

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

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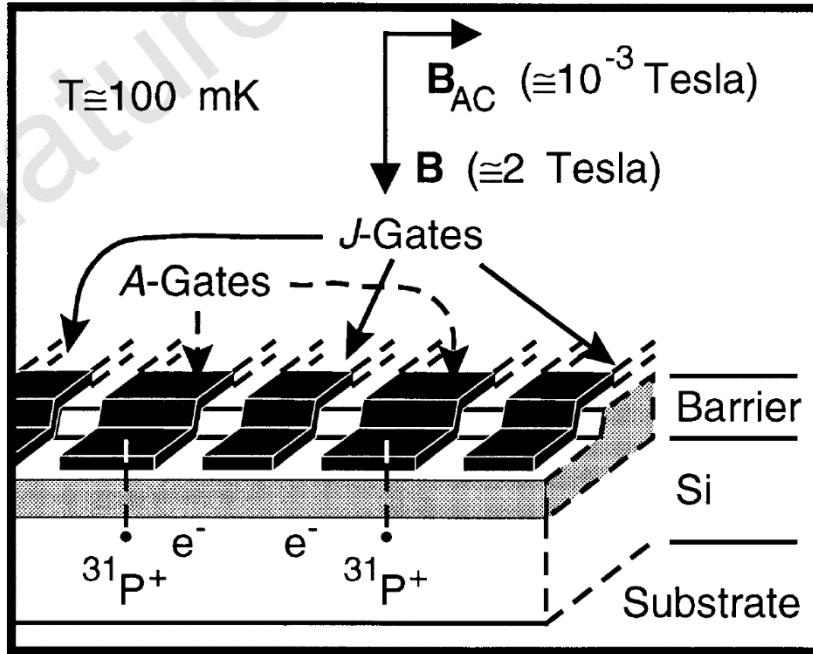
This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. DOE Office of Basic Energy Sciences user facility. The work was supported by Sandia National Laboratories Directed Research and Development Program. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the U. S. Department of Energy under Contract No. DE-AC04-94AL85000.

Outline

- 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

Donor in Si for Qubits

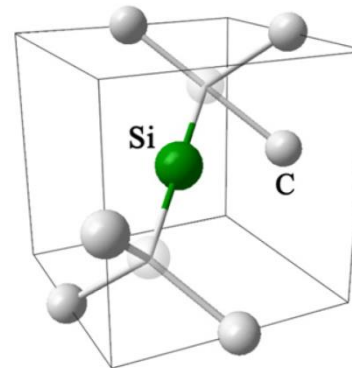


B. E. Kane, Nature **393**, 1998

- 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...

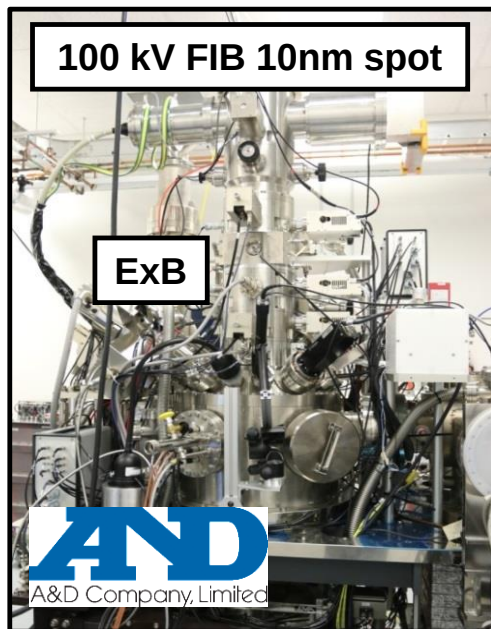


SiV in diamond

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

- Wide range of application from metrology to quantum computation

Fabrication – SNL nanoImplanter (nI)



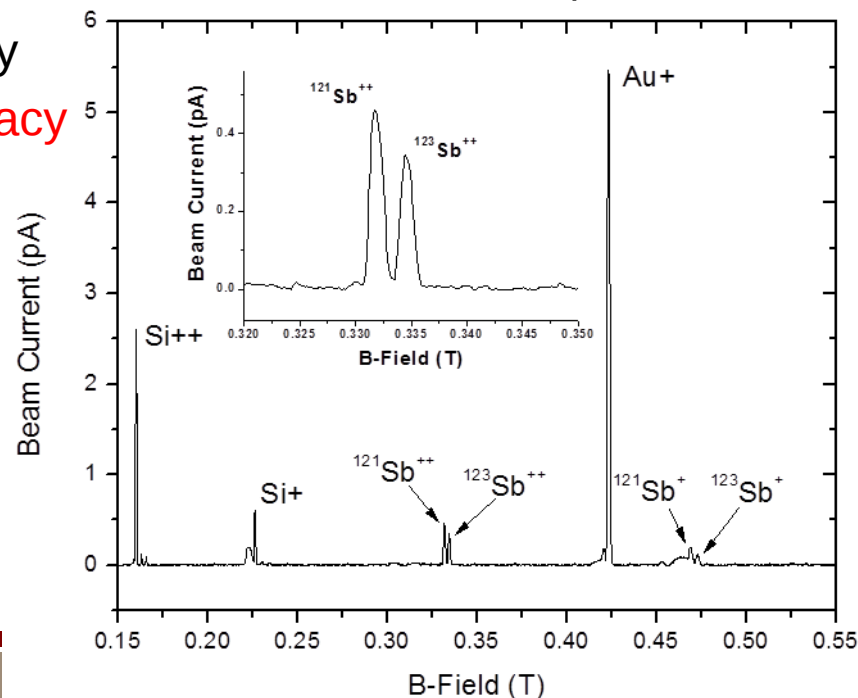
- Focused ion beam system (FIB)
→ nm beam spot size on target
- ExB Filter (Wein Filter)
→ Multiple ion species
→ Li, Si, P, Sb, Bi (separates out ^{28}Si , ^{29}Si , etc...)
- Fast blanking and chopping
→ Single ion implantation
- Direct-write lithography
→ nm targeting accuracy

RAITH
NANOFABRICATION

- Low temperature stage

- In-situ electrical probes

Sb Source: Mass Spectrum



SNL nanoImplanter (nI) - Sources

hydrogen
1
H
1.0079

beryllium
4
Be
9.0122

lithium
3
Li
6.941

magnesium
12
Mg
24.305

sodium
11
Na
22.990

calcium
20
Ca
40.078

potassium
19
K
39.098

strontium
38
Sr
87.62

rubidium
37
Rb
85.468

barium
56
Ba
137.33

caesium
55
Cs
132.91

francium
87
Fr
[223]

57-70
★

89-102
★ ★

scandium
21
Sc
44.956

titanium
22
Ti
47.867

vanadium
23
V
50.942

chromium
24
Cr
51.996

manganese
25
Mn
54.938

iron
26
Fe
55.845

cobalt
27
Co
58.933

nickel
28
Ni
58.693

copper
29
Cu
63.546

zinc
30
Zn
65.39

gallium
31
Ga
69.723

germanium
32
Ge
72.61

arsenic
33
As
74.922

selenium
34
Se
78.96

bromine
35
Br
79.904

krypton
36
Kr
83.80

yttrium
39
Y
88.906

zirconium
40
Zr
91.224

niobium
41
Nb
92.906

molybdenum
42
Mo
95.94

technetium
43
Tc
[98]

ruthenium
44
Ru
101.07

rhodium
45
Rh
102.91

palladium
46
Pd
106.42

silver
47
Ag
107.87

cadmium
48
Cd
112.41

indium
49
In
114.82

tin
50
Sn
118.71

antimony
51
Sb
121.76

tellurium
52
Te
127.60

iodine
53
I
126.90

xenon
54
Xe
131.29

lutetium
71
Lu
174.97

hafnium
72
Hf
178.49

tantalum
73
Ta
180.95

tungsten
74
W
183.84

rhenium
75
Re
186.21

osmium
76
Os
190.23

iridium
77
Ir
192.22

platinum
78
Pt
196.08

gold
79
Au
196.97

mercury
80
Hg
200.59

thallium
81
Tl
204.38

lead
82
Pb
207.2

bismuth
83
Bi
208.98

polonium
84
Po
[209]

astatine
85
At
[210]

radon
86
Rn
[222]

lawrencium
103
Lr
[262]

rutherfordium
104
Rf
[261]

dubnium
105
Db
[262]

seaborgium
106
Sg
[266]

bohrium
107
Bh
[264]

hassium
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Hs
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meitnerium
109
Mt
[268]

ununilium
110
Uun
[271]

unununium
111
Uuu
[272]

ununbium
112
Uub
[277]

ununquadium
114
Uuq
[289]

boron
5
B
10.811

carbon
6
C
12.011

nitrogen
7
N
14.007

oxygen
8
O
15.999

fluorine
9
F
18.998

neon
10
Ne
20.180

aluminum
13
Al
26.982

silicon
14
Si
28.086

phosphorus
15
P
30.974

sulfur
16
S
32.065

chlorine
17
Cl
35.453

argon
18
Ar
39.948

Green – demonstrated at other labs

Gray – demonstrated at SNL

Yellow – attempting at SNL

* Lanthanide series

** Actinide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

After A. Weick University of Bochum

Wide Variety of Ion Species Available

Single Donor Devices for Quantum Computing

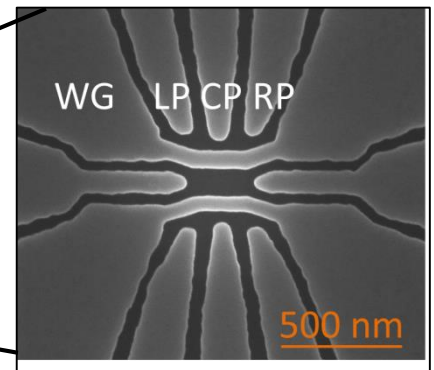
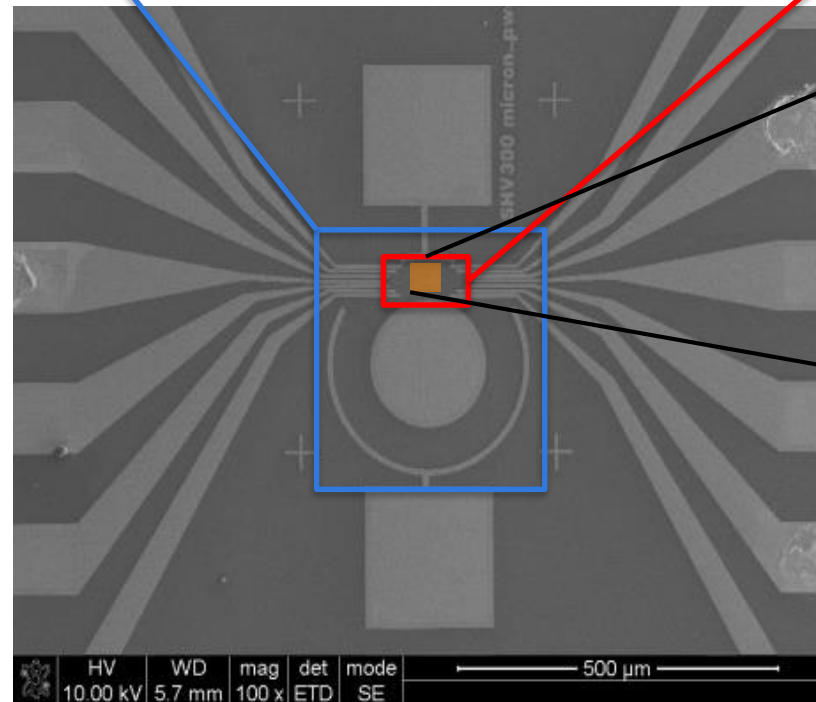
Si-MOS platform integrated with:

- Single Ion Detector
- Nanostructure for Qubit operation

Single Ion Detector

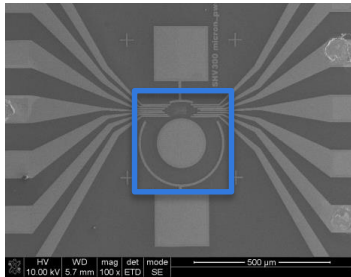
Nanostructure

Cross-sectional view
of the detector

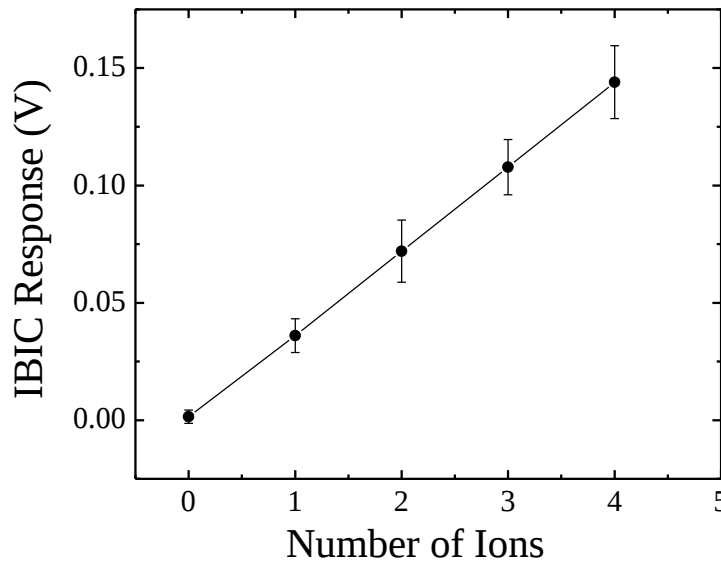
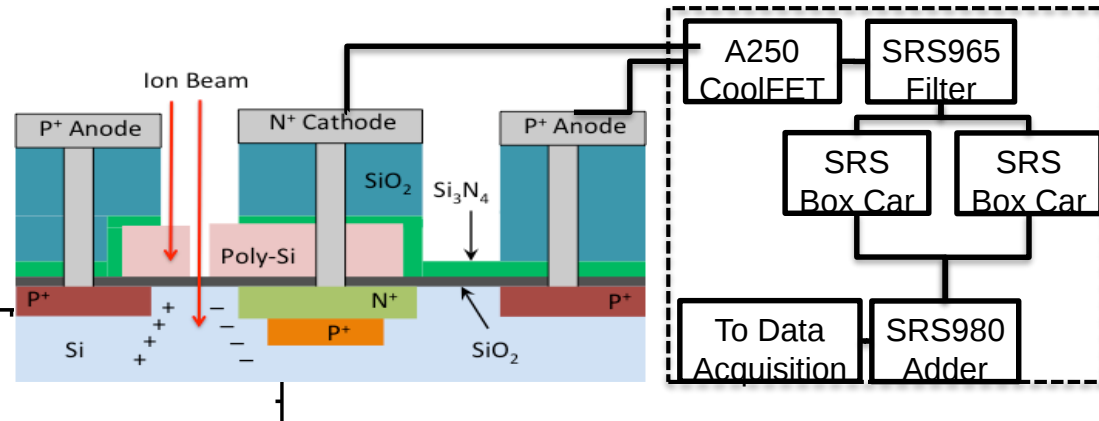
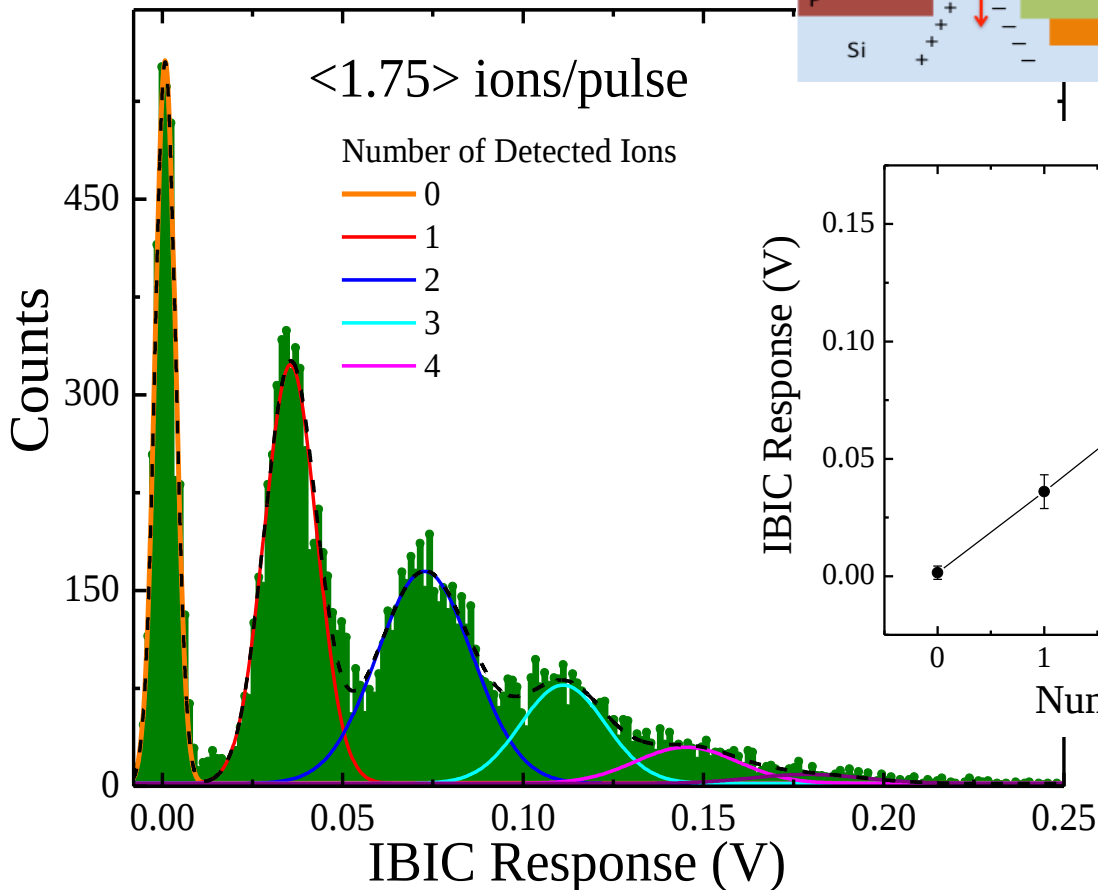


Combined Single Ion Detector and Nanostructures Demonstrated

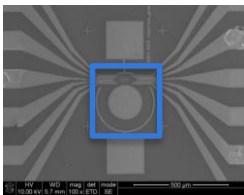
Integrated Single Ion Detectors



200 keV Si Detection



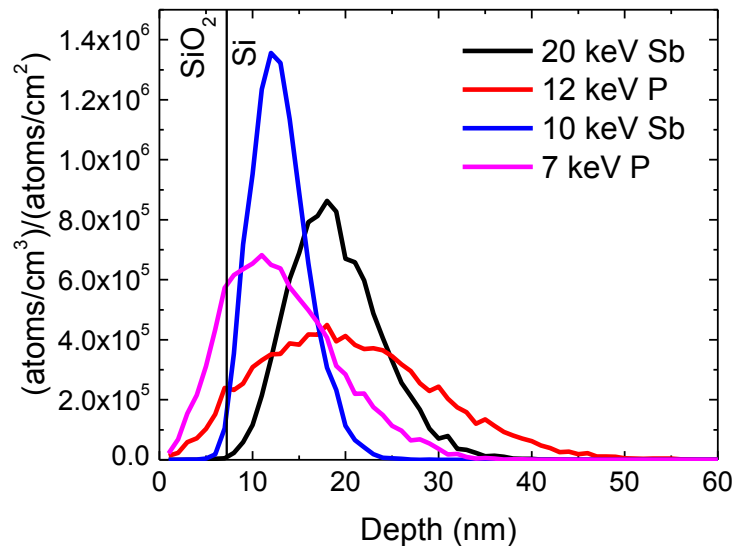
Quantized Single Ion Detection



Low Energy Single Ion Detection

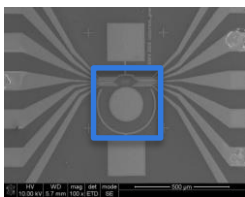
Ion Species	Energy (keV)	SiO ₂ Thickness	Range*($\pm$ Straggle)	SNR	Error Rate
Si	200	7 nm	273 ($\pm$ 76) nm	21.2	<<1%
Sb	120	35 nm	25 ($\pm$ 17.5) nm	5.2	8%
Sb	50	7 nm	25 ($\pm$ 9) nm	4.4	9%
Sb	20	7 nm	11 ($\pm$ 5) nm	2.5	15%

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



Ion	Range below SiO ₂	e-h pairs
20 keV Sb	11.5 $\pm$ 4.9 $\pm$ 4.3 nm	~1500
12 keV P	13.0 $\pm$ 9.3 $\pm$ 7.8 nm	~1100
10 keV Sb	5.5 $\pm$ 3.0 $\pm$ 2.9 nm	~500
7 keV P	5.7 $\pm$ 6.1 $\pm$ 5.1 nm	~500

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

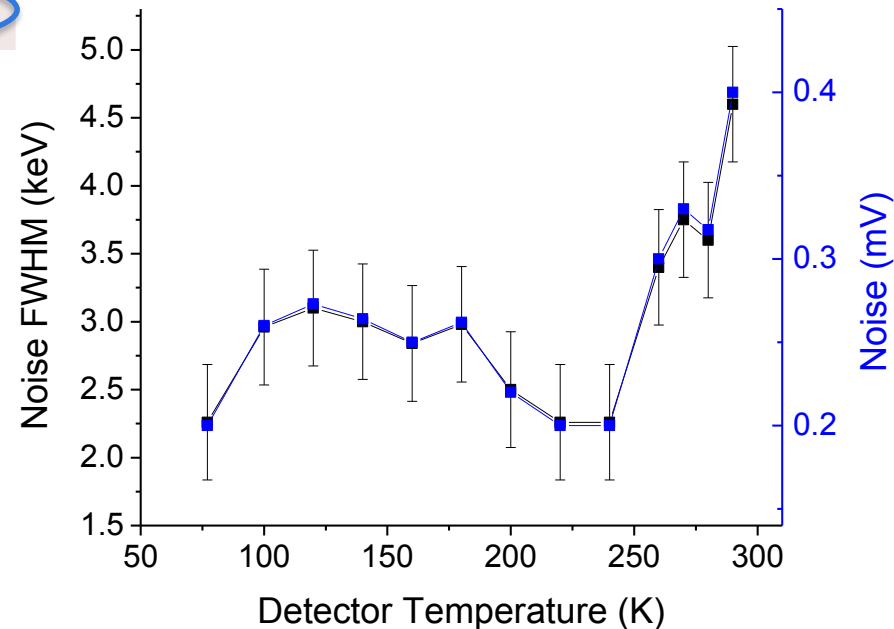


Low Noise Single Ion Detection

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

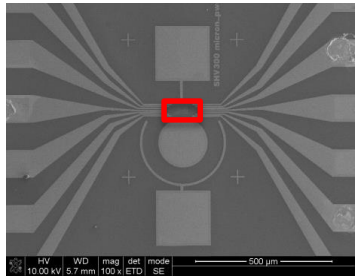
Need SNR of 2 for 500 e/h pairs
→ Noise 0.2 mV

Measured ~0.2 mV noise for cooled preamp

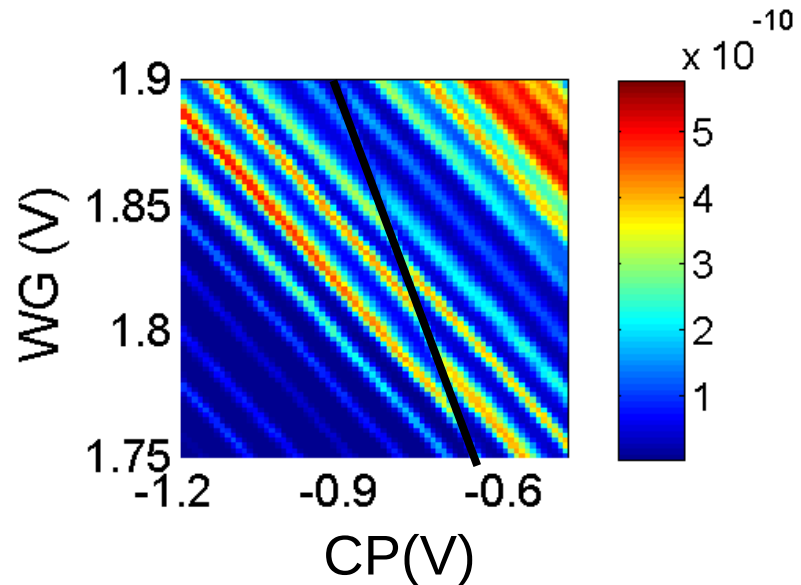
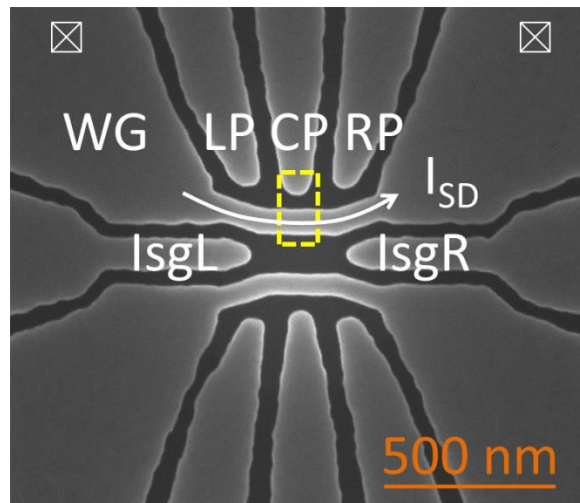


Path forward to low energy <10 keV detection

Transport in Counted Donor Devices



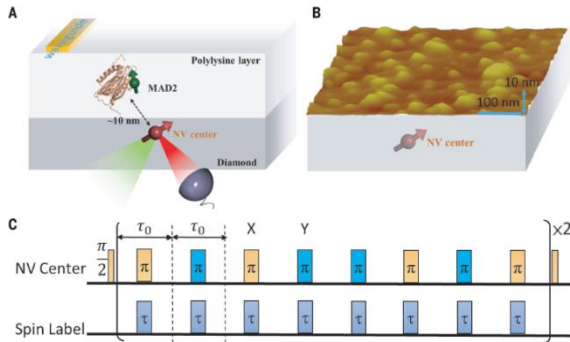
120 keV Sb Transport



Measured low temperature transport on counted donor devices

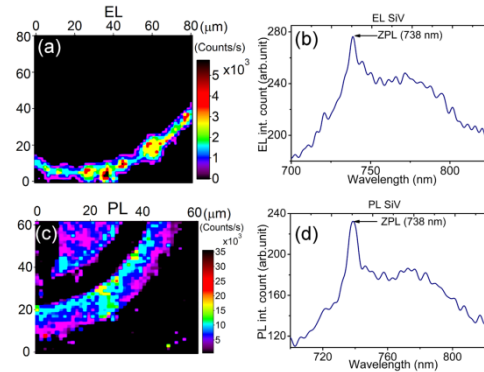
SiV Color Centers in Diamond

Single-protein spin resonance



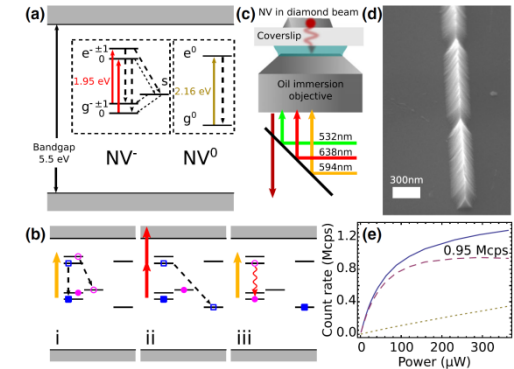
F. Shi *et al.*, Science **347**, 1135 (2015)

Electrically driven SiV



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

Readout of single NV spin

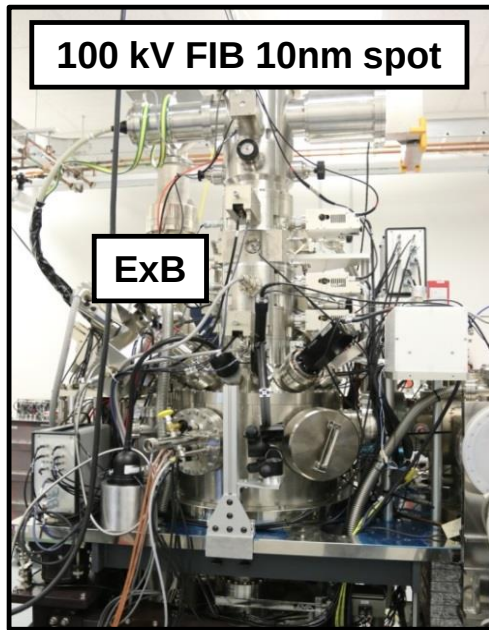


B. J. Shields *et al.*, PRL **114**, 136402 (2015)

- Key question → How to produce a single color center where you want it?

- 1.) Location
- 2.) Yield

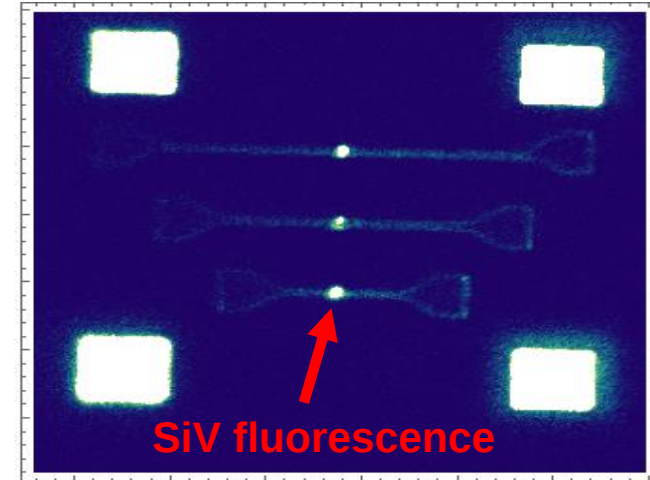
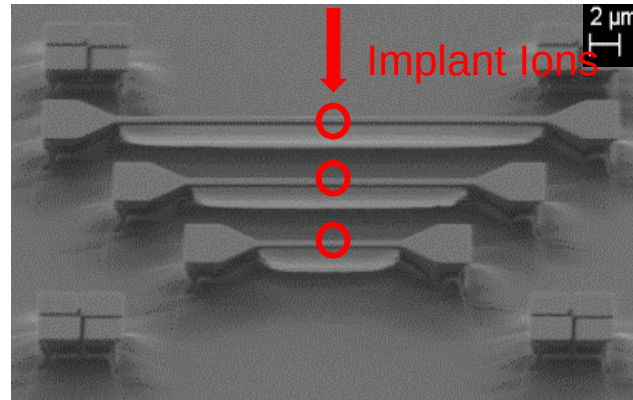
We will use focused ion beam implantation and single ion detectors to determine both location and yield with high accuracy



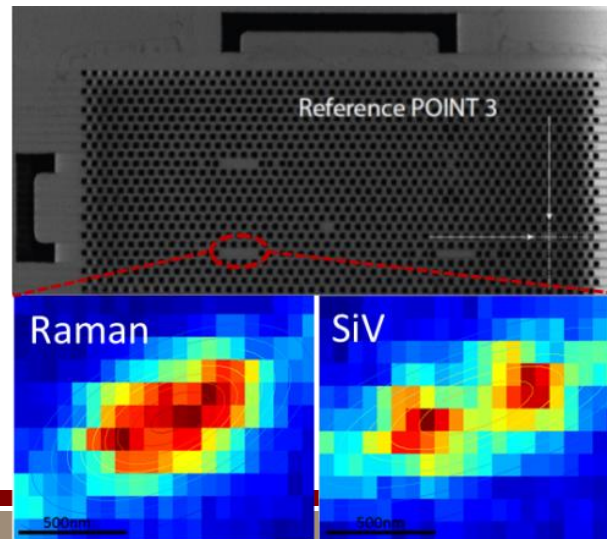
Direct write capability
of the nl allows for
CAD based fabrication

Location Problem is Solved

Diamond Nanobeams (SNL/Harvard collaboration)



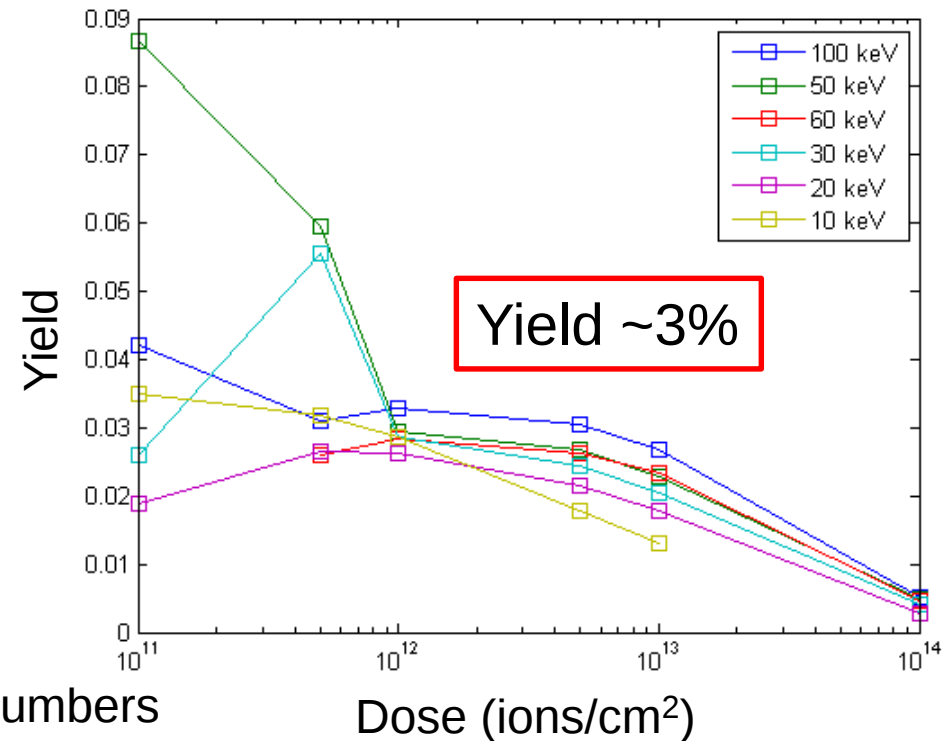
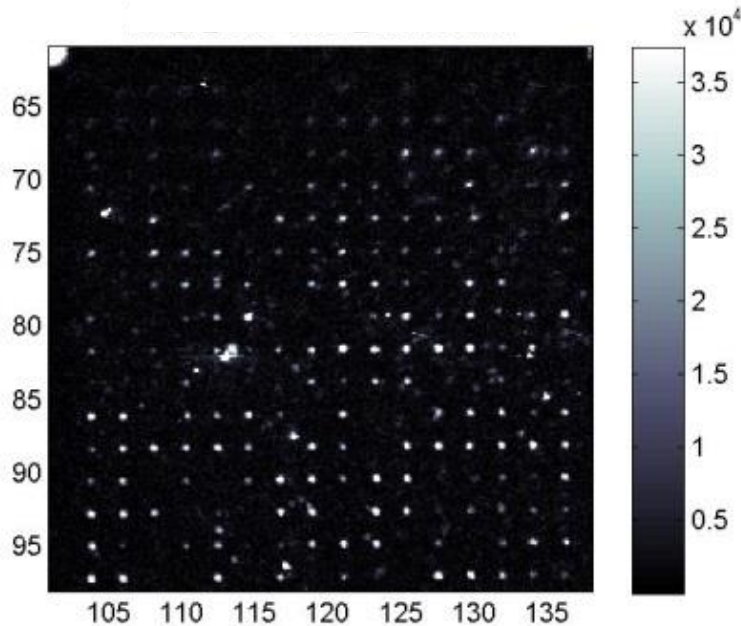
2D Photonic Crystals (SNL/MIT collaboration)



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)

$$\text{Yield} = \# \text{ measured} / \# \text{ implanted}$$

Yield Improvement – Diamond Detectors

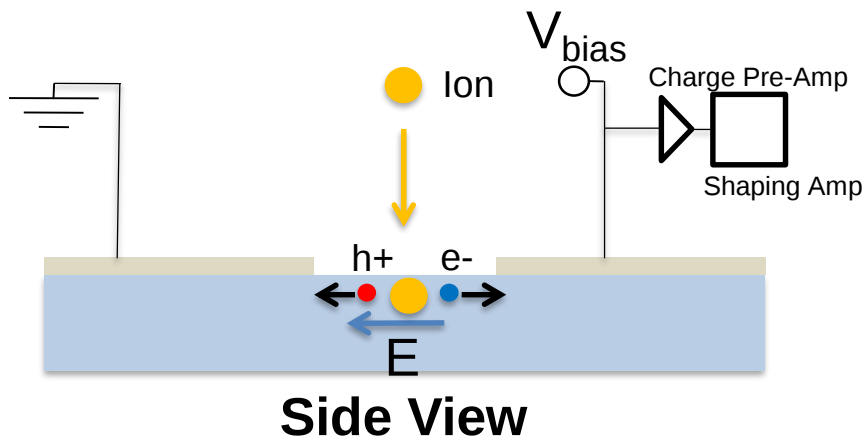
$$\text{Yield} = \# \text{ measured} / \# \text{ implanted}$$

Poisson Statistics

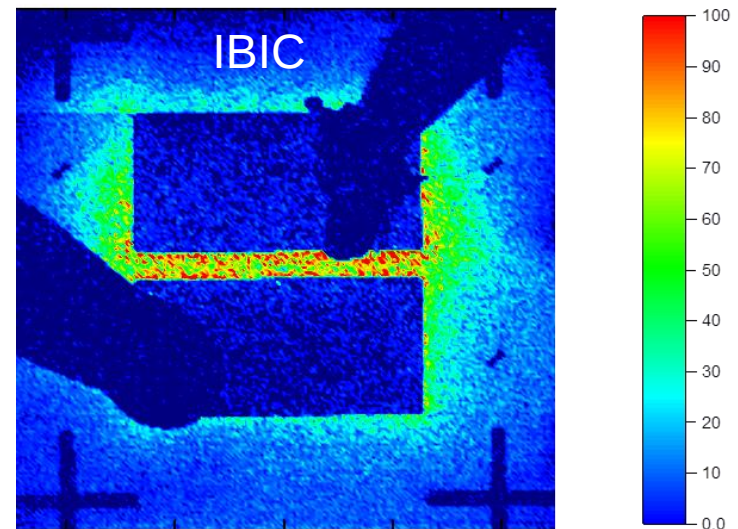
(Uncertainty in number of centers is $\sqrt{N}$)

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

Ion Beam Induced Charge (IBIC):



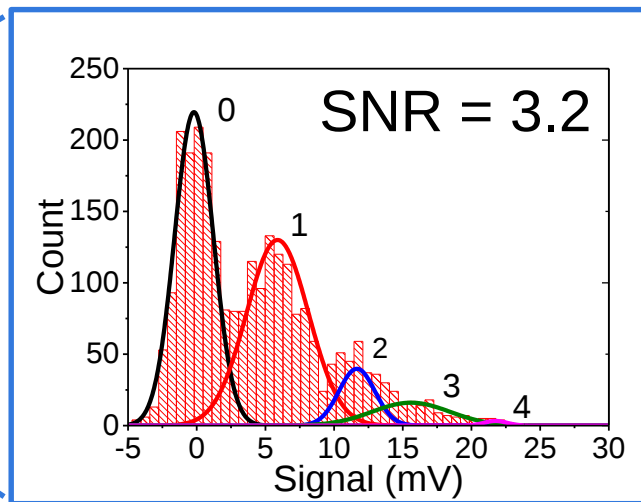
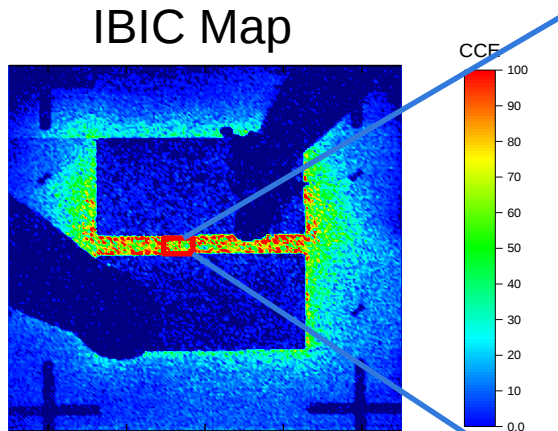
$$\text{CCE} = \frac{\text{Charge Collected}}{\text{Charge Deposited}} \times 100$$



IBIC/Detection Demonstrated for low energy heavy ions

Single Ion Detection in Diamond

Quantized Detection <0.65> ion

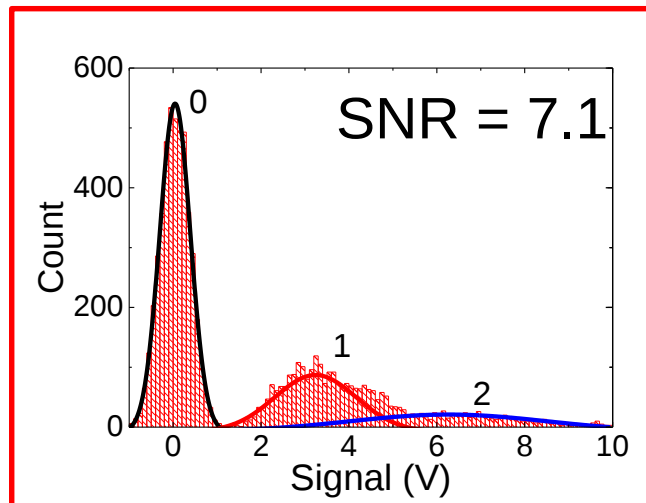


$$SNR = \frac{\mu_{signal}}{\mu_{noise} + \sigma_{noise}}$$

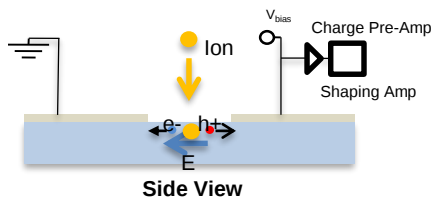
Signal amplitudes match
Poisson statistics to 4%

Optimizing gain
for single ion
detection

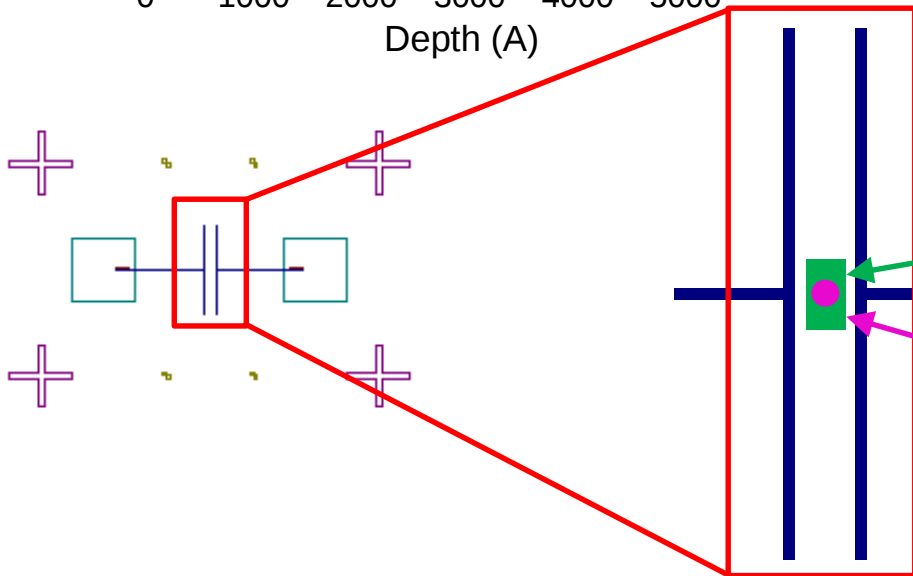
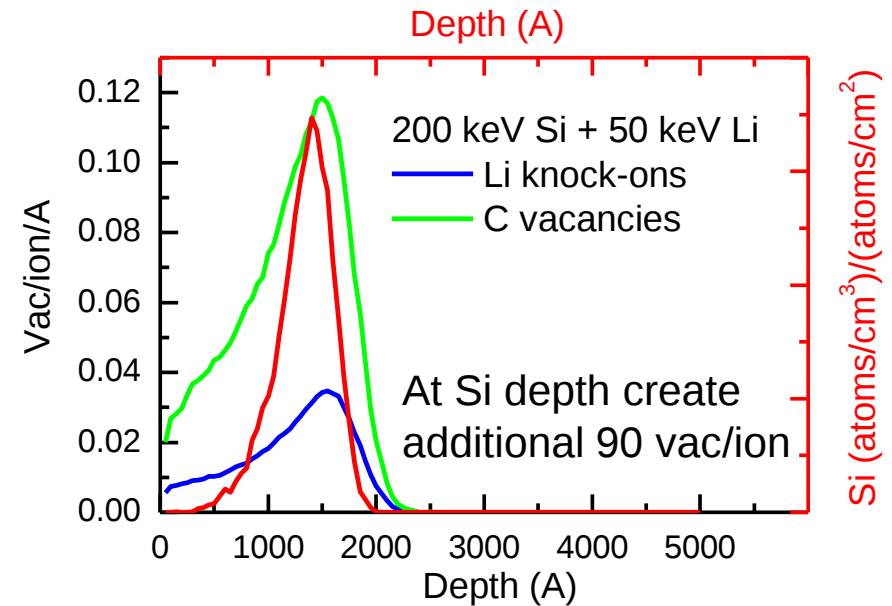
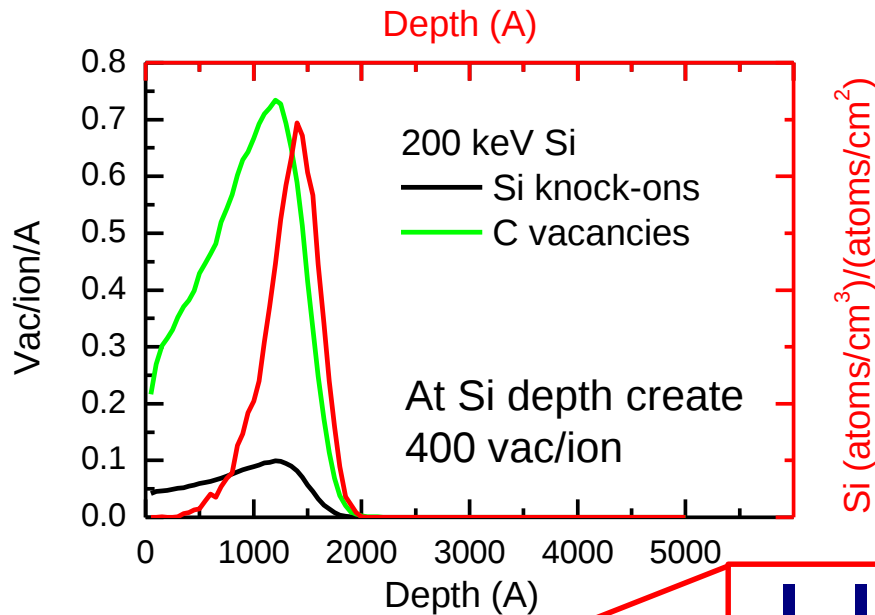
Single Ion Counting <0.2> ion



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

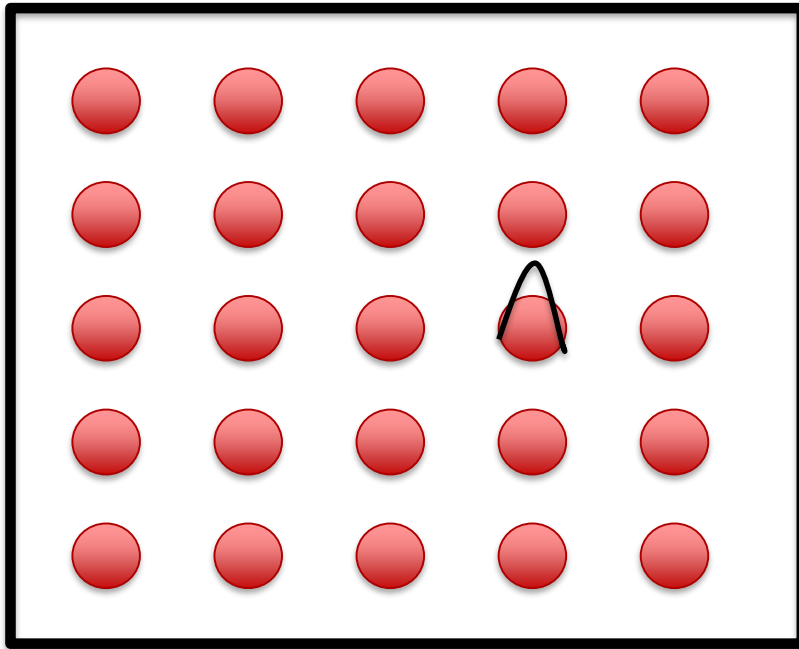
4.) Implant 200 keV Si spots

Alignment with <20 nm resolution

Use the direct write capability of the nl 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) $\rightarrow$ 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

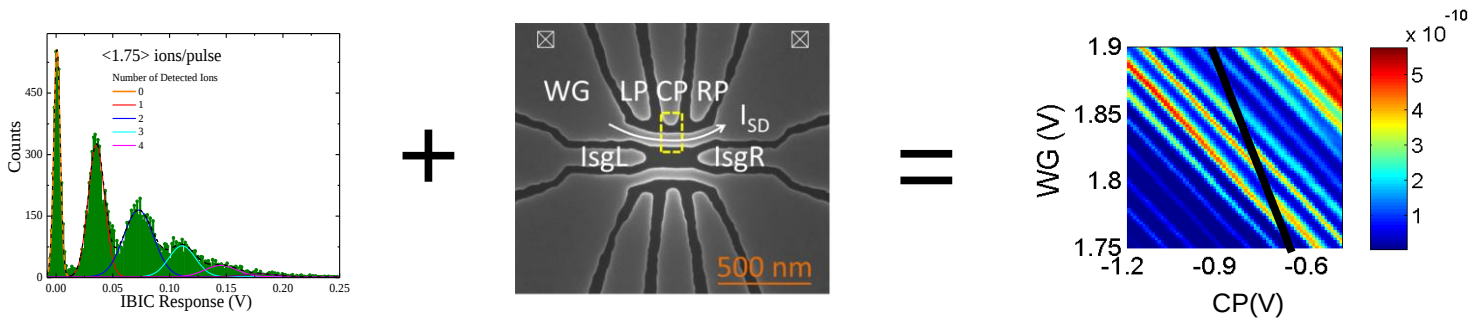
For 200 keV Si implant with 100% detection and
25 nm spot we have the following:

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

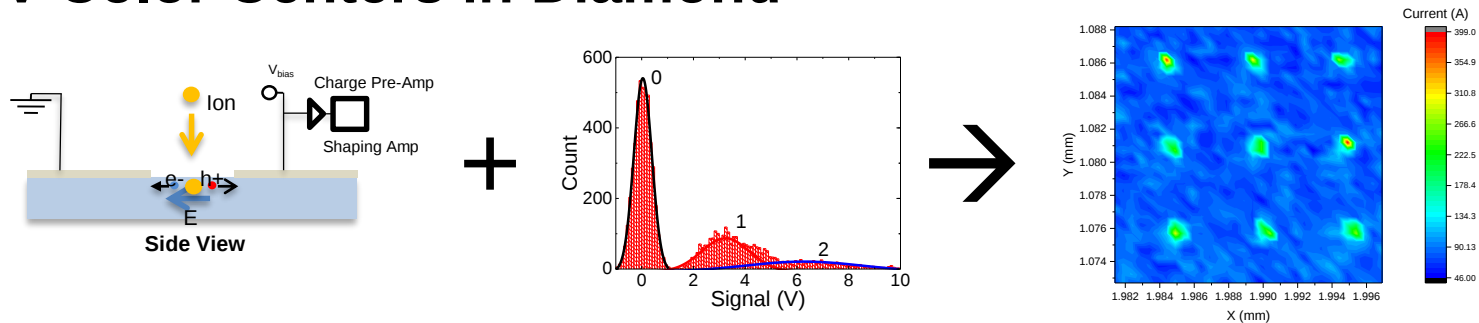
Implant one ion into a 30×30 nm²
per 30 μ s with $>90\%$ confidence

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 nm² per 30 μ s with >90% confidence