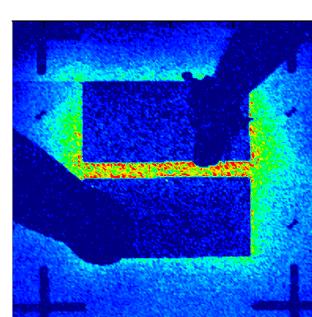




Sandia
National
Laboratories

Focused Ion Beam Implantation for the Fabrication of Single Defect Centers in Wide Bandgap Substrates using in-situ Counting and Photoluminescence



Edward Bielejec

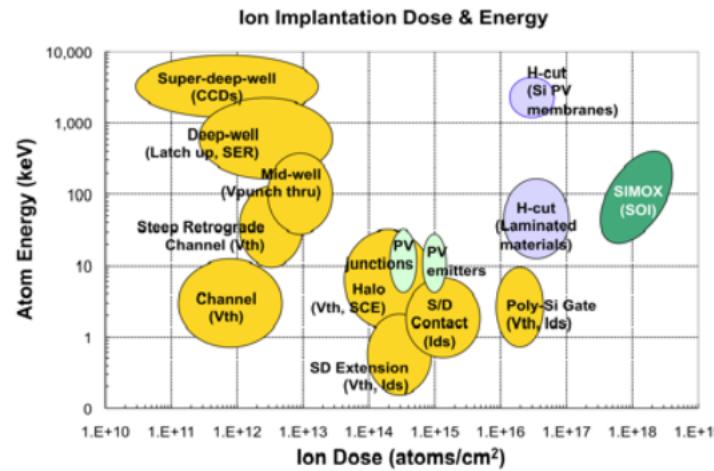
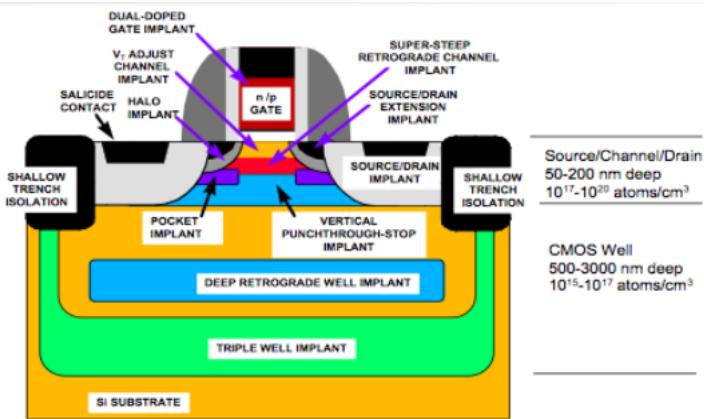
Sandia National Laboratories, Albuquerque, NM 87185

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Ion Implantation and Irradiation for Device Fab

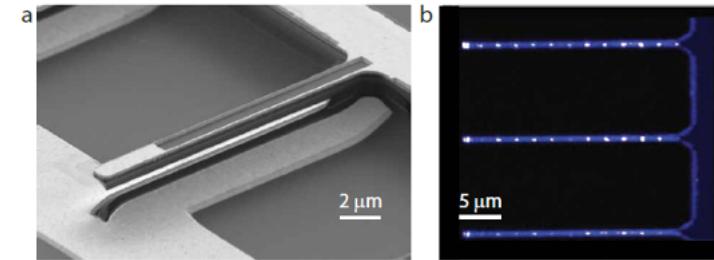


Ion Implantation has been a work-horse for the semiconductor industry

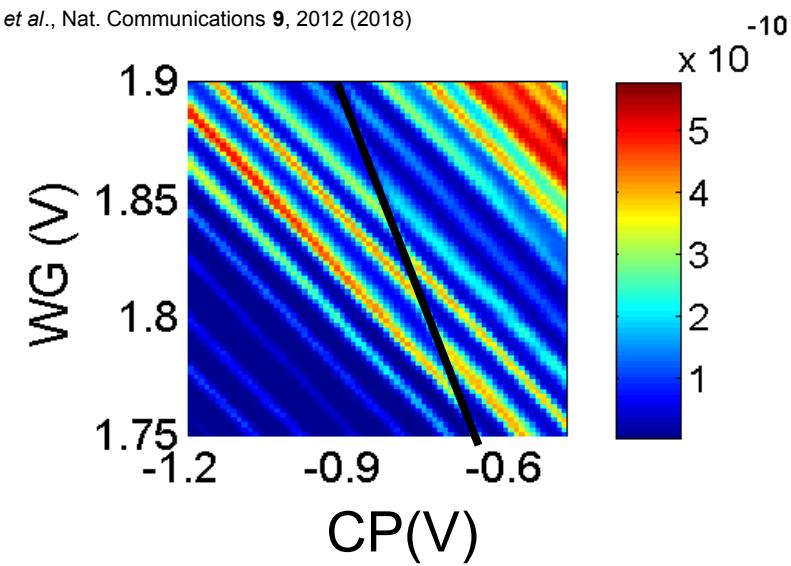


S. B. Felch, et al., Proceedings of PAC2013, Pasadena, CA (2013)

Our work is centered on localized implantation and fabrication based on a deterministic number of implanted ions



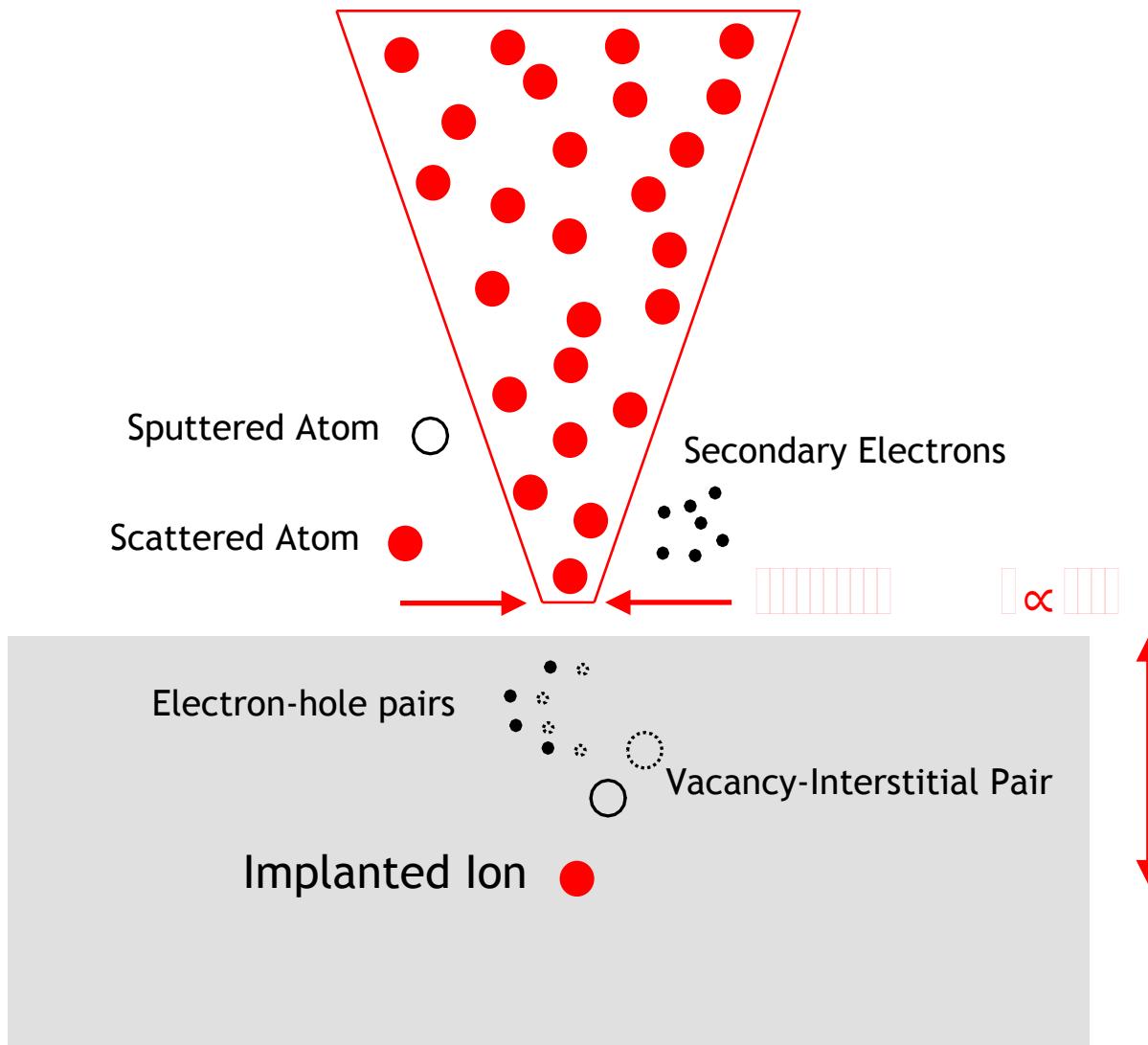
Y. Sohn, et al., Nat. Communications 9, 2012 (2018)



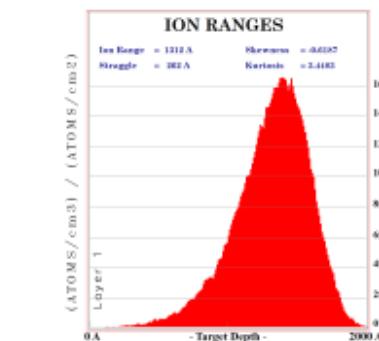
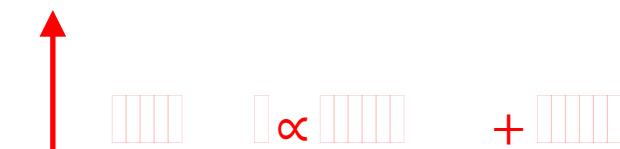
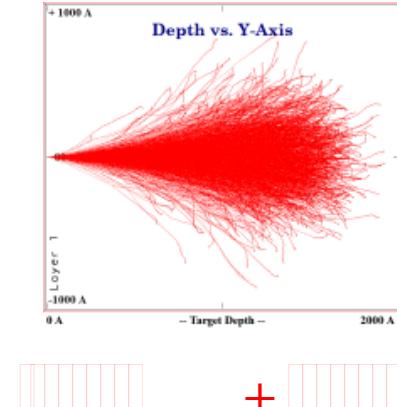
Singh et al. Appl. Phys. Lett. 108, 062101 (2016)

Focused Ion Beam implantation for fabrication of single atom devices and nanofabrication

Overview of the Focused Ion Beam (FIB) Implantation



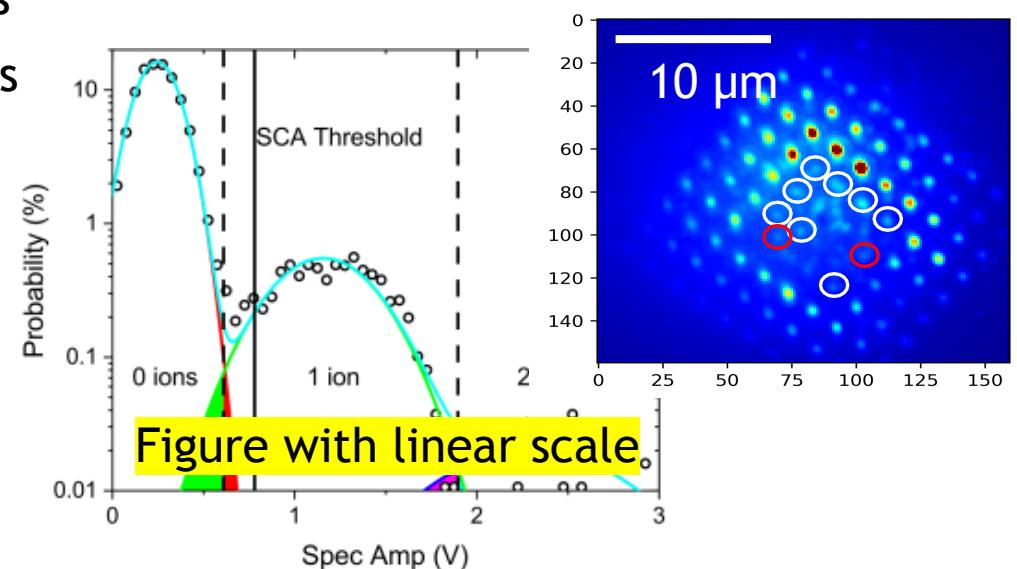
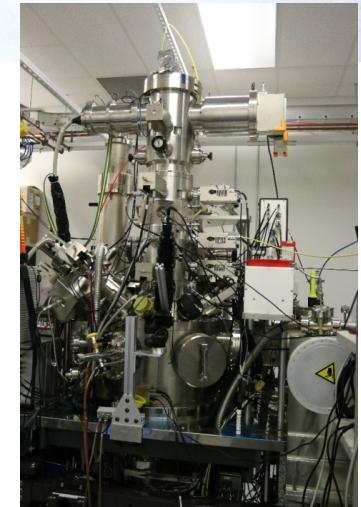
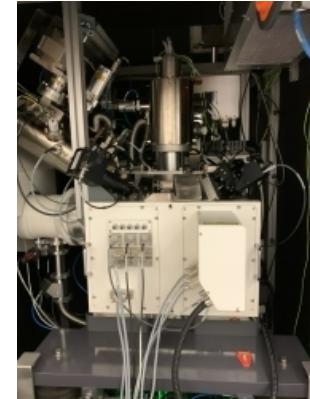
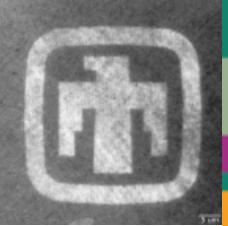
SRIM simulation - XY Straggle



SRIM simulation
200 keV Si into diamond
 131 ± 26 nm

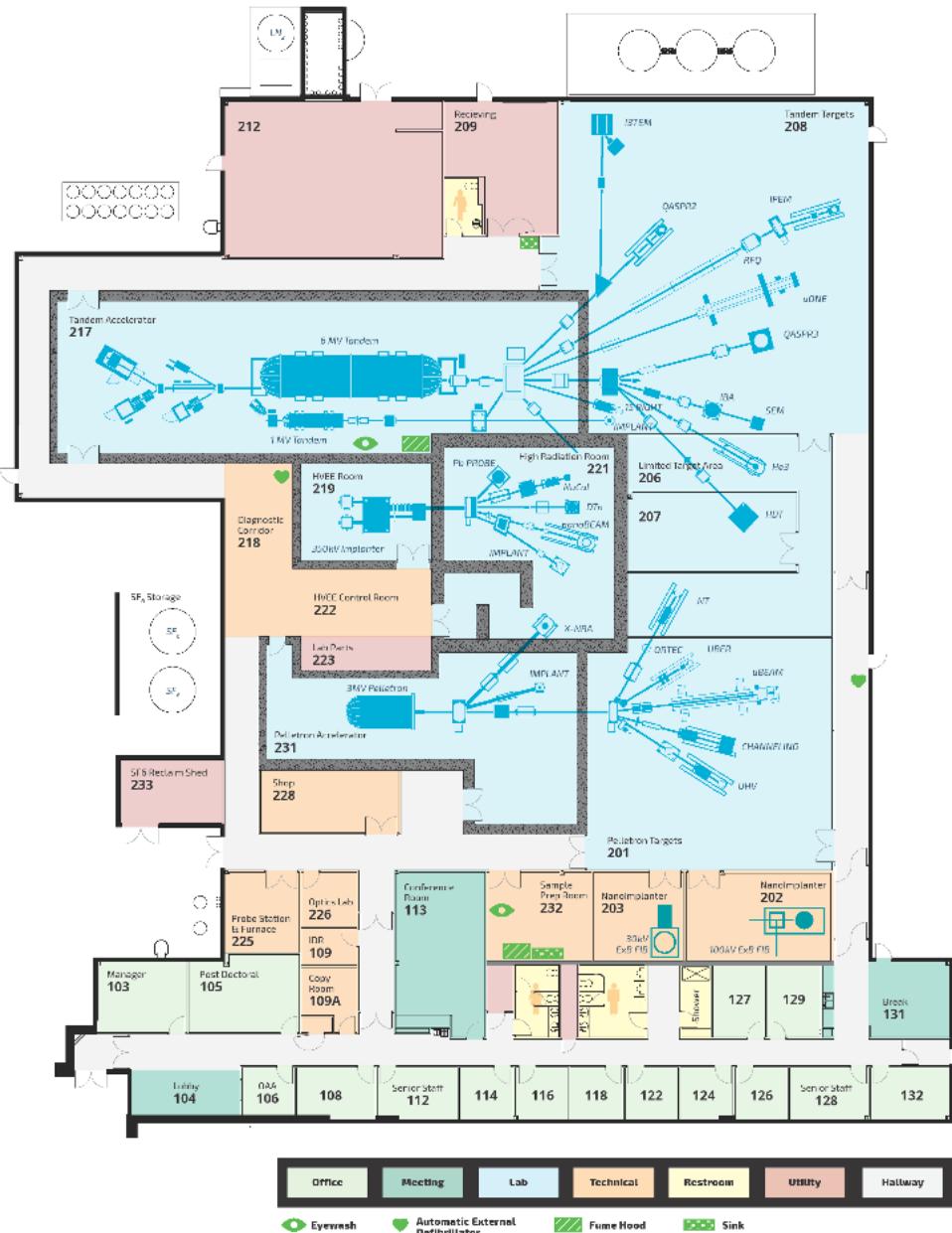
Outline

- Introduction to Sandia's Ion Beam Laboratory (IBL)
- Multi-species Focused Ion Beam (FIB)
 - Sandia's nanolimplanter and Raith Velion
- Single Defect Centers in Wide Bandgap Substrates
 - In-situ Counting - control the # of implanted ions
 - In-situ Photoluminescence - verify defect centers
- Summary





Sandia's Ion Beam Laboratory (IBL)



7 Operational Accelerators and >25 end-stations

(including *in-situ* DLTS, PL, TEM, SEM, 1200°C heating, etc...)

Operational

- (1) 6 MV Tandem Accelerator
- (2) 3 MV Pelletron Accelerator
- (3) 1 MV Tandem Accelerator
- (4) 350 kV HVEE Implanter
- (5) 100 kV ExB FIB nanolimplanter
- (6) 35 kV ExB FIB Raith Velion
- (7) 35 kV Zeiss HelM

Installing

- (8) 35 kV Plasma FIB

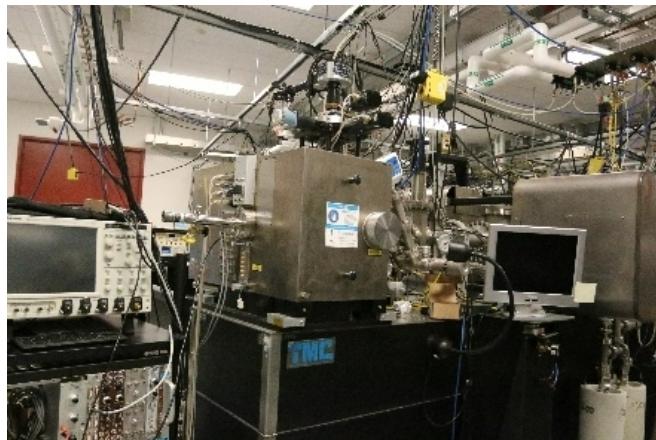
High energy
focused
micobeams
1 μm to mm's

Low energy
focused
nanobeams
<1 to 20 nm

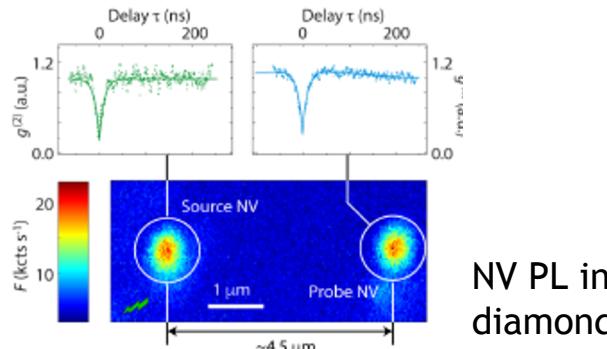
High Energy Focused Ion Beams $\sim 1 \mu\text{m}$ to mm's



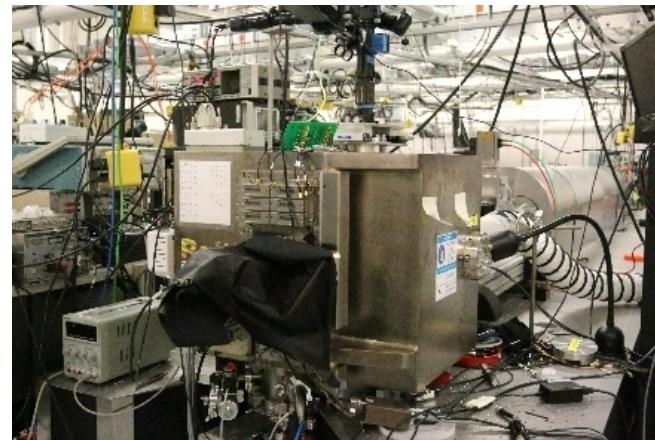
- 6 MV Tandem microbeam
(microONE)



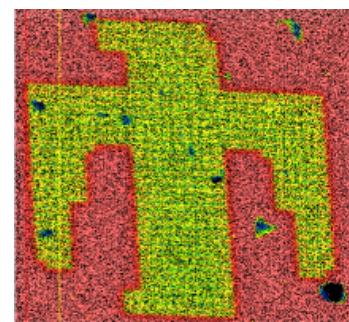
- High resolution laser stage
- Spot size $<1 \mu\text{m}$
- Energy 0.8 - 70 MeV
- H to Au



- 3 MV Pelletron microbeam
(Light Ion Microbeam)

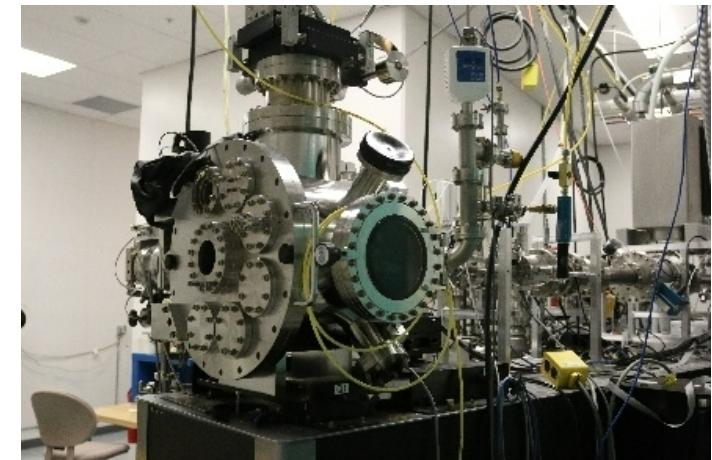


- High resolution laser stage
- Spot size $<600 \text{ nm}$
- Energy 0.25 - 3 MeV
- H, He, N, Ar, Xe, ...

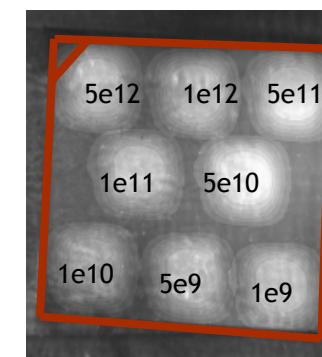


IBIC on
PIN diode

- 350 kV HVEE microbeam
(NanoBeamLine)



- Piezo stage
- Spot size $<1 \mu\text{m}$
- Energy 20 - 350 keV
- H to Au

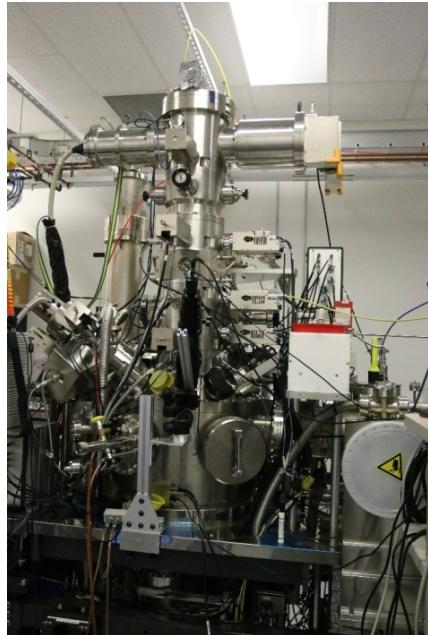


Ni into
diamond

Low Energy Focused Ion Beams <1 to 20 nm



- 100 kV A&D FIB100NI
(nanolmplanter)



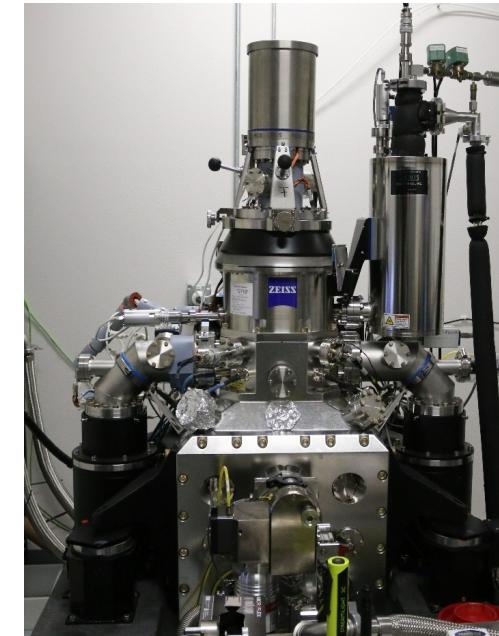
- High resolution laser stage
- Spot size <10 nm (Ga)
- Energy 10 - 200 keV
- 1/3 periodic table

- 35 kV Raith Velion
(Velion)



- High resolution laser stage
- Spot size <6 nm (Ga)
- Energy 5 - 70 keV
- 1/3 periodic table

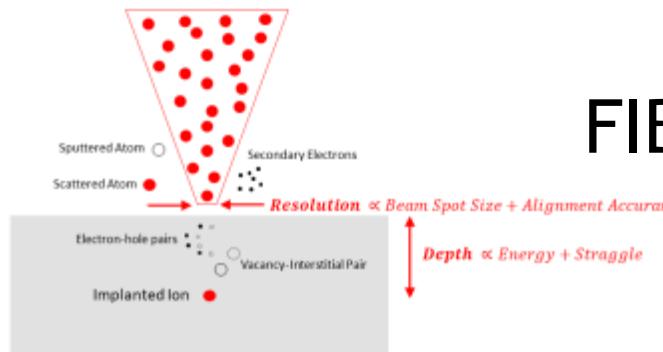
- 35 kV Zeiss Orion Plus
(HeLM)



- Piezo stage
- Spot size <1 nm
- Energy 10 - 35 keV
- He

All equipped with Lithography Software for Patterning

FIB Implantation Resolution



What our resolution?

High Energy FIB

Spot Size $\sim 1 \mu\text{m}$

Alignment accuracy $\sim 1 \mu\text{m}$

Overall resolution $\sim 1\text{-}2 \mu\text{m}$

Low Energy FIB

Spot Size \sim few nm

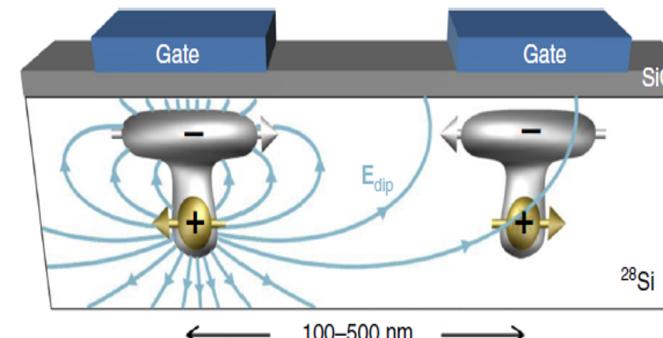
Alignment accuracy $\sim 10\text{'s nm}$

Overall resolution $\sim 20\text{-}50 \text{ nm}$

What is the needed resolution?

Silicon quantum processor with robust long-distance qubit couplings

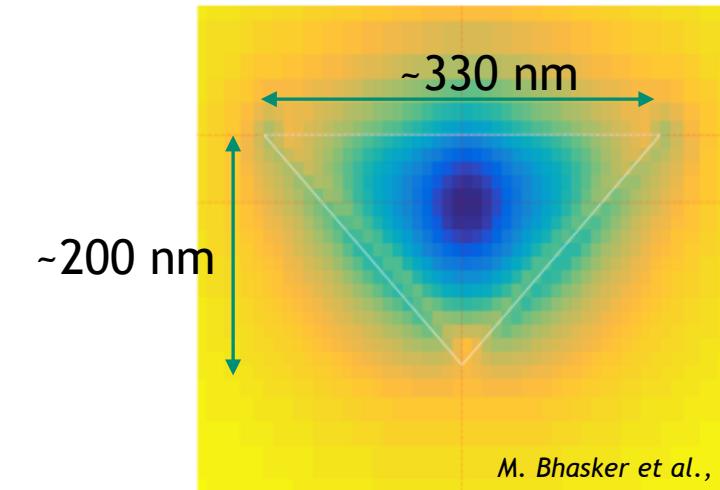
Guilherme Tosi¹, Fahd A. Mohiyaddin^{1,3}, Vivien Schmitt¹, Stefanie Tenberg¹, Rajib Rahman², Gerhard Klimeck² & Andrea Morello¹



G. Tosi et al., *Nat. Comm.* **8**, 450 (2017)

- Depth $z_d = 15\text{-}20 \text{ nm}$
- Separation of 100-500 nm

Nanophotonic Applications



Center of mode is $\sim 55 \text{ nm}$ below the surface of the waveguide

Low Energy Implantation? Lateral Positioning - OK, Target Depth - OK!

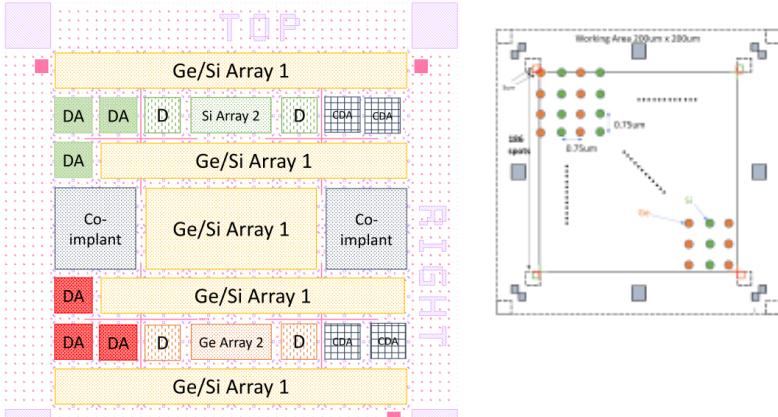
Practical Example of FIB Implantation



Conversation of what is needed?



Design and layout of sample



Capabilities accessible through CINT User Proposals

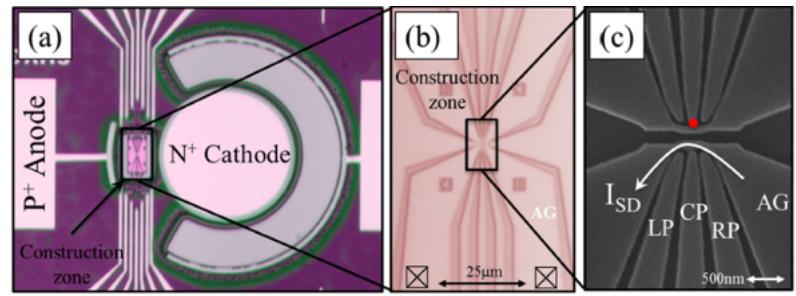
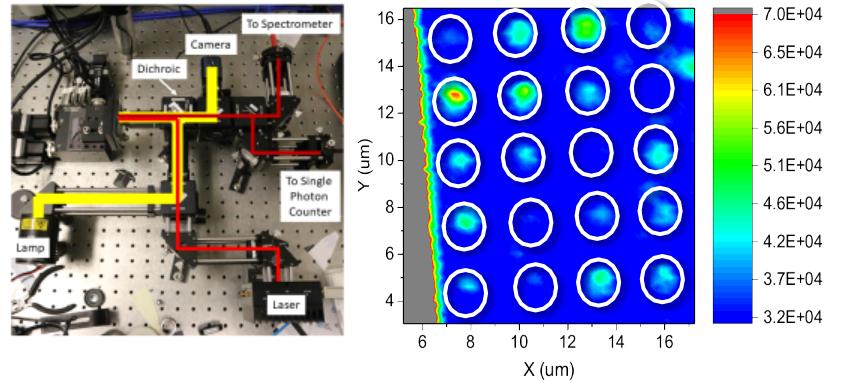
FIB Implantation/Irradiation



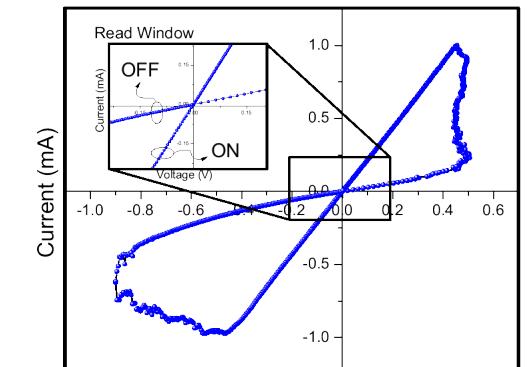
Post Implantation Sample Prep



Post Implantation Characterization

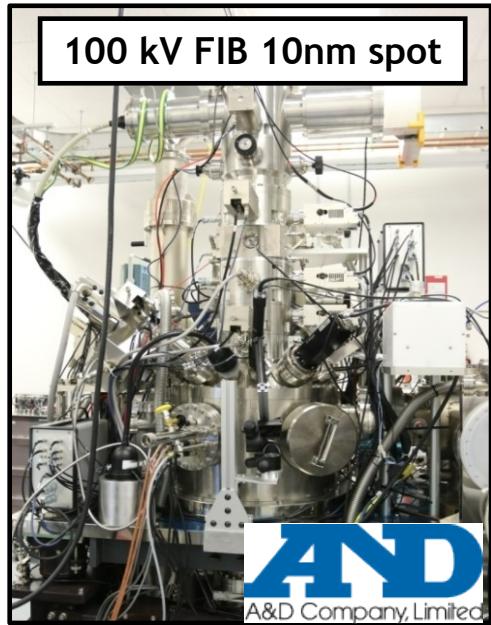


J. Pachaco, et al., Rev. of Sci. Instr. (2017)

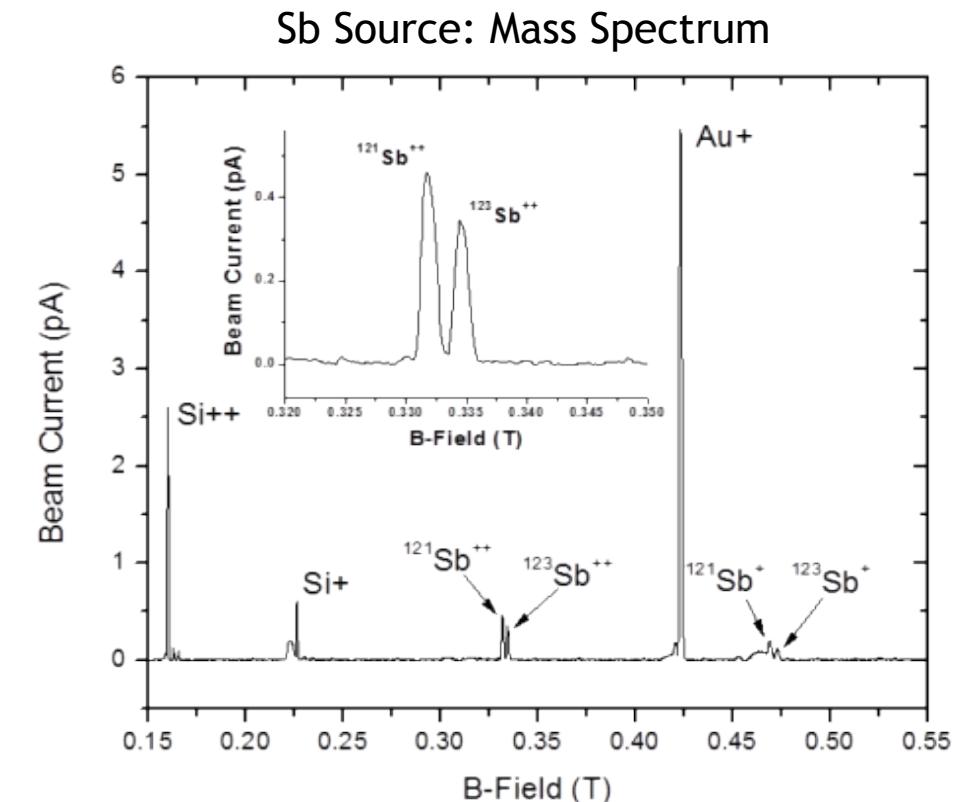
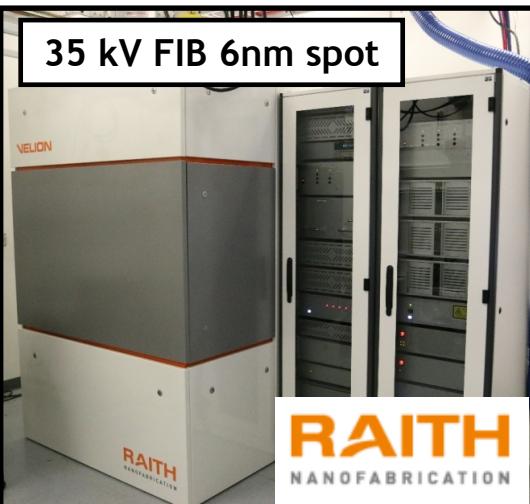


J. Pachaco, et al. Appl. Phys. A 124 626 (2018)

Focused Ion Beam Implantation - nanolimplanter (nl) and Velion



- Focused ion beam system (FIB)
→ nm beam spot size on target
- ExB Filter (Wien Filter)
→ Multiple ion species
e.g., 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
- Low temperature stage
- In-situ electrical probes



Liquid Metal Alloy Ion Sources (LMAIS) for FIB Implantation



hydrogen	1	H	1.0079
lithium	3	Li	6.941
beryllium	4	Be	9.0122
magnesium	12	Mg	24.305
sodium	11	Na	22.990
potassium	19	K	39.098
calcium	20	Ca	40.078
rubidium	37	Rb	85.468
strontium	38	Sr	87.62
caesium	55	Cs	132.91
barium	56	Ba	137.33
franckium	87	Fr	[223]
radium	88	Ra	[226]

Purple - running at SNL
 Yellow - attempting at SNL
 Green - demonstrated at other labs

hydrogen	1	H	1.0079	helium	2	He	4.0026
lithium	3	Li	6.941	beryllium	4	Be	9.0122
beryllium	4	Be	9.0122	magnesium	12	Mg	24.305
sodium	11	Na	22.990	aluminium	13	Al	26.982
potassium	19	K	39.098	silicon	14	Si	28.086
calcium	20	Ca	40.078	nitrogen	7	N	14.007
rubidium	37	Rb	85.468	oxygen	8	O	15.999
strontium	38	Sr	87.62	fluorine	9	F	18.998
caesium	55	Cs	132.91	neon	10	Ne	20.180
barium	56	Ba	137.33	hydrogen	1	H	1.0079
franckium	87	Fr	[223]	helium	2	He	4.0026
radium	88	Ra	[226]	beryllium	4	Be	9.0122
lawrencium	103	Lr	[262]	magnesium	12	Mg	24.305
rutherfordium	104	Rf	[261]	aluminium	13	Al	26.982
dubnium	105	Db	[262]	silicon	14	Si	28.086
seaborgium	106	Sg	[266]	nitrogen	7	N	14.007
bohrium	107	Bh	[264]	oxygen	8	O	15.999
hassium	108	Hs	[269]	fluorine	9	F	18.998
meitnerium	109	Mt	[268]	neon	10	Ne	20.180
uramium	110	Uun	[271]	hydrogen	1	H	1.0079
unununium	111	Uuu	[272]	helium	2	He	4.0026
ununbium	112	Uub	[277]	beryllium	4	Be	9.0122
ununquadium	114	Uuq	[289]	magnesium	12	Mg	24.305

* Lanthanide 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	europerium	63	Eu	151.96	gadolinium	64	Gd	157.25
neptunium	93	Np	[237]	europium	65	Tb	158.93	terbium	66	Dy	162.50	dysprosium	67	Ho	164.93
plutonium	94	Pu	[244]	europium	63	Tb	158.93	terbium	65	Dy	162.50	holmium	67	Ho	164.93
americium	95	Am	[243]	europium	63	Tb	158.93	terbium	66	Dy	162.50	erbium	68	Er	167.26
curium	96	Cm	[247]	europium	63	Tb	158.93	terbium	67	Dy	162.50	thulium	69	Tm	168.93
berkelium	97	Bk	[247]	europium	63	Tb	158.93	terbium	66	Dy	162.50	ytterbium	70	Yb	173.04
californium	98	Cf	[251]	europium	63	Tb	158.93	terbium	67	Dy	162.50	erbium	68	Er	167.26
einsteinium	99	Es	[252]	europium	63	Tb	158.93	terbium	66	Dy	162.50	thulium	69	Tm	168.93
fermium	100	Fm	[257]	europium	63	Tb	158.93	terbium	67	Dy	162.50	ytterbium	70	Yb	173.04
mendelevium	101	Md	[258]	europium	63	Tb	158.93	terbium	66	Dy	162.50	erbium	68	Er	167.26
nobelium	102	No	[259]	europium	63	Tb	158.93	terbium	67	Dy	162.50	thulium	69	Tm	168.93

** Actinide series

Wide Variety of Ion Species Available

New Sources - V, Cr, Fe, Zn, Sn, Tm (easy-ish)



hydrogen	1		helium	2
H	1.0079		He	4.0026
lithium	3			
Li	6.941	boron	5	
beryllium	4	carbon	6	He
Be	9.0122	nitrogen	7	
sodium	11	oxygen	8	
magnesium	12	fluorine	9	
Na	22.990	neon	10	
Mg	24.305			
potassium	19	boron	5	
calcium	20	carbon	6	
K	39.098	nitrogen	7	
Ca	40.078	oxygen	8	
rubidium	37	fluorine	9	
strontium	38	neon	10	
Rb	85.468			
Sr	87.62	boron	5	
cesium	55	carbon	6	
barium	56	nitrogen	7	
Cs	132.91	oxygen	8	
Ba	137.33	fluorine	9	
francium	87	neon	10	
radium	88			
Fr	89-102	boron	5	
Ra	*	carbon	6	
	[223]	nitrogen	7	
		oxygen	8	
		fluorine	9	
		neon	10	

Purple - running at SNL

Yellow - attempting at SNL

Green - demonstrated at other labs

scandium	21	titanium	22	vanadium	23	chromium	24	manganese	25	iron	26	cobalt	27	nickel	28	copper	29	zinc	30	gallium	31	germanium	32	arsenic	33	selenium	34	bromine	35	krypton	36
44.966		47.867		50.942		51.990		54.938		55.845		56.933		58.693		63.546		65.39		69.723		72.61		74.922		78.96		79.904		83.80	
potassium	19	calcium	20	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr												
39.098	40.078			44.966	47.867	50.942	51.990	54.938	55.845	56.933	58.693	63.546	65.39	69.723	72.61	74.922	78.96	79.904	83.80												
rubidium	37	strontium	38	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe												
85.468	87.62			39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54												
cesium	55	barium	56	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Tl	Pb	Bi	Po	At	Rn													
55.91	137.33			71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86												
francium	87	radium	88	La	Rf	Db	Sg	Bh	Hs	Bo	107	108	109	110	111	112	113	114	115												
87.91	137.33			103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	Lu	Rf	Db	Sg	Bh	Hs	Bo	180.95	183.84	186.21	190.23	192.22	195.08	196.97	201.59	204.38												
francium	87	radium	88	La	Rf	Db	Sg	Bh	Hs	Bo	106	107	108	109	110	111	112	113	114												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118												
francium	87	radium	88	103	104	105	106	107	10																						

Purple - running at SNL

Yellow - attempting at SNL

Green - demonstrated at other labs

hydrogen	1	
	H	
1.0079		
lithium	3	beryllium
	Li	4
6.941		Be
		9.0122
sodium	11	
	Na	12
22.990		Mg
		24.306
potassium	19	calcium
	K	20
39.098		Ca
		40.078
rubidium	37	strontium
	Rb	38
85.468		Sr
		87.62
caesium	55	barium
	Cs	56
132.91		Ba
		137.33
francium	87	radium
	Fr	88
223		Ra
		223

scandium	titanium	vanadium	chromium	manganese	iron	cobalt	nickel	copper	zinc	gallium	germanium	arsenic	selenium	brooine	krypton
21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
49.966	47.867	50.942	51.996	54.938	55.845	58.933	58.693	63.546	65.39	69.723	72.61	74.922	78.96	79.904	83.80
yttrium	zirconium	niobium	molybdenum	technetium	ruthenium	rhodium	palladium	silver	cadmium	yttrium	tin	antimony	tellurium	iodine	xenon
39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Ca	In	Sn	Sb	Te	I	Xe
88.906	91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	114.21	114.92	118.71	121.76	127.80	126.90	131.29
lutetium	hafnium	tantulum	tungsten	rhenium	osmium	ridium	platinum	gold	mercury	thallium	lead	bismuth	polonium	astatine	radon
71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
174.97	178.49	180.95	183.84	186.21	190.23	192.22	195.08	196.97	200.59	204.38	207.2	208.98	[209]	[210]	[222]
lawrencium	rutherfordium	dubnium	seaborgium	bohrium	hassium	meitnerium	unnilium	ununium	ununbium	ununquadium	114				
103	104	105	106	107	108	109	110	111	112						
Lr	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						
[162]	[161]	[162]	[162]	[164]	[166]	[170]	[171]	[172]	[177]						

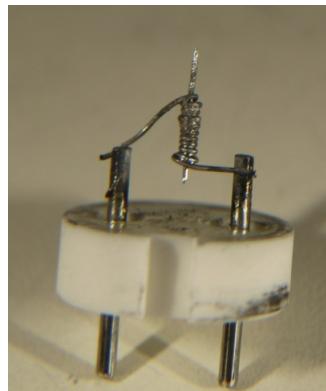
* Lanthanide series

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

**Actinide series

- B
 - Hard to load into the alloy BAuGeNi
 - C, Al, Ce
 - AlCeC alloy oxides while running, killing beam
 - Mg
 - GaMg alloy oxides in the boat
 - Pb
 - PbSn alloys with W tip, working on new materials

SNL SnPb tip on Kovar wire



New Sources - N (How to do???)

Purple - running at SNL
Yellow - attempting at SNL
Green - demonstrated at other labs

hydrogen 1 H 1.0079	beryllium 4 Be 9.0122	boron 5 B 10.811
lithium 3 Li 6.941	magnesium 12 Mg 24.305	aluminum 13 Al 26.982
sodium 11 Na 22.990	calcium 20 Ca 40.078	gallium 31 Ga 69.723
potassium 19 K 39.098	scandium 21 Sc 44.966	indium 49 In 114.82
rubidium 37 Rb 85.468	titanium 22 Ti 47.867	stannum 51 Sn 118.71
caesium 55 Cs 132.91	vanadium 23 V 50.942	tin 50 Tl 112.41
francium 87 Fr 223	chromium 24 Cr 51.996	lead 82 Pb 204.38
radium 88 Ra 226	manganese 25 Mn 54.938	thallium 83 Tl 209.94
lanthanum 57-70 *	iron 26 Fe 55.845	mercury 80 Hg 200.59
cerium 58 Ce 140.912	cobalt 27 Co 58.933	thulium 132 Tm 173.04
neptunium 93 Np 237	nickel 28 Ni 58.933	lutetium 131 Tb 150.919
curium 96 Cm 247	copper 29 Cu 63.546	neptunium 93 Np 237
curium 96 Cm 247	zinc 30 Zn 65.39	curium 96 Cm 247
curium 96 Cm 247	gallium 31 Ga 69.723	curium 96 Cm 247
curium 96 Cm 247	indium 49 In 114.82	curium 96 Cm 247
curium 96 Cm 247	stannum 51 Sn 118.71	curium 96 Cm 247
curium 96 Cm 247	tin 50 Tl 112.41	curium 96 Cm 247
curium 96 Cm 247	lead 82 Pb 204.38	curium 96 Cm 247
curium 96 Cm 247	thallium 83 Tl 112.41	curium 96 Cm 247
curium 96 Cm 247	mercury 80 Hg 200.59	curium 96 Cm 247
curium 96 Cm 247	thulium 132 Tm 173.04	curium 96 Cm 247
curium 96 Cm 247	lutetium 131 Tb 150.919	curium 96 Cm 247
curium 96 Cm 247	neptunium 93 Np 237	curium 96 Cm 247
curium 96 Cm 247	curium 96 Cm 247	curium 96 Cm 247

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	helium 2 He 4.0026
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
gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	seleium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	telurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
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]
ununquadium 114 Uuq [289]					

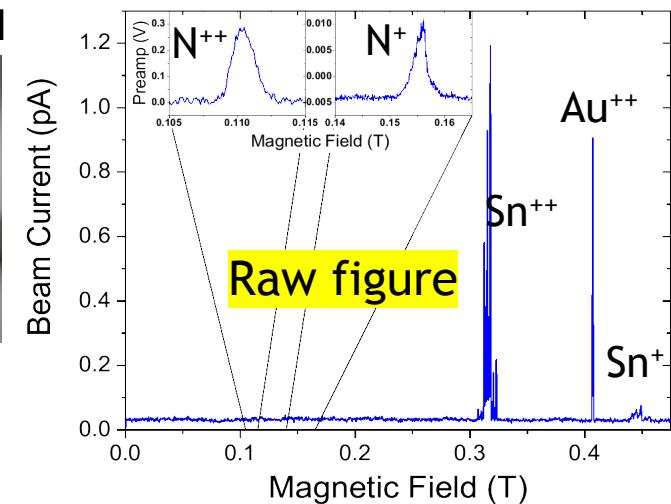
Lanthanide series

**Actinide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	pronethium 61 Pm 145.0	samarium 62 Sm 150.36	euroeuropium 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	yterbium 70 Yb 173.04
actinium 89 Ac [227]	thorium 90 Th [232]	protactinium 91 Pa [231]	uranium 92 U [238]	neptunium 93 Np [244]	plutonium 94 Pu [243]	americium 95 Am [247]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	moscovium 101 Md [258]	nobelium 102 Nb [259]

(1) Liquid metal alloys with implanted N

i.e., AuSn+N, In+N

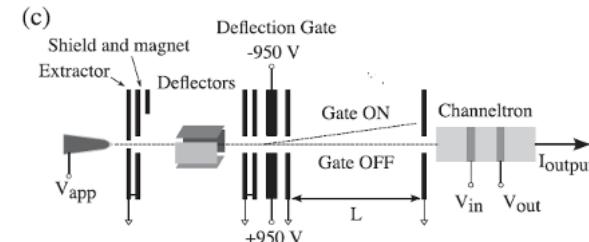
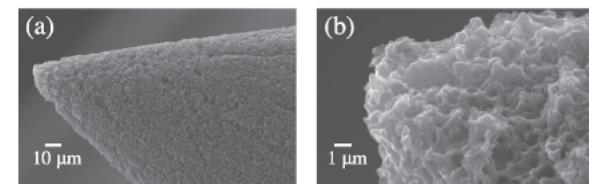


(2) Ionic Liquid Ion Source (with MIT)



(At SNL for testing)

Carbon Xerogel Microtip with ILIS



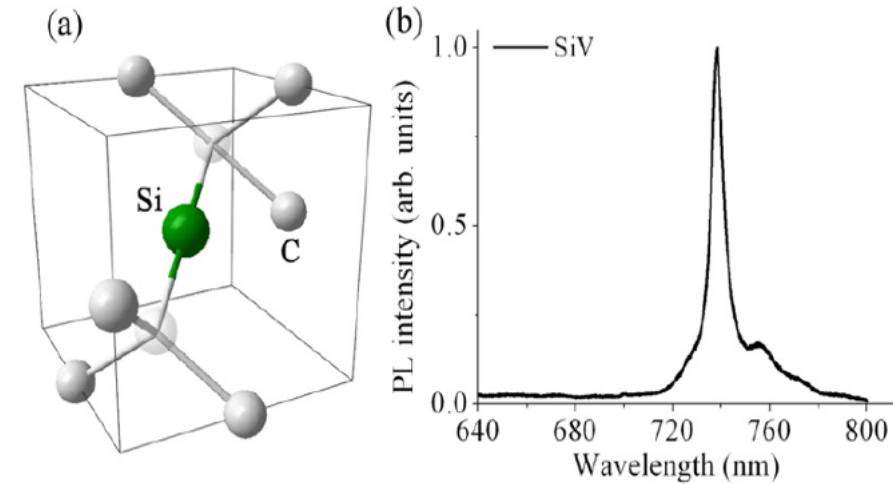
Single Defect Centers in Wide Bandgap Substrates



- Defect centers in wide bandgap substrates have applications from metrology to quantum computation

Ex. Silicon Vacancy Centers in diamond

The ion beam implantation and detection techniques are mainly material agnostic!



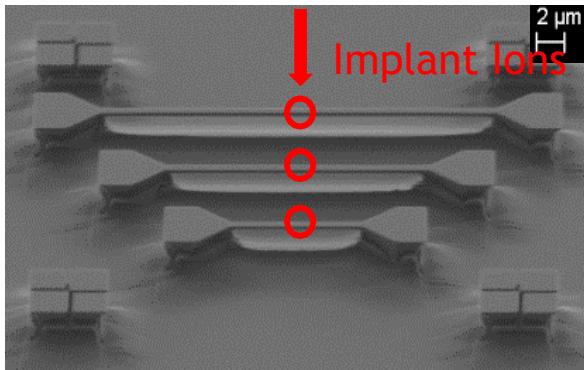
I. Aharonovich *et al.*, Rep. Prog. Phys. 74, 076501 (2011)

- How to produce a single defect center where you want it?
 - 1.) Location - focused ion beam implantation to control location
 - 2.) Yield - counted implantation to control the number of ions and PL to confirm an optically active defect center

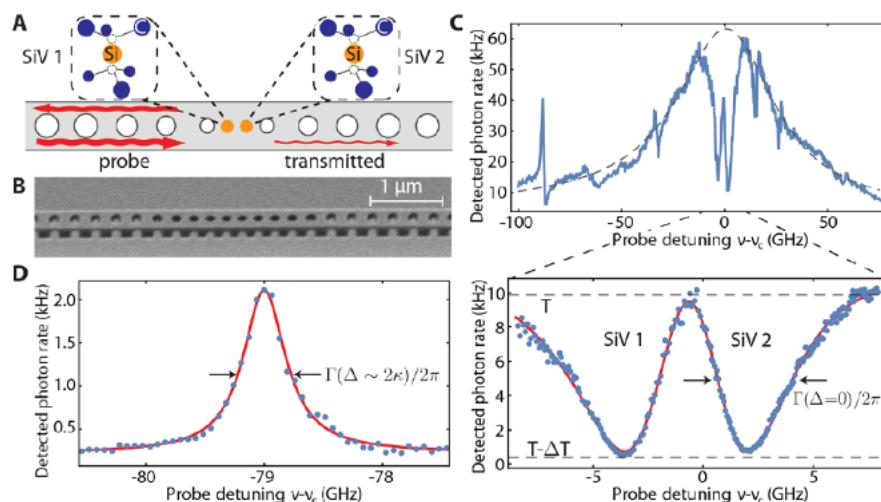
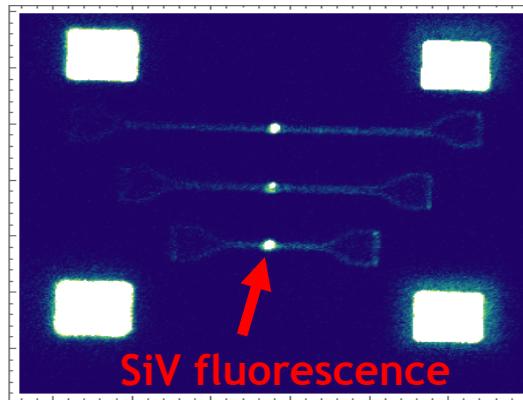
Use FIB implantation to control the spatial location



Diamond Nanobeams (with Harvard)

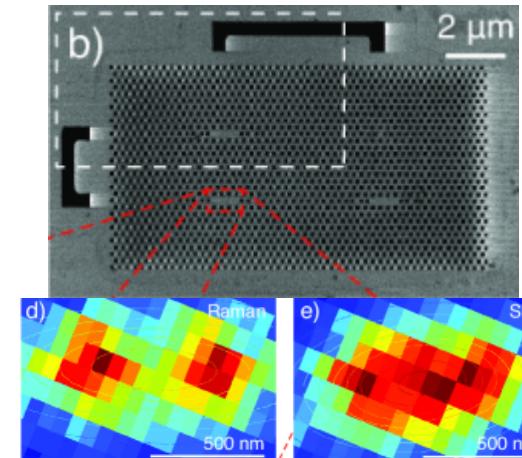


A. Sipahigil, *et al.*, *Science* (2016)



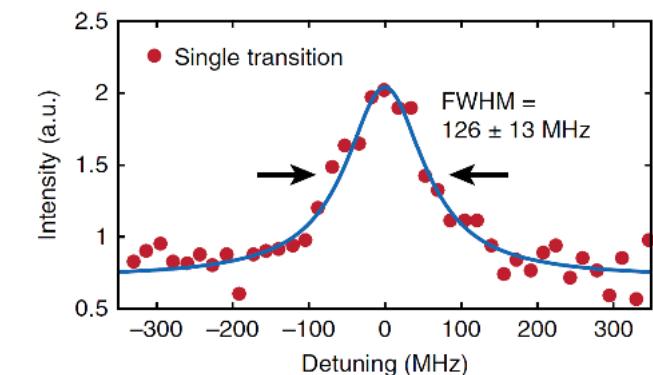
R. E. Evans, *et al.*, *Science* (2018)

2D photonic Crystals (with MIT)



Accuracy is <50 nm

T. Schroder, *et al.*, *Nature Communications* (2017)

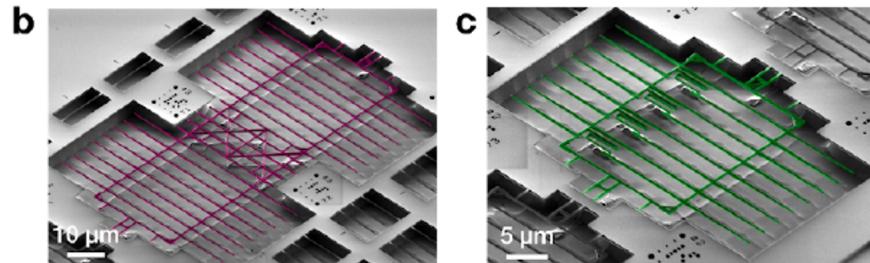


Use FIB implantation to control the spatial location

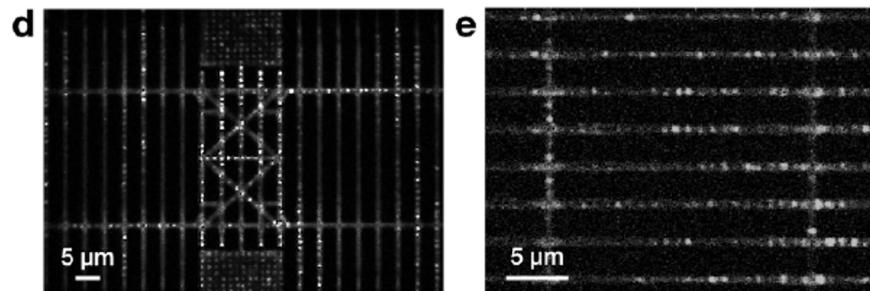


17

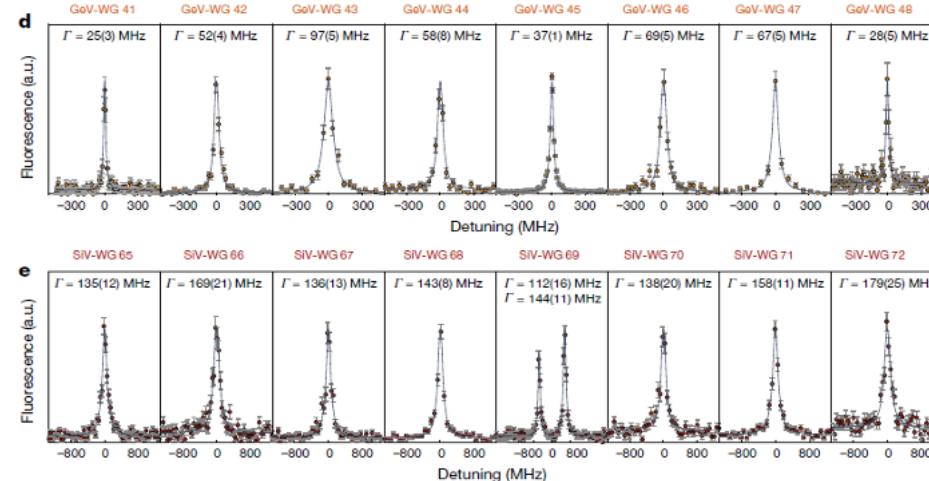
Diamond waveguides with AlN photonics (with MIT)



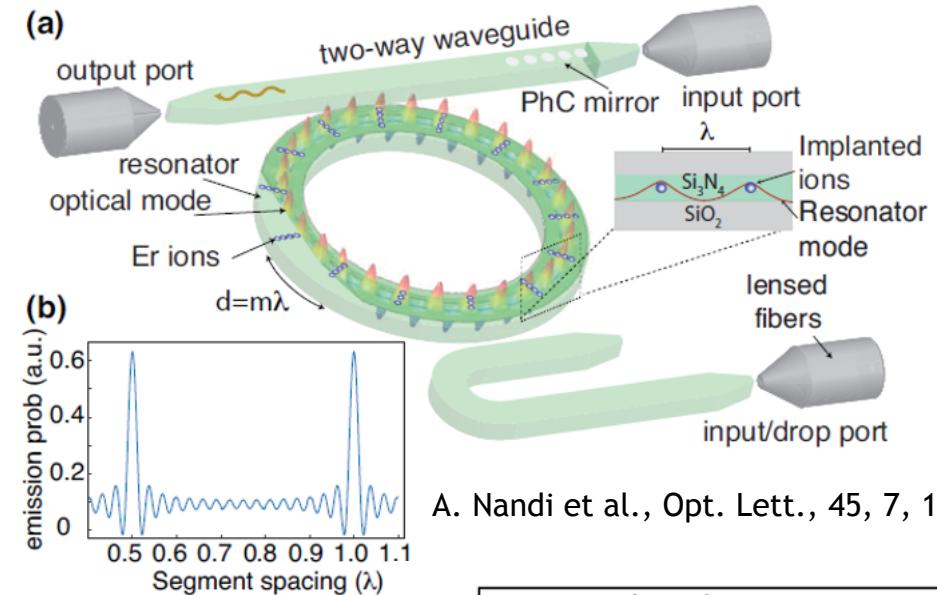
16 and 8 channel
“quantum micro-
chiplets”



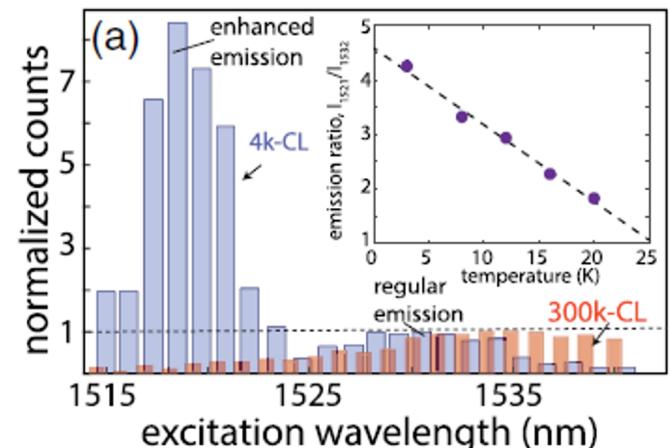
Noel H. Wan et al., Nature,
583, 226-231(2020)



Silicon Photonics (with Purdue)



A. Nandi et al., Opt. Lett., 45, 7, 1631 (2020)



Use Counted Implantation and Photoluminescence to Better Understand Yield



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



In-situ Photoluminescence

- Low activation yield limits our ability to make high yield arrays

(Yield numbers are typically 3-10%)

- In-situ photoluminescence can reduce the error in the number of defect centers

See EQ01.03.03 V. Chandrasekaran for more details

In-situ Counted Implantation

- Timed Implantation dominated by Poisson statistics for small numbers

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

- In-situ counting can reduce the error in the number of implanted ions

See EQ01.09.03 M. Titze for more details

In-situ Counted Ion Implantation

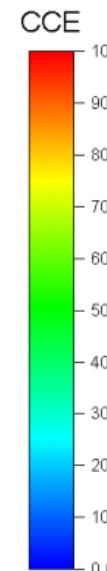
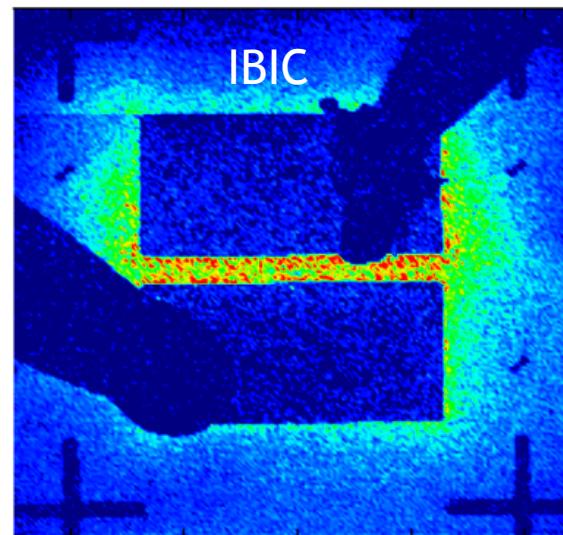
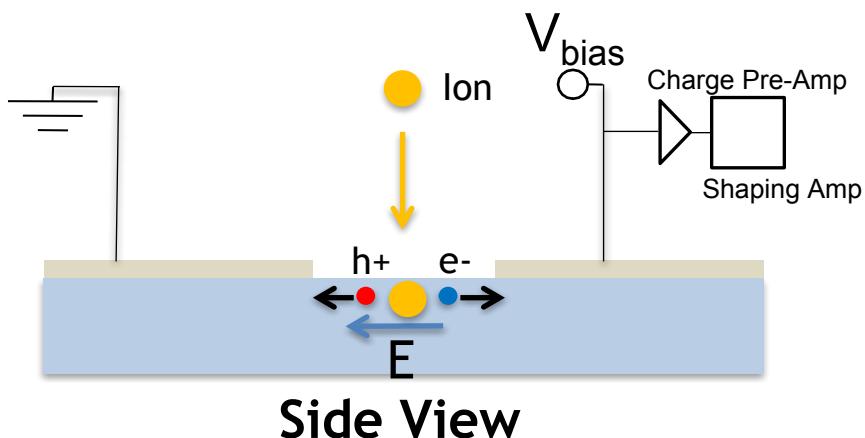


Yield = # measured SiV / # implanted Si

Poisson Statistics

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

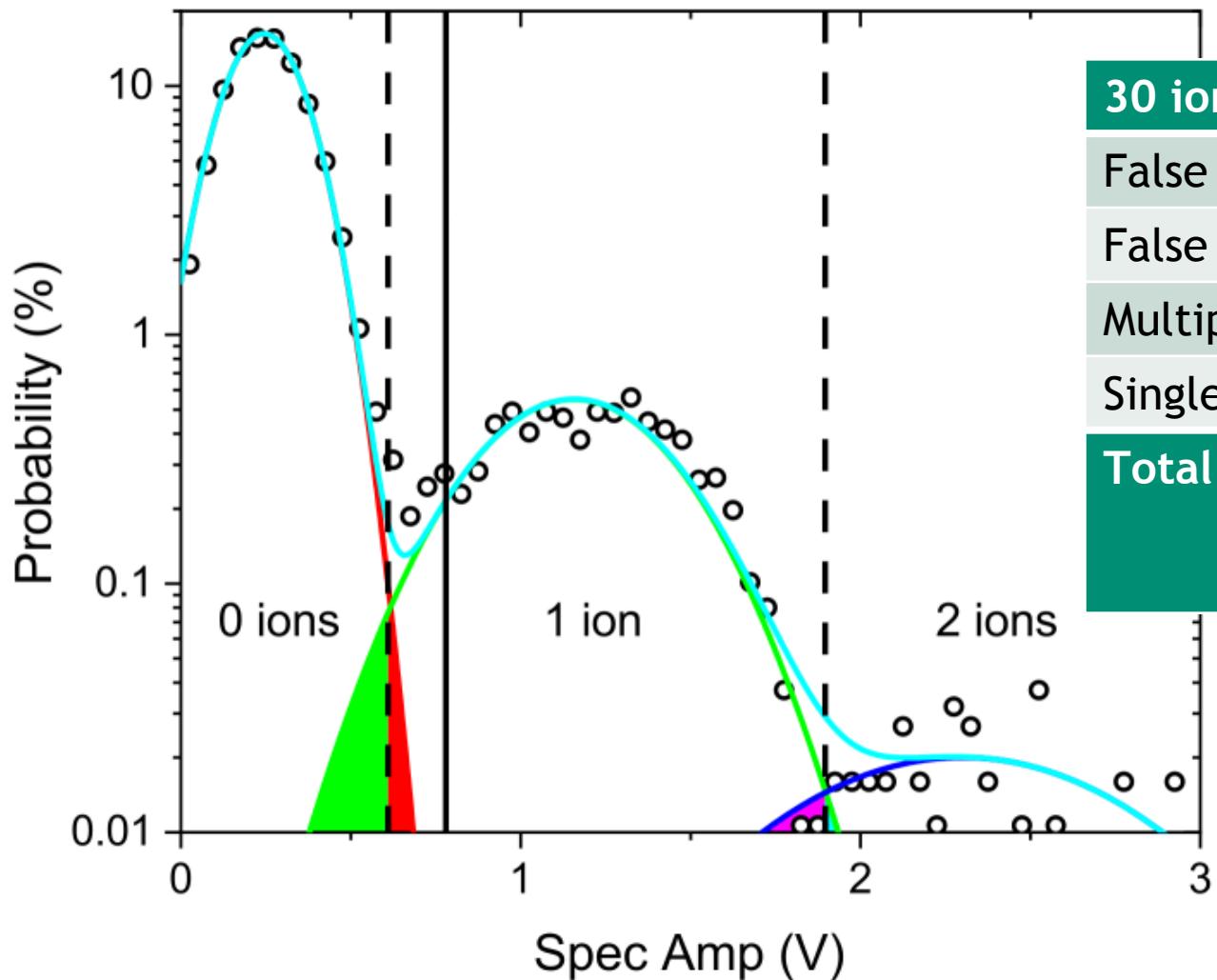
Ion Beam Induced Charge (IBIC)



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

IBIC/detection demonstrated for low energy heavy ions

Single Ion Diamond Detection at <0.1> ions/pulse



30 ions /<1> SiIV	Timed	In-Situ	Post-Analysis
False Positives	-	< -1 ppb	2.3 %
False Negatives	-	8.6 %	-0.9 %
Multiple Ions	-	5.8 %	1.7 %
Single as Double	-	-	-0.2 %
Total	+18.3 / -18.3 %	+14.4 / -0 %	+4.0 / -1.1 %

- 7x improvement in the error in implanted ions as compared to timed implantation

See EQ01.09.03 M. Titze
for more details

In-situ counting to reduce the error in the number of implanted ions

In-situ Photoluminescence



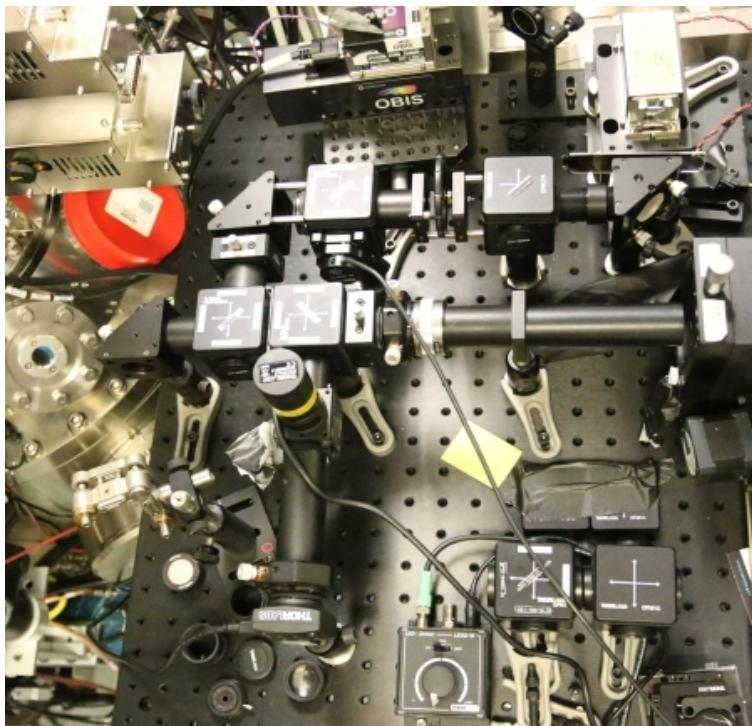
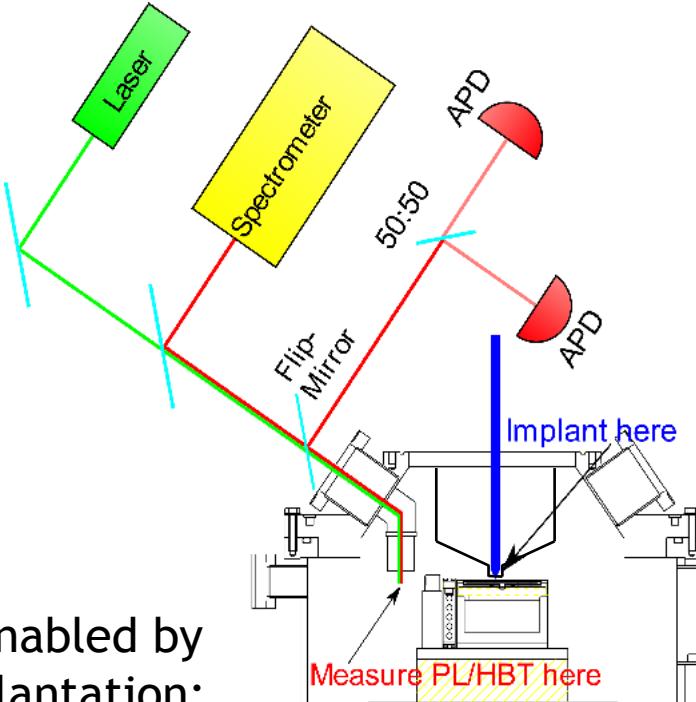
$$\text{Yield} = \# \text{ measured V}_{\text{Si}} / \# \text{ implanted Si}$$

We switched from SiV in diamond to V_{Si} in SiC as can measure as implanted samples without annealing

Two-step process enabled by high resolution implantation:

- (1) Aligned implantation, <40 nm
- (2) Detect PL

In-situ PL to confirm the optically emission from the defect centers

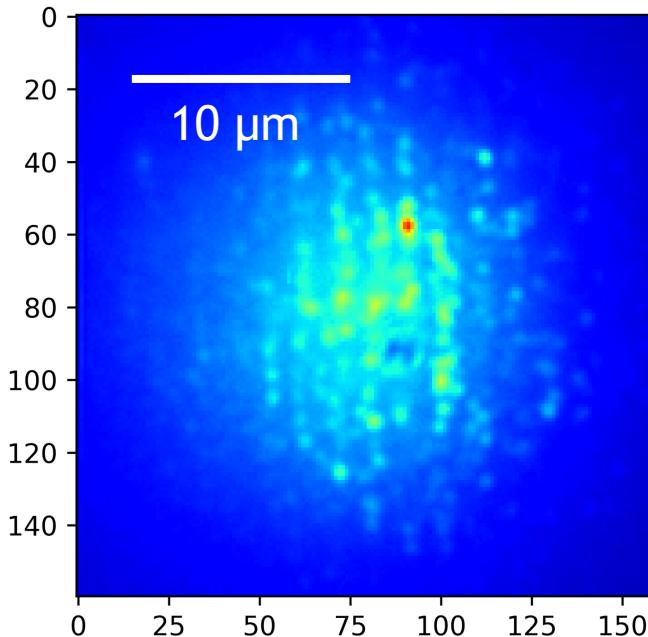


Replace with picture of in-situ setup on nl

In-situ Photoluminescence

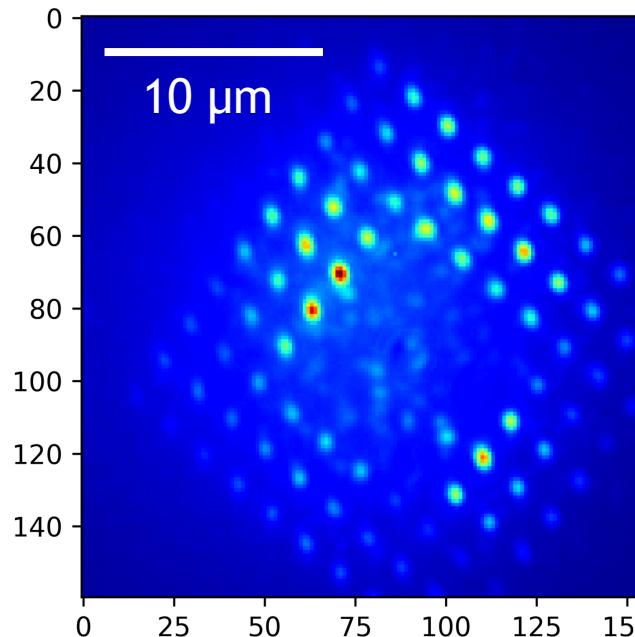


Background PL

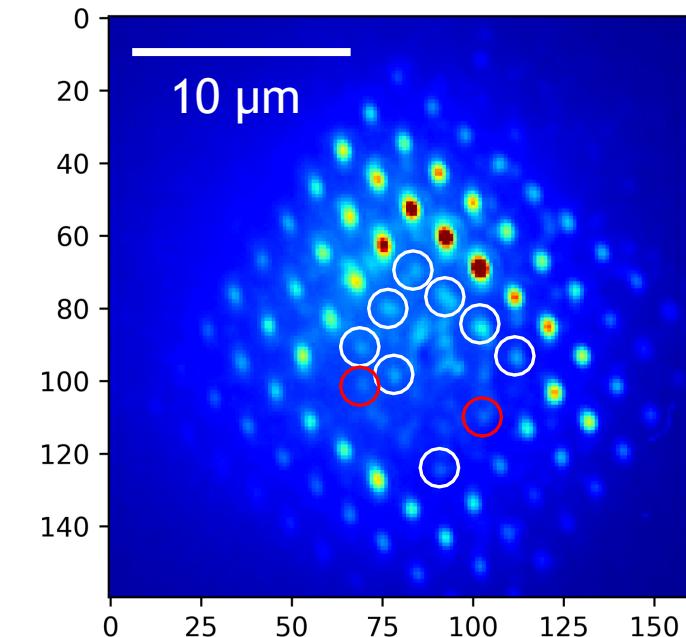


Replace with figure with constant color scale

Implant Alignment Grid



Implant/PL Repeat to fill Array



See EQ01.03.03 V. Chandrasekaran
for more details

Preliminary results suggest this works, BUT limited by high background counts

Acknowledgements



Sandia has developed strong internal **ion beam implantation** and **optical** groups

M. Titze, W. Hardy, J. L. Pacheco, J. B. S. Abraham, G. Burns, A. Flores, G. Vizkelethy (SNL)

M. Zaibari, Jacoby Henshaw, L. Basso, H. Byeon, A. Mounce, P. Keyayias, M. Lilly (SNL)

V. Chandrasekaran, Han Htoon (LANL)

V. Costa (UNM)

And we have continued to support a wide range of user groups through CINT



U.S. DEPARTMENT OF
ENERGY

Office of
Science

Argonne
NATIONAL LABORATORY

UTS
UNIVERSITY
OF TECHNOLOGY
SYDNEY

MIT
Massachusetts
Institute
of
Technology



THE HEBREW
UNIVERSITY
OF JERUSALEM

HARVARD
UNIVERSITY

THE UNIVERSITY OF
CHICAGO

Los Alamos
NATIONAL LABORATORY
EST. 1943

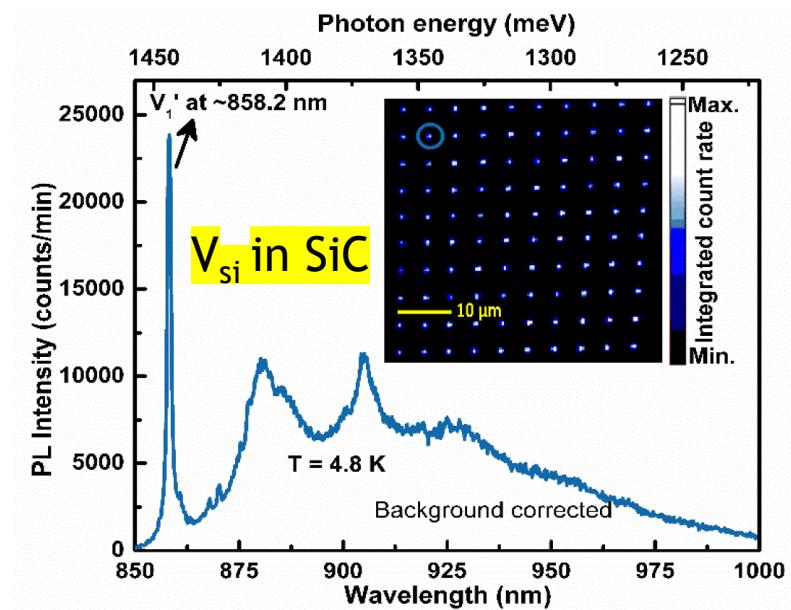
PURDUE
UNIVERSITY

Summary

- We have demonstrated focused ion implantation for fabrication of single atom devices and nanofabrication

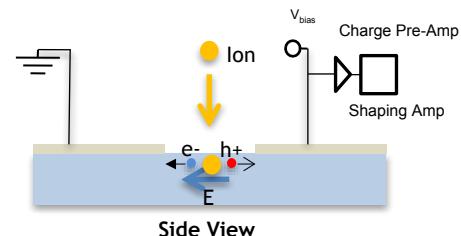
 - Viable solution for prototyping - fast and easy!

 - On-going work in diamond, SiN, SiC, hBN, GaN, AlGaN, etc...

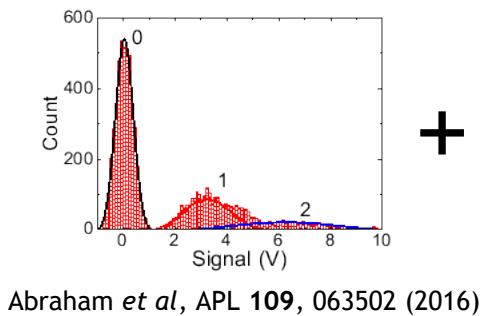


S. Pavunny et al., Scientific Report 11, 3561 (2021)

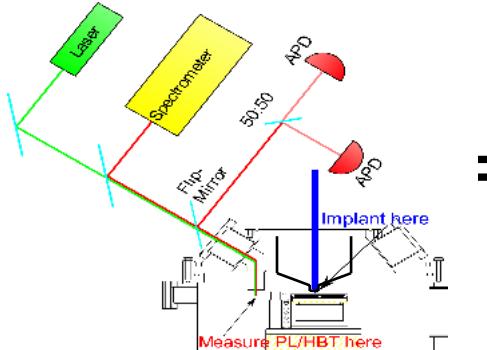
- Path Towards Deterministic Defect Centers in Wide Bandgap Materials



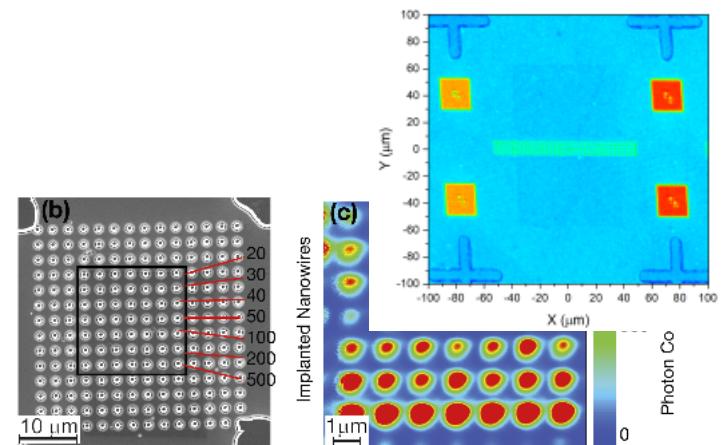
+



+



=



L. Marseglia, et al., Optics Express (2018)

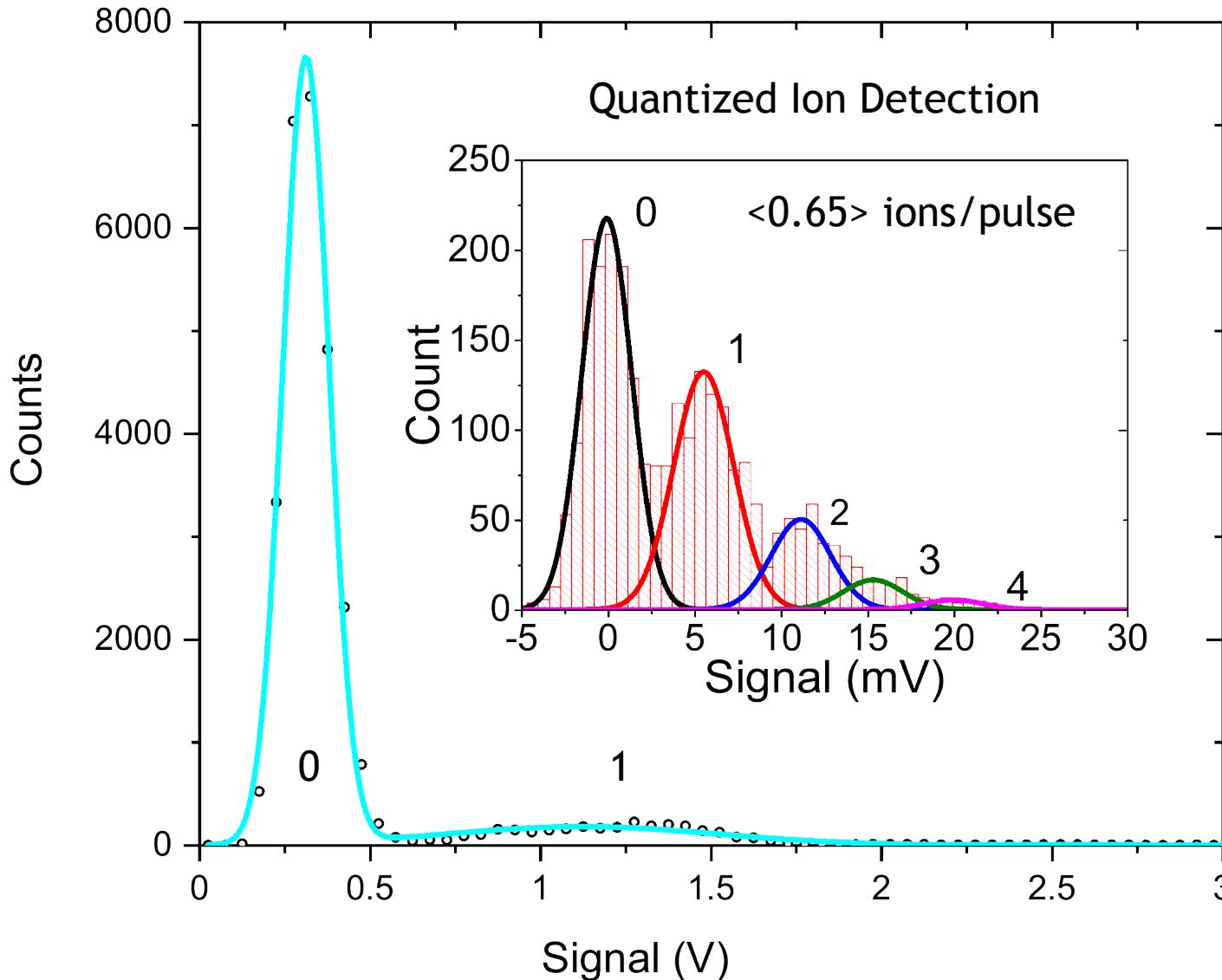
Control the number of ions

Confirm Optically Active Defect Centers

<https://cint.lanl.gov/>



Single Ion Diamond Detection at $<0.1>$ ions/pulse



Signal-to-noise ratio

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

$$SNR = 4.7$$

Good distinction between
0 and ≥ 1 ion

See EQ01.09.03 M. Titze at 2:00 pm
for more details

Overview of High Resolution Implantation Techniques



Resolution

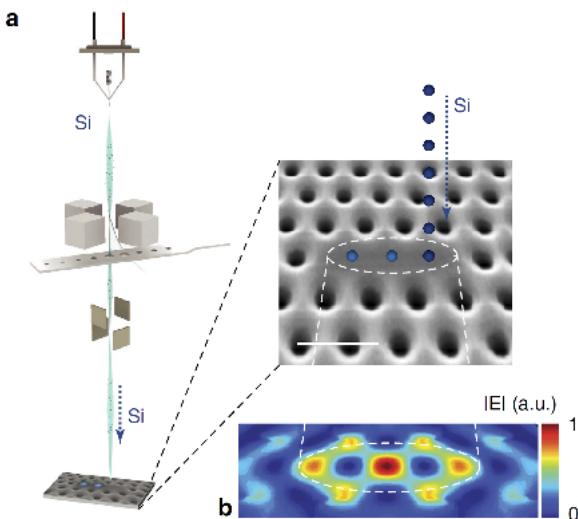
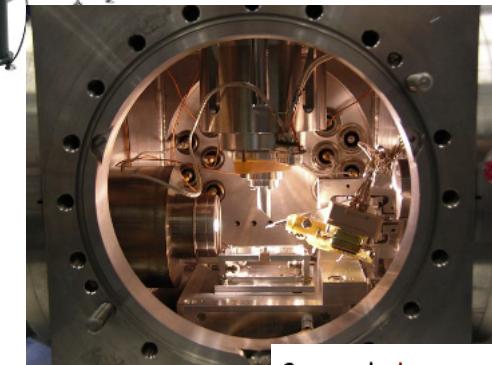


(1) Hydrogen Lithography

(2) Probe Based Implantation

(3) Focused Ion Beam (FIB) Implantation

Speed



Needed Resolution for Si Qubit Applications



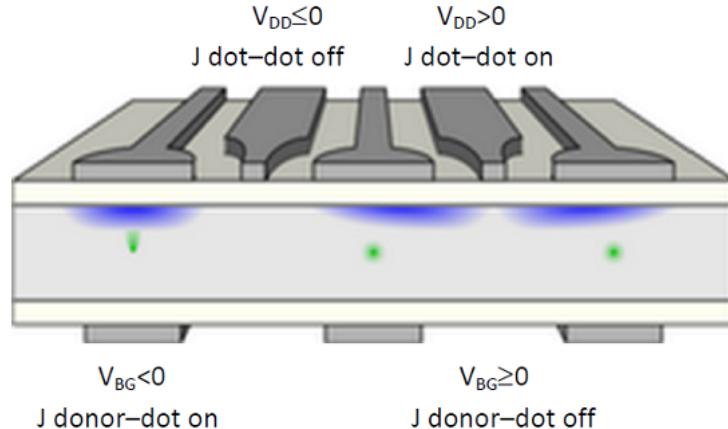
A spin quantum bit architecture with coupled donors and quantum dots in silicon

T. Schenkel¹, C. C. Lo¹, C. D. Weis¹, J. Bokor², A. M. Tyryshkin³, and S. A. Lyon³

¹Ion Beam Technology Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

²Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA

³Electrical Engineering Department, Princeton University, Princeton, NJ, USA
Contact-email: T_Schenkel@LBL.gov
(October 10, 2011)

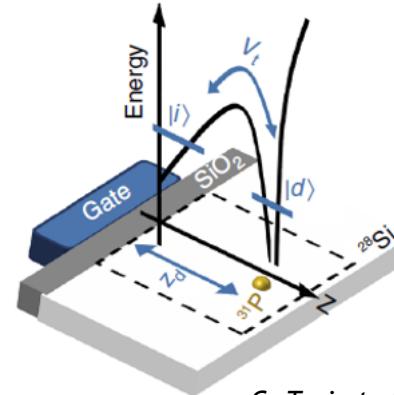
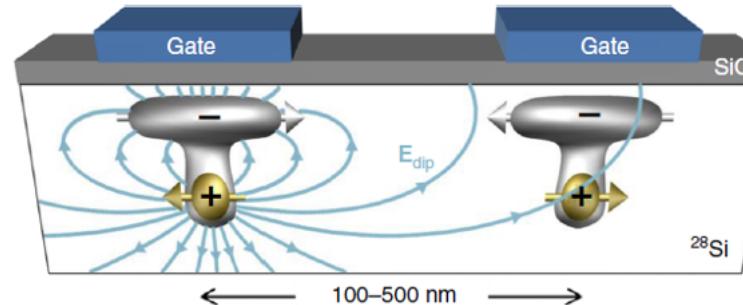


T. Schenkel *et al.*, US 8,816,325 B2 (2014)

- Depth ~20-50 nm
- Donor separation ~100 nm

Silicon quantum processor with robust long-distance qubit couplings

Guilherme Tosi¹, Fahd A. Mohiyaddin^{1,3}, Vivien Schmitt¹, Stefanie Tenberg¹, Rajib Rahman², Gerhard Klimeck² & Andrea Morello¹



- Depth z_d = 15 nm or larger
- Separation of 100-500 nm

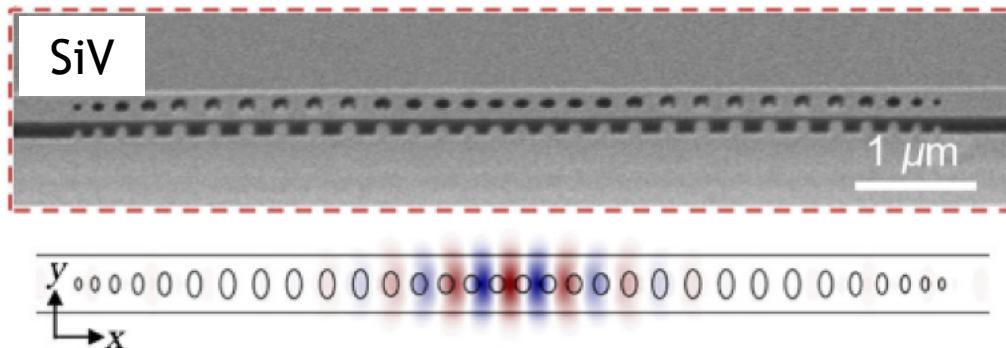
G. Tosi *et al.*, Nat. Comm. 8, 450 (2017)

FIB Implantation? Lateral Resolution - OK, but Depth Resolution requires low energies!

Needed Resolution for Nanophotonics Applications



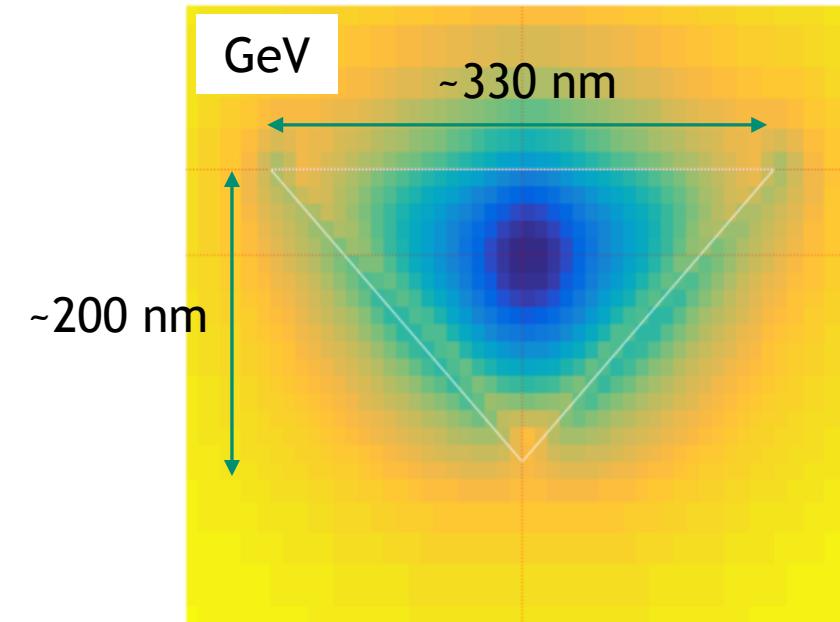
Coupling Diamond defect center to cavity



M. J. Burek *et al.*, *Phys. Rev. Applied* **8**, 024026 (2017)

- Design the cavity around ion straggle
- Linear fall off in coupling strength

Cross-sectional energy profile of cavity mode



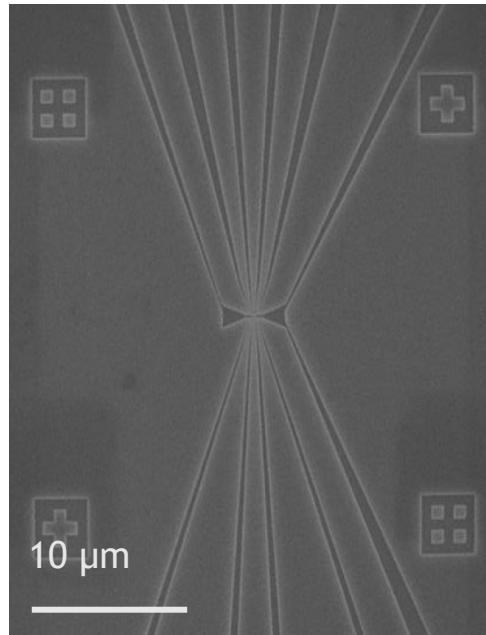
Center of mode is ~ 55 nm below
the surface of the waveguide

M. Bhasker *et al.*,

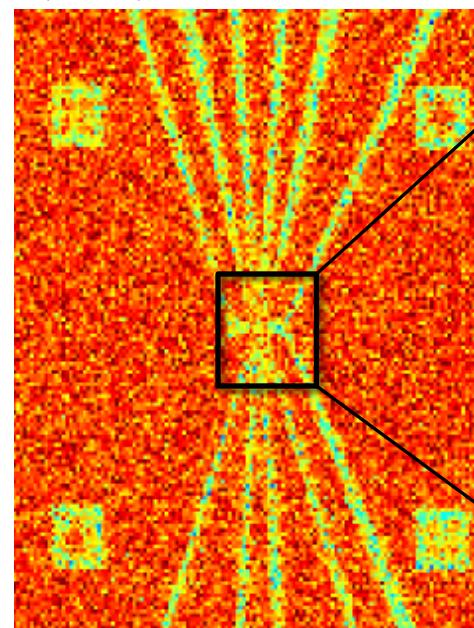
FIB Implantation? Lateral Resolution - OK, Depth Resolution - OK!

Targeting Resolution for FIB Implantation

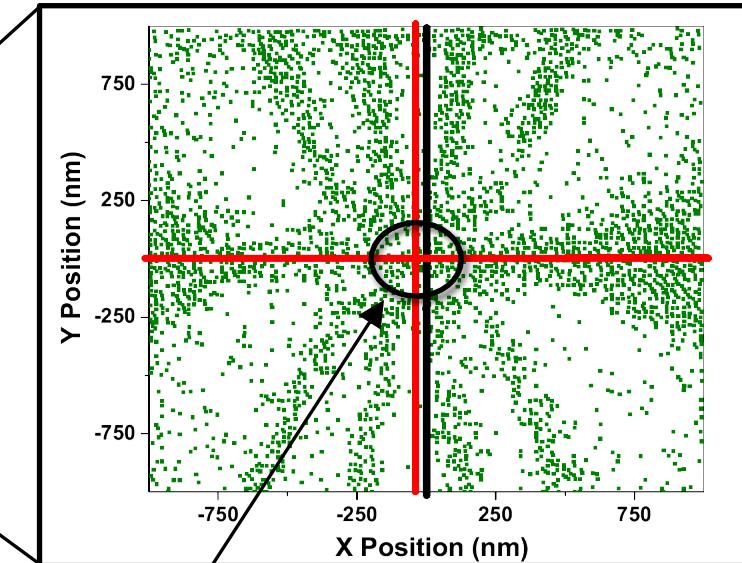
SEM of nanostructure



Ion Beam Induced Charge Collection (IBIC) of nanostructure

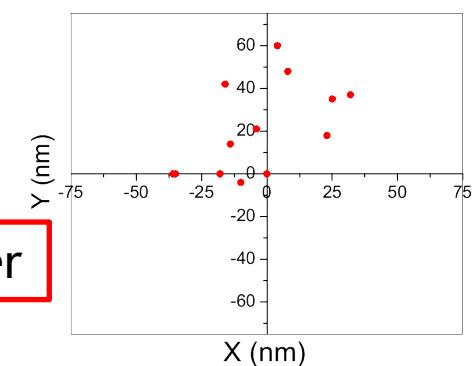


High resolution IBIC for targeting



$\Delta x \sim 35 \text{ nm}$
 $\Delta y \sim 0 \text{ nm}$

Targeting Accuracy



Targeting resolution $<40 \text{ nm}$, new Velion should improve this number

How to address the yield question?

Our Approach is to use single ion detectors to better understand the yield

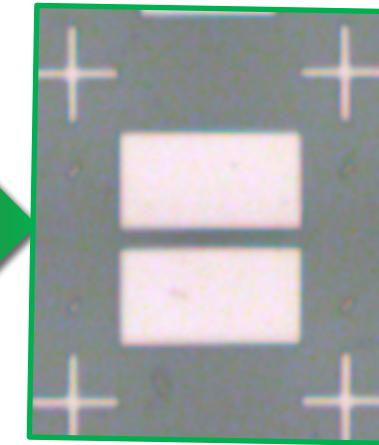
Silicon



J. Seamons, *et. al.* Appl. Phys. Lett, 93, 043124 (2008)

E. Bielejec, *et. al.* Nanotechnology 21, 085201 (2010)

Diamond

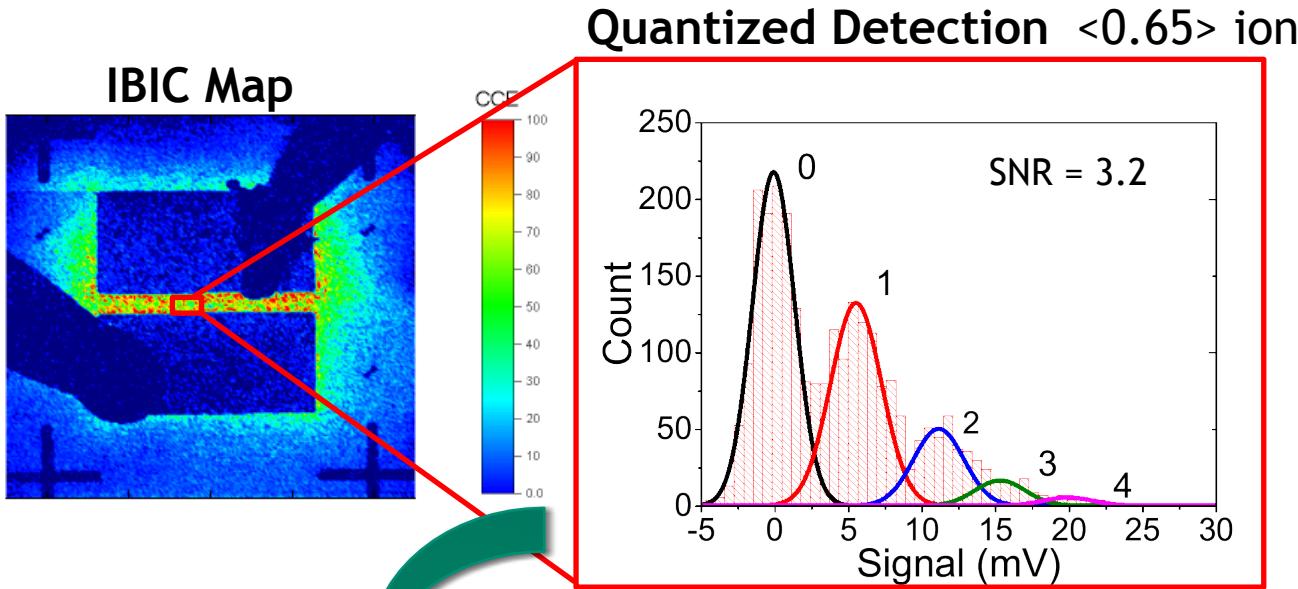


J. Abraham *et al*, APL 109, 063502 (2016)

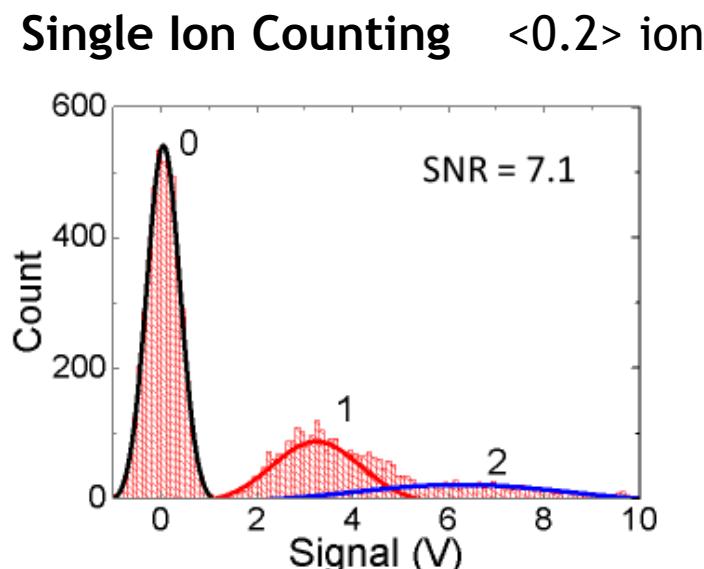
Translating single
ion detection to
diamond

Allows us to improve understanding of the yield by directly counting the number of implanted ions

Single Ion Diamond Detectors



Optimizing gain
for single ion
detection



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

Signal amplitudes match
Poisson statistics to 4%

Single Ion Detection in Diamond
with high SNR

Failure Modes for Single Ion Implantation



Three failure modes:

(1) **Implant Multiple Ions**

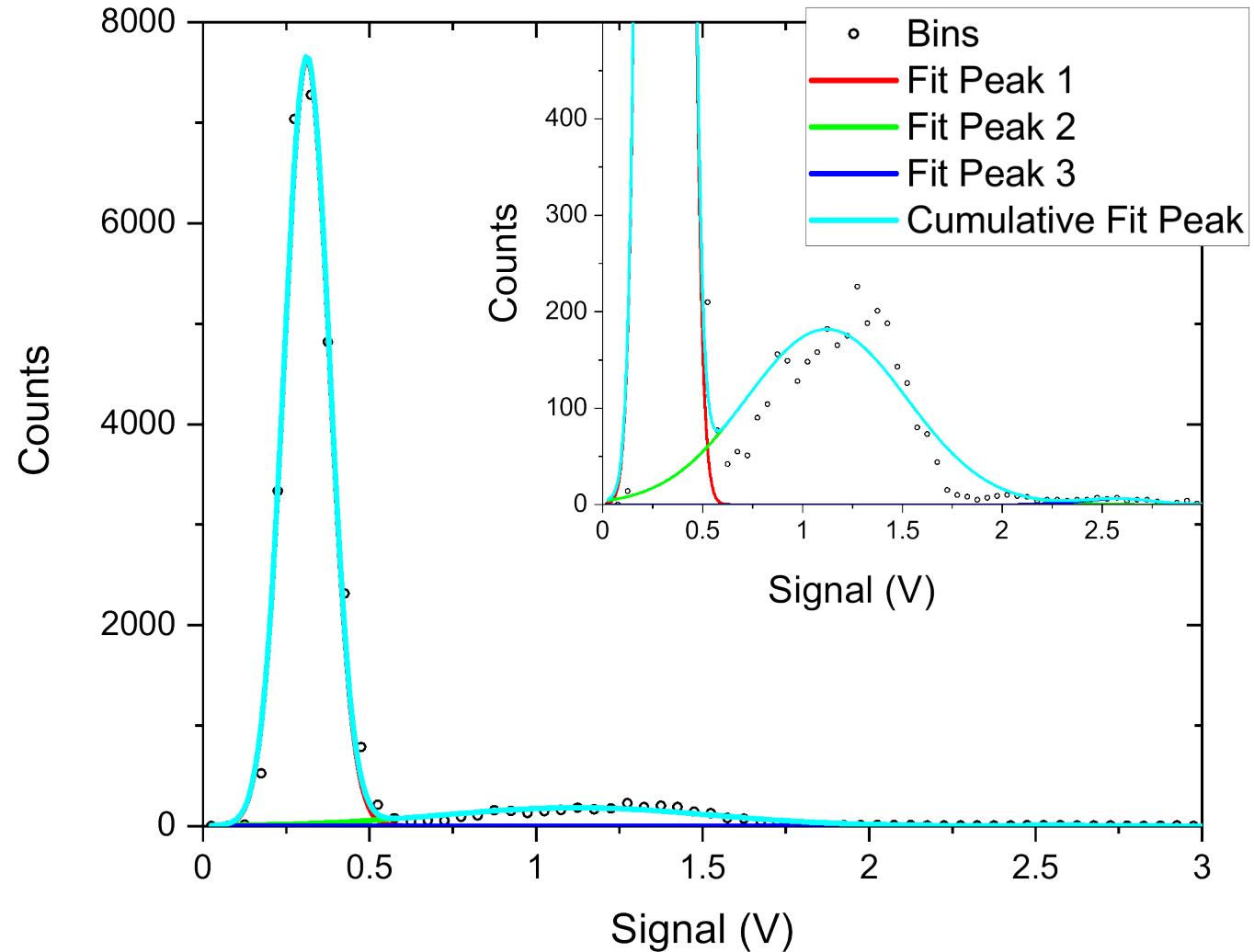
Implant >1 , but count as 1

(2) **False Positive**

Implant 0 ions, but count as 1

(3) **False Negative**

Implant 1 ion, but count as 0



Failure Mode #1: Implanting Multiple Ions



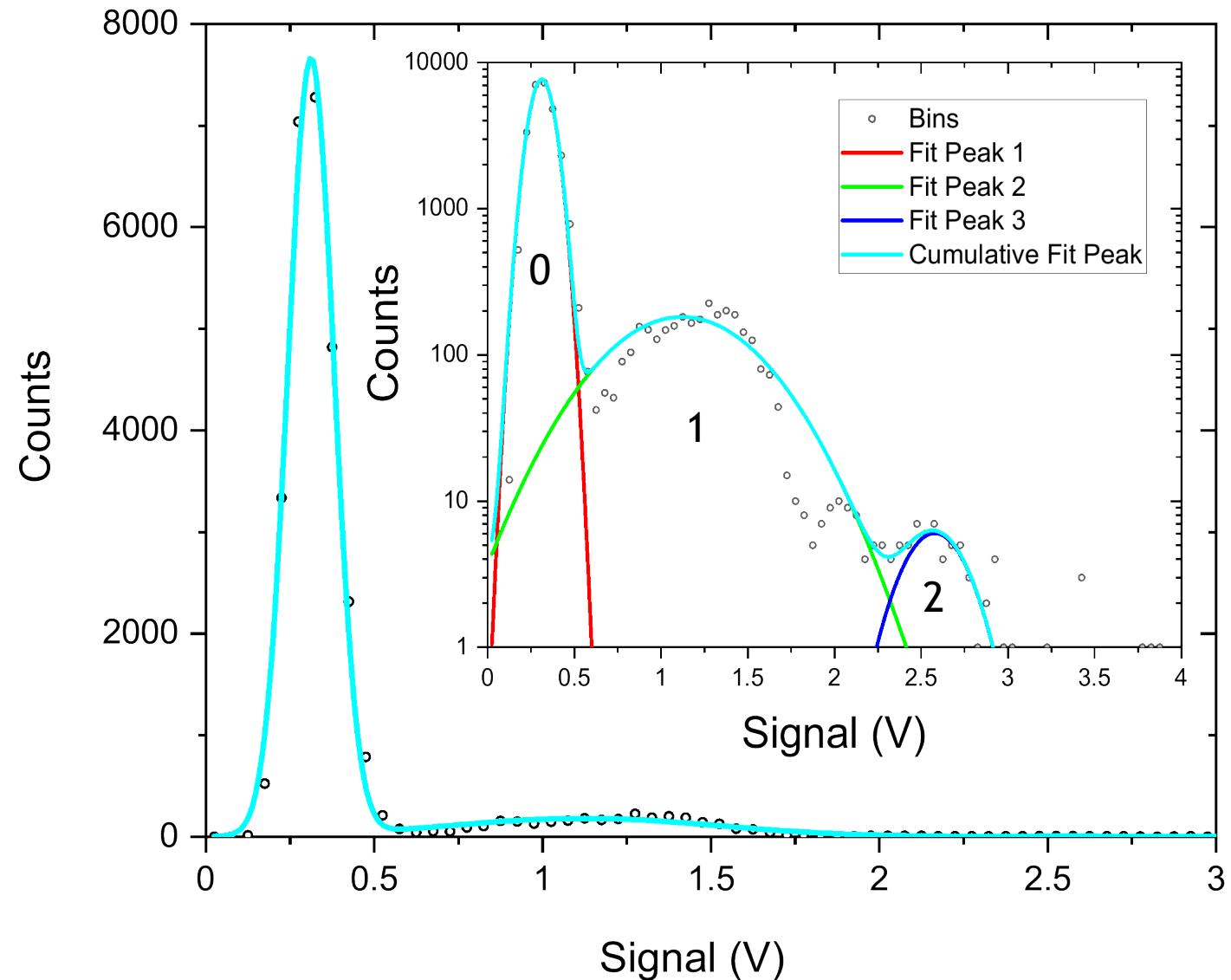
(1) Implant Multiple Ions

Implant >1 , but count as 1

Ion implantation follows a Poisson distribution

$\langle 0.1 \rangle$ ions/pulse: 90% 0's, 9% 1's and 0.45% 2 or more

Effectively 5% error in # of ions, for example count in 20 singles and get 21 ions



Failure Mode #2: False Positives



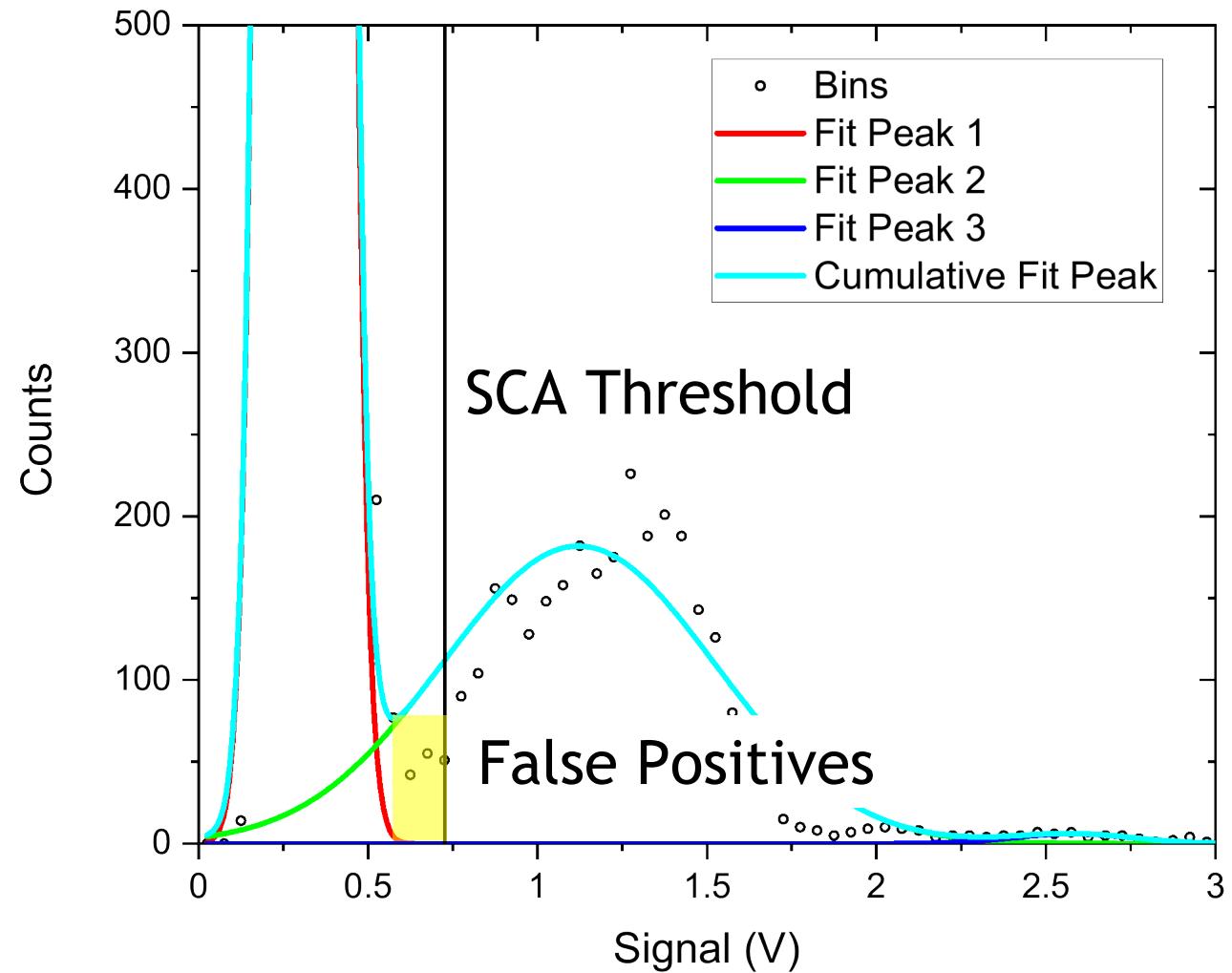
(2) False Positive

Implant 0 ions, but count as 1

In case on right, we have a SNR of 4.7 between 0 and 1

We adjust the SCA threshold to avoid false positives

Leads to practically no (~1 ppb) false positives



Failure Mode #3: False Negatives



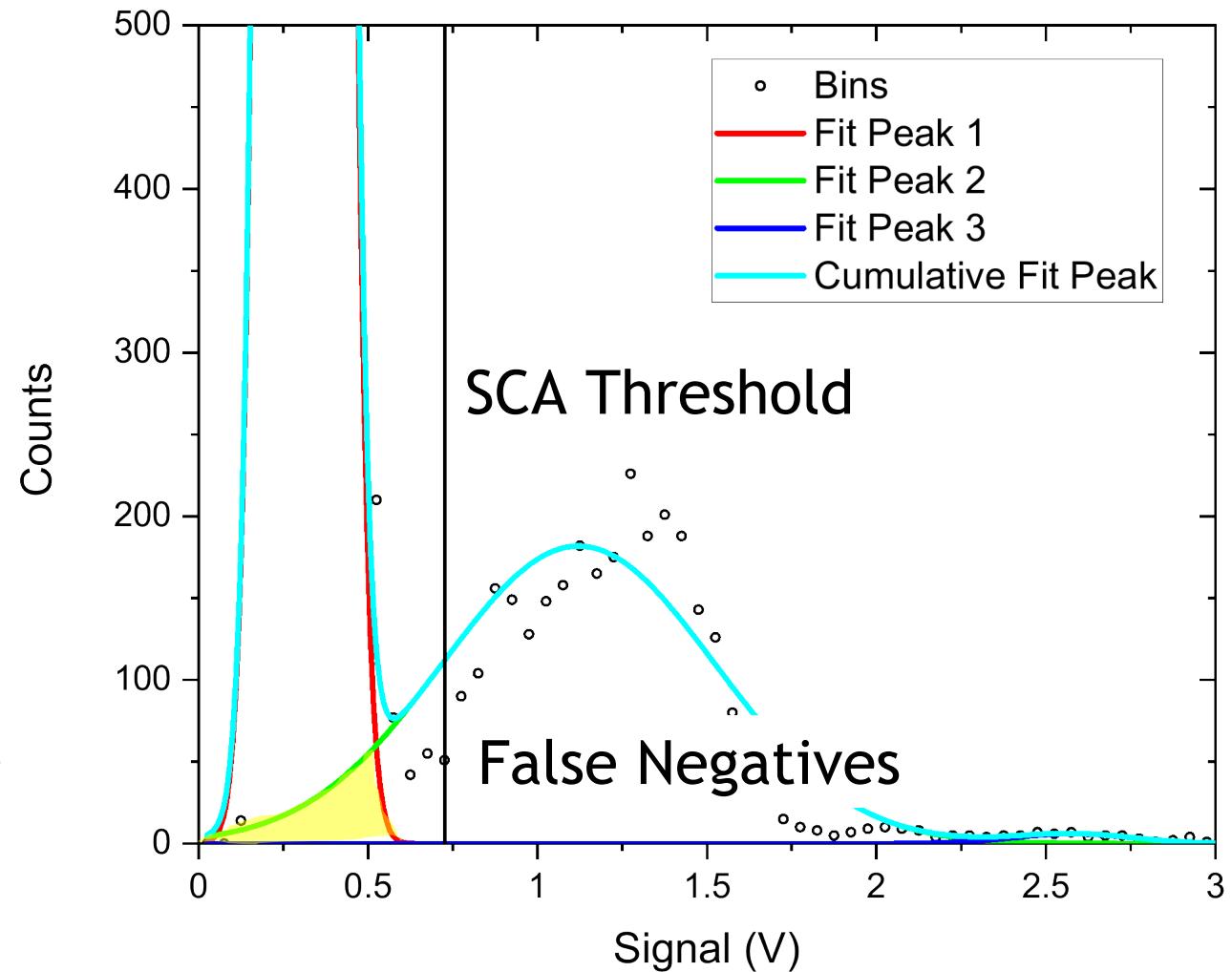
(3) False Negative

Implant 1 ion, but count as 0

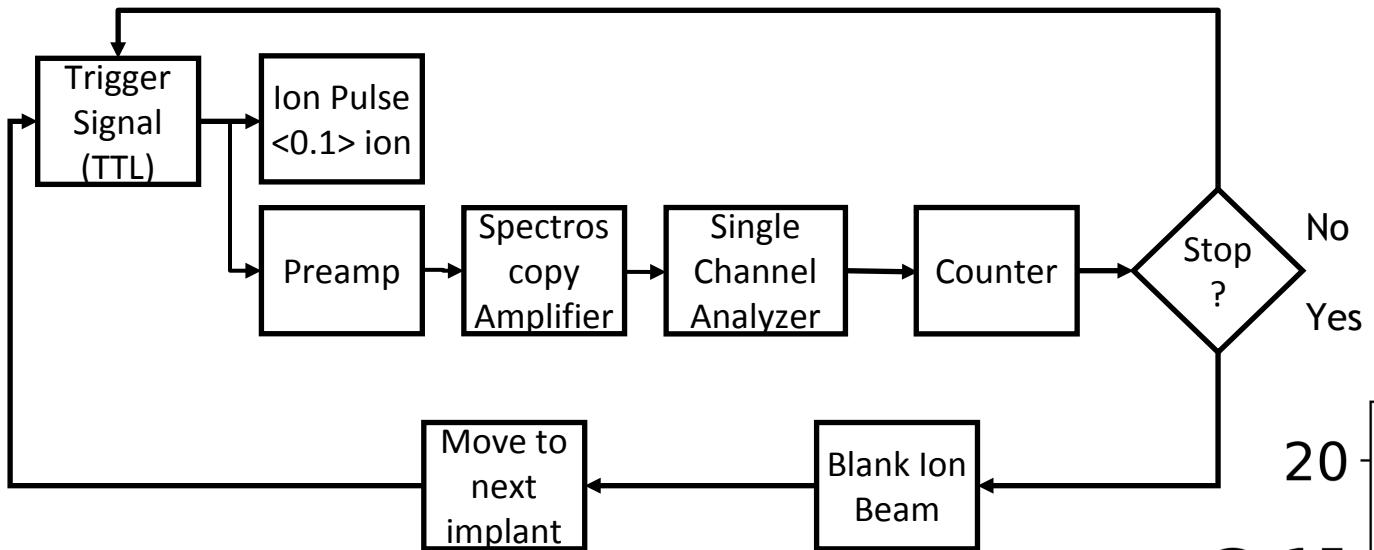
Adjust the SCA threshold to avoid false positives

SCA optimization leads to ~10% false negatives

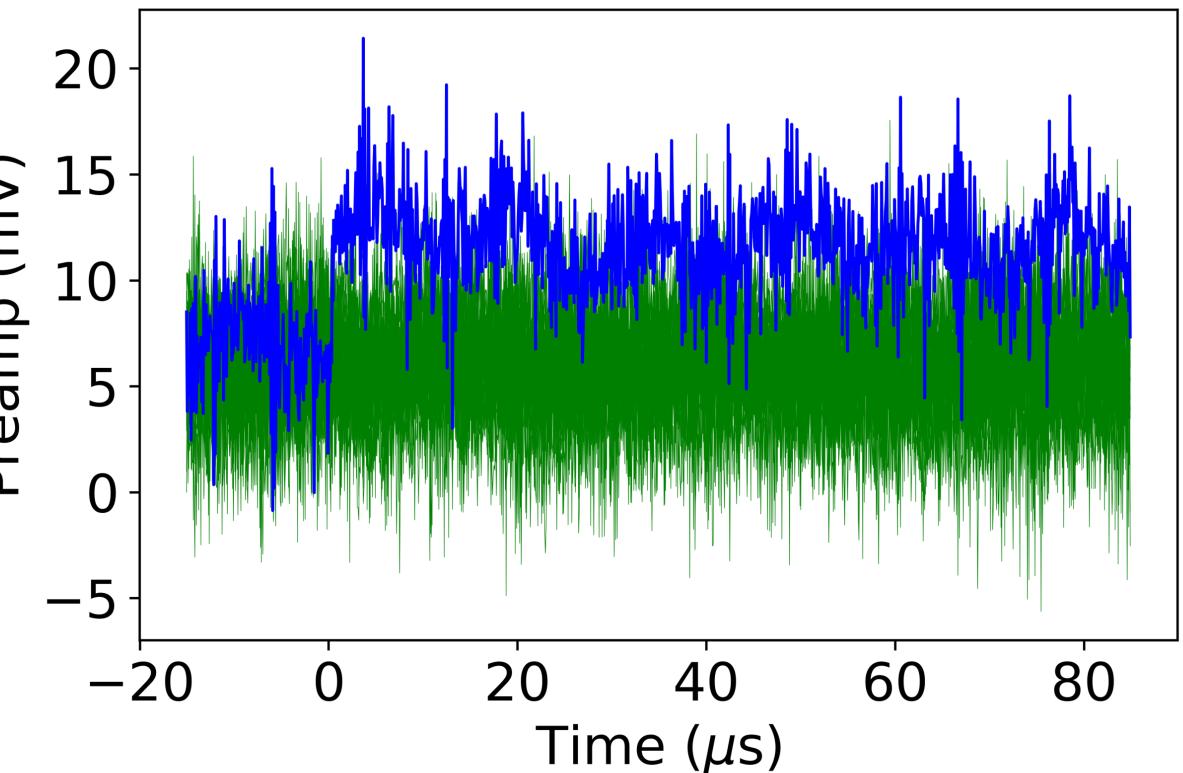
→ Largest source of error in our process



In-situ Counting Experiment



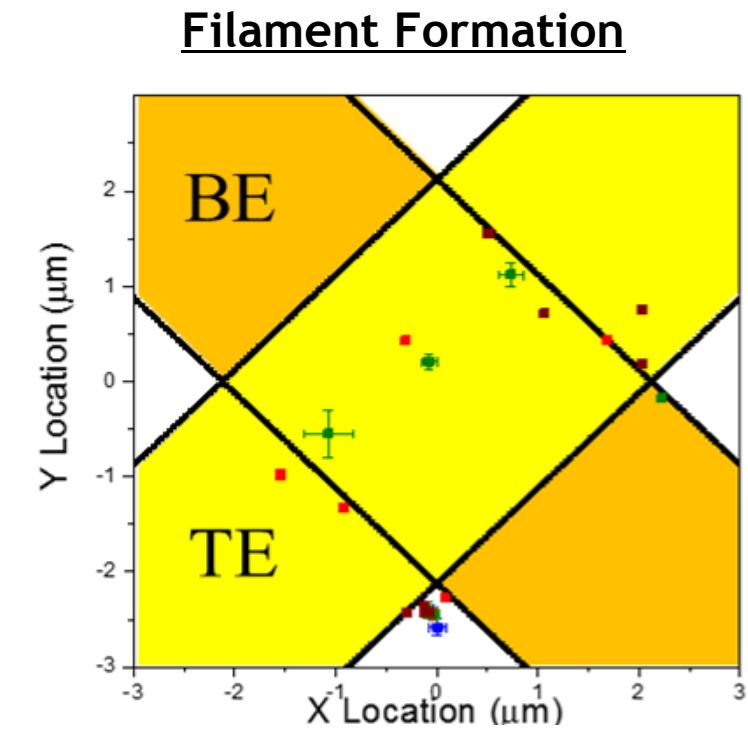
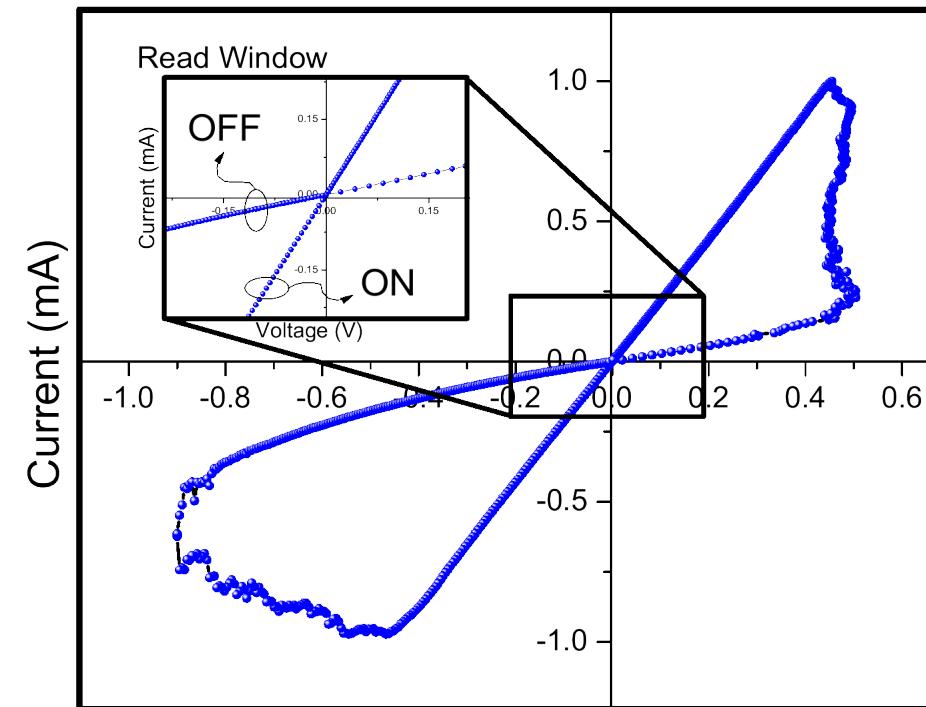
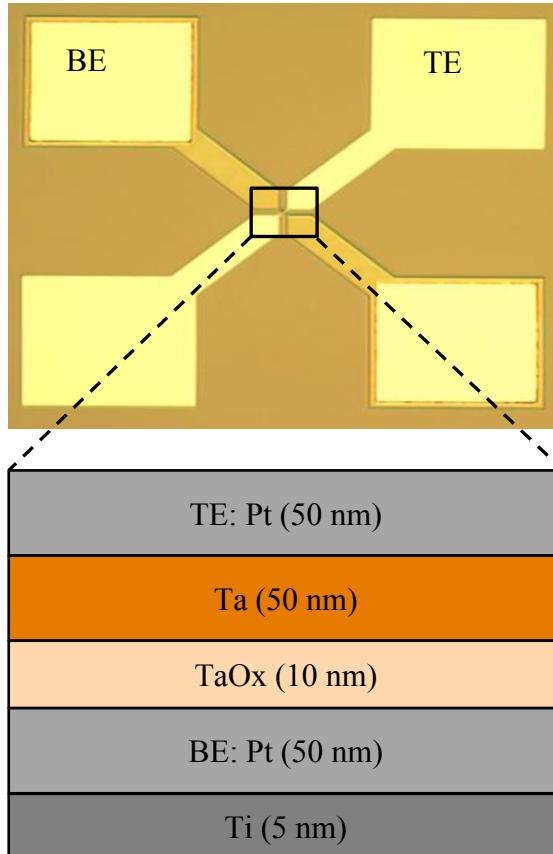
Fully automated process, but still very difficult and slow!!!!



Example - Ion Beam Seeding of Memristors

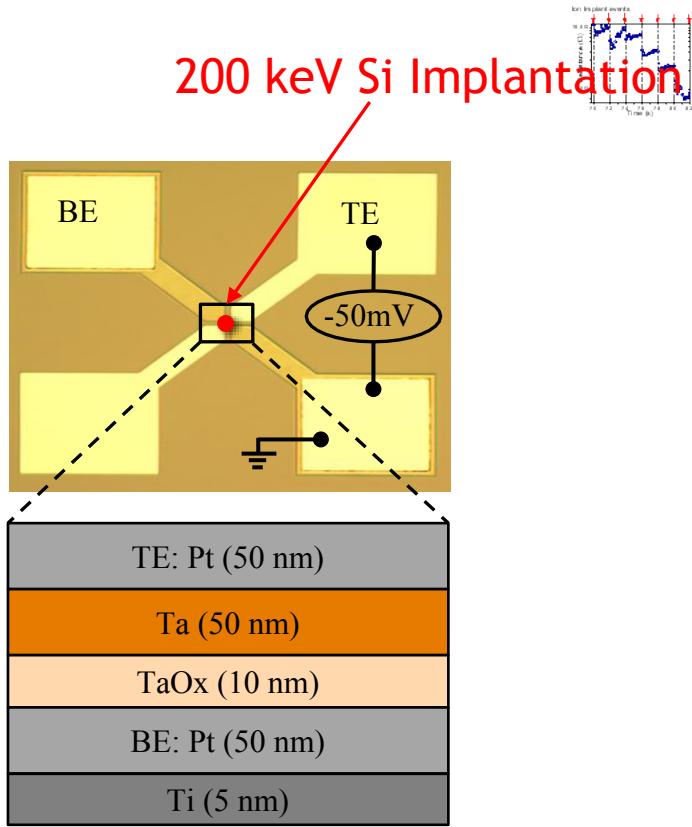


- Memristor based memories are promising solid-state memories with high speed, low power, high density and are naturally radiation hardened

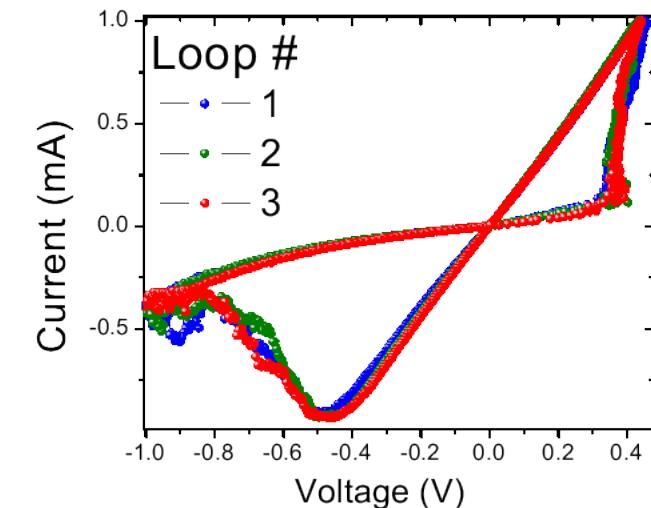
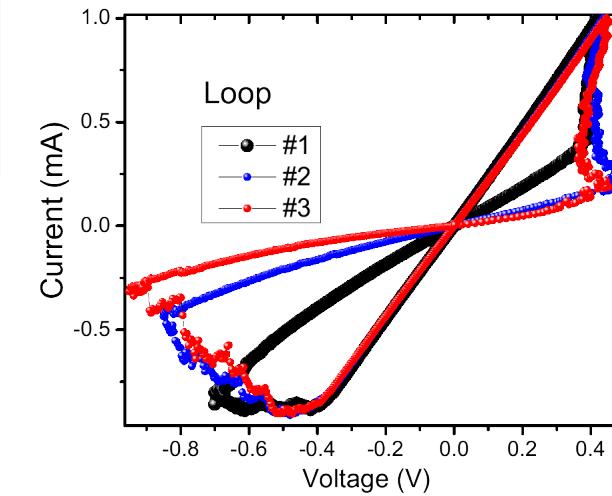
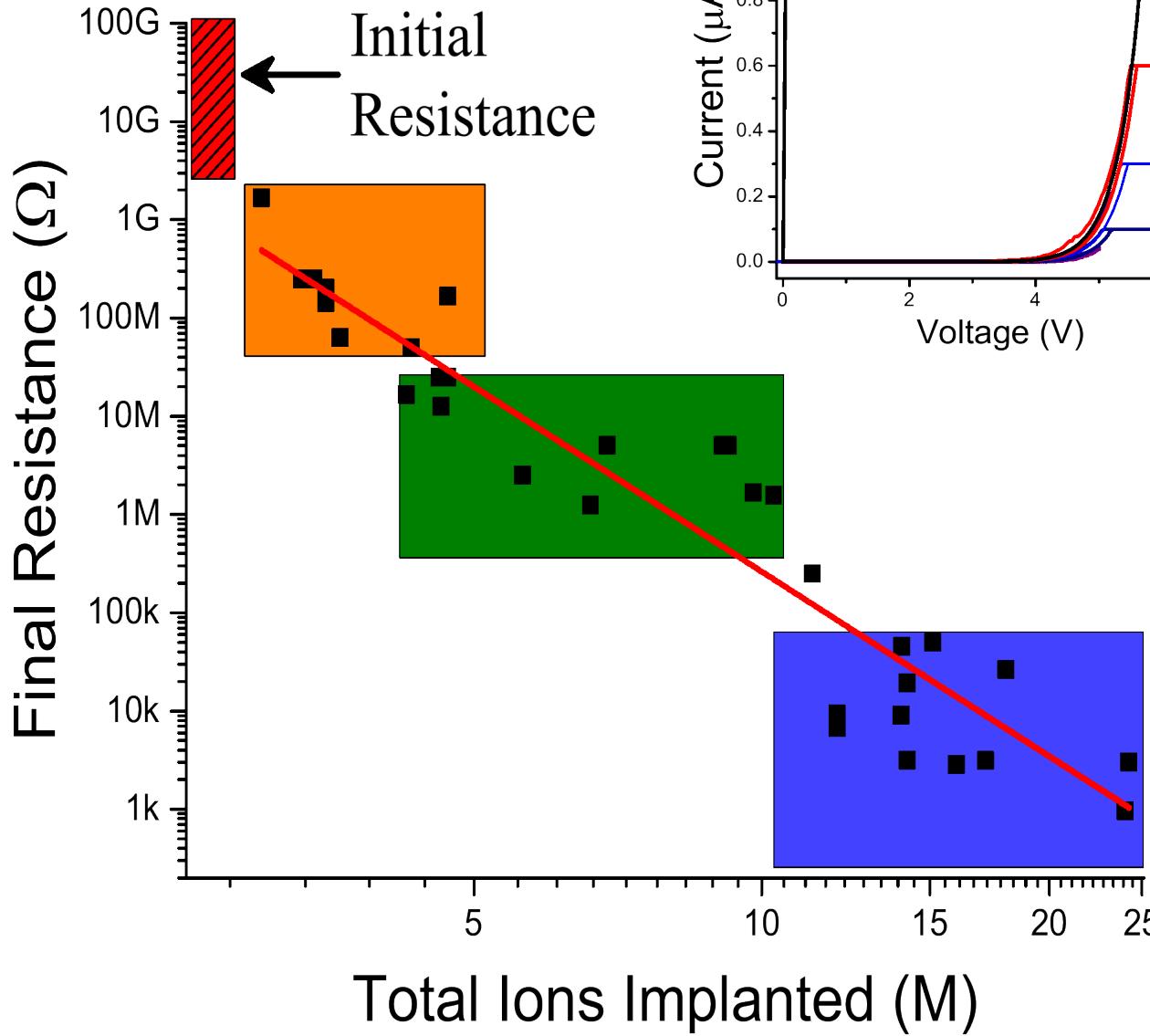


- Can we use focused ion beam implantation to act as seeding sites for the conductive filament formation bypassing electroformation?

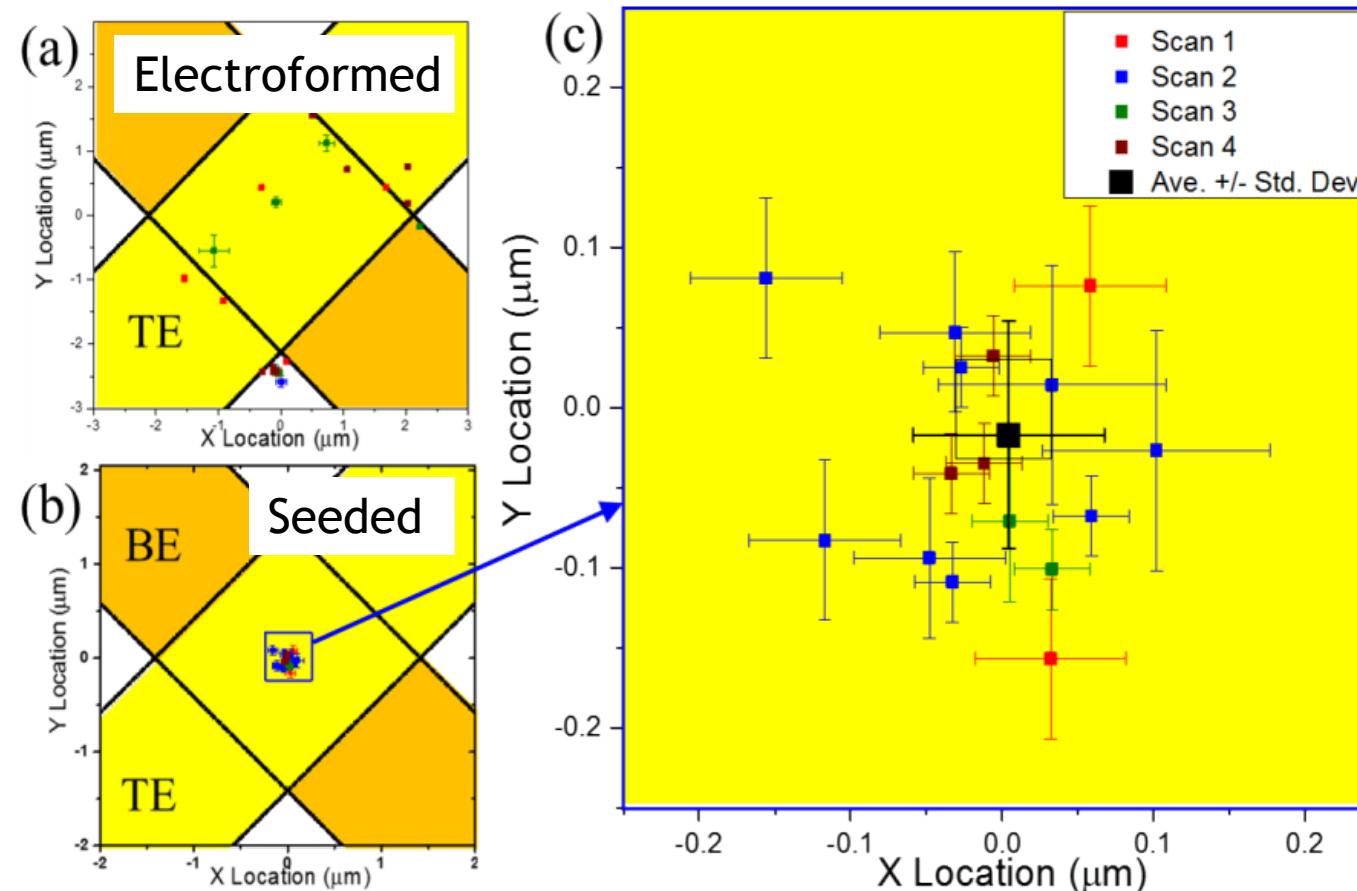
Modification of the TaO_x Film Resistance using Ion Irradiation



J. Pachaco, et al. Appl. Phys. A 124 626 (2018)



Control over Filament Location



Results:

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

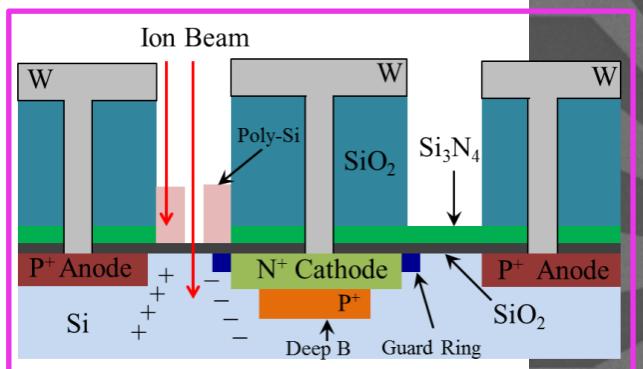
Single Donor Devices for Si Qubits



Si-MOS platform integrated with:

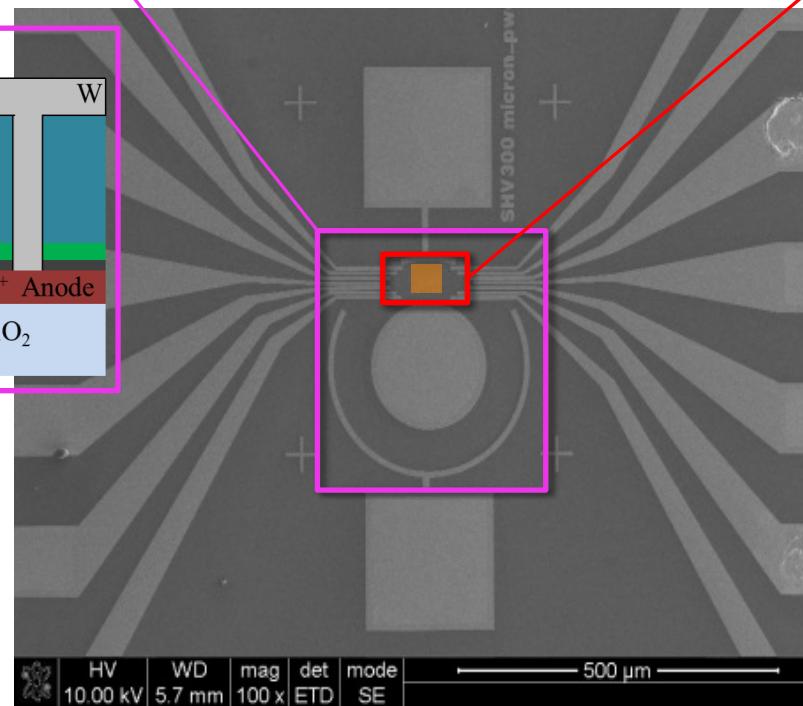
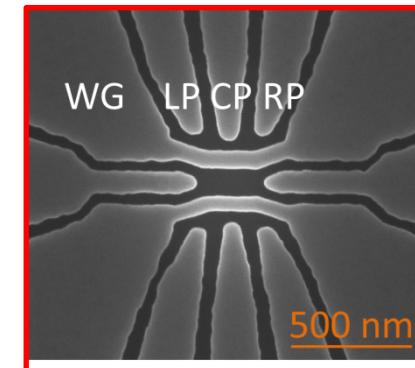
- Single Ion Detector
- Nanostructure for Qubit operation

Single Ion Detector



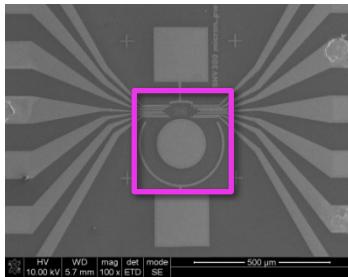
Ion Beam Induced Charge (IBIC)

Nanostructure

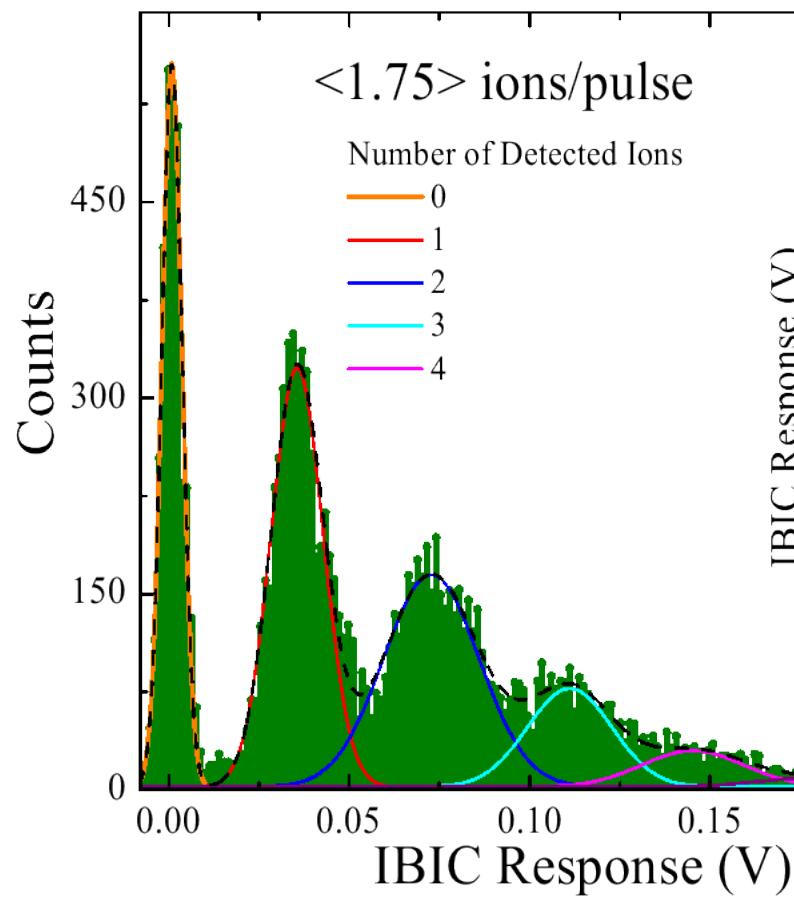


Combined Single Ion Detector and Nanostructures Demonstrated

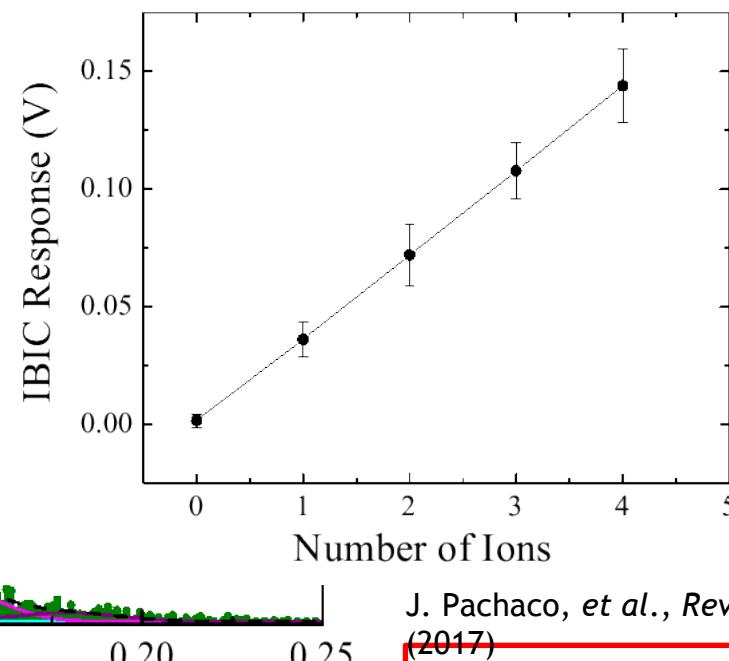
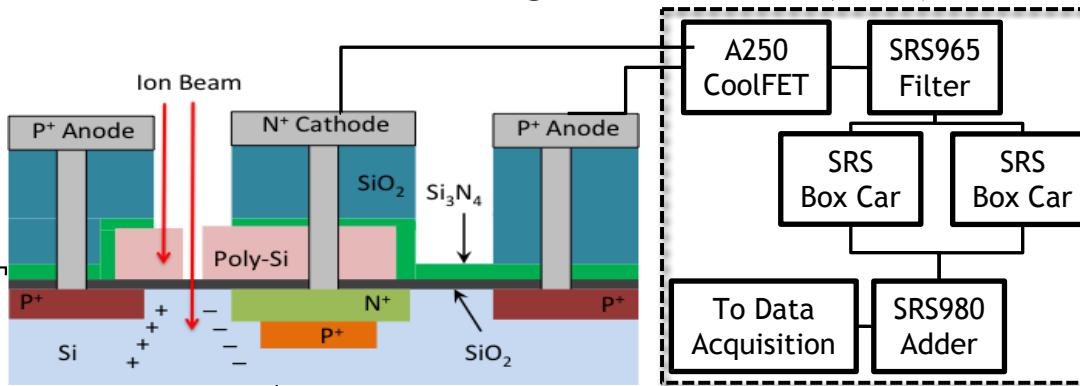
Integrated Single Ion Detectors



200 keV Si Detection

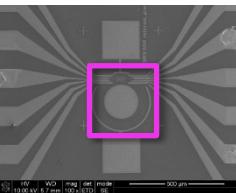


Ion Beam Induced Charge Collection (IBIC)



J. Pachaco, *et al.*, *Rev. of Sci. Instr.*
(2017)

Quantized Single Ion Detection



Lowest SNL Detected Single Ion Implantation



Ion	Energy (keV)	SiO ₂ thickness (nm)	Range ^a (\pm straggle) (nm)	e-h pairs (k) ^a	SNR	Error rate (%)	Detection efficiency (%)
Si	200	7	273 (\pm 76)	39	21.2	$\ll 1$	100
Sb	120	35	25 (\pm 17.5)	8.5	5.2
Sb	50	7	25 (\pm 9)	5.0	4.4
Sb	20	7	11 (\pm 5)	1.4	2.5	15	87.6

^aRange and e-h pairs calculated from the SiO₂/Si interface into the Si substrate.

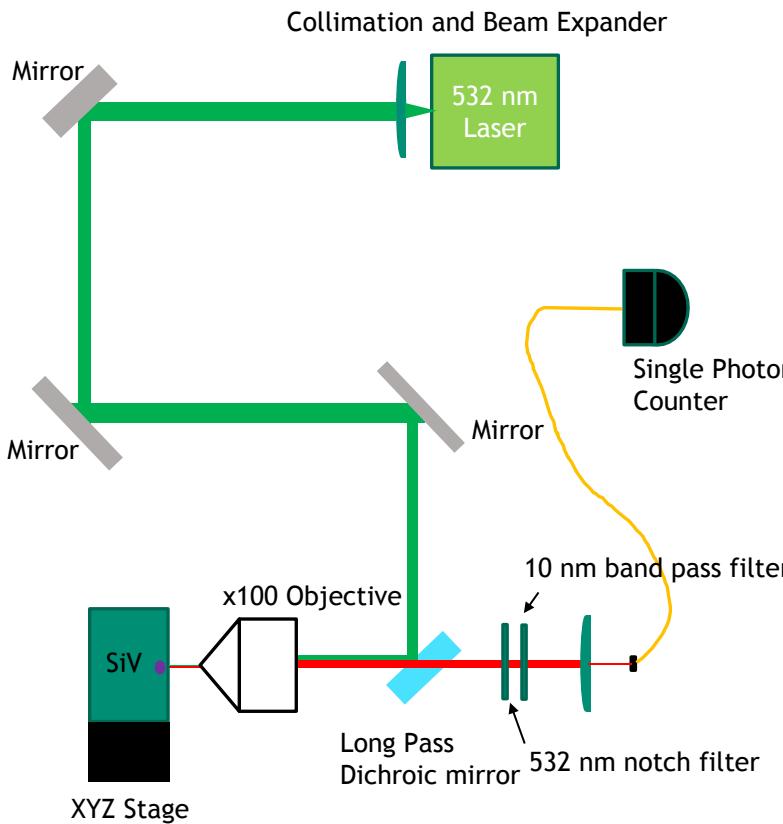
$$SNR = \frac{\mu_S}{\mu_N + \sigma_N} = 2.5$$

How to further improve SNR?

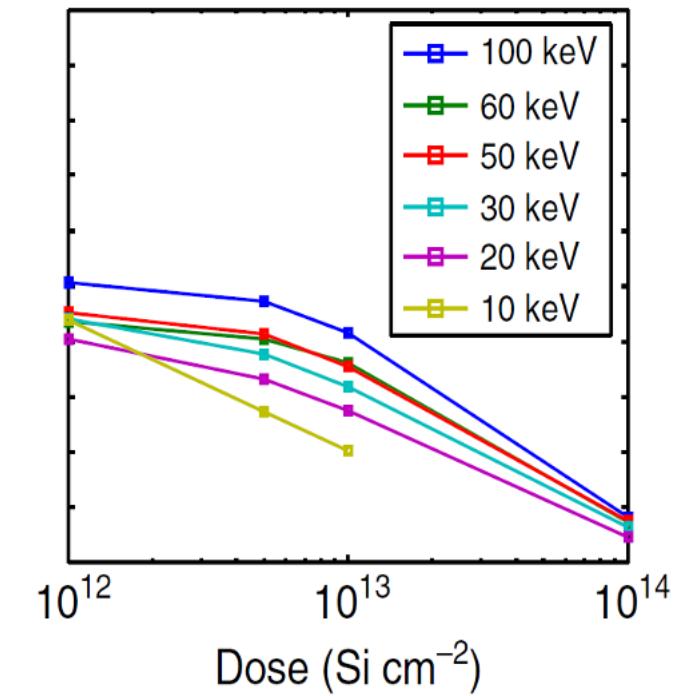
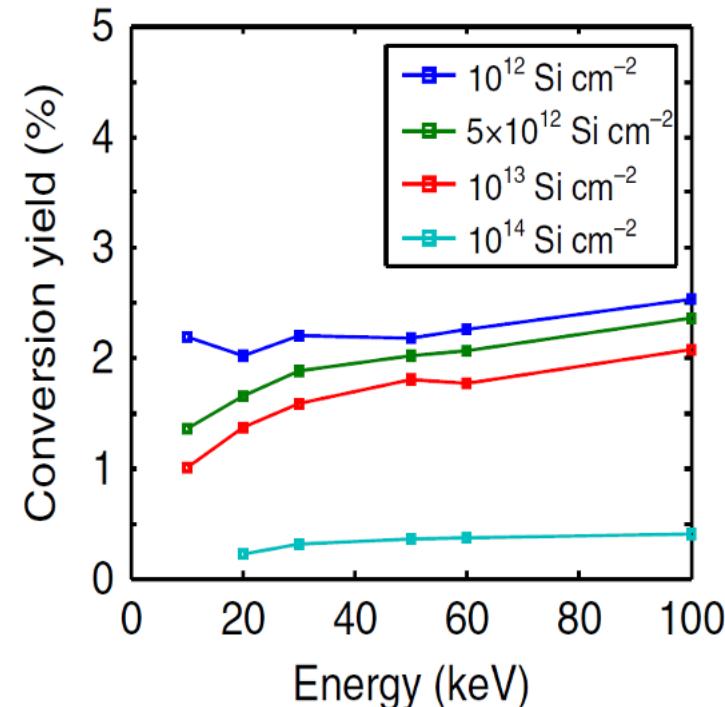
- In-vacuum preamp
- Cool detector and FET

Path forward to low energy <10 nm implantation and detector

Yield: Mapping SiV Photoluminescence



Yield = # measured SiV / # implanted Si



Similar yield to

- S. Sangtawesin et. al. Appl. Phys. Lett. 105, 063107 (2014)
- S. Tamura et. al. Appl. Phys. Express 7, 115201 (2014)

T. Schroder, et al., Nature Communications (2017)

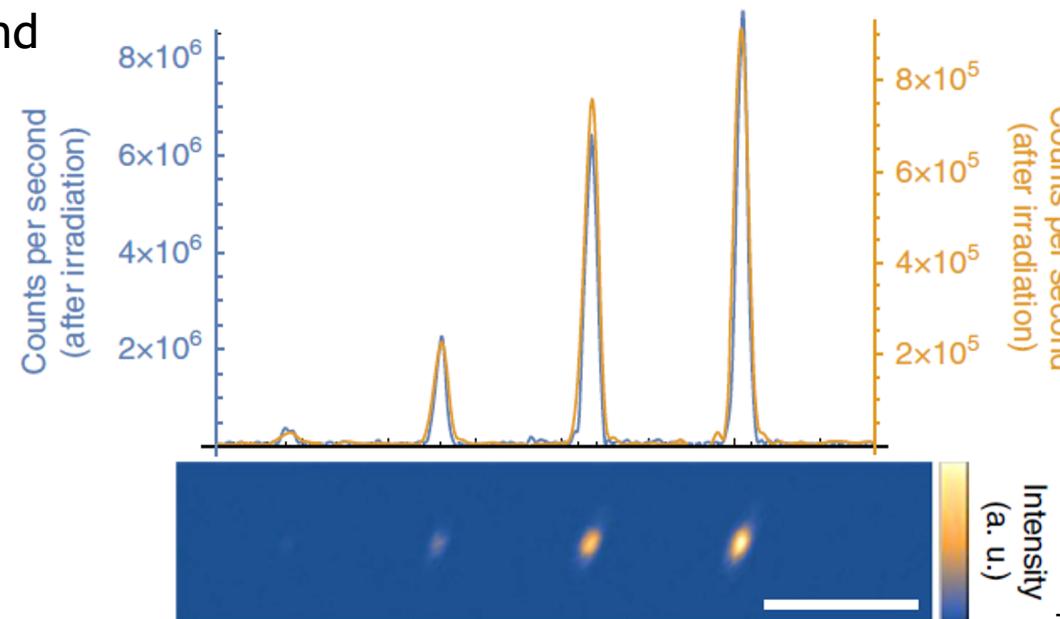
Yield is low and dominated by Poisson Statistics!

Yield Improvements Efforts



- (1) Post electron irradiation
 - (2) Post ion irradiation
 - (3) Sequential ion irradiation
 - (4) Hot ion irradiation
 - (5) Substrate doping
- Create excess vacancies

After electron irradiation and anneal
10x improvement



After ion implant and anneal

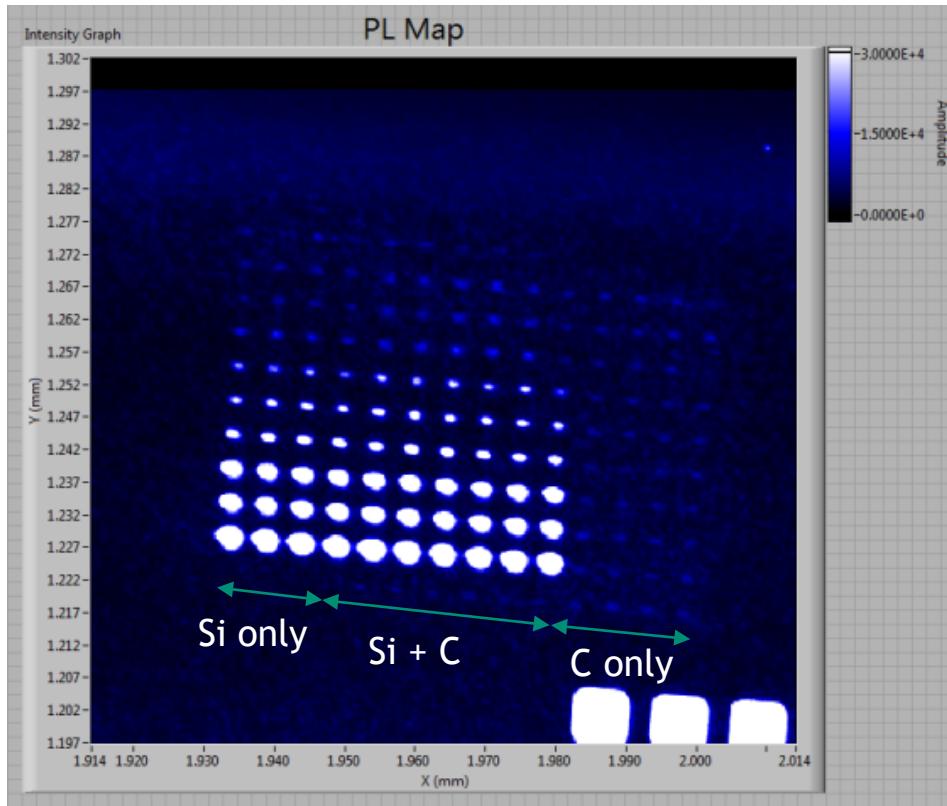
T. Schroder *et al.*, Nature Communications 8, 15376 (2017)

B. Diller *et al.*, arXiv:1909.08778

B. Rose *et al.*, Science 361, 60-63 (2018)

T. Luhmann *et al.*, Nature Comm. 10, 4956 (2019)

Sequential Implantation - μm sized areas

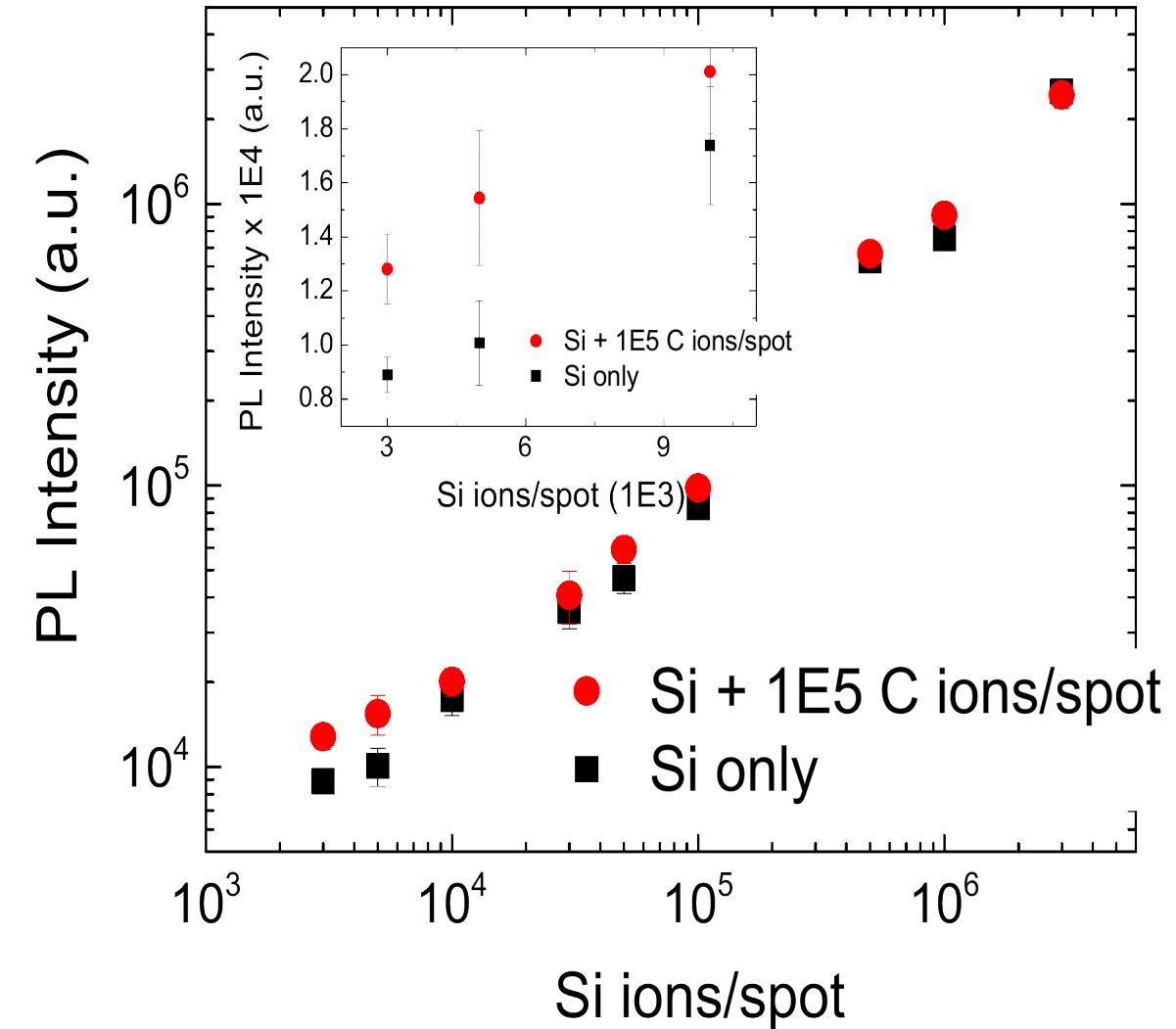


Units

$1\text{E}5$ C ions/spot $\rightarrow \sim 1\text{E}13$ ions/ cm^2

$3\text{E}3$ Si ions/spot $\rightarrow \sim 4\text{E}11$ ions/ cm^2

\rightarrow Below the damage threshold



Si+C PL is ~ 1.4 x larger than Si PL \rightarrow Yield improvement observed in μm spots

Progress on Nitrogen Source Development



Approaches for building a nitrogen source for the nanolimplanter:

- (1) Implant N into a known working source
- (2) Use ionic liquid sources as demonstrated in the literature

Start with a working LMAIS - AuSn, In, AlSi, etc... and implant N

(1) Can we implant N into the LMAIS?

- N implanted into AuSn and In alloys at 200 keV N⁺ to fluences of 5E17 ion/cm²

(2) Does N stay in the alloy?

- N concentration measured by 28 MeV Si⁺⁵ ERD
- AuSn+N → N stays in place at least in the very near surface (figure on right)
- In+N → N concentration is less than calculated:
 - N diffused deeper into the In
 - Or it may have left the sample

(3) Can we form a N containing tip?

- On-going! But, at most we expect ~4e3 N/s

