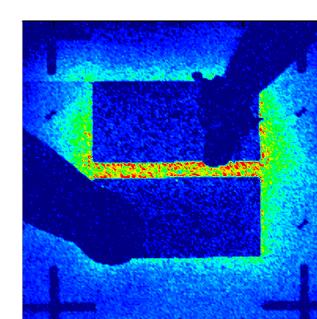
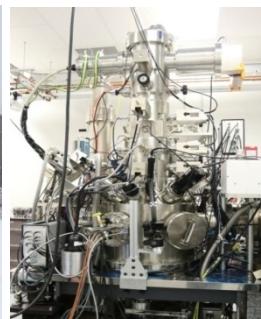




# Towards Deterministic Defect Center Fabrication Using Sandia's Focused Ion Implantation Capabilities

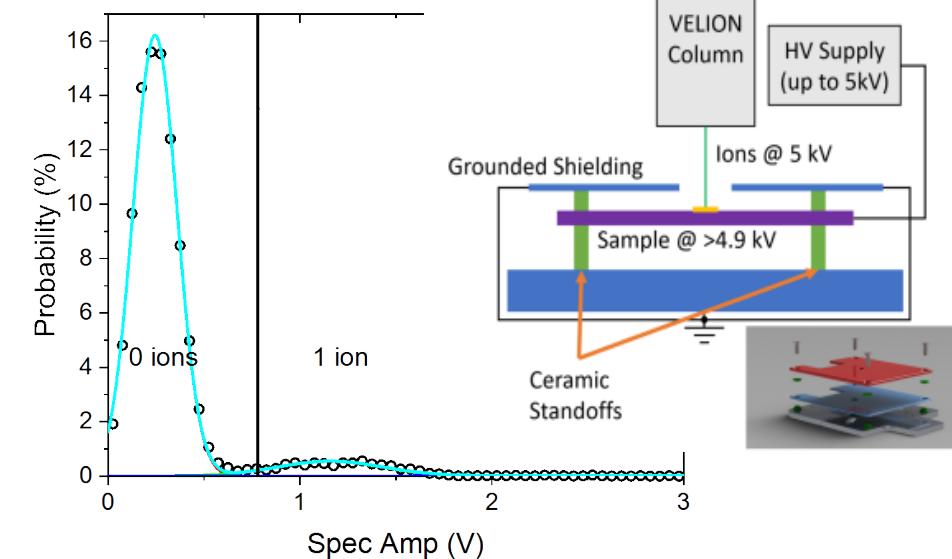
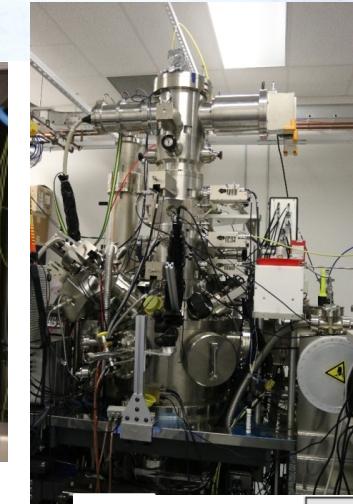
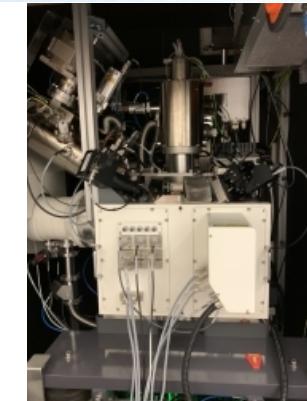


E. Bielejec

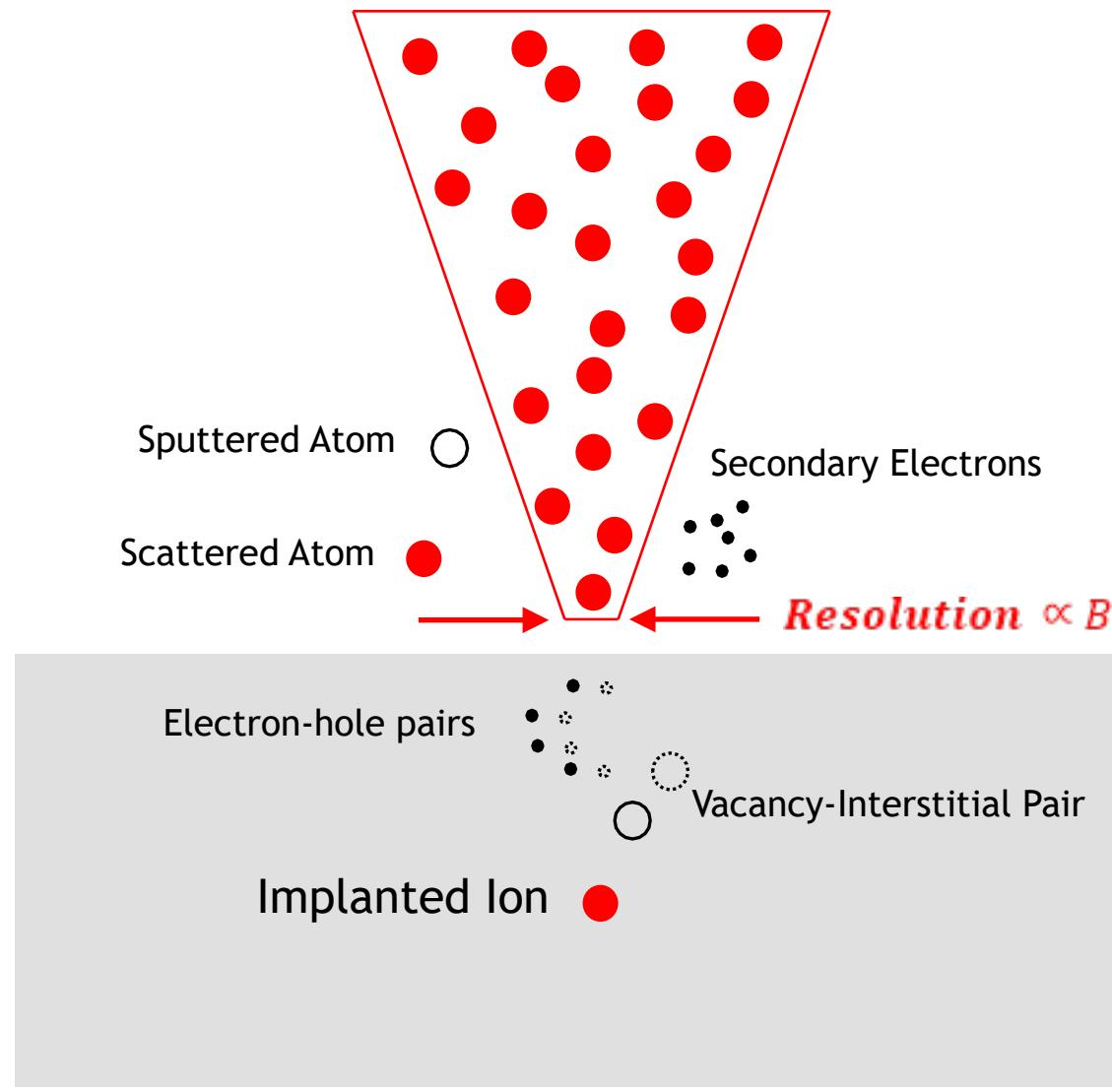
Sandia National Laboratories, Albuquerque, NM 87185

# Outline

- Introduction to Focused Ion Beam Capabilities at Sandia's Ion Beam Laboratory (IBL)
- Multi-species Focused Ion Beam (FIB)
  - Sandia's nanolimplanter and Raith Velion
  - New Liquid Metal Alloy Ion Source Development
- Single Defect Centers in Wide Bandgap Substrates
  - In-situ Counting - control the # of implanted ions
  - In-situ Photoluminescence - verify defect centers
- Single Impurity Centers in 2D Materials
  - Low energy implantation, 10-100 eV, with spatial resolution
- Summary and Outlook for FIB Implantation

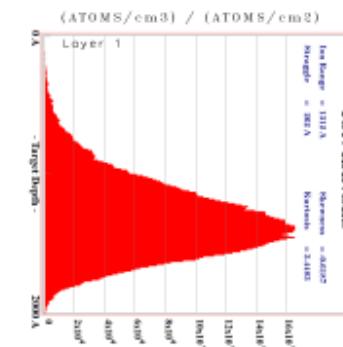


# Nanofabrication using Focused Ion Beam (FIB) Implantation



*Resolution  $\propto$  Beam Spot Size + Alignment Accuracy + XY Straggle*

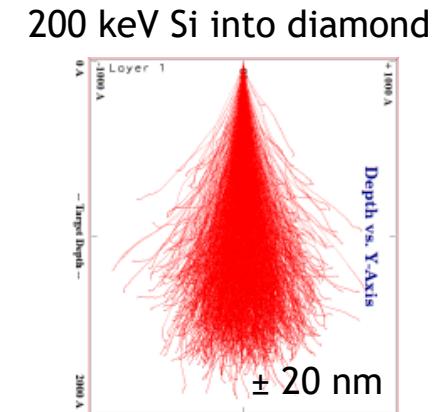
*Depth  $\propto$  Energy + Z Straggle*



**SRIM simulation - Z straggle**

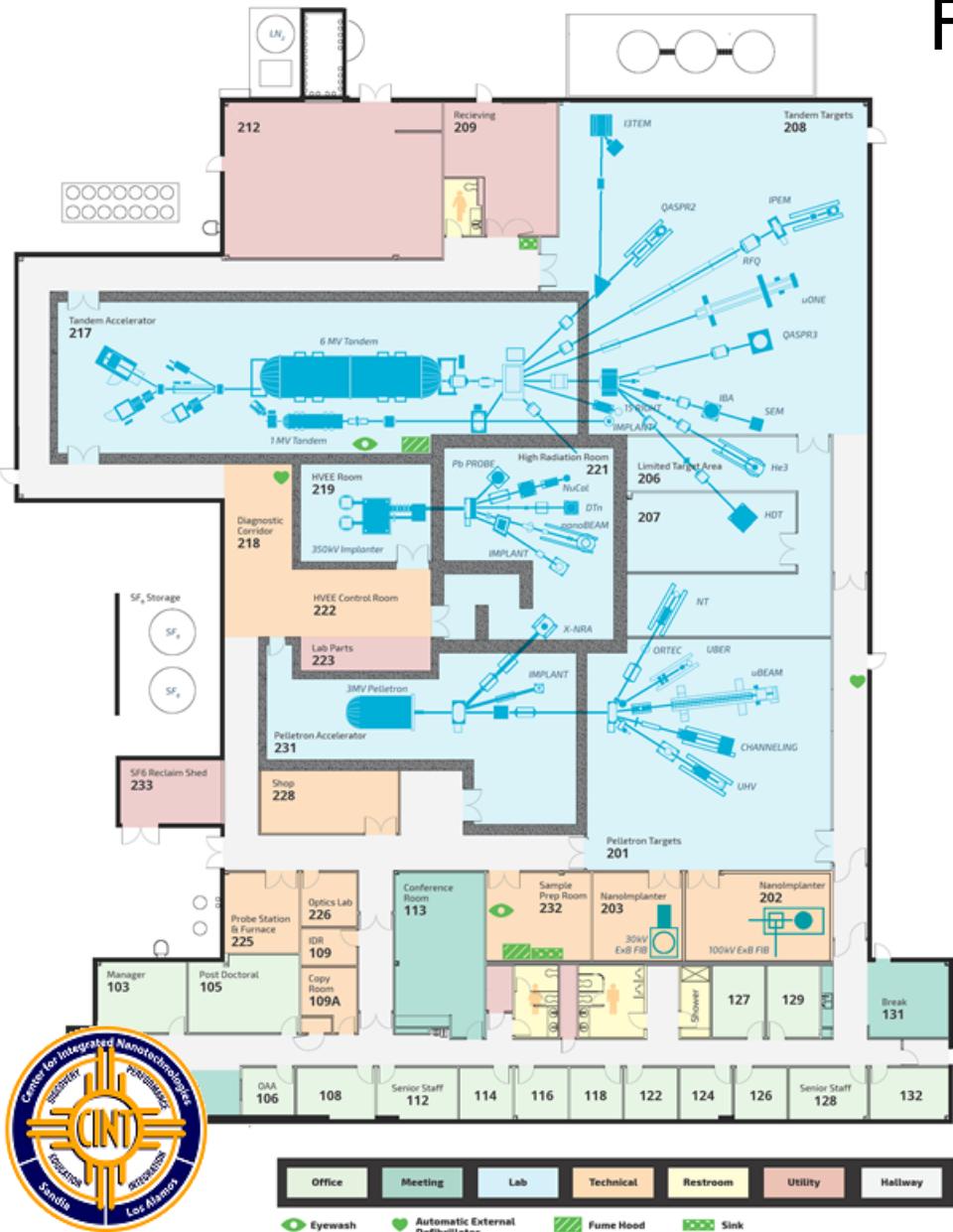
200 keV Si into diamond  
 $131 \pm 26$  nm

**SRIM simulation - XY straggle**





# Overview of Sandia's Ion Beam Laboratory (IBL) Focused Ion Beam (FIB) Capabilities



## 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 nanolplanter
- (6) 35 kV ExB FIB Raith Velion
- (7) 35 kV Zeiss HelM

## Installing

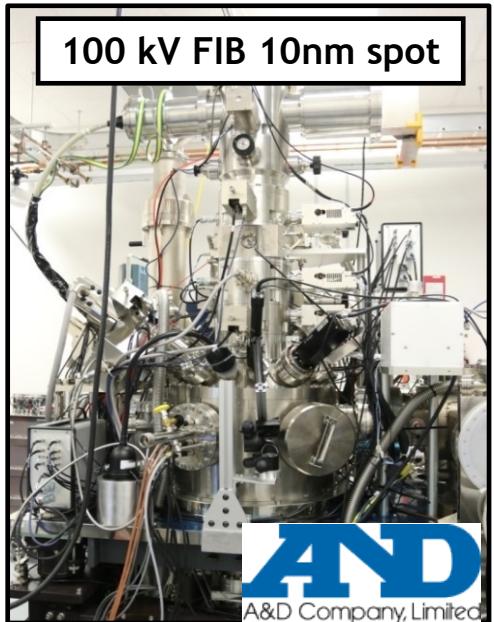
- (8) 35 kV Plasma FIB

High energy  
focused  
micobeams  
 $1 \mu\text{m}$

Low energy  
focused  
nanobeams  
 $<1$  to  $20 \text{ nm}$

25 end-stations including *in-situ* DLTS, PL, TEM, SEM,  $1200^\circ\text{C}$  heating, etc...

# FIB Implantation using the nanolimplanter and Velion

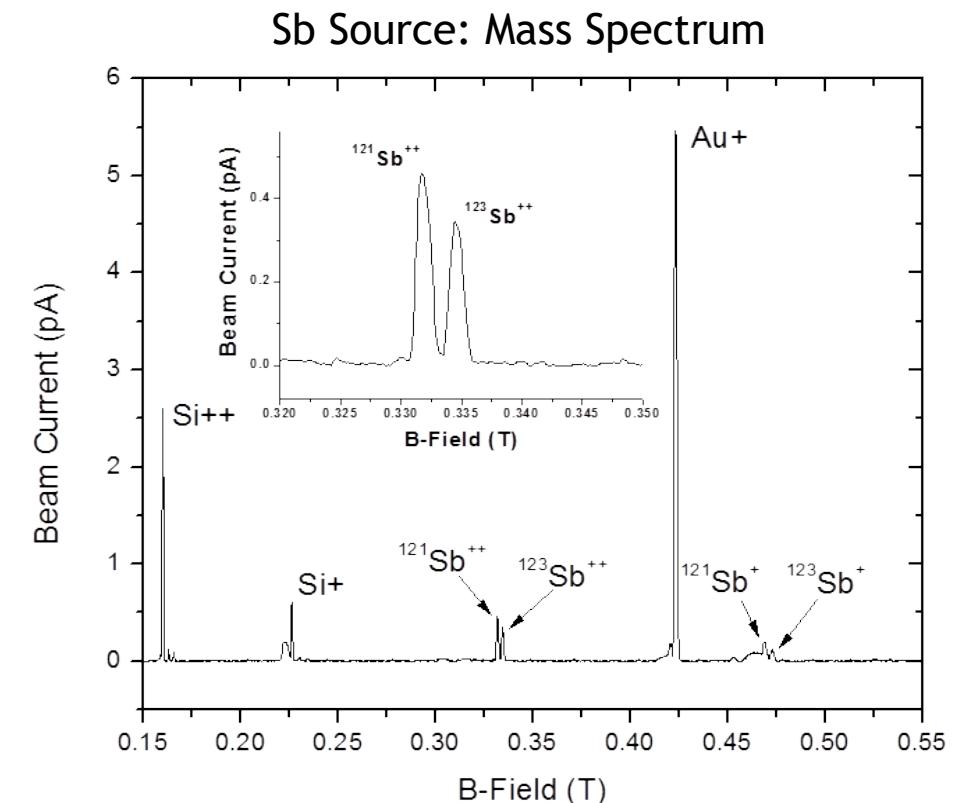


- Focused ion beam system (FIB)  
→ nm beam spot size on target
- ExB Filter (Wien Filter)  
→ Multiple ion species  
e.g., Li, Si, P, Sb, etc... (separating out  $^{28}\text{Si}$ ,  $^{29}\text{Si}$ , etc...)

- Fast blanking and chopping  
→ Single ion implantation

- Direct-write lithography  
→ nm targeting accuracy

- Low temperature stage
- In-situ electrical probes



# Available Liquid Metal Alloy Ion Sources (LMAIS) for FIB Implantation



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

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

boron	5	carbon	6	nitrogen	7	oxygen	8	fluorine	9	helium	2
	B	C	N	O	F		He				
	10.811	12.011	14.007	15.999	18.998		4.0026				
aluminum	13	silicon	14	phosphorus	15	sulfur	16	chlorine	17	neon	10
	Al		Si	P	S	Cl					Ne
	26.982		28.086	30.974	32.065	35.453					
gallium	31	germanium	32	arsenic	33	selenium	34	bromine	35	krypton	36
	Ga		Ge	As	Se	Br					Kr
	69.723		72.61	74.922	78.96	79.904					
indium	49	tin	50	antimony	51	tellurium	52	iodine	53	xenon	54
	In		Sn	Sb	Te						Xe
	114.82		118.71	121.76	127.60						
cadmium	48	cadmium	49	tin	50	iodine	52	iodine	53	xenon	54
	Cd		Ag	In	Sn	Te					Xe
	112.41		107.87	114.82	118.71	127.60					
rhodium	45	palladium	46	silver	47	antimony	51	tellurium	52	iodine	53
	Rh		Pd	Ag	Cd	In	Sn	Te			Xe
	102.91		106.42	107.87	112.41	114.82	118.71	121.76	127.60	126.90	131.29
osmium	76	osmium	77	gold	79	mercury	80	lead	82	astatine	86
	Os		Ir	Pt	Au	Hg	Tl	Pb	Bi		Rn
	190.23		192.22	196.08	196.97	200.59	204.38	207.2	208.98		
rhodium	75	rhodium	77	platinum	78	mercury	81	lead	82	astatine	86
	Rh		Ir	Pt	Au	Hg	Tl	Pb	Bi		Rn
	101.07		102.91	106.42	107.87	112.41	204.38	207.2	208.98		
rhodium	44	rhodium	45	silver	47	mercury	80	lead	82	astatine	86
	Ru		Rh	Pd	Ag	Hg	Tl	Pb	Bi		Rn
	101.07		102.91	106.42	107.87	112.41	204.38	207.2	208.98		
rhodium	43	rhodium	44	silver	47	mercury	80	lead	82	astatine	86
	Tc		Rh	Pd	Ag	Hg	Tl	Pb	Bi		Rn
	[98]		102.91	106.42	107.87	112.41	204.38	207.2	208.98		
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	43	rhodium	44	rhodium	44
	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Hg
	88.906		91.224	92.906	95.94	[98]	101.07	102.91	106.42	107.87	112.41
yttrium	39	zirconium	40	niobium	41	technetium	4				

# Examples of New Sources - Li, V, Cr, Fe, Zn, Sn, Tm (easy-ish)



hydrogen	1	H	1.0079
lithium	3	Li	6.941
beryllium	4	Be	9.0122
sodium	11		
magnesium	12		
Na			22.990
Mg			24.305
potassium	19		
calcium	20	Ca	
K			39.098
	40.078		
rubidium	37		
strontium	38		
Rb			85.468
Sr			87.62
cesium	55		
barium	56		
Cs			132.91
Ba			137.33
	57-70		
lanthanum	71		
lutetium	72		
Lu			174.97
hafnium	73		
tantalum	74		
Ta			178.49
tin	75		
W			183.84
re	76		
Os			186.21
rhodium	77		
Rh			190.23
rhodium	78		
Pt			195.08
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			209.1
astatine	85		
At			210.1
rhenium	86		
Rn			222.1

Purple - running at SNL

Yellow - attempting at SNL

Green - demonstrated at other labs

scandium	21	Sc	44.96
titanium	22	Ti	47.867
vanadium	23	V	50.947
chromium	24	Cr	51.996
manganese	25	Mn	54.028
iron	26	Fe	55.845
cobalt	27	Co	58.033
nickel	28	Ni	58.693
copper	29	Cu	63.546
zinc	30	Zn	65.320
gallium	31	Ga	69.723
germanium	32	Ge	72.61
arsenic	33	As	74.922
selenium	34	Se	79.96
bromine	35	Br	79.994
krypton	36	Kr	83.80
rubidium	37	Rb	85.468
strontium	38	Sr	87.62
yttrium	39	Y	88.906
zirconium	40	Zr	91.224
niobium	41	Nb	92.906
niobium	42	Mo	95.94
technetium	43	Tc	[98]
rhodium	44	Rh	101.07
palladium	46	Pd	102.91
silver	47	Ag	106.42
cadmium	48	Cd	107.87
indium	49	In	111.82
antimony	50	Sb	114.71
tellurium	52	Te	121.76
iodine	53	I	127.60
xenon	54	Xe	126.90
cesium	55	Cs	132.91
barium	56	Ba	137.33
lutetium	71	*	
hafnium	72	Lu	
tantalum	73	Hf	
tin	74	Ta	
tin	75	W	
re	76	Re	
osmium	77	Os	
rhodium	78	Rh	
gold	79	Pt	
mercury	80	Au	
thallium	81	Hg	
lead	82	Tl	
bismuth	83	Pb	
polonium	84	Bi	
astatine	85	Po	
radon	86	At	
rhenium	87	Rn	
radium	88		
lawrencium	103	Lr	
rutherfordium	104	Rf	
dubnium	105	Db	
seaborgium	106	Sg	
bh	107	Bh	
hs	108	Hs	
mt	109	Mt	
metathorium	110	Uun	
ununnilium	111	Uuu	
ununnilium	112	Uub	
uniquadium	114	Uuq	

\*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
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	169.93
ytterbium	70	Yb	173.04

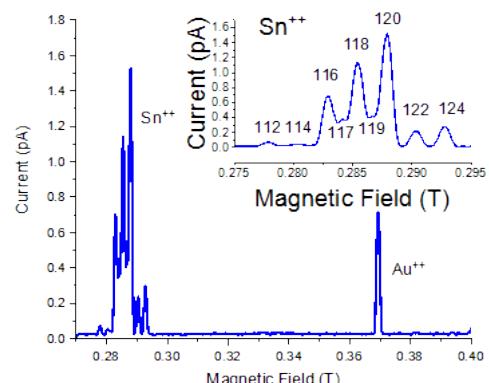
\*\*Actinide series

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]
einsteiniun	99	Es	[252]
fermium	100	Fm	[257]
mandelsteiniun	101	Md	[258]
nobelium	102	No	[259]

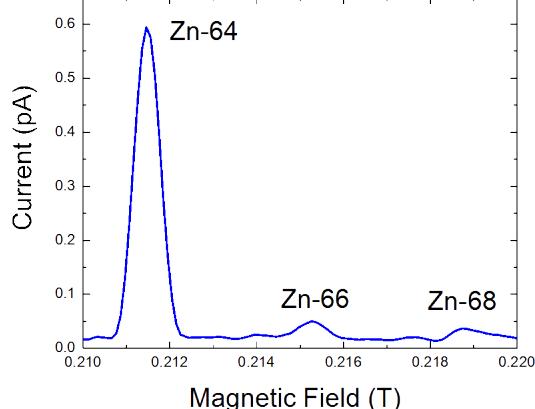
- Based on AuSiX or AuGeX alloys
- Easy to wet the tip and easy to run
- For example, AuSiLi

M. Titze et al., JVST B, 39, 012802 (2021)

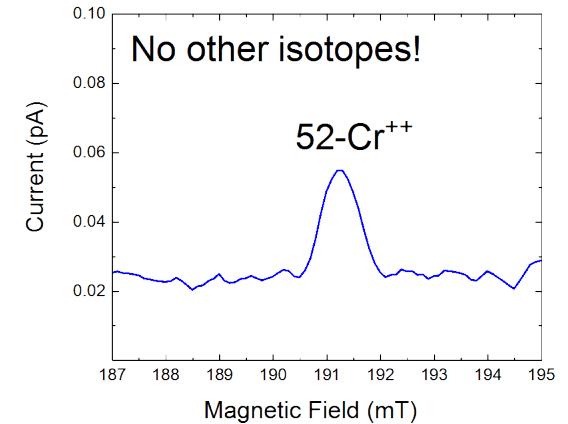
AuSn



AuSiZn



AuGeCr



# Examples of **HARD** New Sources - Pb and N



hydrogen	1	H	1.0079
boron	4	Be	9.0122
lithium	3	Li	6.941
sodium	11	Mg	24.305
potassium	19	Ca	40.078
rubidium	37	Sc	44.96
cesium	55	Ti	47.867
franidium	87	Scandium	21
lanthanide series	57	titanium	22
actinide series	89	vanadium	23
	103	chromium	24
	105	manganese	25
	106	iron	26
	107	cobalt	27
	108	nickel	28
	109	copper	29
	110	zinc	30
	111	gallium	31
	112	germanium	32
	113	arsenic	33
	114	selenium	34
	115	bromine	35
	116	krypton	36
	117	rubidium	37
	118	strontium	38
	119	yttrium	39
	120	zirconium	40
	121	niobium	41
	122	molybdenum	42
	123	technetium	43
	124	ruthenium	44
	125	rhodium	45
	126	palladium	46
	127	silver	47
	128	cadmium	48
	129	indium	49
	130	tin	50
	131	antimony	51
	132	tellurium	52
	133	iodine	53
	134	xenon	54
	135	cesium	55
	136	barium	56
	137	lanthanum	57
	138	cerium	58
	139	praseodymium	59
	140	neodymium	60
	141	promethium	61
	142	samarium	62
	143	europium	63
	144	gadolinium	64
	145	terbium	65
	146	dysprosium	66
	147	holmium	67
	148	erbium	68
	149	thulium	69
	150	ytterbium	70
	151	ytterbium	71
	152	thulium	72
	153	ytterbium	73
	154	thulium	74
	155	ytterbium	75
	156	thulium	76
	157	ytterbium	77
	158	thulium	78
	159	ytterbium	79
	160	thulium	80
	161	ytterbium	81
	162	thulium	82
	163	ytterbium	83
	164	thulium	84
	165	ytterbium	85
	166	thulium	86
	167	ytterbium	87
	168	thulium	88
	169	ytterbium	89
	170	thulium	90
	171	ytterbium	91
	172	thulium	92
	173	ytterbium	93
	174	thulium	94
	175	ytterbium	95
	176	thulium	96
	177	ytterbium	97
	178	thulium	98
	179	ytterbium	99
	180	thulium	100
	181	ytterbium	101
	182	thulium	102
	183	ytterbium	103
	184	thulium	104
	185	ytterbium	105
	186	thulium	106
	187	ytterbium	107
	188	thulium	108
	189	ytterbium	109
	190	thulium	110
	191	ytterbium	111
	192	thulium	112
	193	ytterbium	113
	194	thulium	114
	195	ytterbium	115
	196	thulium	116
	197	ytterbium	117
	198	thulium	118
	199	ytterbium	119
	200	thulium	120
	201	ytterbium	121
	202	thulium	122
	203	ytterbium	123
	204	thulium	124
	205	ytterbium	125
	206	thulium	126
	207	ytterbium	127
	208	thulium	128
	209	ytterbium	129
	210	thulium	130
	211	ytterbium	131
	212	thulium	132
	213	ytterbium	133
	214	thulium	134
	215	ytterbium	135
	216	thulium	136
	217	ytterbium	137
	218	thulium	138
	219	ytterbium	139
	220	thulium	140
	221	ytterbium	141
	222	thulium	142
	223	ytterbium	143
	224	thulium	144
	225	ytterbium	145
	226	thulium	146
	227	ytterbium	147
	228	thulium	148
	229	ytterbium	149
	230	thulium	150
	231	ytterbium	151
	232	thulium	152
	233	ytterbium	153
	234	thulium	154
	235	ytterbium	155
	236	thulium	156
	237	ytterbium	157
	238	thulium	158
	239	ytterbium	159
	240	thulium	160
	241	ytterbium	161
	242	thulium	162
	243	ytterbium	163
	244	thulium	164
	245	ytterbium	165
	246	thulium	166
	247	ytterbium	167
	248	thulium	168
	249	ytterbium	169
	250	thulium	170
	251	ytterbium	171
	252	thulium	172
	253	ytterbium	173
	254	thulium	174
	255	ytterbium	175
	256	thulium	176
	257	ytterbium	177
	258	thulium	178
	259	ytterbium	179
	260	thulium	180
	261	ytterbium	181
	262	thulium	182
	263	ytterbium	183
	264	thulium	184
	265	ytterbium	185
	266	thulium	186
	267	ytterbium	187
	268	thulium	188
	269	ytterbium	189
	270	thulium	190
	271	ytterbium	191
	272	thulium	192
	273	ytterbium	193
	274	thulium	194
	275	ytterbium	195
	276	thulium	196
	277	ytterbium	197
	278	thulium	198
	279	ytterbium	199
	280	thulium	200
	281	ytterbium	201
	282	thulium	202
	283	ytterbium	203
	284	thulium	204
	285	ytterbium	205
	286	thulium	206
	287	ytterbium	207
	288	thulium	208
	289	ytterbium	209
	290	thulium	210
	291	ytterbium	211
	292	thulium	212
	293	ytterbium	213
	294	thulium	214
	295	ytterbium	215
	296	thulium	216
	297	ytterbium	217
	298	thulium	218
	299	ytterbium	219
	300	thulium	220
	301	ytterbium	221
	302	thulium	222
	303	ytterbium	223
	304	thulium	224
	305	ytterbium	225
	306	thulium	226
	307	ytterbium	227
	308	thulium	228
	309	ytterbium	229
	310	thulium	230
	311	ytterbium	231
	312	thulium	232
	313	ytterbium	233
	314	thulium	234
	315	ytterbium	235
	316	thulium	236
	317	ytterbium	237
	318	thulium	238
	319	ytterbium	239
	320	thulium	240
	321	ytterbium	241
	322	thulium	242
	323	ytterbium	243
	324	thulium	244
	325	ytterbium	245
	326	thulium	246
	327	ytterbium	247
	328	thulium	248
	329	ytterbium	249
	330	thulium	250
	331	ytterbium	251
	332	thulium	252
	333	ytterbium	253
	334	thulium	254
	335	ytterbium	255
	336	thulium	256
	337	ytterbium	257
	338	thulium	258
	339	ytterbium	259
	340	thulium	260
	341	ytterbium	261
	342	thulium	262
	343	ytterbium	263
	344	thulium	264
	345	ytterbium	265
	346	thulium	266
	347	ytterbium	267
	348	thulium	268
	349	ytterbium	269
	350	thulium	270
	351	ytterbium	271
	352	thulium	272
	353	ytterbium	273
	354	thulium	274
	355	ytterbium	275
	356	thulium	276
	357	ytterbium	277
	358	thulium	278
	359	ytterbium	279
	360	thulium	280
	361	ytterbium	281
	362	thulium	282
	363	ytterbium	283
	364	thulium	284
	365	ytterbium	285
	366	thulium	286
	367	ytterbium	287
	368	thulium	288
	369	ytterbium	289
	370	thulium	290
	371	ytterbium	291
	372	thulium	292
	373	ytterbium	293
	374	thulium	294
	375	ytterbium	295
	376	thulium	296
	377	ytterbium	297
	378	thulium	298
	379	ytterbium	299
	380	thulium	300
	381	ytterbium	301
	382	thulium	302
	383	ytterbium	303
	384	thulium	304
	385	ytterbium	305
	386	thulium	306
	387	ytterbium	307
	388	thulium	308
	389	ytterbium	309
	390	thulium	310
	391	ytterbium	311
	392	thulium	312
	393	ytterbium	313
	394	thulium	314
	395	ytterbium	315
	396	thulium	316
	397	ytterbium	317
	398	thulium	318
	399	ytterbium	319
	400	thulium	320
	401	ytterbium	321
	402	thulium	322
	403	ytterbium	323
	404	thulium	324
	405	ytterbium	325
	406	thulium	326
	407	ytterbium	327
	408	thulium	328
	409	ytterbium	329
	410	thulium	330
	411	ytterbium	331
	412	thulium	332
	413	ytterbium	333
	414	thulium	334
	415	ytterbium	335
	416	thulium	336
	417	ytterbium	337
	418	thulium	338
	419	ytterbium	339
	420	thulium	340
	421	ytterbium	341
	422	thulium	342
	423	ytterbium	343
	424	thulium	344
	425	ytterbium	345
	426</td		



# Examples of **HARD** New Sources - C

hydrogen	1	H	1.0079
lithium	3	beryllium	4
Li	6.941	Be	9.0122
sodium	11	magnesium	12
Na	22.990	Mg	24.305
potassium	19	calcium	20
K	39.098	Scandium	21
Rb	85.468	Titanium	22
Ca	40.078	Vanadium	23
Yttrium	39	Chromium	24
Rb	87.62	Manganese	25
Sr	88.906	Iron	26
Sc	44.96	Cobalt	27
Nb	50.942	Nickel	28
Ti	47.867	Copper	29
Zr	91.224	Zinc	30
Cr	51.996	Gallium	31
Mo	54.028	Germanium	32
Mn	55.945	Phosphorus	15
Fe	55.845	Sulfur	16
Co	56.003	Chlorine	17
Ni	58.693	Argon	18
Zn	63.546	Aluminum	13
Ga	65.39	Silicon	14
Ge	69.723	Phosphorus	15
As	72.61	Sulfur	16
Se	74.922	Chlorine	17
Br	79.96	Argon	18
Kr	83.80	Bromine	35
Sc	39.908	Selenium	34
Y	40.078	Bromine	35
Rb	85.468	Krypton	36
Sr	87.62	Iodine	53
Ca	40.078	Te	52
Yttrium	39	Antimony	51
Zr	88.906	Tellurium	52
Scandium	44.96	Iodine	53
Nb	50.942	Xenon	54
Ti	47.867	Radon	86
Zr	91.224	Astatine	85
Sc	51.996	Potassium	19
Cr	55.945	Radium	88
Mo	56.003	Thorium	90
Mn	55.845	Protactinium	91
Fe	55.845	Uranium	92
Co	56.003	Neptunium	93
Ni	58.693	Plutonium	94
Zn	63.546	Americium	95
Ga	65.39	Curium	96
Ge	69.723	Berkelium	97
As	72.61	Californium	98
Se	74.922	Einsteiniun	99
Br	79.96	Fermium	100
Kr	83.80	Mendelevium	101
Sc	39.908	Nobelium	102
Y	40.078	No	103
Rb	85.468		104
Sr	88.906		105
Ca	40.078		106
Yttrium	39		107
Zr	88.906		108
Scandium	44.96		109
Nb	50.942		110
Ti	47.867		111
Zr	91.224		112
Sc	51.996		114
Cr	55.945		115
Mo	56.003		116
Mn	55.845		117
Fe	55.845		118
Co	56.003		119
Ni	58.693		120
Zn	63.546		121
Ga	65.39		122
Ge	69.723		123
As	72.61		124
Se	74.922		125
Br	79.96		126
Kr	83.80		127
Sc	39.908		128
Y	40.078		129
Rb	85.468		130
Sr	88.906		131
Ca	40.078		132
Yttrium	39		133
Zr	88.906		134
Scandium	44.96		135
Nb	50.942		136
Ti	47.867		137
Zr	91.224		138
Sc	51.996		139
Cr	55.945		140
Mo	56.003		141
Mn	55.845		142
Fe	55.845		143
Co	56.003		144
Ni	58.693		145
Zn	63.546		146
Ga	65.39		147
Ge	69.723		148
As	72.61		149
Se	74.922		150
Br	79.96		151
Kr	83.80		152
Sc	39.908		153
Y	40.078		154
Rb	85.468		155
Sr	88.906		156
Ca	40.078		157
Yttrium	39		158
Zr	88.906		159
Scandium	44.96		160
Nb	50.942		161
Ti	47.867		162
Zr	91.224		163
Sc	51.996		164
Cr	55.945		165
Mo	56.003		166
Mn	55.845		167
Fe	55.845		168
Co	56.003		169
Ni	58.693		170
Zn	63.546		171
Ga	65.39		172
Ge	69.723		173
As	72.61		174
Se	74.922		175
Br	79.96		176
Kr	83.80		177
Sc	39.908		178
Y	40.078		179
Rb	85.468		180
Sr	88.906		181
Ca	40.078		182
Yttrium	39		183
Zr	88.906		184
Scandium	44.96		185
Nb	50.942		186
Ti	47.867		187
Zr	91.224		188
Sc	51.996		189
Cr	55.945		190
Mo	56.003		191
Mn	55.845		192
Fe	55.845		193
Co	56.003		194
Ni	58.693		195
Zn	63.546		196
Ga	65.39		197
Ge	69.723		198
As	72.61		199
Se	74.922		200
Br	79.96		201
Kr	83.80		202
Sc	39.908		203
Y	40.078		204
Rb	85.468		205
Sr	88.906		206
Ca	40.078		207
Yttrium	39		208
Zr	88.906		209
Scandium	44.96		210
Nb	50.942		211
Ti	47.867		212
Zr	91.224		213
Sc	51.996		214
Cr	55.945		215
Mo	56.003		216
Mn	55.845		217
Fe	55.845		218
Co	56.003		219
Ni	58.693		220
Zn	63.546		221
Ga	65.39		222
Ge	69.723		223
As	72.61		224
Se	74.922		225
Br	79.96		226
Kr	83.80		227
Sc	39.908		228
Y	40.078		229
Rb	85.468		230
Sr	88.906		231
Ca	40.078		232
Yttrium	39		233
Zr	88.906		234
Scandium	44.96		235
Nb	50.942		236
Ti	47.867		237
Zr	91.224		238
Sc	51.996		239
Cr	55.945		240
Mo	56.003		241
Mn	55.845		242
Fe	55.845		243
Co	56.003		244
Ni	58.693		245
Zn	63.546		246
Ga	65.39		247
Ge	69.723		248
As	72.61		249
Se	74.922		250
Br	79.96		251
Kr	83.80		252
Sc	39.908		253
Y	40.078		254
Rb	85.468		255
Sr	88.906		256
Ca	40.078		257
Yttrium	39		258
Zr	88.906		259
Scandium	44.96		260
Nb	50.942		261
Ti	47.867		262
Zr	91.224		263
Sc	51.996		264
Cr	55.945		265
Mo	56.003		266
Mn	55.845		267
Fe	55.845		268
Co	56.003		269
Ni	58.693		270
Zn	63.546		271
Ga	65.39		272
Ge	69.723		273
As	72.61		274
Se	74.922		275
Br	79.96		276
Kr	83.80		277
Sc	39.908		278
Y	40.078		279
Rb	85.468		280
Sr	88.906		281
Ca	40.078		282
Yttrium	39		283
Zr	88.906		284
Scandium	44.96		285
Nb	50.942		286
Ti	47.867		287
Zr	91.224		288
Sc	51.996		289
Cr	55.945		290
Mo	56.003		291
Mn	55.845		292
Fe	55.845		293
Co	56.003		294
Ni	58.693		295
Zn	63.546		296
Ga	65.39		297
Ge	69.723		298
As	72.61		299
Se	74.922		300
Br	79.96		301
Kr	83.80		302
Sc	39.908		303
Y	40.078		304
Rb	85.468		305
Sr	88.906		306
Ca	40.078		307
Yttrium	39		308
Zr	88.906		309
Scandium	44.96		310
Nb	50.942		311
Ti	47.867		312
Zr	91.224		313
Sc	51.996		314
Cr	55.945		315
Mo	56.003		316
Mn	55.845		317
Fe	55.845		318
Co	56.003		319
Ni	58.693		320
Zn	63.546		321
Ga	65.39		322
Ge	69.723		323
As	72.61		324
Se	74.922		325
Br	79.96		326
Kr	83.80		327
Sc	39.908		328
Y	40.078		329
Rb	85.468		330
Sr	88.906		331
Ca	40.078		332
Yttrium	39		333
Zr	88.906		334
Scandium	44.96		335
Nb	50.942		336
Ti	47.867		337
Zr	91.224		338
Sc	51.996		339
Cr	55.945		340
Mo	56.003		341
Mn	55.845		342
Fe	55.845		343
Co	56.003		344
Ni	58.693		345
Zn	63.546		346
Ga	65.39		347
Ge	69.723		348
As	72.61		349
Se	74.922		350
Br	79.96		351
Kr	83.80		352
Sc	39.908		353
Y	40.078		354
Rb	85.468		355
Sr	88.906		356
Ca	40.078		357
Yttrium	39		358
Zr	88.906		359
Scandium	44.96		360
Nb	50.942		361
Ti	47.867		362
Zr	91.224		363
Sc	51.996		364
Cr	55.945		365
Mo	56.003		366
Mn	55.845		367
Fe	55.845		368
Co	56.003		369
Ni	58.693		370
Zn			

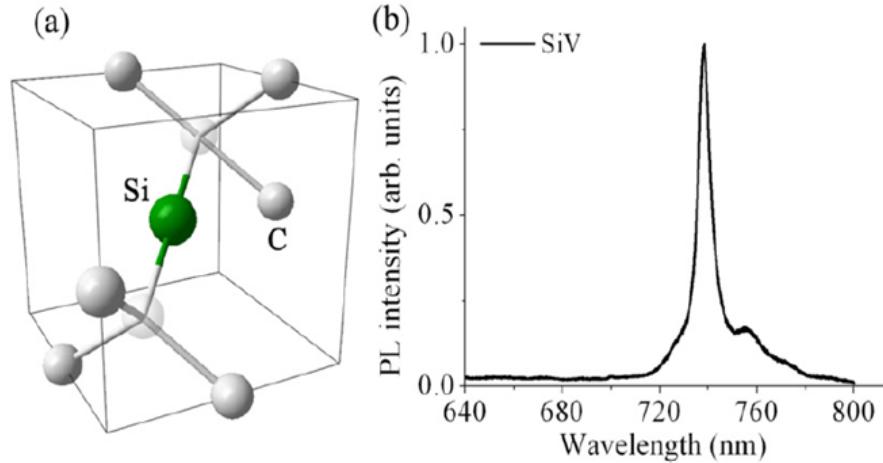
# Creation of Single Defect Centers in Wide Bandgap Substrates



- Defect centers in wide bandgap substrates have applications ranging from metrology, quantum computing, quantum sensing to biological

Ex. Silicon Vacancy Centers in diamond

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

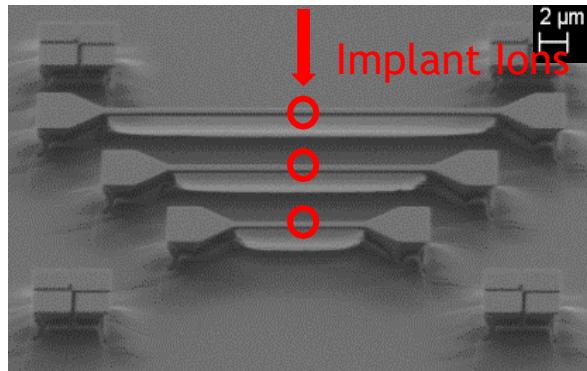


I. Aharonovich *et al.*, Rep. Prog. Phys. **74**, 076501 (2011)

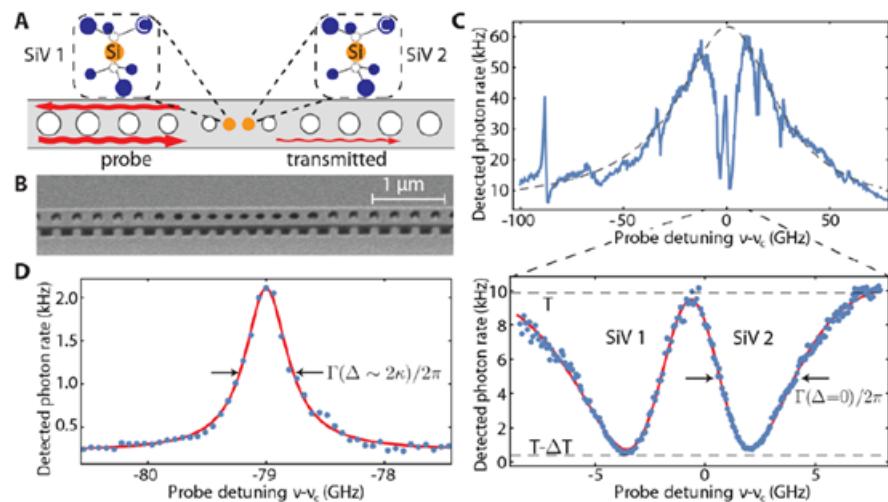
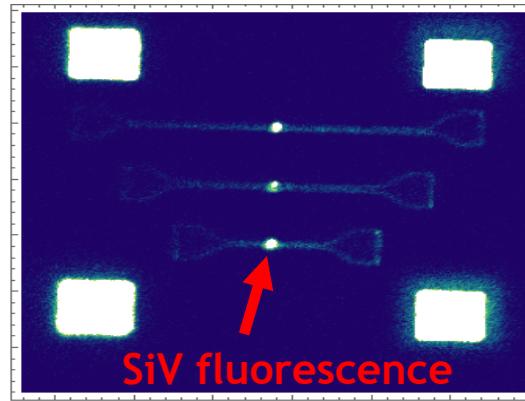
- How to produce a single defect center where you want it?
  - 1.) Location - focused ion beam implantation to control location
  - 2.) Yield - counted implantation to control the number of ions and in-situ PL to confirm an optically active defect center

# Location solved\*, use FIB implantation to control the spatial location

## Diamond Nanobeams (with Harvard)

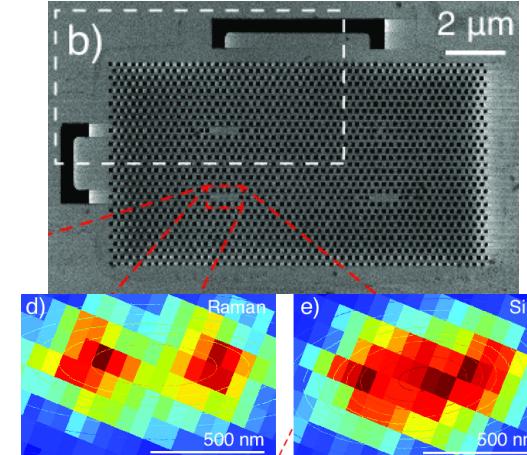


A. Sipahigil, *et al.*, *Science* (2016)

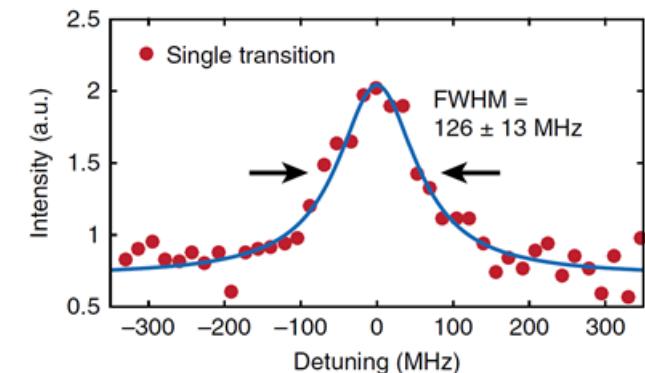


R. E. Evans, *et al.*, *Science* (2018)

## 2D Photonic Crystals (with MIT)



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



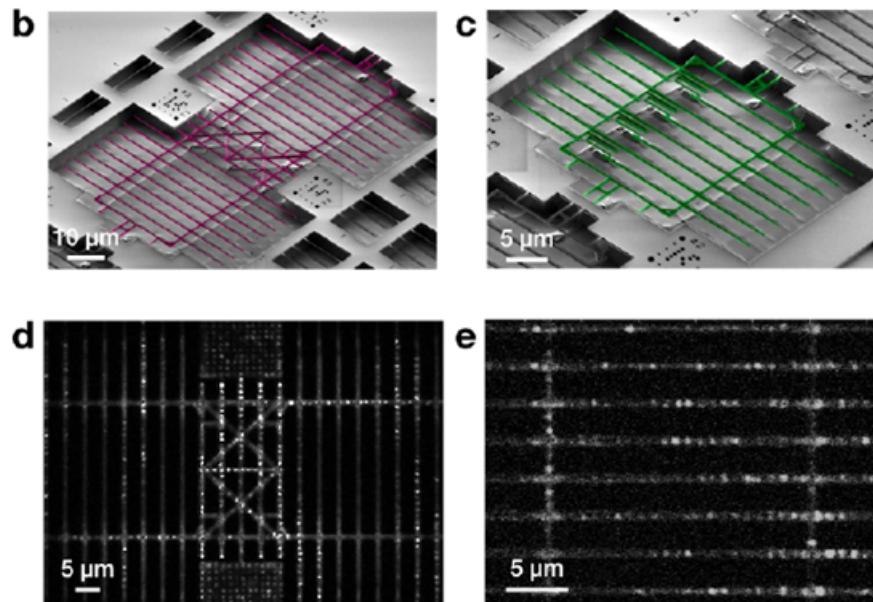
\* Application dependent

**Spatial Accuracy is <50 nm**

# Another set of CINT user projects using FIB Implantation

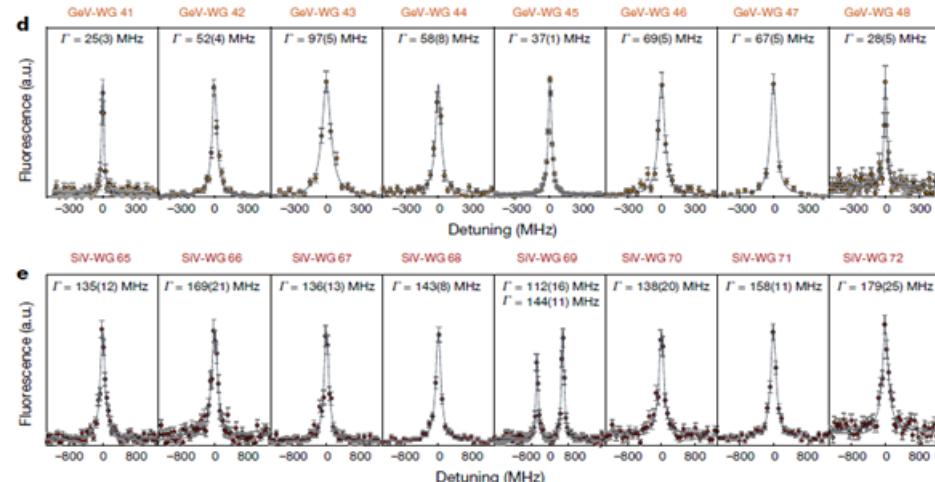


## Diamond waveguides with AlN photonics (with MIT)



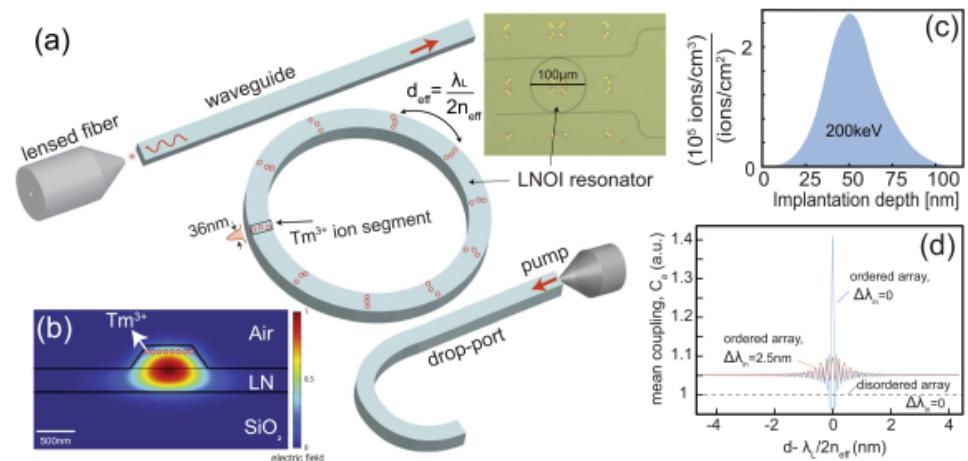
16 and 8 channel  
“quantum micro-  
chiplets”

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

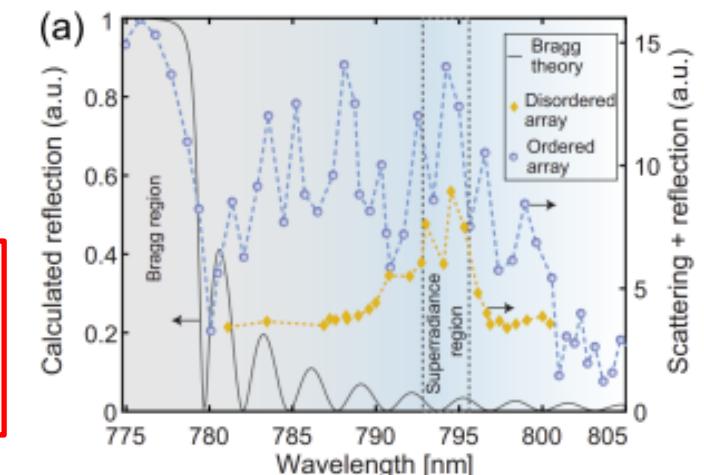


FIB implantation works  
for a wide range of  
substrates

## Lithium Niobate Photonics (with Purdue)



D. Pak *et al.*, *Comm. Physics*, 5, 89 (2022)



# We Use Counted Implantation and Photoluminescence to Better Understand the 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

## 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

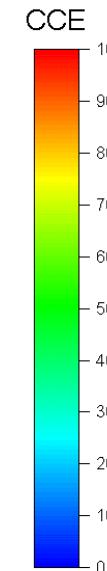
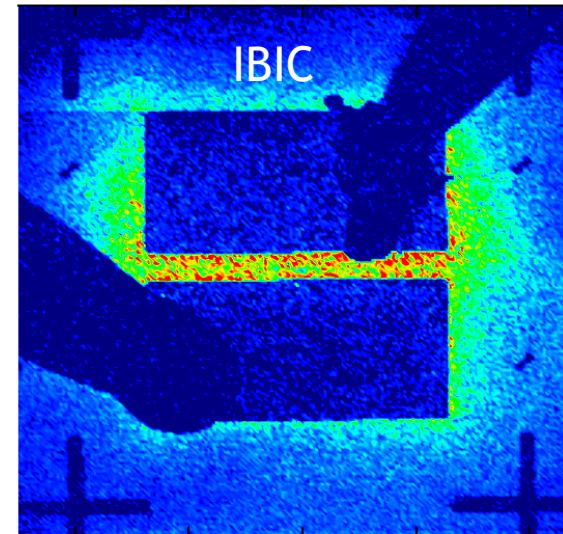
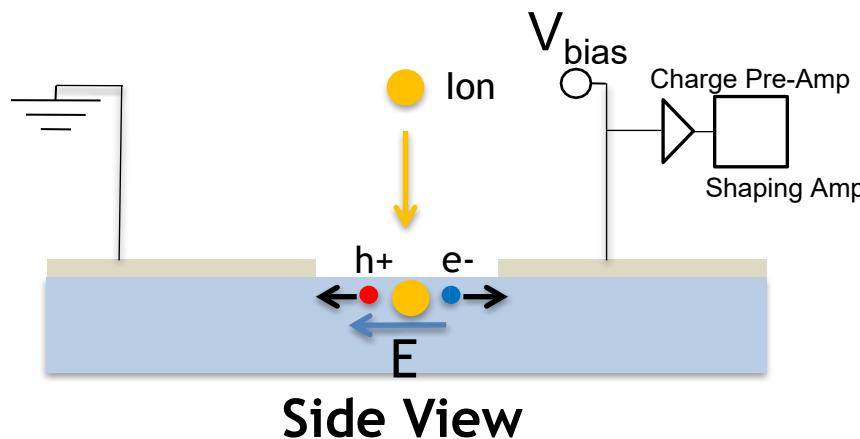
# In-situ Counted Ion Implantation to control the number of implanted ion

Yield = # measured SiV / # implanted Si

## Poisson Statistics

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

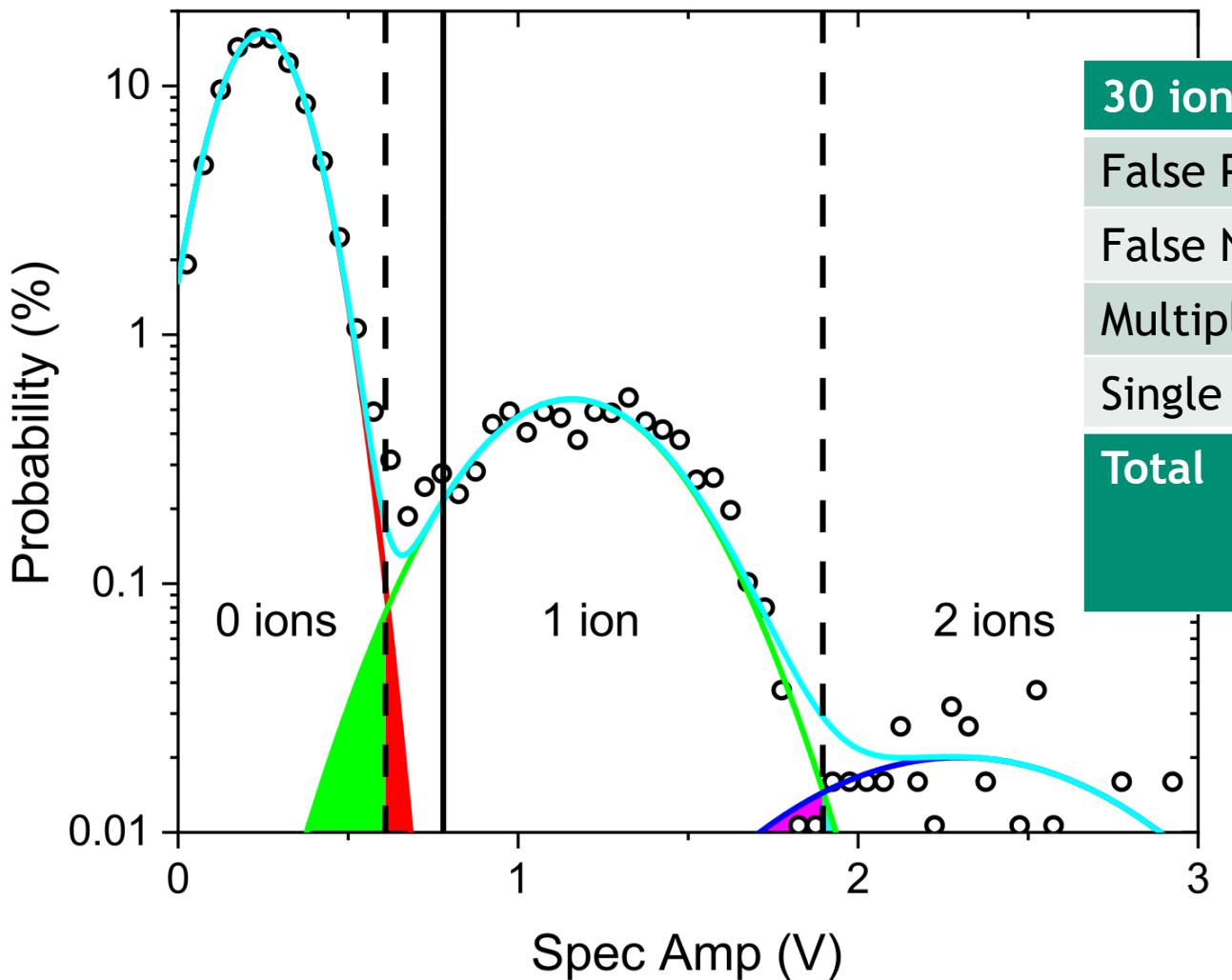
### Ion Beam Induced Charge (IBIC)



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

IBIC/detection demonstrated for low energy heavy ions

# Demonstrated 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 %
<b>Total</b>	+18.3 / -18.3 %	+14.4 / -0 %	+4.0 / -1.1 %

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

Titze *et al*, Nano Letters 22, 3212-3218 (2022)

- Aside,  $<0.1>$  ions/pulse using a 1  $\mu$ s pulse length needs ~30 fA of beam current or ~100k ions/s

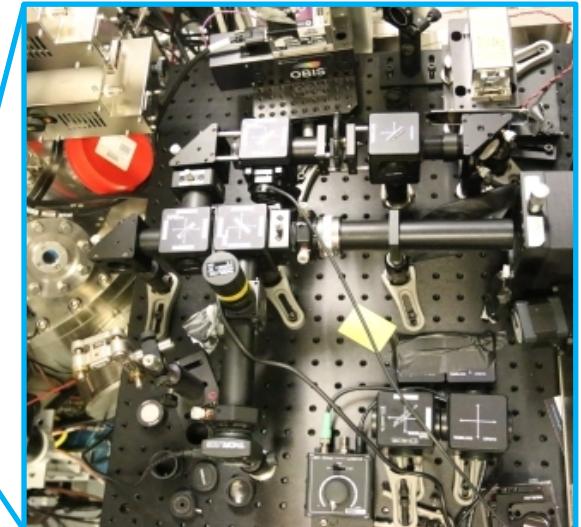
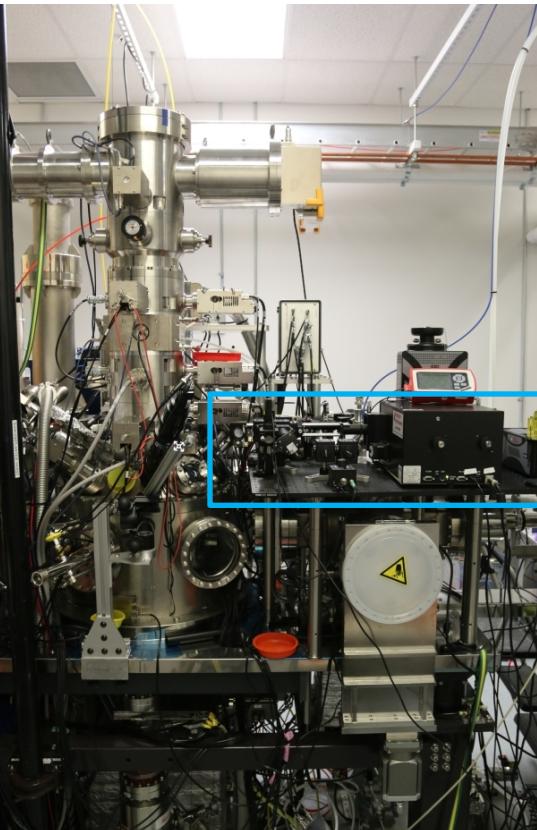
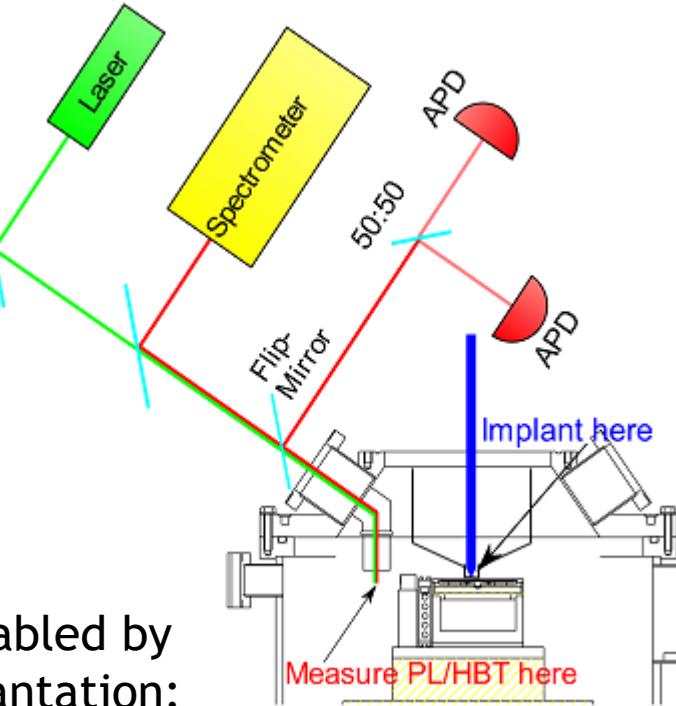
In-situ counting to reduce the error in the number of implanted ions

# In-situ Photoluminescence to confirm optical defect center



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

We switched from SiV in diamond to V<sub>Si</sub> in SiC as can measure as implanted samples without annealing

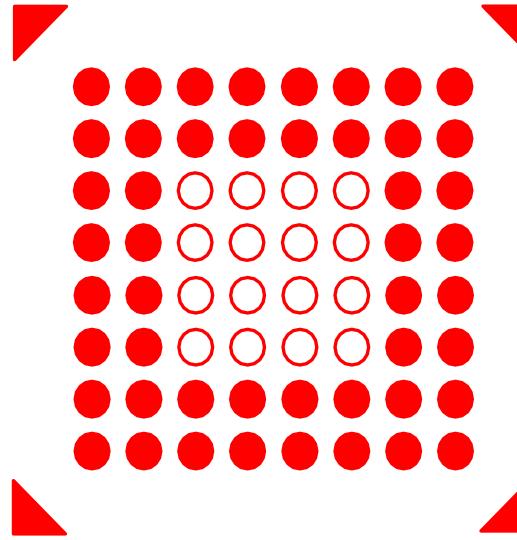


In-situ PL to confirm the optically emission from the defect centers

# Demonstration of In-situ Photoluminescence in SiC



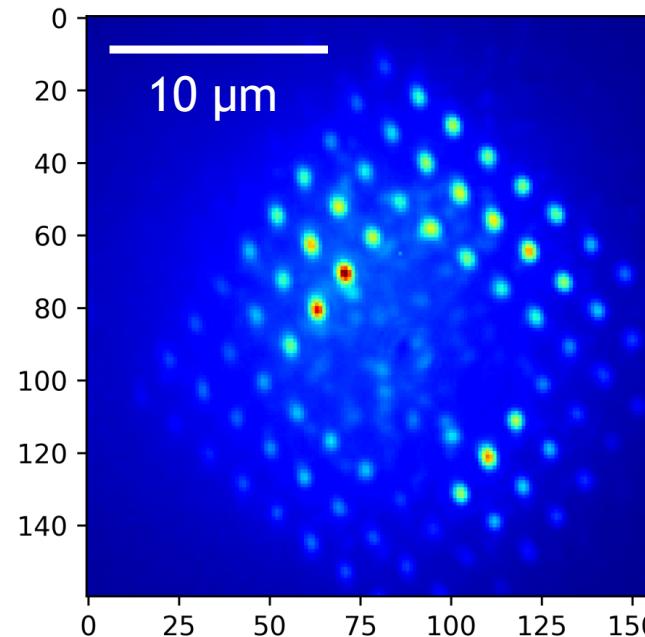
Design of array



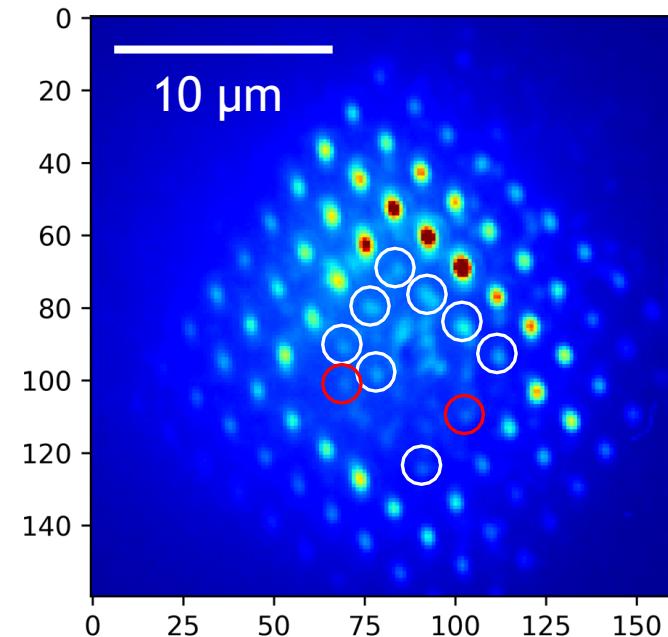
► Alignment markers

- <500> Ions/spot implanted once that acts as landmark to find in-situ arrays during PL check
- In-situ array points to be filled

Implant Alignment Grid



Implant/PL Repeat to fill Array

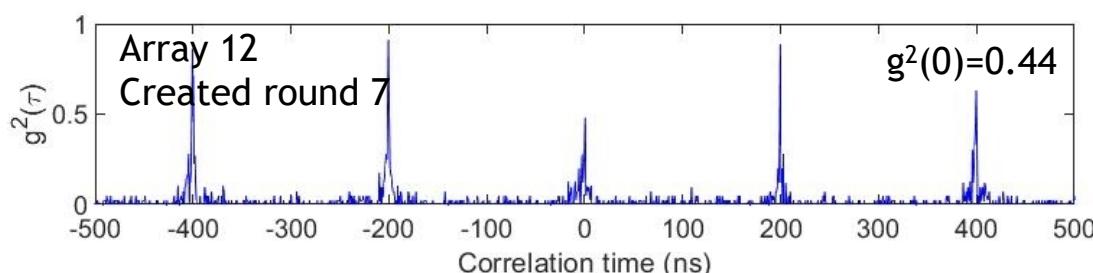
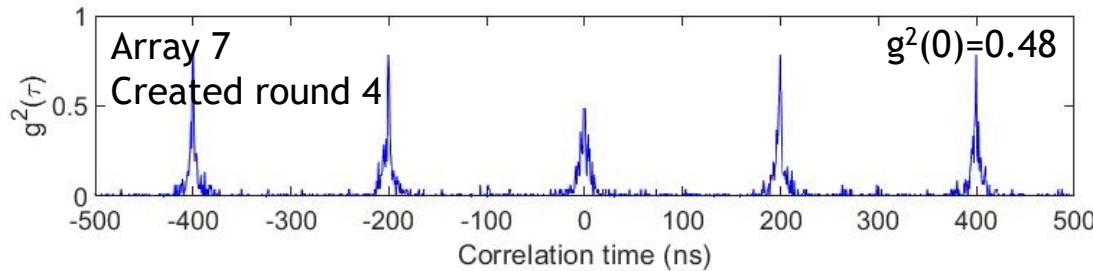
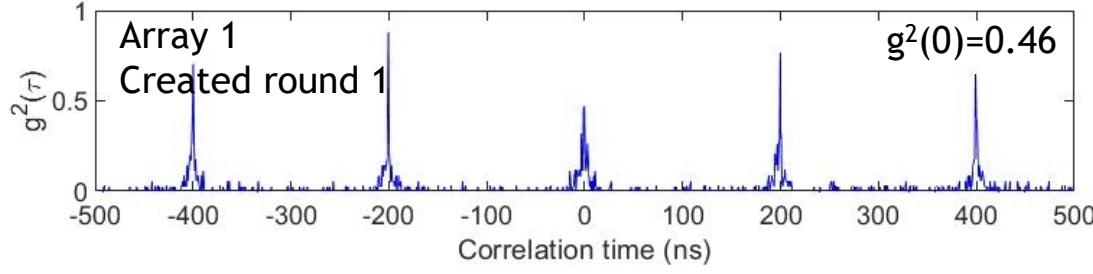
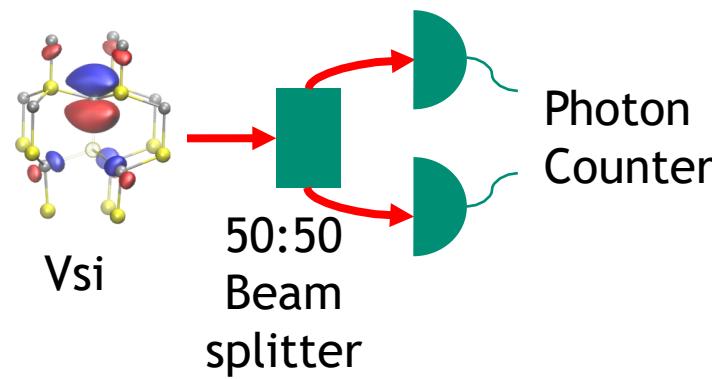
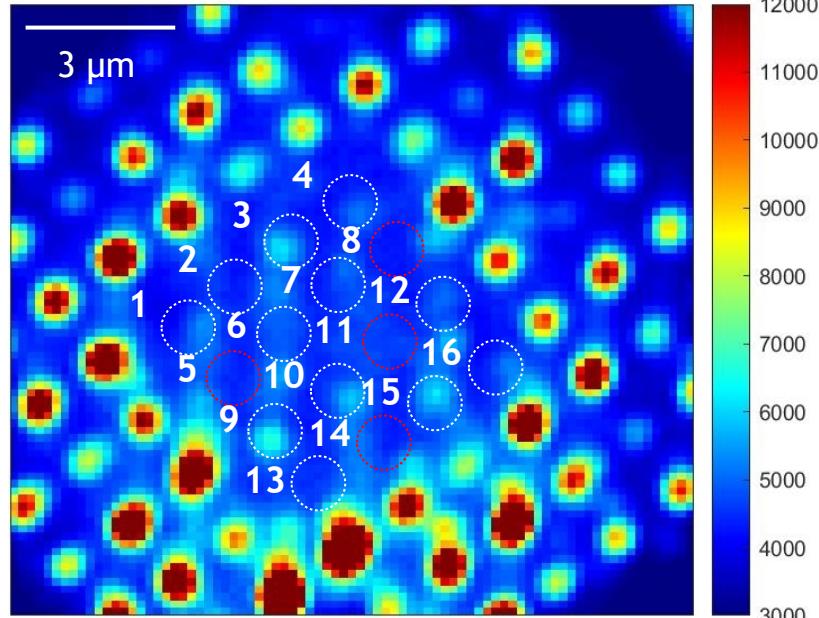


Chandrasekaran *et al*, Adv. Sci., 2300190 (2023)

Preliminary results suggest the in-situ PL works, BUT is limited by high background counts

# Ex-situ $g^2(\tau)$ check on <3> ions/spot arrays shows single defects

3 representative examples (okay, good examples 😊!)



\*No background correction

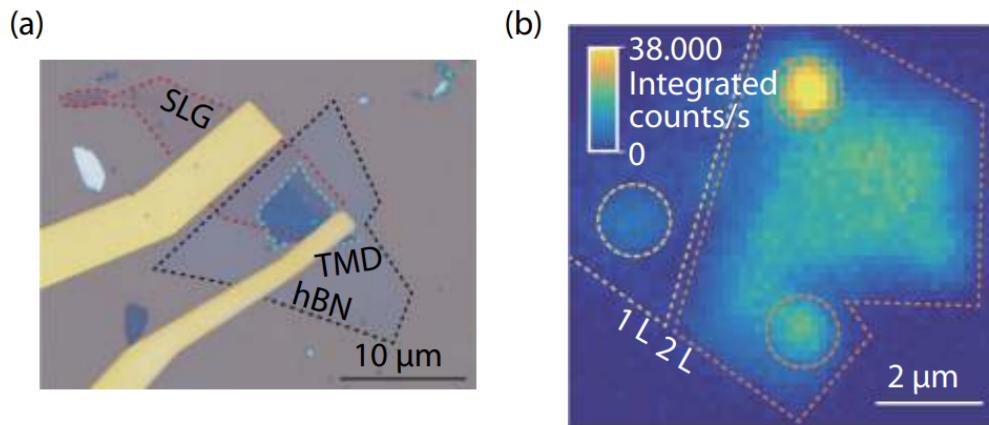
Chandrasekaran et al, Adv. Sci., 2300190 (2023)

9/16 (56%) of filled array points showed  $g^2(0) < 0.5$  without background correction → single defects

# Fabrication of Impurity based Single Photon Emitters in 2D Mat'l's



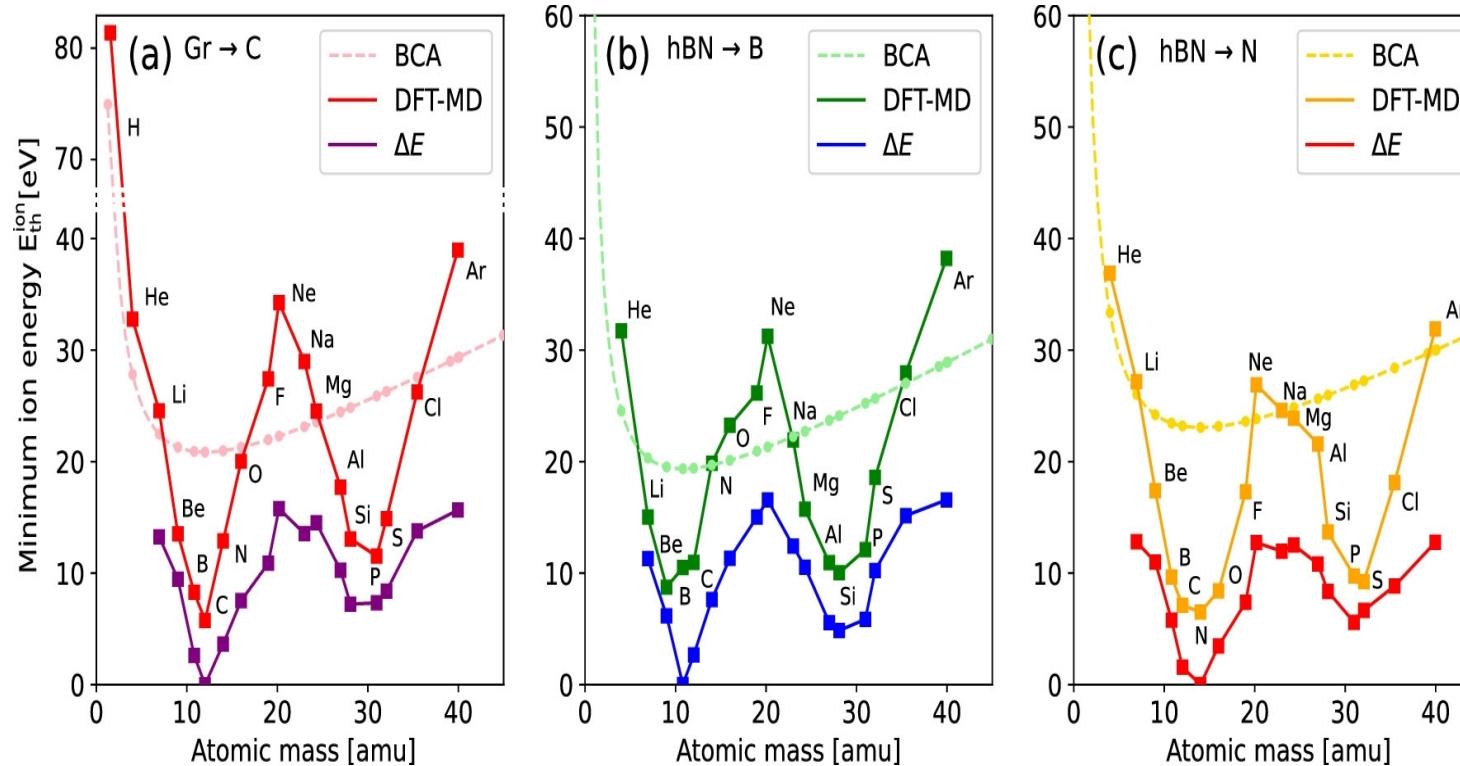
- Quantum emitters in 2D Materials have the potential to enable electrical operations and integration into conventional CMOS devices



S. L. Ren *et al.*, J. Semicond., 40, 071903 (2019)

- Deterministic placement of single impurity type defects is a challenge
  - 1.) Energy - what energy is needed to enable implantation into a monolayer material? How to achieve these energies?
  - 2.) Location - how to maintain spatial resolution at these low energy?

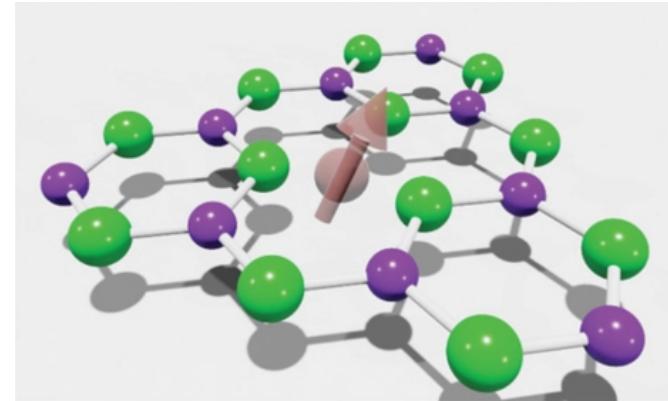
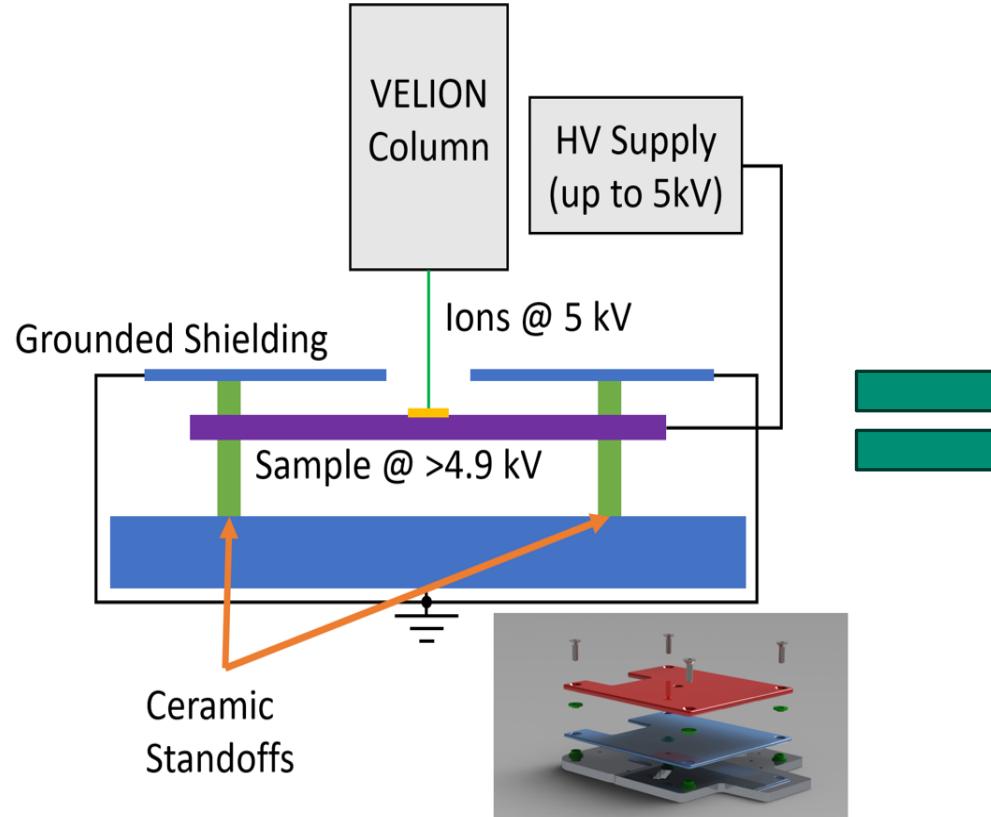
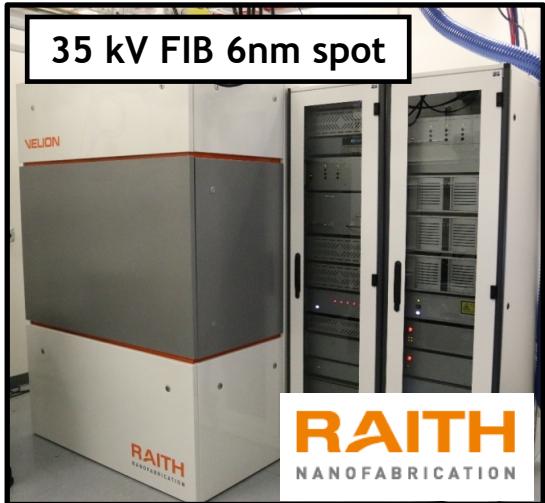
# What energy is needed to stop in a 2D monolayer?



S. Kretschmer et al., J. Phys. Chem. Lett., 13, 2, 514 (2022)

Literature predicts energies of ~10-100 eV is needed to implant an impurity atom in a monolayer

# We are developing a new ultra low energy (<<1 keV) FIB capability for Impurity based emitters in 2D materials

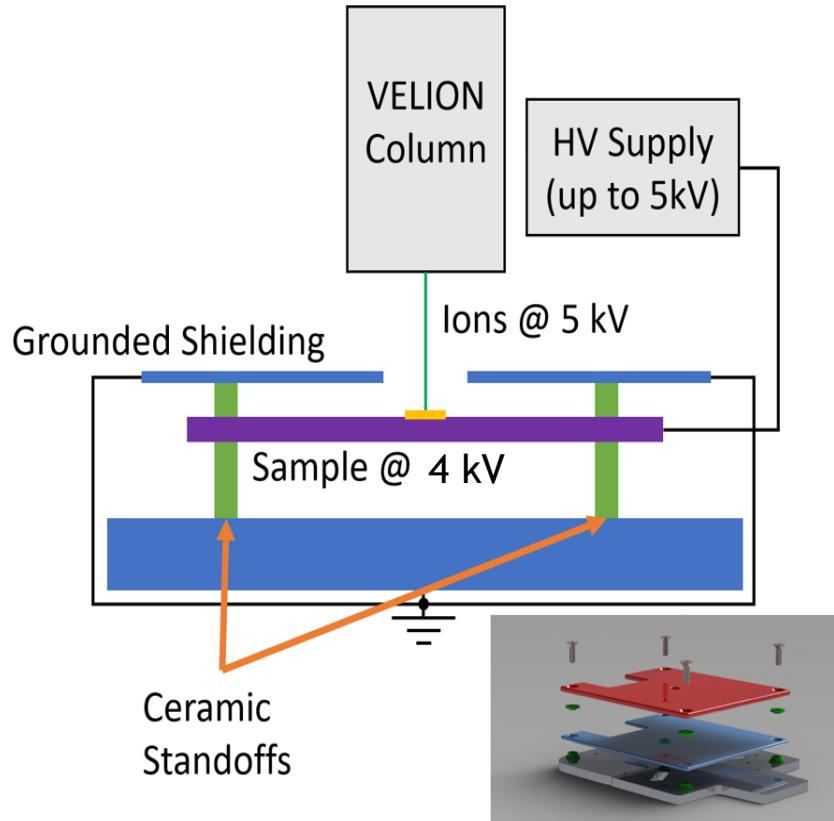


Adapted from N. Mendelson et al., Adv. Mater., 34, 2106046 (2022)

Enables lower energy implantation, albeit with a loss of spatial resolution

# Ultra Low Energy Implantation with *spatial* resolution

## FIB with Biased Sample Holder for Implantation



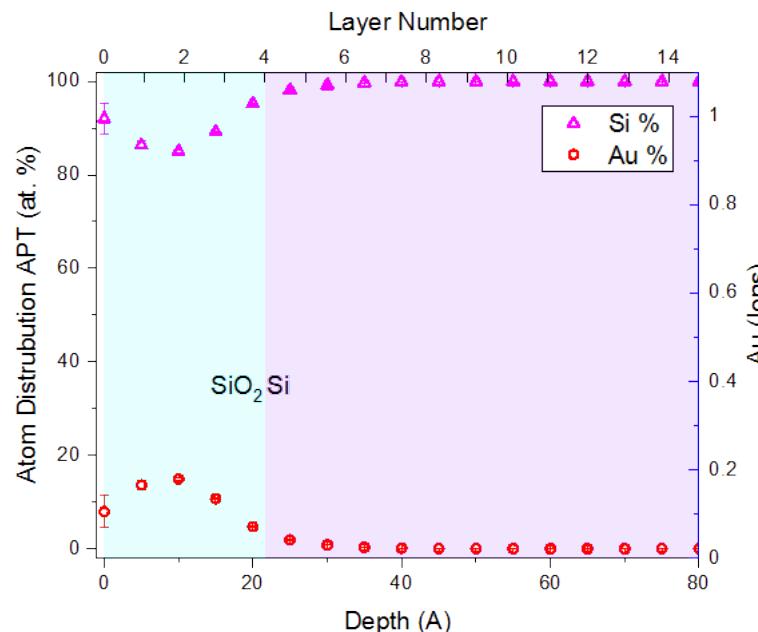
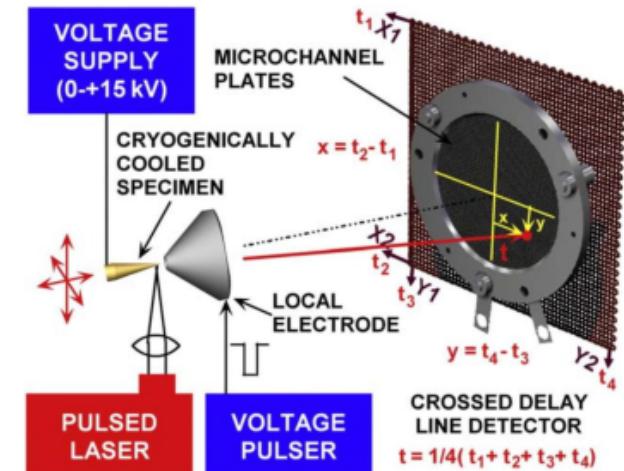
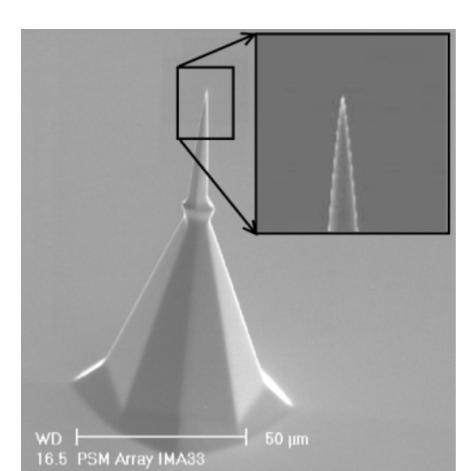
Example of capability:

$V_{acc} = 5$  kV

$V_{plate} = 4.0$  kV

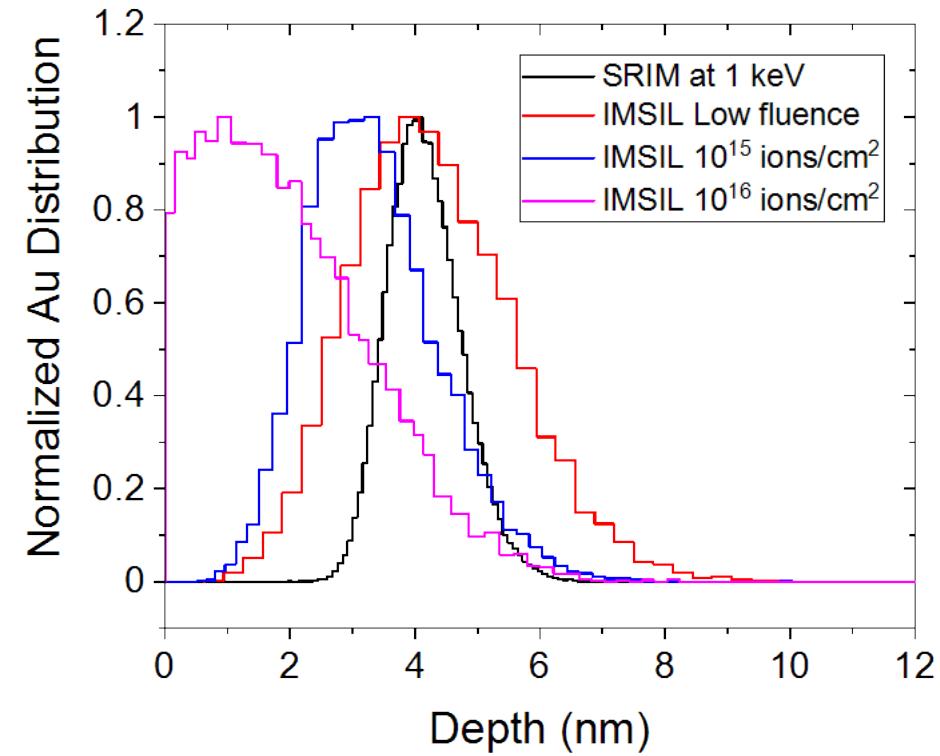
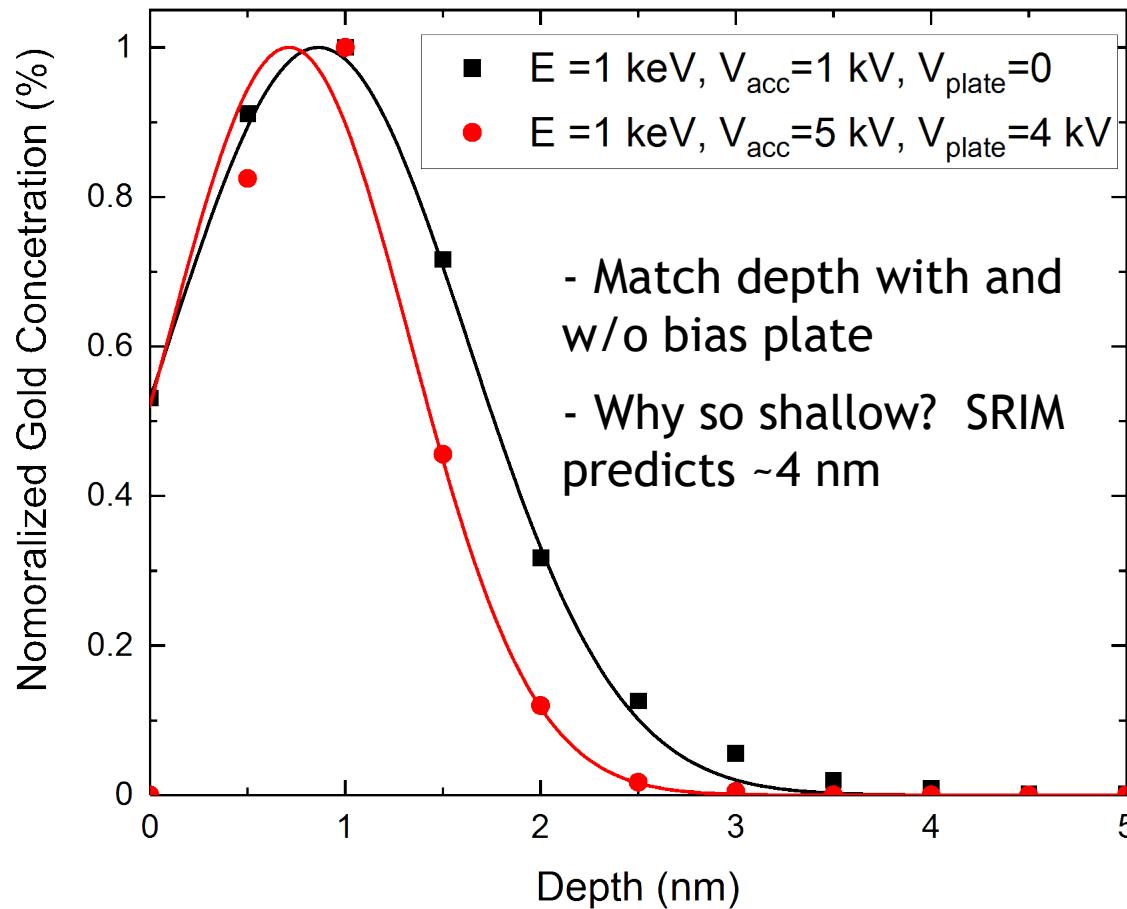
Ion Landing Energy  
1 keV

## Atom-Probe Tomography for characterization



Low energy implantation with biased plate, verified with APT!

# Does the low energy implantation with and without the plate agree?



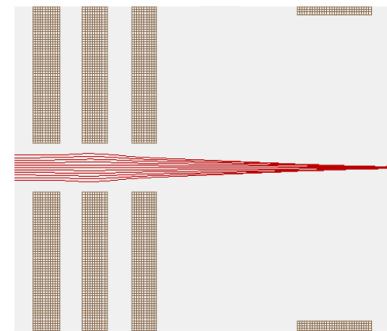
- Monte Carlo code IMSIL takes into account surface sputtering at high fluence values

G. Hobler Nucl. Instr. and Meth. B, 96, 155 (1995)

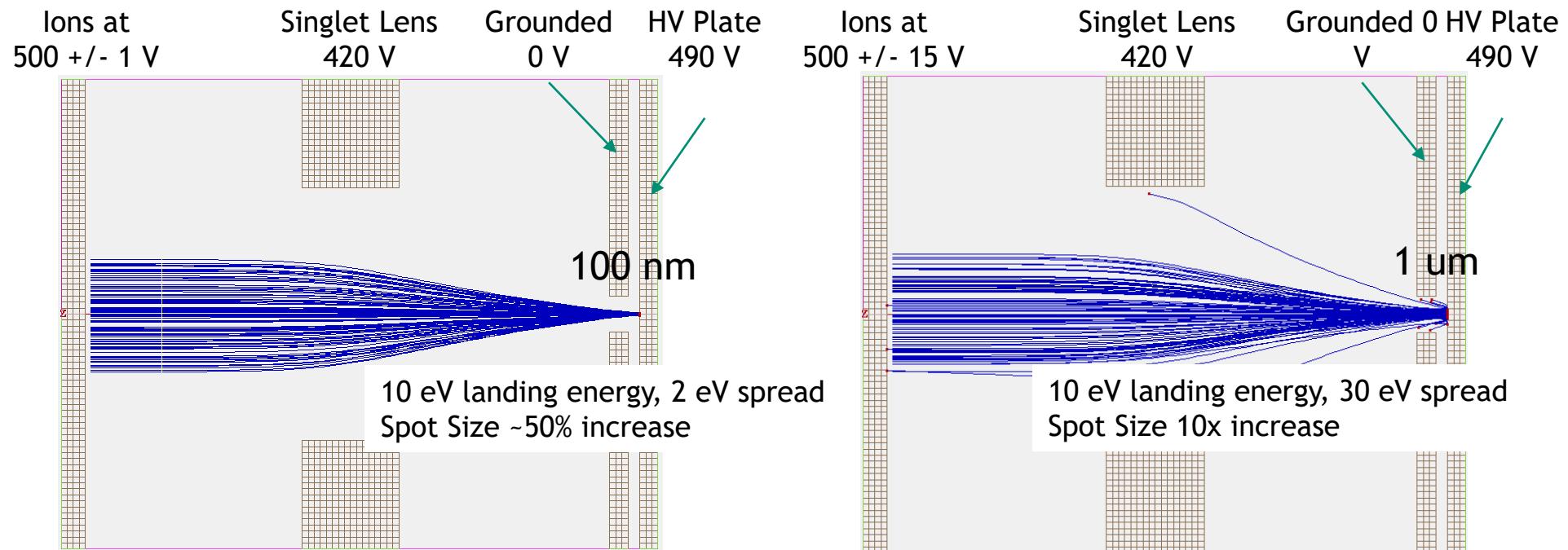
Demонstrated low energy implantation using the biased sample plate,  
shallow depth likely due to sputtering

# What is the Expected Spot Size at Low Energy?

- SIMION ion optics simulation
- Take into account: chromatic aberrations, energy spread of the ions



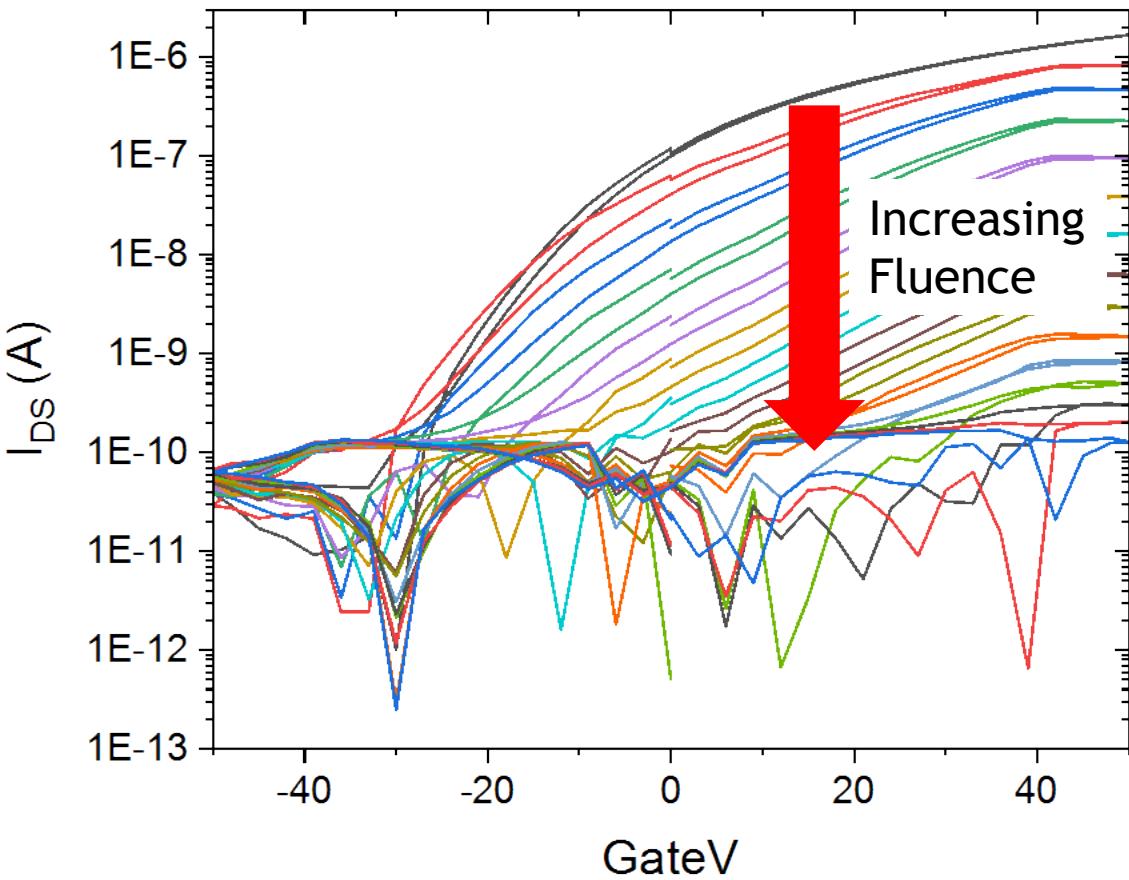
5 keV Au<sup>+</sup> ions with a 60  $\mu$ m diameter to a 4 kV plate - 60 nm optimized beam spot



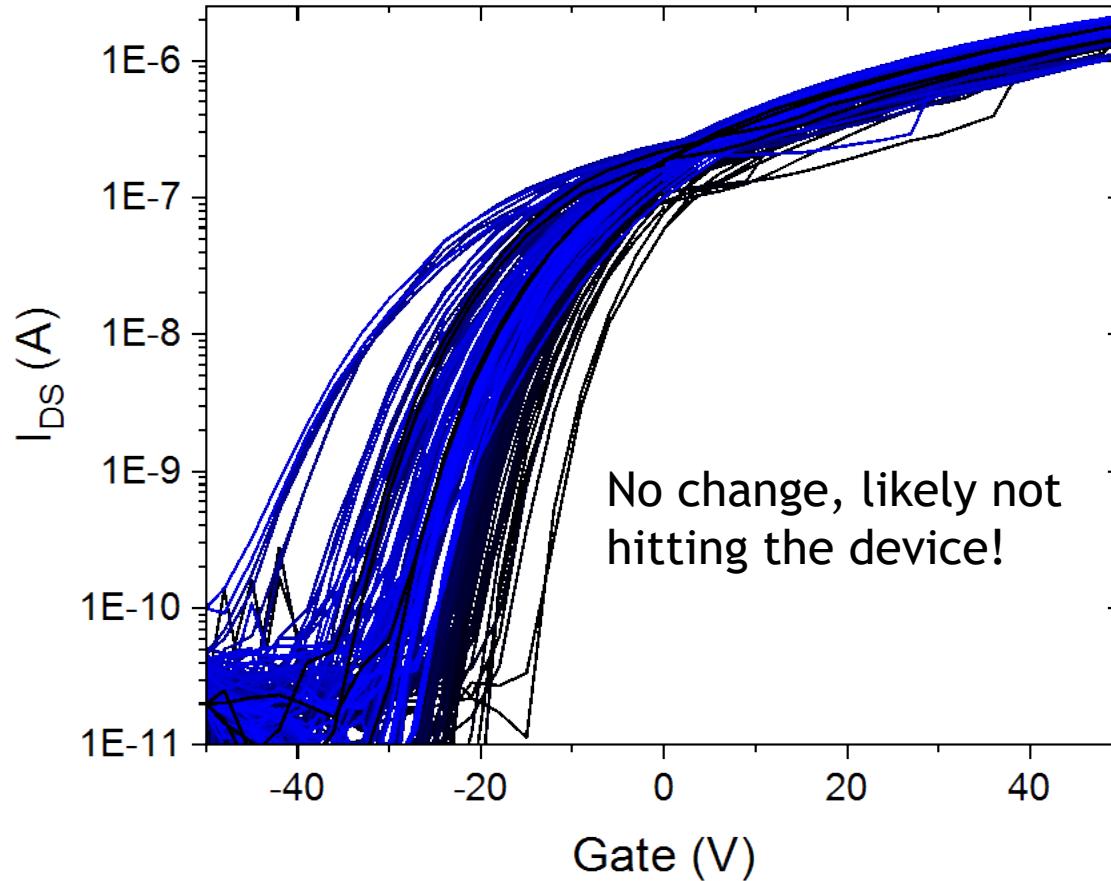
At ~10 eV landing energy, we expect <2X spot size increase, targeting ~100 - 300 nm

# But, targeting is a challenge

1 keV Au Beam w/o Bias Plate



1 keV Au Beam with Bias Plate



We can achieve low energy (verified with APT), BUT we need to figure out fluence and targeting!

# 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, Jacob Henshaw, L. Basso, H. Byeon, A. Mounce, P. Kehayias, M. Lilly (SNL)

V. Chandrasekaran, Han Htoon (LANL)

V. Acosta (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

CUNY  
175  
ANNIVERSARY

UTS  
UNIVERSITY  
OF TECHNOLOGY  
SYDNEY

Los Alamos  
NATIONAL LABORATORY  
EST. 1943

OAK  
RIDGE  
National Laboratory



HARVARD  
UNIVERSITY

THE UNIVERSITY OF  
CHICAGO

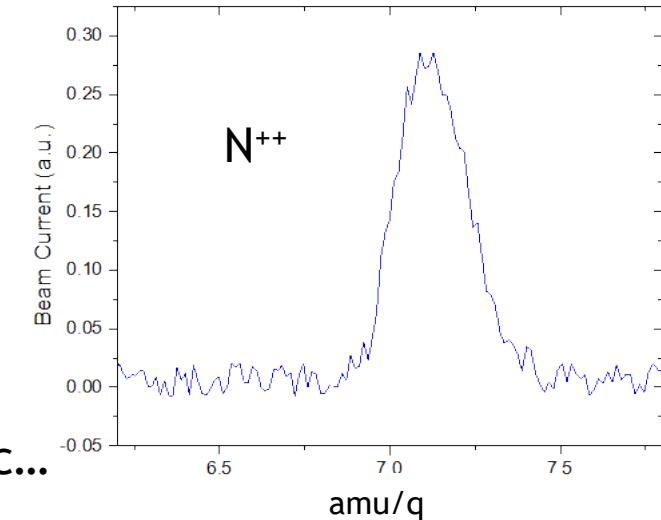
PURDUE  
UNIVERSITY

# Summary



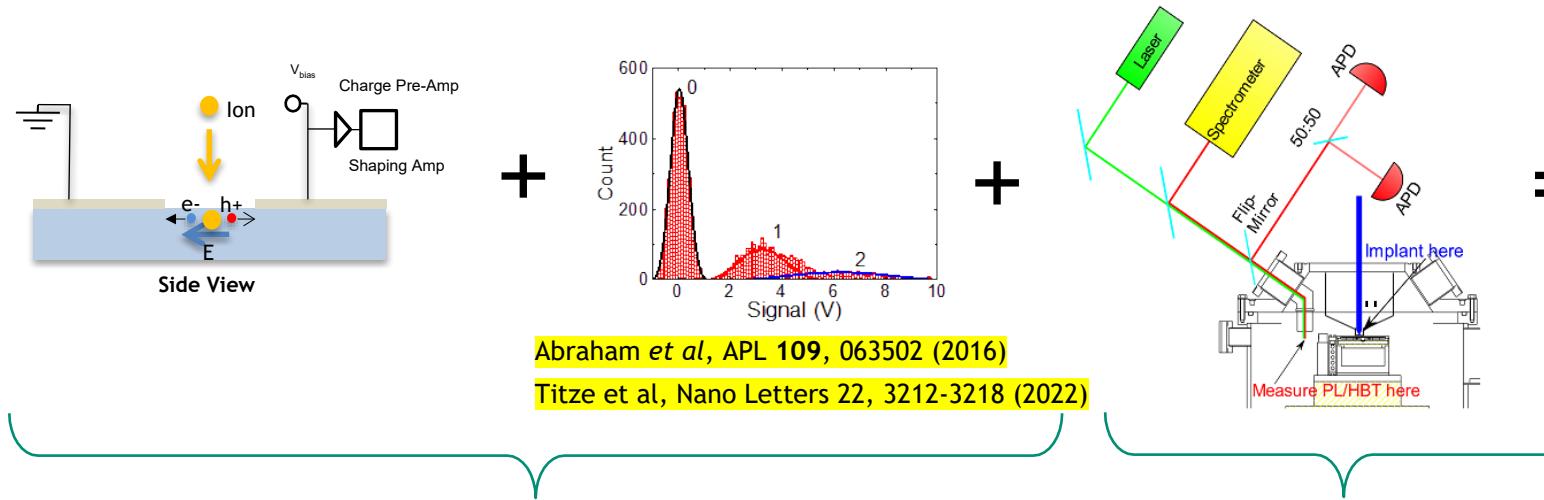
- We have demonstrated focused ion implantation for fabrication of single atom devices and nanofabrication

- Viable solution for prototyping - fast and easy!
- On-going work in diamond, SiN, SiC, hBN, GaN, AlN, GaOx, etc...
- LMAIS for 42/114 elements and development still on-going



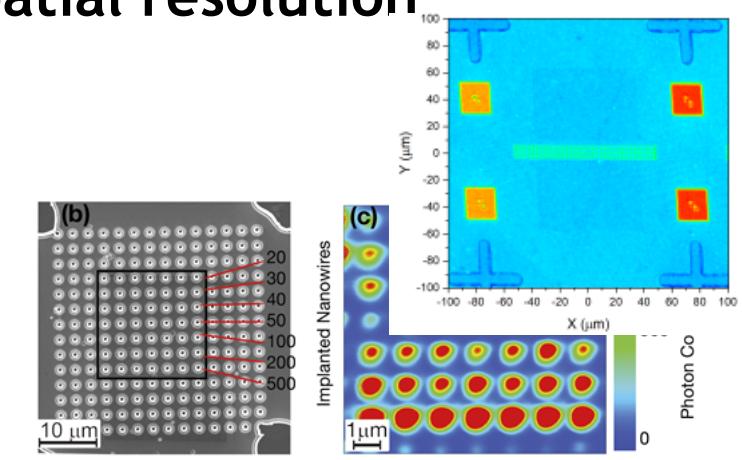
Multiple sources run, with ~1.5 days of runtime

- Pathway Towards Deterministic Defect Centers in Wide Bandgap Materials using FIB Implantation and now ultra-low energy with spatial resolution



Control the number of ions

Confirm Optically Active Defect Centers

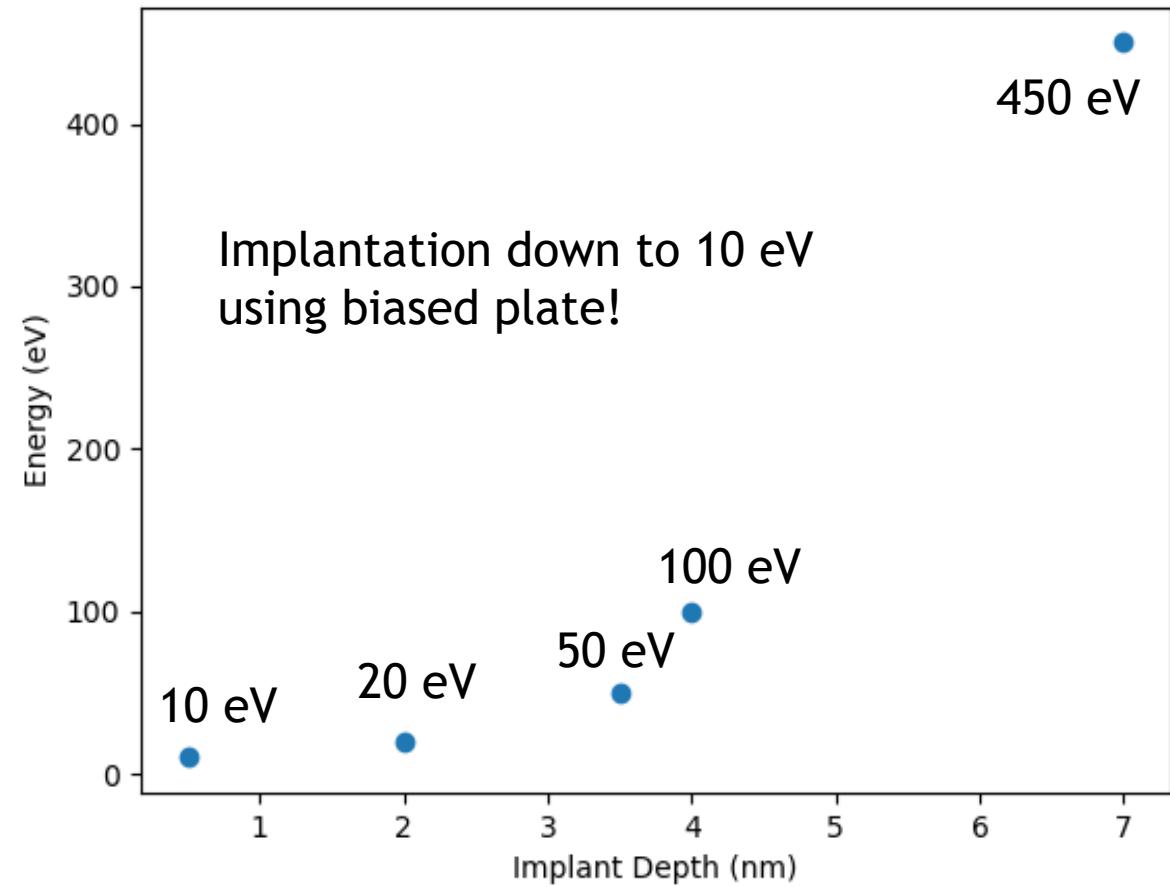
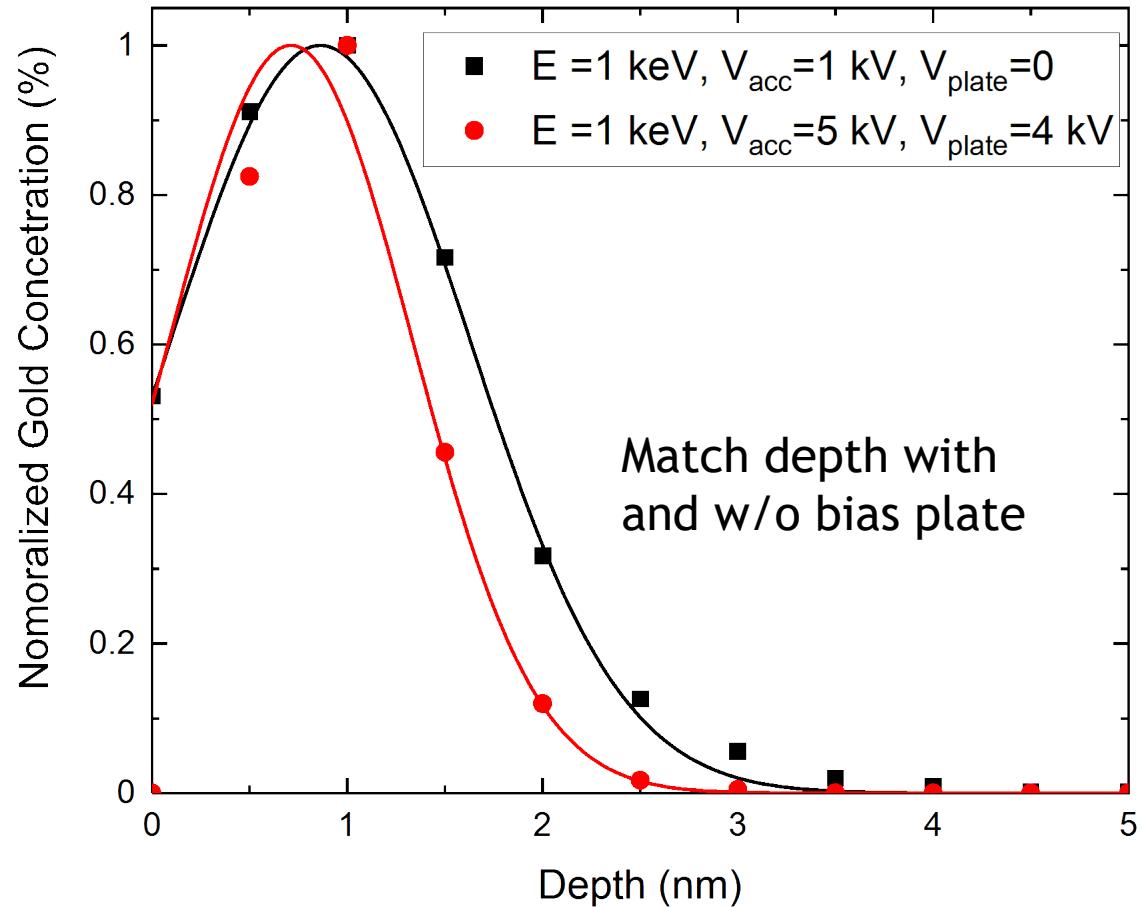


L. Marseglia, *et al.*, Optics Express (2018)

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



# Does the low energy implantation with and without the plate agree?

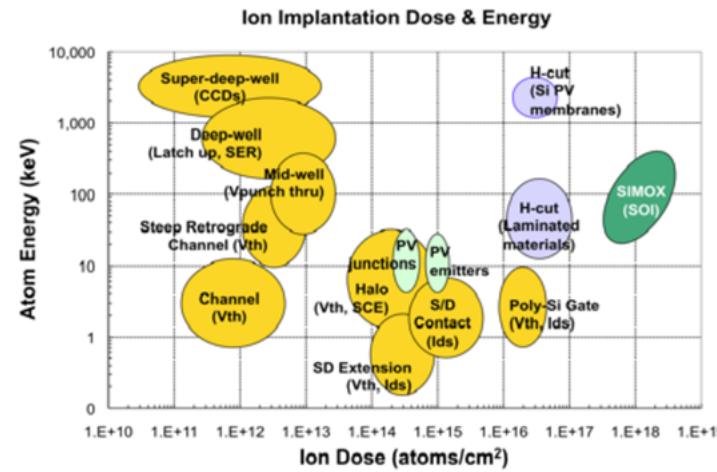
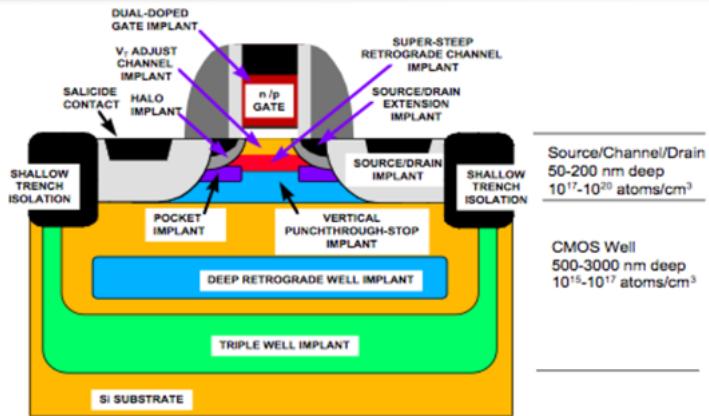


Demonstrated low energy implantation using the biased sample plate, difference in depth between 1 keV and eV range is likely due to sputtering

# Ion Implantation and Irradiation for Device Fab

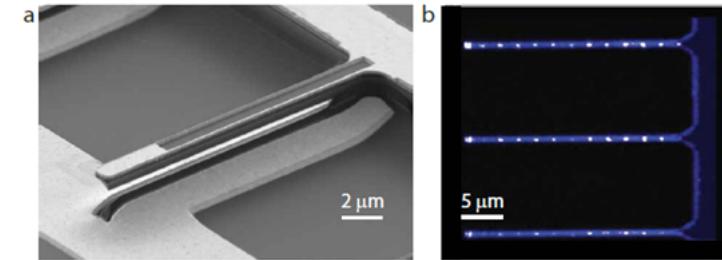


Ion Implantation has been a work-horse for the semiconductor industry

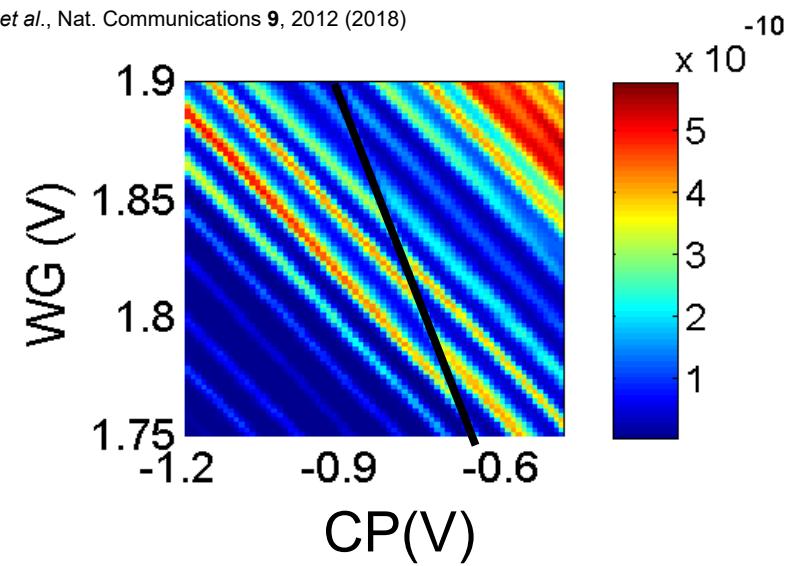


S. B. Felch, et al., Proceedings of PAC2013, Pasadena, CA (2013)

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)



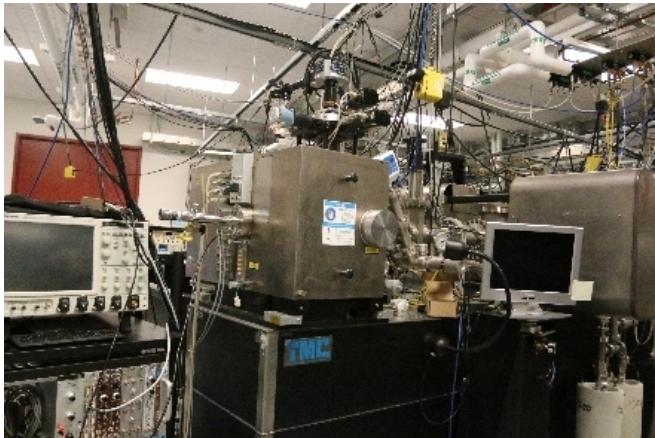
Singh et al. Appl. Phys. Lett. 108, 062101 (2016)

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

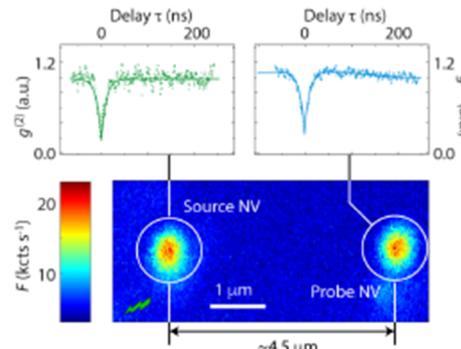
# High Energy Focused Ion Beams $\sim 1 \mu\text{m}$



- 6 MV Tandem microbeam (microONE)

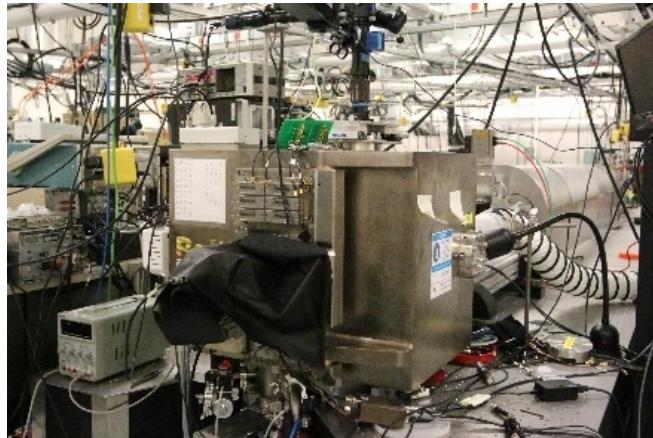


- High resolution laser stage
- Spot size  $<1 \mu\text{m}$
- Energy 0.8 - 70 MeV
- H to Au



NV PL in diamond

- 3 MV Pelletron microbeam (Light Ion Microbeam)

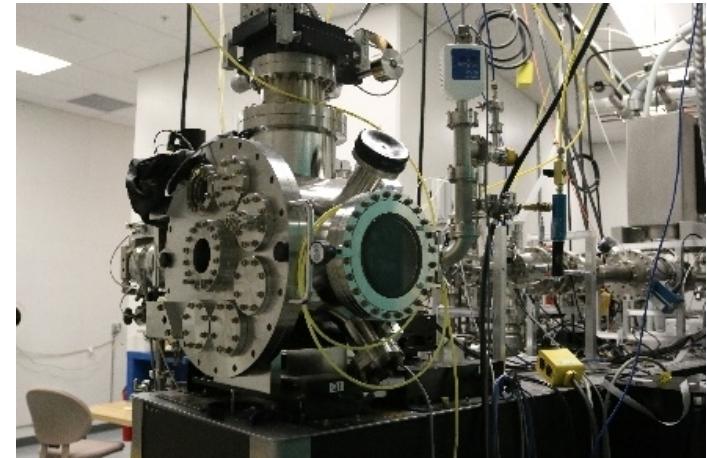


- High resolution laser stage
- Spot size  $<600 \text{ nm}$
- Energy 0.25 - 3 MeV
- H, He, N, Ar, Xe, ...

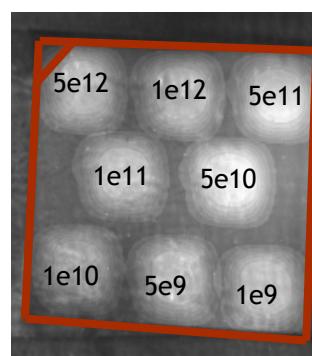


IBIC on PIN diode

- 350 kV HVEE microbeam (NanoBeamLine)



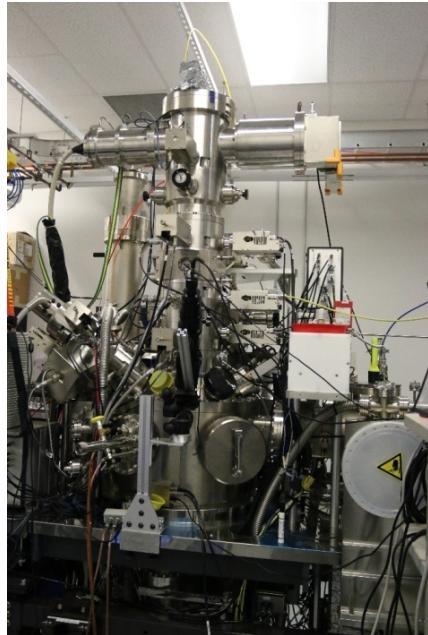
- Piezo stage
- Spot size  $<1 \mu\text{m}$
- Energy 20 - 350 keV
- H to Au



Ni into diamond

# Low Energy Focused Ion Beams <1 to 20 nm

- 100 kV A&D FIB100NI  
(nanolmplanter)



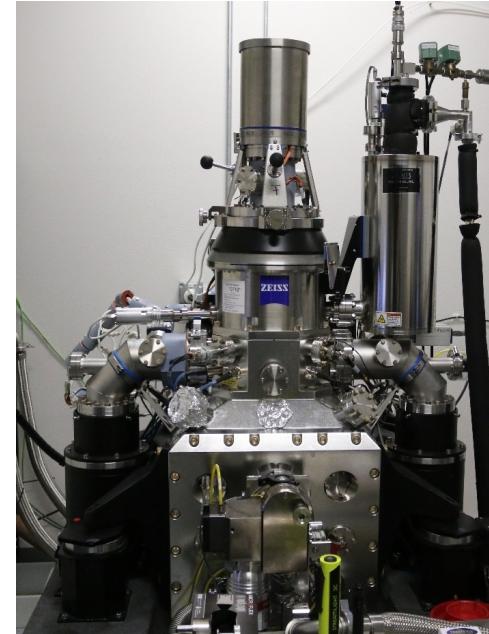
- High resolution laser stage
- Spot size <10 nm (Ga)
- Energy 10 - 200 keV
- 1/3 periodic table

- 35 kV Raith Velion  
(Velion)



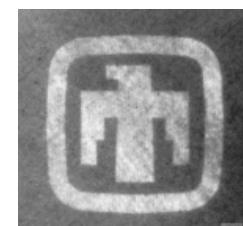
- High resolution laser stage
- Spot size <6 nm (Ga)
- Energy 5 - 70 keV
- 1/3 periodic table

- 35 kV Zeiss Orion Plus  
(HeLM)

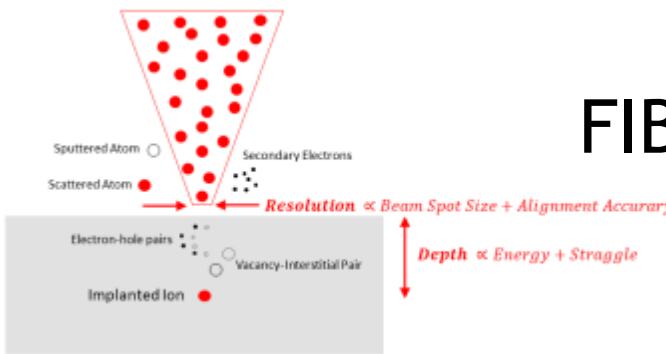


- Piezo stage
- Spot size <1 nm
- Energy 10 - 35 keV
- He

*All three equipped with Raith 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

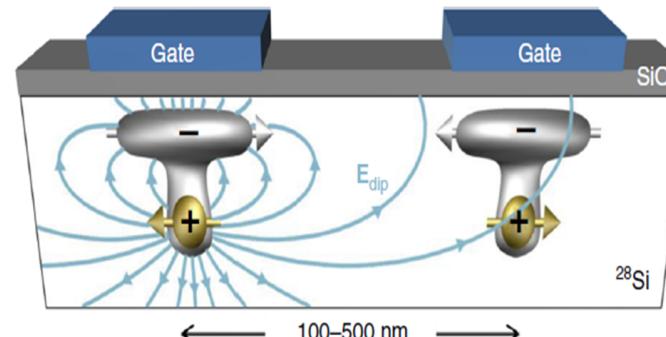
Alignment accuracy  $\sim 10\text{'s nm}$

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

## *What is the needed resolution?*

Silicon quantum processor with robust long-distance qubit couplings

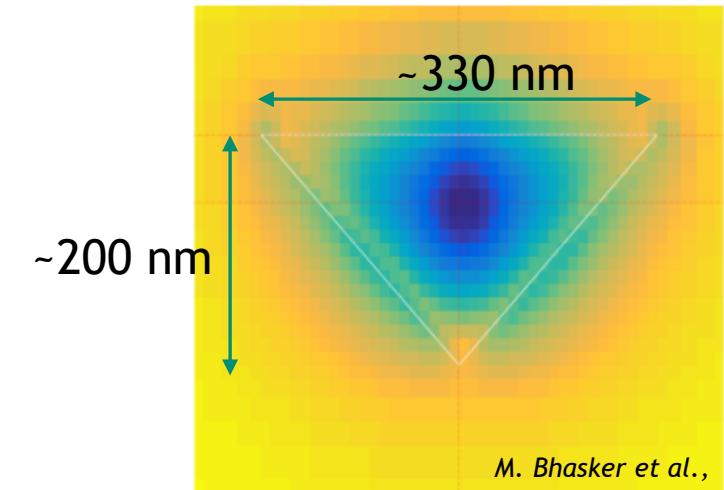
Guilherme Tosi<sup>1</sup>, Fahd A. Mohiyaddin<sup>1,3</sup>, Vivien Schmitt<sup>1</sup>, Stefanie Tenberg<sup>1</sup>, Rajib Rahman<sup>2</sup>, Gerhard Klimeck<sup>2</sup> & Andrea Morello<sup>1</sup>



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!

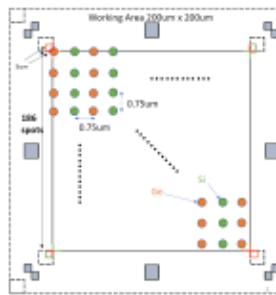
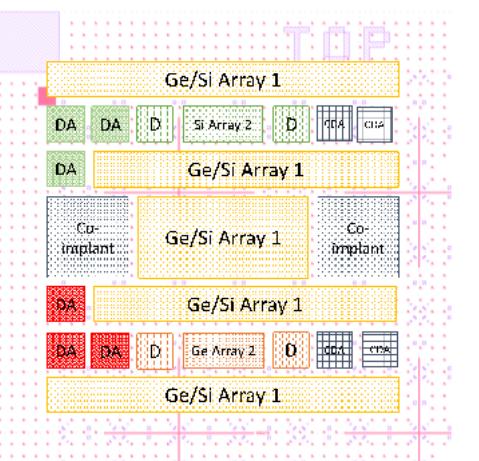
# Practical Example of FIB Implantation



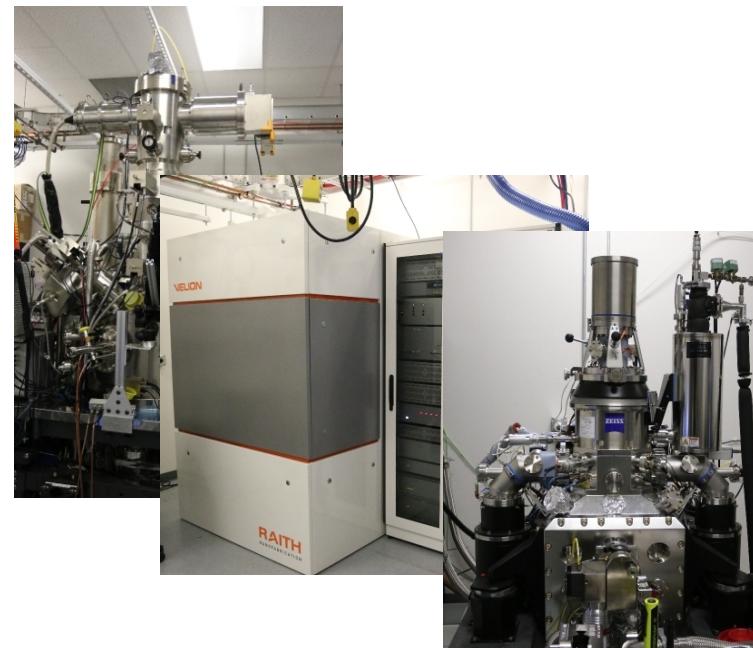
## Conversation of what is needed?



## Design and layout of sample



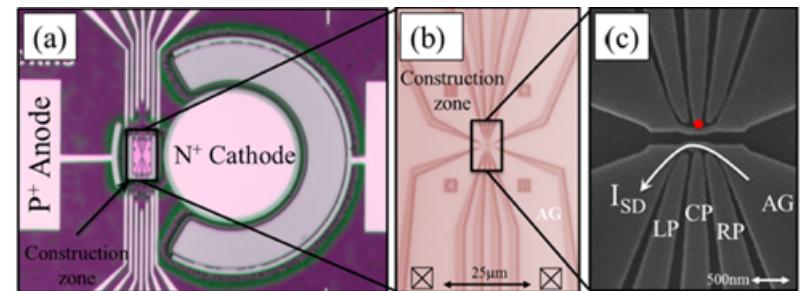
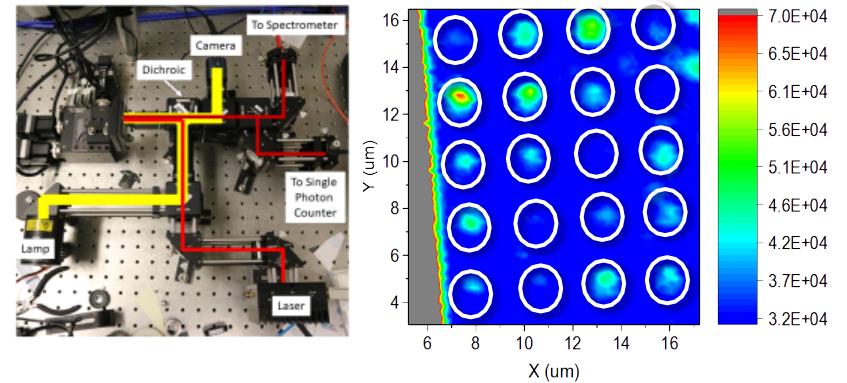
## FIB Implantation/Irradiation



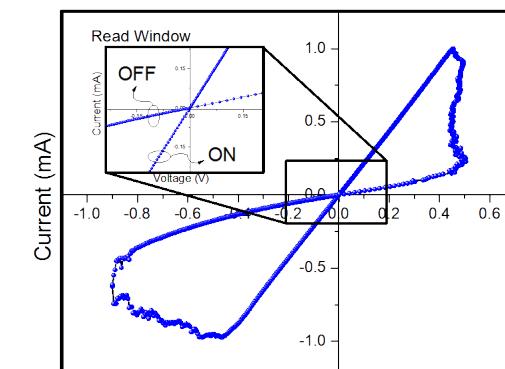
## Post Implantation Sample Prep



## Post Implantation Characterization



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



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



# How can you access these capabilities? CINT User Proposals

**THE CENTER FOR INTEGRATED NANOTECHNOLOGIES**

**Center for Integrated Nanotechnologies**  
DISCOVERY PERFORMANCE  
EDUCATION INTEGRATION  
Sandia Los Alamos

**One Scientific Community Focused on Nanoscience Integration**  
The Center for Integrated Nanotechnologies (CINT) is a Department of Energy Office of Science Nanoscale Science Research Center. CINT offers world-leading scientific expertise and specialized capabilities to create, characterize, and integrate nanostructured materials at a range of length scales, from the nano- to meso-scale. It is jointly operated by Los Alamos and Sandia national laboratories and leverages the unmatched scientific and engineering expertise of the host labs.

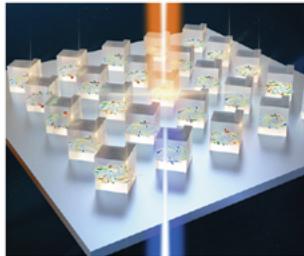
## Science Thrusts

Integration is the key to exploiting the novel properties of nanoscale materials and creating new technologies. CINT's scientific staff and capabilities are organized around four interdisciplinary science thrusts which address different challenges in nanoscience integration.



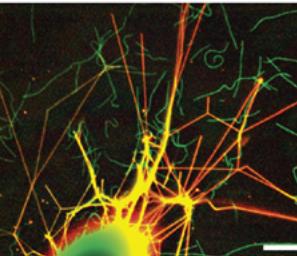
### *In-Situ Characterization and Nanomechanics*

Developing and implementing world-leading capabilities to study the dynamic response of materials and nanosystems to mechanical, electrical, or other stimuli.



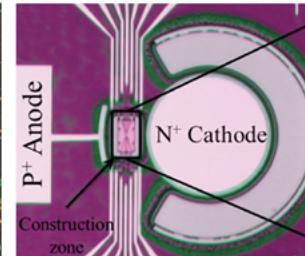
### *Nanophotonics & Optical Nanomaterials*

Synthesis, excitation, and energy transformations of optically active nanomaterials and collective or emergent electromagnetic phenomena (plasmonics, metamaterials, photonic lattices).



### *Soft, Biological & Composite Nanomaterials*

Synthesis, assembly, and characterization of soft, biomolecular, and composite nanomaterials that display emergent functionality.



### *Quantum Materials Systems*

Understanding and controlling quantum effects of nanoscale materials and their integration into systems spanning multiple length scales.

## User Program

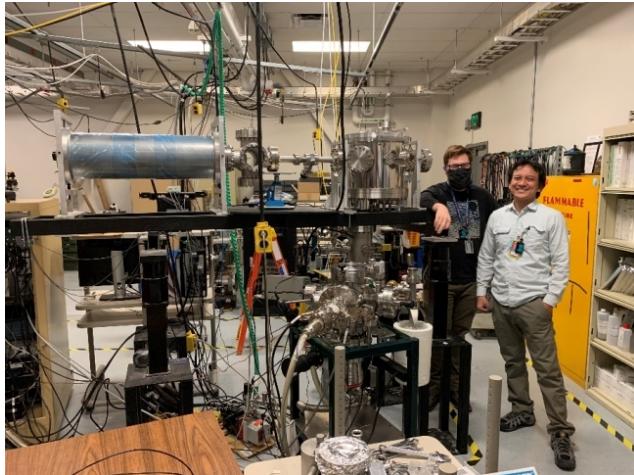
CINT is an Office of Science national user facility. CINT helps the international research community perform cutting-edge research in the areas of nanoscience and nanotechnology, and is available free of charge for open science. As a user facility, CINT has the structure and mission to collaborate widely across academia, industry, and within DOE labs. Access is via peer-reviewed technical proposals. Proprietary research may be conducted in accordance with Federal regulations for full-cost recovery. CINT cannot provide funding to users.

**The Center for Integrated Nanotechnologies (CINT) has both regular Fall and Spring call for proposals and Rapid Access available**

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

# Capability Currently Under Development

## Pulsed Power Electron Gun

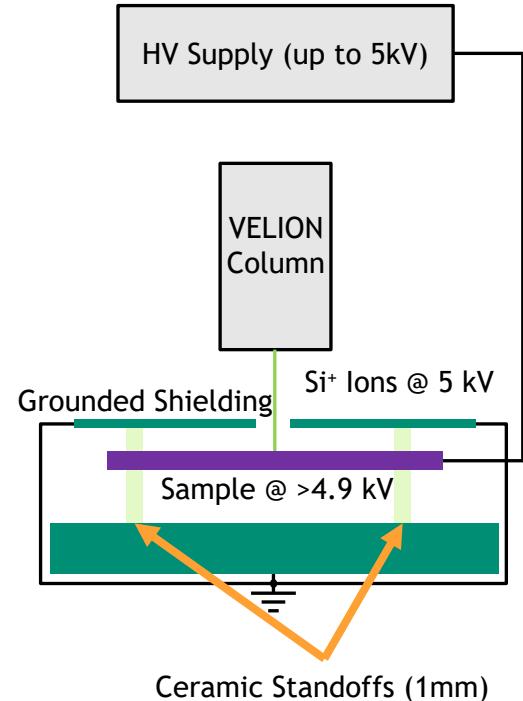


## Specifications

- 300 keV
- $>>10$  A of beam current
- $<25$  ns pulse lengths

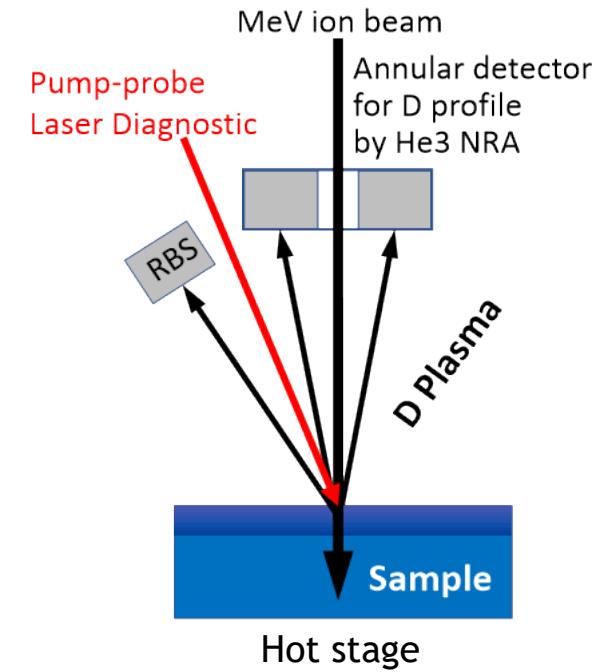
*Enables improved yield for wide bandgap defect centers*

## Low Energy Implantation Stage



*Enables lower energy implantation, albeit with a loss of spatial resolution*

## Combined Ion Irradiation + Ion Beam Analysis + Plasma Exposure



*Enables exploration of real-time evolution in sample properties including erosion and redeposition*

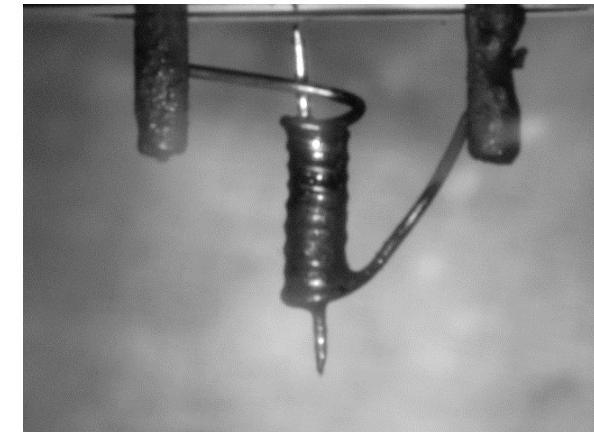
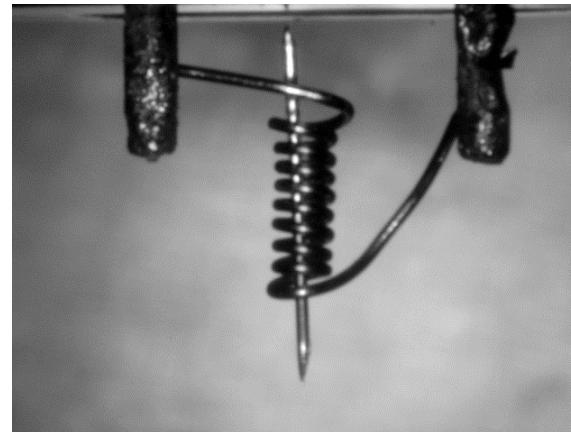


# Pb Source based on SnPb alloy

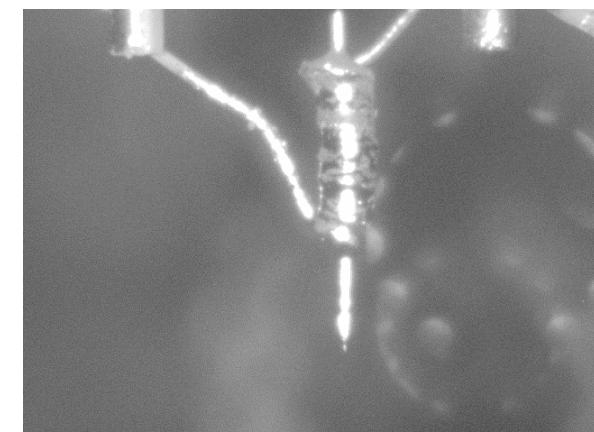
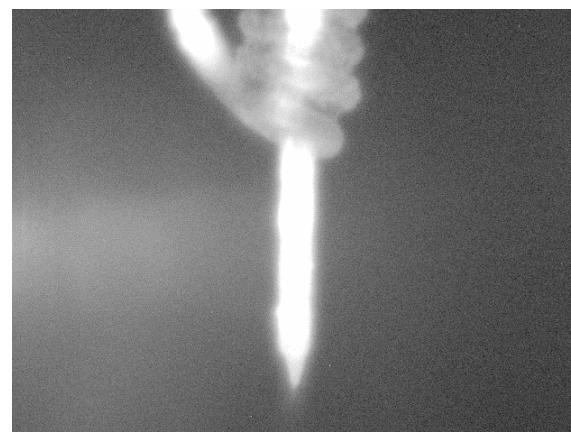
- Solder (SnPb) does not wet W, but Solder does wet a soldering iron
- We attempted multiple homemade sources made from Fe, Monel, Kanthal, Kovar. Of these Kovar (Fe-Ni-Co) gave the best performance
- We tested both mechanically cut and electrochemically etched tips welded to the reservoir to improve alloy flow and heating

As tested in the Raith Velion these tips achieve lifetimes of  $<2000 \mu\text{A}^*\text{hr}$  and spot sizes of  $<40 \text{ nm}$

Mechanically cut tips



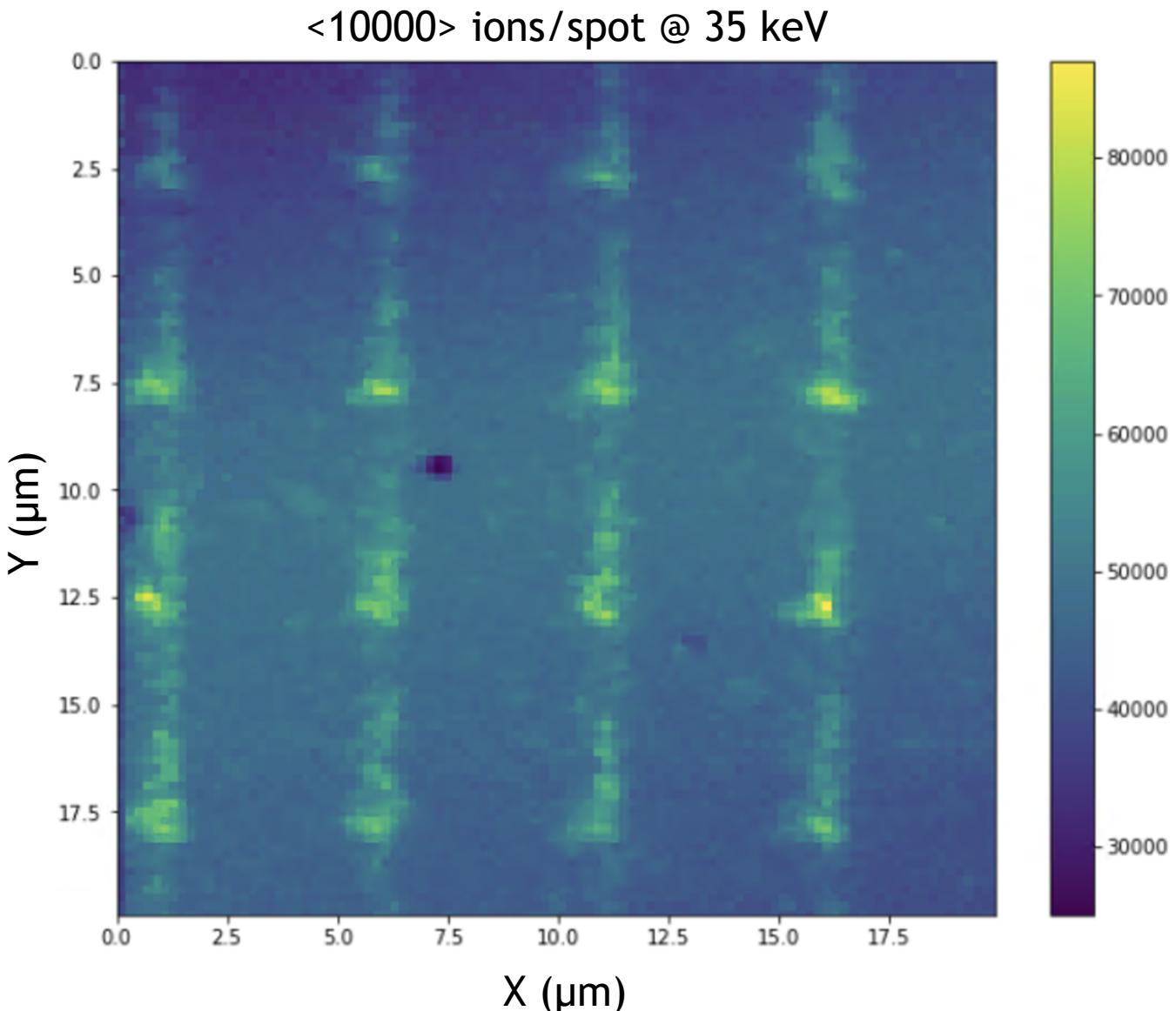
Electrochemically etched tips using Iron Chloride





# Preliminary Example of PbV in Diamond Substrate

- Observed PbV spectral signature in diamond substrates using FIB implantation
- Vertical stripes in the datasets?
  - Different Pb isotopes?
    - $^{208}\text{Pb}$  ( $\approx 52\%$ )
    - $^{206}\text{Pb}$  ( $\approx 24\%$ )
    - $^{207}\text{Pb}$  ( $\approx 23\%$ )
    - $^{204}\text{Pb}$  ( $\approx 1\%$ )
  - In the Raith Velion our  $m/\Delta m$  is not large enough to isolate the individual isotopes





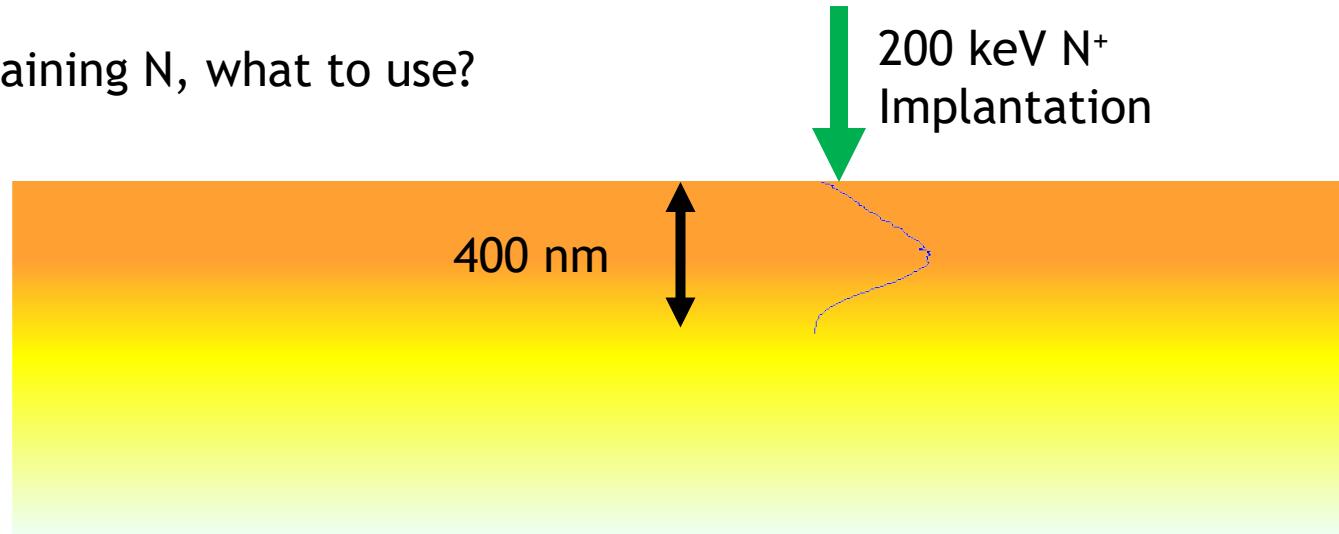
# Fabrication of a Nitrogen Liquid Metal Alloy Ion Source

Need a low melting point (200-500C) alloy containing N, what to use?

## Implantation

Implanted a 200  $\mu\text{m}$  thick  $\text{Au}_{80}\text{Sn}_{20}$  foil with Nitrogen to  $5 \times 10^{17}$  ions/cm<sup>2</sup>

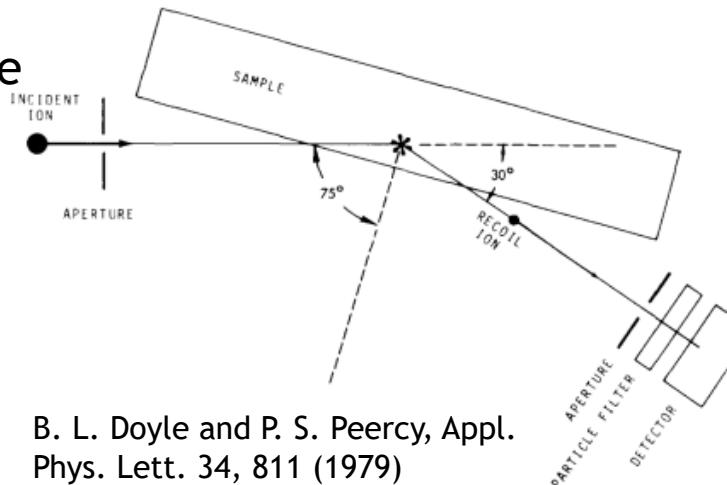
→ Implantation level chosen based on solid-solubility limit for H



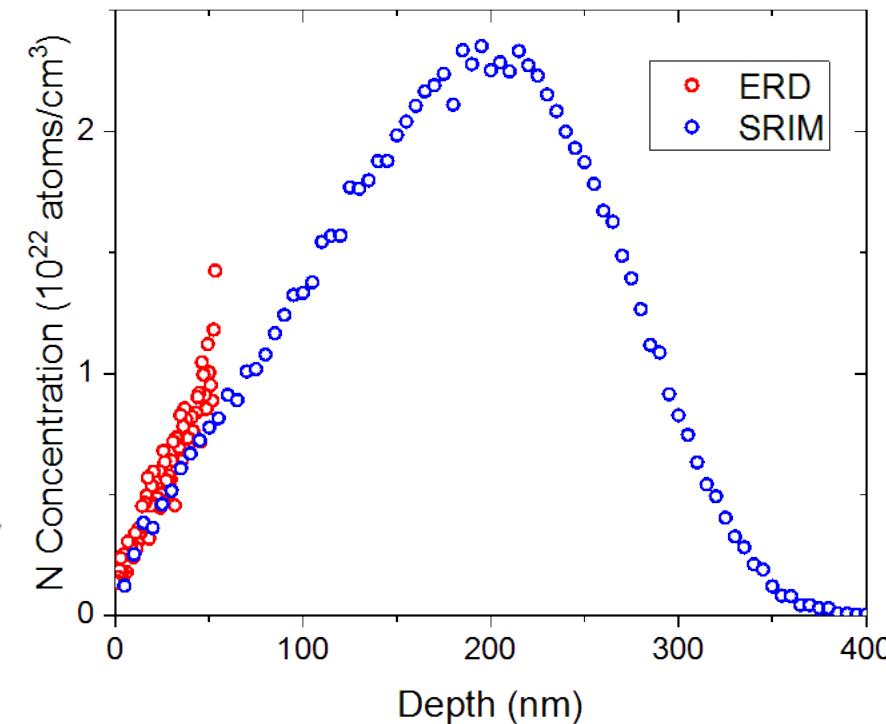
## Characterization

Elastic Recoil Detection (ERD) is used to probe the first 100 nm of the implanted foil

→ Limited interrogate depth due to multiple scattering of ions



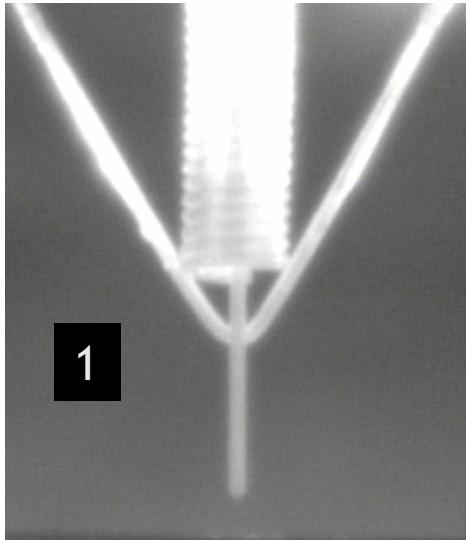
We can produce the material, but can we make a usable LMAIS?



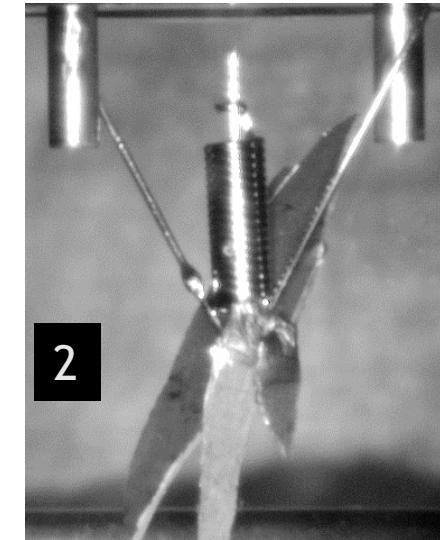


# Tip fabrication from implanted AuSnN foil

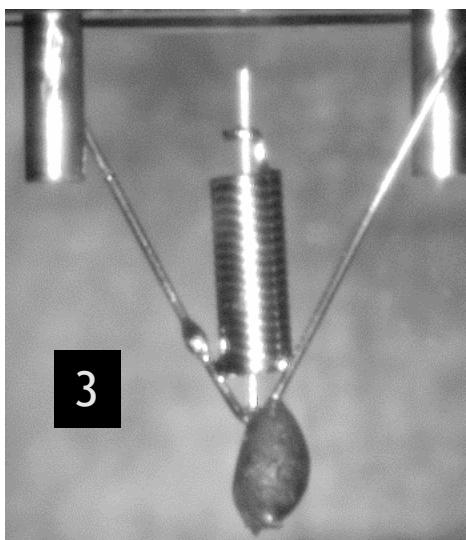
(1) Heat W tip to remove surface contaminants



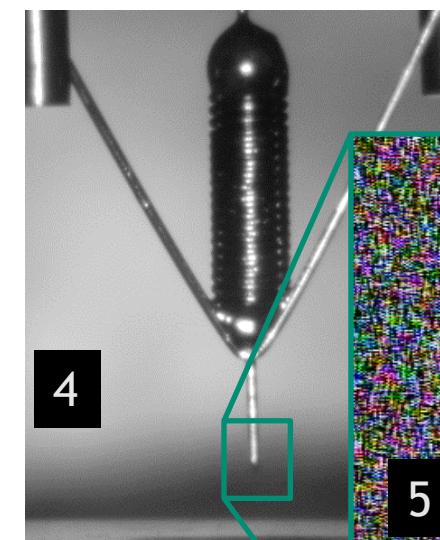
(2) Tack weld on implanted foil to the tip



(3) Heat tip to melt the foil onto the tip

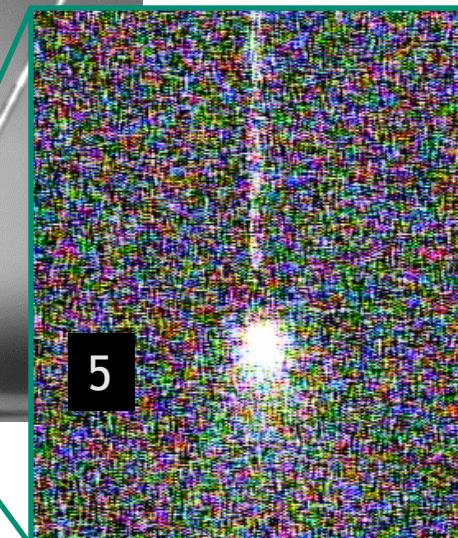


(4) Repeat steps (2) and (3) until tip and the reservoir is filled



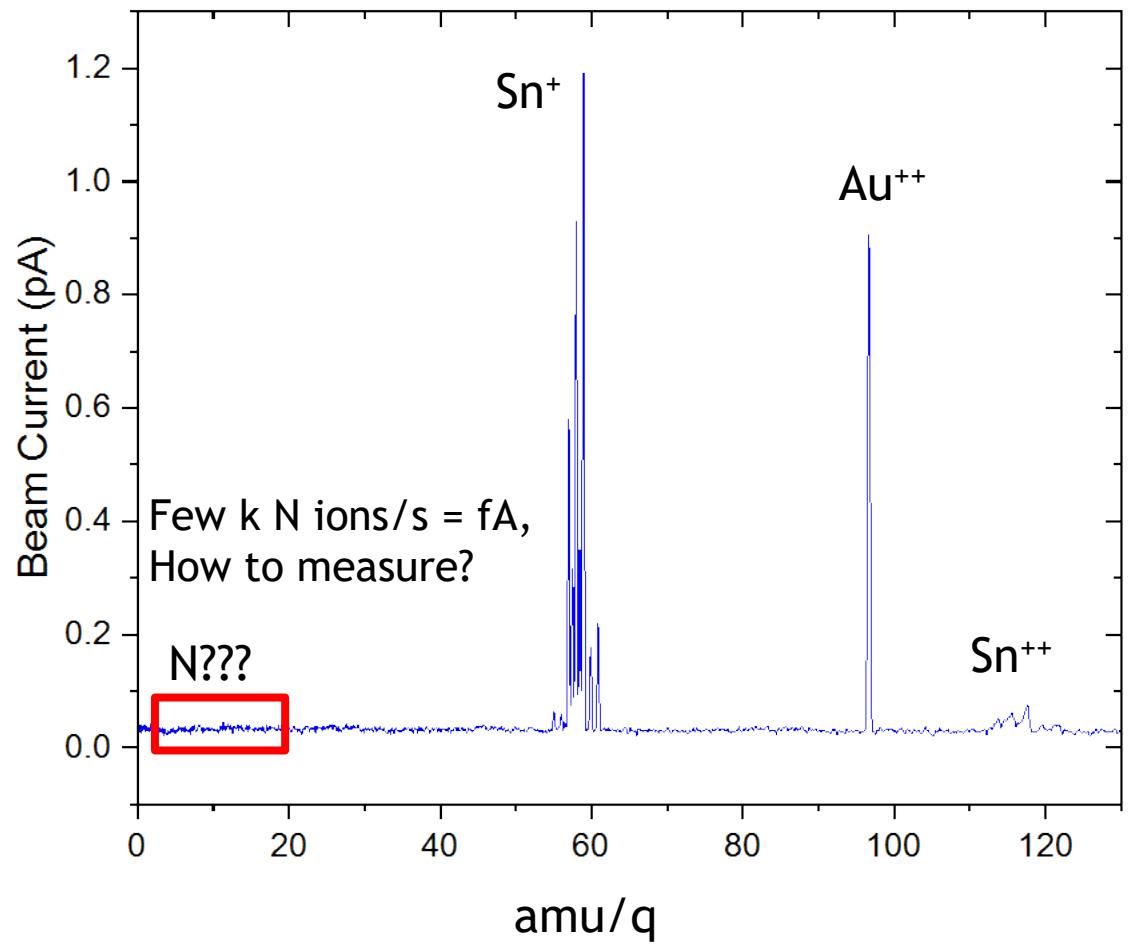
(5) Test tip for emission

(6) Install tip into nanolimplanter

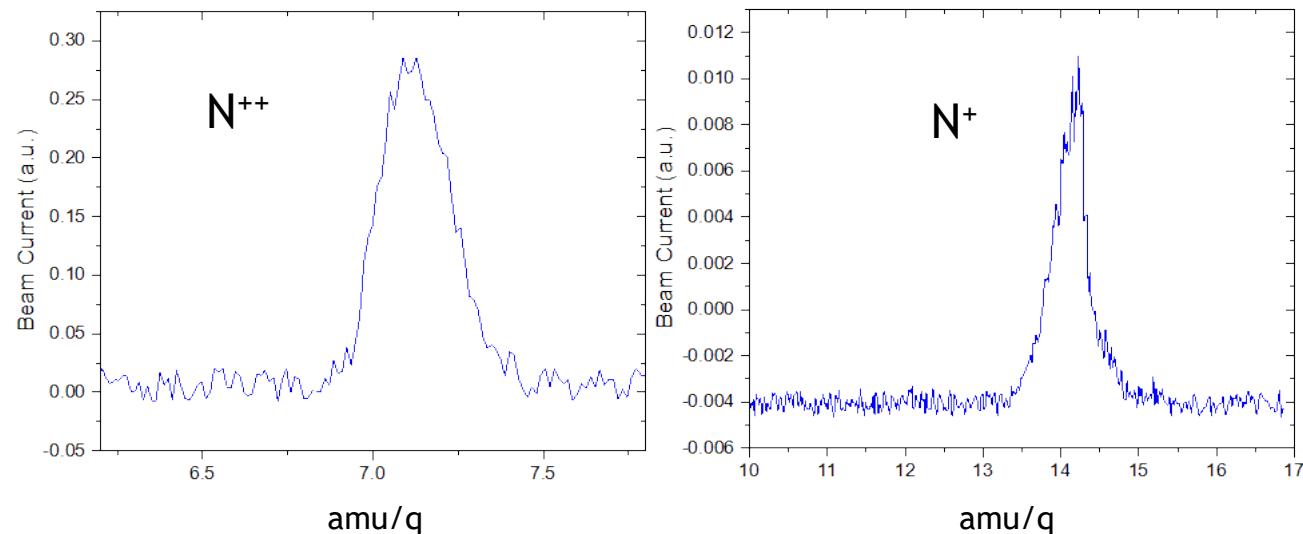
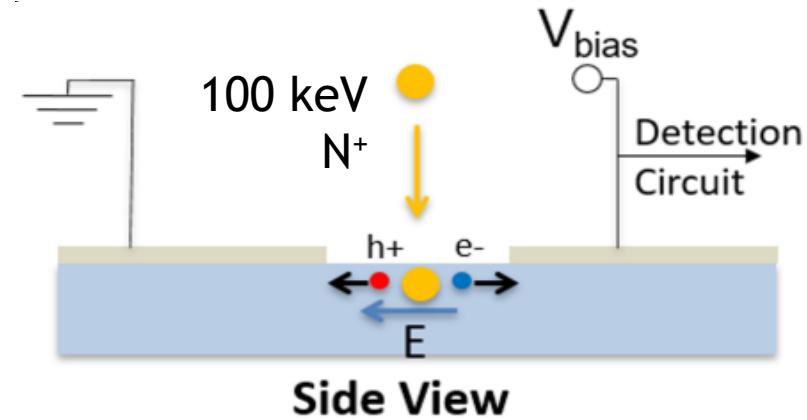


Very challenging source preparation! How well does the N LMAIS run?

# N Source Characterization - Mass Spectrum via IBIC

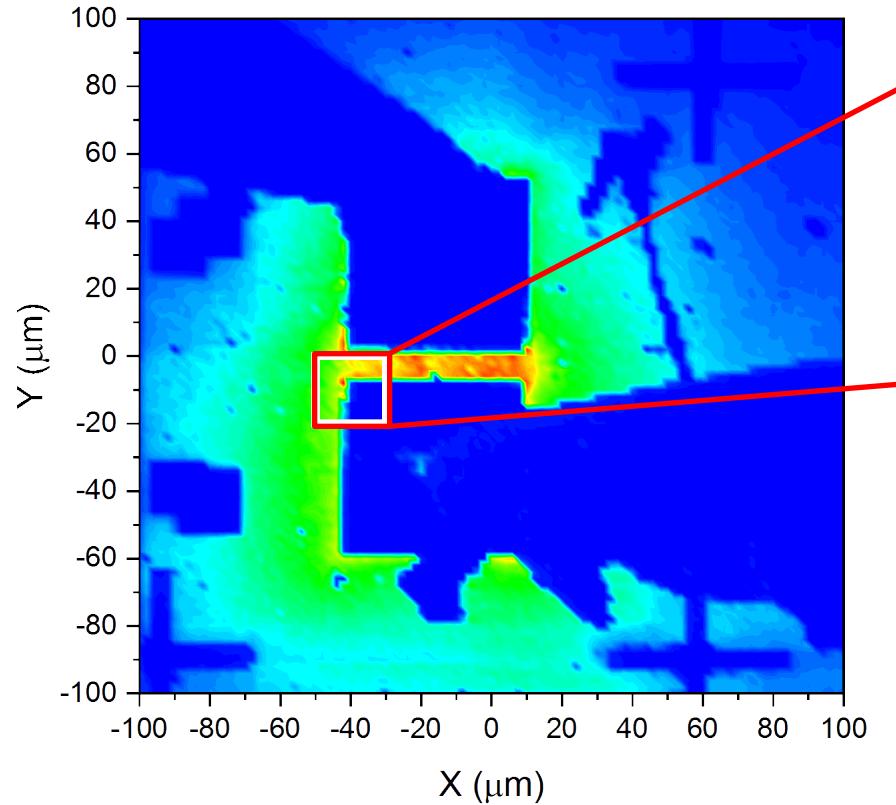


Ion Beam Induced Charge (IBIC) to measure N beam

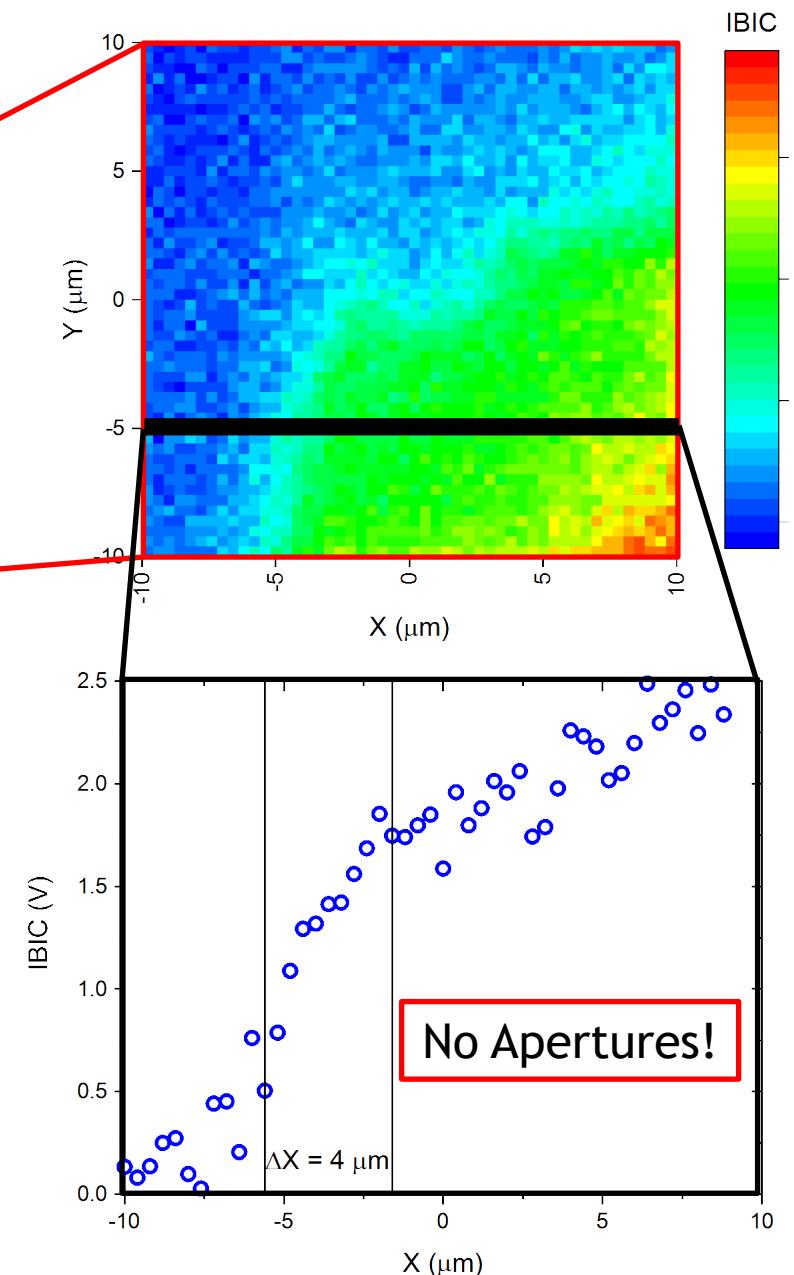


Observe Atomic nitrogen single and doubly charged ions in the source at ~20k ions/s

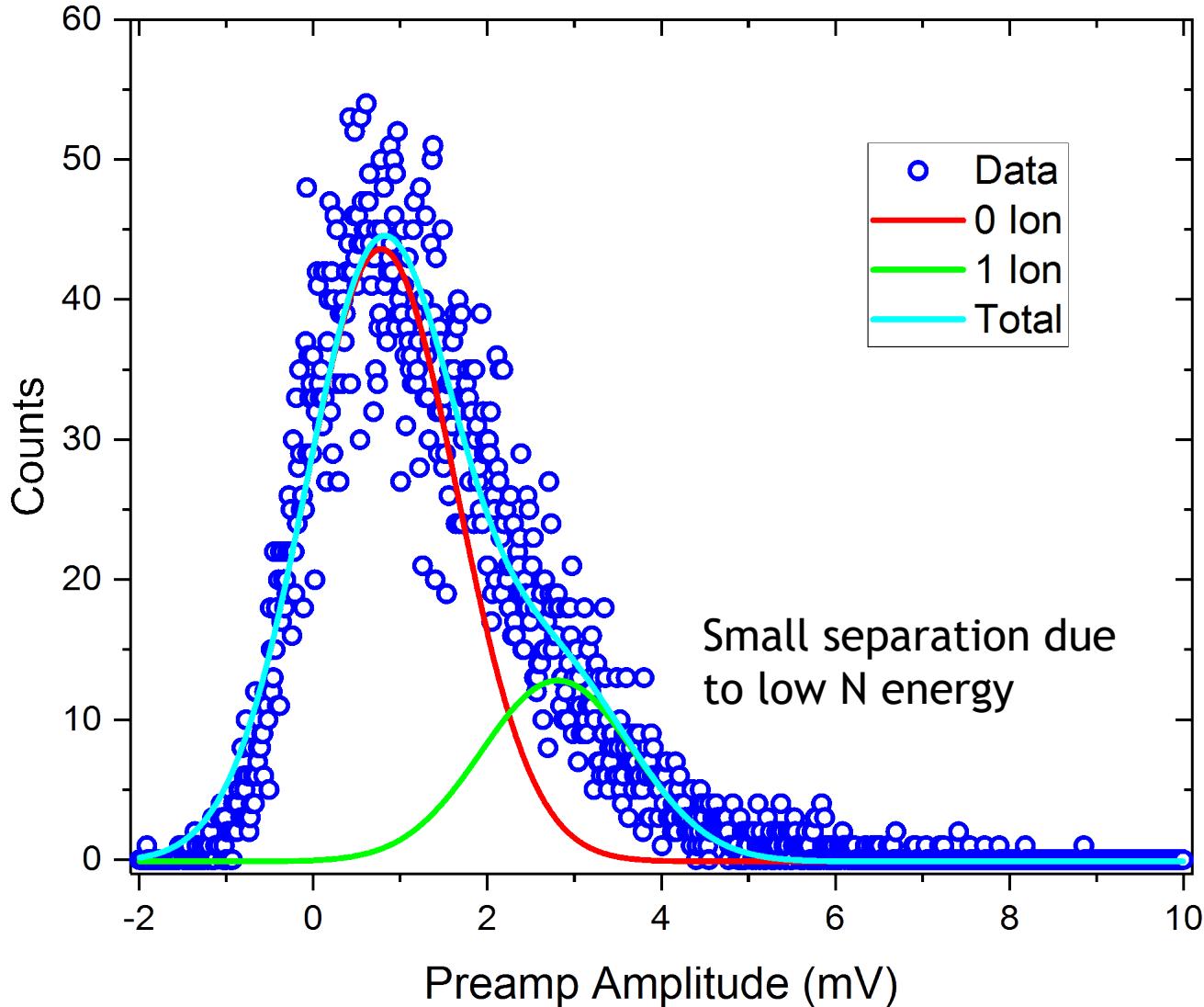
# N Source Characterization - Spot Size via IBIC



As tested in the A&D nanolimplanter these tips achieve lifetimes of  $\sim 100\text{-}200 \mu\text{A}^*\text{hr}$  and spot sizes of  $< 4 \mu\text{m}$



# Characterization - Beam Current measured via IBIC



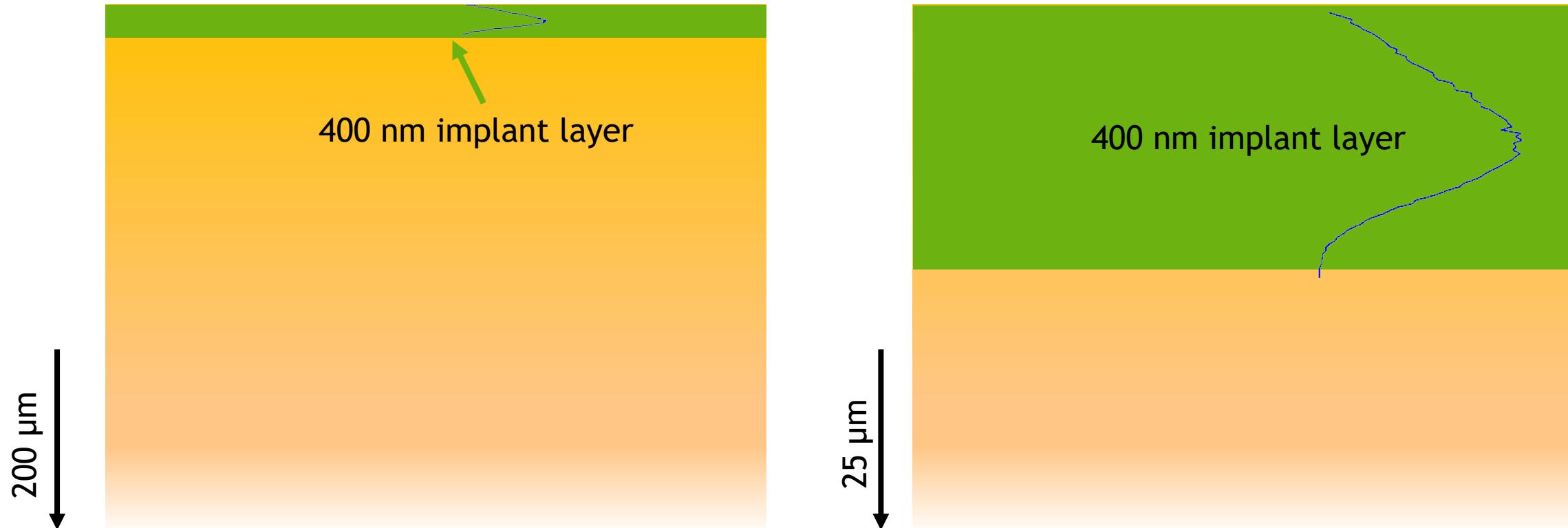
1. Fit peak to Gaussians
2. Area under peak corresponds to likelihood of event

$<1>$  ion every 50  $\mu$ s  $\equiv$  20 k ions/s

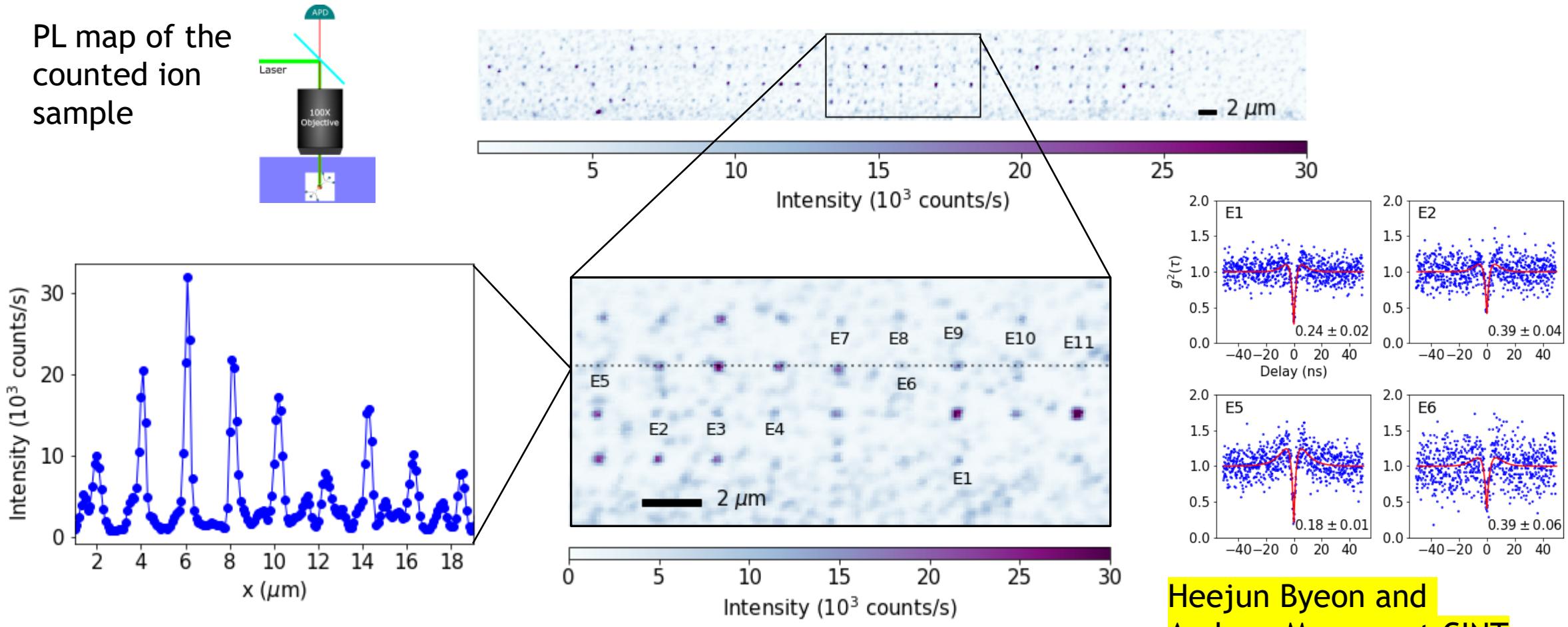
# N Source – Improvements

Higher beam current

- Thinner foil to same fluence → higher overall concentration
- Fabrication in N atmosphere → additional N absorption



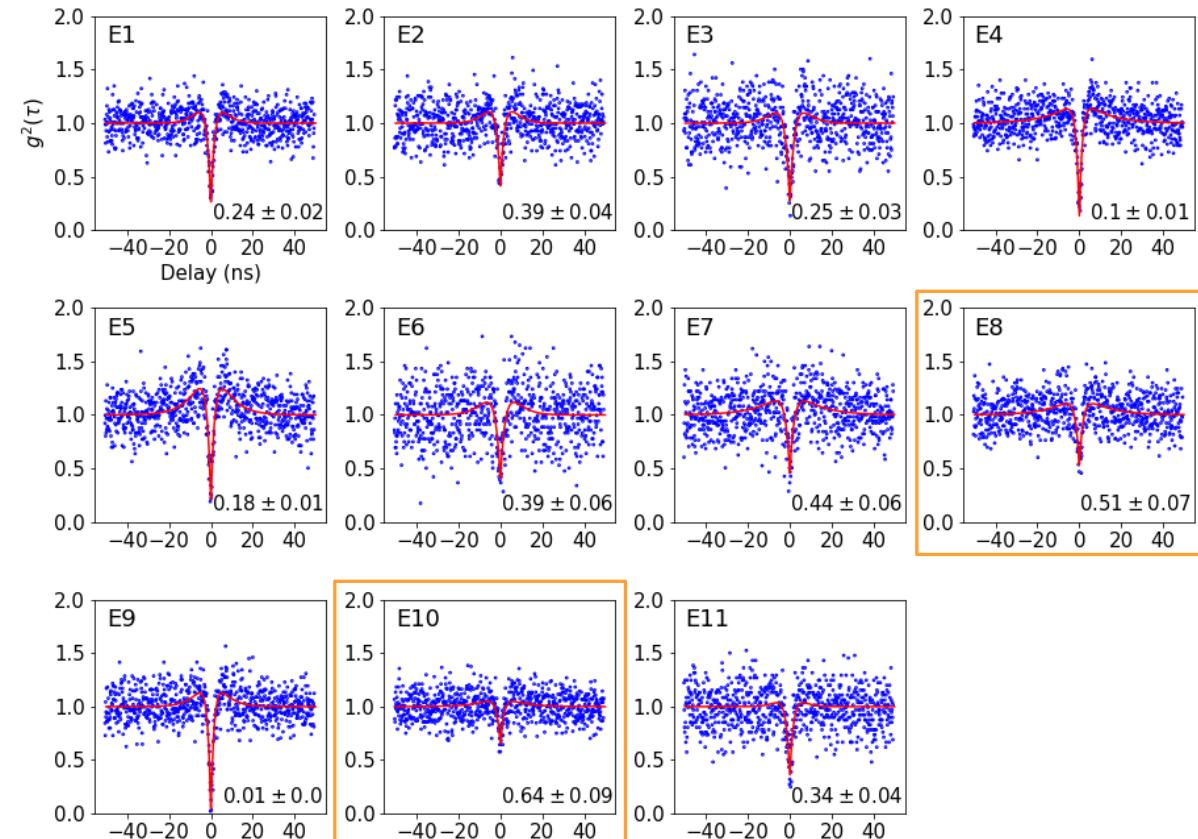
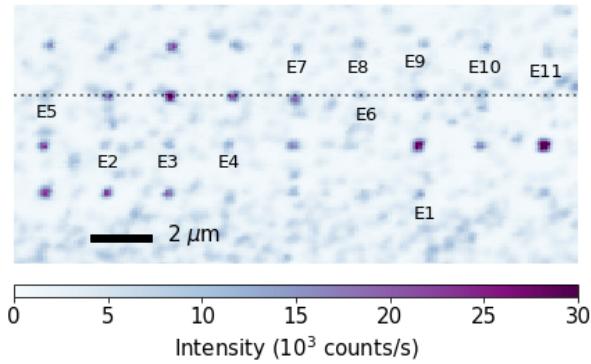
# Photoluminescence of the counted sample shows single defects



Heejun Byeon and  
Andrew Mounce at CINT

High confidence in the number of implanted Si ions → confirmed by  $g^2(\tau)$

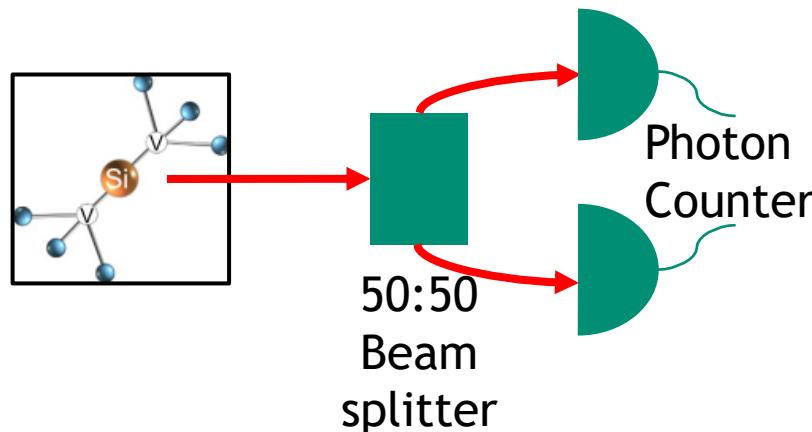
# Hanbury-Brown-Twiss Interferometry



Single emitter will emit only 1 photon at a time

2<sup>nd</sup> order autocorrelation

Only 1 photon at each counter at any time



Not all locations identified as single emitters from PL are single emitters

# Sputtering Effects

