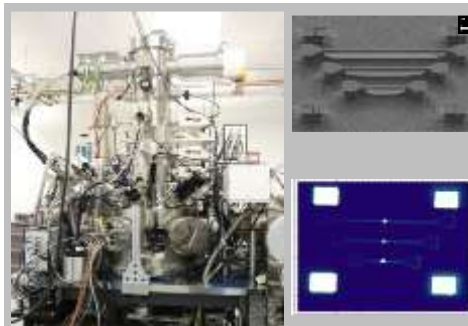
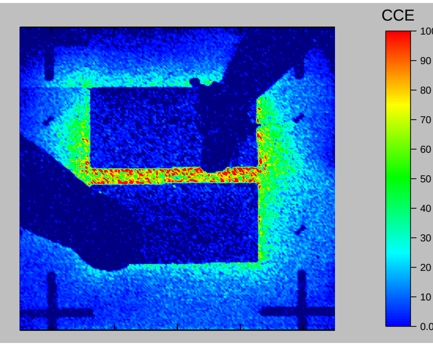
SAND2017-5630C

Exceptional service in the national interest

Sandia National Laboratories





Fabrication of Single Atom Devices by Direct Write Nanofabrication

Edward Bielejec

Sandia National Laboratories, Albuquerque, NM 87185

QIST Quantum Information S&T

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Outline

- Sandia's Ion Beam Laboratory

    Focused Ion Beam Capabilities

    → nanoImplanter

- Single Atom Devices and Nanofabrication

    - Case 1: Counted Ion Implantation for Si Qubits

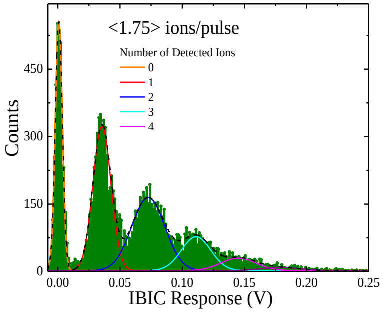
        Demonstration of counted implantation and transport

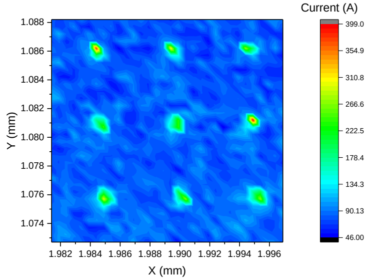
    - Case 2: Defect center formation in Diamond

        Localized implantation and single ion detection

    - Case 3: Electroforming-free TaOx memristor devices

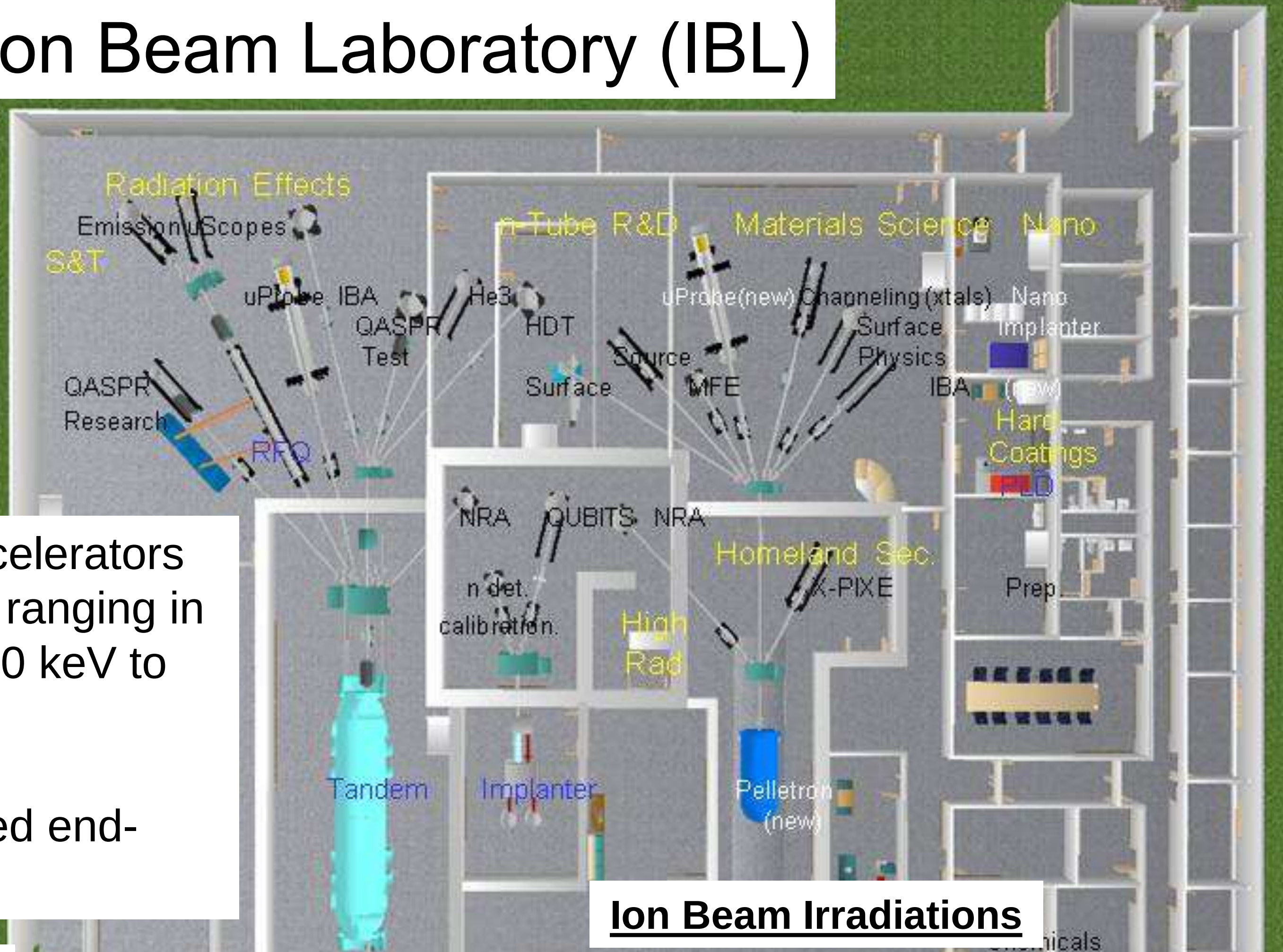
        Localized implantation to form fully functional devices





- Summary

Sandia's Ion Beam Laboratory (IBL)

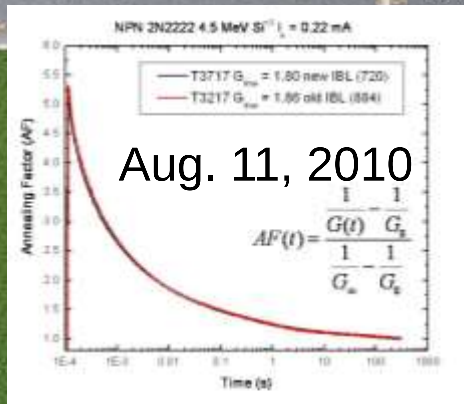


- Four main accelerators producing ion ranging in energy from 10 keV to 480 MeV
- >20 specialized end-stations

Ground Breaking

<20 months

Ion Beam Irradiations



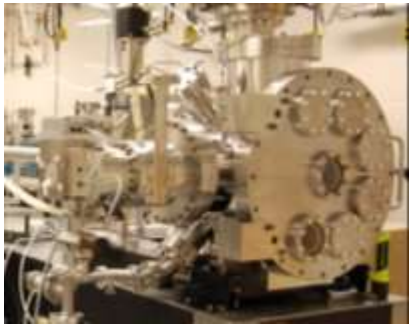
Focused Ion Beam Capabilities at the IBL

Sandia National Laboratories

MicroOne (Tandem Accelerator)

- Light to Heavy Ions – H to I
- Energy range from ~800 keV to >70 MeV
- Spot size as small as ~800 nm

NanoBeamLine (HVEE Implanter)

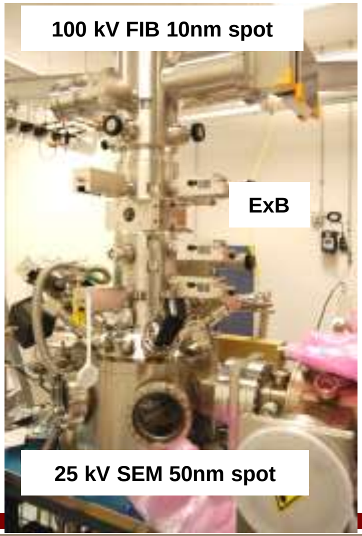


- Light to Heavy Ions – H to Xe
- Energy range from ~10 keV to 350 keV
- Spot size as small as ~800 nm

Light Ion Microbeam (Pelletron)

- Light Ions – H, He3, He4, N (lower resolution spots)
- Energy range from ~300 keV to 3 MeV
- Spot size as small as ~150 nm

NanoImplanter

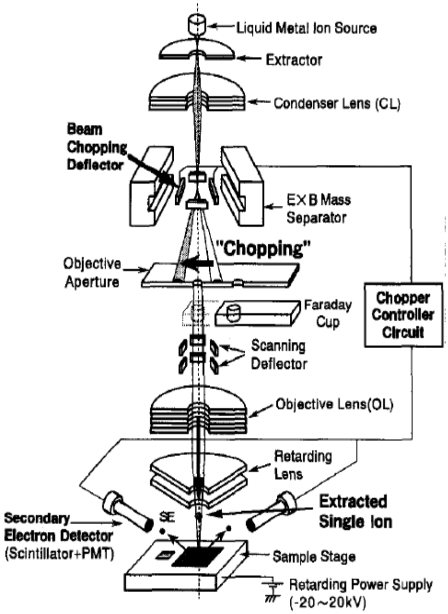


- Liquid Metal Ion Sources – Ga, Au, Si, Sb, P, etc…
- Energy range from 10 keV to 200 keV
- Spot size as small as ~10 nm

One Slide History of Multi-species Focused Ion Beams

Instrument development

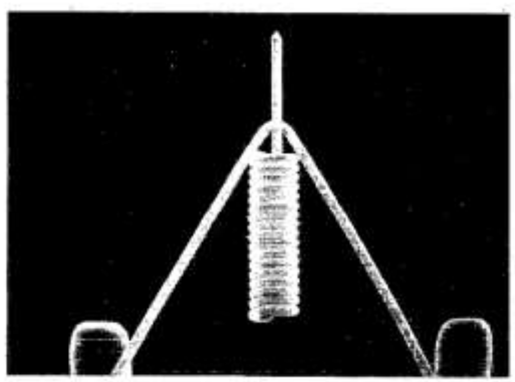
Swanson, Orloff, Melngailis,
Gamo, Namba, Ohdomari,
Aihara, Sawaragi,…



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

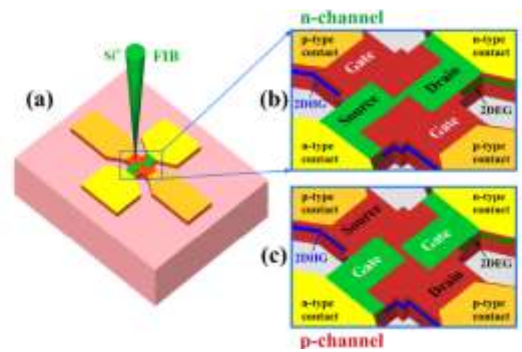
Source development

Swanson, Ishitani, Kebedgiev,
Muhle, Bischoff, Mazarov, Wieck,…



Application development

Wieck, Shinada, Stecki, Takai,….



M. Draghici Dissertation Bochum 2006

One Slide History of Multi-species Focused Ion Beams

Instrument development

Swanson, Orloff, Melngailis,
Gamo, Namba, Ohdomari,
Aihara, Sawaragi,…

Source development

Swanson, Ishitani, Kebedgiev,
Muhle, Bischoff, Mazarov, Wieck,…

Application development

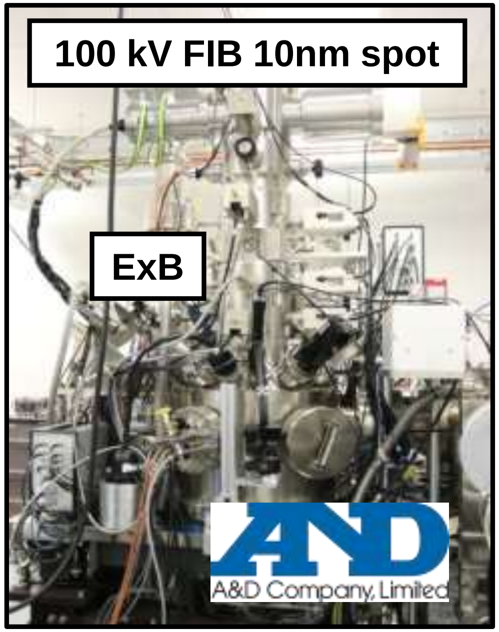
Wieck, Shinada, Stecki, Takai,….

None was put into practice because the fabrication times were unacceptably long and in some cases the alloy ion sources were difficult to operate

Nanofabrication Using Focused Ion and Electron Beam, 2012 p 762

Build on the strengths and minimize the weaknesses → Single Ion Implantation

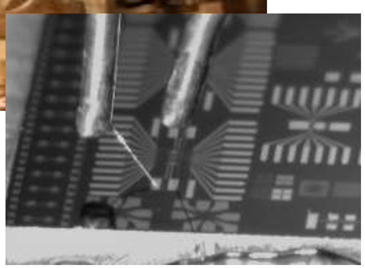
SNL nanoImplanter (nI)



- Focused ion beam system (FIB)
  - →nm beam spot size on target
- ExB Filter (Wien Filter)
  - →Multiple ion species
    - → 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

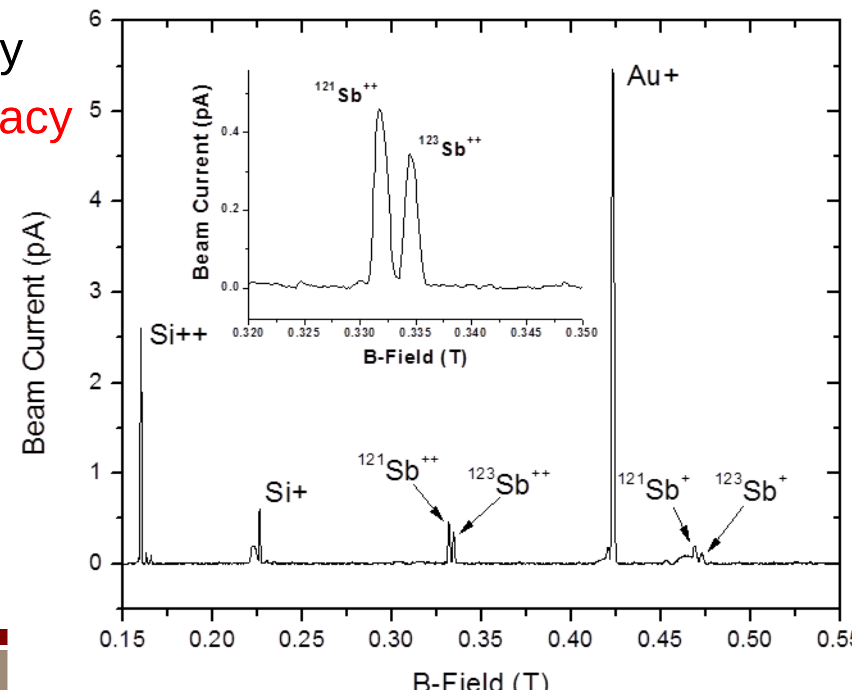
RAITH NANOFABRICATION

- Low temperature stage



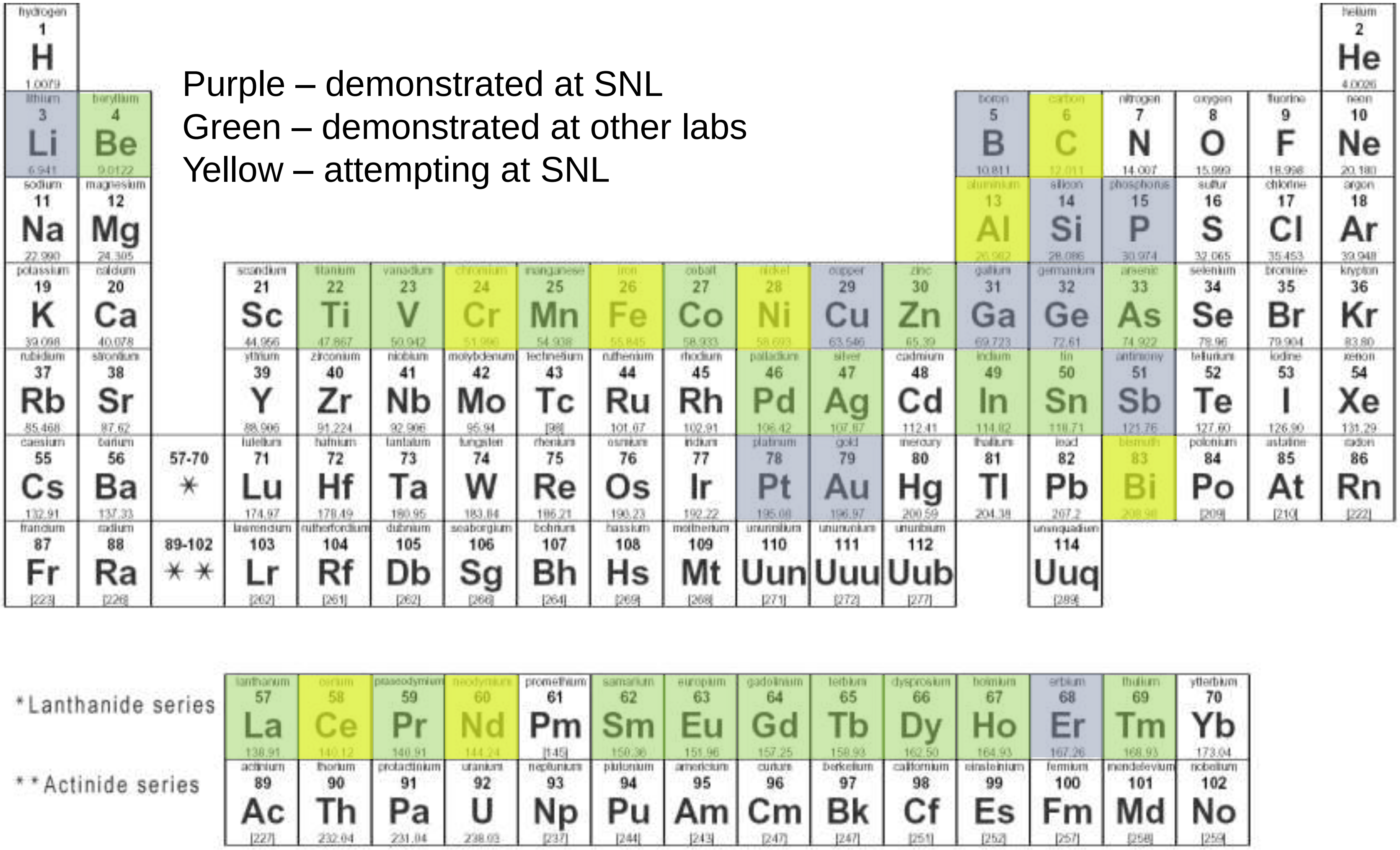
- In-situ electrical probes

Sb Source: Mass Spectrum



SNL nanoImplanter (nI) - Sources

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

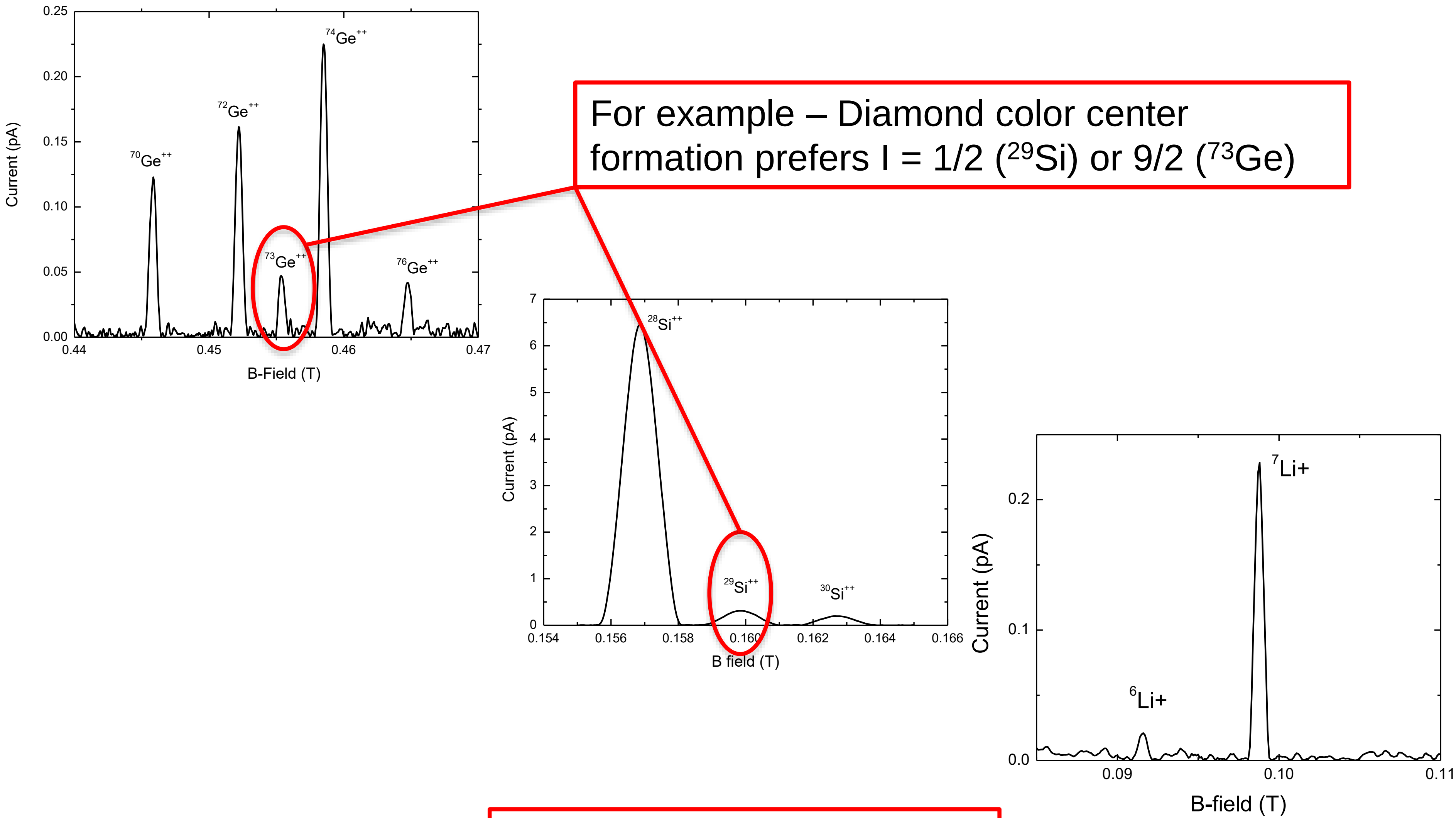


After A. Weick University of Bochum

Wide Varity of Ion Species Available

SNL nanoImplanter (nI) – Mass Resolution

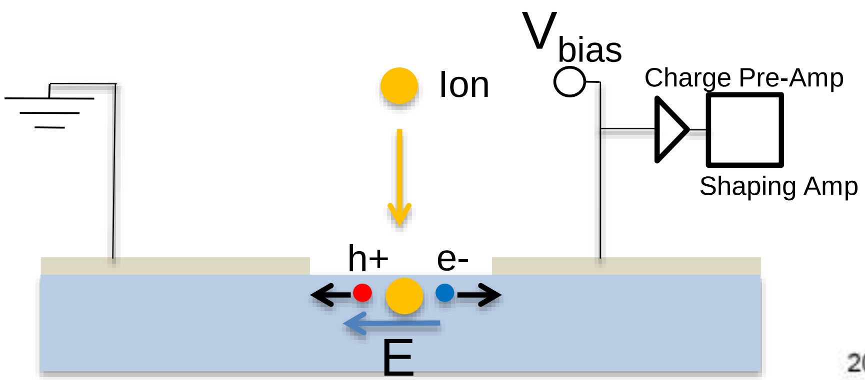
For example – Diamond color center formation prefers I = 1/2 (^{29}Si) or 9/2 (^{73}Ge)



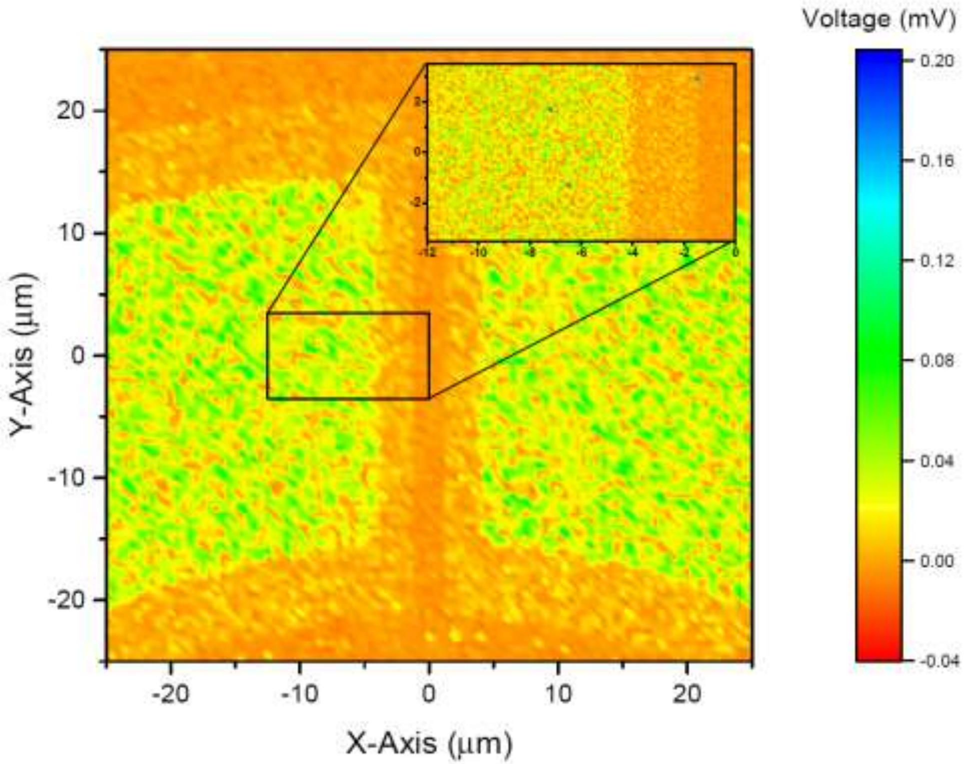
Examples isotope separation

SNL nanoImplanter (nI) – IBIC

Ion Beam Induced Charge Collection (IBIC)

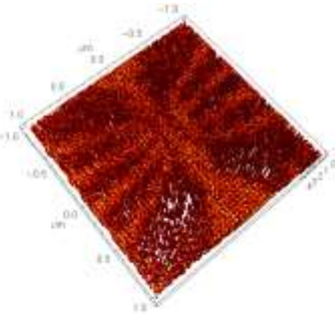


Side View

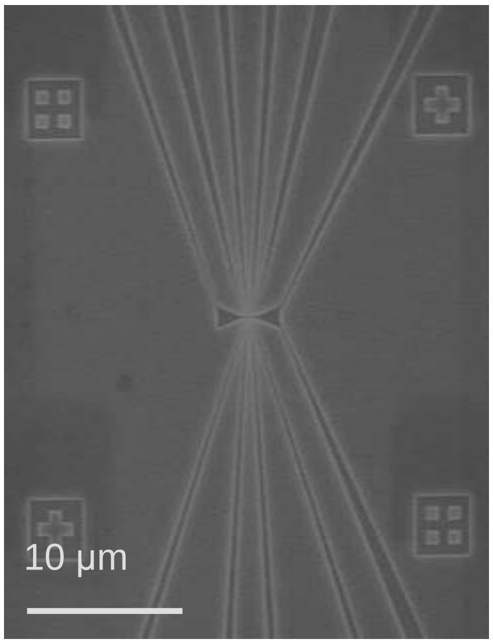


IBIC resolution is spot size limited, ~20 nm

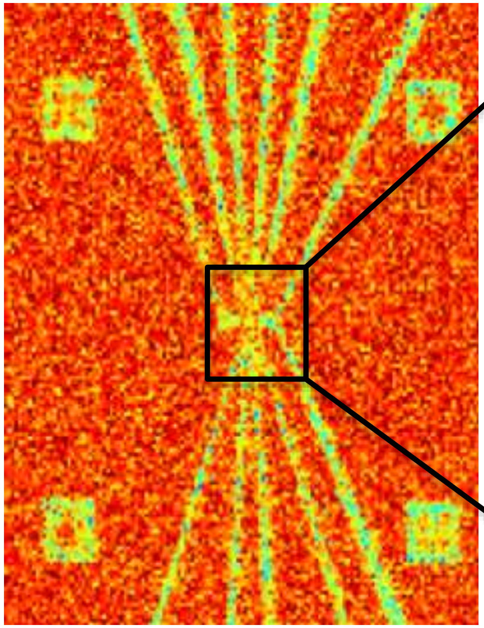
SNL nanoImplanter (nI) – Targeting Resolution



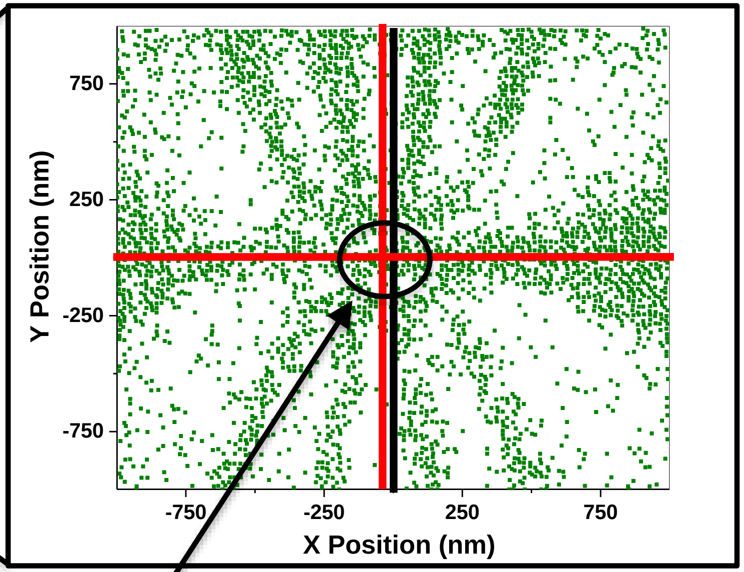
SEM of nanostructure



Ion Beam Induced Charge Collection (IBIC) of nanostructure

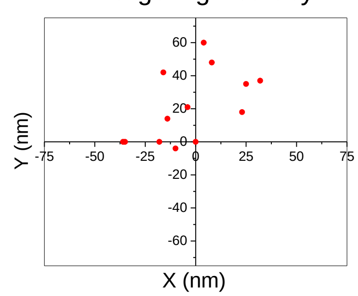


High resolution IBIC for targeting



Δx ~35 nm
Δy ~0 nm

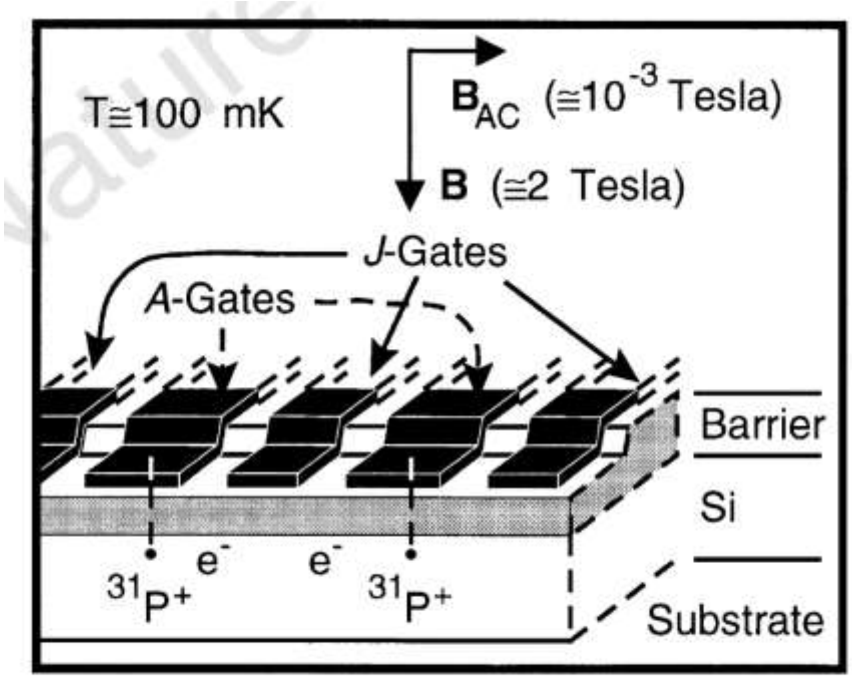
Targeting Acuracy



Targeting resolution <40 nm

Motivation – Donor Based Qubit – ^{31}P in Silicon

Donors in Si for Qubits



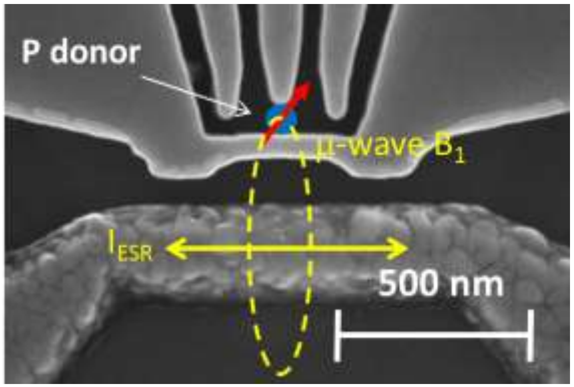
B. E. Kane, Nature **393**, 1998

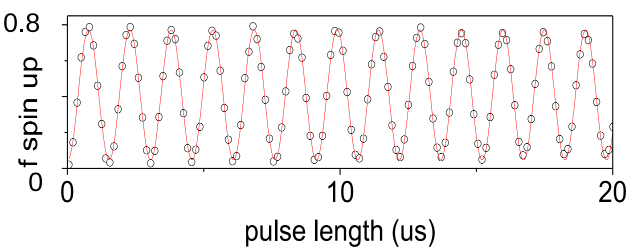
- We will discuss donor qubit fabrication on a *Si-MOS platform with integrated* ***single ion detectors*** *and* ***nanostructures for transport***

Donor Based Qubit – ^{31}P in Silicon

Sandia National Laboratories

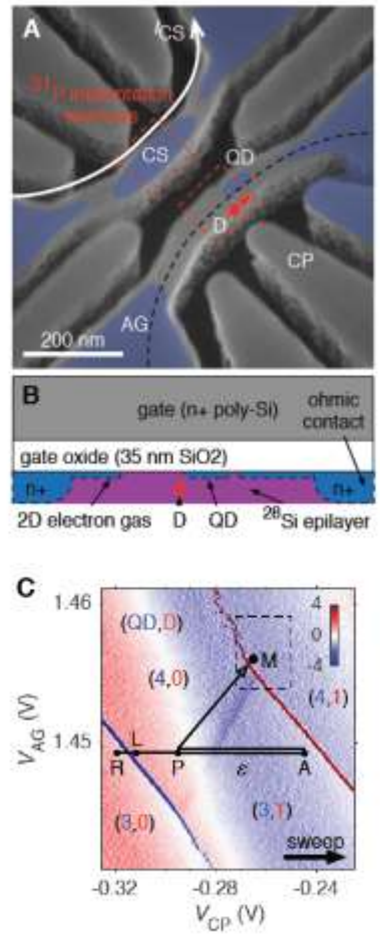
Single Qubit Control

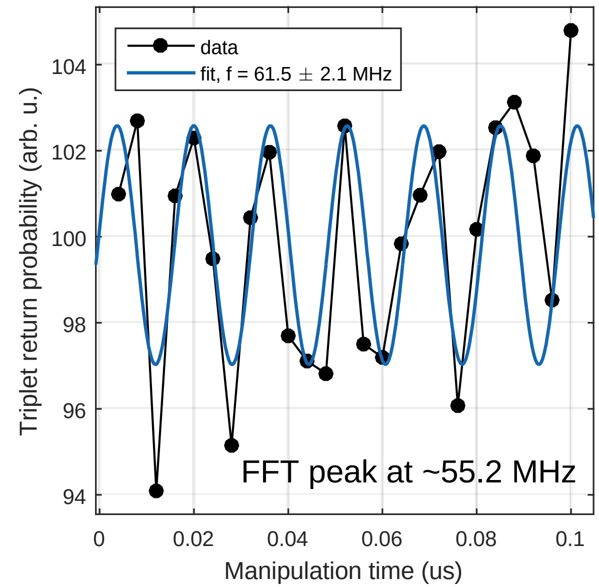




*L. A. Tracy et al., APL **108**, 063101 (2016)*

Coherent Coupling of Single Donor to QD





P. Harvey-Collard et al., arXiv:1512.01606v1

Experiments performed on ^{31}P donors in ^{28}Si epi using timed implants

What Capability is needed to fabricate these devices?

<u>Controlled Location of Donor Site(s)</u>

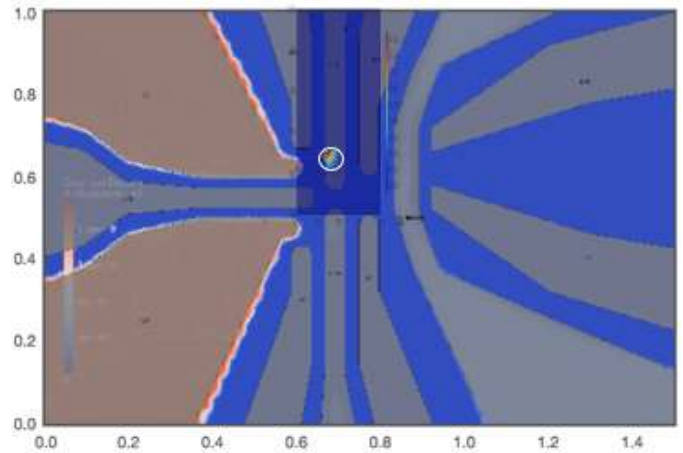
- Control of X,Y donor site(s)
  - Focused Ion Beam (FIB) Implantation
  - Electron Beam Lithography (EBL) mask
- Minimize Straggle in depth (Z)
  - Low Energy Ion Implants

<u>Controlled Alignment of Donor Site(s) and Gates</u>

- Self-Aligned Poly-Si

<u>Controlled Number of Donors</u>

- Timed/Counted single ion implantation



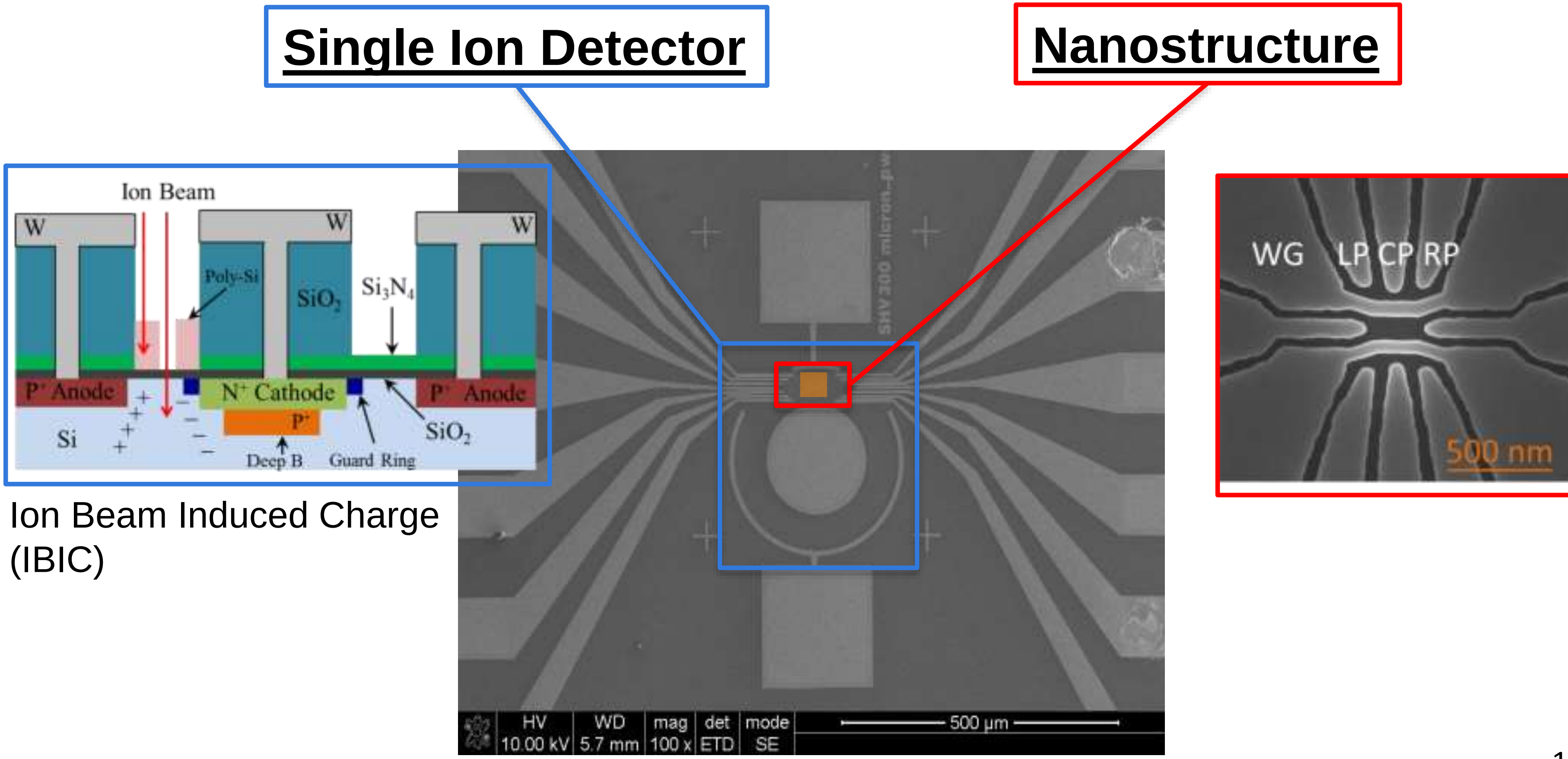
QCAD simulations show simultaneous electron occupation and donor ionization are possible

Donor-QD (few electron) requires:
- Target depth of <10 nm
- D-QD lateral spacing of <20 nm

} Can be accomplished with counted focused ion beam implantation

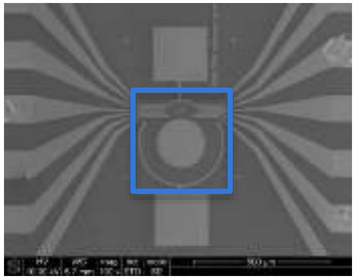
Single Donor Devices for Si Qubits

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



Ion Beam Induced Charge (IBIC)

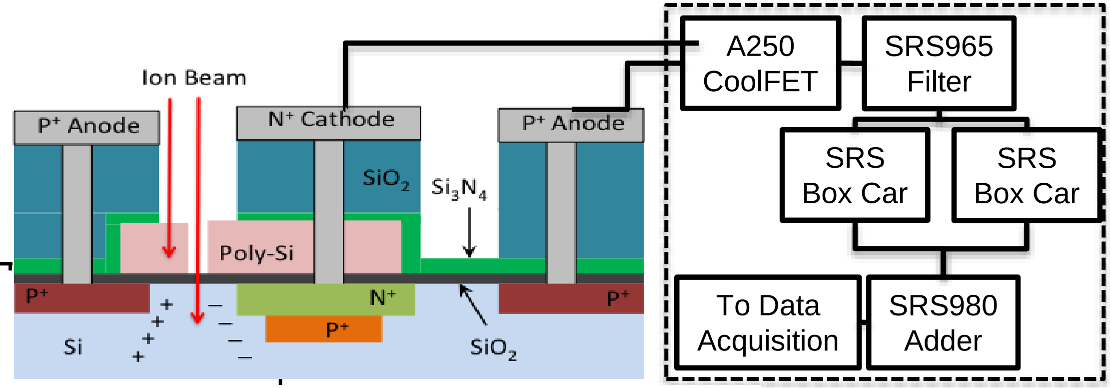
Combined Single Ion Detector and Nanostructures Demonstrated



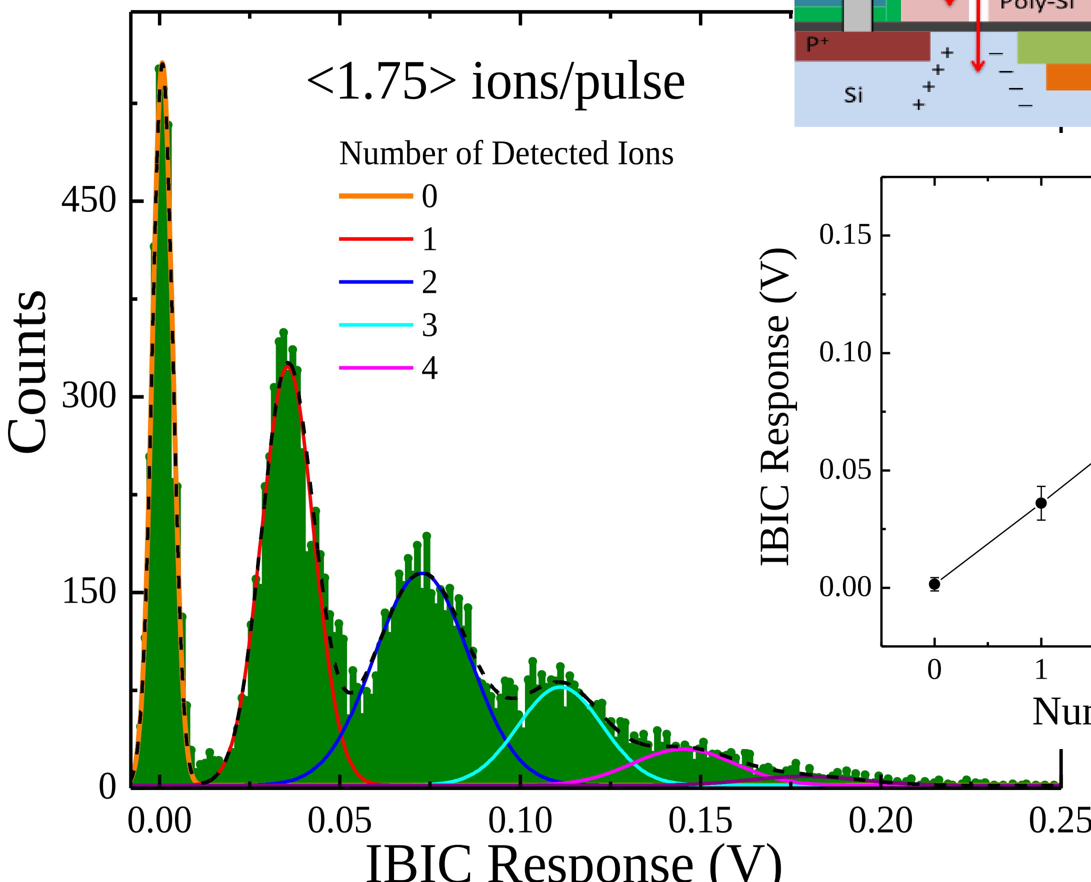
Integrated Single Ion Detectors

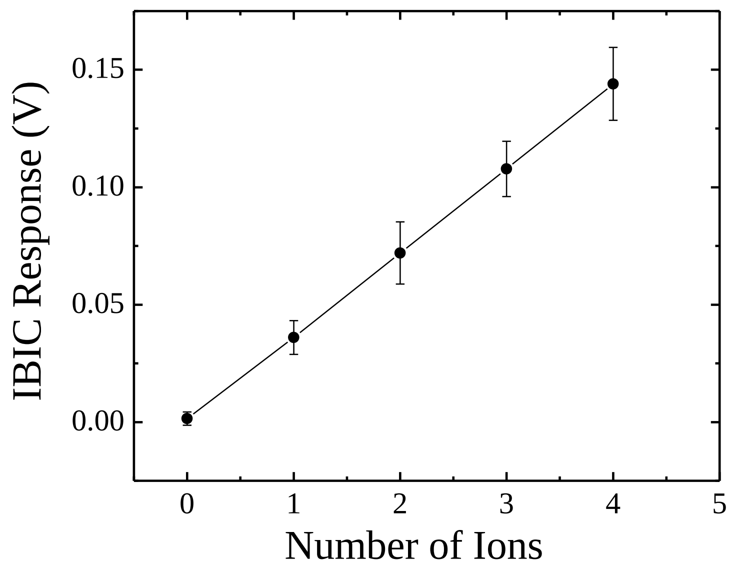
Sandia National Laboratories

Ion Beam Induced Charge Collection (IBIC)

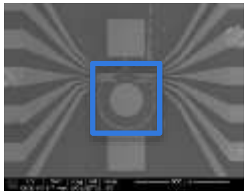


200 keV Si Detection

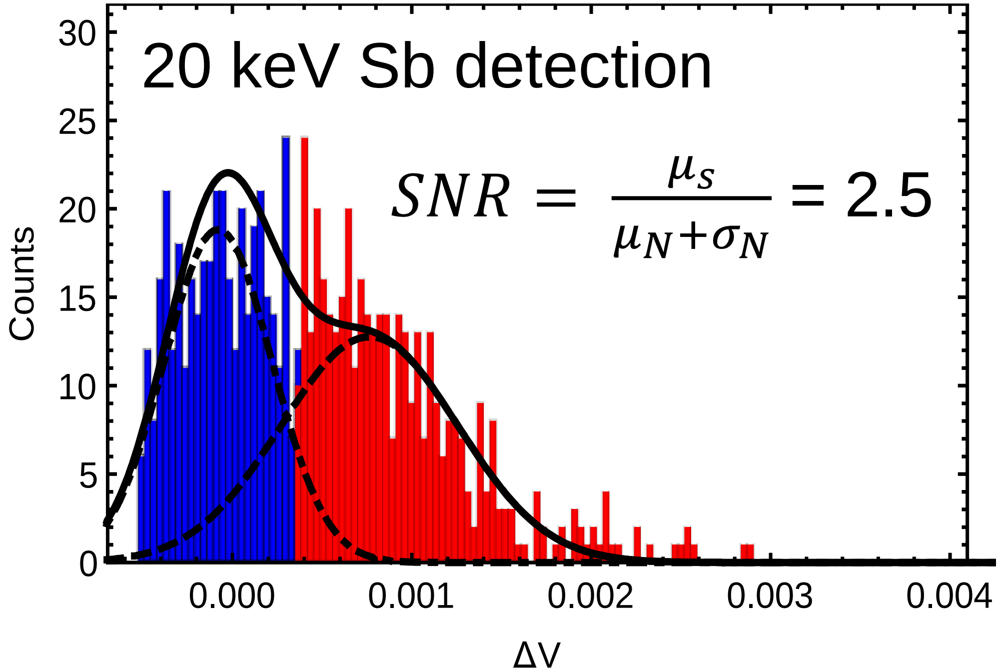




Quantized Single Ion Detection

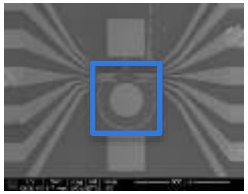


Lowest SNL Detected Single Ion Implantation



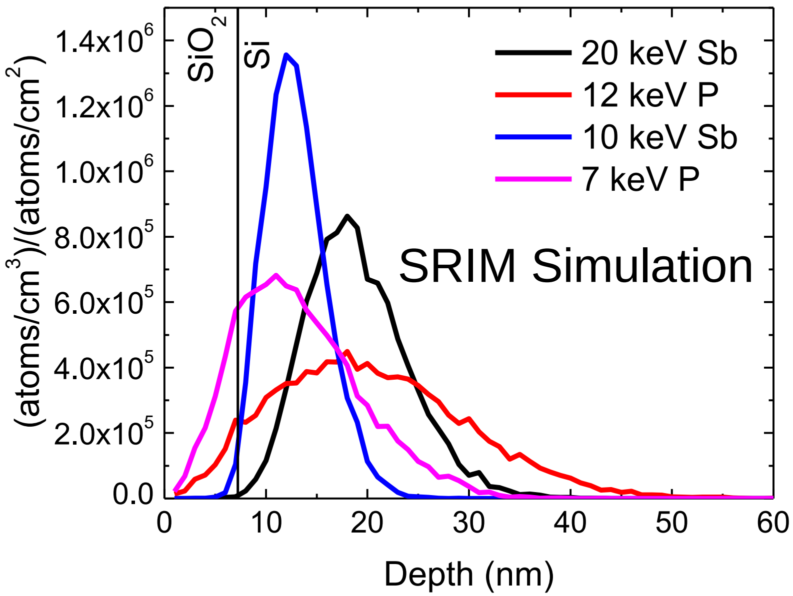
Ion Species	Energy (keV)	SiO2 Thickness	Range*(± Straggle)	SNR	Error Rate
Si	200	7 nm	273 (± 76) nm	21.2	<<1%
Sb	120	35 nm	25 (± 17.5) nm	5.2	8%
Sb	50	7 nm	25 (± 9) nm	4.4	9%
Sb	20	7 nm	11 (± 5) nm	2.5	15%

* Range measured from the SiO2/Si interface into the Si substrate



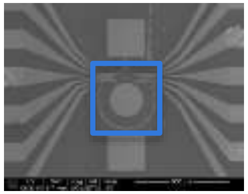
Implantation Target?

Target depth <10 nm below SiO_2 and minimize straggle



Ion	Range below SiO_2	e-h pairs
20 keV Sb	11.5±4.9±4.3 nm	~1500
12 keV P	13.0±9.[illegible]±7.8 nm	~1100
10 keV Sb	5.5±3.0±2.9 nm	~500
7 keV P	5.7±6.1±5.1 nm	~500

How to go from 20 keV Sb to 7 keV P Detection?

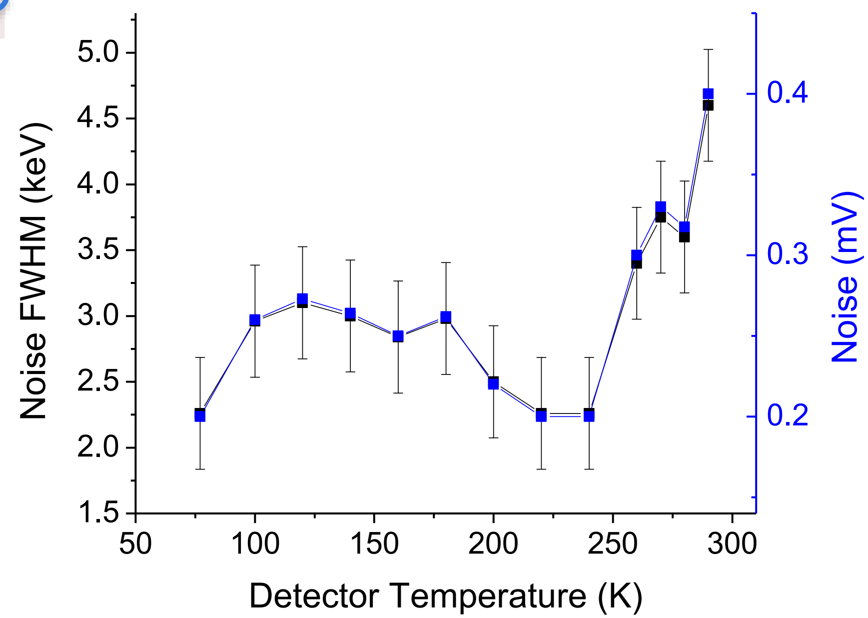


Low Noise Single Ion Detection

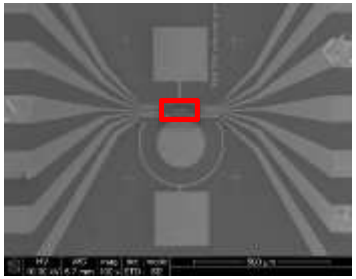
Ion	Range below SiO_2	e-h pairs
20 keV Sb	11.5±4.9±4.3 nm	~1500
12 keV P	13.0±9.3±7.8 nm	~1100
10 keV Sb	5.5±3.0±2.9 nm	~500
7 keV P	5.7±6.1±5.1 nm	~500

- Need to reduce noise, improve SNR
  - ***SNR of 2 for 500 e/h pairs → Noise 0.2 mV***
- How to do so?
  - In-vacuum preamp ☑
  - Cool detector and FET ☑

Measured ~0.2 mV noise for cooled preamp

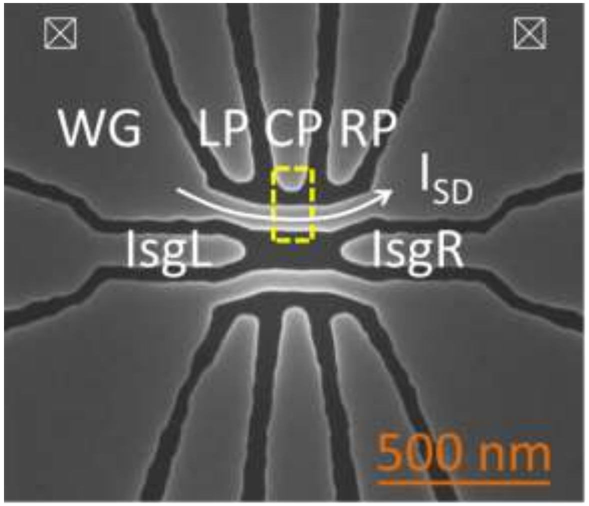


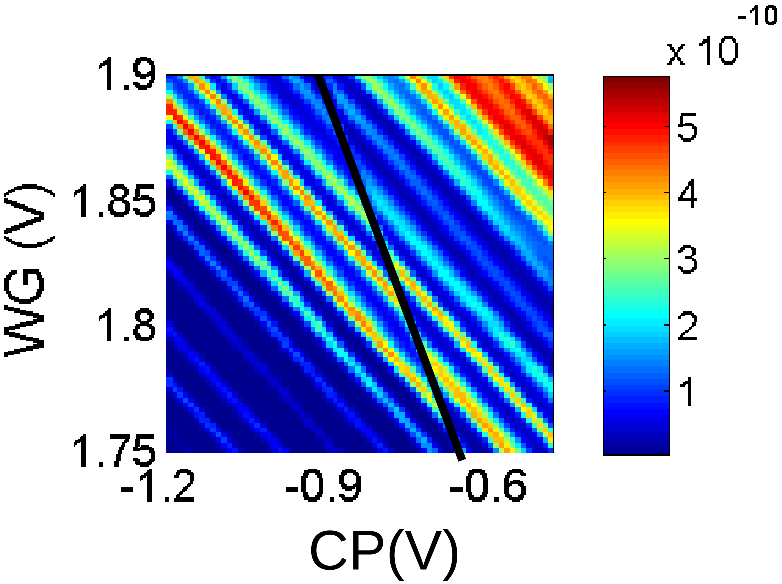
Path forward to low energy <10 keV detection



Transport in Counted Donor Devices

120 keV Sb Transport





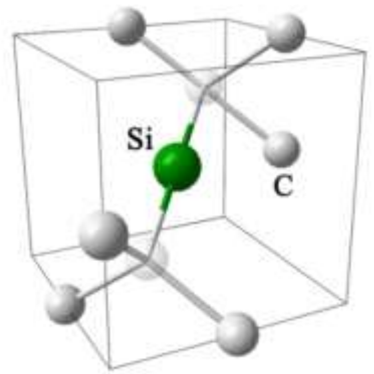
Singh et al. APL 108 062101 (2016)

Measured low temperature transport on counted donor devices

Motivation – Color Centers in Diamond

Color Centers in Diamond

- Color centers (defect complex) in diamond include NV^-, SiV plus many more…



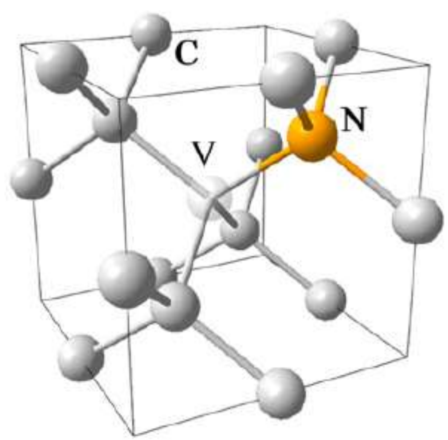
SiV in diamond

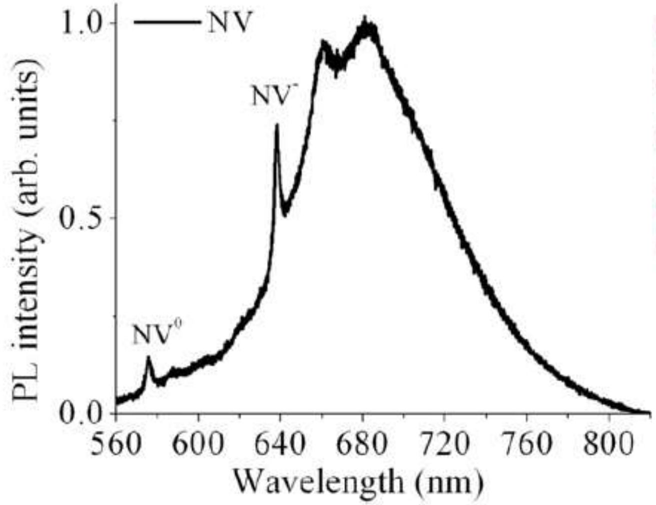
I. Aharonovich *et al*., Rep. Prog. Phys. **74**,076501 (2011)

- Wide range of application from metrology to quantum computation
- Outstanding issues are ***location*** and ***yield***

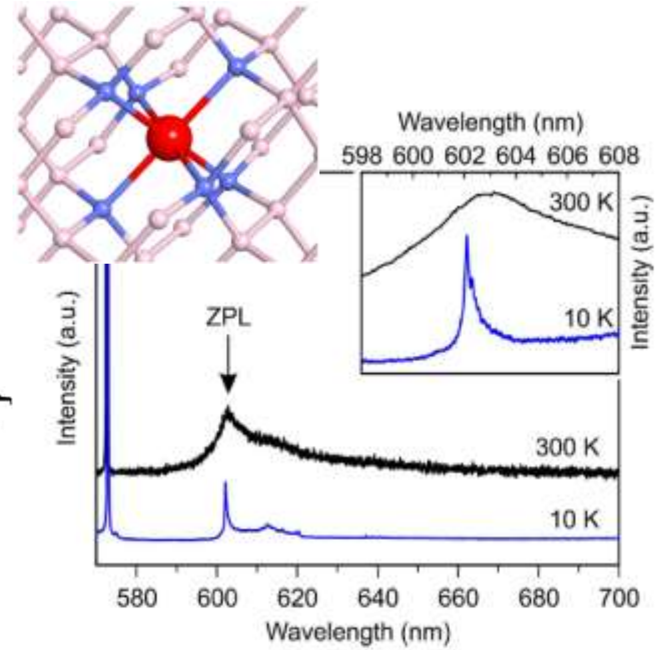
Examples of Color Centers in Diamond

NV in diamond



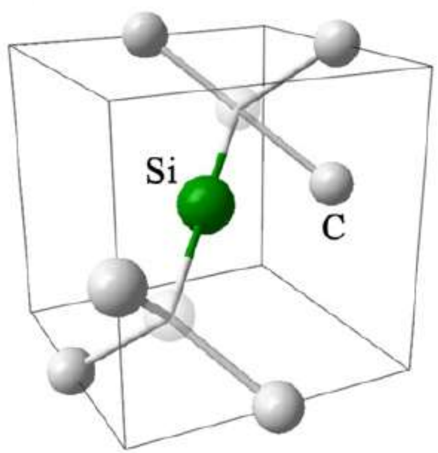


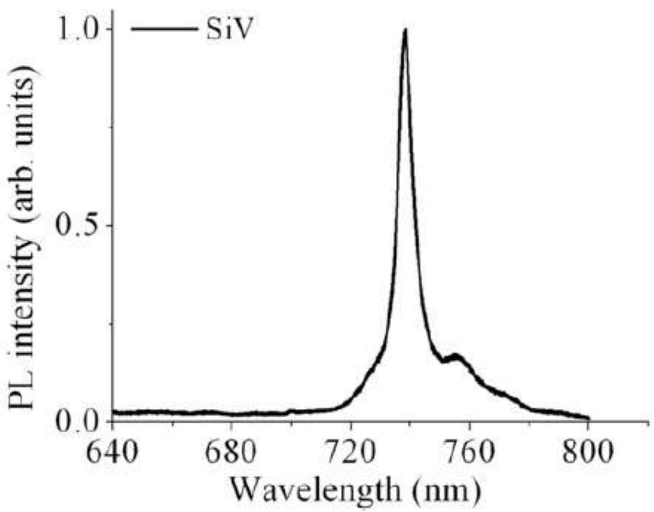
GeV in diamond (2015)



T. Iwasaki*et al*., Sci. Rep. **5**, 12882 (2015)

SiV in diamond

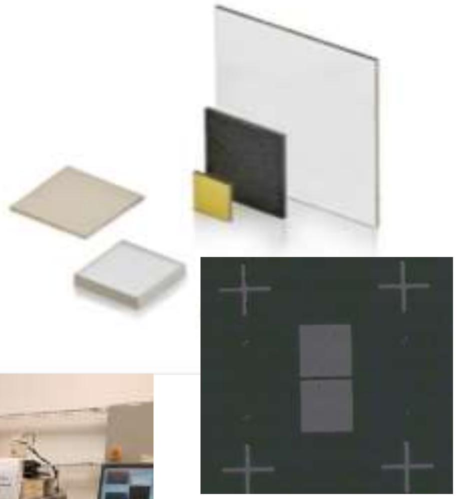




I. Aharonovich *et al*., Rep. Prog. Phys. **74**, 076501 (2011)

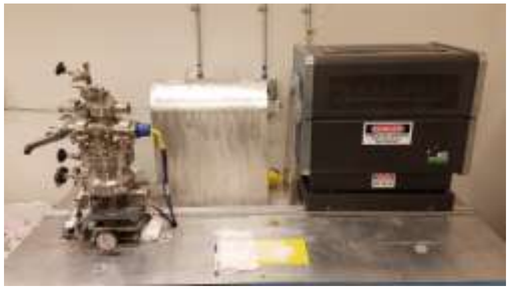
How do we fabricate the SiV Centers?

Electronic Grade Diamond Substrates

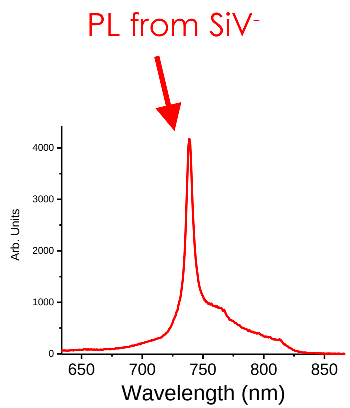


Surface Clean/Oxygen Termination

CINT fab to prepare the samples, Si ion implantation at IBL



Vacuum anneal to create SiV centers



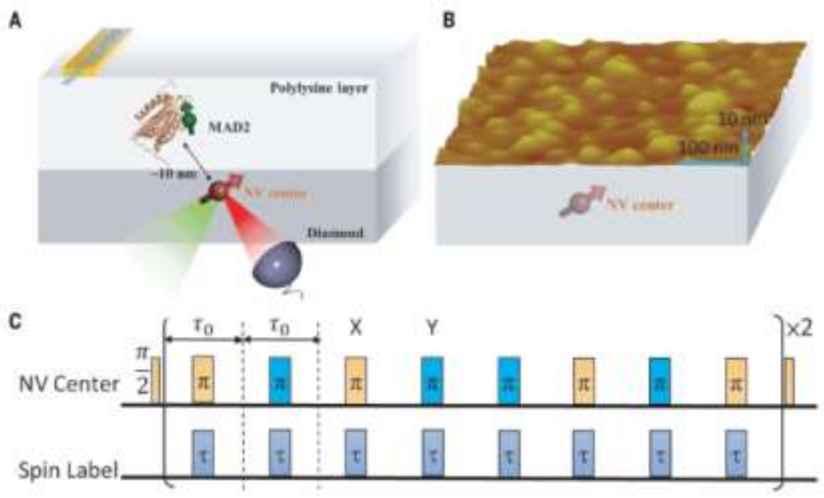
μ-PL from focused ion implanted SiV centers

All New Capability Developed at the CINT User Facility

J. Nogan, W. Ross, A. James, D. Webb (CINT)

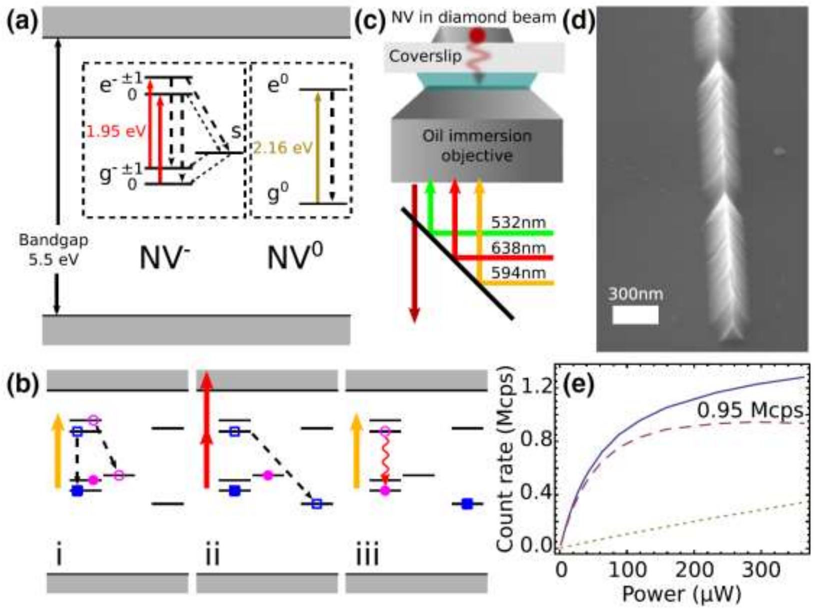
Examples of Color Center Applications

<u>Single-protein spin resonance</u>



F. Shi *et al*., Science **347**, 1135 (2015)

<u>Readout of single NV spin</u>



B. J. Shields *et al*., PRL **114**,136402 (2015)

What is the problem?

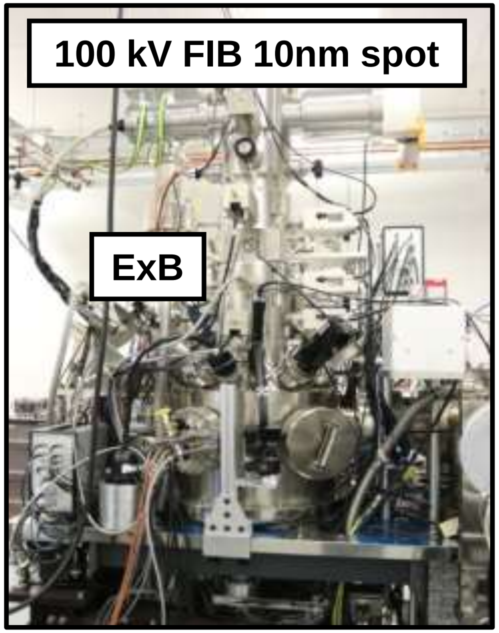
How to produce a ***<u>single</u>*** color center ***<u>where</u>*** you want it?

1.) Location

2.) Yield

Location Problem is Solved

Sandia National Laboratories

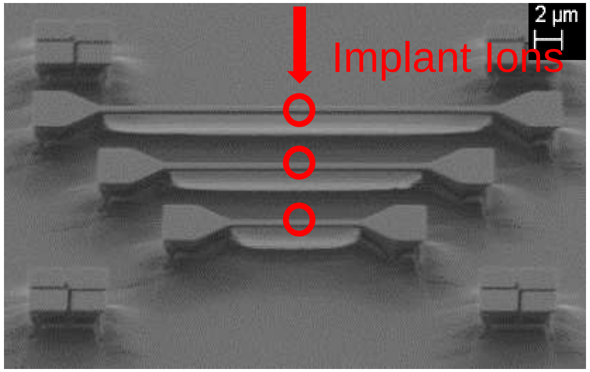


<u>SNL NanoImplanter (nI)</u>

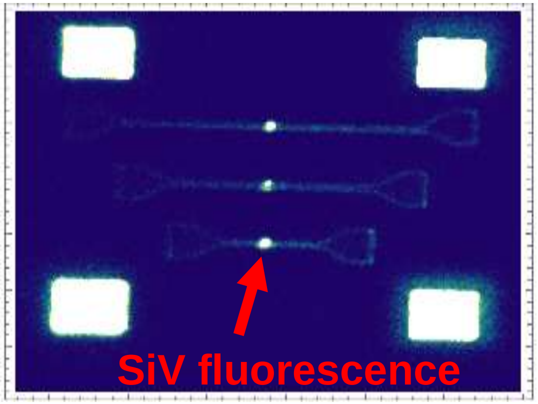
- Variable energy 10-200 keV
- Mass-Velocity Filter (ExB)
  - → Liquid metal alloy ion source
  - → 1/3 Periodic Table
- Direct write lithography platform
  - → Single ion implantation
  - → nm targeting accuracy

Diamond Nanobeams (SNL/Harvard collaboration)

A. Sipahigil, R. Evans, D. Sukachev, H. Atikian, M. Loncar and M. Lukin



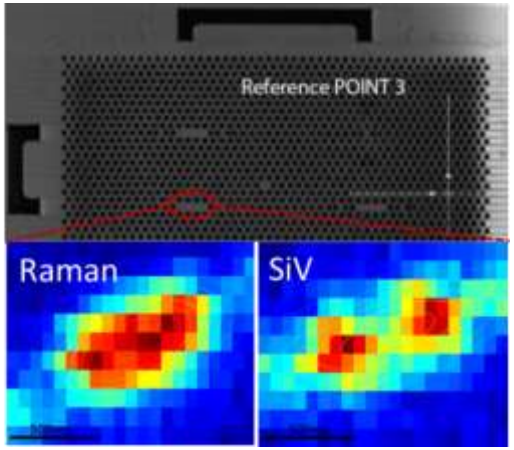
A. Sipahigil *et al.*, *Science* (2016)



2D Photonic Crystals (SNL/MIT collaboration)

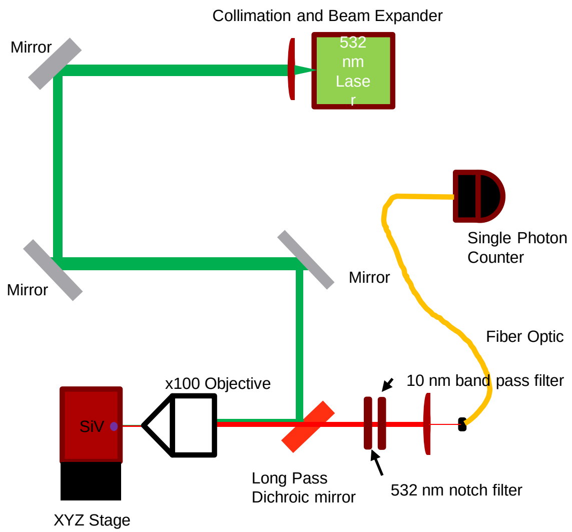
T. Schroder, M. E. Trusheim, and D. Englund

arXiv:1610.09492 accepted into Nature Comm.



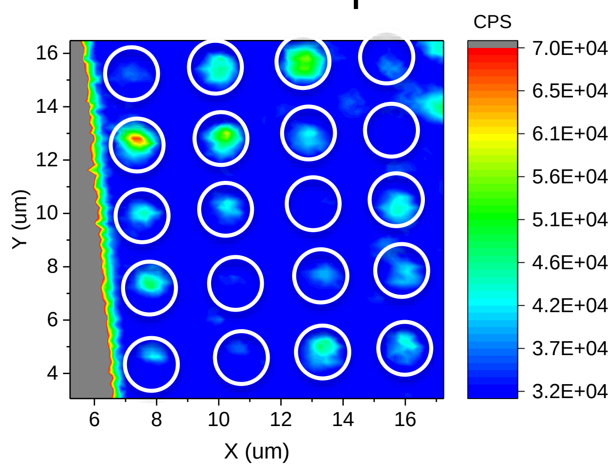
Targeting accuracy is spot size limited to 10's of nm

Yield: Mapping SiV Photoluminescence

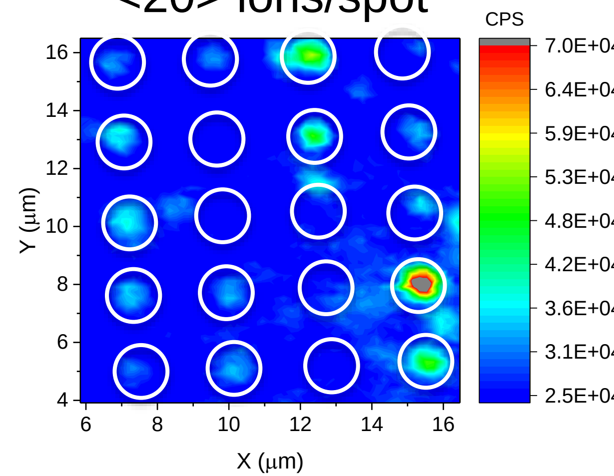


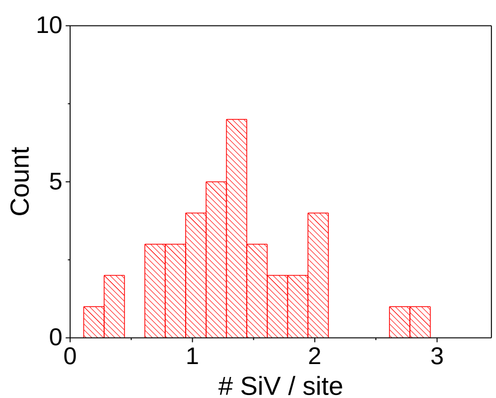
Yield = # measured SiV / # implanted Si

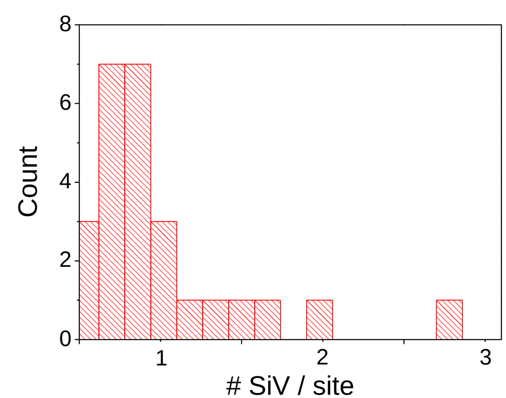
<50> ions/spot



<20> ions/spot







Yield is low and distribution matches Poisson statistics

Yield: 2.5%

Yield: 3.75%

Similar yield to

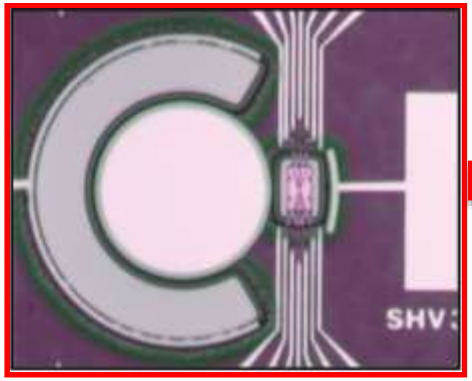
S. Sangtawesin et. al. Appl. Phys. Lett. 105, 063107 (2014)

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

How to Improve the Activation Yield?

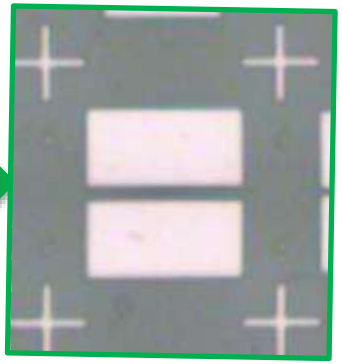
Single Ion Detectors to Understand Yield

Silicon



Translating single ion detection to diamond

Diamond

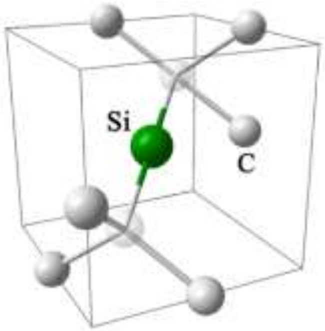


J.A. Seamons, et. al. Appl. Phys. Lett, 93, 043124 (2008)
E Bielejec, et. al. Nanotechnology 21, 085201 (2010)

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

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

Sequential Implantation to Improve the Yield



- Yield limited by the number of accessible vacancies

→ Improve yield by producing excess vacancies in the immediate neighborhood of the implanted Si

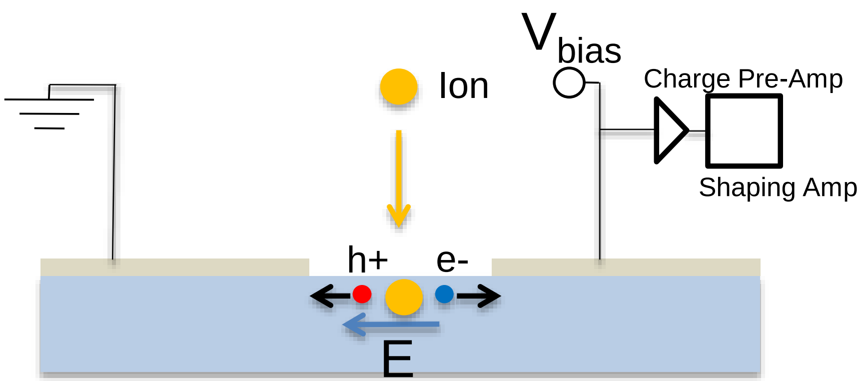
Using Diamond Detectors to Understand Yield

Yield = # measured SiV / # implanted Si

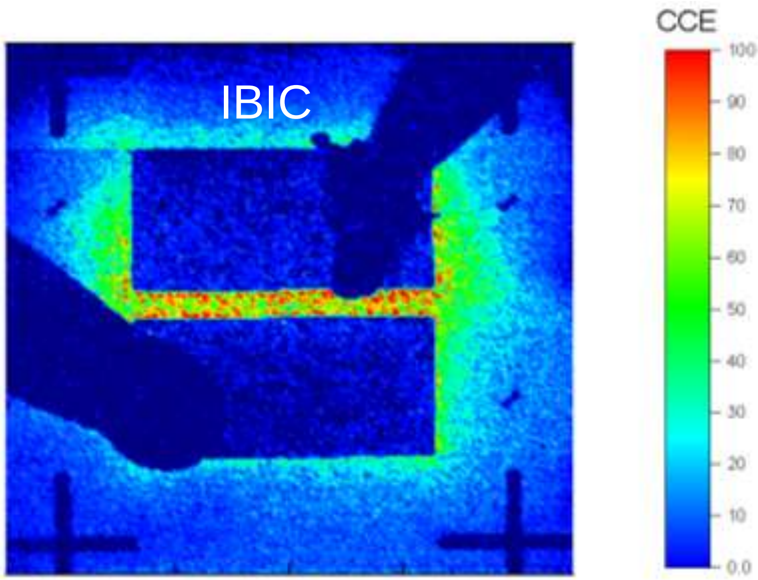
<u>Poisson Statistics</u>

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

Ion Beam Induced Charge (IBIC)



Side View



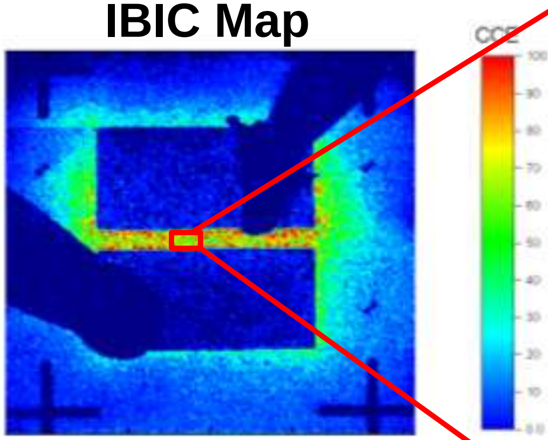
$$\text{CCE} = \frac{\textit{Charge Collected}}{\textit{Charge Depositied}}\, x\ 100$$

IBIC/Detection Demonstrated for low energy heavy ions

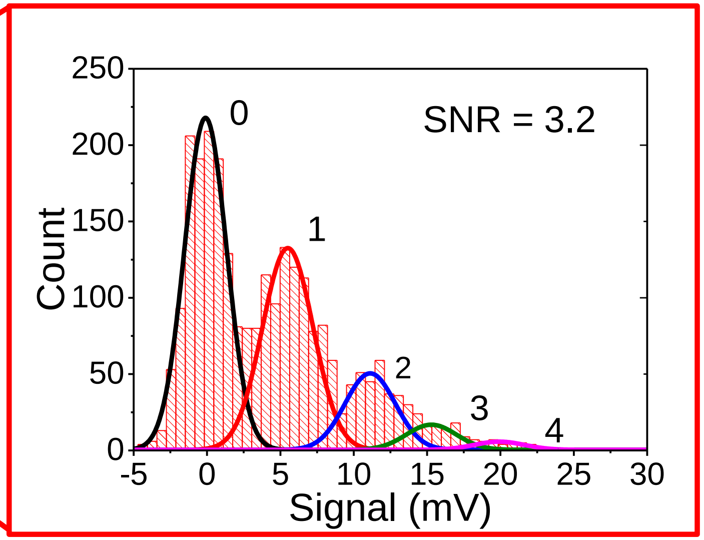
Abraham *et al*, APL **109**, 063502 (2016)

Single Ion Diamond Detectors

IBIC Map



Quantized Detection <0.65> ion

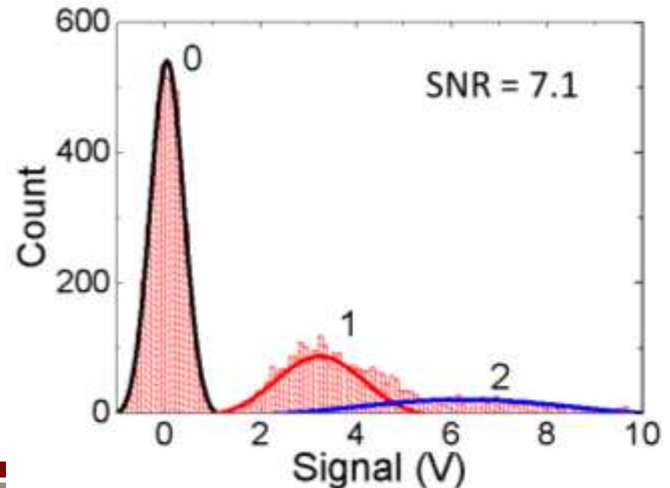


$$SNR = \frac{\mu_{signal}}{\mu_{noise} + \sigma_{noise}}$$

Signal amplitudes match Poisson statistics to 4%

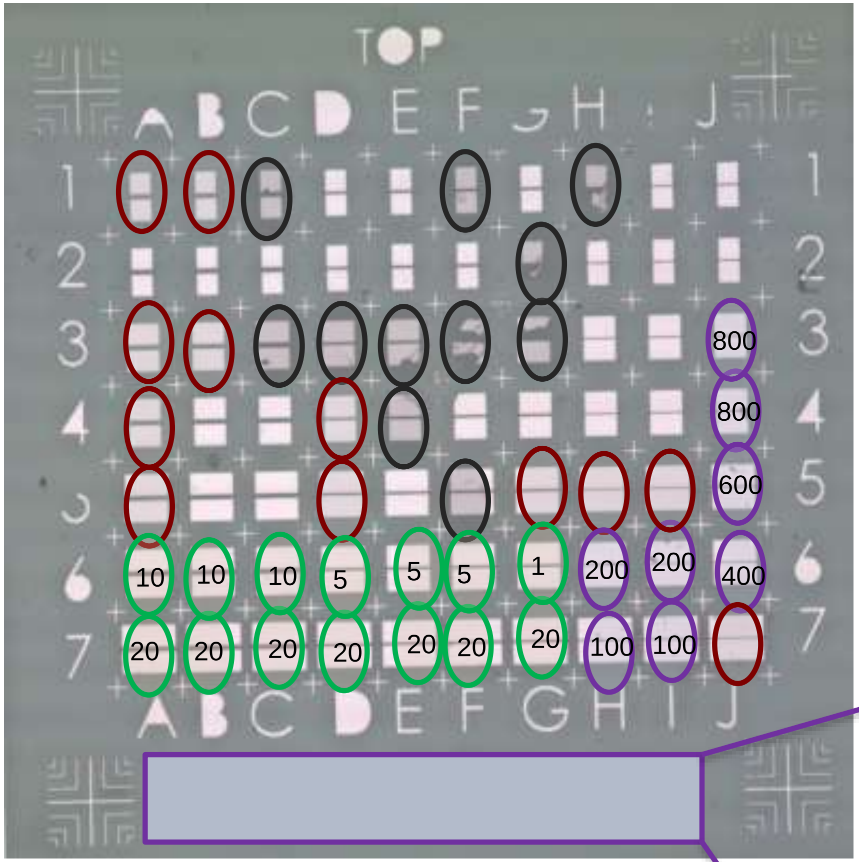
Optimizing gain for single ion detection

Single Ion Counting <0.2> ion



Single Ion Detection in Diamond with SNR ~10

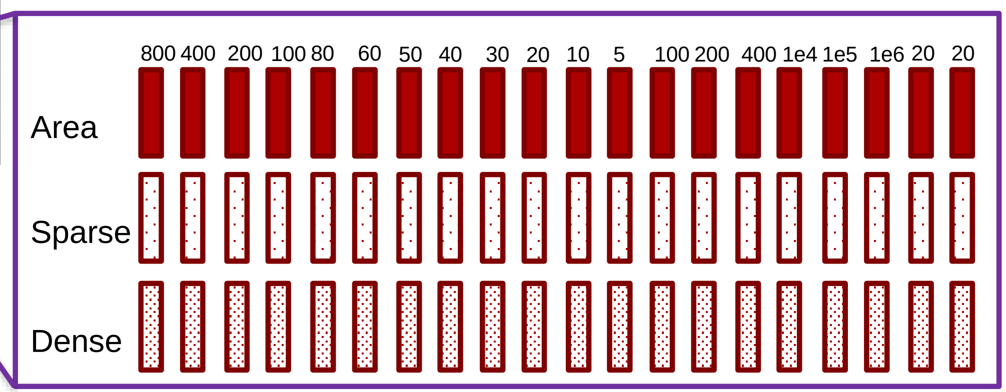
Timed and Counted SiV Arrays



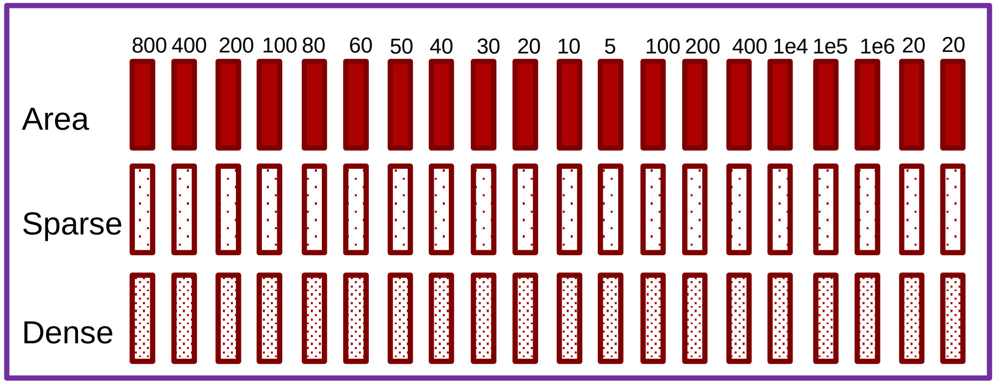
Legend:

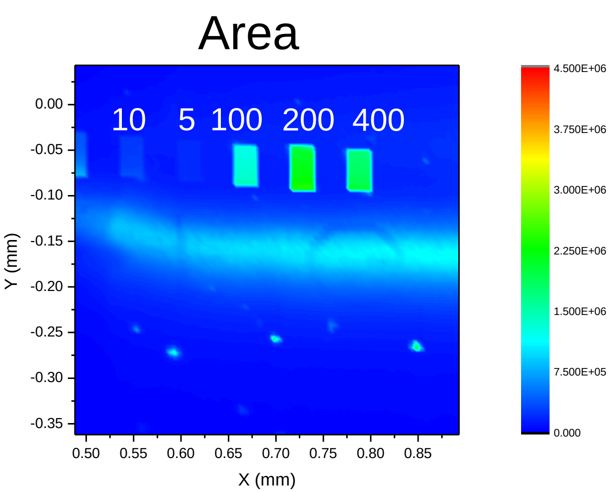
- Device Characterization
- Counted Implants
- Timed Implants
- Questionable Devices

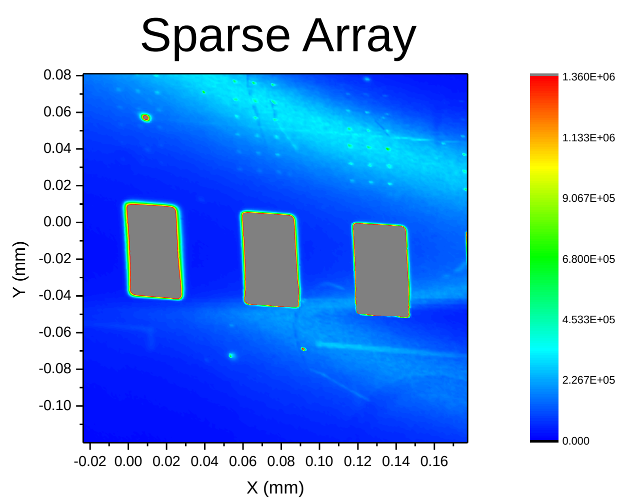
is <average> number of either timed or counted ions

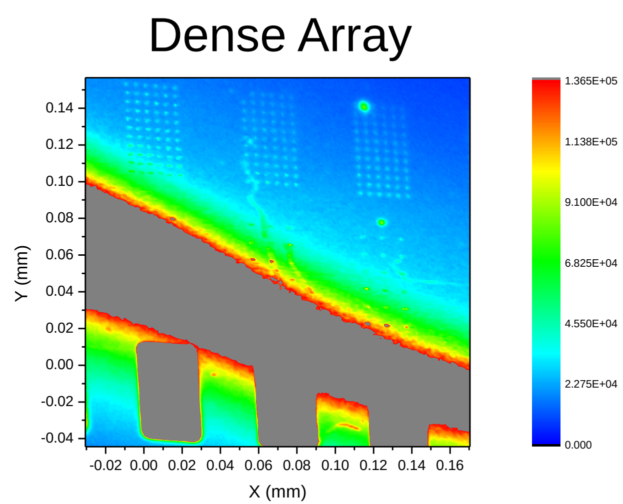


Timed SiV Arrays



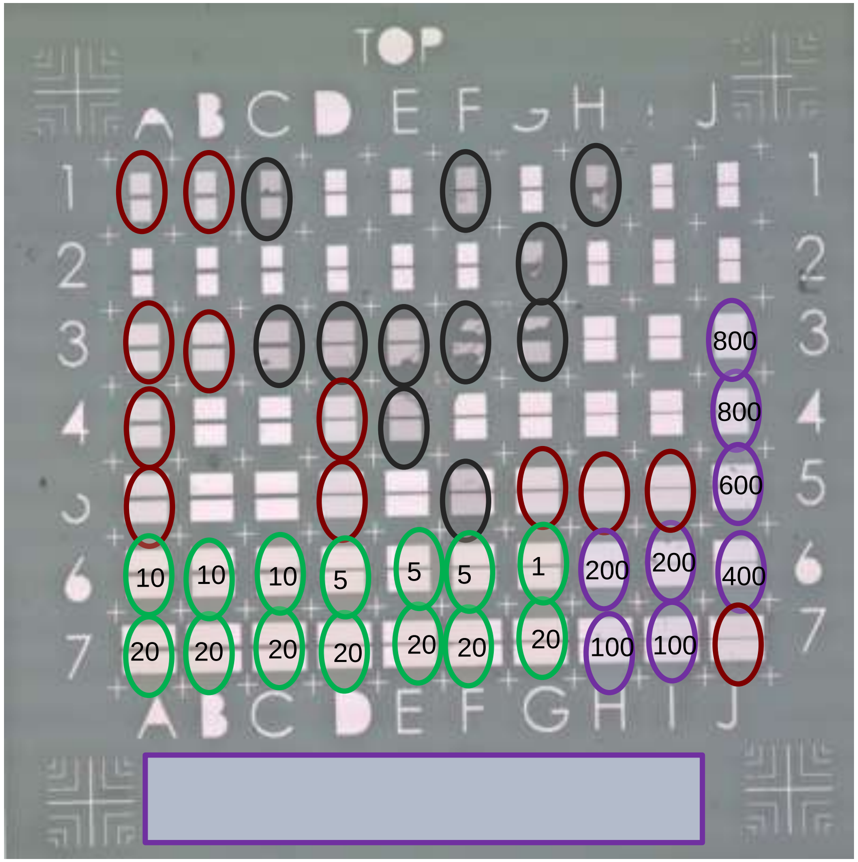






Measure the area, sparse and dense timed arrays with any issues

Counted SiV Arrays



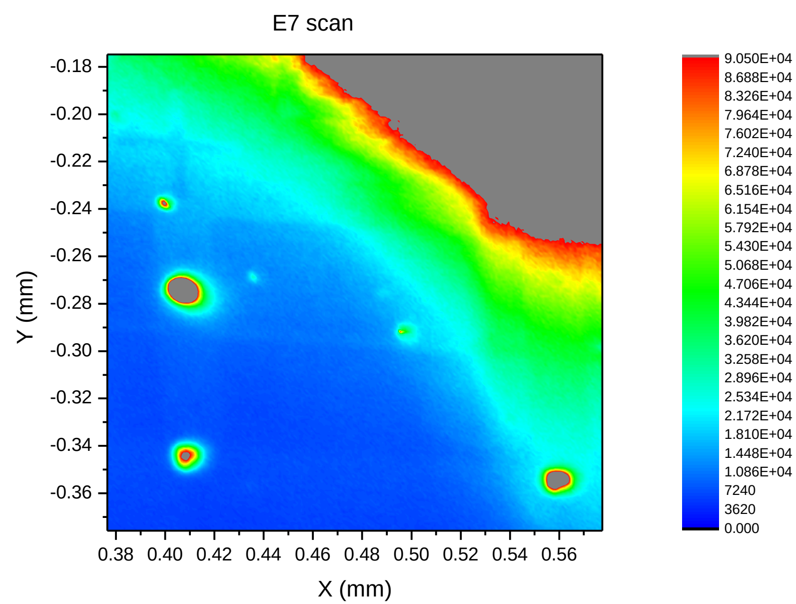
Legend:

~~Device Characterization~~

~~Counted Implants~~

~~Timed Implants~~

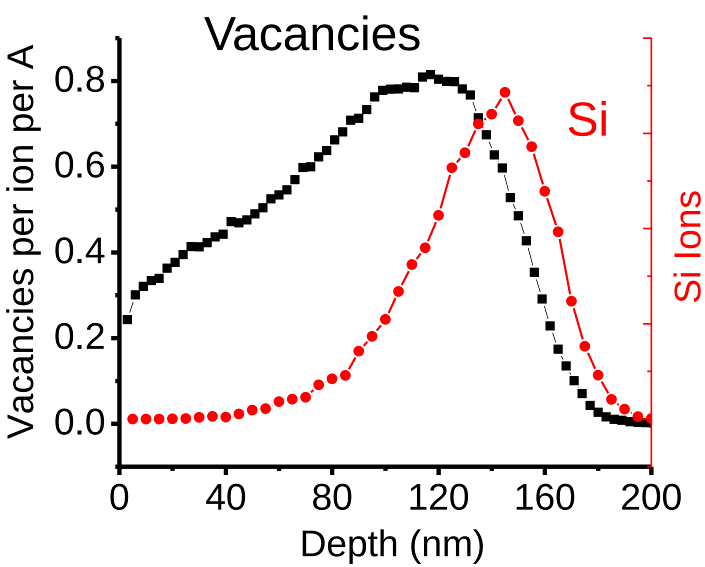
Questionable Devices



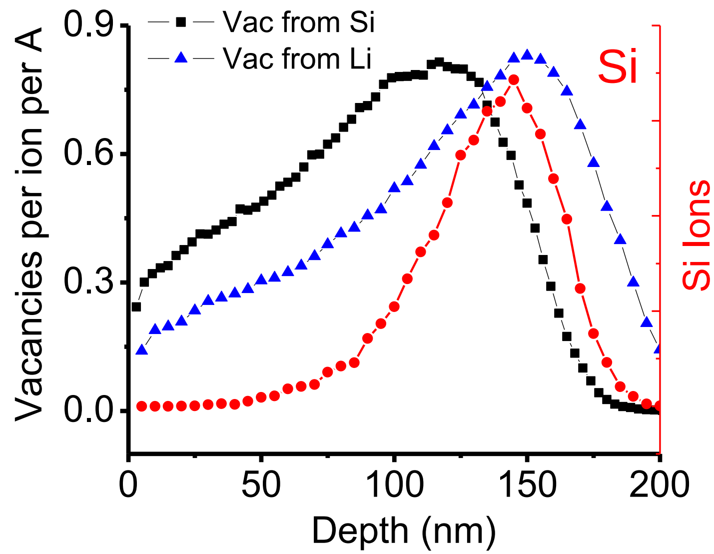
Do not observe any SiV in the detector regions of either timed or counted configurations

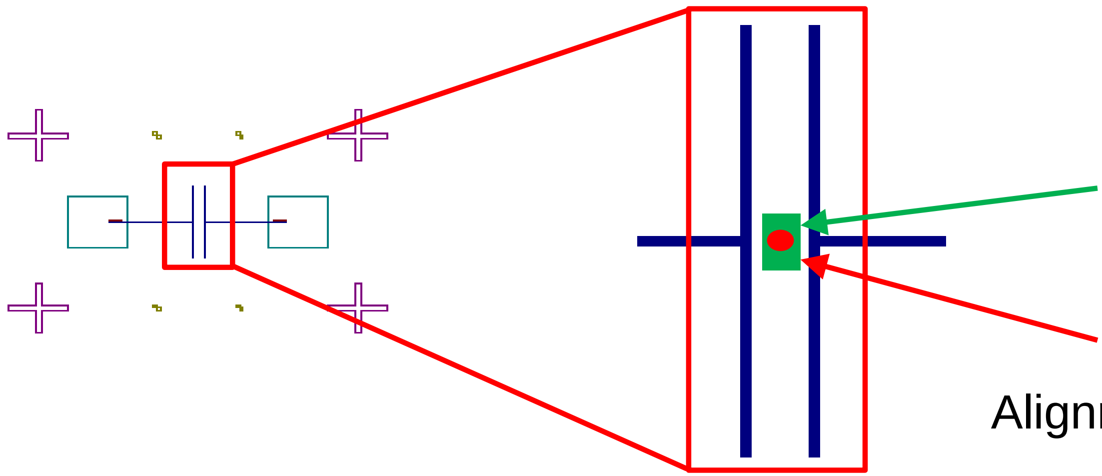
Yield Improvement - Sequential Implantation

200 keV Si Implant



200 keV Si + 50 keV Li Implant





1.) Align to markers

2.) Vacancy creation

3.) Switch to Si beam, realign

4.) Implant Si

Alignment with <20 nm resolution

Sequential Implantation

Sequential implant Species	Fluorescence background	Systems with Spatial Control
Light Ions (H, He, Li)	Yes	Excellent - 1 nm with HeIM
Carbon	No	Fair - 1 um with Tandem and nI (needs source development)
Electrons(>100 keV)	No	Requires Development

<u>MicroOne (Tandem Accelerator)</u>

- Light to Heavy Ions – H to I
- Energy range from ~800 keV to >70 MeV
- Spot size as small as ~800 nm

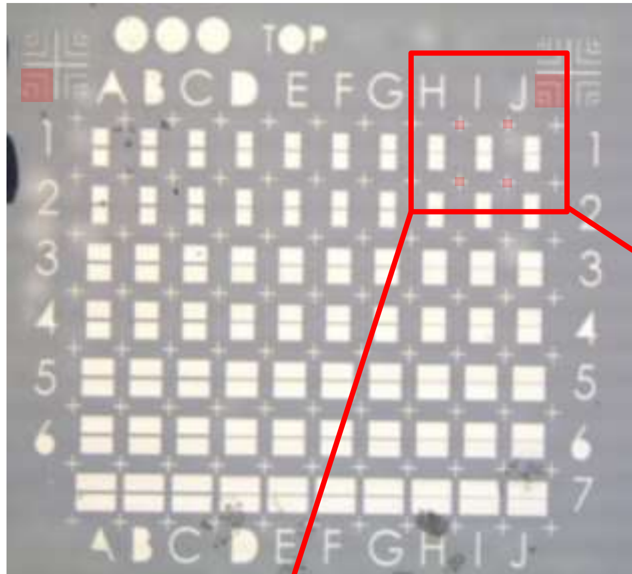
We have four focused ion beam systems ranging from 10 nm to 1 μm spots with a range of energies from 10 keV to 100 MeV

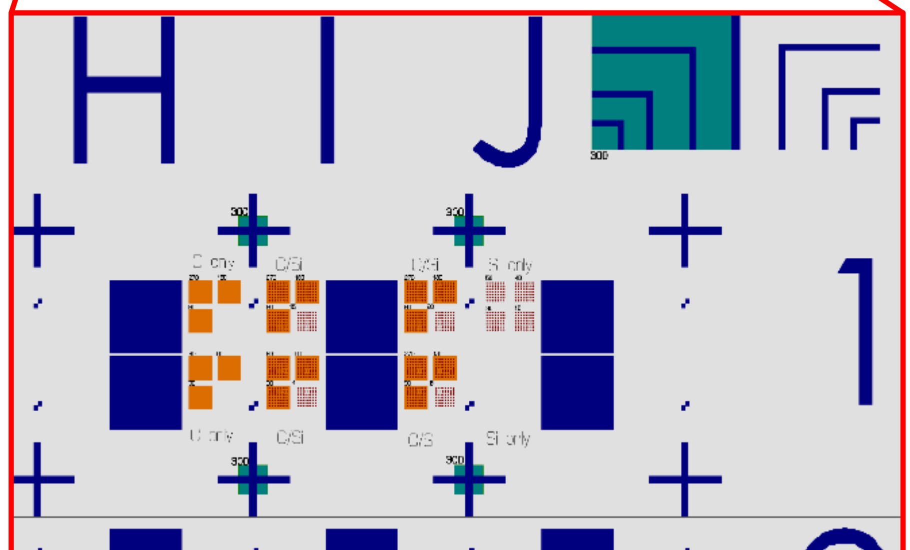
Sequential Implantation using Carbon

Order of implants
- 1.2 MeV C
- 2 MeV Si

1.2 MeV C
874+/-50 nm
262 vac/ion

2 MeV Si
874+/-60 nm
977 vac/ion

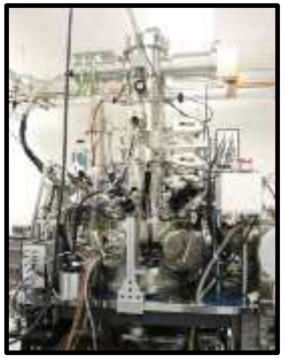




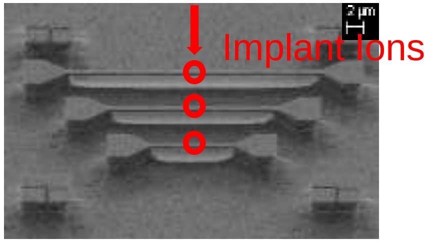
Potential issue with high vacuum anneal – we do not observe any SiV centers

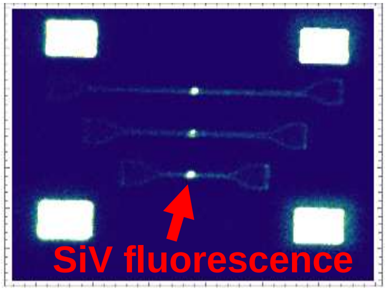
Status of SiV Centers at SNL

1.) **Localization** → Focused Ion Beam Implantation ☑



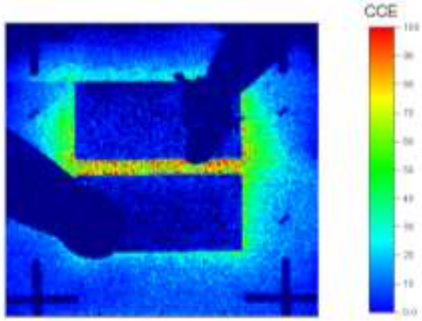
(with Loncar/Lukin Harvard)

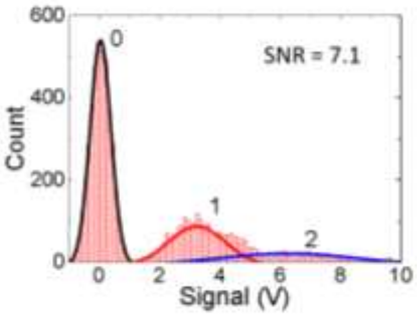




Targeting with ~10's nm resolution

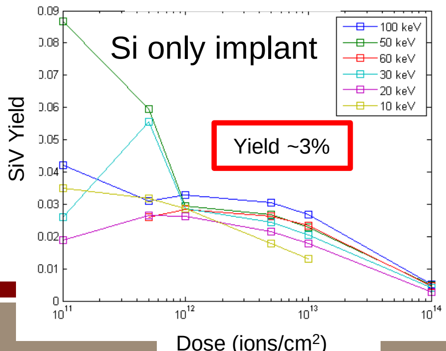
2.) **Understanding Yield - Single Ion Detection** → e-h pair detection ☑





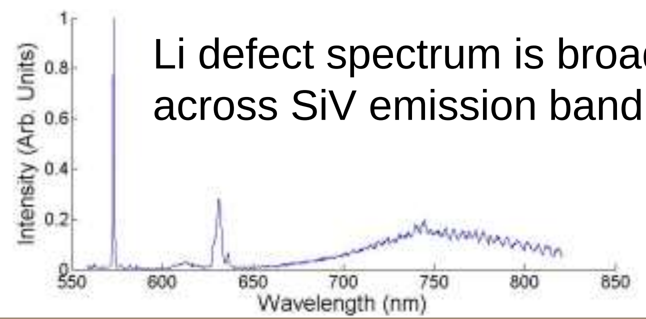
Single ion detection with SNR ~ 10

3.) **Yield Improvements – Sequential Implants** → Li to form vacancies



Li+Si implants performed, post implantation processing underway

(with Englund MIT)

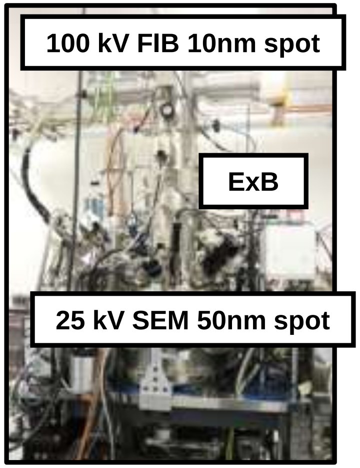


Li defect spectrum is broad across SiV emission band

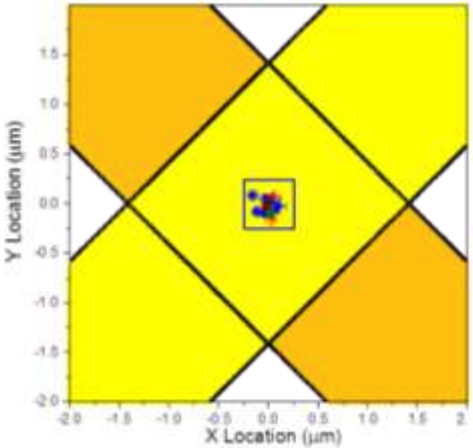
Motivation – Seeding of Memristors

- Use focused ion beam implantation to act as seeding sites for the conductive filament formation.

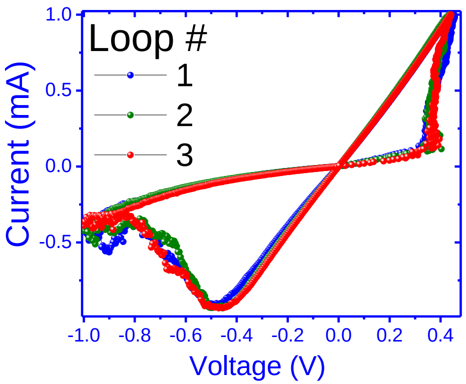
nanoImplanter



+

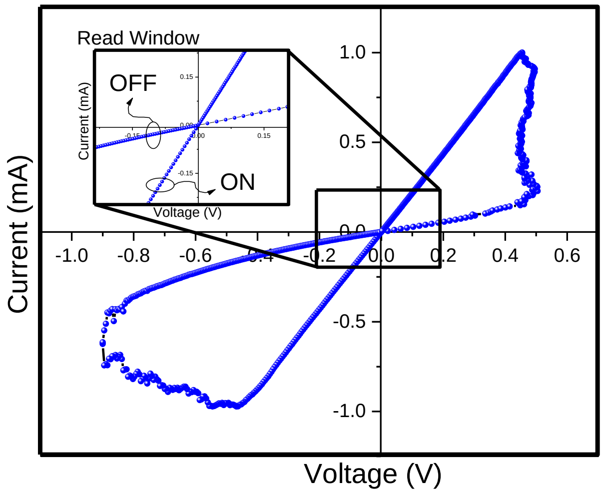


=



- This will reduce the variation induced by the electroforming of the device improving both uniformity and variability

Memristor Operation

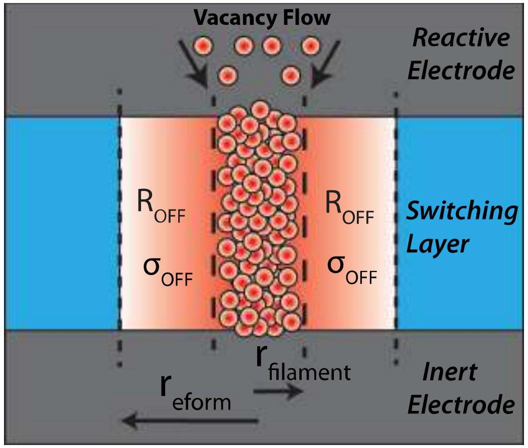


Unknowns:

- Switching mechanism ☐
- Filament location ☑

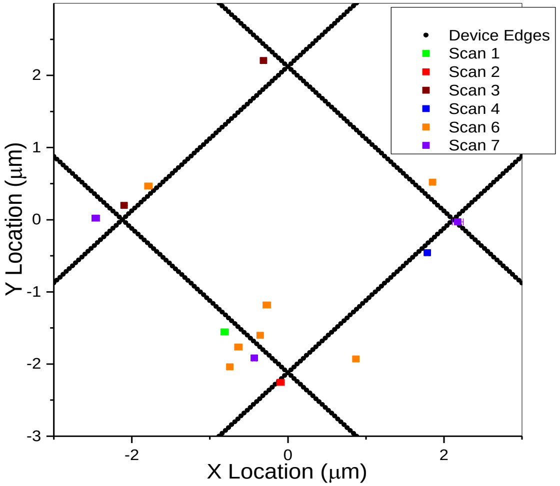
Switching Mechanism

Filamentary conduction



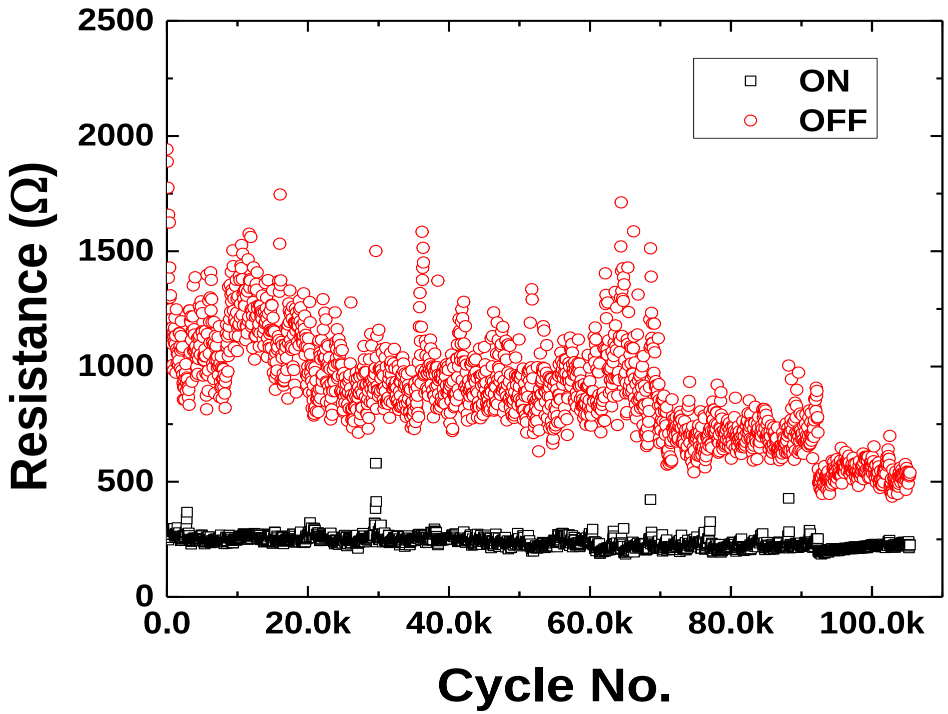
Modulation of oxygen vacancies

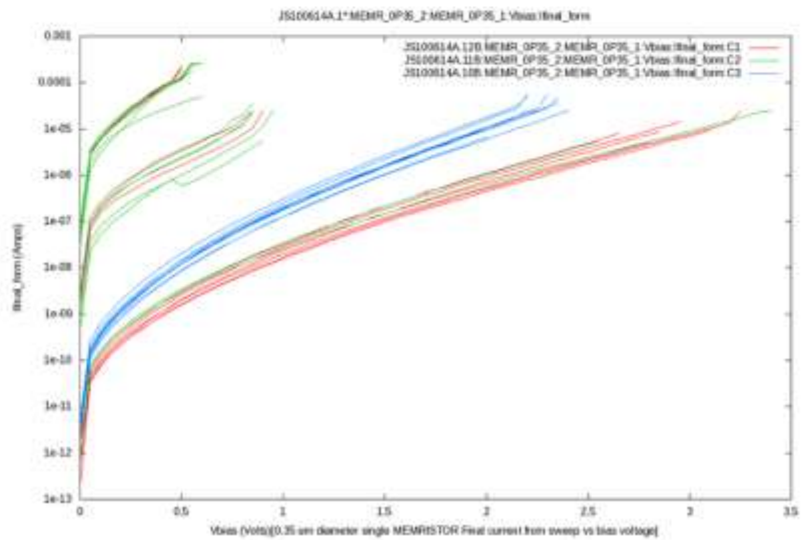
Filament Location



Problem: Variability introduced by electroformation process

Memristor Variability – This is a potential issue

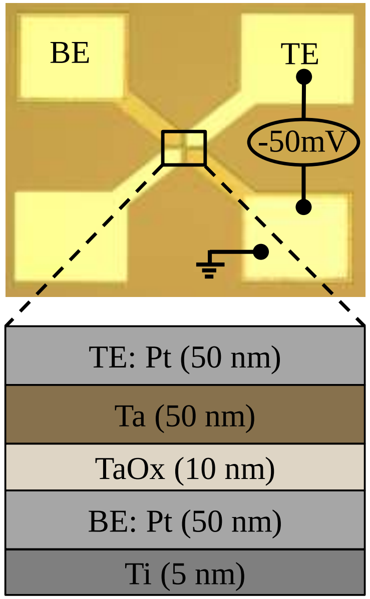


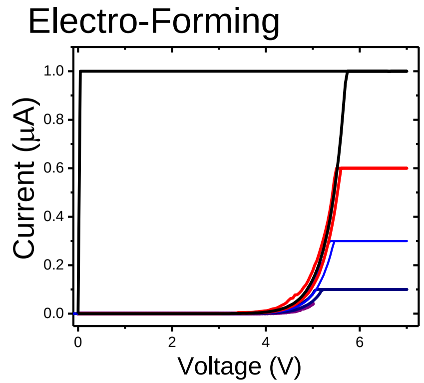


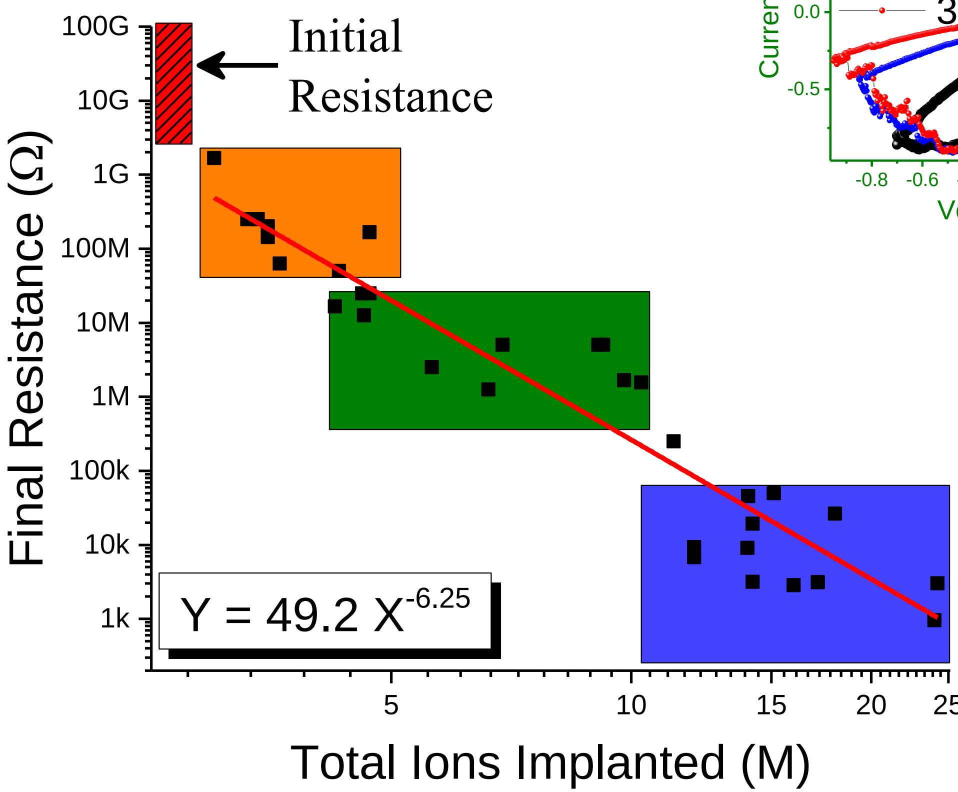
Why is this a problem?

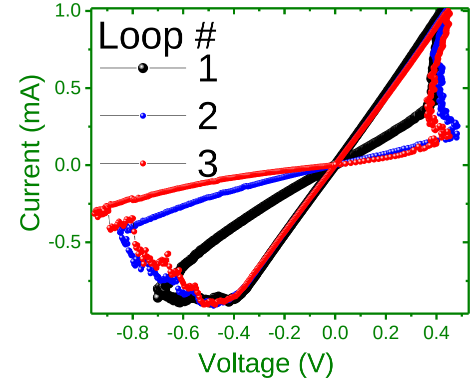
- Switching variability between device-to-device is bad for scaling
- As you aggressive scale the device size the filament variability may increase

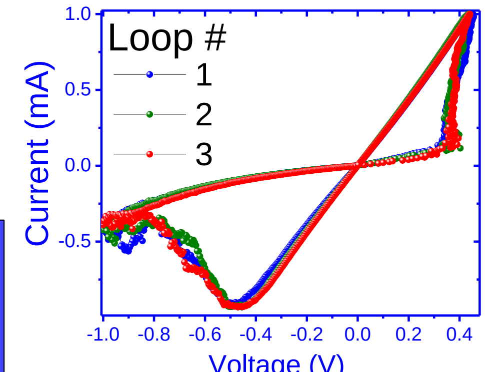
Demonstration of Ion Beam Seeding of Memristors





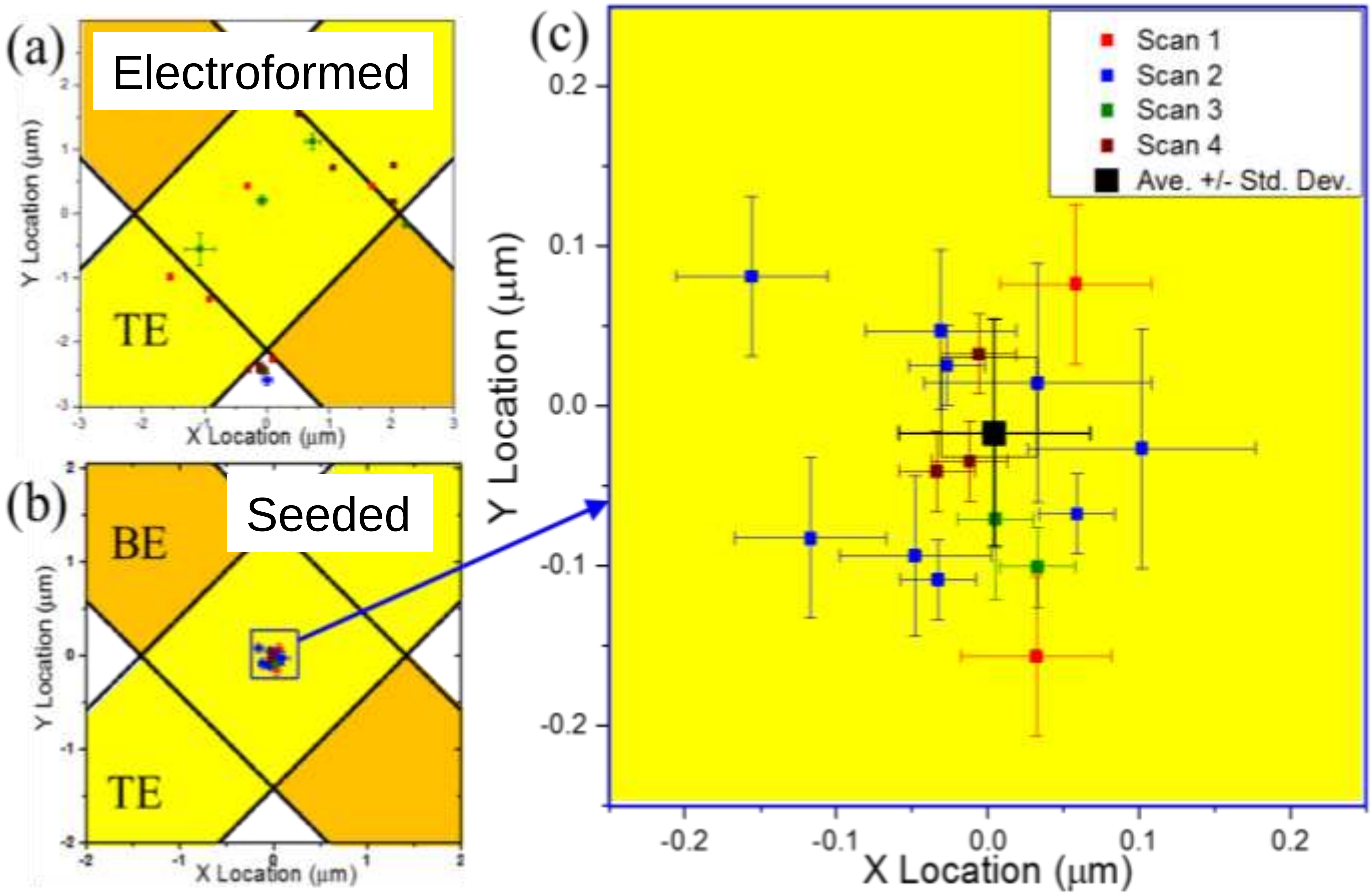






No electroforming!

Demonstration of Ion Beam Seeding of Memristors

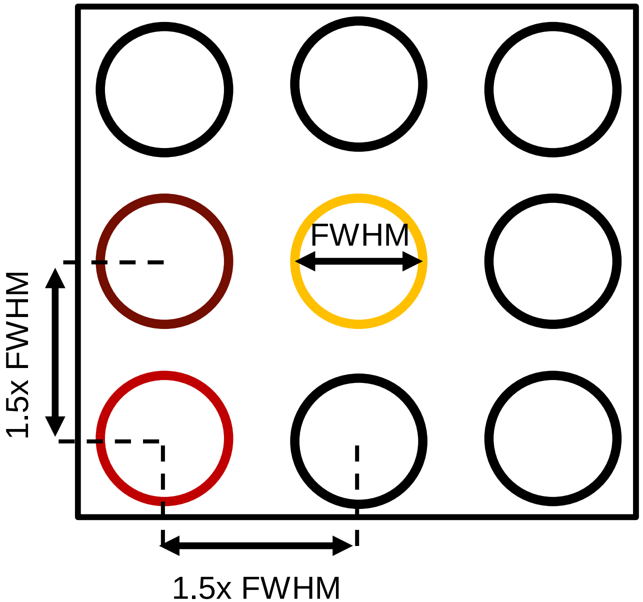


Results:

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

Limits on ‘top-down’ device fabrication

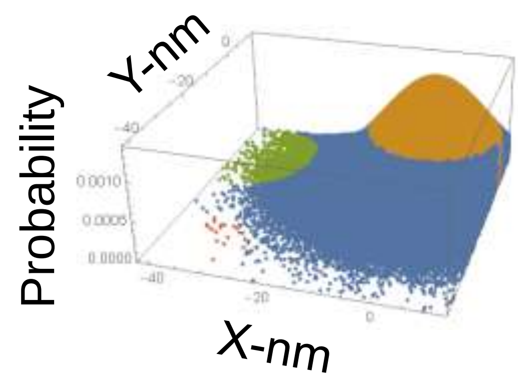
Assume array of ions (donors or color centers) → 1 and only 1 ion per site with PMMA masking



- What is the minimal pitch?

- What is the implant time?

- How large an area can we implant?



For 200 keV Si implant with 100% detection and 25 nm spot we have the following:

- Pitch: ~37.5 nm for 96% confidence
- Time: <0.1>/pulse at 400kHz, 30 μs per implant
- Area: 4 inch wafer, <50 nm stitching resolution

Implant one ion into a 38 x 38 nm^2 per 30 μs with >96% confidence

‘Top-down’ ion beam fabrication can make high resolution arrays

Acknowledgements

Donor Device in Si Fab/Measurement

Ion Beam Laboratory (IBL) Team

J. L. Pacheco, **E. Garratt**, D. Perry, B. McWatters, D. Serkland

Fabrication Team

G. Ten Eyck, D. Ward, **J. B. S. Abraham**, J. Dominguez, B. Silva, M. Carroll

Measurement Team

M. Singh, Tzu-Ming Lu, D. Luhman, M. Lilly

Diamond Color Center Fab/Measurement

J. L. Pacheco, **J. B. S. Abraham**, **B. Aguirre**, R. Camacho (SNL)

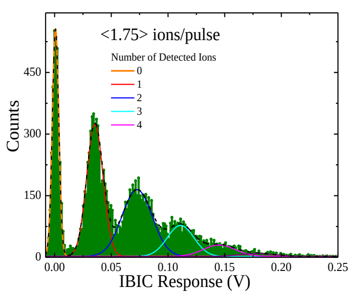
A. Sipahigil, R. Evans, D. Sukachev, H. Atikian, M. Loncar and M. Lukin (Harvard)

M. E. Trusheim, T. Schroder, J. Zheng, S. Mouradi and D. Englund (MIT)

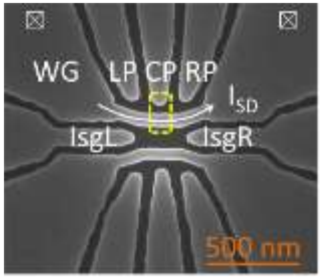
Conclusions

Sandia National Laboratories

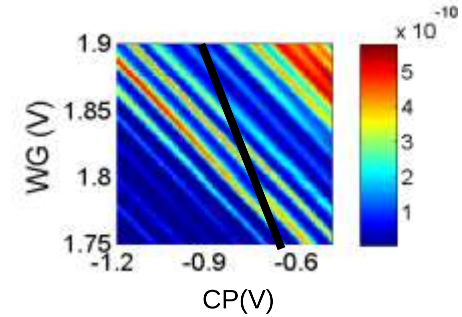
- Single Donor devices in Si for Quantum Computing



+

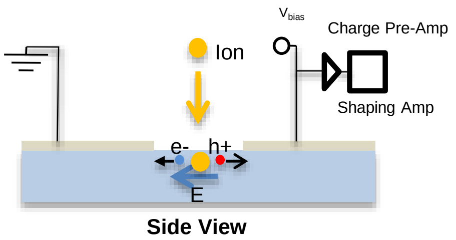


=

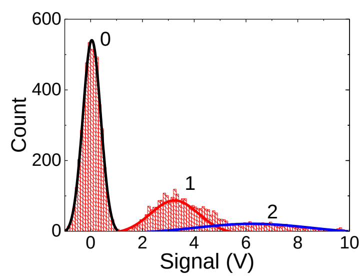


Singh et al. APL 108 062101 (2016)

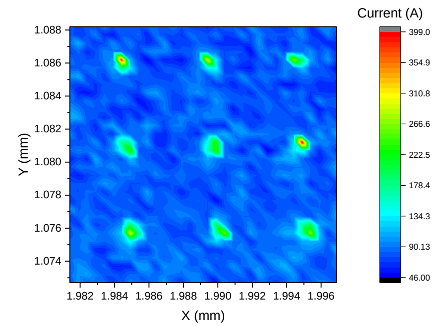
- SiV Color Centers in Diamond



+



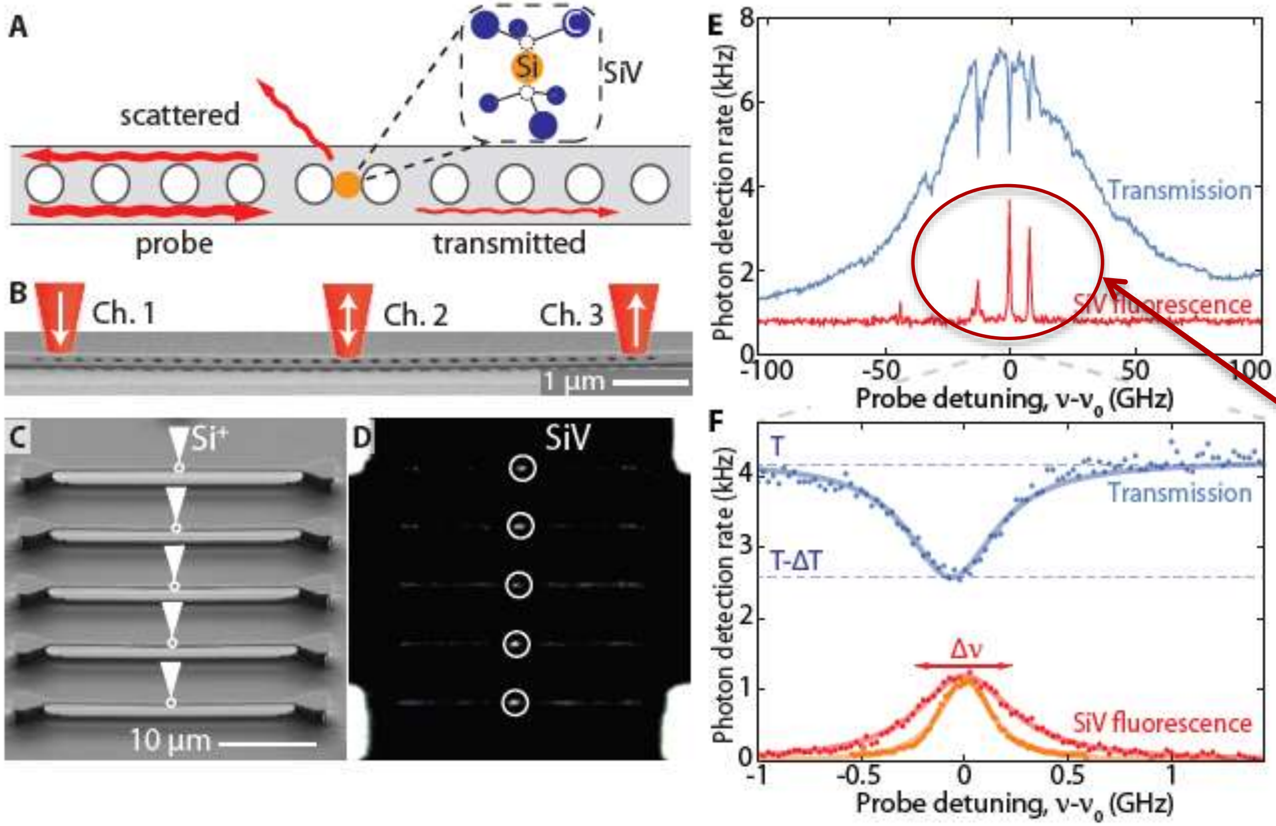
→



- Focused ion implantation is a direct pathway to fabrication of single atom devices

Quantum Nano-photonics with Diamond Color Centers

<u>SiV integrated with diamond cavities (Harvard/SNL Collaboration)</u>



Ch. 1: 737 nm tunable probe

Ch. 2: SiV Control and Characterization (red)

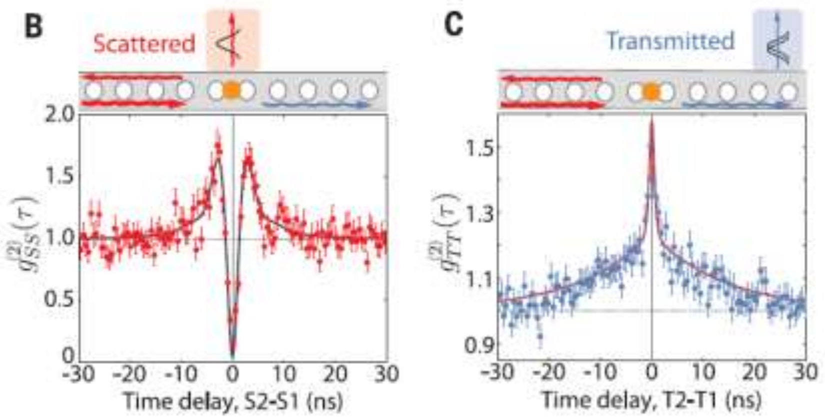
Ch. 3: Transmission (blue)

3 SiV coupled to the cavity

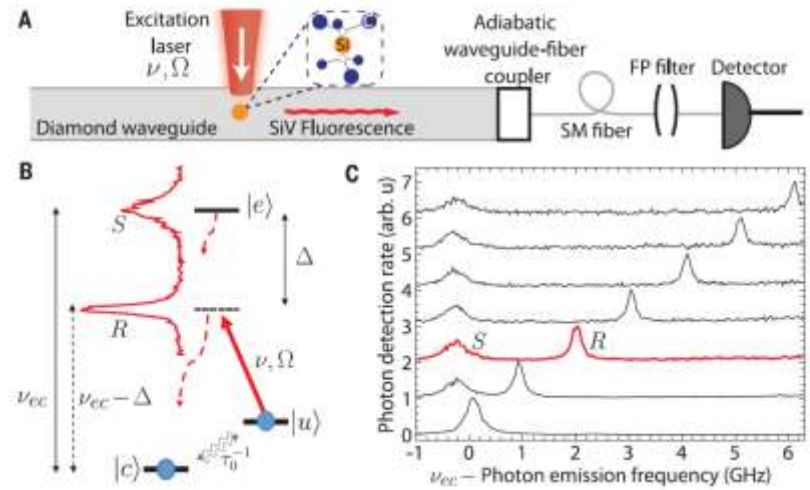
Measurement enabled by focused ion beam implantation – C ~ 1

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

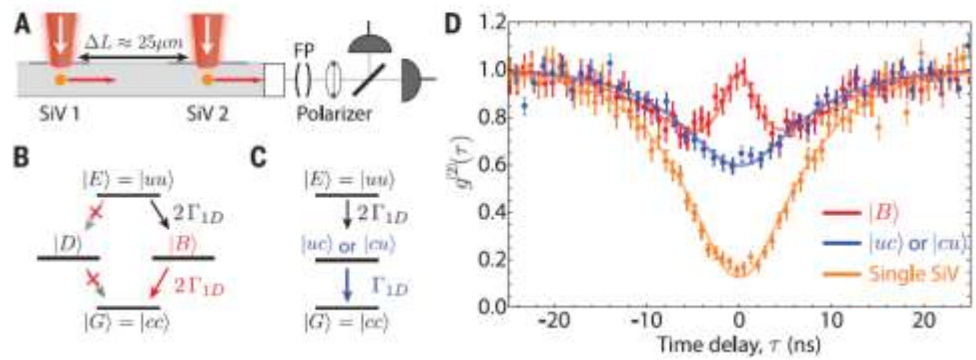
Quantum Nano-photonics with Diamond Color Centers



Quantum-optical switch controlled by a single color center



Spectral tunable single photons

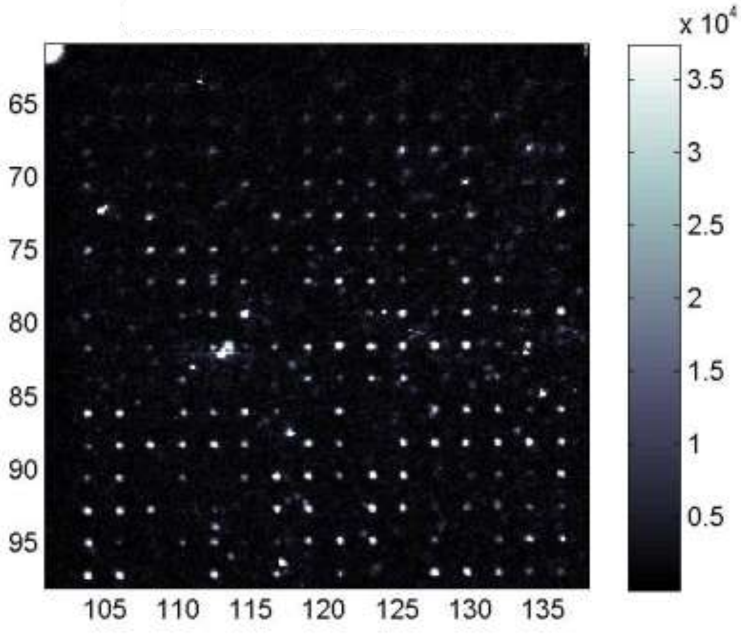


Quantum interference effect due to two entangled SiV centers

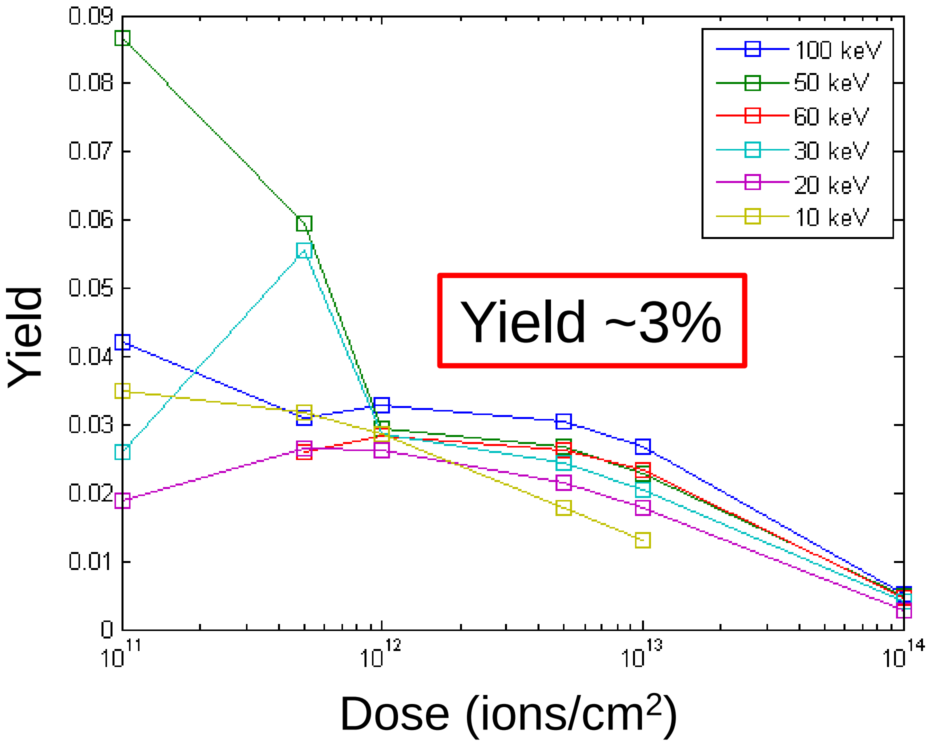
A. Sipahigil *et al.*, *Science* (2016)

Activation Yield is a Major Issue

Yield (SNL/MIT collaboration)



Yield = # measured SiV / # implanted Si



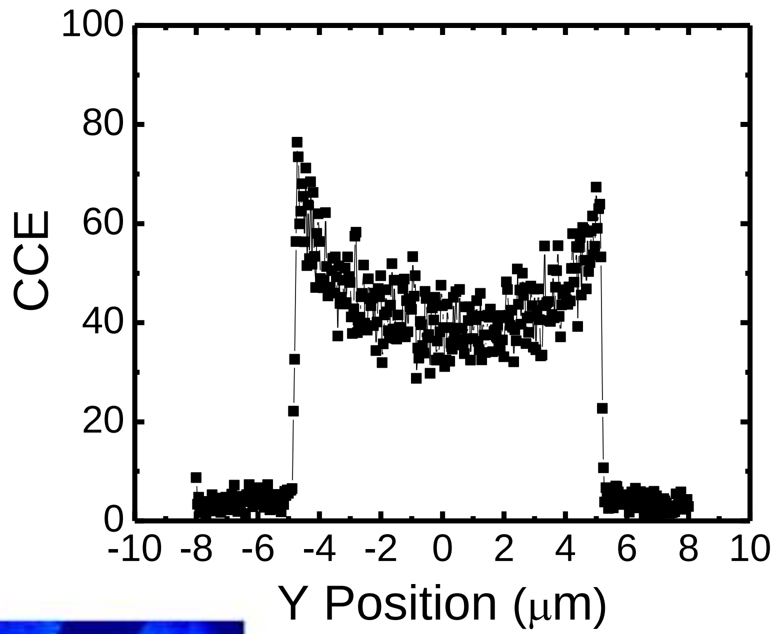
Similar yield numbers to previous work:

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

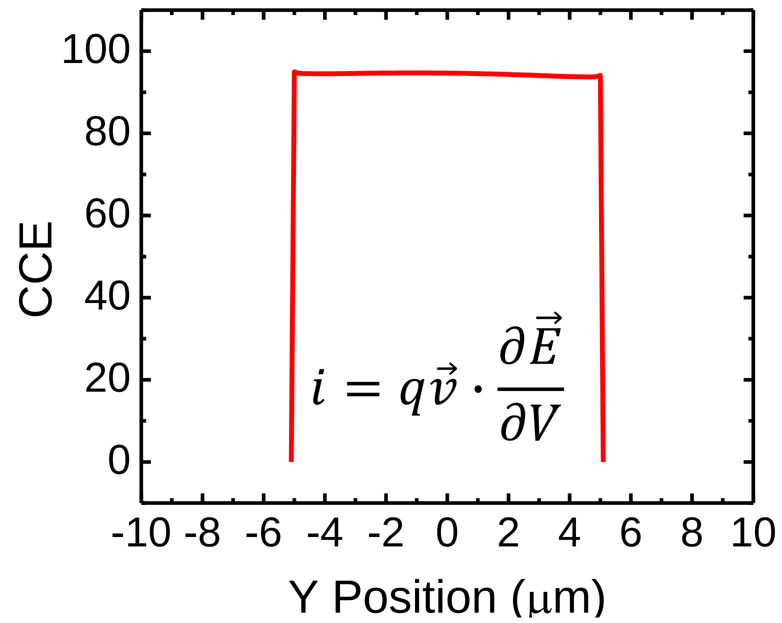
S. Sangtawesin et. Al. Appl. Phys. Lett. 105, 063107 (2014)

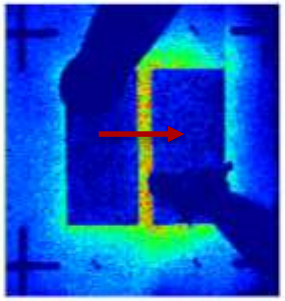
Experimental IBIC vs. Simulation

Experimental IBIC Dataset



Simulation – No damage





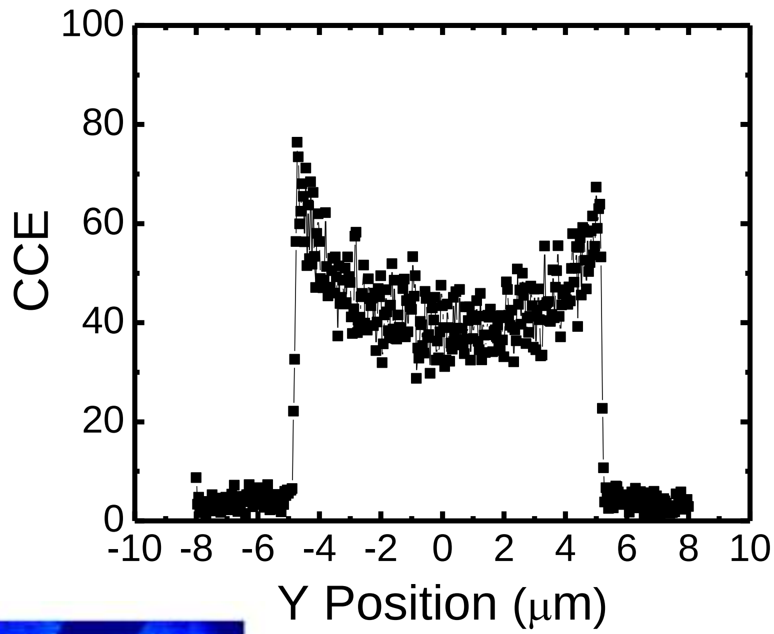
Experimental curve ≠ predicted curve

→ Shape is incorrect

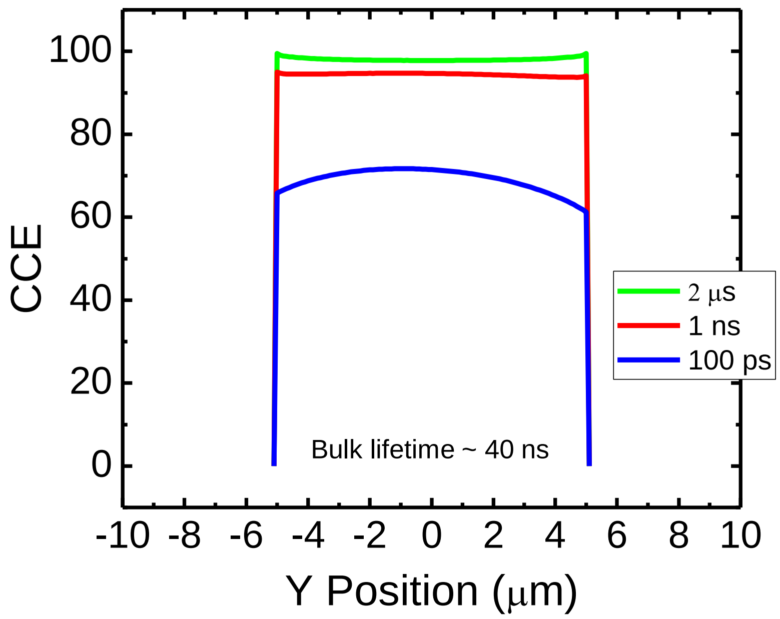
How to account for these differences? Reduce Bulk Lifetime

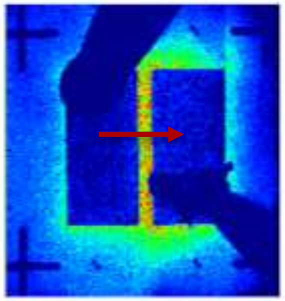
Reducing the Bulk Lifetime

Experimental IBIC Dataset



Simulation Changing Bulk Lifetime





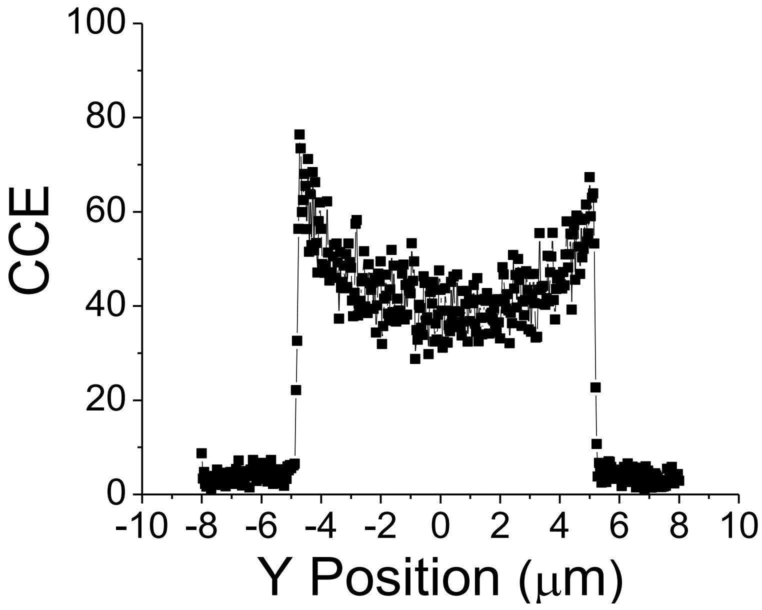
Experimental curve ≠ predicted curve

→ Shape is incorrect and is not simply just a function of bulk lifetime

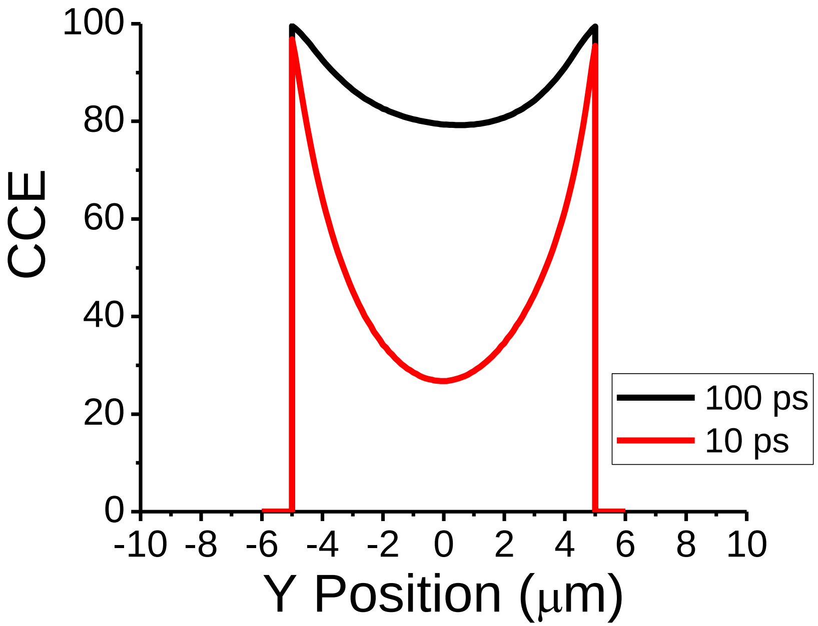
How to account for these differences? Lifetime vs Depth

Depth Dependent Lifetime

Experimental IBIC Dataset

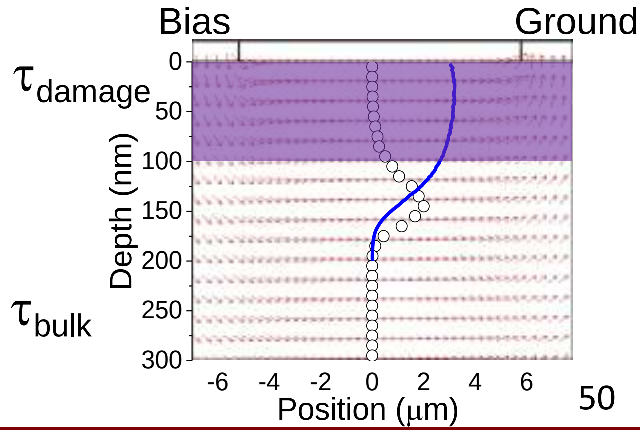


Simulation with Damage



→ Model the damage as a reduced lifetime only near the sub-surface region of the detectors

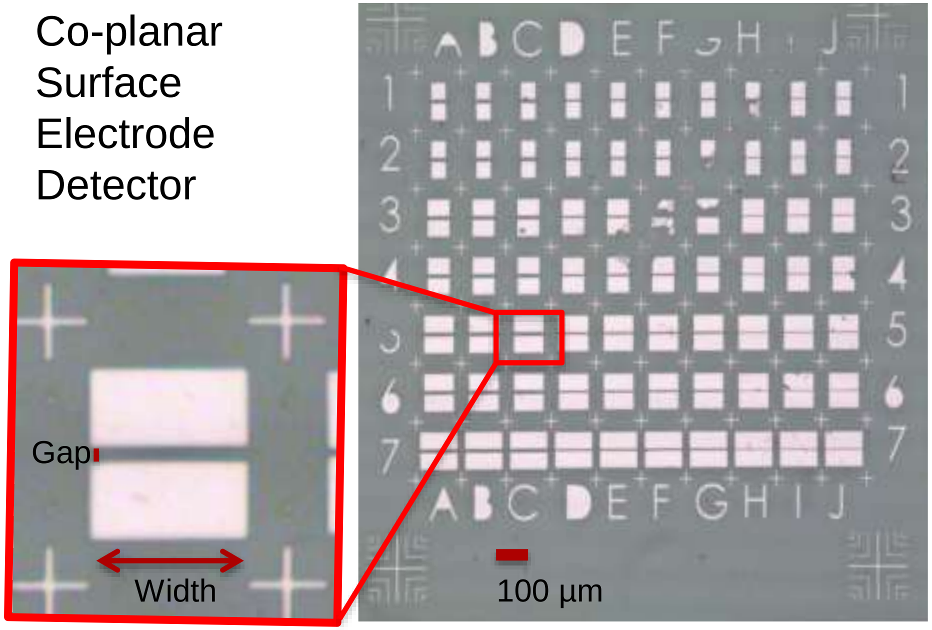
Detectors probe sub-surface damage



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

Fabrication

Co-planar
Surface
Electrode
Detector

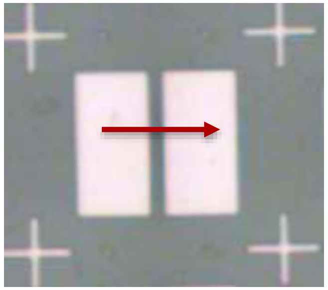


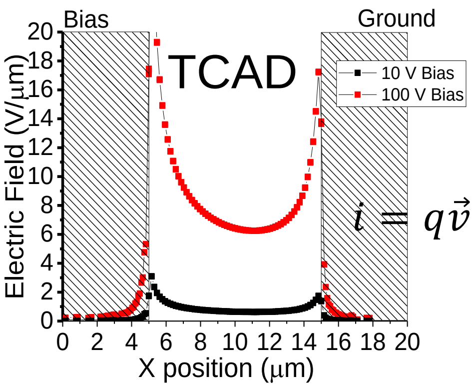
Process

1. RIE $Ar/Cl_2:O_2$
2. Piranha Clean (20 min)
3. Dehydration bake 180C (5 min)
4. Mount Sample on 1 um Oxide Si wafer with PMMA
5. Bake 180C (1 min)
6. Spin HMDS (4K, 30 sec)
7. Bake 90C (90sec)
8. Spin AZ5214EZ (4K, 30 sec)
9. Bake 90C (90 sec)
10. MA6 Aligner (Hard Contact, 5 sec exposure)
11. AZ400K 1:4 Developer (40 sec – over developed)
12. Descum – 10 W, 3 min
13. Metalization (Ti/Pt/Au, 30/50/100 nm)
14. Acetone 30 min with spray

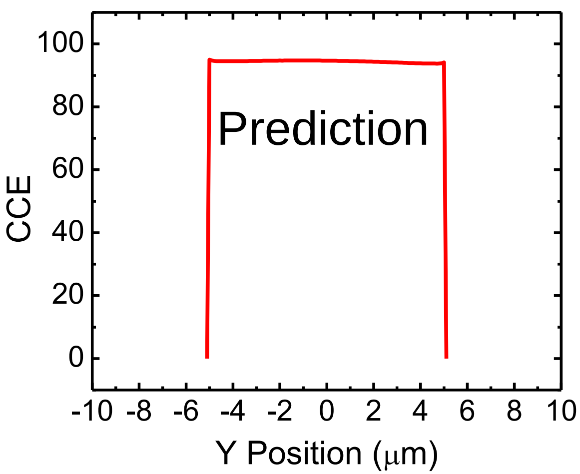
- Electronic grade single crystal diamond (Element 6)
- 200 nm Ti/Pt/Au Electrodes
- Varied width and gap spacing
  - 50-125 um width
  - 2 – 10 um gaps

Characterization of Diamond Detectors

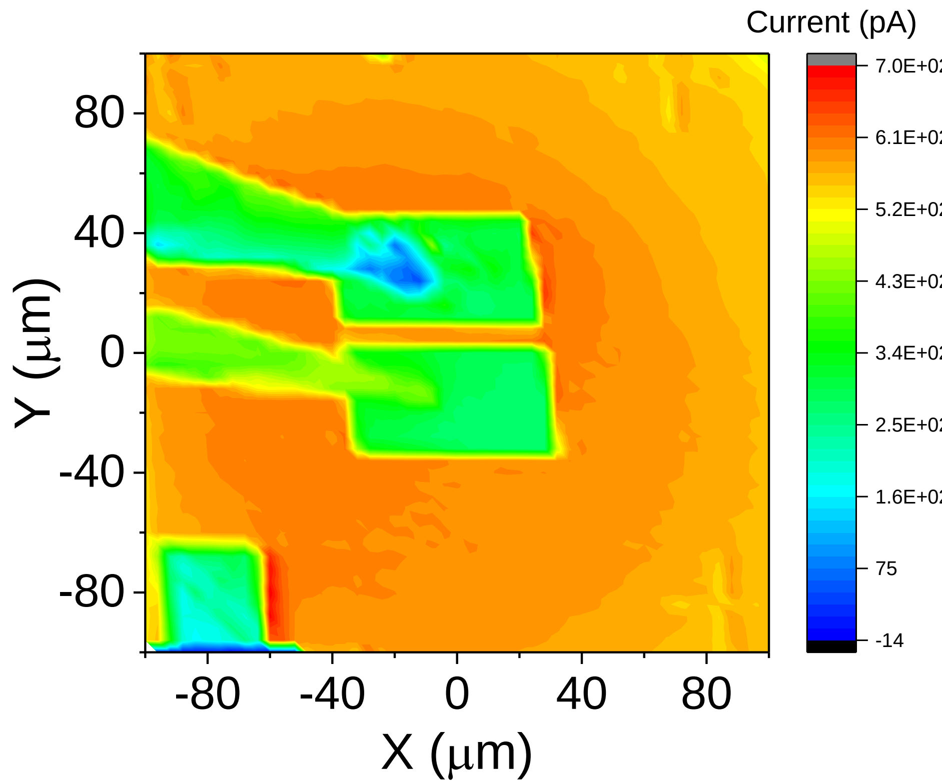




$$i = q\vec{v} \cdot \frac{\partial \vec{E}}{\partial V}$$



Electron Beam Induced Current (EBIC)

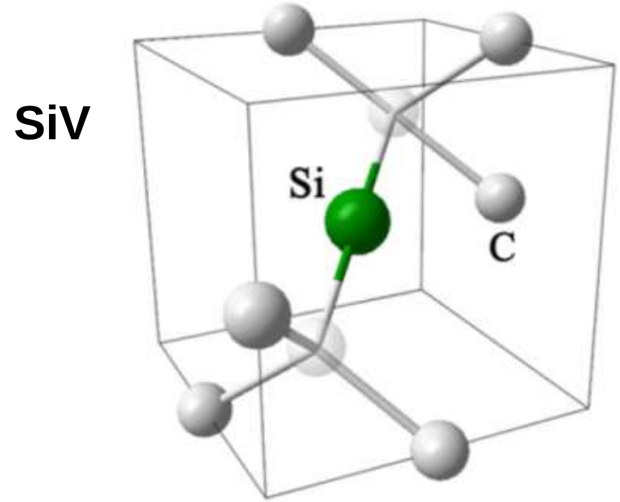


EBIC datasets match the predicted response

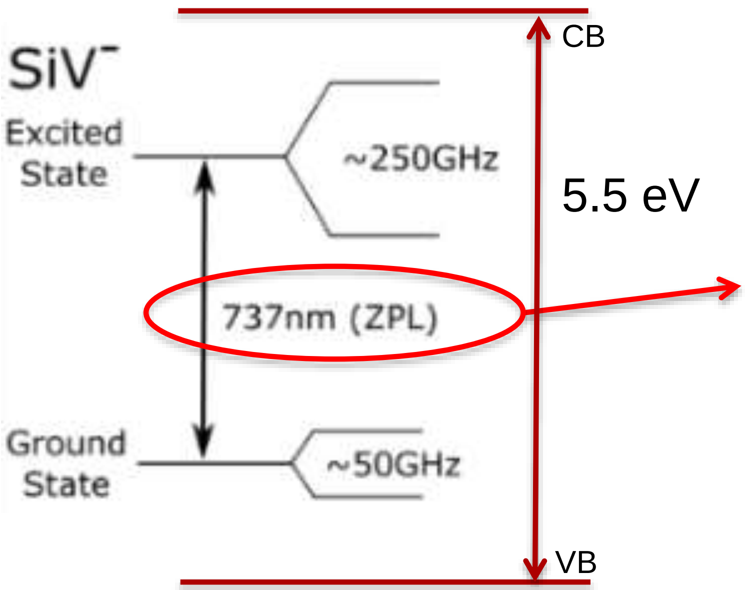
What are Color Centers in Diamond?

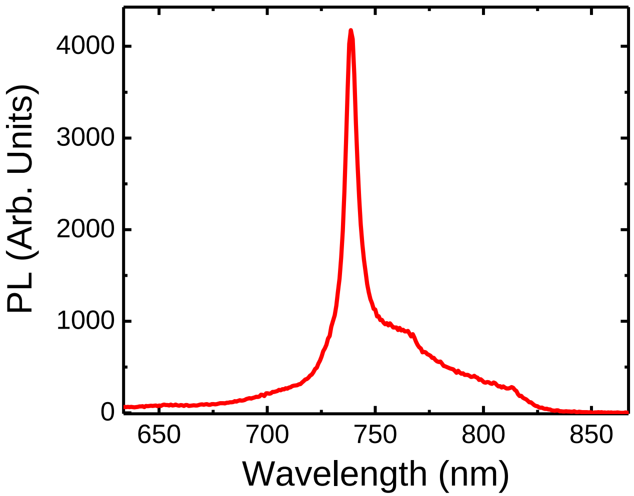
- Range of defect complexes – such as NV, SiV

- Diamond substrate with 5.5 eV band gap – allows RT operation of the defect centers



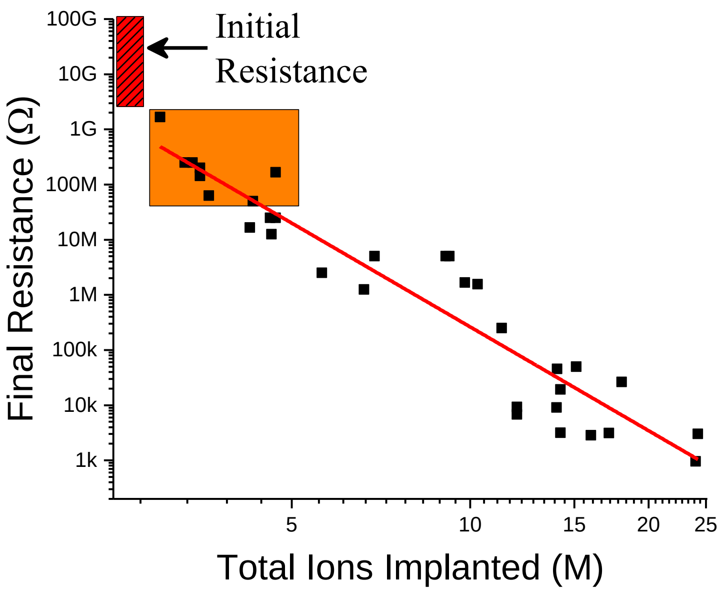
I. Aharonovich *et al*., Rep. Prog. Phys. **74**,076501 (2011)

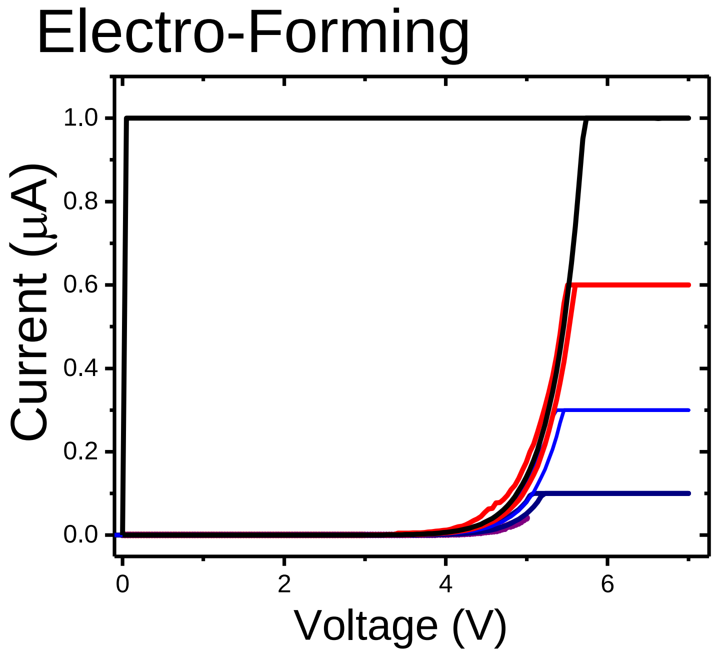




Defect centers act as "Artificial Atoms"

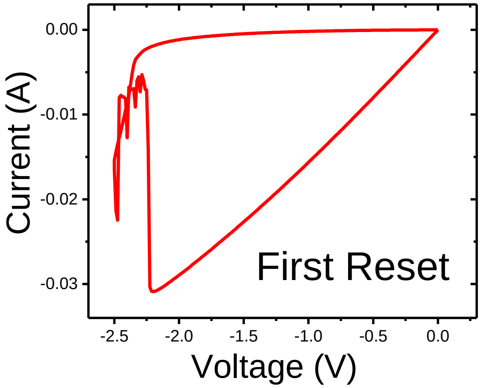
Focused Ion Beam Formation of Filaments: -- High Resistance

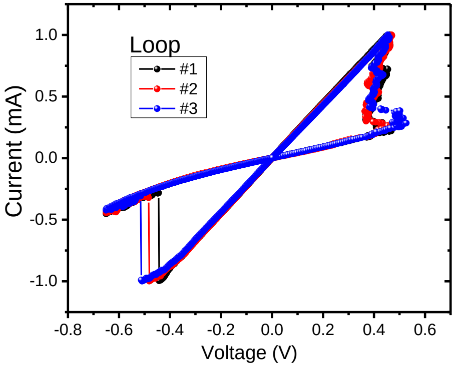




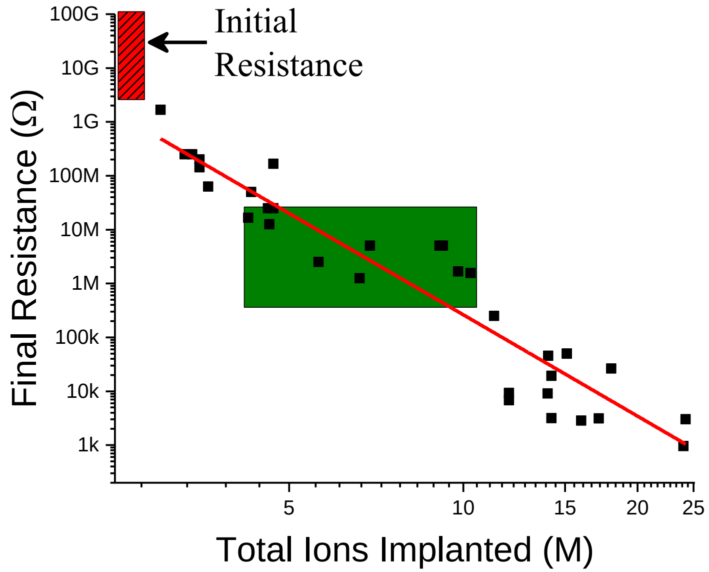
>50 MΩ Regime:

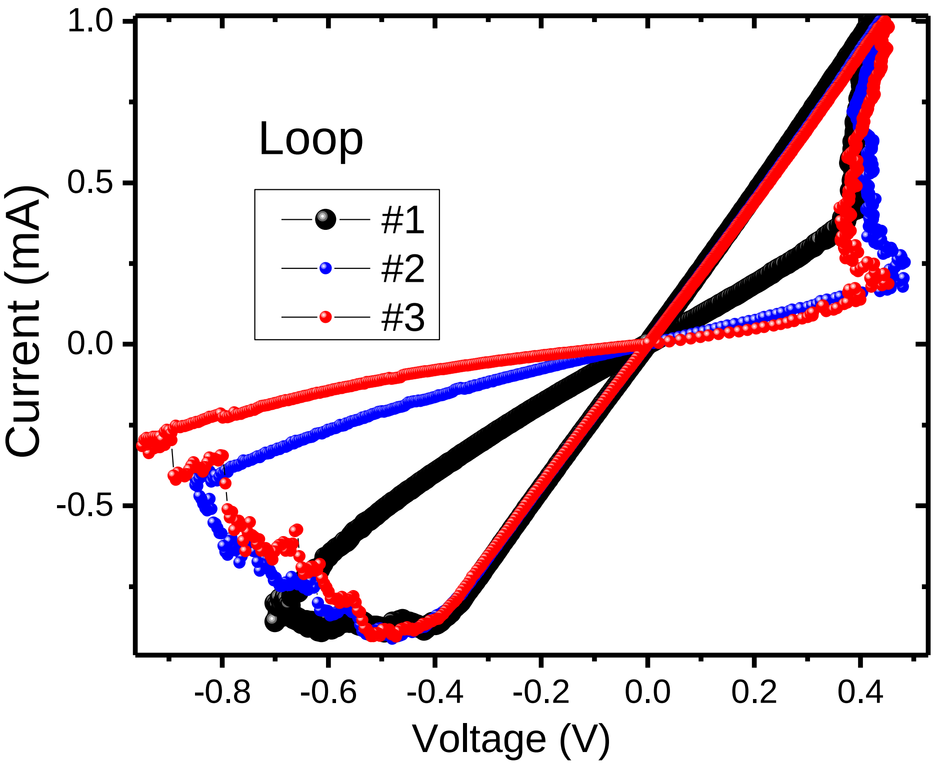
- **Electroforming needed**
- **Some devices do not form**





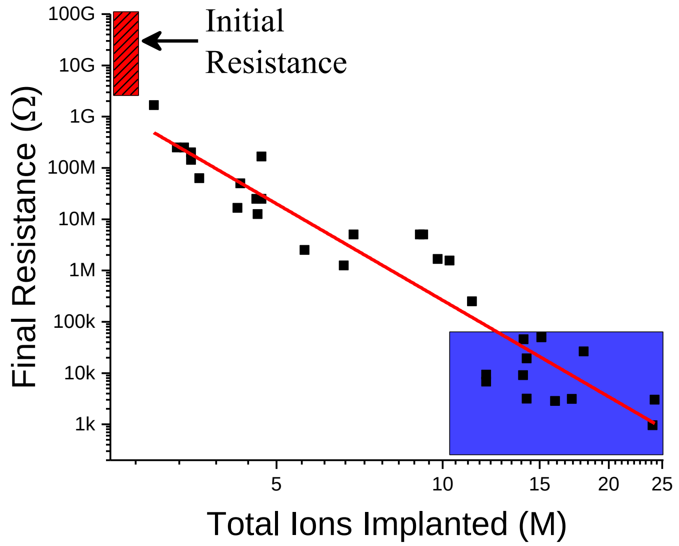
Focused Ion Beam Formation of Filaments:
-- Intermediate Resistance





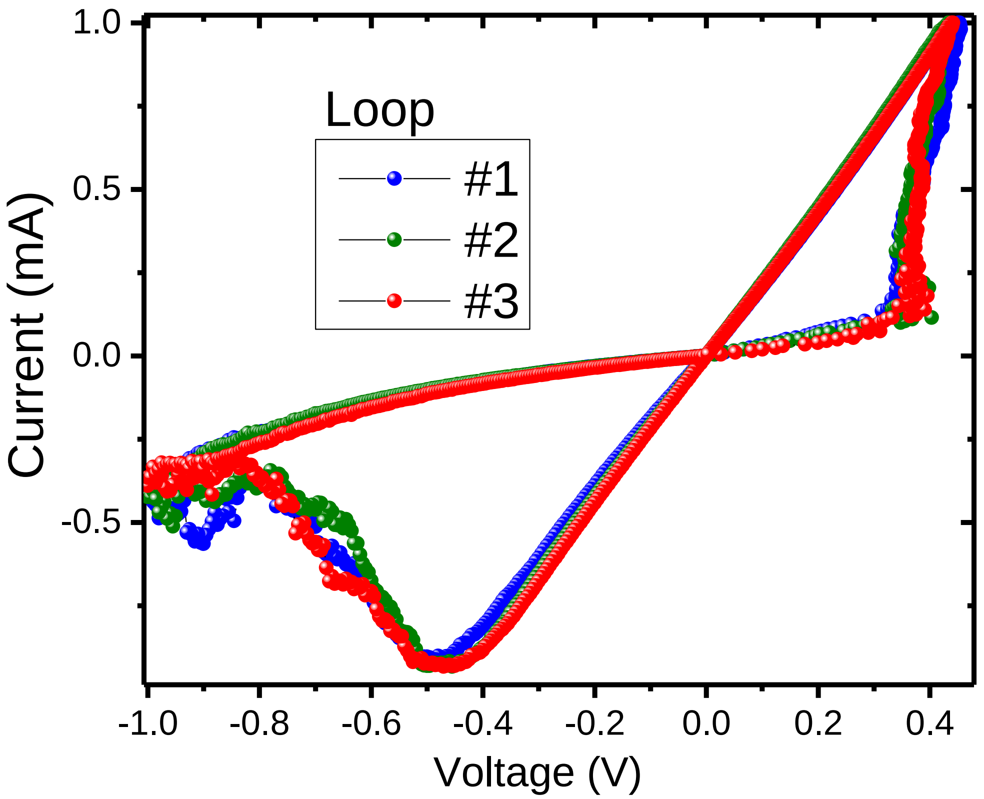
500kΩ to 5MΩ Regime:
- **No Electroforming**
- **3-5 loops to normal looping**

Focused Ion Beam Formation of Filaments:
-- Low Resistance

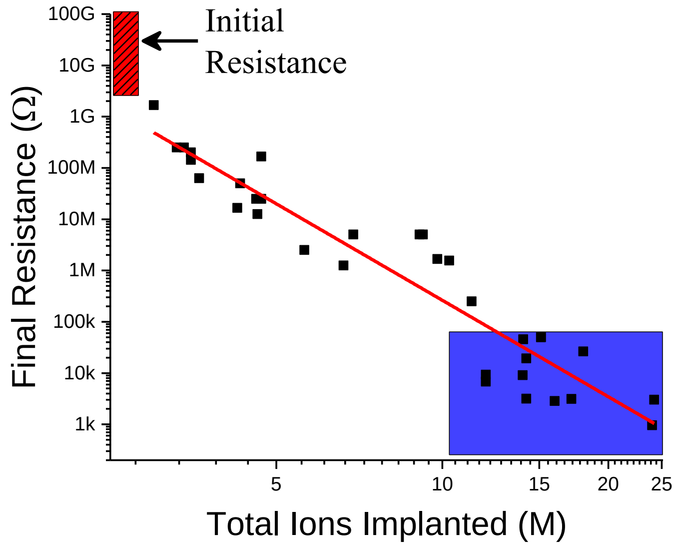


< 100kΩ Regime:

- **No Electroforming**
- **Immediate looping**

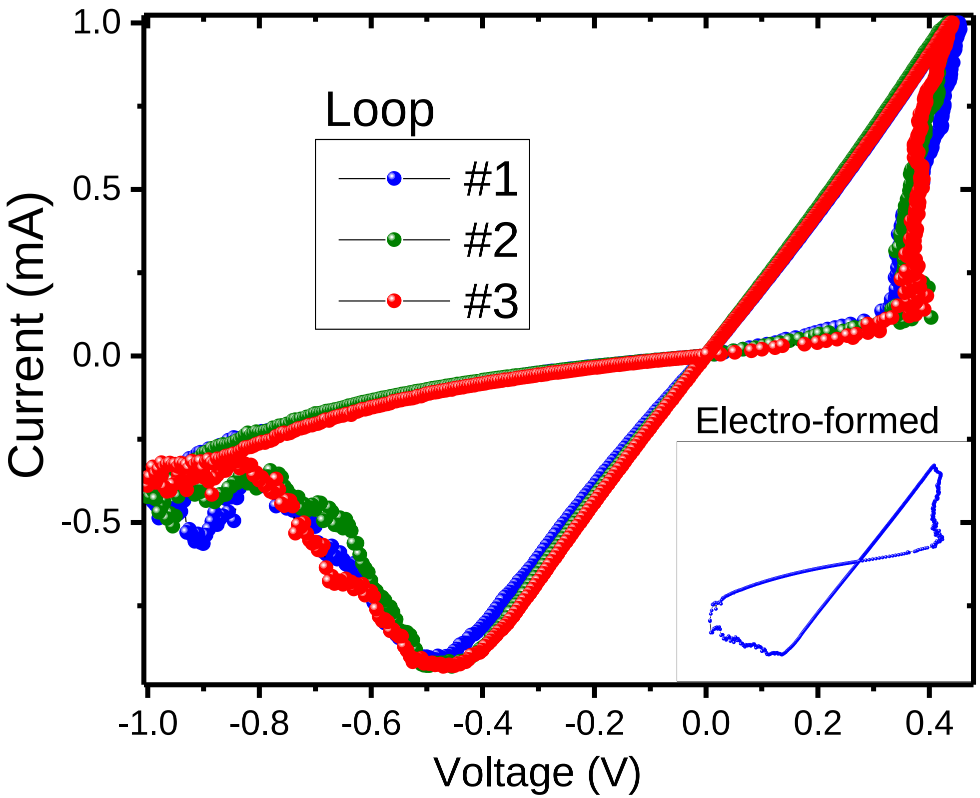


Focused Ion Beam Formation of Filaments: -- Low Resistance



< 100kΩ Regime:
- **No Electroforming**
- **Immediate looping**

- Looping identical to electroformed devices



Immediate hysteretic looping without electroforming