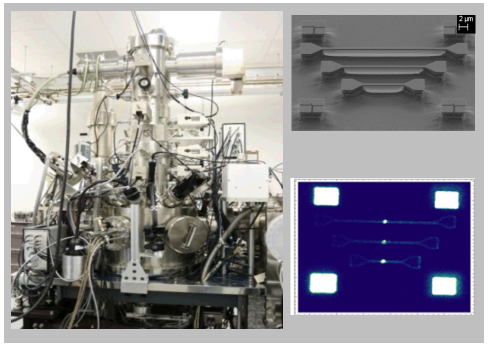
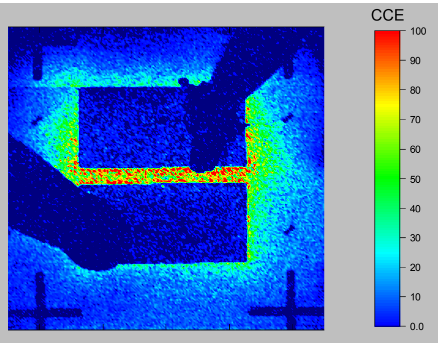
SAND2017-4125C

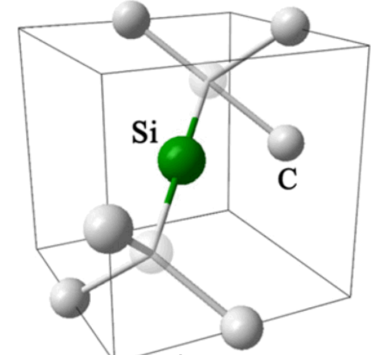




Focused Ion Beam Implantation with Single Ion Detection for SiV Center Creation in Diamond

E. Bielejec, J. B. S. Abraham and R. M. Camacho
Sandia National Laboratories, Albuquerque, NM 87185

Why Color Centers in Diamond?



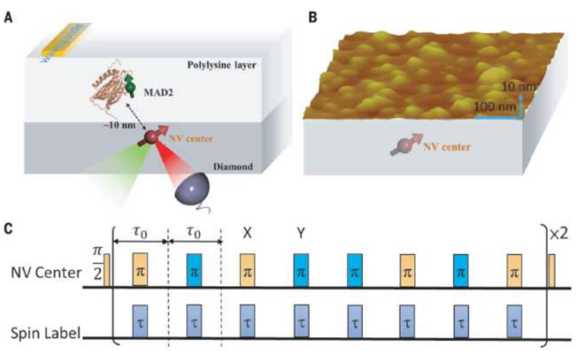
SiV in diamond

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

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

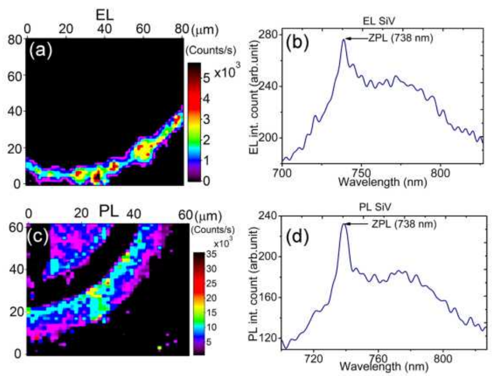
- Wide range of application from metrology to quantum computation

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



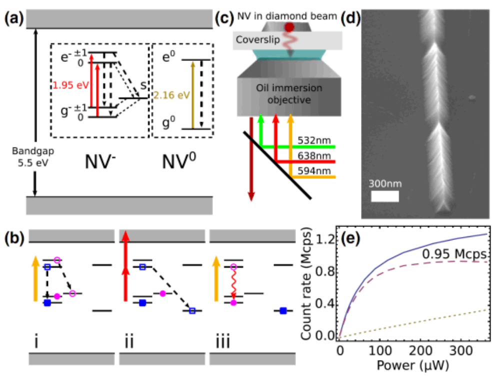
F. Shi *et al.*, Science **347**, 1135 (2015)

<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?

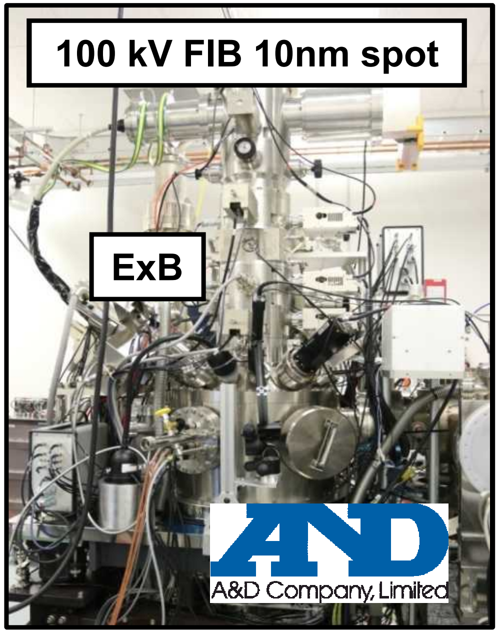
1.) Location

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

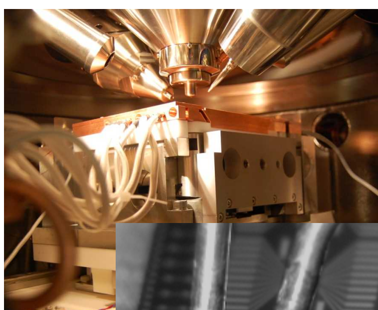
Fabrication – SNL nanoImplanter (nI)

Sandia National Laboratories

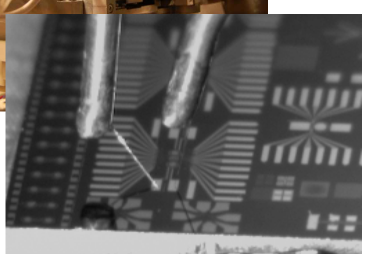


- Focused ion beam system (FIB)
  - →nm beam spot size on target
- ExB Filter (Wien Filter)
  - →Multiple ion species
    - → Li, Si, P, Sb, etc… (separating out ^{28}Si, ^{29}Si, etc…)
- Fast blanking and chopping
  - →Single ion implantation
- Direct-write lithogra
  - →nm targeting ac

RAITH NANOFABRICATION

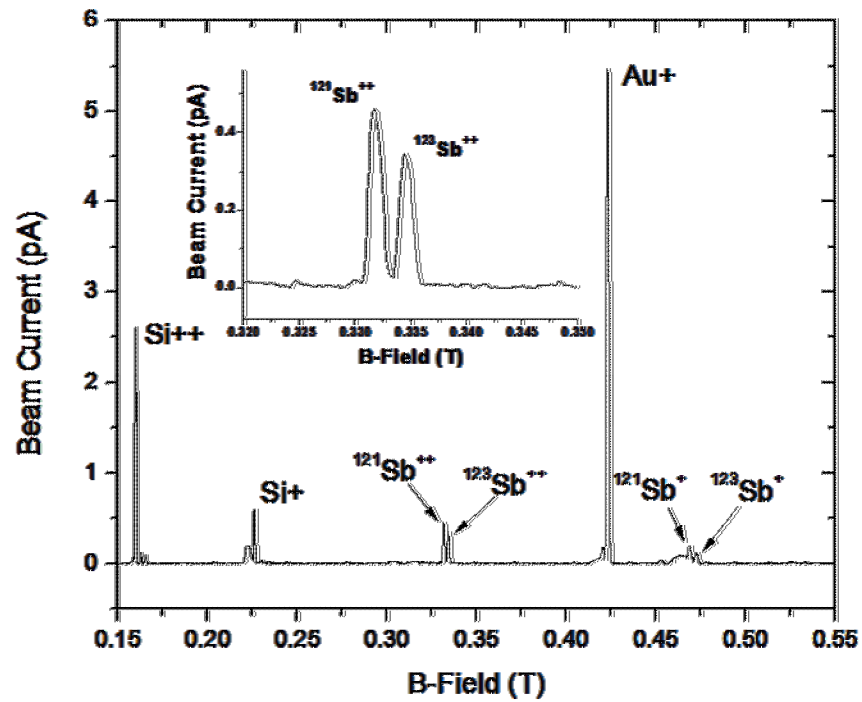


- Low temperature stage

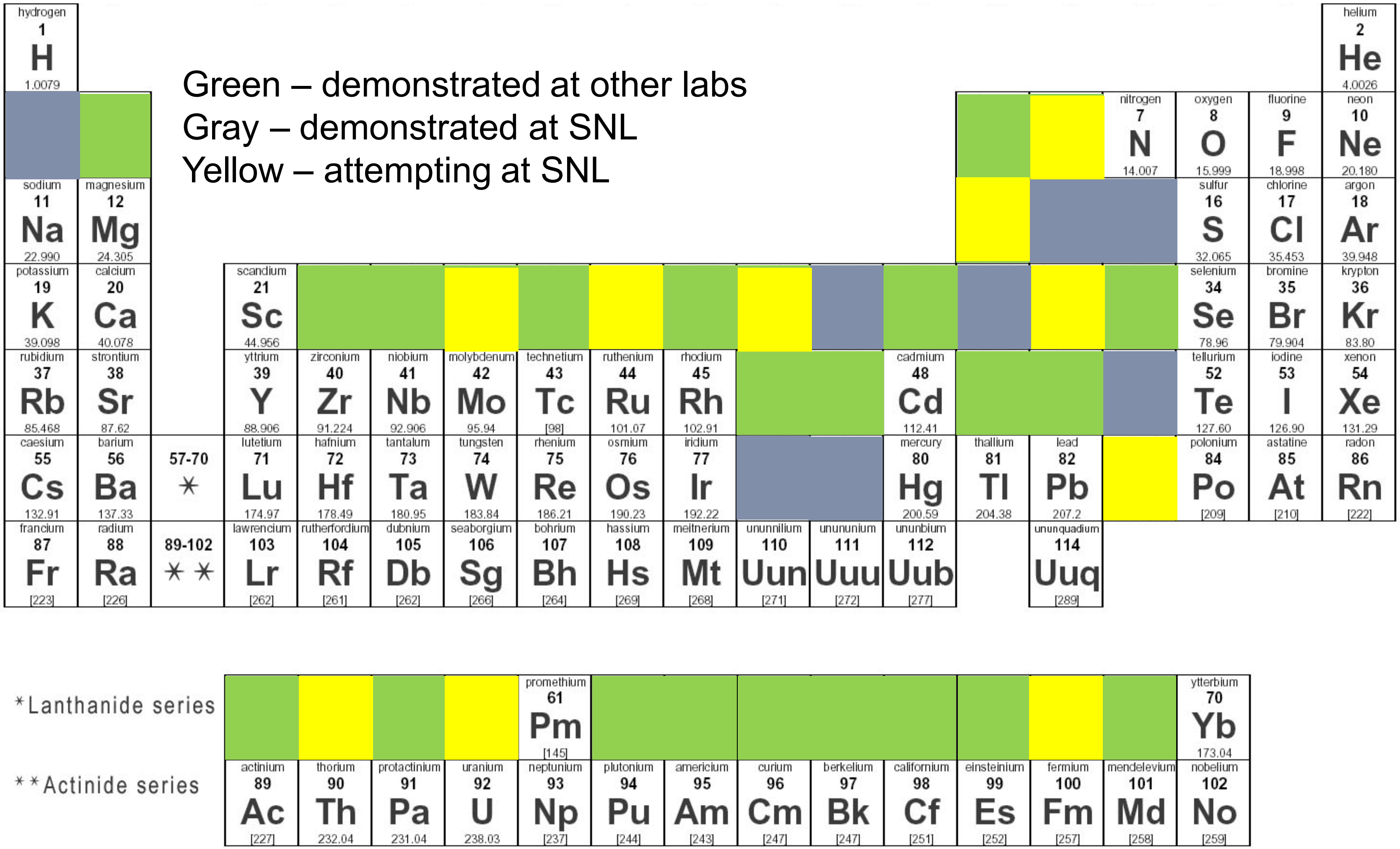


- In-situ electrical probes

Sb Source: Mass Spectrum



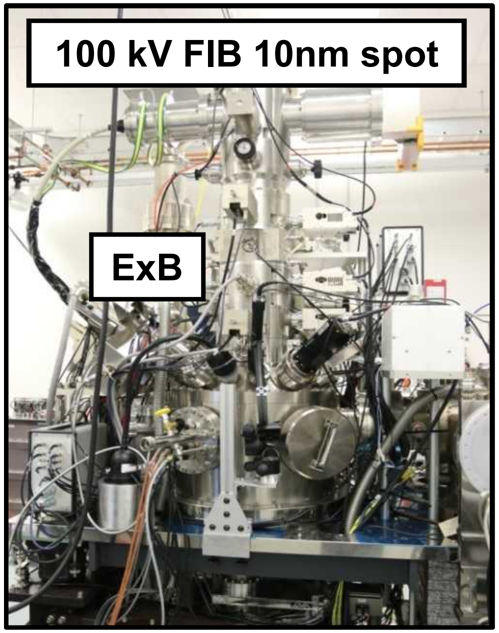
SNL nanoImplanter (nI) - Sources



After A. Weick University of Bochum

Wide Varity of Ion Species Available

Location Problem is Solved

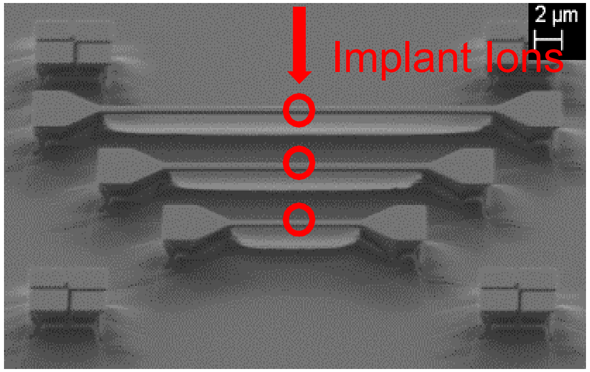


SNL NanoImplanter (nI)

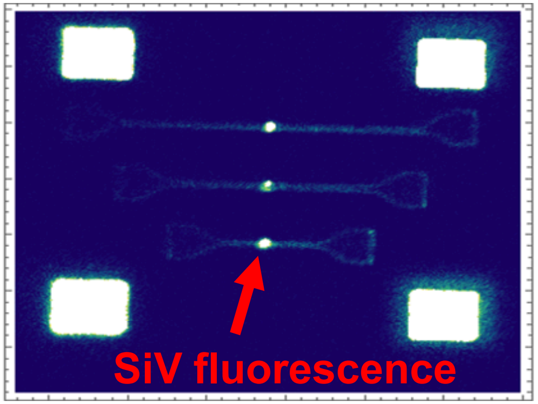
- Variable energy 10-200 keV
- Mass-Velocity Filter (ExB)
  - → Liquid metal alloy ion source
  - → 1/3 Periodic Table
- Direct write lithography platform
  - → Single ion implantation
  - → nm targeting accuracy

Diamond Nanobeams (SNL/Harvard collaboration)

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



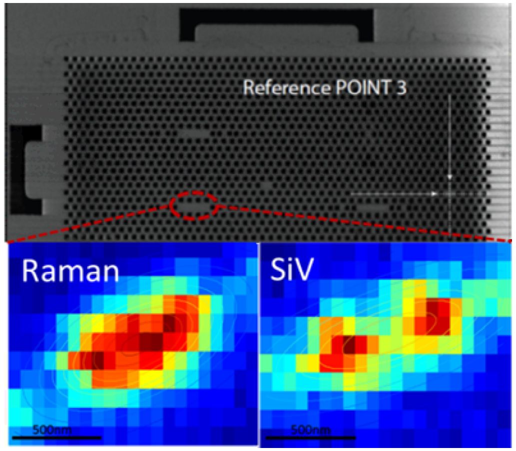
A. Sipahigil *et al*., *Science* (2016)



2D Photonic Crystals (SNL/MIT collaboration)

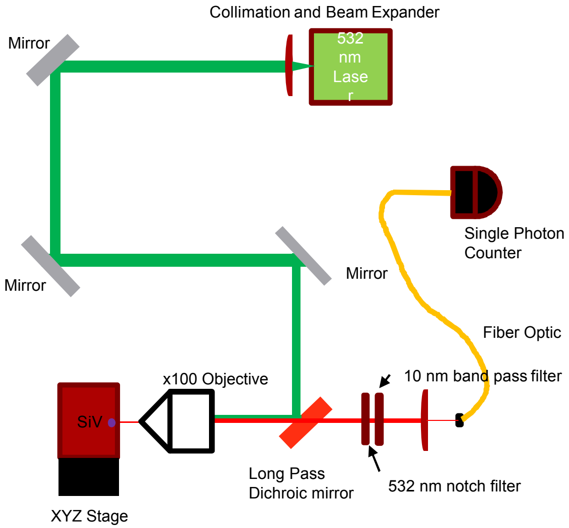
T. Schroder, M. E. Trusheim, and D. Englund

arXiv:1610.09492 accepted into Nature Comm.



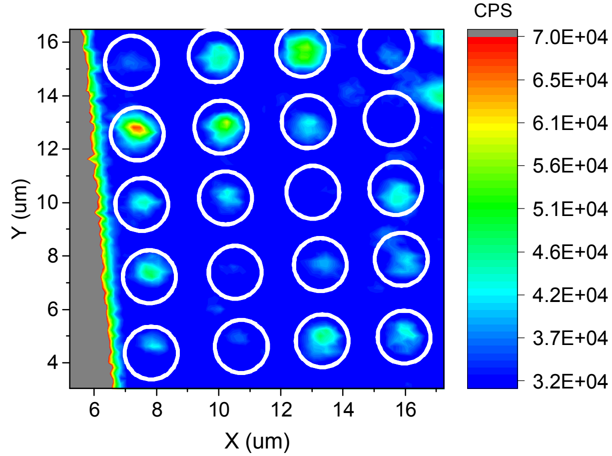
Targeting accuracy is spot size limited to 10's of nm

Yield: Mapping SiV Photoluminescence

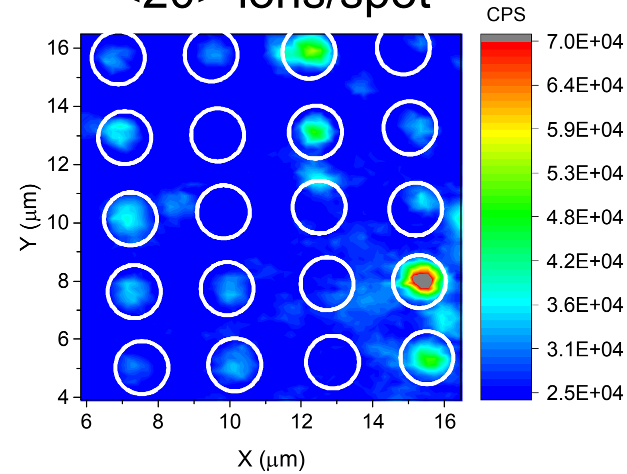


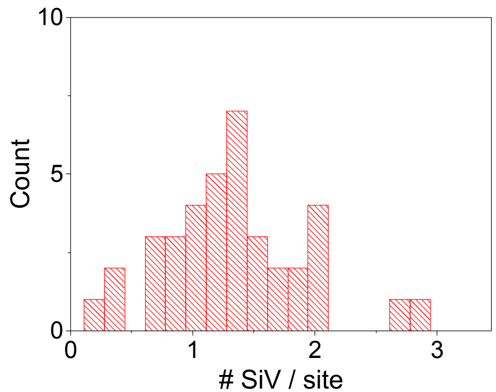
Yield = # measured SiV / # implanted Si

<50> ions/spot

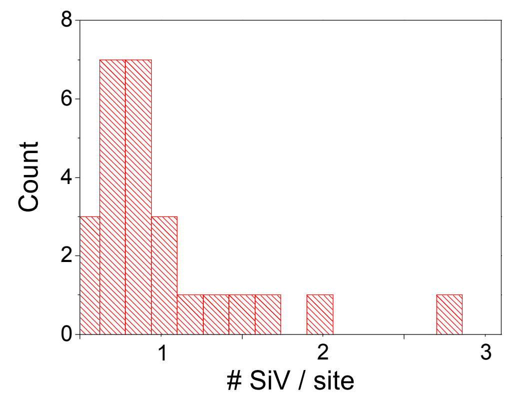


<20> ions/spot





Yield: 2.5%



Yield: 3.75%

Yield is low and distribution matches Poisson statistics

Similar yield to

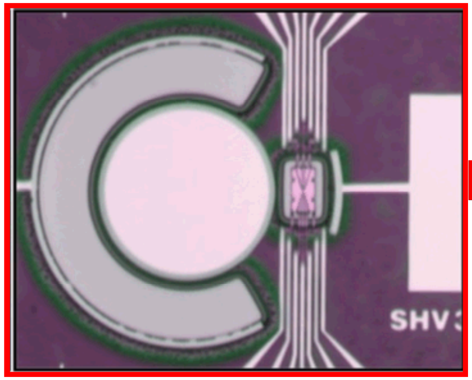
S. Sangtawesin et. al. Appl. Phys. Lett. 105, 063107 (2014)

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

How to Improve the Activation Yield?

Single Ion Detectors to Understand Yield

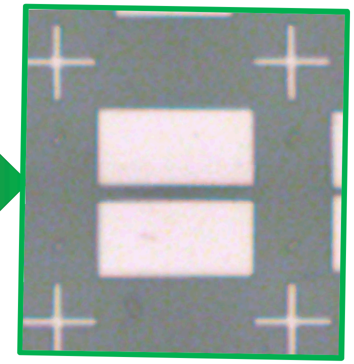
Silicon



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

Translating single ion detection to diamond

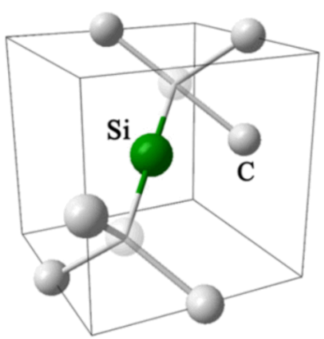
Diamond



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

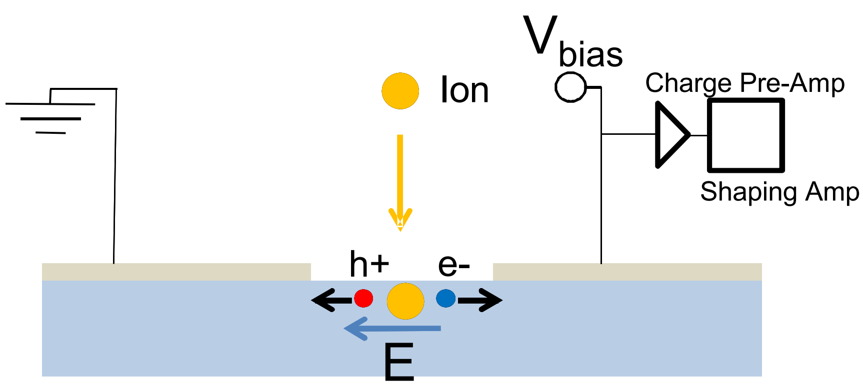
Using Diamond Detectors to Understand Yield

Yield = # measured SiV / # implanted Si

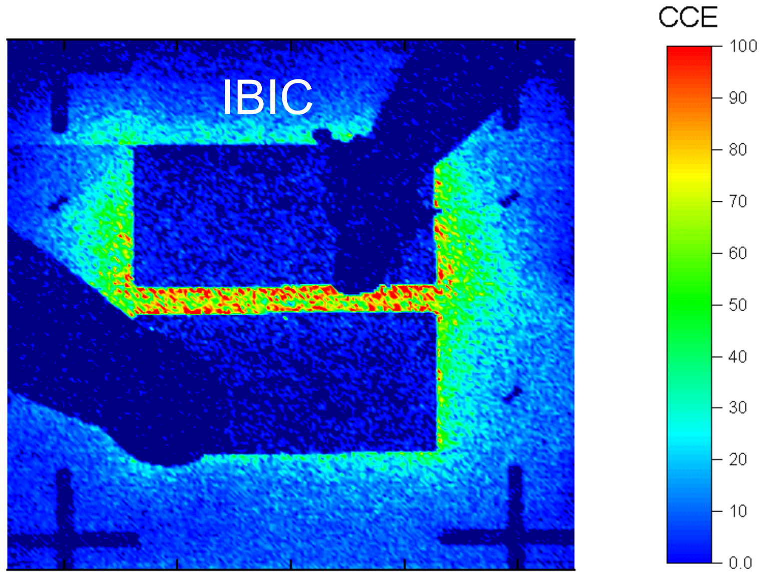
Poisson Statistics

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

Ion Beam Induced Charge (IBIC)



Side View



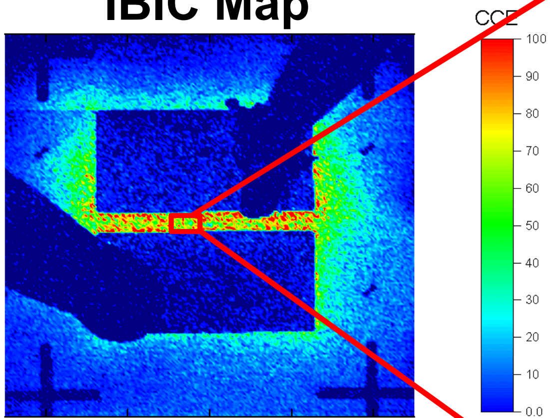
$$\mathrm{CCE} = \frac{\mathit{Charge\ Collected}}{\mathit{Charge\ Depositied}}\, x\ 100$$

IBIC/Detection Demonstrated for low energy heavy ions

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

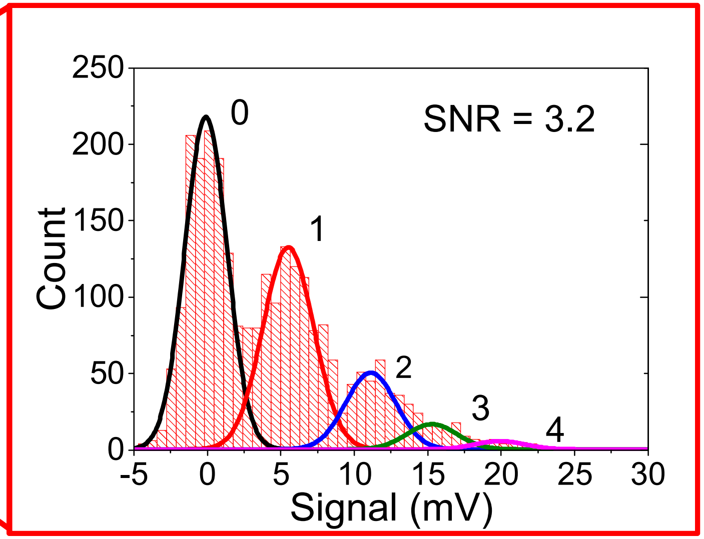
Single Ion Diamond Detectors

IBIC Map



Optimizing gain for single ion detection

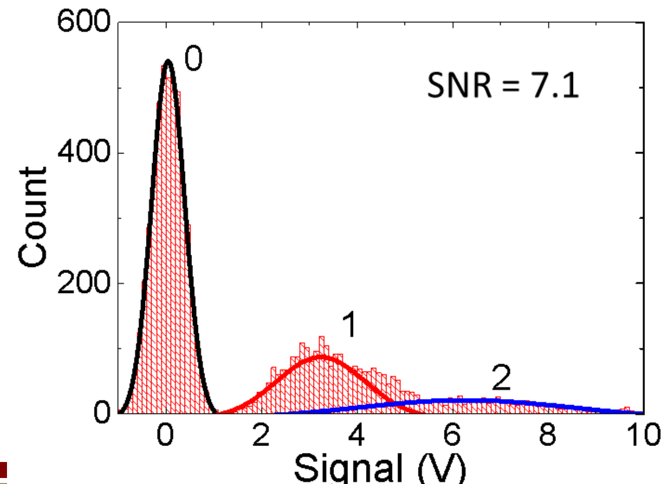
Quantized Detection <0.65> ion



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

Signal amplitudes match Poisson statistics to 4%

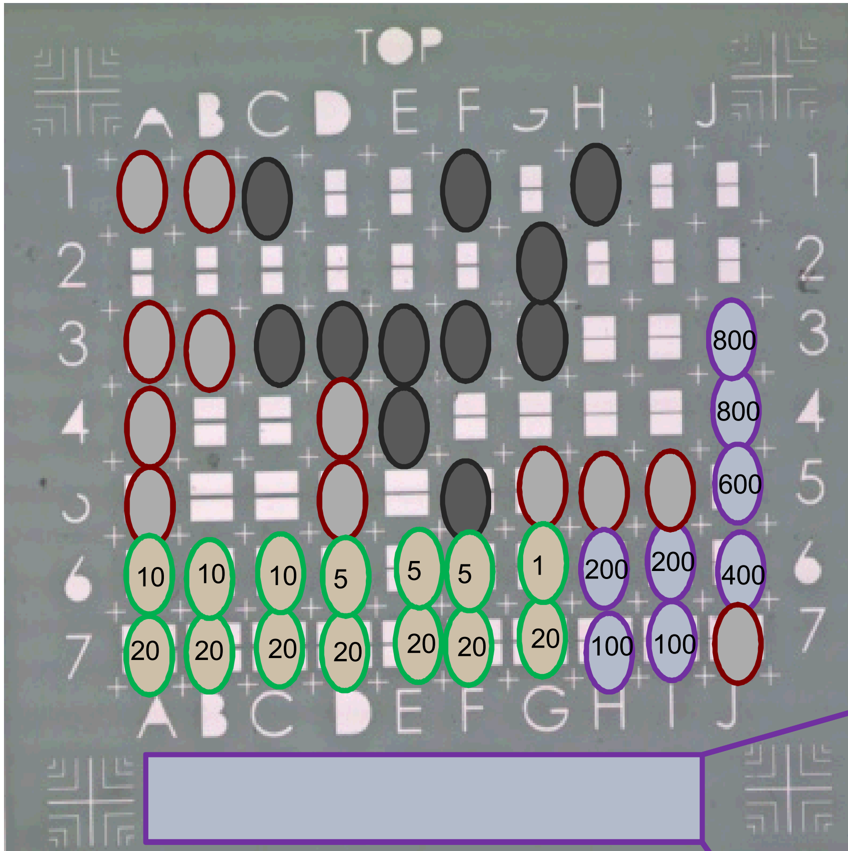
Single Ion Counting <0.2> ion



Single Ion Detection in Diamond with SNR ~10

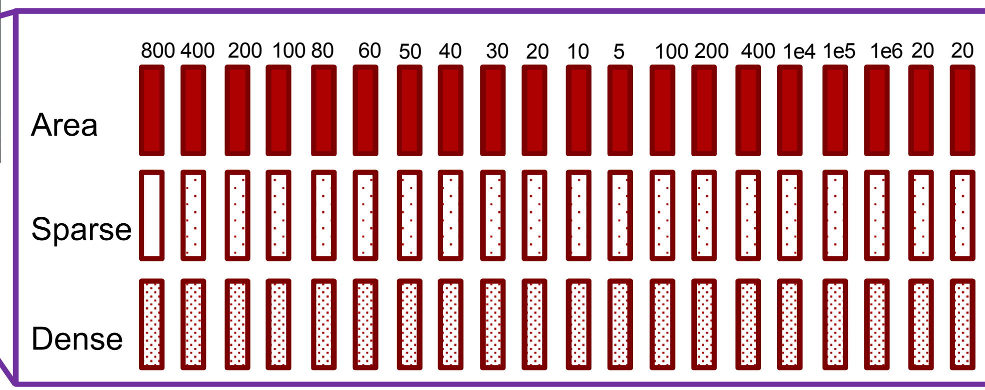
Timed and Counted SiV Arrays

Sandia National Laboratories



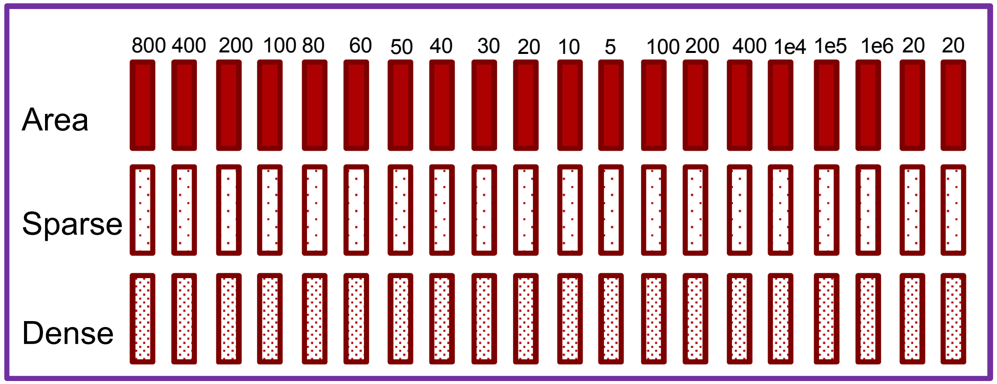
Legend:

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

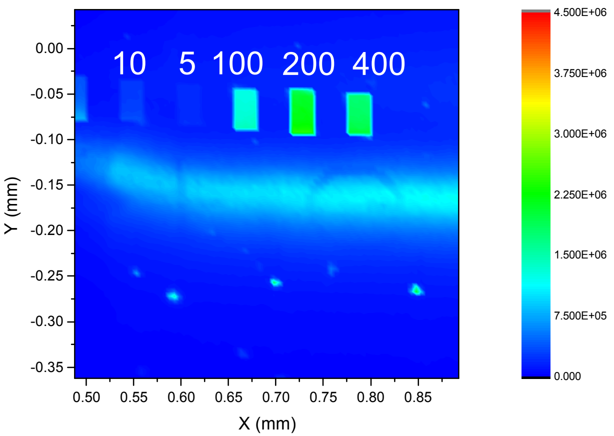


is <average> number of either timed or counted ions

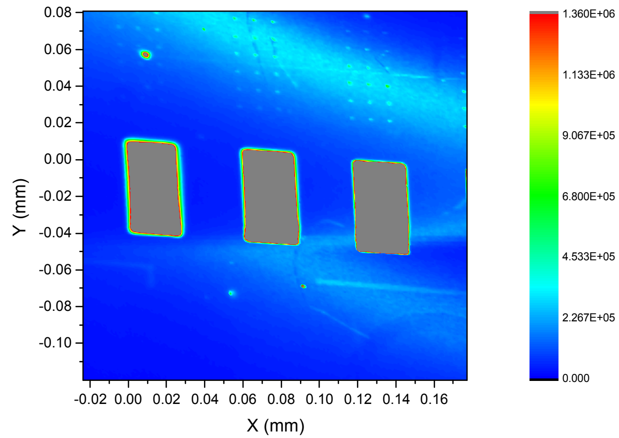
Timed SiV Arrays



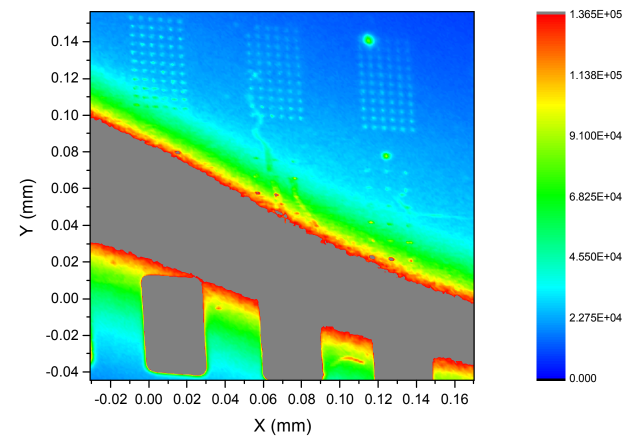
Area

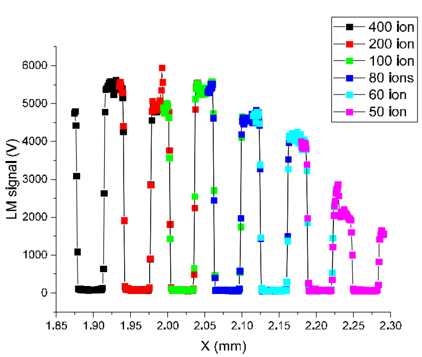


Sparse Array



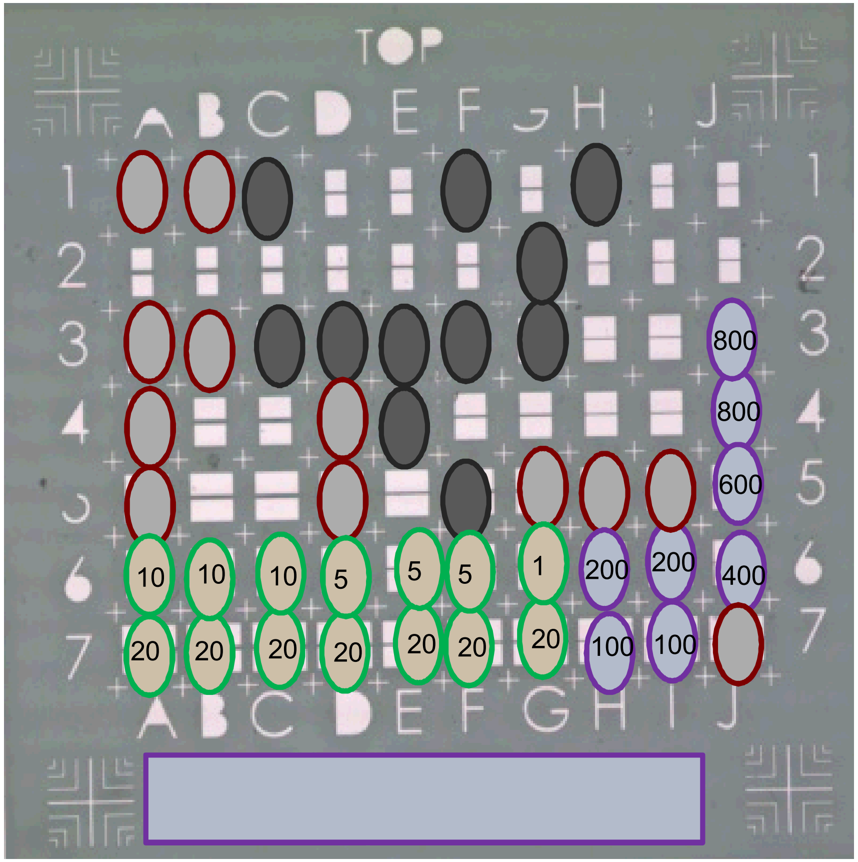
Dense Array





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

Counted SiV Arrays



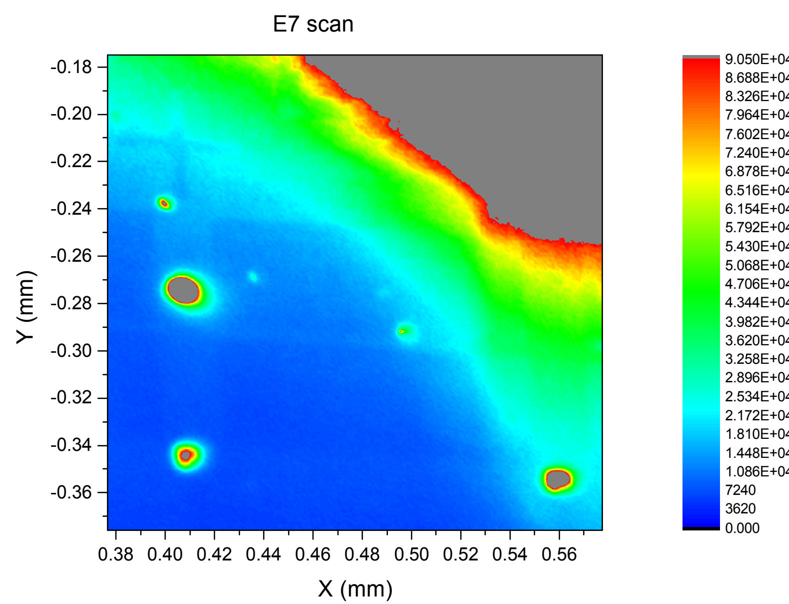
Legend:

Device Characterization

Counted Implants

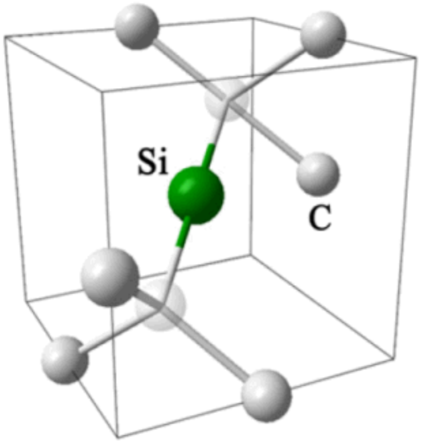
Timed Implants

Questionable Devices



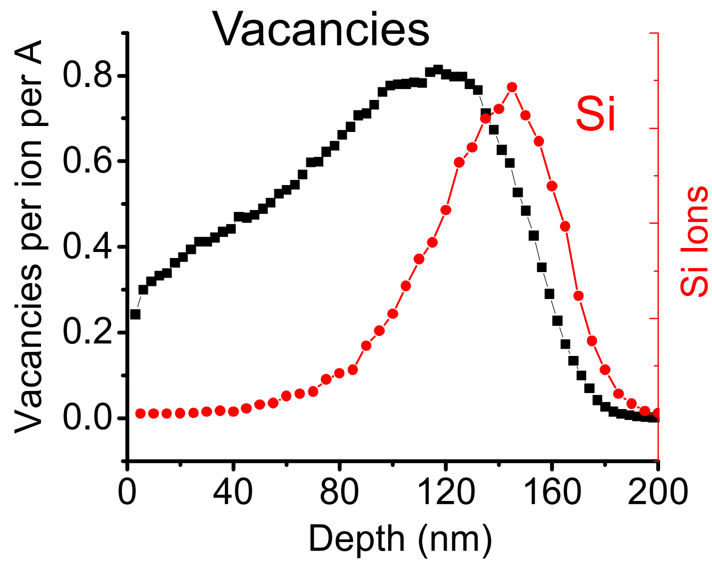
Do not observe any SiV in the detector regions of either timed or counted configurations

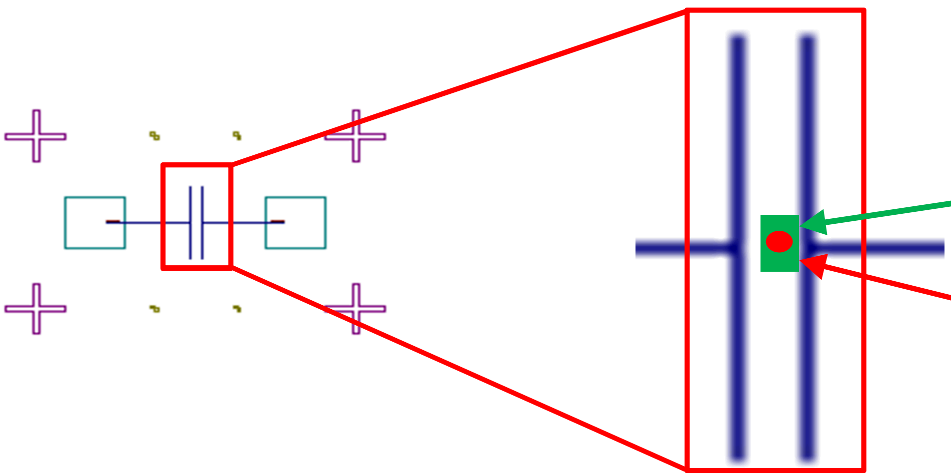
Yield Improvement - Sequential Implantation



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

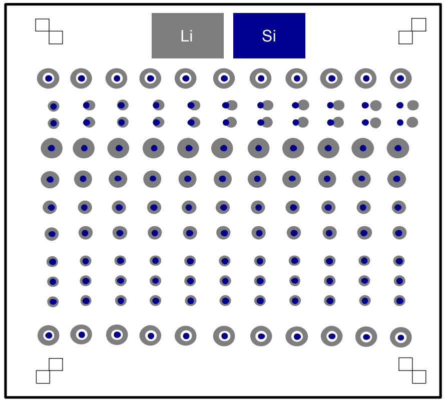
4.) Implant 200 keV Si spots

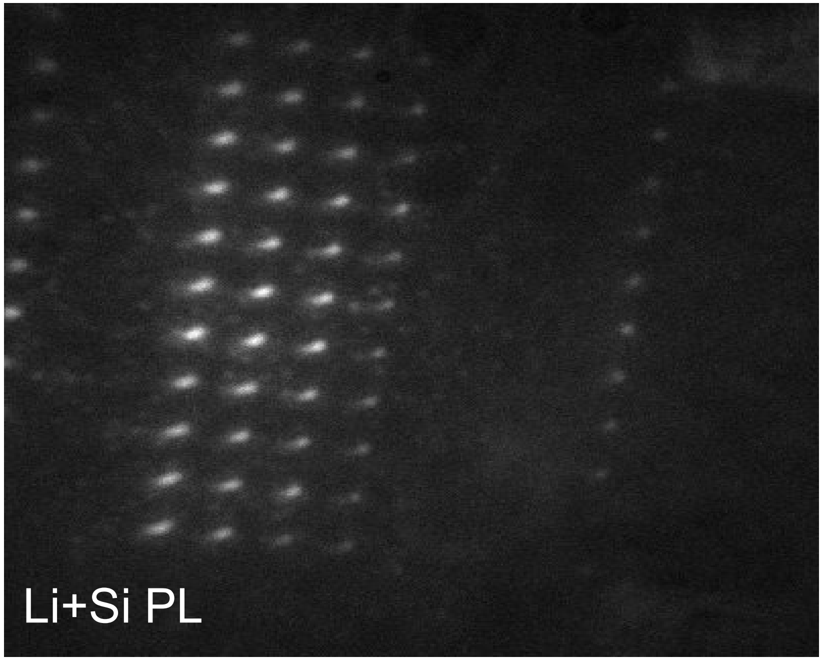
Alignment with <20 nm resolution

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

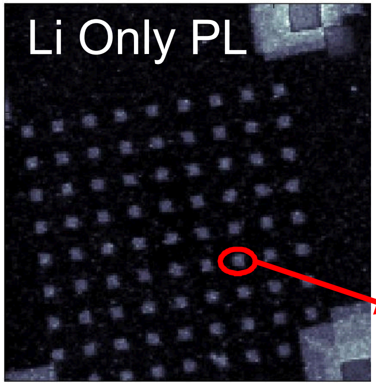
Sequential Implantation Experiment

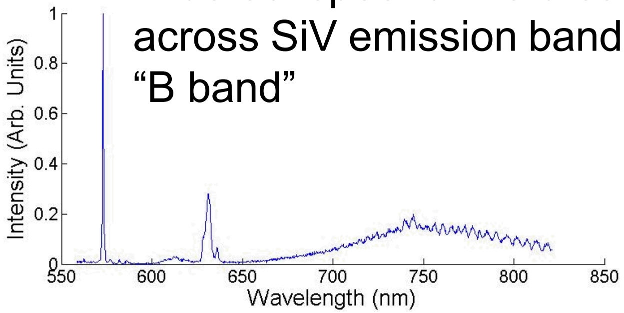
Implant Li to create vacancies, then Si → SiV





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

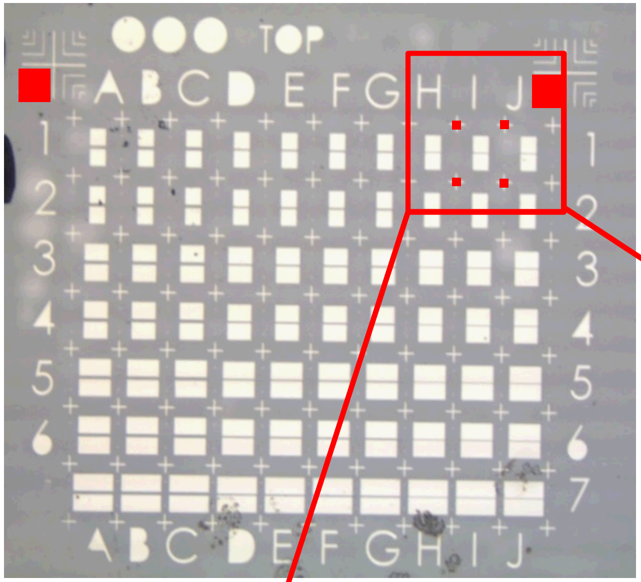
→ First samples made and annealed, measurement on-going

Sequential Implantation Experiment #2

Order of implants
- 1.2 MeV C
- 2 MeV Si

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

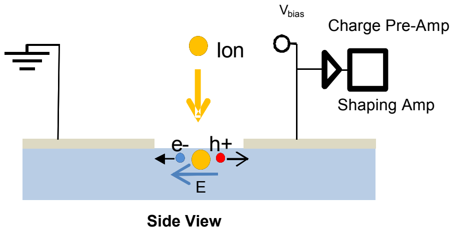
2 MeV Si
874+/-60 nm
977 vac/ion



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

Conclusions

+



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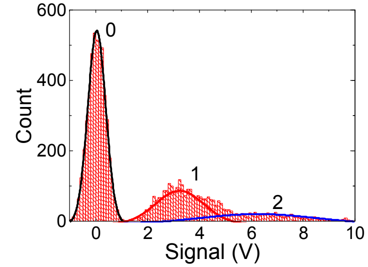
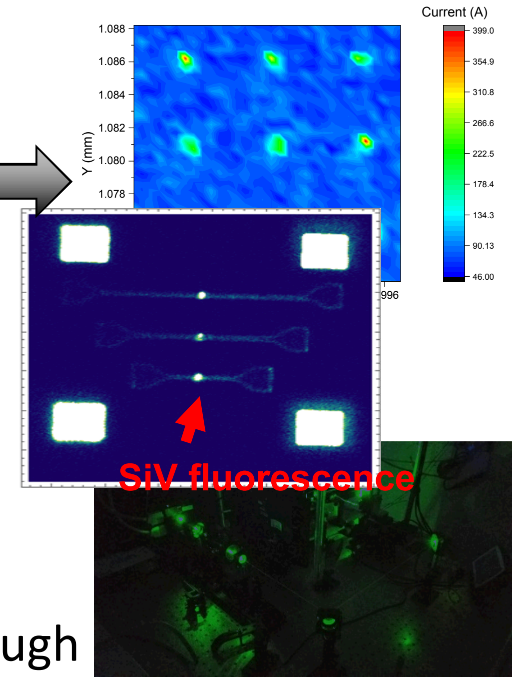




How to produce a ***single*** color center ***where*** you want it?

1.) Location → solved using focused ion implantation

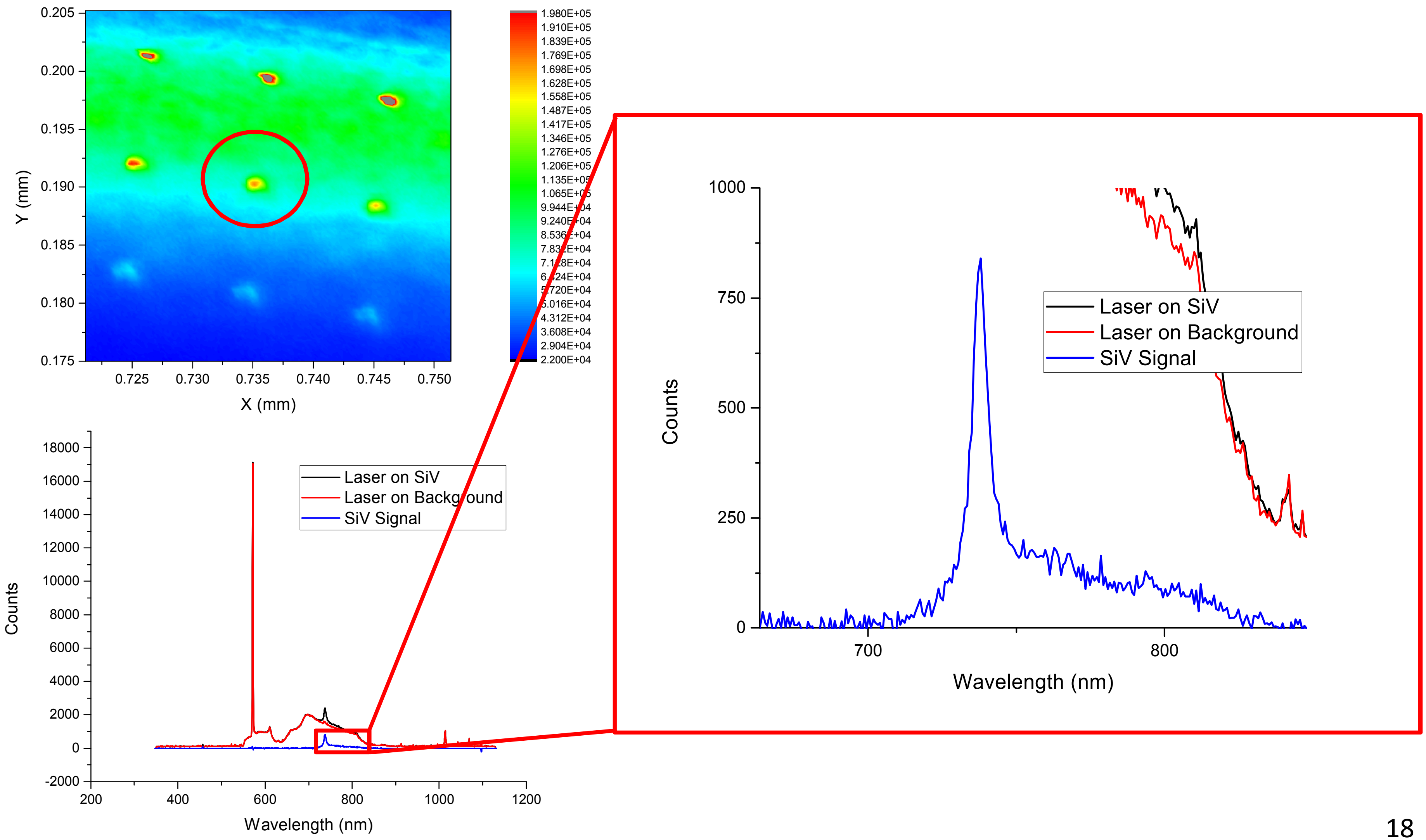
2.) Yield → on-going effort to understand yield issues through

Counted implantation demonstration

Sequential implantation with C/Si measurement on-going

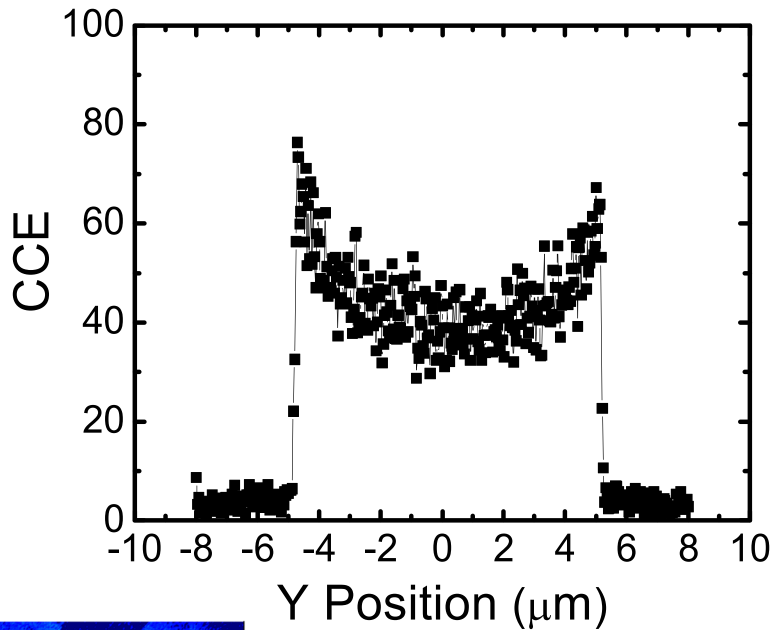
SiV Spectrum

<30> Dense Array

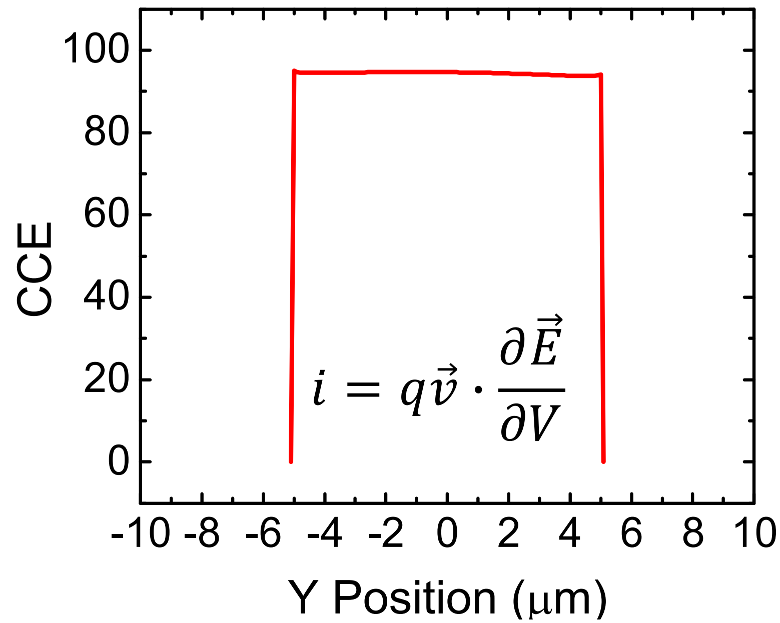


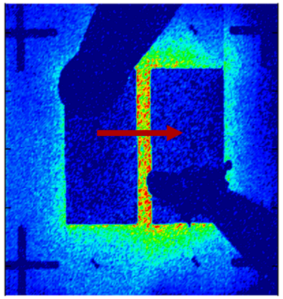
Experimental IBIC vs. Simulation

Experimental IBIC Dataset



Simulation – No damage





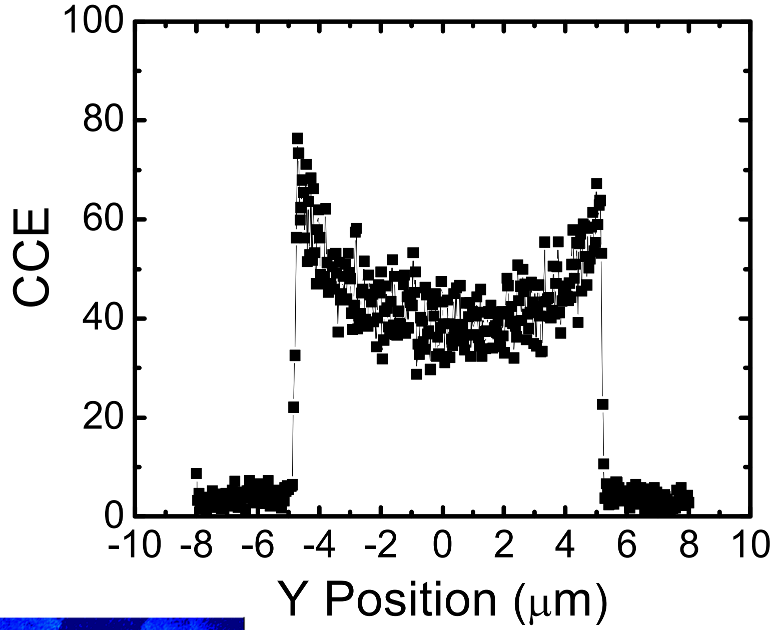
Experimental curve ≠ predicted curve

→ Shape is incorrect

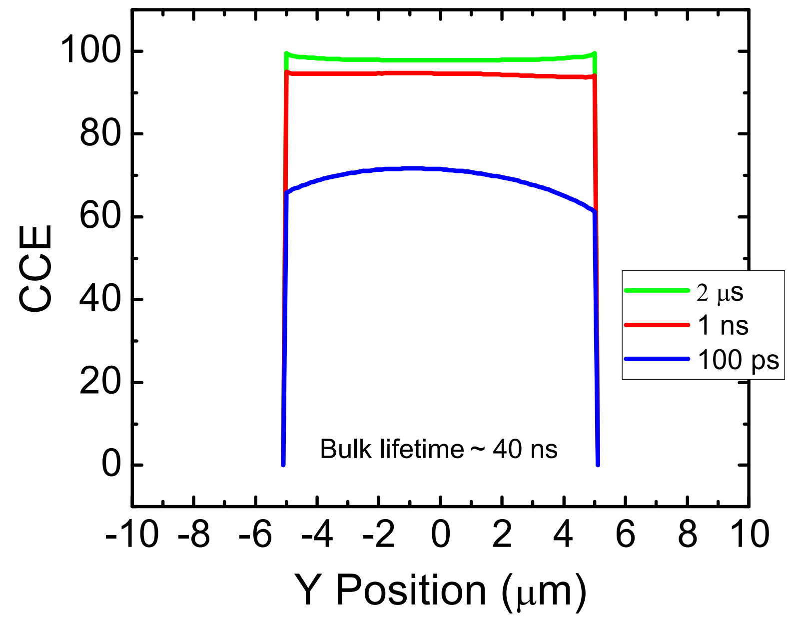
How to account for these differences? Reduce Bulk Lifetime

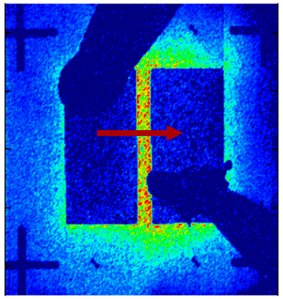
Reducing the Bulk Lifetime

Experimental IBIC Dataset



Simulation Changing Bulk Lifetime





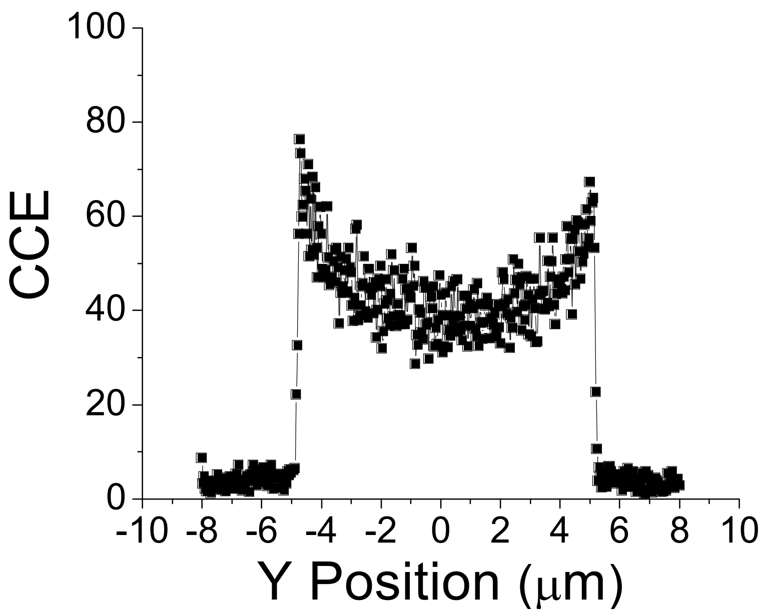
Experimental curve ≠ predicted curve

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

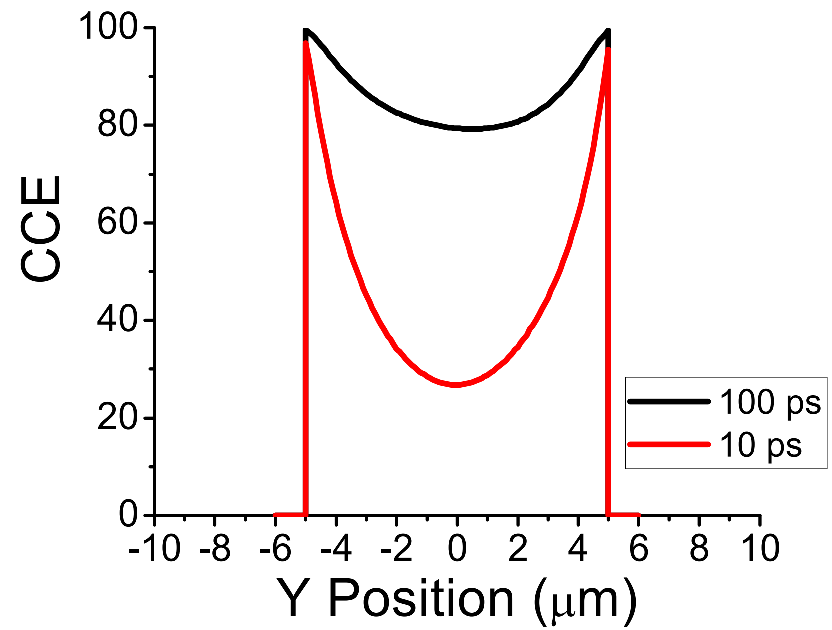
How to account for these differences? Lifetime vs Depth

Depth Dependent Lifetime

Experimental IBIC Dataset

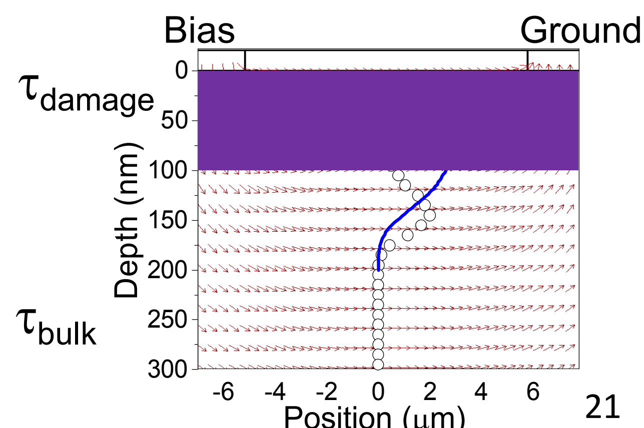


Simulation with Damage



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

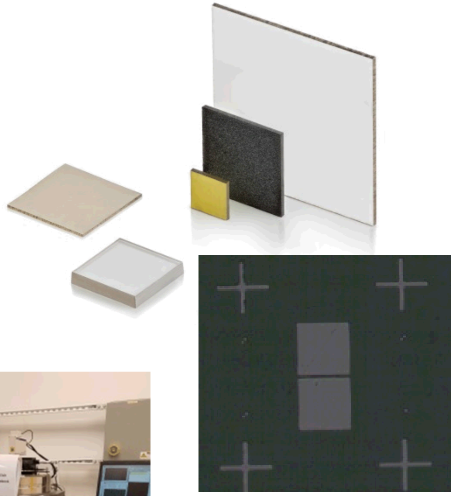
Detectors probe sub-surface damage



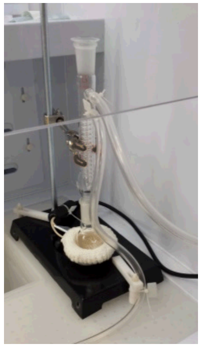
Abraham *et al*, APL **109**, 063502 (2016)

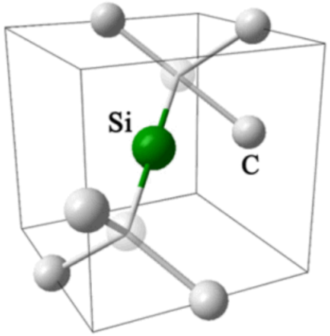
How do we fabricate the SiV Centers?

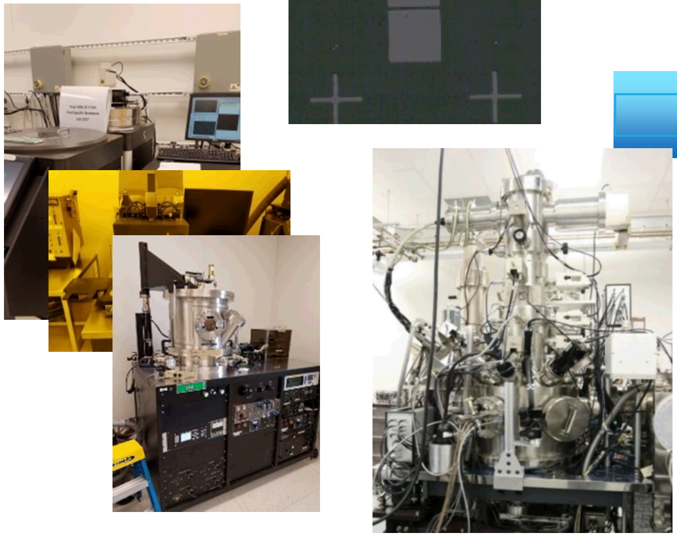
Electronic Grade Diamond Substrates



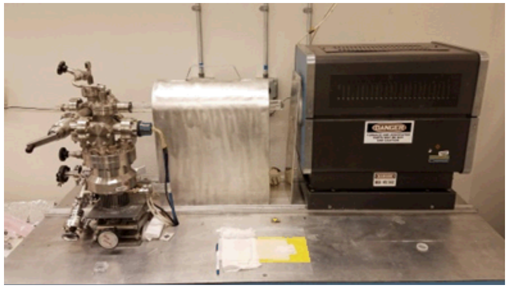
Surface Clean/Oxygen Termination





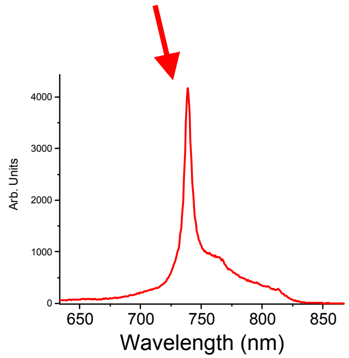


CINT fab to prepare the samples, Si ion implantation at IBL



Vacuum anneal to create SiV centers

PL from SiV^{-}



m-PL from focused ion implanted SiV centers

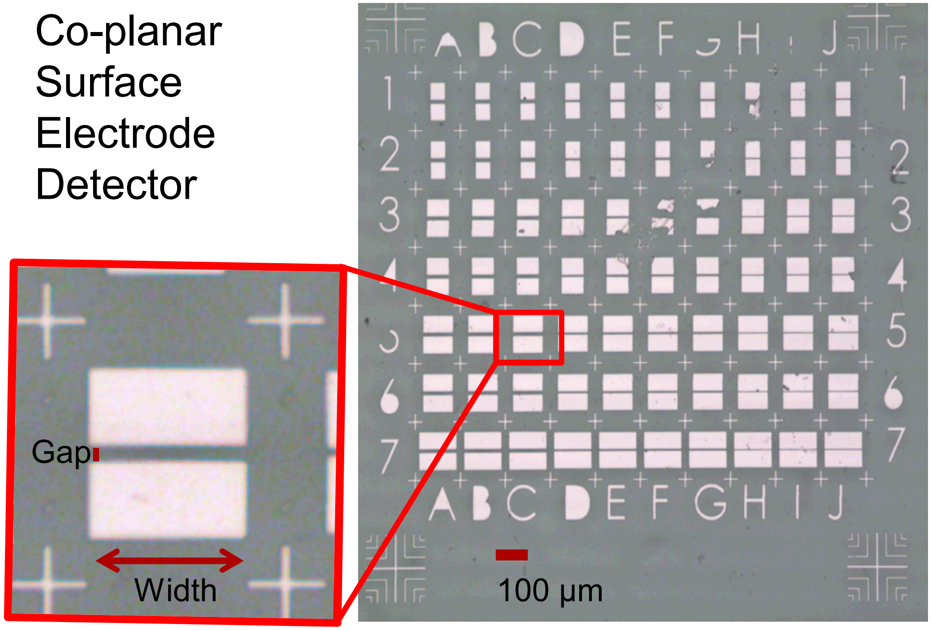
All New Capability Developed at the CINT User Facility

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

Fabrication

Sandia National Laboratories

Co-planar Surface Electrode Detector

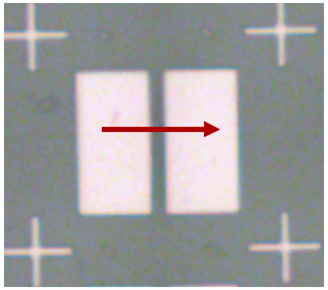


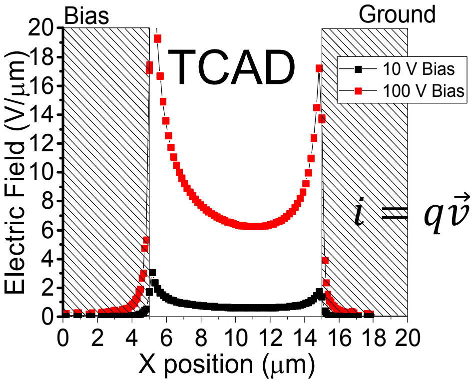
- Electronic grade single crystal diamond (Element 6)
- 200 nm Ti/Pt/Au Electrodes
- Varied width and gap spacing
  - 50-125 um width
  - 2 – 10 um gaps

Process

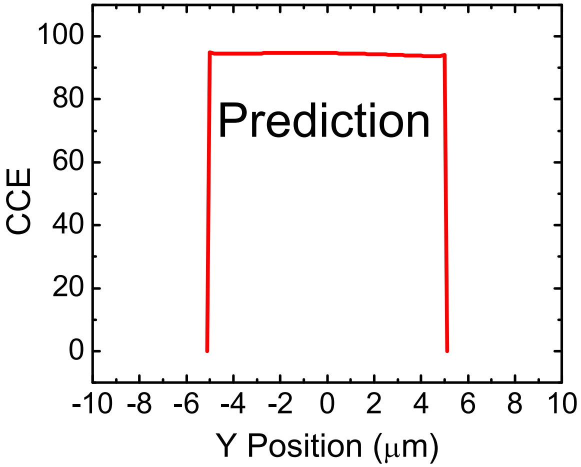
1. RIE Ar/Cl2:O2
2. Piranha Clean (20 min)
3. Dehydration bake 180C (5 min)
4. Mount Sample on 1 um Oxide Si wafer with PMMA
5. Bake 180C (1 min)
6. Spin HMDS (4K, 30 sec)
7. Bake 90C (90sec)
8. Spin AZ5214EZ (4K, 30 sec)
9. Bake 90C (90 sec)
10. MA6 Aligner (Hard Contact, 5 sec exposure)
11. AZ400K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

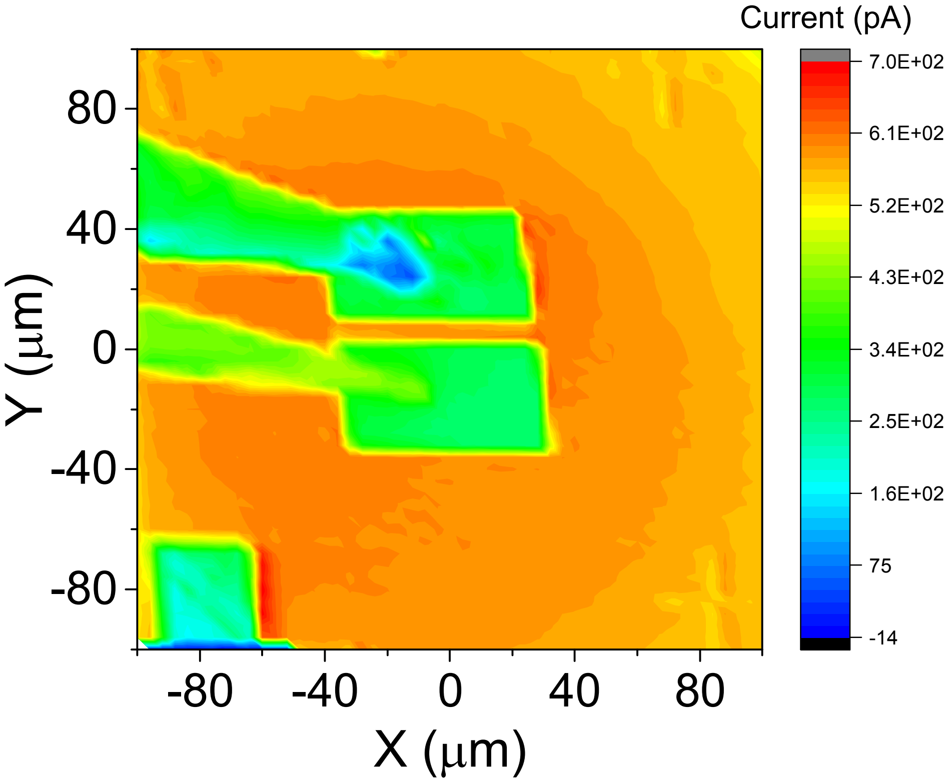




$$i = q\vec{v} \cdot \frac{\partial \vec{E}}{\partial V}$$



Electron Beam Induced Current (EBIC)



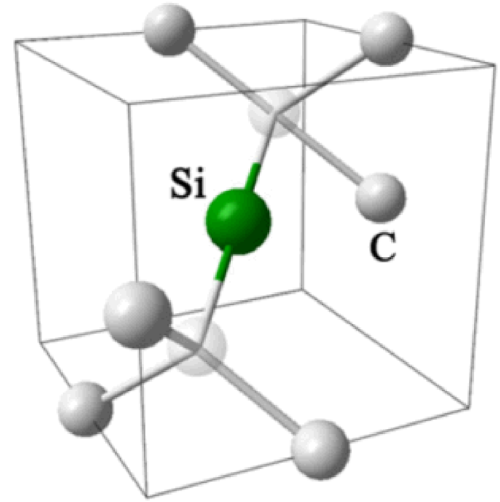
EBIC datasets match the predicted response

What are Color Centers in Diamond?

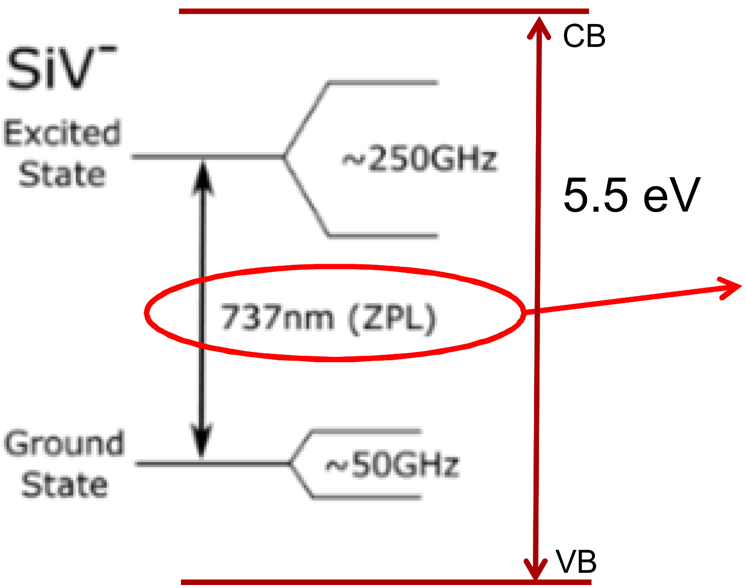
- Range of defect complexes – such as NV, SiV

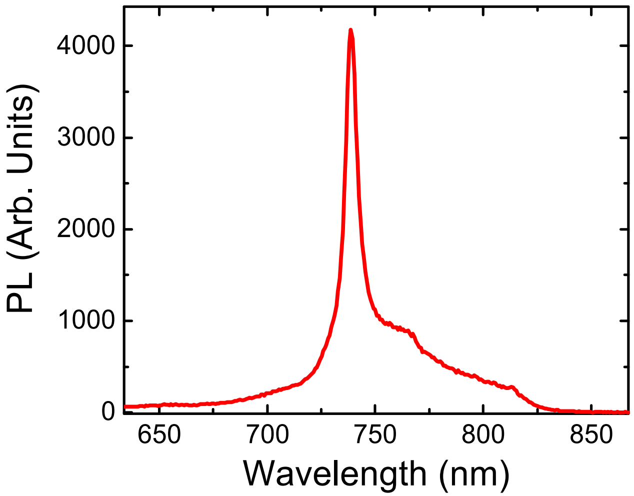
- Diamond substrate with 5.5 eV band gap – allows RT operation of the defect centers

SiV



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

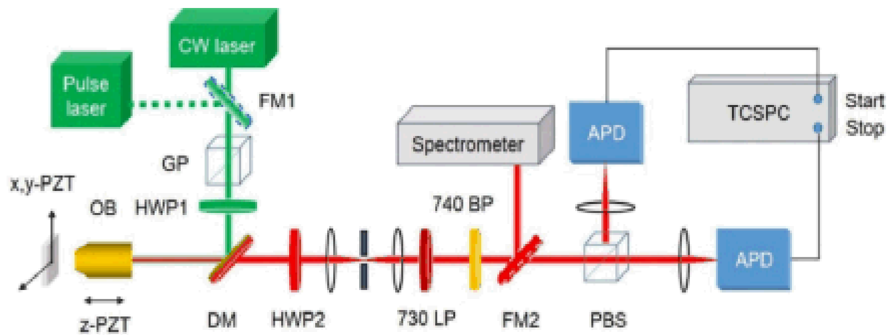


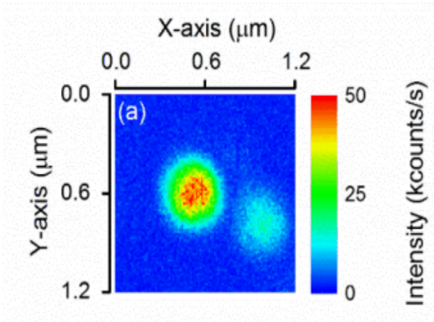


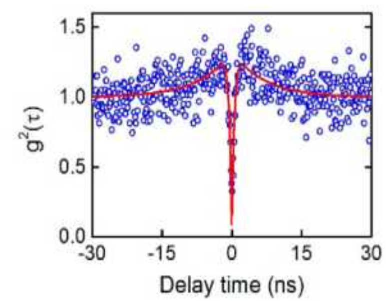
Defect centers act as “Artificial Atoms”

Applications for Color Centers in Diamond

SiV Single Photon Source

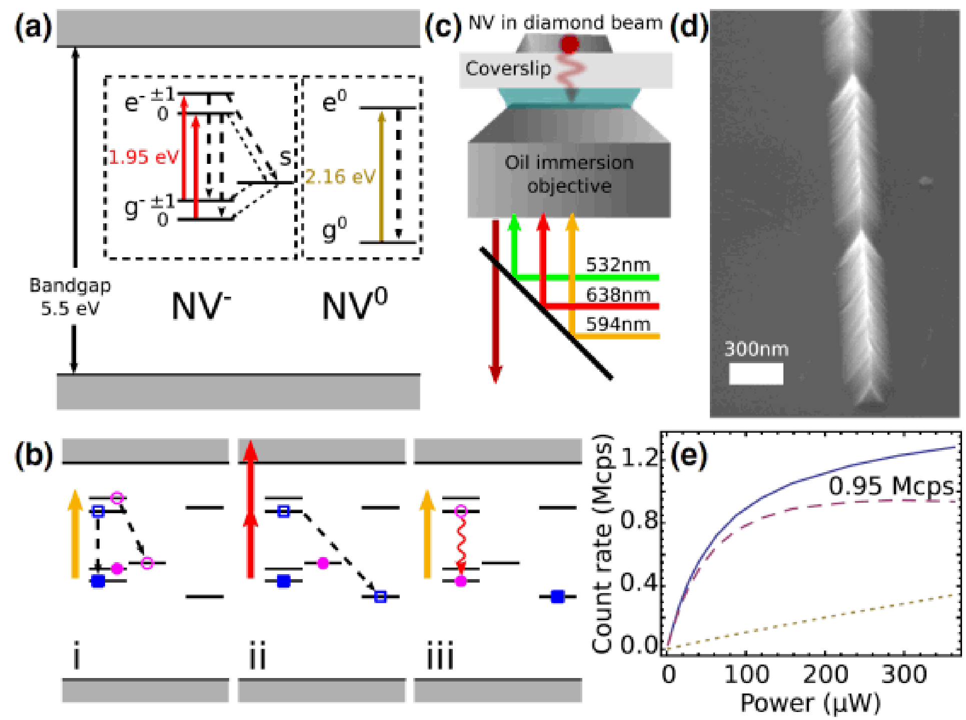






Y. Liu *et al.*, Opt. Express **23**, 032961 (2015)

Readout of single NV spin



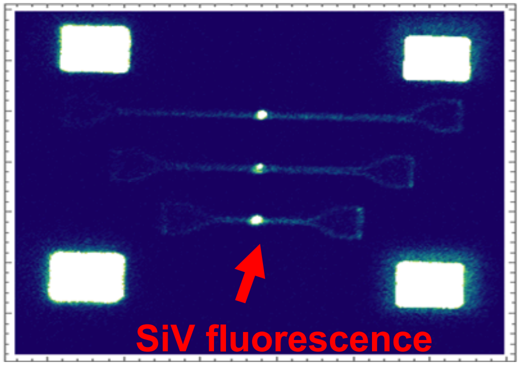
B. J. Shields *et al.*, PRL **114**,136402 (2015)

“Artificial Atoms” in Diamond at Ambient Conditions!

What is the Problem?

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

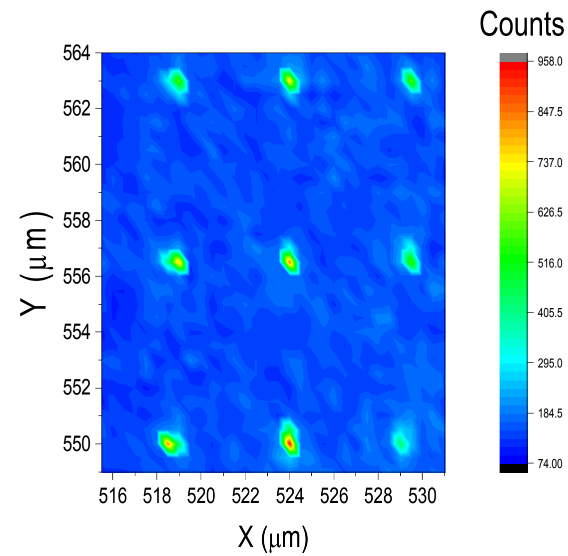
1.) Location:



- Need to demonstrate spatial control for device integration

  Cavity applications need <100 nm

2.) Yield:



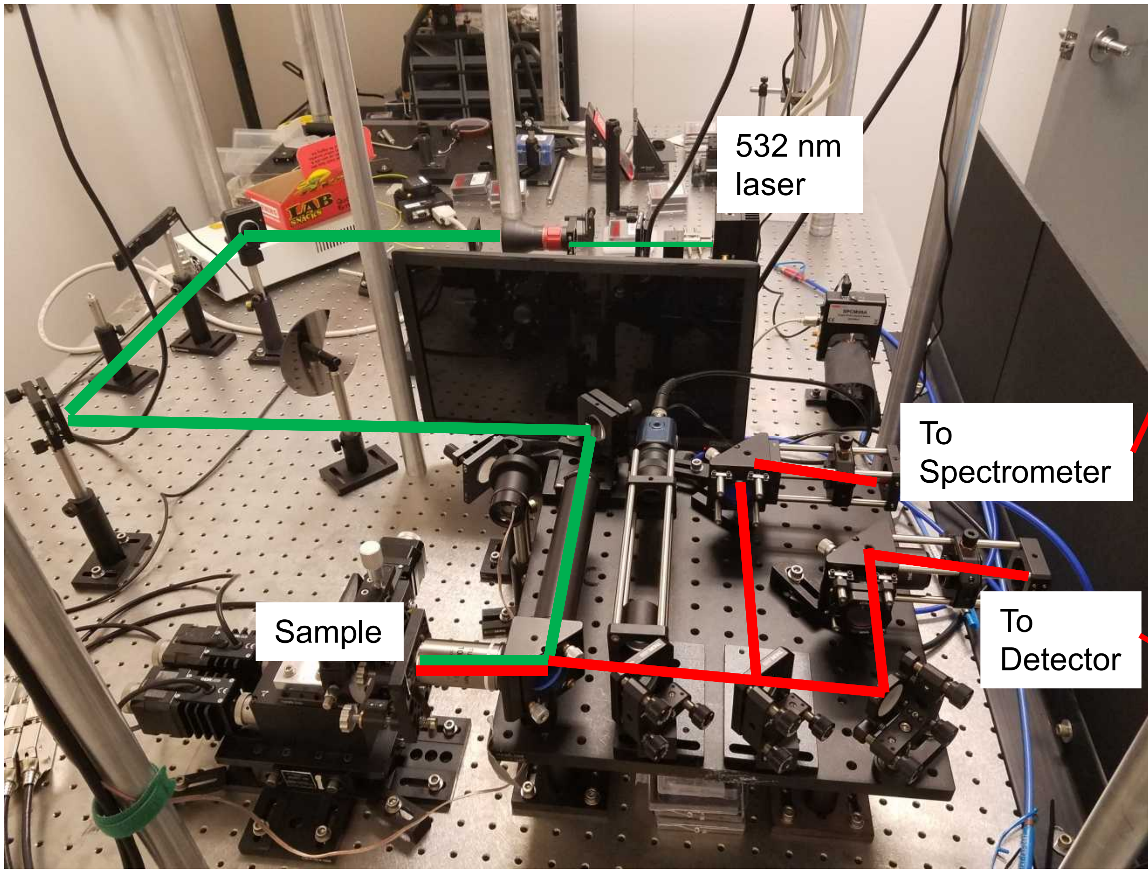
- Low color center yield will limit device yield

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

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

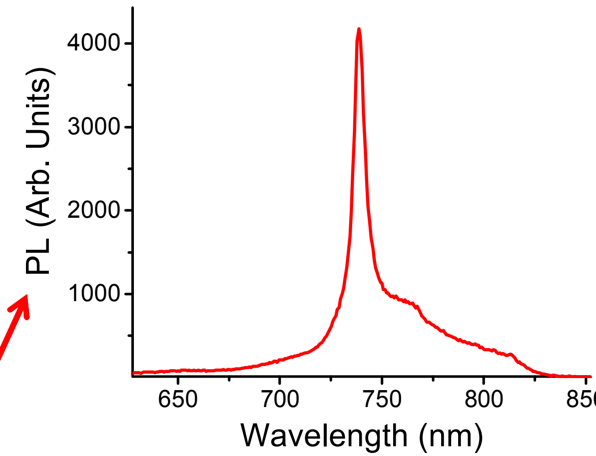
Characterization – Photoluminescence of SiV^-

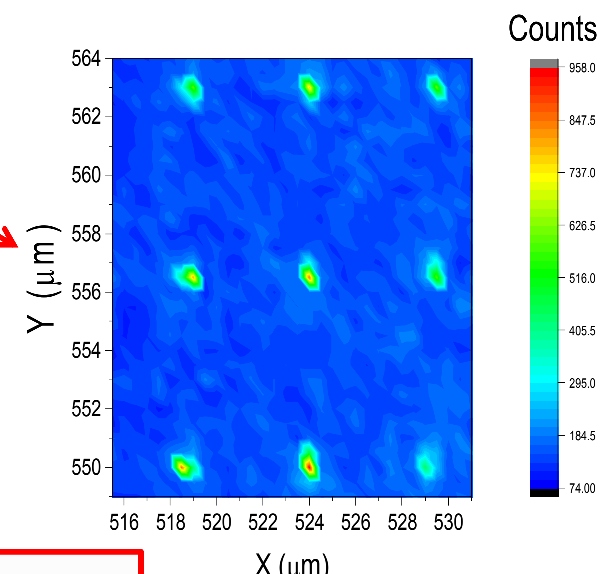
Sample scanning confocal microscope



pump

emission

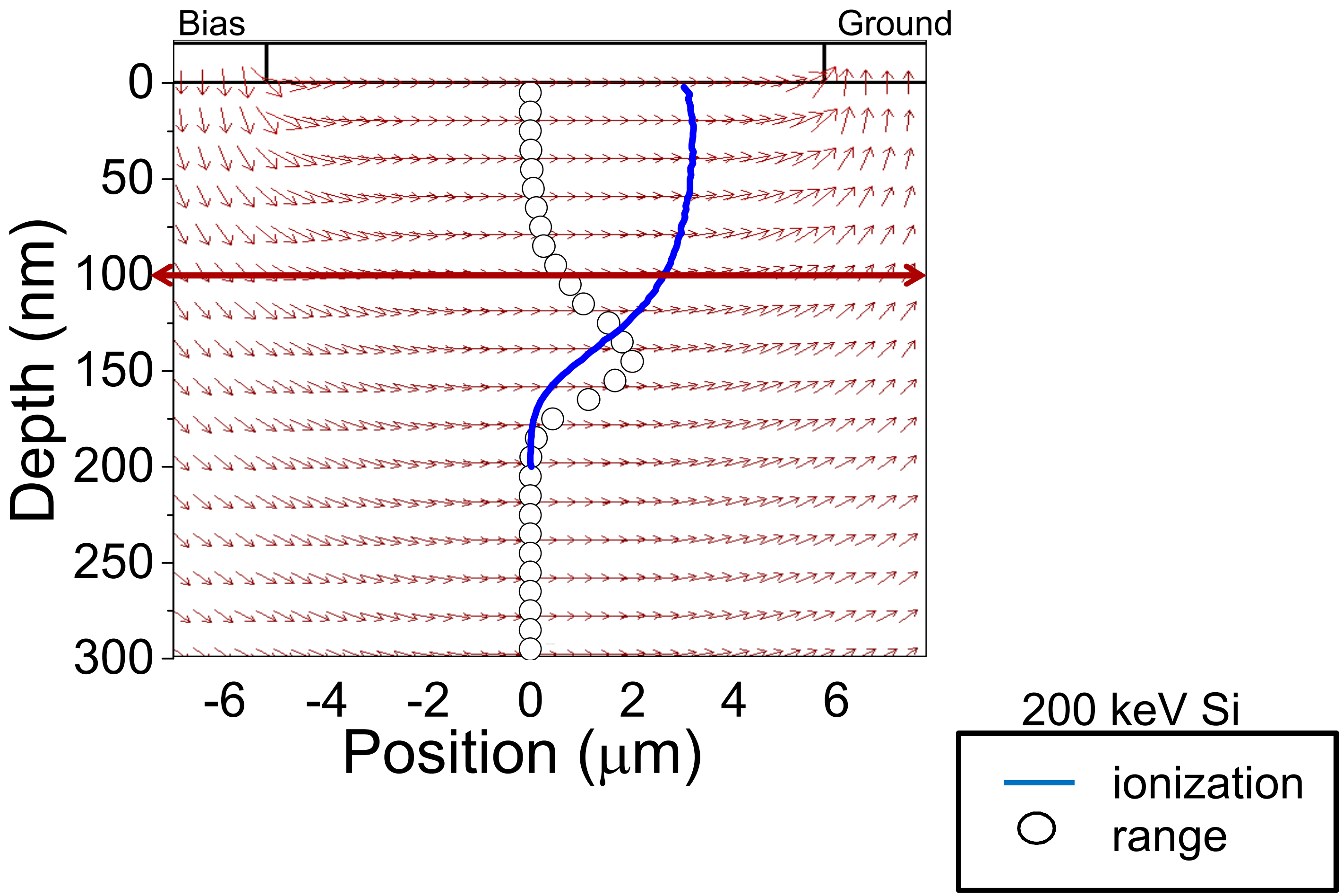




Spatially Resolved PL Map of SiV Centers

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

TCAD/SRIM Modeling of the Detectors



Detectors are optimized for sub-surface detection

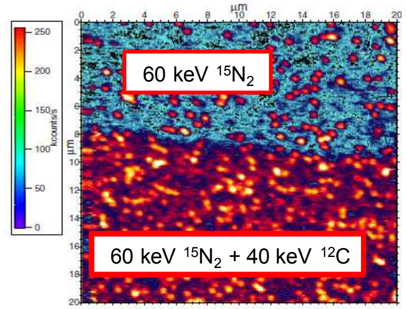
Current Understanding of Yield

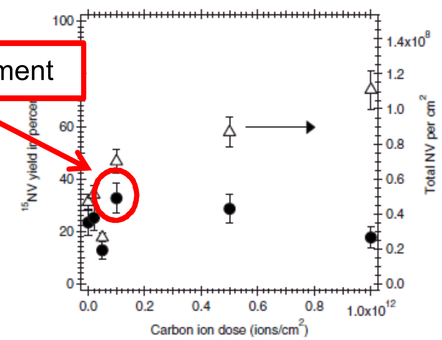
$$Yield = \frac{\#Color\ centers\ observed}{\#\ impurities\ implanted}(\underbrace{\#vacancies, anneal\ parameters}_{\text{Forming the Center}}, charge\ state)$$

Occupation of the center

Co-Implantation:

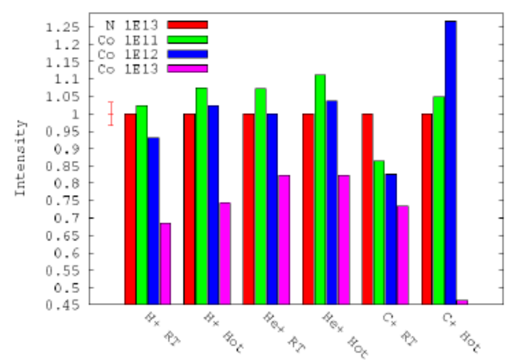
Naydenov et al. Appl. Phys. Lett. 96, 163108 (2010)





Anneal Parameters:

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

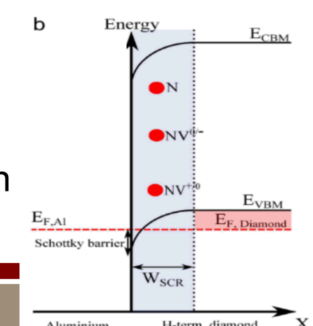


25% improvement with combined elevated temperature + C implant

Charge State:

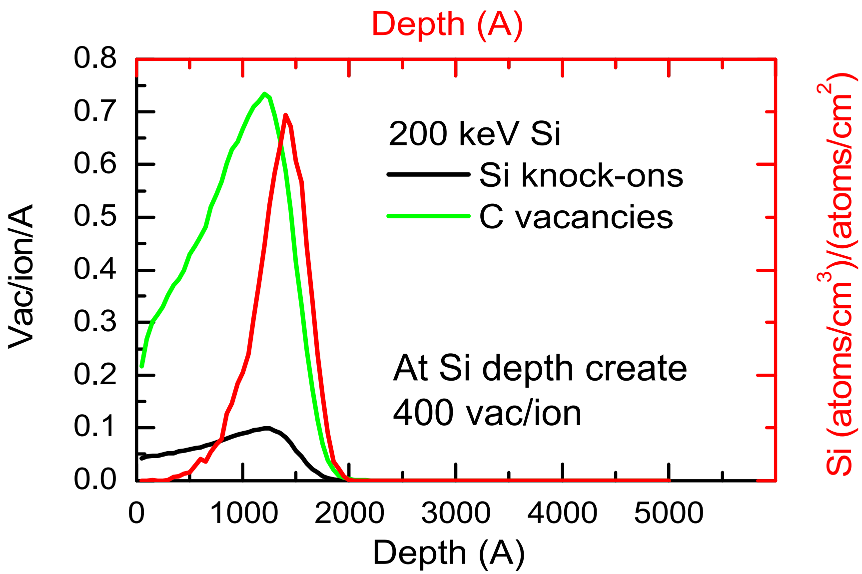
Schreyvogel, C. et al., Sci. Rep. 5, 12160 (2015)

Tuning the occupation of states via reverse bias

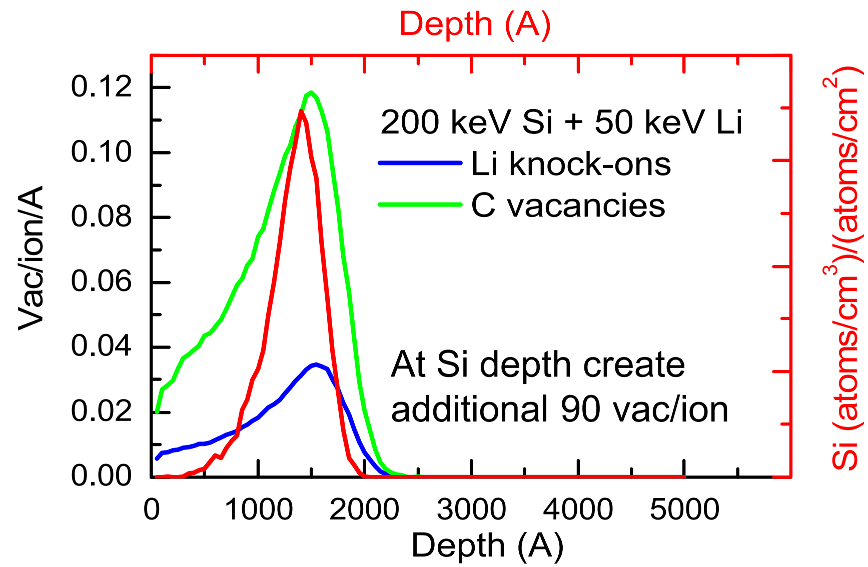


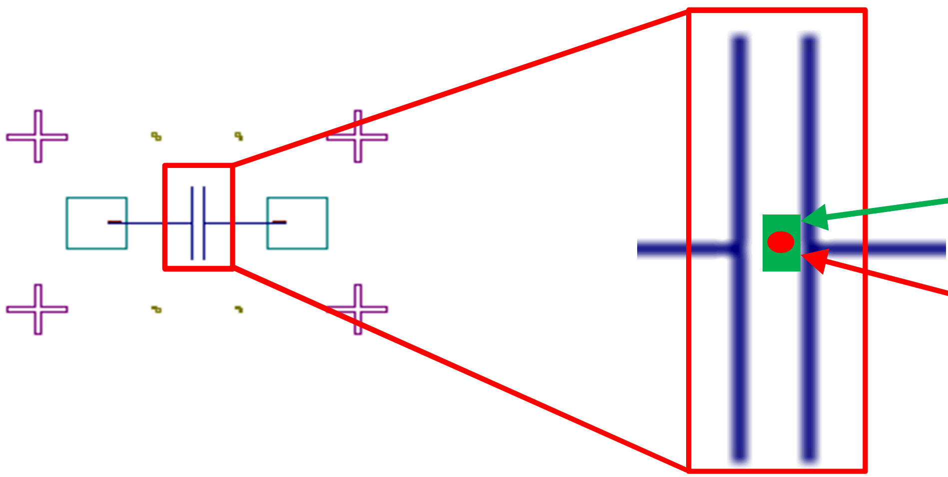
Yield Improvement – Introduce Excess Vacancies

200 keV Si



200 keV Si + 50 keV Li





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

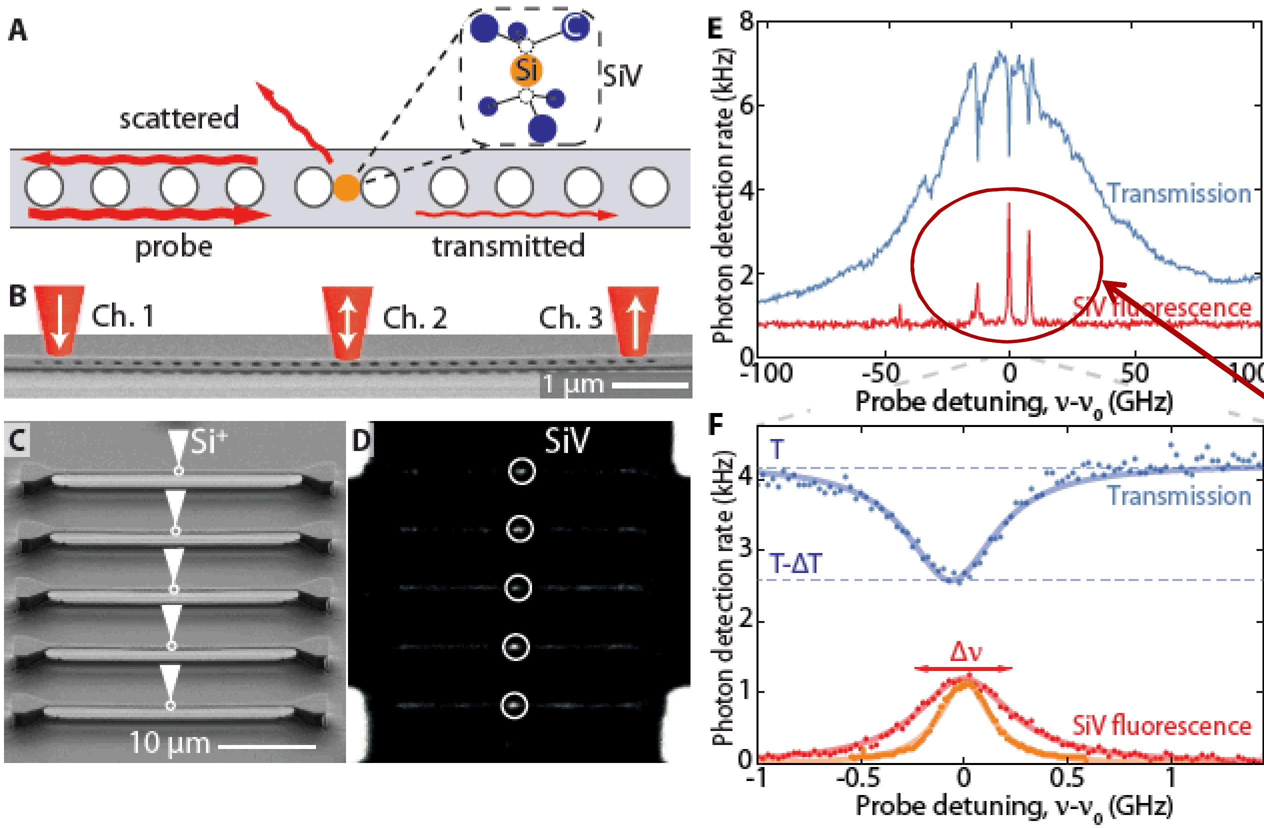
Use the direct write capability of the nI to introduce excess C vacancies at the appropriate depth relative to the Si implants

Quantum Nano-photonics

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

Sandia National Laboratories

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)