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Direct Write Nanofabrication for Quantum Computing in Silicon and Color Centers in Diamond

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Outline

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1.) Motivation: Single Atom Devices

2.) Making the devices – focused ion beam fabrication

- nanoImplanter (nI)

3.) Single Donor devices in Si for Quantum Computing

- What is needed for deterministic single donor devices
- Experimental results looking at counted donor devices

4.) SiV Color Centers in Diamond

- Outstanding issues are location and yield

5.) Limits of top-down devices – Si and Diamond

Motivation – Single Atom Devices

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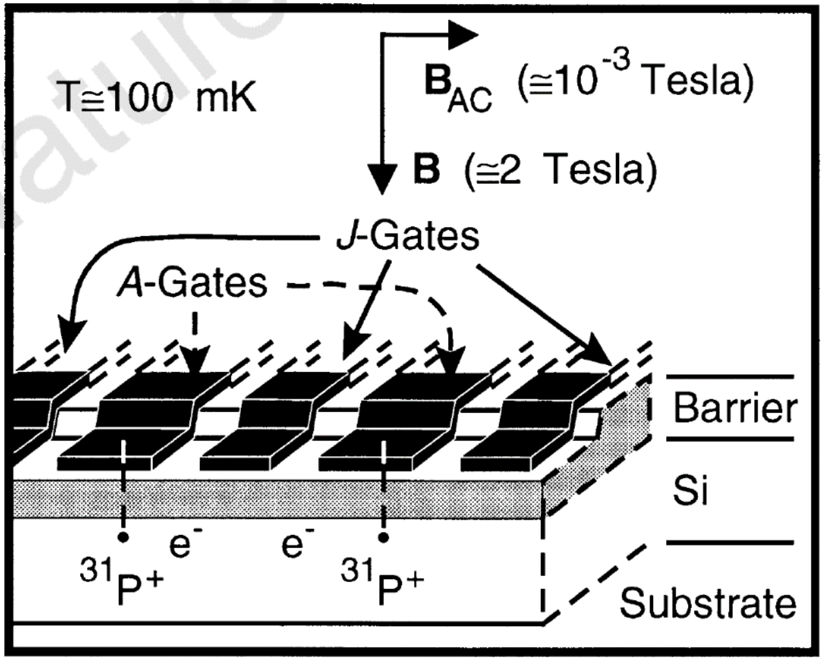
Donor in Si for Qubits

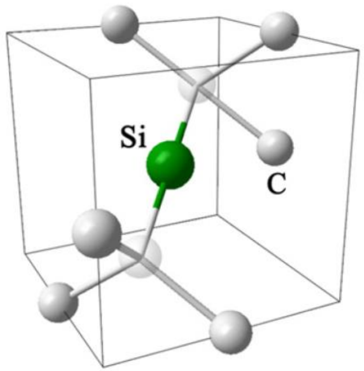


B. E. Kane, Nature **393**, 1998

- Donor qubit fabrication with a Si-MOS platform and integrated single ion detectors

Color Centers in Diamond

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

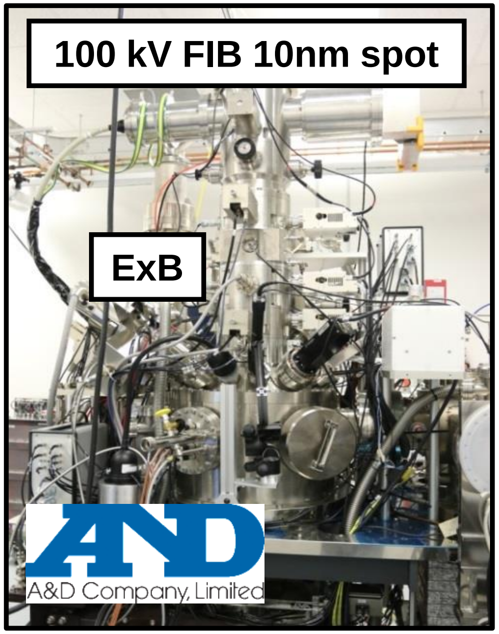


SiV in diamond

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

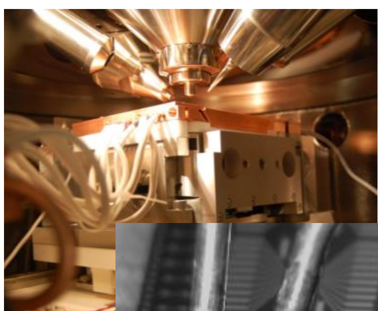
- Wide range of application from metrology to quantum computation

Fabrication – SNL nanoImplanter (nI)

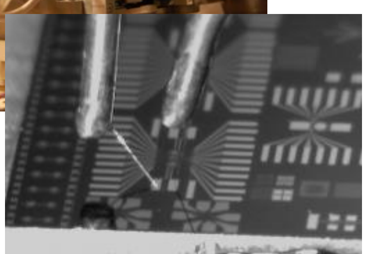


- Focused ion beam system (FIB)
  - →nm beam spot size on target
- ExB Filter (Wein Filter)
  - →Multiple ion species
    - → Li, Si, P, Sb, Bi (separates out ^{28}Si, ^{29}Si, etc…)
- Fast blanking and chopping
  - →Single ion implantation
- Direct-write lithography
  - →nm targeting accuracy

RAITH NANOFABRICATION

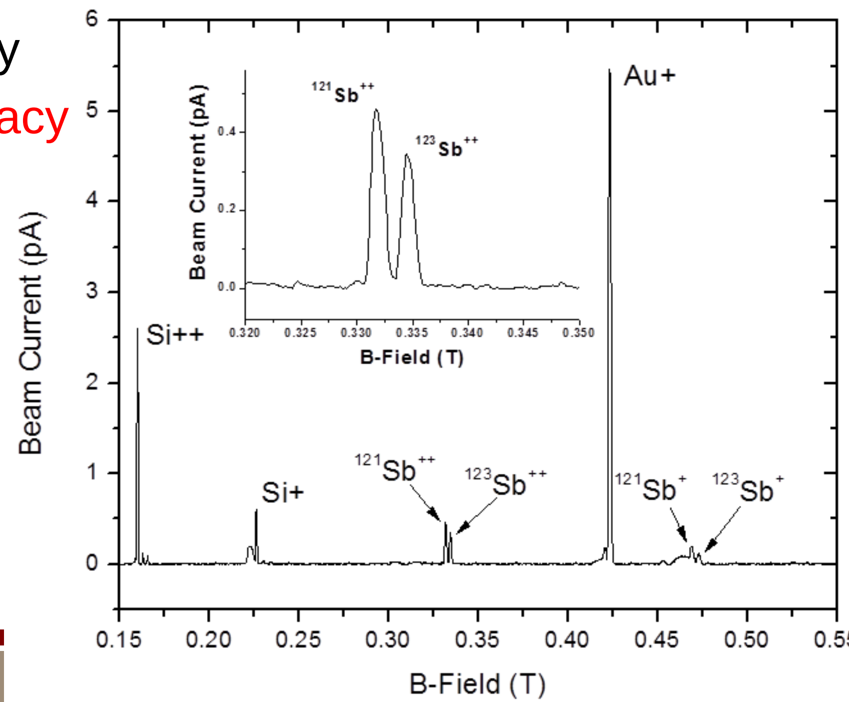


- Low temperature stage



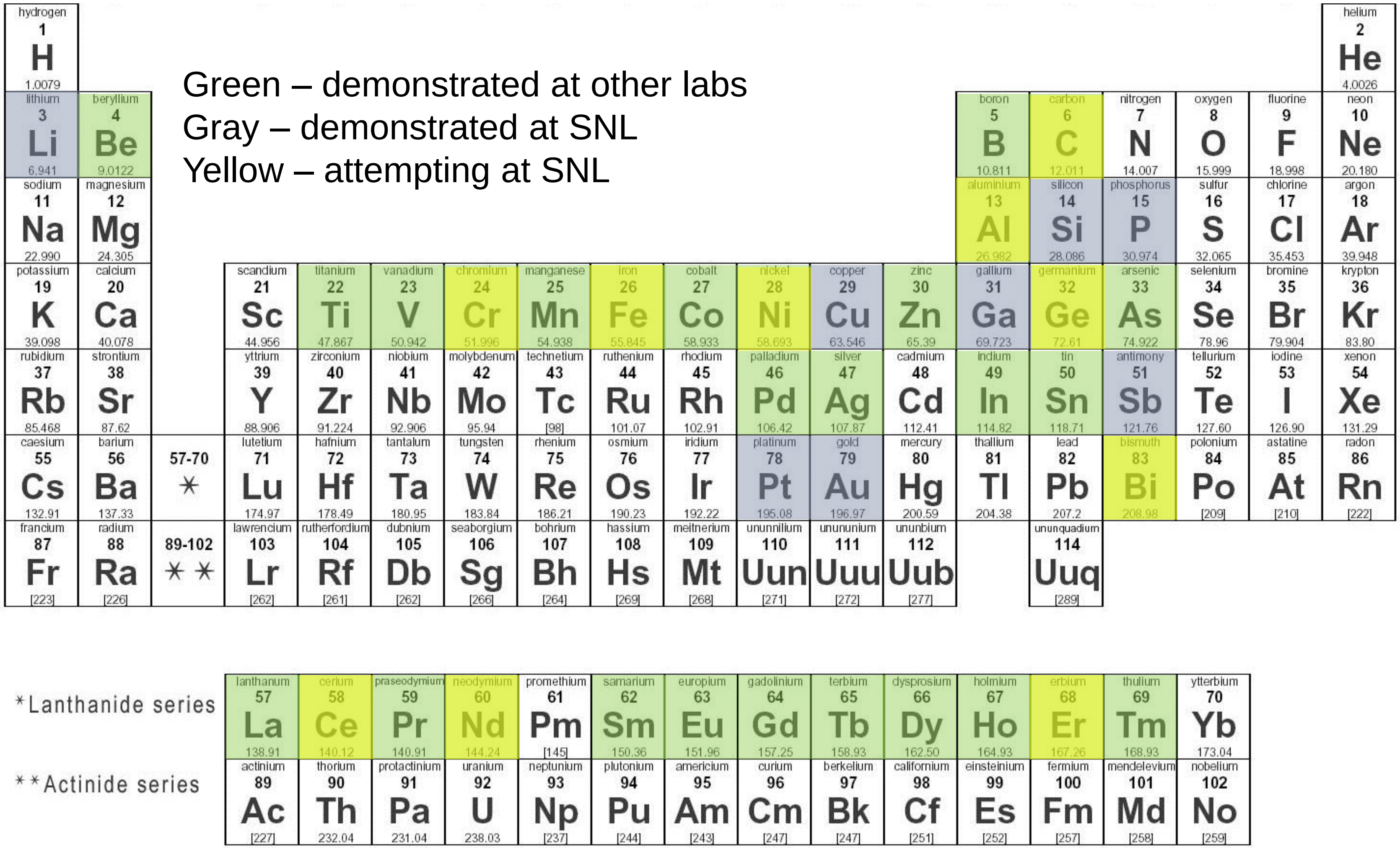
- In-situ electrical probes

Sb Source: Mass Spectrum



SNL nanoImplanter (nI) - Sources

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



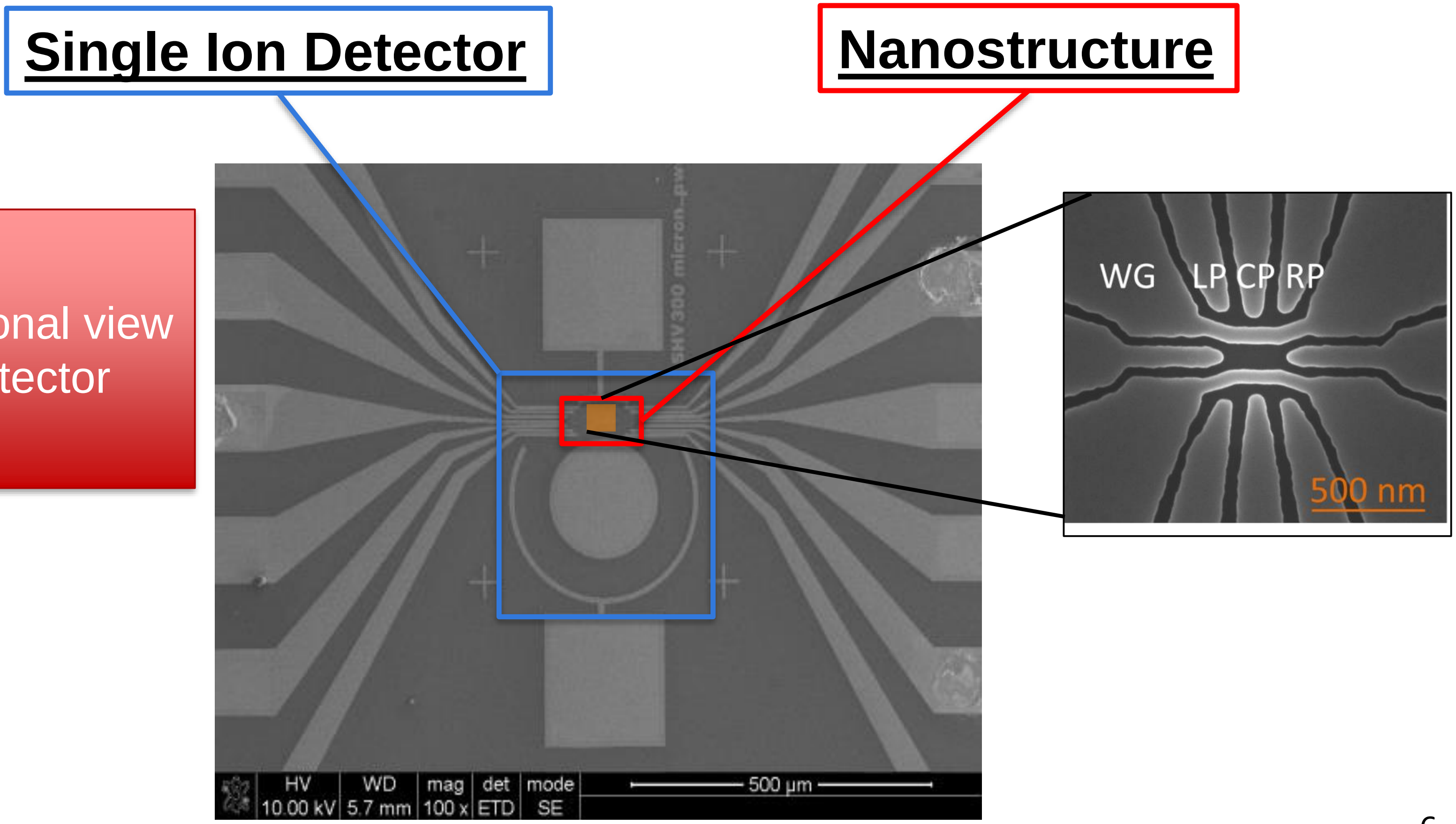
After A. Weick University of Bochum

Wide Varity of Ion Species Available

Single Donor Devices for Quantum Computing

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

Cross-sectional view of the detector



Combined Single Ion Detector and Nanostructures Demonstrated

Integrated Single Ion Detectors

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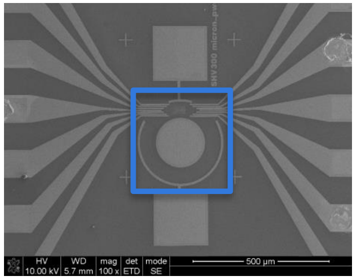
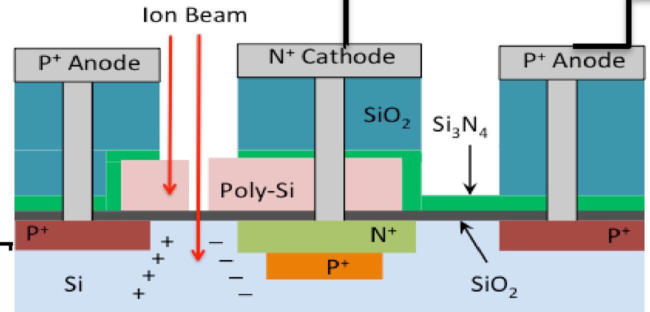
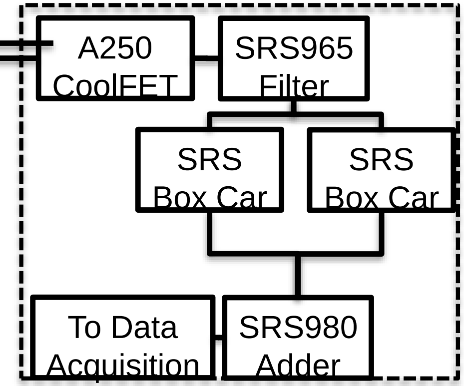
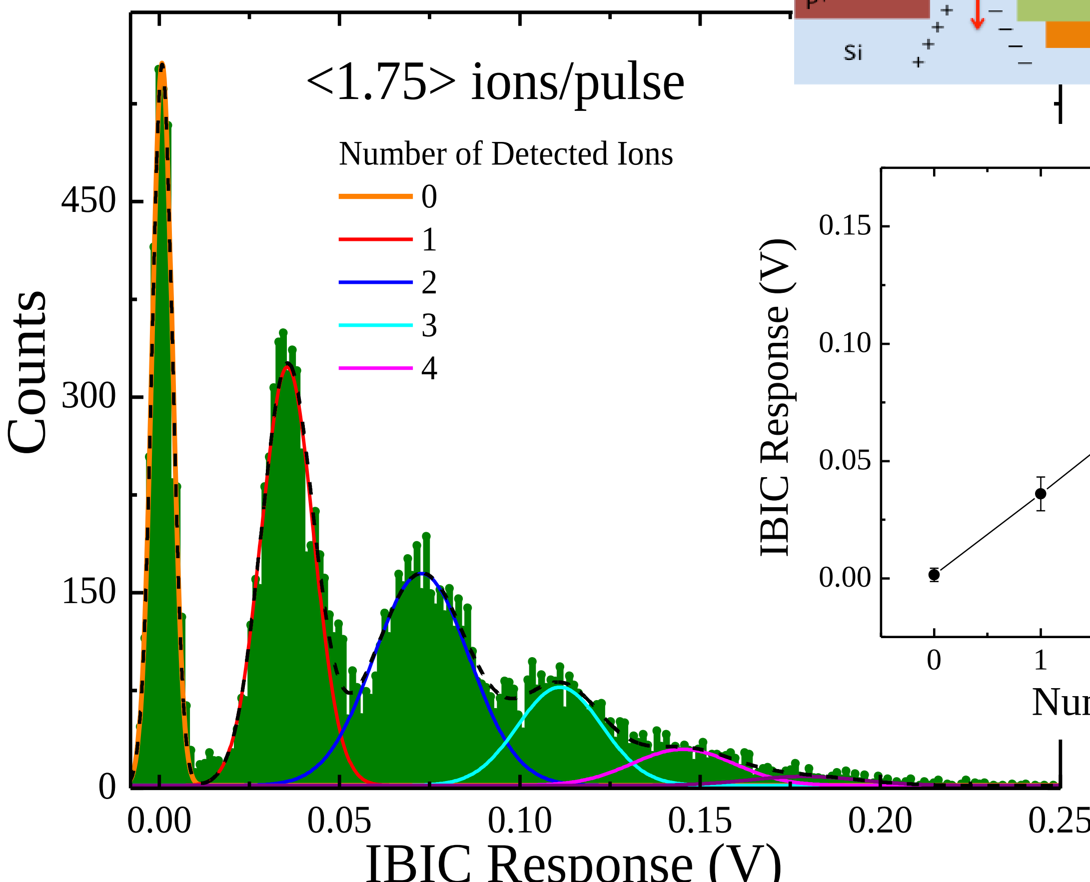


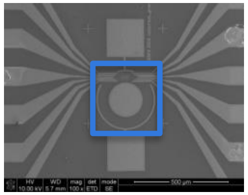




200 keV Si Detection



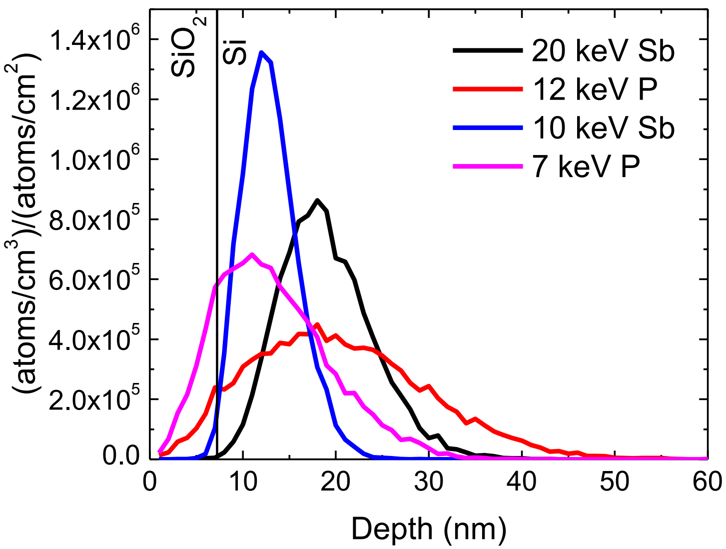
Quantized Single Ion Detection



Low Energy Single Ion Detection

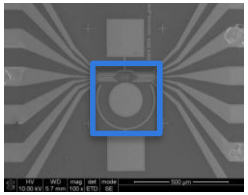
Ion Species	Energy (keV)	SiO2 Thickness	Range*(± Straggle)	SNR	Error Rate
Si	200	7 nm	273 (± 76) nm	21.2	<<1%
Sb	120	35 nm	25 (± 17.5) nm	5.2	8%
Sb	50	7 nm	25 (± 9) nm	4.4	9%
Sb	20	7 nm	11 (± 5) nm	2.5	15%

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



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

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



Low Noise Single Ion Detection

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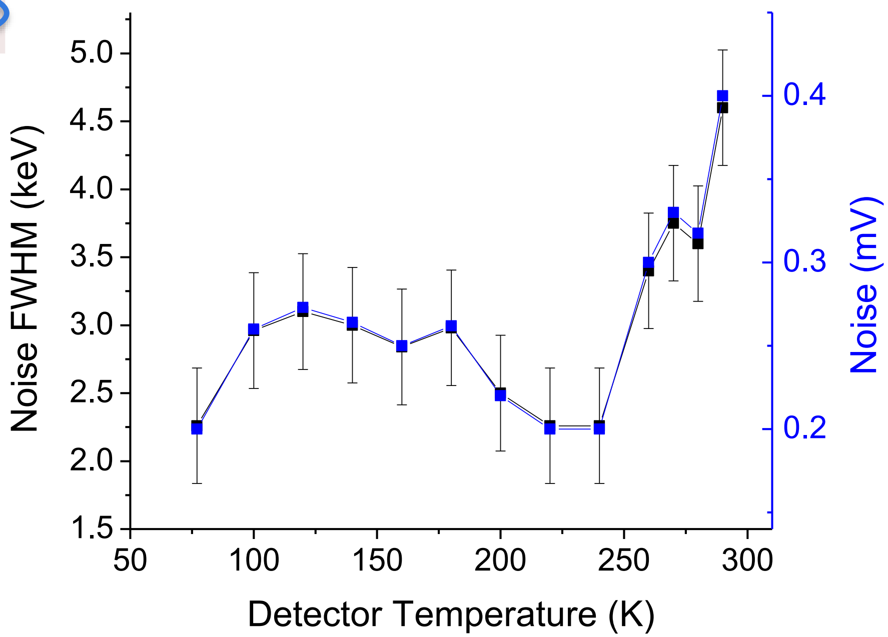
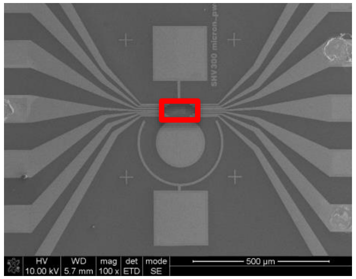
Ion	Range below SiO_2	e-h pairs
20 keV Sb	11.5±4.9±4.3 nm	~1500
12 keV P	13.0±9.3±7.8 nm	~1100
10 keV Sb	5.5±3.0±2.9 nm	~500
7 keV P	5.7±6.1±5.1 nm	~500

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

Measured ~0.2 mV noise for cooled preamp

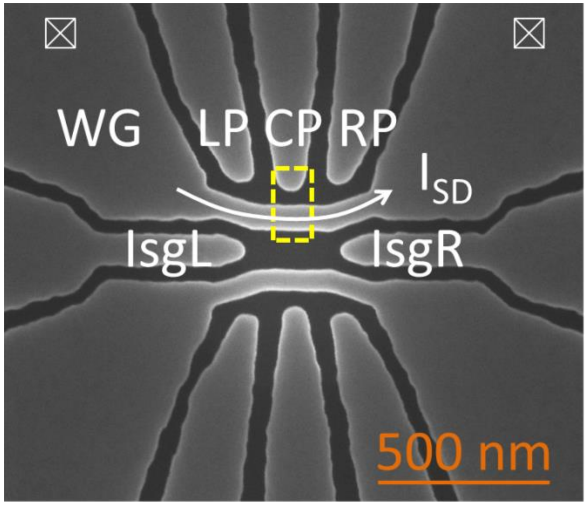


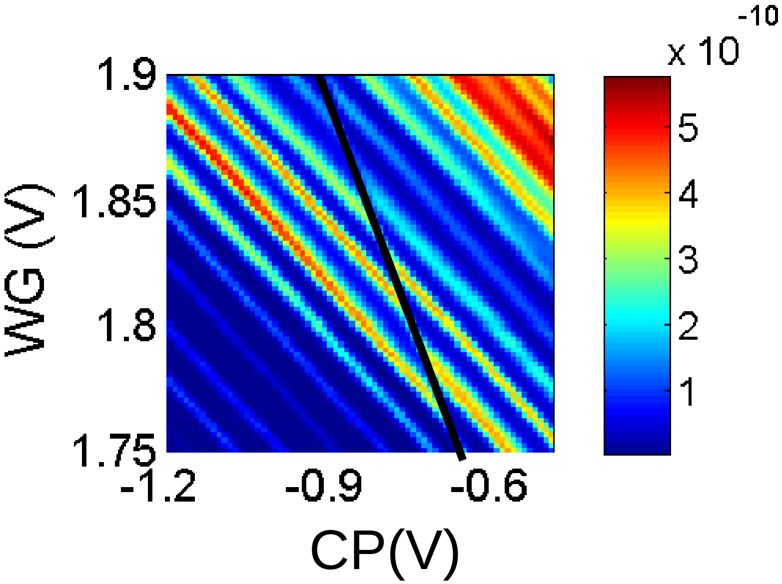
Path forward to low energy <10 keV detection



Transport in Counted Donor Devices

120 keV Sb Transport





Measured low temperature transport on counted donor devices

SiV Color Centers in Diamond

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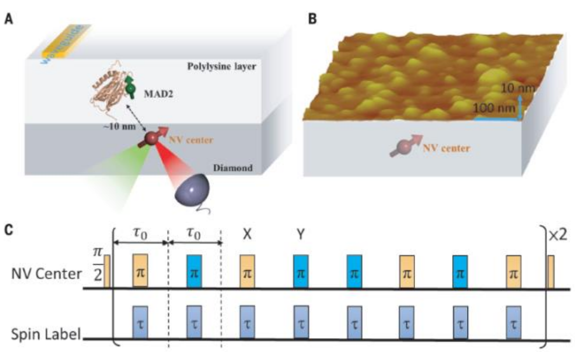
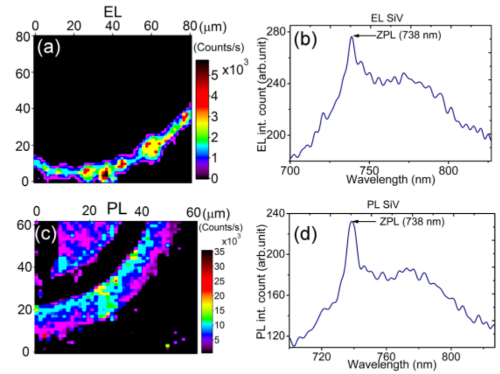
<u>Single-protein spin resonance</u>



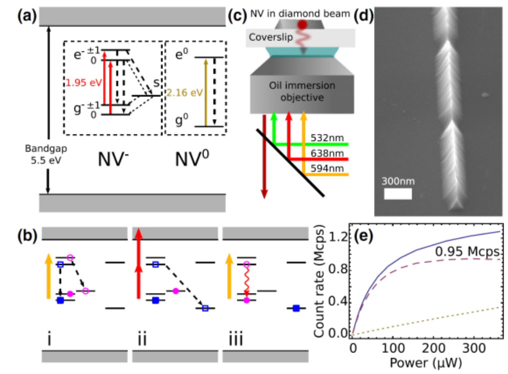
F. Shi *et al.*, Science **347**, 1135 (2015)

<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)

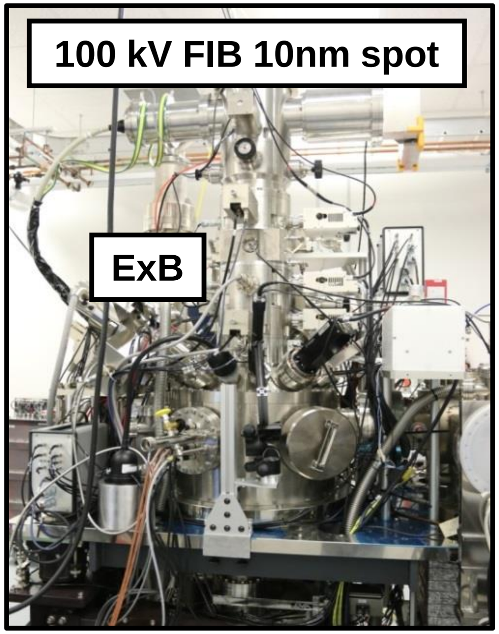
- Key question → How to produce a ***<u>single</u>*** color center ***<u>where</u>*** you want it?

1.) Location

2.) Yield

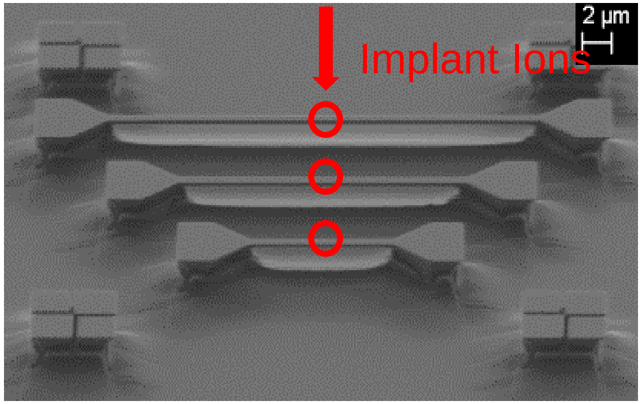
We will use ***<u>focused ion beam implantation</u>*** and ***<u>single ion detectors</u>*** to determine both location and yield with high accuracy

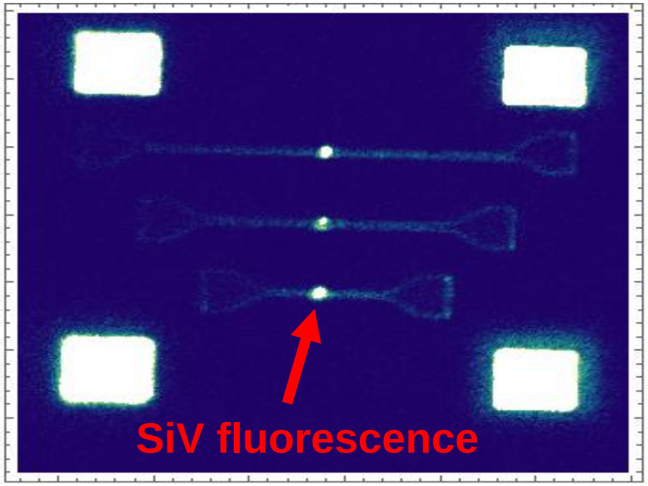
Location Problem is Solved



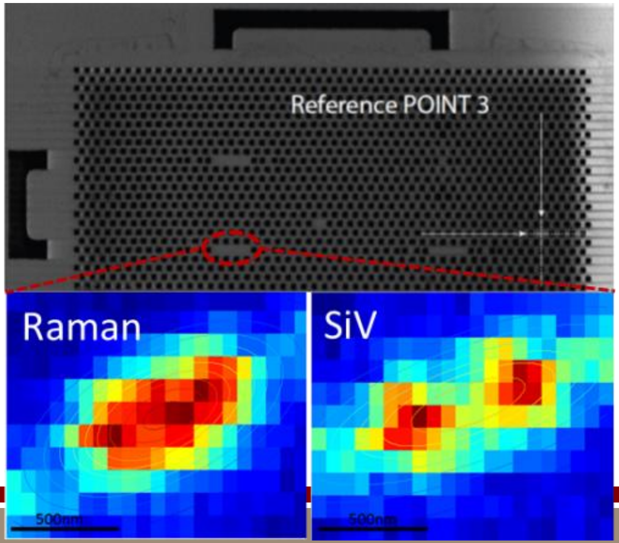
Direct write capability of the nI allows for CAD based fabrication

Diamond Nanobeams (SNL/Harvard collaboration)





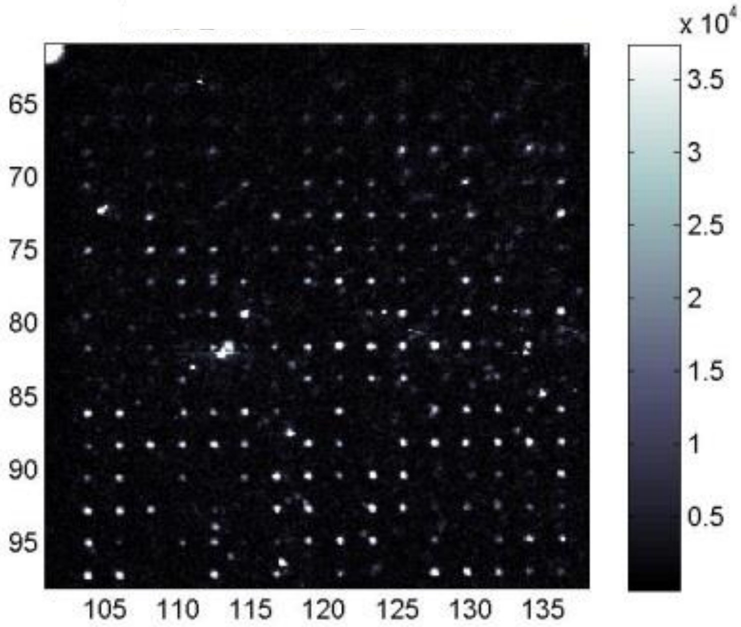
2D Photonic Crystals (SNL/MIT collaboration)

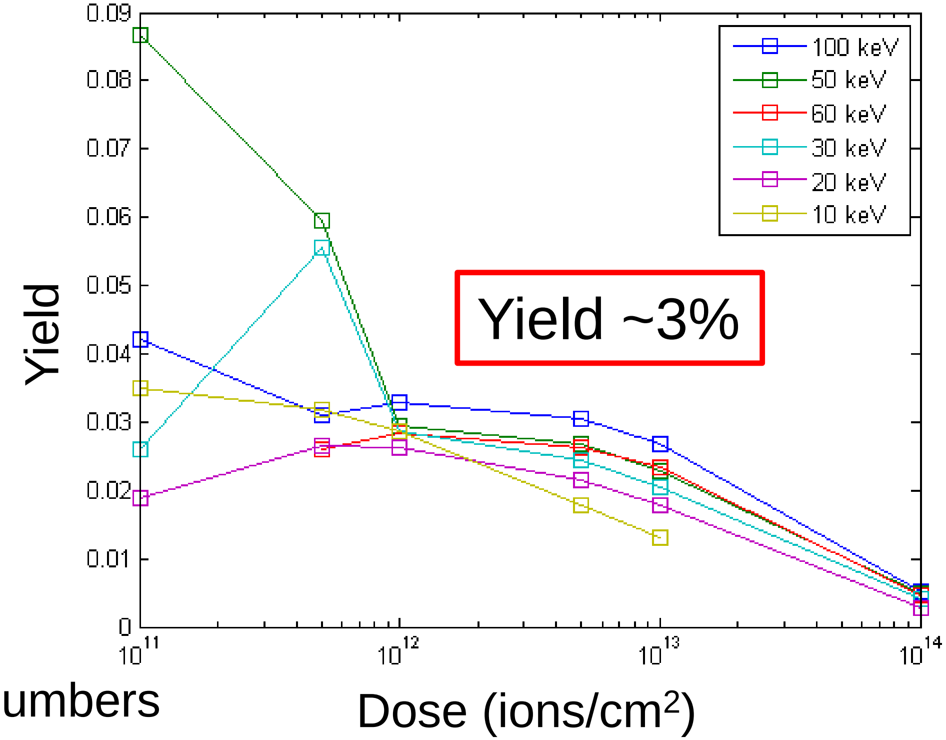


Targeting accuracy is spot size limited to 10's of nm

Activation Yield is a Major Issue

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 / # implanted

Yield Improvement – Diamond Detectors

Yield = # measured / # implanted

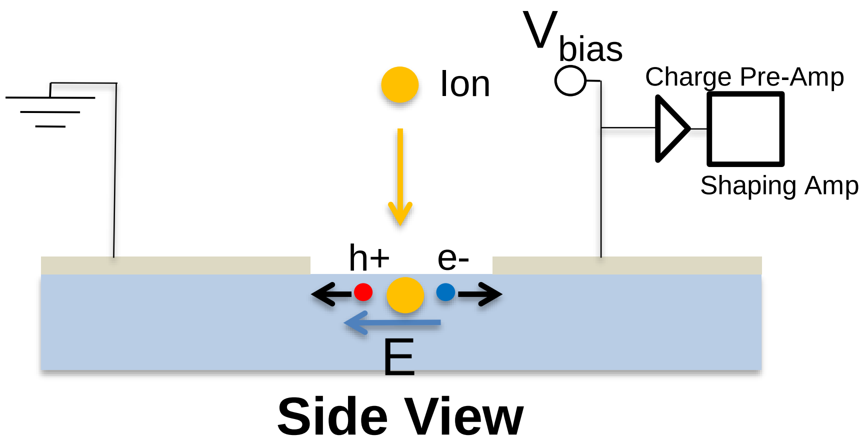
Poisson Statistics

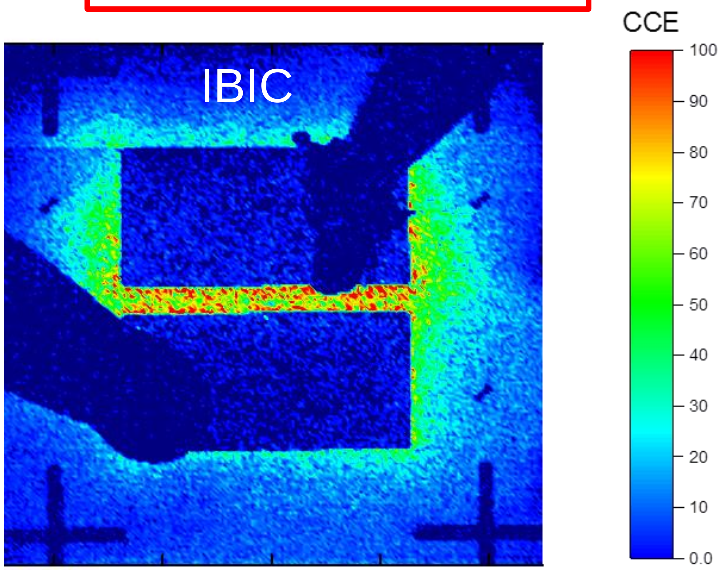
(Uncertainty in number of centers is $\sqrt{N}$)

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

$$CCE = \frac{Charge\ Collected}{Charge\ Deposited} \times 100$$

Ion Beam Induced Charge (IBIC):

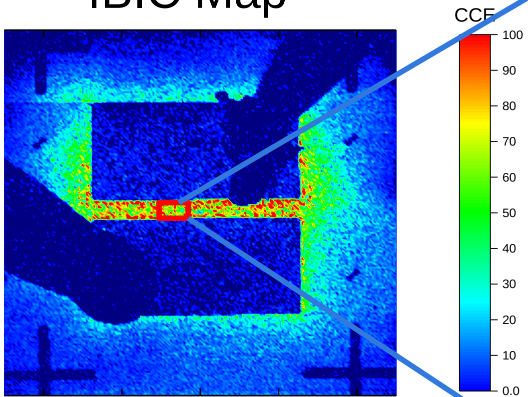




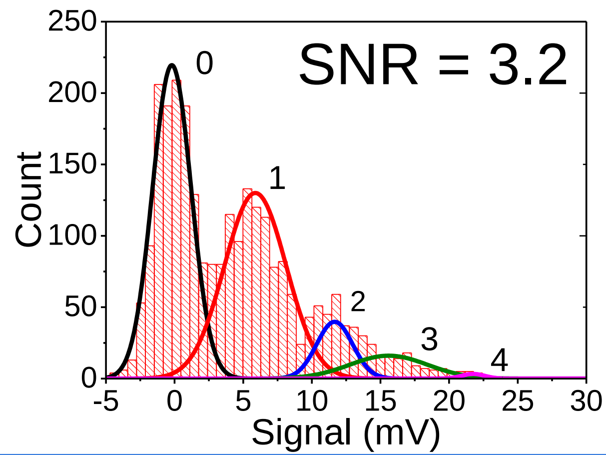
IBIC/Detection Demonstrated for low energy heavy ions

Single Ion Detection in Diamond

IBIC Map



Quantized Detection <0.65> ion

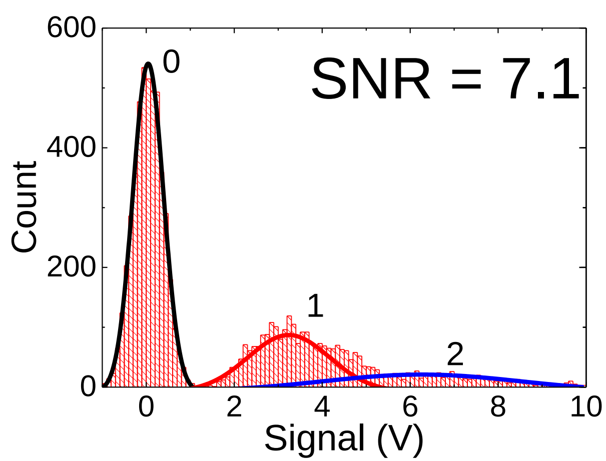


$$SNR = \frac{\mu_{signal}}{\mu_{noise} + \sigma_{noise}}$$

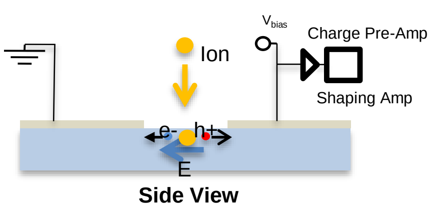
Signal amplitudes match Poisson statistics to 4%

Optimizing gain for single ion detection

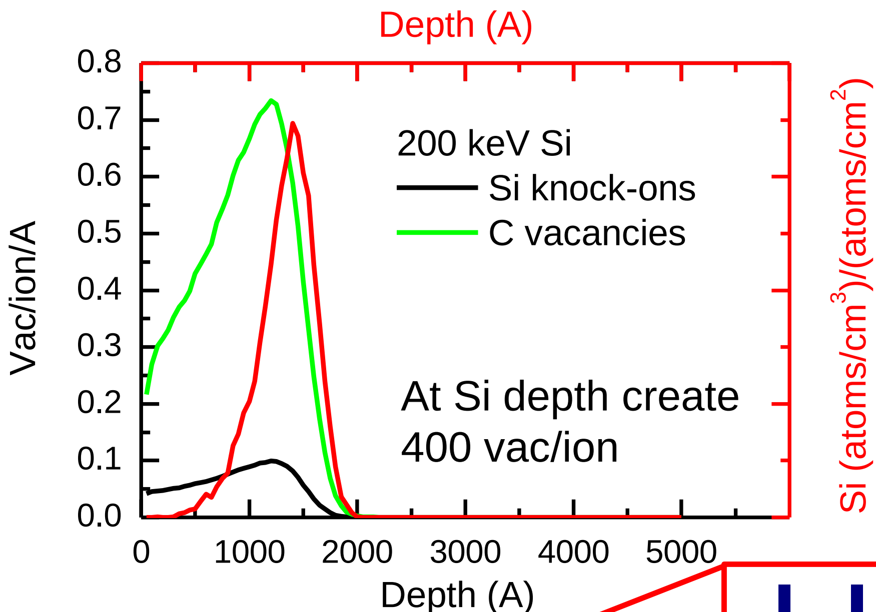
Single Ion Counting <0.2> ion

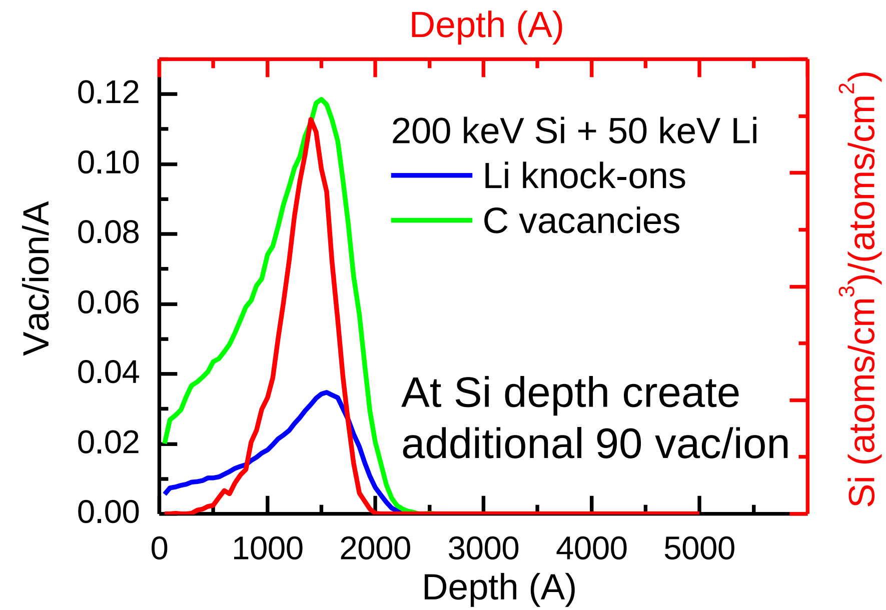


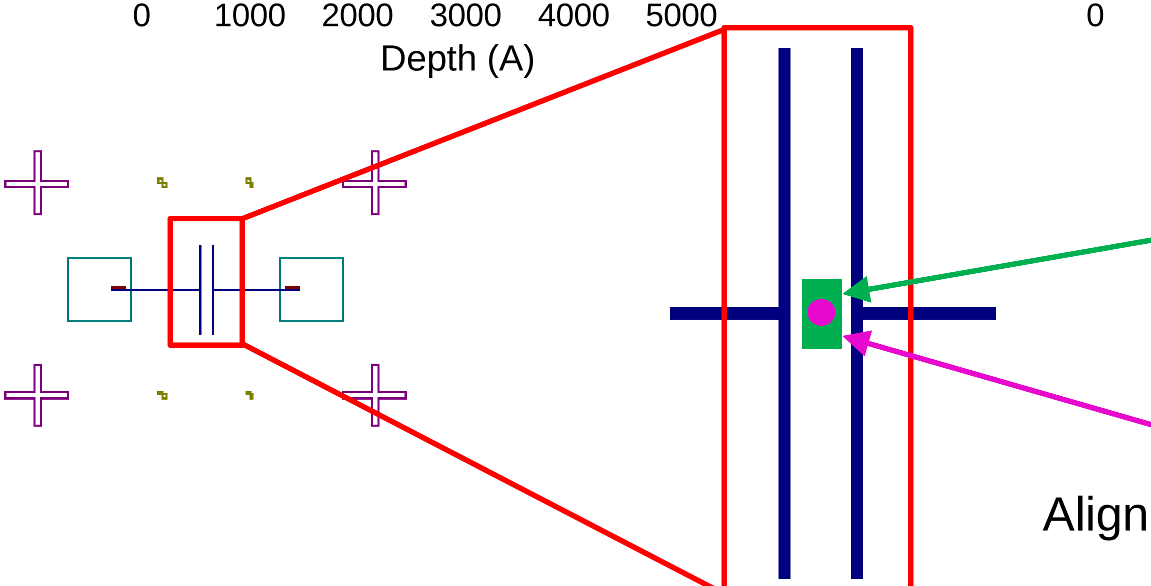
Single Ion Detection in Diamond with SNR ~10



Yield Improvement – Excess Vacancies







1.) Align to markers

2.) Implant 50 keV Li area

3.) Switch to Si beam, realign

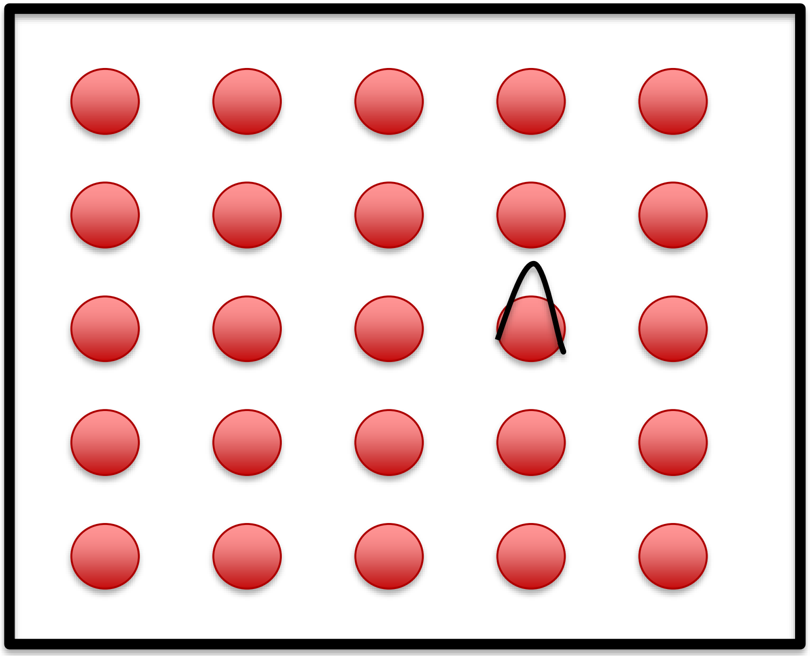
4.) Implant 200 keV Si spots

Alignment with <20 nm resolution

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

Limits on 'top-down' device fabrication

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



- What is the minimal pitch?
- What is the implant time?
- How large an area can we implant?

'Top-down' ion beam fabrication can make high resolution arrays

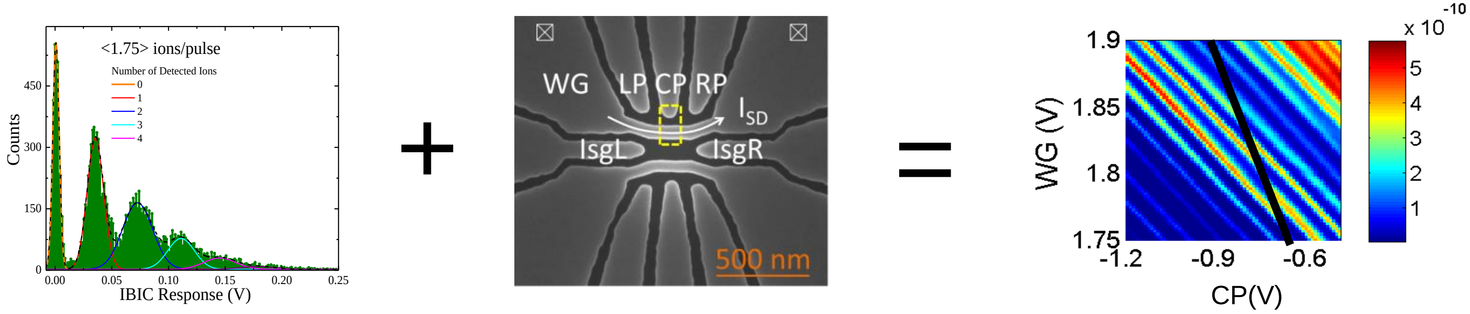
For 200 keV Si implant with 100% detection and 25 nm spot we have the following:

- Pitch: ~30 nm for 90% confidence
- Time: <0.1>/pulse at 400kHz, 30 μs per implant
- Area: 4 inch wafer with X nm stitching resolution

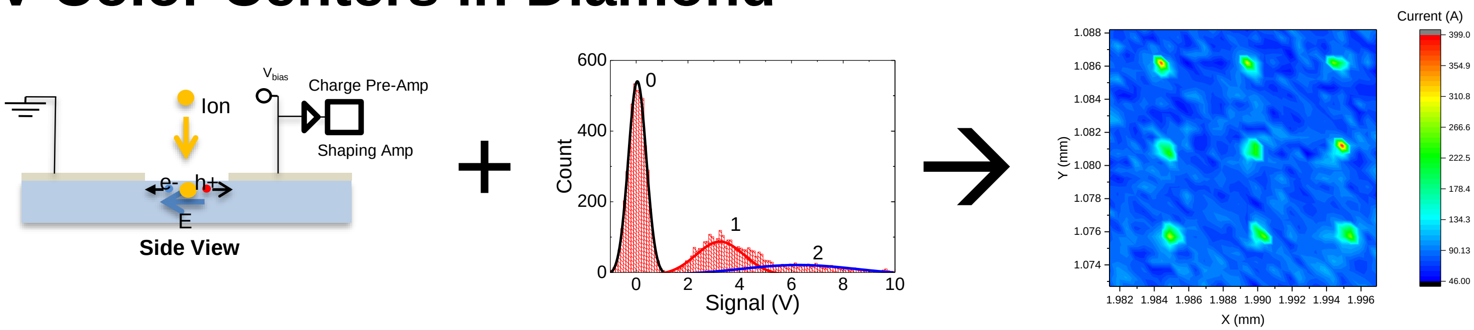
Implant one ion into a 30 x 30 nm^2 per 30 μs with >90% confidence

Conclusions/Future Directions

- Single Donor devices in Si for Quantum Computing



- SiV Color Centers in Diamond



- Limits of top-down devices – Si and Diamond

Implant one ion into a 30 x 30 nm^2 per 30 μs with >90% confidence