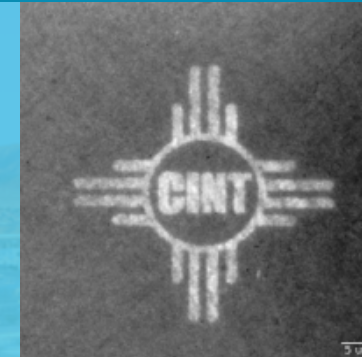
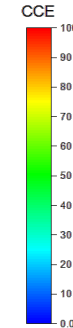
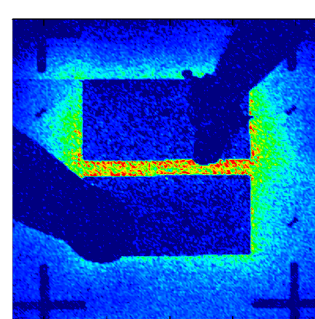
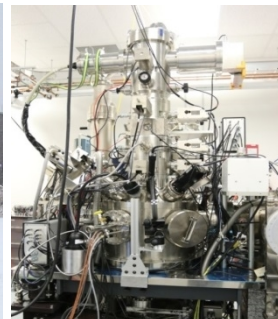




Towards Deterministic Defect Center Fabrication Using Sandia's Focused Ion Implantation Capabilities



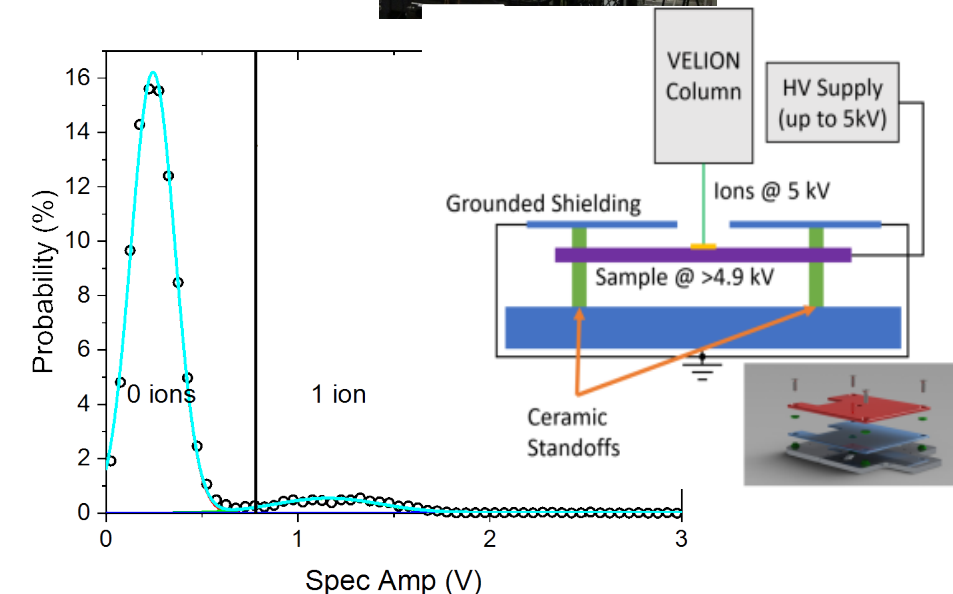
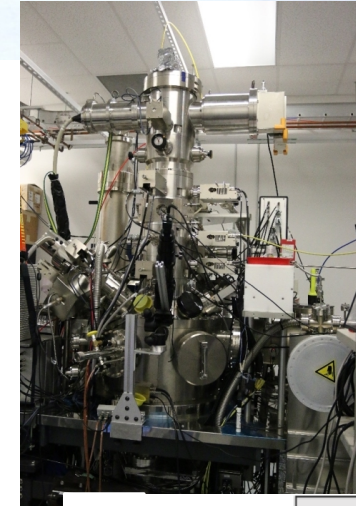
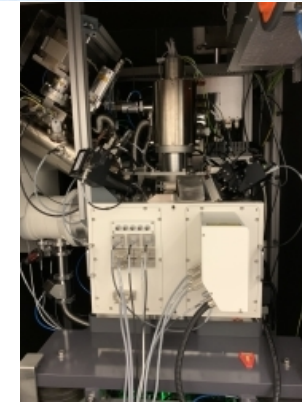
E. Bielejec

Sandia National Laboratories, Albuquerque, NM 87185

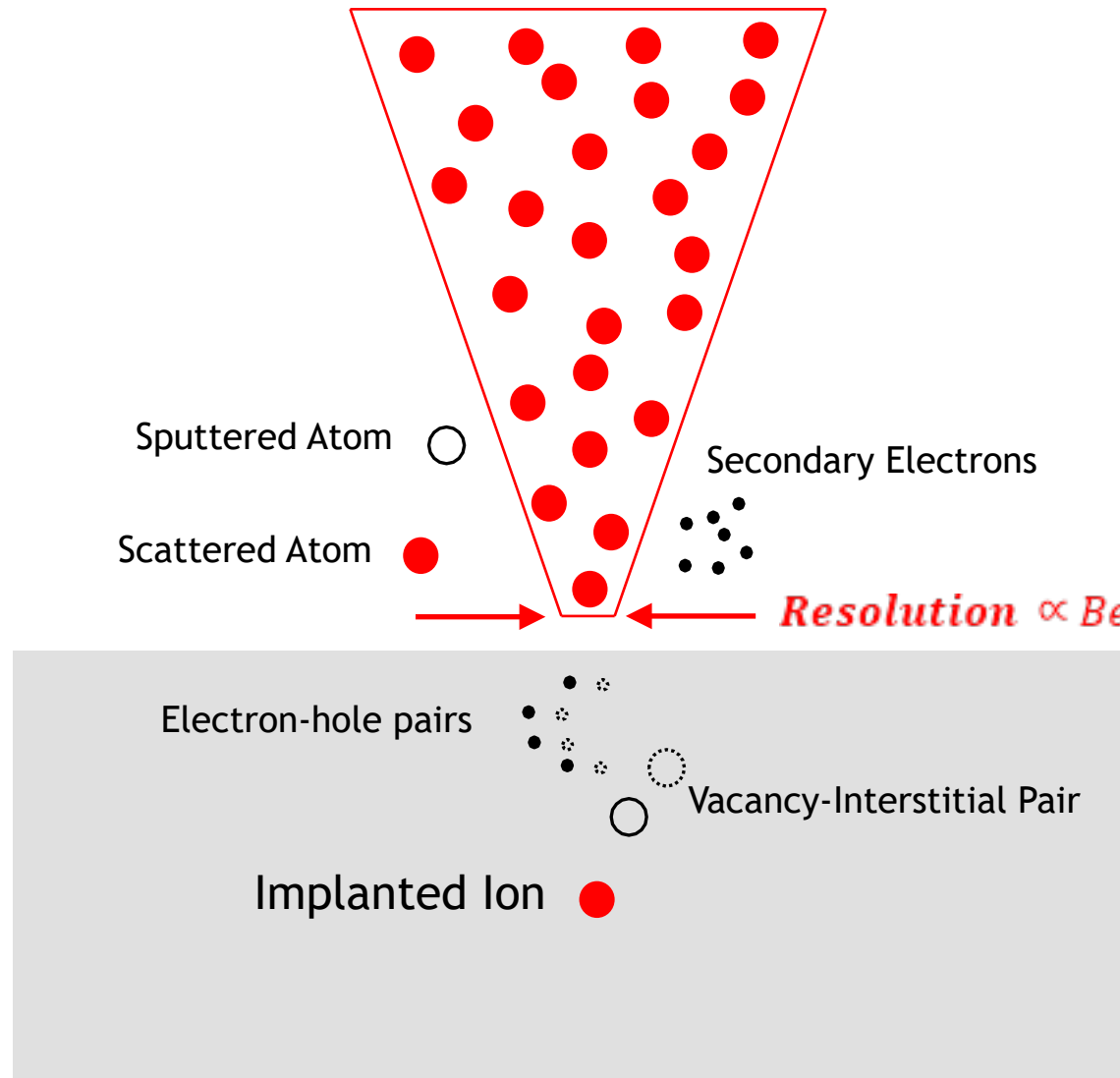


Outline

- Introduction to Focused Ion Beam Capabilities at Sandia's Ion Beam Laboratory (IBL)
- Multi-species Focused Ion Beam (FIB)
 - Sandia's nanoImplanter 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



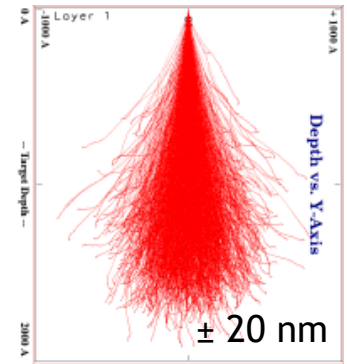
Nanofabrication using Focused Ion Beam (FIB) Implantation



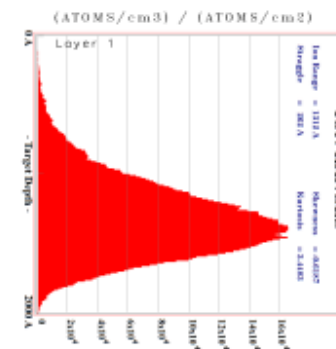
Resolution \propto Beam Spot Size + Alignment Accuracy + XY Straggle

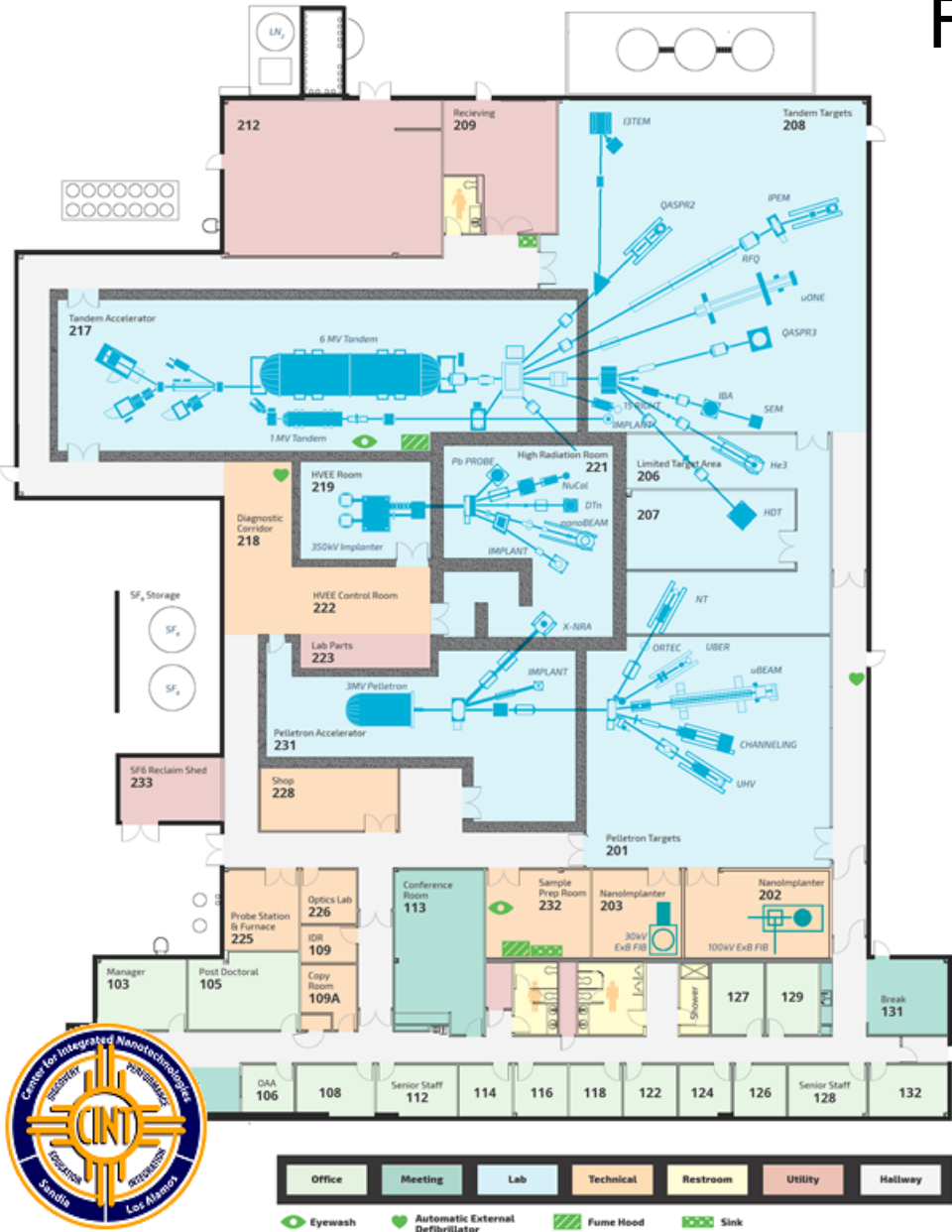
Depth \propto Energy + Z Straggle

SRIM simulation - XY straggle
200 keV Si into diamond



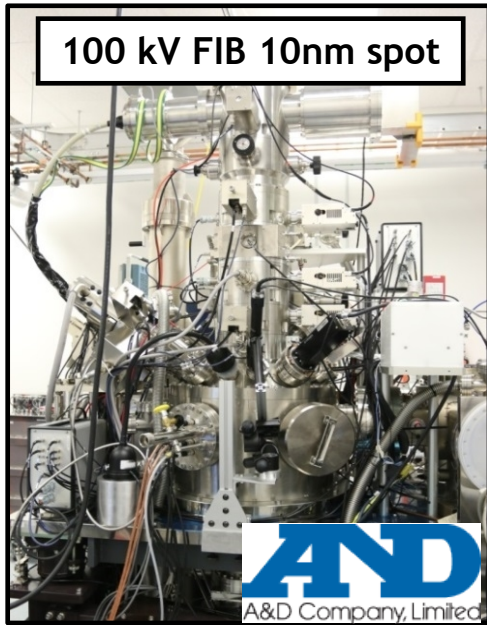
SRIM simulation - Z straggle
200 keV Si into diamond
 131 ± 26 nm



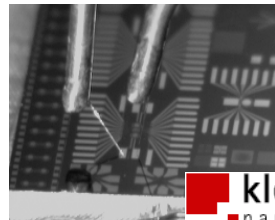
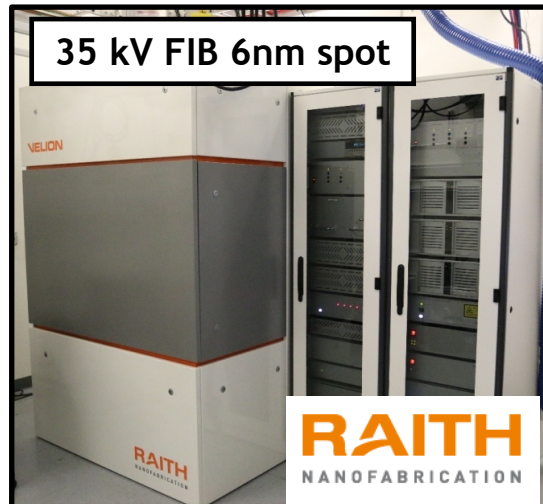


25 end-stations including *in-situ* DLTS, PL, TEM, SEM, 1200°C heating, etc...

FIB Implantation using the nanoImplanter and Velion

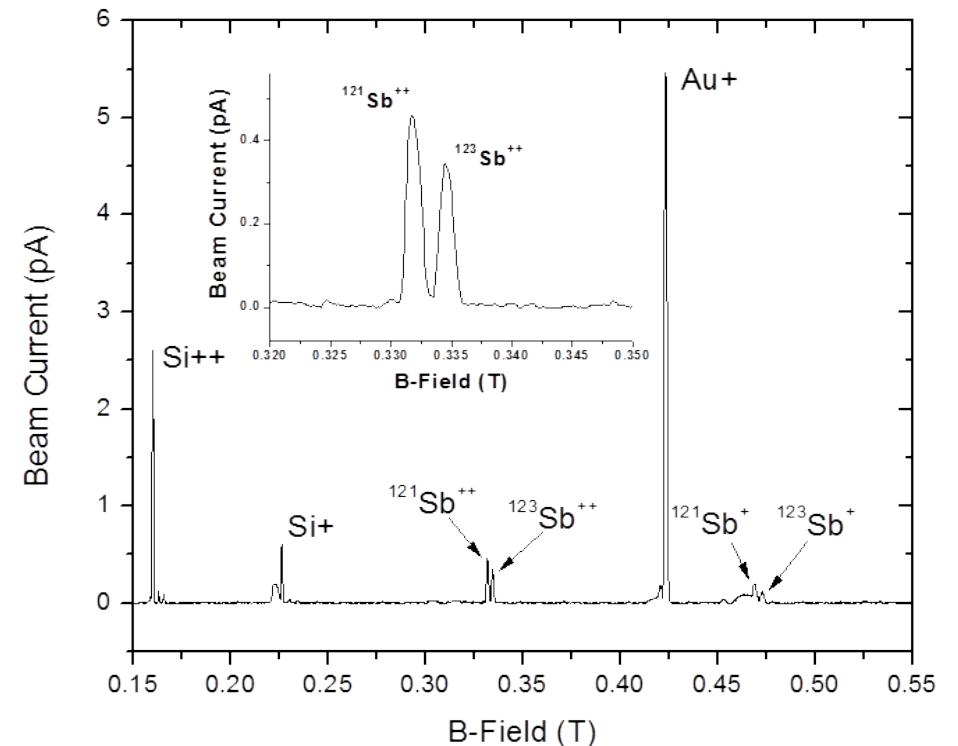


- Focused ion beam system (FIB)
→ nm beam spot size on target
- ExB Filter (Wien Filter)
→ Multiple ion species
e.g., Li, Si, P, Sb, etc... (separating out ^{28}Si , ^{29}Si , etc...)
- Fast blanking and chopping
→ Single ion implantation
- Direct-write lithography
→ nm targeting accuracy
- Low temperature stage
- In-situ electrical probes



kleindiek
nanotechnik

Sb Source: Mass Spectrum



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

SNL PtPSb



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

hydrogen

1

H

1.0079

lithium

3

Li

6.941

sodium

11

Na

22.990

potassium

19

K

39.098

rubidium

37

Rb

85.468

caesium

55

Cs

132.91

francium

87

Fr

[223]

beryllium

4

Be

9.0122

magnesium

12

Mg

24.305

calcium

20

Ca

40.078

strontium

38

Sr

87.62

barium

56

Ba

137.33

radium

88

Ra

[226]

57-70

*

89-102

* *

boron

5

B

10.811

aluminium

13

Al

26.982

carbon

6

C

12.011

silicon

14

Si

28.086

nitrogen

7

N

14.007

phosphorus

15

P

30.974

arsenic

33

As

74.922

antimony

51

Sb

121.76

bismuth

83

Bi

208.98

oxygen

8

O

15.999

sulfur

16

S

32.065

selenium

34

Se

78.96

tellurium

52

Te

127.60

polonium

84

Po

[209]

fluorine

9

F

18.998

chlorine

17

Cl

35.453

bromine

35

Br

79.904

iodine

53

I

126.90

astatine

85

At

[210]

neon

10

Ne

20.180

argon

18

Ar

39.948

krypton

36

Kr

83.80

xenon

54

Xe

131.29

radon

86

Rn

[222]

scandium

21

Sc

44.956

yttrium

39

Y

88.906

lutetium

71

Lu

174.97

lawrencium

103

Lr

[262]

titanium

22

Ti

47.867

zirconium

40

Zr

91.224

hafnium

72

Hf

178.49

rutherfordium

104

Rf

[261]

vanadium

23

V

50.942

niobium

41

Nb

92.906

tantalum

73

Ta

180.95

dubnium

105

Db

[262]

chromium

24

Cr

51.996

molybdenum

42

Mo

95.94

tungsten

74

W

183.84

seaborgium

106

Sg

[266]

manganese

25

Mn

54.938

technetium

43

Tc

[98]

rhenium

75

Re

186.21

bohrium

107

Bh

[264]

iron

26

Fe

55.845

ruthenium

44

Ru

101.07

osmium

76

Os

190.23

hassium

108

Hs

[269]

cobalt

27

Co

58.933

rhodium

45

Rh

102.91

iridium

77

Ir

192.22

meitnerium

109

Mt

[268]

nickel

28

Ni

58.693

palladium

46

Pd

106.42

platinum

78

Pt

195.08

unnilium

110

Uun

[271]

copper

29

Cu

63.546

silver

47

Ag

107.87

gold

79

Au

196.97

ununium

111

Uuu

[272]

zinc

30

Zn

65.39

cadmium

48

Cd

112.41

mercury

80

Hg

200.59

unubium

112

Uub

[277]

gallium

31

Ga

69.723

indium

49

In

114.82

thallium

81

Tl

204.38

ununquadium

114

Uuq

[289]

germanium

32

Ge

72.61

tin

50

Sn

118.71

lead

82

Pb

207.2

purple - running at SNL

yellow - attempting at SNL

green - demonstrated at other labs

* Lanthanide series

** Actinide series

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

After A. Weick University of Bochum

L. Bischoff, *et al.*, Applied Physics Reviews 3, 021101 (2016)

Wide Variety of Ion Species Available and Developing More!

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



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

1 H 1.0079	2 He 4.0026
3 Li 6.941	4 Be 9.0122
11 Na 22.990	12 Mg 24.305
19 K 39.098	20 Ca 40.078
37 Rb 85.468	38 Sr 87.62
55 Cs 132.91	56 Ba 137.33
87 Fr [223]	88 Ra [226]
21 Sc 44.956	22 Ti 47.867
39 Y 88.906	40 Zr 91.224
57-70 * [223]	71 Lu 174.97
89-102 ** [227]	103 Lr [262]
23 V 50.942	24 Cr 51.996
25 Mn 54.938	26 Fe 55.845
27 Co 58.933	28 Ni 58.693
29 Cu 63.546	30 Zn 65.38
31 Ga 69.723	32 Ge 72.61
33 As 74.922	34 Se 78.96
35 Br 79.904	36 Kr 83.80
37 Rb 85.468	38 Sr 87.62
39 Y 88.906	40 Zr 91.224
41 Nb 92.906	42 Mo 95.94
43 Tc [98]	44 Ru 101.07
45 Rh 102.91	46 Pd 106.42
47 Ag 107.87	48 Cd 112.41
49 In 114.82	50 Sn 118.71
51 Sb 121.76	52 Te 127.60
53 I 126.90	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33
57-70 * [223]	71 Lu 174.97
89-102 ** [227]	103 Lr [262]
104 Rf [261]	105 Db [262]
106 Sg [266]	107 Bh [264]
108 Hs [269]	109 Mt [268]
110 Uun [271]	111 Uuu [272]
112 Uub [277]	114 Uuq [289]

*Lanthanide series

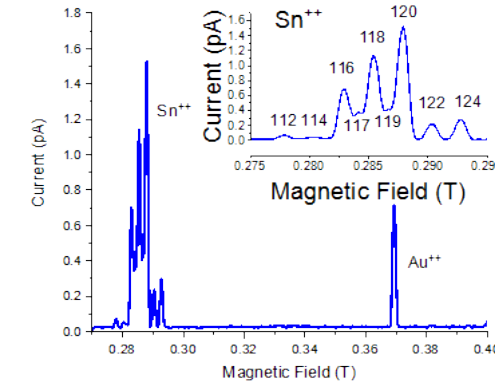
** Actinide series

57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm [145]	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04
89 Ac [227]	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np [237]	94 Pu [244]	95 Am [243]	96 Cm [247]	97 Bk [247]	98 Cf [251]	99 Es [252]	100 Fm [257]	101 Md [258]	102 No [259]

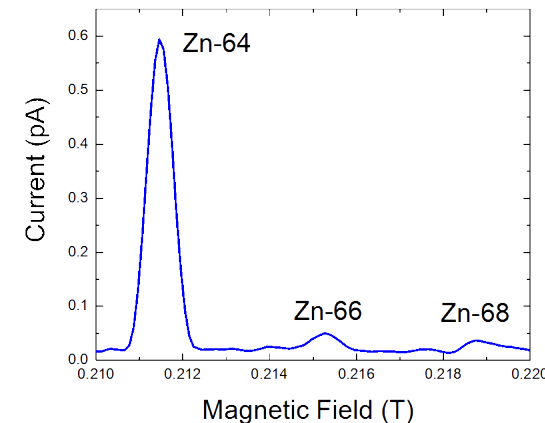
- Based on AuSiX or AuGeX alloys
- Easy to wet the tip and easy to run
- For example, AuSiLi

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

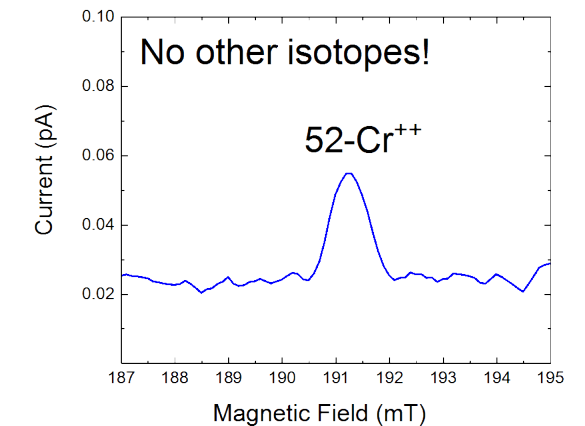
AuSn



AuSiZn



AuGeCr



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



1 H 1.0079	2 He 4.0026
3 Li 6.941	4 Be 9.0122
11 Na 22.990	12 Mg 24.305
19 K 39.098	20 Ca 40.078
37 Rb 85.468	38 Sr 87.62
55 Cs 132.91	56 Ba 137.33
87 Fr [223]	88 Ra [226]
21 Sc 44.956	22 Ti 47.867
39 Y 88.906	40 Zr 91.224
57-70 * [223]	71 Lu 174.97
89-102 * [227]	103 Lr [262]
23 V 50.942	24 Cr 51.996
41 Nb 92.906	42 Mo 95.94
59 Pr 140.91	60 Nd 144.24
75 Re 186.21	76 Os 190.23
91 Pa 231.04	92 U 238.03
107 Bh [264]	108 Hs [269]
125 Nh [289]	126 Ds [291]
133 Nh [289]	134 Ds [291]
151 Nh [289]	152 Ds [291]
169 Nh [289]	170 Ds [291]
187 Nh [289]	188 Ds [291]
205 Nh [289]	206 Ds [291]
223 Nh [289]	224 Ds [291]
241 Nh [289]	242 Ds [291]
259 Nh [289]	260 Ds [291]
277 Nh [289]	278 Ds [291]
295 Nh [289]	296 Ds [291]
313 Nh [289]	314 Ds [291]
331 Nh [289]	332 Ds [291]
349 Nh [289]	350 Ds [291]
367 Nh [289]	368 Ds [291]
385 Nh [289]	386 Ds [291]
403 Nh [289]	404 Ds [291]
421 Nh [289]	422 Ds [291]
439 Nh [289]	440 Ds [291]
457 Nh [289]	458 Ds [291]
475 Nh [289]	476 Ds [291]
493 Nh [289]	494 Ds [291]
511 Nh [289]	512 Ds [291]
529 Nh [289]	530 Ds [291]
547 Nh [289]	548 Ds [291]
565 Nh [289]	566 Ds [291]
583 Nh [289]	584 Ds [291]
601 Nh [289]	602 Ds [291]
619 Nh [289]	620 Ds [291]
637 Nh [289]	638 Ds [291]
655 Nh [289]	656 Ds [291]
673 Nh [289]	674 Ds [291]
691 Nh [289]	692 Ds [291]
709 Nh [289]	710 Ds [291]
727 Nh [289]	728 Ds [291]
745 Nh [289]	746 Ds [291]
763 Nh [289]	764 Ds [291]
781 Nh [289]	782 Ds [291]
799 Nh [289]	800 Ds [291]
817 Nh [289]	818 Ds [291]
835 Nh [289]	836 Ds [291]
853 Nh [289]	854 Ds [291]
871 Nh [289]	872 Ds [291]
889 Nh [289]	890 Ds [291]
907 Nh [289]	908 Ds [291]
925 Nh [289]	926 Ds [291]
943 Nh [289]	944 Ds [291]
961 Nh [289]	962 Ds [291]
979 Nh [289]	980 Ds [291]
997 Nh [289]	998 Ds [291]
1015 Nh [289]	1016 Ds [291]
1033 Nh [289]	1034 Ds [291]
1051 Nh [289]	1052 Ds [291]
1069 Nh [289]	1070 Ds [291]
1087 Nh [289]	1088 Ds [291]
1105 Nh [289]	1106 Ds [291]
1123 Nh [289]	1124 Ds [291]
1141 Nh [289]	1142 Ds [291]
1159 Nh [289]	1160 Ds [291]
1177 Nh [289]	1178 Ds [291]
1195 Nh [289]	1196 Ds [291]
1213 Nh [289]	1214 Ds [291]
1231 Nh [289]	1232 Ds [291]
1249 Nh [289]	1250 Ds [291]
1267 Nh [289]	1268 Ds [291]
1285 Nh [289]	1286 Ds [291]
1303 Nh [289]	1304 Ds [291]
1321 Nh [289]	1322 Ds [291]
1339 Nh [289]	1340 Ds [291]
1357 Nh [289]	1358 Ds [291]
1375 Nh [289]	1376 Ds [291]
1393 Nh [289]	1394 Ds [291]
1411 Nh [289]	1412 Ds [291]
1429 Nh [289]	1430 Ds [291]
1447 Nh [289]	1448 Ds [291]
1465 Nh [289]	1466 Ds [291]
1483 Nh [289]	1484 Ds [291]
1501 Nh [289]	1502 Ds [291]
1519 Nh [289]	1520 Ds [291]
1537 Nh [289]	1538 Ds [291]
1555 Nh [289]	1556 Ds [291]
1573 Nh [289]	1574 Ds [291]
1591 Nh [289]	1592 Ds [291]
1609 Nh [289]	1610 Ds [291]
1627 Nh [289]	1628 Ds [291]
1645 Nh [289]	1646 Ds [291]
1663 Nh [289]	1664 Ds [291]
1681 Nh [289]	1682 Ds [291]
1699 Nh [289]	1700 Ds [291]
1717 Nh [289]	1718 Ds [291]
1735 Nh [289]	1736 Ds [291]
1753 Nh [289]	1754 Ds [291]
1771 Nh [289]	1772 Ds [291]
1789 Nh [289]	1790 Ds [291]
1807 Nh [289]	1808 Ds [291]
1825 Nh [289]	1826 Ds [291]
1843 Nh [289]	1844 Ds [291]
1861 Nh [289]	1862 Ds [291]
1879 Nh [289]	1880 Ds [291]
1897 Nh [289]	1898 Ds [291]
1915 Nh [289]	1916 Ds [291]
1933 Nh [289]	1934 Ds [291]
1951 Nh [289]	1952 Ds [291]
1969 Nh [289]	1970 Ds [291]
1987 Nh [289]	1988 Ds [291]
2005 Nh [289]	2006 Ds [291]
2023 Nh [289]	2024 Ds [291]
2041 Nh [289]	2042 Ds [291]
2059 Nh [289]	2060 Ds [291]
2077 Nh [289]	2078 Ds [291]
2095 Nh [289]	2096 Ds [291]
2113 Nh [289]	2114 Ds [291]
2131 Nh [289]	2132 Ds [291]
2149 Nh [289]	2150 Ds [291]
2167 Nh [289]	2168 Ds [291]
2185 Nh [289]	2186 Ds [291]
2203 Nh [289]	2204 Ds [291]
2221 Nh [289]	2222 Ds [291]
2239 Nh [289]	2240 Ds [291]
2257 Nh [289]	2258 Ds [291]
2275 Nh [289]	2276 Ds [291]
2293 Nh [289]	2294 Ds [291]
2311 Nh [289]	2312 Ds [291]
2329 Nh [289]	2330 Ds [291]
2347 Nh [289]	2348 Ds [291]
2365 Nh [289]	2366 Ds [291]
2383 Nh [289]	2384 Ds [291]
2401 Nh [289]	2402 Ds [291]
2419 Nh [289]	2420 Ds [291]
2437 Nh [289]	2438 Ds [291]
2455 Nh [289]	2456 Ds [291]
2473 Nh [289]	2474 Ds [291]
2491 Nh [289]	2492 Ds [291]
2509 Nh [289]	2510 Ds [291]
2527 Nh [289]	2528 Ds [291]
2545 Nh [289]	2546 Ds [291]
2563 Nh [289]	2564 Ds [291]
2581 Nh [289]	2582 Ds [291]
2599 Nh [289]	2600 Ds [291]
2617 Nh [289]	2618 Ds [291]
2635 Nh [289]	2636 Ds [291]
2653 Nh [289]	2654 Ds [291]
2671 Nh [289]	2672 Ds [291]
2689 Nh [289]	2690 Ds [291]
2707 Nh [289]	2708 Ds [291]
2725 Nh [289]	2726 Ds [291]
2743 Nh [289]	2744 Ds [291]
2761 Nh [289]	2762 Ds [291]
2779 Nh [289]	2780 Ds [291]
2797 Nh [289]	2798 Ds [291]
2815 Nh [289]	2816 Ds [291]
2833 Nh [289]	2834 Ds [291]
2851 Nh [289]	2852 Ds [291]
2869 Nh [289]	2870 Ds [291]
2887 Nh [289]	2888 Ds [291]
2905 Nh [289]	2906 Ds [291]
2923 Nh [289]	2924 Ds [291]
2941 Nh [289]	2942 Ds [291]
2959 Nh [289]	2960 Ds [291]
2977 Nh [289]	2978 Ds [291]
2995 Nh [289]	2996 Ds [291]
3013 Nh [289]	3014 Ds [291]
3031 Nh [289]	3032 Ds [291]
3049 Nh [289]	3050 Ds [291]
3067 Nh [289]	3068 Ds [291]
3085 Nh [289]	3086 Ds [291]
3103 Nh [289]	3104 Ds [291]
3121 Nh [289]	3122 Ds [291]
3139 Nh [289]	3140 Ds [291]
3157 Nh [289]	3158 Ds [291]
3175 Nh [289]	3176 Ds [291]
3193 Nh [289]	3194 Ds [291]
3211 Nh [289]	3212 Ds [291]
3229 Nh [289]	3230 Ds [291]
3247 Nh [289]	3248 Ds [291]
3265 Nh [289]	3266 Ds [291]
3283 Nh [289]	3284 Ds [291]
3301 Nh [289]	3302 Ds [291]
3319 Nh [289]	3320 Ds [291]
3337 Nh [289]	3338 Ds [291]
3355 Nh [289]	3356 Ds [291]
3373 Nh [289]	3374 Ds [291]
3391 Nh [289]	3392 Ds [291]
3409 Nh [289]	3410 Ds [291]
3427 Nh [289]	3428 Ds [291]
3445 Nh [289]	3446 Ds [291]
3463 Nh [289]	3464 Ds [291]
3481 Nh [289]	3482 Ds [291]
3499 Nh [289]	3500 Ds [291]
3517 Nh [289]	3518 Ds [291]
3535 Nh [289]	3536 Ds [291]
3553 Nh [289]	3554 Ds [291]
3571 Nh [289]	3572 Ds [291]
3589 Nh [289]	3590 Ds [291]
3607 Nh [289]	3608 Ds [291]
3625 Nh [289]	3626 Ds [291]
3643 Nh [289]	3644 Ds [291]
3661 Nh [289]	3662 Ds [291]
3679 Nh [289]	3680 Ds [291]
3697 Nh [289]	3698 Ds [291]
3715 Nh [289]	3716 Ds [291]
3733 Nh [289]	3734 Ds [291]
3751 Nh [289]	3752 Ds [291]
3769 Nh [289]	3770 Ds [291]
3787 Nh [289]	3788 Ds [291]
3805 Nh [289]	3806 Ds [291]
3823 Nh [289]	3824 Ds [291]
3841 Nh [289]	3842 Ds [291]
3859 Nh [289]	3860 Ds [291]
3877 Nh [289]	3878 Ds [291]
3895 Nh [289]	3896 Ds [291]
3913 Nh [289]	3914 Ds [291]
3931 Nh [289]	3932 Ds [291]
3949 Nh [289]	3950 Ds [291]
3967 Nh [289]	3968 Ds [291]
3985 Nh [289]	3986 Ds [291]
4003 Nh [289]	4004 Ds [291]
4021 Nh [289]	4022 Ds [291]
4039 Nh [289]	4040 Ds [291]
4057 Nh [289]	4058 Ds [291]
4075 Nh [289]	4076 Ds [291]
4093 Nh [289]	4094 Ds [291]
4111 Nh [289]	4112 Ds [291]
4129 Nh [289]	4130 Ds [291]
4147 Nh [289]	4148 Ds [291]
4165 Nh [289]	4166 Ds [291]
4183 Nh [289]	4184 Ds [291]
4201 Nh [289]	4202 Ds [291]
4219 Nh [289]	4220 Ds [291]
4237 Nh [289]	4238 Ds [291]
4255 Nh [289]	4256 Ds [291]
4273 Nh [289]	4274 Ds [291]
4291 Nh [289]	4292 Ds [291]
4309 Nh [289]	4310 Ds [291]
4327 Nh [289]	4328 Ds [291]
4345 Nh [289]	4346 Ds [291]
4363 Nh [289]	4364 Ds [291]
4381 Nh [289]	4382 Ds [291]
4399 Nh [289]	4400 Ds [291]
4417 Nh [289]	4418 Ds [291]
4435 Nh [289]	4436 Ds [291]
4453 Nh [289]	4454 Ds [291]
4471 Nh [289]	4472 Ds [291]
4489 Nh [289]	4490 Ds [291]
4507 Nh [289]	4508 Ds [291]
4525 Nh [289]	4526 Ds [291]
4543 Nh [289]	4544 Ds [291]
4561 Nh [289]	4562 Ds [291]
4579 Nh [289]	4580 Ds [291]
4597 Nh [289]	4598 Ds [291]
4615 Nh [289]	4616 Ds [291]
4633 Nh [289]	4634 Ds [291]
4651 Nh [289]	4652 Ds [291]
4669 Nh [289]	4670 Ds [291]
4687 Nh [289]	4688 Ds [291]
4705 Nh [289]	4706 Ds [291]
4723 Nh [289]	4724 Ds [291]
4741 Nh [289]	4742 Ds [291]
4759 Nh [289]	4760 Ds [291]
4777 Nh [289]	4778 Ds [291]
4795 Nh [289]	4796 Ds [291]
4813 Nh [289]	4814 Ds [291]
4831 Nh [289]	4832 Ds [291]
4849 Nh [289]	4850 Ds [291]
4867 Nh [289]	4868 Ds [291]
4885 Nh [289]	4886 Ds [291]
4903 Nh [289]	4904 Ds [291]
4921 Nh [289]	4922 Ds [291]
4939 Nh [289]	4940 Ds [291]
4957 Nh [289]	4958 Ds [291]
4975 Nh [289]	4976 Ds [291]
4993 Nh [289]	4994 Ds [291]
5011 Nh [289]	5012 Ds [291]
5029 Nh [289]	5030 Ds [291]
5047 Nh [289]	5048 Ds [291]
5065 Nh [289	



9

Examples of **HARD** New Sources - C

hydrogen

1

H

1.0079

lithium

3

Li

6.941

sodium

11

Na

22.990

potassium

19

K

39.098

rubidium

37

Rb

85.468

caesium

55

Cs

132.91

francium

87

Fr

[223]

beryllium

4

Be

9.0122

magnesium

12

Mg

24.305

calcium

20

Ca

40.078

strontium

38

Sr

87.62

barium

56

Ba

137.33

radium

88

Ra

[226]

57-70

*

89-102

* *

scandium

21

Sc

44.956

yttrium

39

Y

88.906

lutetium

71

Lu

174.97

lanthanum

57

La

[139]

cerium

58

Ce

[140]

praseodymium

59

Pr

[141]

neodymium

60

Nd

[144]

promethium

61

Pm

[145]

europium

62

Eu

[152]

gadolinium

63

Gd

[157]

terbium

64

Tb

[159]

dysprosium

65

Dy

[163]

holmium

66

Ho

[165]

erbium

67

Er

[167]

thulium

68

Tm

[169]

ytterbium

69

Yb

[173]

lanthanum

57

La

[139]

cerium

58

Ce

[140]

praseodymium

59

Pr

[141]

neodymium

60

Nd

[144]

promethium

61

Pm

[145]

europium

62

Eu

[152]

gadolinium

63

Gd

[157]

terbium

64

Tb

[159]

dysprosium

65

Dy

[163]

holmium

66

Ho

[165]

erbium

67

Er

[167]

thulium

68

Tm

[169]

ytterbium

69

Yb

[173]

lutetium

71

Lu

174.97

hafnium

72

Hf

178.49

tantalum

73

Ta

180.95

tungsten

74

W

183.84

rhenium

75

Re

186.21

osmium

76

Os

190.23

iridium

77

Ir

192.22

platinum

78

Pt

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]

astatine

85

At

[210]

radon

86

Rn

[222]

boron

5

B

10.811

aluminum

13

Al

26.982

gallium

31

Ga

69.723

indium

49

In

114.82

tin

50

Sn

118.71

antimony

51

Sb

121.76

tellurium

52

Te

127.60

iodine

53

I

126.90

xenon

54

Xe

131.29

carbon

6

C

12.011

silicon

14

Si

28.086

germanium

32

Ge

72.61

arsenic

33

As

74.922

selenium

34

Se

78.96

bromine

35

Br

79.904

krypton

36

Kr

83.80

nitrogen

7

N

14.007

phosphorus

15

P

30.974

sulfur

16

S

32.065

chlorine

17

Cl

35.453

argon

18

Ar

39.948

oxygen

8

O

15.999

fluorine

9

F

18.998

neon

10

Ne

20.180

helium

2

He

4.0026

purple

running at SNL

yellow

attempting at SNL

green

demonstrated at other labs

Purple - running at SNL

Yellow - attempting at SNL

Green - demonstrated at other labs

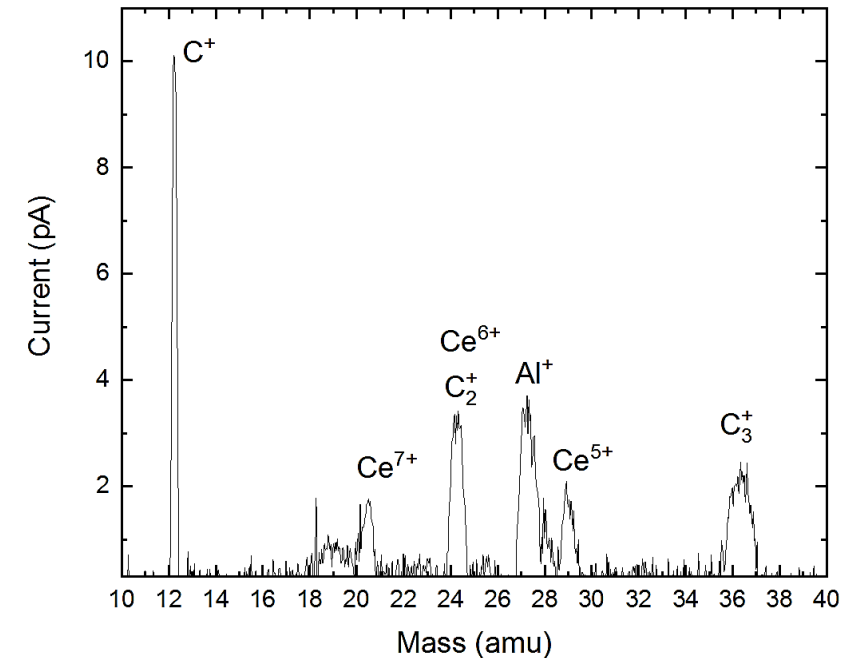
*Lanthanide series

57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm [145]	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04
89 Ac [227]	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np [237]	94 Pu [244]	95 Am [243]	96 Cm [247]	97 Bk [247]	98 Cf [251]	99 Es [252]	100 Fm [257]	101 Md [258]	102 No [259]

** Actinide series

- C

→ CeC alloy with



(1) Source fabricated at Helmholtz-Zentrum Dresden-Rossendorf

(2) Source tested at Raith

(3) Source used at SNL to implant Si sample

In collaboration with Nico Klinger, Gregor Hlawacek and Paul Mazarov

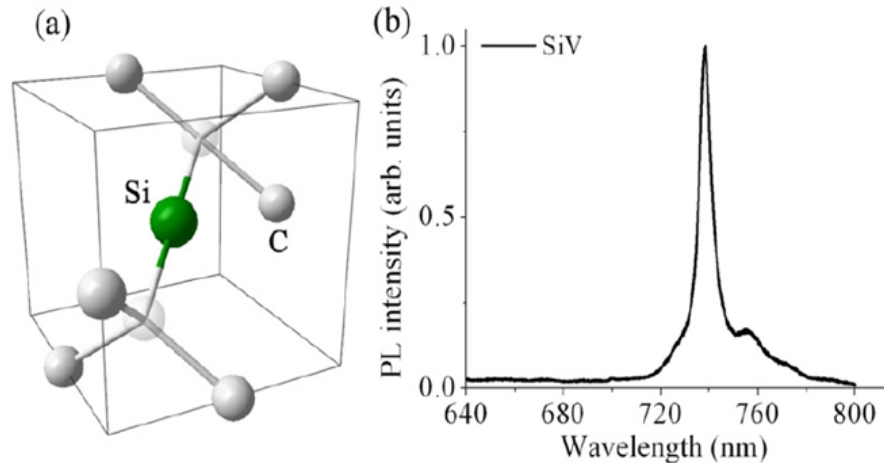
Creation of Single Defect Centers in Wide Bandgap Substrates



- 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!

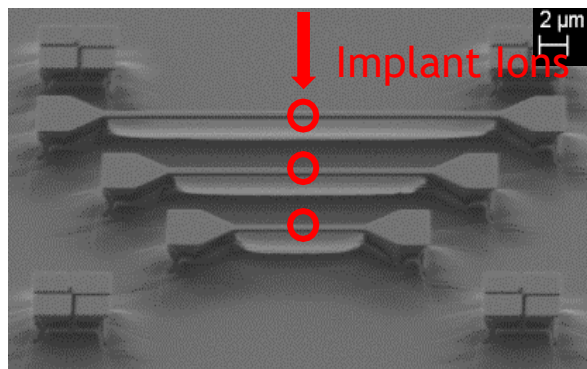


I. Aharonovich *et al.*, Rep. Prog. Phys. **74**,076501 (2011)

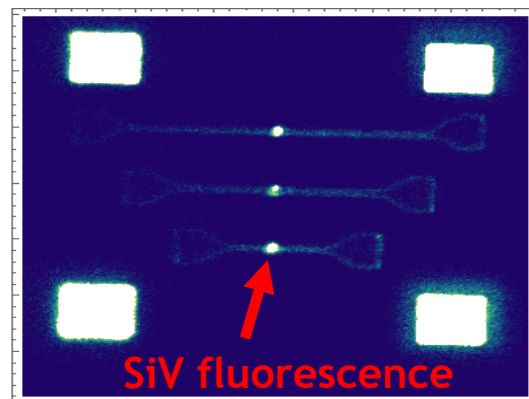
- How to produce a single defect center where you want it?
 - 1.) Location - focused ion beam implantation to control location
 - 2.) Yield - counted implantation to control the number of ions and in-situ PL to confirm an optically active defect center

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

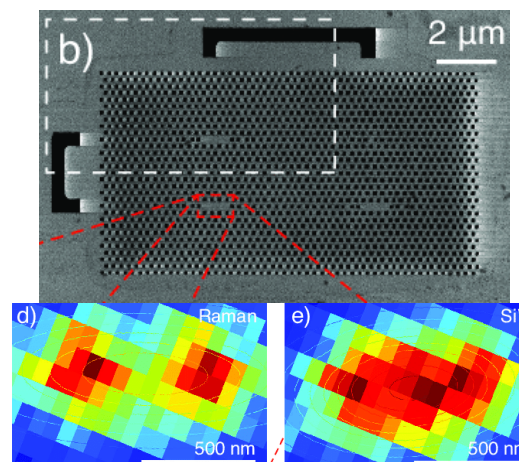
Diamond Nanobeams (with Harvard)



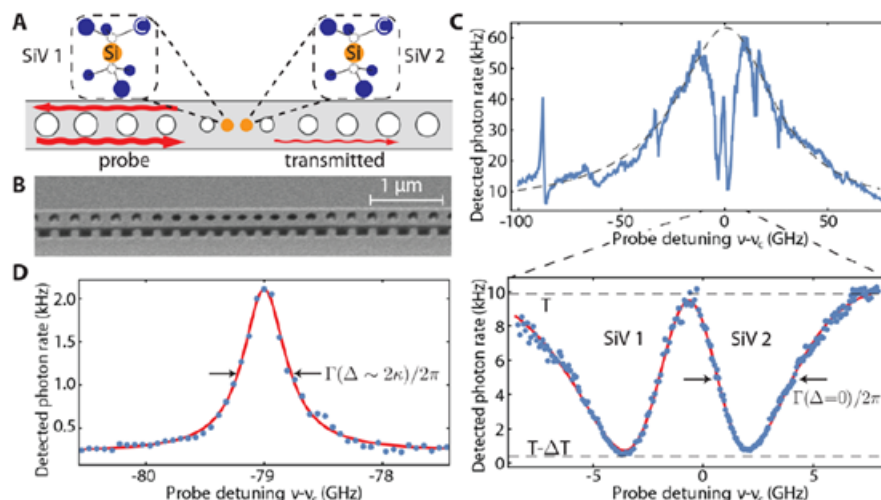
A. Sipahigil, *et al.*, *Science* (2016)



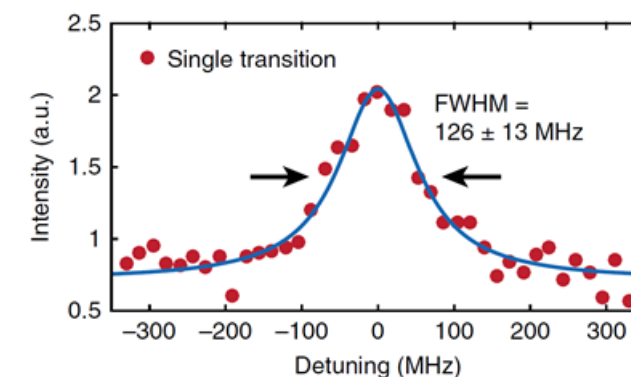
2D Photonic Crystals (with MIT)



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



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

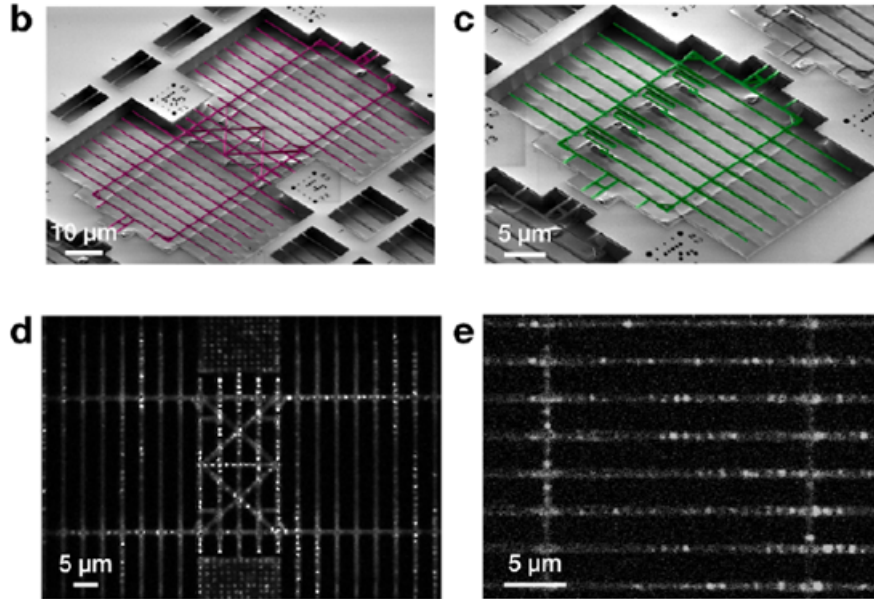


Spatial Accuracy is <50 nm

Another set of CINT user projects using FIB Implantation



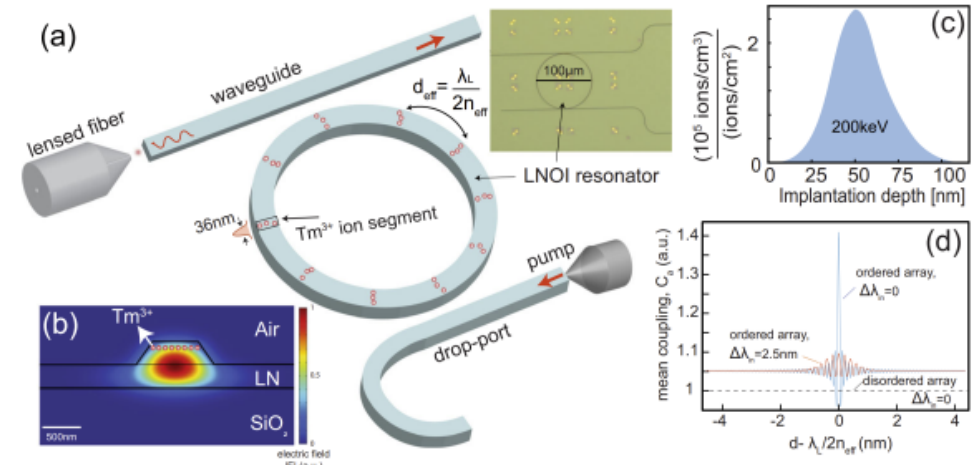
Diamond waveguides with AlN photonics (with MIT)



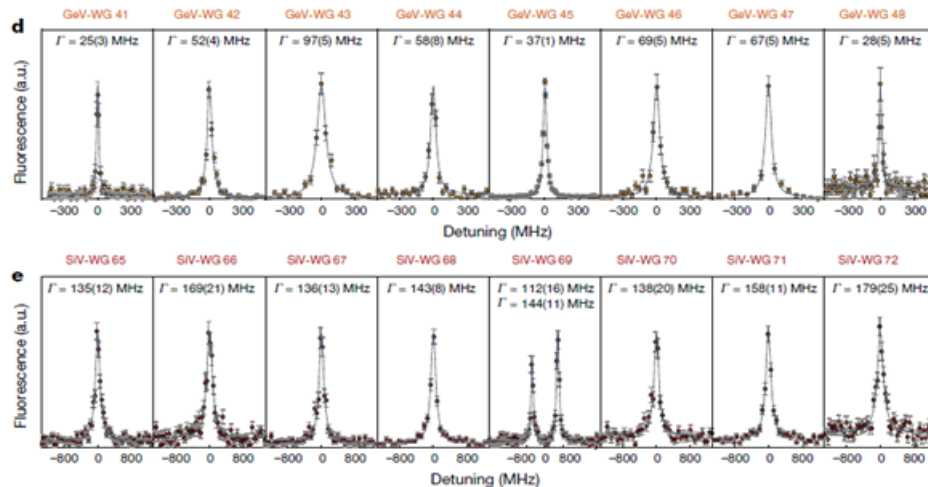
16 and 8 channel
“quantum micro-
chips”

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

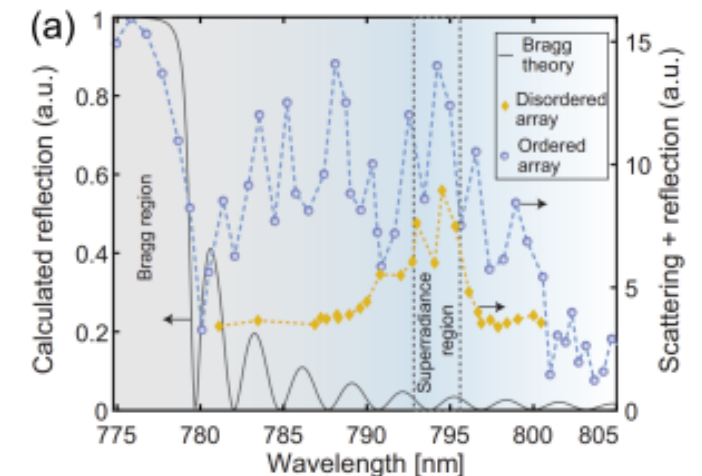
Lithium Niobate Photonics (with Purdue)



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



FIB implantation works
for a wide range of
substrates



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

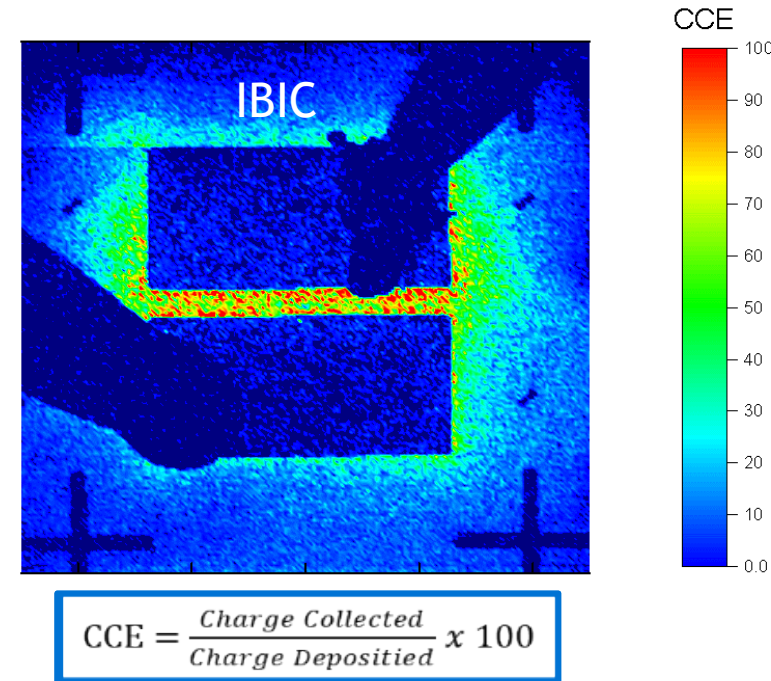
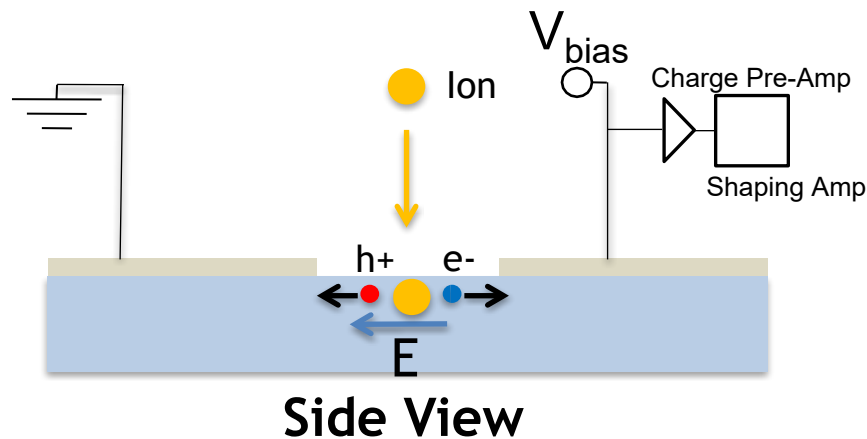
In-situ Counted Ion Implantation to control the number of implanted ion

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

Poisson Statistics

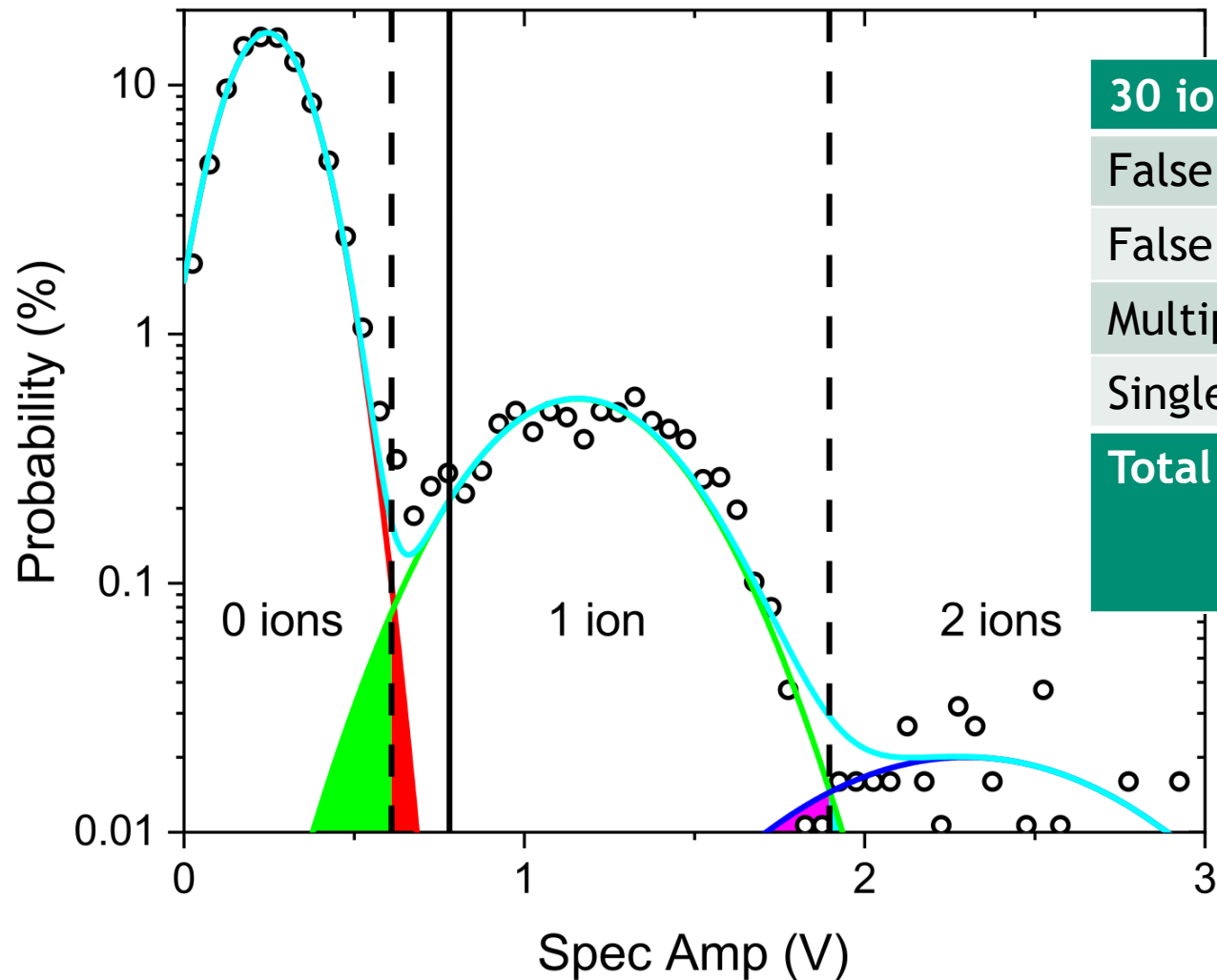
(Uncertainty in number of ion is \sqrt{N})

Ion Beam Induced Charge (IBIC)



IBIC/detection demonstrated for low energy heavy ions

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



30 ions / $<1>$ SiV	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

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

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

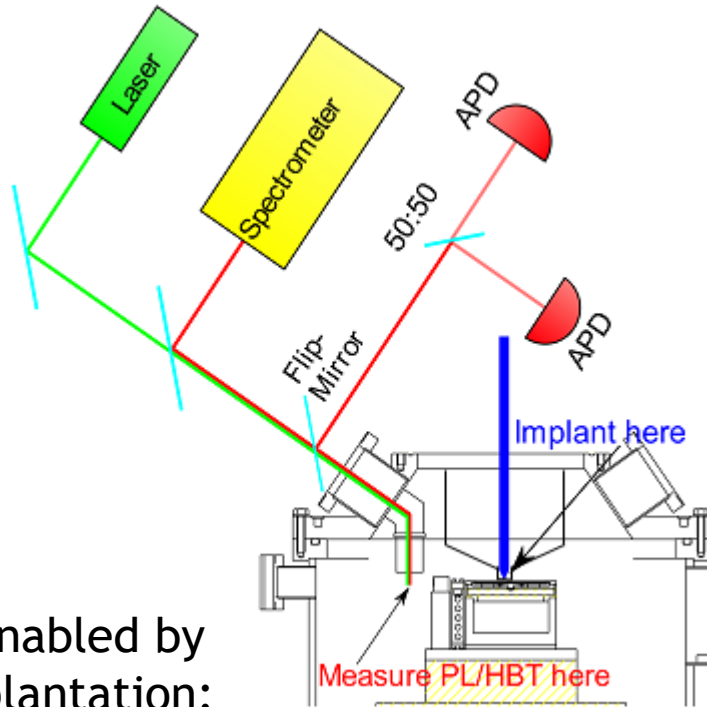
In-situ counting to reduce the error in the number of implanted ions

In-situ Photoluminescence to confirm optical defect center



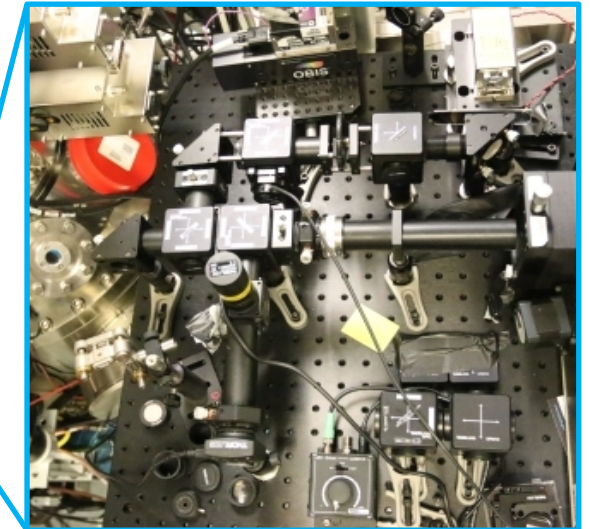
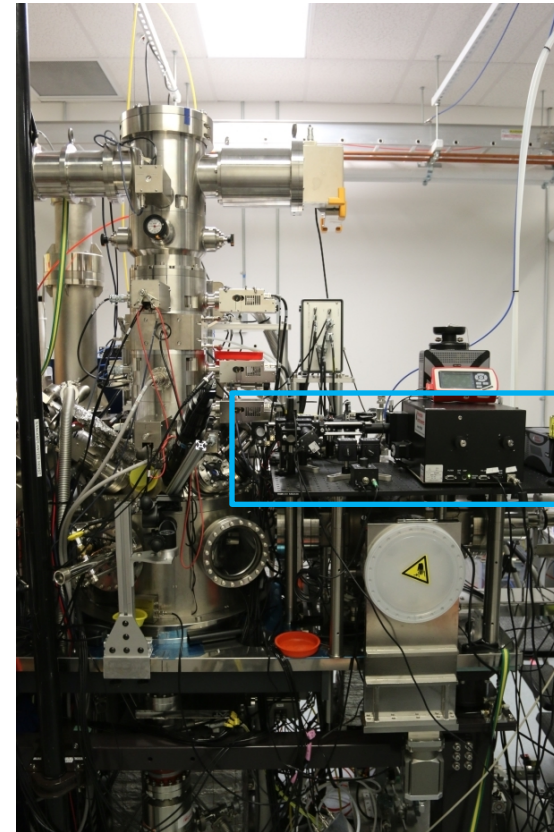
$$\text{Yield} = \# \text{ measured Vsi} / \# \text{ implanted Si}$$

We switched from SiV in diamond to Vsi 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

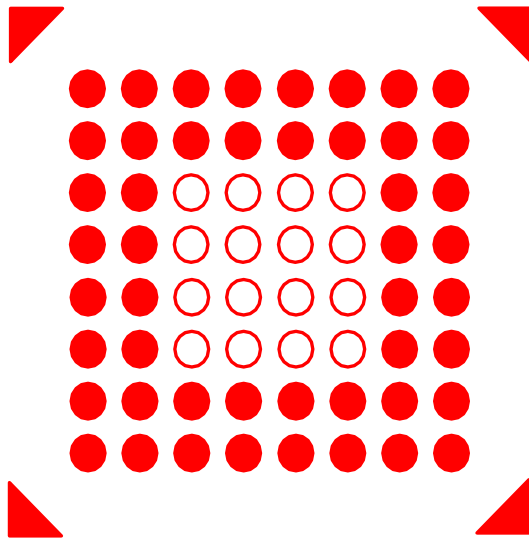


In-situ PL to confirm the optically emission from the defect centers



Demonstration of In-situ Photoluminescence in SiC

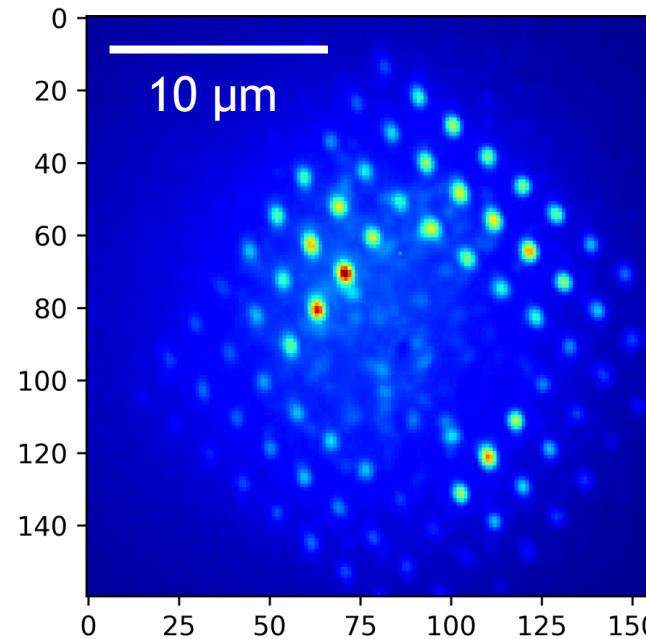
Design of array



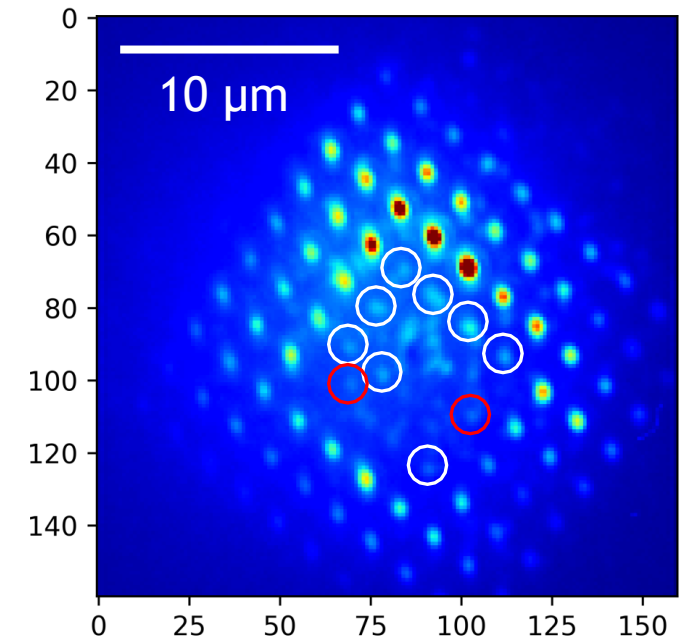
Alignment markers

- $\langle 500 \rangle$ 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



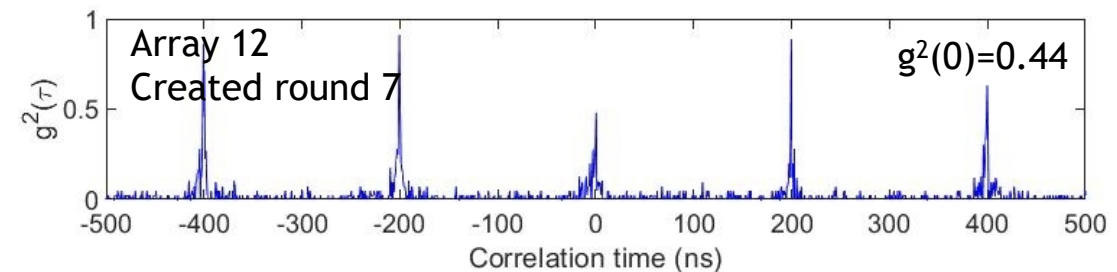
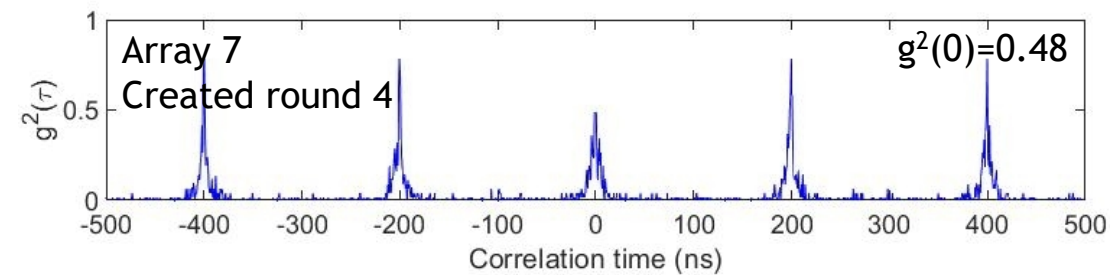
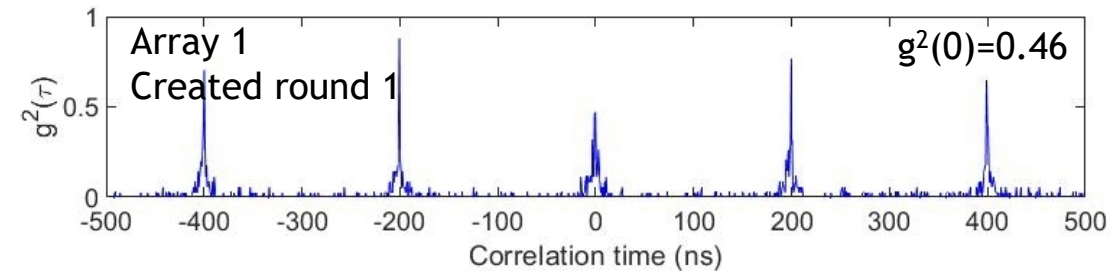
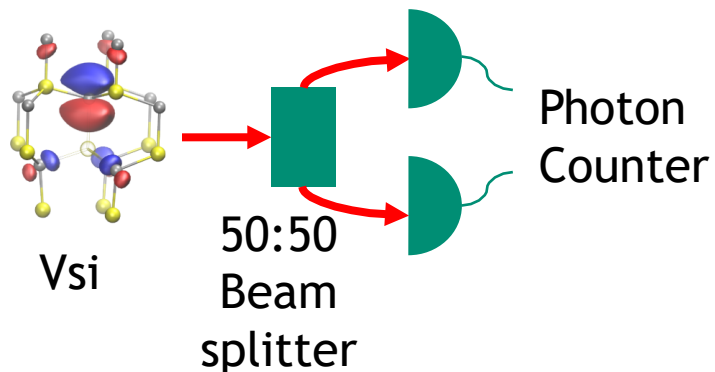
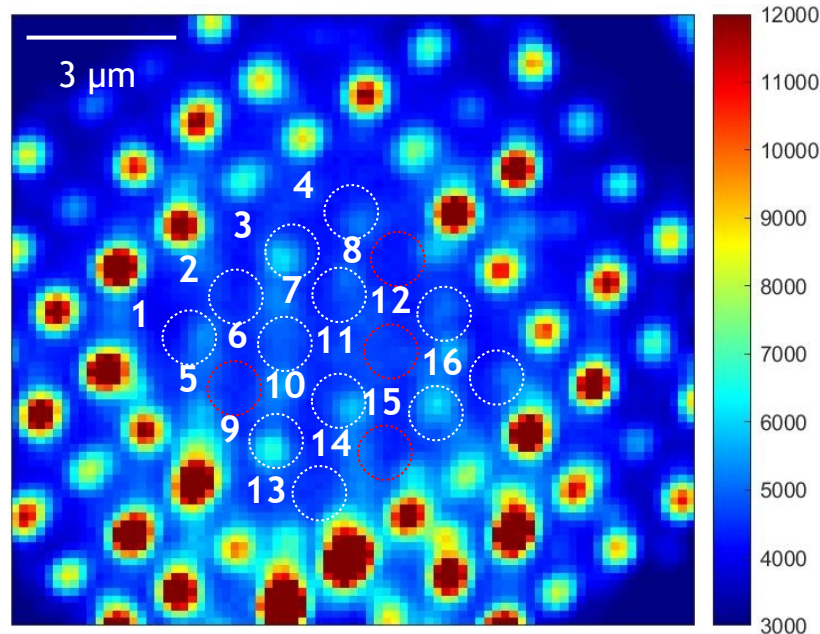
Chandrasekaran *et al*, Adv. Sci., 2300190 (2023)

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



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

3 representative examples (okay, good examples ☺!)



*No background correction

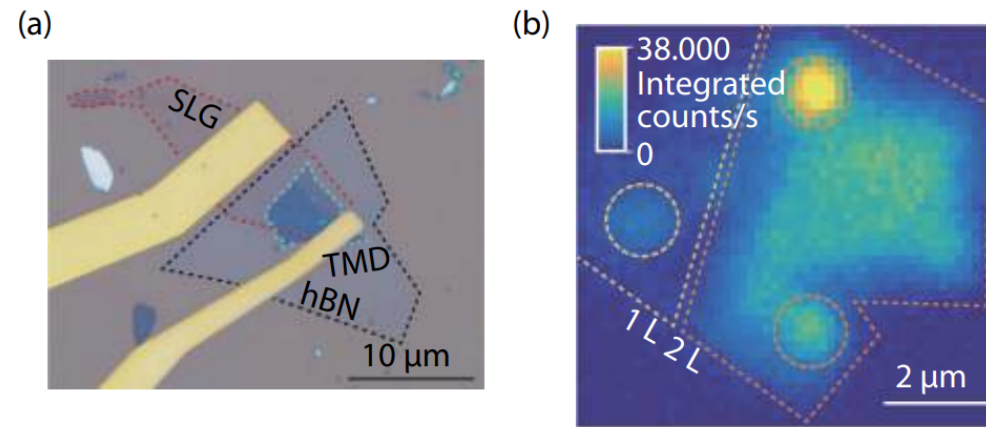
Chandrasekaran *et al*, Adv. Sci., 2300190 (2023)

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'ls



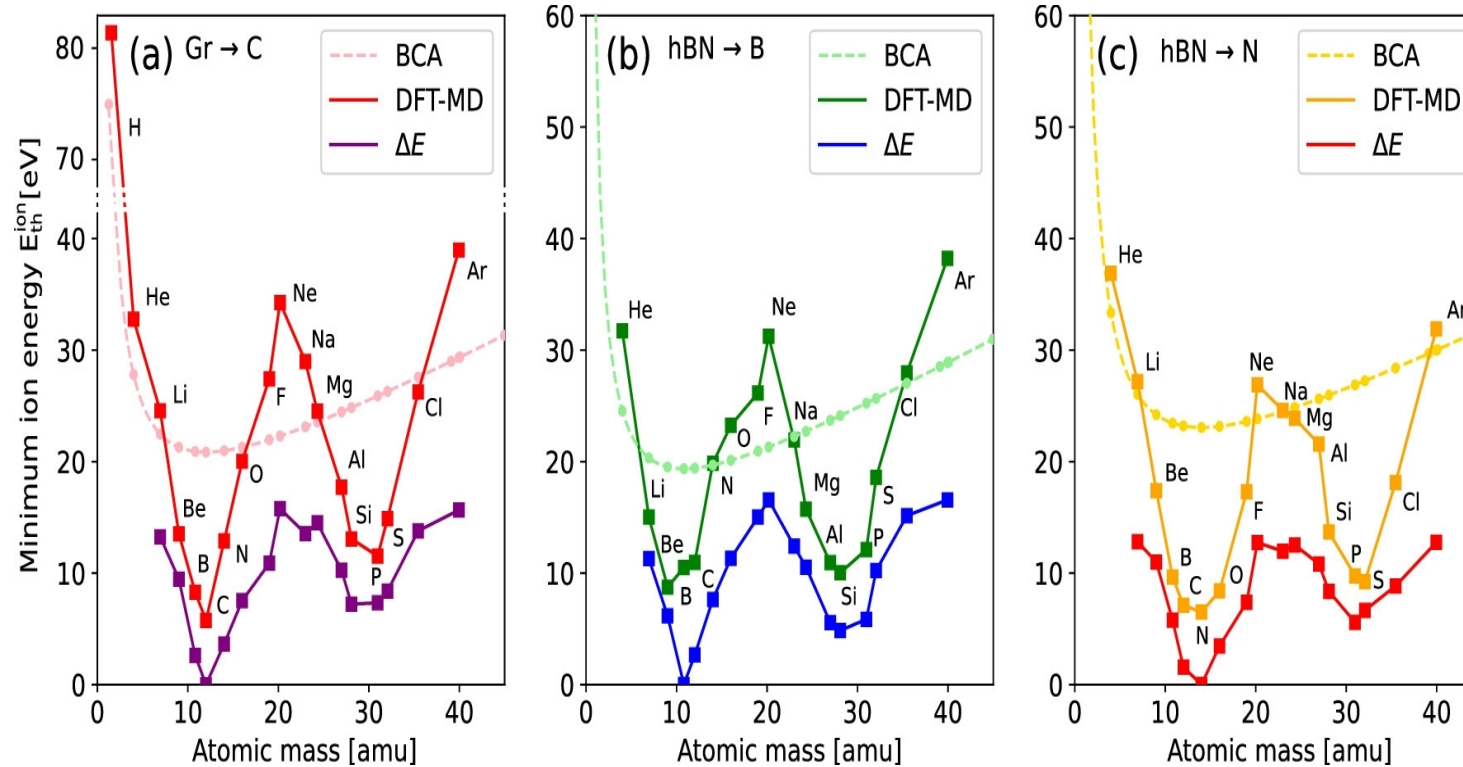
- Quantum emitters in 2D Materials have the potential to enable electrical operations and integration into conventional CMOS devices



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?

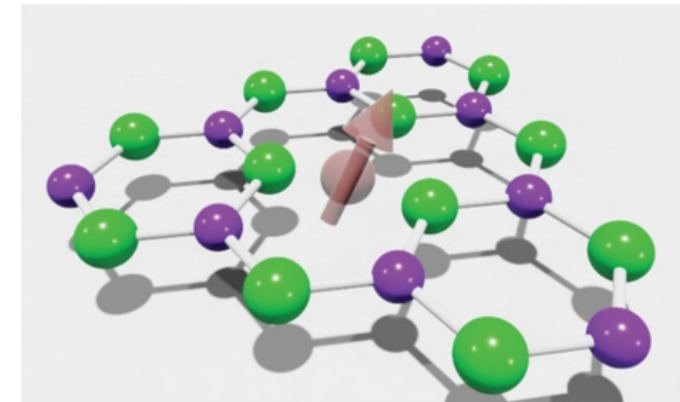
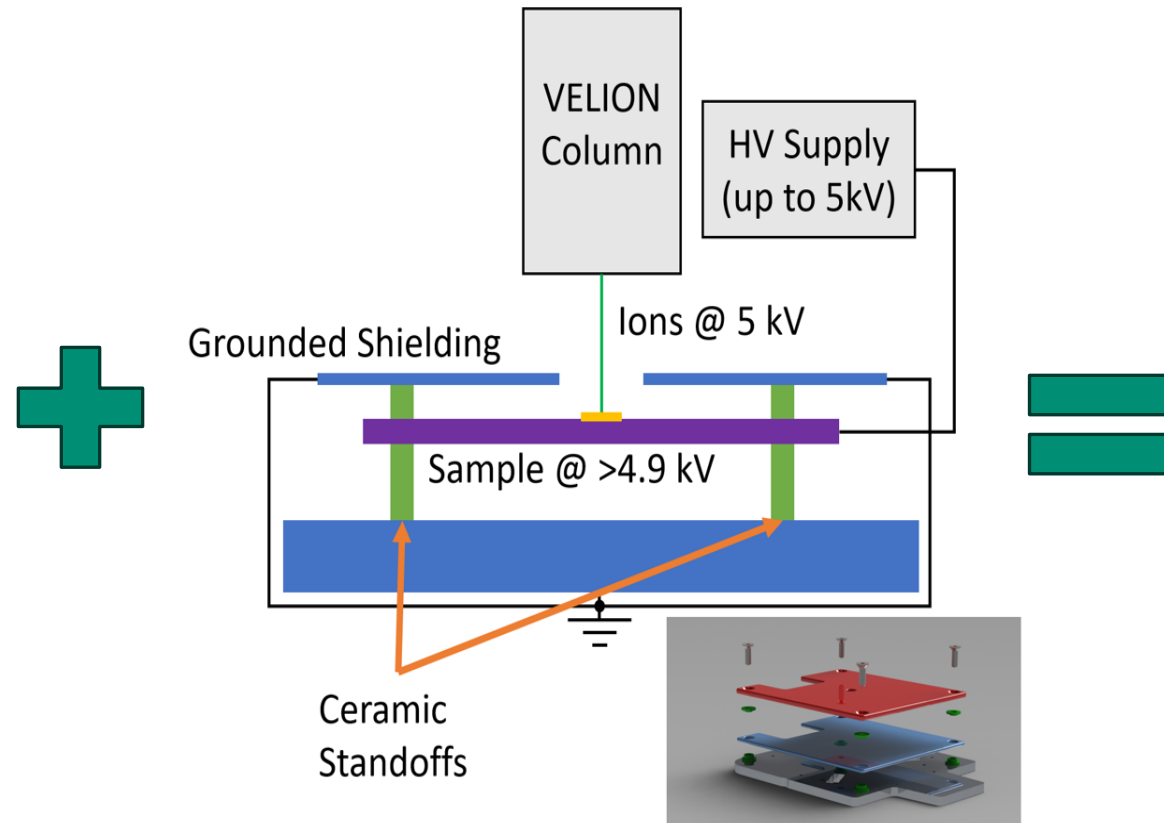
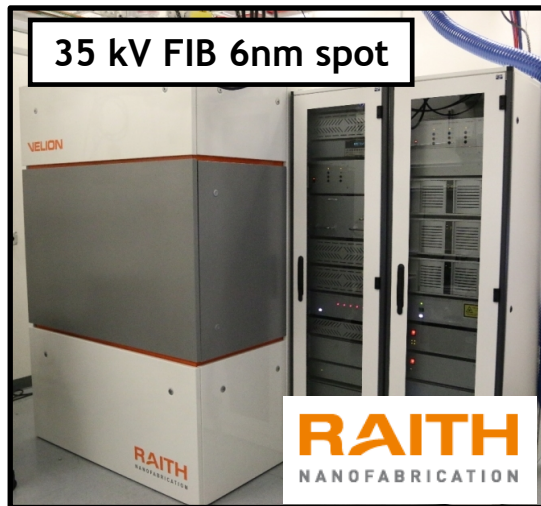
What energy is needed to stop in a 2D monolayer?



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 ($\ll 1$ keV) FIB capability for Impurity based emitters in 2D materials



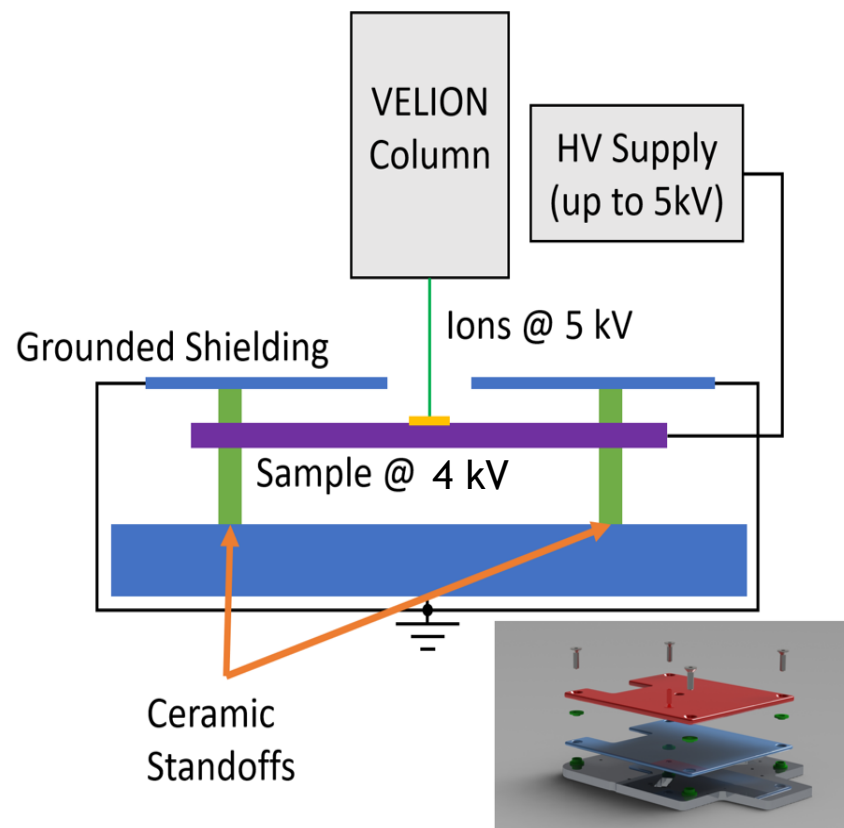
Adapted from N. Mendelson et al., Adv. Mater., 34, 2106046 (2022)

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



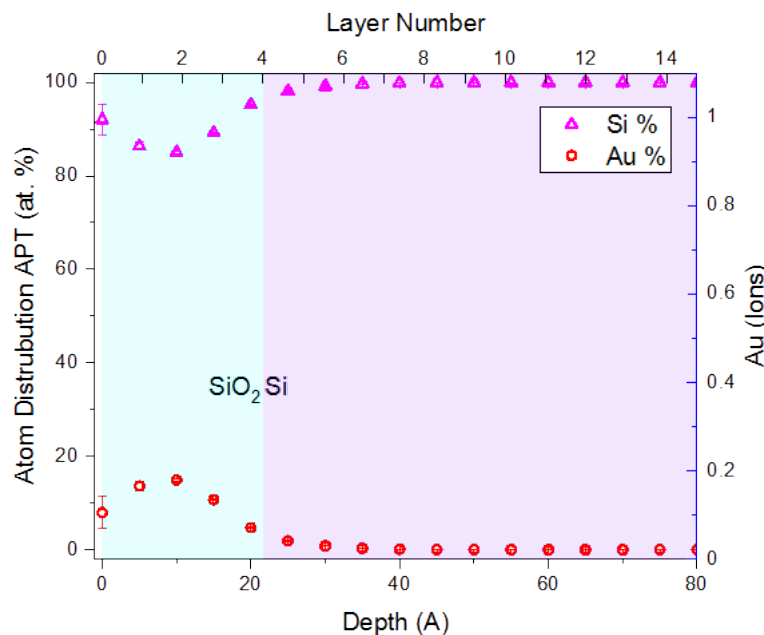
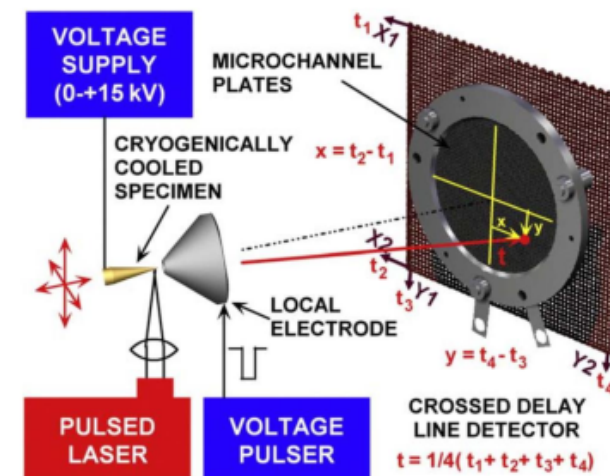
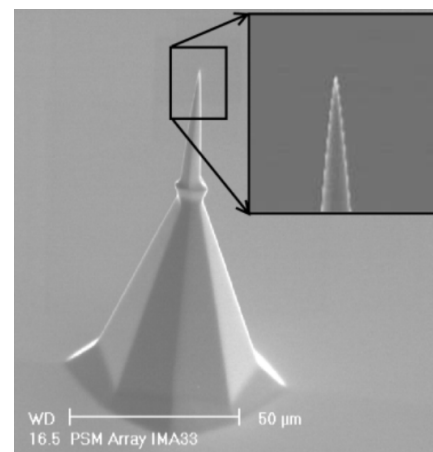
Example of capability:

$V_{acc} = 5 \text{ kV}$

$V_{plate} = 4.0 \text{ kV}$

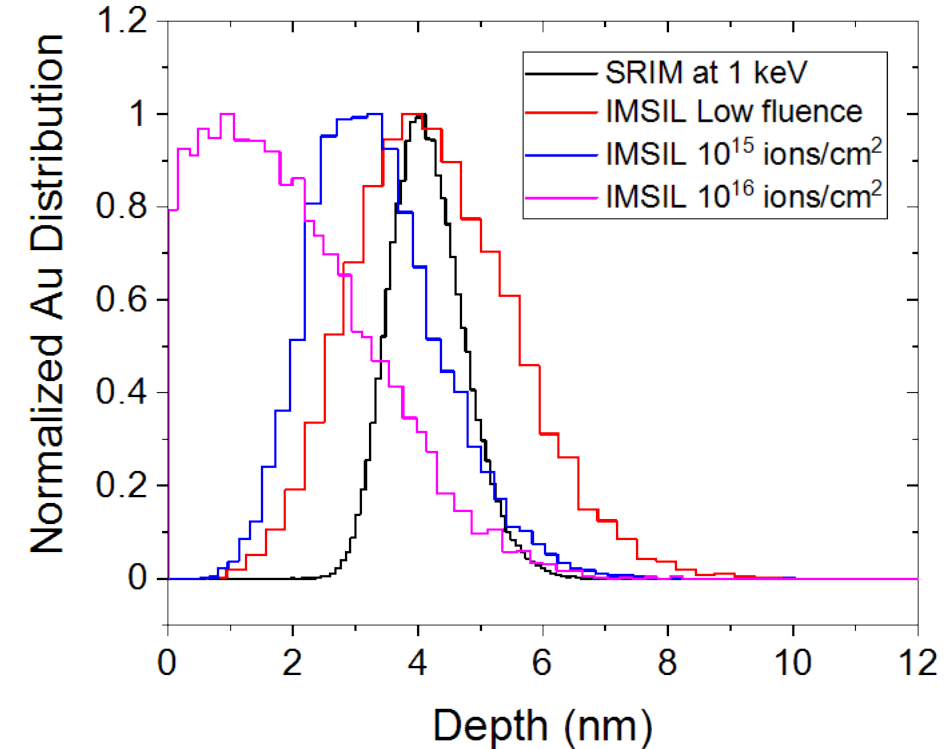
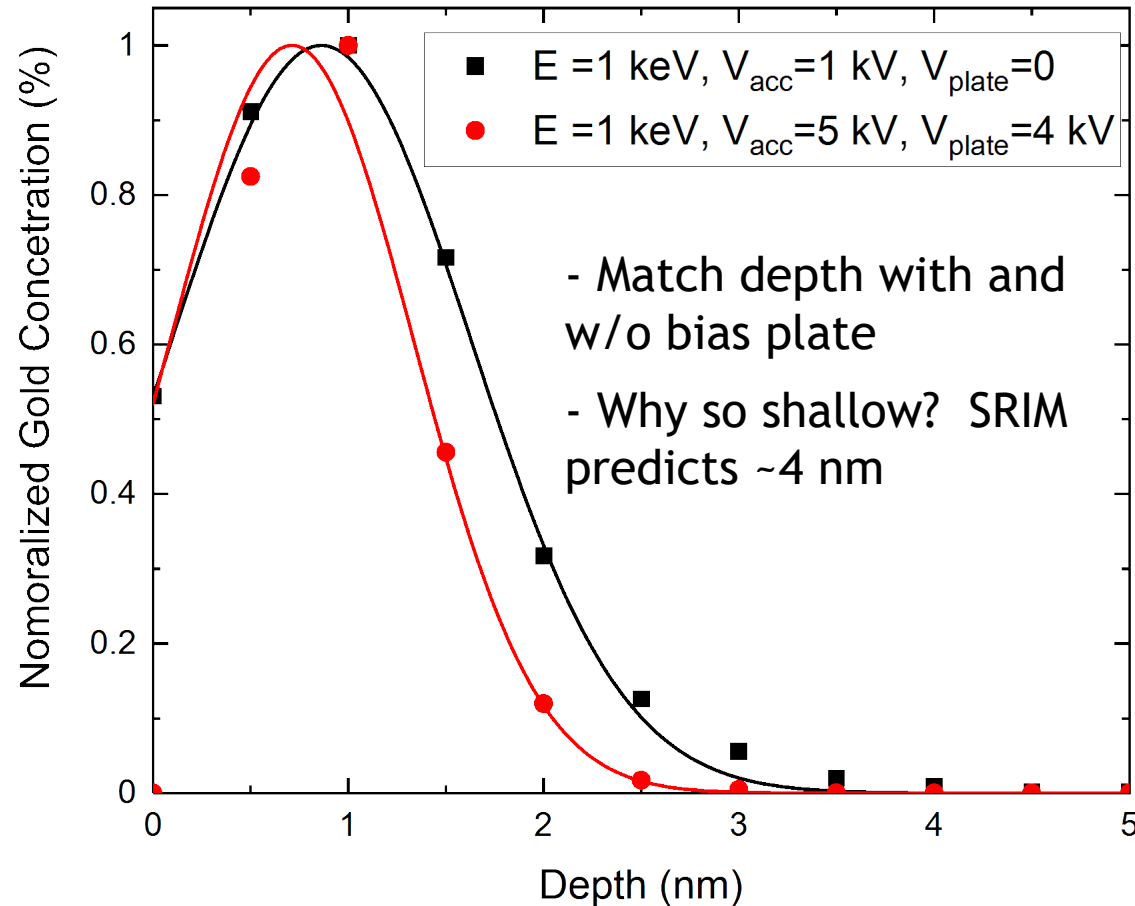
Ion Landing Energy
1 keV

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?



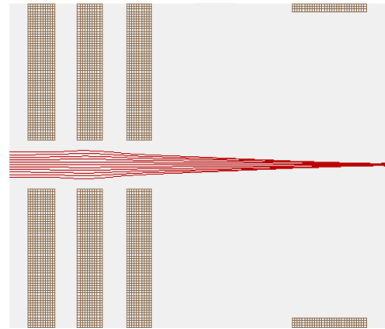
- Monte Carlo code IMSIL takes into account surface sputtering at high fluence values

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

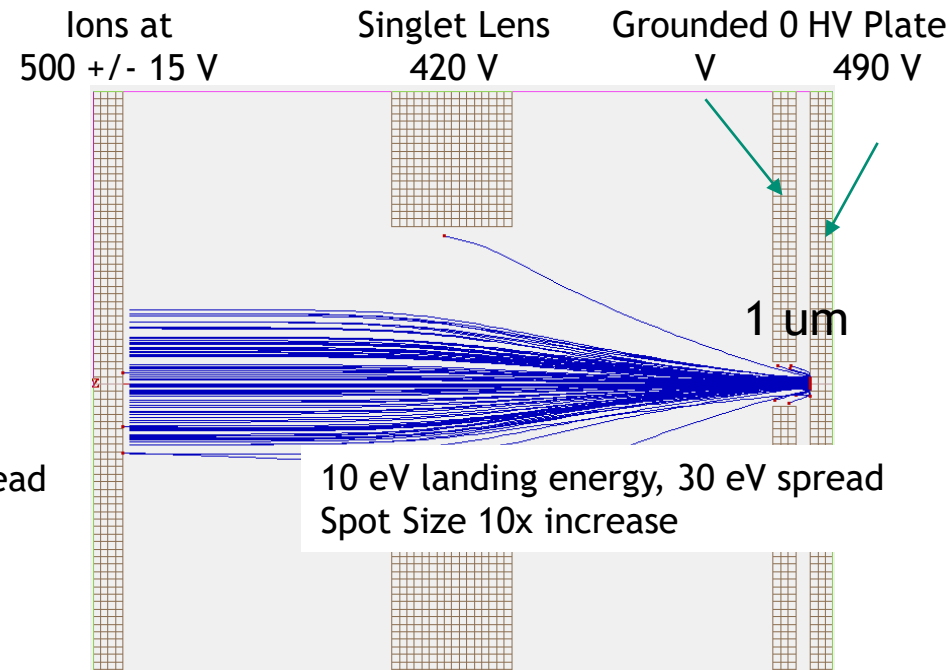
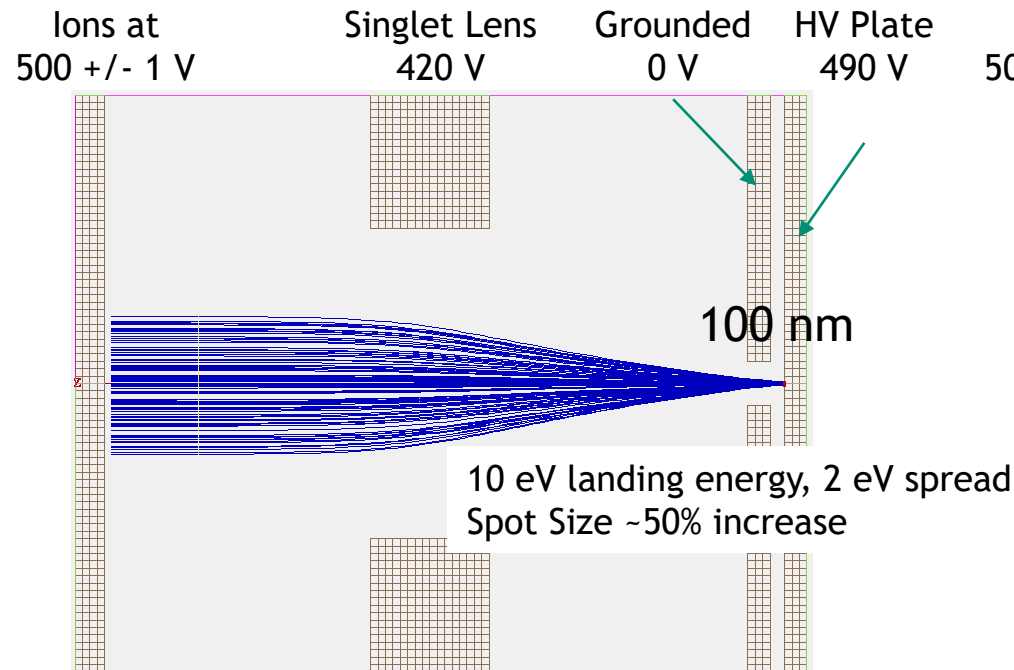
Demonstrated low energy implantation using the biased sample plate, shallow depth likely due to sputtering

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⁺ ions with a 60 μm diameter to a 4 kV plate - **60 nm** optimized beam spot

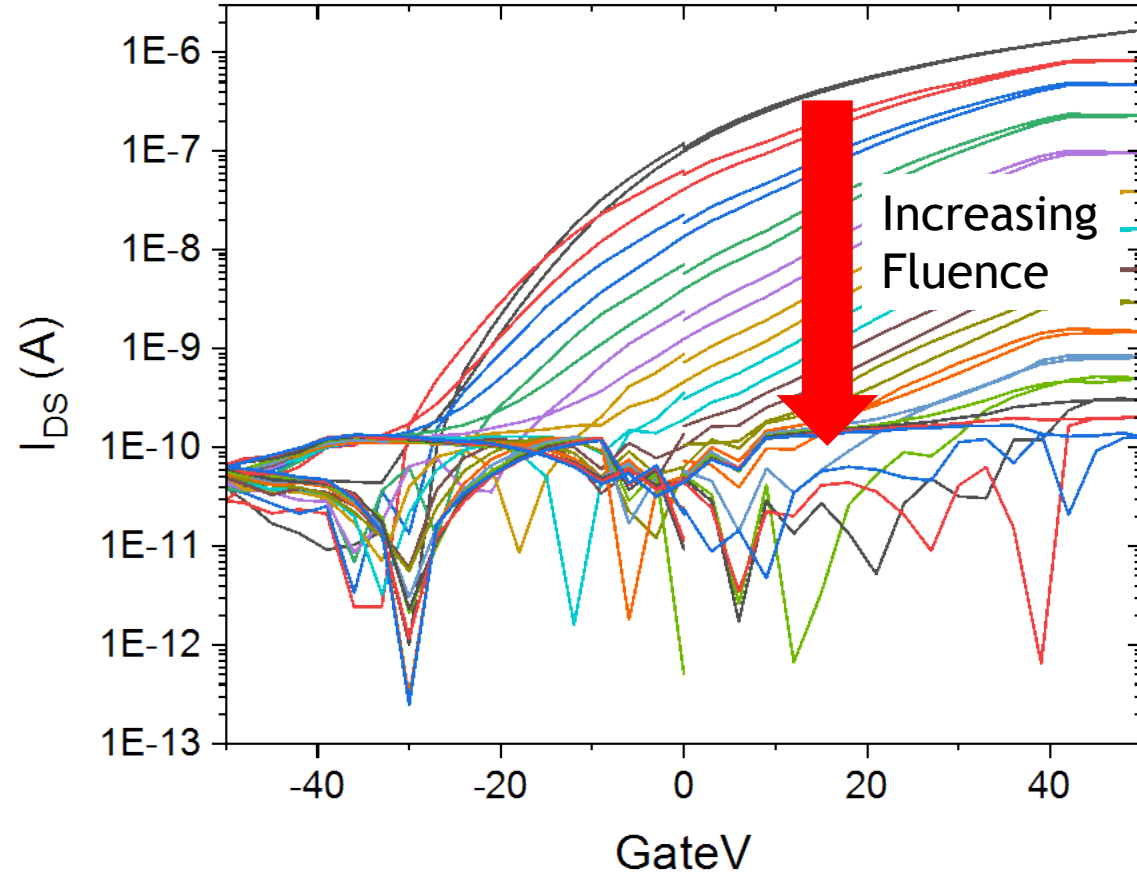


At ~10 eV landing energy, we expect <2X spot size increase, targeting ~100 - 300 nm

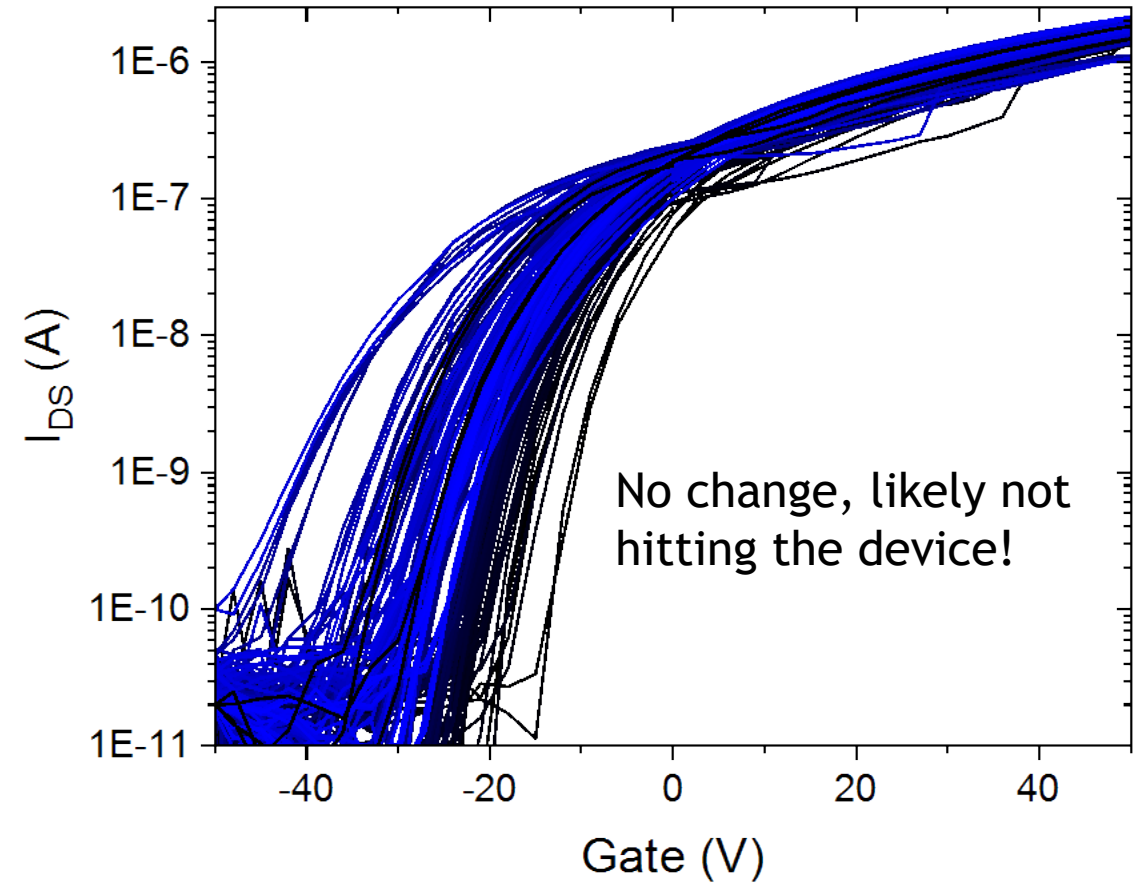


But, targeting is a challenge

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)

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U.S. DEPARTMENT OF
ENERGY

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Science



Massachusetts
Institute of
Technology



HARVARD
UNIVERSITY



Argonne
NATIONAL LABORATORY



THE UNIVERSITY OF
CHICAGO



Los Alamos
NATIONAL LABORATORY
EST. 1943

PURDUE
UNIVERSITY



UNIVERSITY
OF TECHNOLOGY
SYDNEY



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RIDGE
National Laboratory

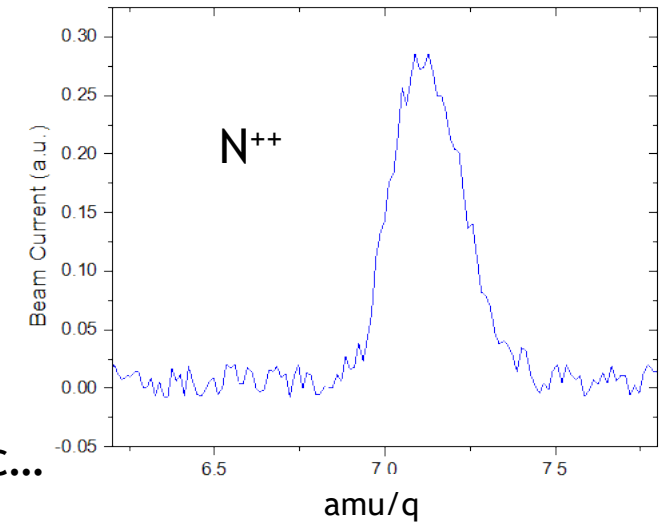
Summary

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

→ Viable solution for prototyping - fast and easy!

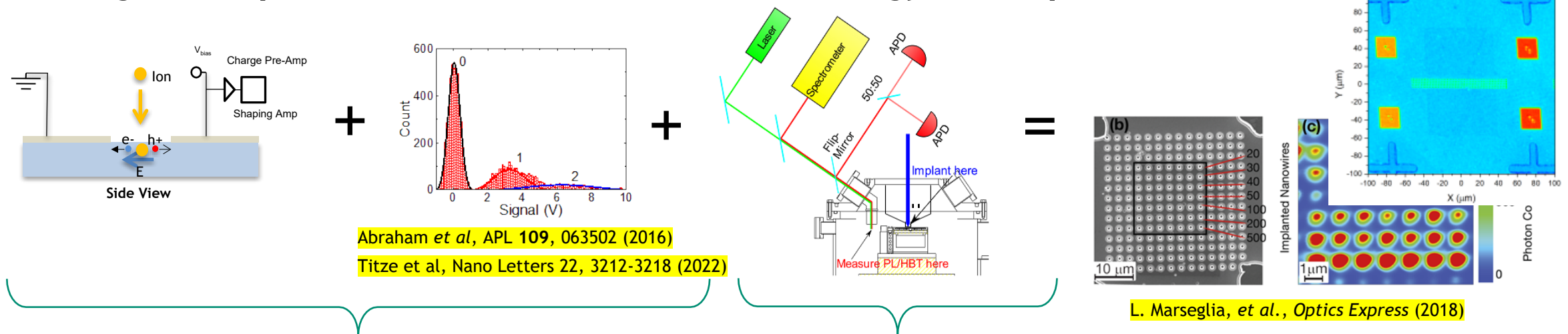
→ On-going work in diamond, SiN, SiC, hBN, GaN, AlN, GaOx, etc...

→ 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



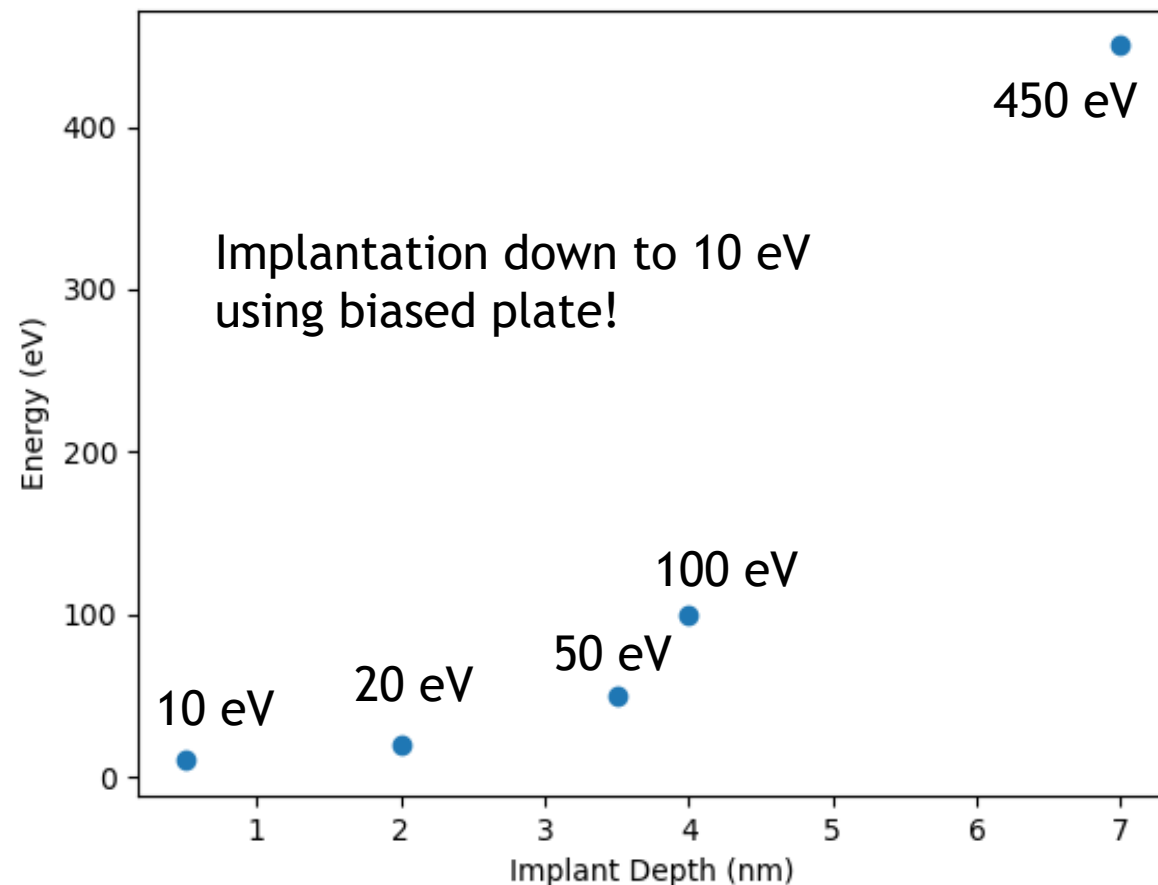
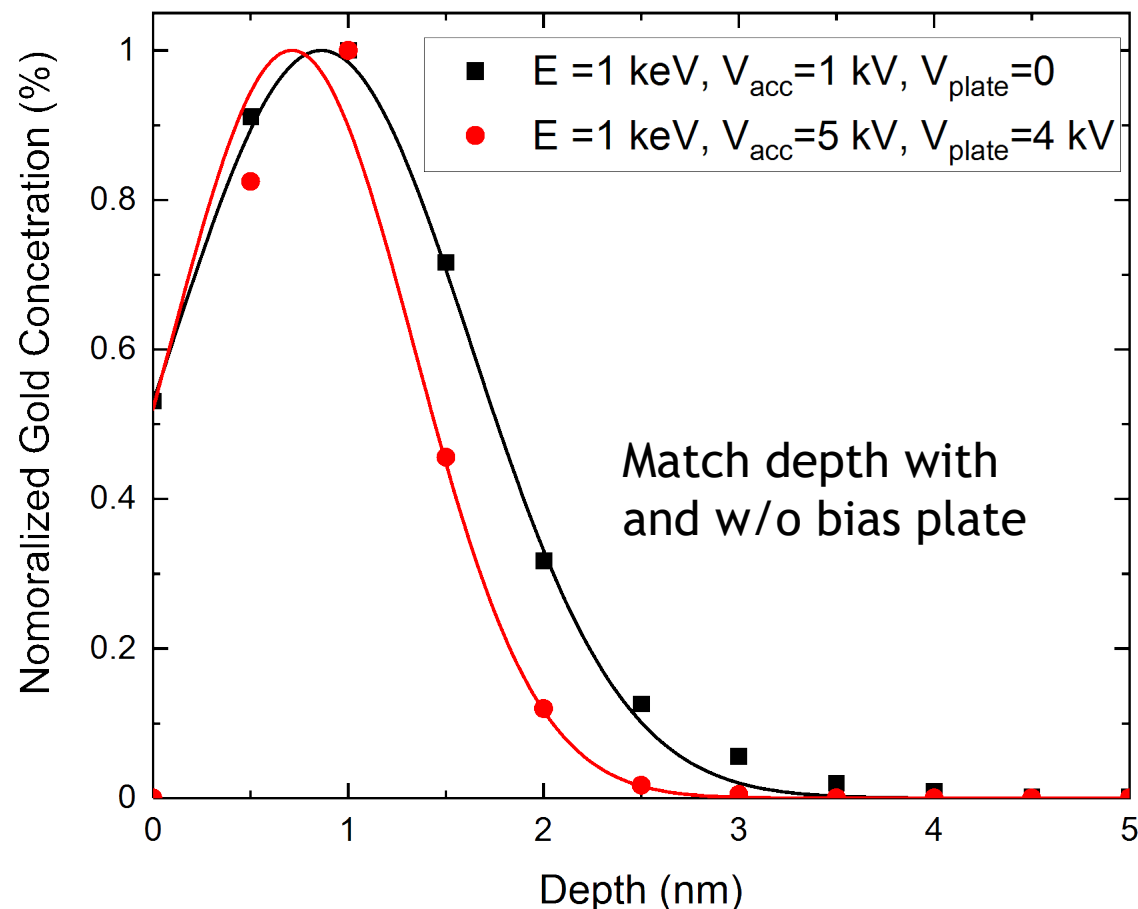
Control the number of ions

Confirm Optically Active Defect Centers

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



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

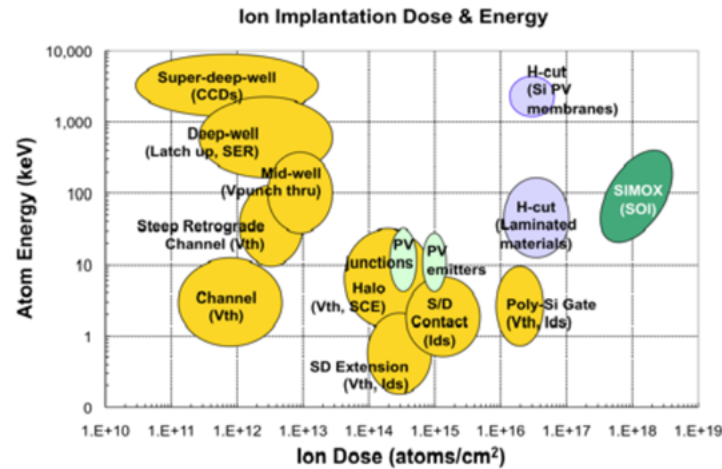
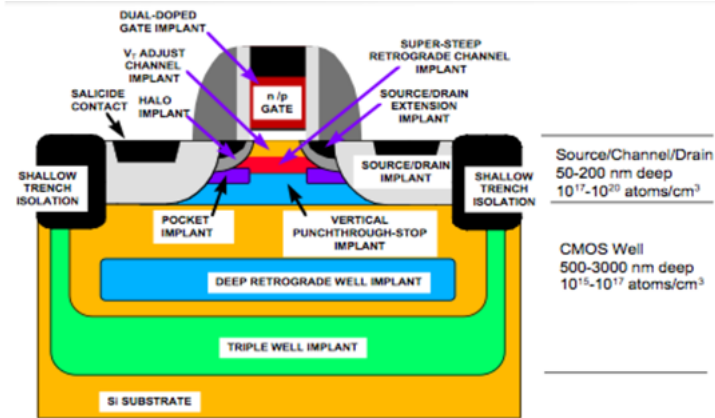


Demonstrated low energy implantation using the biased sample plate, difference in depth between 1 keV and eV range is likely due to sputtering

Ion Implantation and Irradiation for Device Fab

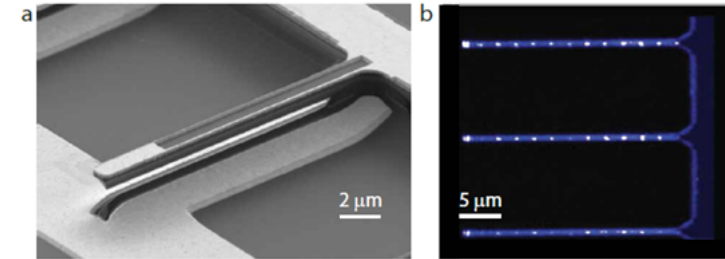


Ion Implantation has been a work-horse for the semiconductor industry

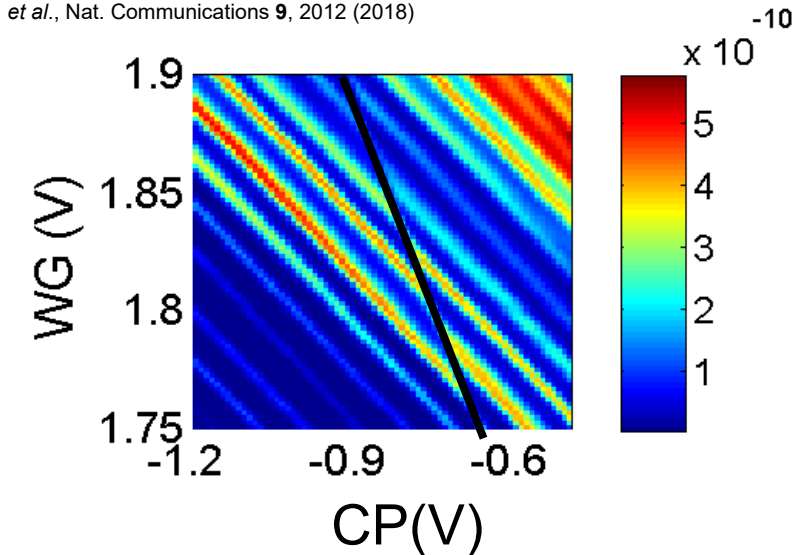


S. B. Felch, *et al.*, Proceedings of PAC2013, Pasadena, CA (2013)

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)

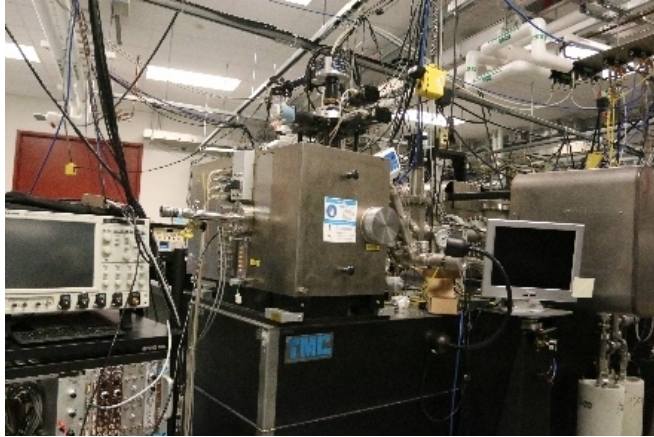


Singh *et al.* Appl. Phys. Lett. **108**, 062101 (2016)

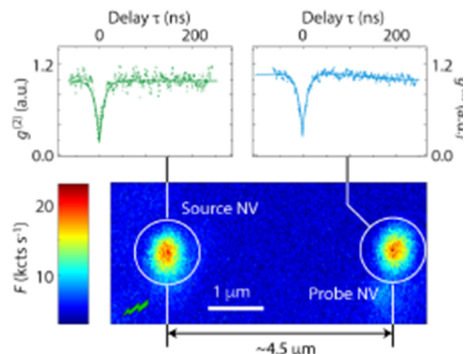
Focused Ion Beam implantation for fabrication of single atom devices and nanofabrication

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

- 6 MV Tandem microbeam (microONE)

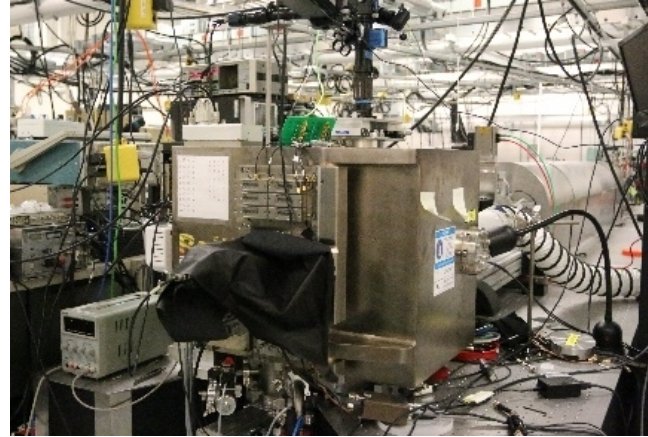


- High resolution laser stage
- Spot size $< 1 \mu\text{m}$
- Energy 0.8 - 70 MeV
- H to Au

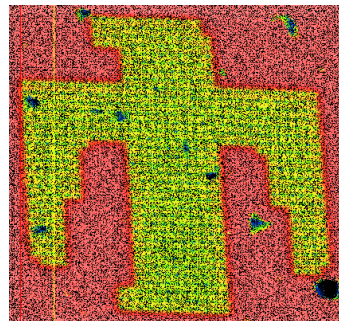


NV PL in diamond

- 3 MV Pelletron microbeam (Light Ion Microbeam)



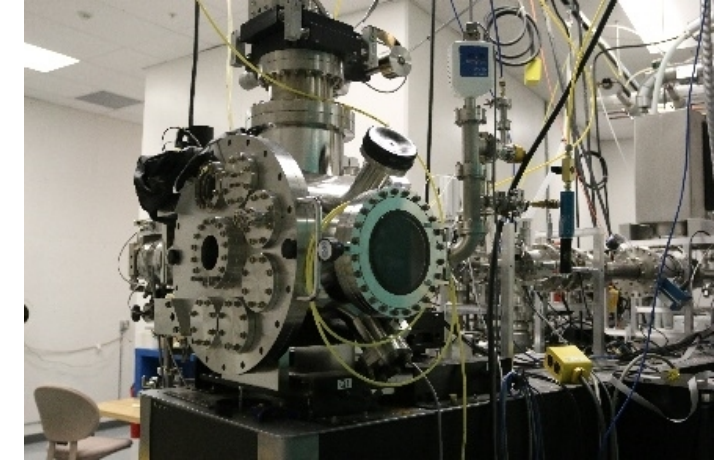
- High resolution laser stage
- Spot size $< 600 \text{ nm}$
- Energy 0.25 - 3 MeV
- H, He, N, Ar, Xe, ...



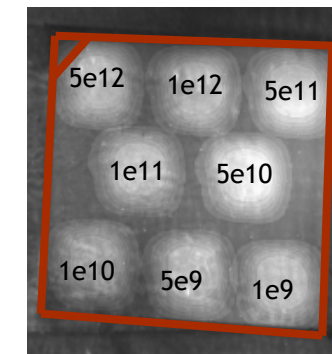
IBIC on PIN diode



- 350 kV HVEE microbeam (NanoBeamLine)



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

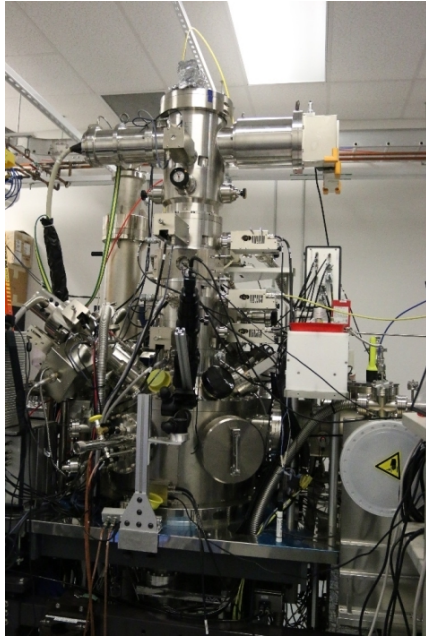


Ni into diamond



Low Energy Focused Ion Beams <1 to 20 nm

- 100 kV A&D FIB100NI (nanolimplanter)



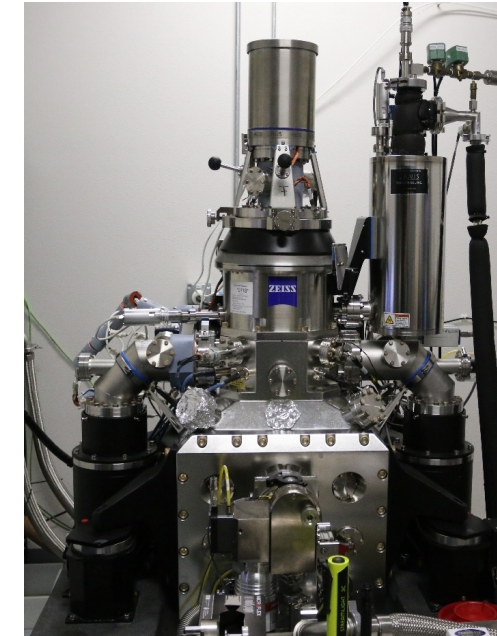
- High resolution laser stage
- Spot size <10 nm (Ga)
- Energy 10 - 200 keV
- 1/3 periodic table

- 35 kV Raith Velion (Velion)



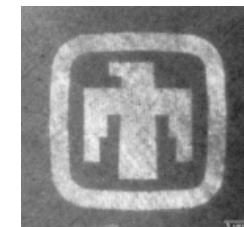
- High resolution laser stage
- Spot size <6 nm (Ga)
- Energy 5 - 70 keV
- 1/3 periodic table

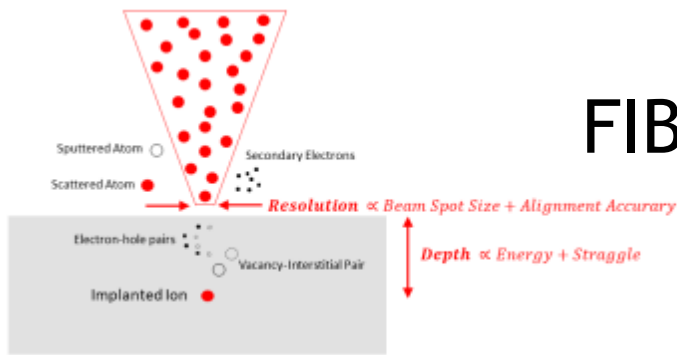
- 35 kV Zeiss Orion Plus (HeIM)



- 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 ~ 1 μm
- Alignment accuracy ~ 1 μm
- Overall resolution ~ 1-2 μm

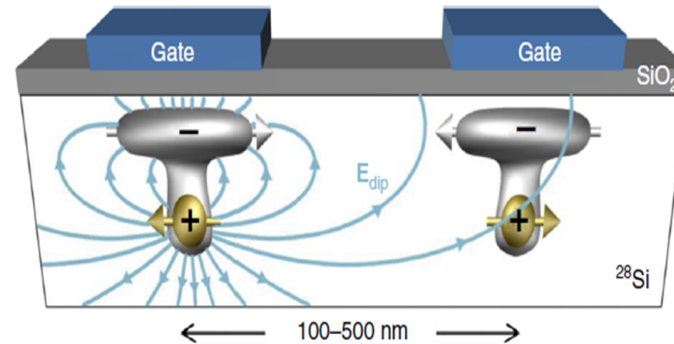
Low Energy FIB

- Spot Size ~ few nm
- Alignment accuracy ~ 10's nm
- Overall resolution ~ 20-50 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

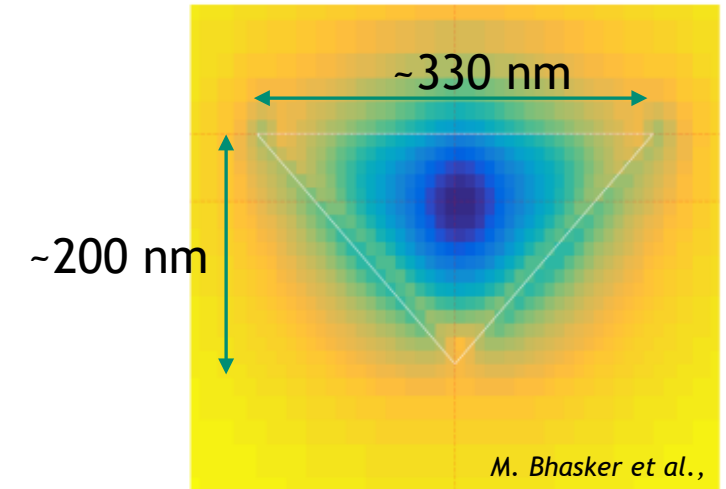


G. Tosi et al., Nat. Comm. 8, 450 (2017)

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



Nanophotonic Applications



M. Bhasker et al.,

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



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

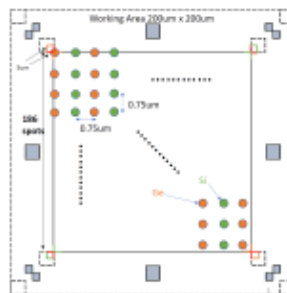
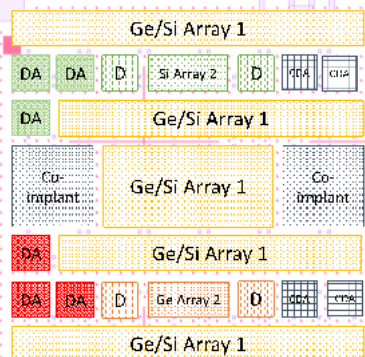
Practical Example of FIB Implantation



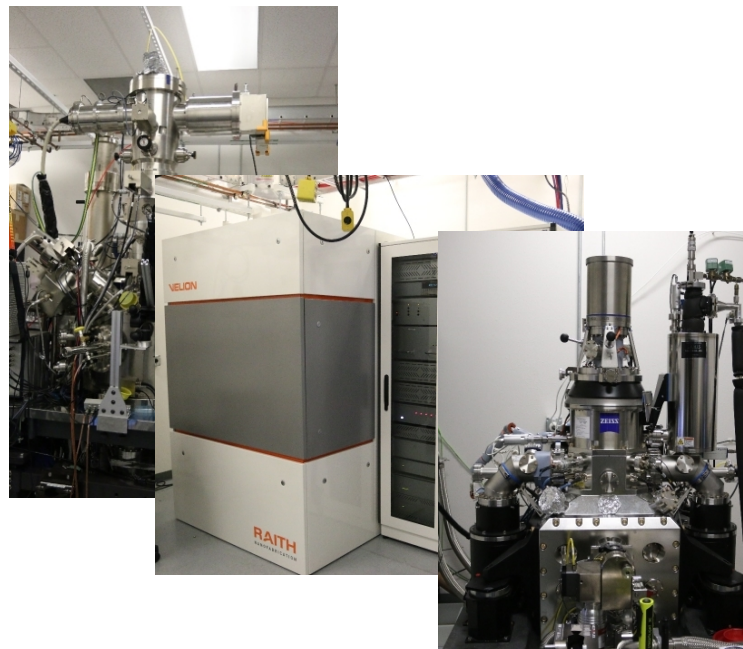
Conversation of what is needed?



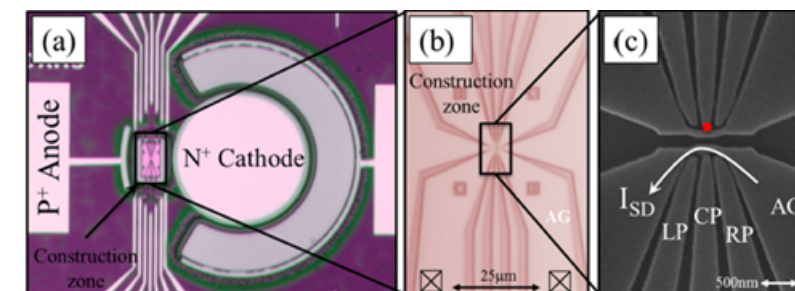
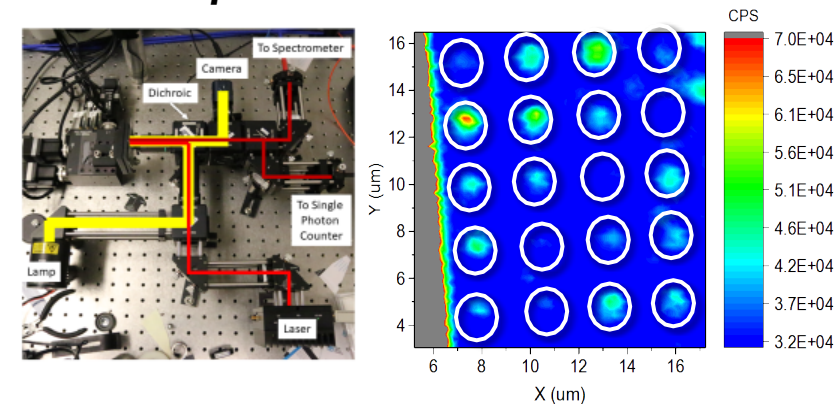
Design and layout of sample



FIB Implantation/Irradiation

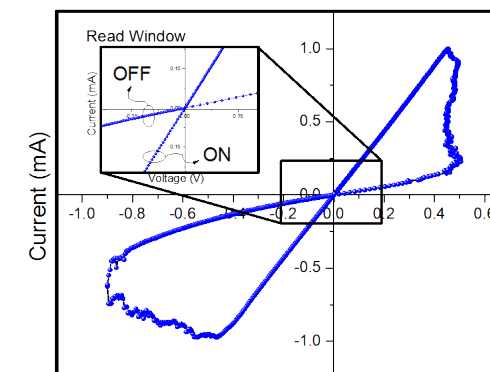


Post Implantation Characterization



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

Post Implantation Sample Prep



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

How can you access these capabilities? CINT User Proposals





THE CENTER FOR INTEGRATED NANOTECHNOLOGIES

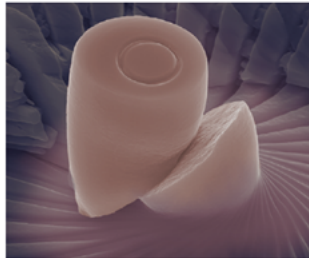


One Scientific Community Focused on Nanoscience Integration

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.

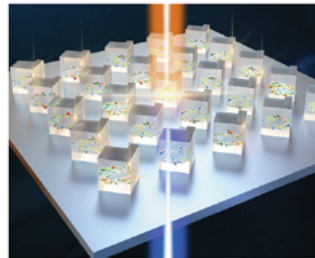
Science Thrusts

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.



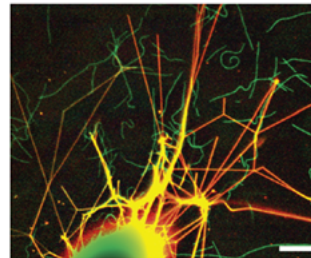
In-Situ Characterization and Nanomechanics

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



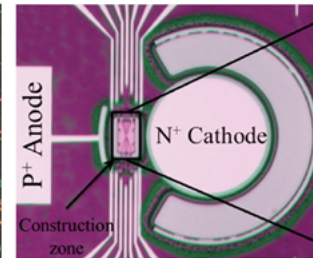
Nanophotonics & Optical Nanomaterials

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.

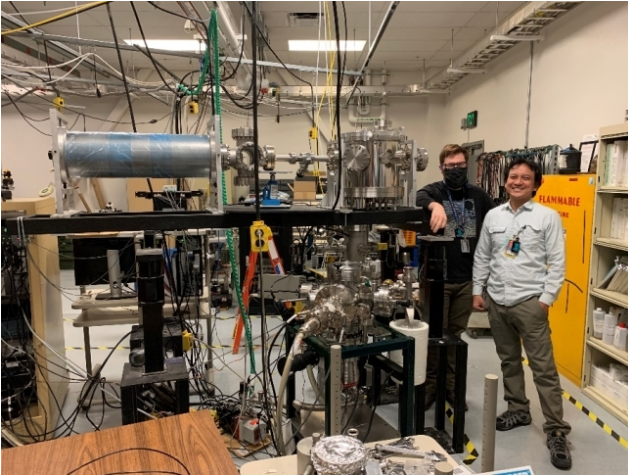
The Center for Integrated Nanotechnologies (CINT) has both regular Fall and Spring call for proposals and Rapid Access available

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

Capability Currently Under Development



Pulsed Power Electron Gun

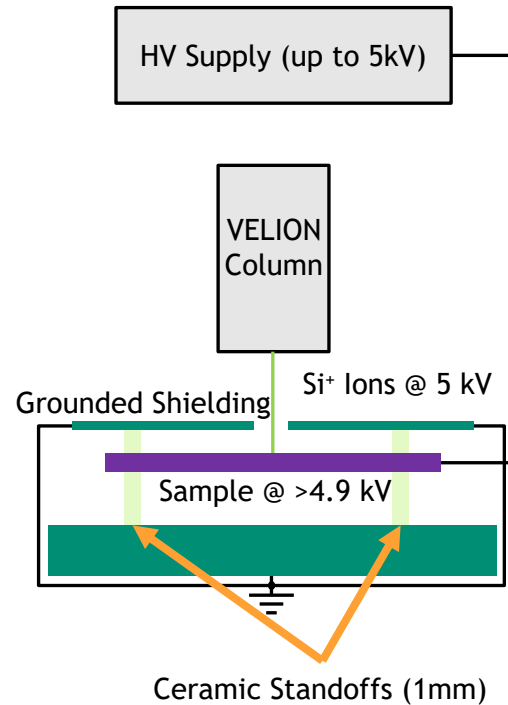


Specifications

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

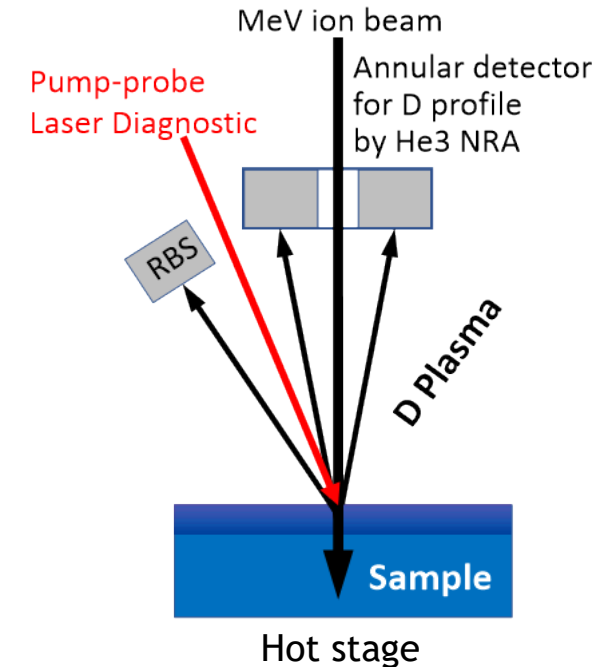
Enables improved yield for wide bandgap defect centers

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

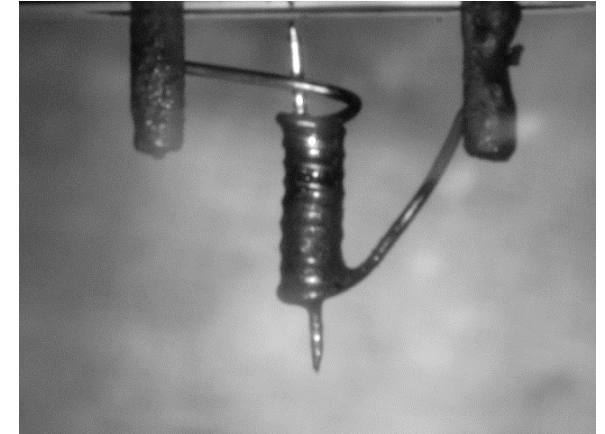
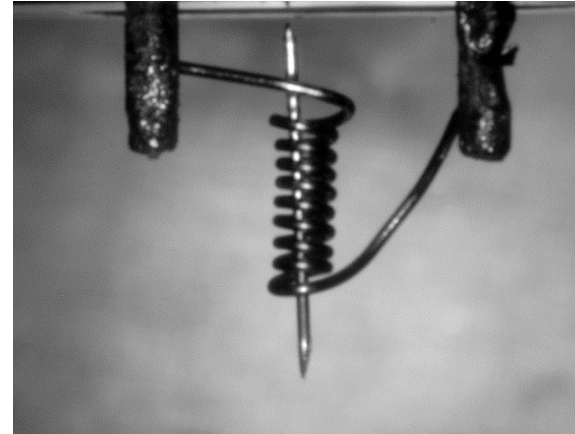
Pb Source based on SnPb alloy

- 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

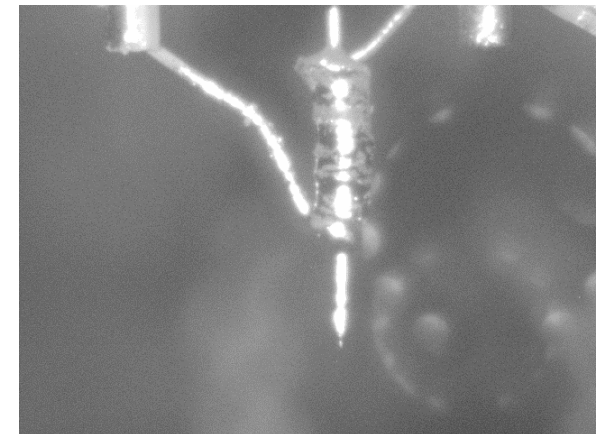
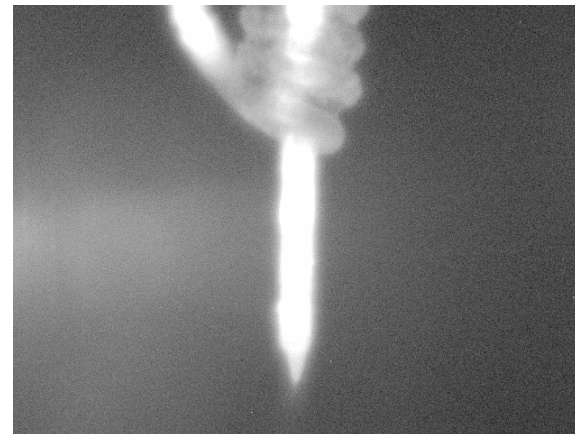
As tested in the Raith Velion these tips achieve lifetimes of $<2000 \mu\text{A}\cdot\text{hr}$ and spot sizes of <40

nm

Mechanically cut tips

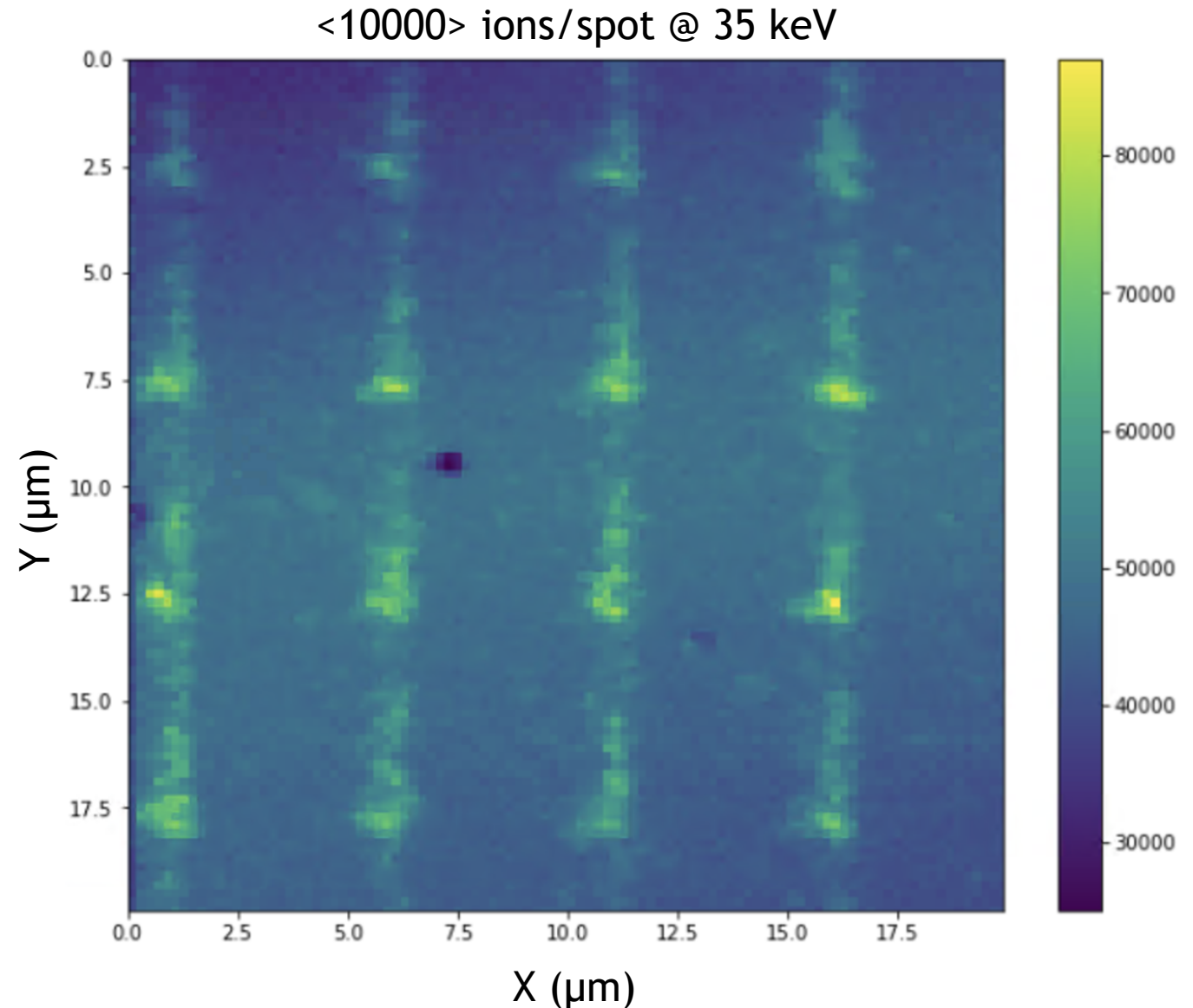


Electrochemically etched tips using Iron Chloride



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}Pb ($\approx 52\%$)
 - ^{206}Pb ($\approx 24\%$)
 - ^{207}Pb ($\approx 23\%$)
 - ^{204}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

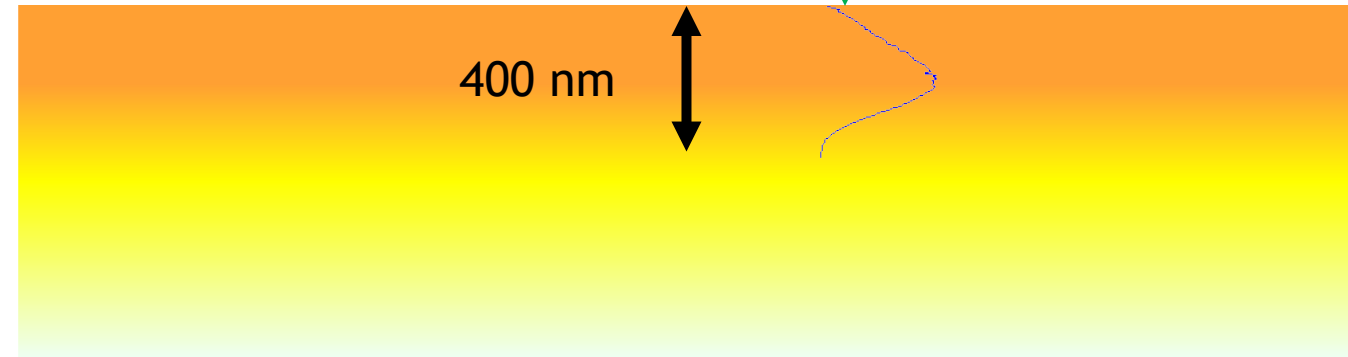
Need a low melting point (200-500C) alloy containing N, what to use?

Implantation

Implanted a 200 μm thick $\text{Au}_{80}\text{Sn}_{20}$ foil with Nitrogen to 5×10^{17} ions/cm²

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

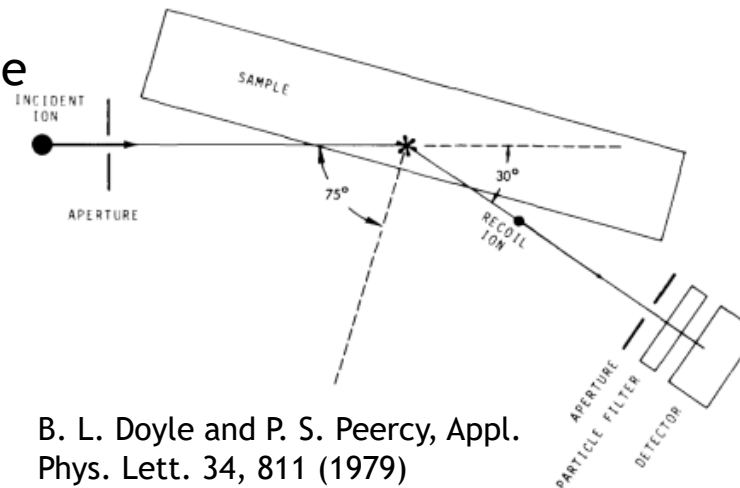
200 keV N⁺
Implantation



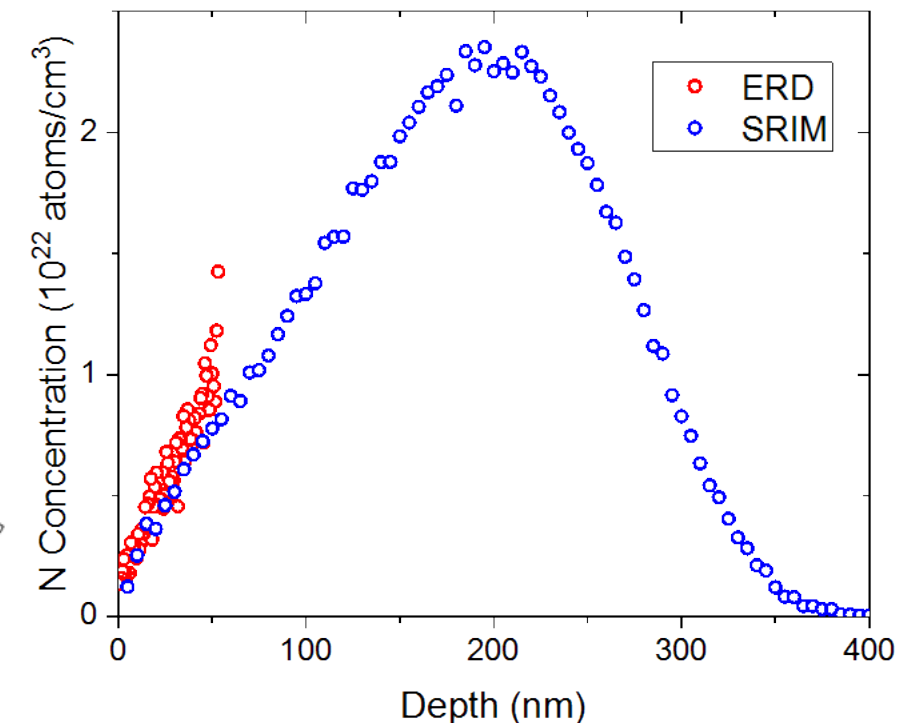
Characterization

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



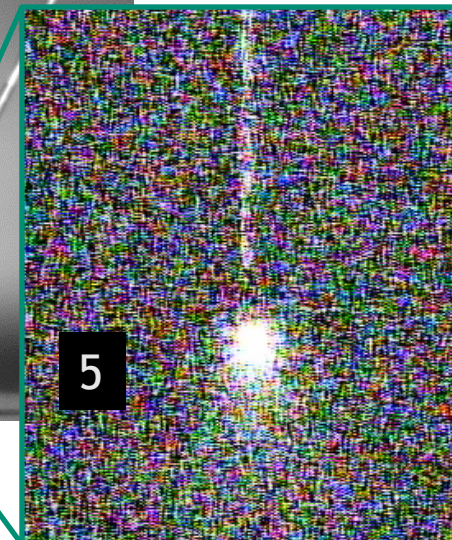
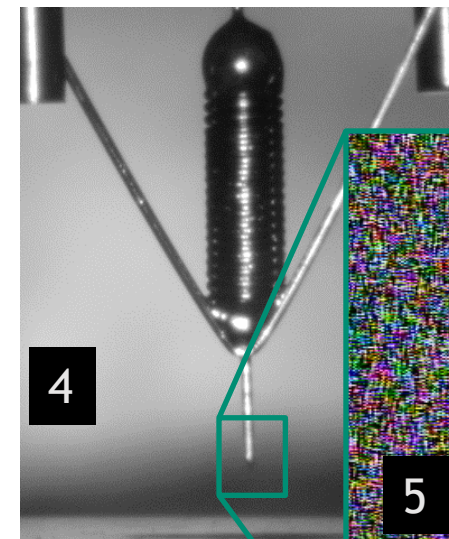
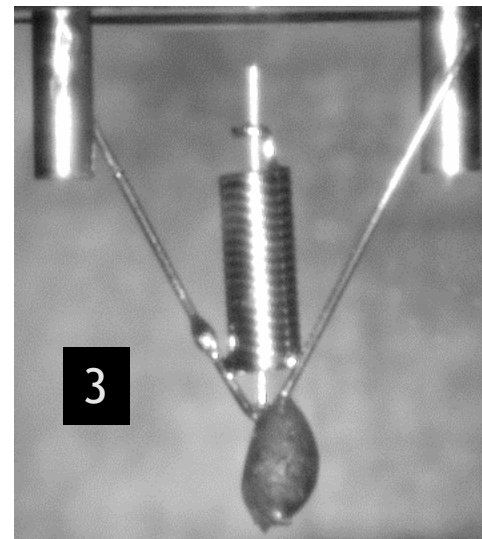
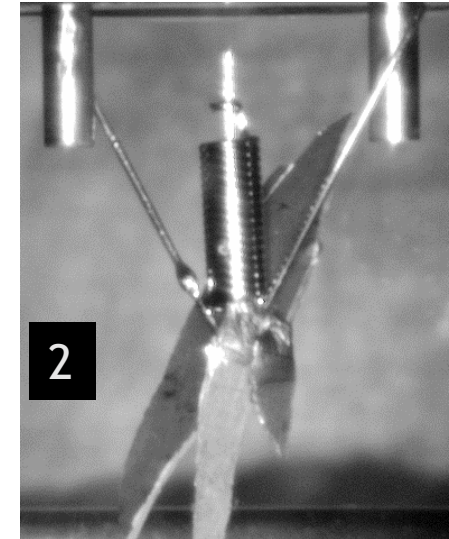
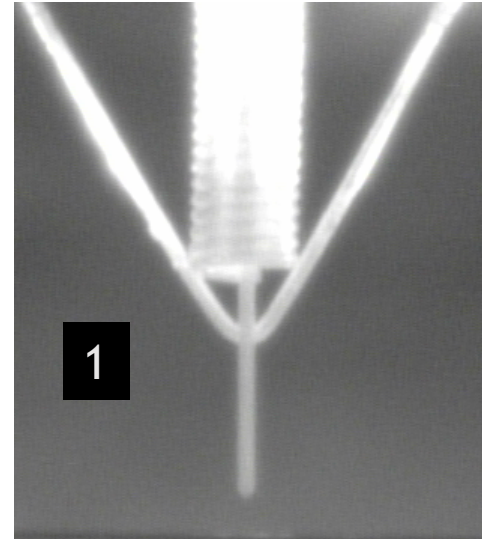
B. L. Doyle and P. S. Peercy, Appl. Phys. Lett. 34, 811 (1979)



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

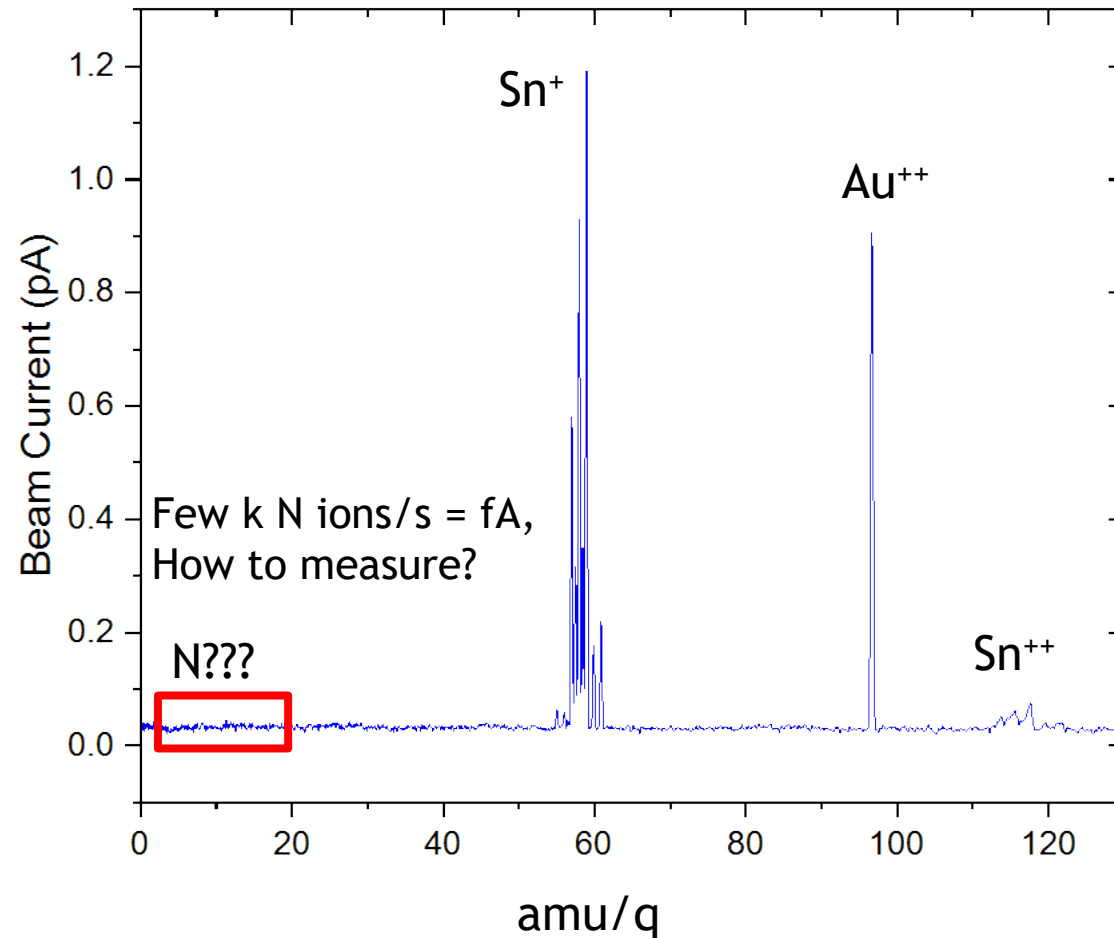
Tip fabrication from implanted AuSnN foil

- (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 nanoImplanter

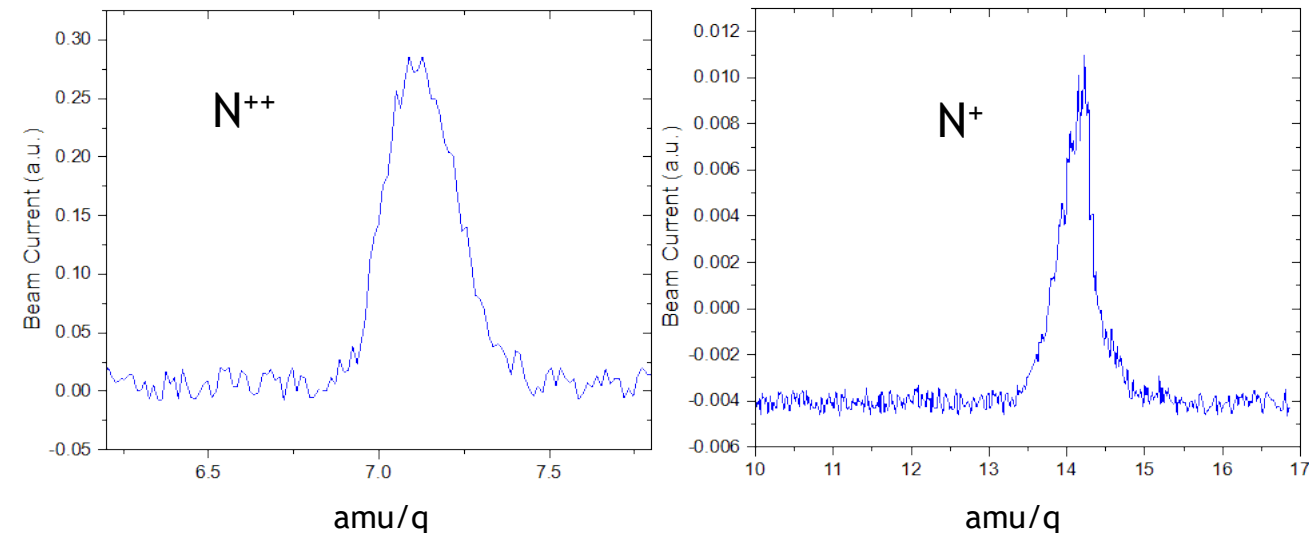
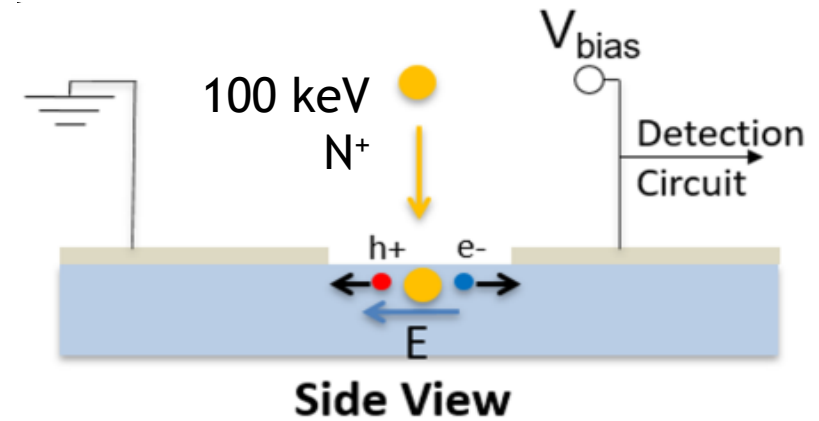


Very challenging source preparation! How well does the N LMAIS run?

N Source Characterization - Mass Spectrum via IBIC

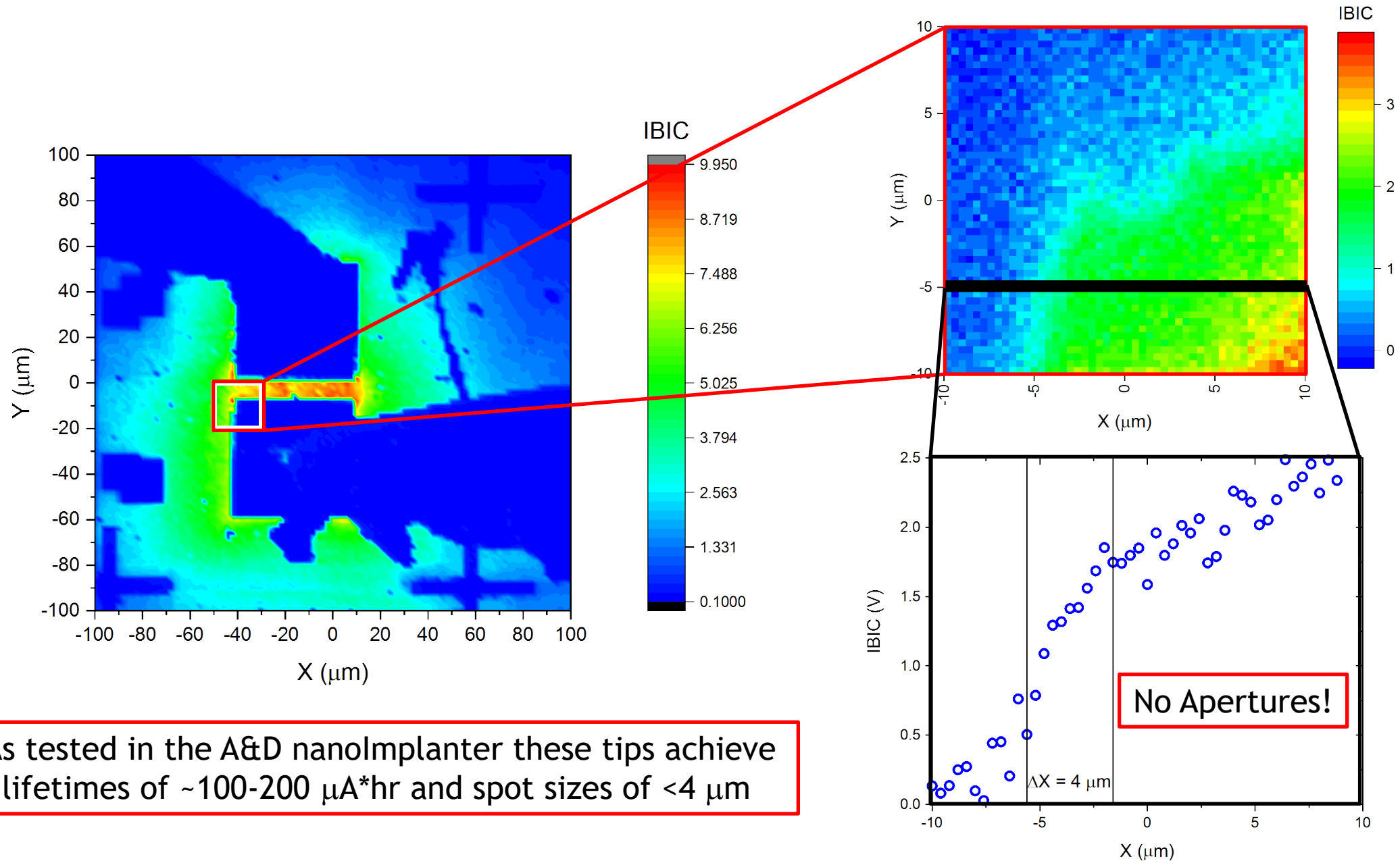


Ion Beam Induced Charge (IBIC) to measure N beam



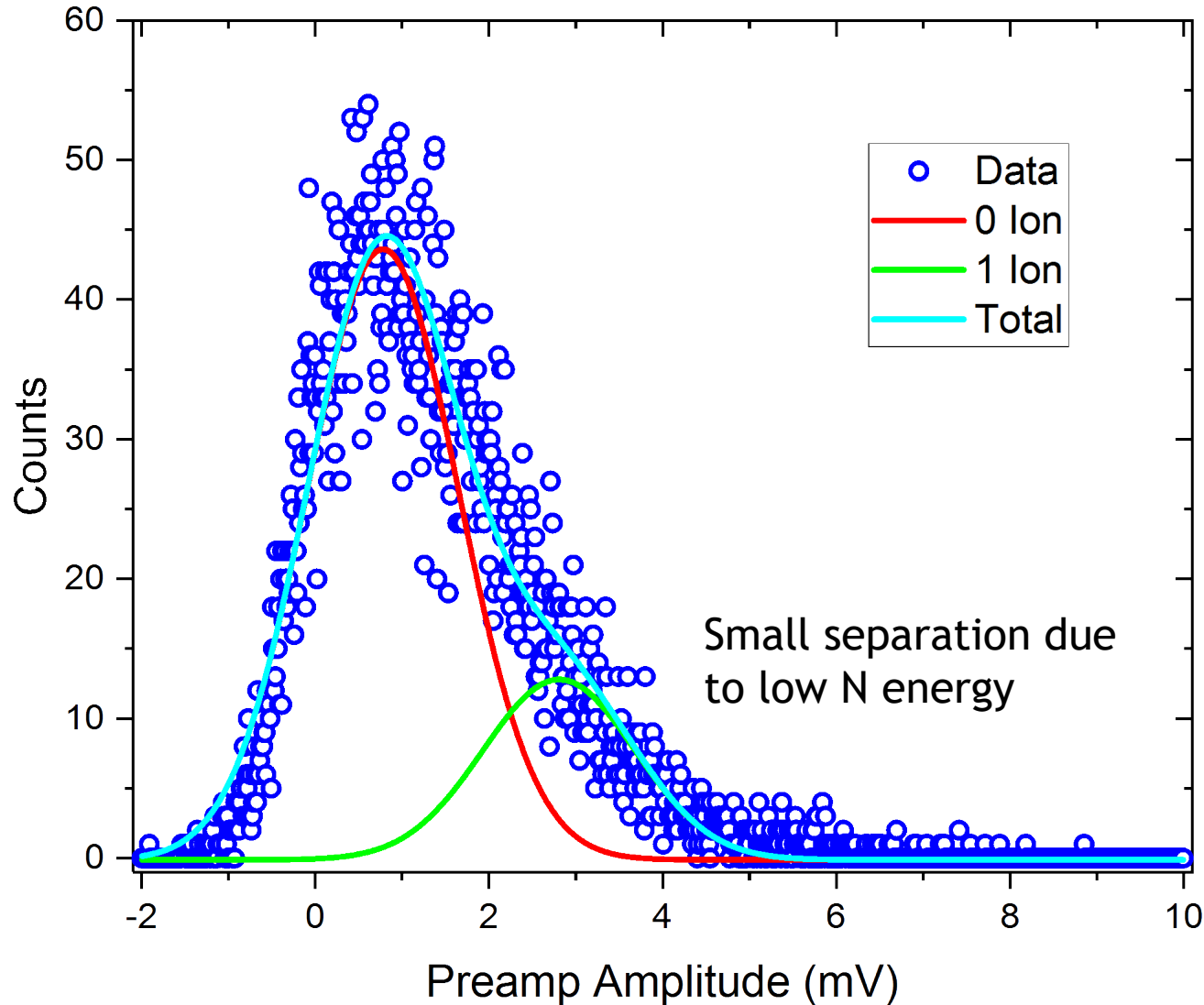
Observe Atomic nitrogen single and doubly charged ions in the source at ~20k ions/s

N Source Characterization - Spot Size via IBIC



As tested in the A&D nanoImplanter these tips achieve lifetimes of $\sim 100\text{-}200 \mu\text{A}\cdot\text{hr}$ 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

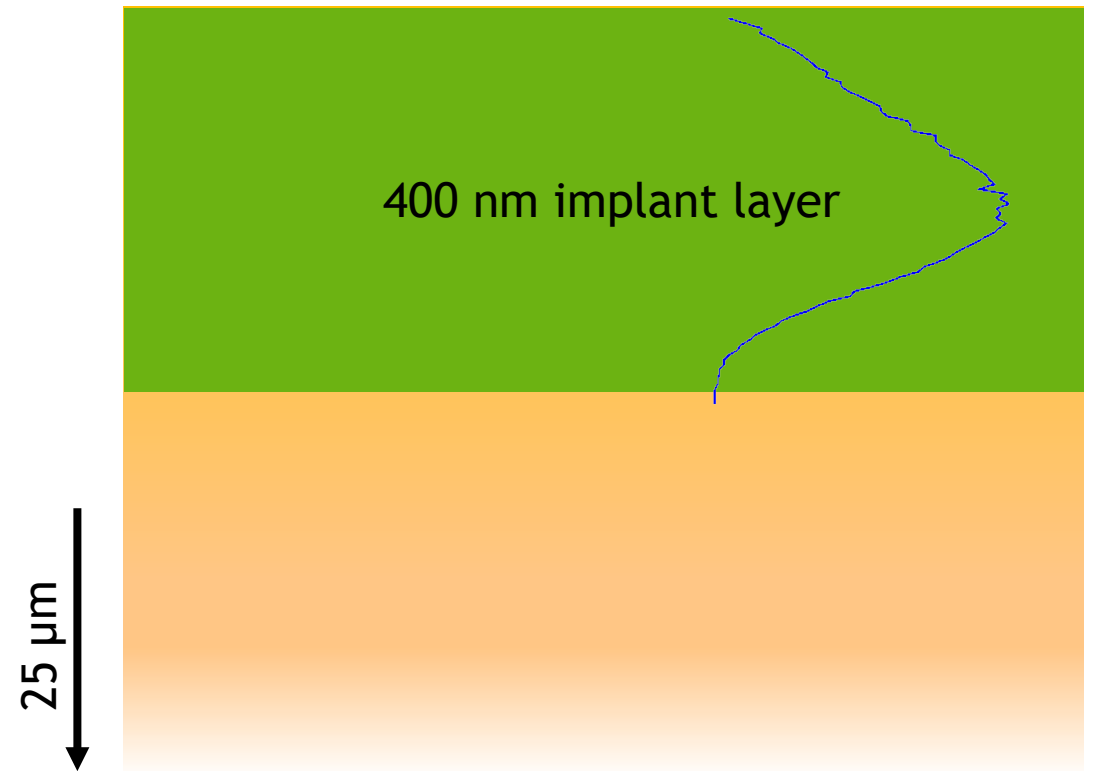
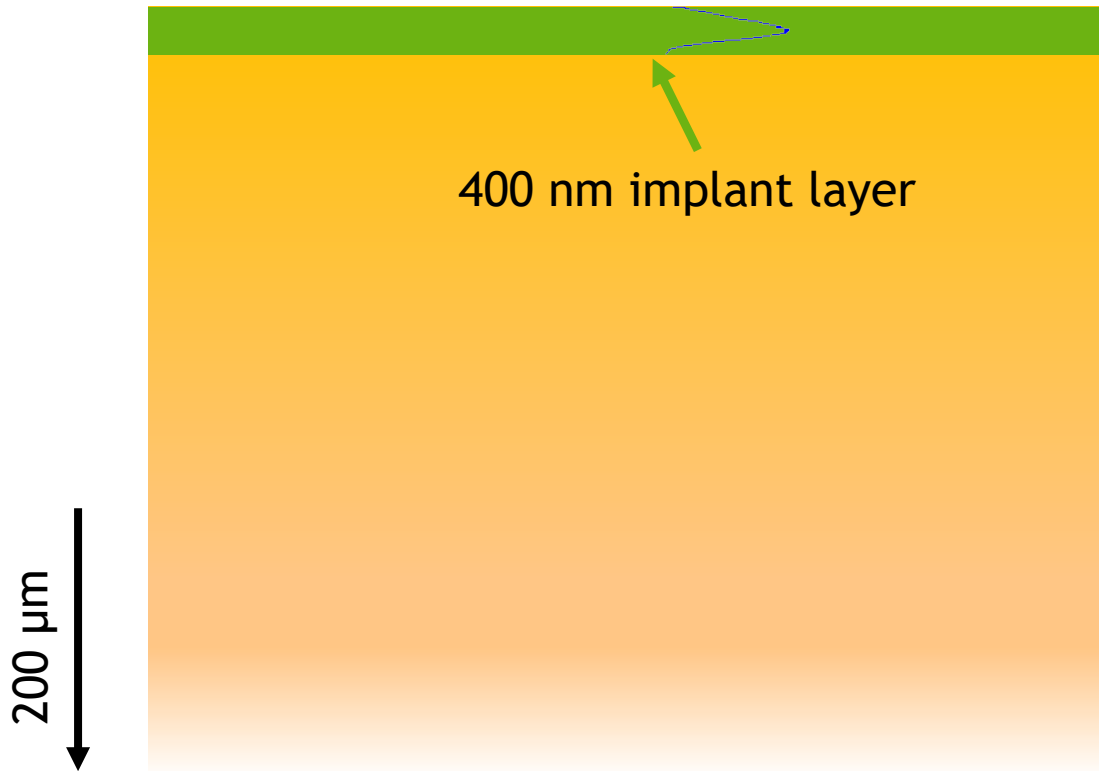
$\langle 1 \rangle$ ion every $50 \mu\text{s} \equiv 20 \text{ k ions/s}$

N Source – Improvements



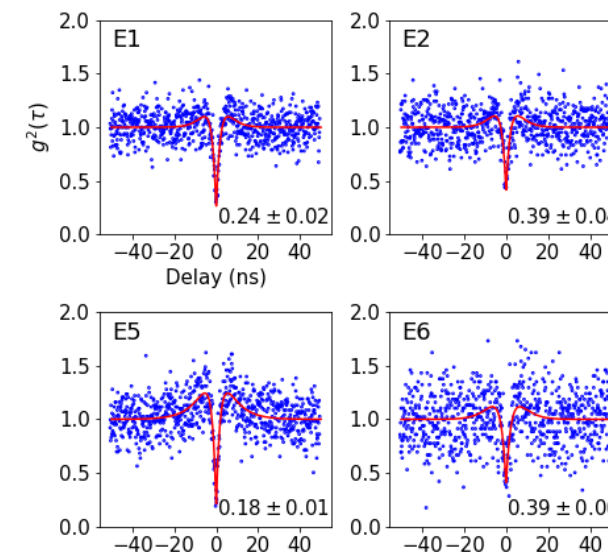
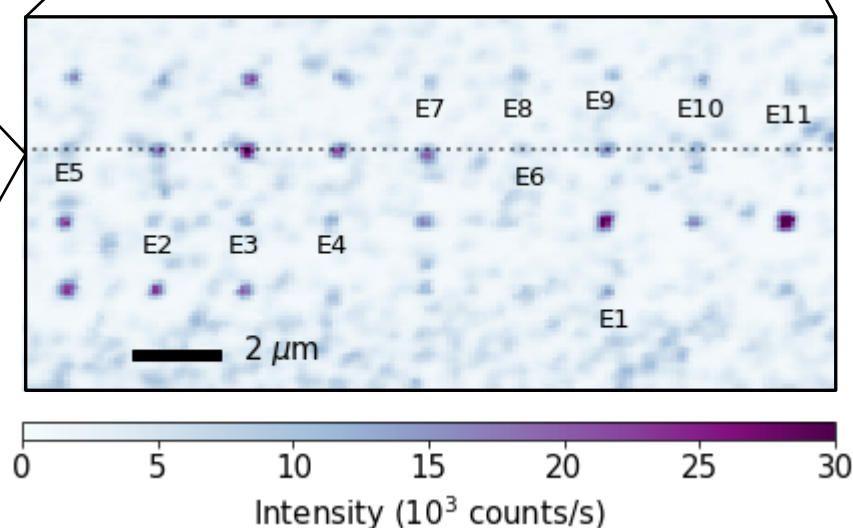
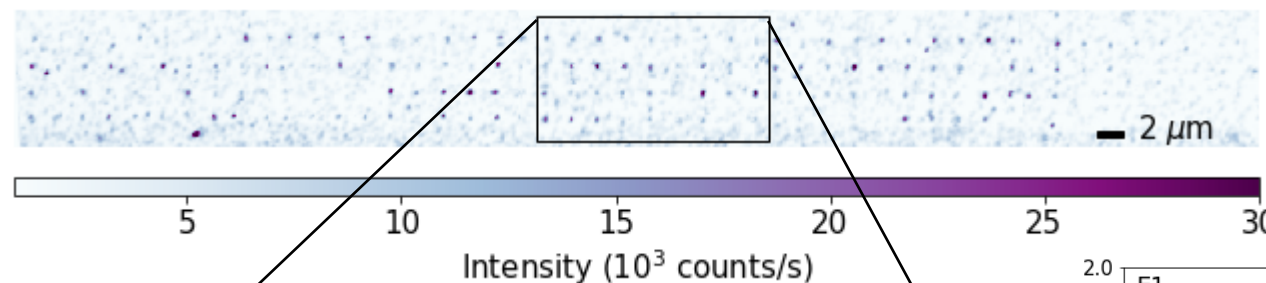
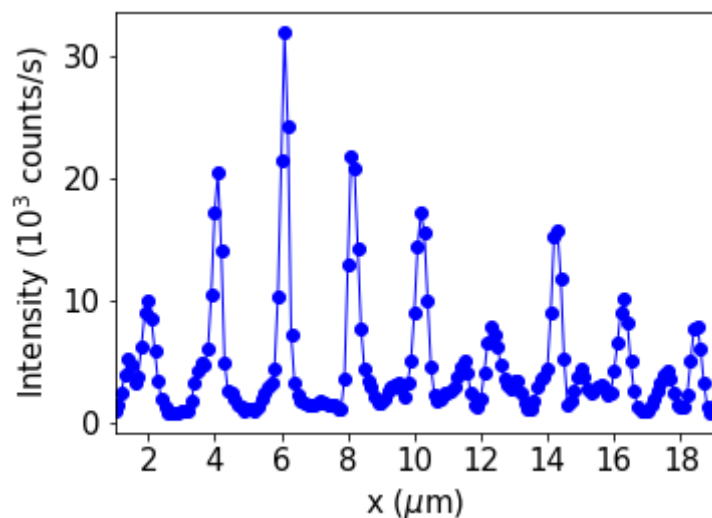
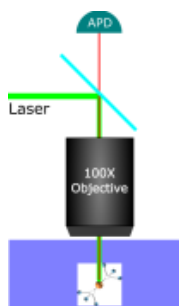
Higher beam current

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



Photoluminescence of the counted sample shows single defects

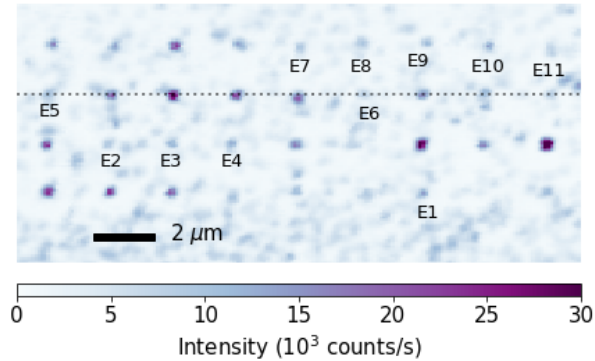
PL map of the counted ion sample



Heejun Byeon and
Andrew Mounce at CINT

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

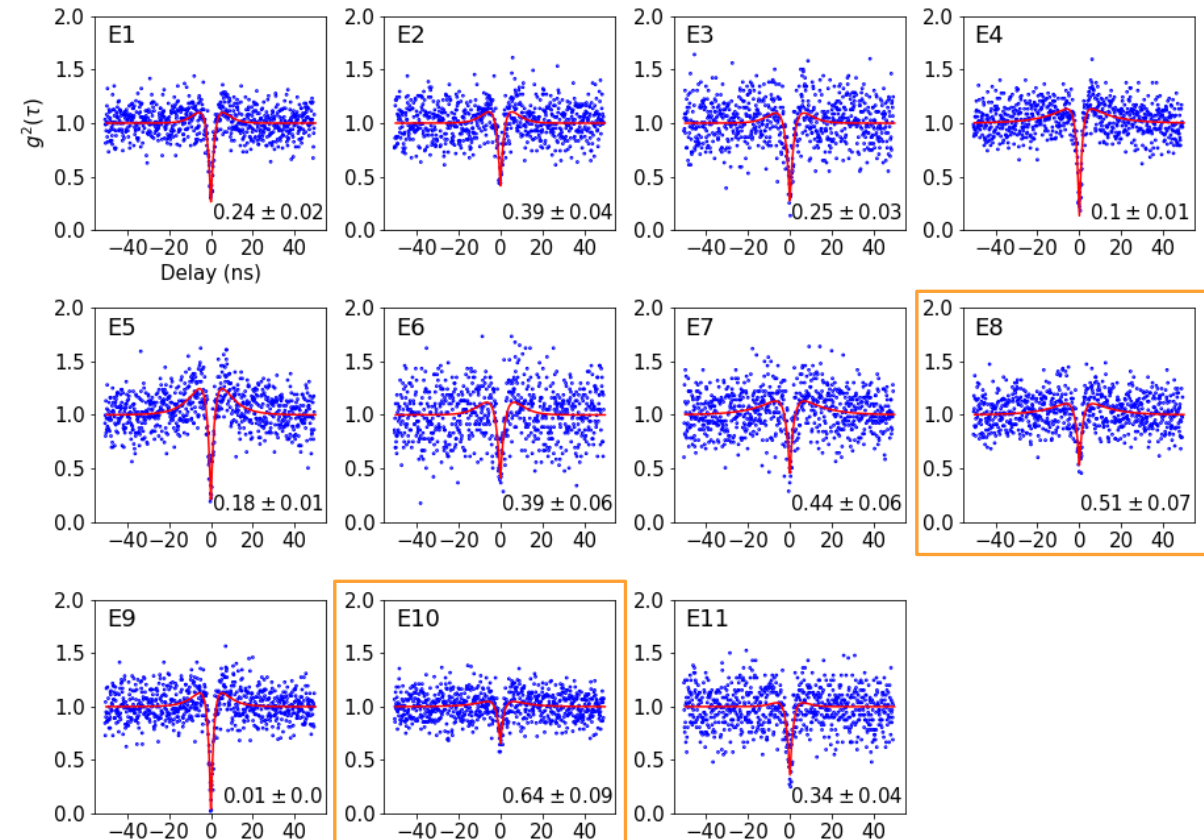
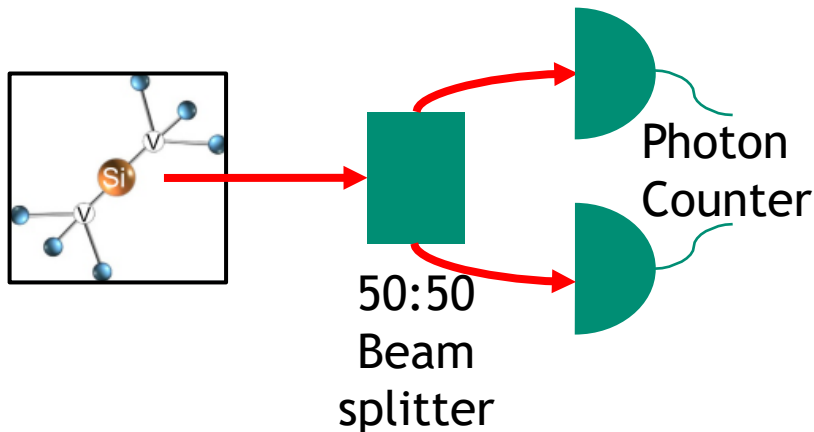
Hanbury-Brown-Twiss Interferometry



Single emitter will emit only 1 photon at a time

2nd order autocorrelation

Only 1 photon at each counter at any time



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

