SAND2011-6847 C

SAND2011-6847C

Path Forward for Deterministic Single Donor Devices using Top-Down Implantation

E. Bielejec, N. Bishop and M. S. Carroll

Sandia National Laboratories, Albuquerque, NM 87185

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

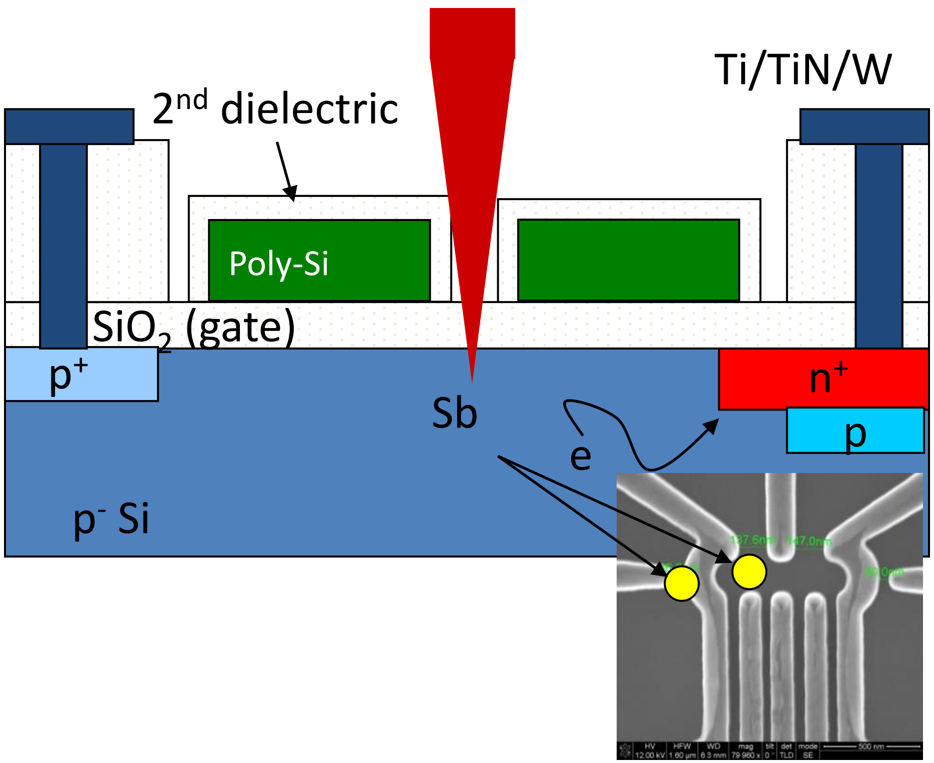
Deterministic Single Ion Devices

Combining Donors with Si Double Quantum Dots for Solid State Quantum Computing Applications

- Why Si Double Quantum Dots?
  - Spin-to-Charge Conversion
- Why Donors?
  - Proven long coherence times

T. Schenkel *et al.*, APL **88** (2006)

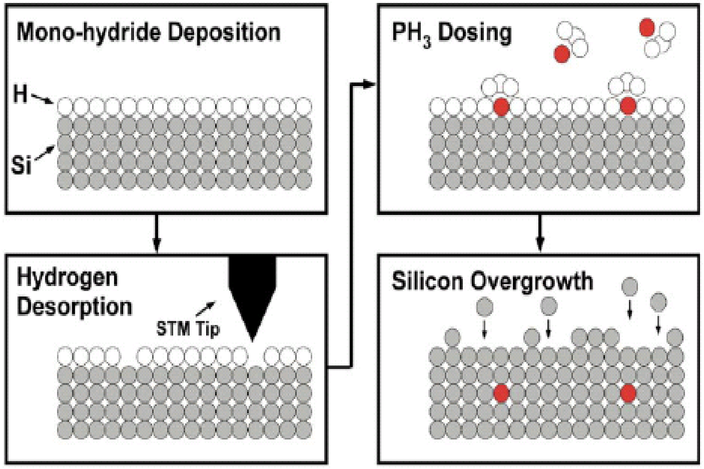
Sample	Interface	Peak depth (nm)	T_1 (ms)	T_2 (ms)
120 keV	Si/SiO$_2$	50	15±2	0.30±0.03
120 keV	Si—H	50	16±2	0.75±0.04
400 keV	Si/SiO$_2$	150	16±1	1.5±0.1
400 keV	Si—H	150	14±1	2.1±0.1



- Single donor implantation within the Si MOS DQD devices, what do we need?
  - Single Ion Detection
  - Integrated with nanostructured devices
  - Focused Ion Beam Implantation

Single-Ion Implantation (Donor) Approaches

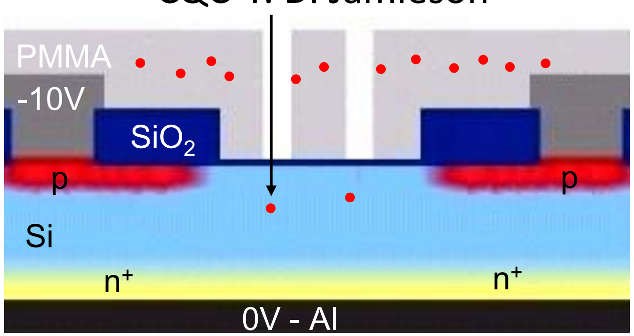
Atomic Scale Fabrication



J. L. O'Brien *et al*, PRB **64**, 161401 (R), 2001

Ion Implantation: LT PIN

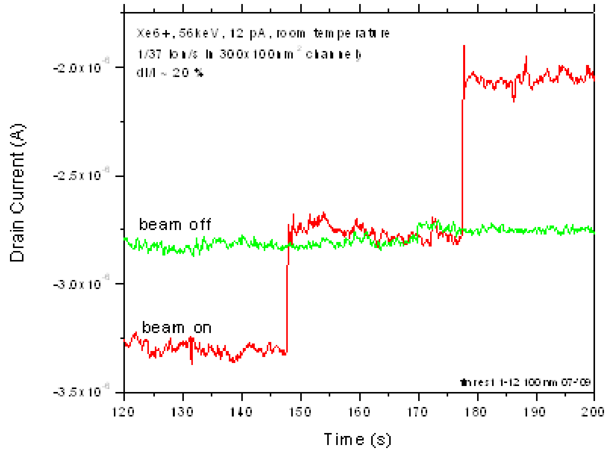
CQC^{2}T: D. Jamieson

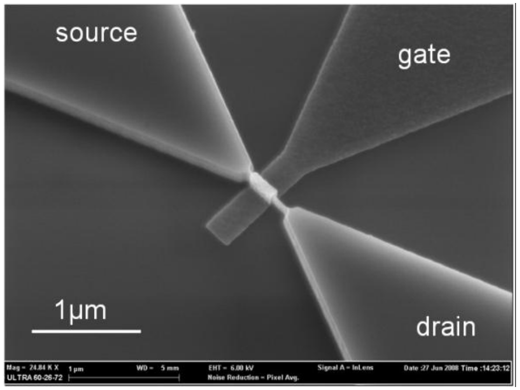


D. N. Jamieson *et al*., Appl. Phys. Lett. **86**, 202101 (2005)

Ion Implantation: RT Detection

LBNL: T. Schenkel

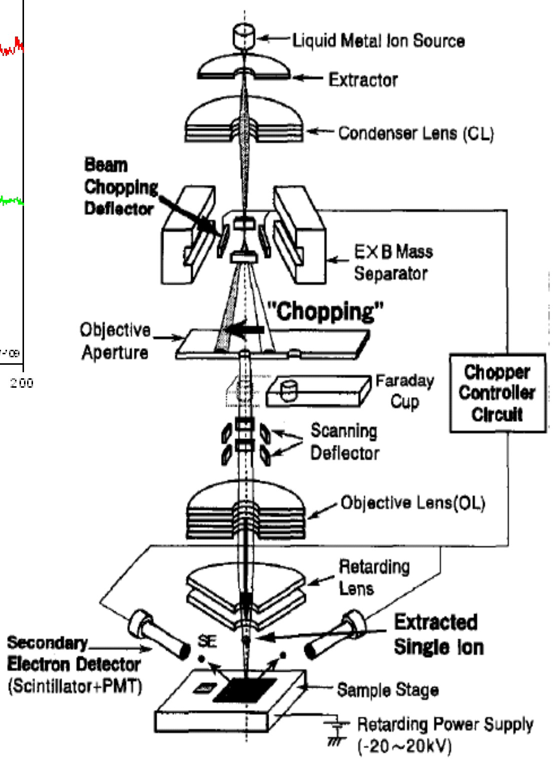




C. D. Weis, *et al*., NIMB, 267, 1222-1225 (2009)

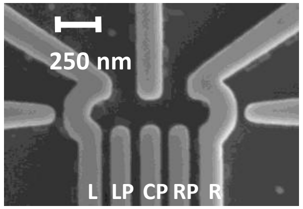
FIB Implantation

Waseda: T. Sinada

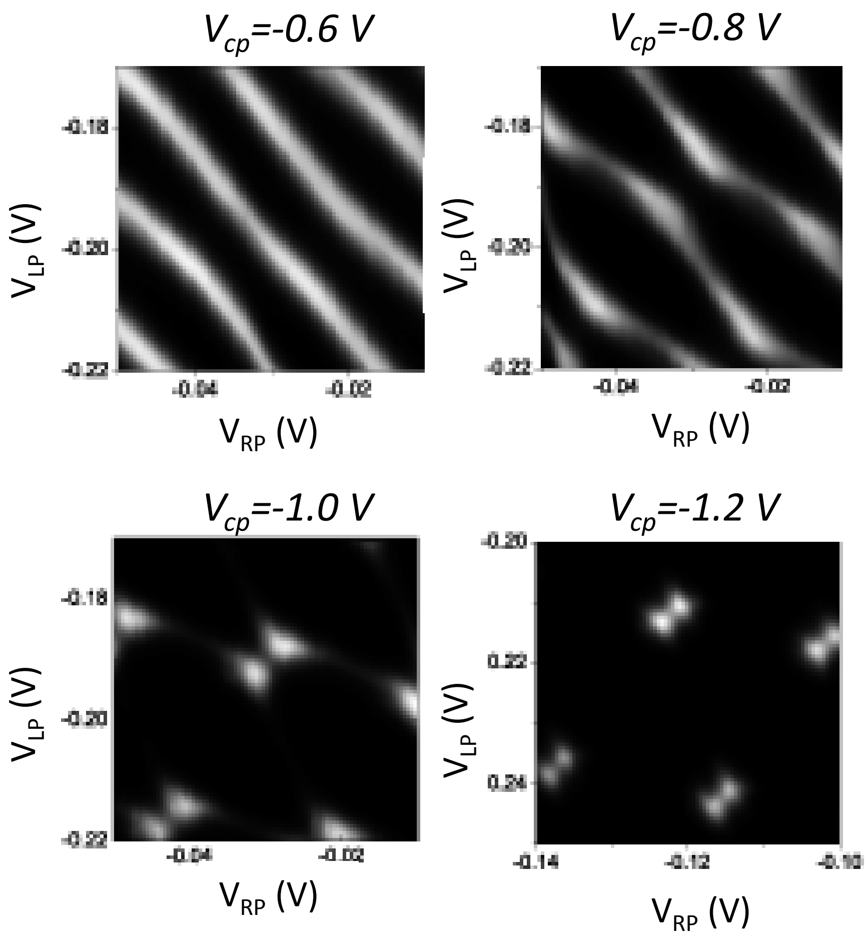


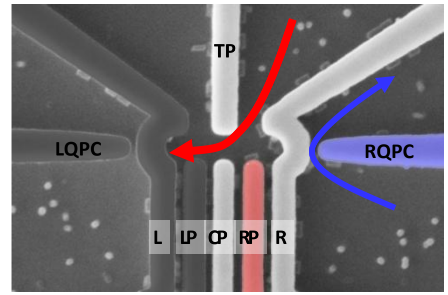
T. Matsukawa *et al*, Appl. Sur. Sci. **117/118**, 677 (1997)
T. Shinada, *et al*., Nature **437**, 1128 (2005)
M. Hori, *et al*., Applied Physics Express **4**, 046501 (2011)

Status of the SNL Double Quantum Dot Devices

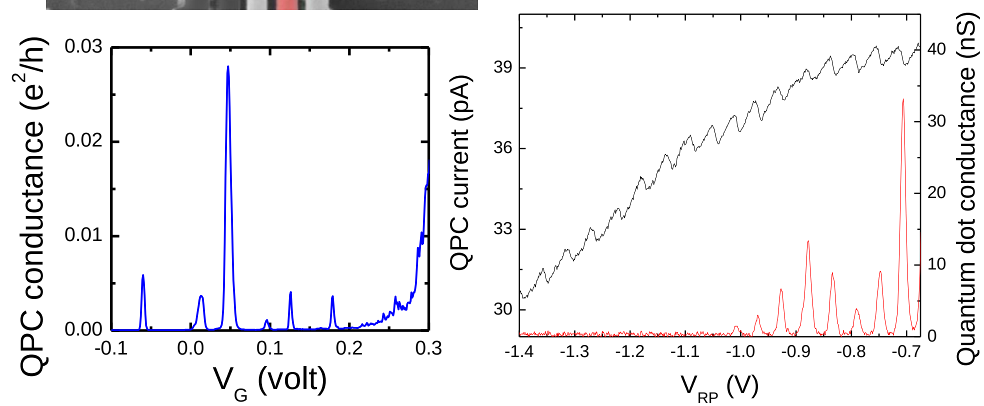


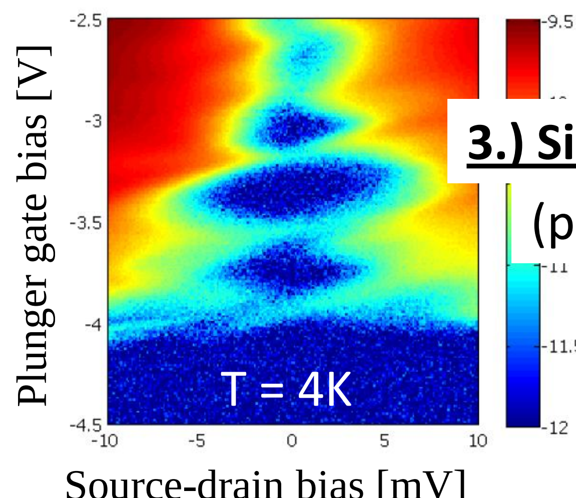
1.) Double Dot Formation





2.) Charge Sensing





3.) Single Electron Dot

(preliminary results)

Nordberg, APL 2009; Nordberg, PRB 2009; Tracy, APL 2010

Outline:

1.) Single Ion Detection

2.) Integration with Nanostructured Devices

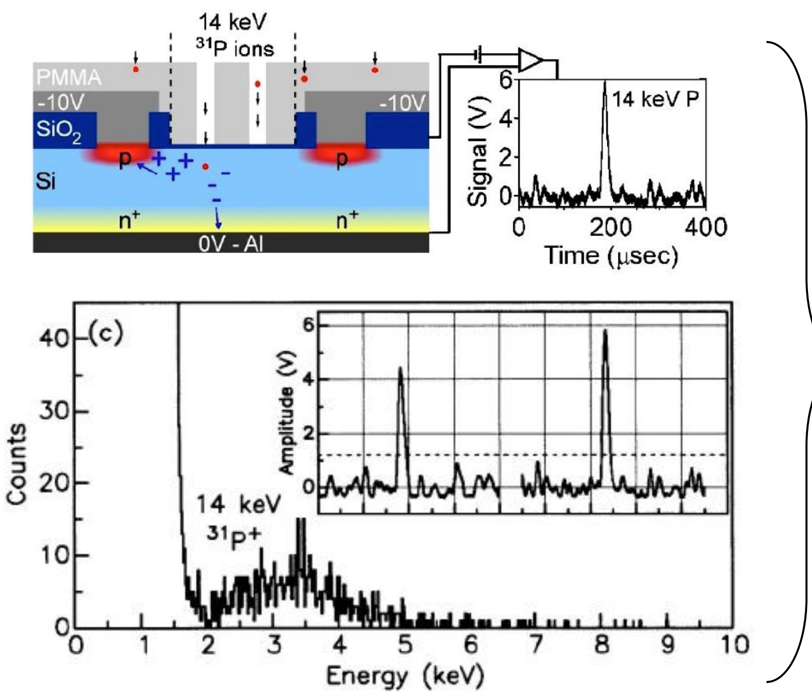
3.) Focused Ion Beam Development

4.) Conclusions

Requirements for Single Ion Detectors

Ion Implantation resolution will depend on multiple factors including:

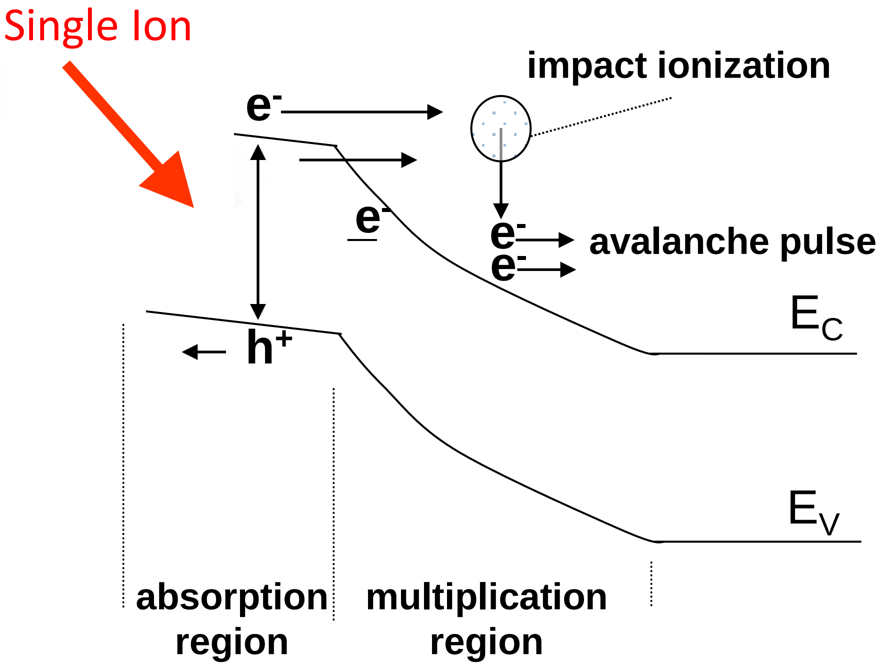
- Ion straggle (dependence on ion/energy combination and channeling)
- Detector sensitivity for low energy implants
- Diffusion length for the post activation anneal
- Damage due to the implantation
- Electron beam lithography and shadow mask limitations

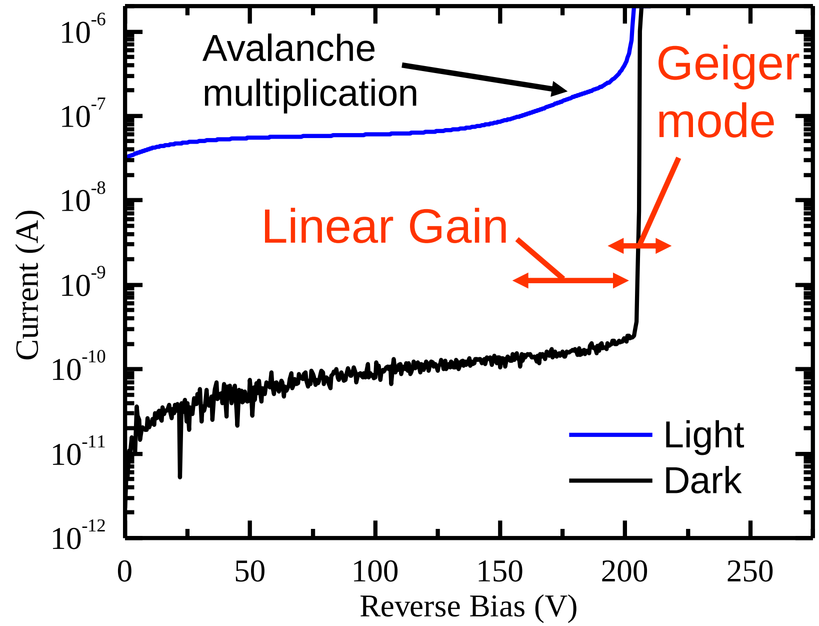


Need to improve the noise threshold to enable lower energy implantation (minimize straggle)!

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

Avalanche Photodiode (APD)





- APD produces internal gain due to high field impact ionization
- Sensitive to single photon detection (single e-h pair!)
- We run the APDs in Geiger Mode for Single Ion Detection

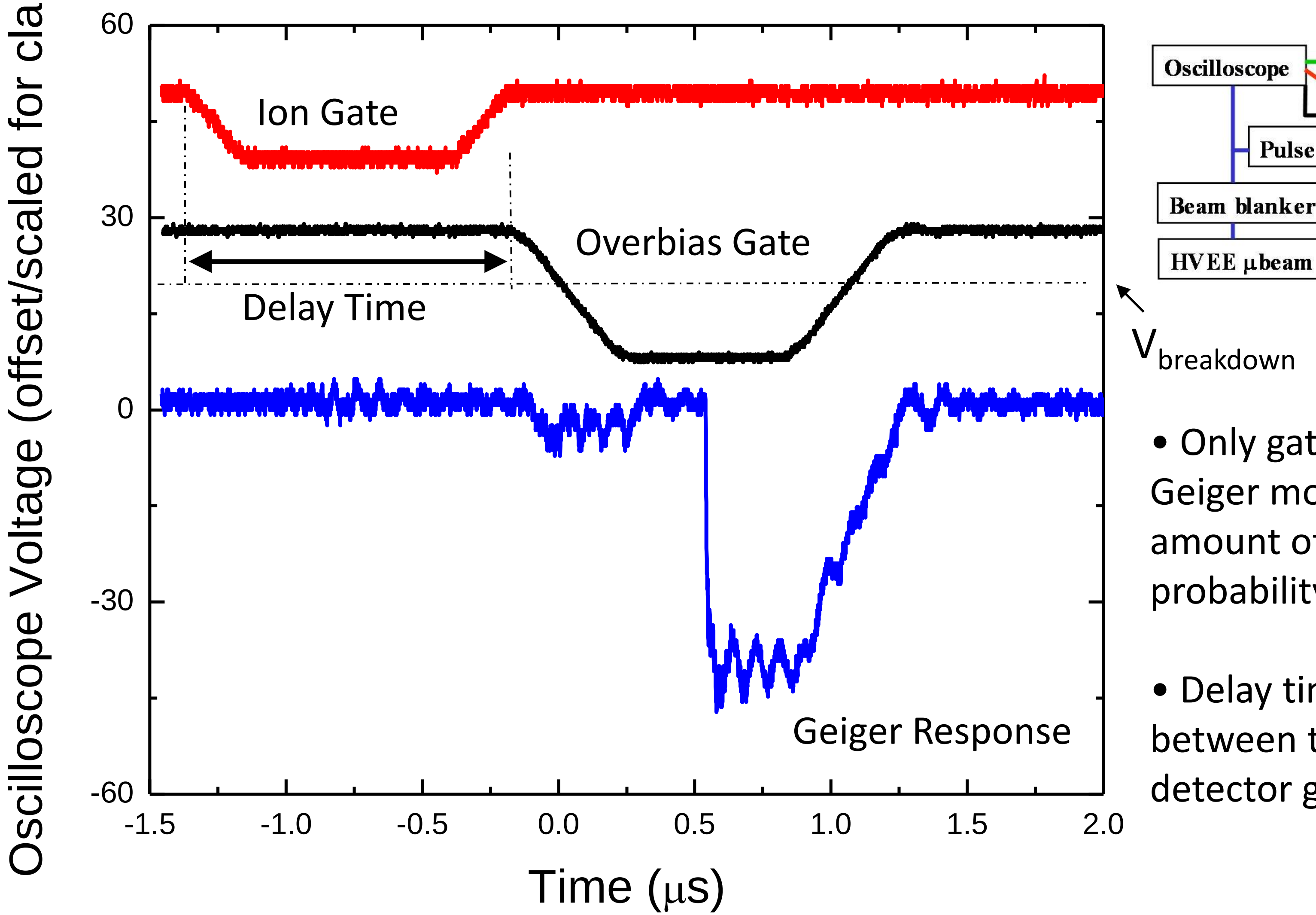
Avalanche Photodiode

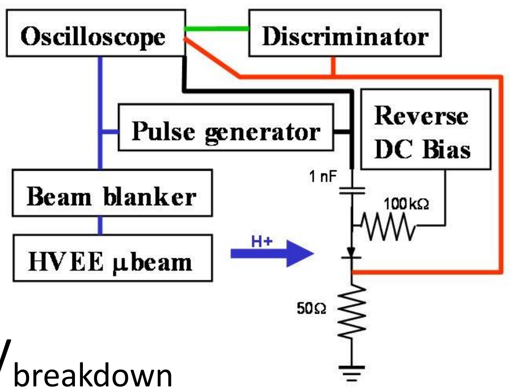
- Bias below breakdown
- Linear-mode: Amplifier
- Gain: limited < 1000

Geiger Mode Operation

- Pulse bias above breakdown
- Geiger-mode: gated device operation
- Gain meaningless (digital signal)

Single Ion Geiger Mode Avalanche (SIGMA) Detector



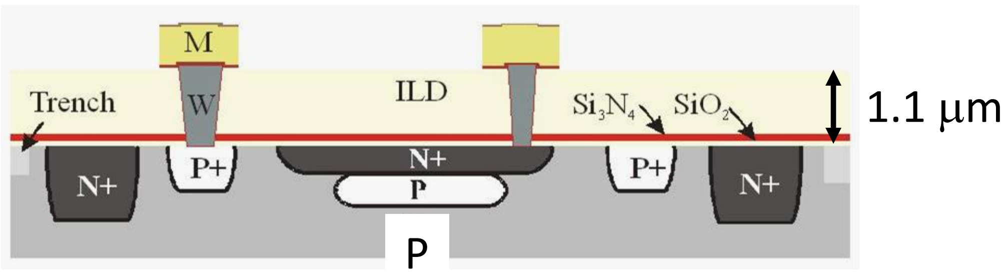


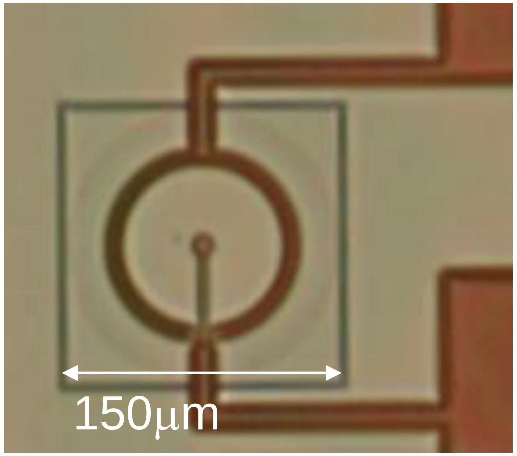
- Only gate the detector into Geiger mode for a finite amount of time to limit probability of dark counts

- Delay time controls timing between the ion strikes and detector gating

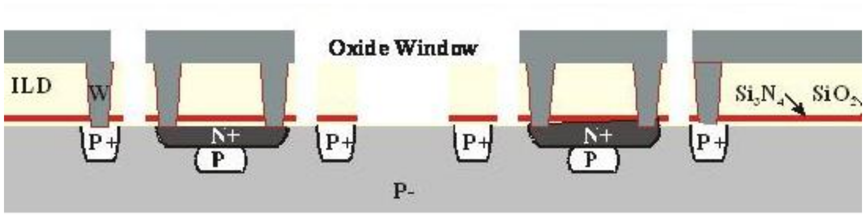
APD Structures

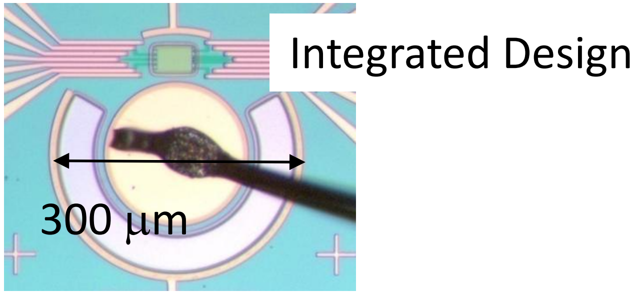
SIGMA Detectors - Discrete



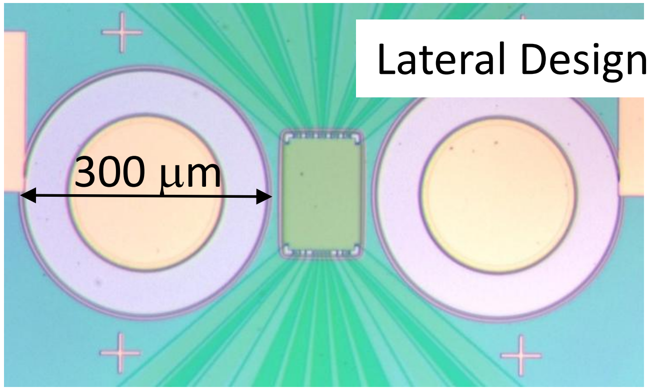


SIGMA Detectors – Integrated with Si DQD

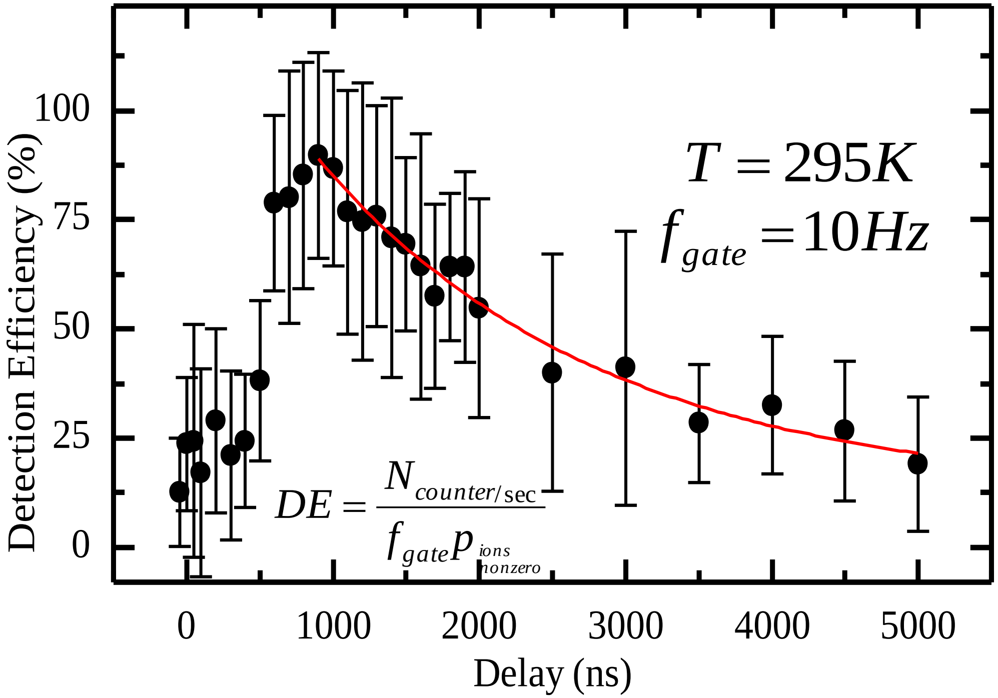


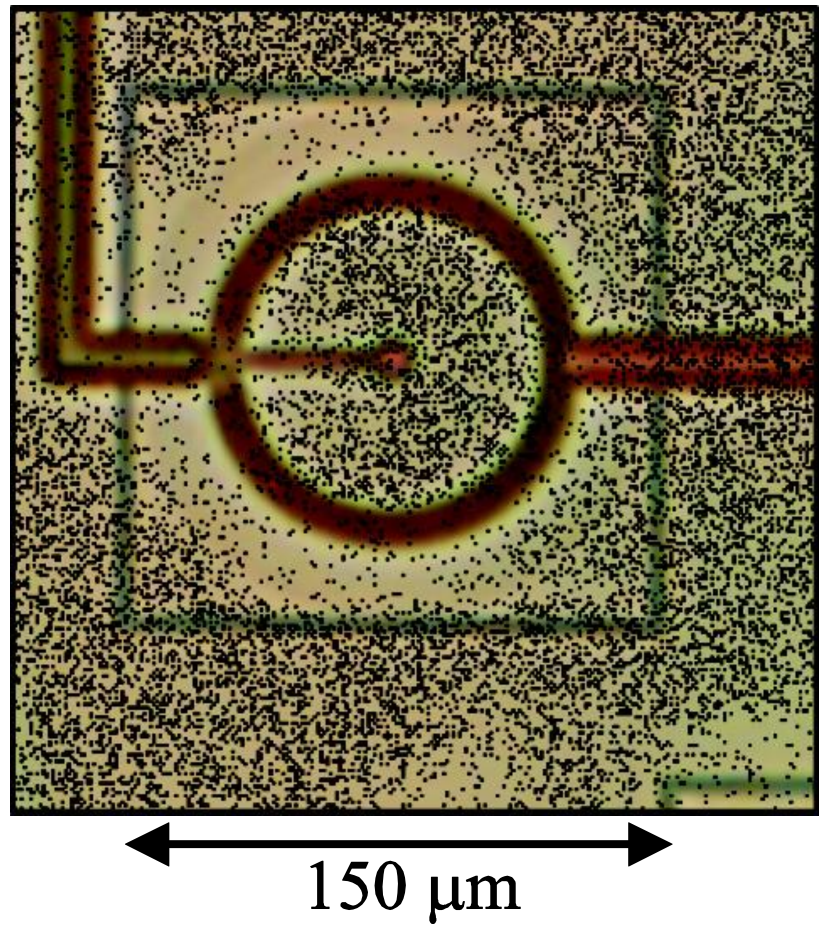


- Reduce oxide thickness to 7, 10 or 35 nm
- Change from p to p- substrate, back to p
- Change the APD doping profiles and geometry



Diffused Carriers Detection: Discrete SIGMA



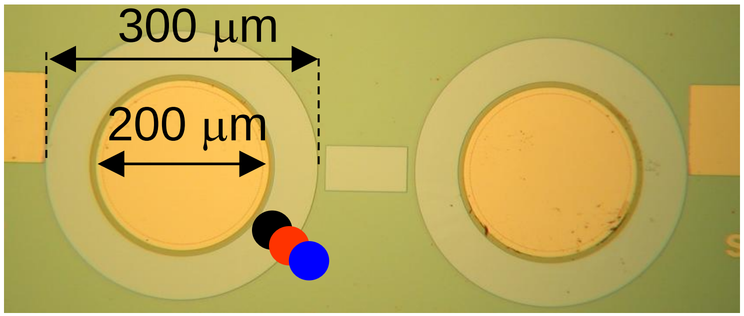


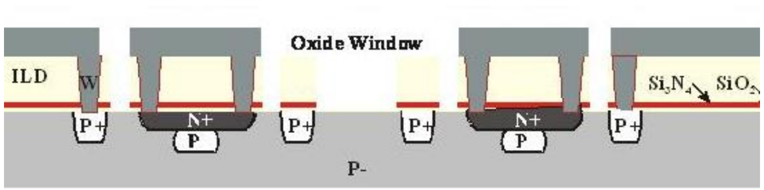
Detect single ions with ~100% detection efficiency for diffused carriers

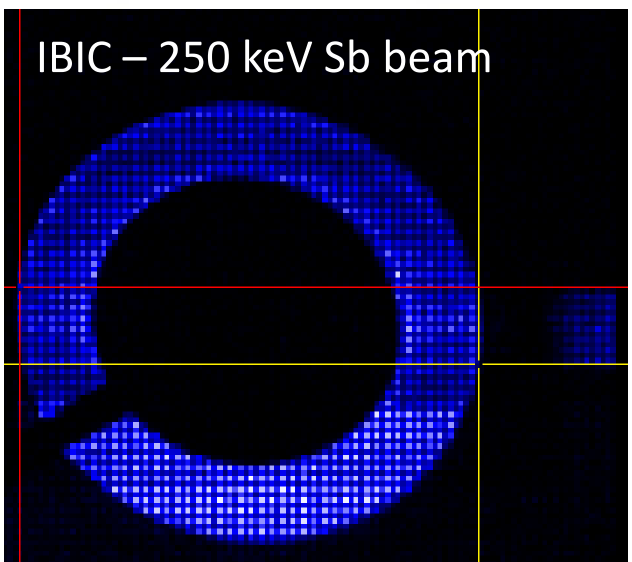
IBIC of SIGMA in Geiger Mode, showing diffused carrier collection

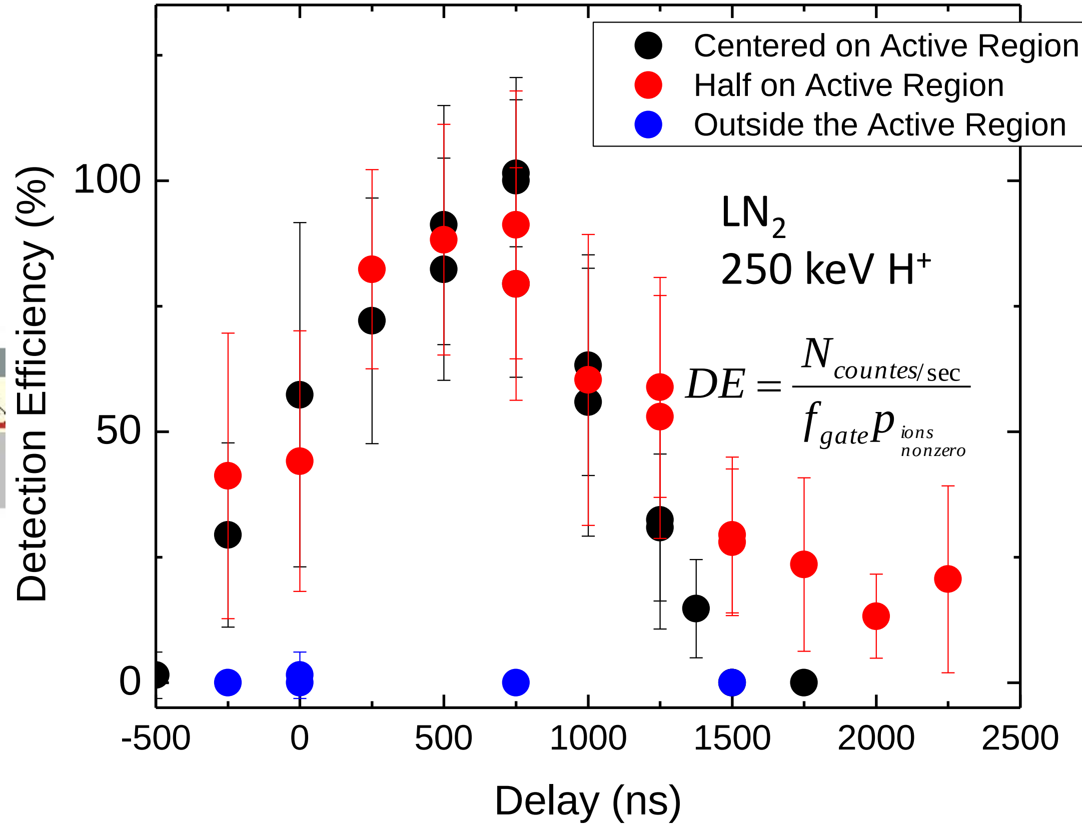
E. Bielejec *et al*., Nanotechnology **21**, 085201 (2010).
J. A. Seamons *et al*., Appl. Phys. Lett. **93**, 043124 (2008)

Lateral SIGMA Devices (p- substrate)



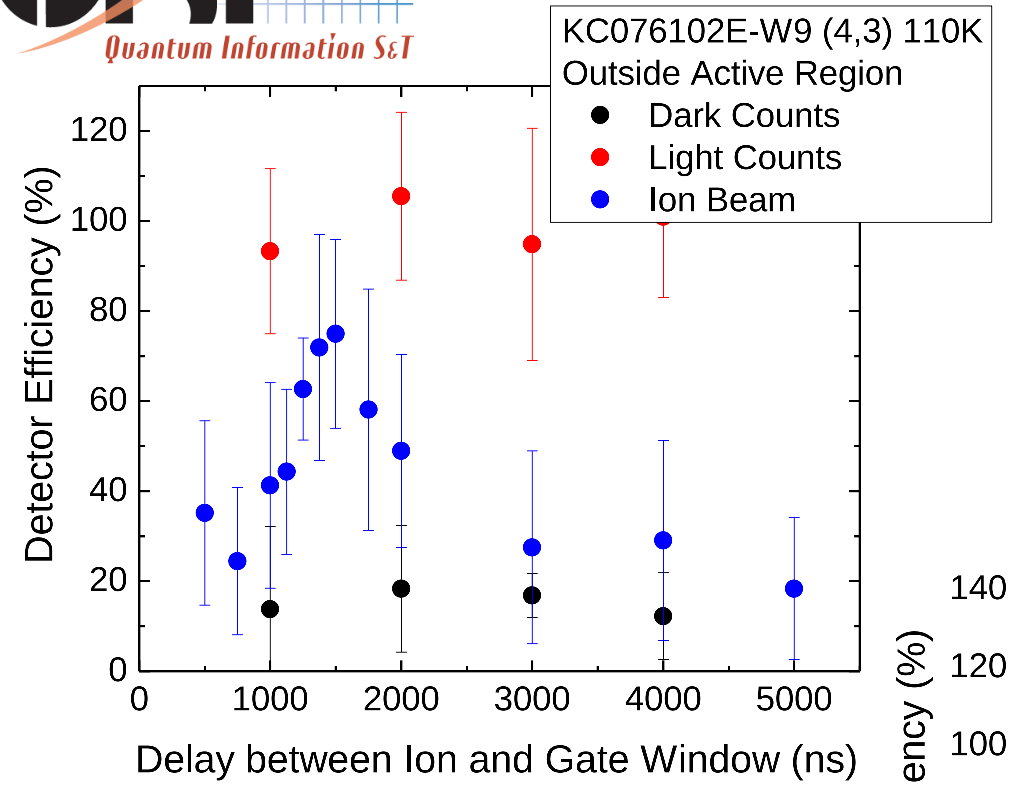


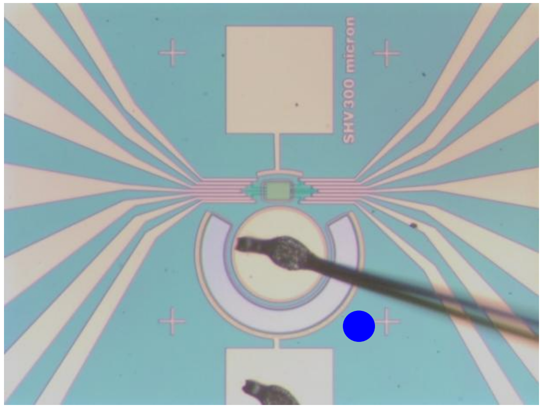




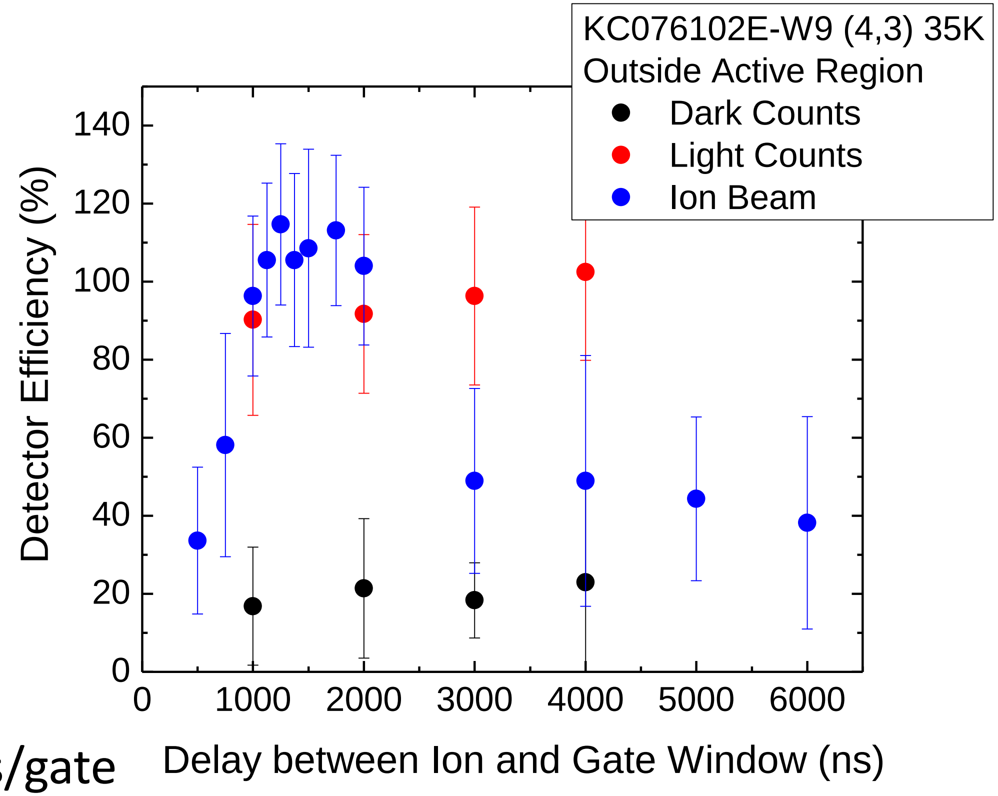
Results were encouraging and additional testing/redesign is on-going – reduced background doping leads an increased DCR, lower DE

Integrated SIGMA Devices (p substrate)





$$DE = \frac{N_{countes/\sec}}{f_{gate} p_{\substack{ions \\ nonzero}}}$$



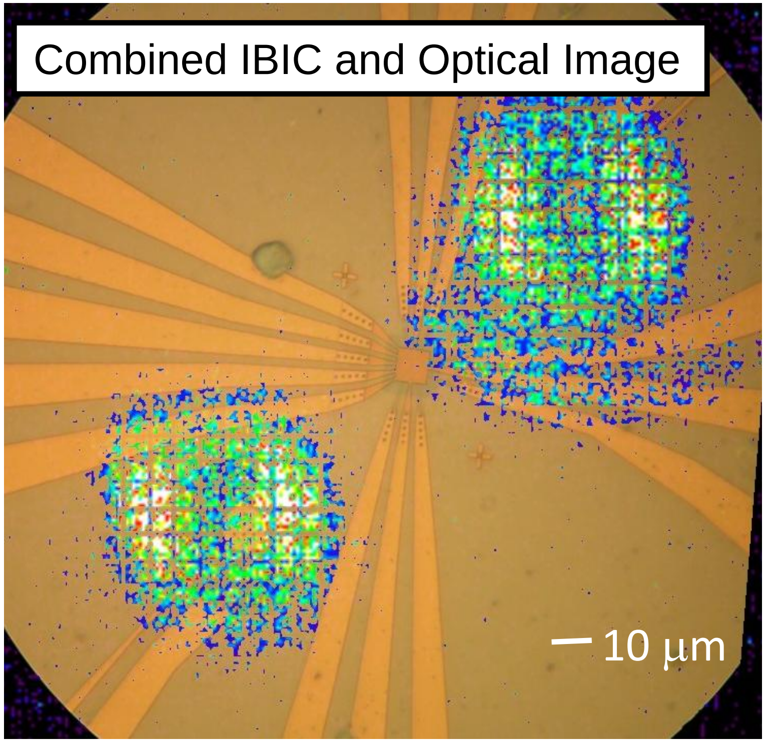
Next Experiments

- GM IBIC map of detection extent
- Switch to 50 keV Sb (25 keV P) for low energy detection

Detect single ions with ~100% detection efficiency for diffused carriers with RS761

Ion Irradiation with 120 keV H+ at ~1 ions/gate

Single Ion Detector Requirements



- Two laterally coupled APDs run simultaneously
- Scanning a focused ion beam over the device to produce the IBIC map – overlay with optical image

Detect low energy ions (low number of e-h pairs produced)

- Lower energy to minimize donor straggle
- SIGMAs sensitive to <1000 e-h pairs!

Detection signal only from an implanted ion

- Low dark counts are required
- SIGMAs have 100% DE with low DCR!

Diffused carrier detection

- Allows the detector to be located far (10's of μm) from the ion implantation site (less restrictions on architecture layout)

SIGMAs can detect diffused carriers with 100% DE at 75 μm from the detector!

Outline:

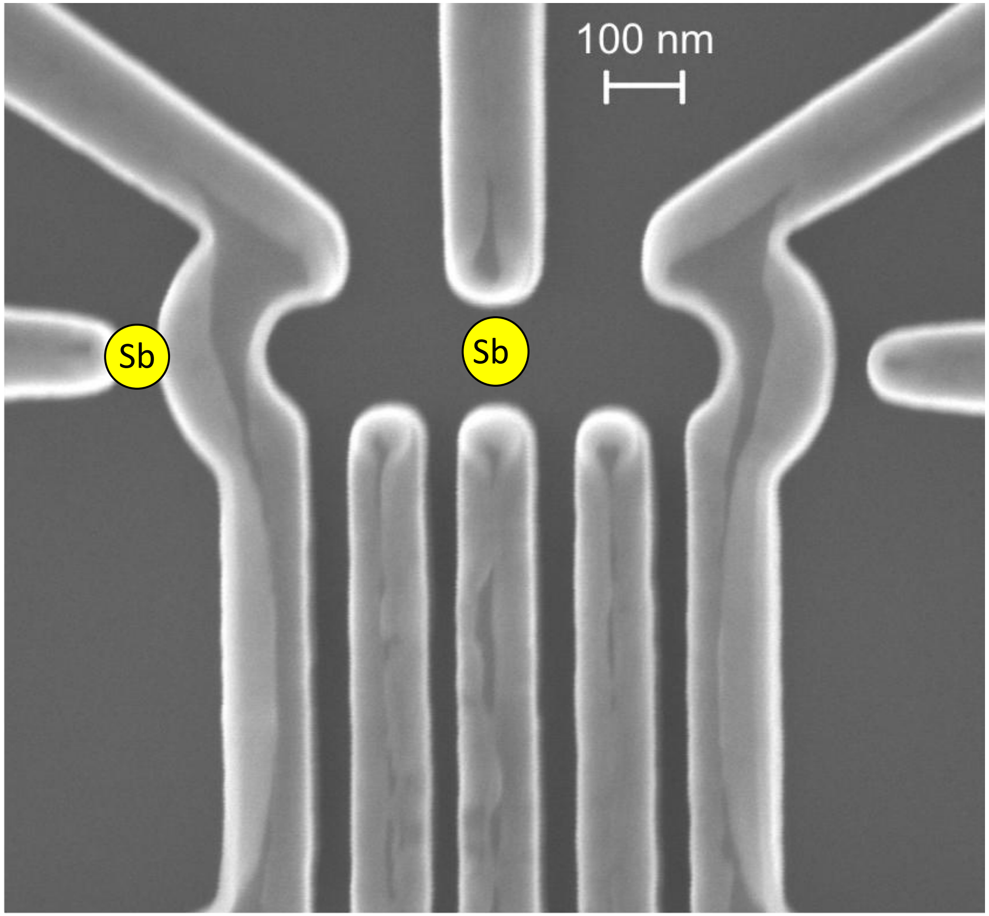
1.) Single Ion Detection

2.) Integration with Nanostructured Devices

3.) Focused Ion Beam Development

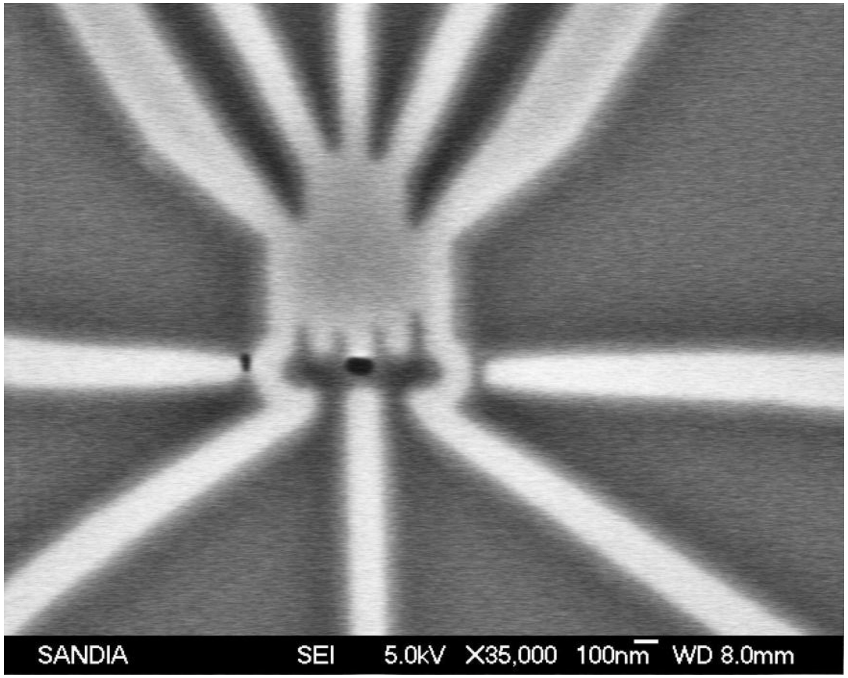
4.) Conclusions

Initial Timed Donor Devices:



• We have implanted a series of devices with Sb and Si (produces damage, but no doping)

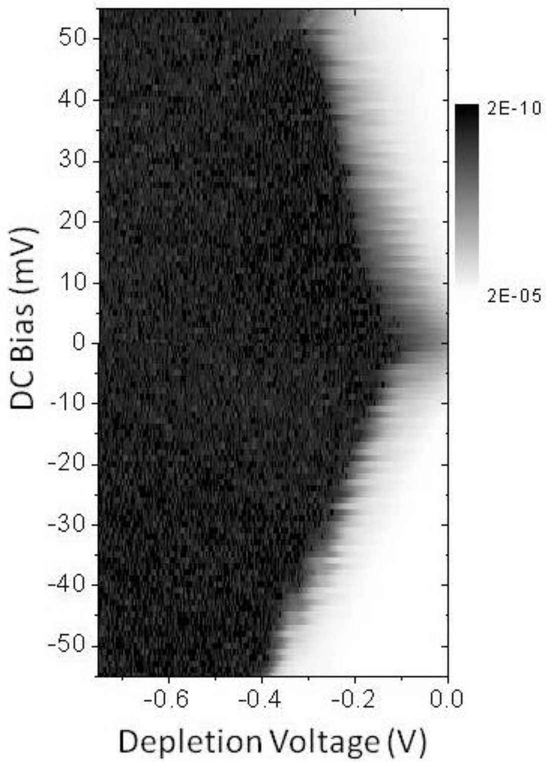
SEM Image after EBL Patterning



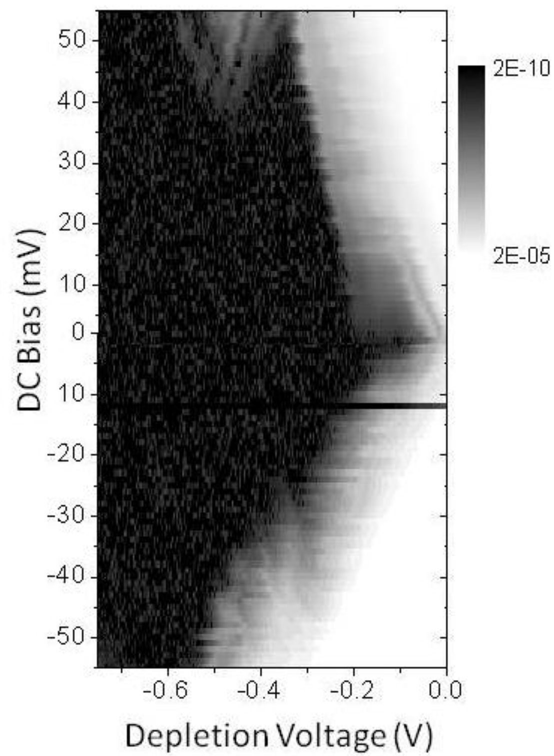
- Designed opening ~80 x 80 nm
- Defines the ion spot size required for localized position dependence, <100 nm

Comparison between Control, Si and Sb

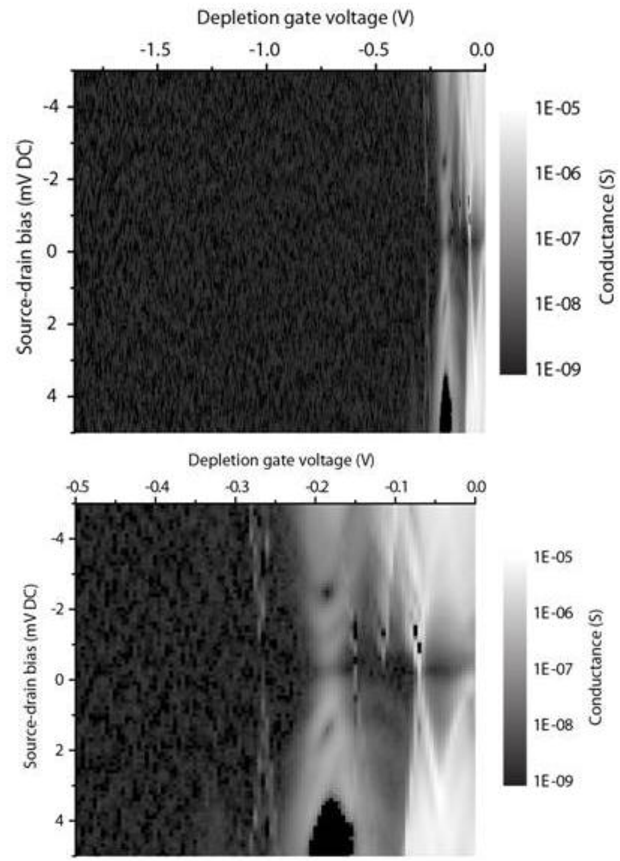
No implant

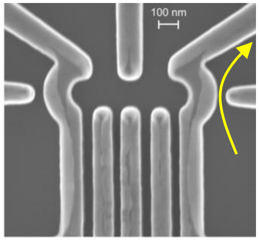


40 keV Si implant



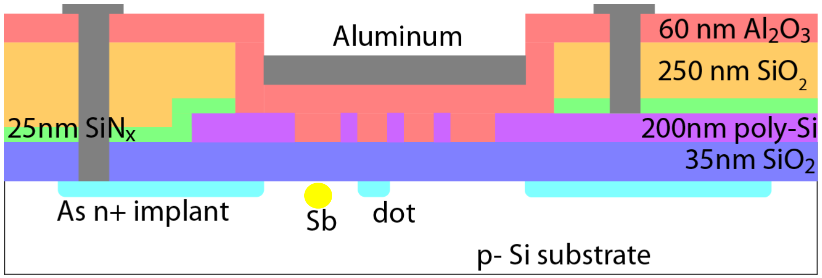
100 keV Sb implant



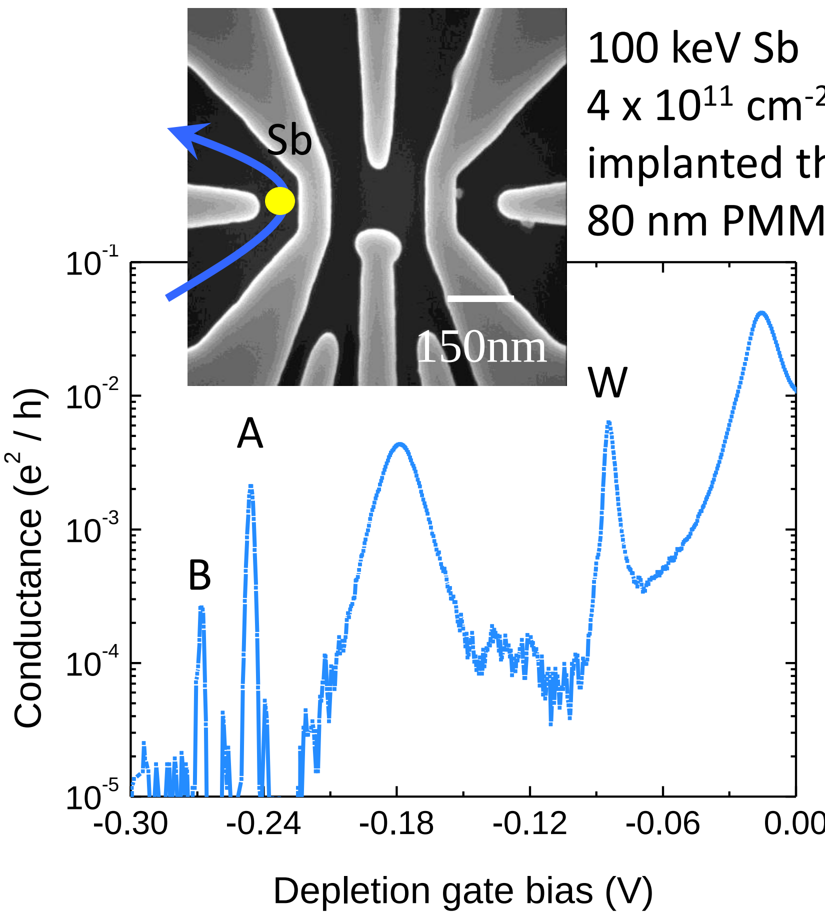


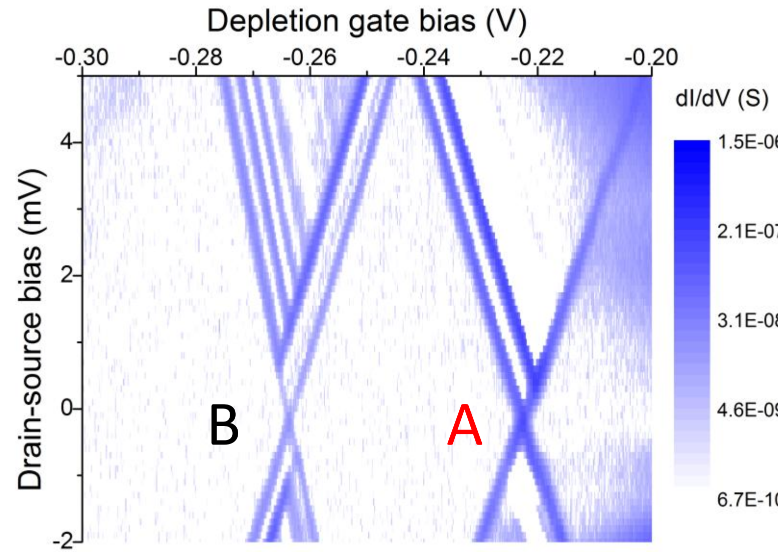
Sandia National Laboratories

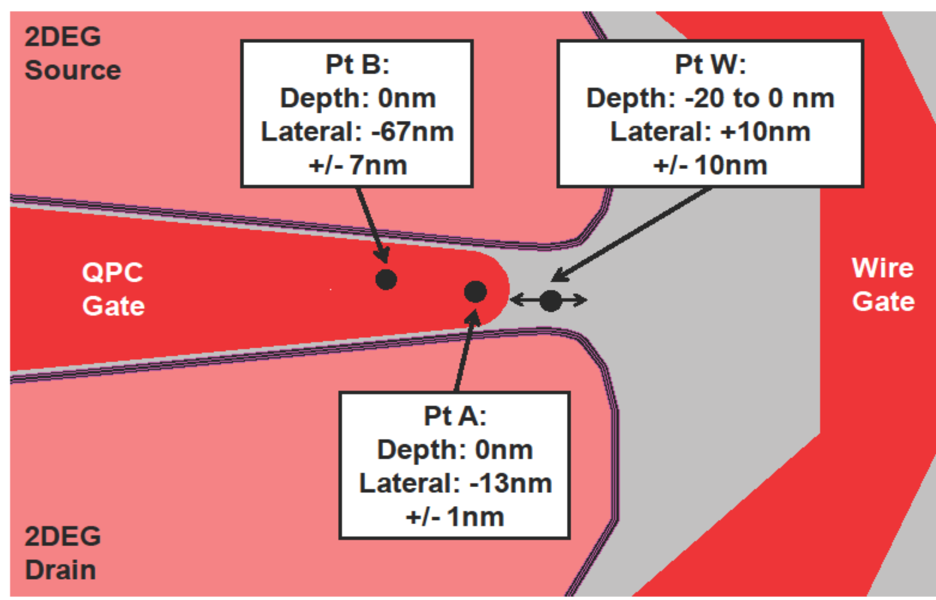
Initial Timed Donor Devices Results



100 keV Sb
4 x 10^{11} cm^{-2} dose
implanted through
80 nm PMMA mask







Outline:

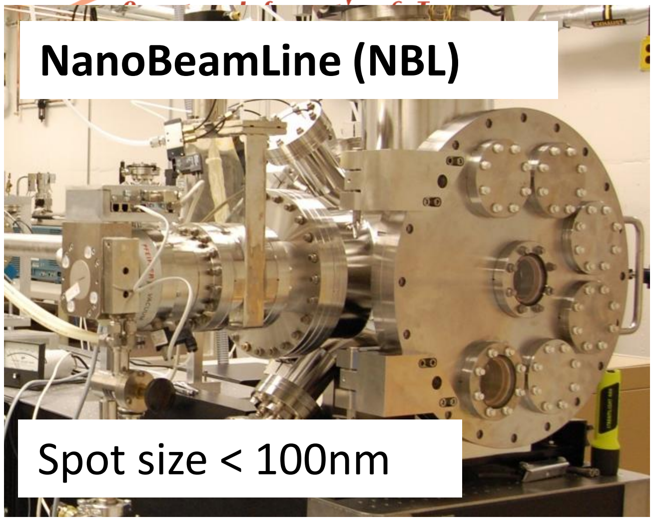
1.) Single Ion Detection

2.) Integration with Nanostructured Devices

3.) Focused Ion Beam Development

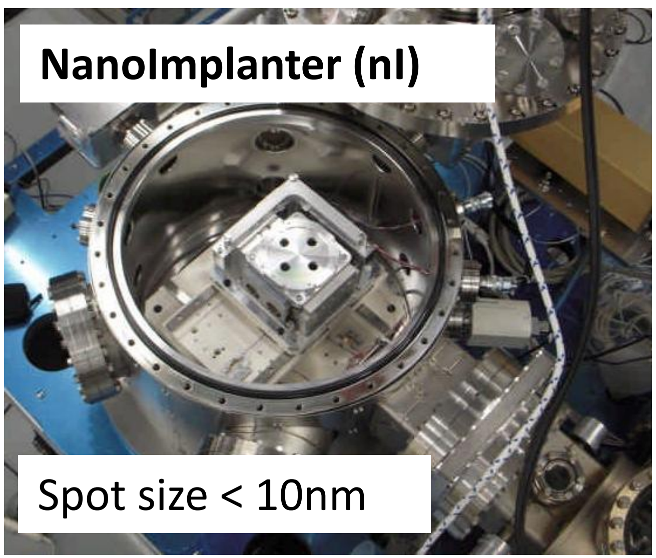
4.) Conclusions

Focused Ion Beam Development at the IBL



NanoBeamLine (NBL) on 400 kV HVEE Implanter

- Attached to the 400 kV HVEE implanter with sources for P, Sb, B, etc… readily available from 20 to 400 keV
- New LN2/LHe sample stage with 100 mm of travel will allow for discrete device and wafer level implantation
- Targeting spot size of <100 nm in the third version of this beam-line at the IBL



NanoImplanter (nI) 100 kV FIB

- New 100 kV FIB with ExB filter for multiple ion sources. Liquid metal ion sources (LMIS) for Sb and P under development.
- New nI sample stage 100 mm of travel with 2.5 nm resolution will allow for large scale implantation
- New nI with spot size <10 nm with 1 pA of beam current including capabilities for lithography, gas assisted etching and deposition and SEM

Sandia National Laboratories

70,000 ft view of NanoImplanter (nI)

Brief History of Machines with Similar Capabilities

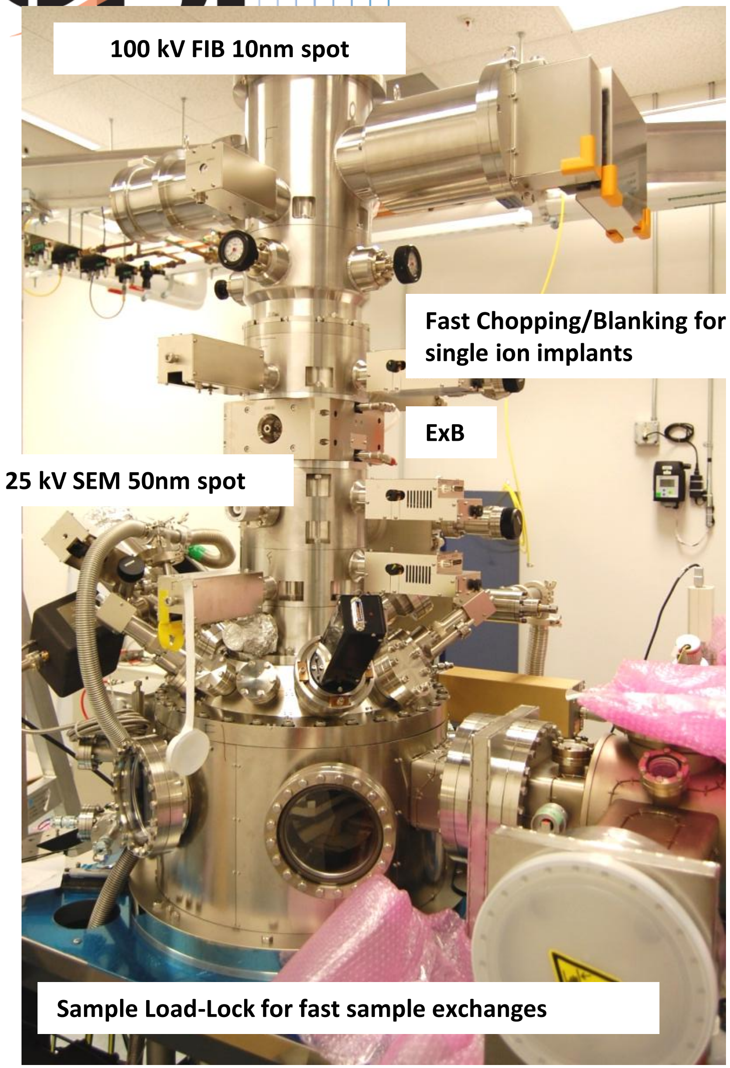
- 1980s-2000s a series of instruments were produced from several vendors, most notably the MicroBeam NanoFab150, these instruments were used in a series of university and government labs for nm-um scale modifications of electrical and optical properties of semiconductor materials

High Level NanoImplanter Capabilities –

- High ***Resolution*** of a FIB
- 100 kV Accelerating Voltage
- ***Variable Current*** from pAs to ***Single Ion***
- Broad Range of ***Ion Sources*** (Ion Species)

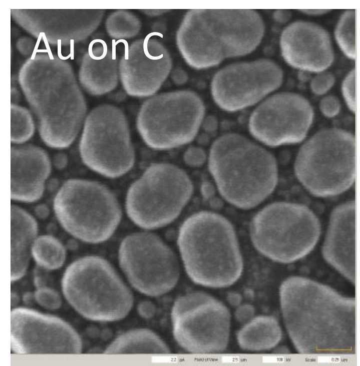
Nanoscale fabrication and material modification for new materials/devices

NanoImplanter (nI) Status at SNL

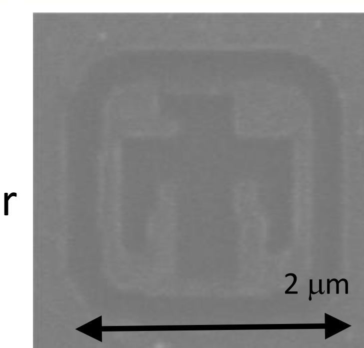


<u>Current Status</u>

- Installation Started on January 17, 2011
- System Accepted March 12, 2011
- Demonstrated ~10nm spot Ga+ beam at 100 keV
- Demonstrated dual-beam operation using the FIB and 25 keV SEM
- Demonstrated ~15nm spot Si++ beam at 200 keV
- Expect to be fully operational in Q4 FY11

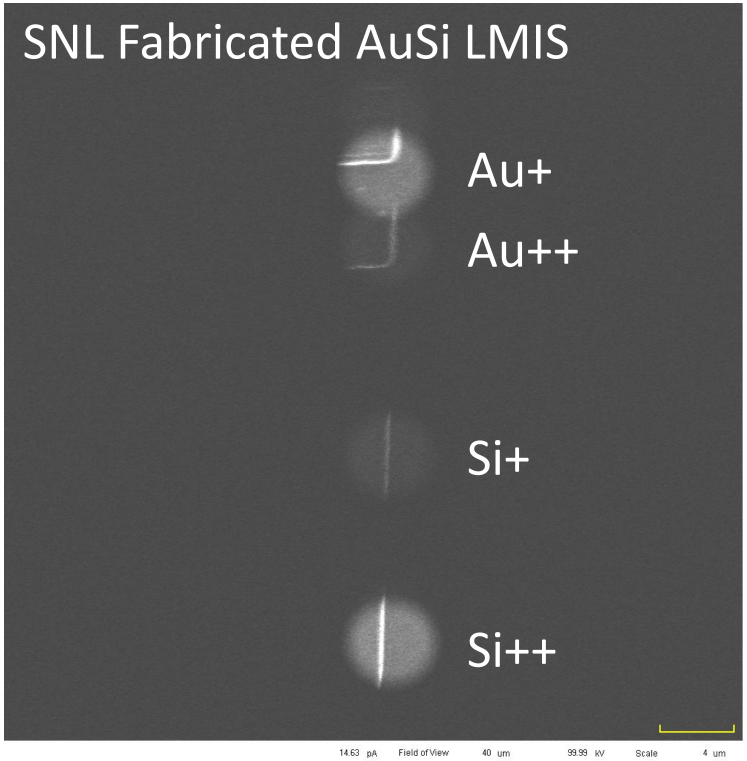


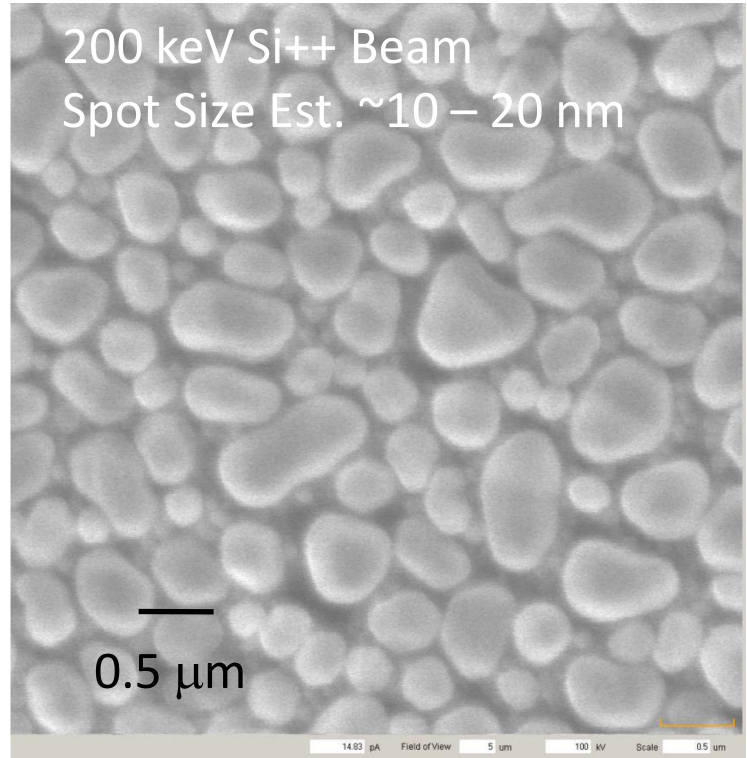
Examples of FIB imaging and machining using 100 keV Ga+ beam and Raith ELPHY+ Pattern Generator



A&D Company, Limited

Demonstration of AuSi LMIS using the ExB Filter running at SNL



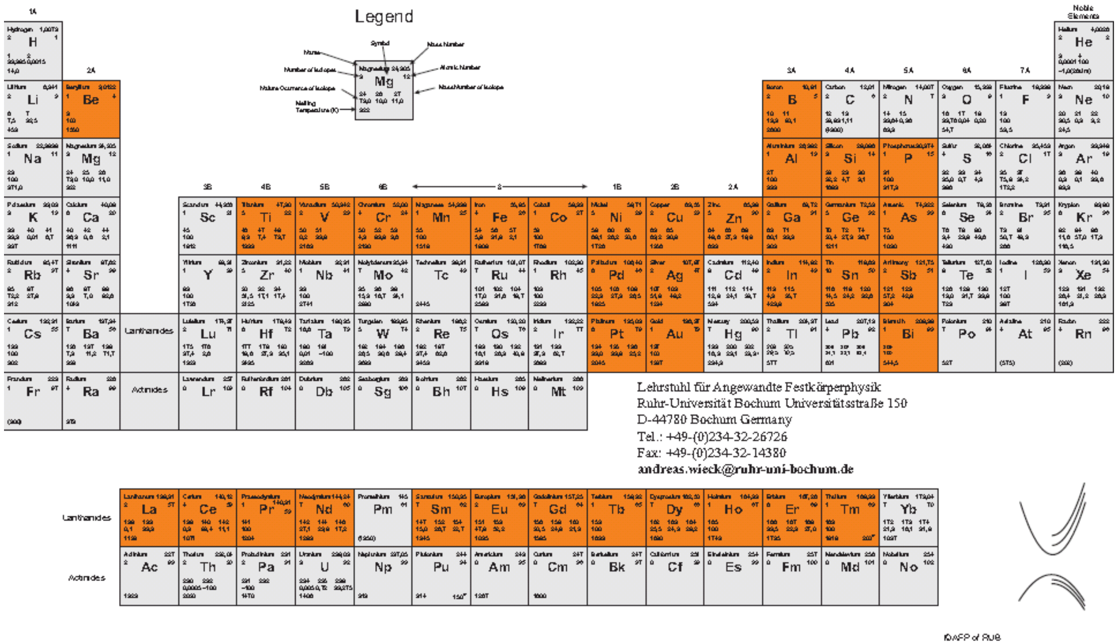


- Using a ***SNL fabricated*** AuSi sources we have demonstrated the ability to mass and velocity separate Au+, Au++, Si+ and Si++ using our system
- This is a key demonstration showing the ability to control the implantation species and energy (key distinguishing feature between the nI and standard FIB systems)

ExB Settings for Si++:

Set E = 1 kV/cm, final aperture at 60 μm
Set B to 0.085 T (calculated), 0.1186 T (expt)

Liquid Metal Ion Source (LMIS) Development



From Professor Weick Ruhr Uni Bochum

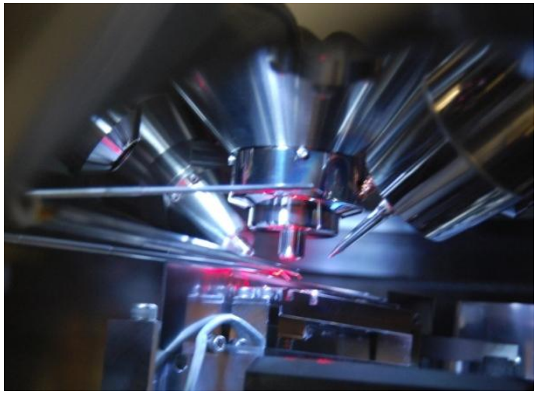
- Production of LMIS using our in-house source preparation unit allowing us to customize a wide variety of LMIS alloys
- Working with Professor Weick's group to develop the a series of standard Si processing LMIS including P, Sb and Bi
- Developing a working relationship with Raith USA to develop a series of LMIS

Sandia National Laboratories

Additional Capabilities

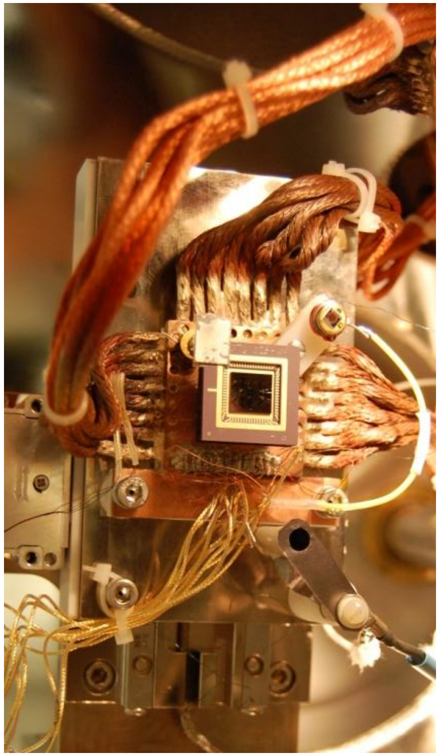
• **Micro-Manipulators for electric probing and sample manipulation**

Allows for probing of wafer level devices with 10 nm resolution



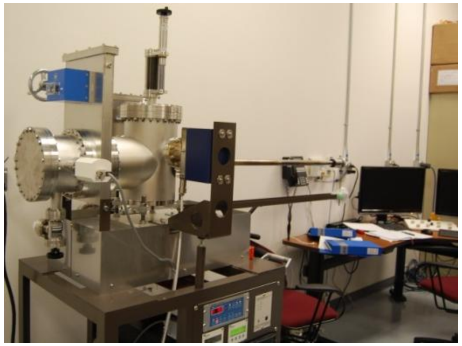
Kleindike probes installed in nI

• **Low Temperature Stage** *



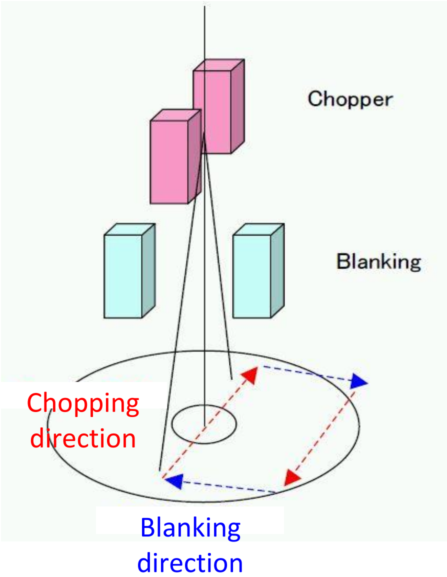
* Under development

• **Vacuum Suitcase Transfer System**



Vacuum Suitcase for sample transfers

• **Fast Blanking/Chopping**



Deterministic Single Ion Implantation Status

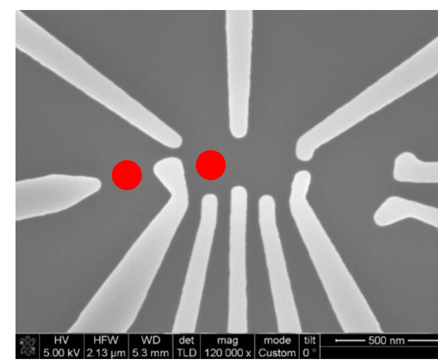
- ***<u>Multiple Ion Sources</u>*** – **Ready, P, Sb on hand (CuPtP, AuSiSb LMIS from Weick)**

- Need … ion of the ExB filter re… Sb beams

Ran Sb source on 9/13/2011

- Sources for P, Sb, Si, Au, Pt, Cu, Bi and Ga on-hand

- ***<u>Single Ion</u>*** – **Single Ion Implantation and Detection ready using SEDs**
  - Initial work will use Secondary Electron Detectors (SEDs)
  - Question of detection efficiency – we assume about 80% (typically for SEDs) (Newest work by Shinada suggests ~100% possible)
  - Need to build cold stage for other detection work (APDs)



- ***<u>Resolution</u>*** – **Achieved beams ~10 nm diameter**
  - Devices ready for deterministic implants of P, Sb and Si into the self-aligned poly-Si gated structures for single electron spin transport experiments

- ***<u>Why nI?</u>***
  - ***<u>Good localization</u>*** (10nm hard, 20 nm easy), ***<u>Good detection</u>*** (>80% out of the box), ***<u>Good sample control</u>*** (2.5 nm resolution on the stage)

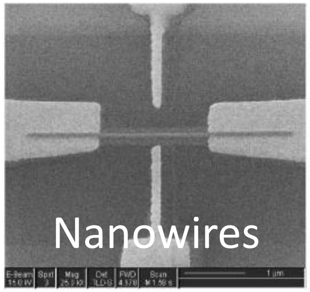
Conclusions

- We explored the Sandia approach to Quantum Information Processing through the combination of Si MOSFET devices and single donor implantation.
  - Single Ion Detection
    - Demonstrated SIGMA detectors with 100% detection efficiency for diffused carriers at RT and at 77K.
    - Demonstrated 100% detector efficiency generating only ~1000 e-h pairs in the Si body of the device.
  - Integration with Nanostructured Devices
    - Timed Donor Implanted devices show potential and pitfalls for single electron spin transport
  - Focused Ion Beam Implantation
    - A new nanoimplanter is operational with <10 nm spot size

NanoImplanter Application Space

Rapid Prototyping through Nanostructural and Nanoelectronic Modifications: → **needs resolution, multiple ion sources**

- Nanoelectronics – In-plane transistors, deterministic doping for FinFETs, Nanowires, Memreistors, etc…
- Nanostructural modifications of material systems (implantation), MEMS structures (milling)



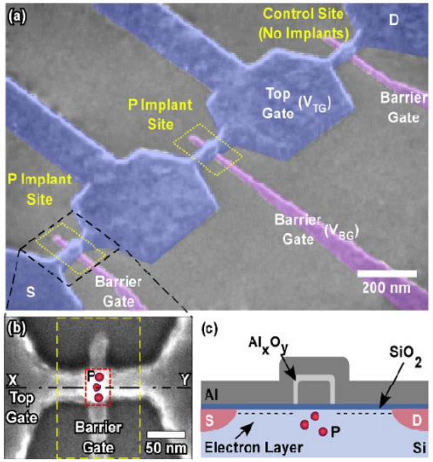
Y. Tsukutani *et al.*, J. J. App. Phys. **44**, 5683 (2005)

Fundamental Nanoscience R&D: → **needs resolution, variable current, multiple ion sources**

- Nanopatterning to produce localized defect concentrations

Deterministic Single Ion Implantation: → **needs resolution, single ion, multiple ion sources**

- Donor Based Solid State Qubits for Quantum Computing
- Defects in Diamond for Quantum Computing, Single Photon Sources
- Magnetic Impurities in GaAs Nanostructures



K. Tan *et al.*, Nano Lett. **10**, 11 (2010)

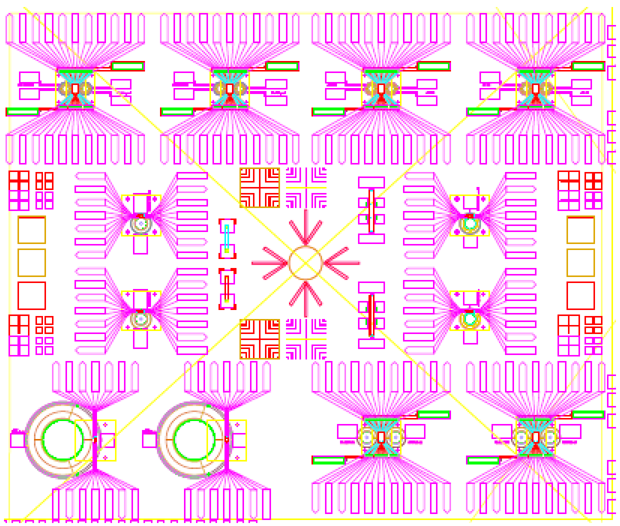
Future Work Development: → **using combinations of the following - high resolution, single ion, multiple ion sources, gas assisted etching and deposition, …**

Sandia National Laboratories

Extra Slides

Layout of the RS761 Devices

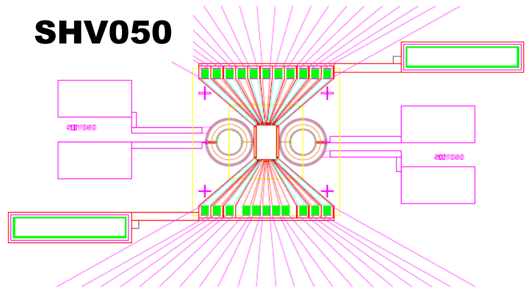
Overview of the Layout



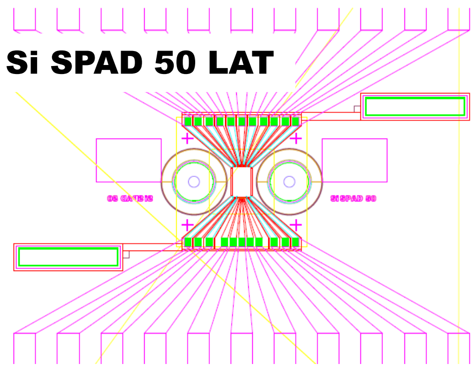
- **Lateral Devices** – implant region outside active region, rely on diffused carrier detection, but clearer implant region
- **Integrated Devices** – rely on active region detection, but potential issues with internal electric fields

Lateral Devices

SHV050

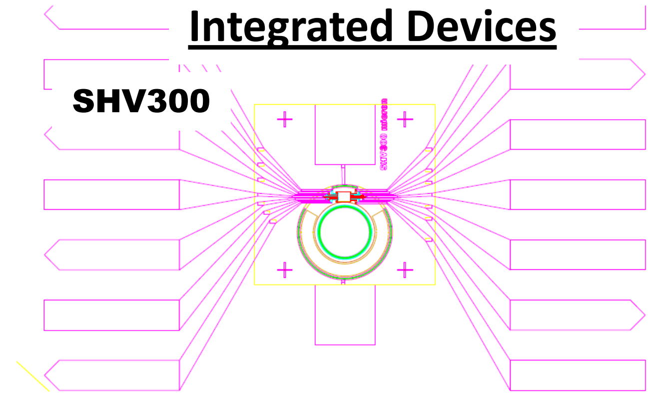


Si SPAD 50 LAT

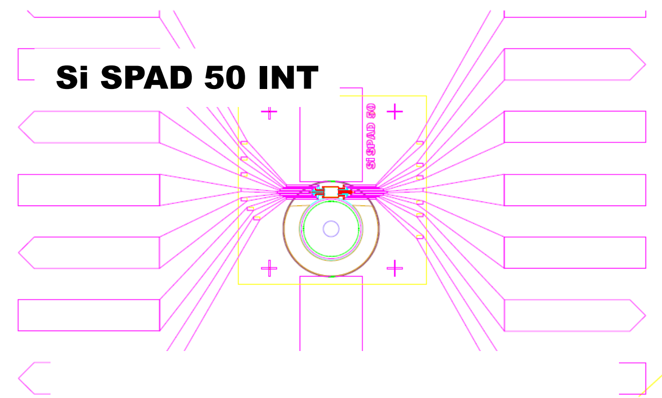


Integrated Devices

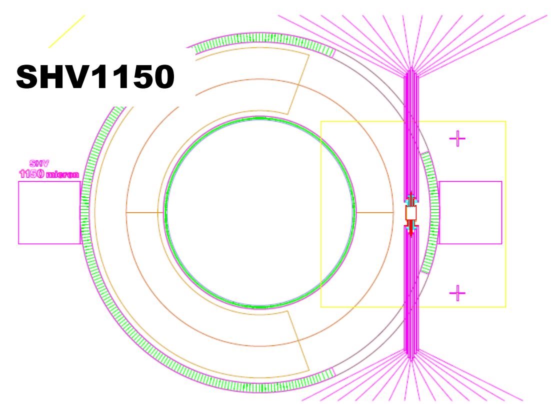
SHV300



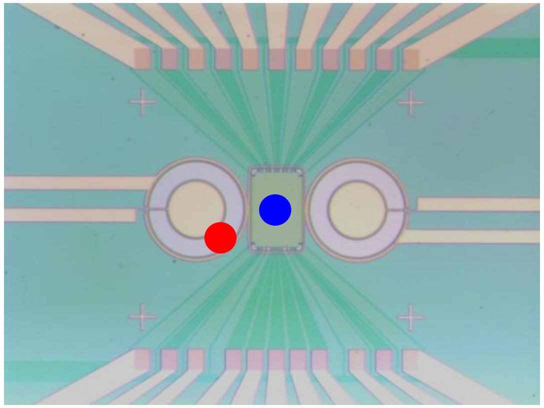
Si SPAD 50 INT

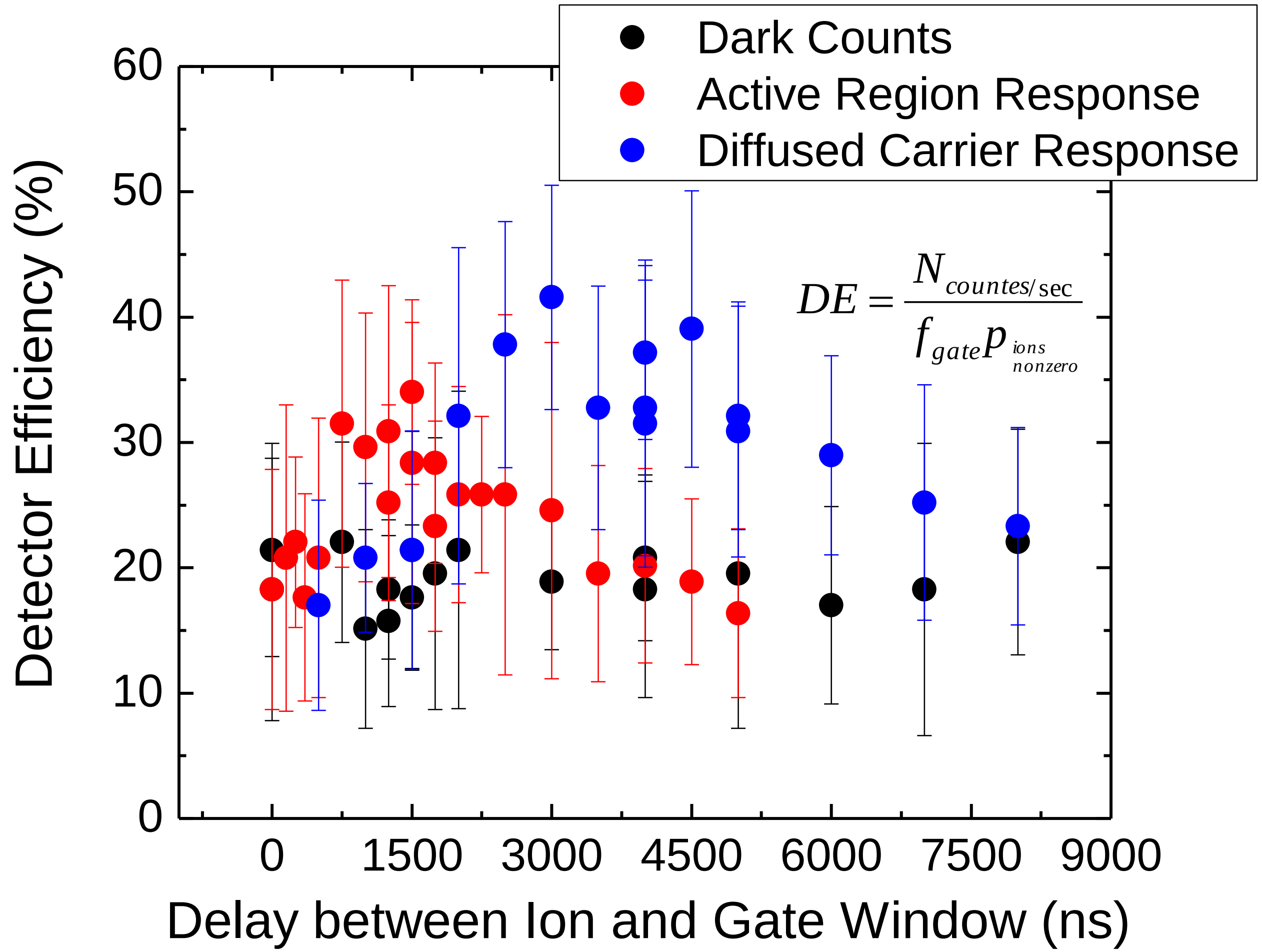


SHV1150



Integrated SIGMA Devices (p substrate)

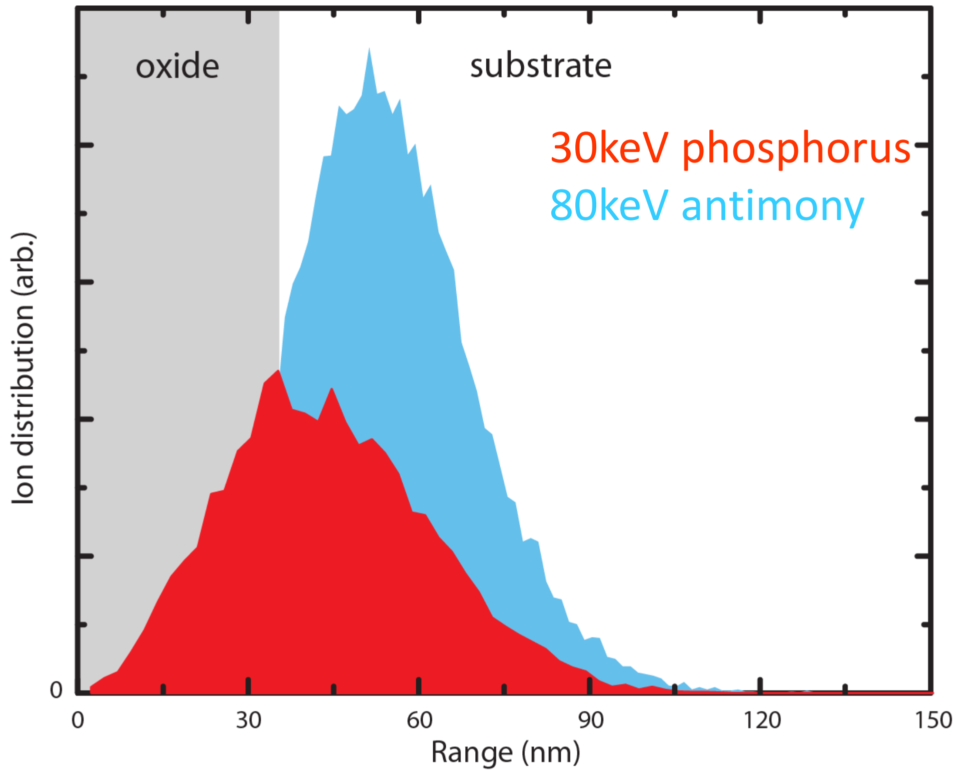




Detect single ions with ~30-40% detection efficiency for active and diffused carriers with RS761 at ~235K

Ion Irradiation with 120 keV H+ at ~1 ions/gate

Implanted donor distribution: Why Sb?



Antimony:

- More implant damage
- Activates at higher temp (900+ ^{0}C)
- Low diffusivity
- Low straggle

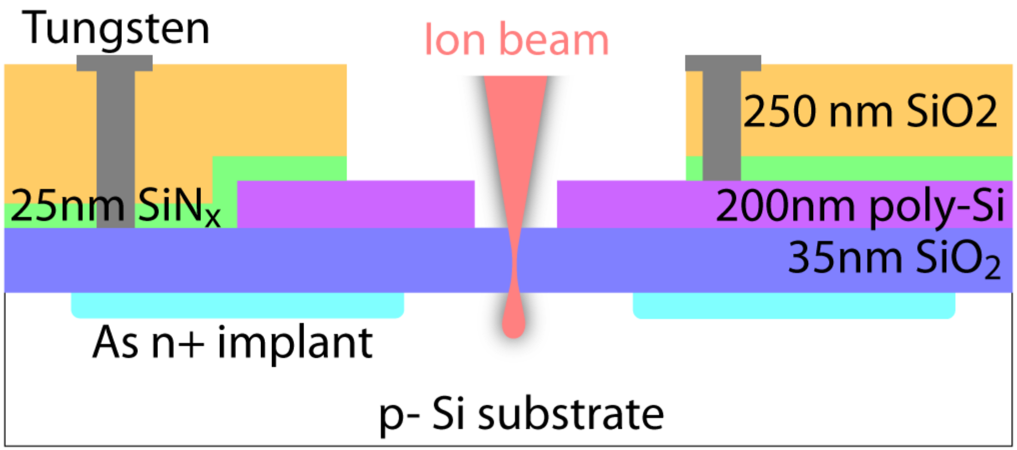
	30 seconds	24 minutes
Phosphorus	30 nm	200 nm
Antimony	0.8 nm	6 nm

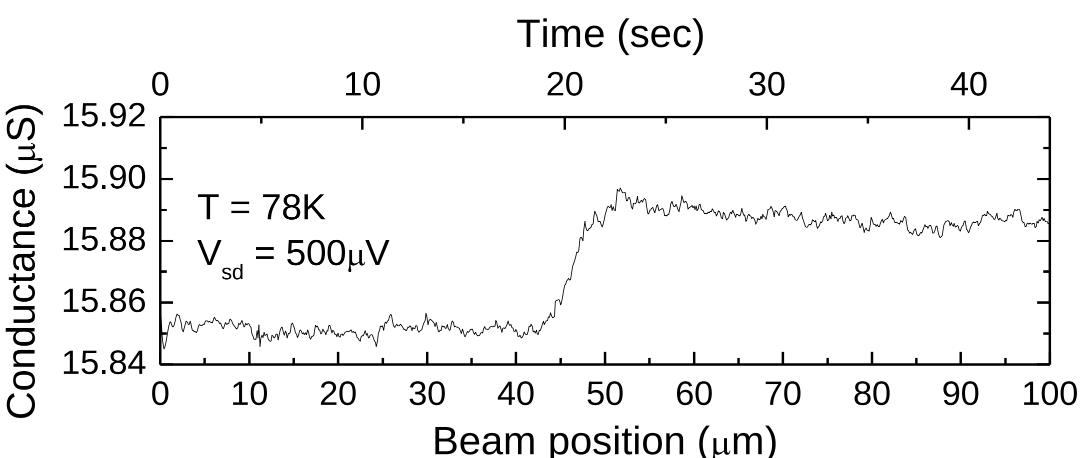
donor diffusivity

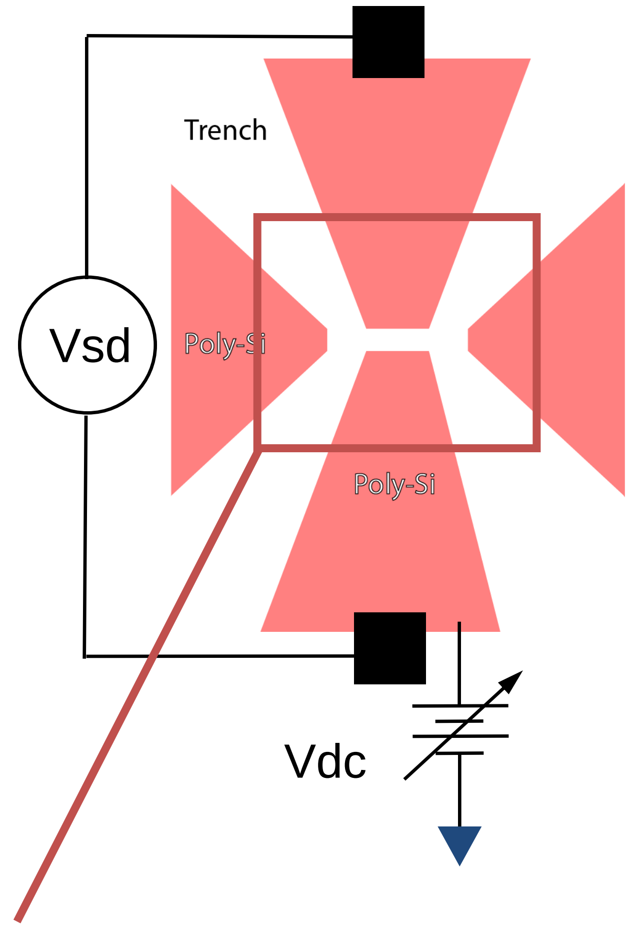
S. Matsumoto, et al., Japan. J. Appl. Phys. (1972), A. N. Gorban and V. A. Gorodokin, RPJ (1989), M. Yoshida, Japan. J. Appl. Phys.(1983), N. Larsen, et al., J. Appl. Phys. (1996), R. B. Fair, et al., J. Mater. Res. **1**, 705 (1986).

Another Detection Scheme - Single Ion Detection in the Device

Single Poly Test Structure –







250 keV Proton beam raster window

Coupling to Modeling Effort

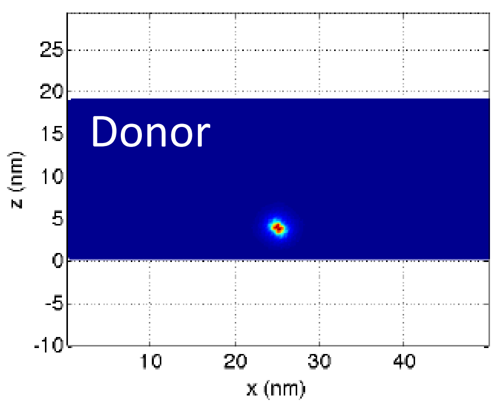
Start addressing questions such as the optimal donor depth and field needed for coupling

- Too shallow and dominated by the donor potential independent of the DQD configuration?
- Too deep and requires too large and field to couple, and tunneling rates greatly reduced?

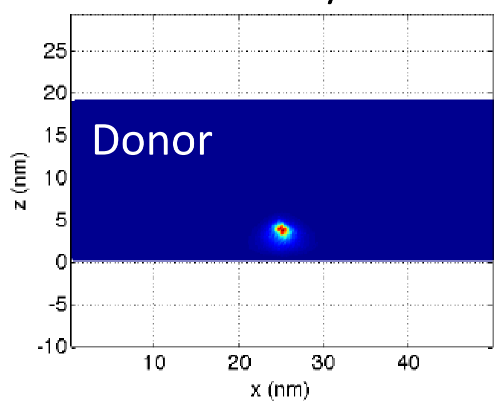
Donor to Dot tunneling: Parabolic SQD coupled to a donor at 3.8 nm from the barrier

Ground state

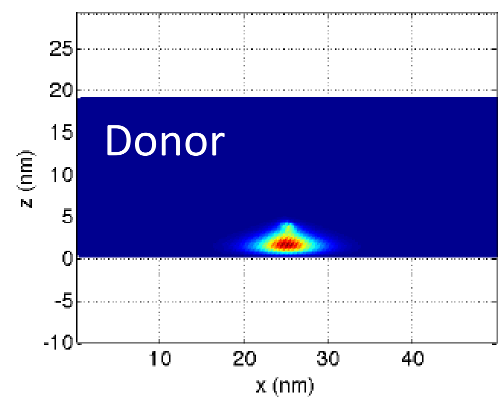
E=0 MV/m



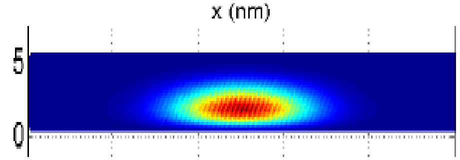
E=20 MV/m



E=40 MV/m

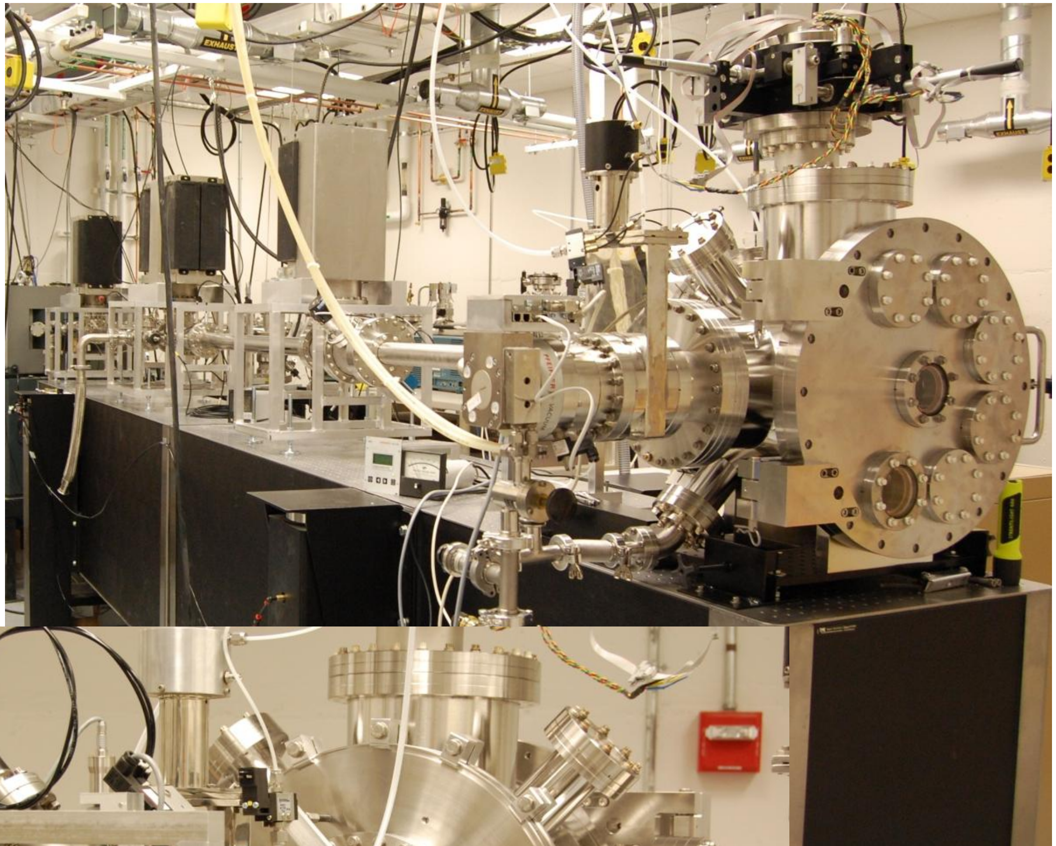


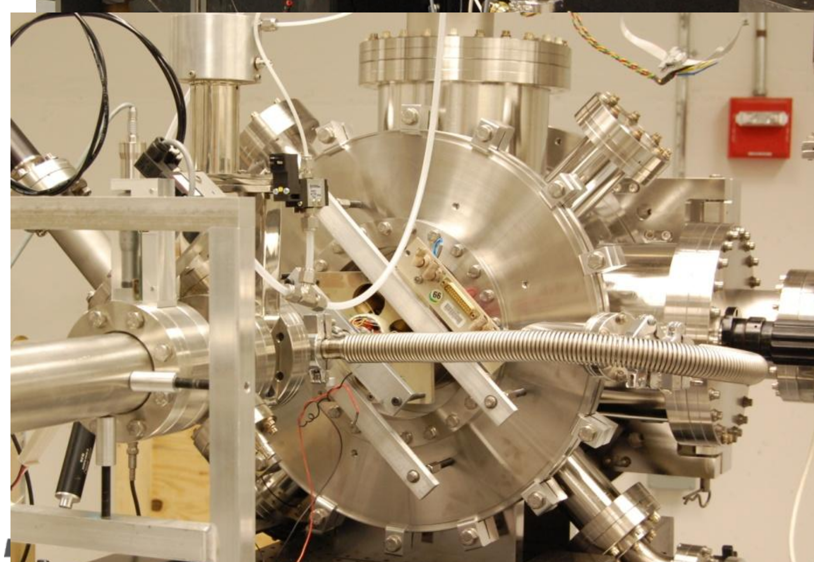
E=20 no donor
SQD Potential



Rajib Rahman

New Beam-line under construction to further reduce spot size





- Existing system spot size <800nm
- Need to push down to <100nm for single ion implantation.
- How to get there?
  - Optical table to reduce vibration
  - New end-station (recessed focusing magnet) and increased beam-line length to maximize demagnification on target
- We are targeting a spot size on the order of 25 x 25 nm

Completion expected in Summer 2010

Sandia National Laboratories

Beam-line Modeling Results using PBOLabs Software

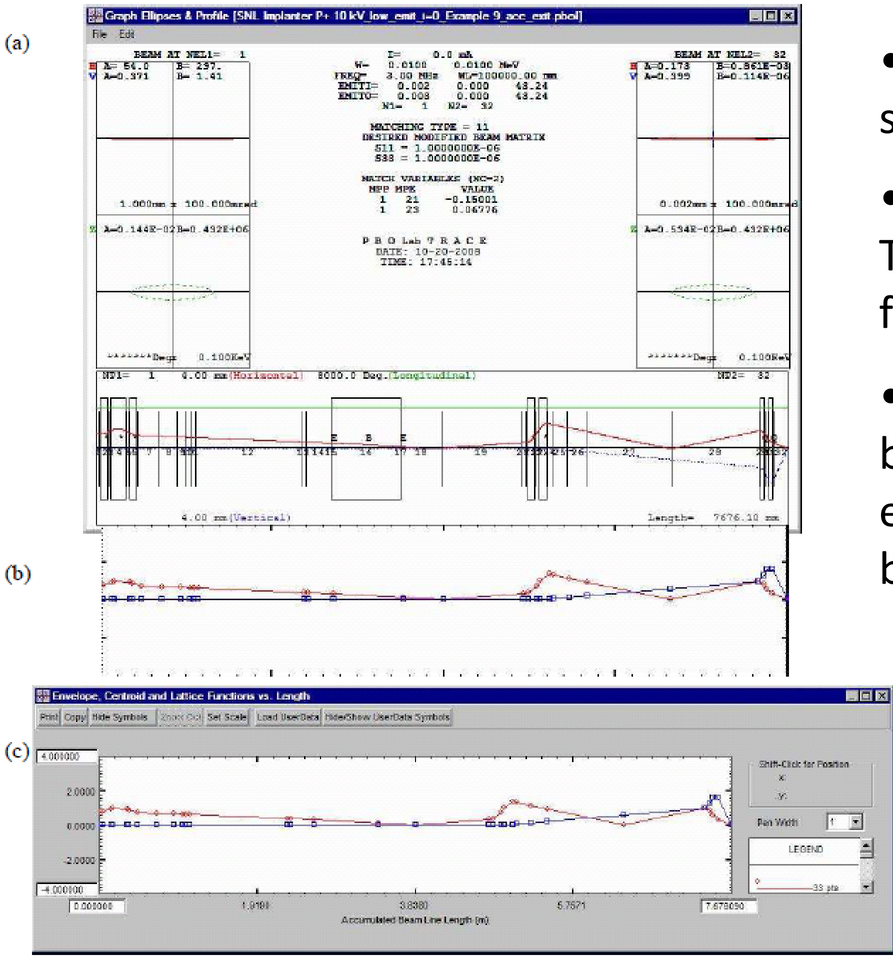


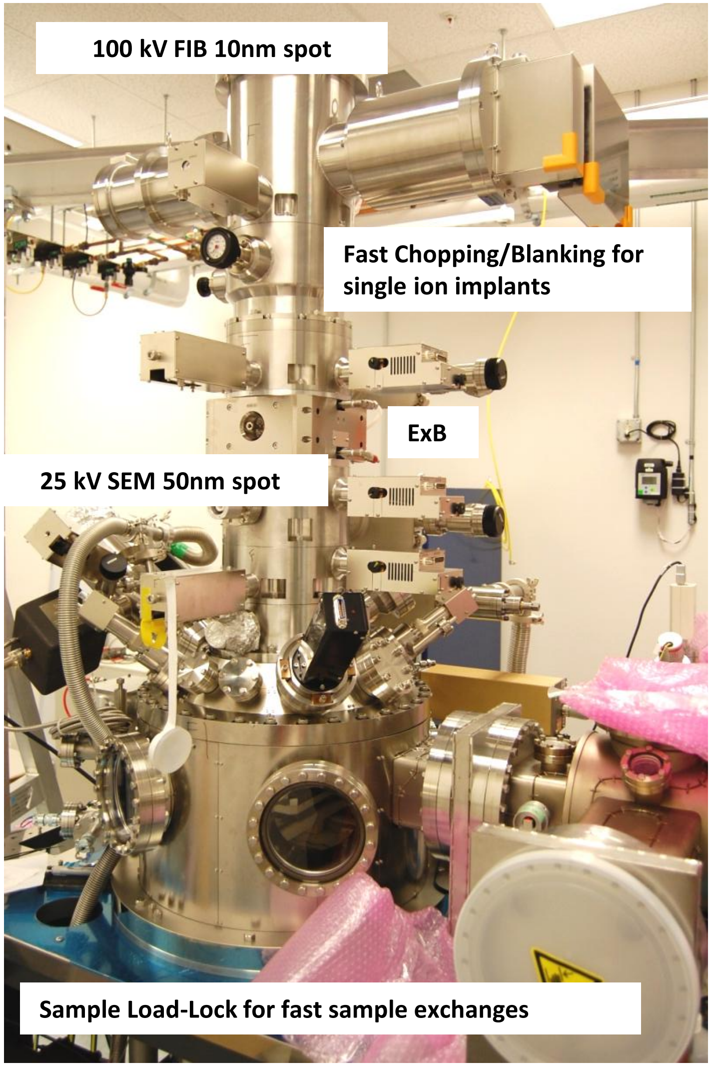
Figure I-6. Comparison of the "Example 9" TRACE 3-D envelopes (a) with the TRANSPORT envelopes (b and c) for the SNL HVEE beamline from the accelerator exit to the target plane. The vertical scale in the TRANSPORT plot window (c) has been set to correspond to the TRACE 3-D envelope vertical scale (4 mm). To further help facilitate the comparison, the middle (b) TRANSPORT plot has been scaled from the lower plot (c) to approximate the TRACE 3-D window display size.

- Complete model of the beam-line from source to target.
- New electrostatic quadruple model added to TRANSPORT and TURTLE modules to improve fidelity of models.
- Use the modeling to determine optimal beam-line configuration. Additional electrostatic focusing elements, spacing between focusing elements, etc…

- For 250 keV P^+ we calculate a 20 nm spot
- For 100 keV Sb^+ we calculate a 100 nm spot (our current donor implant beam)
- Horizontal spot size determined by dispersion occurring in the analyzing magnet.
- Beam currents on target ≥1 ion/s

NanoImplanter (nI) Overview

Unique features of the NanoImplanter in RED



- Combined Focused Ion Beam (FIB) and Scanning Electron Microscope (SEM) Dual-Beam system
- **Ion Accelerating Voltages up to 100 kV – higher energies allow deeper ion implants and sub-surface modifications**
- Ion Probe diameter less than 10 nm at 1 pA at 100 keV for Ga+ (demonstrated 20 nm for Si to-date)
- **Multiple Ion Species to include P, Sb, Pt, Si, Au, Ga, etc… using LMIS - allowing for wide range of ion species to be available for applications**
- **ExB Filter – allows for multiple charge states and ions to be resolved ex. AuSi – Au+, Au++, Si+, Si++ (better than 50 amu/charge mass resolution)**
- Internal sample stage 100 mm of travel with 2.5 nm resolution
- Focused ion beam implantation and lithography using Raith ELPHY+ lithography system, gas assisted etching/deposition
- Development of LMIS using in-house source preparation unit, collaboration with external universities and commercial company

Quantum Information S&T

LOCKHEED MARTIN A&D Company, Limited

Sandia National Laboratories

Outline:

1.) Single Ion Detection

2.) Integration with Nanostructured Devices

3.) Focused Ion Beam Development

4.) Conclusions