SAND2012-1038 C

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# Status of Top-Down Ion Implantation at Sandia

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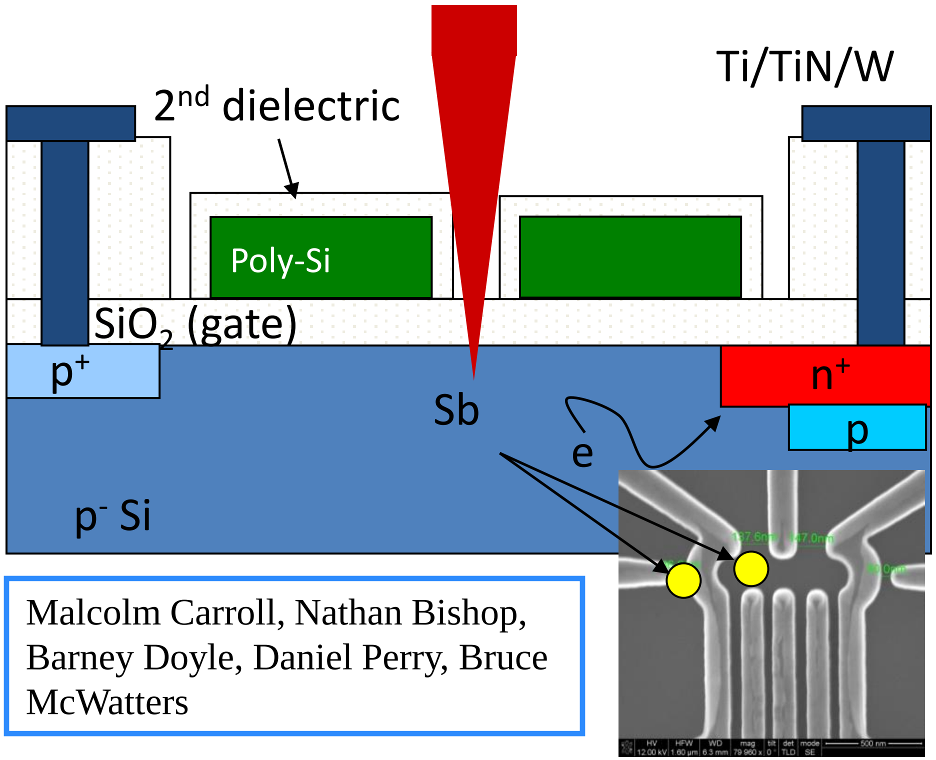
# Deterministic Single Ion Devices

*Goal:* ***Combining Donors with Si Quantum Dots for Solid State Quantum Computing Applications***




Malcolm Carroll, Nathan Bishop, Barney Doyle, Daniel Perry, Bruce McWatters

***Single ion implantation into self-aligned poly-Si defined nanostructures***

- Why Self-Aligned Poly-Si?
  - Path forward to 1 + 2 donor system
- Why Donors?
  - Proven long coherence times

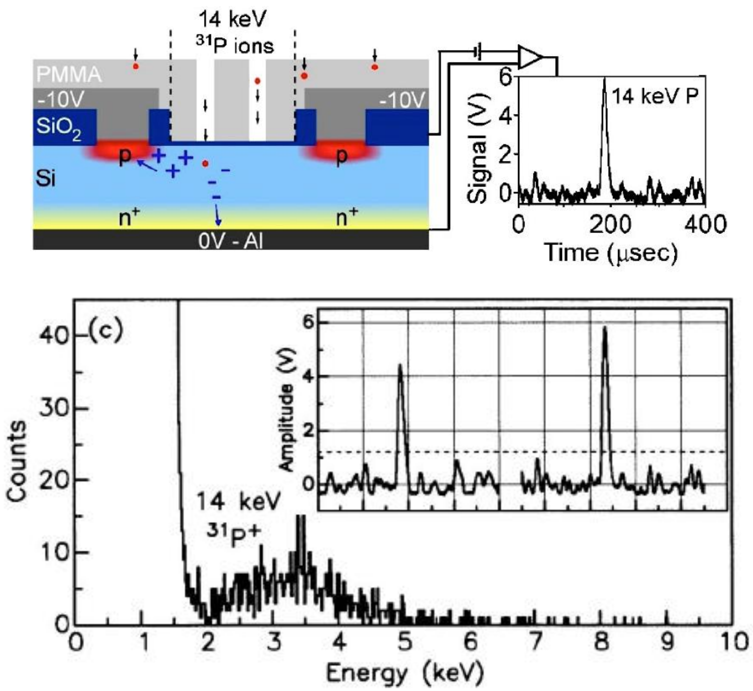
T. Schenkel *et al*., APL **88** (2006)

| 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

# Factors Affecting Ion Implantation Resolution

- 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** or improve **gain** to enable lower energy implantation!

| Ion | Energy (keV) | Range (A) | # e-h pair |
|---|---|---|---|
| **P** | **7** | **129 +/- 62** | **~700** |
| P | 14 | 224 +/- 103 | ~1400 |
| **Sb** | **10** | **124 +/- 30** | **~900** |
| Sb | 20 | 185 +/- 49 | ~1900 |

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



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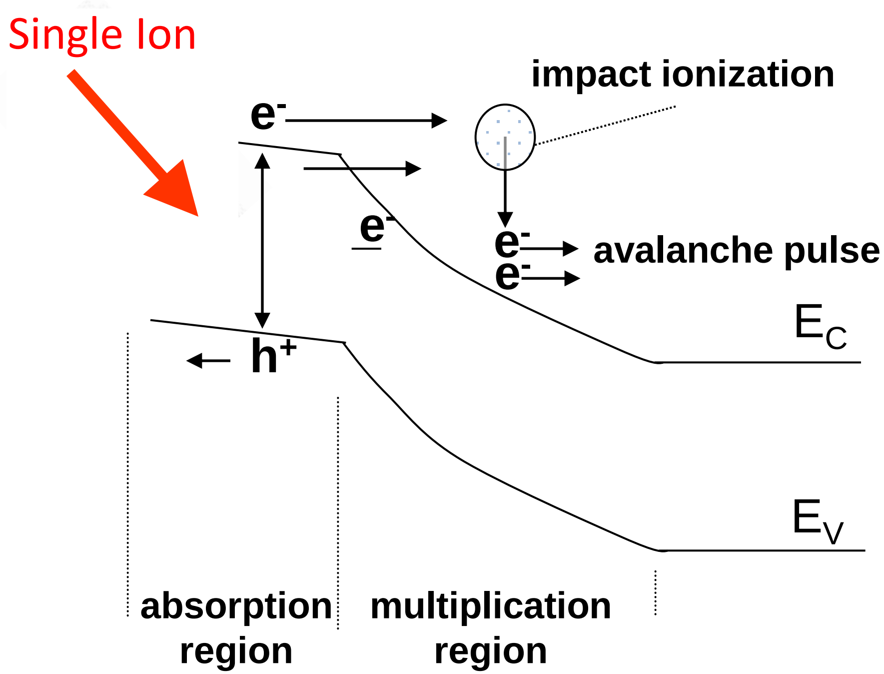
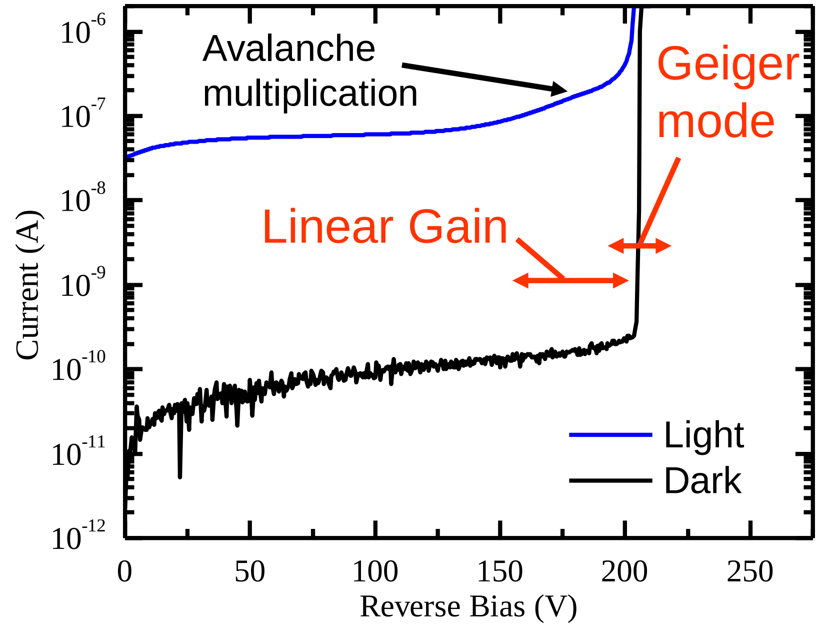
# Avalanche Photodiode (APD)




**Avalanche Photodiode**

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

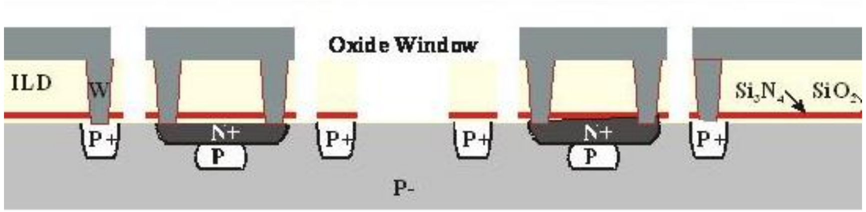
**Geiger Mode Operation**

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

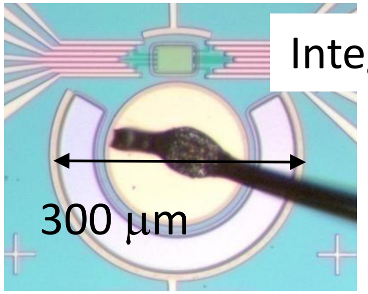
- APD produces internal gain due to high field impact ionization
- Sensitive to single photon detection (single e-h pair!)
- We run the APDs in Geiger Mode for Single Ion Detection

# Detector Structures

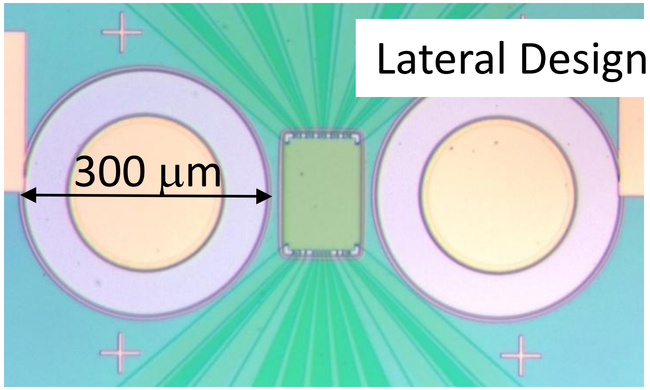
[SIGMA Detectors – Integrated with Si QD](#)




- Oxide thicknesses of 7, 10 or 35 nm
- Fabricate devices on p and p- substrates
- Vary doping profiles and geometry




Integrated Design



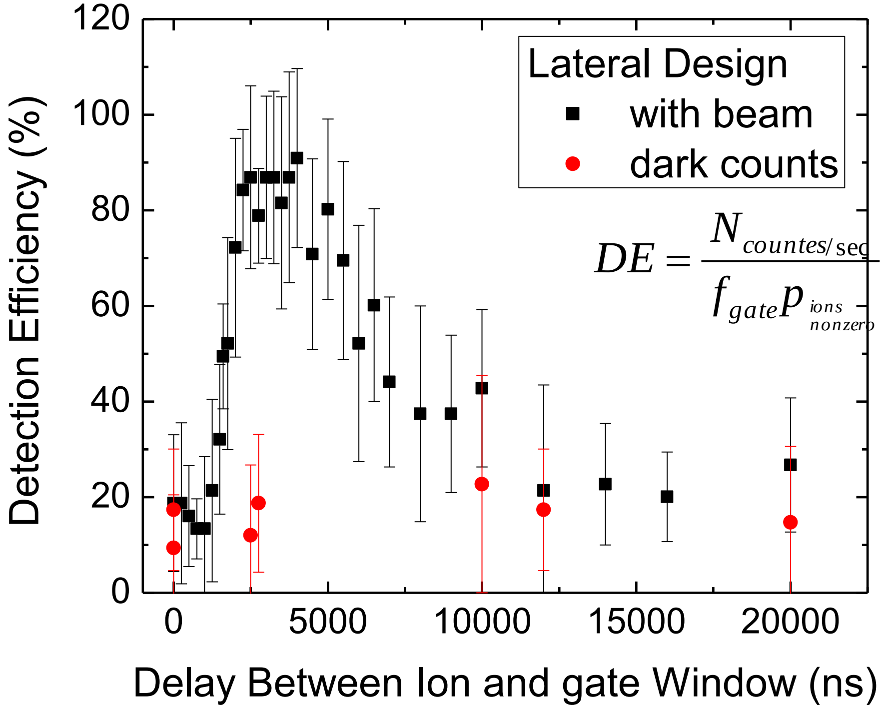

Lateral Design

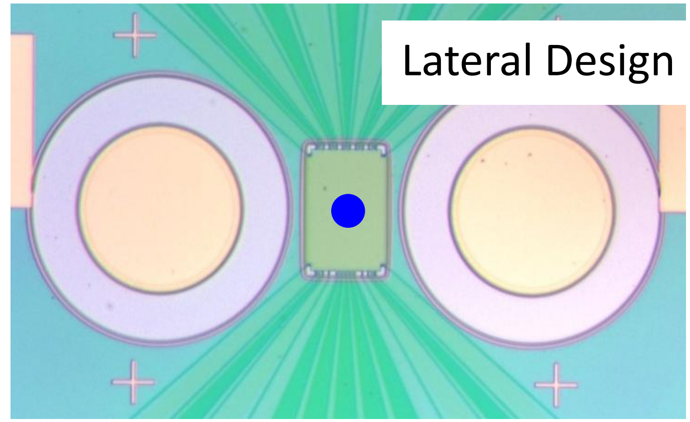
- **Integrated Devices** – rely on active region detection, but potential issues with internal electric fields

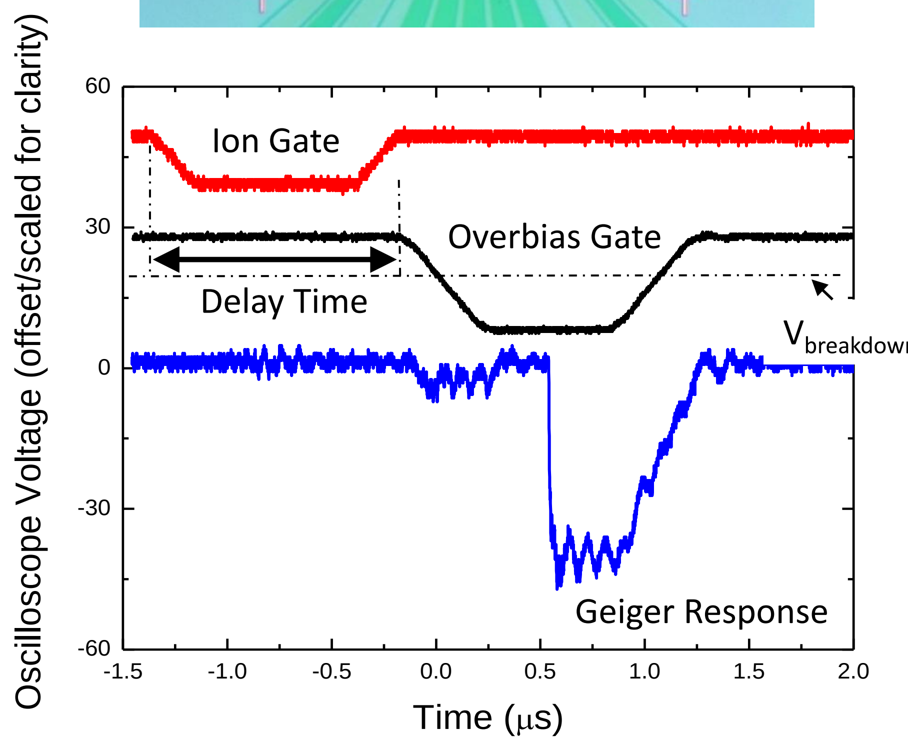
- **Lateral Devices** – implant region outside active region, rely on diffused carrier detection, but cleaner implant region

# Integrated SIGMA Devices (p substrate)

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

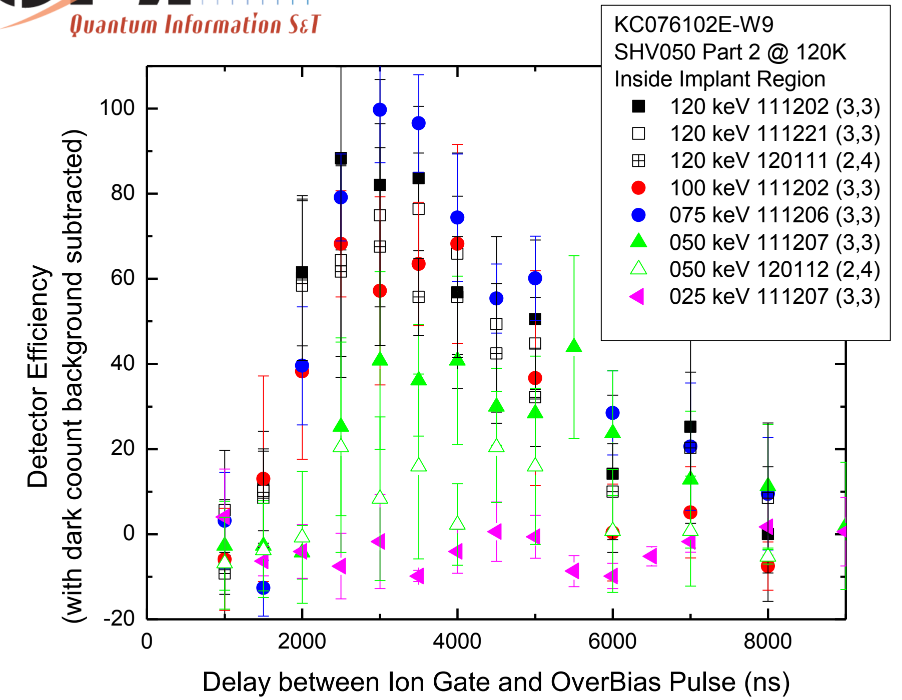


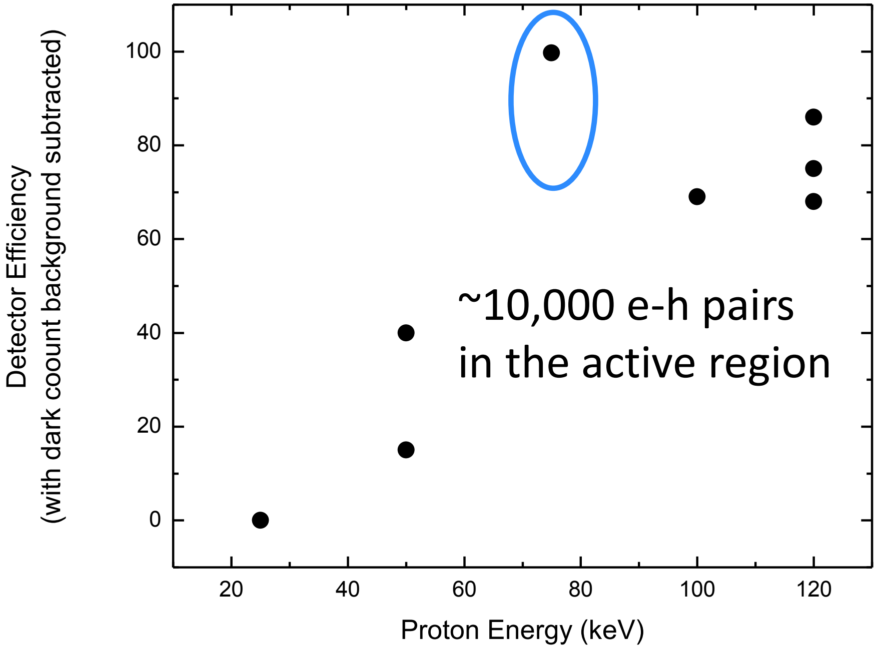



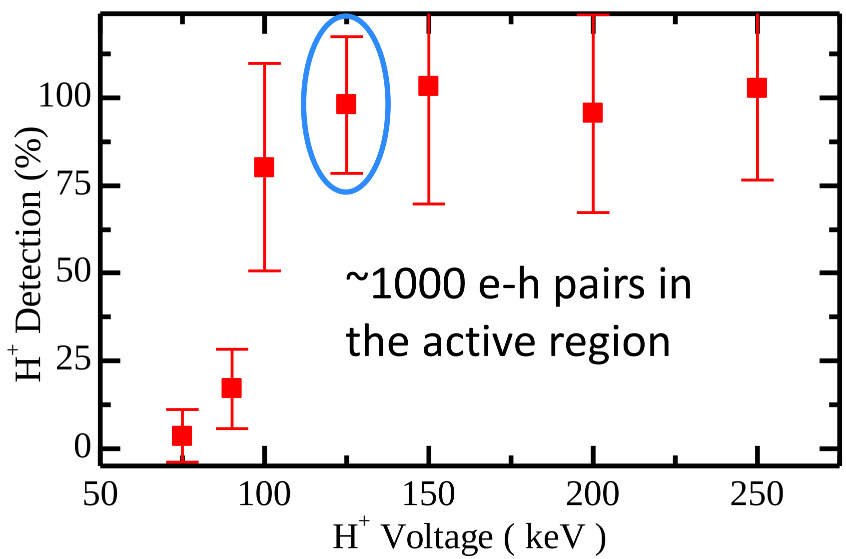

Detect single ion detection efficiency approaching 100% for diffused carriers

# Integrated SIGMA Devices (p substrate)



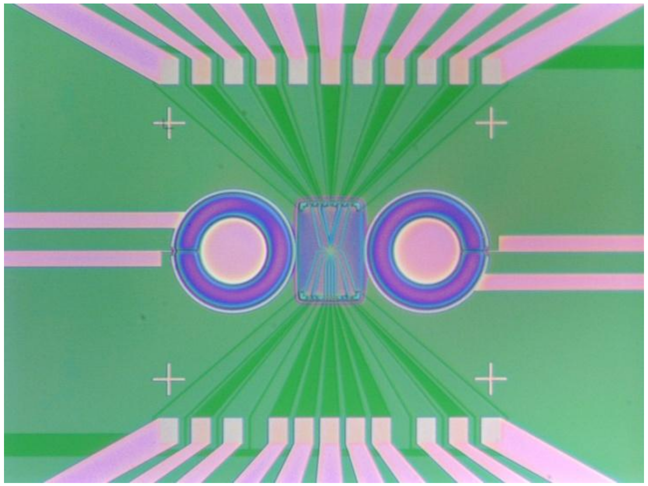

Integrated SIGMA poor low energy sensitivity compared to the discrete SIGMA devices, why?



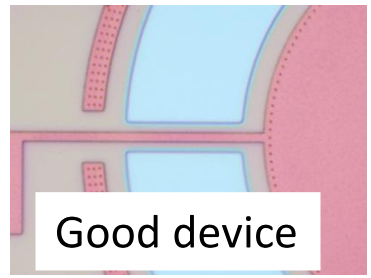

Next experiment – remove the poly Si and test with low energy heavy ion directly

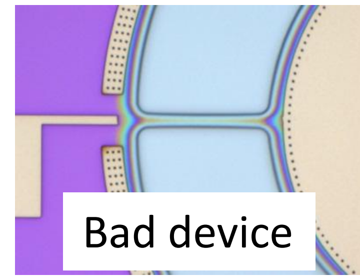
# Self-Aligned Poly Si Devices -> SIGMA + QD

**SVH050 with Gated Wire Design**



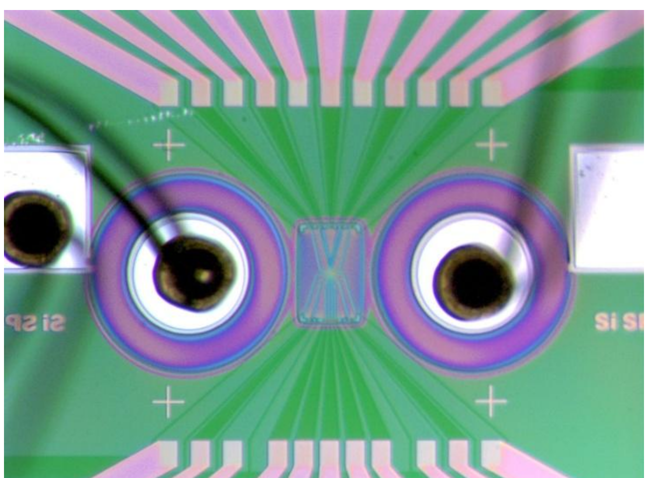
- Processing issue with the SVH050 devices most likely due to over-etch of implant windows

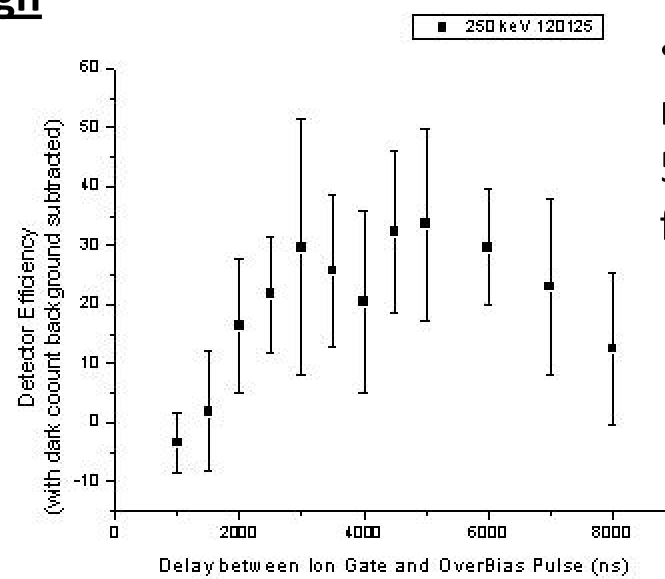



- Work around in place, started new series of devices

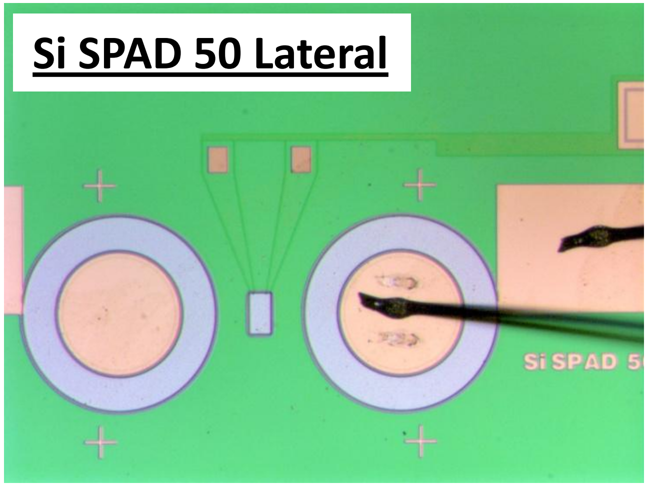
**Si SPAD 50 Lateral with Gated Wire Design**

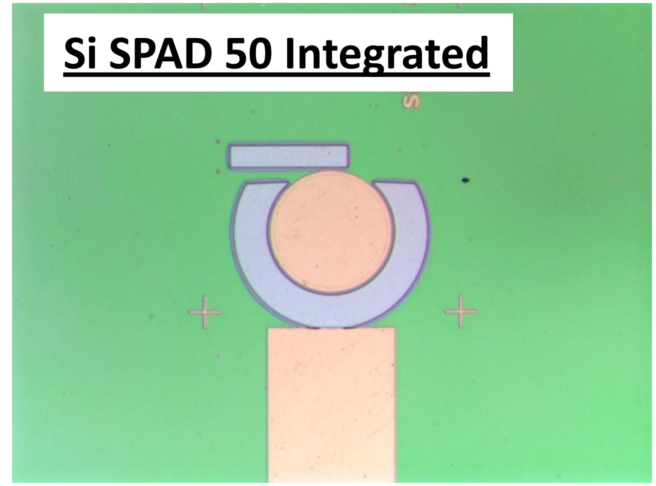


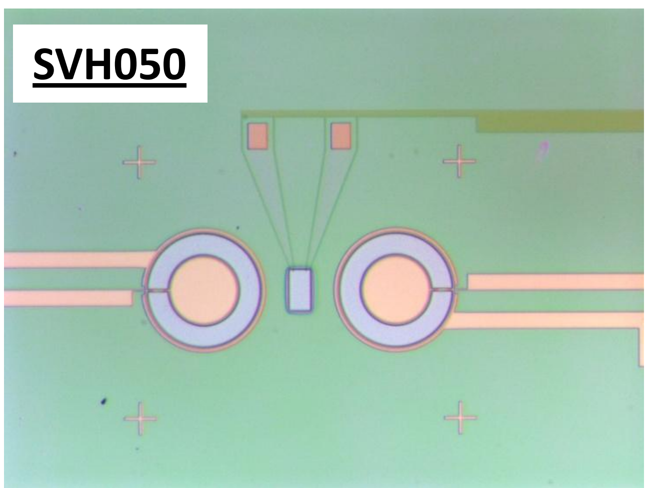


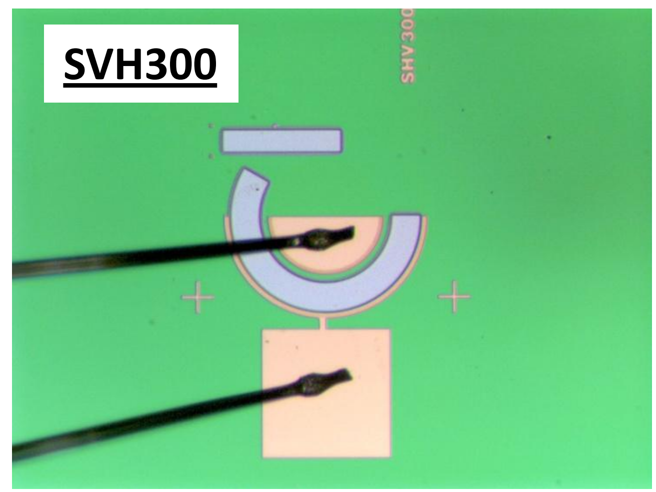

- Measure GM response to Si SPAD 50 devices for the first time.

# Al-SET Compatible CQC$^2$T Single Ion Detectors




- Wafer fab completed
- RT tested completed – DC IV and GM response
- LT tested started – DC IV, next will test with ion beam



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# Single Ion Detector Requirements and **our Results**

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

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

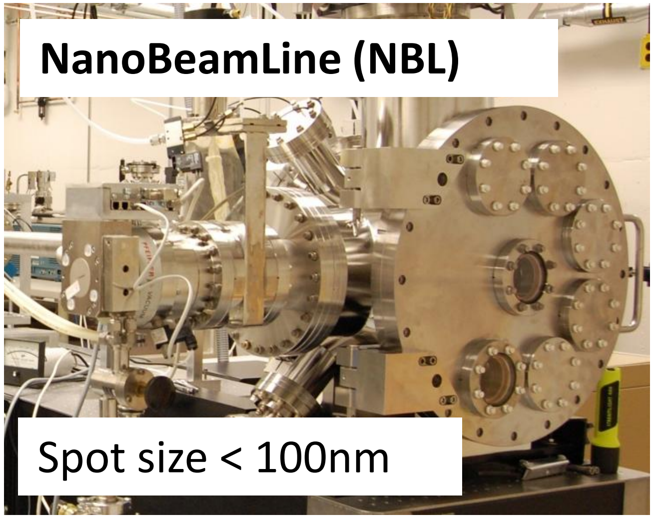
2.) Detection signal only from an implanted ion

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

3.) Diffused carrier detection

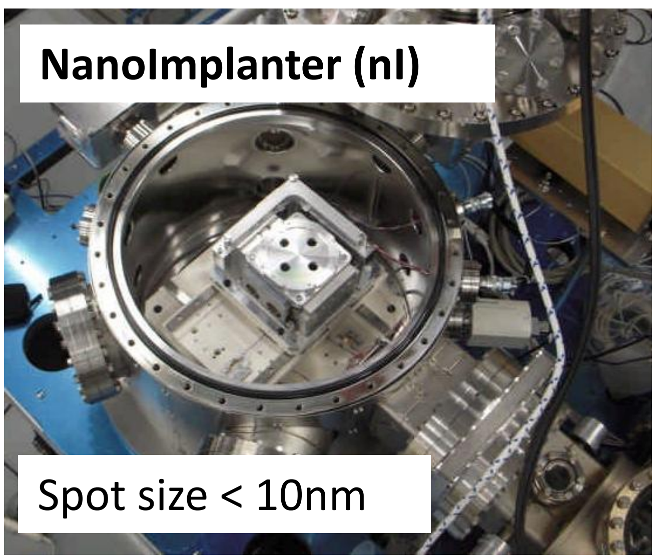
- Allows the detector to be located far (10's of μm) from the ion implantation site (less restrictions on architecture layout)
- **SIGMAs can detect diffused carriers with 100% DE at 75 μm from the detector!**

# Focused Ion Beam Development at the IBL




**<u>NanoBeamLine (NBL) on 400 kV HVEE Implanter</u>**

- Attached to standard semiconductor implanter
- ***<u>Wide range</u>*** of ion energies 10-400 keV
- ***<u>Variable Current</u>*** from µAs to ***<u>Single Ion</u>***
- Broad Range of ***<u>Ion Sources</u>*** (Ion Species)
- Targeting a spot size of <100 nm in the third version of this beam-line - ***<u>On-hold time spent on APD development</u>***




**<u>NanoImplanter (nI) 100 kV FIB</u>**

- High ***<u>Resolution</u>*** of a FIB
- 100 kV Accelerating Voltage
- ***<u>Variable Current</u>*** from pAs to ***<u>Single Ion</u>***
- Broad Range of ***<u>Ion Sources</u>*** (Ion Species)
- **<u>Ultimate resolution limit</u>** of the top-down approach will be tested using the nI



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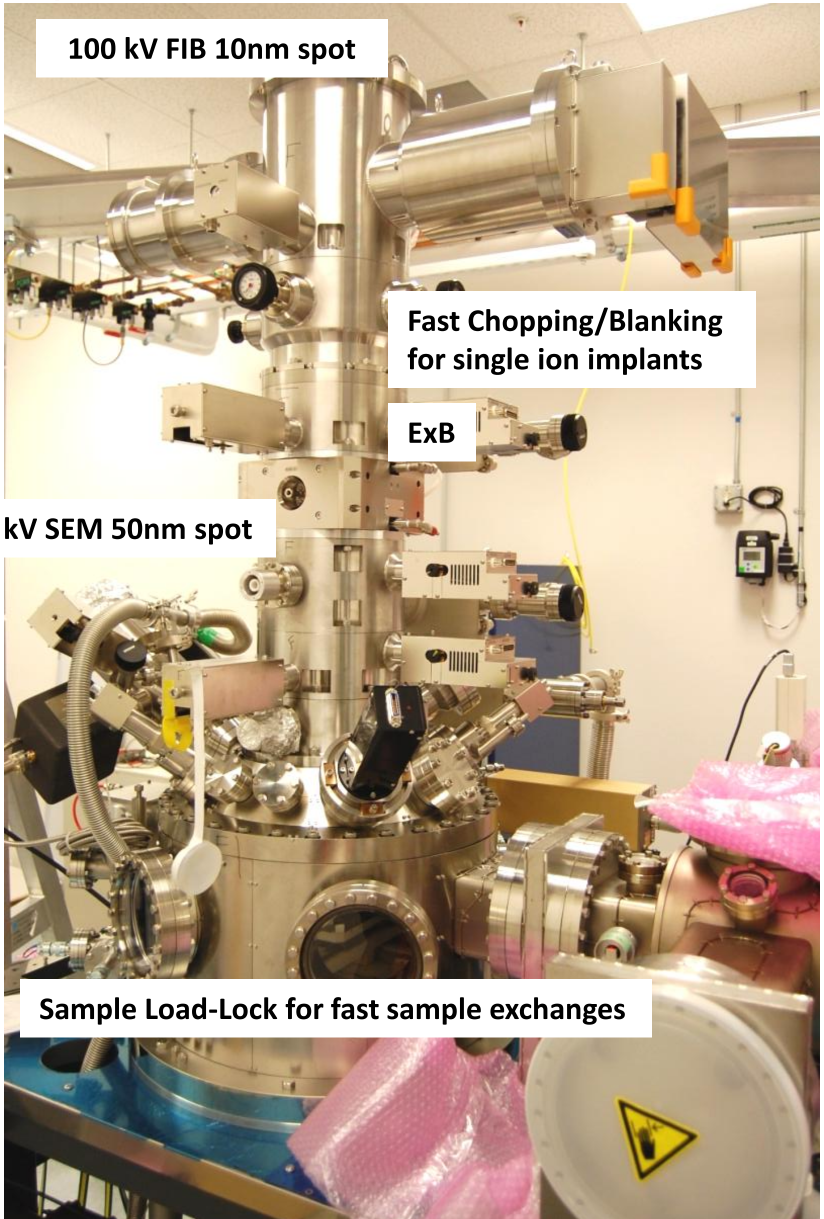
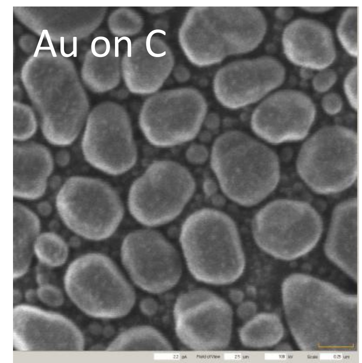
# NanoImplanter (nI) Status at SNL

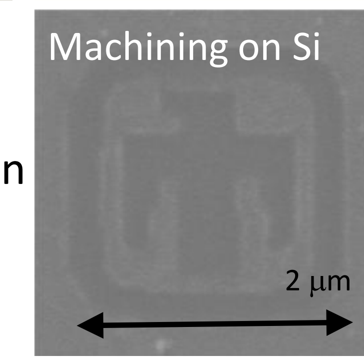



<u>Current Status</u>

- Installation Started on January 17, 2011
- System Accepted March 12, 2011
- Demonstrated ~10nm spot Ga+ beam at 100 keV
- Demonstrated ~15nm spot Si++ beam at 200 keV








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

A&D Company, Limited



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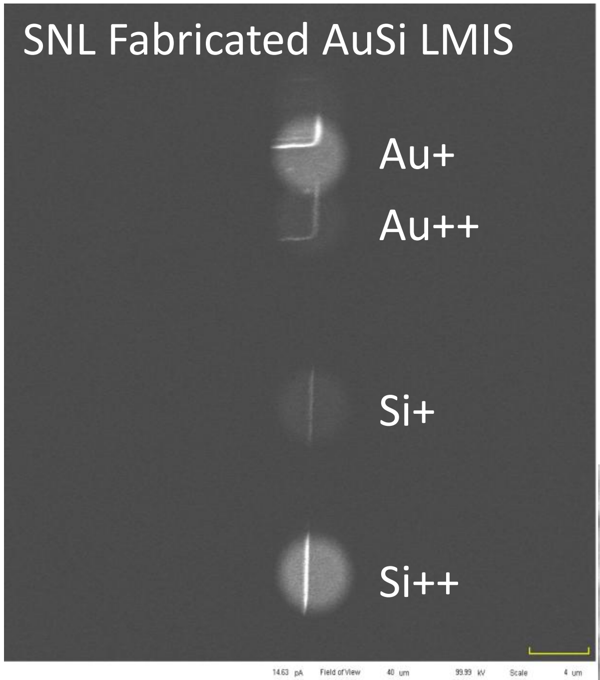
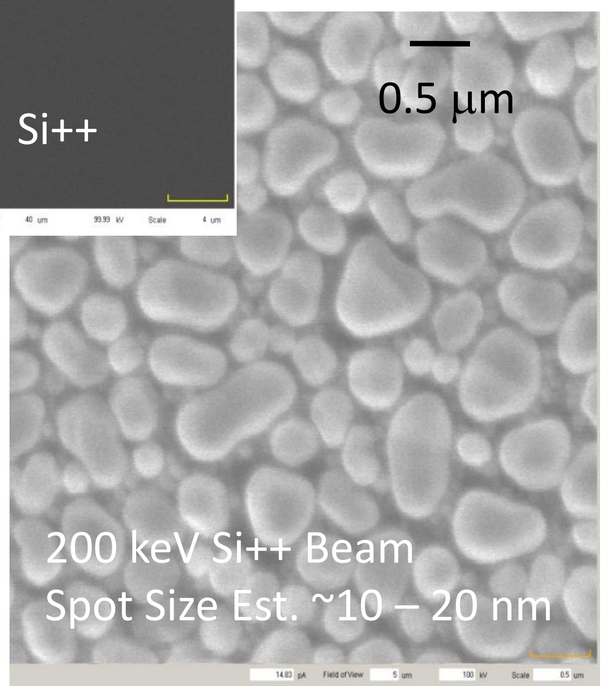
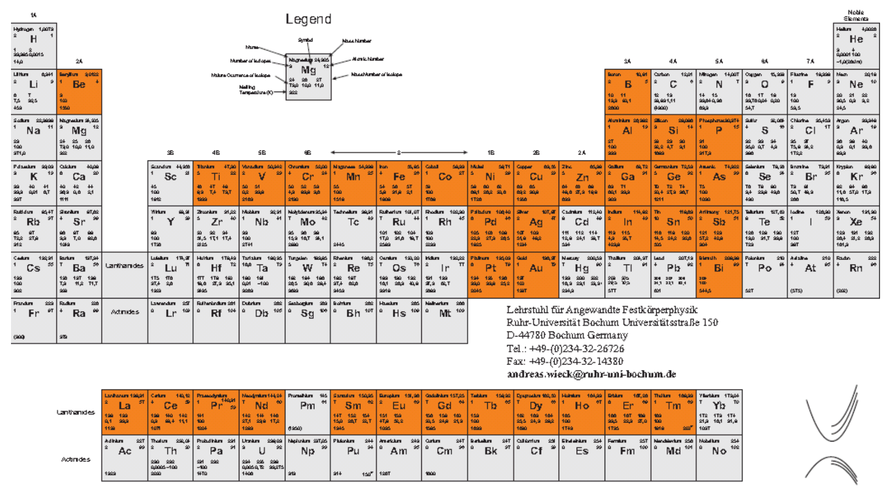
# Liquid Metal Ion Source (LMIS) Development - AuSi



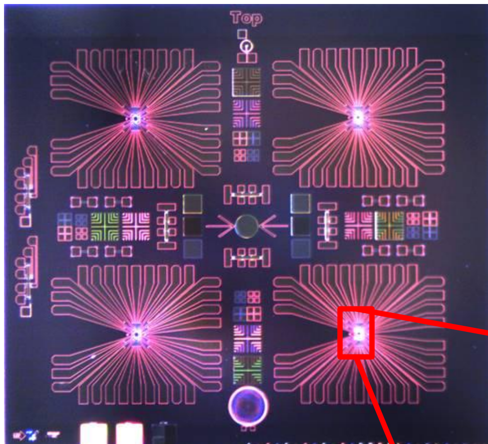





From Professor Weick Ruhr Uni Bochum

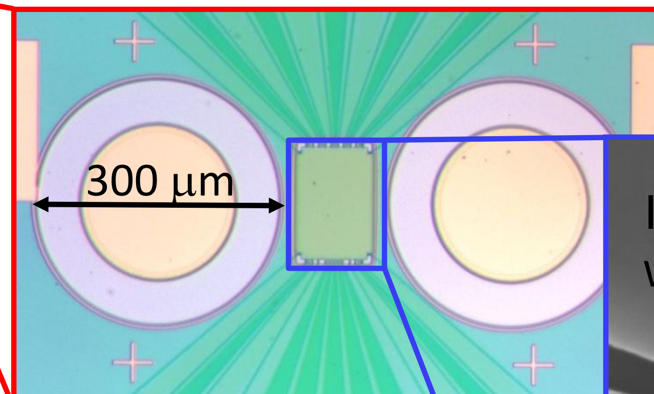
# NanoImplanter for Deterministic Single Ion Implants

Wafer Level

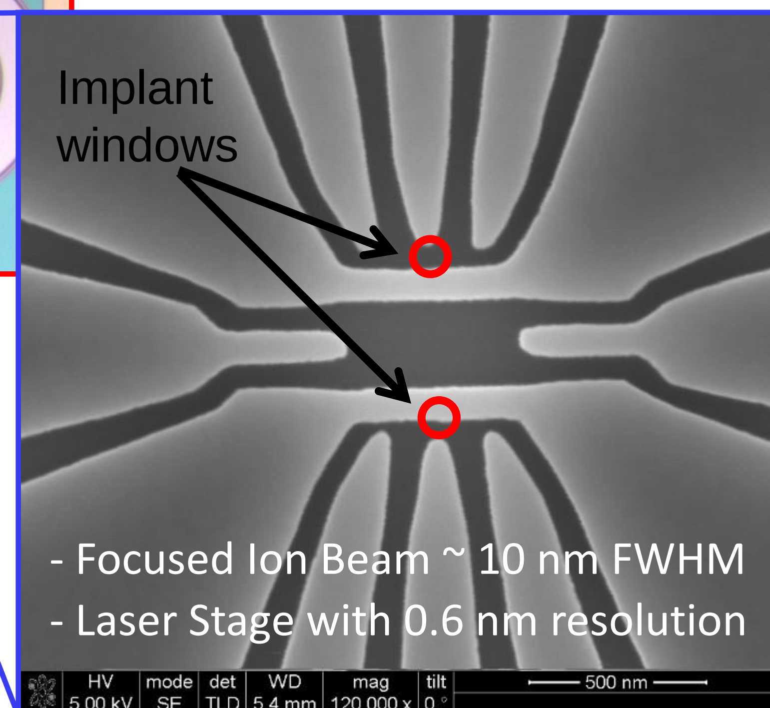



High resolution wafer level to single donor navigation required (making use of the Raith Lithography Software and Laser Stage)

Individual Device Level




Individual Donor Level





Raith
INNOVATIVE SOLUTIONS FOR NANOFABRICATION AND SEMICONDUCTOR NAVIGATION

# Path Forward to Self-Aligned Poly Si DQD + Donor Devices

• ***Multiple Ion Sources*** – **Ready, P, Sb on hand (CuPtP, AuSiSb LMIS from Weick)**

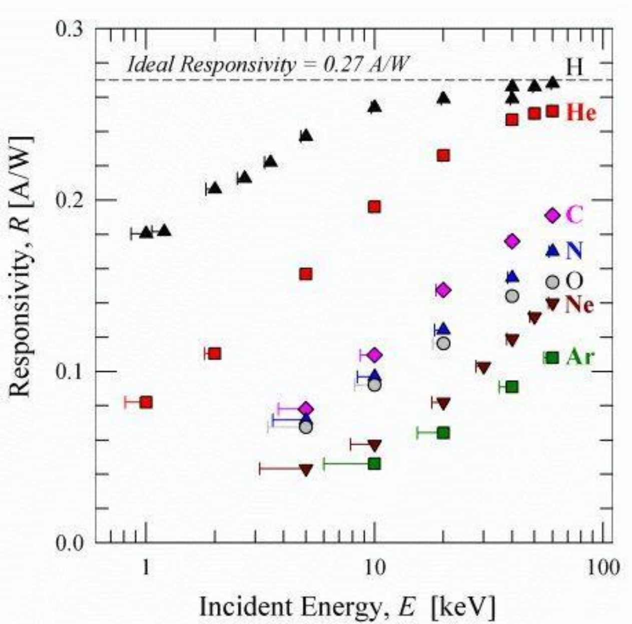

• Need … ion of the ExB filter re … Sb beams

Ran Sb source on 9/13/2011

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

• Sb source – low current w/o ExB (40-100 fA), very low current (<10 fA) with ExB (easily separated and measured Au, Si but Sb was very hard to measure)

• ***Solution*** – **Use AXUV100 Diodes for ion detection/focusing**



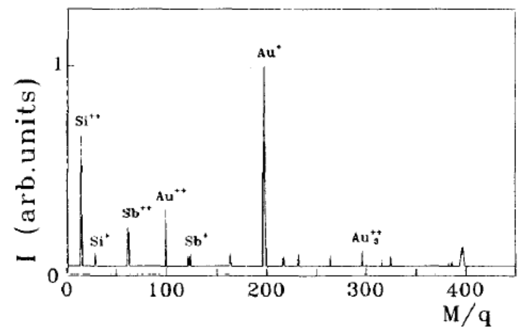




**Figure 3.** A typical mass spectrum of the AuSiSb LMIS.

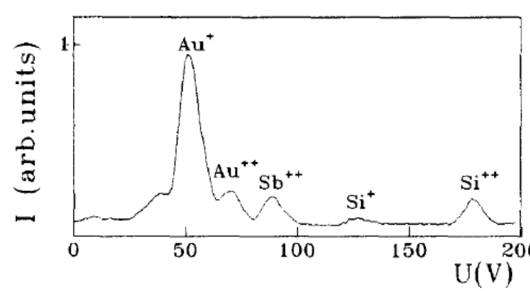



**Figure 4.** Mass spectrum of the AuSiSb LMIS measured by means of a Wien filter.

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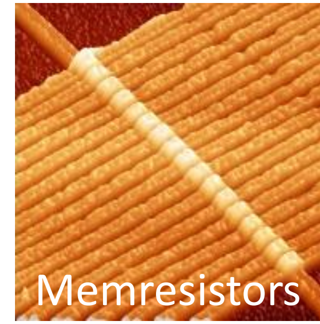
# Conclusions

We have discussed an approach to Quantum Information Processing using a combination of Si MOSFET devices and single donor implants

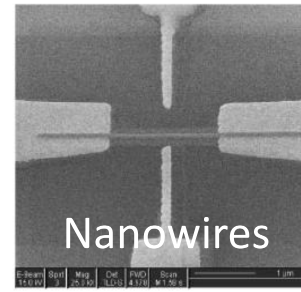
- Single Ion Detection
  - Demonstrated SIGMA detectors with high detection efficiency for diffused carriers with our newest integrated designs
- Focused Ion Beam Implantation
  - Both a new NanoBeamLine (NBL) and the NanoImplanter (nI) are being brought online for enhanced localization

# NanoImplanter Application Space




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

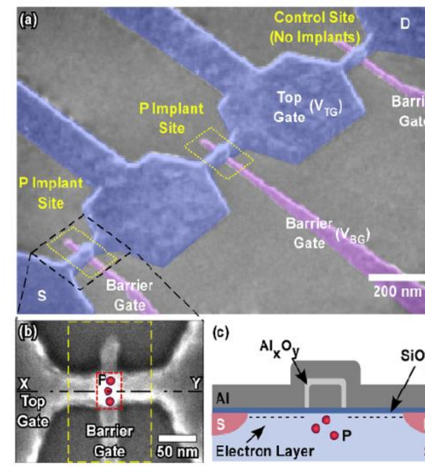
- Nanoelectronics – In-plane transistors, deterministic doping for FinFETs, Nanowires, Memreistors, etc…
- Nanostructural modifications of material systems (implantation), MEMS structures (milling)




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




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

**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

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

# Extra Slides

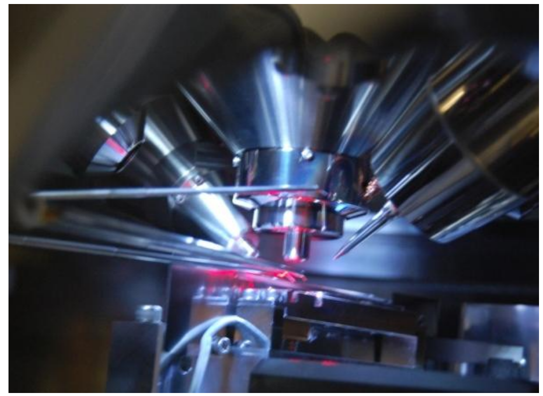
# Immediate Status and Path Forward

- Detector Work
  - re-Test detectors low energy proton irradiation
  - Test detectors with etched Poly-Si to low energy heavy ion strikes
  - Continue efforts in testing/modeling SIGMAs to improve design
- Device Work
  - Timed/Counted Ion Implantation using HVEE (broad beam)
  - Timed/Counted Ion Implantation using nI (focused beam)

# Additional Capabilities on nI

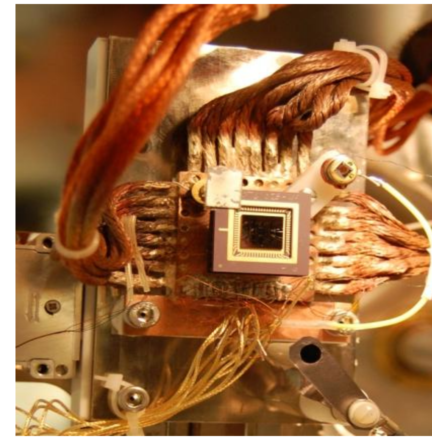
- **Micro-Manipulators for electric probing and sample manipulation**

Allows for probing of wafer level devices with 10 nm resolution



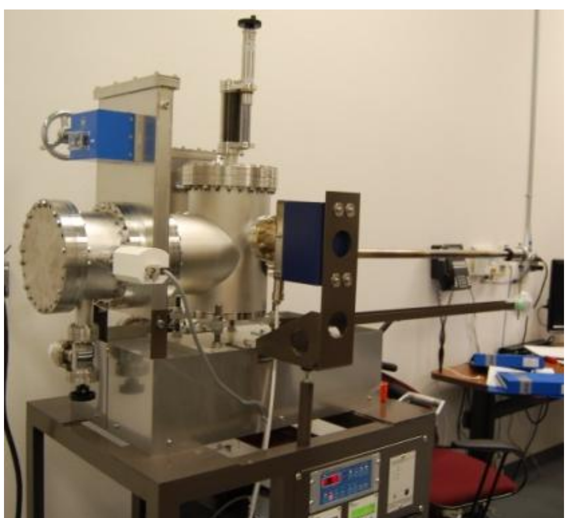
Kleindike probes installed in nI

- **Low Temperature Stage** *

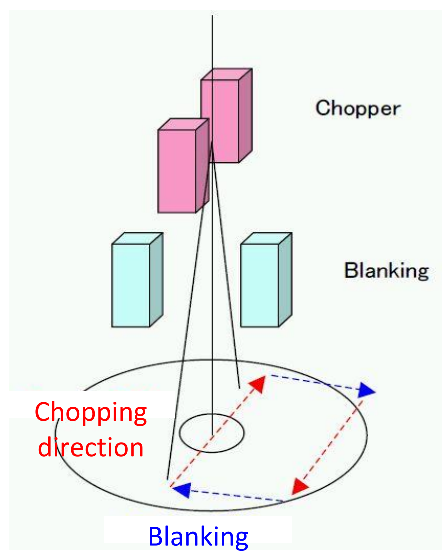


* Under development

- **Vacuum Suitcase Transfer System**



- **Fast Blanking/Chopping**




- **Lithography Pattern Generator**



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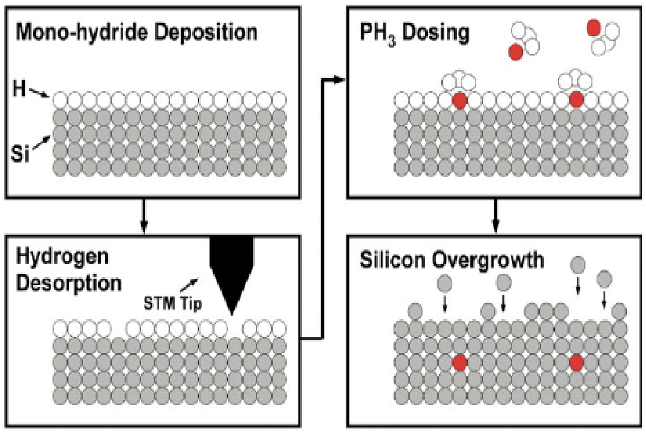
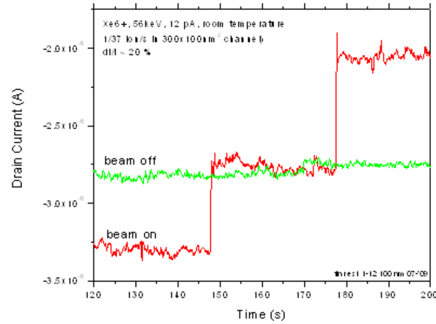
# Single-Ion Implantation (Donor) Approaches

## Atomic Scale Fabrication SNL and CQC$^2$T



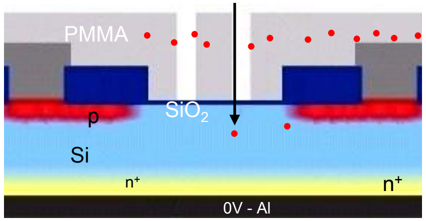

J. L. O'Brien *et al*, PRB **64**, 161401 (R), 2001

## LBNL: RT Drain Current



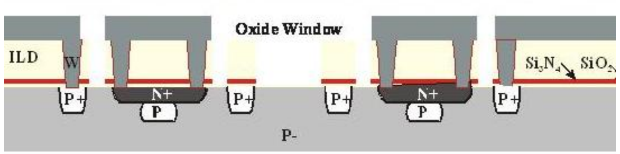

C. D. Weis, *et al*., NIMB, 267, 1222-1225 (2009)

## CQC$^2$T: Low Temperature PINs

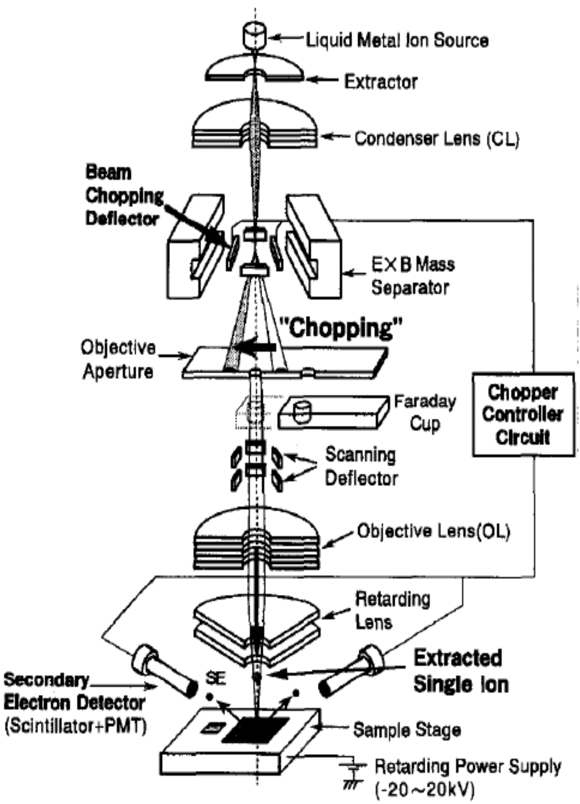



D. N. Jamieson *et al*., Appl. Phys. Lett. **86**, 202101 (2005)

## SNL: Low Temperature APDs

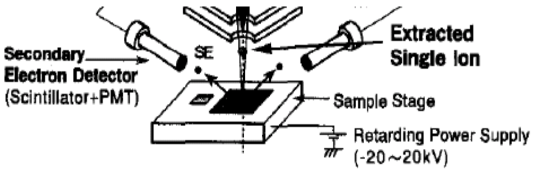



## Focused Ion Beam Implantation SNL and Waseda University




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

## Waseda: RT Secondary Electron Detectors



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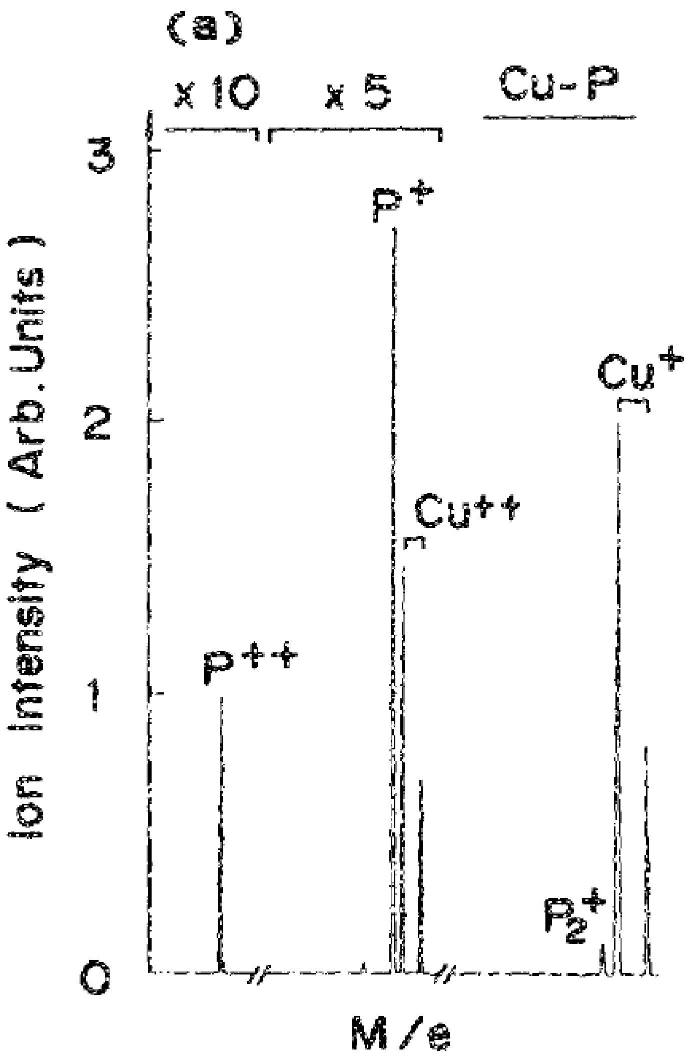
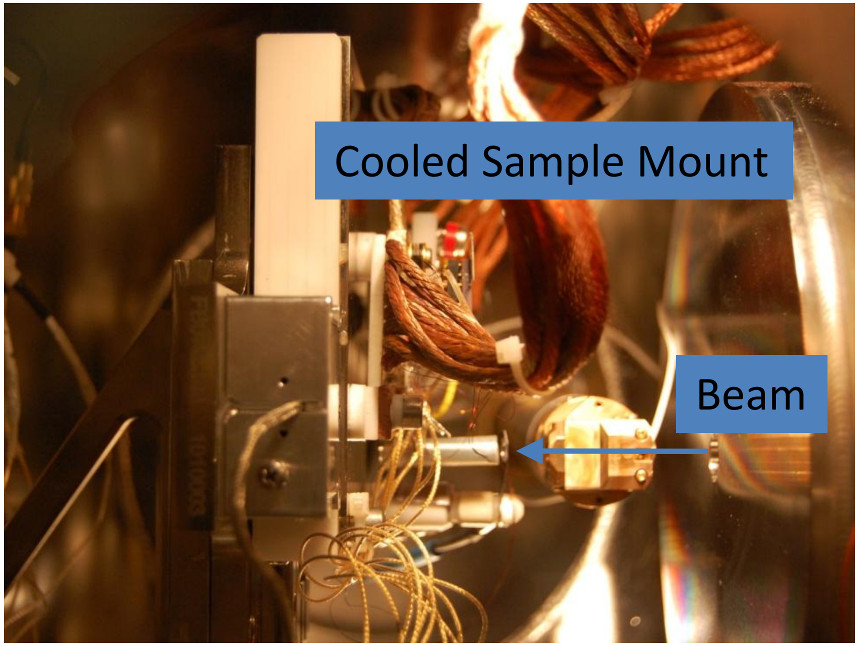
# CuPtP LMIS

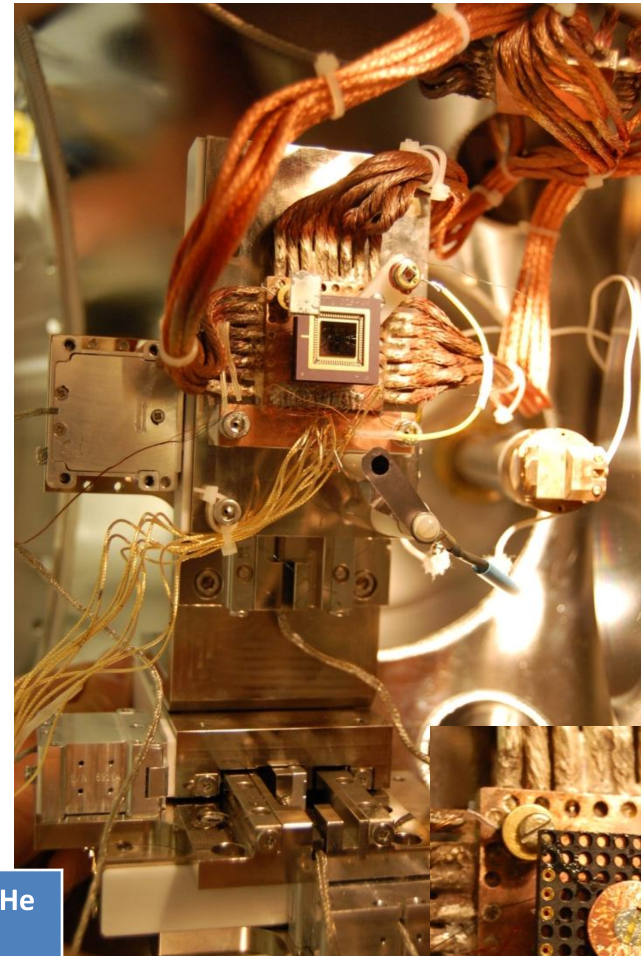


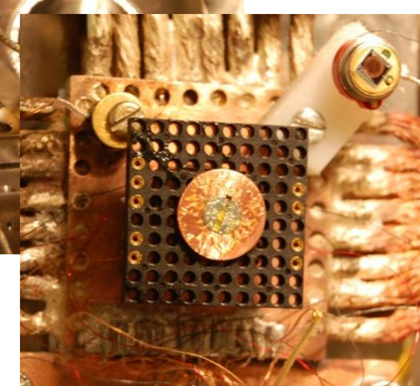

T. Ishitani et al., J. Appl. Phys. 61, 749 (1987)

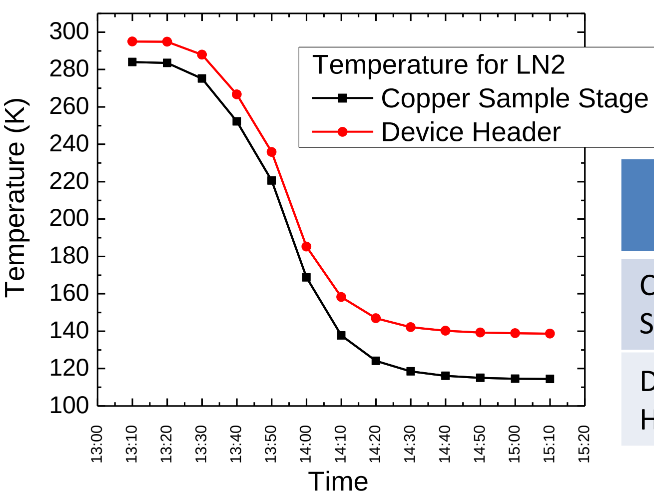
- $P^+$ is 31 and $Cu^{++}$ is 63/2 = 31.5 that is tough! Corresponds to $\Delta m/m$ of 0.016
- Demonstrated Ga-69 and Ga-71 separation corresponds to $\Delta m/m$ of 0.028 (easy)
- Addition of Pt increases the ratio of $P^{++}$ to $P^+$ by a factor of 2.2
- Desired energies
  - **P implant** at 35 + 21 nm = 56 +/- 23 A corresponds to **40 keV**
  - **Sb implant** at 35 + 19 nm = 54 +/- 14 A corresponds to **100 keV**
  - **Si implant** at 35 + 20 nm = 55 +/- 23 A corresponds to **40 keV**

# NanoBeamLine (NBL) – new sample mount



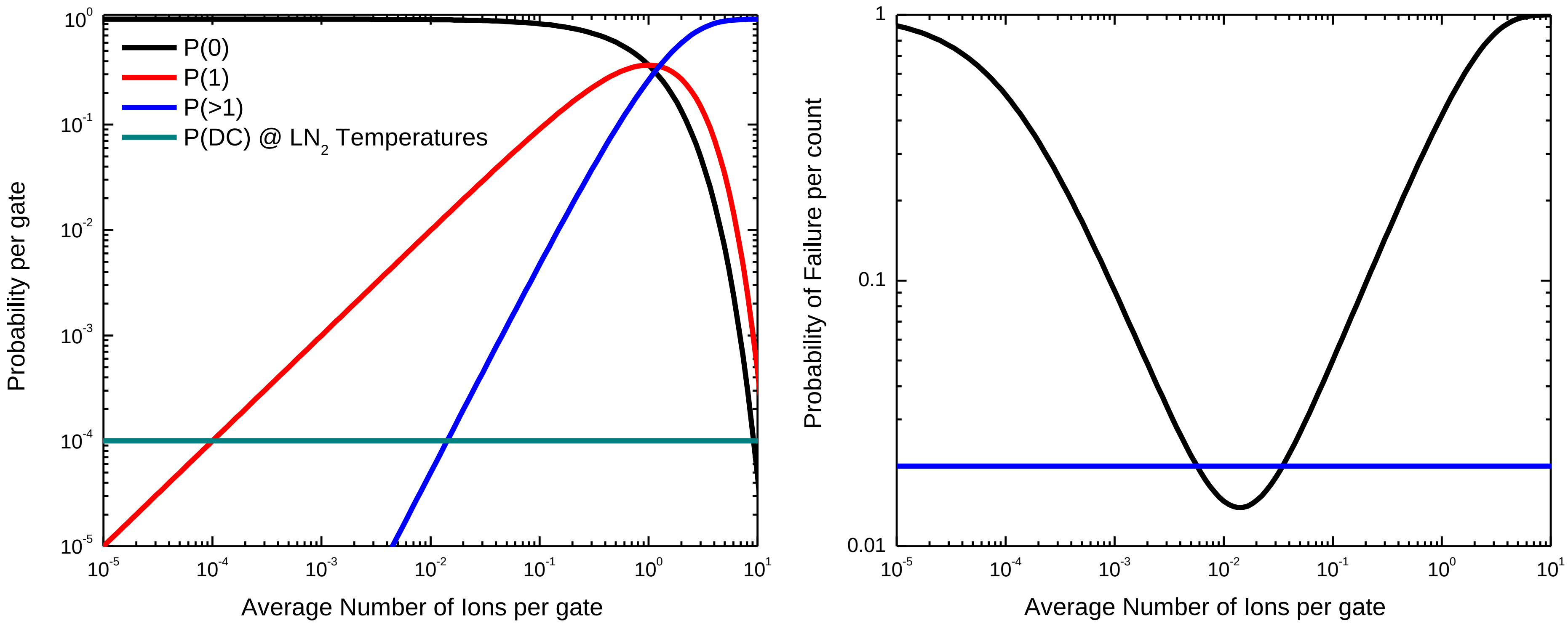








| | LN2 | LHe |
|---|---|---|
| Cu Sample Stage | 114K | 36K |
| Device Header | 140K | 65K |

# Expected Limitations: Single Ion Detection

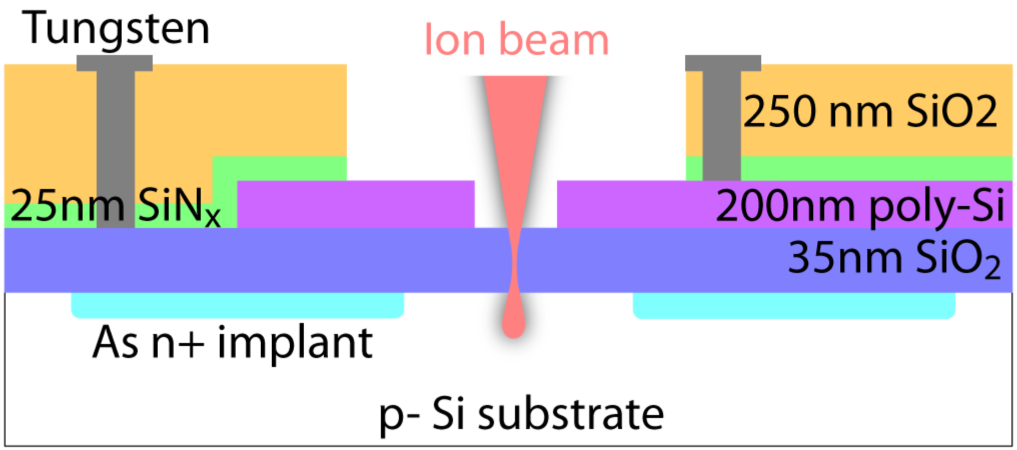


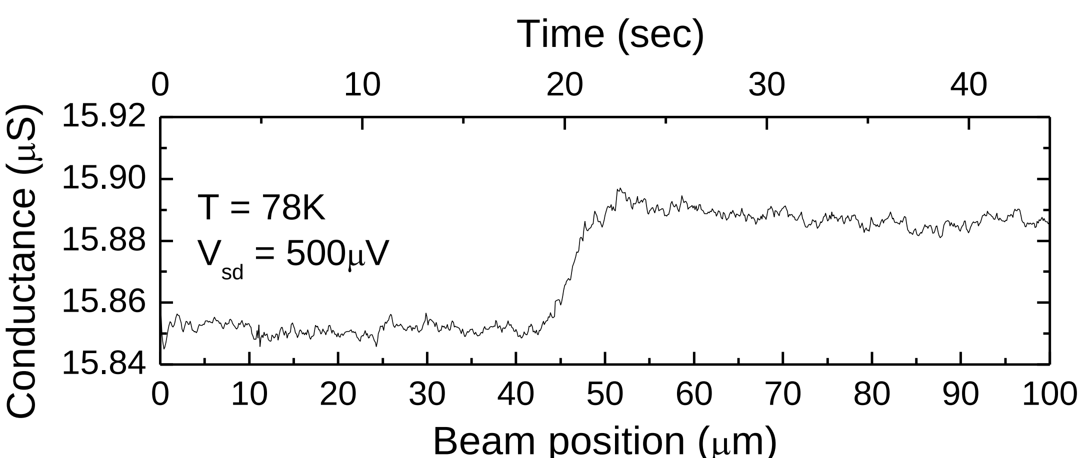

- Success rate of 98.6% calculated based on measured DCR which can be further reduced by several orders of magnitude
  - Success is one and only one donor implanted
  - Interplay of probability of *single ion per gate* and *dark count rate* (assumes 100% DE)

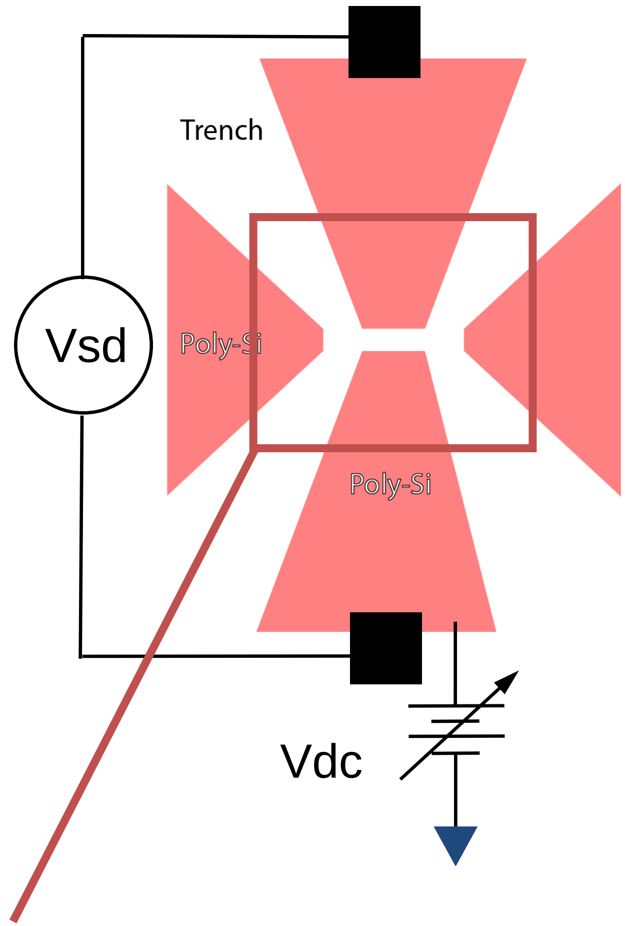
One and only ion implanted – no dark counts – Success rate >98%

# Another Detection Scheme - Single Ion Detection in the Device

Single Poly Test Structure –



# Coupling to Modeling Effort

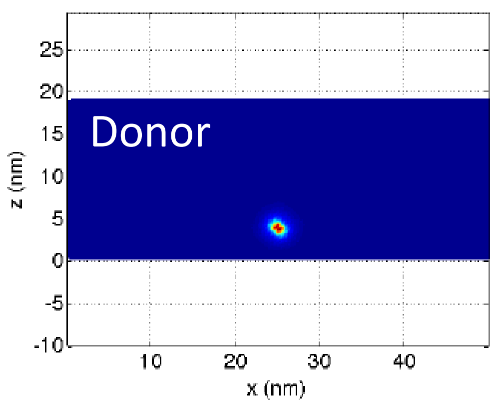
Start addressing questions such as the optimal donor depth and field needed for coupling

- 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?

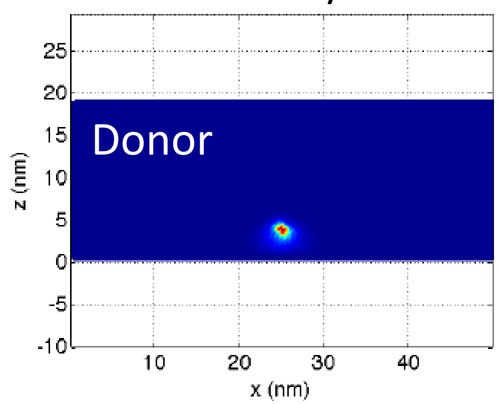
Donor to Dot tunneling: Parabolic SQD coupled to a donor at 3.8 nm from the barrier

Ground state

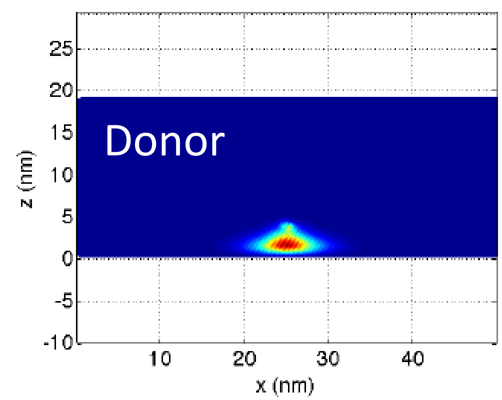
E=0 MV/m



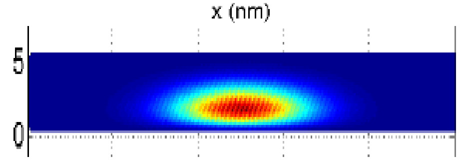

E=20 MV/m




E=40 MV/m

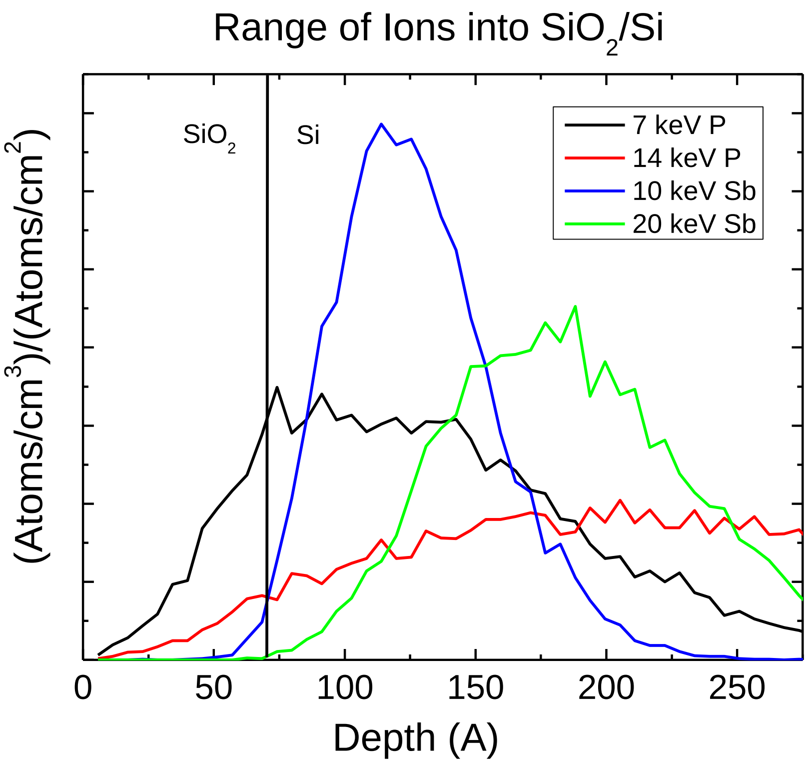


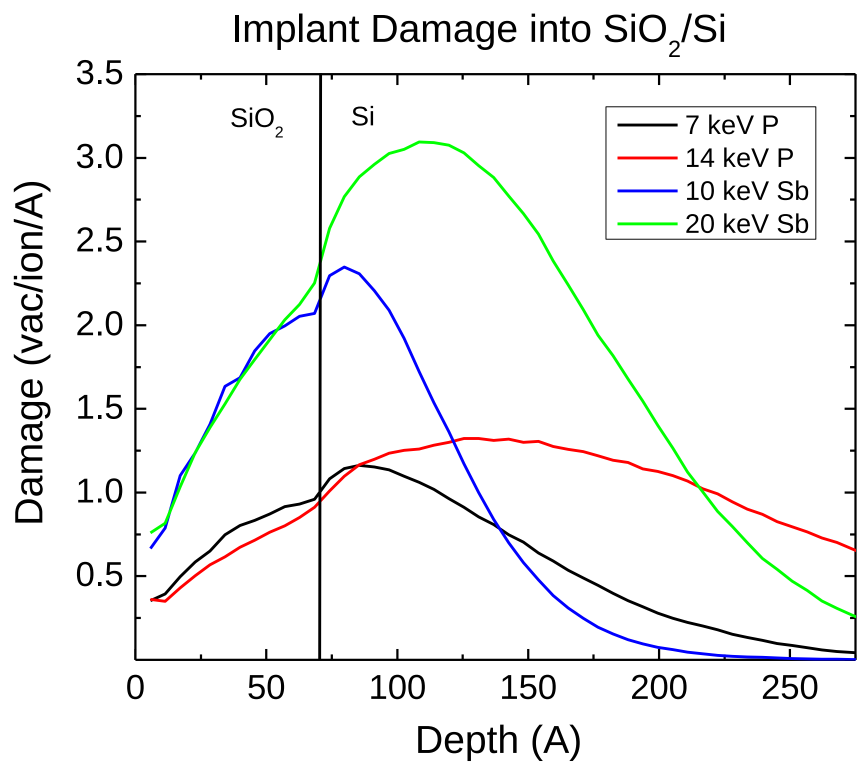

E=20 no donor
SQD Potential



Rajib Rahman

# Ion/Energy Combination – Range and Damage




Assume 7 nm $SiO_2$

| Ion | Energy (keV) | Range (A) | # e-h pair |
|---|---|---|---|
| **P** | **7** | **129 +/- 62** | **~700** |
| P | 14 | 224 +/- 103 | ~1400 |
| **Sb** | **10** | **124 +/- 30** | **~900** |
| Sb | 20 | 185 +/- 49 | ~1900 |

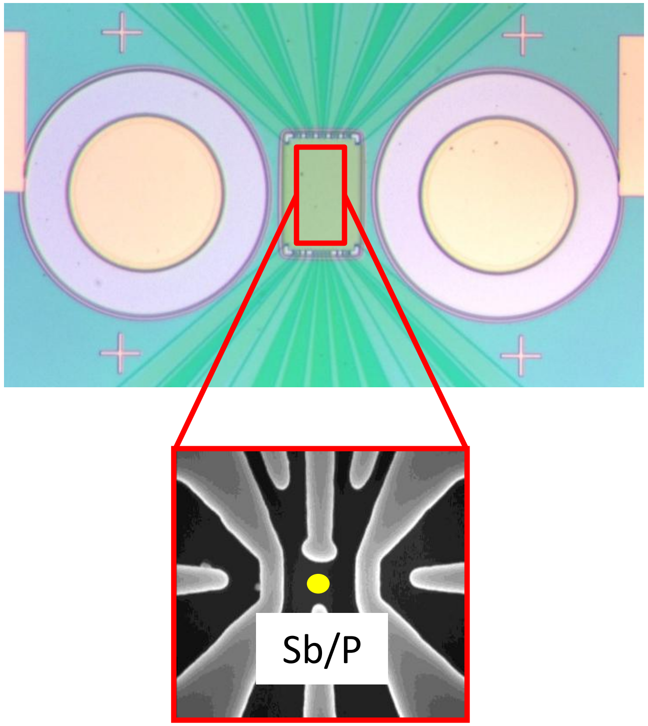
# Status of the APD devices to Ion Strikes – SVH050 Diffused Carrier Detection

| KC076102E-W9 | GM Response with Beam | Status |
|---|---|---|
| (2,2) | Yes | Broken – IBIC tester |
| (3,3) | Yes | Ready for Processing |
| (5,3) | Yes | Ready for Processing |
| (4,3) | Yes (SVH300) – not tested with SVH050 | Broken – SVH300 tester |
| (4,6) | ?? - Good IV curves at RT and LT | Broke during LT testing |
| (2,4), (3,6) | Poor IV curves at RT | Re-test at LT? |
| **KC076102E-W10** | | |
| (3,3) | Yes | Ready for Processing |
| (4,4) | Yes | Broke using DC beam |
| (3,4) | No – Good IV curves at RT and LT | No response to beam |

**KC076102E-W9/10 We yielded 6/10 with good response to beam!**

## Path Forward to Self-Aligned Poly Si DQD + Donor Devices

(*HVEE Implanter Path*)




**Status -**

- Test the devices using 120 keV proton irradiation – test the detectors while introducing **low damage** and **no donors**
- Next step is hand off the working detectors to fab folks to pattern into self-aligned poly-Si gate structures
- Then we are ready for deterministic single ion implantation into self-aligned poly-Si nanostructures using large area ion implantation

**Next Steps -**

- re-Test SVH050 devices to the lower energy proton – verify previous results
- Test SVH050 devices to the appropriate energy Sb – need to etch off the poly-Si
- Timed/Counted Implants of EBL patterned nanostructures using low energy heavy ion implantation
  - Start running P source
  - Work to improve beam spot size

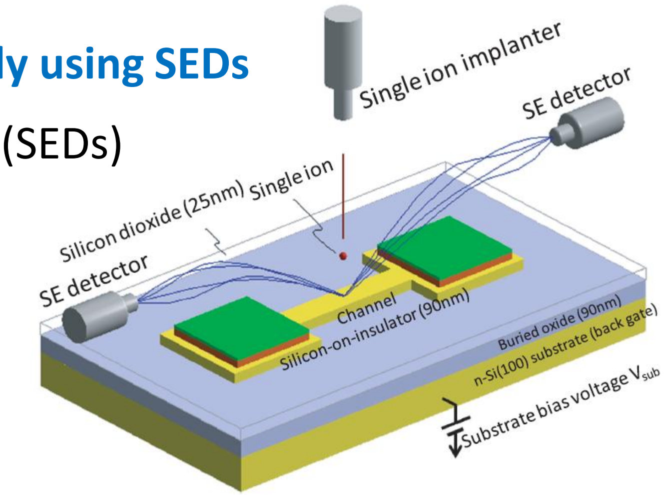
**Issues -**

- Spot size (~20 $\mu$m)
- 2014 Wafer, issues?
- 2075 Wafer testing now

Path Forward to Self-Aligned Poly Si DQD + Donor Devices

*(NanoImplanter Path)*

- ***Single Ion*** – **Single Ion Implantation and Detection ready using SEDs**
  - Initial work will use Secondary Electron Detectors (SEDs)
  - Developing a cold stage for SIGMA detectors

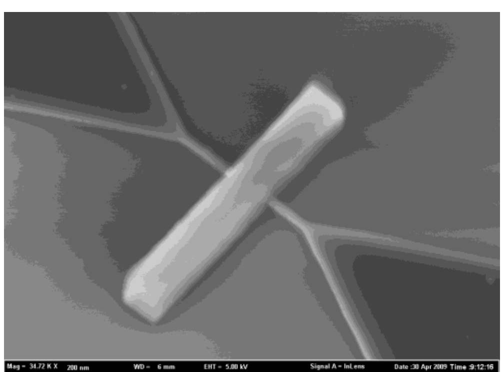



M. Hori, *et al*., Applied Physics Express **4**, 046501 (2011)

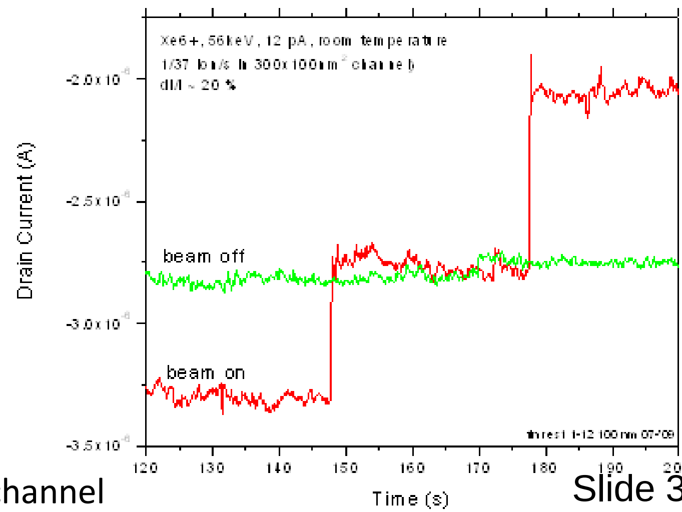
**SED Advantages** –
- Easy to use
- Works at room temperature

**SED Disadvantages** –
- Requires a focused beam
- Will generate a signal regardless of implant location
- Detector efficiency is an open question (typically 80%) – newest work by Hori, *et al*., suggests 100% is possible by biasing the sample

- **Collaboration with Schenkel (LBNL)** to test the detector efficiency of the SEDs using a FINFET resistor

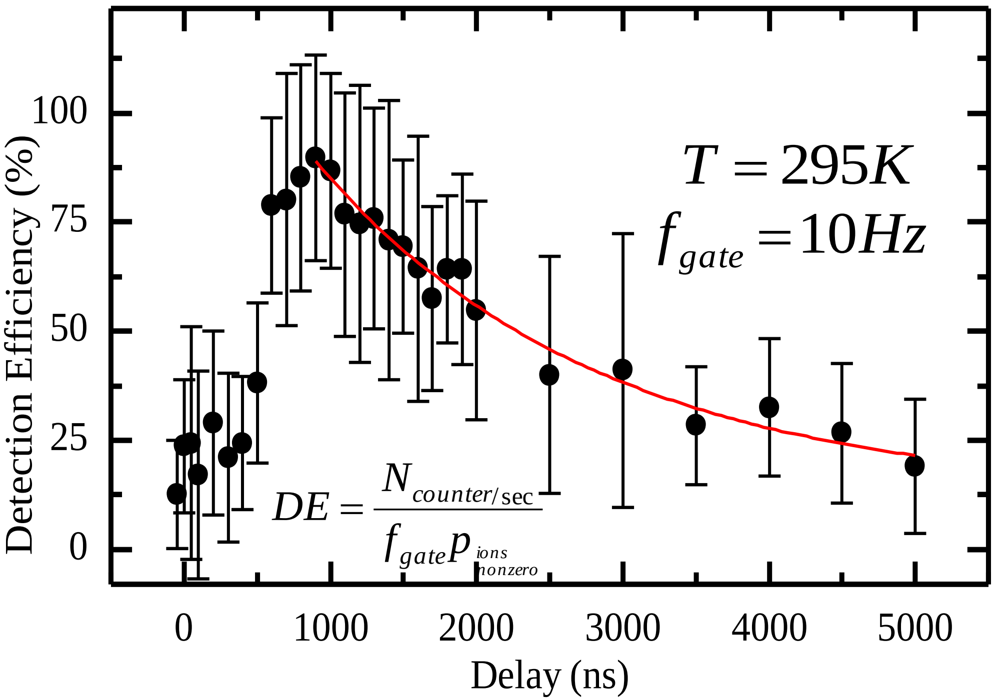


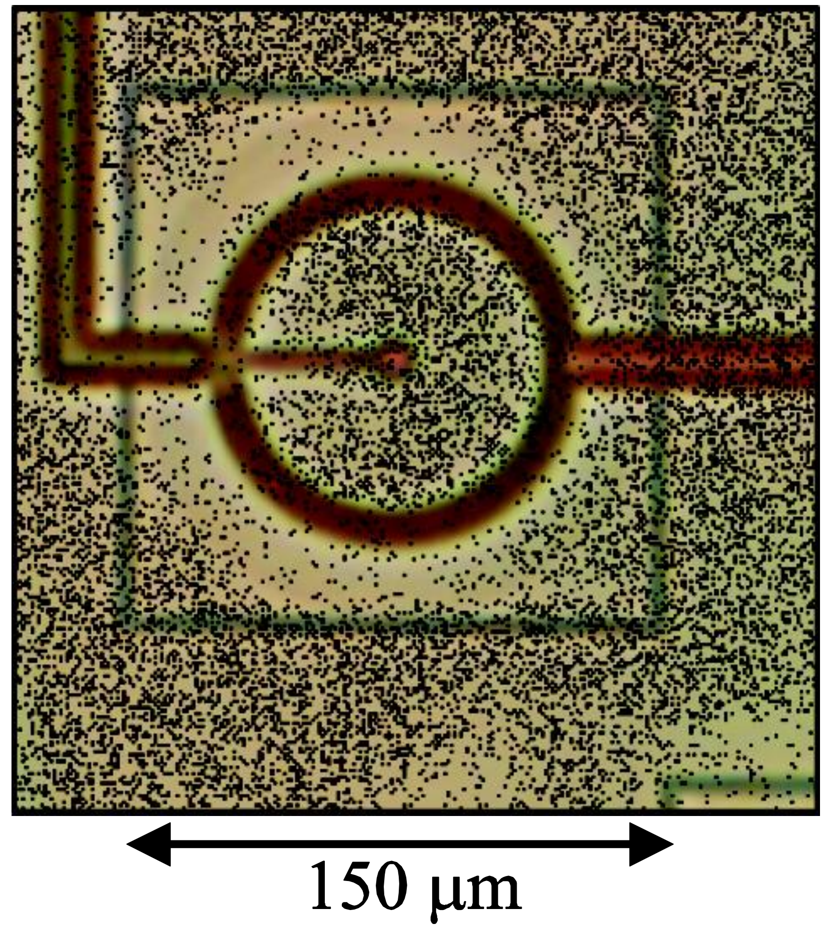
SEM of FinRes with implant mask over section of channel




- Devices at SNL
- SEDs ready for testing

# Diffused Carriers Detection: Discrete SIGMA



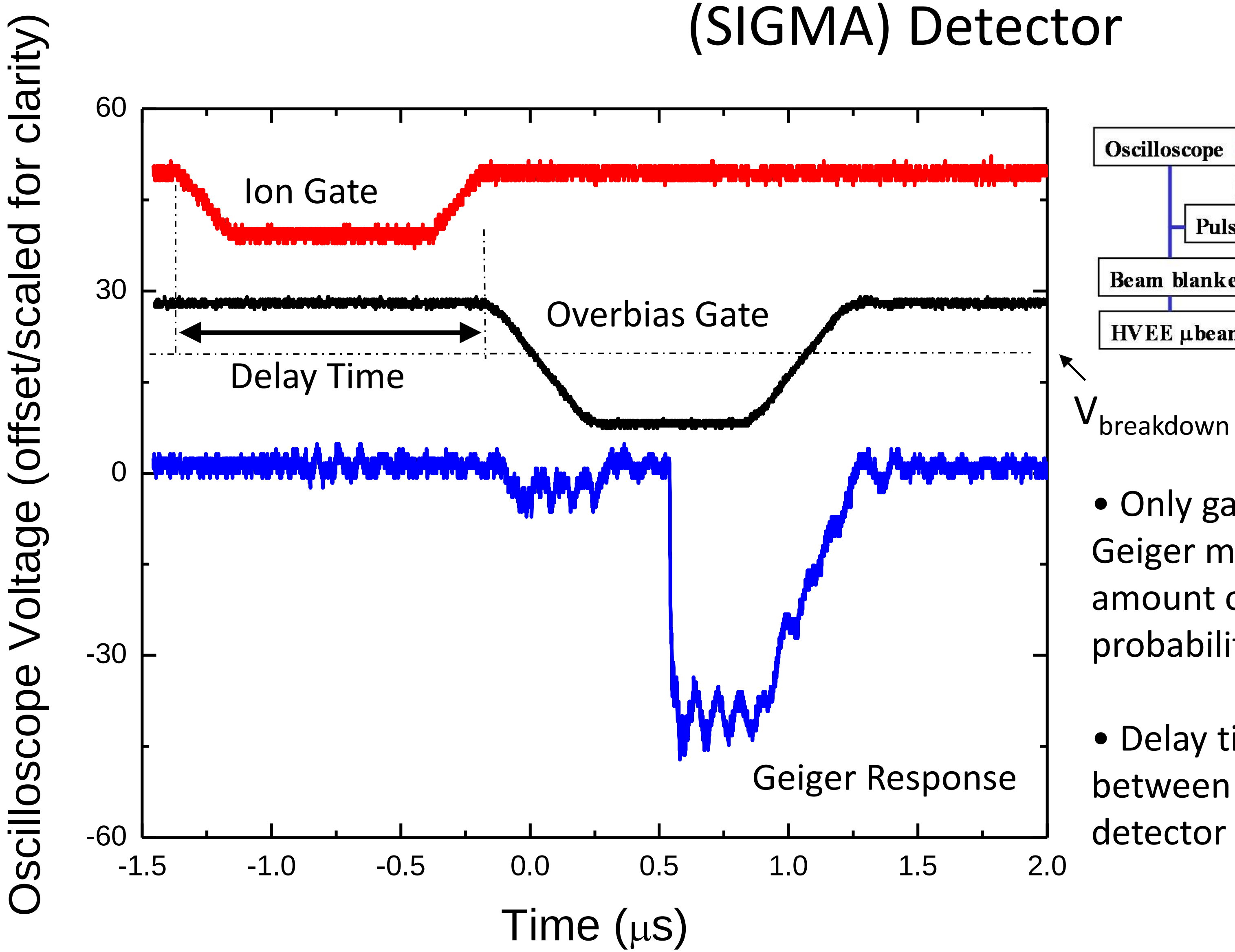



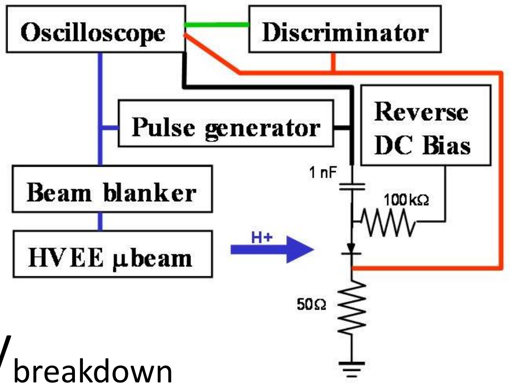

Detect single ions with ~100% detection efficiency for diffused carriers

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)

# 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

# Deterministic Single Ion Devices

**Why Donor-Dot? -**

Donor alone – tight spacing requirements
Dots alone – potentially limited coherence times
Donor-Dot – tolerance on donor spacing, long coherence times expected

**Which Donor? -**

Sb – limited thermal annealing diffusion, lower T1 times?
P – well defined thermal activation, larger T1 times?

**What Single Ion Detection Method? -**

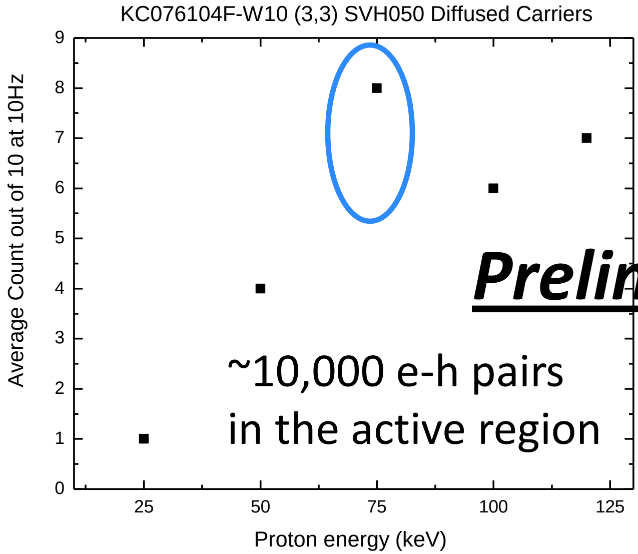
SIGMA Detectors – good low energy detection expected both for active/diffused
Other techniques – PIN, SD Current, SEDs as needed

**Why NanoImplanter? -**

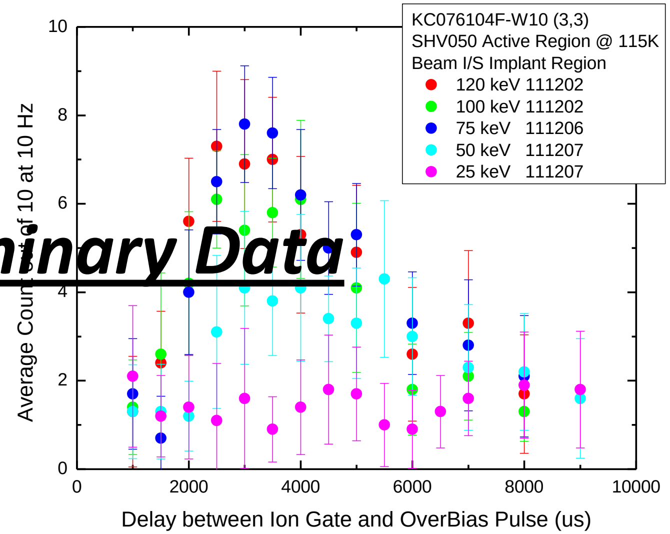
NanoImplanter == Lithography Platform
NanoImplanter

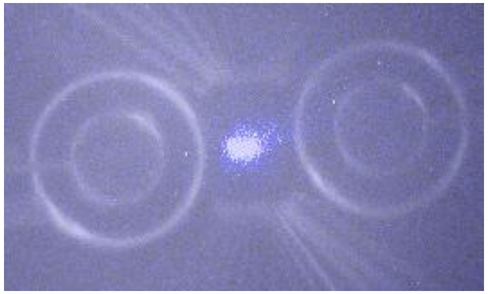
- 10 nm spot size (20 nm easy)
- Laser Stage with 100 mm travel at 0.6 nm resolution
- Mass-Velocity Filter for ion/energy selection
- Acceleration Voltage 10 to 100 kV

# Status of the APD devices to Ion Strikes – SVH050 Diffused Carrier Detection



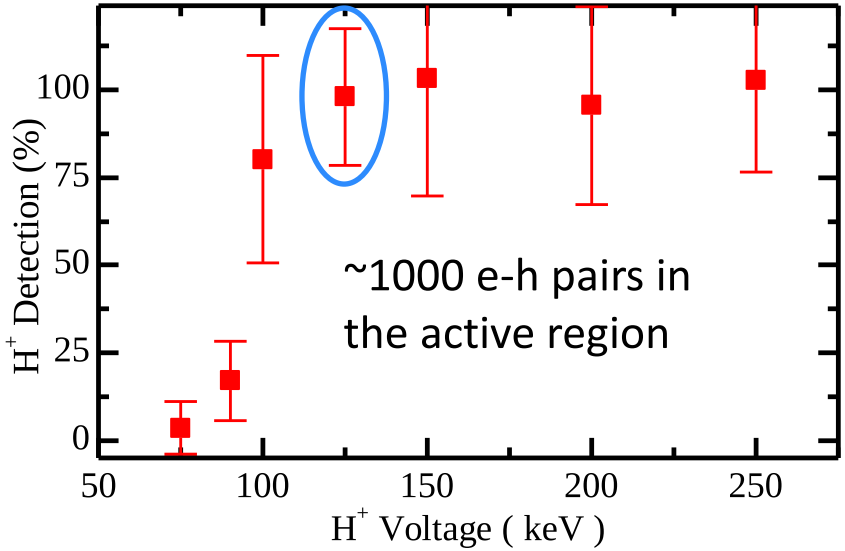

***Preliminary Data***

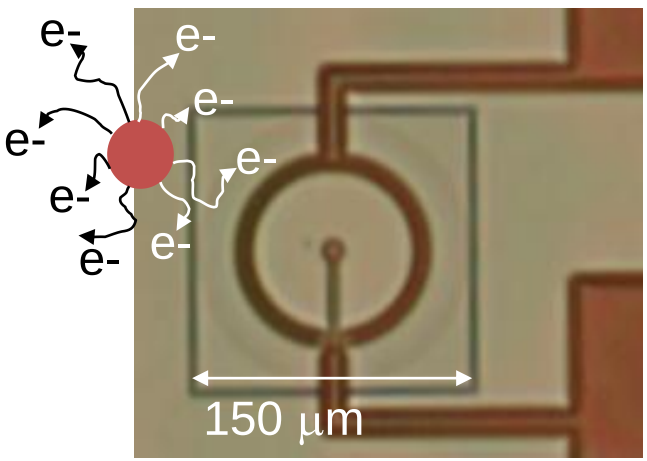


Next experiment – remove the ploy Si and test with low energy heavy ion directly

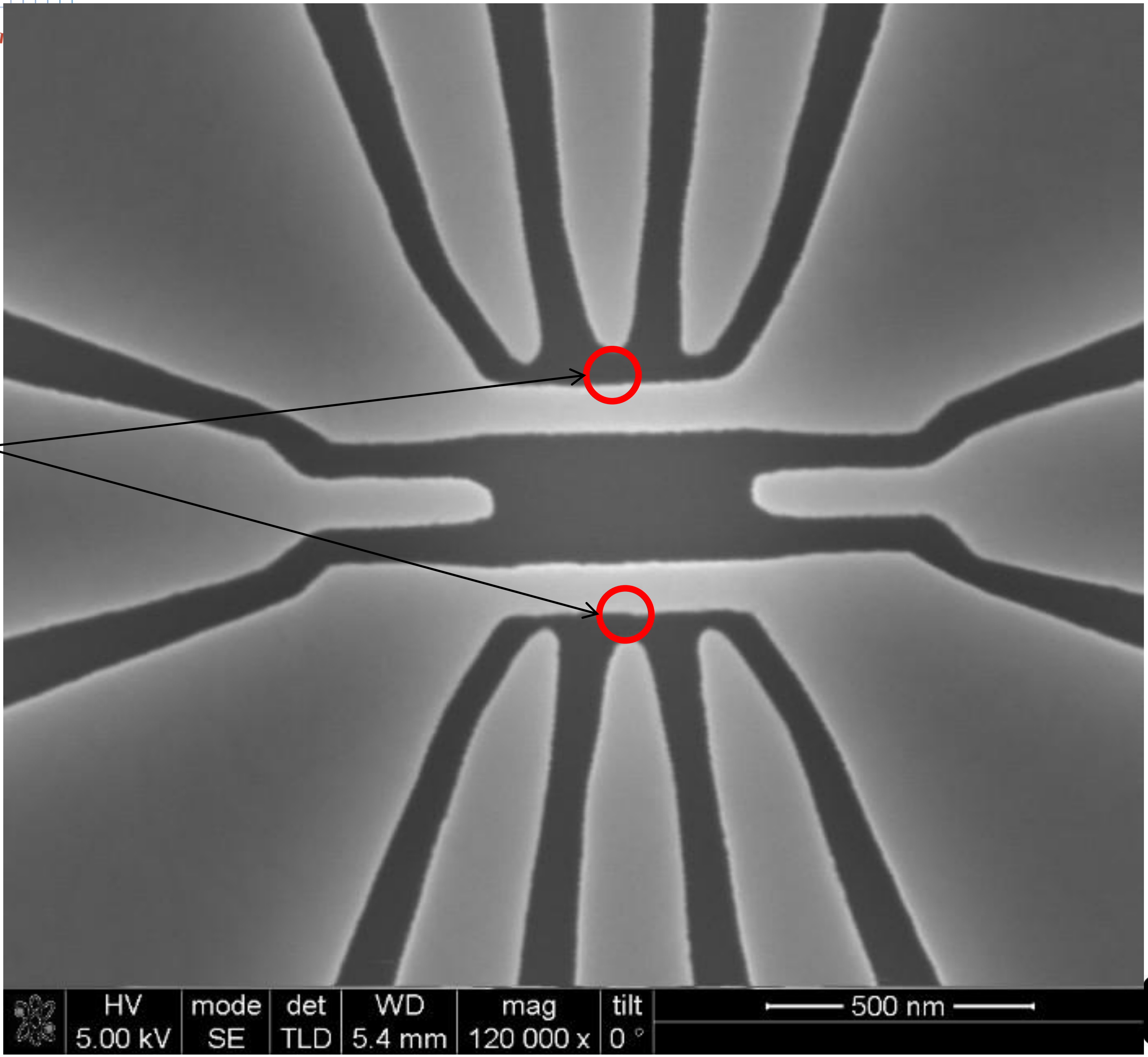
# Compared to Discrete SIGMA – Diffused Carrier Detection



# SEM 752 LR device

Implant
windows



# Deterministic Single Ion Implantation Status

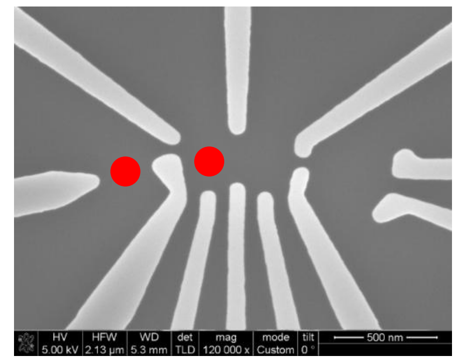
- ***Multiple Ion Sources*** – **Ready, P, Sb on hand (CuPtP, AuSiSb LMIS from Weick)**


- 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

- ***Single Ion*** – **Single Ion Implantation and Detection ready using SEDs**
  - Initial work will use Secondary Electron Detectors (SEDs)
  - Developing a cold stage for SIGMA detectors




- ***Resolution*** – **Achieved beams ~10 nm diameter**

- ***Why nI?***
  - ***Good localization*** (10nm hard, 20 nm easy), ***Good detection*** (>80% out of the box), ***Ultimate top-down implant resolution***

- ***Experimental Status***
  - Devices ready for deterministic implants of P, Sb and Si into the self-aligned poly-Si gated structures for single electron spin transport experiments