SAND2017-1666C

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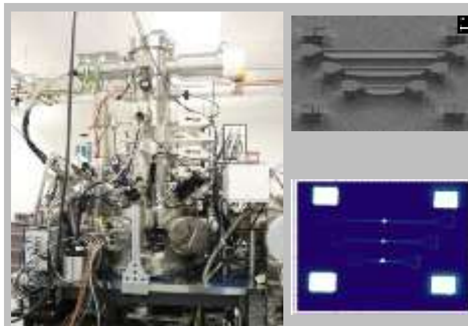
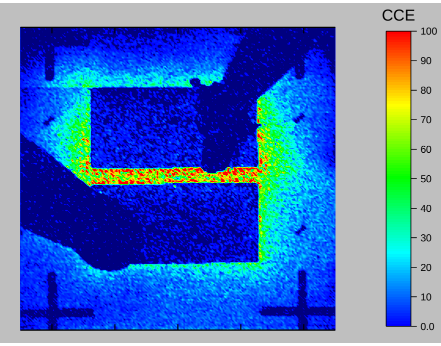
Sandia National Laboratories





Single Atom Device Fabrication using Focused Ion Implantation

Edward Bielejec

Sandia National Laboratories, Albuquerque, NM 87185

QIST Quantum Information S&T

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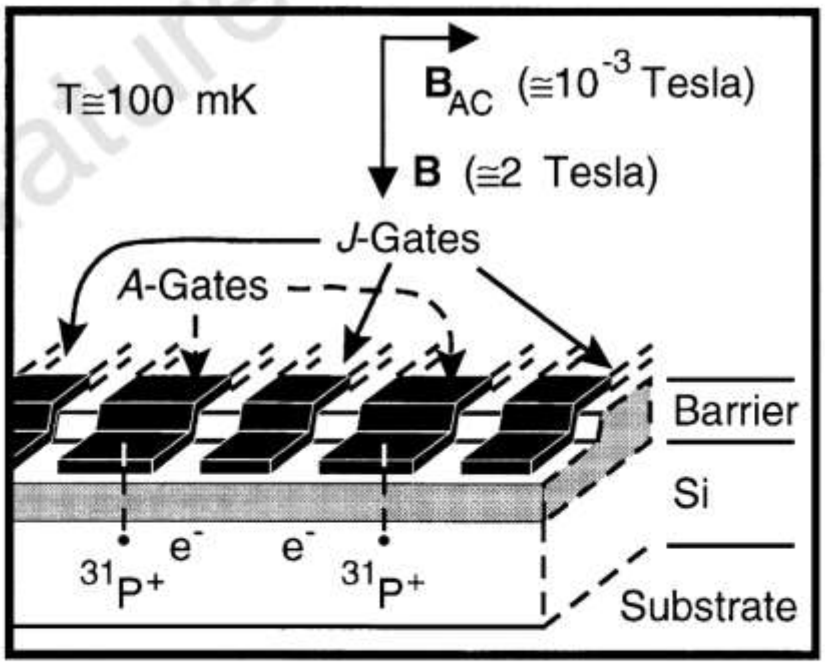
Outline

- Motivation – Single Atom Devices
- Sandia's Ion Beam Laboratory
    - Focused Ion Beam Capabilities
    - → nanoImplanter
- Counted Ion Implantation for Si Qubits
    - Demonstration of counted implantation and transport
- Defect center formation in Diamond
    - Localized Implantation
    - Demonstration of single ion detection
    - Path forward to electroluminescence and charge state control
- Summary and Outlook

Motivation – Single Atom Devices

Donors in Si for Qubits

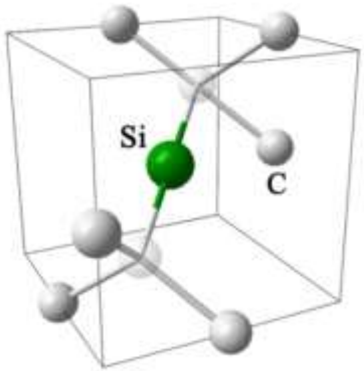


B. E. Kane, Nature **393**, 1998

- Donor qubit fabrication on a *Si-MOS platform with integrated* ***single ion detectors*** *and* ***nanostructures for transport***

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***

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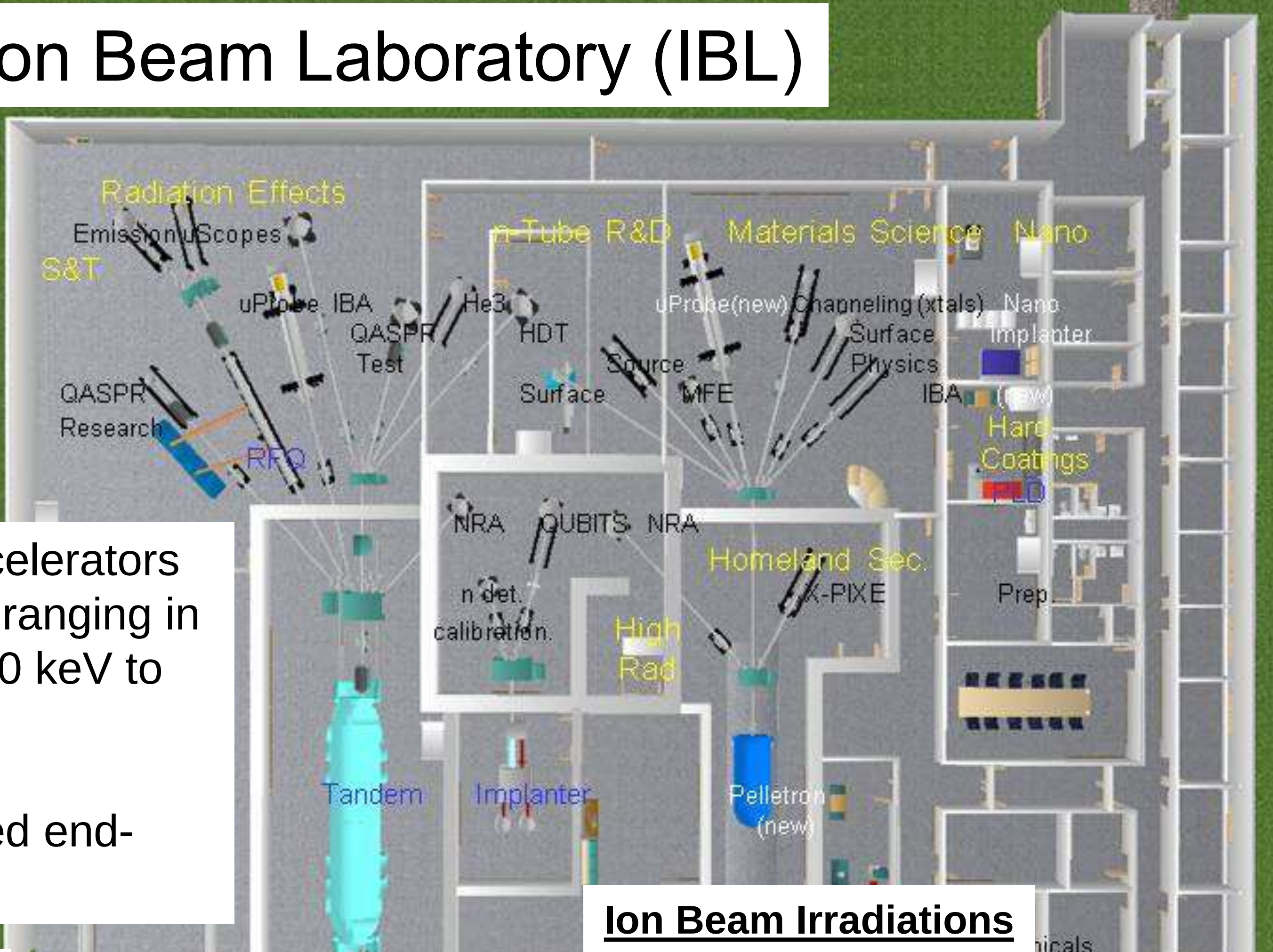
Sandia's Ion Beam Laboratory (IBL)

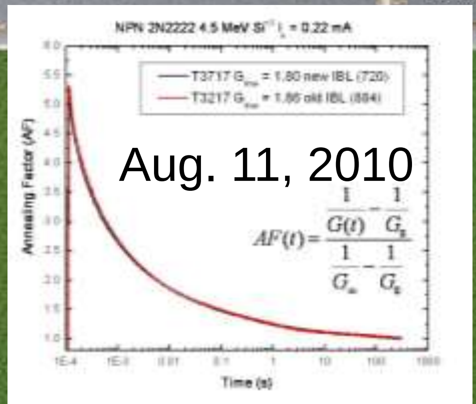


- Four main accelerators producing ion ranging in energy from 10 keV to 480 MeV
- >20 specialized end-stations

Ground Breaking

<20 months

Ion Beam Irradiations

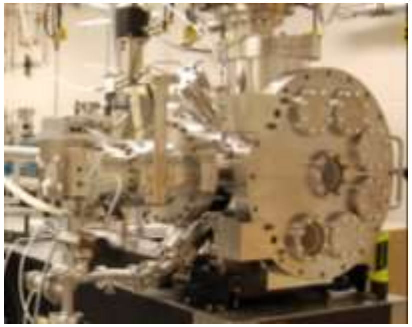


Focused Ion Beam Capabilities at the IBL

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)

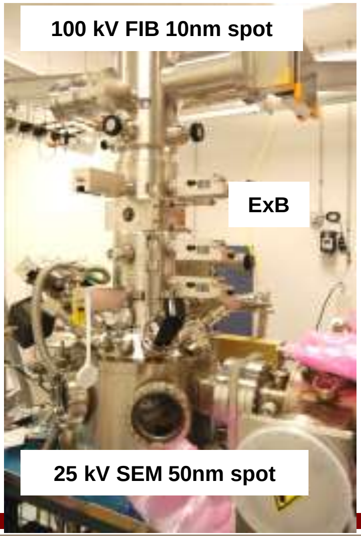


- Light to Heavy Ions – H to Xe
- Energy range from ~10 keV to 350 keV
- Spot size as small as ~800 nm

Light Ion Microbeam (Pelletron)

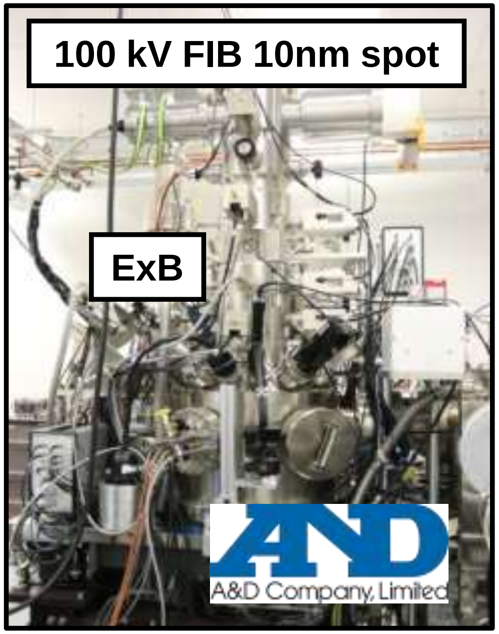
- Light Ions – H, He3, He4, N (lower resolution spots)
- Energy range from ~300 keV to 3 MeV
- Spot size as small as ~150 nm

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

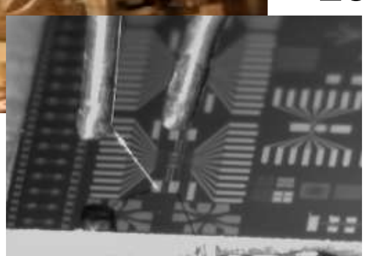
SNL nanoImplanter (nI)



- 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

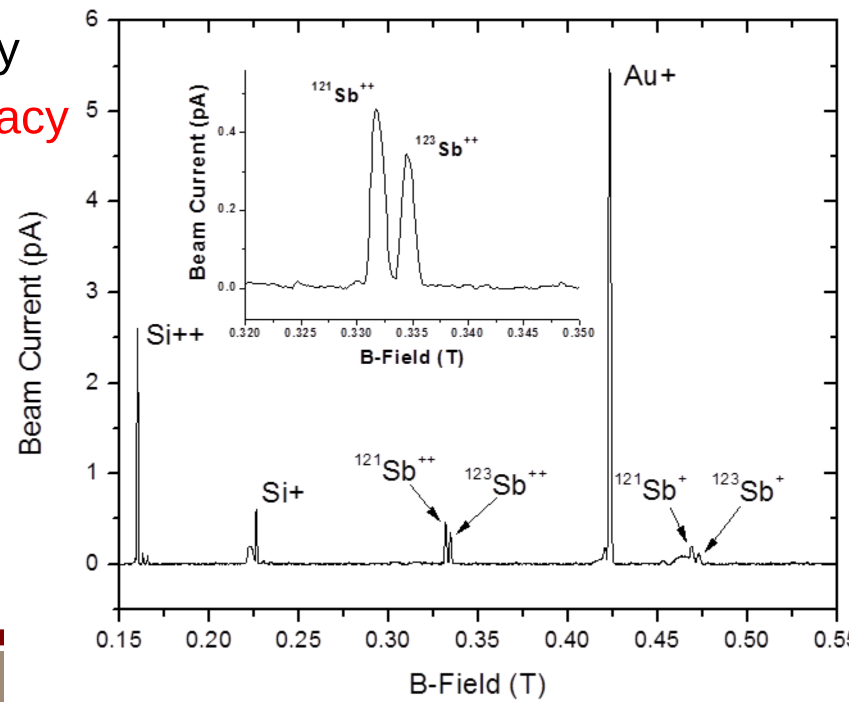
RAITH NANOFABRICATION

- Low temperature stage



- In-situ electrical probes

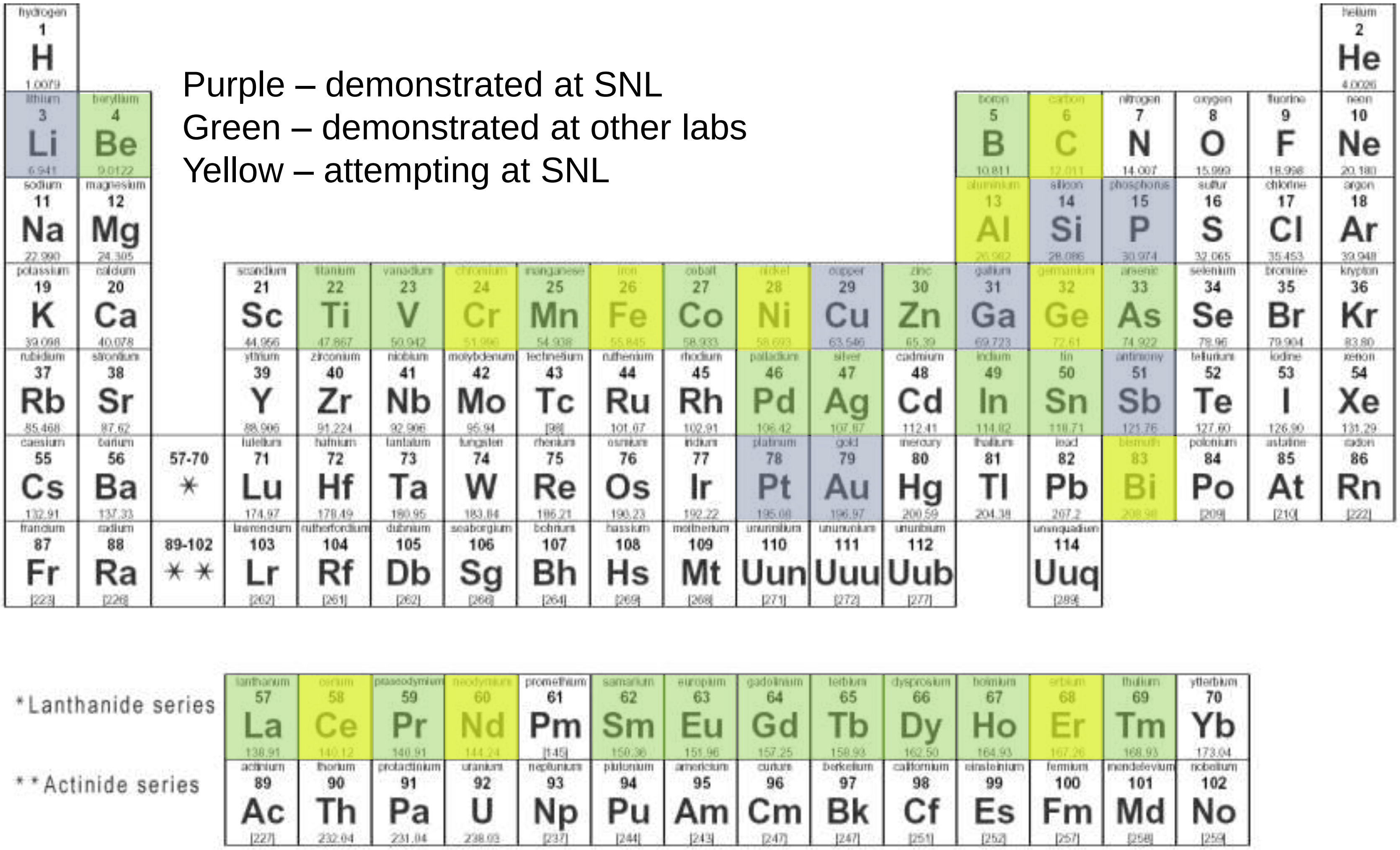
Sb Source: Mass Spectrum



SNL nanoImplanter (nI) - Sources

Sandia National Laboratories

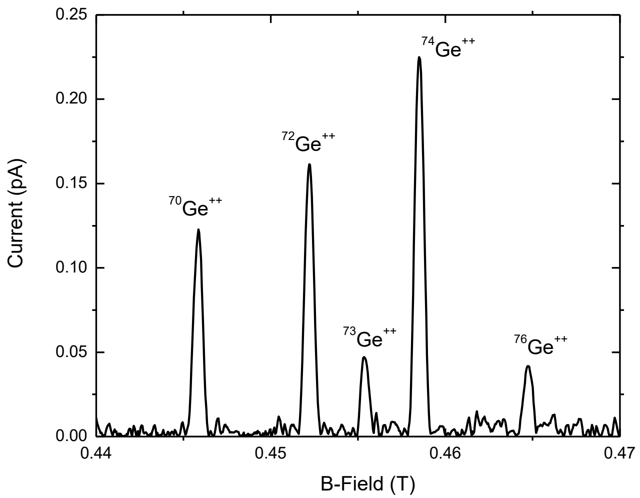
Purple – demonstrated at SNL
Green – demonstrated at other labs
Yellow – attempting at SNL

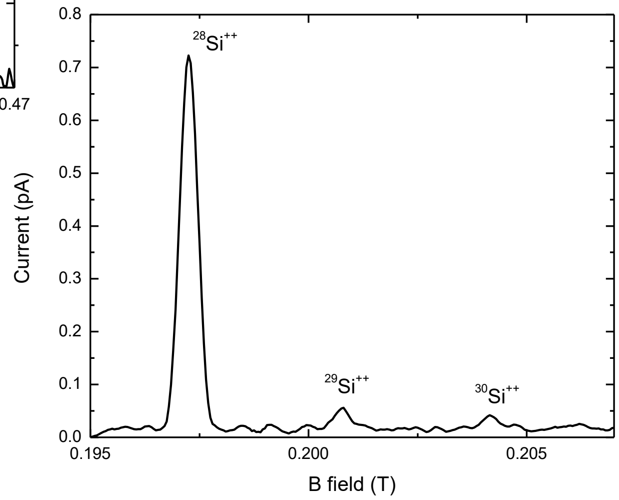


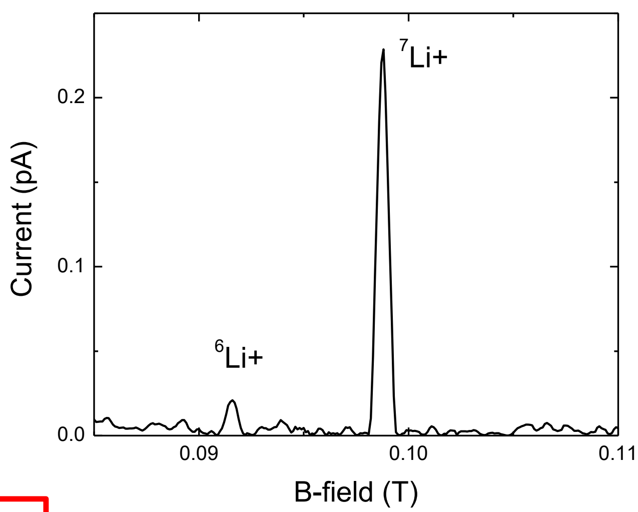
After A. Weick University of Bochum

Wide Varity of Ion Species Available

SNL nanoImplanter (nI) – Mass Resolution

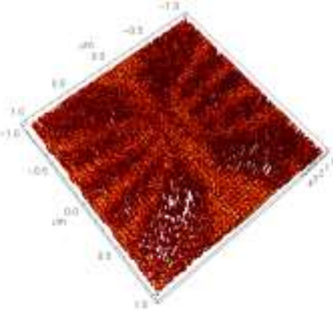




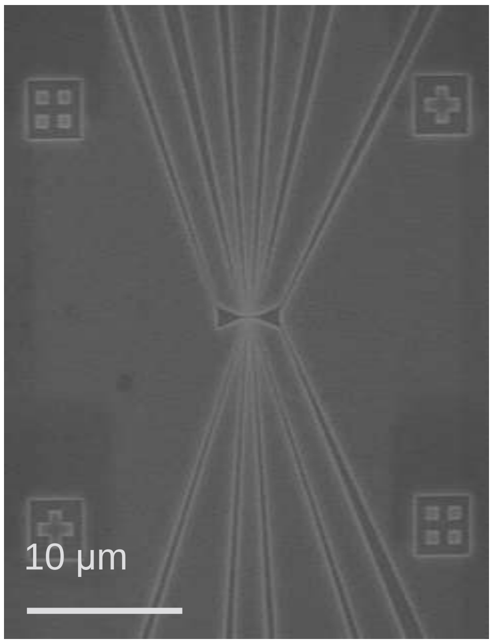


Examples isotope separation

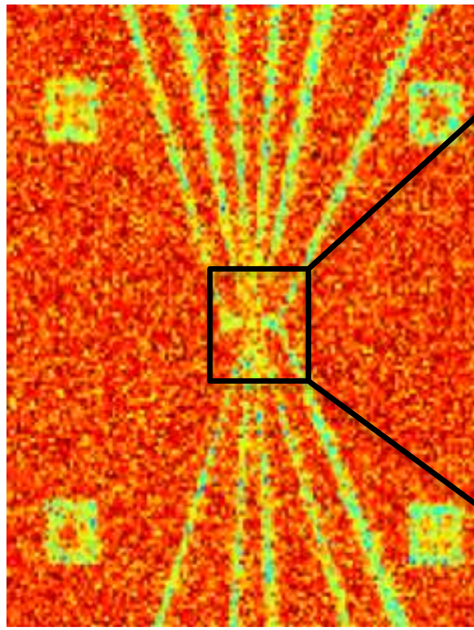
SNL nanoImplanter (nI) – Targeting Resolution



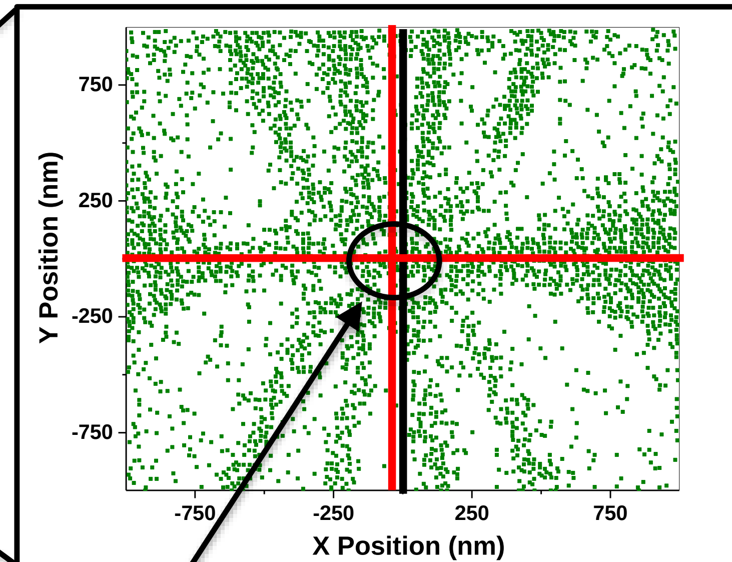
SEM of nanostructure



Ion Beam Induced Charge Collection (IBIC) of nanostructure

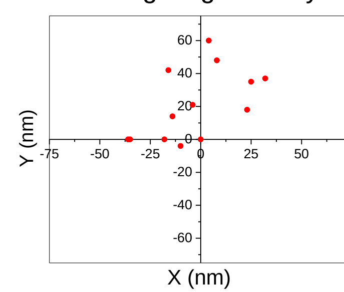


High resolution IBIC for targeting



Δx ~35 nm
Δy ~0 nm

Targeting Acuracy



Targeting resolution <40 nm

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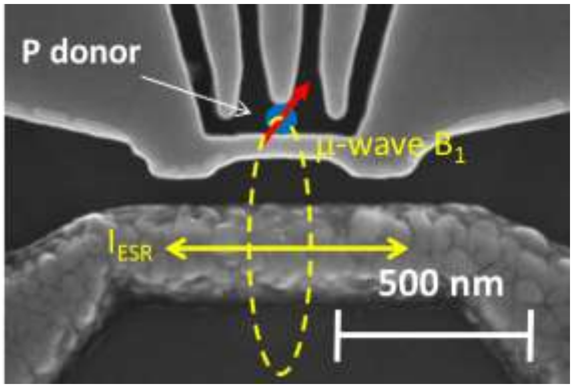
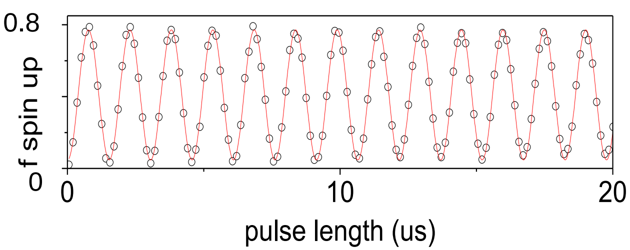
Donor Based Qubit – ^{31}P in Silicon

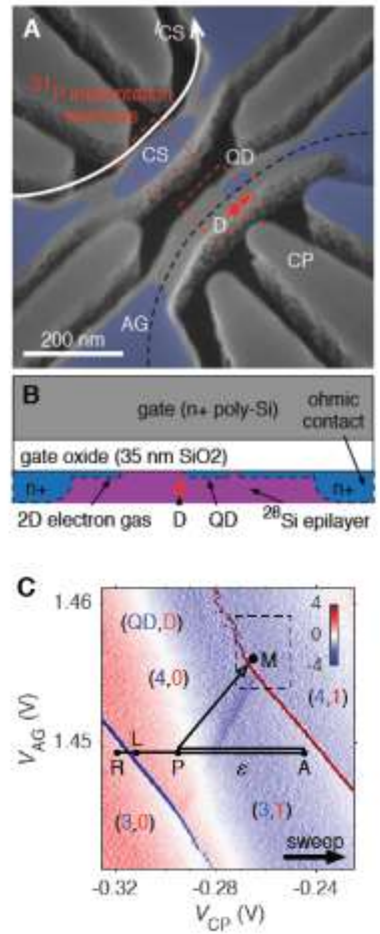
Single Qubit Control

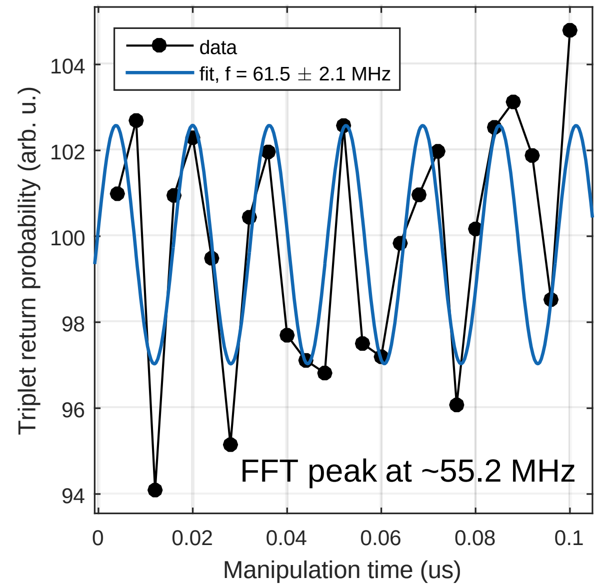




*L. A. Tracy et al., APL **108**, 063101 (2016)*

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?

Controlled Location of Donor Site(s)

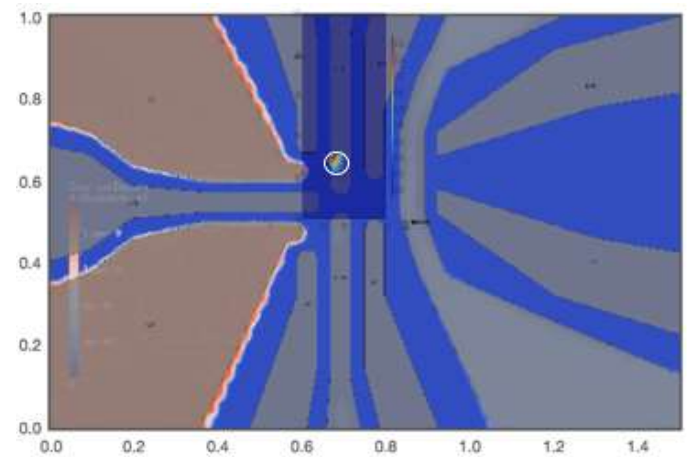
- Minimize Straggle in depth (Z)
  - Low Energy Ion Implants
- Control of X,Y donor site(s)
  - Focused Ion Beam (FIB) Implantation
  - Electron Beam Lithography (EBL)

Controlled Alignment of Donor Site(s) and Gates

- Self-Aligned Poly-Si

Controlled Number of Donors

- 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

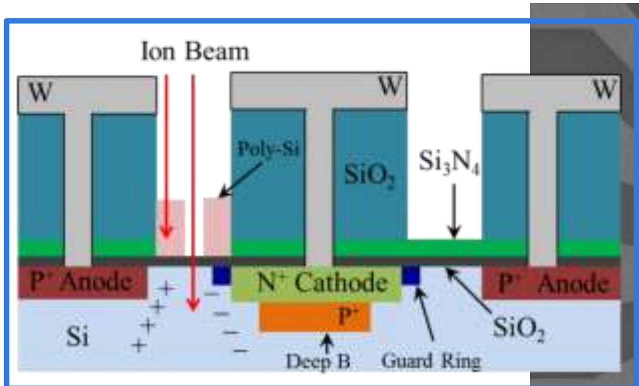
Single Donor Devices for Quantum Computing

Si-MOS platform integrated with:

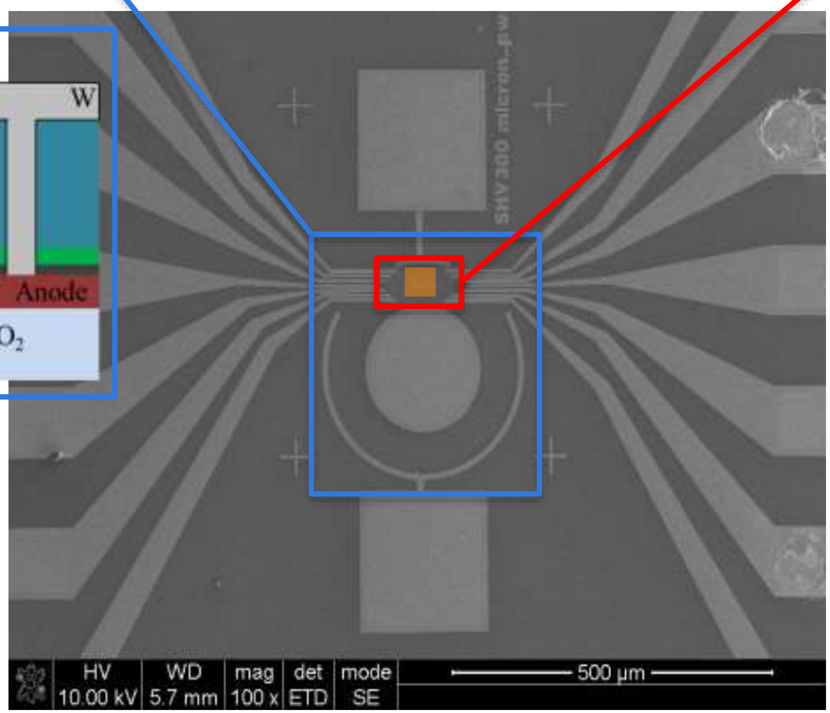
- Single Ion Detector
- Nanostructure for Qubit operation

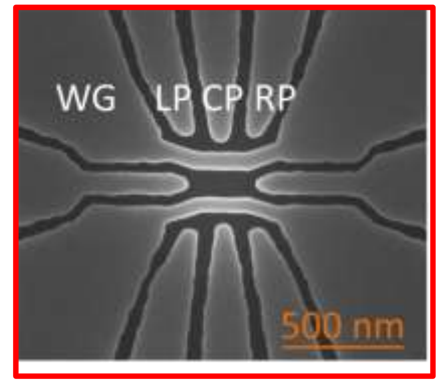
Single Ion Detector

Nanostructure

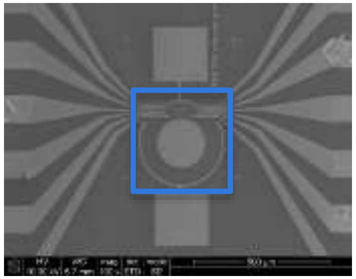


Ion Beam Induced Charge (IBIC)



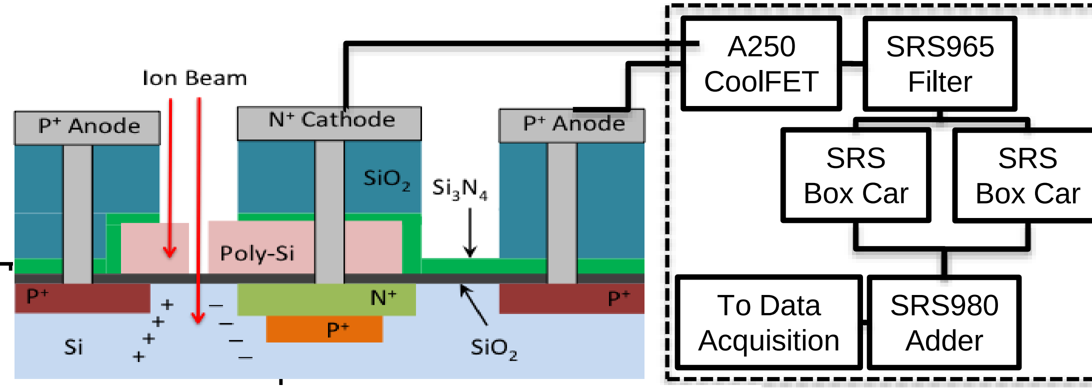


Combined Single Ion Detector and Nanostructures Demonstrated

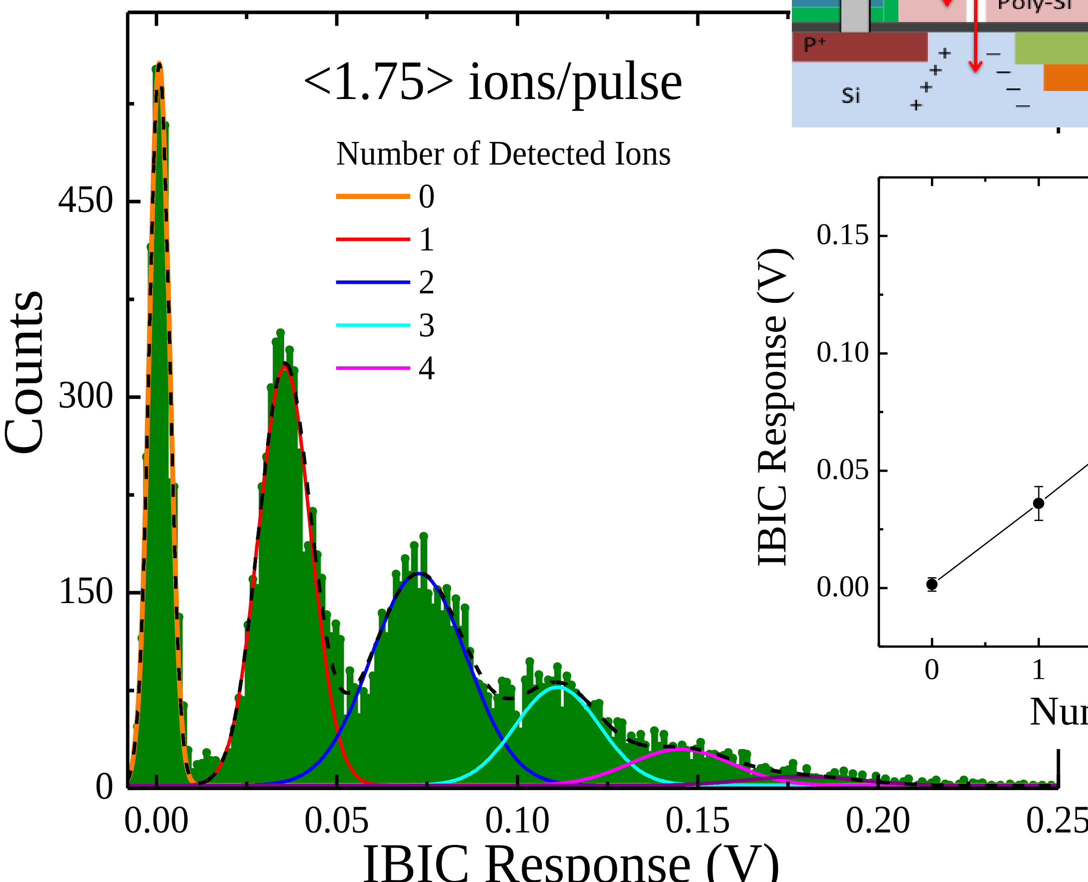


Integrated Single Ion Detectors

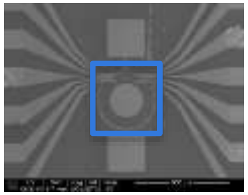
Ion Beam Induced Charge Collection (IBIC)



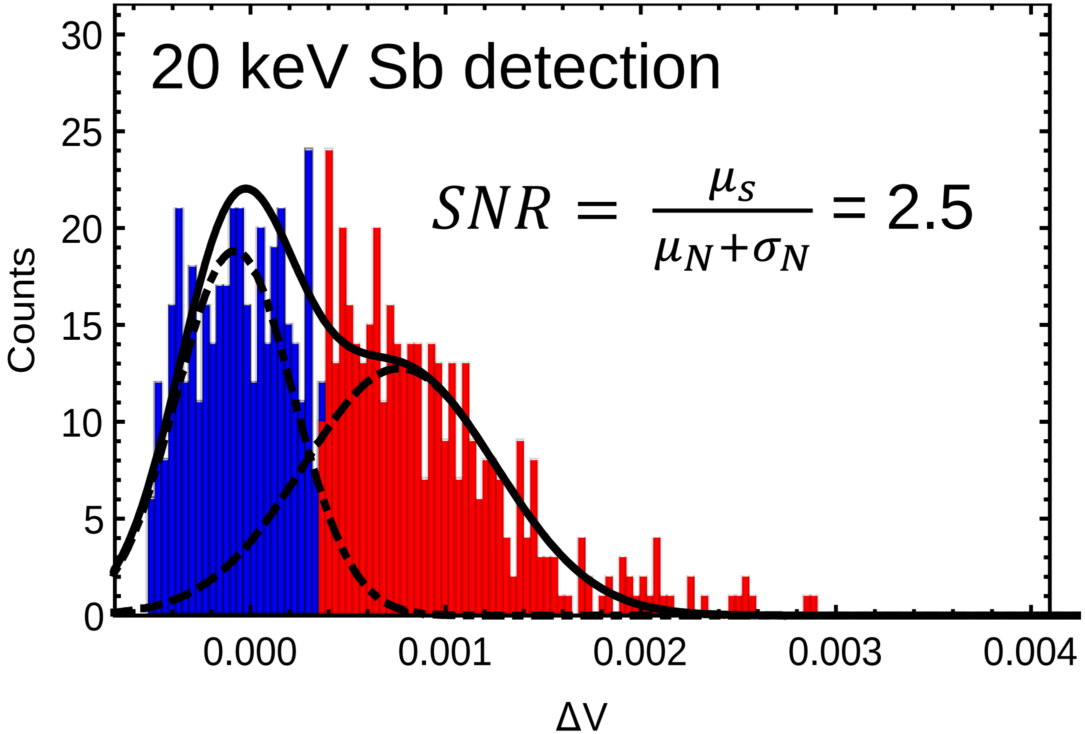
200 keV Si Detection



Quantized Single Ion Detection

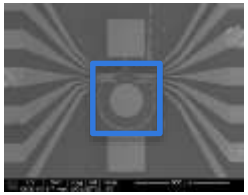


Lowest SNL Detected Single Ion Implantation



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%

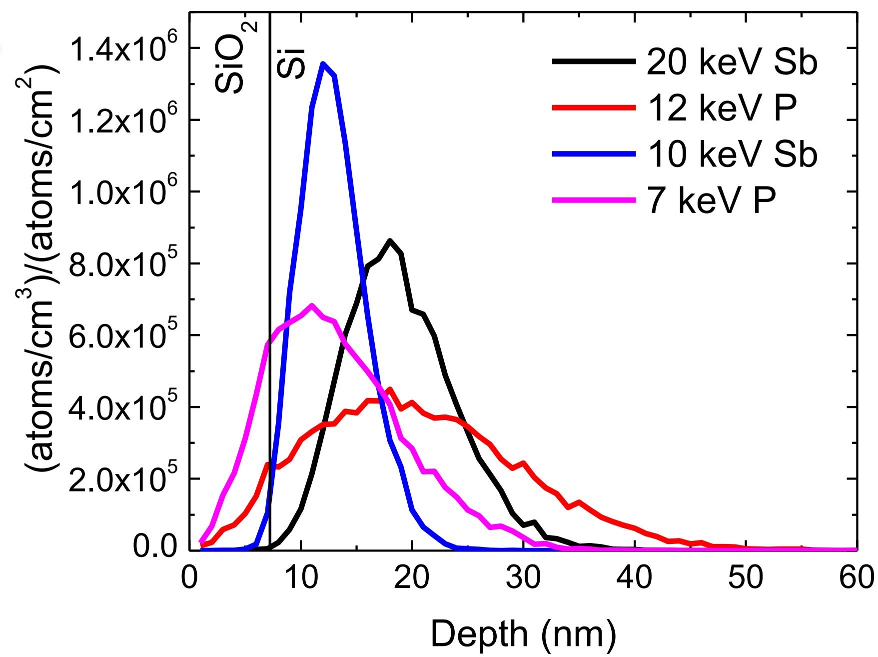
* Range measured from the SiO2/Si interface into the Si substrate



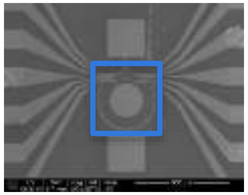
Implantation Target?

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.[illegible]±2.9 nm	~500
7 keV P	5.7±6.1±5.1 nm	~500

SRIM Simulation of Range/Straggle



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



Low Noise Single Ion Detection

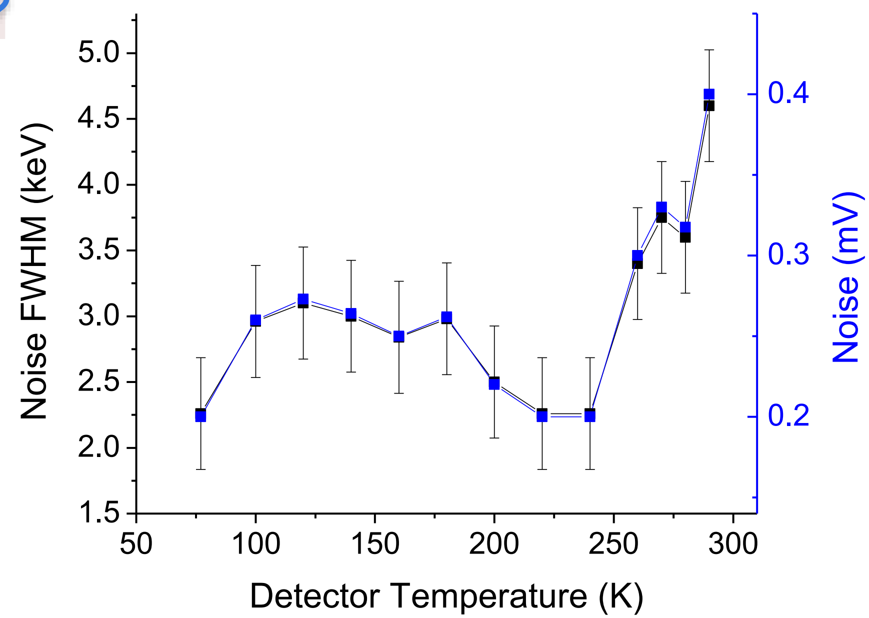
Ion	Range below SiO_2	e-h pairs
20 keV Sb	11.5±4.9±4.3 nm	~1500
12 keV P	13.0±9.3±7.8 nm	~1100
10 keV Sb	5.5±3.0±2.9 nm	~500
7 keV P	5.7±6.1±5.1 nm	~500

- Need to reduce noise, improve SNR

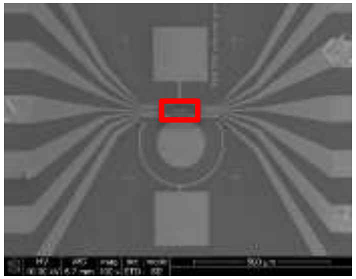
  - SNR of 2 for 500 e/h pairs
  → Noise 0.2 mV

- How to do so?
  - In-vacuum preamp ☑
  - Cool detector and FET ☑

Measured ~0.2 mV noise for cooled preamp

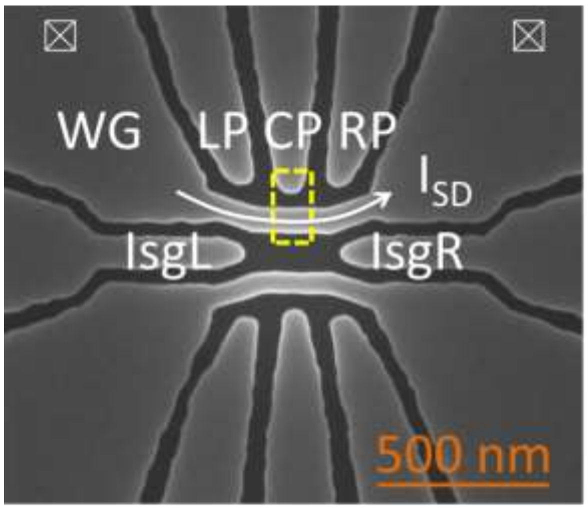


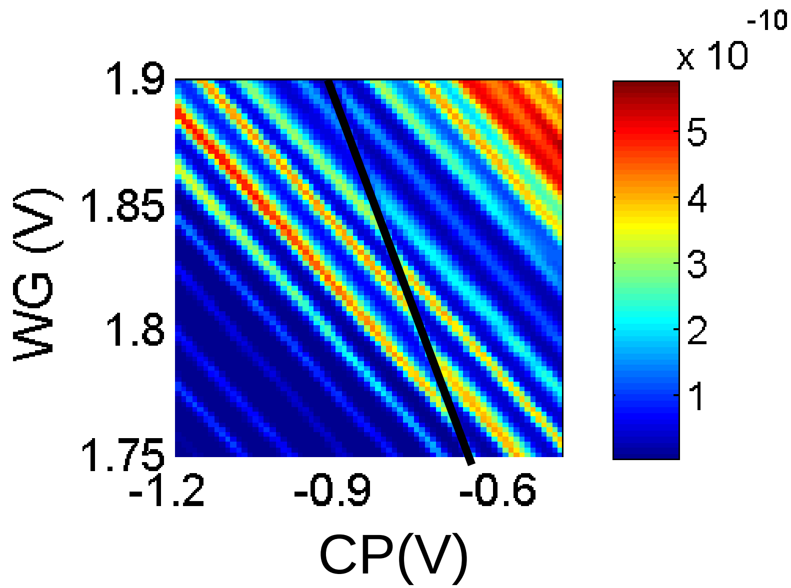
Path forward to low energy <10 keV detection



Transport in Counted Donor Devices

120 keV Sb Transport





Singh et al. APL 108 062101 (2016)

Measured low temperature transport on counted donor devices

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- Defect center formation in Diamond

  Localized Implantation

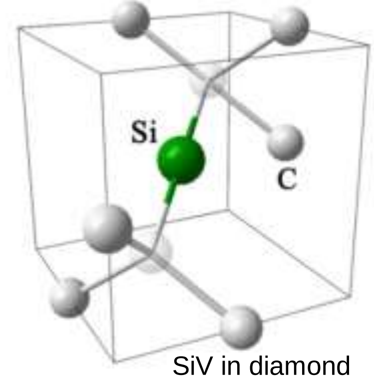
  Demonstration of single ion detection

  Path forward to electroluminescence and charge state control
- Summary and Outlook

Why Color Centers in Diamond?

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

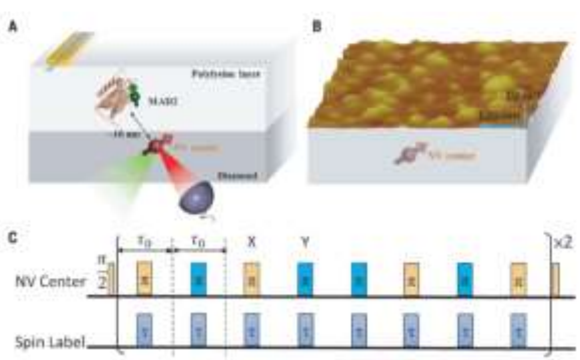
- Wide range of application from metrology to quantum computation



SiV in diamond

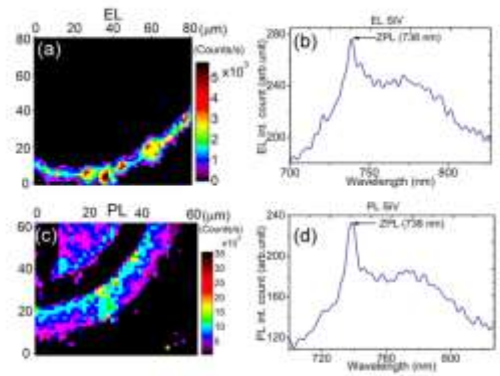
I. Aharonovich *et al*., Rep. Prog. Phys. **74**,076501 (2011)

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



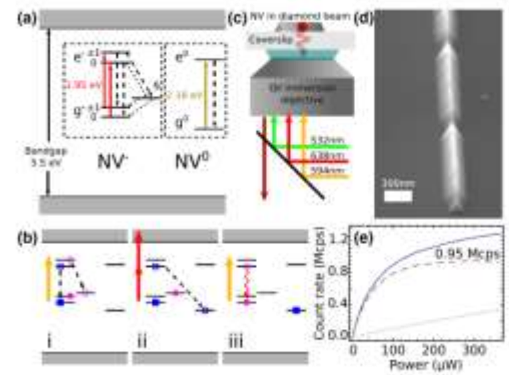
F. Shi *et al*., Science **347**, 1135 (2015)

<u>Electrically driven SiV</u>



A. M. Berhane *et al*., APL **106**, 171102 (2015)

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



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

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

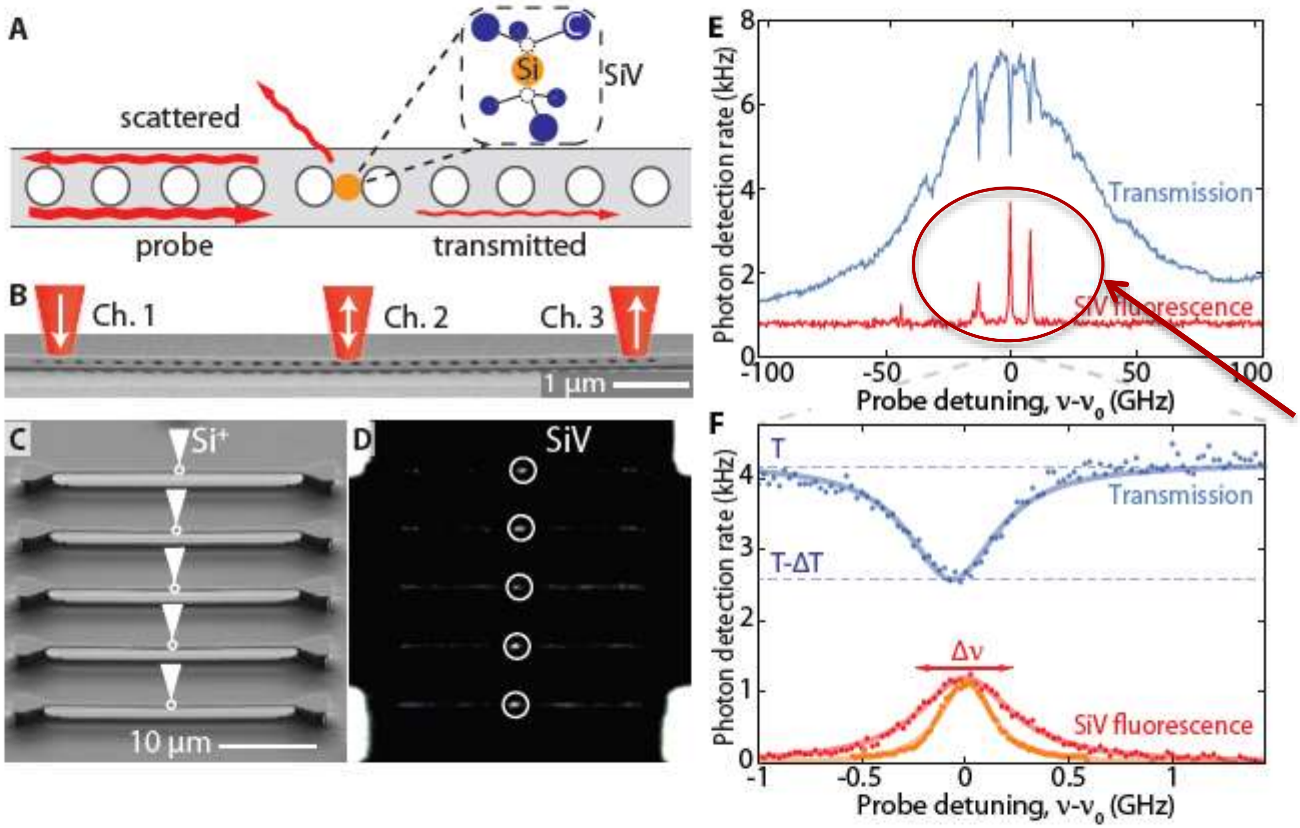
1.) Location

2.) Yield

We will use ***<u>focused ion beam implantation</u>*** and ***<u>single ion detection</u>*** to determine both location and yield with high accuracy

Quantum Nano-photonics with Diamond Color Centers

SiV integrated with diamond cavities



Ch. 1: 737 nm tunable probe

Ch. 2: SiV Control and Characterization (red)

Ch. 3: Transmission (blue)

3 SiV coupled to the cavity

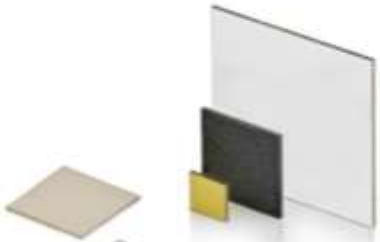
A. Sipahigil *et al*., *Science* (2016)

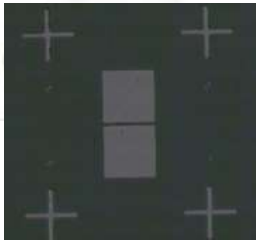
(SNL/Harvard collaboration)

How do we fabricate the SiV Centers?

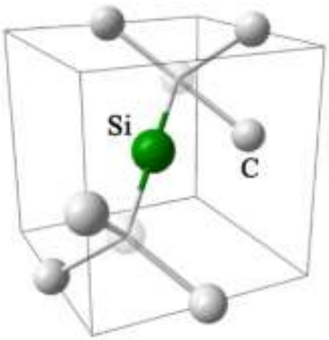
Sandia National Laboratories

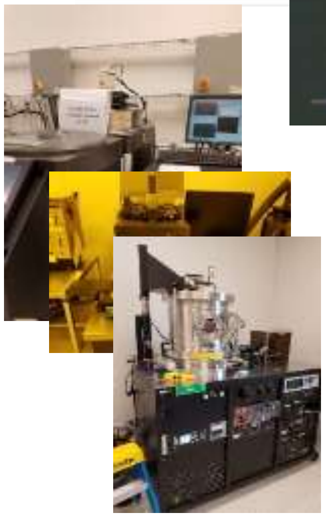
Electronic Grade Diamond Substrates



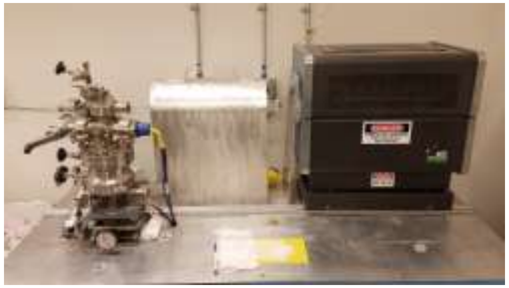


Surface Clean/Oxygen Termination

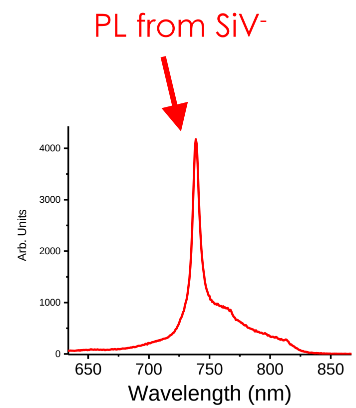




CINT fab to prepare the samples, Si ion implantation at IBL



Vacuum anneal to create SiV centers

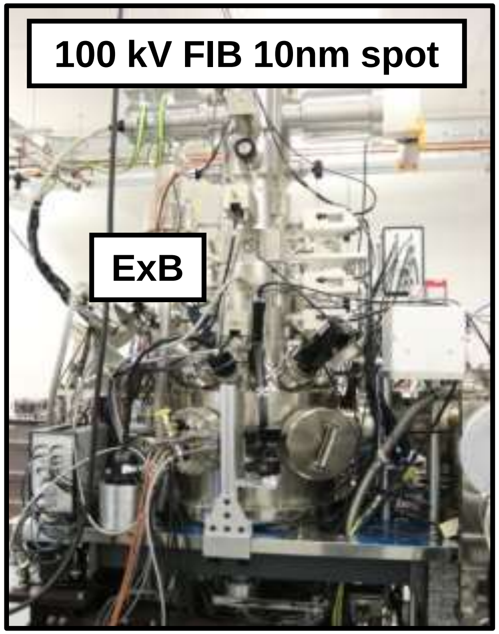


μ-PL from focused ion implanted SiV centers

All New Capability Developed at the CINT User Facility

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

Location Problem is Solved

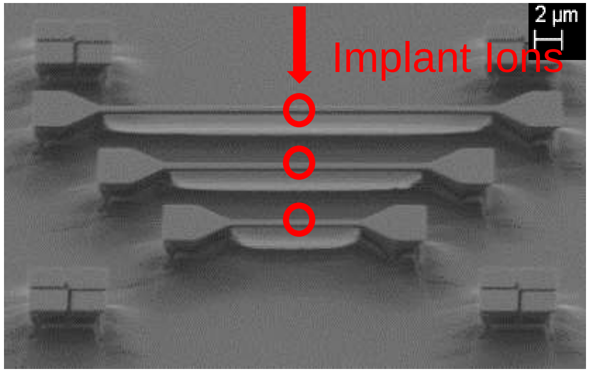


SNL nanoImplanter (nI)

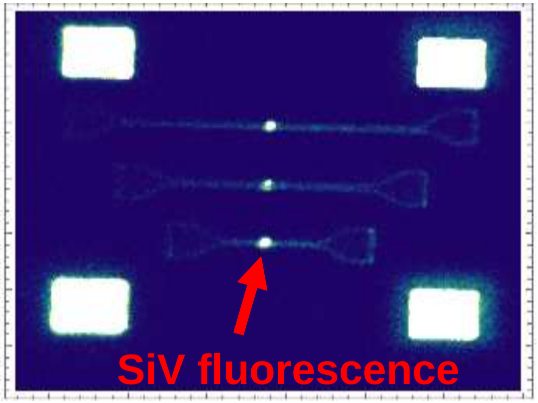
- Variable energy 10-200 keV
- Mass-Velocity Filter (ExB)
  - → Liquid metal alloy ion source
  - → 1/3 Periodic Table
- Direct write lithography platform
  - → Single ion implantation
  - → nm targeting accuracy

Diamond Nanobeams (SNL/Harvard collaboration)

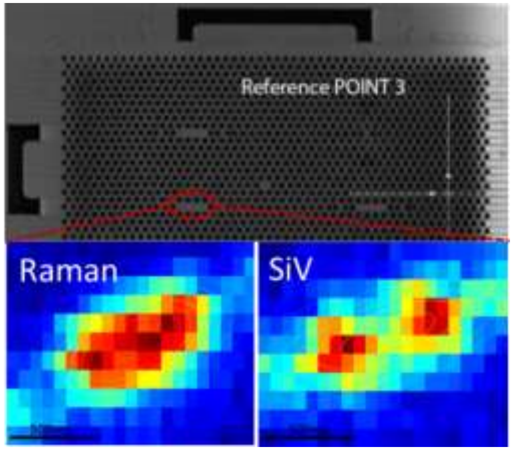
A. Sipahigil, R. Evans, D. Sukachev, H. Atikian, M. Loncar and M. Lukin



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



2D Photonic Crystals (SNL/MIT collaboration)



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

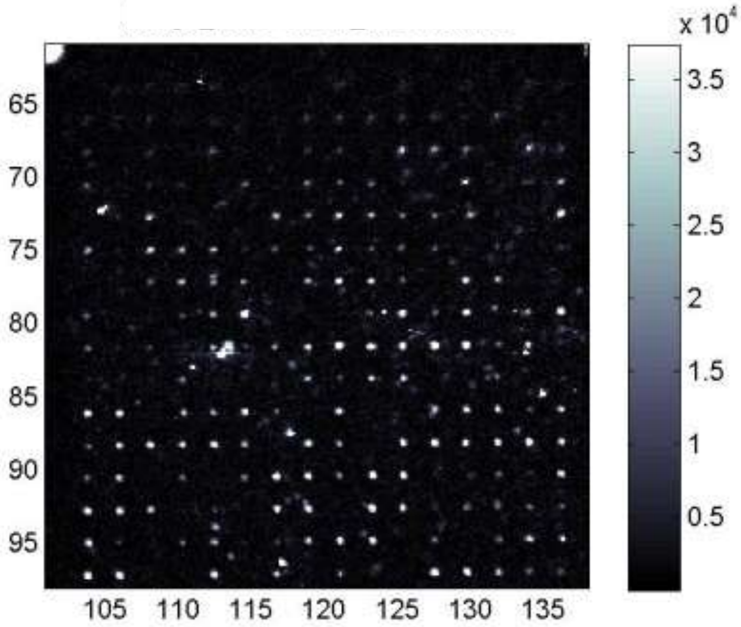
arXiv:1610.09492

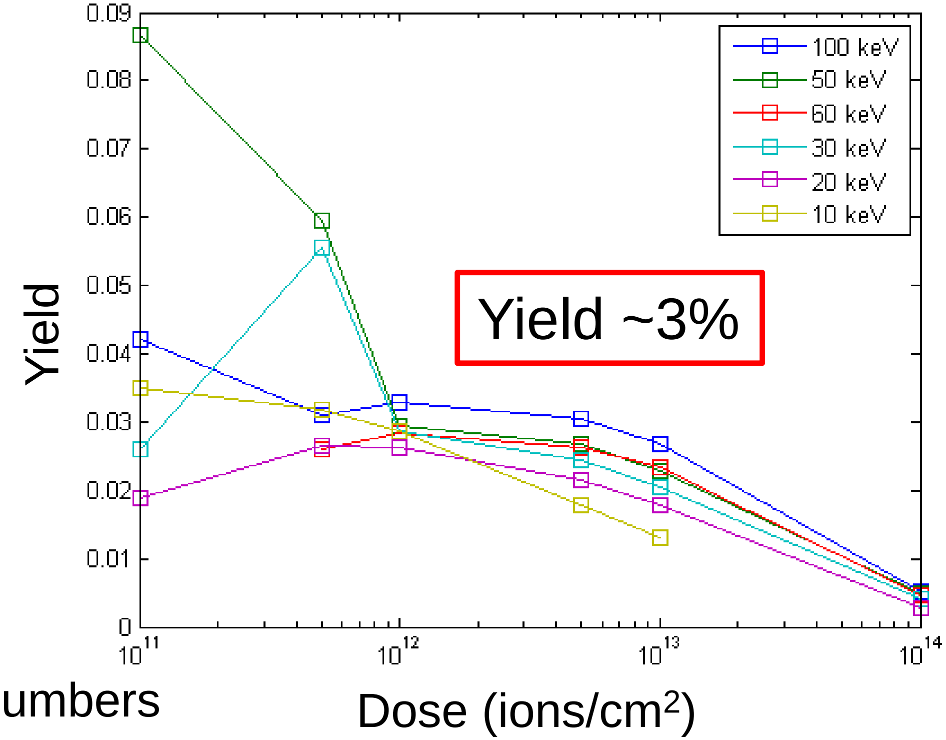
Targeting accuracy is spot size limited to 10's of nm

Activation Yield is a Major Issue

Sandia National Laboratories

Yield (SNL/MIT collaboration)





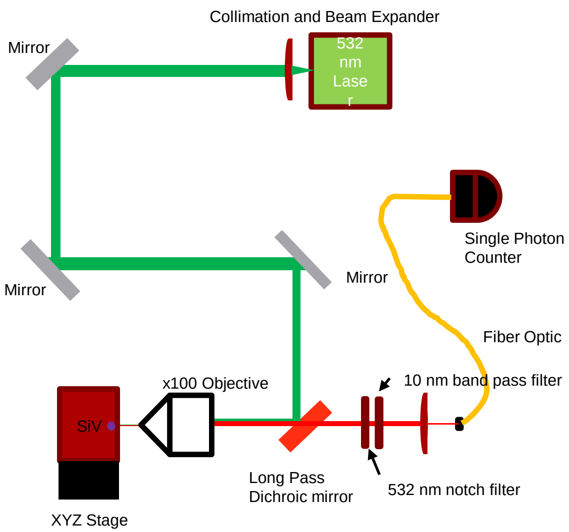
Sub-set of previous work similar yield numbers

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

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

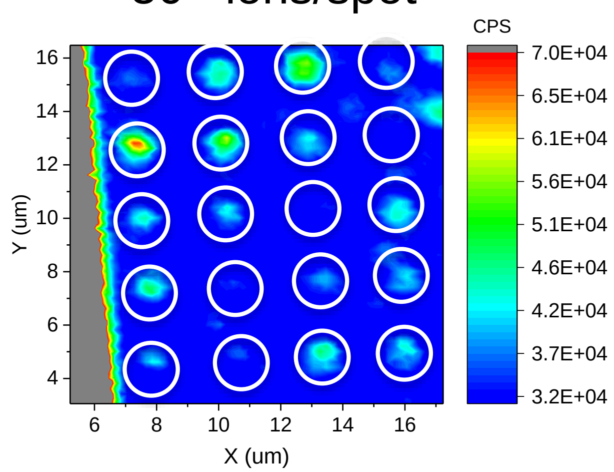
Yield = # measured SiV / # implanted Si

Yield: Mapping SiV Photoluminescence

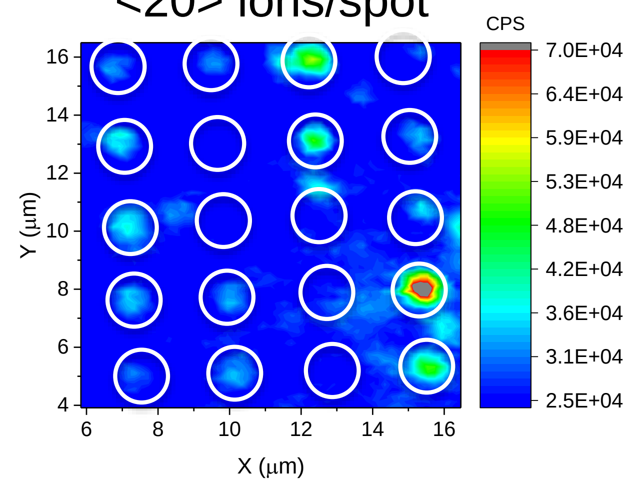


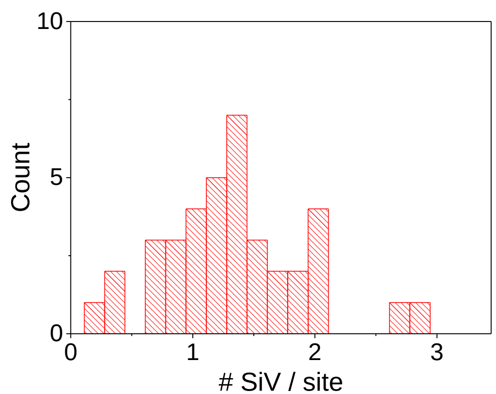
Yield = # measured SiV / # implanted Si

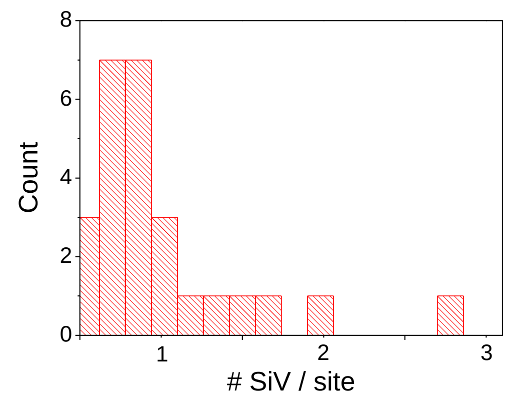
<50> ions/spot



<20> ions/spot







Yield is low and distribution matches Poisson statistics

Similar yield to

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

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

Yield: 2.5%

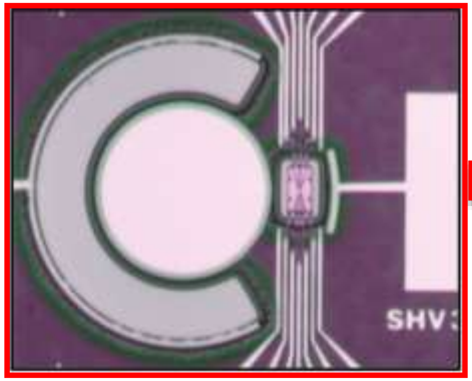
Yield: 3.75%

How to Improve the Activation Yield?

Sandia National Laboratories

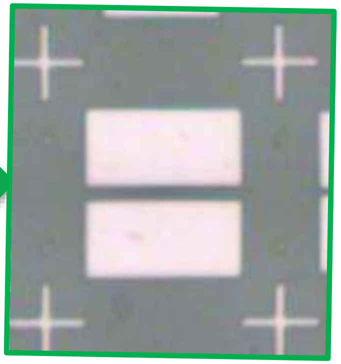
Single Ion Detectors to Understand Yield

Silicon



Translating single ion detection to diamond

Diamond

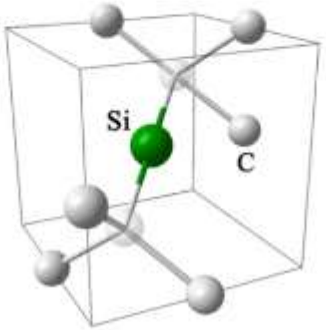


J.A. Seamons, et. al. Appl. Phys. Lett, 93, 043124 (2008)
E Bielejec, et. al. Nanotechnology 21, 085201 (2010)

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

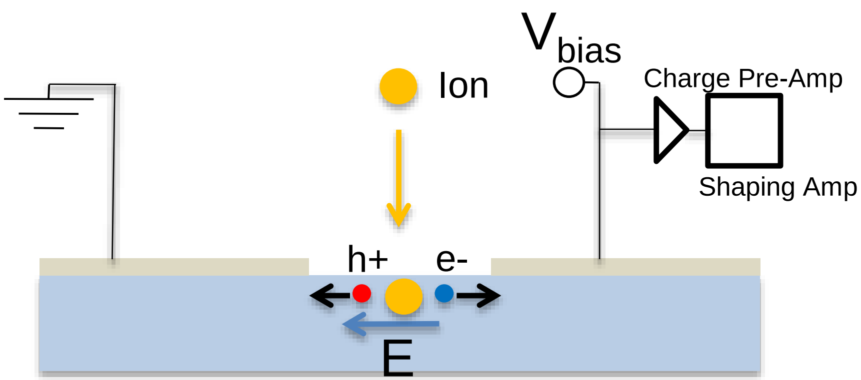
Using Diamond Detectors to Understand Yield

Yield = # measured SiV / # implanted Si

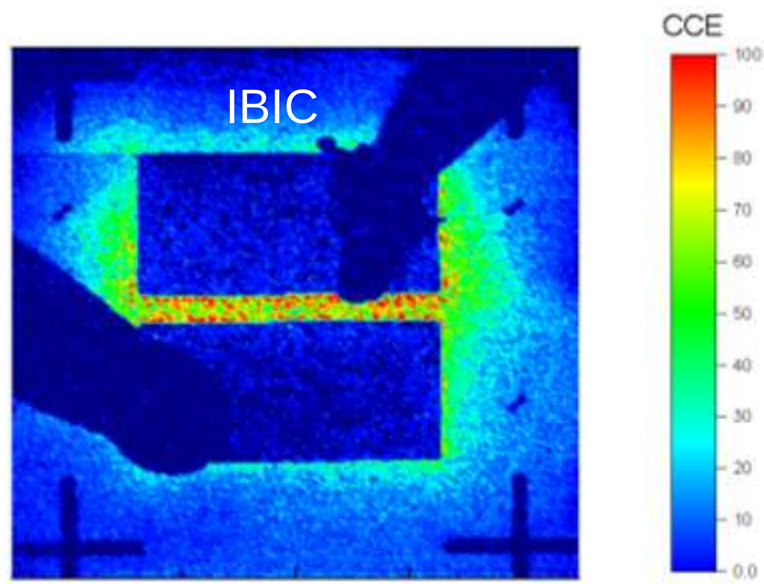
Poisson Statistics

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

Ion Beam Induced Charge (IBIC)



Side View



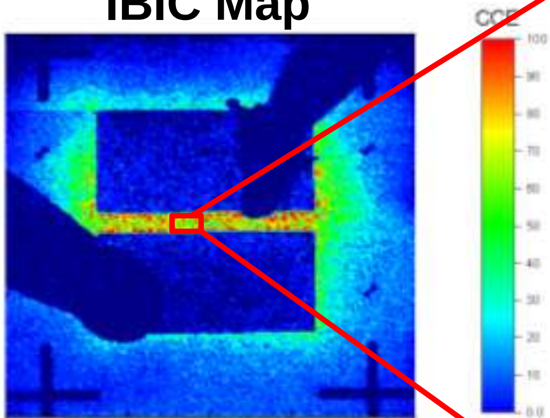
$$\text{CCE} = \frac{\textit{Charge Collected}}{\textit{Charge Depositied}}\, x\ 100$$

IBIC/Detection Demonstrated for low energy heavy ions

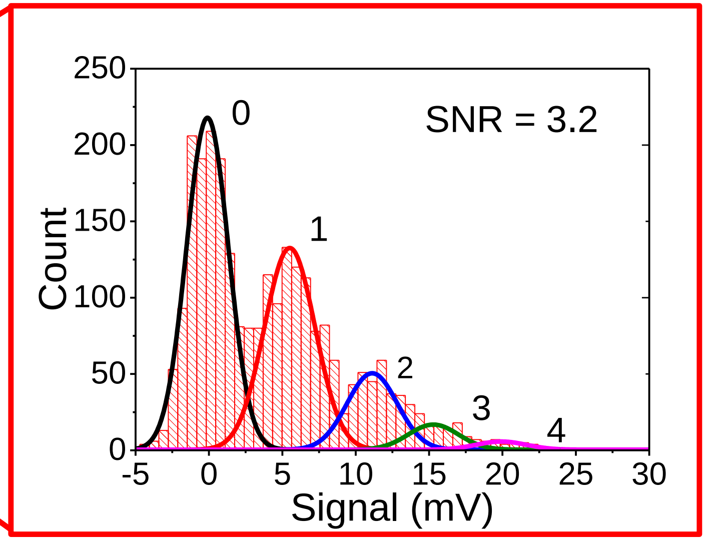
Abraham *et al*, APL **109**, 063502 (2016)

Single Ion Diamond Detectors

IBIC Map



Quantized Detection <0.65> ion

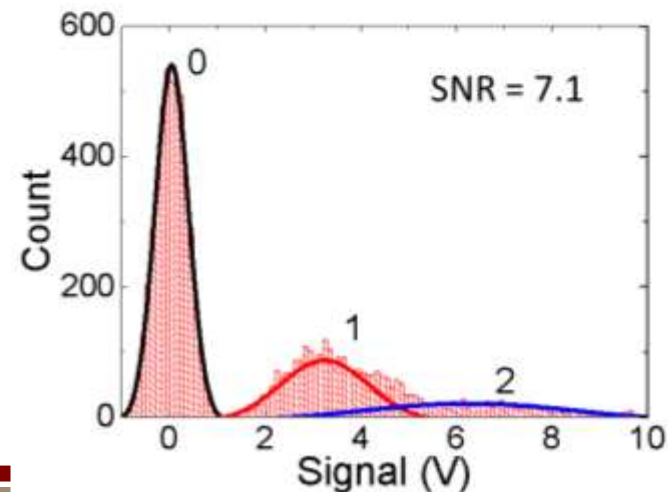


$$SNR = \frac{\mu_{signal}}{\mu_{noise} + \sigma_{noise}}$$

Signal amplitudes match Poisson statistics to 4%

Optimizing gain for single ion detection

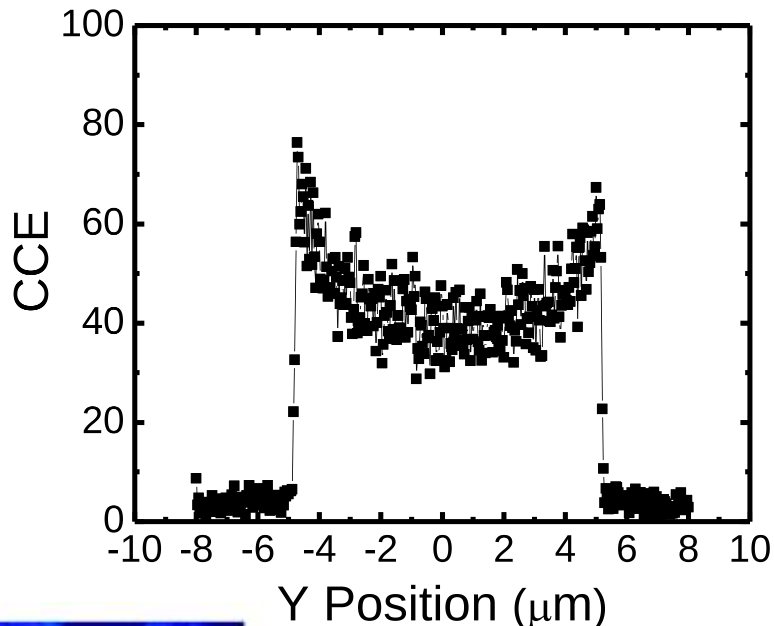
Single Ion Counting <0.2> ion



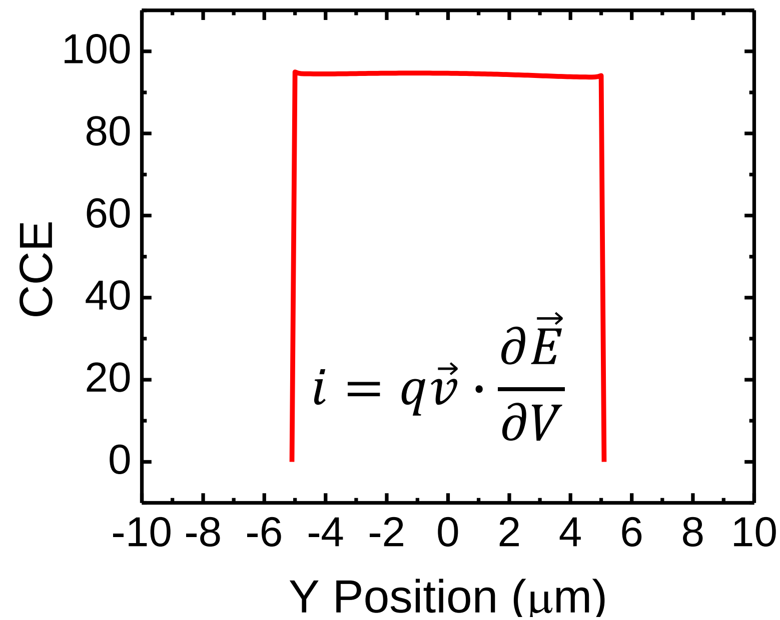
Single Ion Detection in Diamond with SNR ~10

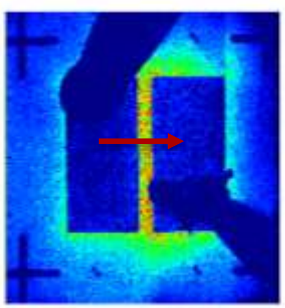
Experimental IBIC vs. Simulation

Experimental IBIC Dataset



Simulation – No damage





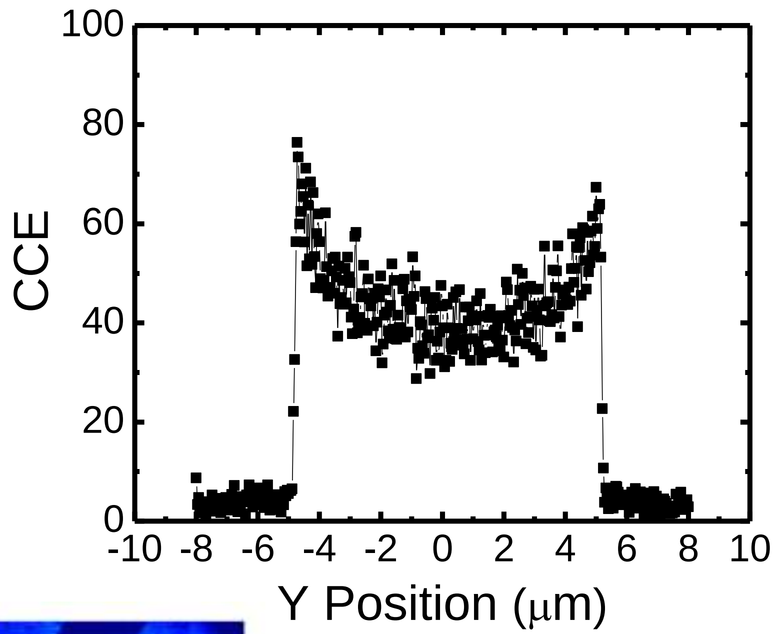
Experimental curve ≠ predicted curve

→ Shape is incorrect

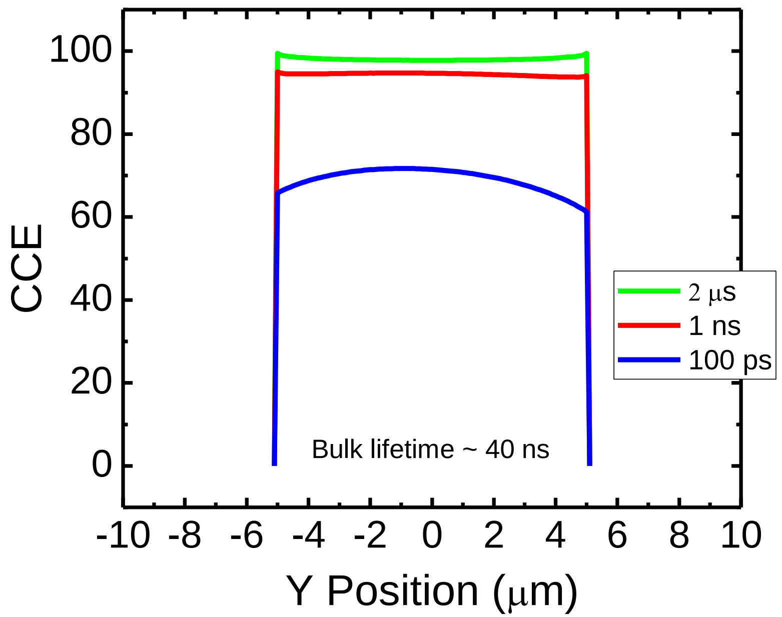
How to account for these differences? Reduce Bulk Lifetime

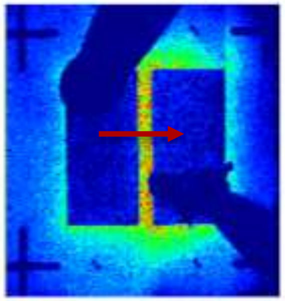
Reducing the Bulk Lifetime

Experimental IBIC Dataset



Simulation Changing Bulk Lifetime





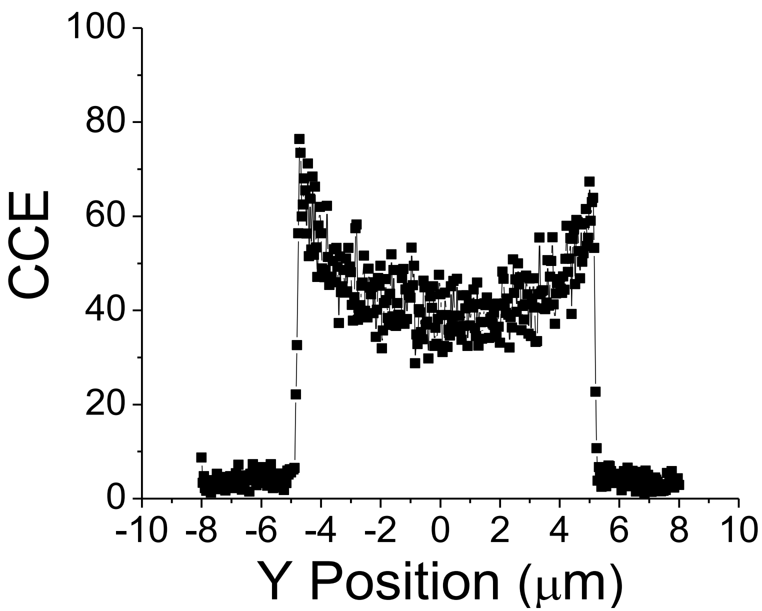
Experimental curve ≠ predicted curve

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

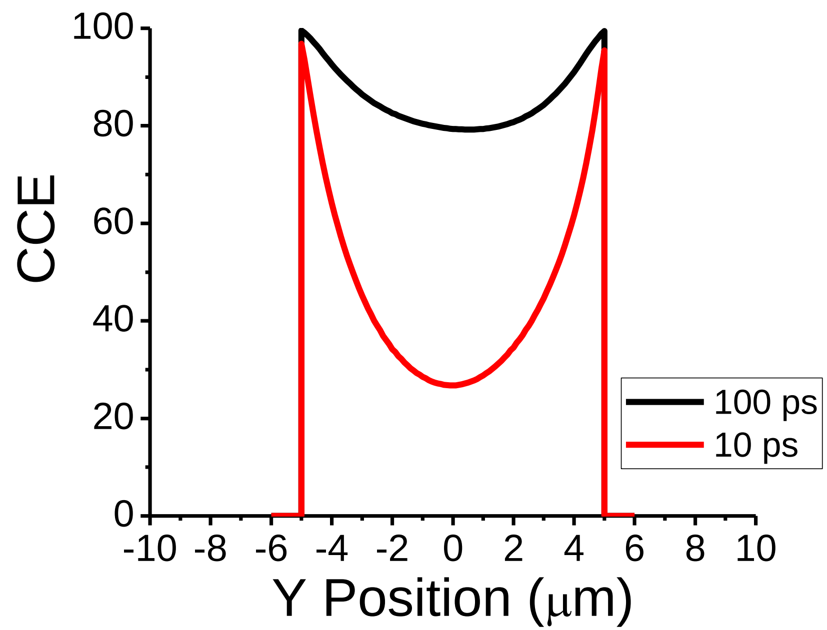
How to account for these differences? Lifetime vs Depth

Depth Dependent Lifetime

Experimental IBIC Dataset

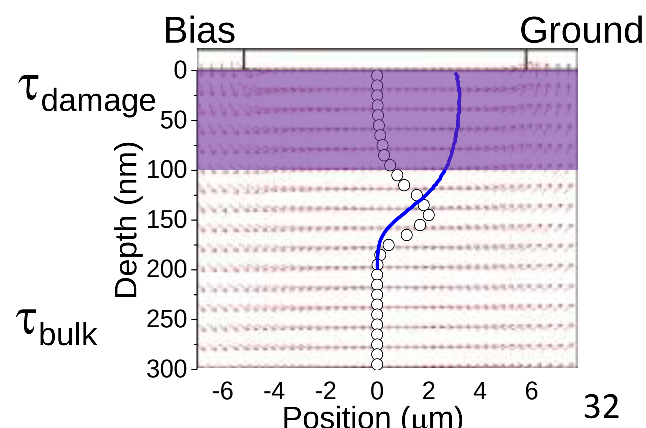


Simulation with Damage



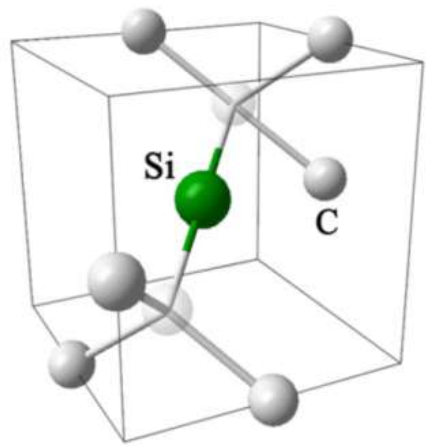
→ Model the damage as a reduced lifetime only near the sub-surface region of the detectors

Detectors probe sub-surface damage



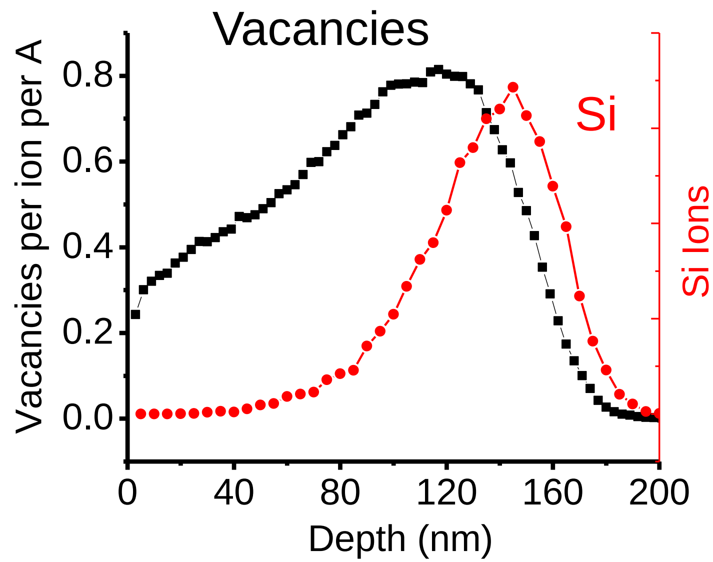
Abraham *et al*, APL **109**, 063502 (2016)

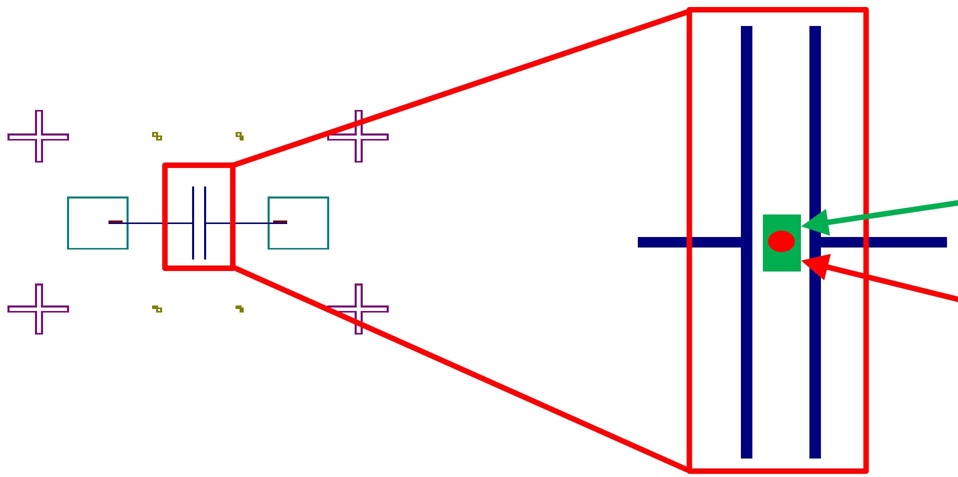
Yield Improvement - Sequential Implantation



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

200 keV Si Implant





1.) Align to markers

2.) Implant 50 keV Li area

3.) Switch to Si beam, realign

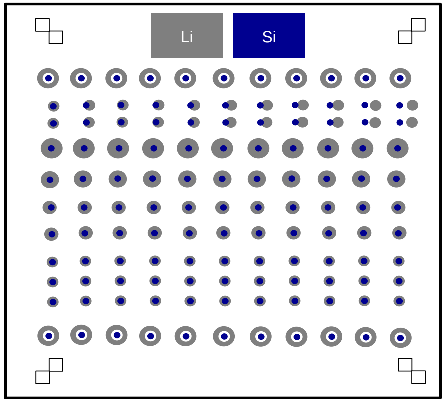
4.) Implant 200 keV Si spots

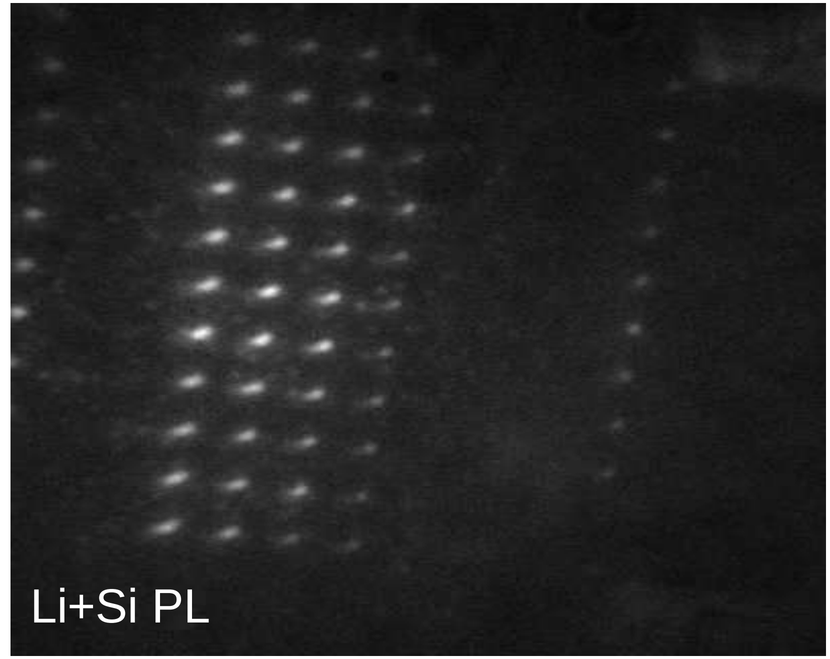
Alignment with <20 nm resolution

Use the direct write capability of the nI to introduce excess C vacancies at the appropriate depth relative to the Si implants

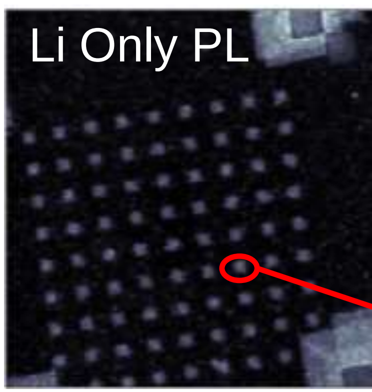
Sequential Implantation Experiment

Implant Li to create vacancies,
then Si → SiV

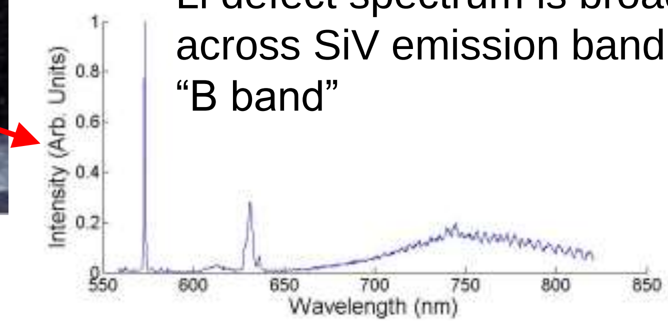




M. E. Trusheim, T. Schroder and D. Englund



Li defect spectrum is broad
across SiV emission band
"B band"



Unexpected Li emission

One reference to unpublished work

Next step for Sequential Implantation

Choosing the source of vacancies:

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

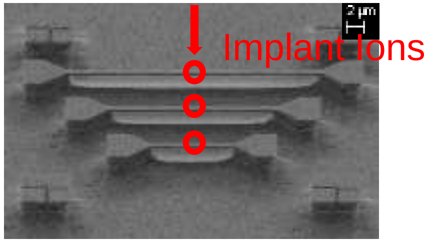
Increase # of vacancies without introducing background luminescence

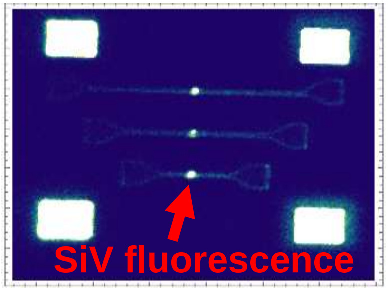
→ First samples made and annealed, awaiting measurement

Status of SiV Centers at SNL

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

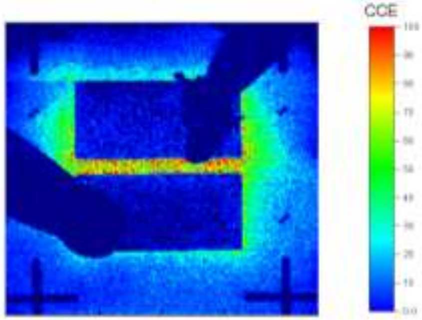
(with Loncar/Lukin Harvard)

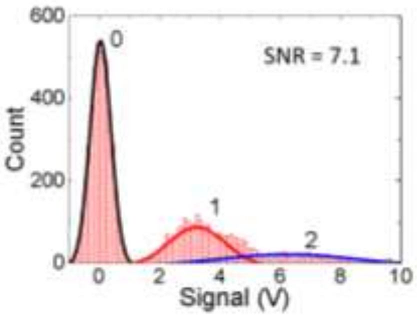




Targeting with ~10's nm resolution

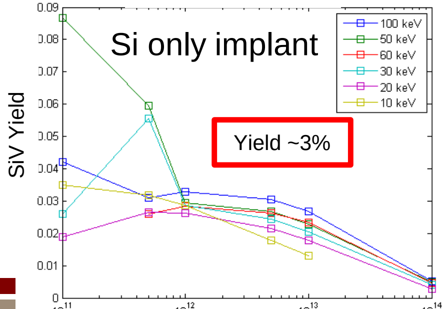
2.) **Single Ion Detection** → e-h pair detection ☑





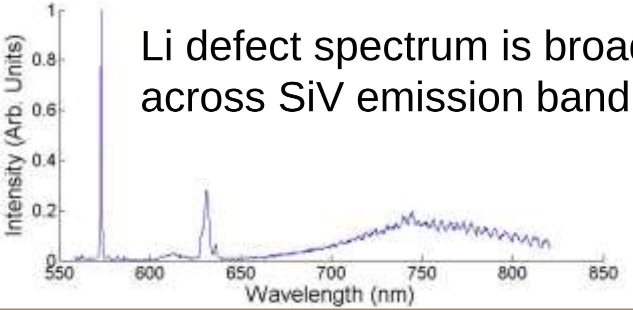
Single ion detection with SNR ~ 10

3.) **Yield Improvements** → Li implants to form vacancies



Li+Si implants performed, post implantation processing underway

(with Englund MIT)

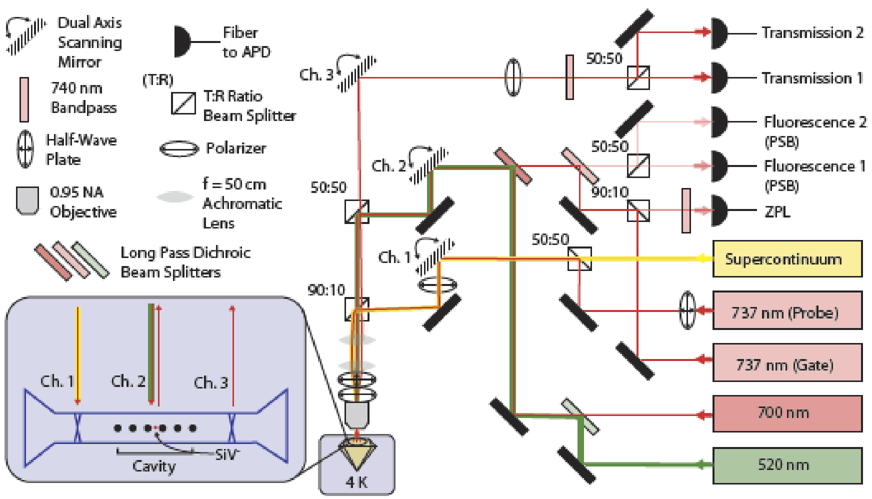


Li defect spectrum is broad across SiV emission band

Future Directions - Electro-optical control of SiV

Sandia National Laboratories

Optical Setup



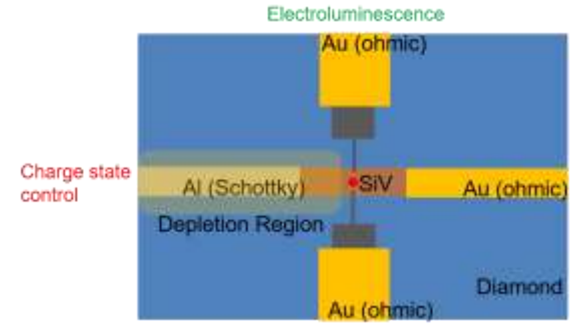
Complex optical setup controls a ***single*** SiV color center!

1.) 520 nm for initialization via photoionization to SiV^-

2.) 700 nm pump for non-resonant excitation

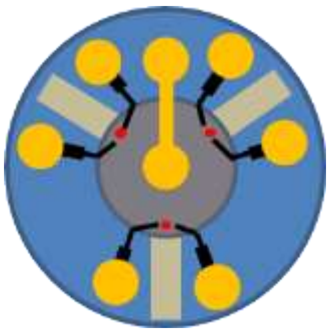
3.) 737 nm for cavity transmission

Electro-optical Setup



Initialization: Charge state control

Emission: Electroluminescence



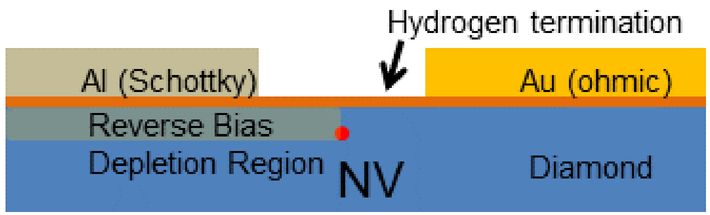
Electro-optical setup scaled to control multiple SiV centers

Take Diamond from a one-off demonstration to wafer scale fabrication

Charge State Control of NV

State-of-the-art (NV only)

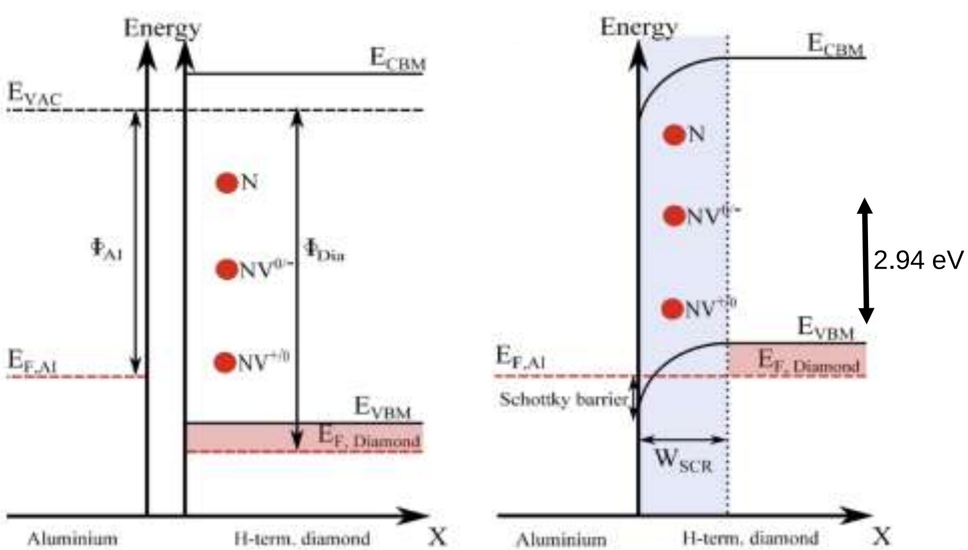
Schottky Diode:
Charge state control via band bending



C. Schreyvogel, *et al.*, Sci. Rep. **5**, 12160 (2015)

Why do we care?

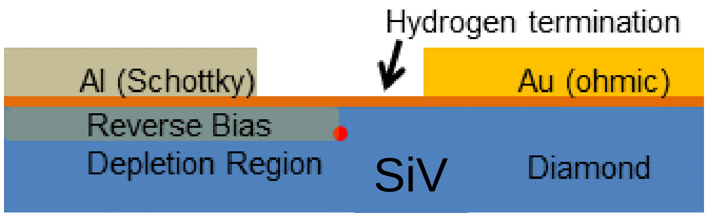
Only the specific charge states are coherent emitters (NV^-, SiV^-) → ***Yield***



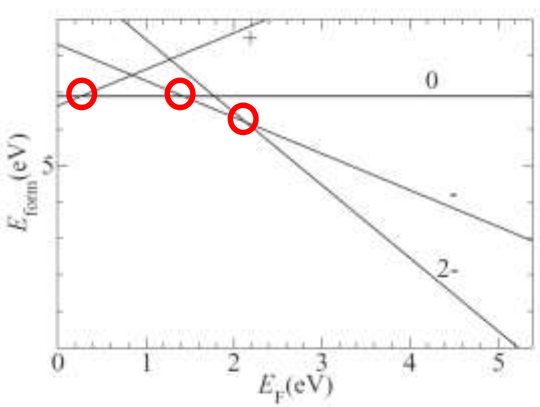
Experientially demonstrated tuning of **NV^+ → NV^0 → NV^-** via reverse bias

Charge State Control of SiV

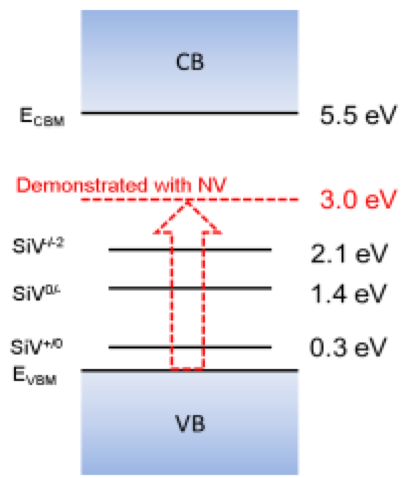
Extend charge state control to SiV

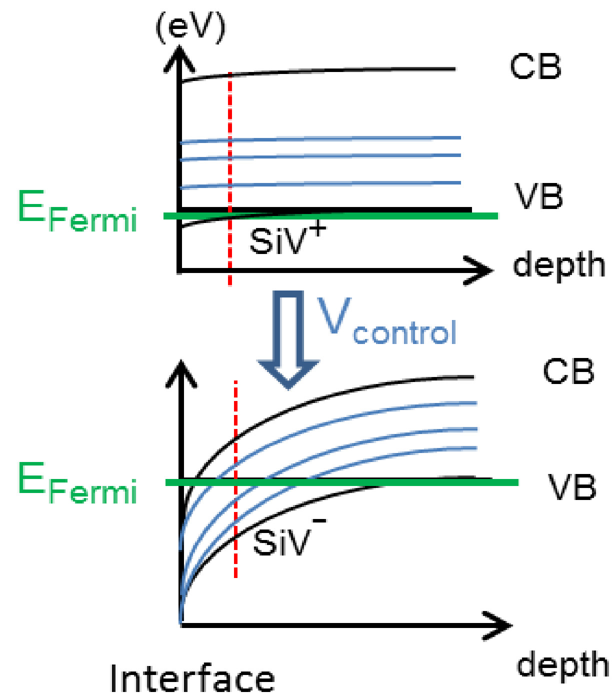


DFT calculation of transitions



A. Gali and J. Maze, PRB **88**, 235205 (2013)





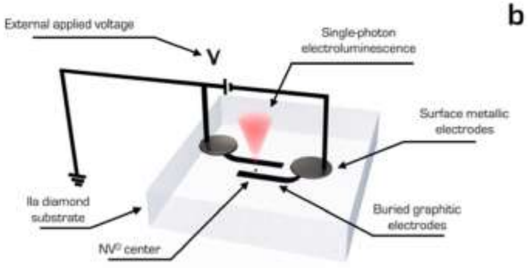
Based on calculated SiV levels we believe that charge state control is possible

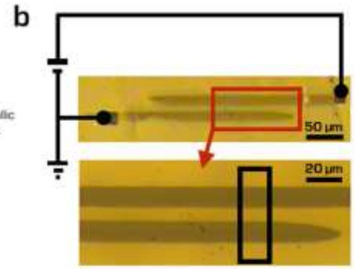
→ Impact on yield

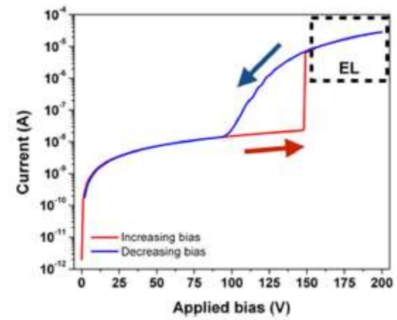
Lead to the first demonstration of SiV charge state control

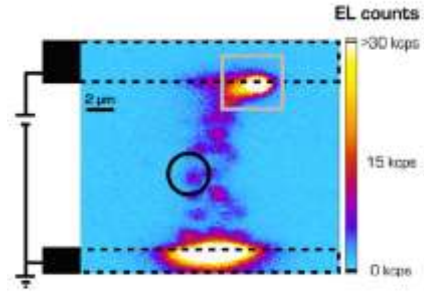
Electroluminescence of NV/SiV

State-of-the-art (NV) → Graphitized Electrodes



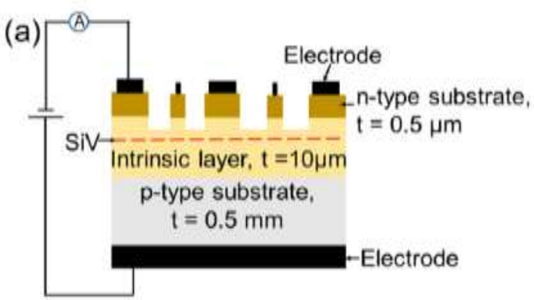


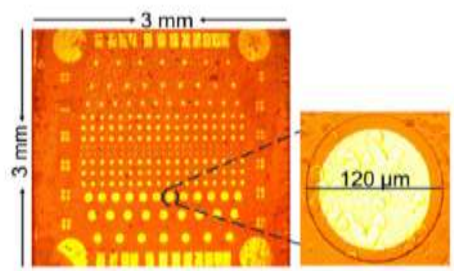


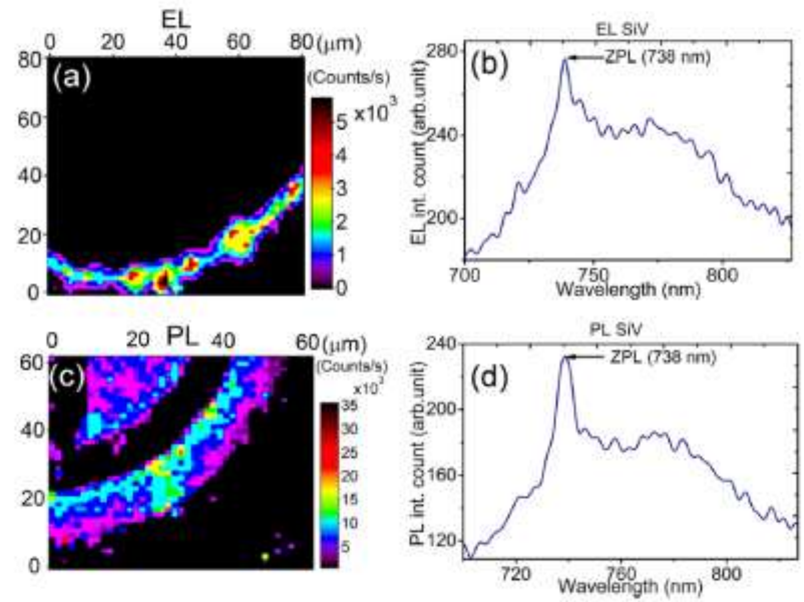


J. Forneris, *et al.*, Sci. Rep. **5**, 15901 (2015)

State-of-the-art (SiV) → PIN Devices







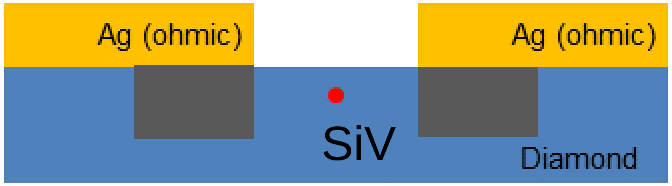
A. Berhane, *et al.*, APL **106**, 171102 (2015)

NV and SiV electroluminescence demonstrated in literature

Improved Electroluminescence of SiV

Extend the graphitized electrode design to smaller scale

Graphitized Electrodes: Electroluminescence via carrier recombination local to the defect

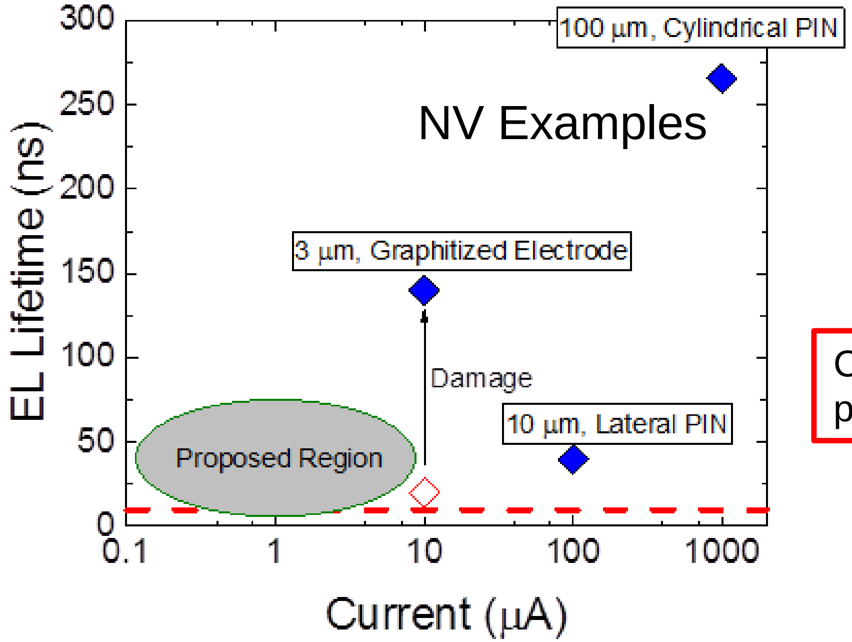


J. Forneris, *et al*., Sci. Rep. **5**, 15901 (2015)

Why do we care?

Electrical control of optical emission is key to scaling of devices

Potential Advantages of smaller scale devices



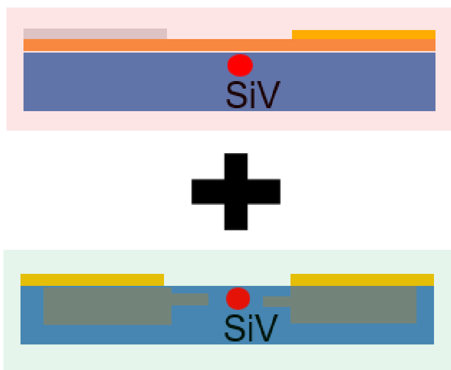
Compact devices with low damage promise low current and high bandwidth

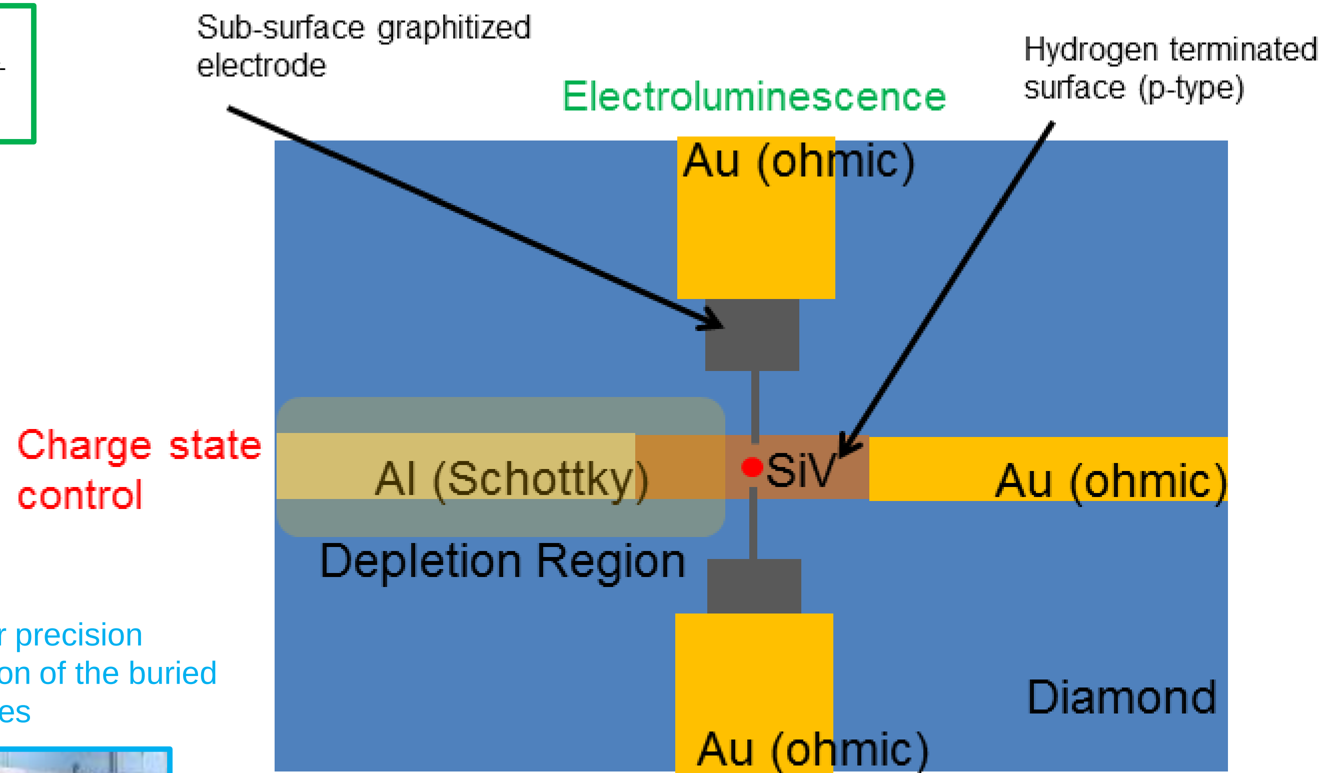
Lead to improved performance of the SiV electroluminescence

Our Approach of combined ***Charge State Control*** and ***Electroluminescence***

Sandia National Laboratories

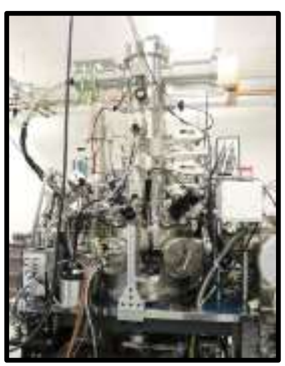
Integrated device to allow for
- Charge state control of SiV → SiV^-
- Emission from SiV^-





Focused ion implant for control over spatial location of SiV

HeIM for precision fabrication of the buried electrodes



<10 nm spot

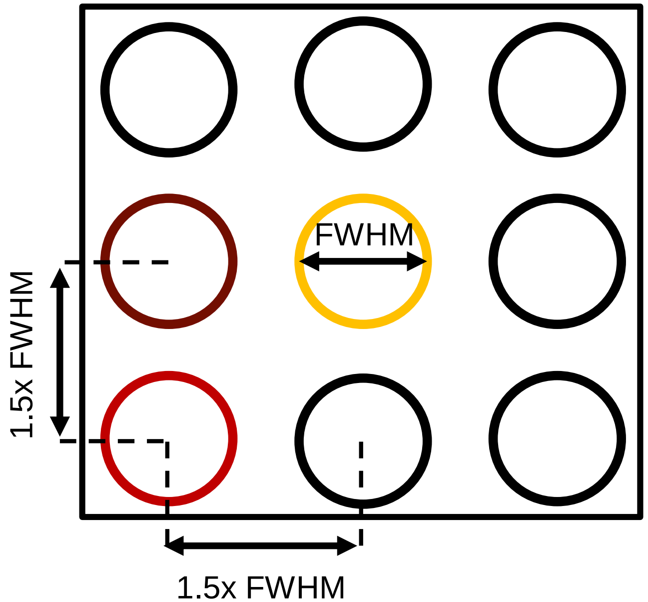
<1 nm spot

- Previous work 10-100 μm scale
- We believe that we can easily target <100 nm

Results in electrically addressable color center

Limits on ‘top-down’ device fabrication

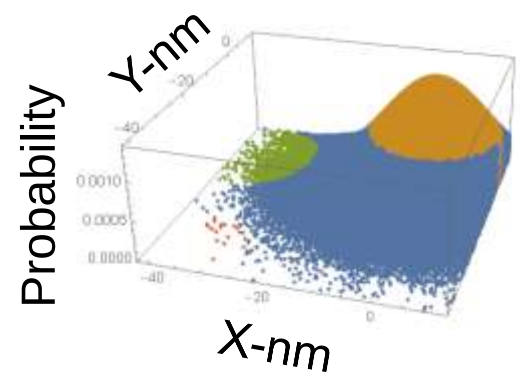
Assume array of ions (donors or color centers) → 1 and only 1 ion per site with PMMA masking



- 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

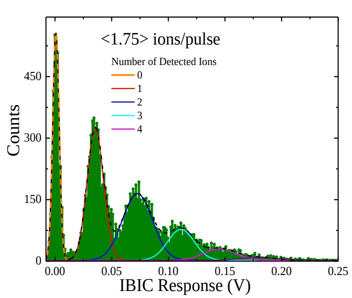
J. L. Pacheco, **J. B. S. Abraham**, **B. Aguirre**, R. Camacho (SNL)

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

- Single Donor devices in Si for Quantum Computing



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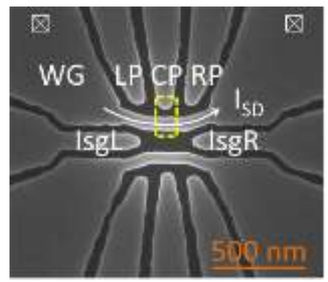

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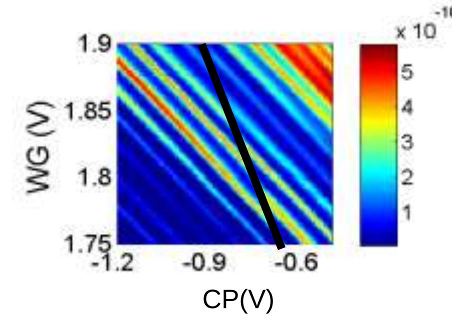
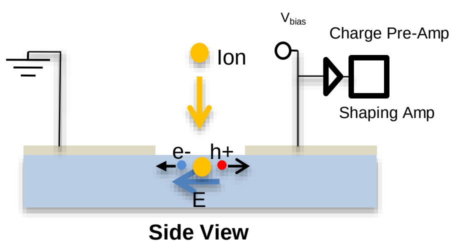


Singh et al. APL 108 062101 (2016)

- SiV Color Centers in Diamond



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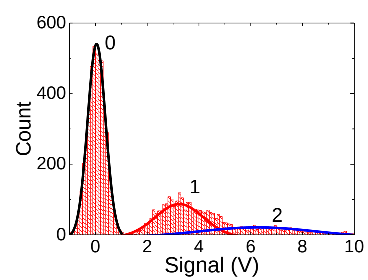
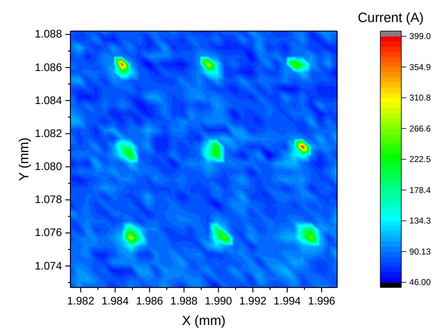


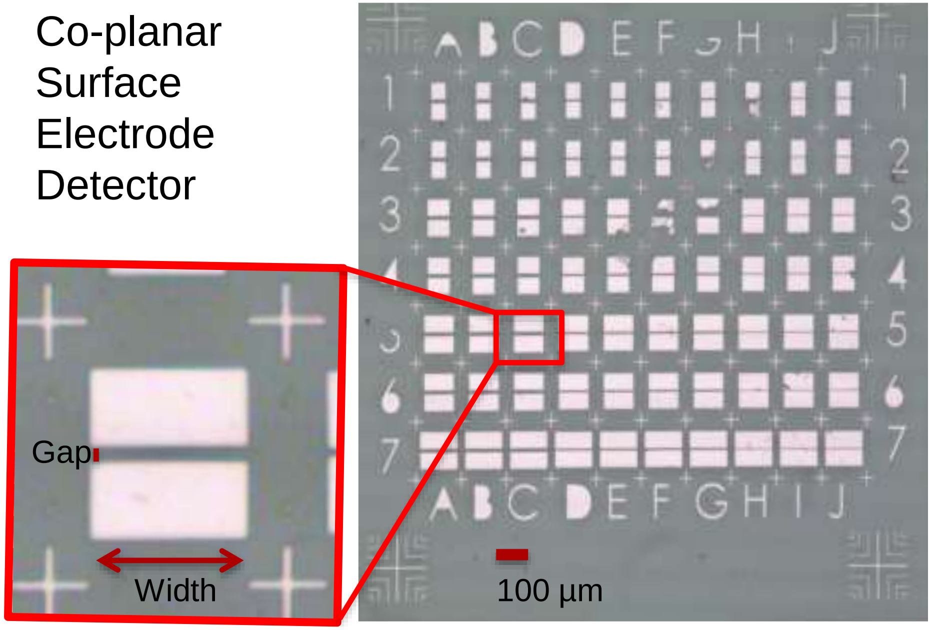
→



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

Fabrication

Co-planar Surface Electrode Detector

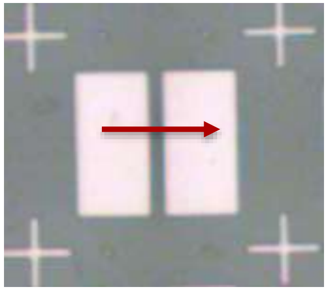


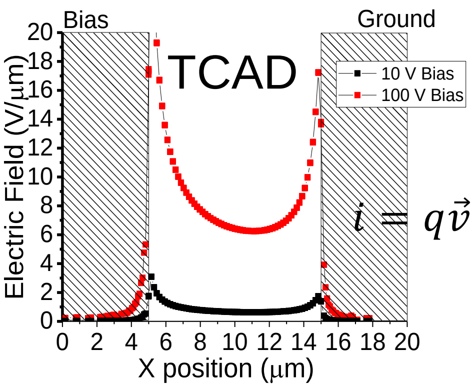
- Electronic grade single crystal diamond (Element 6)
- 200 nm Ti/Pt/Au Electrodes
- Varied width and gap spacing
  - 50-125 um width
  - 2 – 10 um gaps

Process

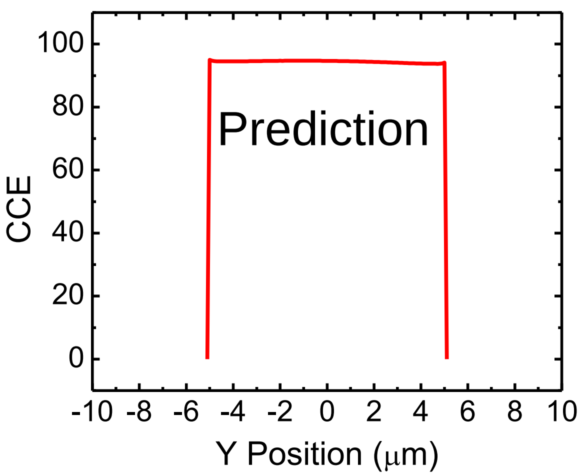
1. RIE Ar/Cl2:O2
2. Piranha Clean (20 min)
3. Dehydration bake 180C (5 min)
4. Mount Sample on 1 um Oxide Si wafer with PMMA
5. Bake 180C (1 min)
6. Spin HMDS (4K, 30 sec)
7. Bake 90C (90sec)
8. Spin AZ5214EZ (4K, 30 sec)
9. Bake 90C (90 sec)
10. MA6 Aligner (Hard Contact, 5 sec exposure)
11. AZ400K 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

Characterization of Diamond Detectors

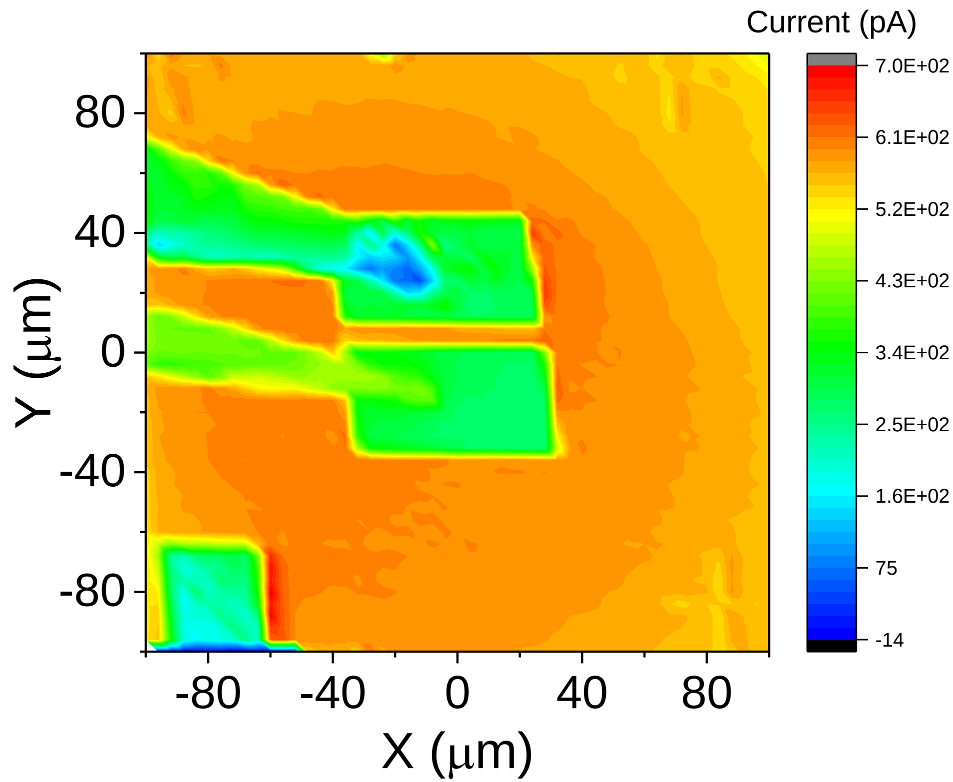




$$i = q\vec{v}\cdot\frac{\partial\vec{E}}{\partial V}$$



Electron Beam Induced Current (EBIC)



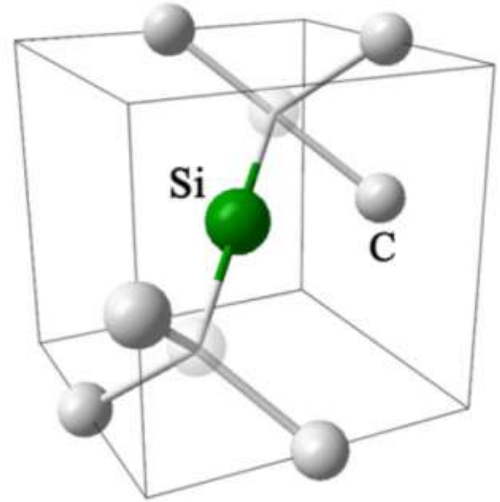
EBIC datasets match the predicted response

What are Color Centers in Diamond?

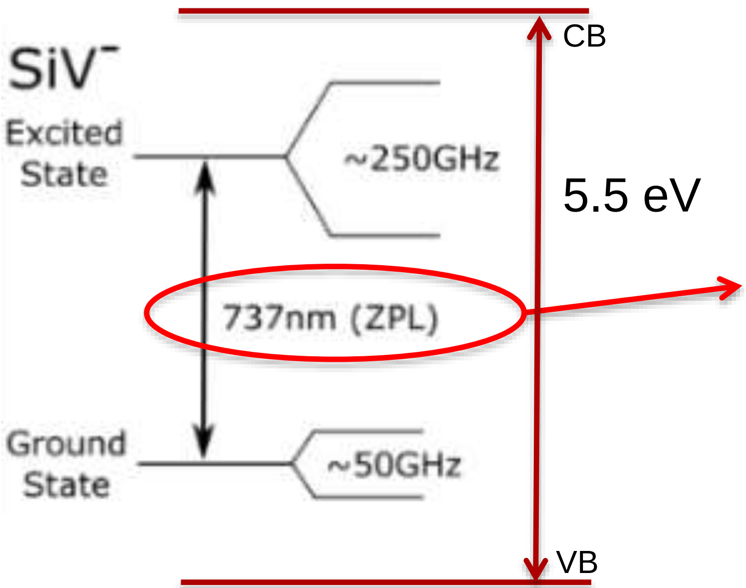
- Range of defect complexes – such as NV, SiV

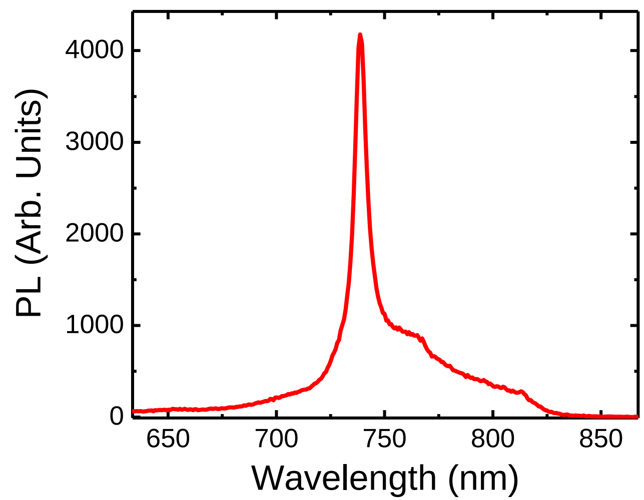
- Diamond substrate with 5.5 eV band gap – allows RT operation of the defect centers

SiV



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

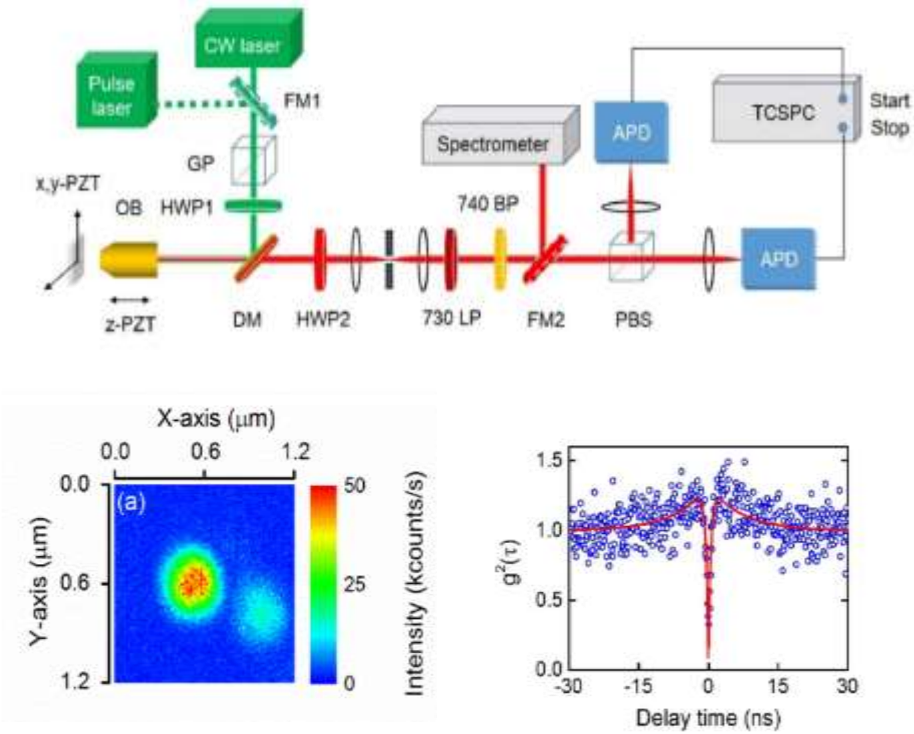




Defect centers act as "Artificial Atoms"

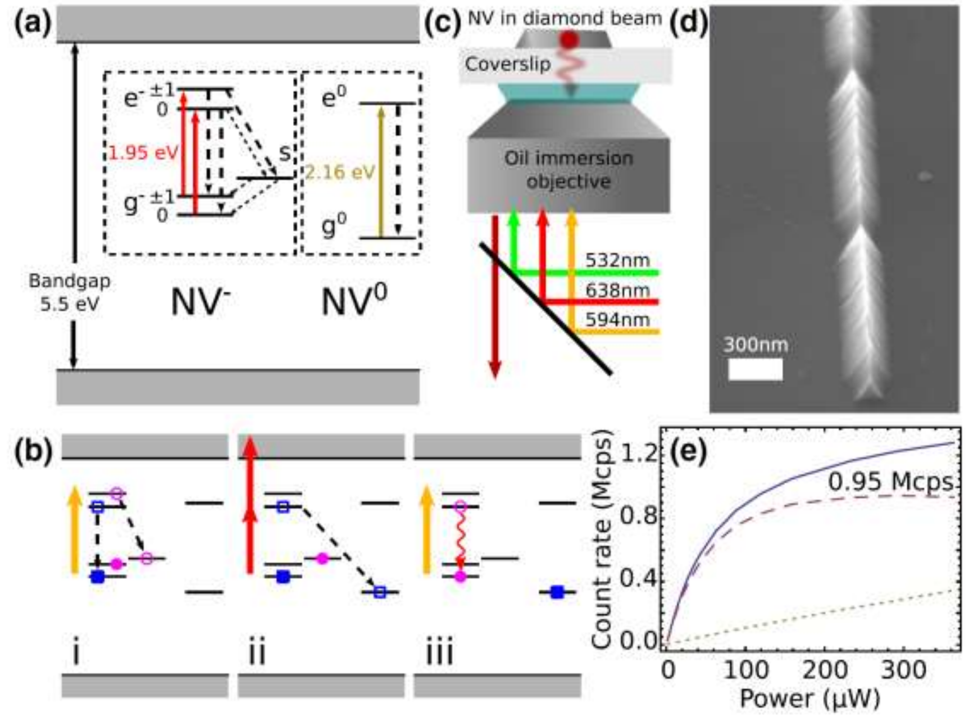
Applications for Color Centers in Diamond

<u>SiV Single Photon Source</u>



Y. Liu *et al*., Opt. Express **23**, 032961 (2015)

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



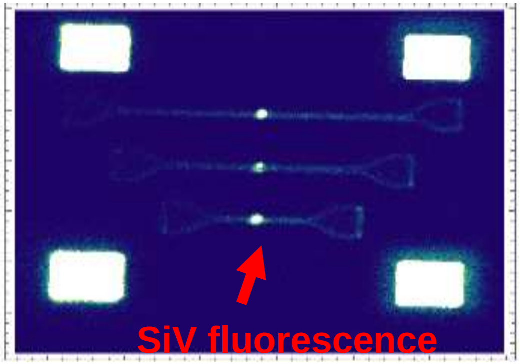
B. J. Shields *et al*., PRL **114**,136402 (2015)

"Artificial Atoms" in Diamond at Ambient Conditions!

What is the Problem?

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

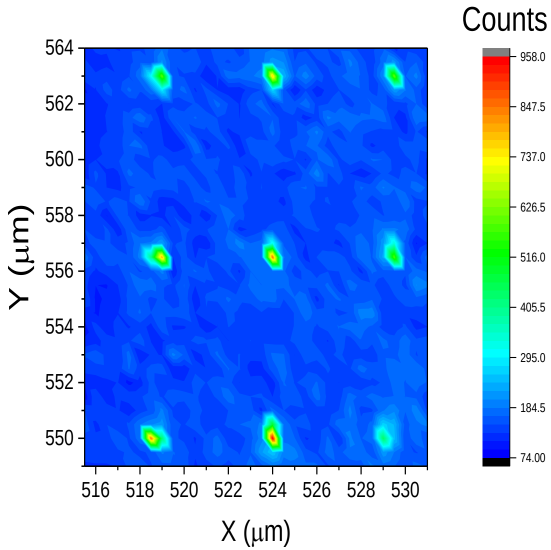
1.) Location:



- Need to demonstrate spatial control for device integration

Cavity applications need <100 nm

2.) Yield:



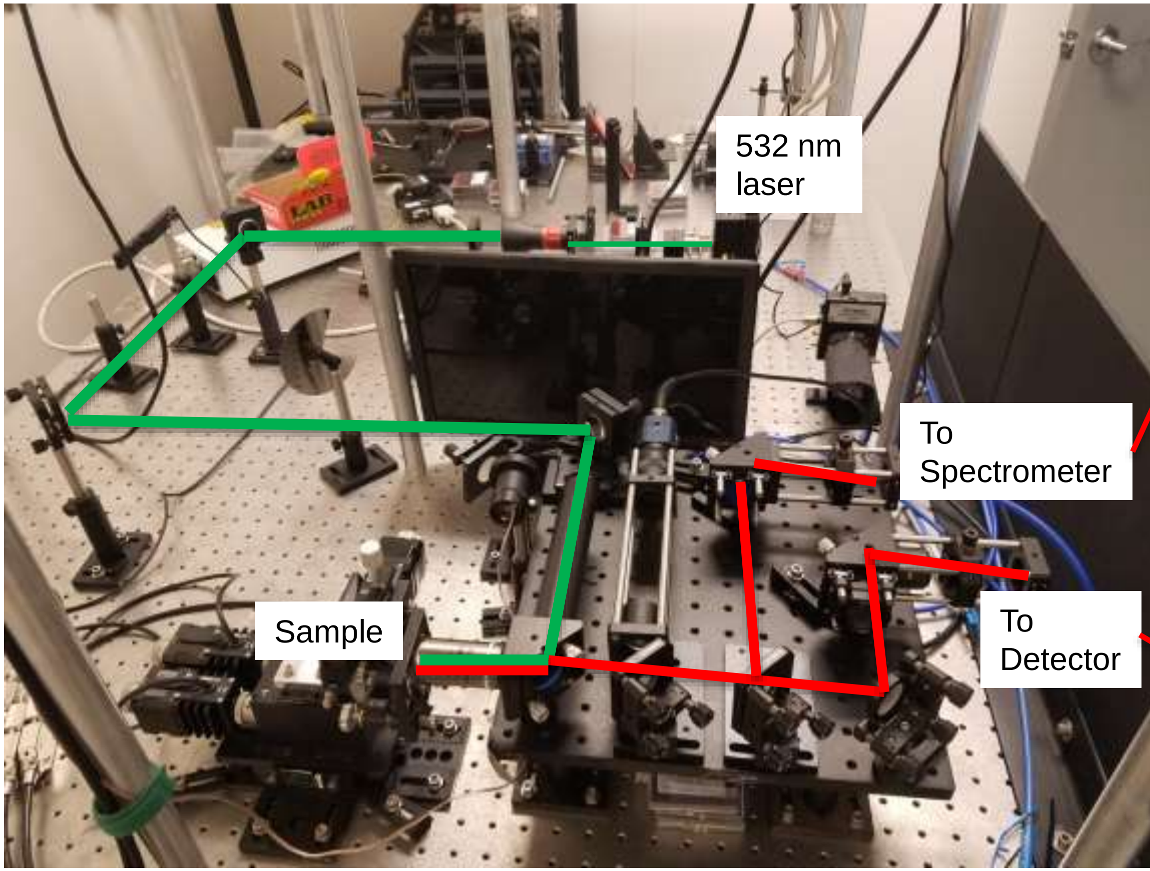
- Low color center yield will limit device yield

Yield $= \frac{\#Color\ centers\ observed}{\#\ impurities\ introduced}$ is ~3%

We use ***focused ion beam implantation*** and ***single ion detectors*** to engineering the color centers

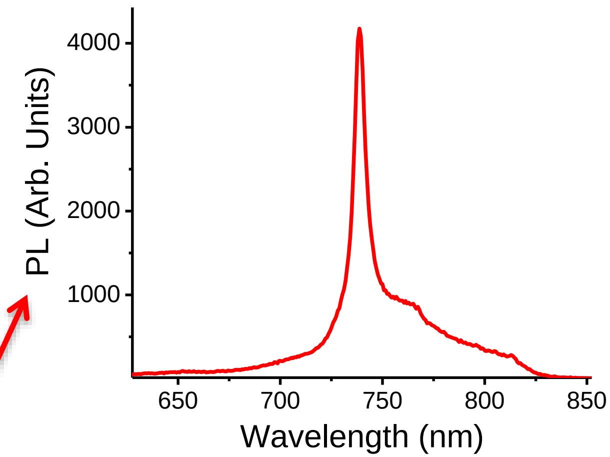
Characterization – Photoluminescence of SiV^-

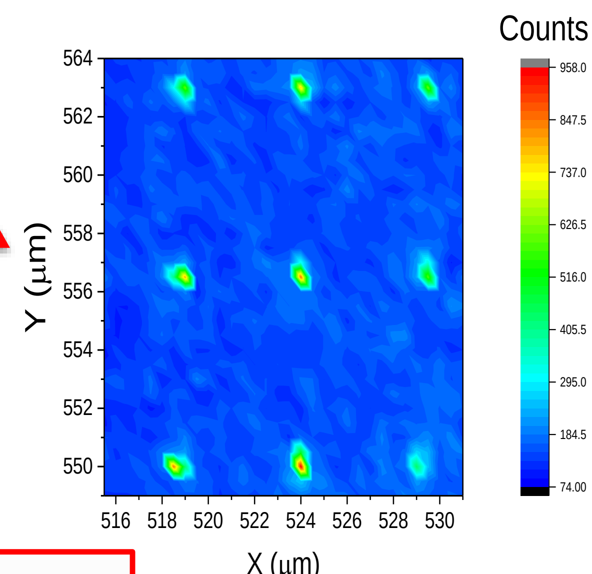
Sample scanning confocal microscope



pump

emission

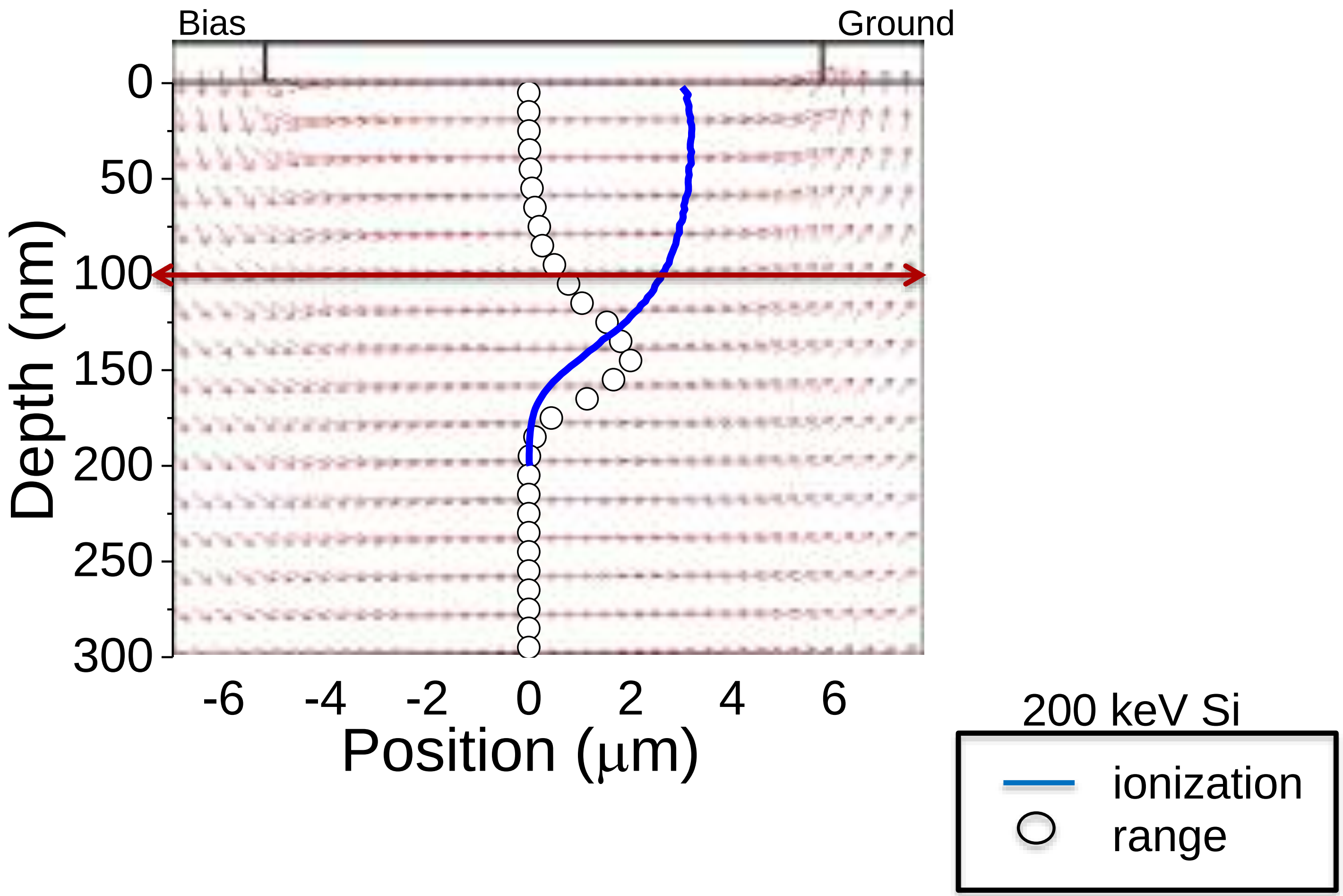




Spatially Resolved PL Map of SiV Centers

Collaborators: A. Fischer (SNL) and H. Htoon (LANL, CINT)

TCAD/SRIM Modeling of the Detectors



Detectors are optimized for sub-surface detection

Current Understanding of Yield

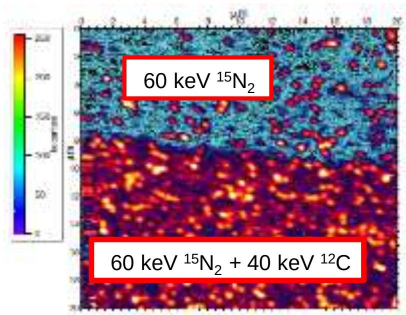
$$Yield = \frac{\#Color\ centers\ observed}{\#\ impurities\ implanted}(\#vacancies, anneal\ parameters, charge\ state)$$

Forming the Center

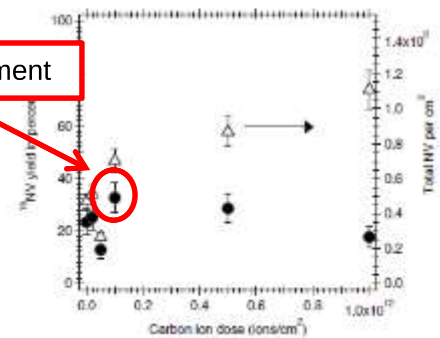
Occupation of the center

Co-Implantation:

Naydenov et al. Appl. Phys. Lett. 96, 163108 (2010)

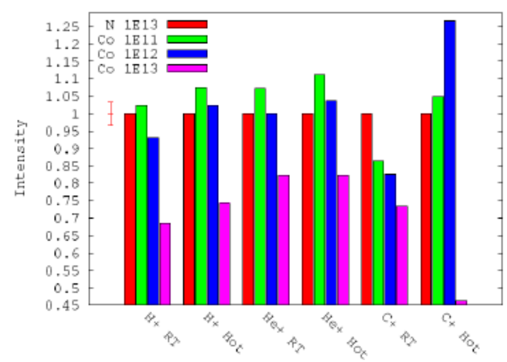


50% improvement



Anneal Parameters:

Schwartz et al., New J. Phys. 13 (2011) 035022

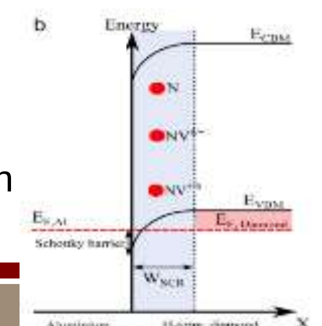


25% improvement with combined elevated temperature + C implant

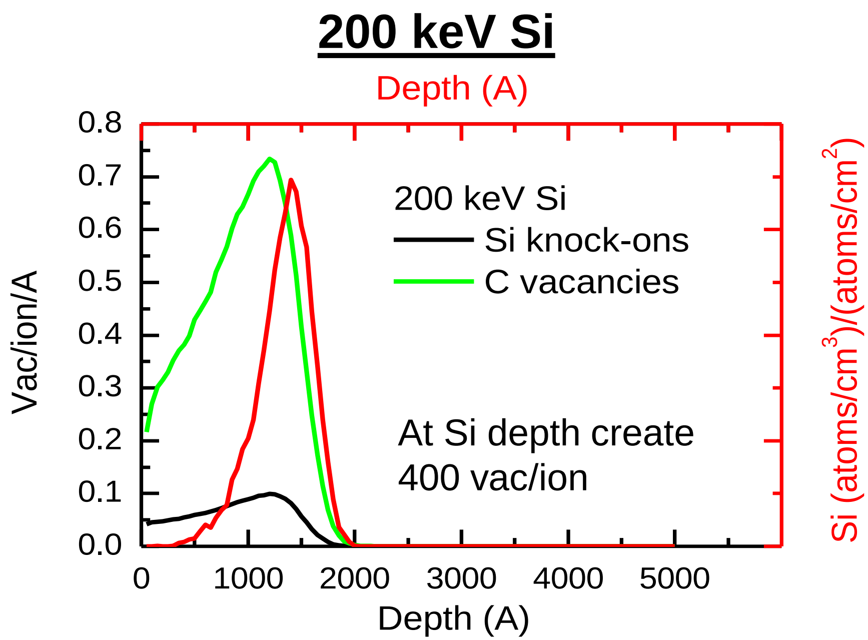
Charge State:

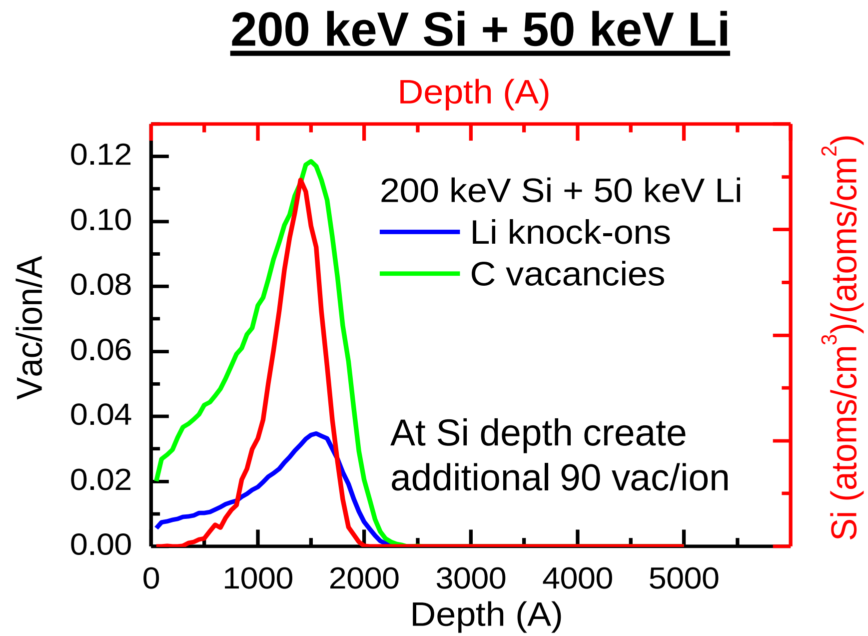
Schreyvogel, C. et al., Sci. Rep. 5, 12160 (2015)

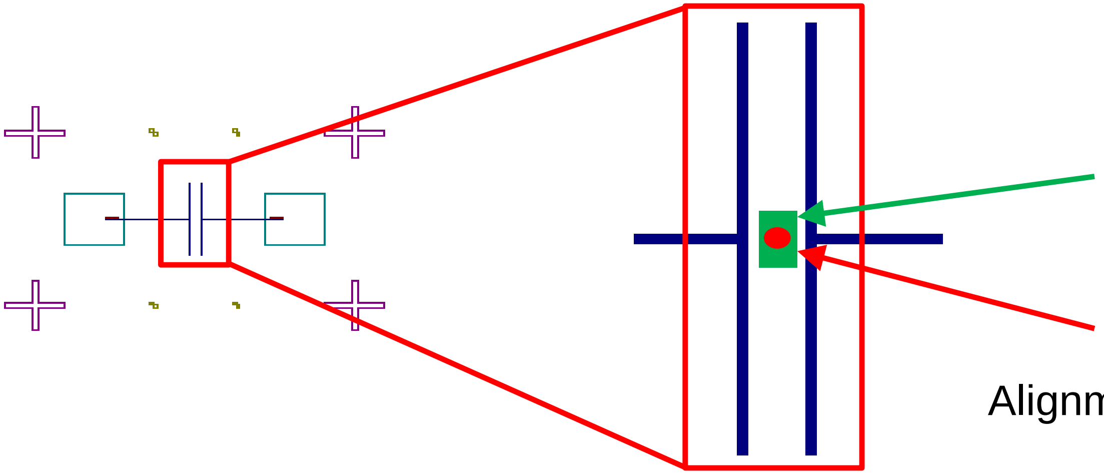
Tuning the occupation of states via reverse bias



Yield Improvement – Introduce Excess Vacancies







1.) Align to markers

2.) Implant 50 keV Li area

3.) Switch to Si beam, realign

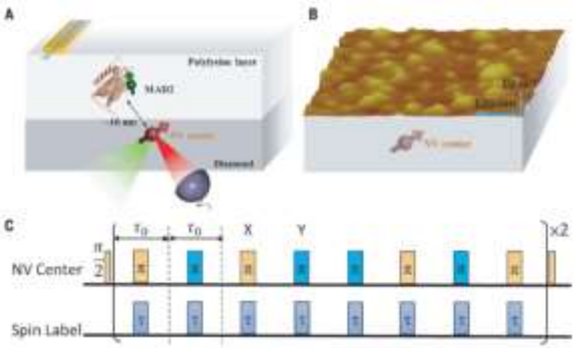
4.) Implant 200 keV Si spots

Alignment with <20 nm resolution

Use the direct write capability of the nI to introduce excess C vacancies at the appropriate depth relative to the Si implants

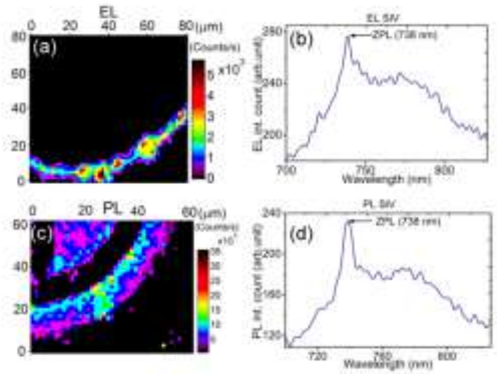
SiV Color Centers in Diamond

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



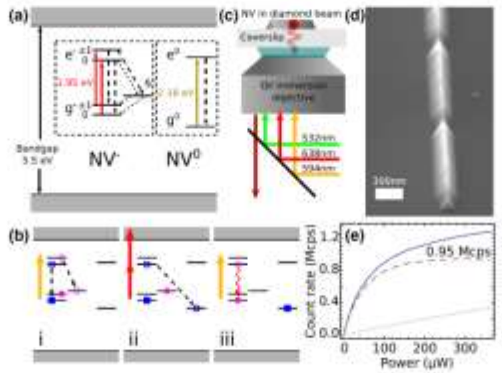
F. Shi *et al*., Science **347**, 1135 (2015)

<u>Electrically driven SiV</u>



A. M. Berhane *et al*., APL **106**, 171102 (2015)

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



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

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

1.) Location

2.) Yield

We will use ***<u>focused ion beam implantation</u>*** and ***<u>single ion detectors</u>*** to determine both location and yield with high accuracy

Diamond Processing (Detector Fab)

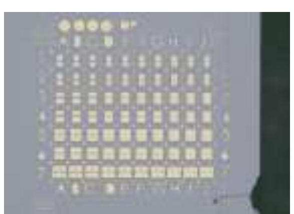
Sandia National Laboratories

RIE etcher

PR spinner

Mask aligner

Metal dep

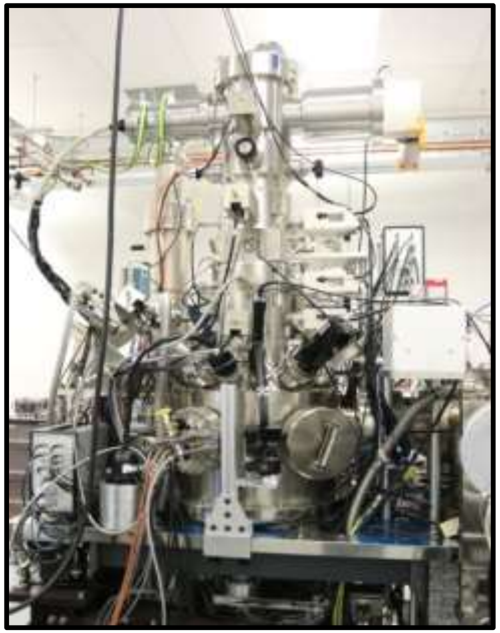


Process

1. RIE Ar/Cl2:O2
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

Diamond Processing (SiV Fab)

200 keV Si



Introduce Si and vacancies

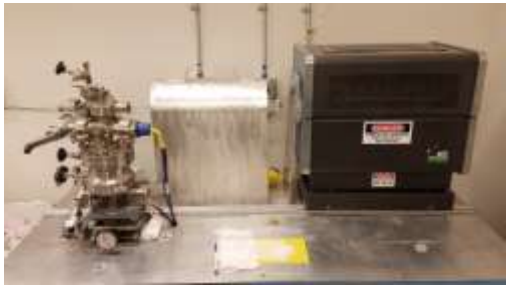
nI

$1:1:1\ HNO_3:H_2SO_4:HClO_4$

Remove surface contaminants prior to anneal

Tri-acid clean

1000 C, 1×10^{-7} torr



Form SiV and repair residual lattice damage

Vacuum anneal

$1:1:1\ HNO_3:H_2SO_4:HClO_4$

Remove surface graphite from anneal and Oxygen terminate surface for charge state control

Tri-acid clean