SAND2013-10566C

QIST Progress

Dwight Luhman
Sandia National Laboratories

Outline

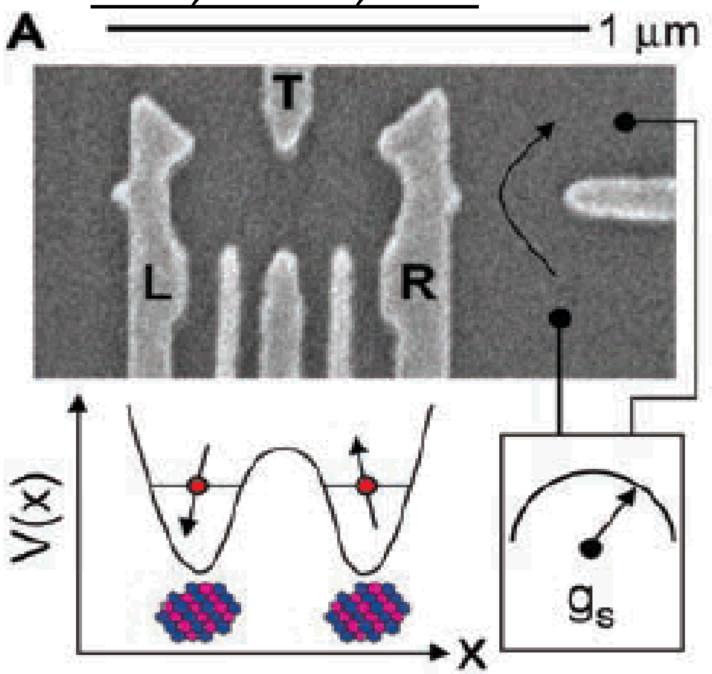
- Quantum computing with semiconductors
- Deterministic Ion Implantation
- Top Down Two Qubits
- One Qubit Efforts

This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. DOE, Office of Basic Energy Sciences user facility. This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. 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.

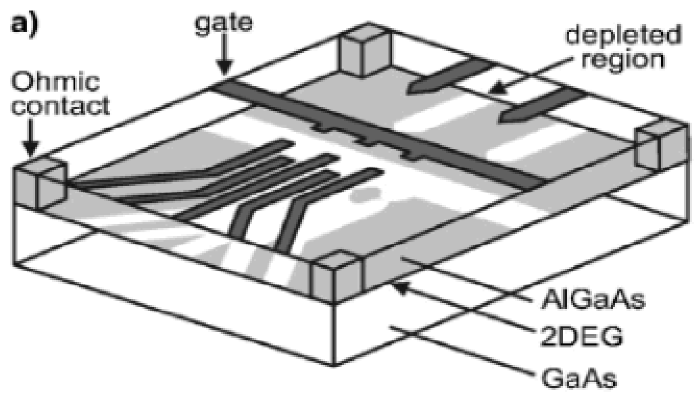
Double Quantum Dot Qubit in GaAs

- Demonstration of GaAs qubits has spurred quantum do semiconductor qubit research (e.g., Petta et al. in 2005)

<u>*Petta, Science, 2005*</u>



<u>*Hanson, Rev. Mod. Phys. 2007*</u>



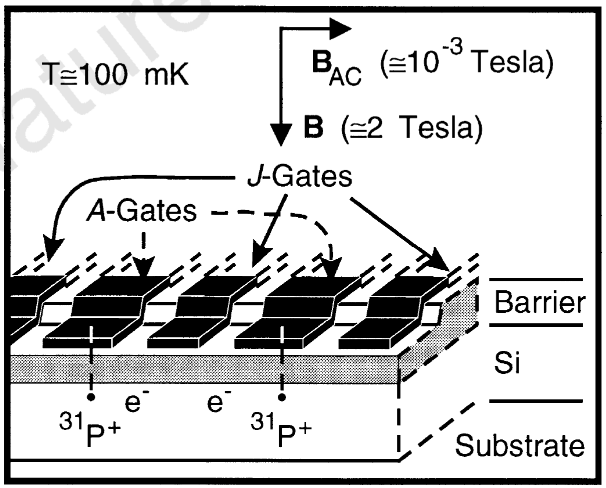
Need
- Isolate singlet triplet system
- Electrically tunable rotations
- Charge sense (fast is desirable)

Donor qubit

In silicon, the natural potential defined by a donor provides an alternative to surface dot approaches in semiconductors.

Kane architecture

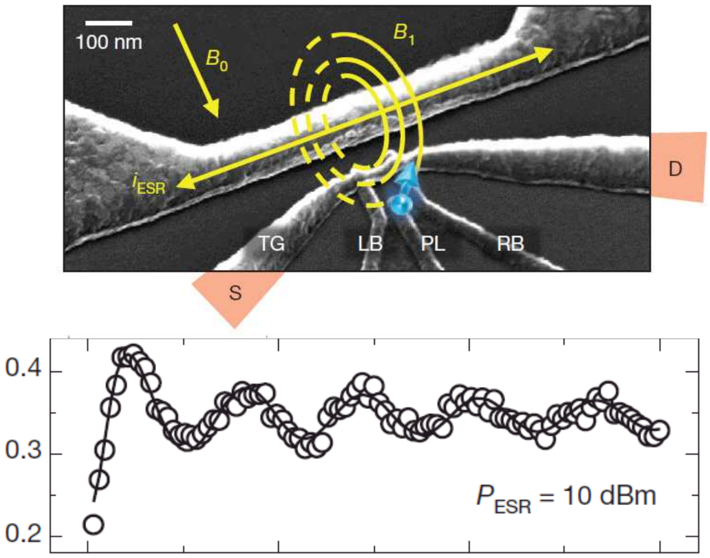
*B. E. Kane, Nature **393**, 1998*



Silicon donor research efforts

Australian CQC2T group (MOS, STM)

*J. Pla, Nature **489**, 2012*



Much of the work in the silicon qubit field is supported by NEMO from Purdue group lead by Gerhard Klimeck)

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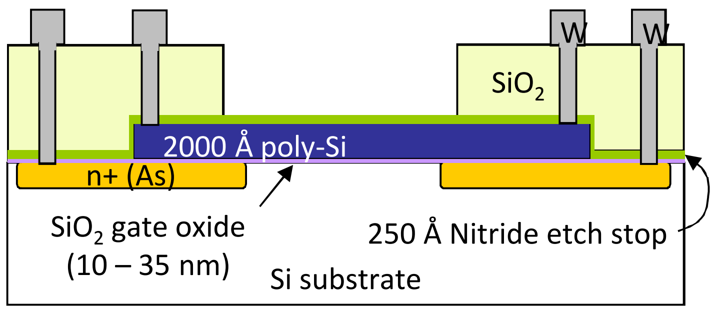
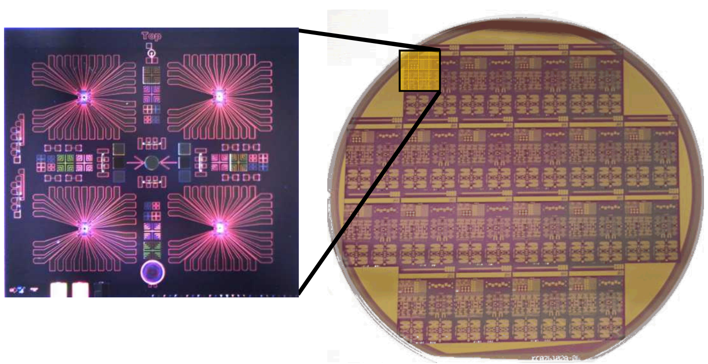
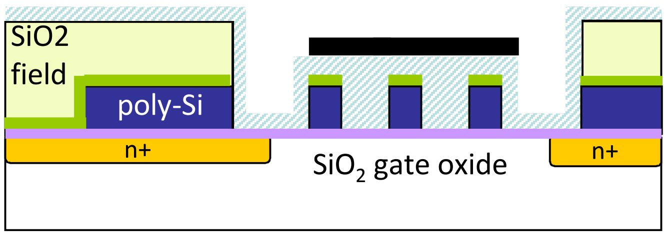
Si MOS Fabrication

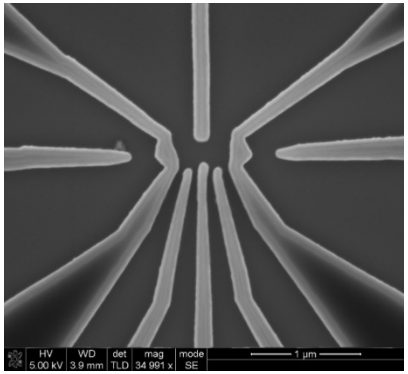
Front-end in silicon fab





Back-end nanolithography





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MOS devices

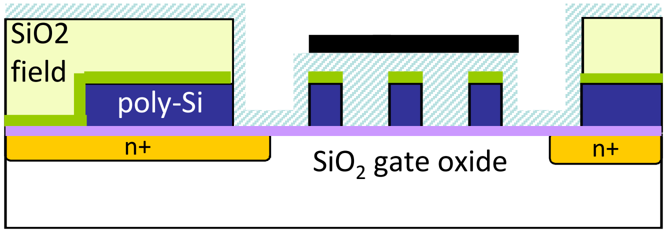
Details of MOS device

- Double top gate process – poly for depletion, Al for top gate
- Barriers are non-monotonic, as with most MOS devices
- Stability is acceptable when gate voltages are not changed significantly

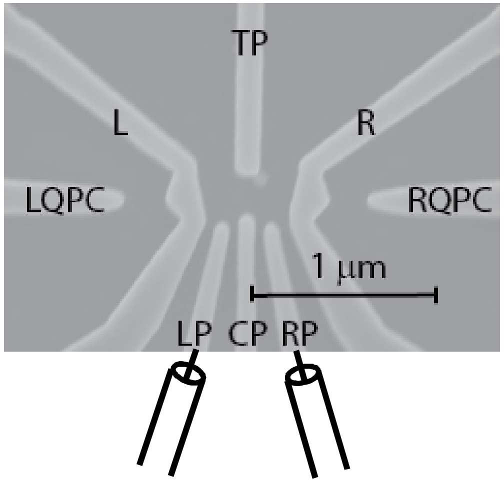
Device variations

- Donor implant in either dot or barrier regions
- Accumulation mode sSi/SiGe with poly depletion gates

Cross-section of MOS device



Ottawa flat 270 double quantum dot

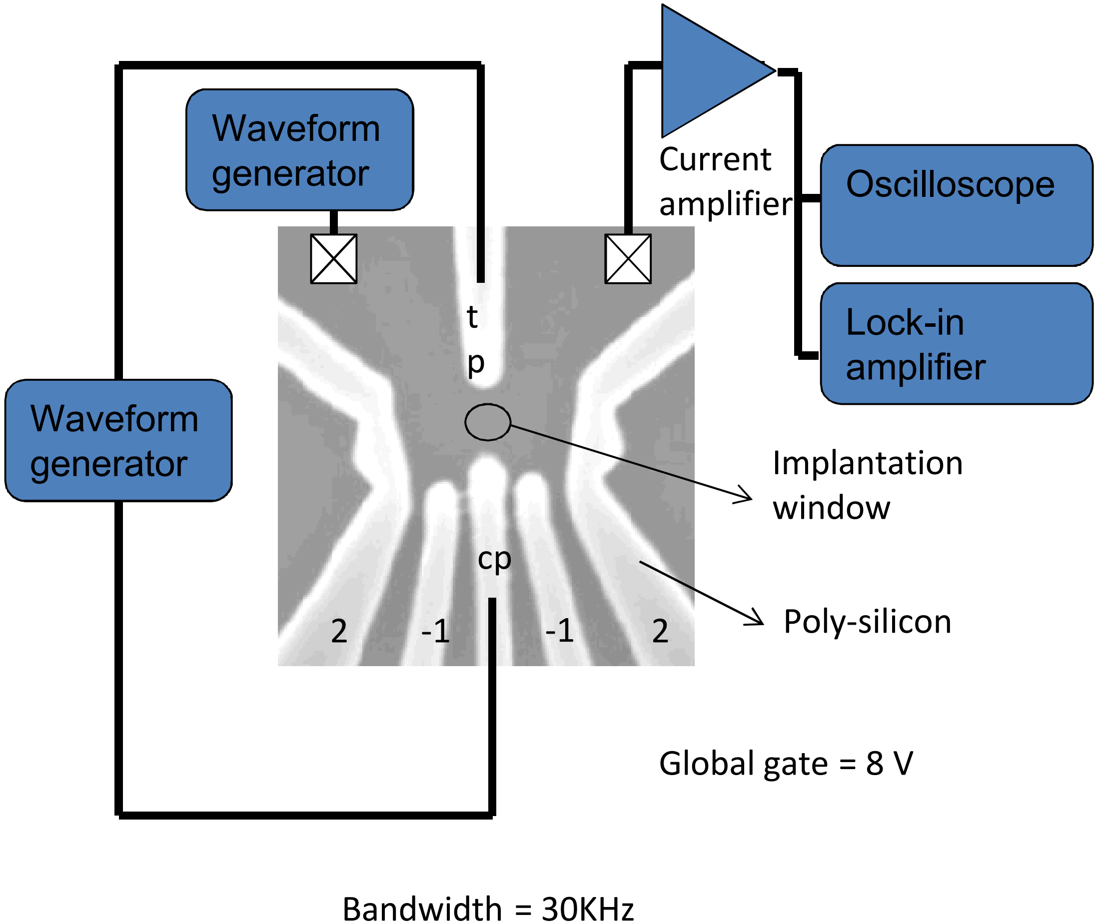


Simple Approach to Addressing Donor

Device fabrication

1. Wafer level processing of front-end.
2. Nano-patterned poly-silicon gates were defined by e-beam lithography and etching.
3. Implantation window was defined, followed by timed implantation of Sb at 120 KeV. Estimated number donors in the window ~ 5.
4. Second dielectric and global gate were deposited.

Device top view and electronics setup



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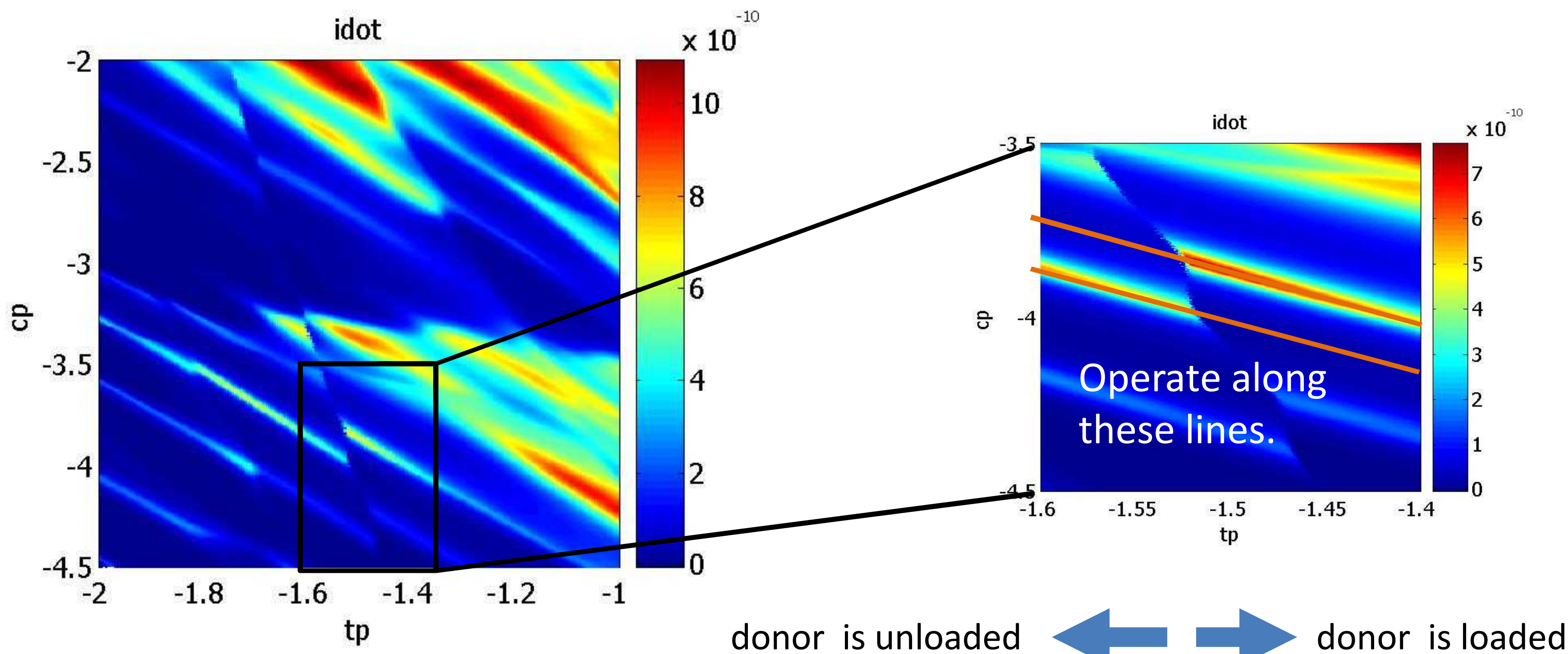
Quantum Dot Electrometer

Donor induced charge offset observed in transport through the quantum dot



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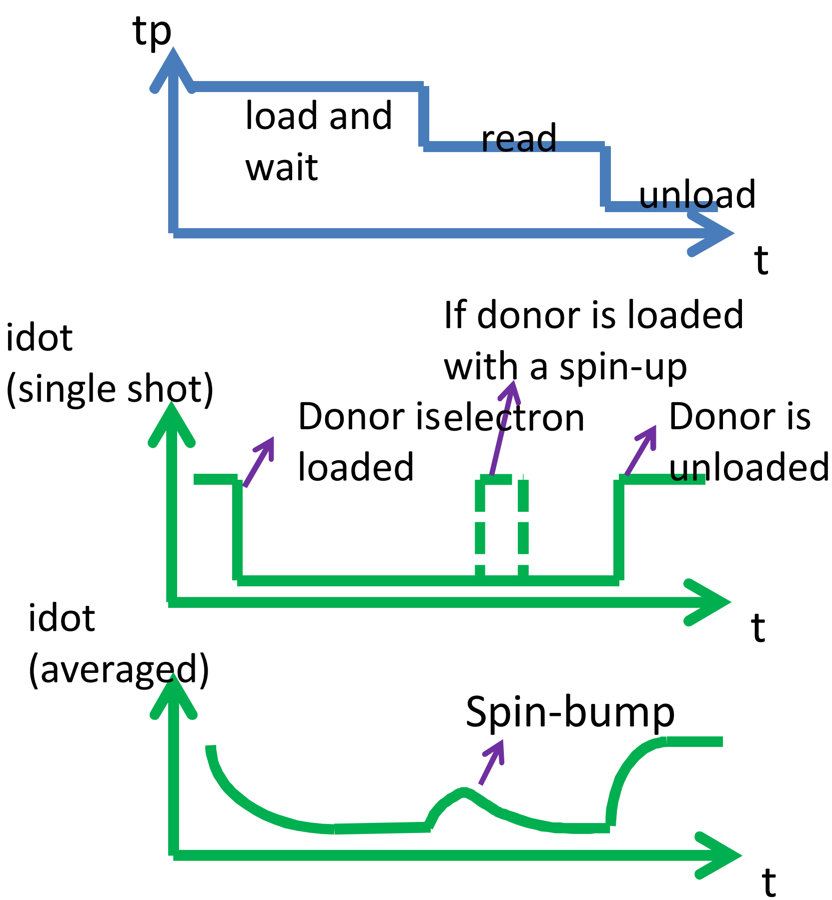
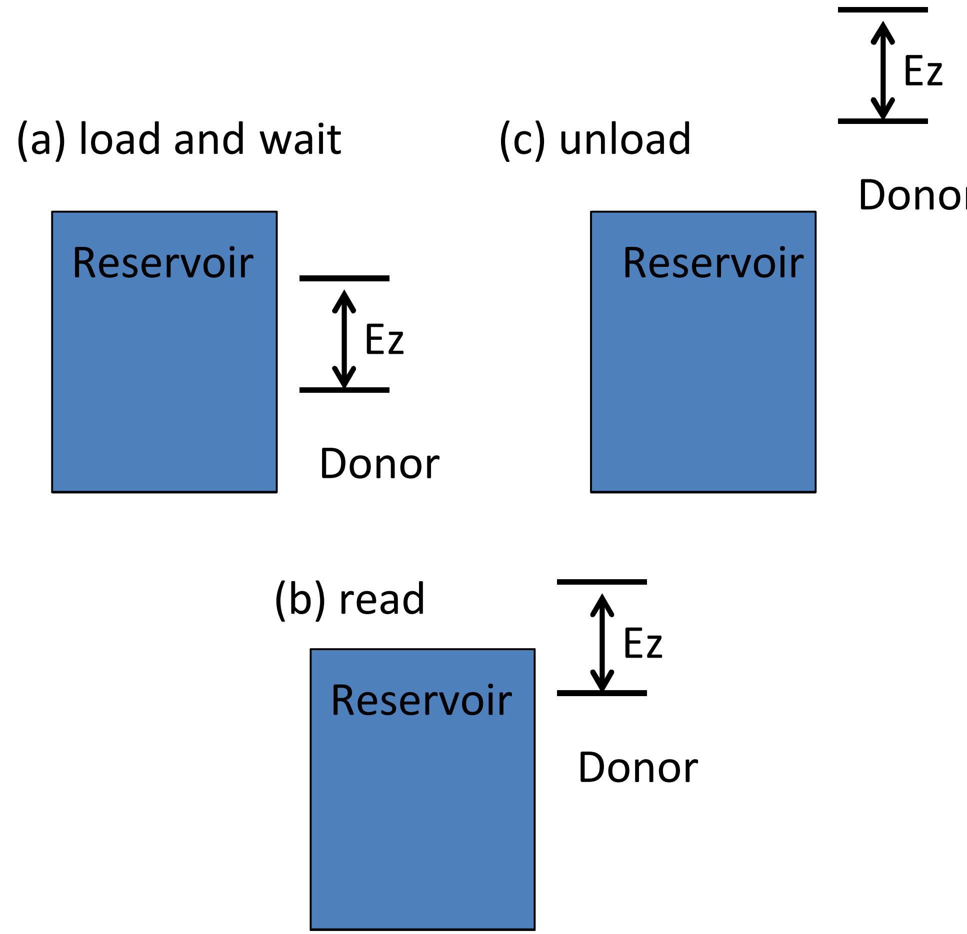
Pulse Sequence

Three-level probing sequence



Energy level alignment



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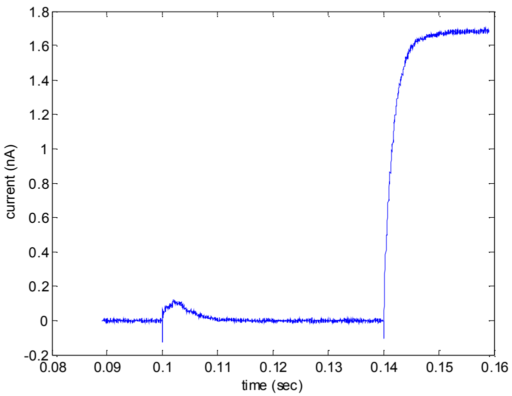
Spin Signals

Example of averaged current response

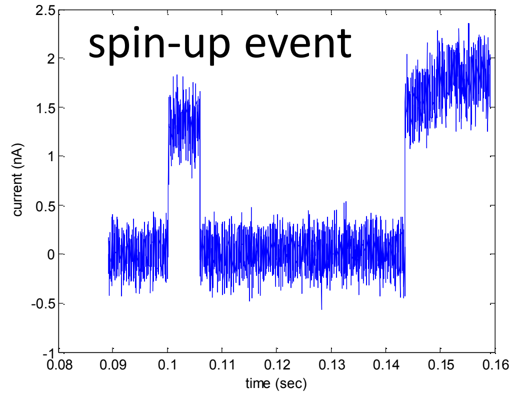
(read = 0.1-0.14 sec)

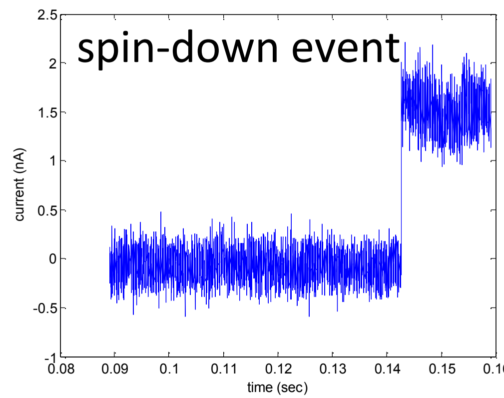


The bump between t = 0.10 sec and 0.11 sec is due to a spin-up electron hopping off the donor, followed by a spin-down electron hopping onto the donor.

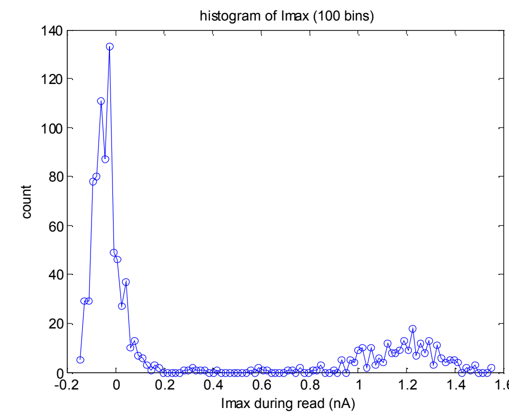
Examples of single-shot current response

(read = 0.1-0.14 sec)





The distribution of the maximum current during the read period show two well isolated peaks. The right one corresponds to spin-up events.



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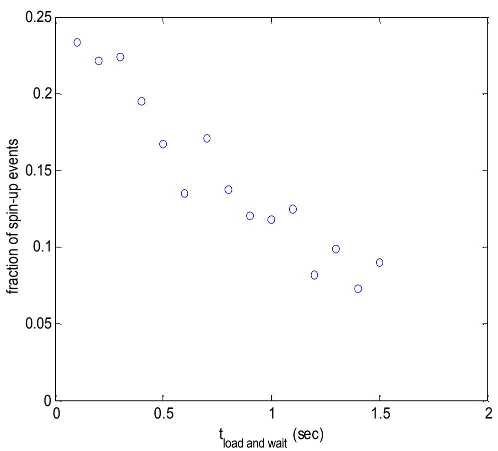
Relaxation Time

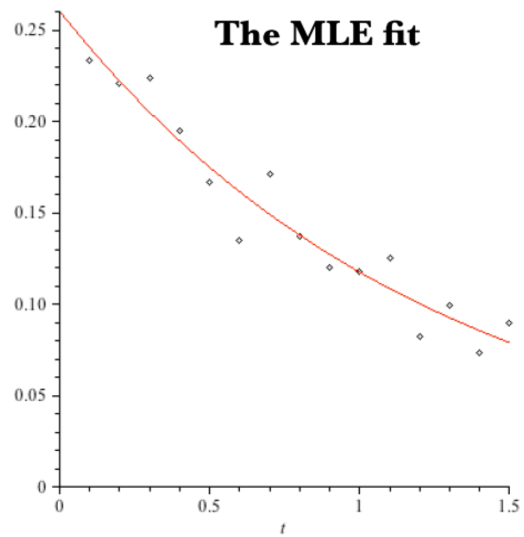
N single-shot traces are recorded at each load and wait time. The fraction of spin-up events decays exponentially with a time constant T_1.

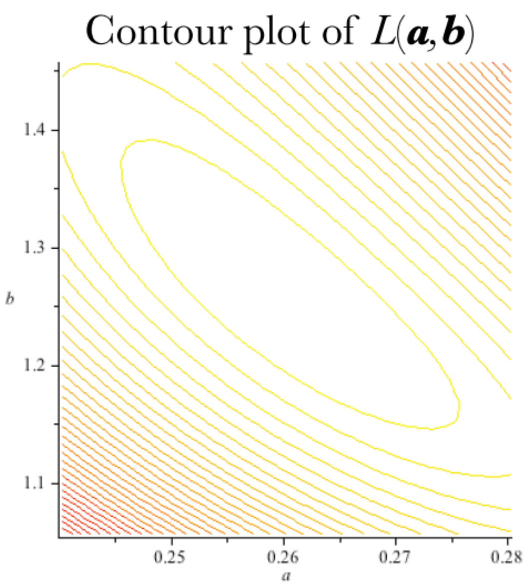
Model: $p(t) = a\, e^{-t/b}$

Likelihood function L(a,b) = Pr(Data | a,b)

Example: B = 3.25T, N = 1000







T1 = b = 1.27±0.15 sec
(with 95% confidence)

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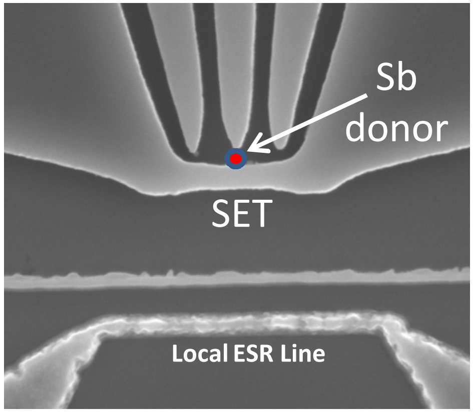
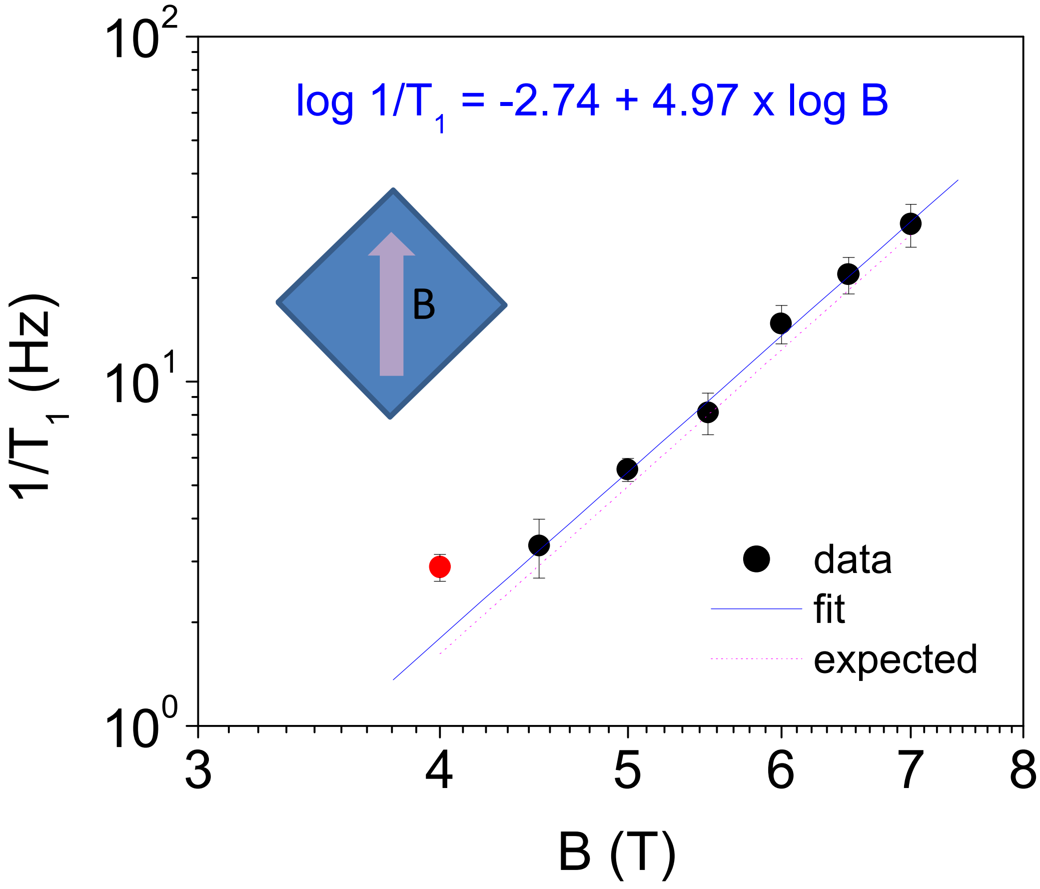
Magnetic field dependence of T1

Sb donors implanted near silicon SET



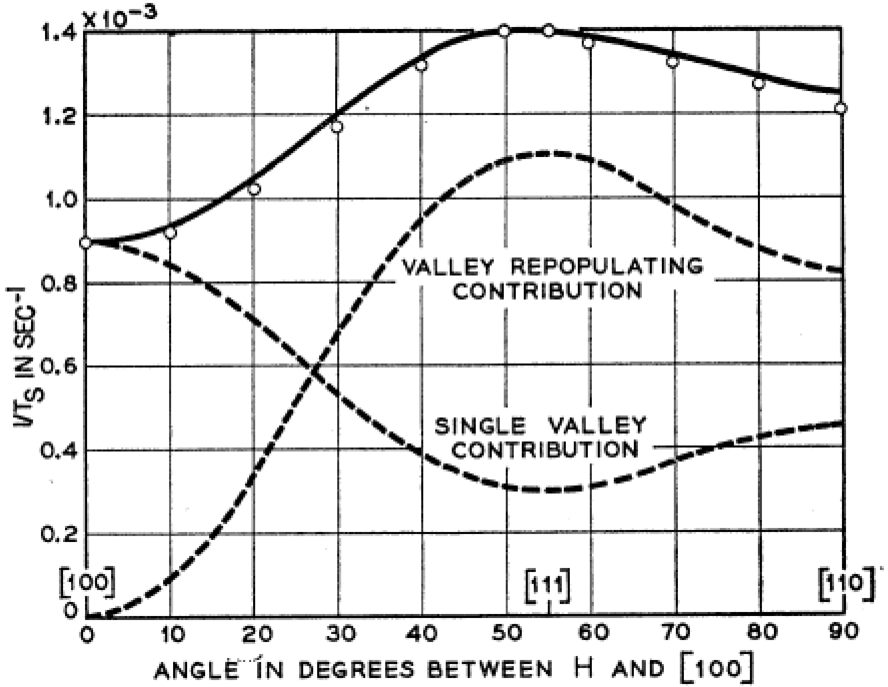
- B5 dependence expected for electron on donor
- Long T1 times beneficial for silicon qubit.

T1 decreases with increasing field



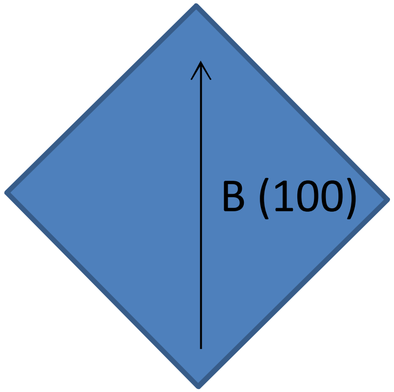
Lisa Tracy

Spin relaxation in silicon



Phys. Rev. 124, 1068 – 1083 (**1961**).

Sample orientation in dry fridge



For B in (100) direction, expect single valley contribution only to T_1 relaxation.
Due to change in g-factor from mixing between bands with strain.

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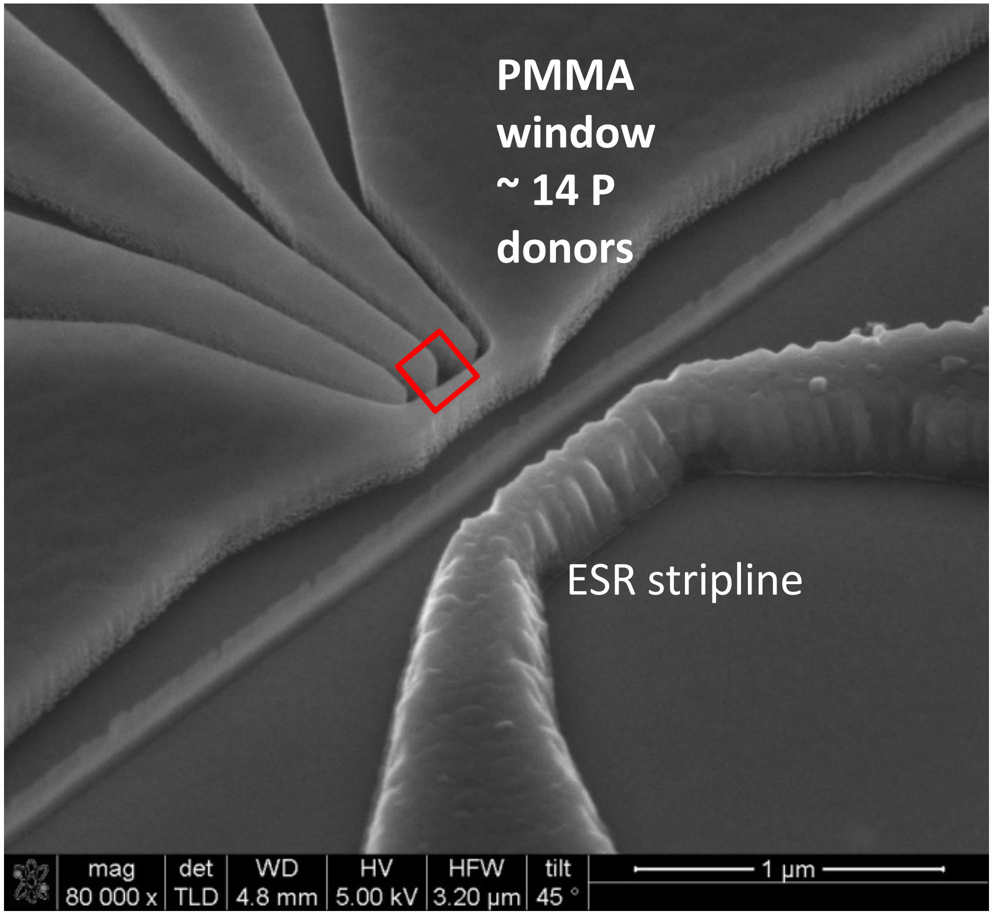
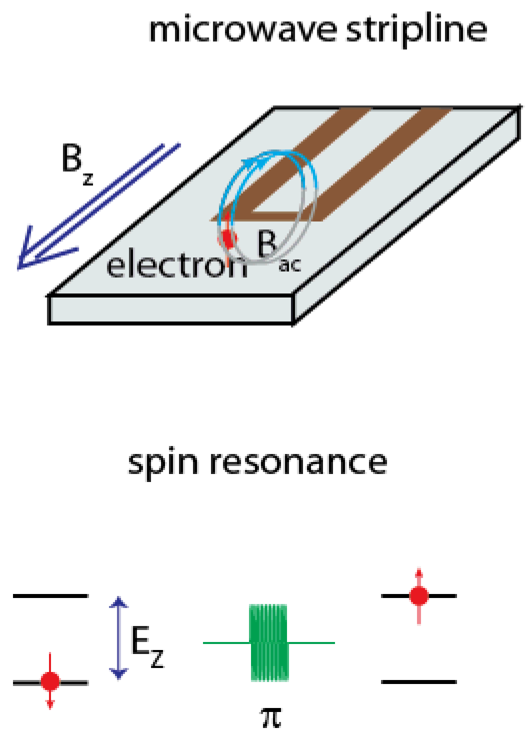
Next Steps: Local Electron Spin Resonance

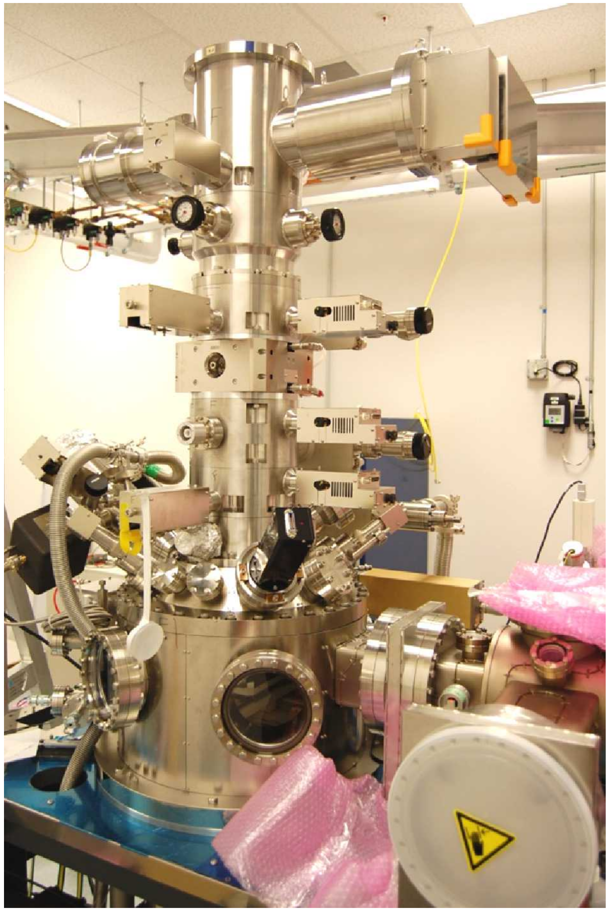




Lisa Tracy, Dwight Luhman, Khoi Nguyen

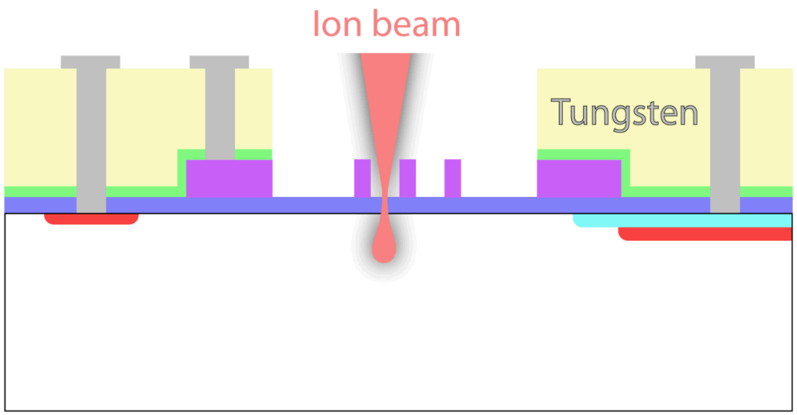
Deterministic implants using ion detection

nanoImplanter



- AuSiSb source
- ExB filter to select ion species and ionization
- Super-FIB for focus and steering donor ions
- Built in detectors surround silicon nanostructure regime

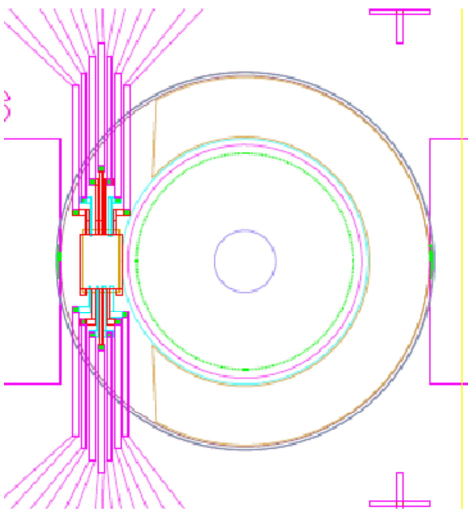
Detector schematic



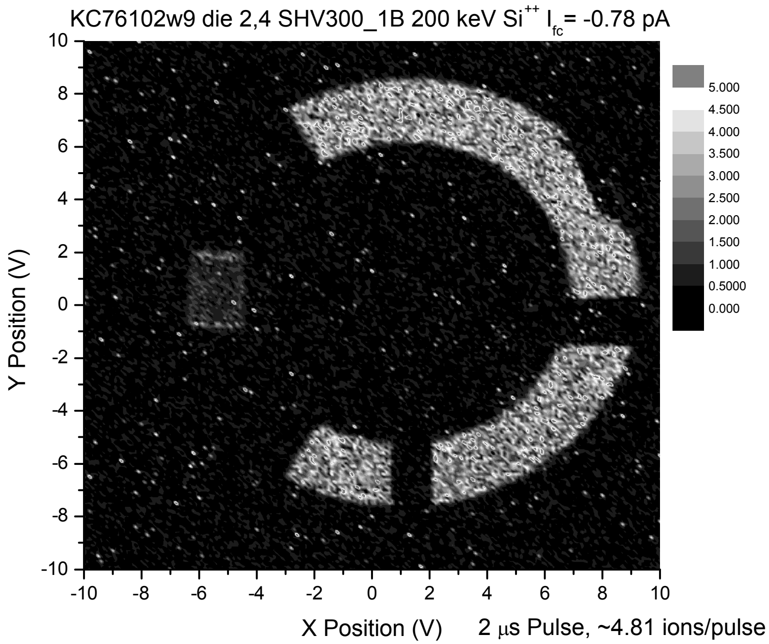
Ed Bielejec, Eli Garratt

Ion detector operation

CAD for detector and nanostructure construction zone



200 keV silicon



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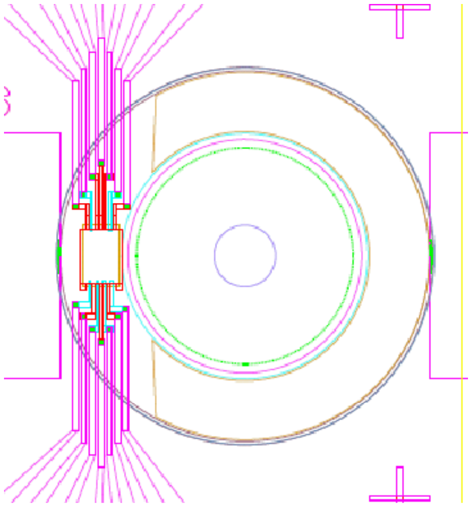
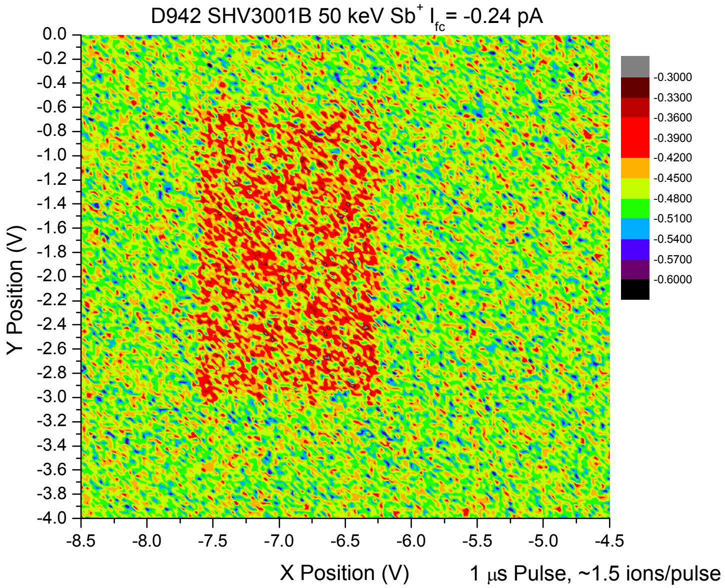
Ion detector operation

Detected single donor implantation of Sb ions allows multi-donor devices

CAD for detector and nanostructure construction zone



50 keV Sb, 1.5 ions/pulse

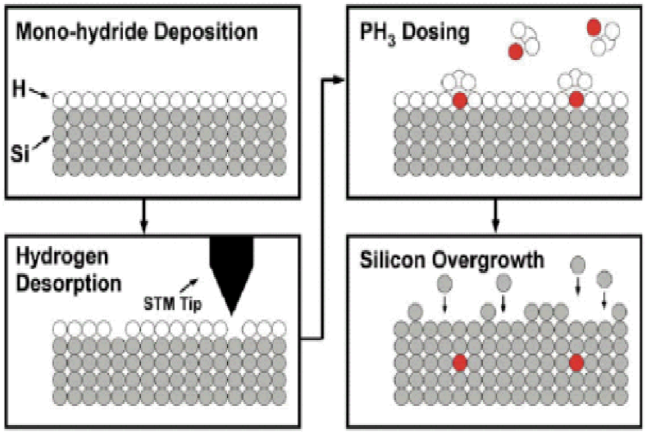


Ed Bielejec, Eli Garratt

Single Donor Approaches

Bottom-Up

Atomic Scale Fabrication
SNL and CQC^2T

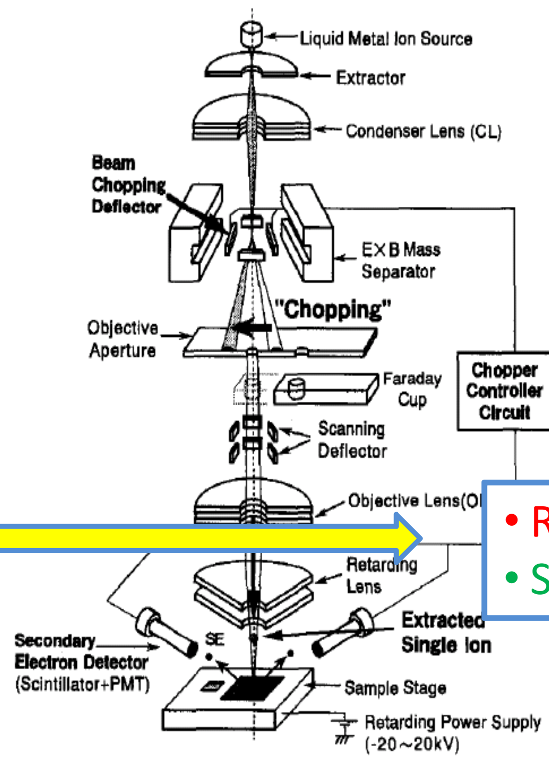


J. L. O'Brien *et al*, PRB **64**, 161401 (R), 2001

- Resolution
- Speed

Top-Down

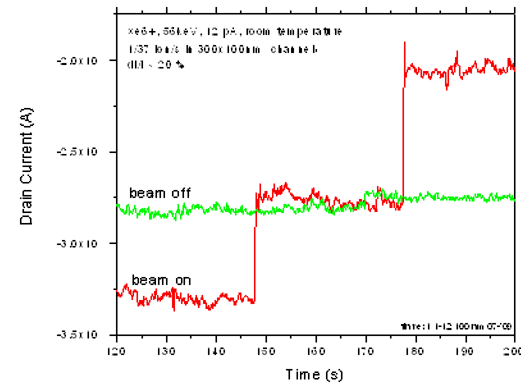
Focused Ion Implantation
SNL and Waseda



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)

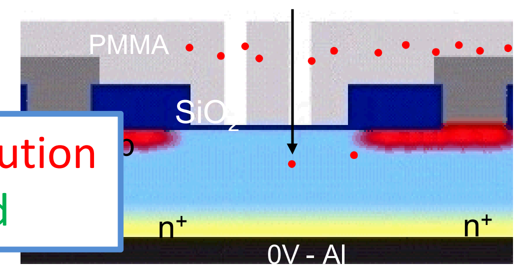
- Resolution
- Speed

LBNL: RT Drain Current



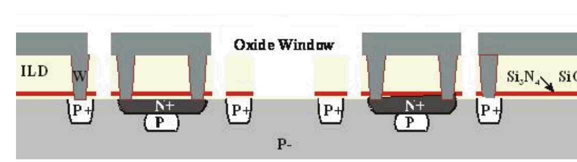
C. D. Weis, *et al.*, NIMB, 267, 1222-1225 (2009)

CQC^2T: Low Temperature PINs

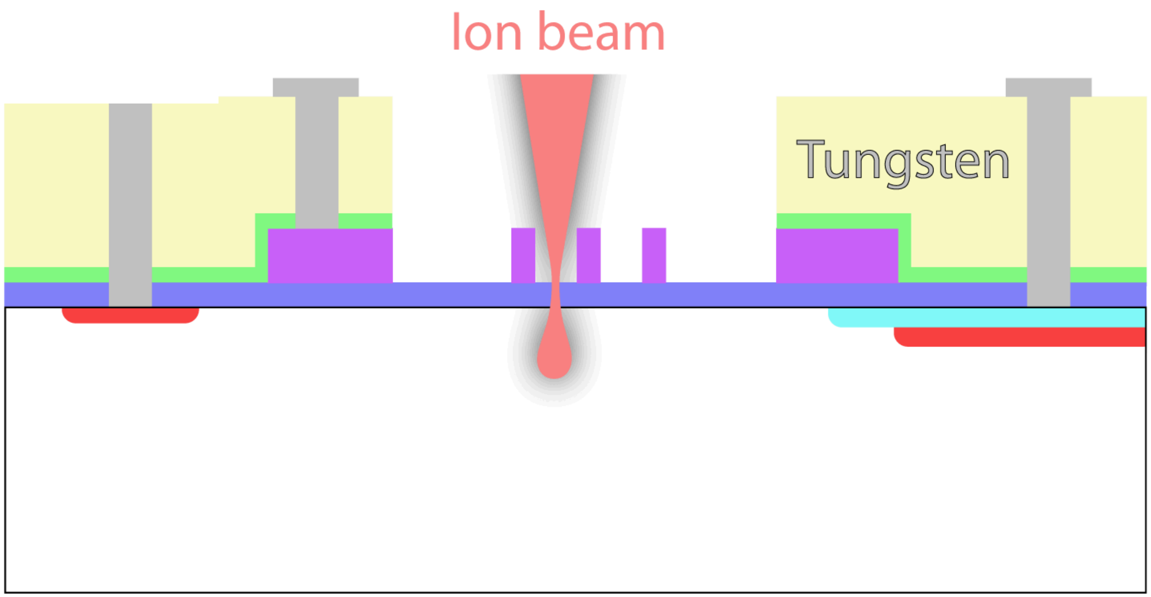


D. N. Jamieson *et al.*, Appl. Phys. Lett. **86**, 202101 (2005)

SNL: Low Temperature APDs



Goal: Fabrication of Deterministic Single Ion Devices



- Enhancement mode Si MOS device
- Integrated single ion detectors
- Self-aligned Poly-Si nanostructures
- Focused low energy P, Sb or Bi ion beam
- Accurate controllable placement of single donors

Every step is difficult and we have to get all right to have success!

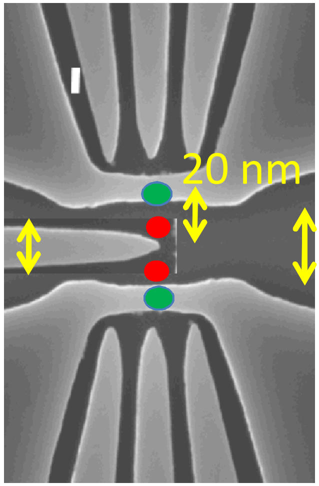
1Q donors: How deep?

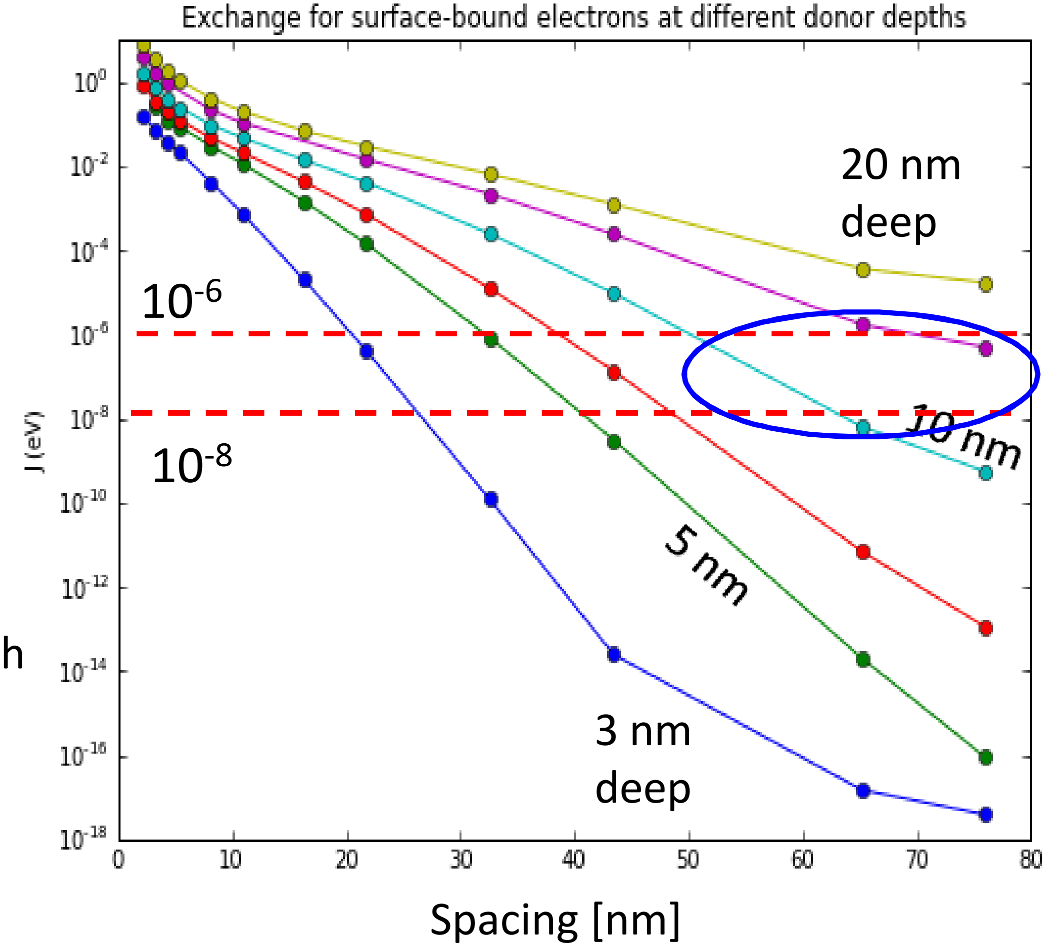
- For 1Q we need are initially targeting a depth of ~29 nm below the surface

2Q donors: How deep and with what spacing?

Photoshop lay-out

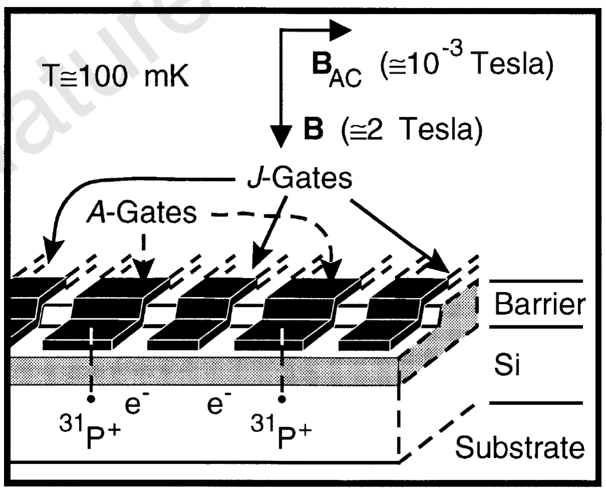
60 nm





- For 2Q we need to target a donor depth (10-15 nm) and spacing (50-80 nm)

Deterministic Single Ion Devices



B. E. Kane, Nature **393**, 1998

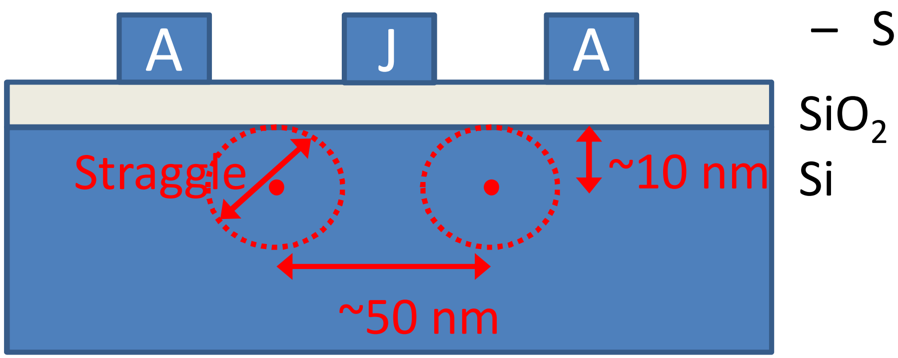
What capability is needed to fabricate these devices?

Controlled Location of Donor Site(s)

- Minimize Straggle in depth (Z)
  - Low Energy Ion Implants
- Control of X,Y donor site(s)
  - Focused Ion Beam (FIB) Implantation
  - Electron Beam Lithography (EBL)

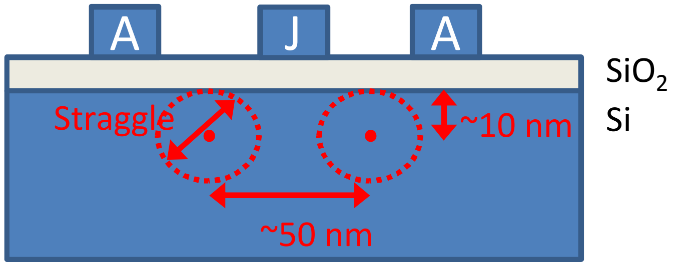
Controlled Alignment of Donor Site(s) and Gates

- Self-Aligned Poly-Si



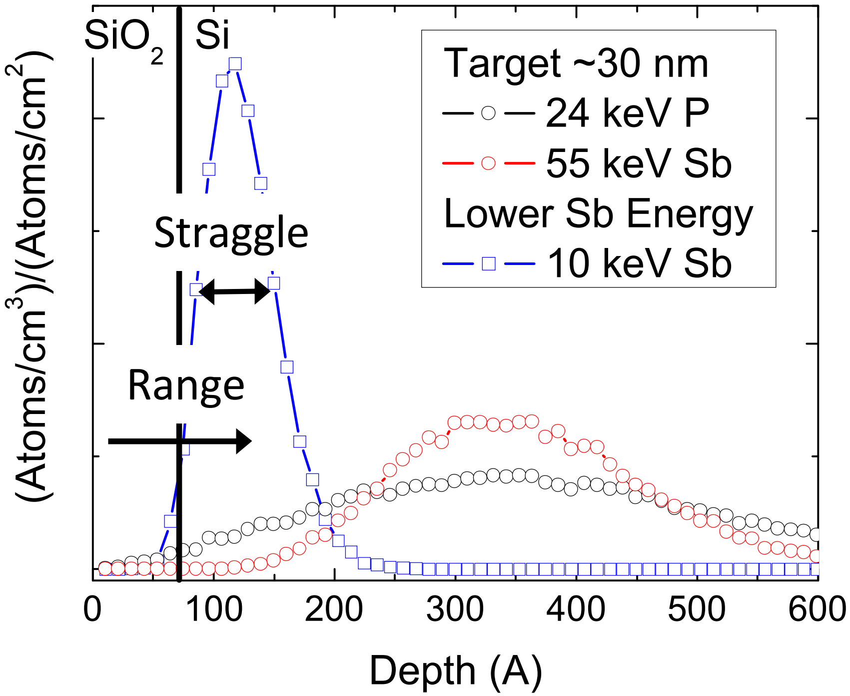
Path forward to 1 and 2 donor systems

Controlled Location of Donor Site(s)



Minimize Straggle in depth (Z)

- **<u>Low Energy Ion Implants</u>** -> Detector Gain



Assuming 7 nm SiO_2

Ion	Energy (keV)	Range (nm)	# e-h pair
P	24	36 ± 16 ± 13	~2500
Sb	55	36 ± 10 ± 8	~4600
Sb	10	12 ± 3 ± 3	~600

Range

Depth Straggle

XY Projection Straggle

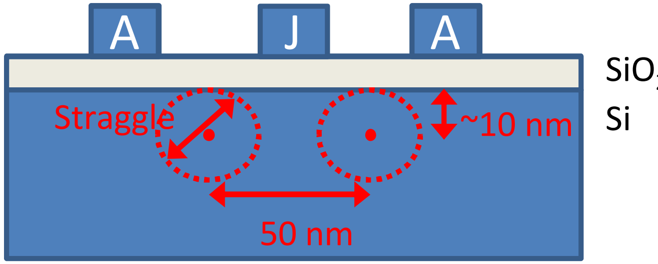
Ultimately Need Detector sensitivity of <1000 e-h pairs

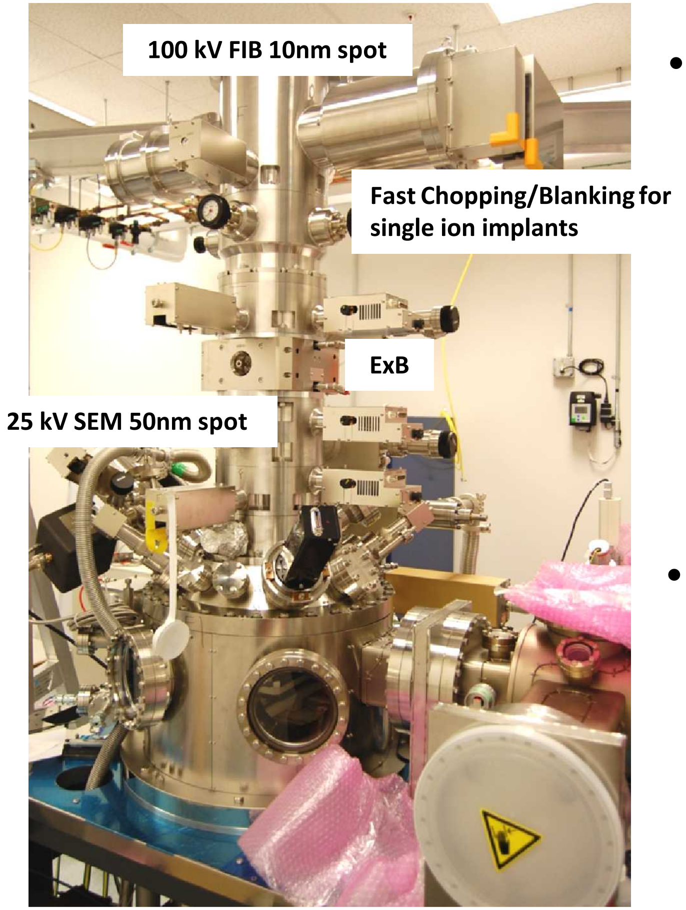
-> *<u>Geiger Mode Detection using Avalanche Diodes can detect single e-h pair (single photon) at 10-30% DE</u>*

Controlled Location of Donor Site(s)

Control of X,Y donor site(s)

- **<u>Focused Ion Beam Implantation</u>** -> Placement of multiple donors with good spatial resolution





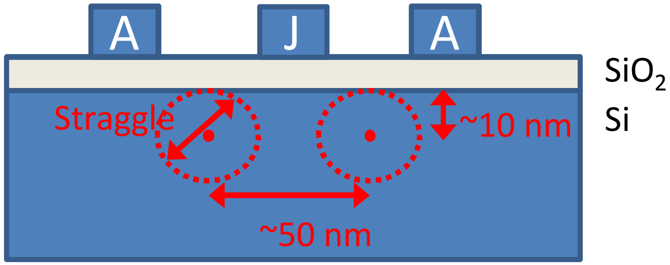
- <u>NanoImplanter (nI)</u>
  - Variable Energy 10-100 kV
  - Liquid Metal Alloy Ion Source (LMAIS)
  - Mass Velocity Filter to pick out ion of interest
  - Fast Blanking and Chopping for single ion implants
  - Demonstrated
    - ~10 nm 100 keV Ga^+
    - ~26 nm 200 keV Si^{++}

- <u>Beam Spot Size depends on</u>
  - $\Delta E/E$ spread
    - Ion Mass ($\propto m^{1/3}$)
    - Accelerating Voltage ($\propto E^{1/3}$)
  - ***Expect ~50 nm spot at 55 keV Sb^+ (1Q)***
  - ***Expect ~100 nm spot at 10 keV Sb^+ (2Q)***

Controlled Location of Donor Site(s)

Control of X,Y donor site(s)

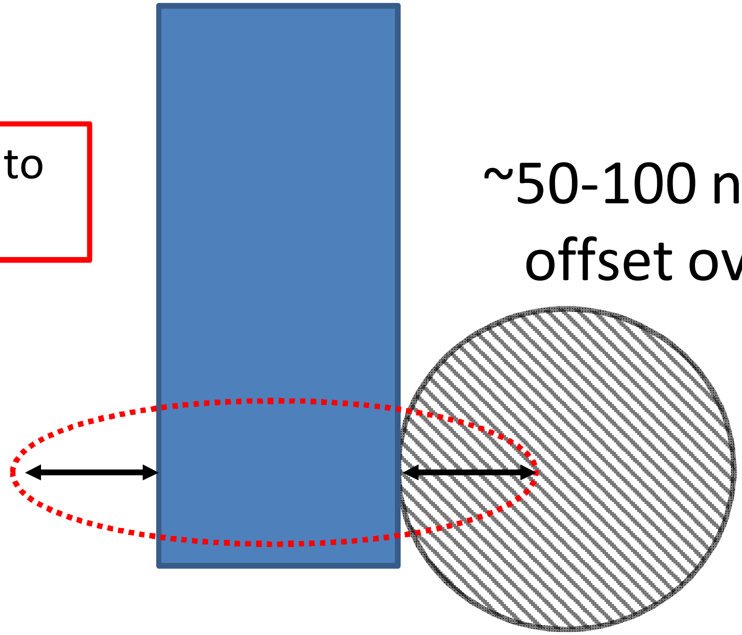
- **Electron Beam Lithography**-> Placement of multiple donors with good spatial resolution



J Gate 40 nm Poly-Si

Immediate path forward to two donor devices!

~50-100 nm Ion Beam Spot offset over PMMA mask

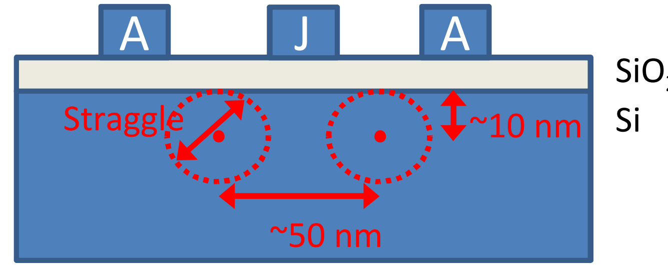


~10 nm PMMA masks openings

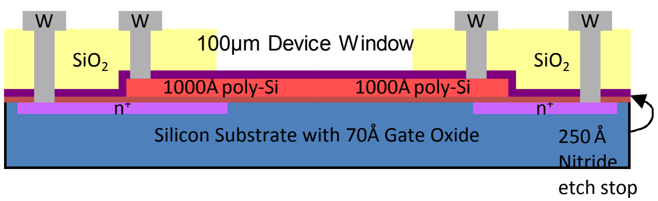
Controlled Alignment of Donor Site(s) and Gates

Self-Aligned Poly-Si

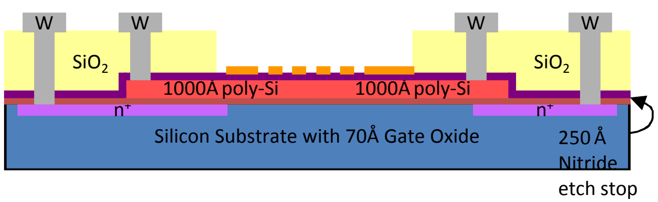
- **Patterned Poly-Si is first, then EBL and FIB aligned to it** -> Path forward to 1 and 2 donor systems



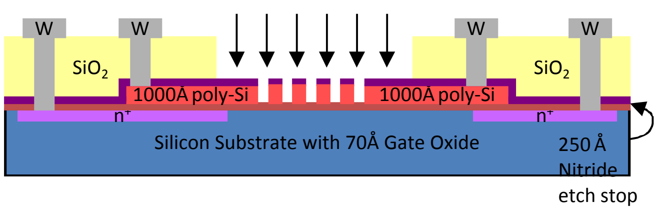
1.) As-Received MDL Parts



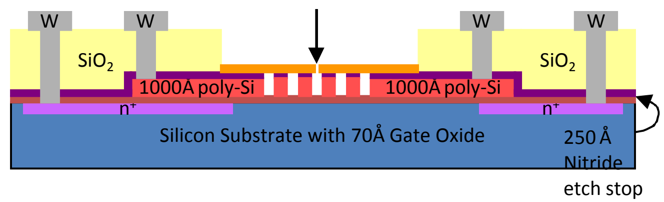
2.) EBL Patterning



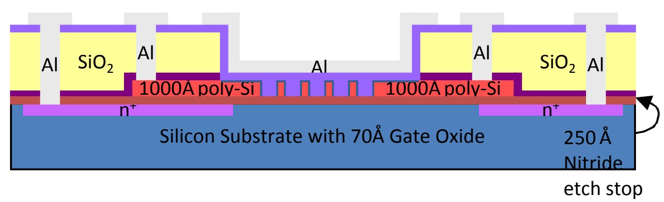
3.) Poly-Si Etch



4.) 55 keV Sb Implantation

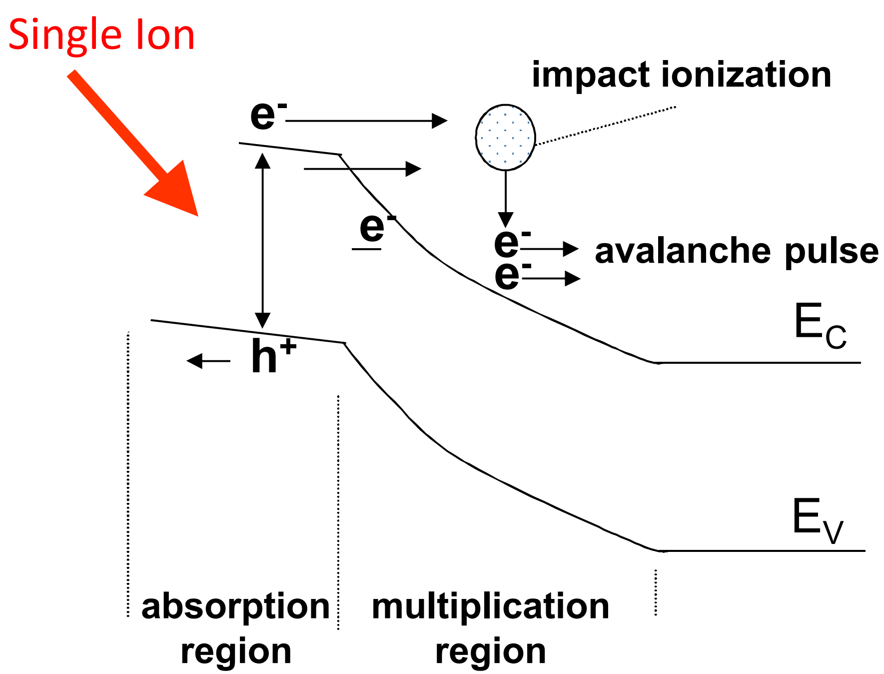


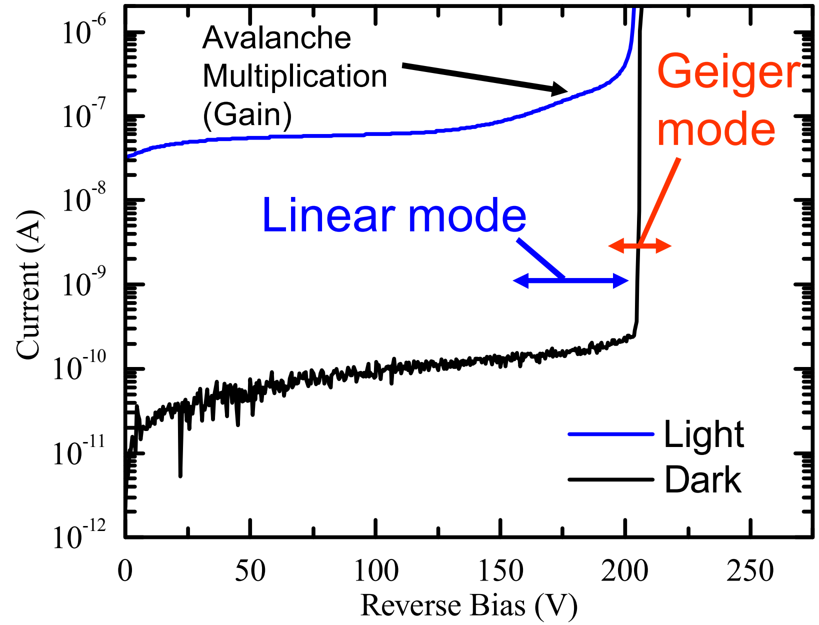
5.) Aluminum Pad Metal Liftoff



Self-Aligned Process flow -> registration between poly Si gates and donor site(s)

Avalanche Photodiode (APD) for Ion Detection





- APD produces internal gain due to high field impact ionization (sensitive to local doping profile)

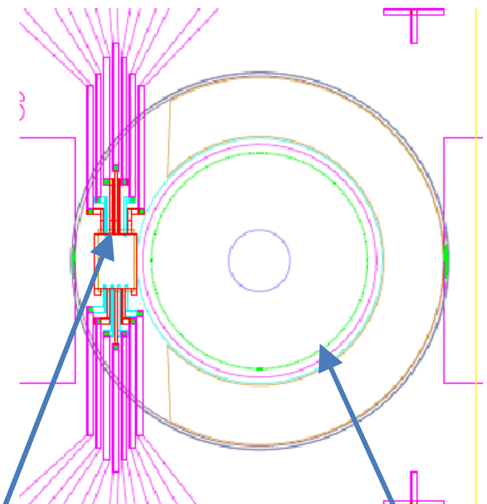
Linear Mode Operation

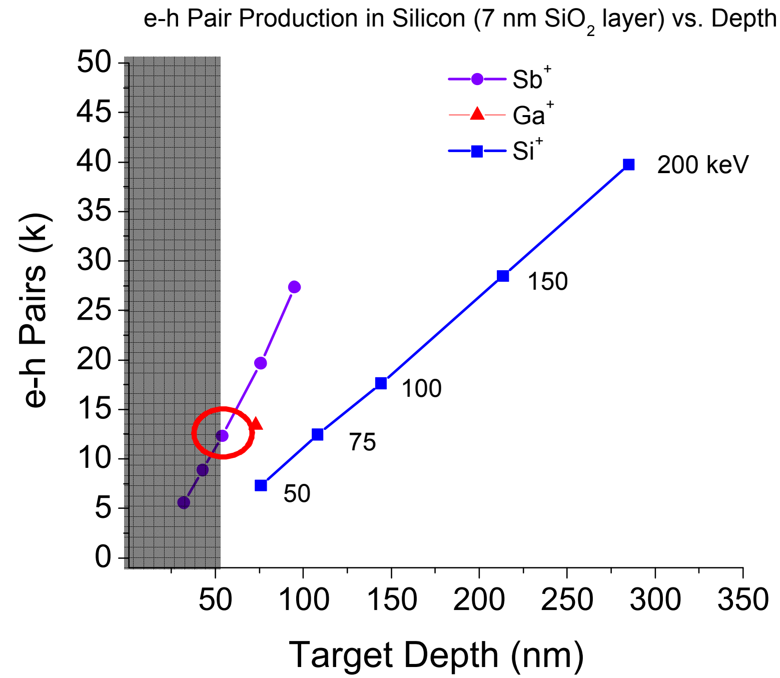
- Bias below breakdown
- Linear-mode: Amplifier
- Gain: limited 1 to <1000

Geiger Mode Operation

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

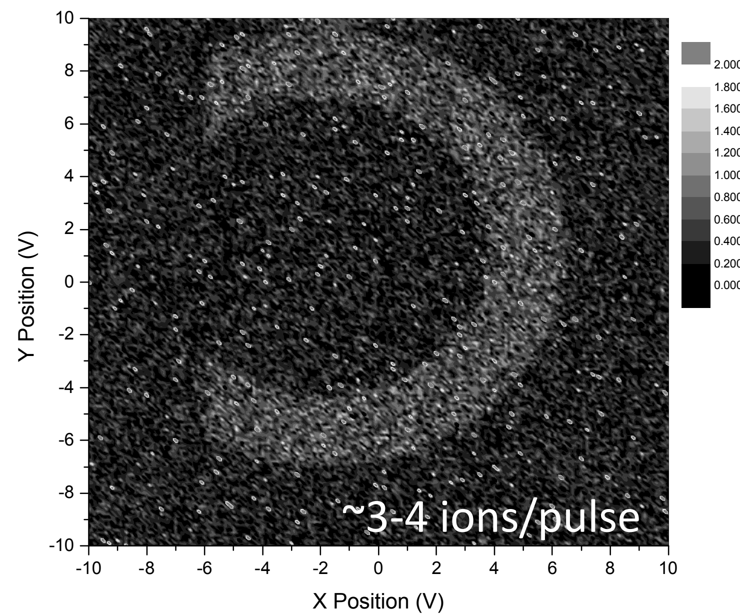
Linear Mode Active Carrier Detection under Sb Irradiations – what to expect?





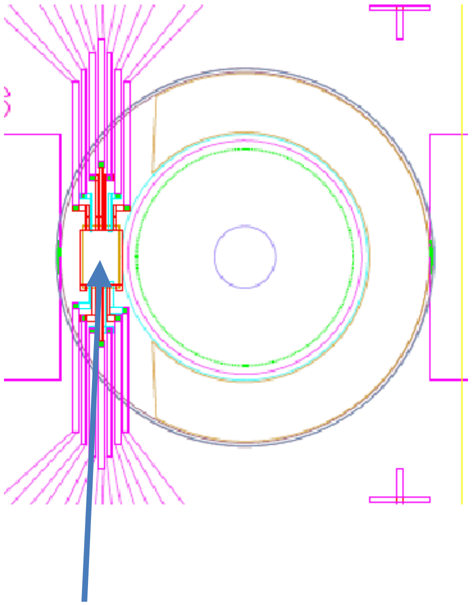
Thin oxide window – 35 nm SiN + 7 nm SiO2

Construction Zone – 35 nm SiN + 200 nm Poly Si + 7 nm SiO2



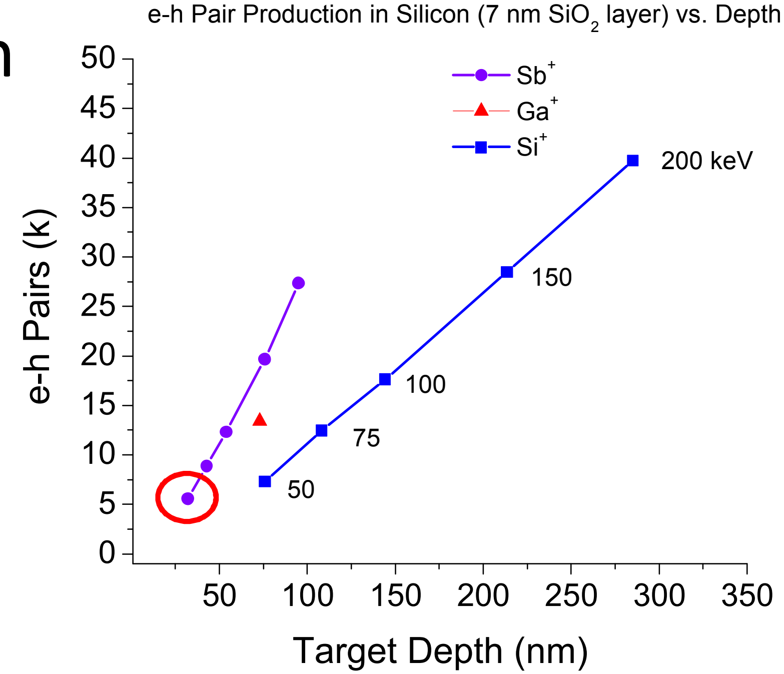
100 keV Sb only gets through the thin oxide window!

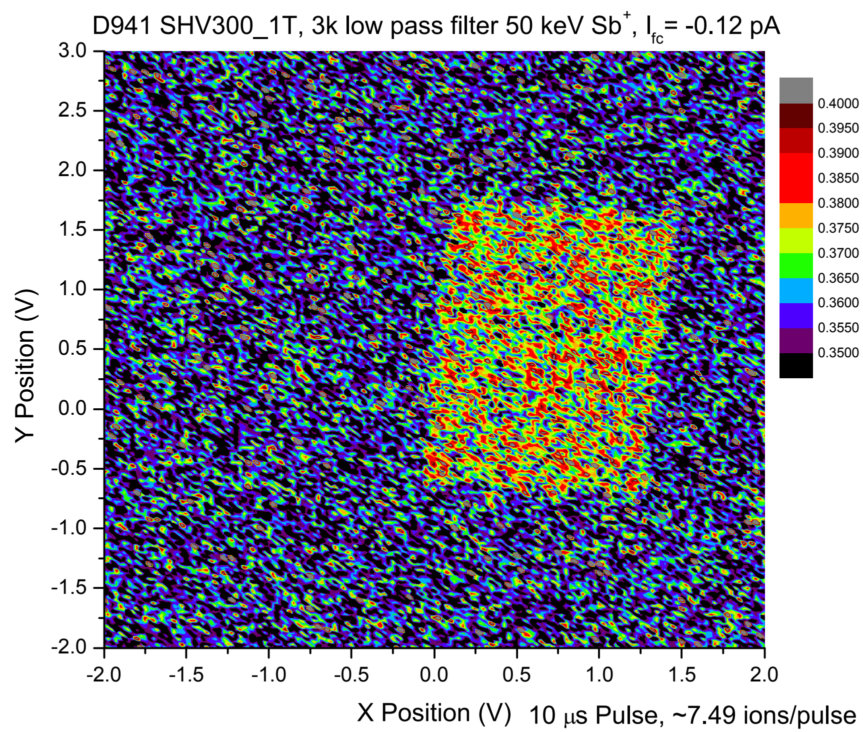
Linear mode 50 keV Sb detection in etched construction zone



Construction Zone – 7 nm SiO2

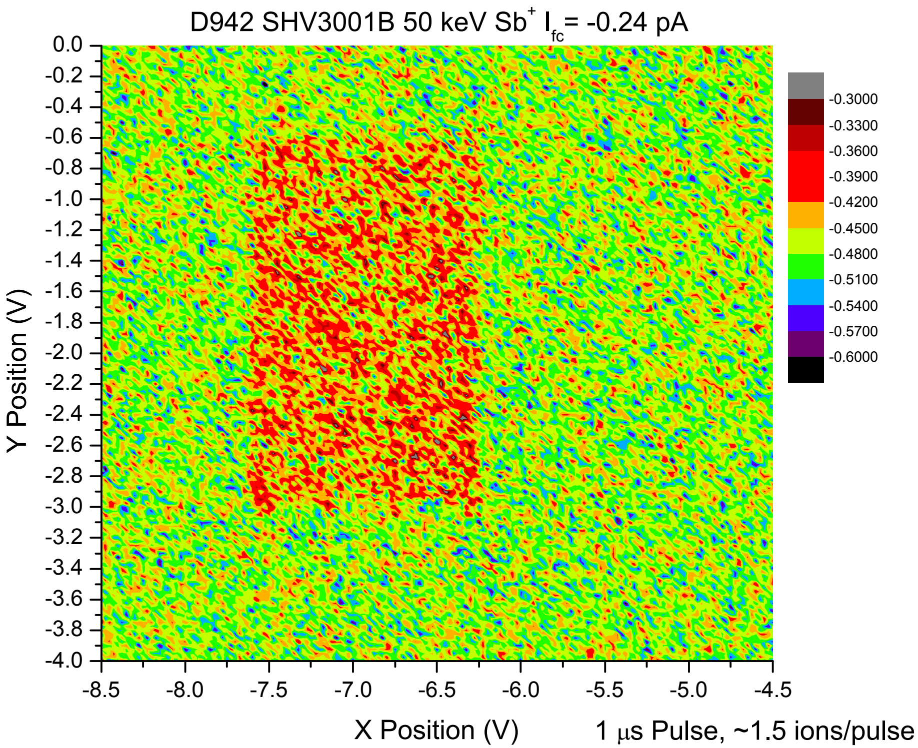
- Linear mode etched construction zone
  - Response to 50 keV Sb^+ down to ~2 ions/pulse in linear mode

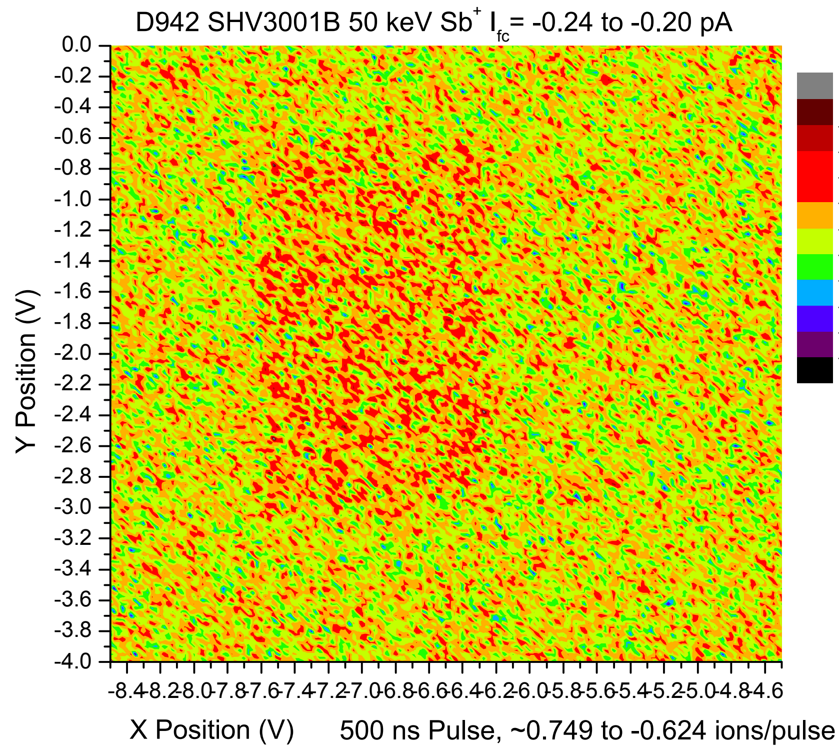




Linear mode 50 keV Sb detection in etched construction zone

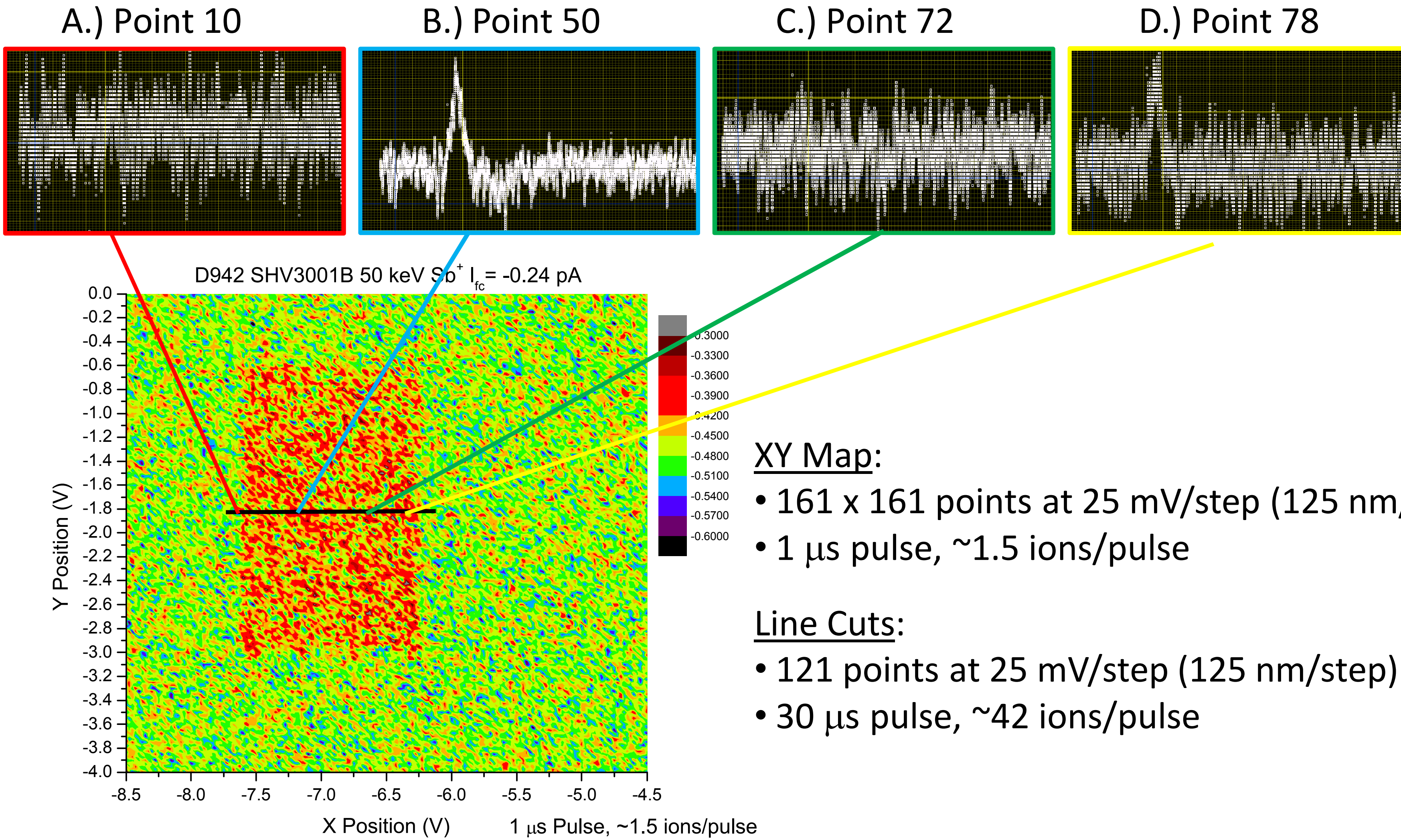
Improved the s/n and pushed down detection sensitivity





Linear mode 50 keV Sb detection for <1 ion/pulse!

Single Pulse Single Ion Detection



XY Map:

- 161 x 161 points at 25 mV/step (125 nm/step)
- 1 μs pulse, ~1.5 ions/pulse

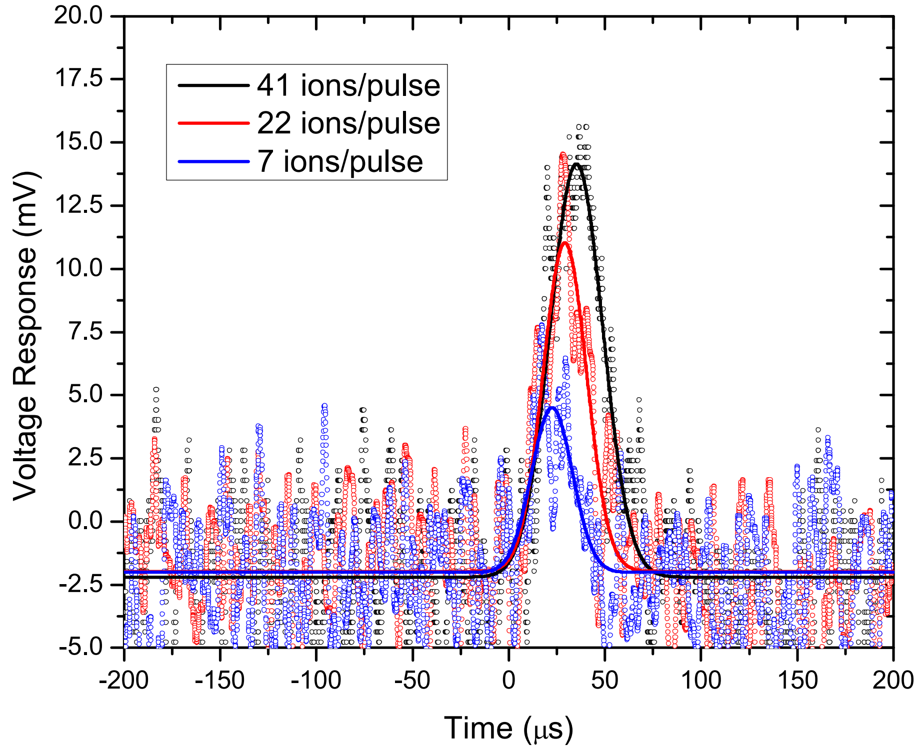
Line Cuts:

- 121 points at 25 mV/step (125 nm/step)
- 30 μs pulse, ~42 ions/pulse

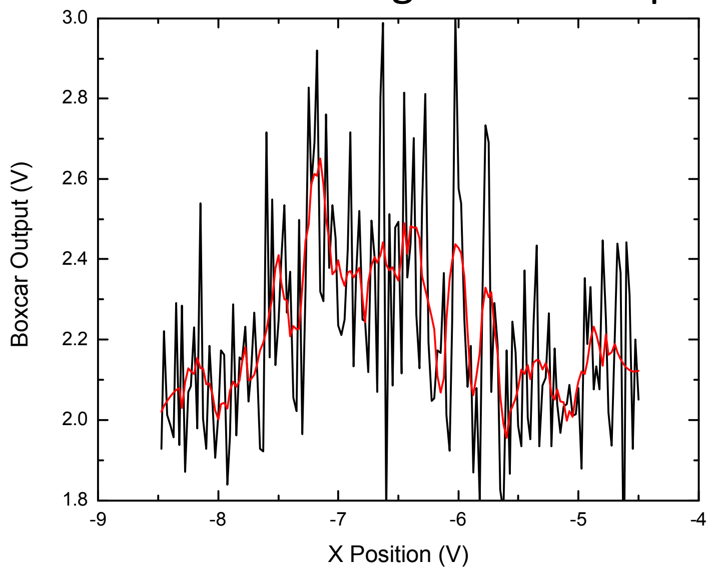
The structure in the XY map is reproducible, indicating issue with underlying detector (or etching) and not DE

Single Pulse Single Ion Detection

Raw signal from the shaping amp



Line cut through the XY map



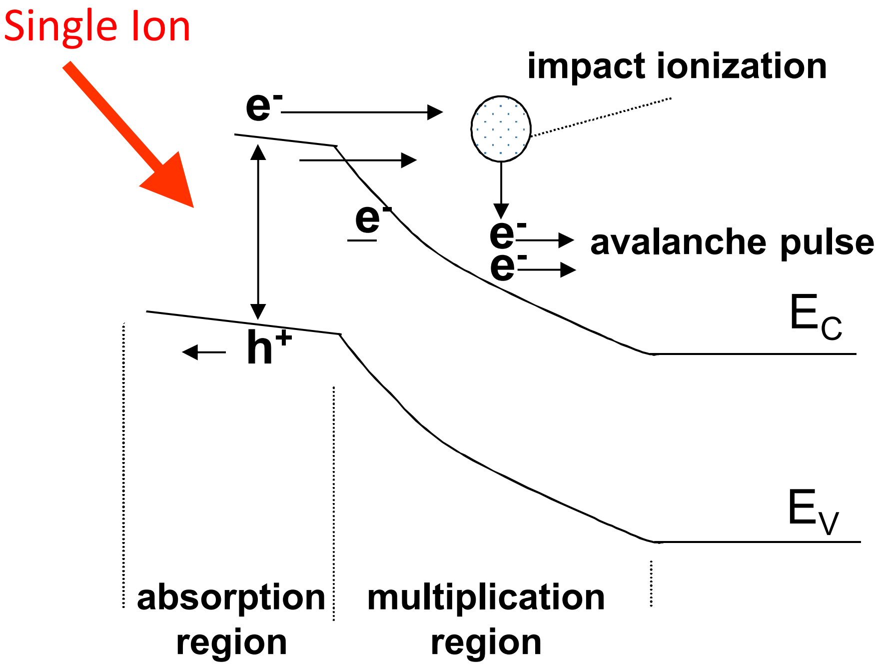
- Boxcar integration of the peak improves signal visibility
- s/n ~8 at 1.5 ions/pulse
- 3.2e-5 error rate (Gurrieri)
- Not bad, but we can do better!

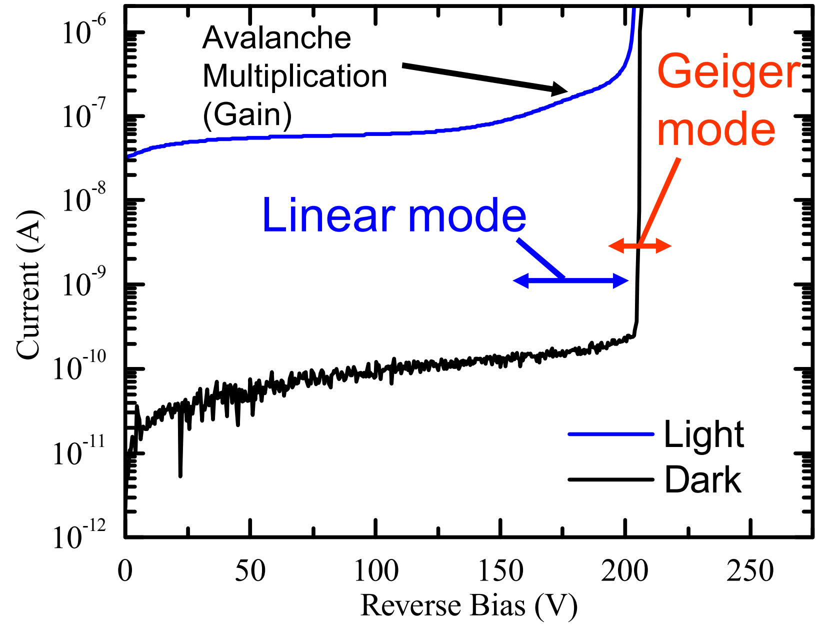
While we can easily detect and observe <1 ion/pulse in the XY maps, doing so in a single pulse is hindered by the s/n

→ Improve s/n using shielded probes and *in-situ* cooled FET

→ Improve signal amplitude using GM detection

Avalanche Photodiode (APD) for Ion Detection





- APD produces internal gain due to high field impact ionization (sensitive to local doping profile)

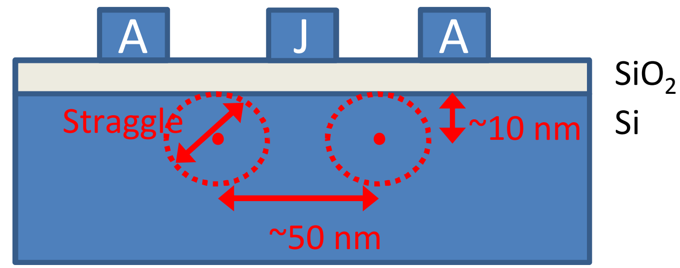
Linear Mode Operation

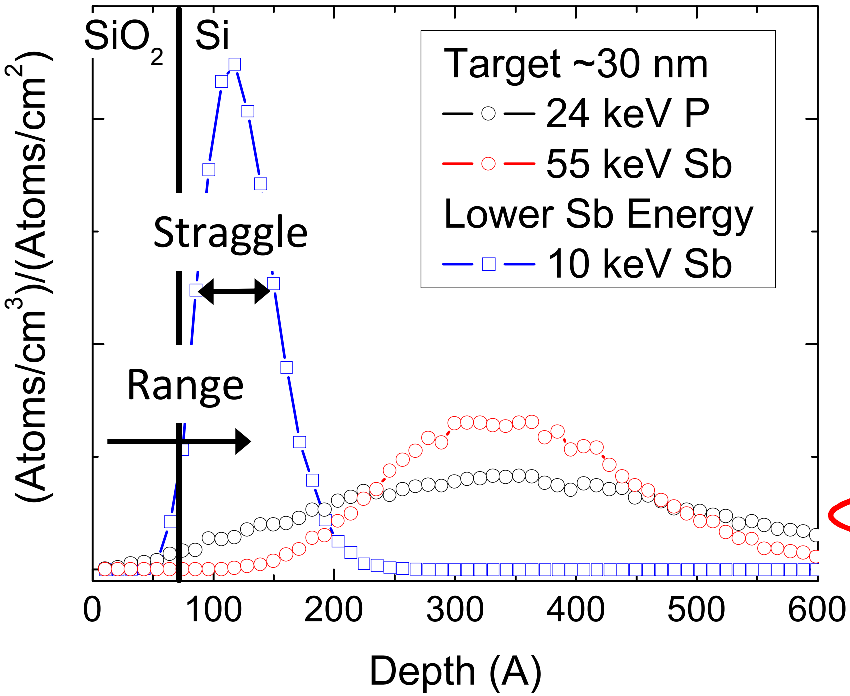
- Bias below breakdown
- Linear-mode: Amplifier
- Gain: limited 1 to <1000

Geiger Mode Operation

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

How to push down to <600 e-h detection?





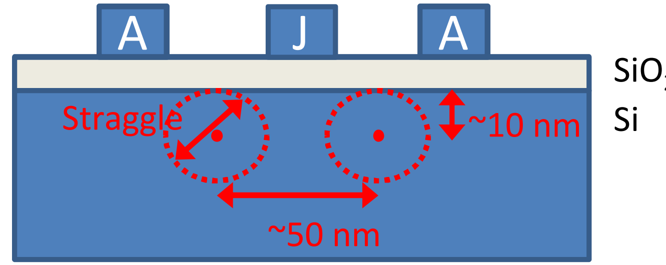
Assuming 7 nm SiO_2

Ion	Energy (keV)	Range (nm)	# e-h pair
P	24	36 ± 16 ± 13	~2500
Sb	55	36 ± 10 ± 8	~4600
Sb	10	12 ± 3 ± 3	~600

Range
Depth Straggle
XY Projection Straggle

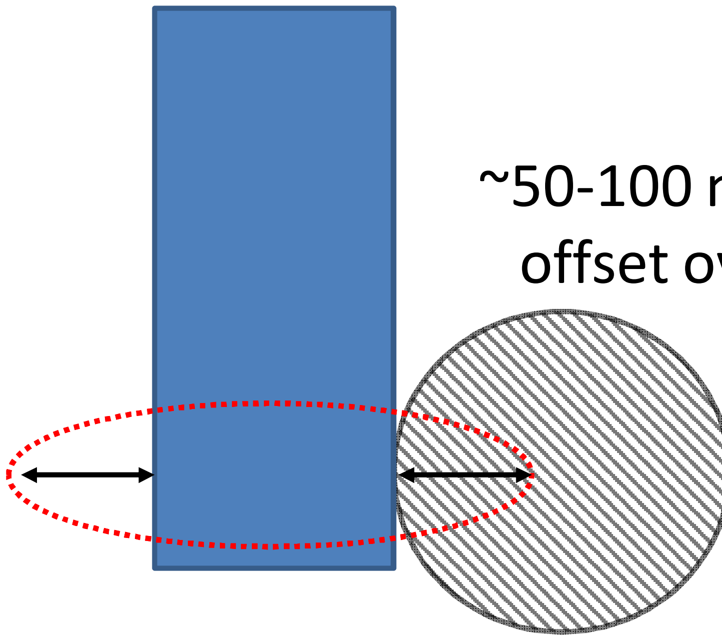
- For 2Q fabrication we need to push down to <600 e-h detection limit to ensure an acceptable Z straggle limit (for two interacting donors)

How to push down to smaller nI spot size?



J Gate 40 nm Poly-Si

~50-100 nm Ion Beam Spot offset over PMMA mask



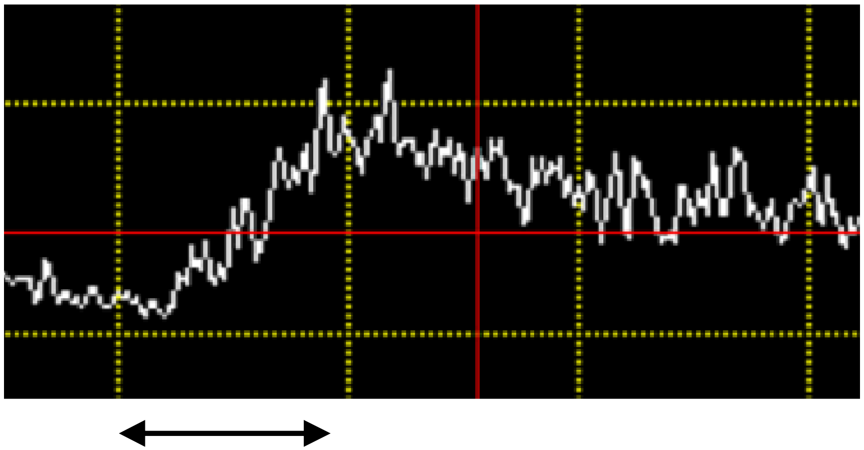
~10 nm PMMA masks openings

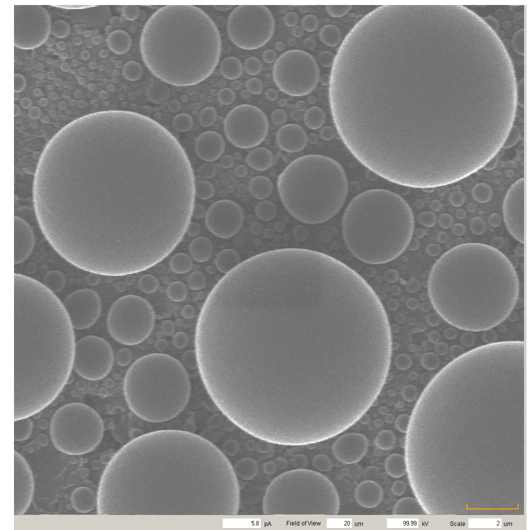
- For 2Q fabrication we need to push down the low energy Sb spot size in the nI to ensure an acceptable spacing between the donors

nI Spot Size

100 kV Accelerating Voltage → 200 keV Si++ on target

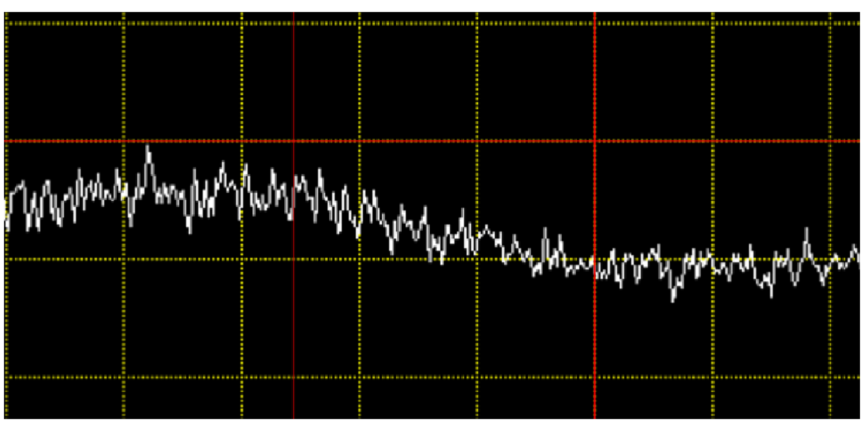
Line cut over a Sn on Au sample showing a 20-80% line-width of **~26 nm**





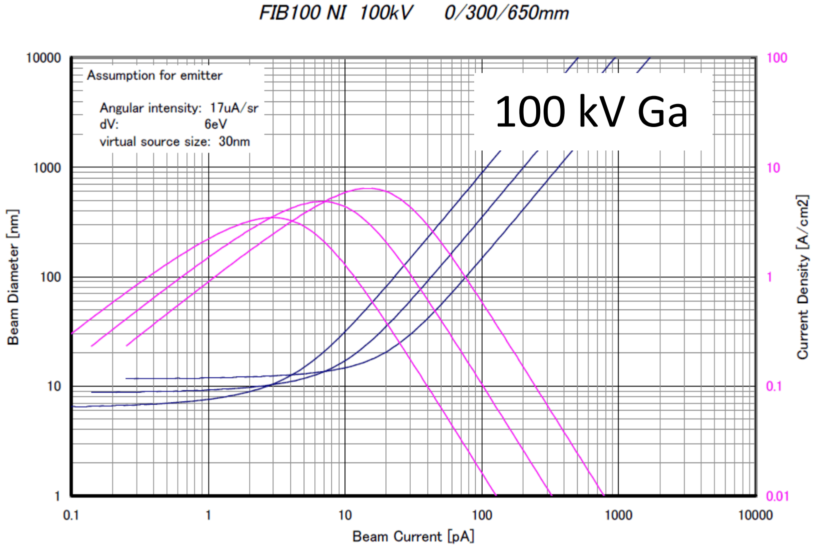
50 kV Accelerating Voltage → 100 keV Si++ on target

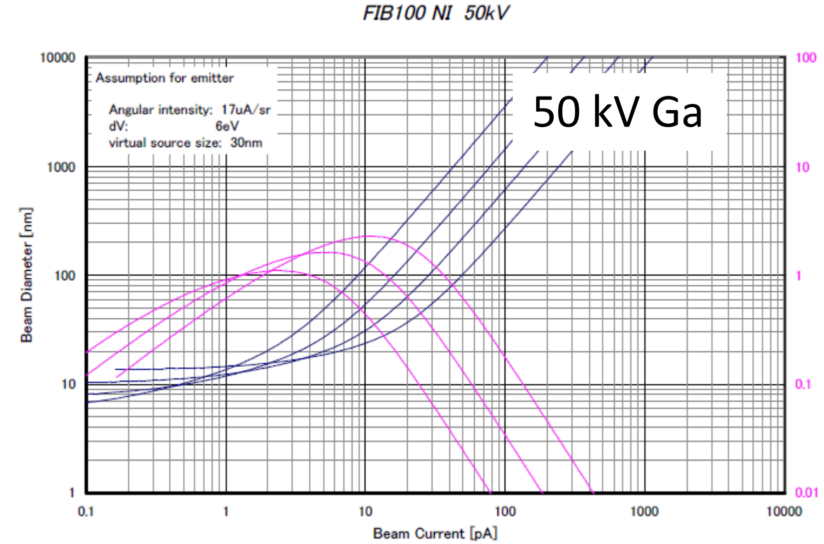
Line cut over a Sn on Au sample showing a 20-80% line-width of **~100 nm**

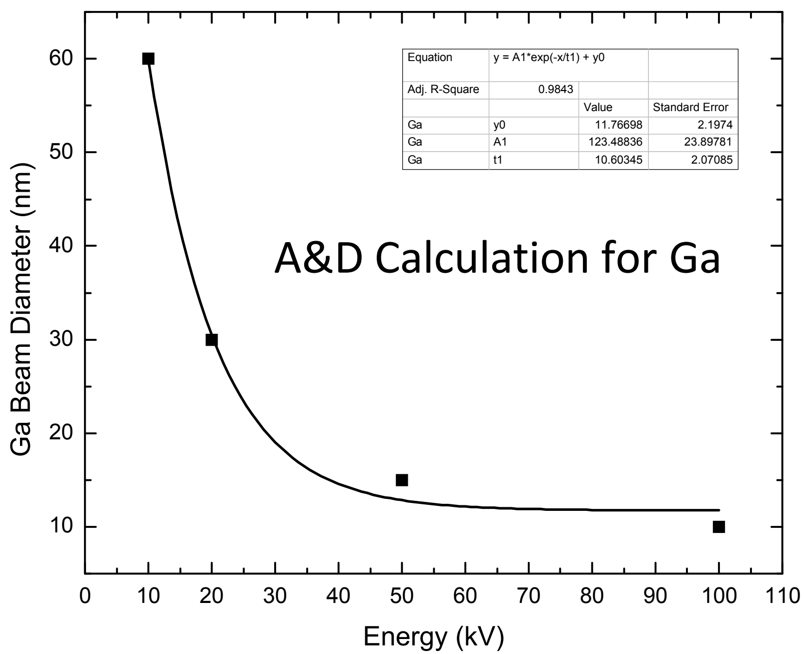


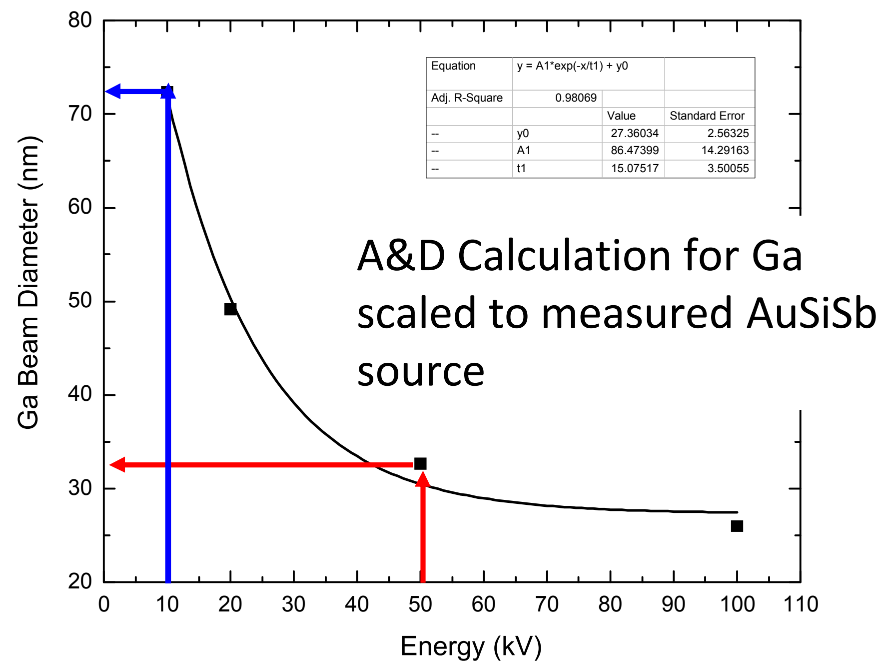
Best Sb spot to-date
→ 50 keV Sb+ spot ~200 nm

nI Spot Size





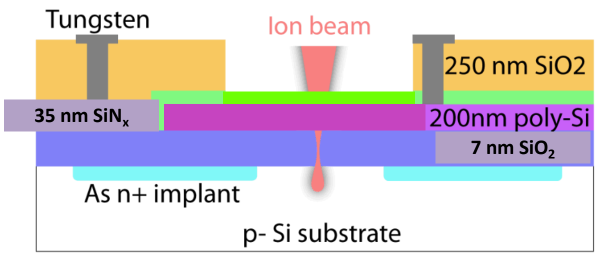




Expect <35 nm spot at 50 kV (we measured much larger!) and <75 nm spot at 10 kV for Si

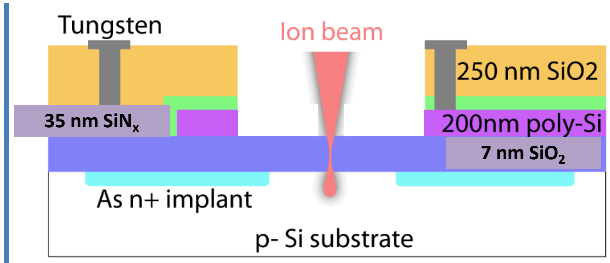
Overview of the APD Stacks

Thick Stack



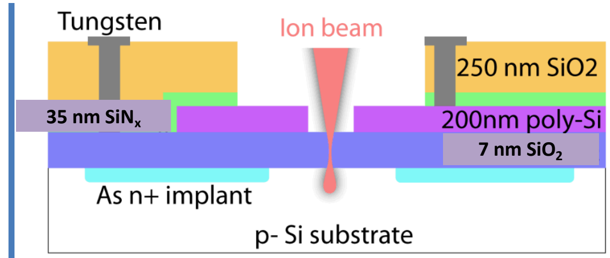
- Good DE, but only at high energy (overlayers)
- Tested using large diameter (50 µm) ion beams
- **Tested with protons and laser, Sb ions range in over-layers**

Thin Stack



- Allows for testing using large area beams and the correct ion/energy combination
- **Tested with protons,laser, and Sb (nI)->** *<1 ion/pulse detection observed*

Nanostructured Device



- **Real devices**
- 50 keV Sb tests -> series of timed implants using the nI into nanostructured devices completed

For nanostructured devices we need small spot size, high flux and lithography software → NanoImplanter

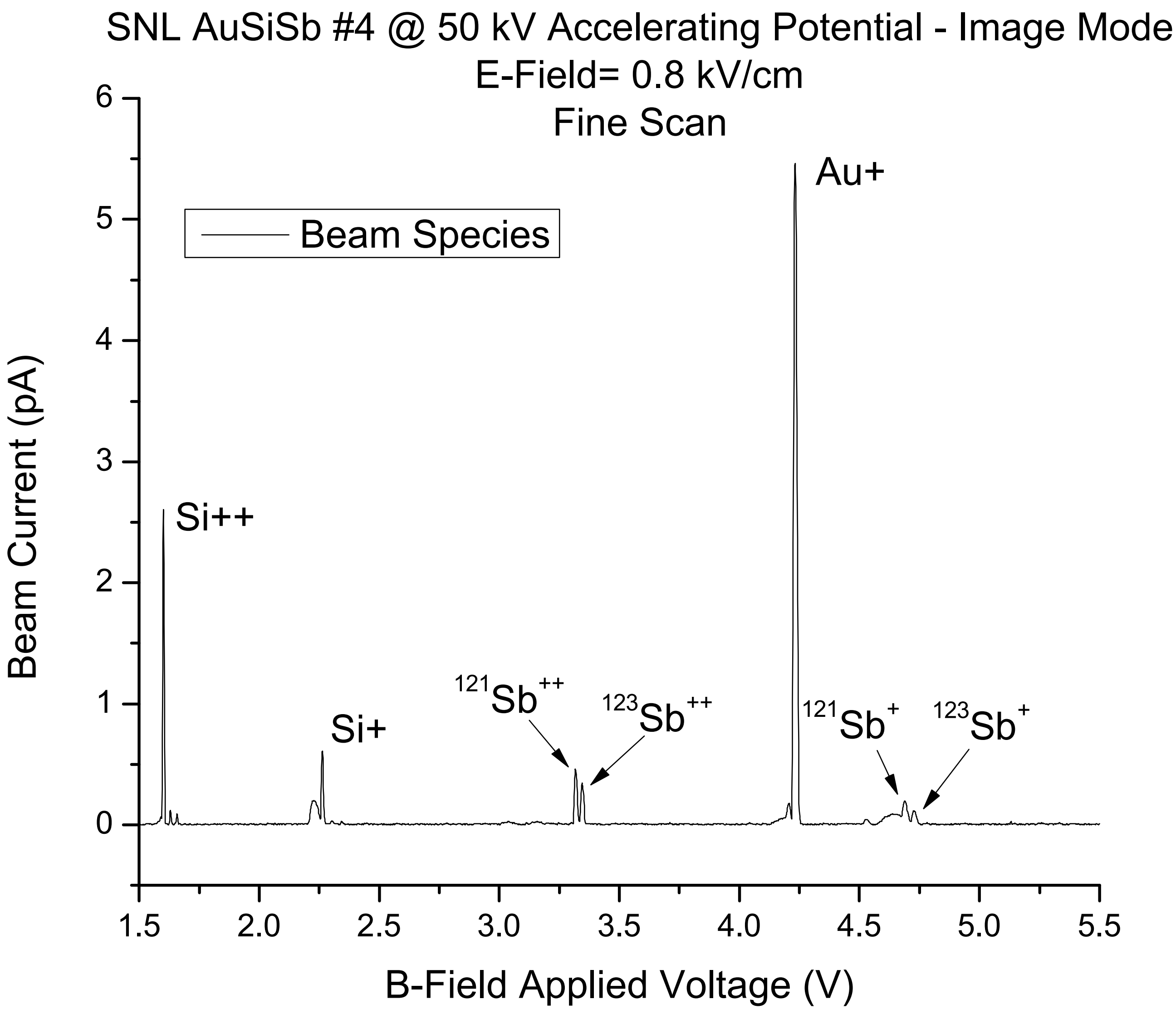
Summary of the nI Implant Capability

Notes on what we can do:

- Un-processed MDL devices: KC76102w9 die 2,4
  - Oxide Window → 35 nm SiN + 7 nm SiO2 need **at least 100 keV Sb** to get through
  - Construction Zone → 200 nm Poly Si+ 35 nm SiN + 7 nm SiO2 need **at least 200 keV Si** to get through
  - **Results**
    - Oxide Window → We have observed 100 keV Sb ~1 ion/pulse detection
    - Construction Zone → We have observed 200 keV Si detection

- "Thin Stack" devices (etched construction zone, mimics real devices): D941
  - Oxide Window → 35 nm SiN + 7 nm SiO2 need **at least 100 keV Sb** to get through
  - Construction Zone → 7 nm SiO2 can use **50 keV Sb** for testing
  - **Results**
    - Oxide Window → We have observed 100 keV Sb ~1 ion/pulse detection
    - Construction Zone → We have observed 50 keV Sb <1 ion/pulse detection

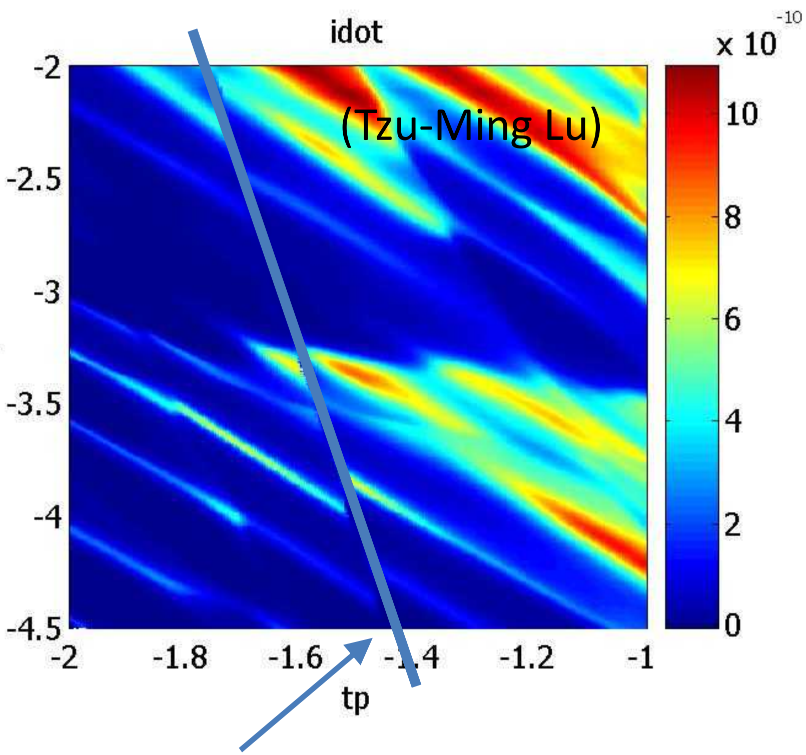
LMAIS for the nI



Top-Down Path for Donor Devices

Timed Ions

- P, Sb and Si implants
- Target several donors per site
- Transport and ESR in progress



Offset caused by a charge center (likely a Sb donor)

Counted Ions

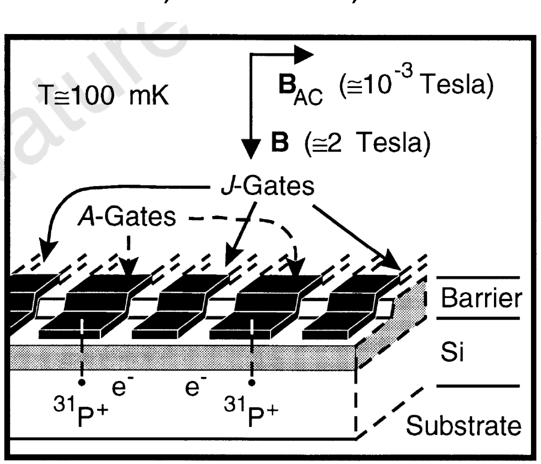
- Started with our integrated devices and ran a combination of **timed** and **timed/counted** implants:
  - Ran 7 chips with
  - 4 wired devices per chip – timed/counted
  - 6 un-wired devices per chip – timed only
  - Implanted 50 keV Sb ions targeting 3-10 ions per implant site
- Issues:
  - How to remove sample from IBL header?
    - Switch to Carbon tape – good enough thermal conductivity and low enough residue for the post-implant processing
  - Interplay between beam current on target and beam diameter?
    - Need to move to NanoImplanter

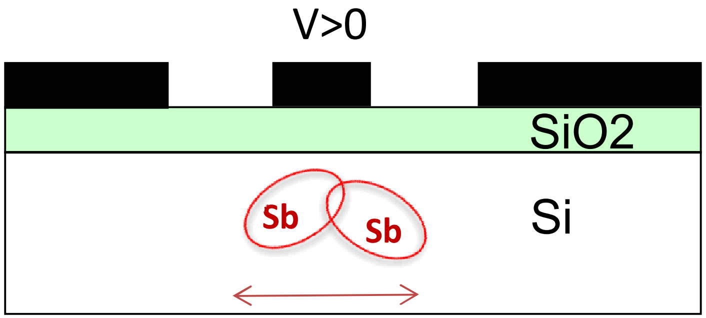
- This path forward will allow us to get samples from the IBL to the processing team and start exploring the implant energy effect on tunneling rates, etc…

Top Down Two-Qubit Design

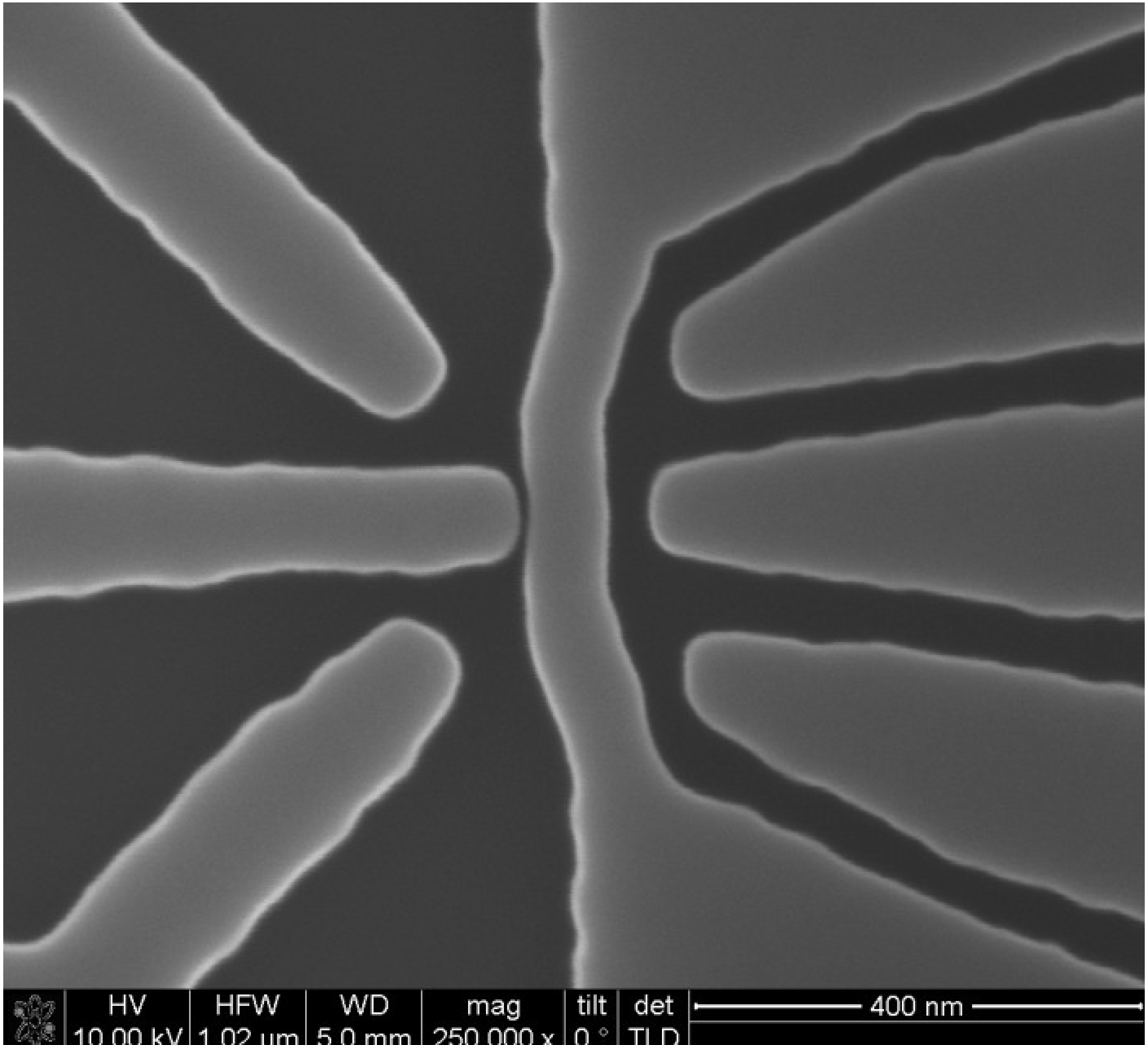
- Load donor in known state
- Induce exchange through J-gate
- Read out spin

B. E. Kane, Nature **393**, 1998

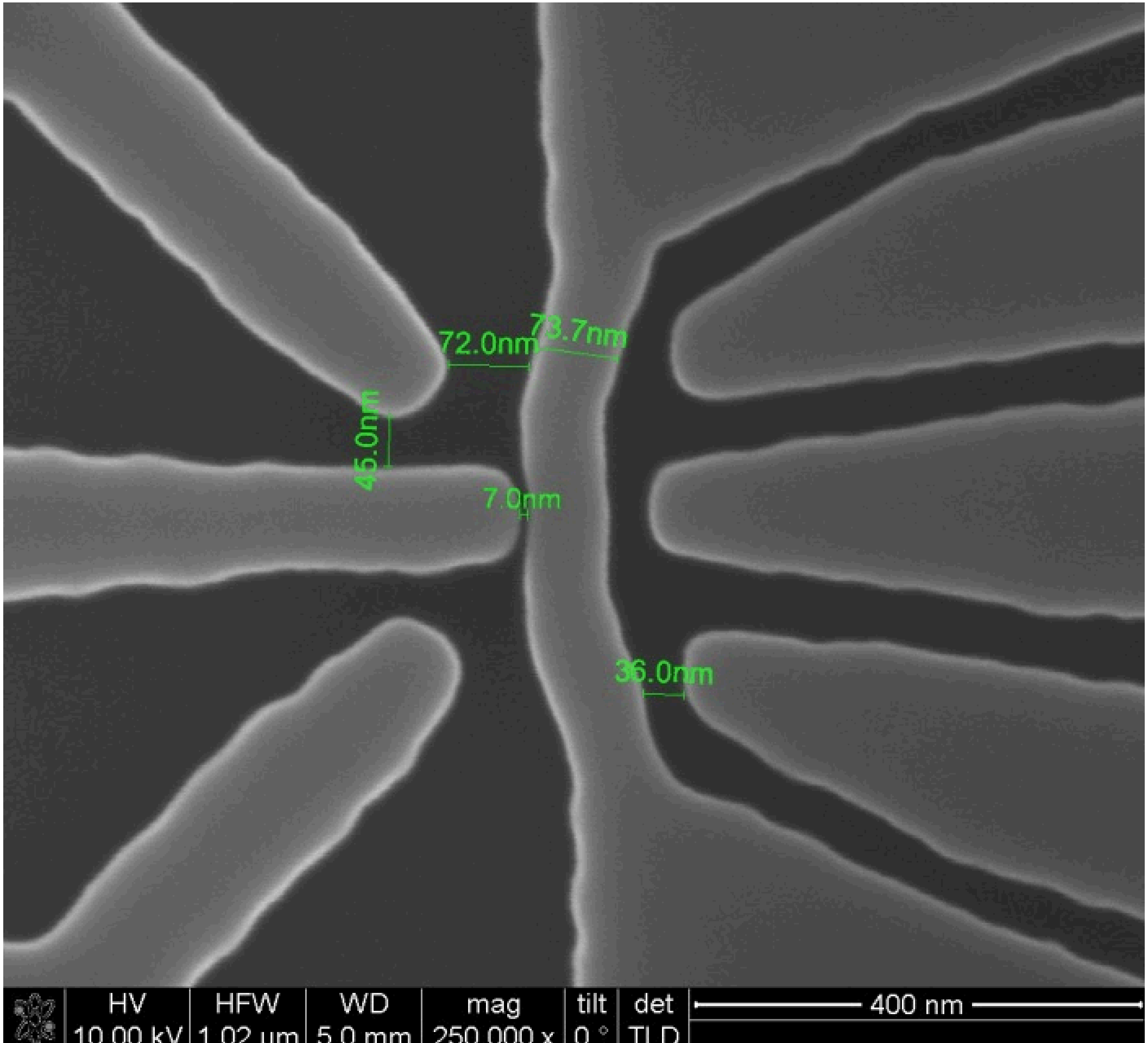




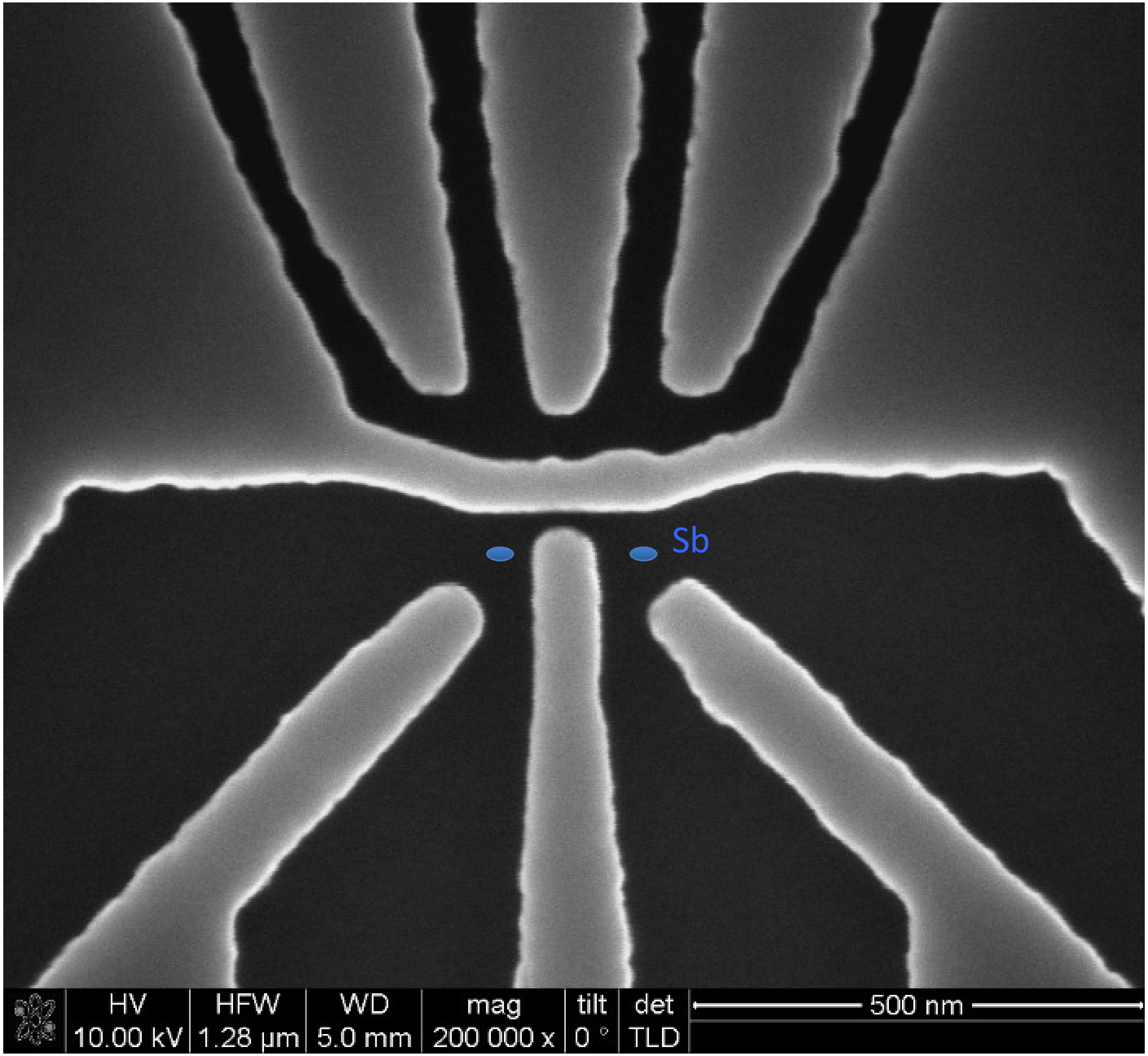
EBL Test device



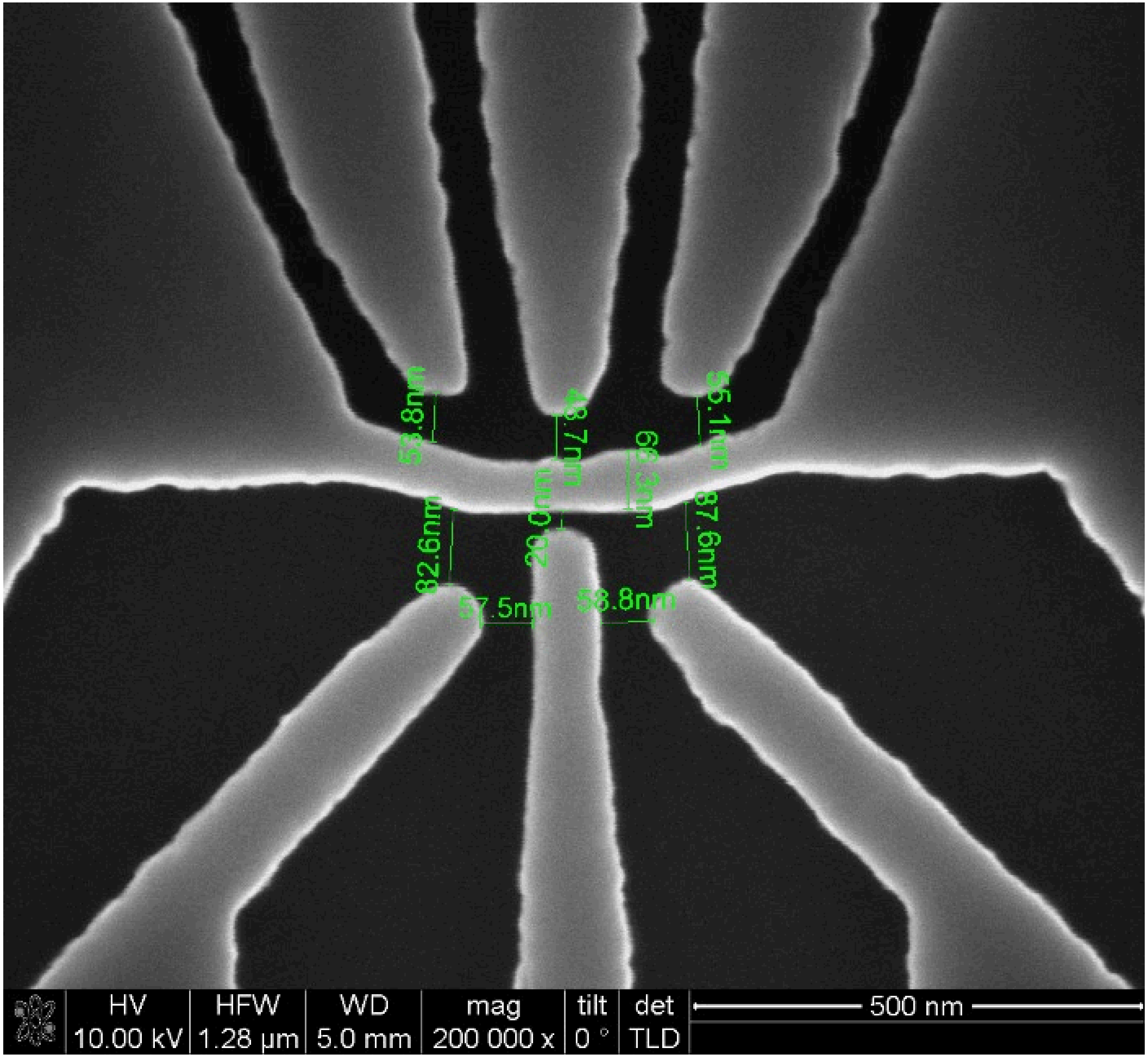
EBL Test device



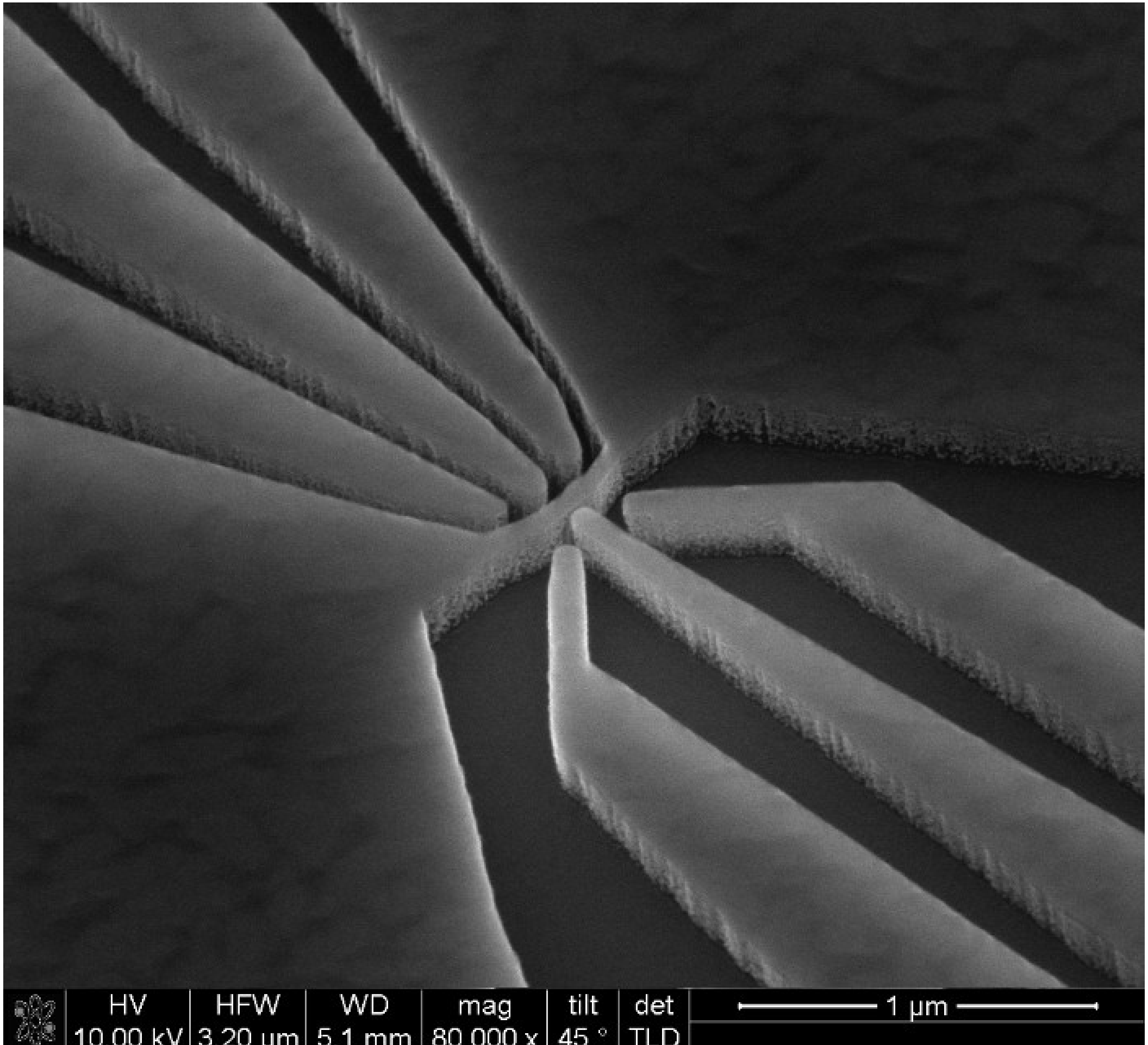
Actual Device



Actual Device



Actual Device



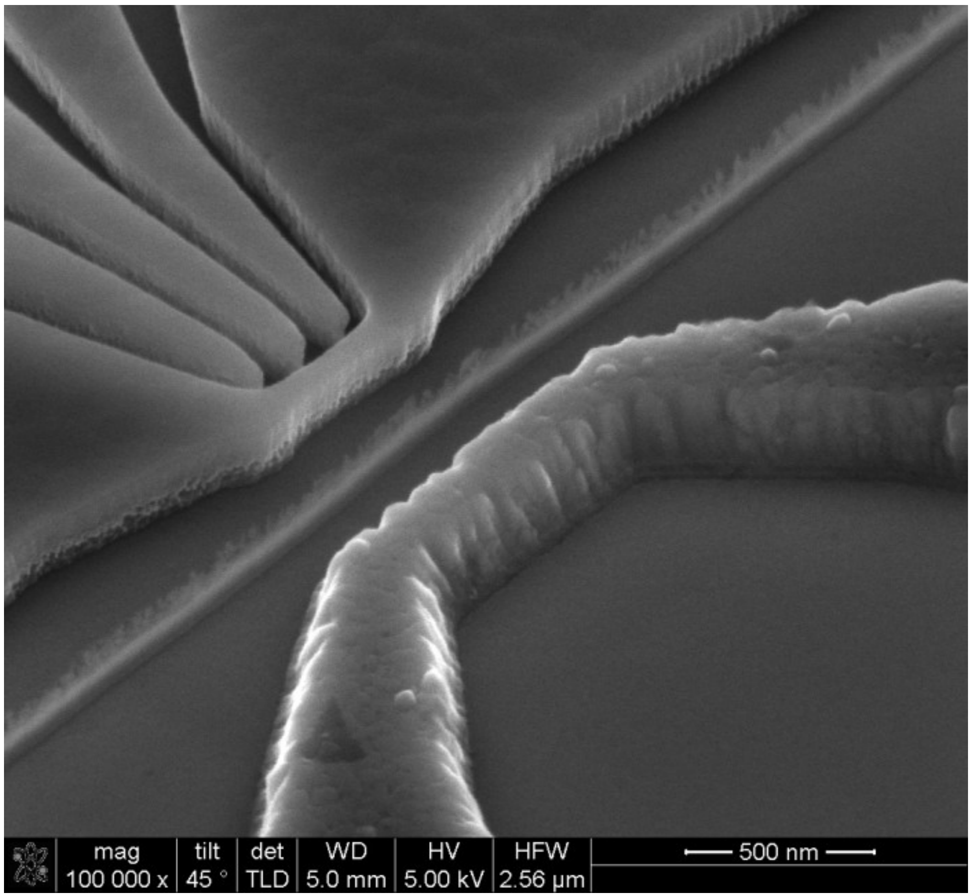
Current Status

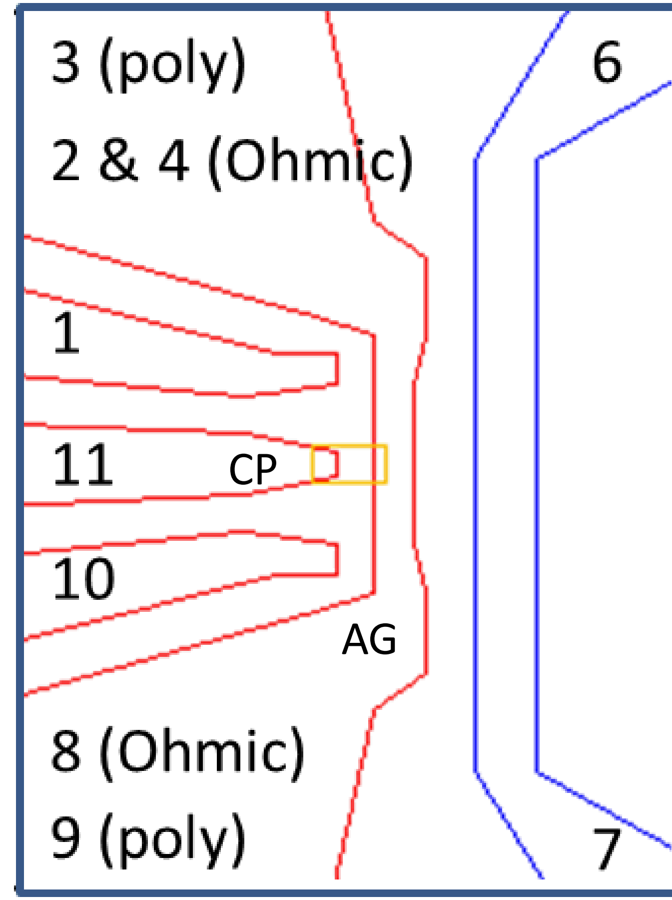
- Devices fabricated
- Undergoing many donor implant with nanoimplanter
- Measurements to follow soon

One Qubit Project

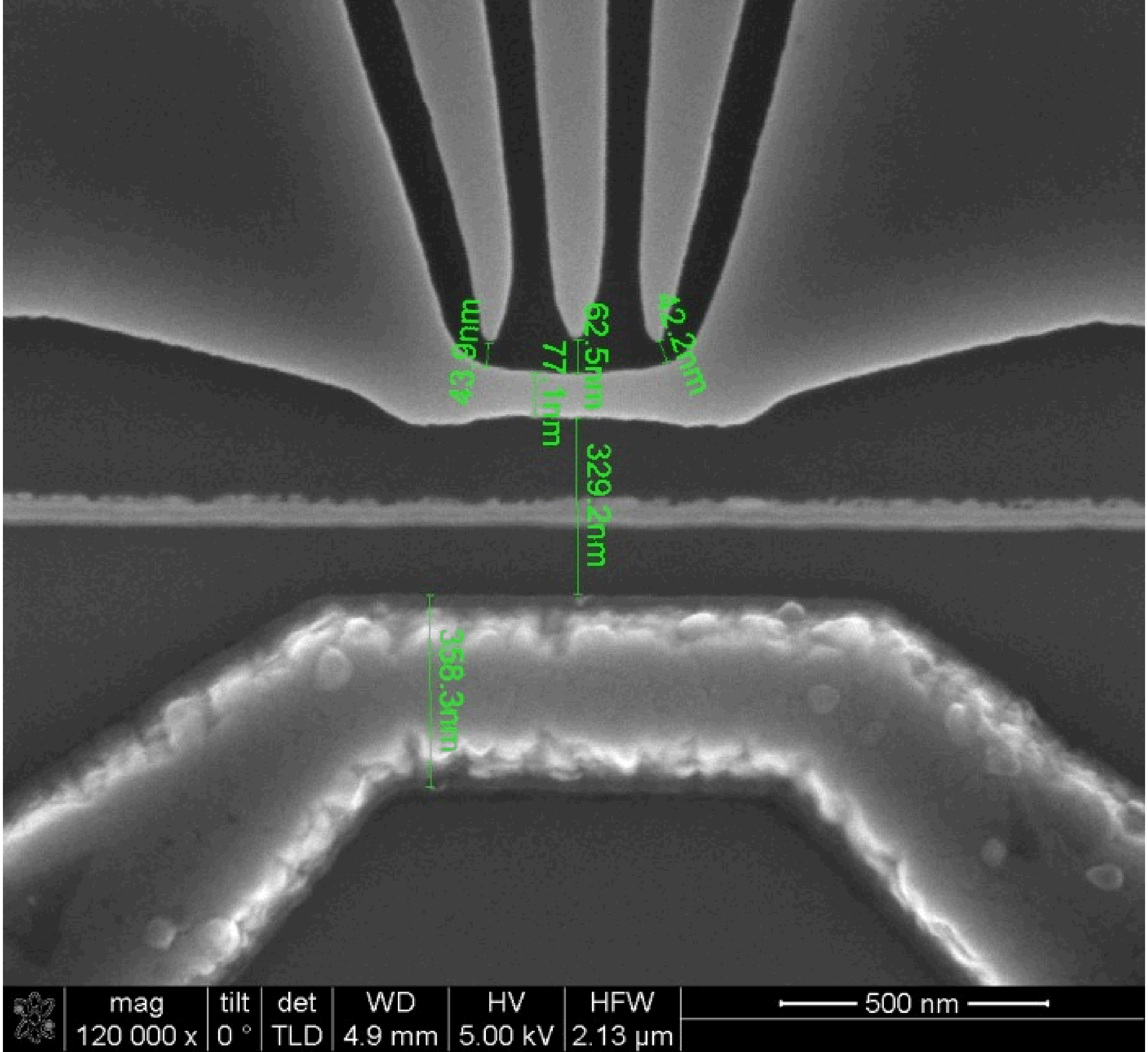
Samples:

SEM 1166



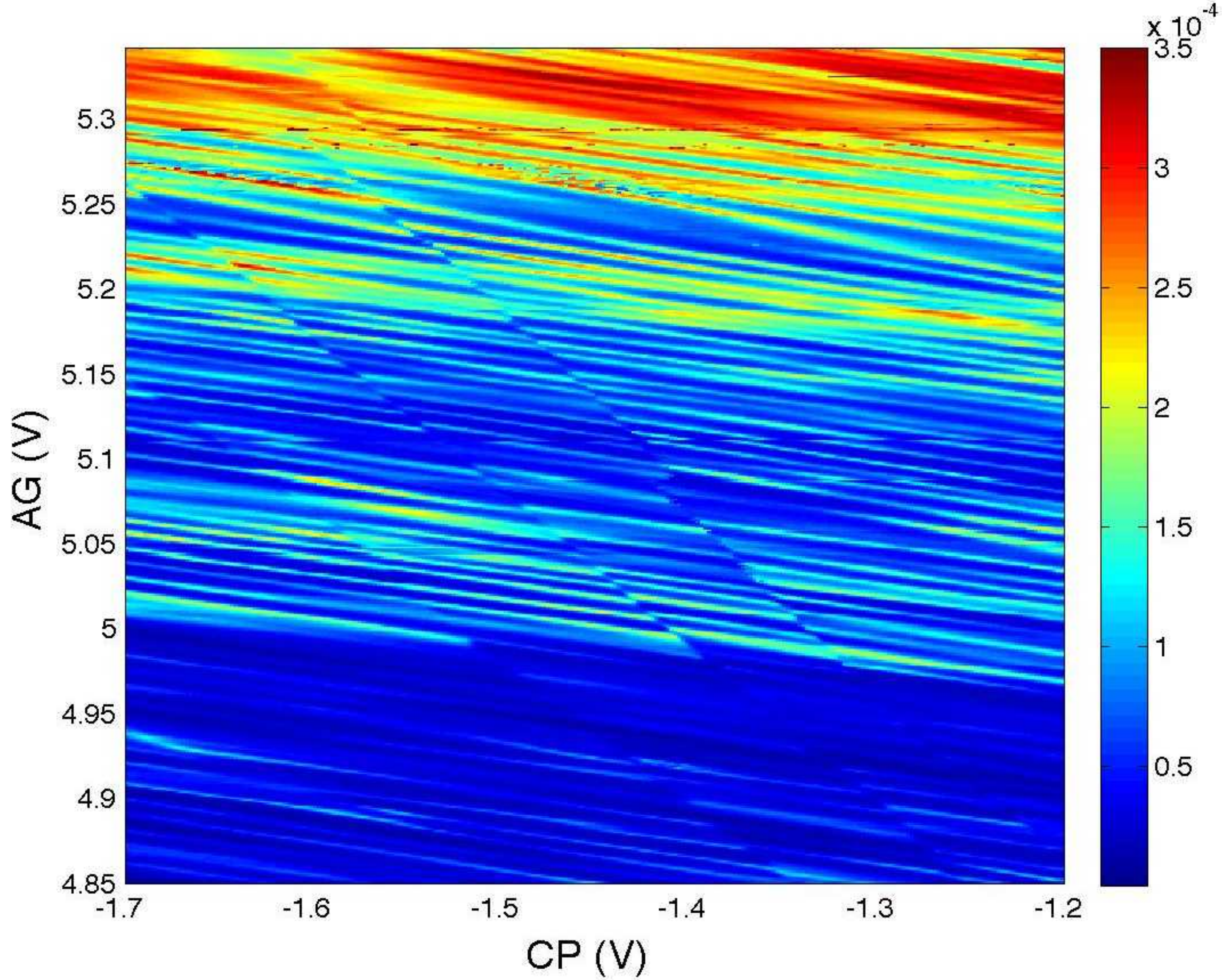


Donor window overlaps CP and AG


43.9nm
62.5nm
42.2nm
77.1nm
329.2nm
358.3nm
mag
120 000 x
tilt
0 °
det
TLD
WD
4.9 mm
HV
5.00 kV
HFW
2.13 µm
500 nm

Sample 1166:

T=11 mK
B=0 T



Sample 1166:

T=11 mK
B=0 T

Many approximately parallel Coulomb blockade lines

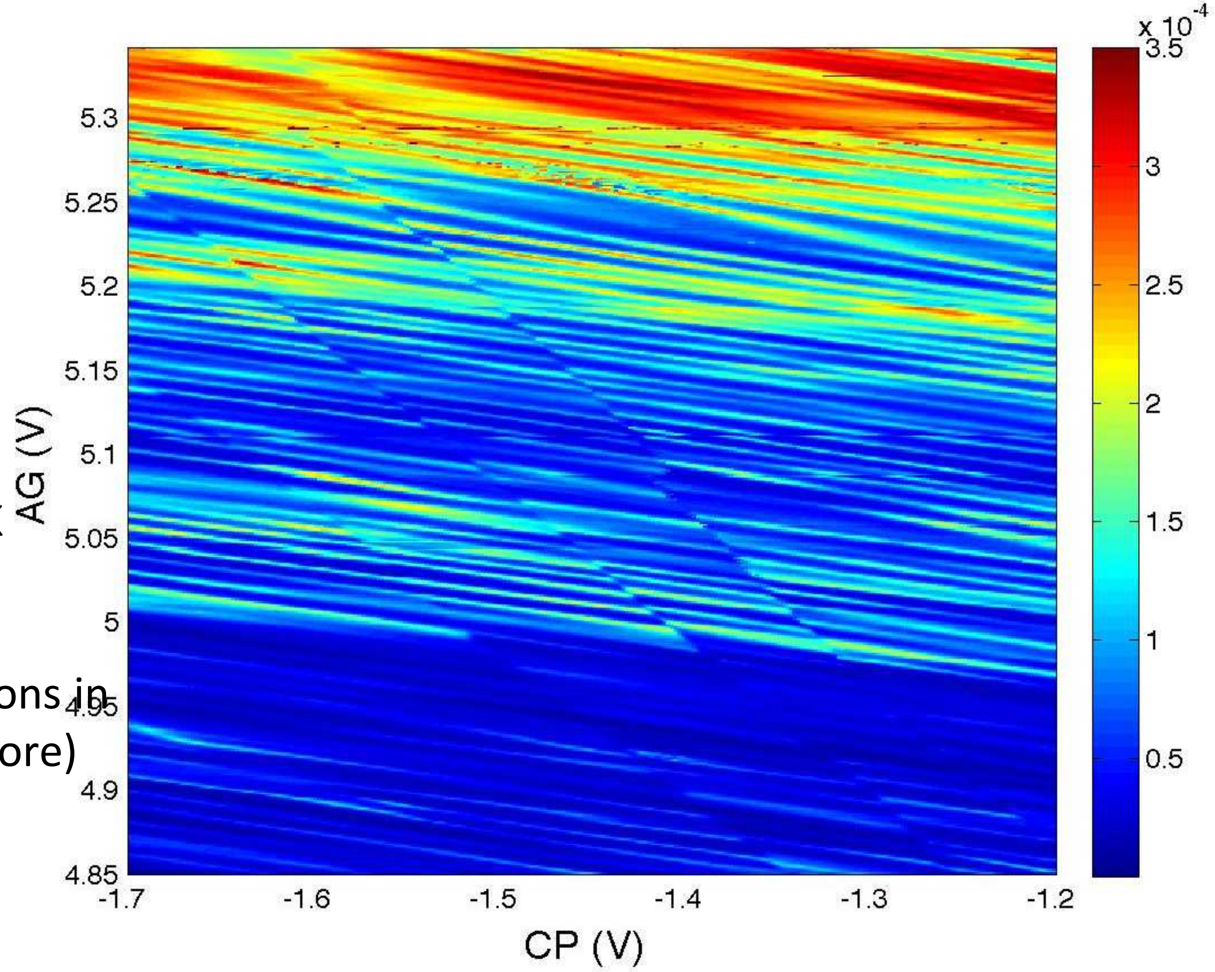
Slope AG/CP~0.2

Charging energy ~ 5 meV

Electron Temperature ~ 300 mK

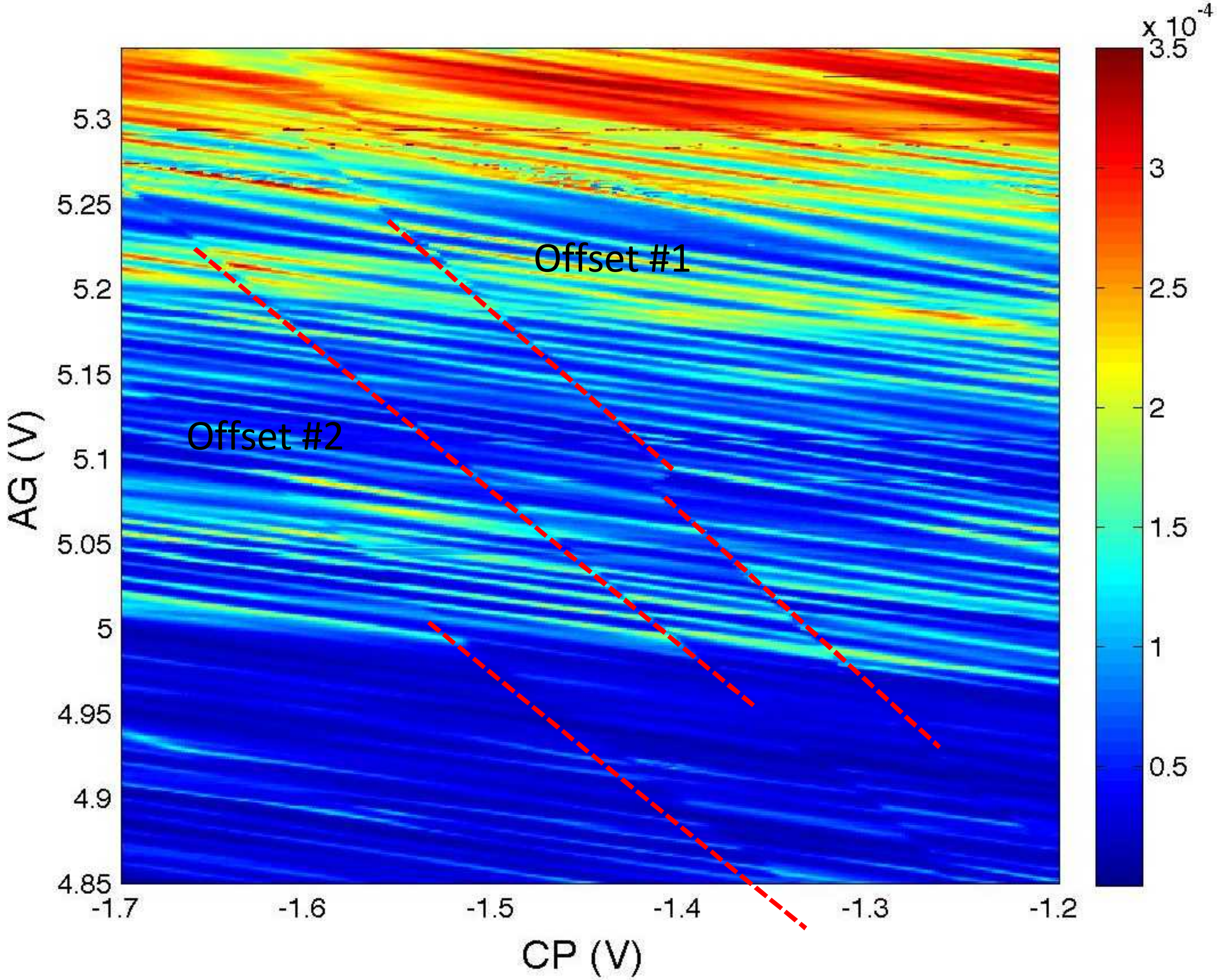
For AG>5 V:

More than ~30 electrons in dot (possibly many more)



T=11 mK

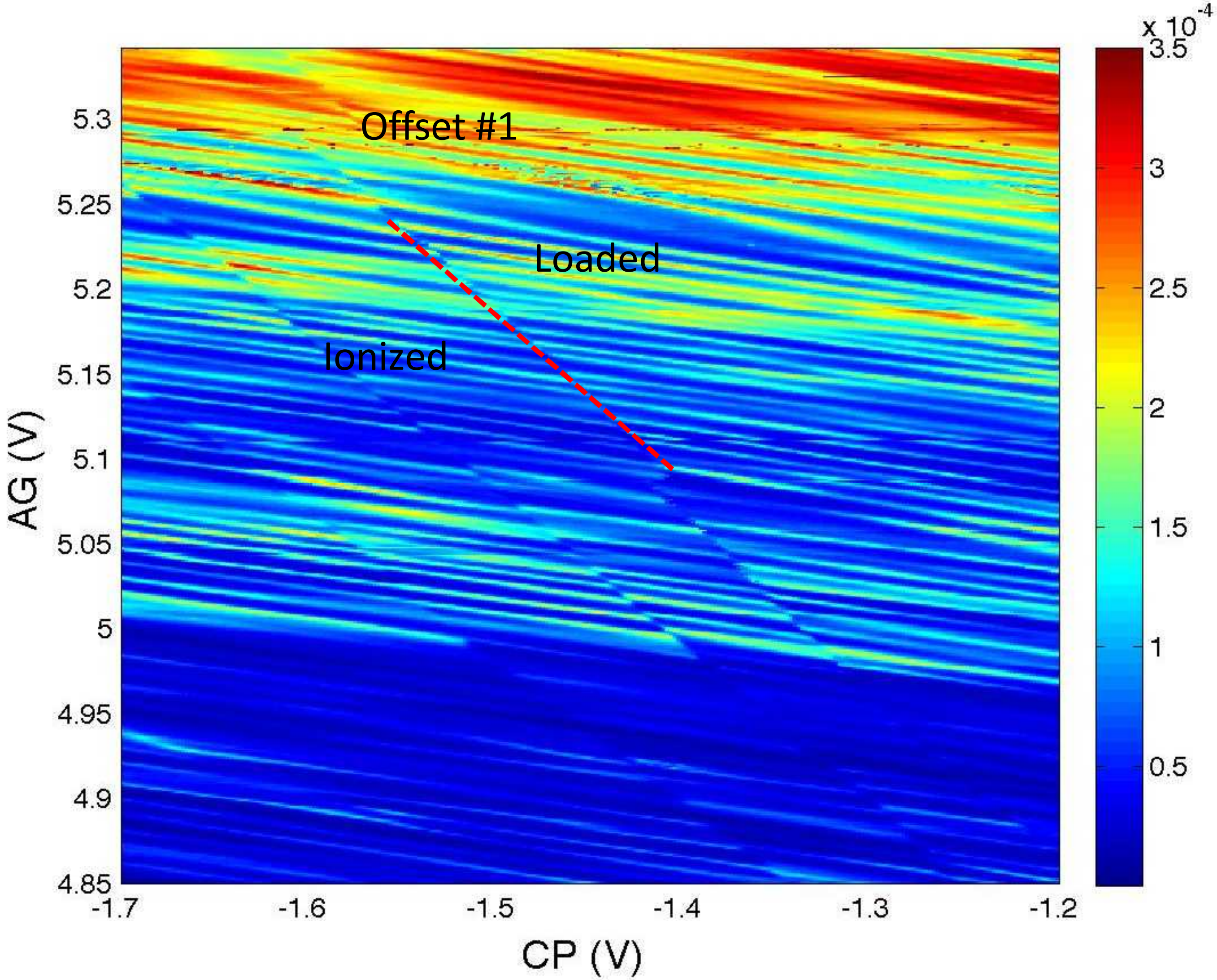
Sample 1166:



Several offsets: slopes very similar

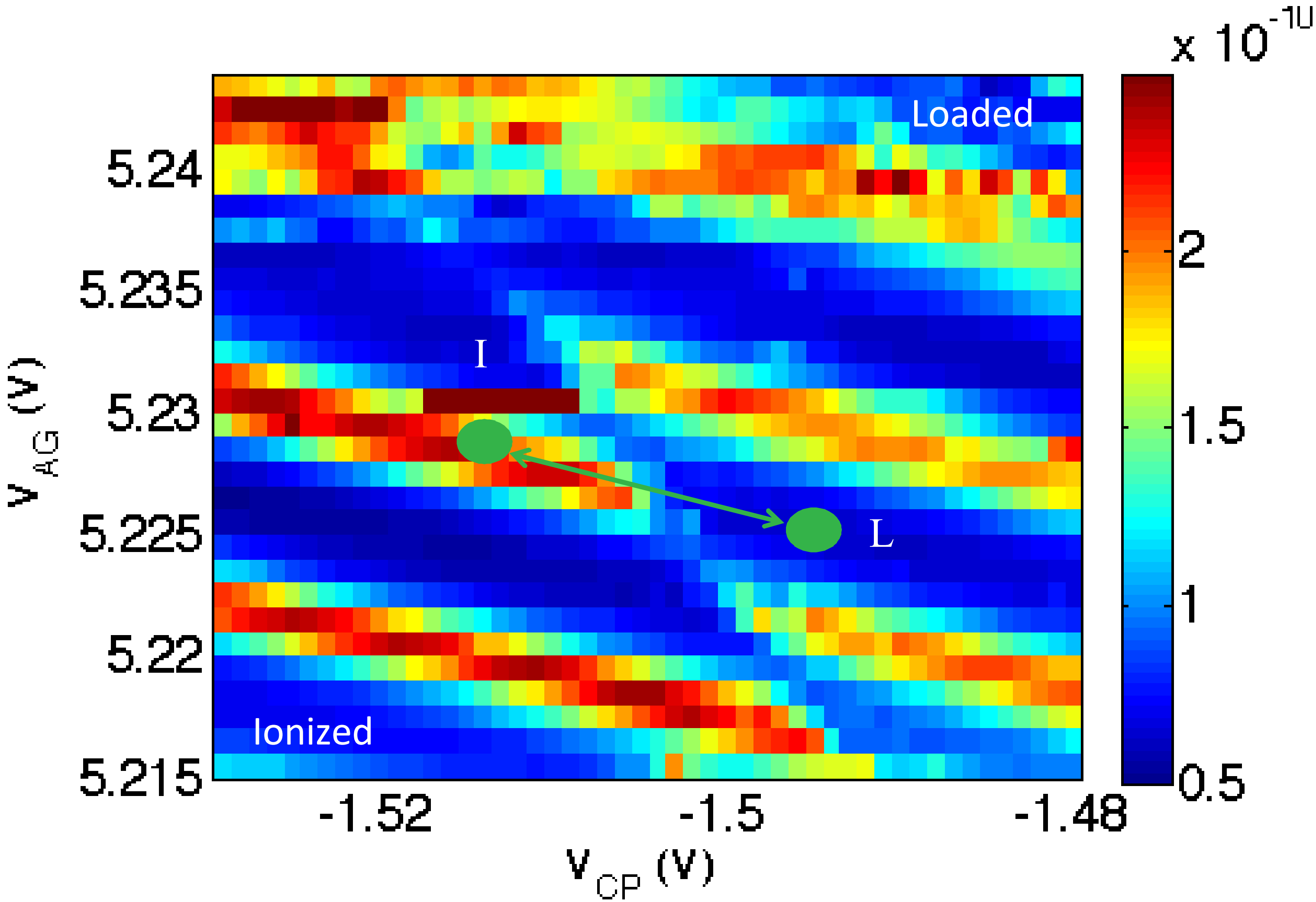
T=11 mK

Sample 1166:



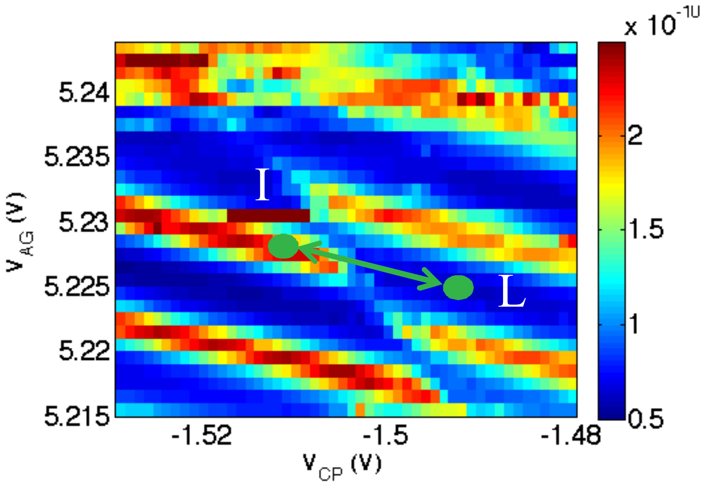
Several offsets

Offset #1; B=2 T—Tunneling Time Measurement



Apply two level pulse between I and L

Offset #1:
Tunneling Time
Measurement

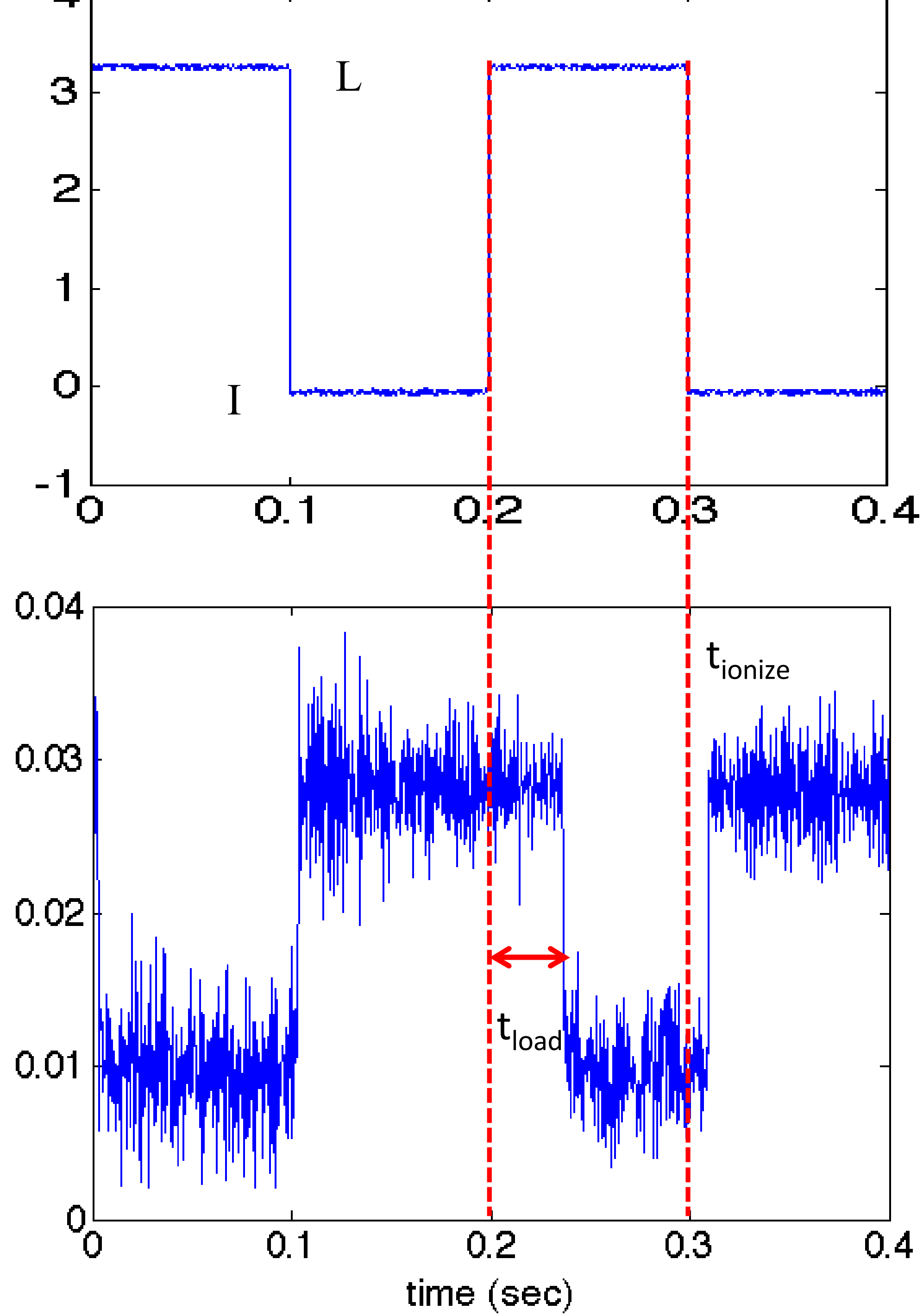


DC Bias device (100 μV)

Amplified output on oscilloscope

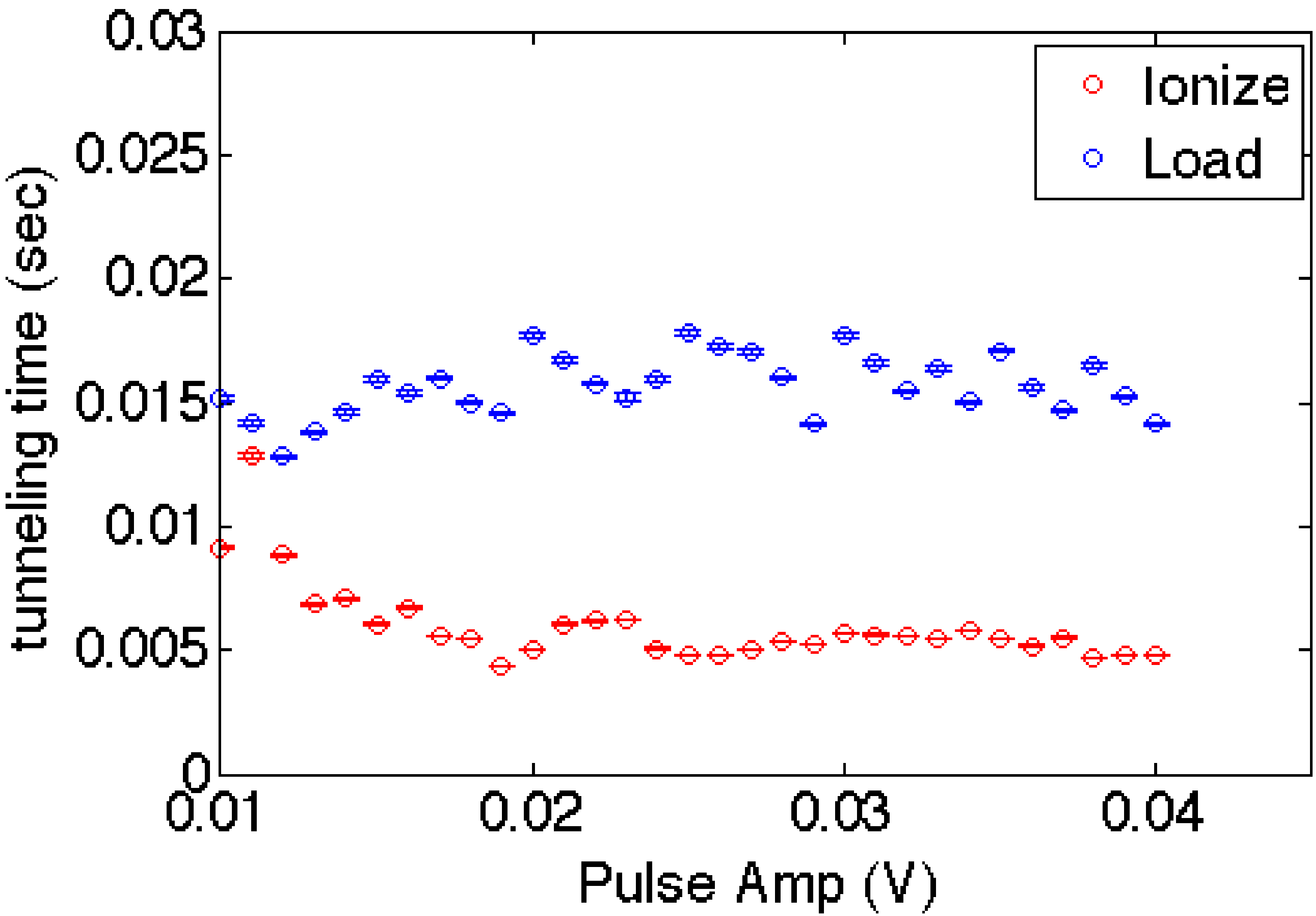
Single shot data for B=0 T

Applied Pulse



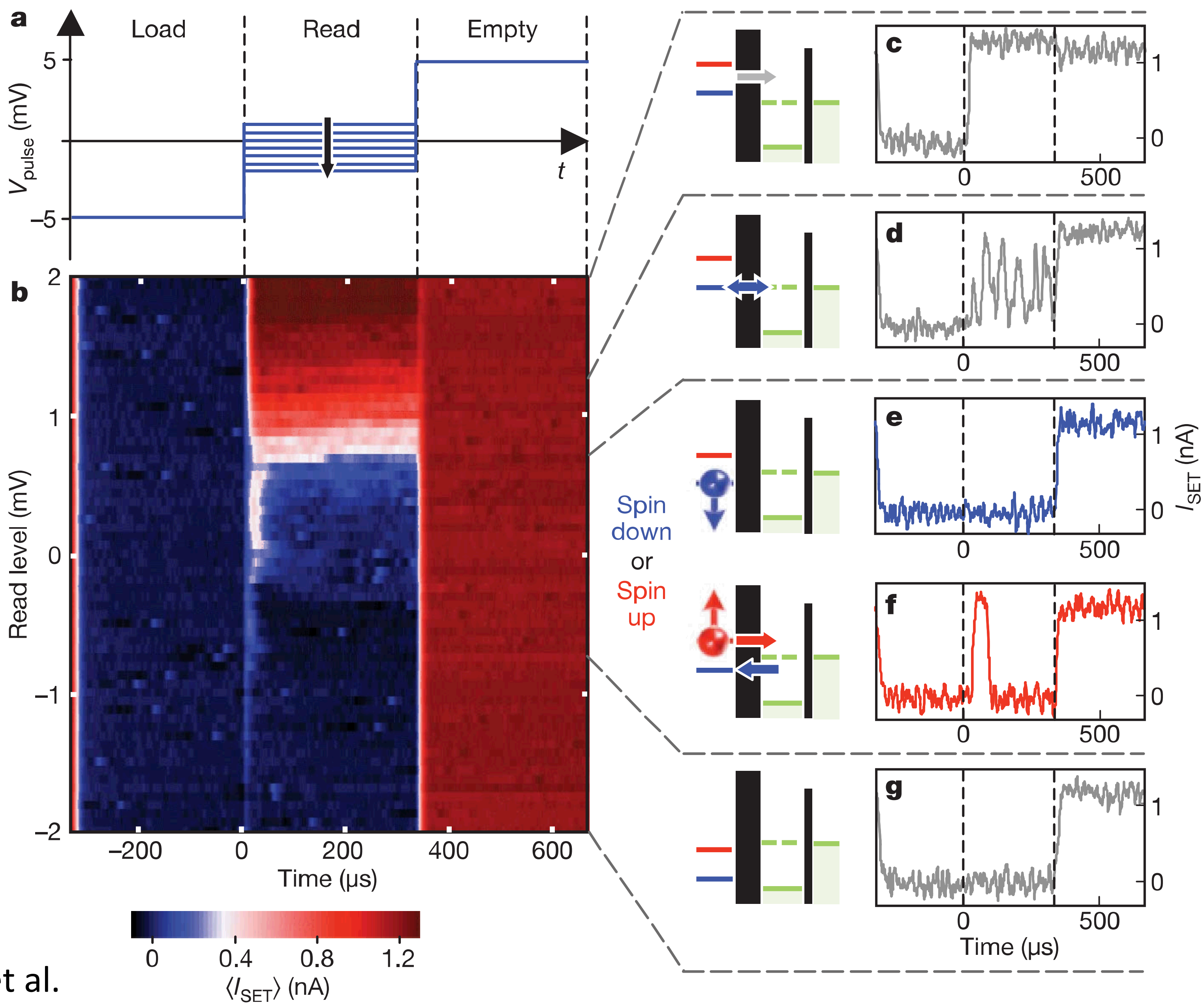
Offset #1—Tunneling Time Measurement

B=2 T



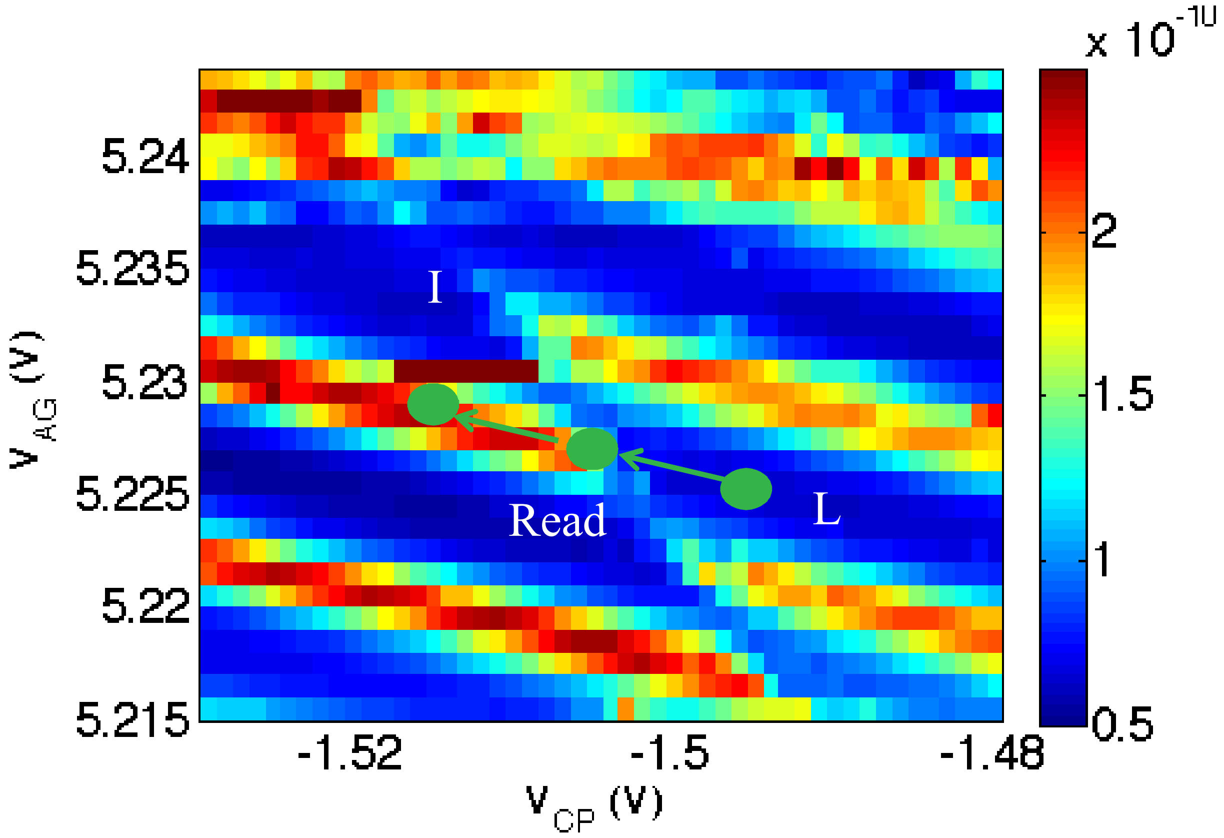
Other offsets: Too fast to measure $\tau<2.5\ \mu s$

Spin Readout:

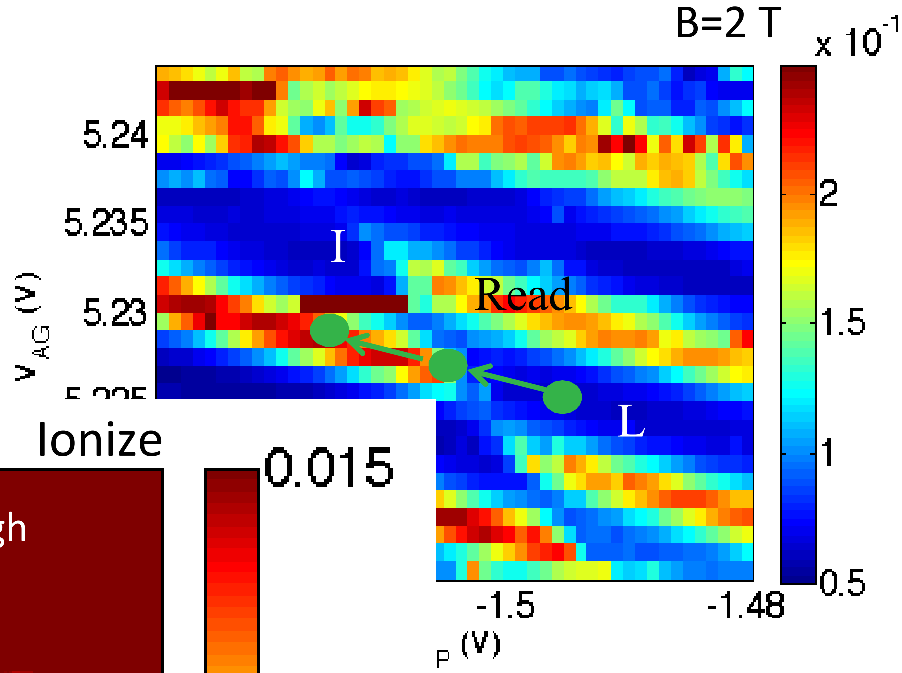


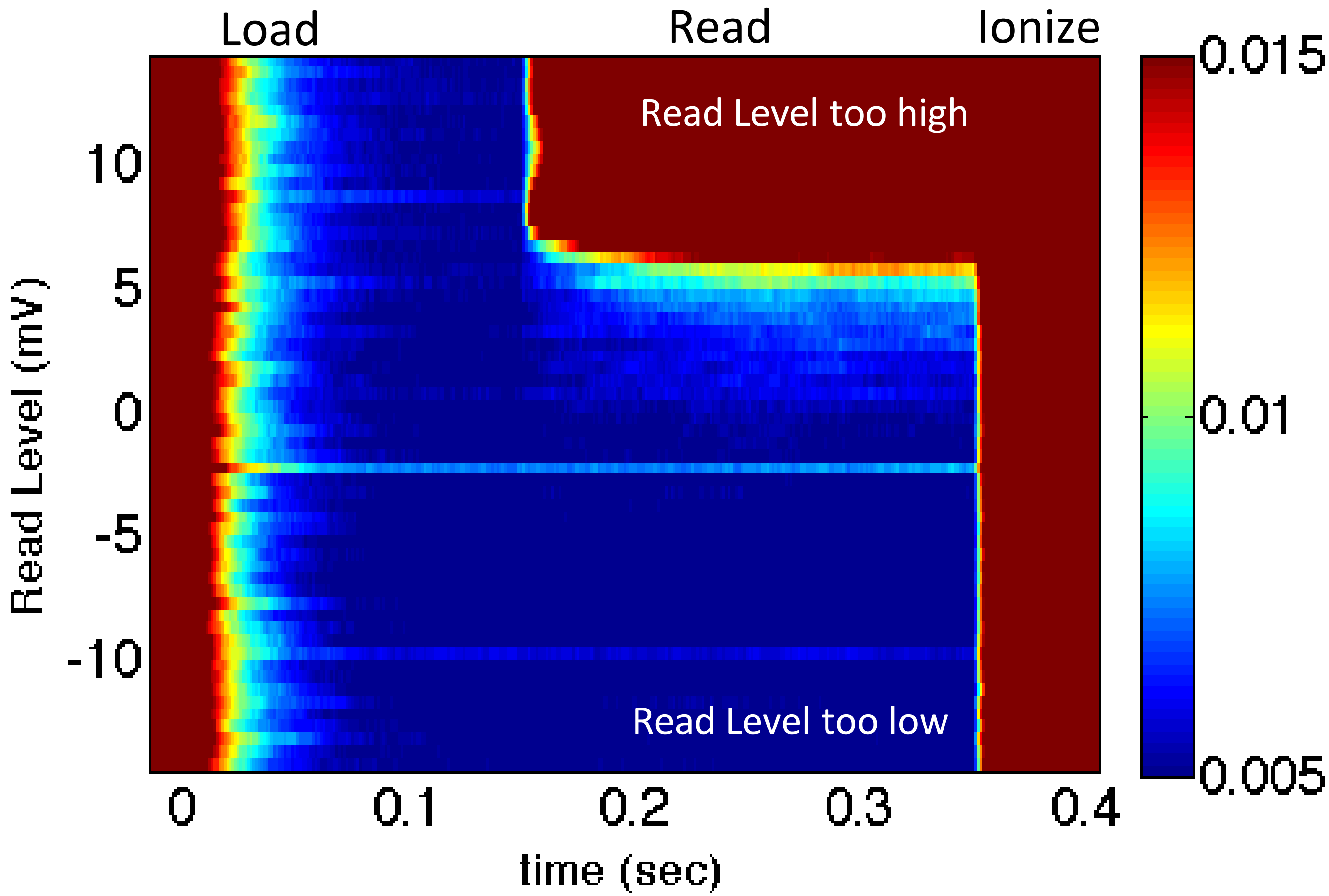
Morello et al.

Spin Readout on Offset 1 in 1166:



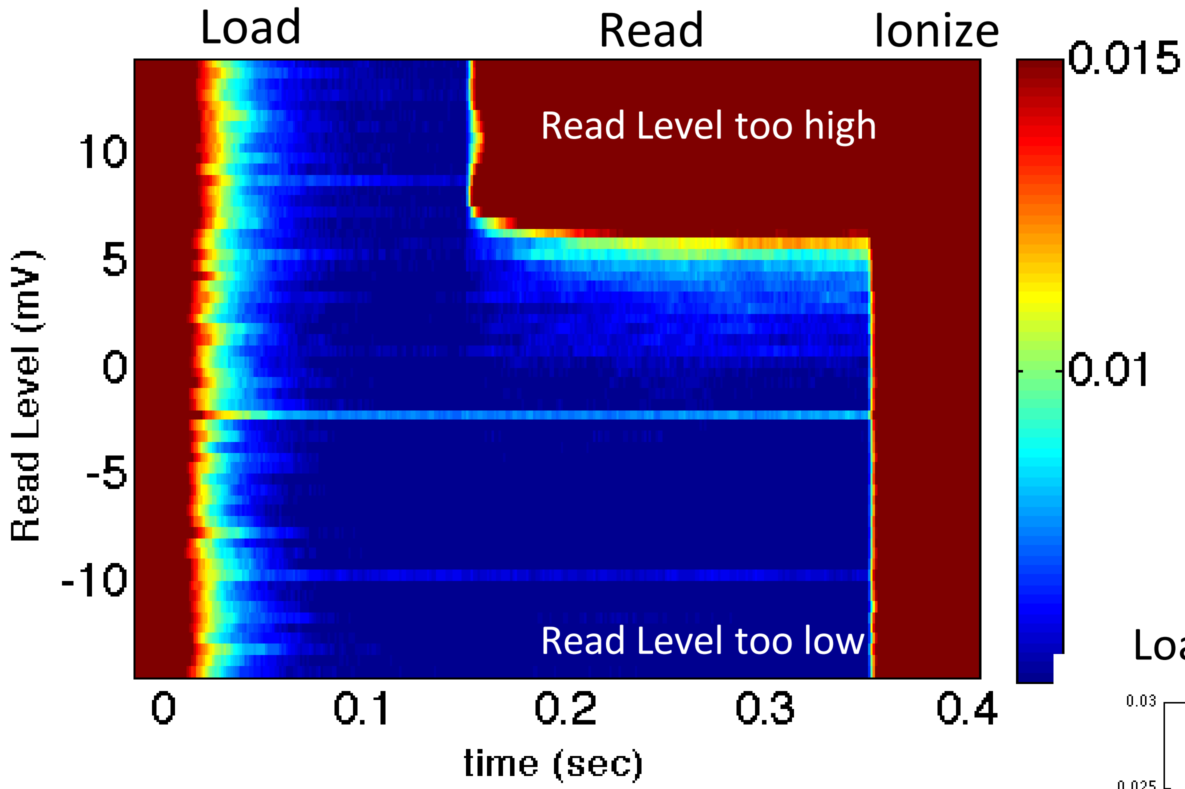
Spin Readout on Offset 1 in 1166:

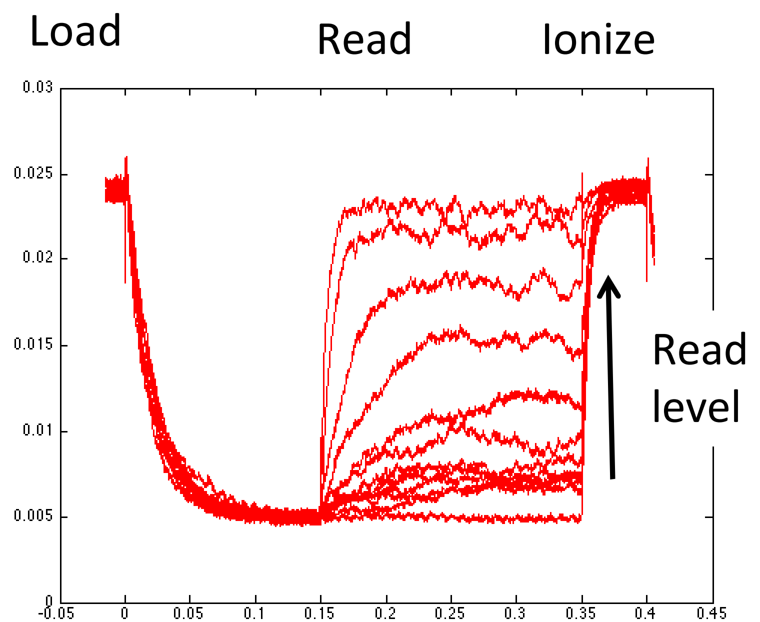




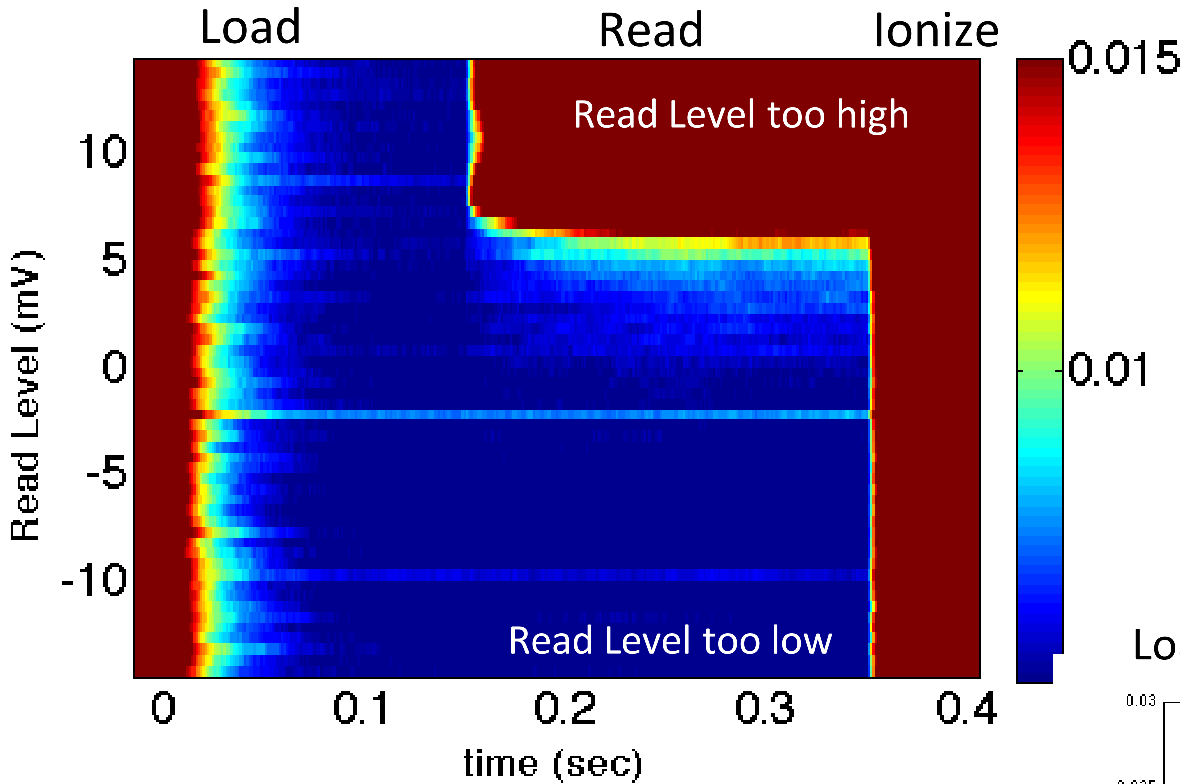
1024 averages

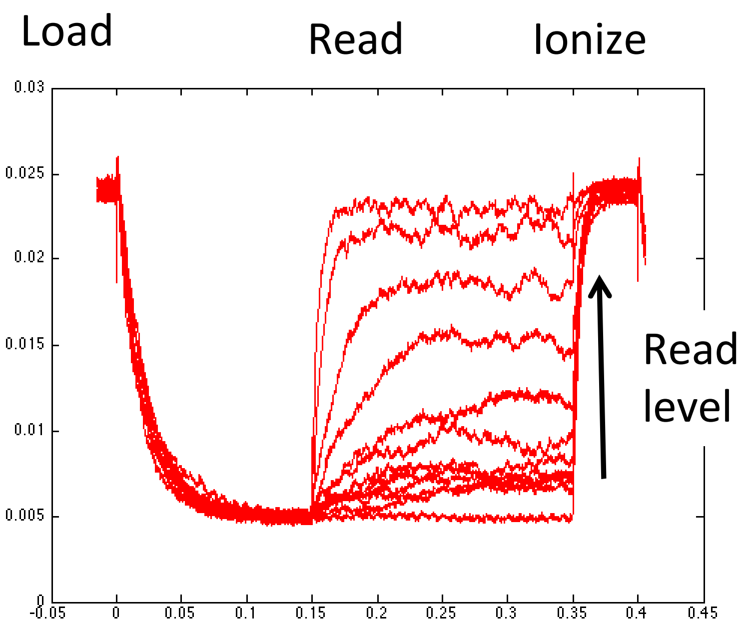
Spin Readout on Offset 1 in 1166:





Spin Readout on Offset 1 in 1166:

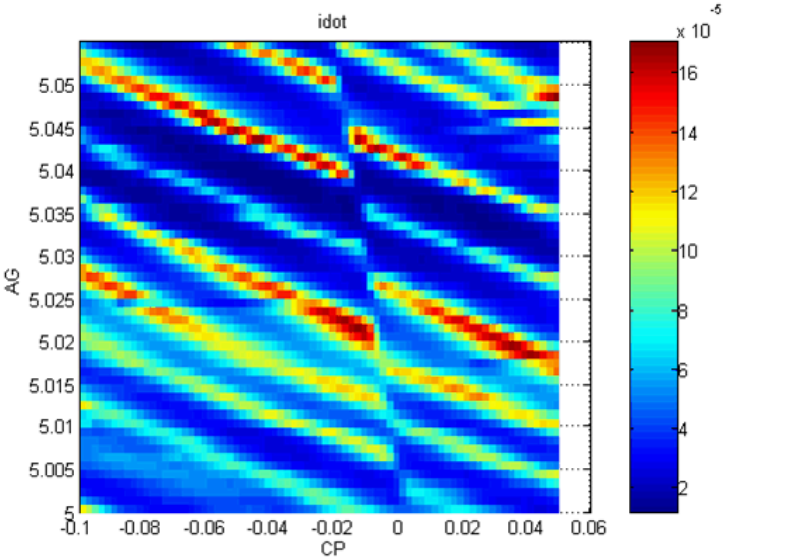


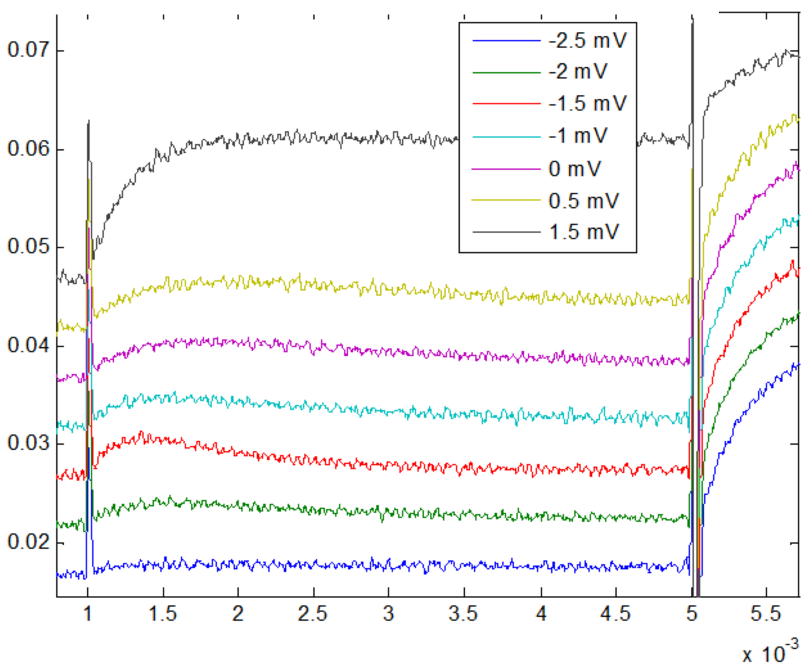


No evidence of spin bump

Same result with longer read window and shorter load time

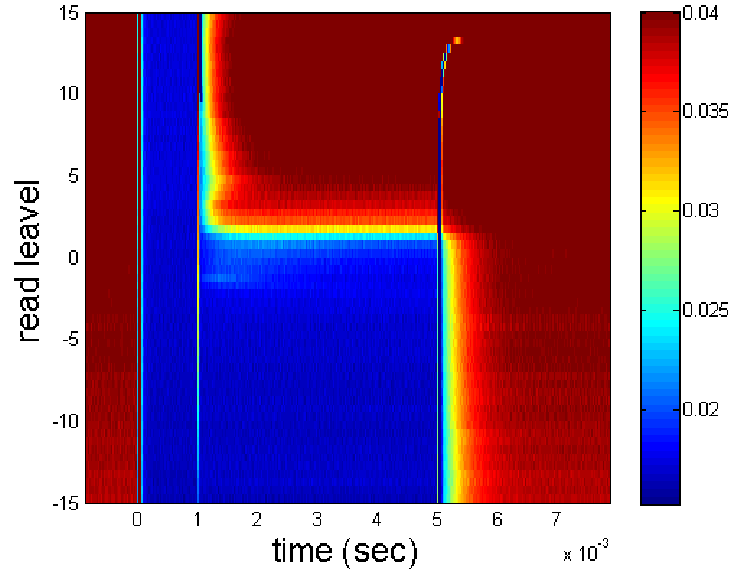
Different Offset Spin Readout:





B= 2 T

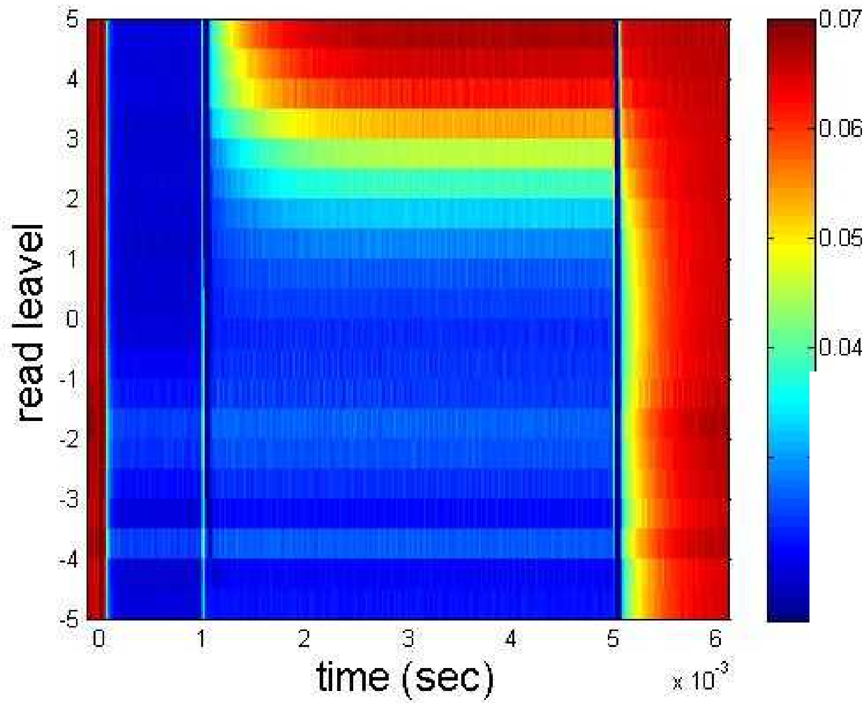
16384 averages



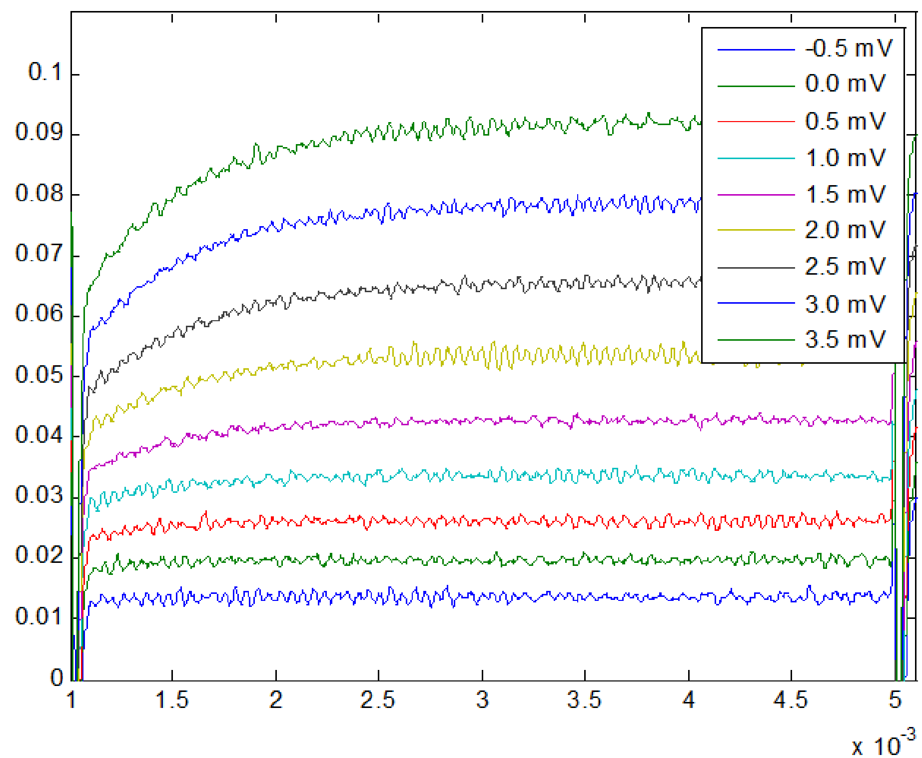
Spin Bump

B=0 T:

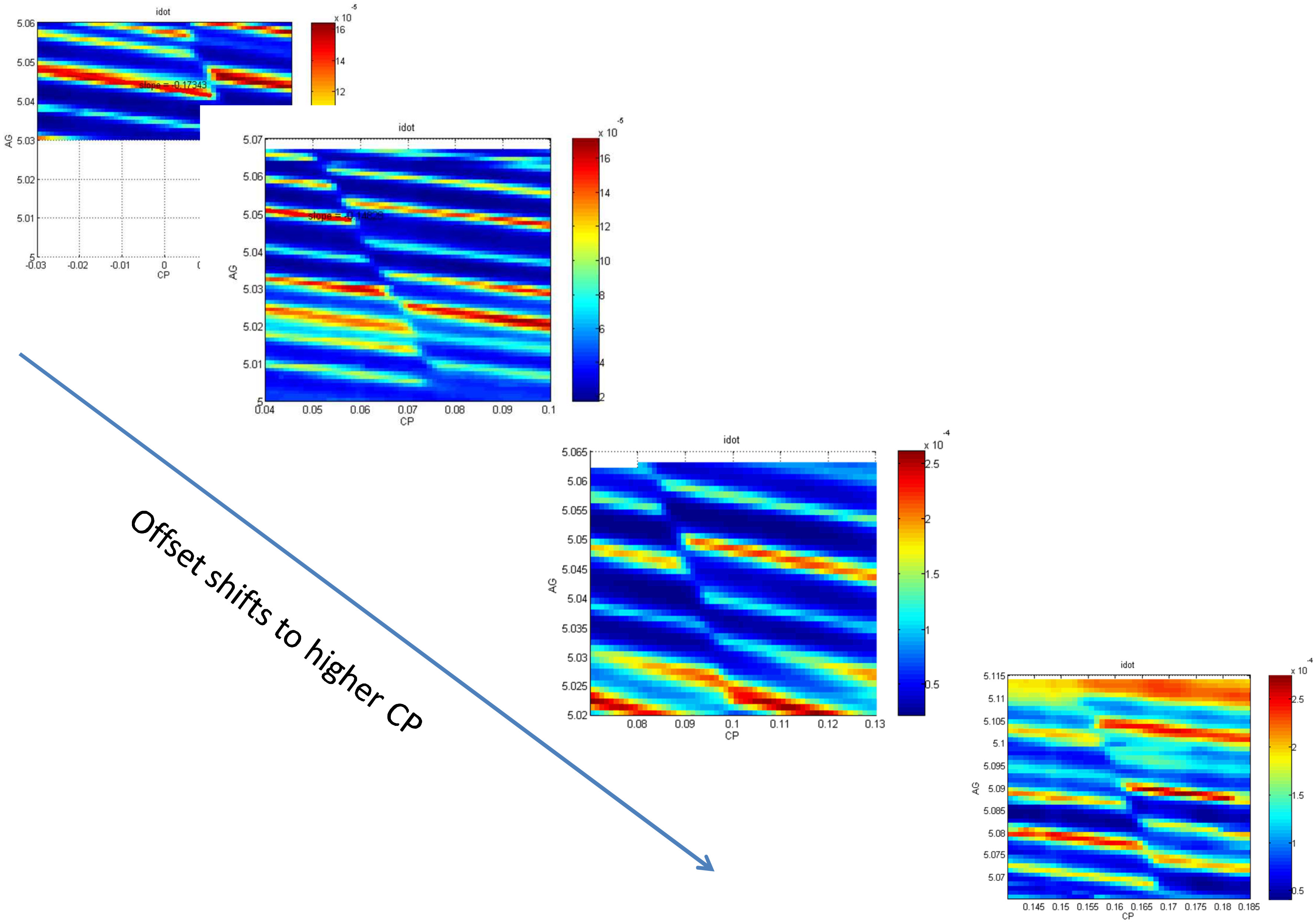
B= 0 T 16384 averages



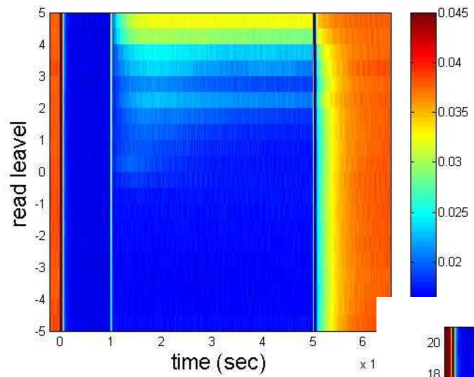
No evidence of Spin bump

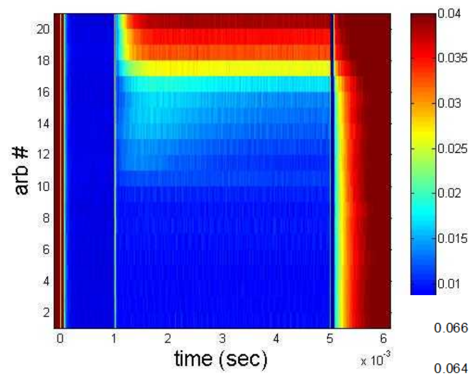


Offset shifts:

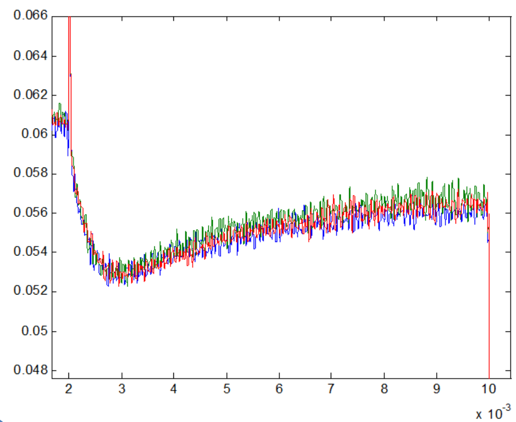


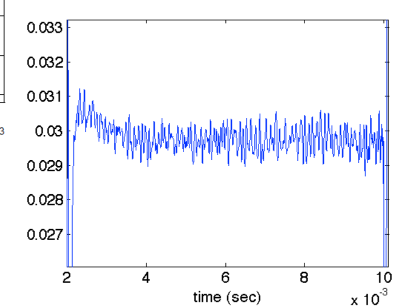
Spin Bump:





But the spin bump persists

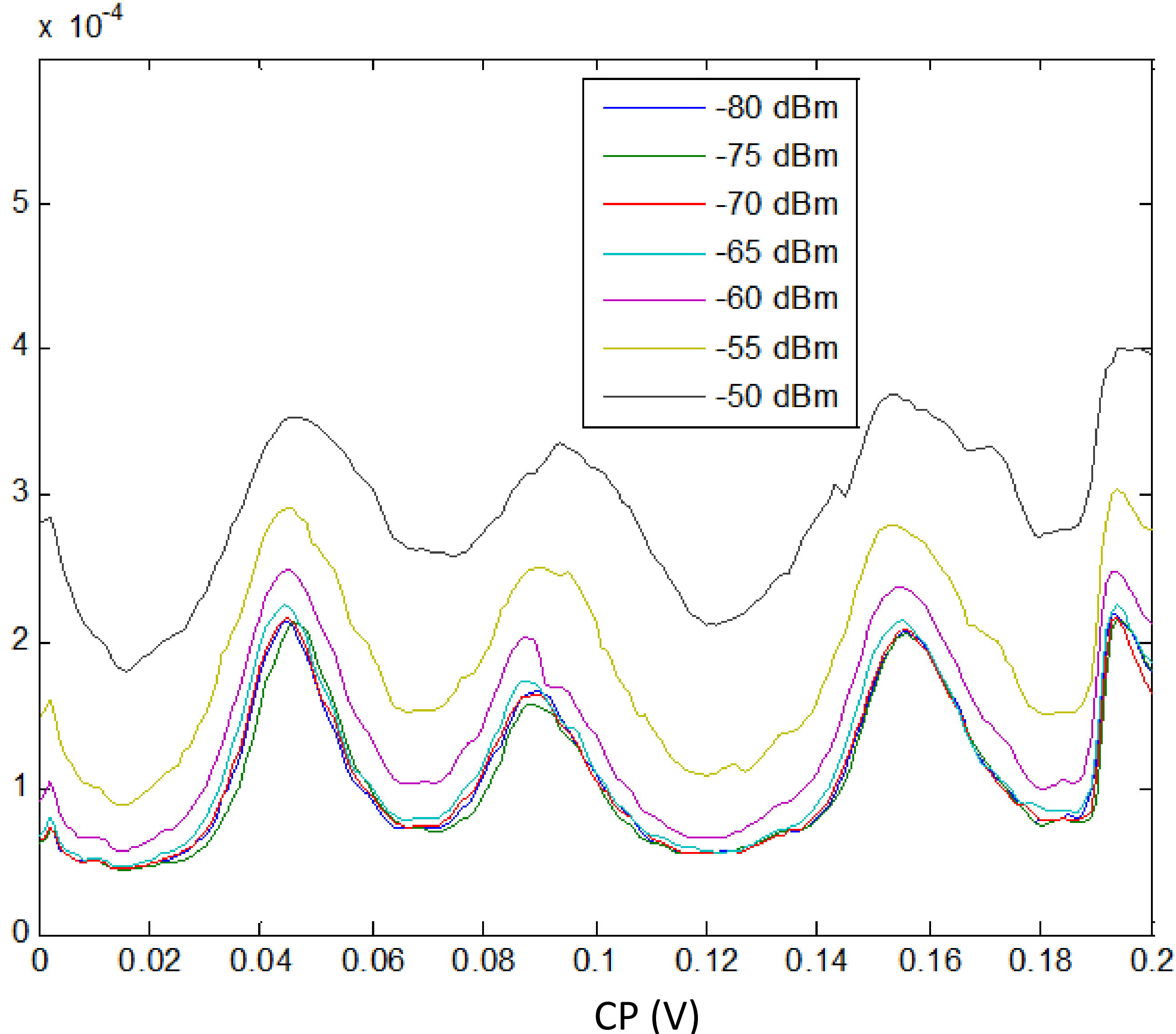




Heating due to microwaves:

Continuous Wave

f=33 GHz



Noticeable change for P>-65 dBm

Current Challenges:

- Spin readout not visible on every offset
- Instability of offsets with pulsing
- Heating due to microwaves
- Long average times necessary due to noise