SAND2018-10454C

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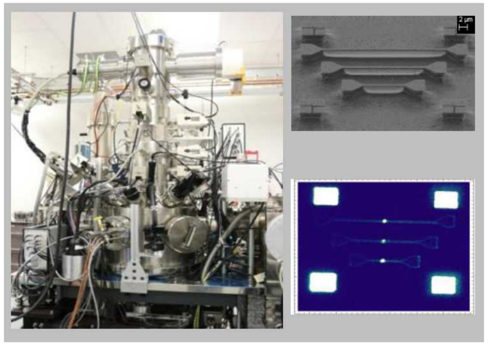

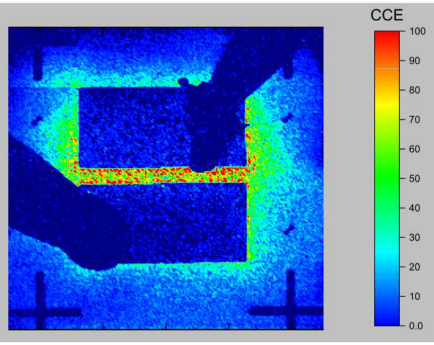

Overview of Techniques for Single Atom Implantation

Edward Bielejec

Sandia National Laboratories, Albuquerque, NM 87185

QIST Quantum Information S&T

Center for Integrated Nanotechnologies CINT

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration   LDRD Laboratory Directed Research & Development

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Implantation Depth and Lateral Resolution

(1) Where do we need the atom to be located?

(2) With what resolution do we care about the placement?

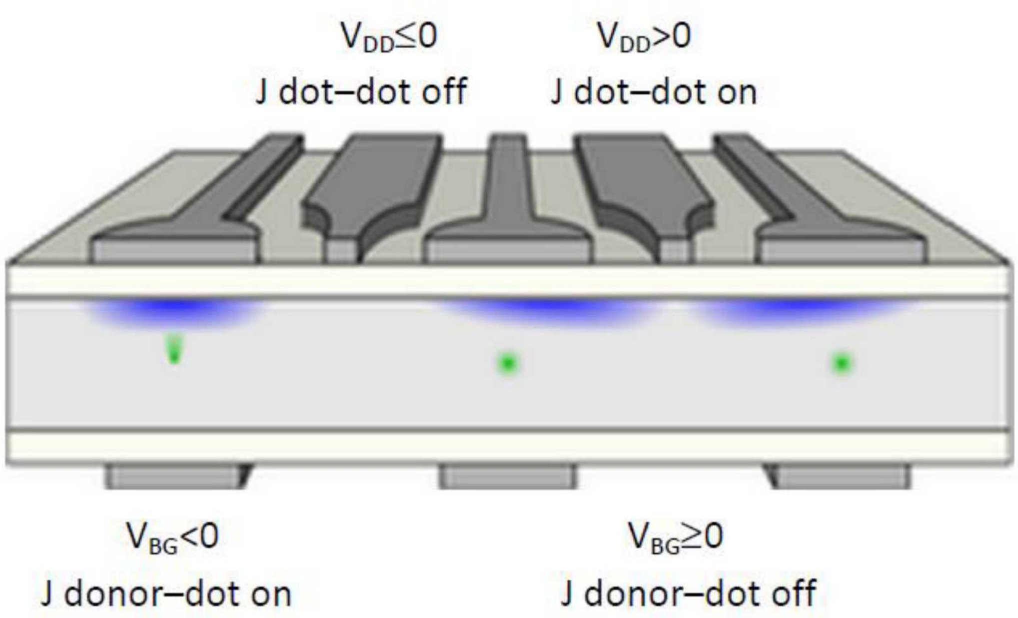
(3) What error bar is acceptable?

(4) How do we create a deterministic single atom device?

Example of Needed Resolution – Si Qubit

Example Architecture: **A spin quantum bit architecture with coupled donors and quantum dots in silicon**

T. Schenkel[1], C. C. Lo[1], C. D. Weis[1], J. Bokor[2], A. M. Tyryshkin[3], and S. A. Lyon[3]
[1]Ion Beam Technology Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[2]Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA
[3]Electrical Engineering Department, Princeton University, Princeton, NJ, USA
Contact-email: T_Schenkel@LBL.gov
(October 10, 2011)



(1) Accumulation mode device

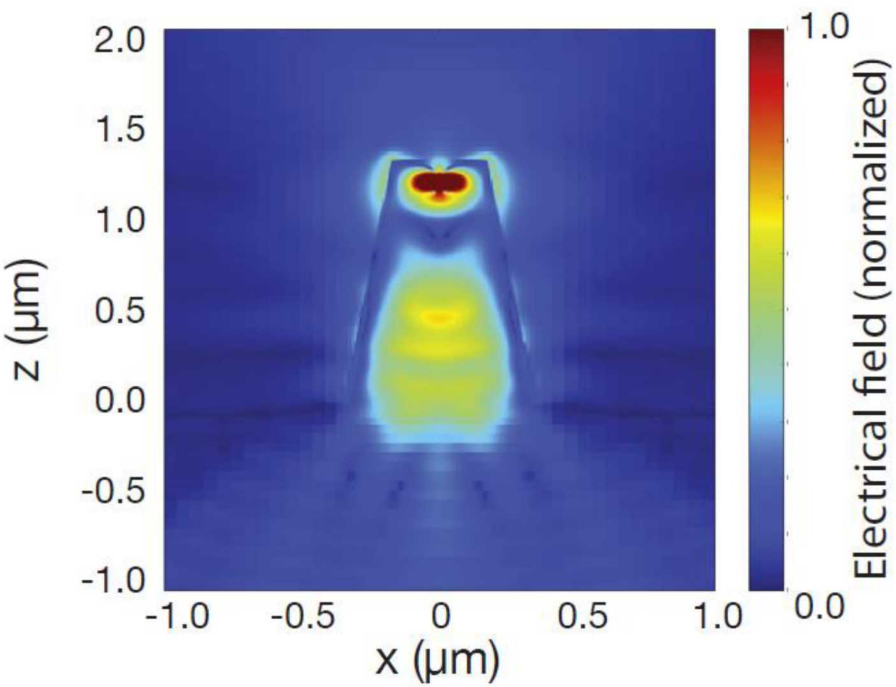
(2) Apply positive gate voltage to pull carriers into the channel

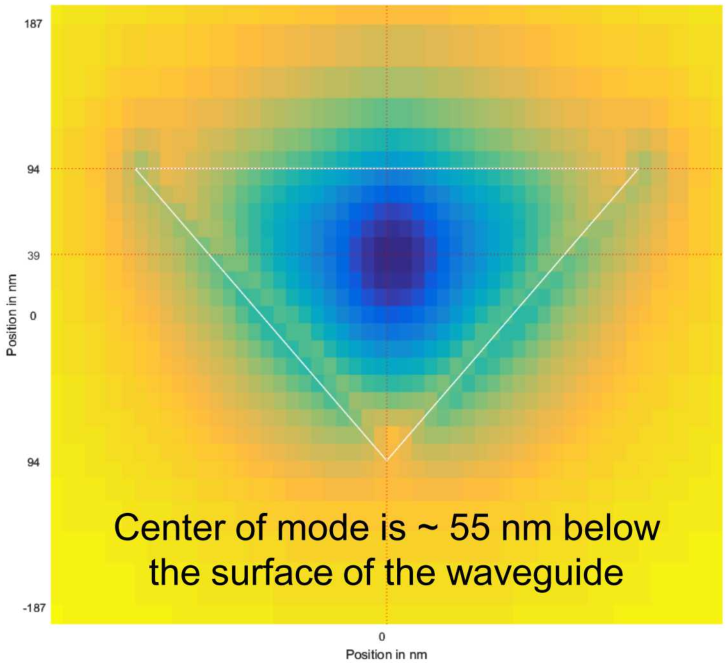
(3) Apply negative gate voltage to electrostatically define quantum dots

(4) Use a back gate to control coupling between the donor and the dot

Requires 10's of nm control of the donor location

Example of Needed Resolution - Nanophotonics





L. Marseglia *et al.*, Optics Express **26**, 80-89 (2018)

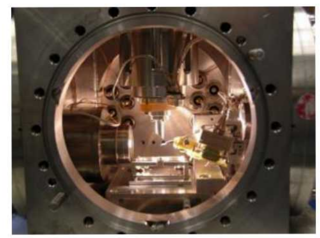
Requires 100's of nm control of the donor location

Overview of High Resolution Implantation

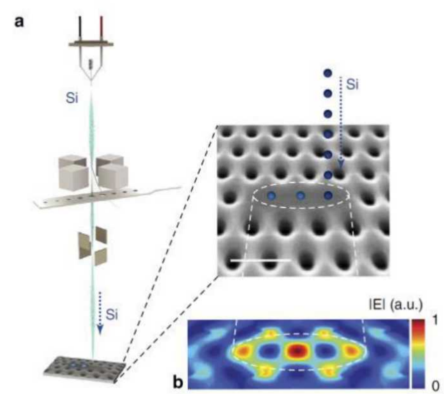
Resolution

(1) Hydrogen Lithography

(2) Probe Based Implantation



(3) Focused Ion Beam Implantation

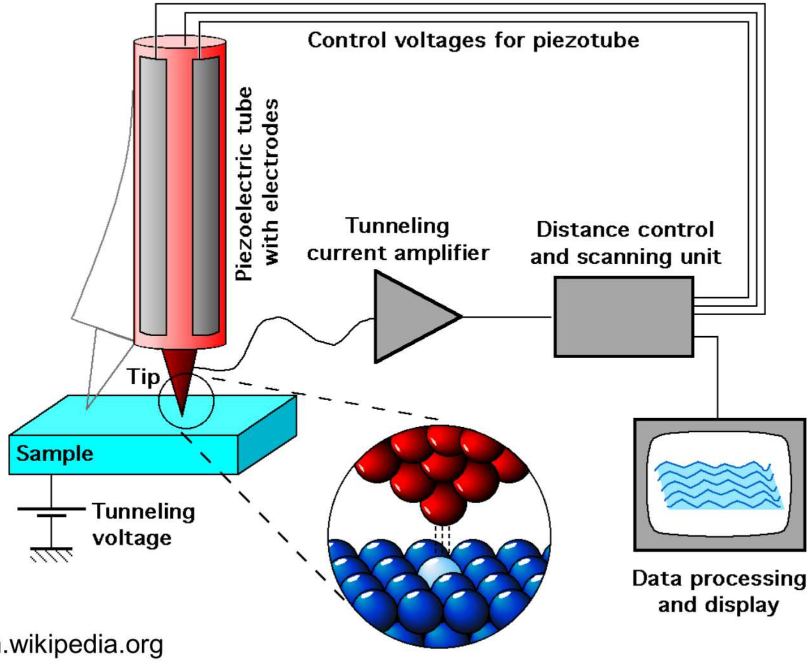


(4) Masked Implantation

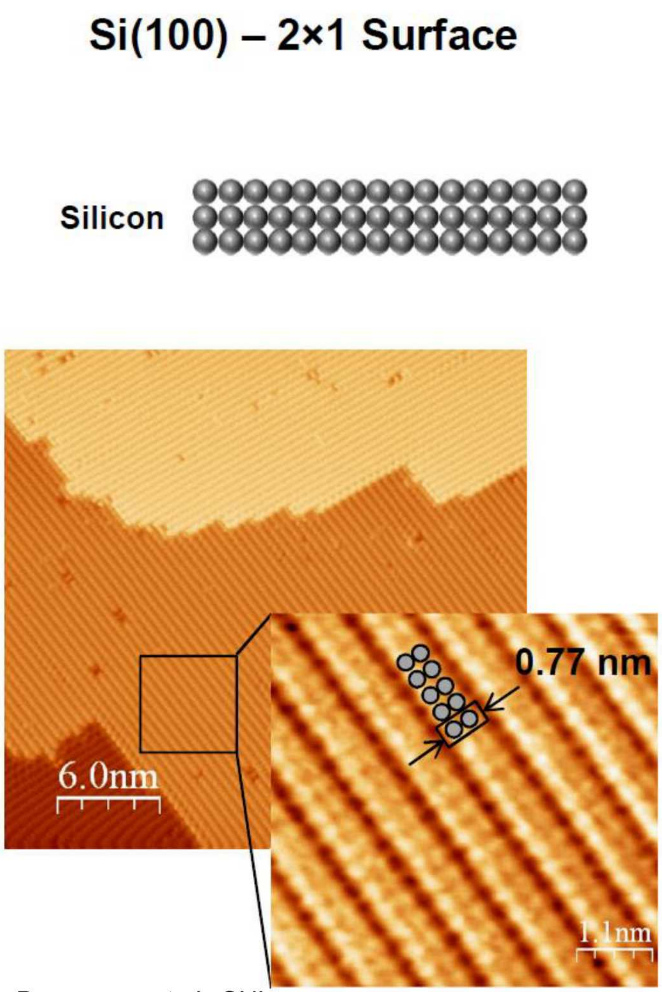
Speed

Hydrogen Lithography

Quick Introduction to Scanning Tunneling Microscopy (STM)

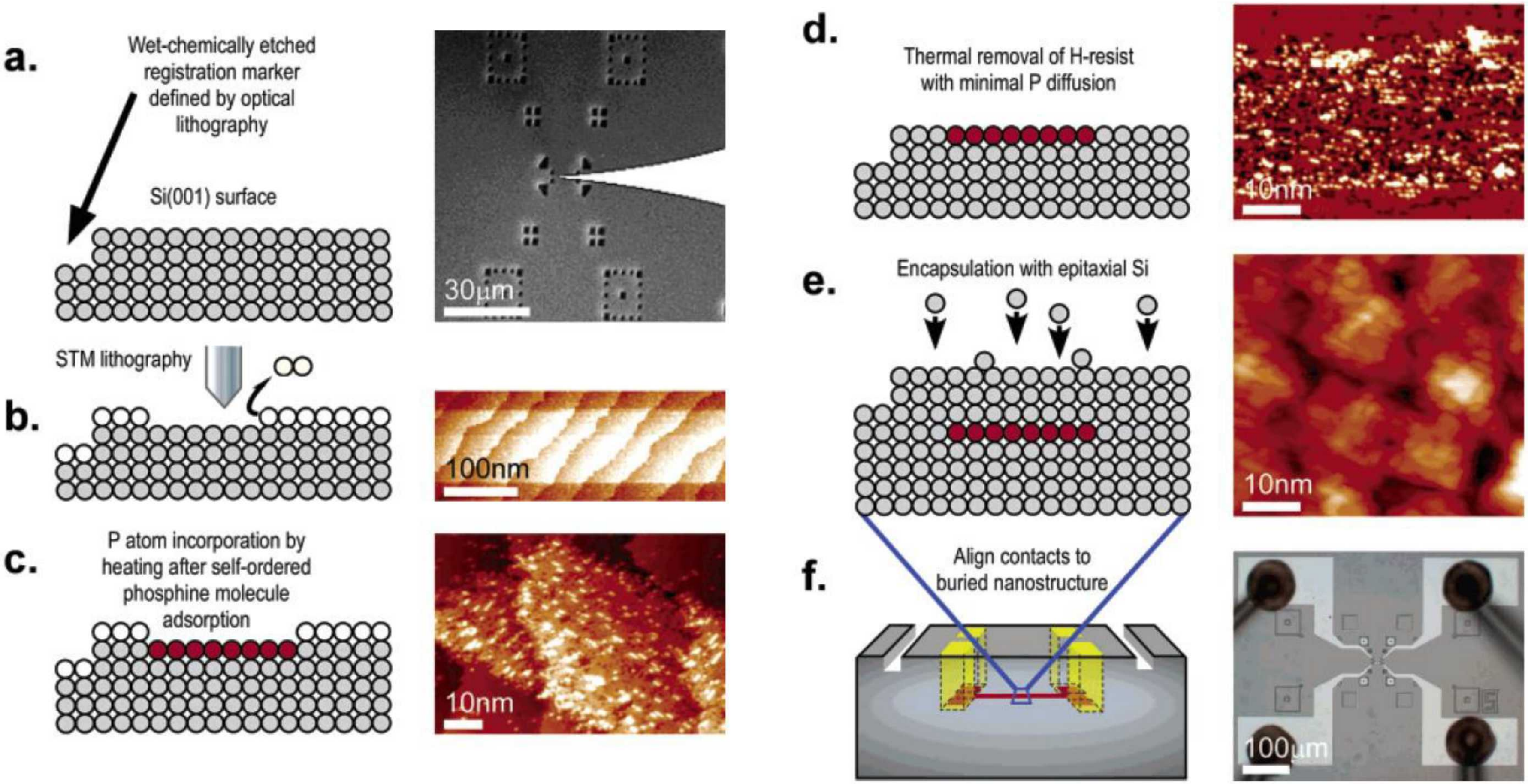


en.wikipedia.org



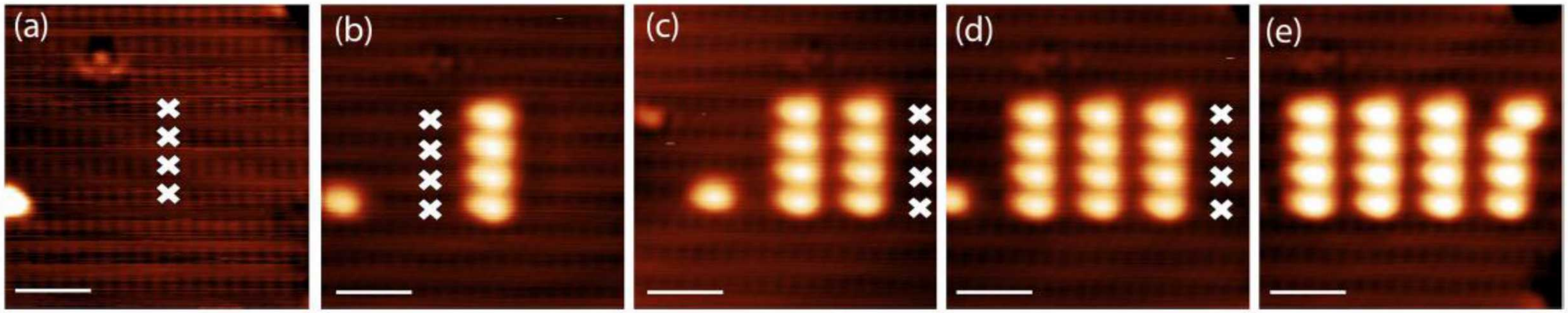
Bussmann *et al.*, SNL

Hydrogen Lithography Overview



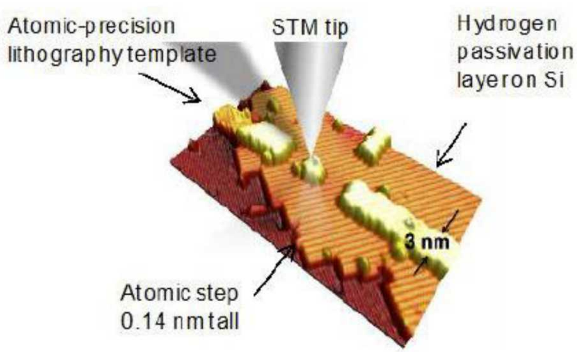
F. J. Ruess *et al*., Nano Lett. **4**, 1969-1973 (2004)

Hydrogen Lithography Resolution



M. Moller *et al.*, Nanotechnology **28**, 075302 (2017)

But, this requires a UHV STM



E. Bussmann, CINT SNL https://cint.lanl.gov/

Hydrogen Lithography Limitations

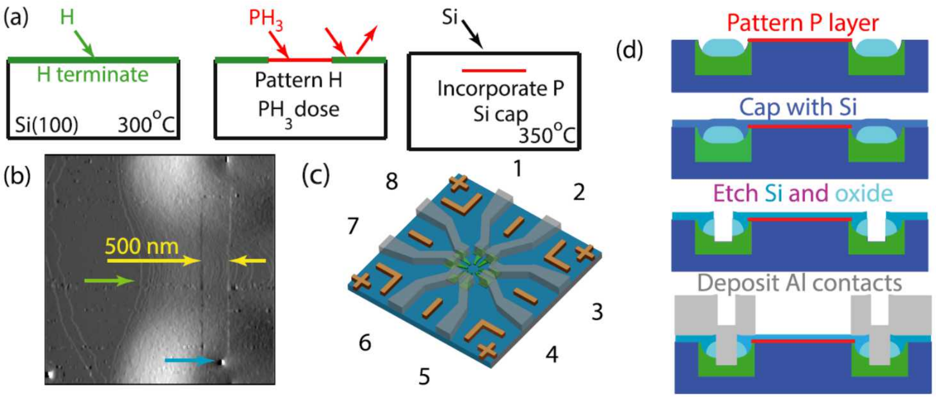
(1) Speed, yield and UHV

Scale resolution → slow

Field emission → trade off resolution for speed

M. Rudolph *et al.*, Appl. Phys. Lett. **105**, 163110 (2014)

(2) Atomic Scale → how to contact to outside world?



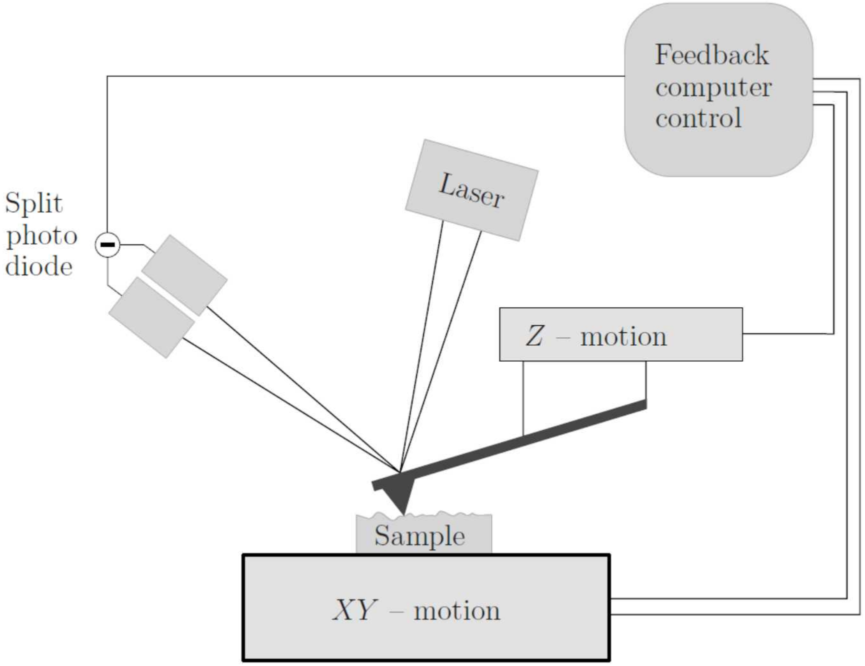
D. R. Ward *et al.*, Appl. Phys. Lett. **111**, 193101 (2017)

(3) Ion Species and Substrates

Limited resists, limited ion species, limited substrate choice

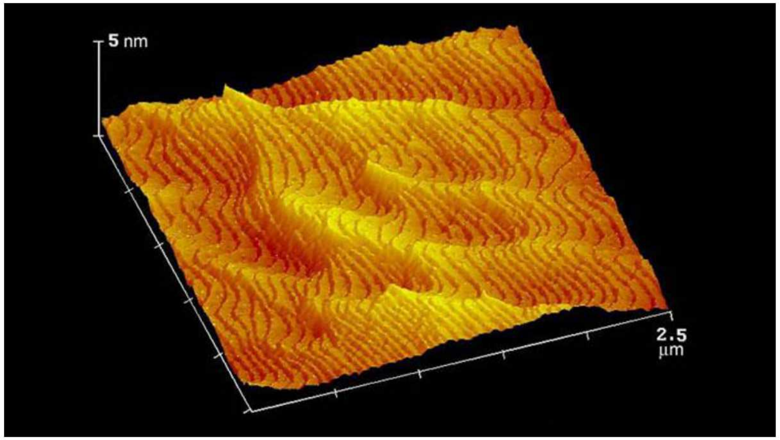
Probe Based Implantation Overview

Quick Introduction to Atomic Force Microscopy (AFM)



Aligned Ion Implantation using Scanning Probe by A. Persaud Thesis

Atomic Steps on sputter Palladium



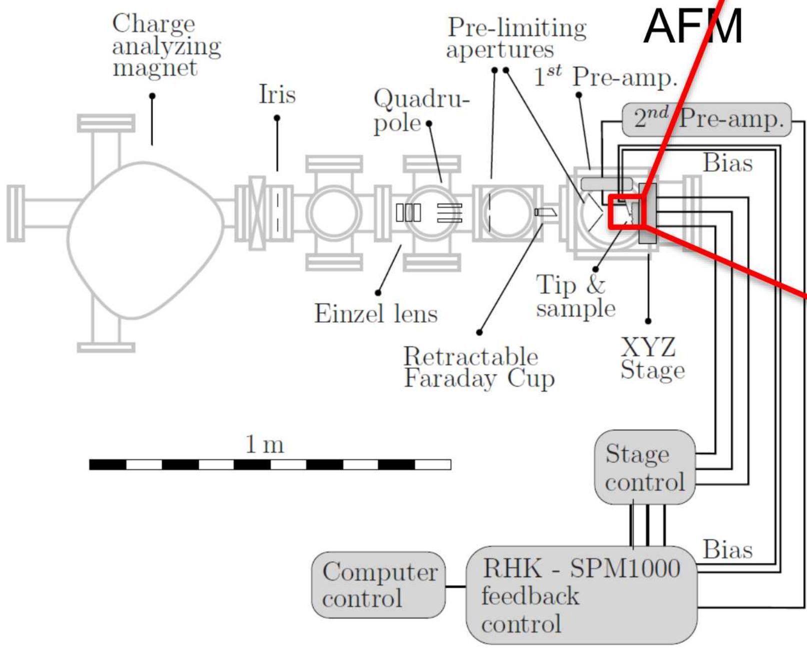
https://www.nanoandmore.com/afm-gallery#&gid=1&pid=49

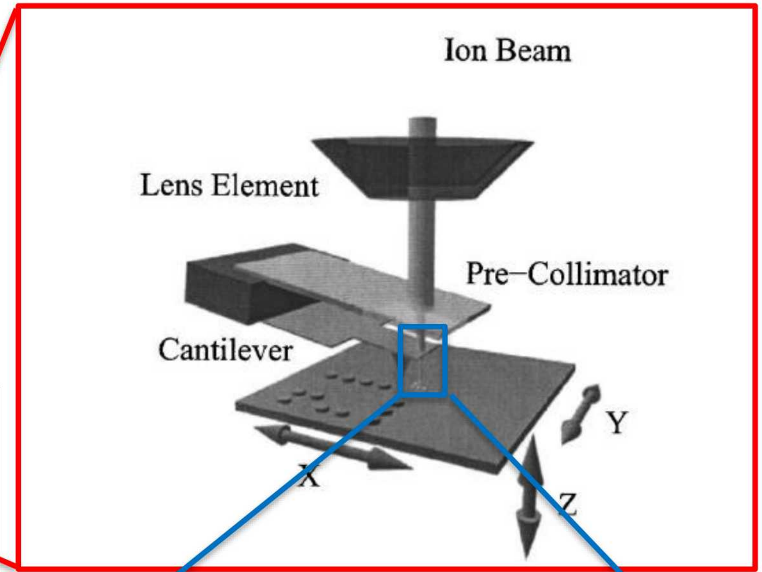
Probe Based Implantation

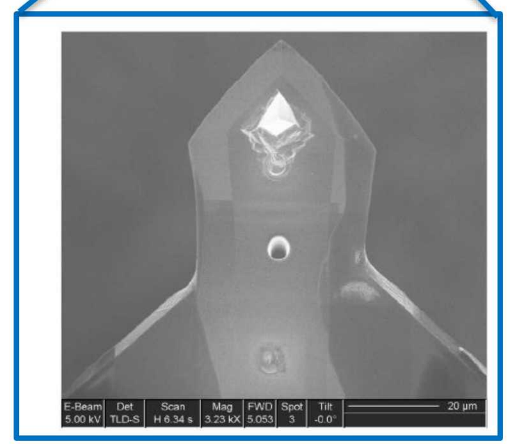
Beamline

AFM

Ion Accelerator



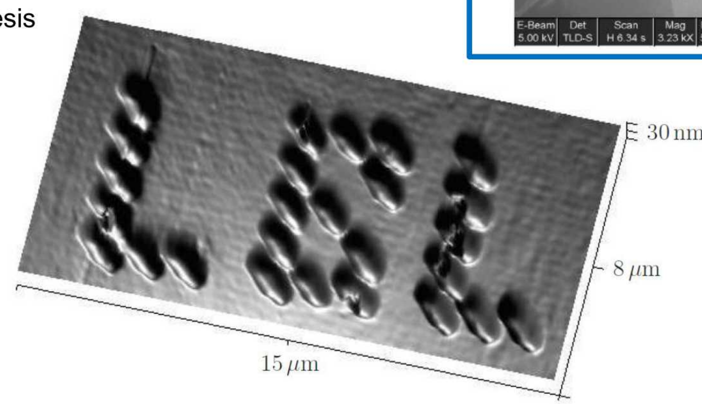




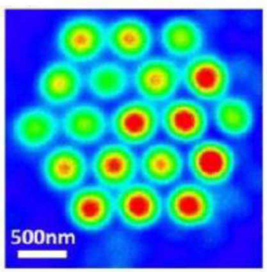
Aligned Ion Implantation using Scanning Probe by A. Persaud Thesis

Similar setups:

- J. Meijer's group at Leipzig
- I. Rangelow's group
- D. Jamieson's group at Melbourne



NV centre



T. Luhmann *et al.*, Accepted into J. of Phys. D

Probe Based Implantation Limitations

(1) Speed

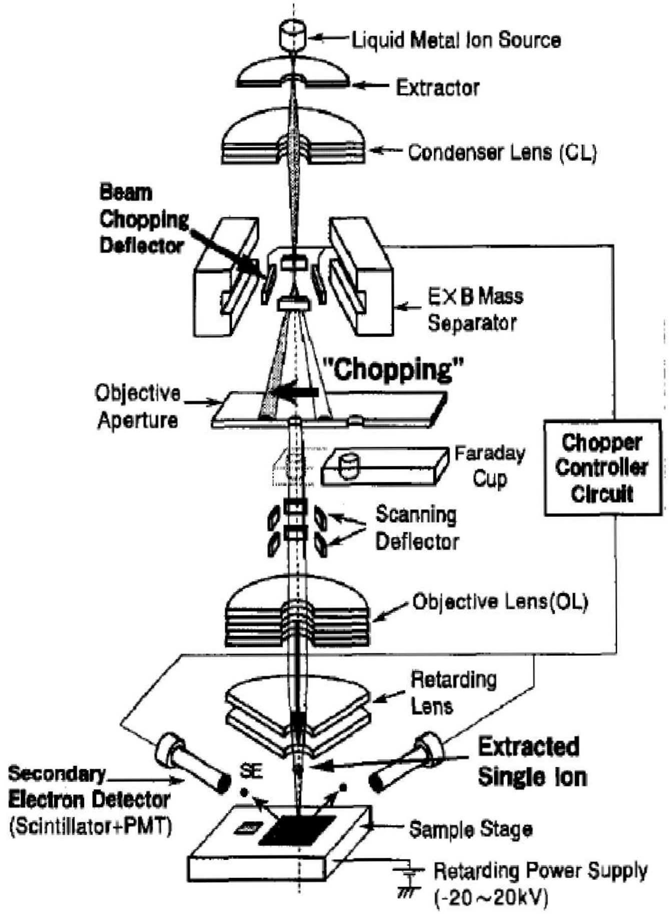
Probe system

(2) Resolution

FIB milling of the cantilever tip to produce a mask

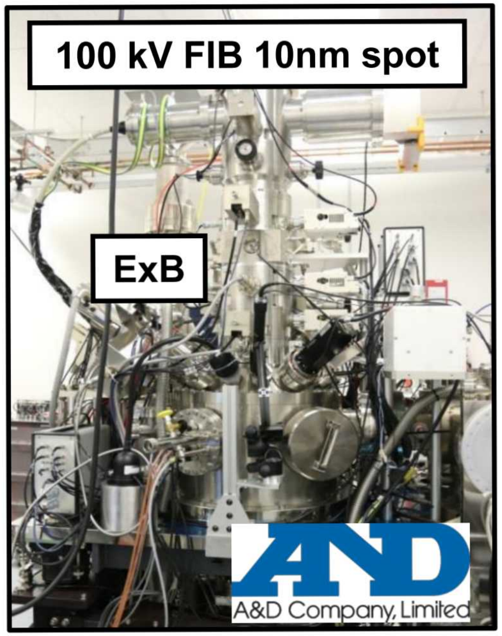
Slit scattering off the aperture

Focused Ion Beam Implantation



M. Hori, *et al.*, Applied Physics Express **4**, 046501 (2011)

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

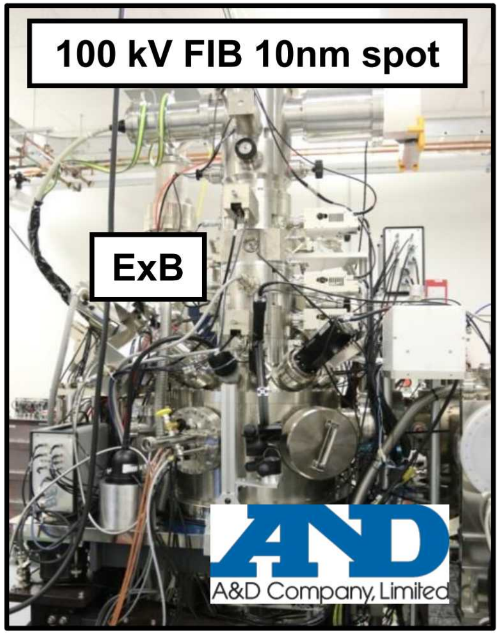


Microbeam Nano Fab 150 Machine

Orsay Cobra ExB

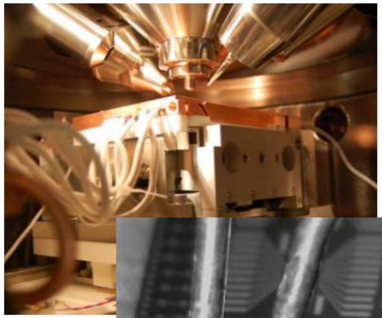
Raith Velion

SNL nanoImplanter (nI)

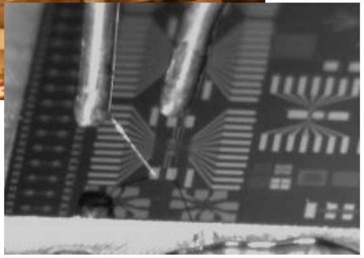


- Focused ion beam system (FIB)
  - →nm beam spot size on target
- ExB Filter (Wien Filter)
  - →Multiple ion species
    - → Li, Si, P, Sb, etc… (separating out ^{28}Si, ^{29}Si, etc…)
- Fast blanking and chopping
  - →Single ion implantation
- Direct-write lithography
  - →nm targeting accuracy

RAITH NANOFABRICATION

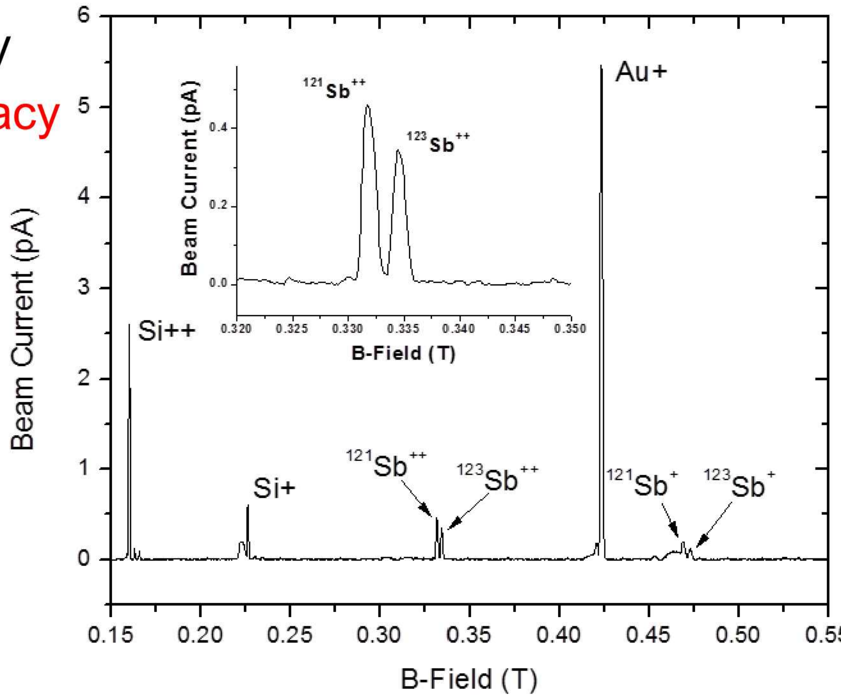


- Low temperature stage



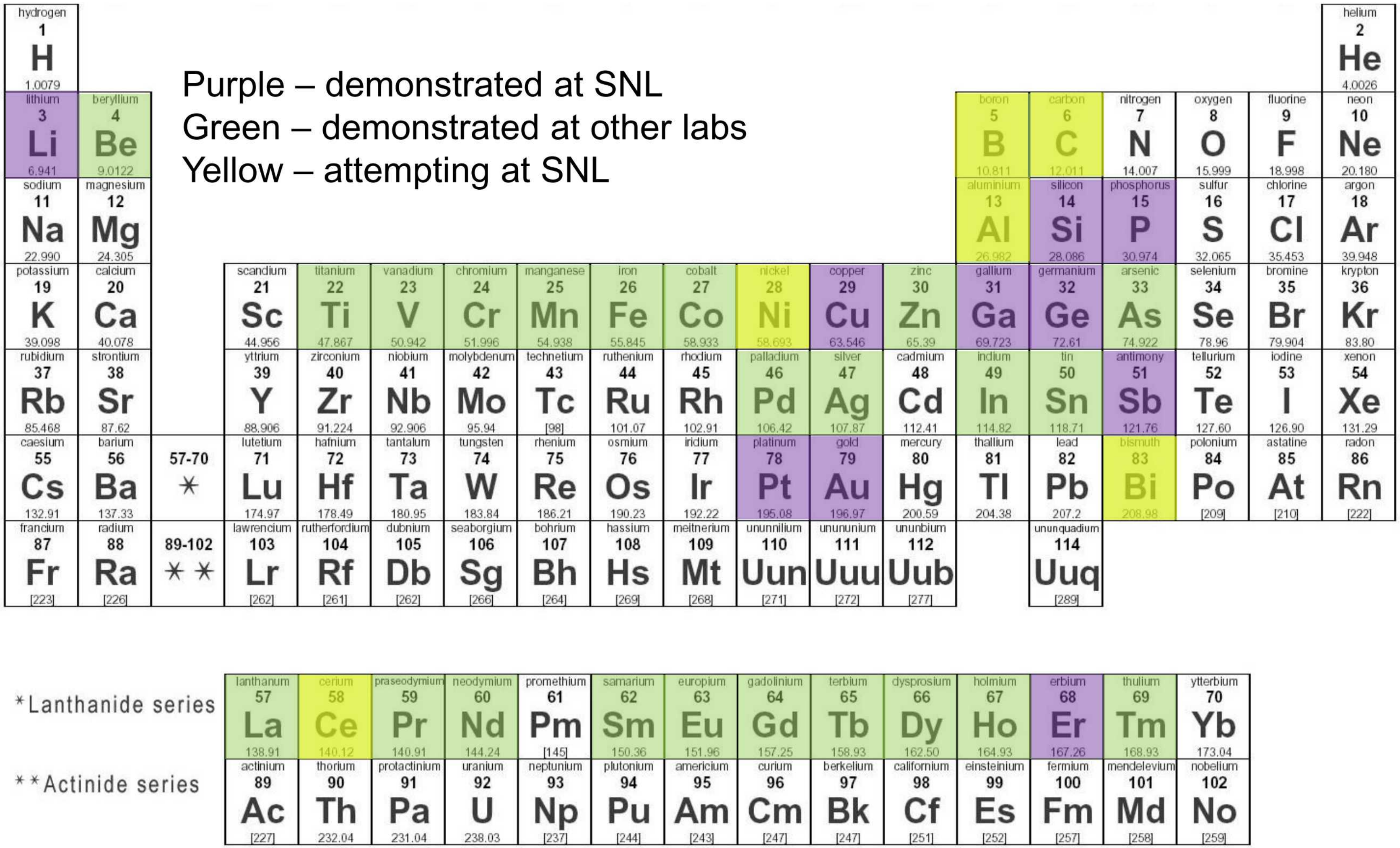
- In-situ electrical probes

Sb Source: Mass Spectrum



SNL nanoImplanter (nI) - Sources

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

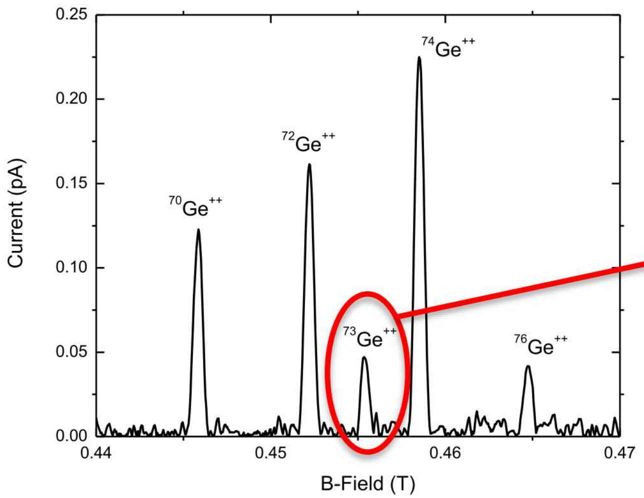


After A. Weick University of Bochum

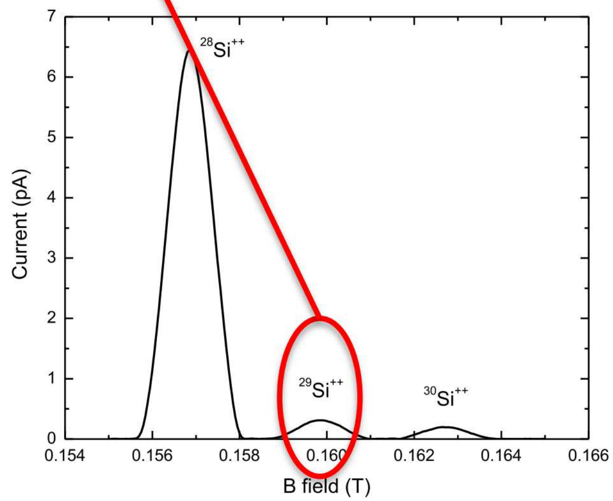
L. Bischoff, *et al*., Applied Physics Reviews **3**, 021101 (2016)

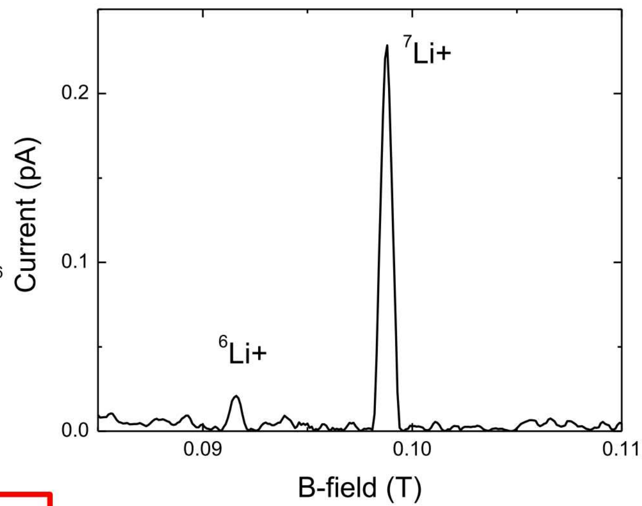
Wide Varity of Ion Species Available

SNL nanoImplanter (nI) – Mass Resolution



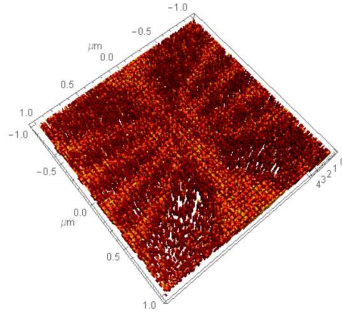
For example – Diamond color center formation prefers I = 1/2 (^{29}Si) or 9/2 (^{73}Ge)



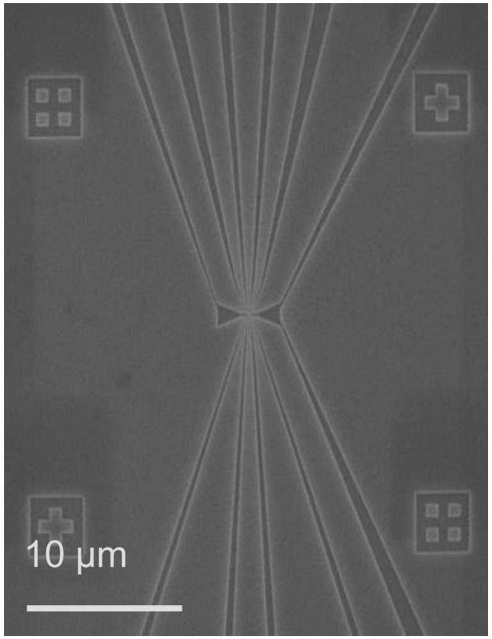


Examples isotope separation

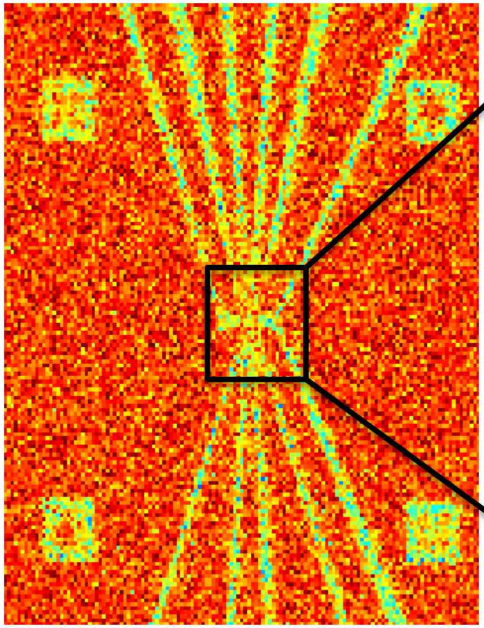
SNL nanoImplanter (nI) – Targeting Resolution



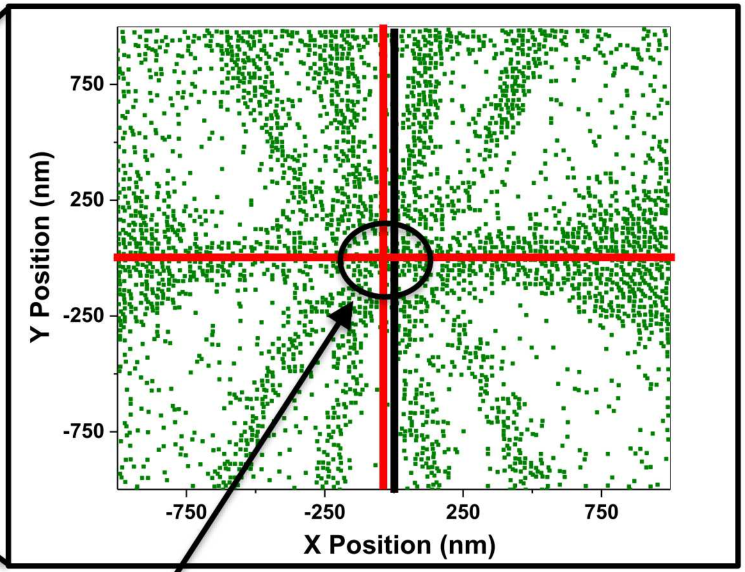
SEM of nanostructure



Ion Beam Induced Charge Collection (IBIC) of nanostructure

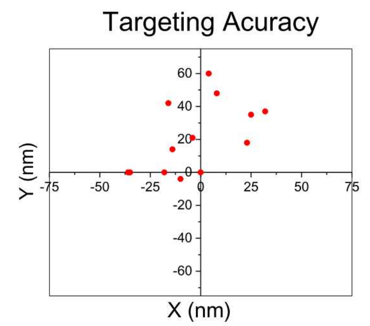


High resolution IBIC for targeting



Δx ~35 nm
Δy ~0 nm

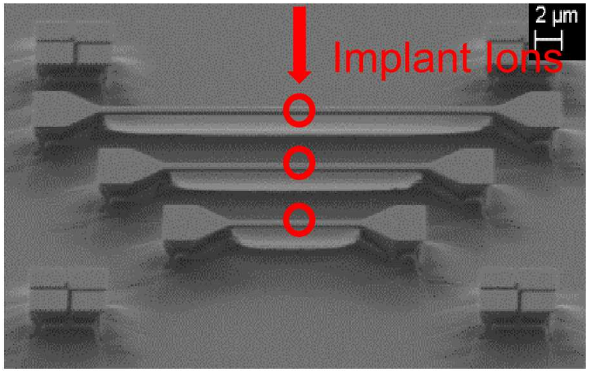
FIB + Lithography Hardware

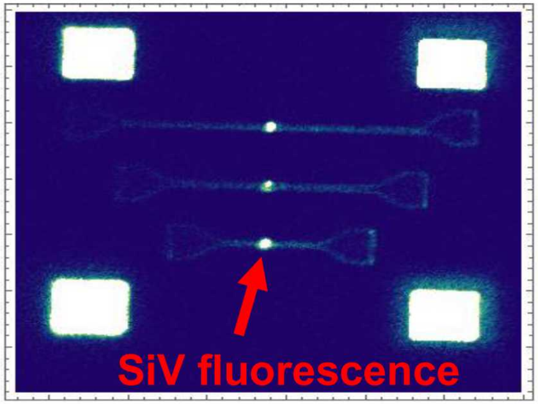


Targeting resolution <40 nm

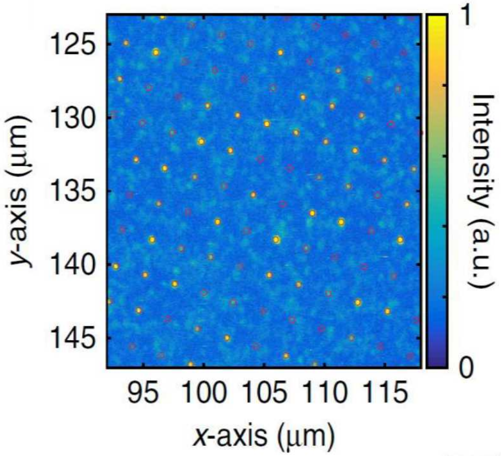
J. Pachaco, *et al.*, *Rev. of Sci. Instr.* **88**, 123301 (2017)

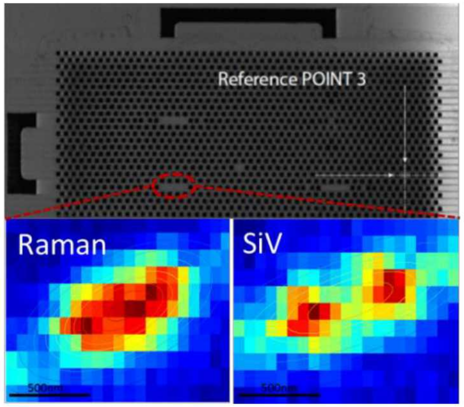
Focused Ion Beam Resolution





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





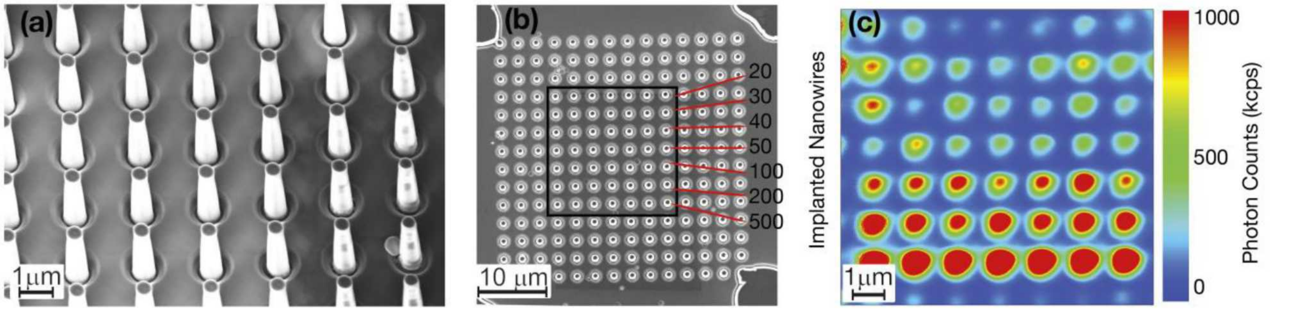
T. Schroder, *et al.*, Nature Communications (2017)

Arrays are easy!

(1) Vary dose

(2) Vary energy

(3) Vary ion species



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

Focused Ion Beam Implantation Limitations

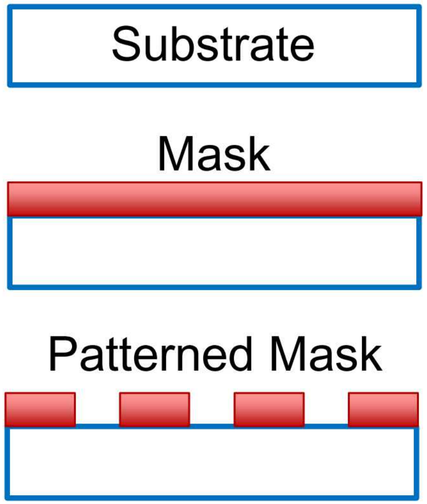
(1) Resolution

Limited by the ion-solid interactions

(2) Ion Sources

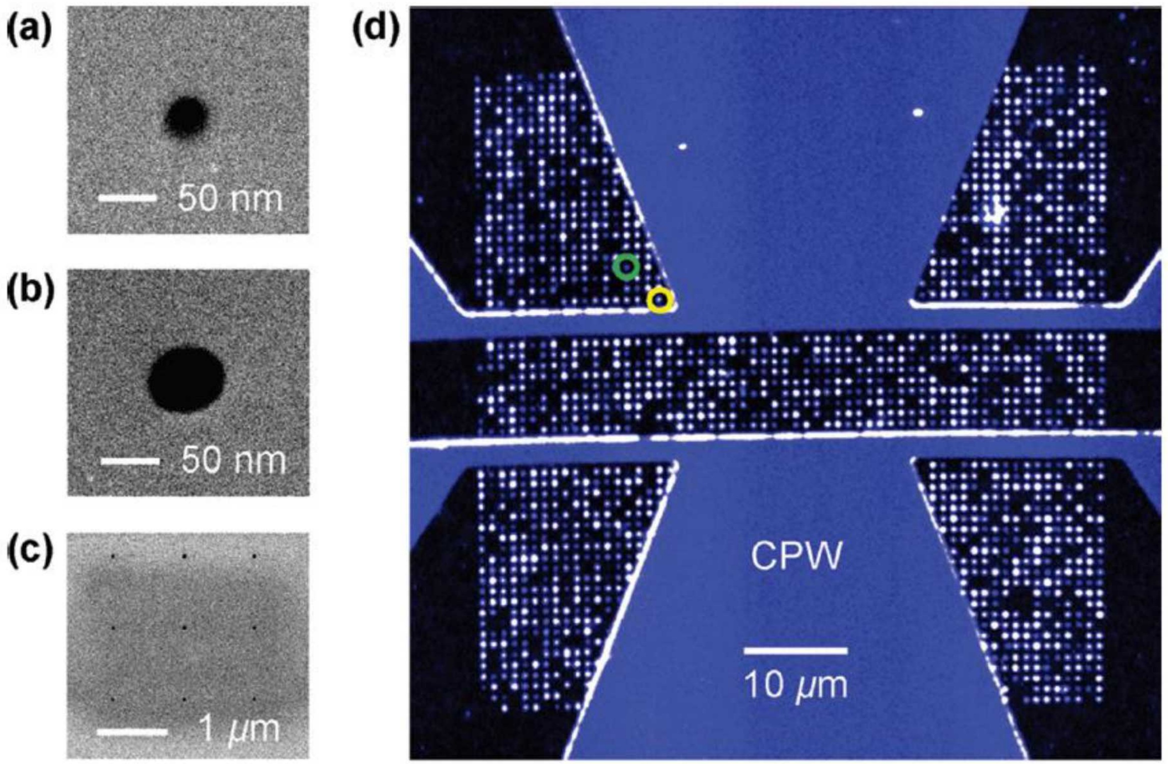
Need a usable LMAIS – no nitrogen for example

Masked Implantation



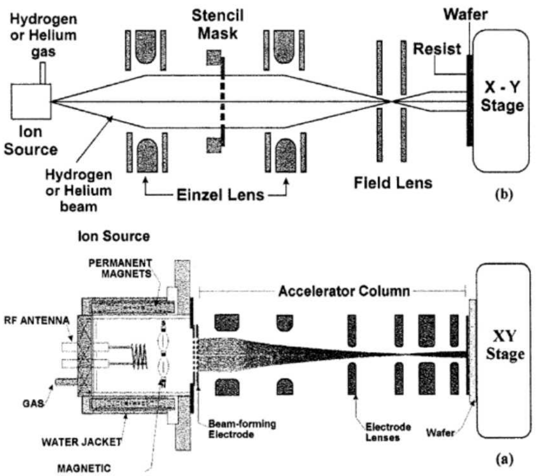
Mask materials

Photoresist, PMMA, HQS, hard masks SiN, SiO2, etc…



D. M. Toyli, *et al.*, Nano Lett. **10**, 3168-3172 (2010)

Other options - maskless



V. V. Ngo, *et al.*, JVST B **17**, 2783 (1999)

Masked Implantation Limitations

(1) Resolution

Limited by aperture size, EBL down to <10 nm is possible

Limited by the ion-solid interactions

(2) Implantation Flexibly

Need either multiple mask steps or multiple samples to vary implantation parameters

Summary of High Resolution Implantation

	Resolution	Speed	Flexibly	Patterning
Hydrogen Lithography	Atomic	Slow	Limited	Limited
Probe Based Implantation	10's nm	Medium	Great	Yes
Focused Ion Beam Implantation	10's nm	Fast	Great	Yes
Masked Implantation	10's nm	Vary Fast	Great	Limited

Deterministic Implantation

We control both the location of the atom and the number of atoms

- How can we do this?

(1) Hydrogen Lithography

Easy in principle, but slow and hard in reality → check each location to ensure we have a donor and repeat as needed

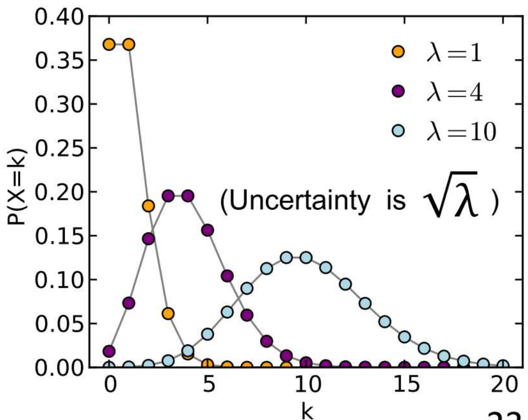
(2) Probe Based Implantation

(3) Focused Ion Beam Implantation

Need to develop a technique for single ion detection

(4) Masked Implantation

Impossible, dominated by Poisson Distribution



Techniques for Deterministic Implantation

(1) Single Ion Sources

(2) Secondary Electron Detection (SED)

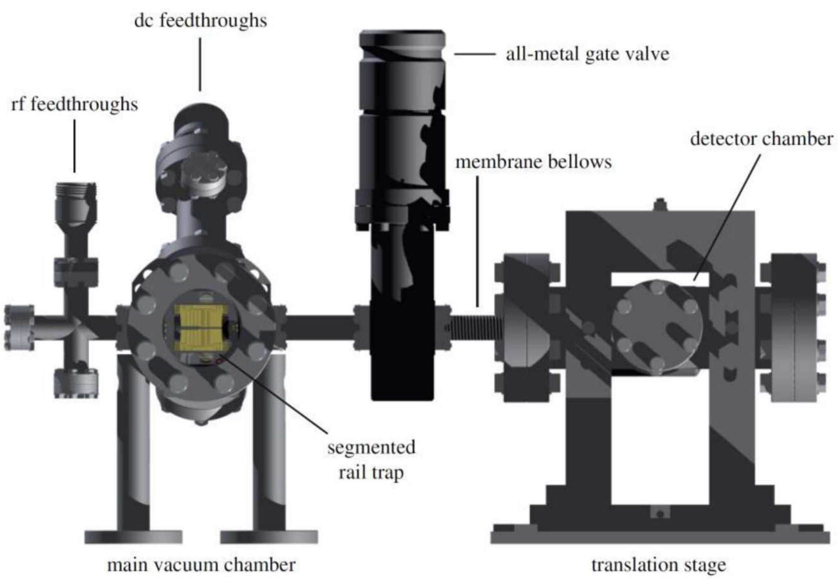
(3) Device Response itself

(4) Ion Beam Induced Charge Collection (IBIC)

Single Ion Sources

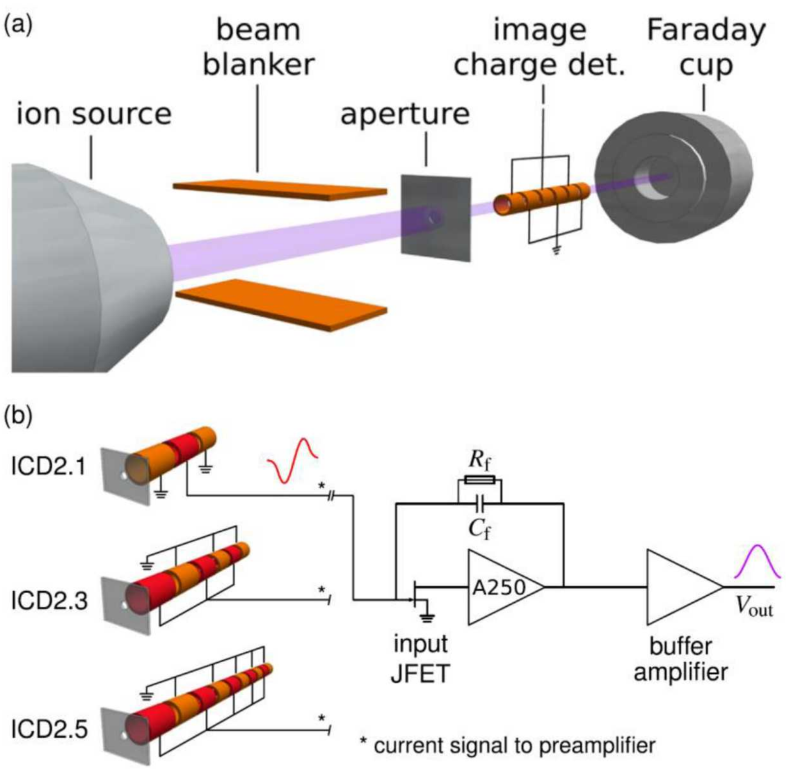
Produce a single ion and then launch it down a beamline for implantation

Use a linear Paul trap to trap a single ion



W. Schnitzler, *et al.*, New Journal of Physics **12**, 065023 (2010)

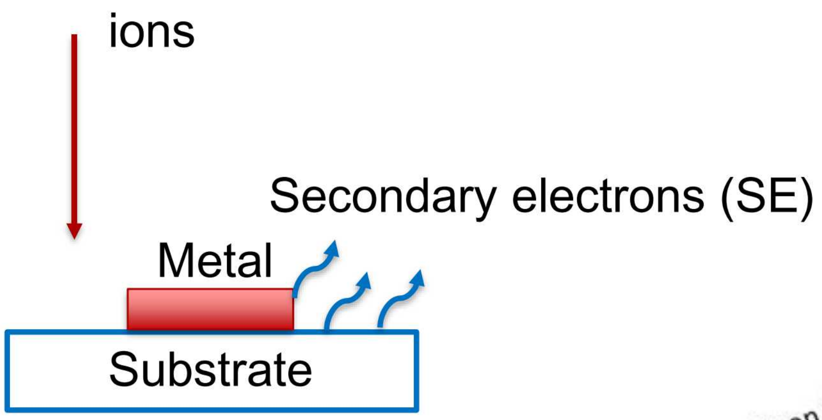
Measure single ion by image charge

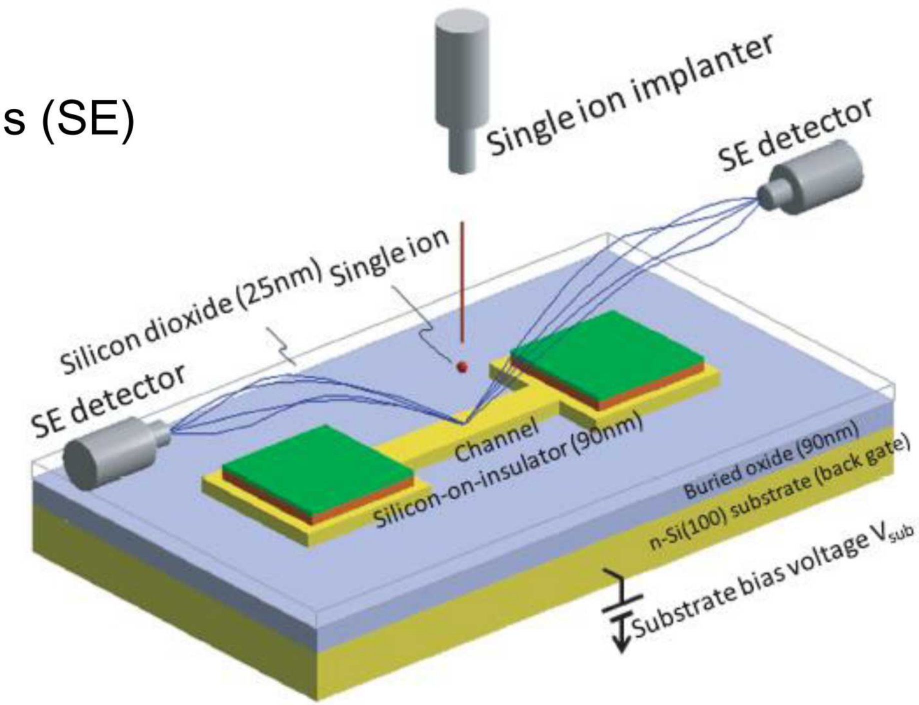


P. Racke, *et al.*, Scientific Reports **8**, 9781 (2018)

Secondary Electron Detection

Use the ion beam to produce secondary electrons which we then collect





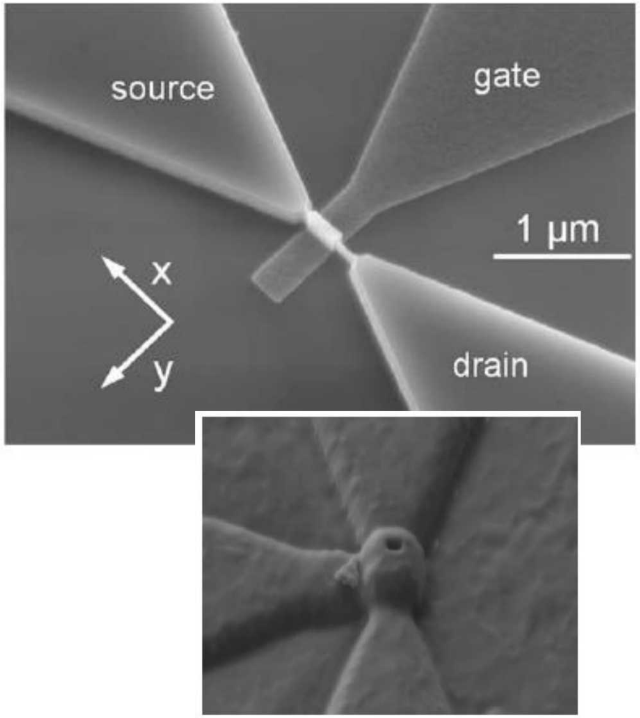
M. Hori, *et al.*, Appl. Phys. Express **4**, 046501 (2011)

SE yield is affected by topology, materials, etc…

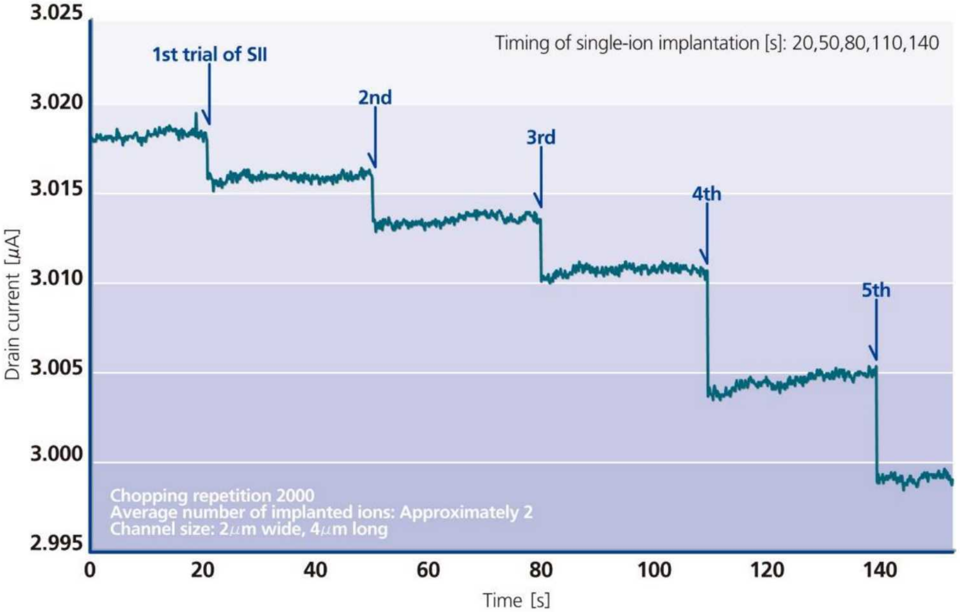
Device Response

Use the drain current response in a finFET to detect single ions

This is usual as displacement damage is not typically though of modifying majority carrier device response



C. D. Weis, *et al.*, NIM B **267**, 1222-1225 (2009)

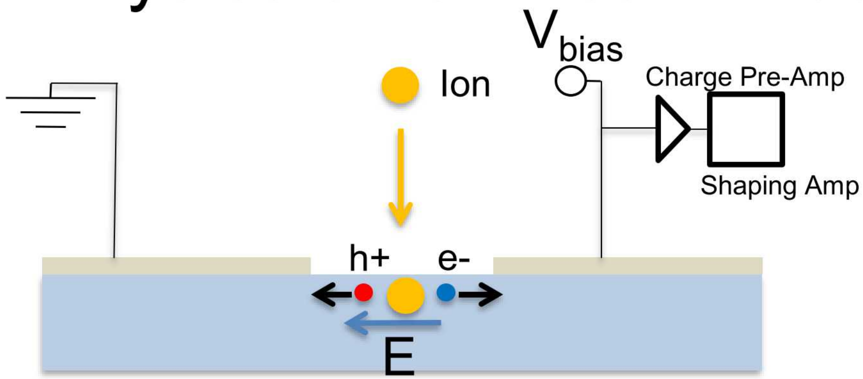


T. Shinada, *et al.*, Nanotechnology **19**, 345202 (2008)

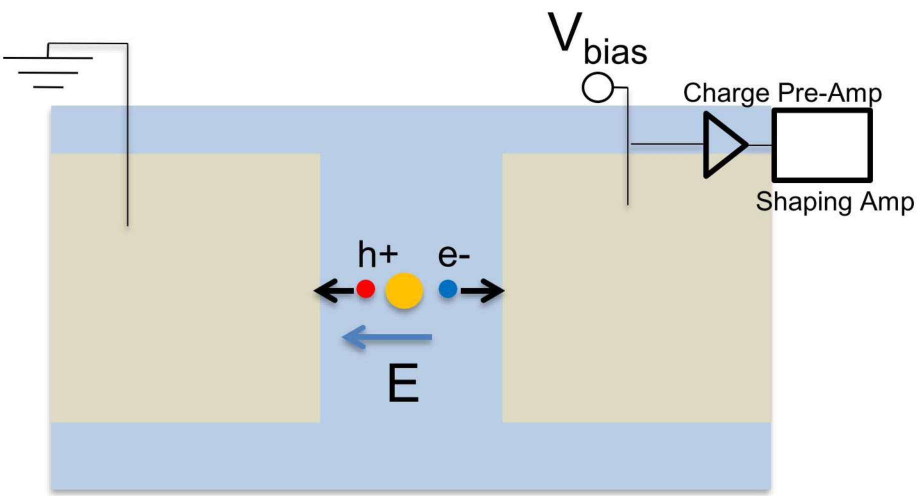
Similar experiments where able to distinguish between hits in the channel (low energy) and trapped charge in the BOX (high energy)

B. C. Johnson, *et al.*, Appl. Phys. Lett. **96**, 264102 (2010)

Physics of Ion Beam Induced Charge Collection



Side View



Top View

Shockley-Ramo Theorem:

$$\boxed{i = q\vec{v} \cdot \vec{E}}$$

Moving charges in an electrical field will induce a current on the electrodes applying the bias

Charge Collection Efficiency (CCE):

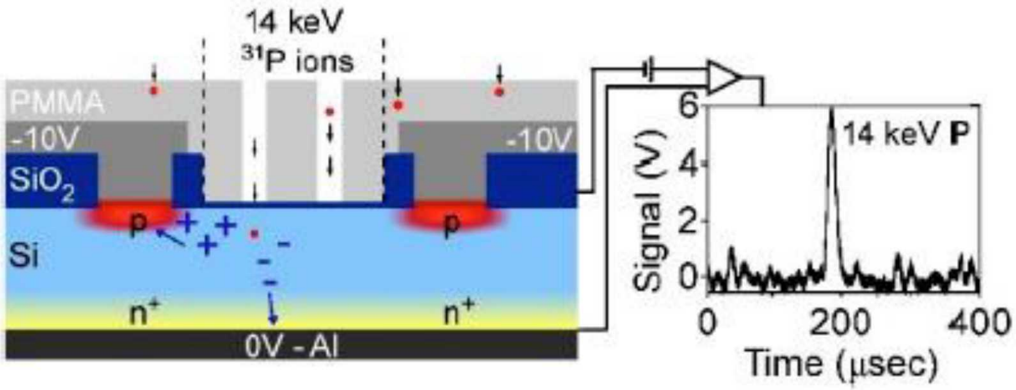
$$\boxed{\mathrm{CCE} = \frac{\mathit{Charge\ Collected}}{\mathit{Charge\ Depositied}}\ x\ 100}$$

Ion Beam Induced Charge (IBIC):

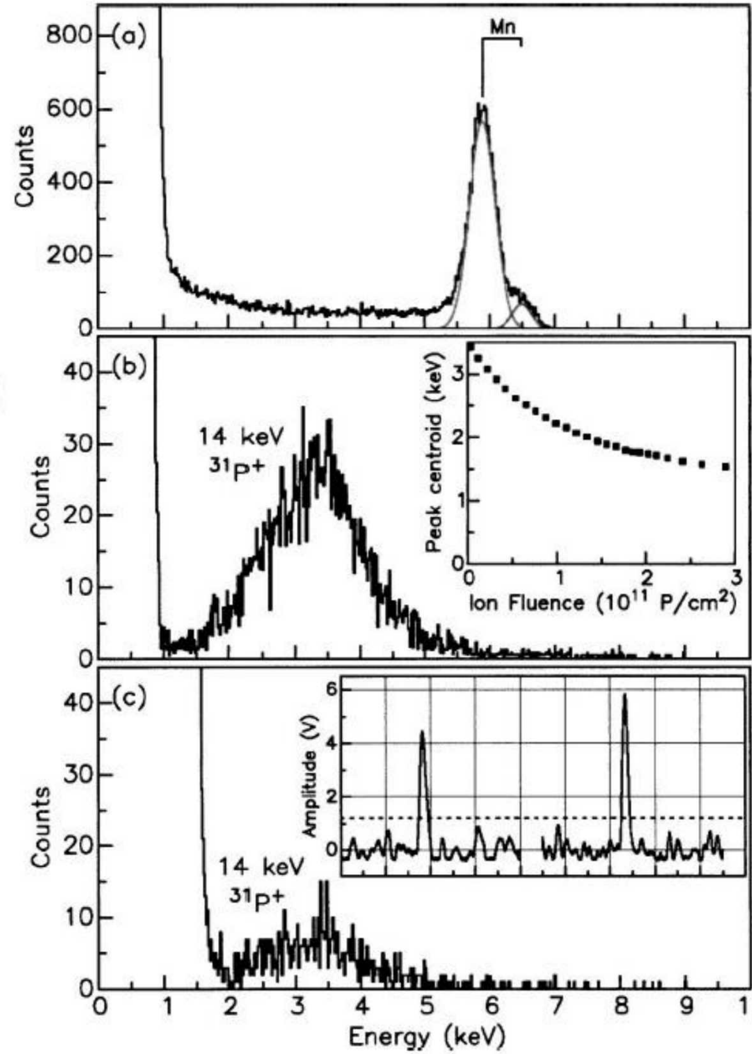
Ion Beam is rastered across device to measure the Charge Collection Efficiency (CCE) as a function of position

Ion Beam Induced Charge Collection

Use the e-h pairs generated by the ion beam to induce a charge on the electrodes



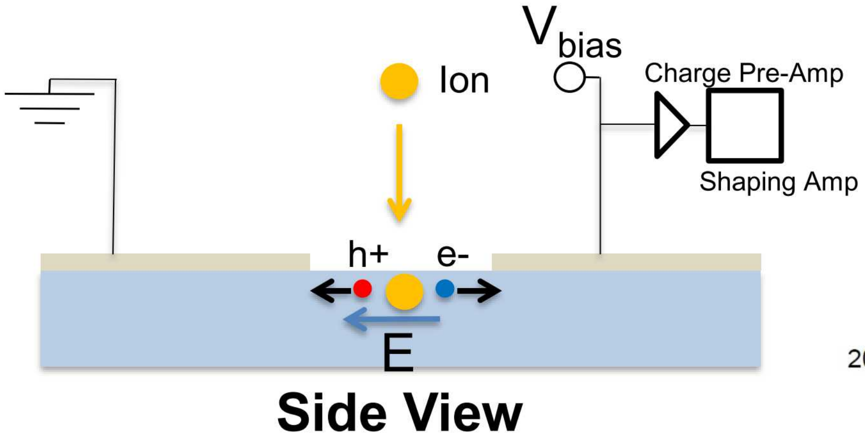
D. Jamieson, *et al.*, Appl. Phys. Lett. **86**, 202101 (2005)

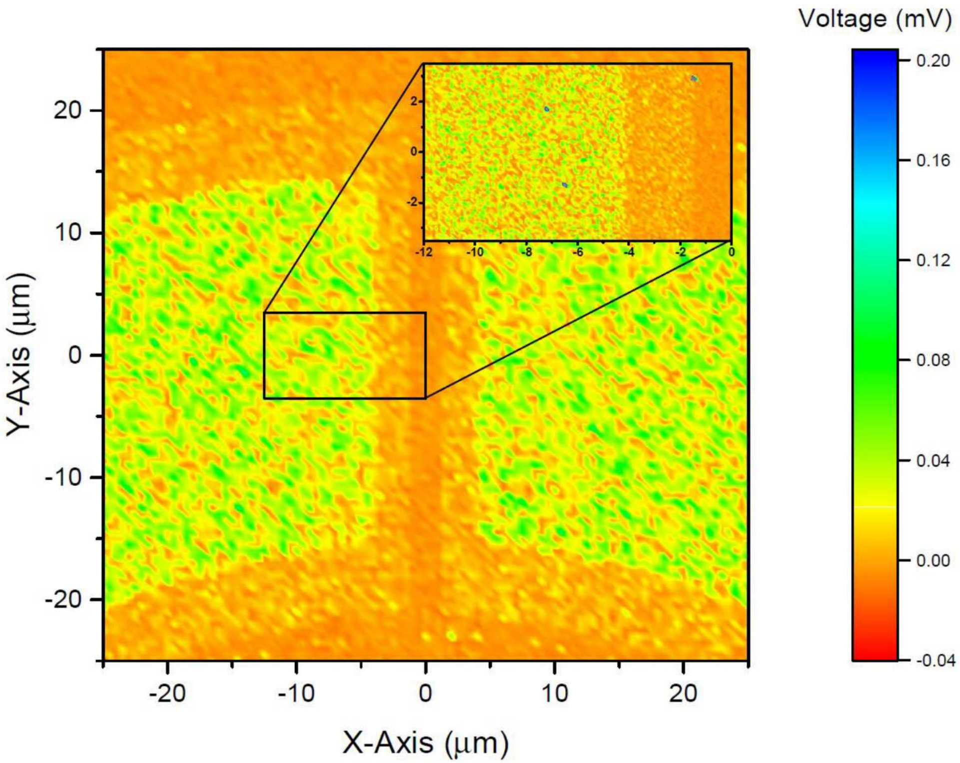


- Device is the detector
- Commonly used to map out collection volumes
- Can be sensitive to single ion strikes

SNL nanoImplanter (nI) – IBIC Resolution

Ion Beam Induced Charge Collection (IBIC)





IBIC resolution is spot size limited, ~20 nm

Summary of Deterministic Implantation

	Sensitivity	Speed	Flexibly	Is the ion in the correct location?
Single Ion Source	Single Ion	Slow	Any device and any material	No information
SEDs	Single Ion?	Vary Fast	Any device, but topology and material dependent	No information
Device Response	Single Ion, energy dependence?	Fast	Needs specialized device	Yes
IBIC	Single Ion, depends on ion energy	Vary Fast	Needs specialized device	Yes

Summary and Review (1)

Implantation Technique

	Resolution	Speed	Flexibly	Patterning
Hydrogen Lithography	Atomic	Slow	Limited	Limited
Probe Based Implantation	10's nm	Medium	Great	Yes
Focused Ion Beam Implantation	10's nm	Fast	Great	Yes
Masked Implantation	10's nm	Vary Fast	Great	Limited

No technique is perfect, but FIB is a good compromise

Summary and Review (2)

Single Ion Detection Technique

	Sensitivity	Speed	Flexibly	Is the ion in the correct location?
Single Ion Source	Single Ion	Slow	Any device and any material	No information
SEDs	Single Ion?	Vary Fast	Any device, but topology and material dependent	No information
Device Response	Single Ion, energy dependence?	Fast	Needs specialized device	Yes
IBIC	Single Ion, depends on ion energy	Vary Fast	Needs specialized device	Yes

No detection scheme is perfect, but IBIC is a good compromise