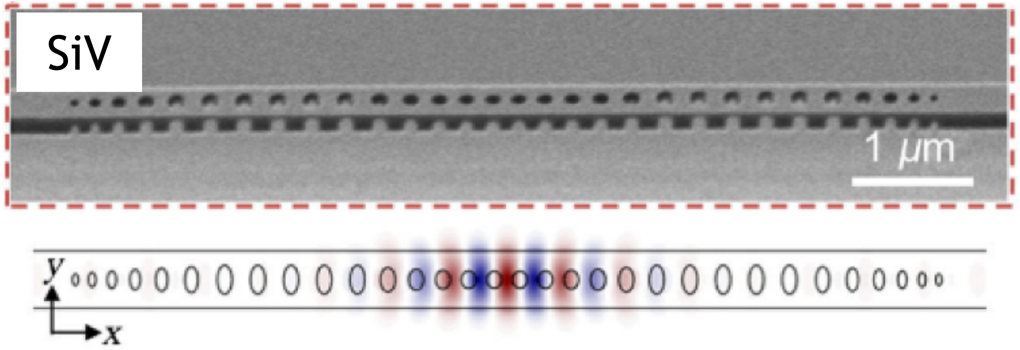
- Depth z_d = 15 nm or larger
- Separation of 100-500 nm

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

FIB Implantation? Lateral Resolution – OK, but Depth Resolution requires low energies!

Needed Resolution for Nanophotonics Applications

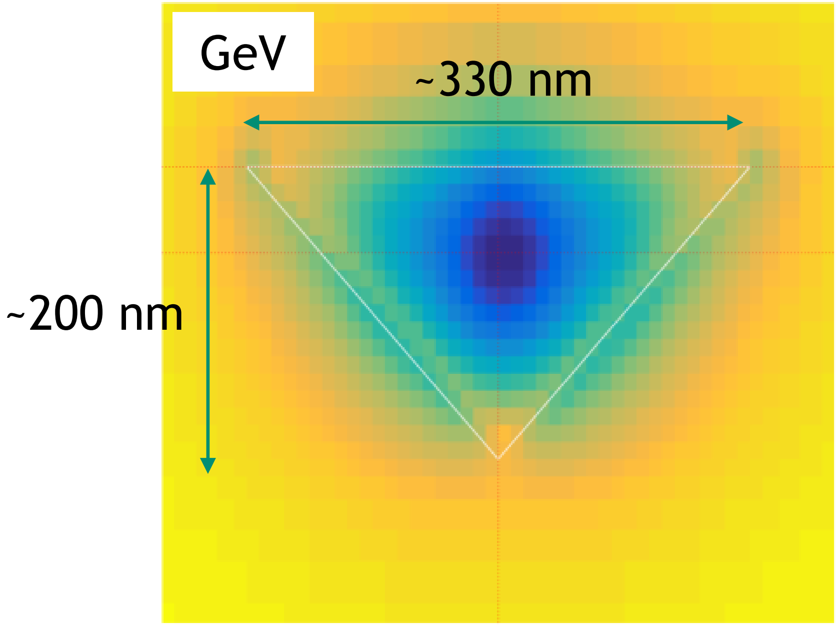
Coupling Diamond defect center to cavity



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

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

Cross-sectional energy profile of cavity mode



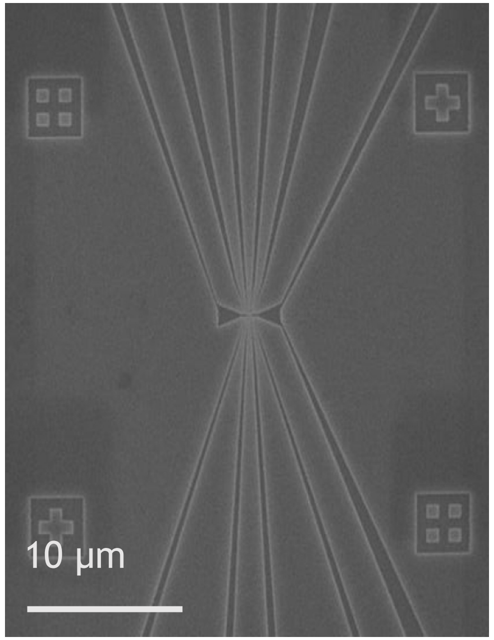
Center of mode is ~ 55 nm below the surface of the waveguide

M. Bhasker et al.,

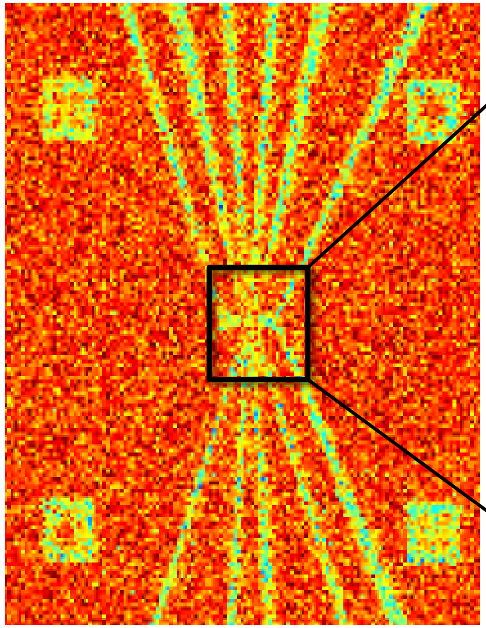
FIB Implantation? Lateral Resolution – OK, Depth Resolution – OK!

Targeting Resolution for FIB Implantation

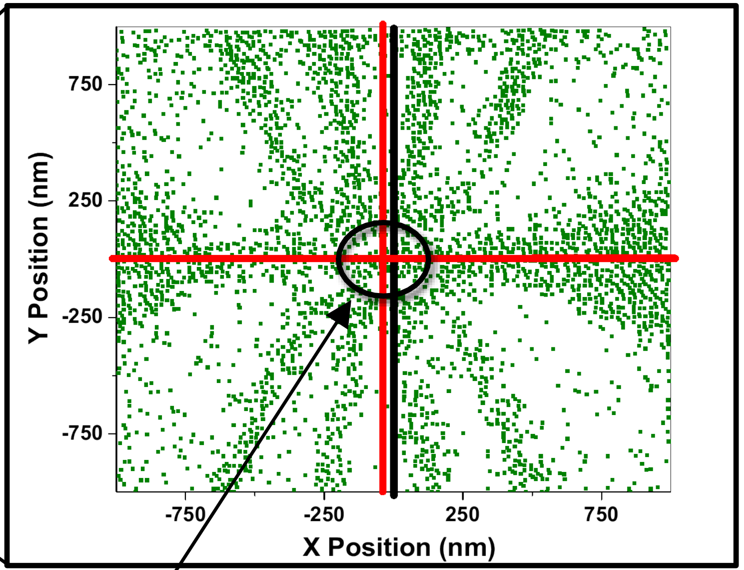
SEM of nanostructure



Ion Beam Induced Charge Collection (IBIC) of nanostructure

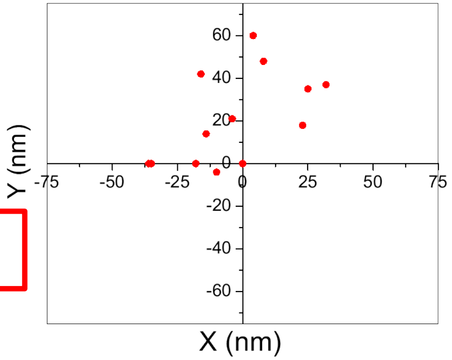


High resolution IBIC for targeting



Δx ~35 nm
Δy ~0 nm

Targeting Acuracy

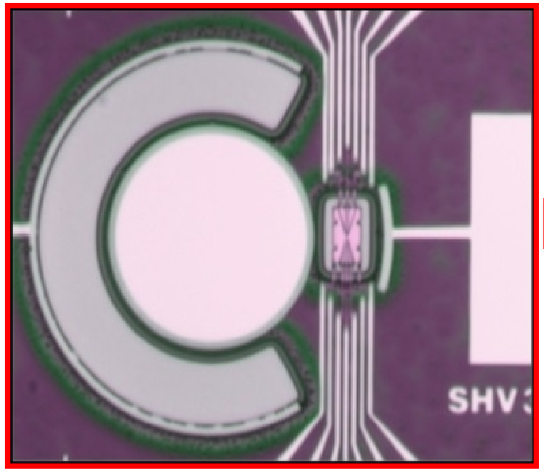


Targeting resolution <40 nm, new Velion should improve this number

How to address the yield question?

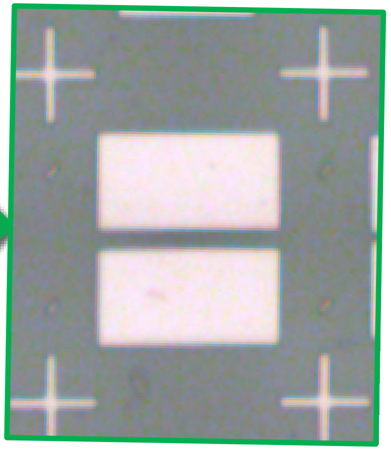
Our Approach is to use single ion detectors to better understand the yield

Silicon



Translating single ion detection to diamond

Diamond



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

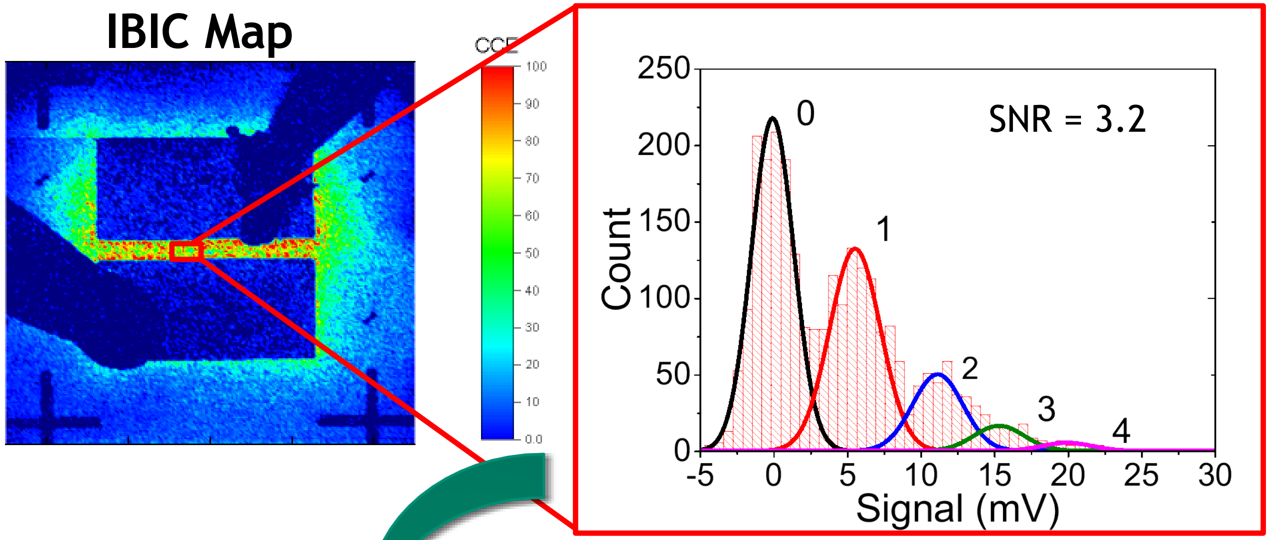
E. Bielejec, *et. al*. Nanotechnology 21, 085201 (2010)

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

Allows us to improve understanding of the yield by directly counting the number of implanted ions

Single Ion Diamond Detectors

IBIC Map **Quantized Detection** <0.65> ion

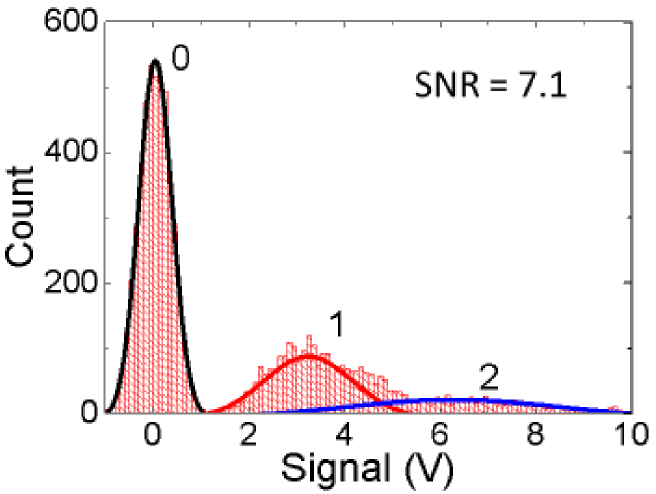


$$SNR = \frac{\mu_{signal}}{\mu_{noise} + \sigma_{noise}}$$

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)

Failure Modes for Single Ion Implantation

Three failure modes:

(1) ***Implant Multiple Ions***

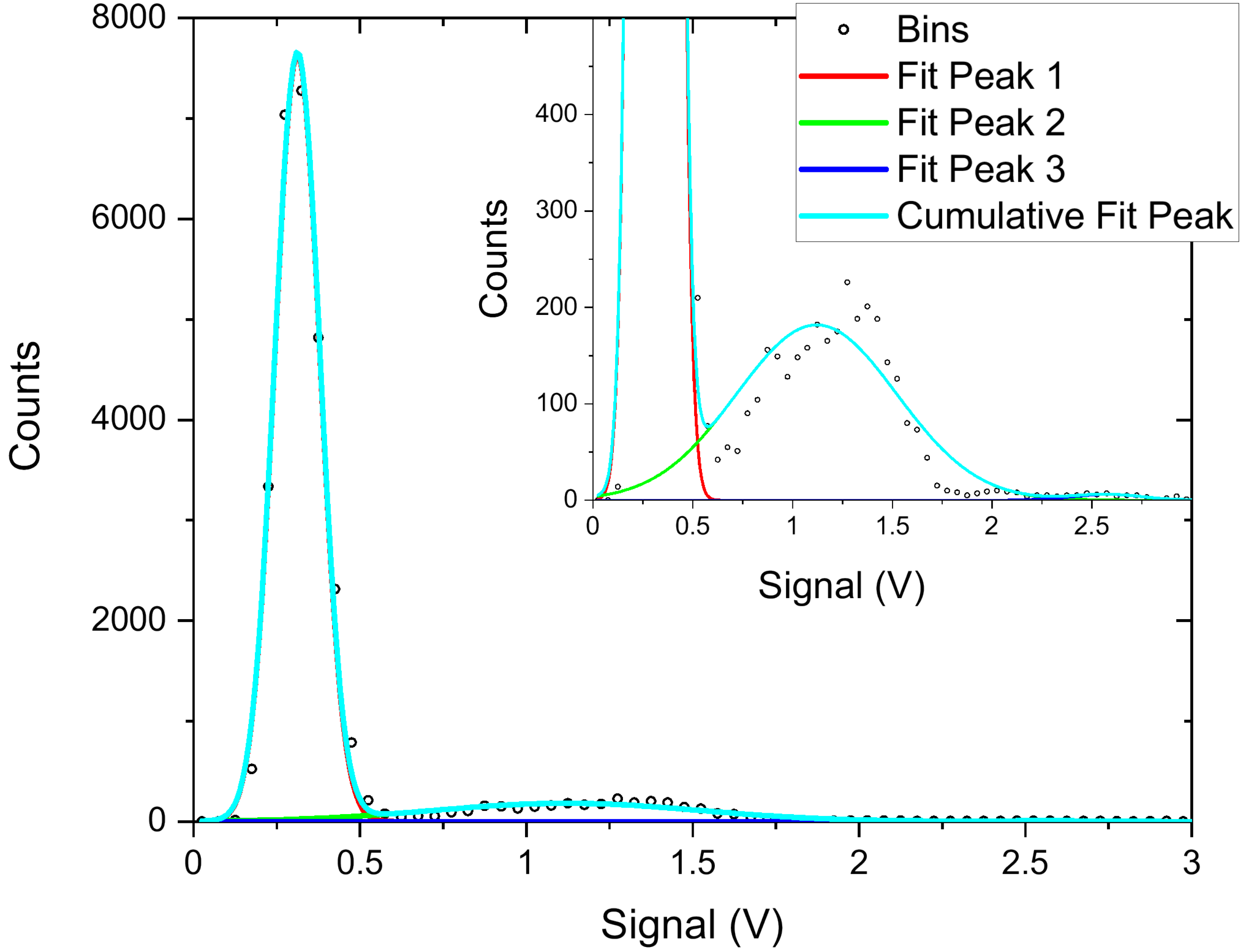
Implant >1, but count as 1

(2) ***False Positive***

Implant 0 ions, but count as 1

(3) ***False Negative***

Implant 1 ion, but count as 0



Failure Mode #1: Implanting Multiple Ions

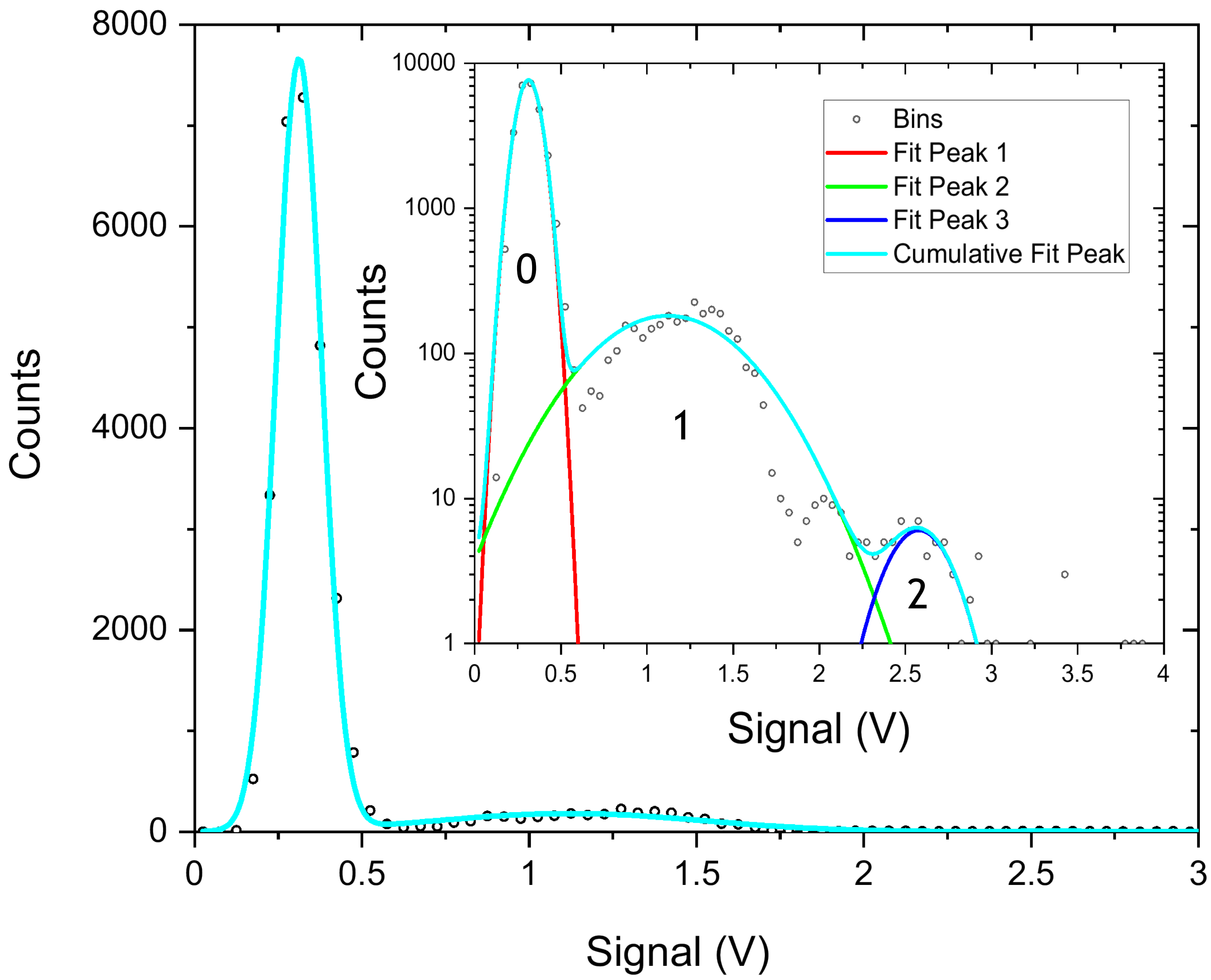
(1) ***Implant Multiple Ions***

Implant >1, but count as 1

Ion implantation follows a Poisson distribution

<0.1> ions/pulse: 90% 0's, 9% 1's and 0.45% 2 or more

Effectively 5% error in # of ions, for example count in 20 singles and get 21 ions



Failure Mode #2: False Positives

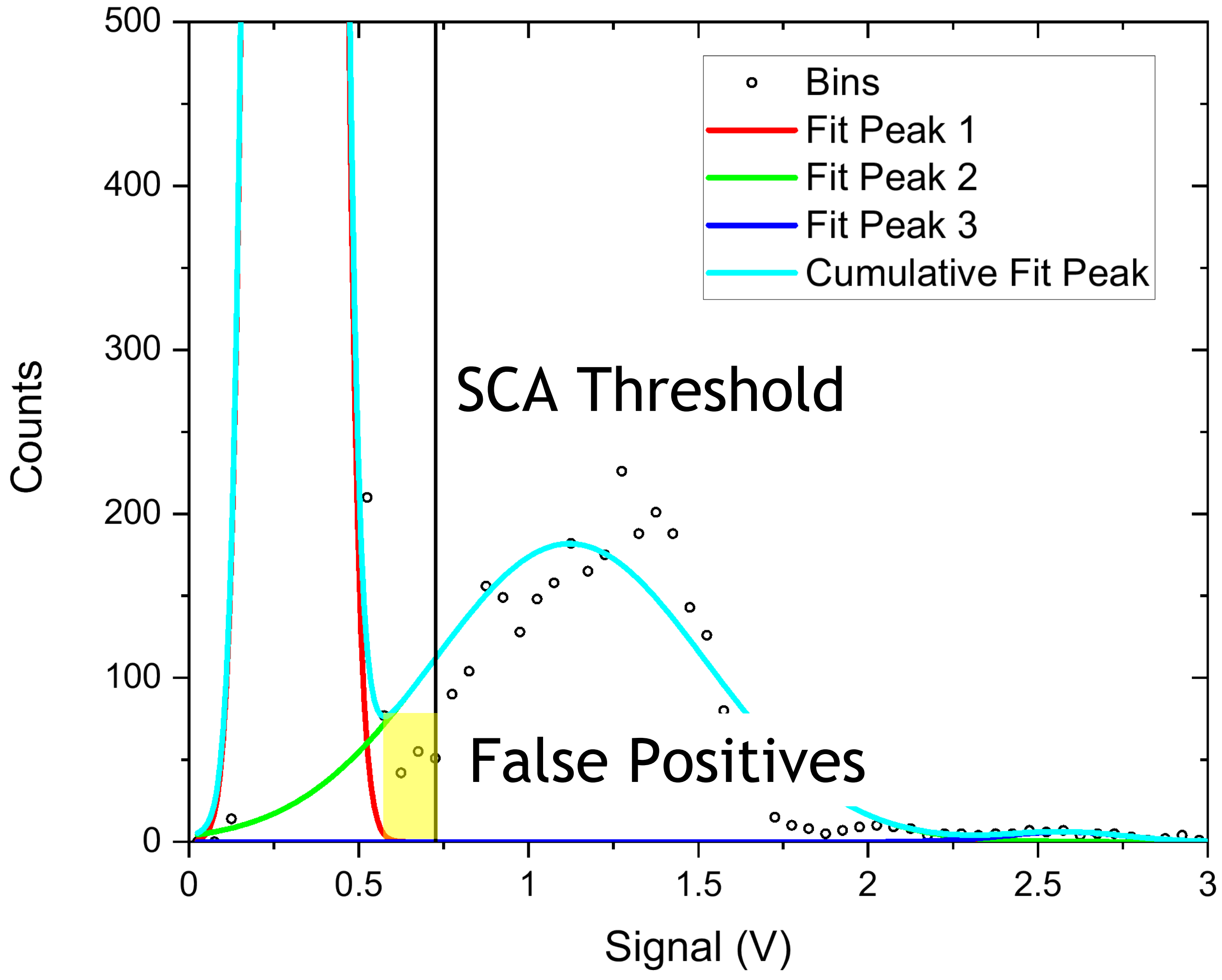
(2) ***False Positive***

Implant 0 ions, but count as 1

In case on right, we have a SNR of 4.7 between 0 and 1

We adjust the SCA threshold to avoid false positives

Leads to practically no (~1 ppb) false positives



Failure Mode #3: False Negatives

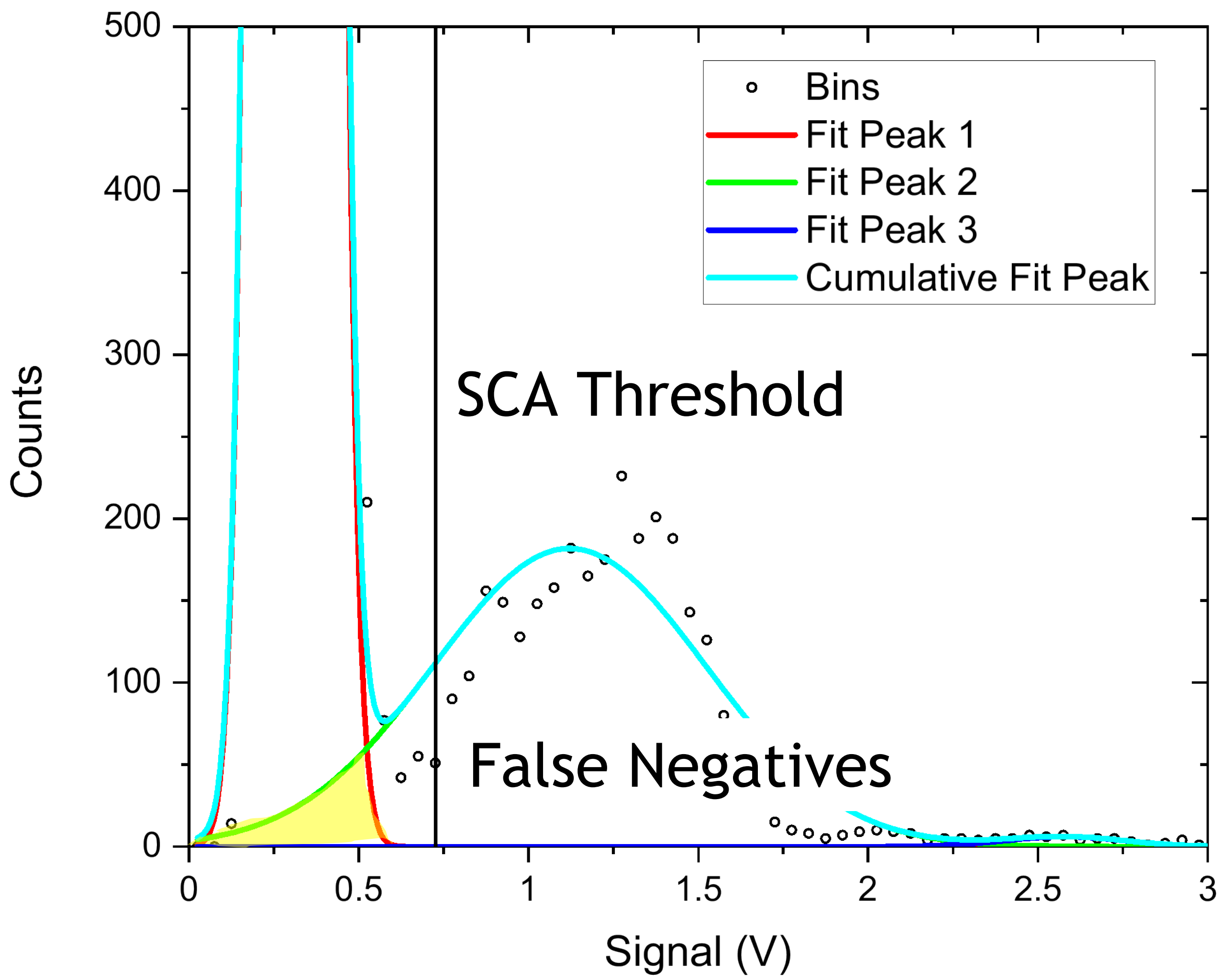
(3) ***False Negative***

Implant 1 ion, but count as 0

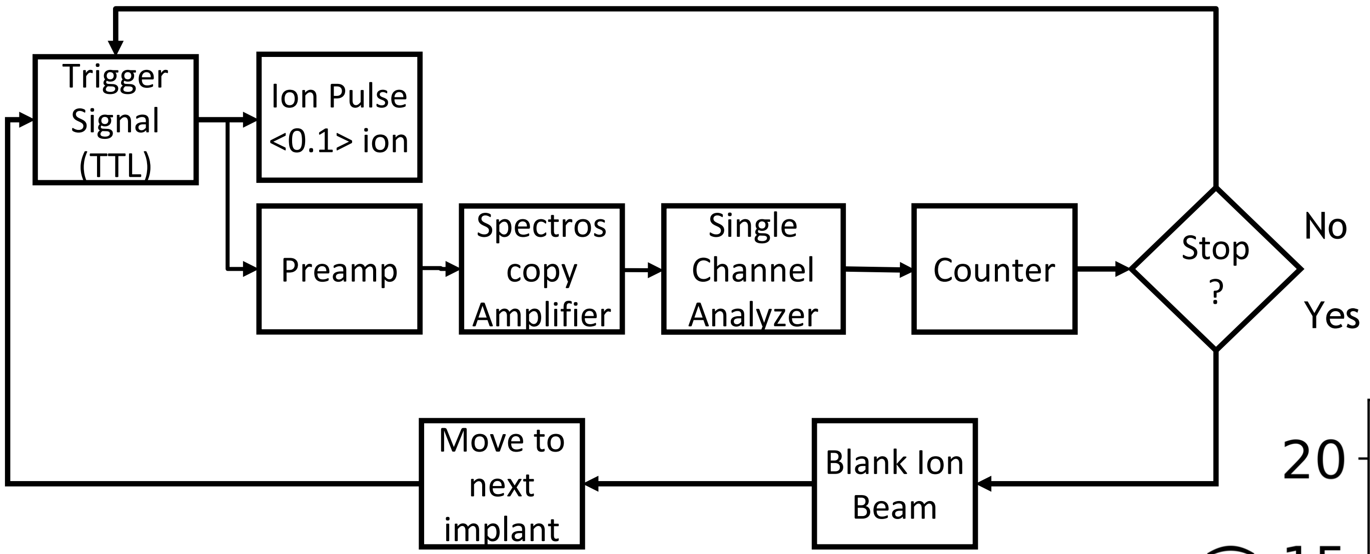
Adjust the SCA threshold to avoid false positives

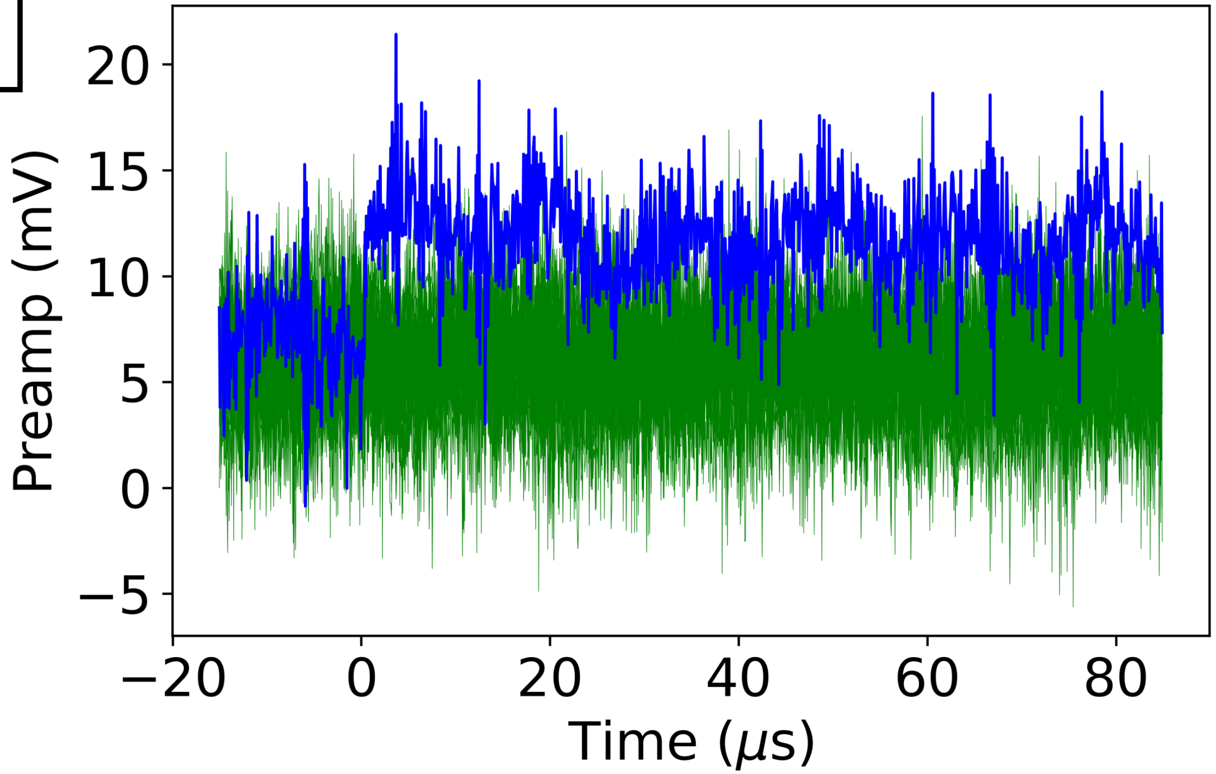
SCA optimization leads to ~10% false negatives

→ Largest source of error in our process



In-situ Counting Experiment

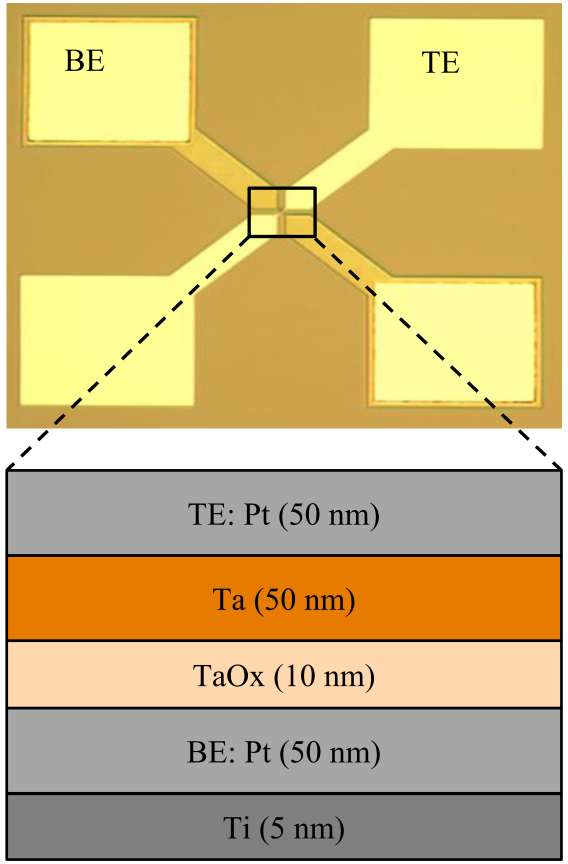


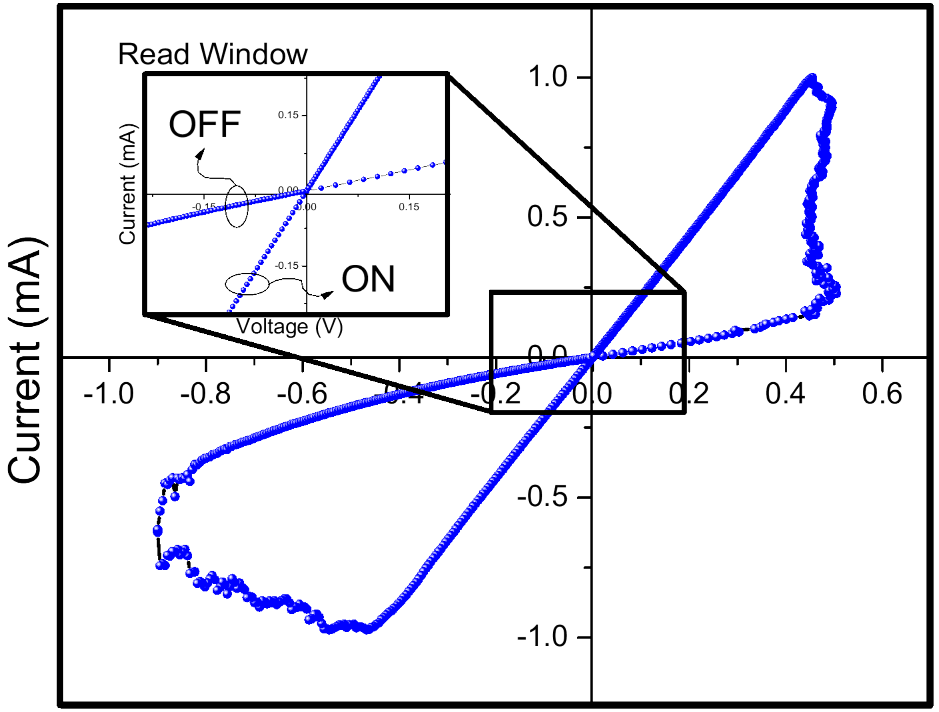


Fully automated process, but still very difficult and slow!!!!

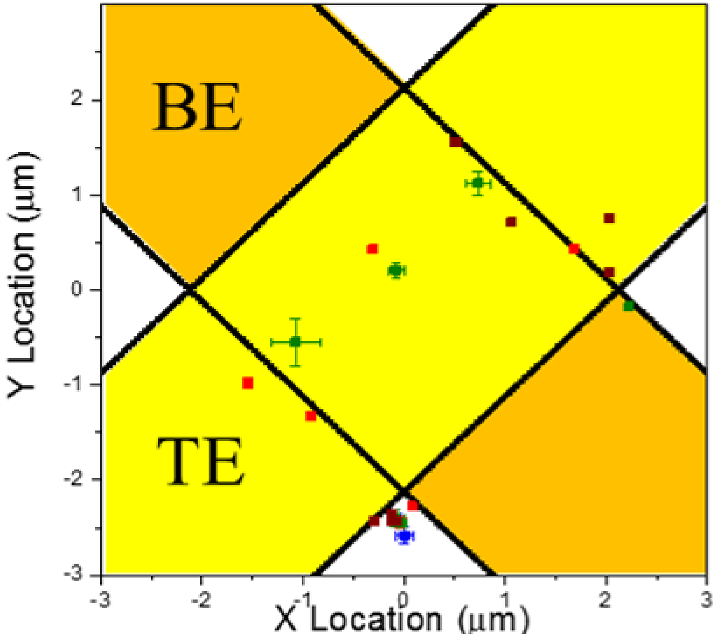
Example – Ion Beam Seeding of Memristors

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



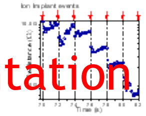


Filament Formation

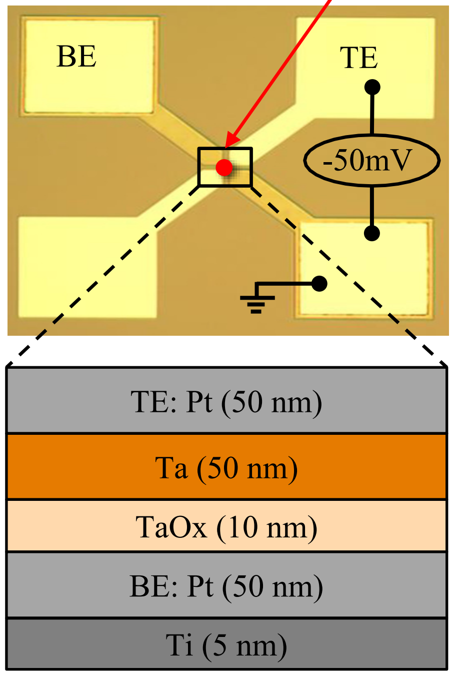


- Can we use focused ion beam implantation to act as seeding sites for the conductive filament formation bypassing electroformation?

Modification of the TaOx Film Resistance using Ion Irradiation

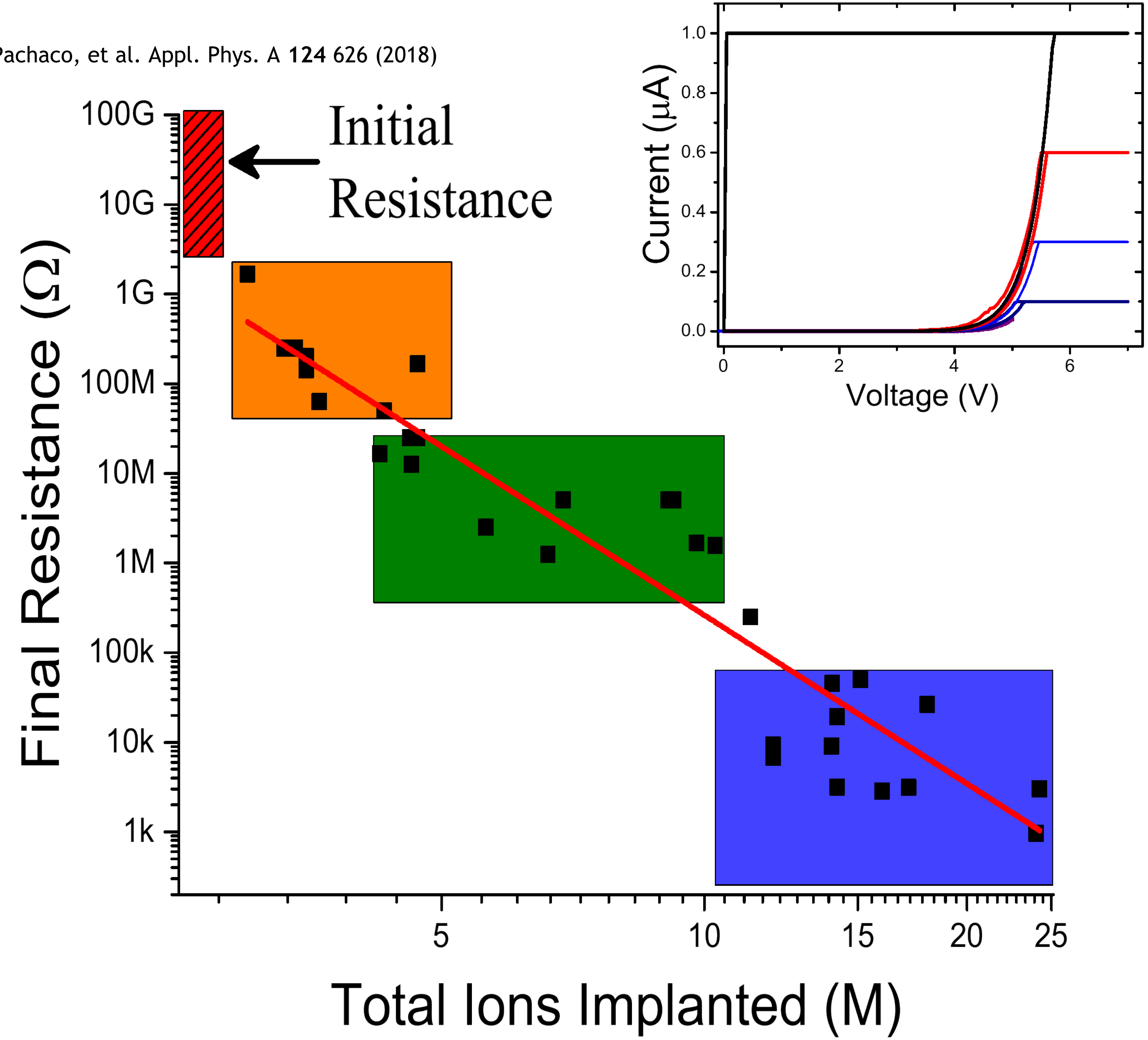


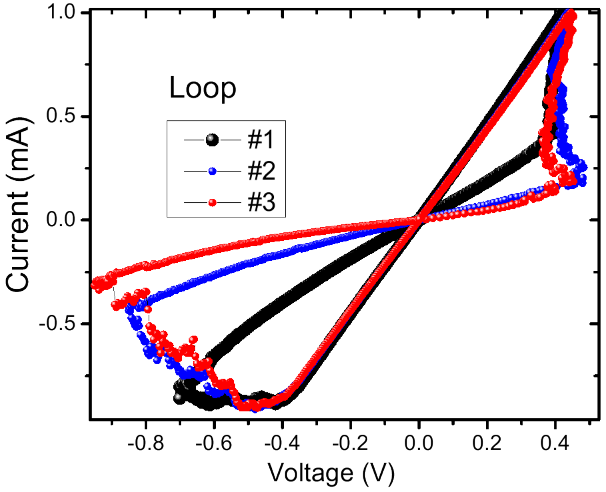
200 keV Si Implantation

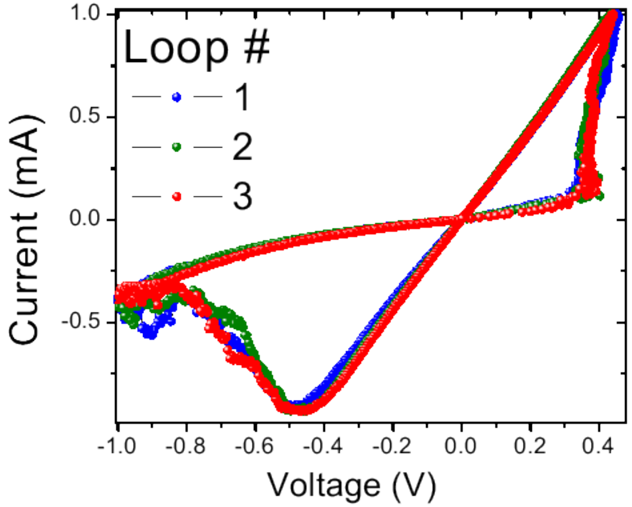


Ion Beam Seeding of Memristor Filament

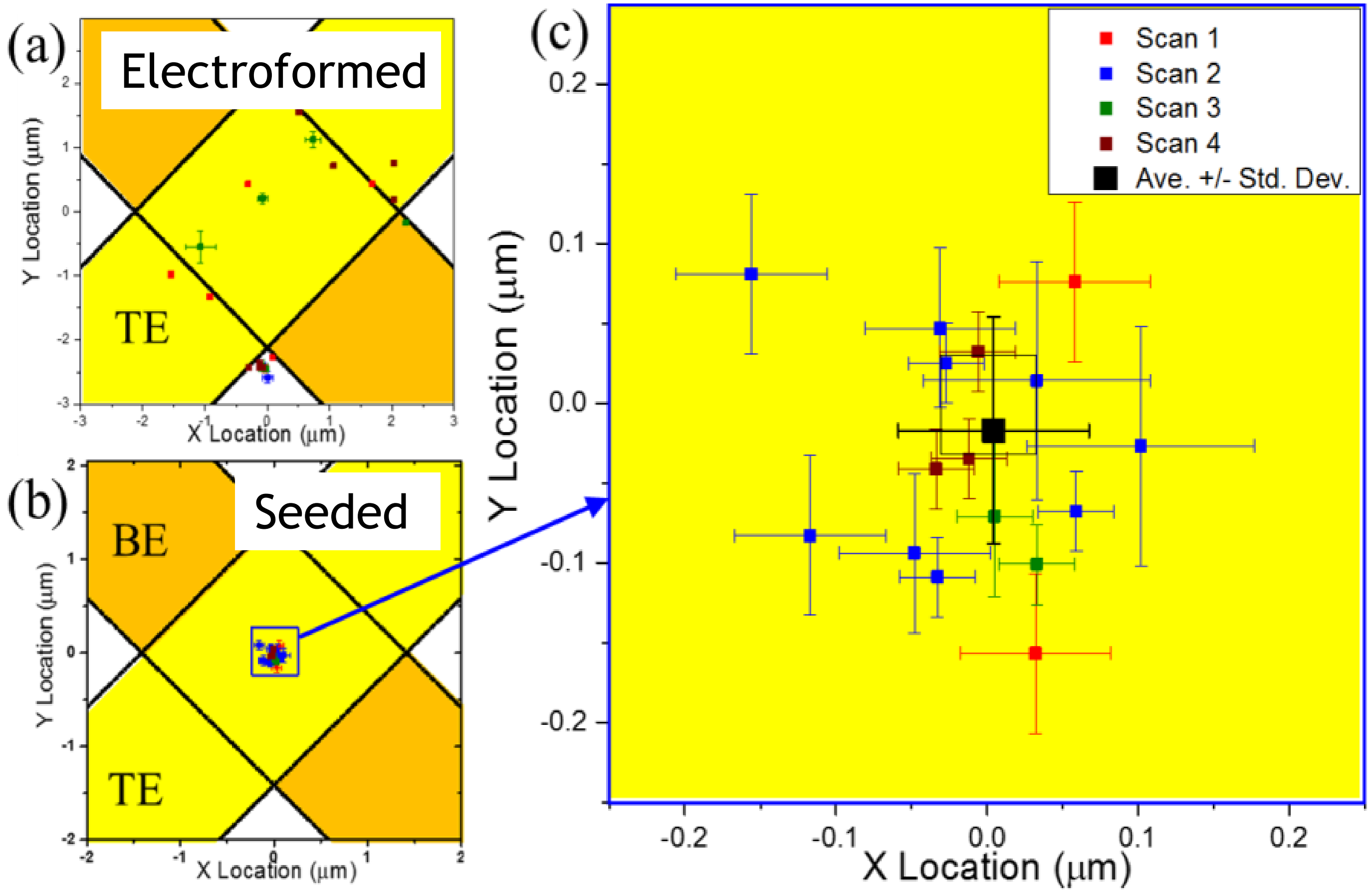
J. Pachaco, et al. Appl. Phys. A **124** 626 (2018)







Control over Filament Location



Results:

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

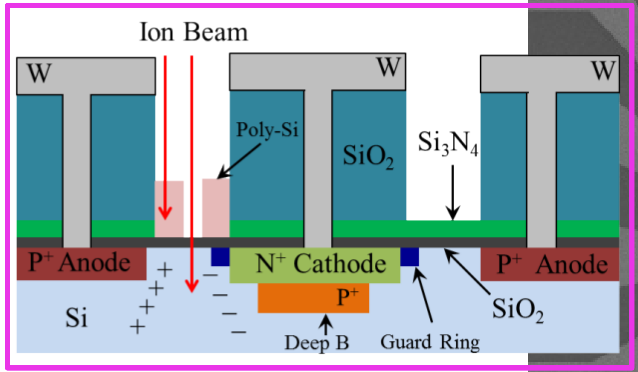
J. Pachaco, et al. Appl. Phys. A **124** 626 (2018)

Single Donor Devices for Si Qubits

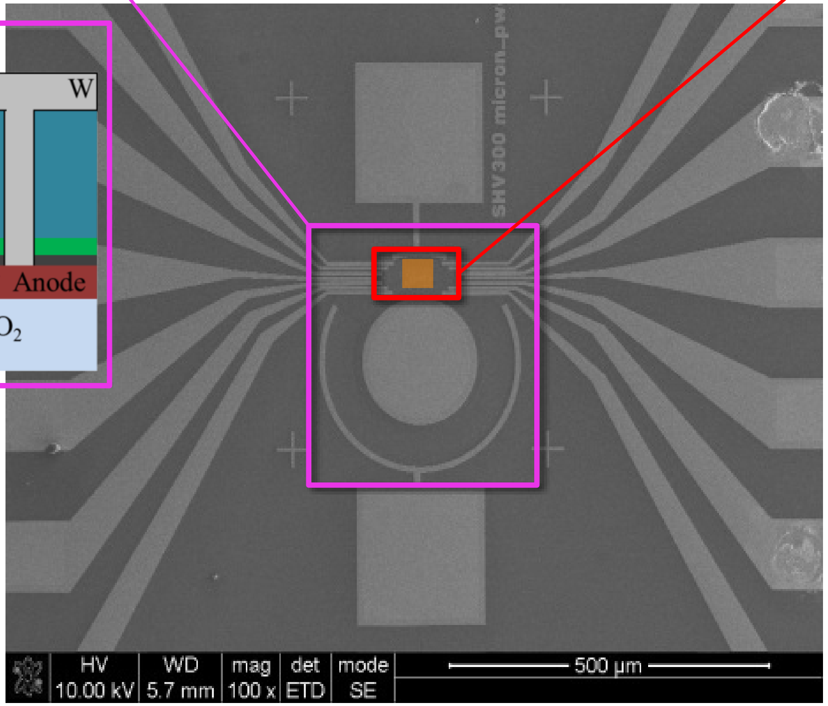
Si-MOS platform integrated with:
- Single Ion Detector
- Nanostructure for Qubit operation

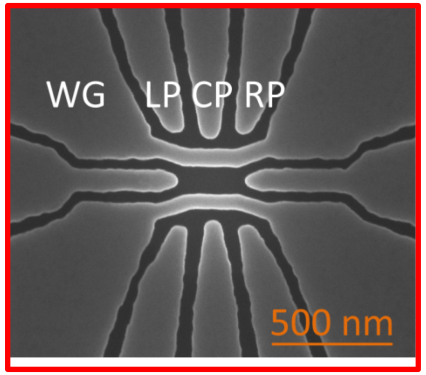
Single Ion Detector

Nanostructure

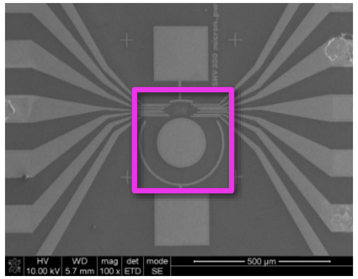


Ion Beam Induced Charge (IBIC)



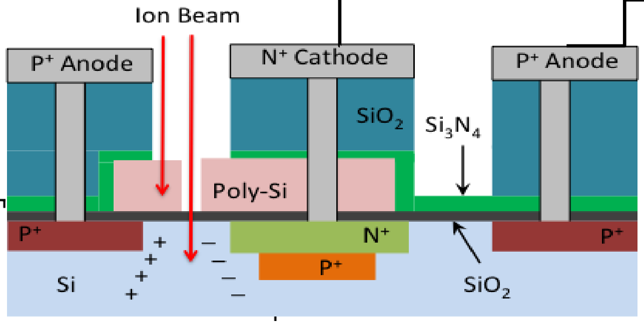


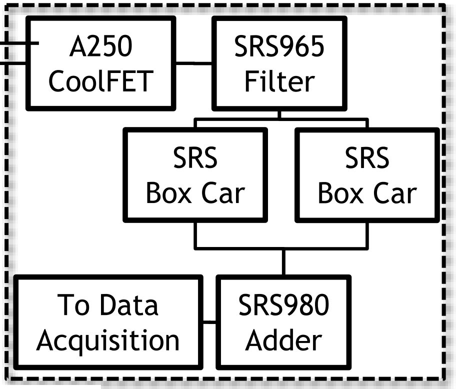
Combined Single Ion Detector and Nanostructures Demonstrated



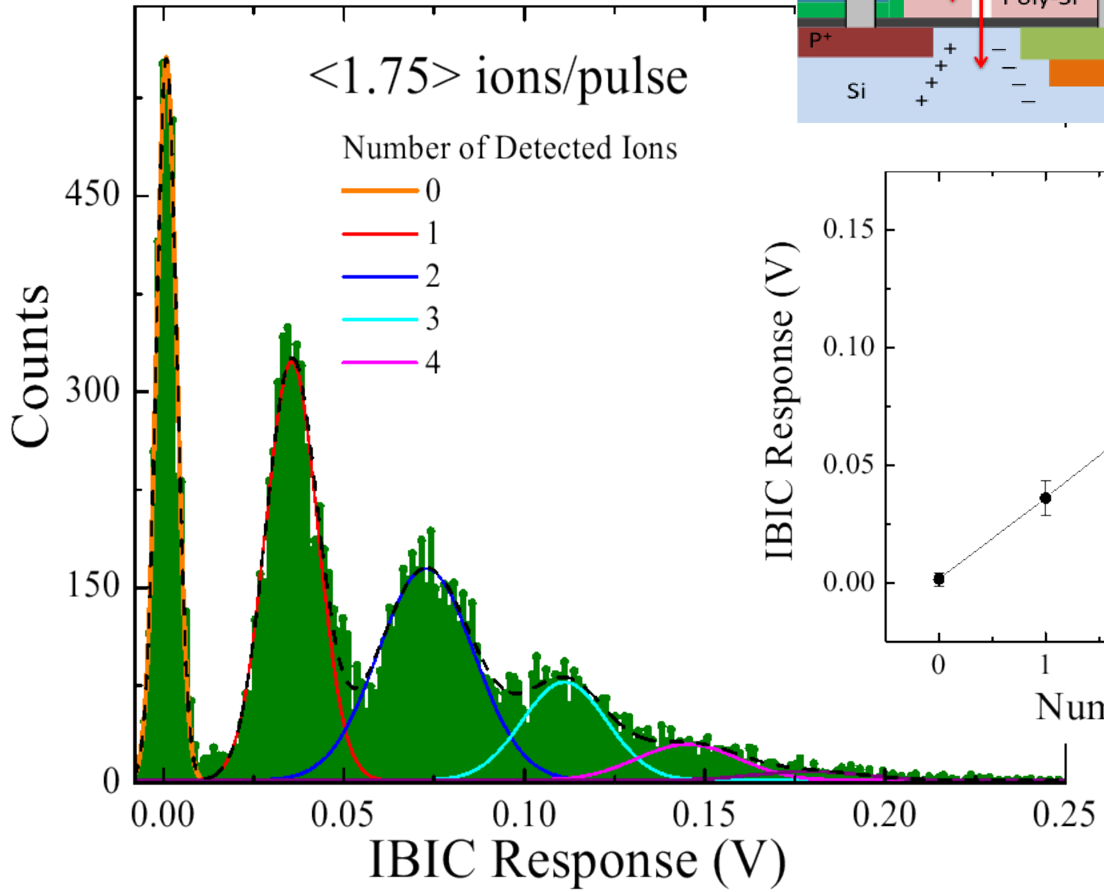
Integrated Single Ion Detectors

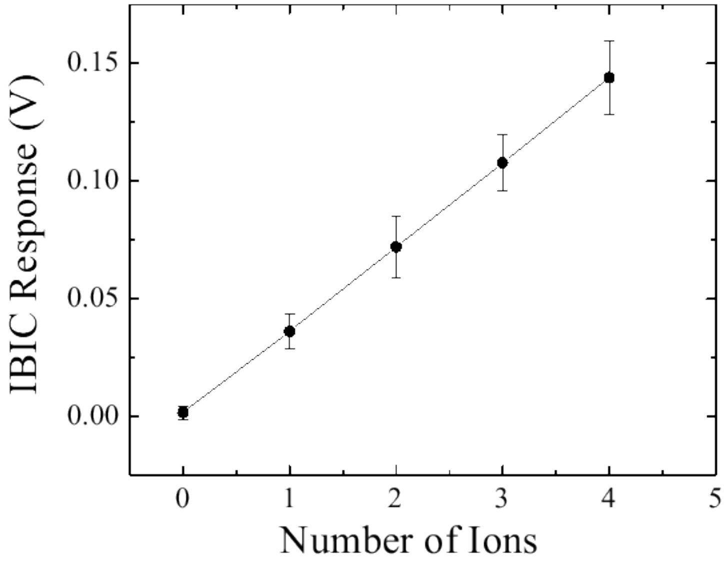
Ion Beam Induced Charge Collection (IBIC)





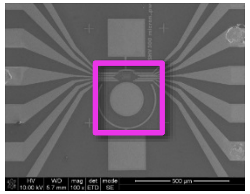
200 keV Si Detection





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.

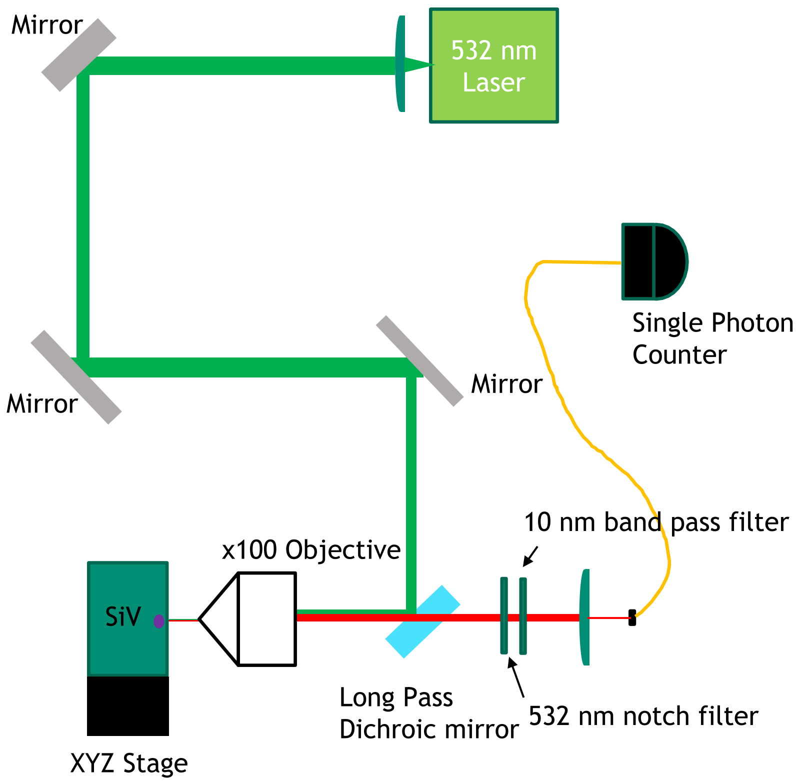
$$SNR = \frac{\mu_S}{\mu_N + \sigma_N} = 2.5$$

How to further improve SNR?

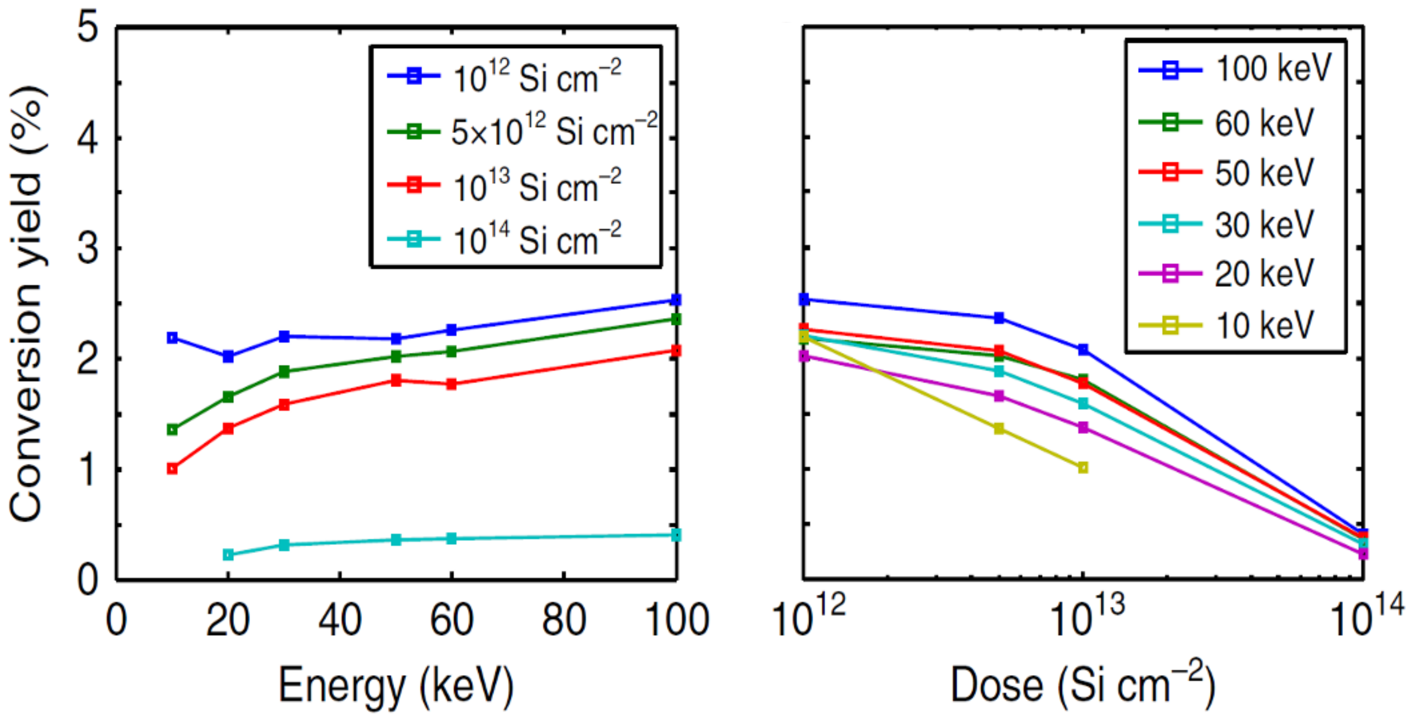
- In-vacuum preamp ☑
- Cool detector and FET ☑

Path forward to low energy <10 nm implantation and detector

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

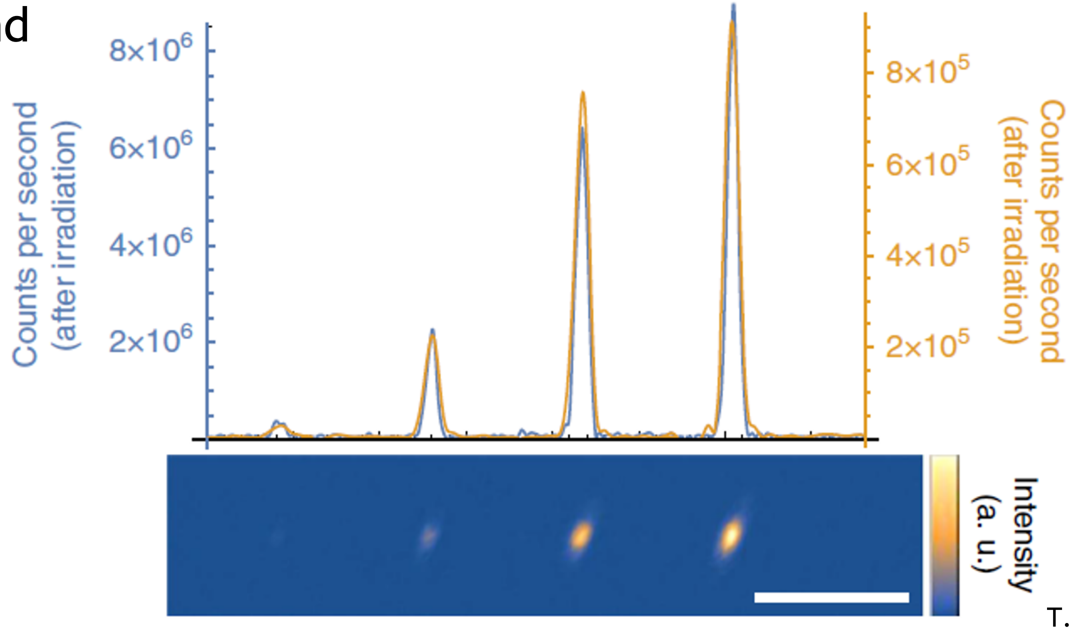
(5) Substrate doping — Enable preferential defect formation?

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

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

After electron irradiation and anneal

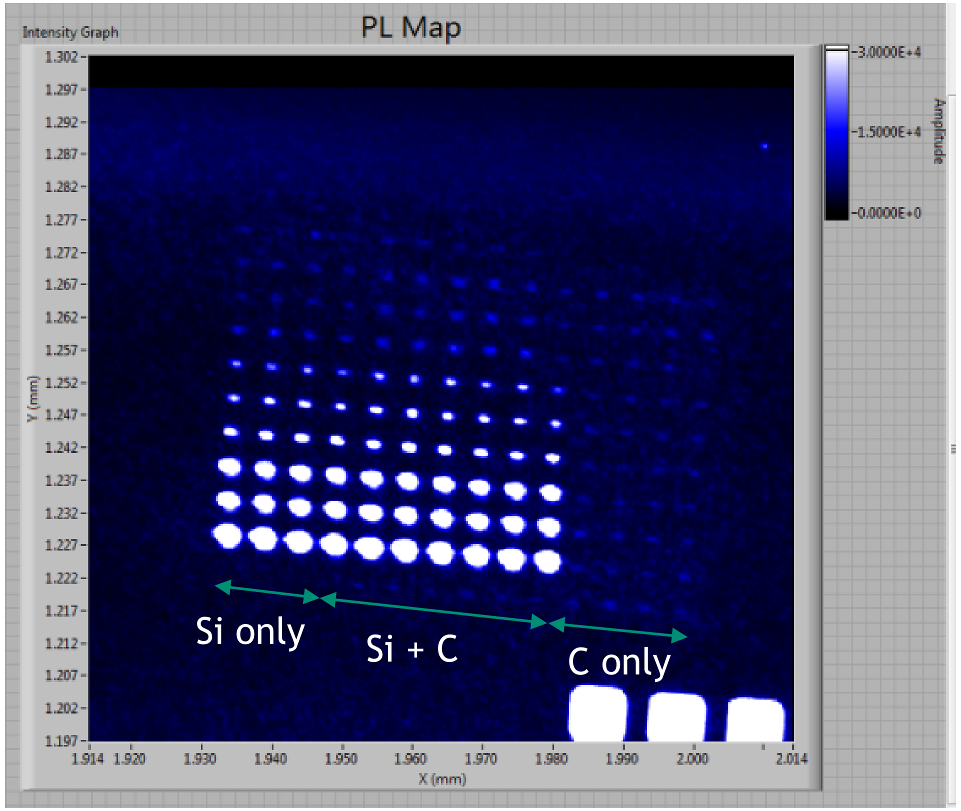
10x improvement

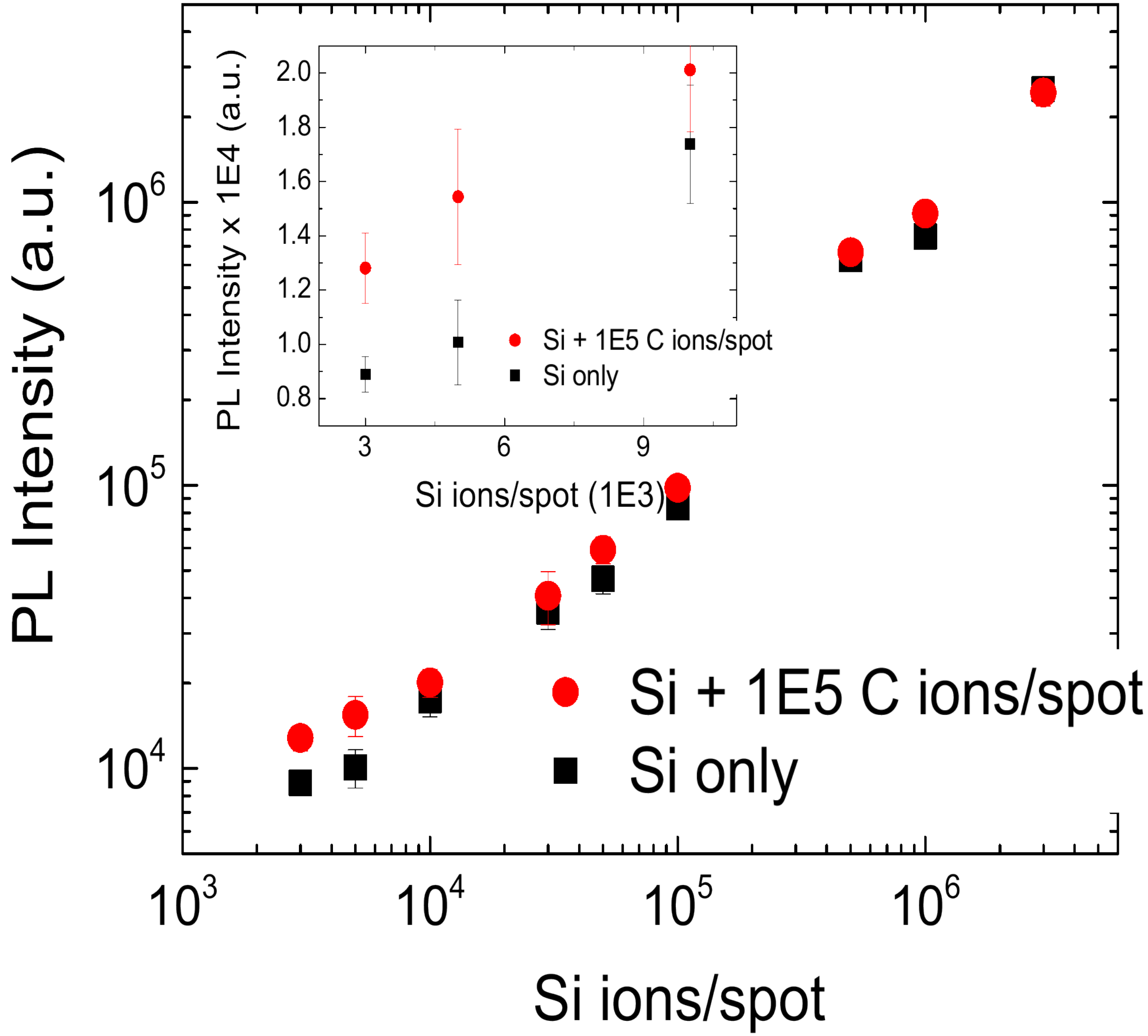


After ion implant and anneal

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

Sequential Implantation – μm sized areas





Units

1E5 C ions/spot → ~1E13 ions/cm^2

3E3 Si ions/spot → ~4E11 ions/cm^2

→ 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