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Fabrication of Counted Donor Devices using Top-Down Ion Implantation

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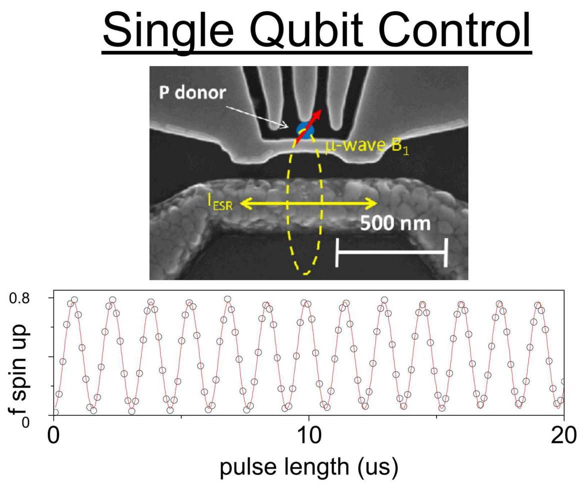
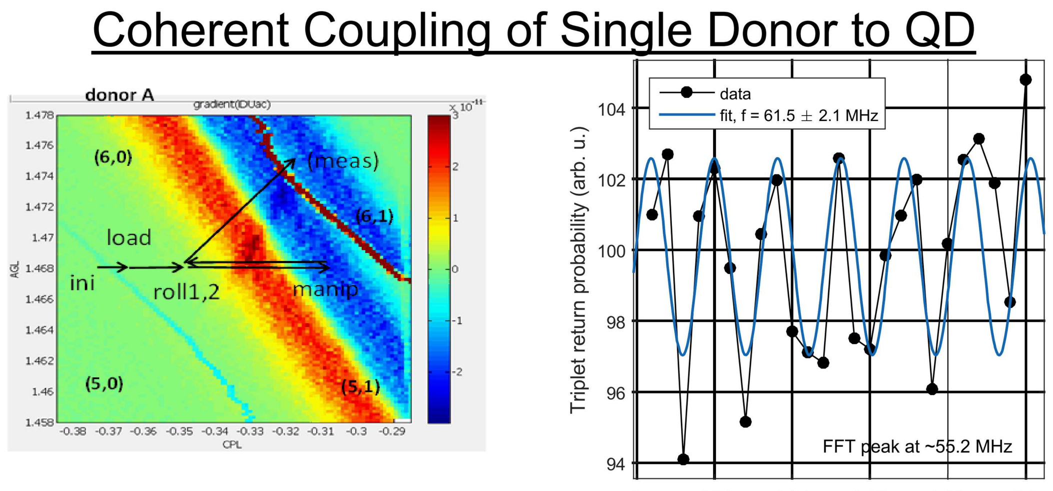
Motivation of Work

Single Qubit Control



Coherent Coupling of Single Donor to QD



Experiments performed on ^{31}P donors in ^{28}Si epi using timed implants

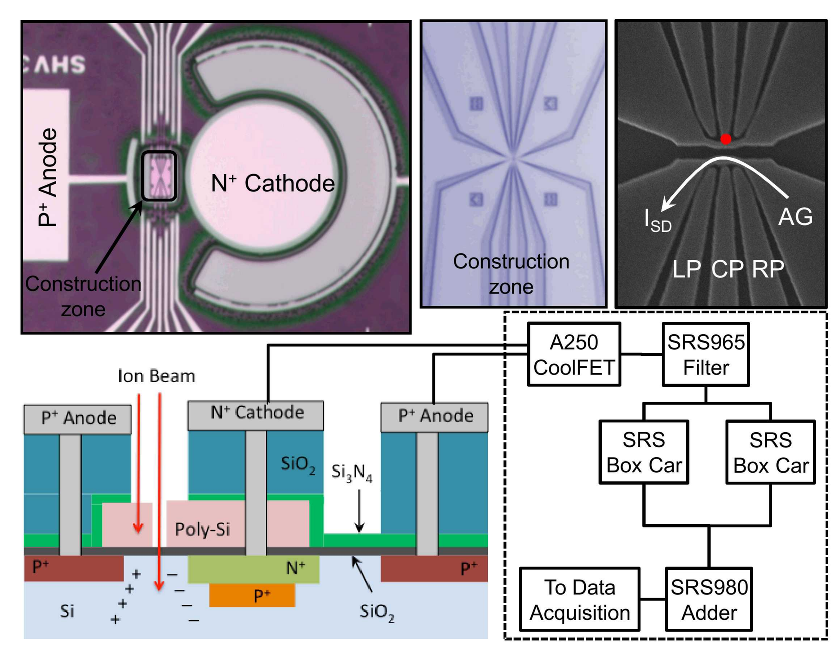
→ Outstanding donor results point towards the need for deterministic implants!

Single ion implantation can be used for the following:

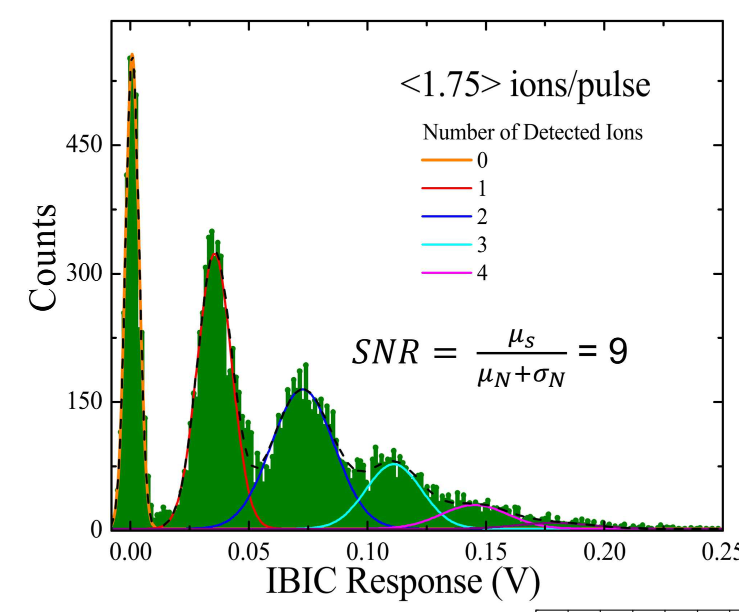
1.) Respond to discovery on timed implant path
2.) Tool for understanding donor 'activation'
3.) Evaluation of different ion species (P, Sb and Bi)
4.) Rapid turn-around for high yield single donor devices

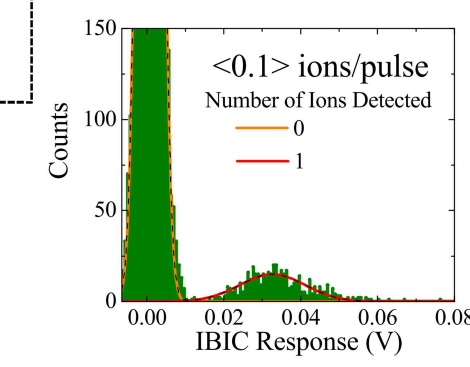
Single Ion Detection

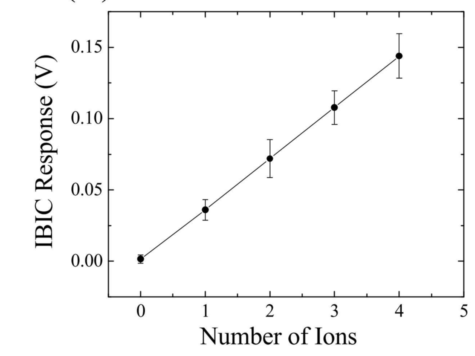
Integrated single ion detector with Si MOS nanostructure



200 keV Si – Quantized Ion Detection







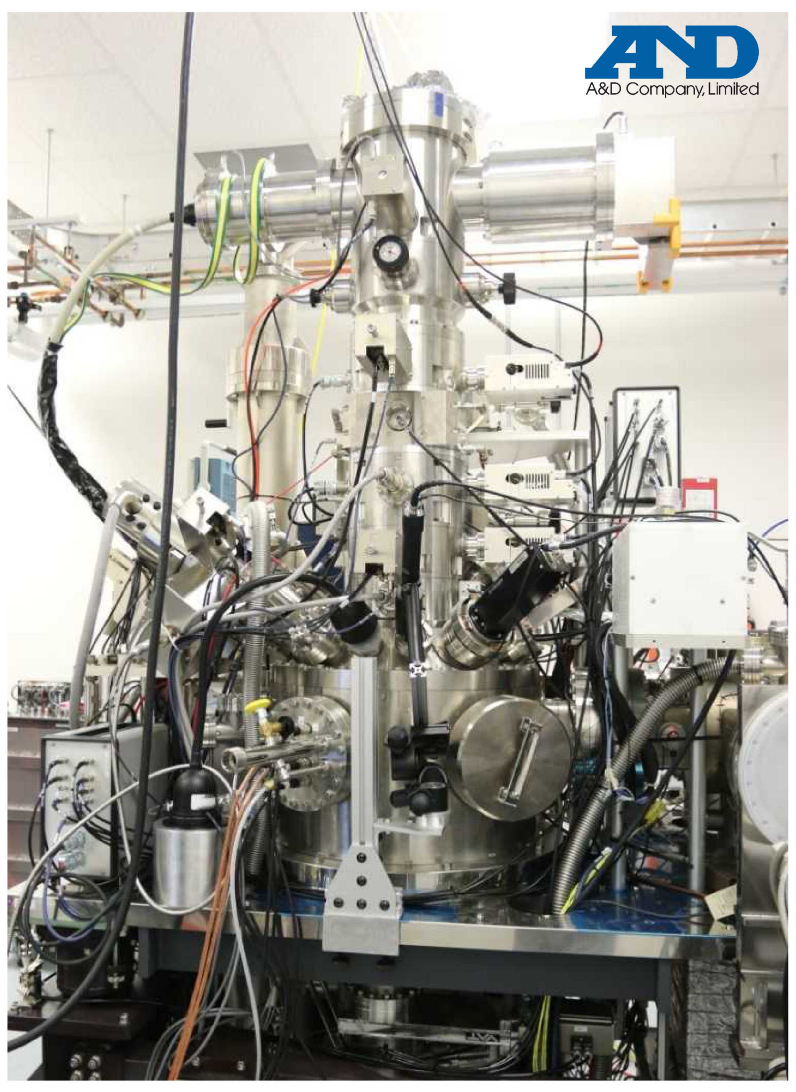
Excellent agreement between the ratio of number of detected ions to Poisson probability distribution.

→ Single ion detection now down to 20 keV (50 keV last yr.) and improving!

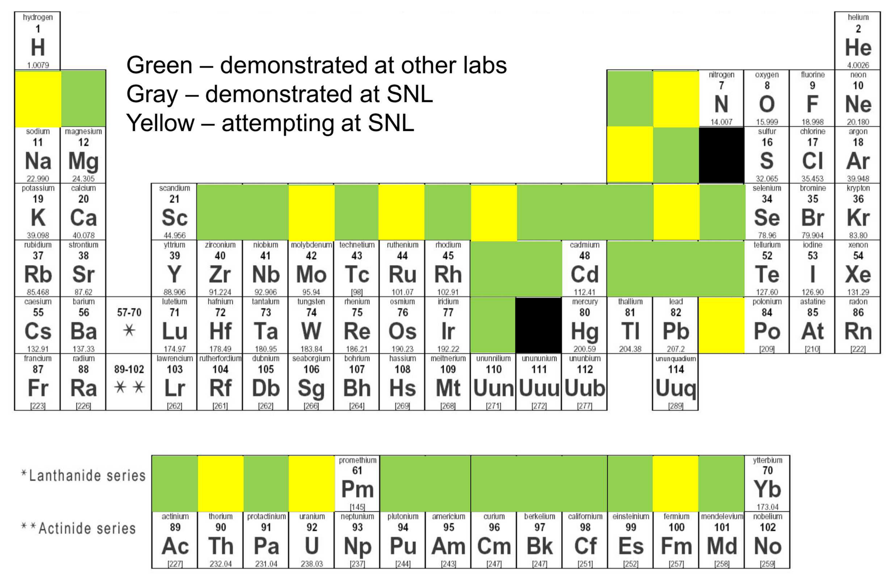
Nanoscale Top-Down Ion Implant

nanoImplanter

- Focused ion beam system (FIB)
  →nm beam spot size on target
- ExB Filter (Wein Filter)
  →Multiple ion species
- Fast blanking and chopping
  →Single ion implantation
- Direct-write lithography
  →nm targeting accuracy

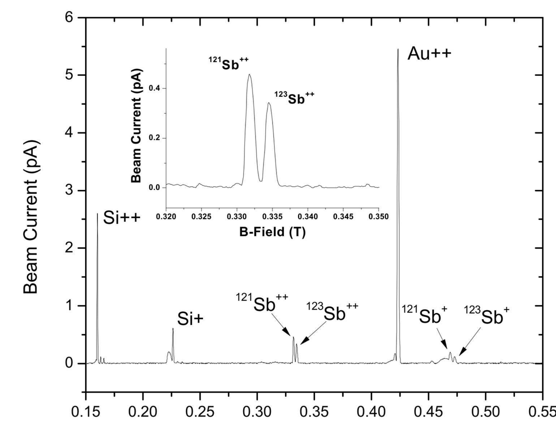


What ion species are possible?



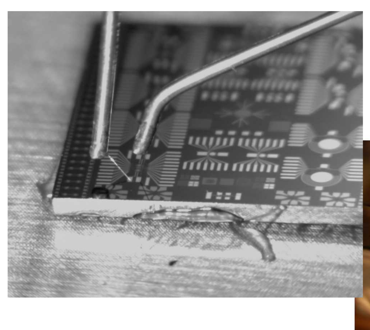
~1/3 the periodic table are available – including P, Sb and Bi

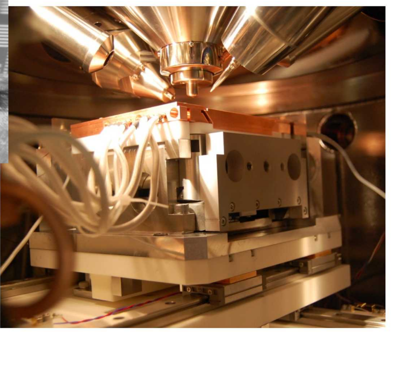
What mass resolution is possible?



$\Delta m/m \sim 0.016$, separates out isotopes of Sb and Si in this AuSiSb source

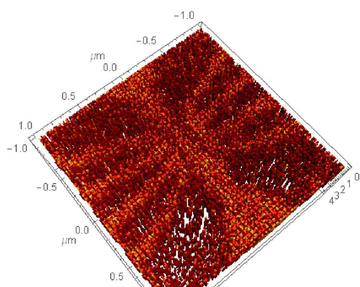
Direct write platform and in-situ electrical probes





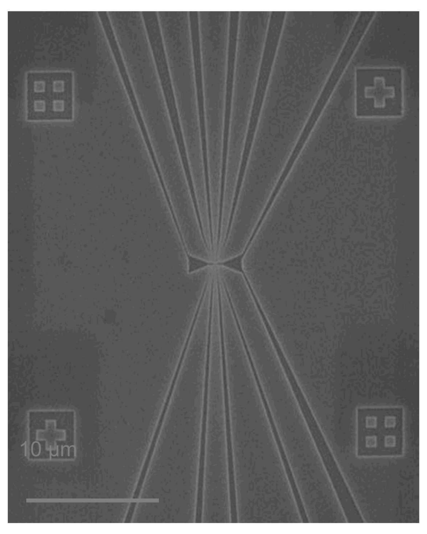
- In-situ electrical probes for measurement of ion strikes as they occur
- Low temperature stage
- Built-in lithography software (Raith ELPHY Plus) capable of sub-nm resolution

RAITH NANOFABRICATION

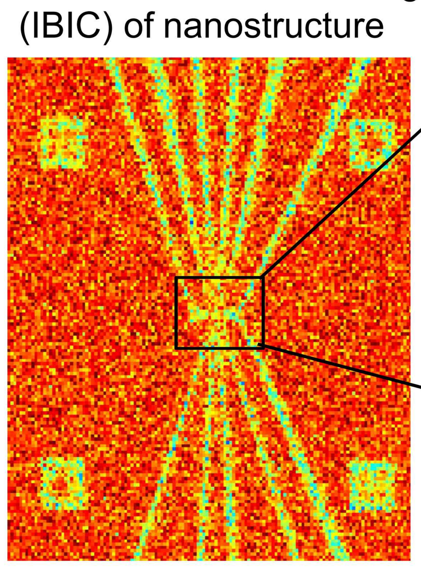


Alignment resolution

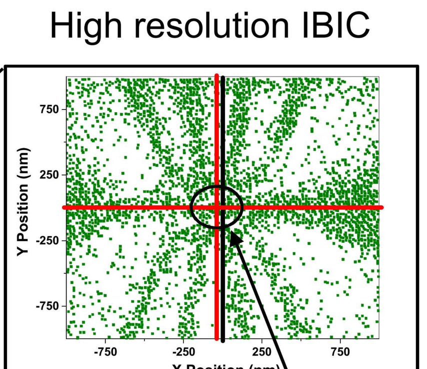
SEM of nanostructure



Ion Beam Induced Charge (IBIC) of nanostructure



High resolution IBIC

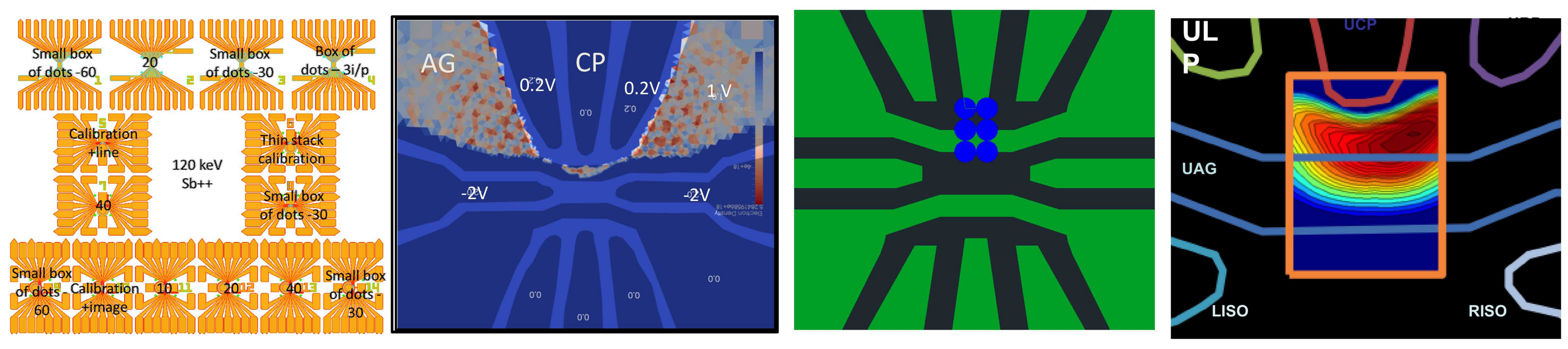


Δx ~35 nm
Δy ~0 nm

→ Alignment resolution is dominated by beam spot size

Counted Donor-SET Devices

How to make counted donor devices? 120 keV Sb into a 35 nm oxide layer

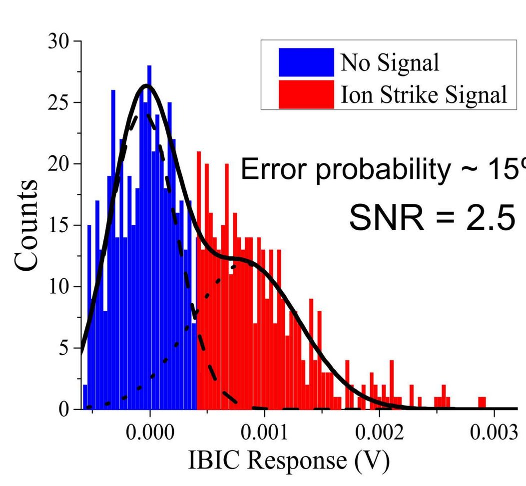


Implantation plan | SET location (QCAD) | Detail of implant locations | Triangulation

Counted Ion Detection and Transport

- Iteration process to Improve donor-SET coupling by donor positioning
- Low energy implantation for reduced straggle – 20 keV Sb

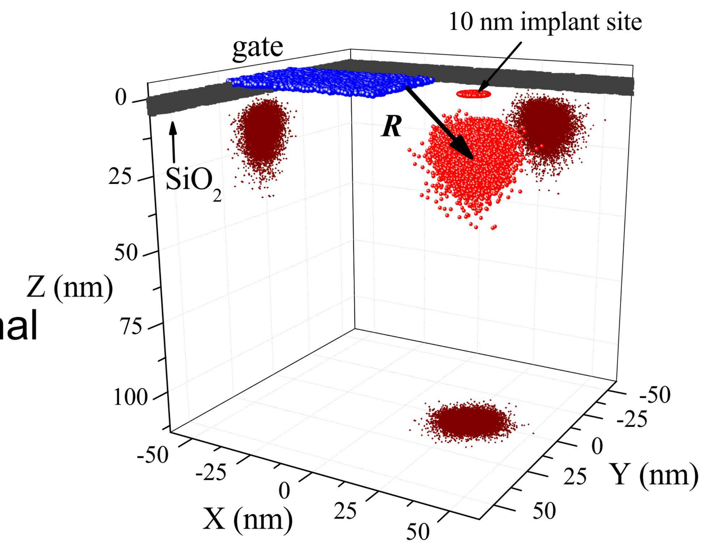
<0.5> ions/pulse



20keV Sb + 10nm opening
→13.5nm ± 5nm ± 4nm

Triangulation from operational qbit device estimate*:
→ 13.5 ± 2.5nm ± 2.5nm

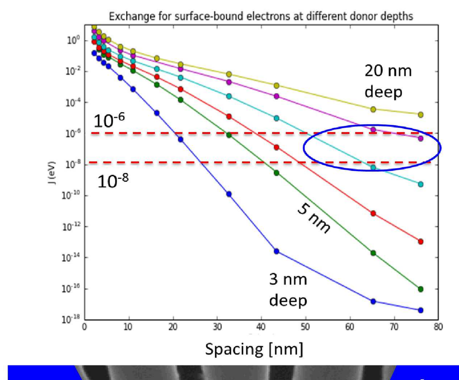
*F. Mohiyaddin, Nanolett. 2013



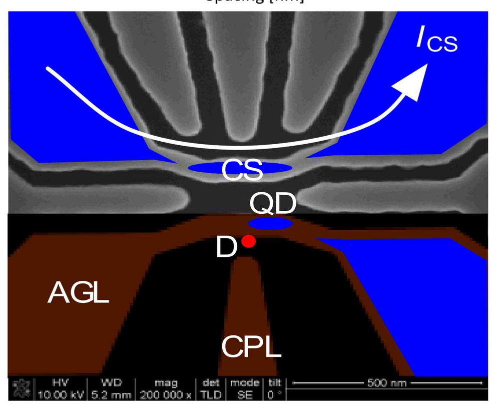
Counted implantation of 20 keV Sb → Deterministic and improved donor positioning

Outlook for 2 Donor: D-QD-QD-D

Previously, donor-donor coupling required strict placement, new designs relax donor placement requirements



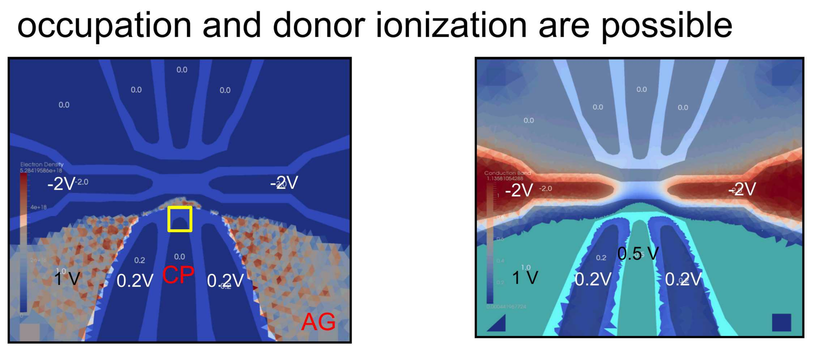
Very difficult to hit these targets using top down ion implantation!



Make use of the donor-QD coupling to reduce donor placement requirements

Work to extend this design to donor-QD-QD-donor

QCAD simulations show simultaneous electron occupation and donor ionization are possible

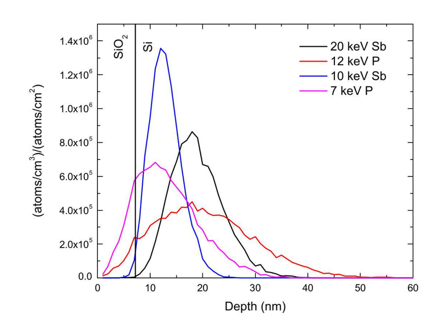


Electron density at interface | Green areas have electrons

Donor-QD (few electron) will require a **target depth** of **<15 nm** with a **lateral spacing** of **~35 nm** between the donor and QD.

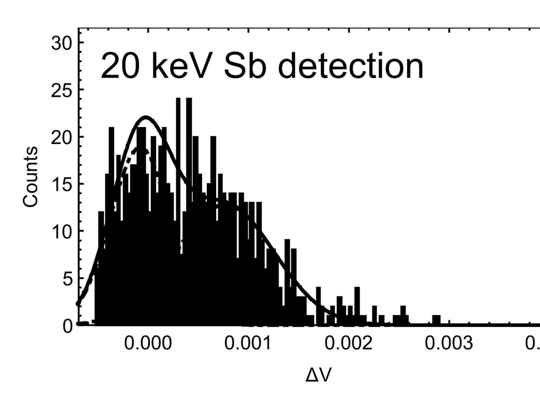
What is needed to make this device?

1.) Target ion depth of ~5-15 nm below the SiO_2



Ion	Range below SiO_2	e-h pairs
20 keV Sb	11.5±4.9±4.3 nm	~1500
12 keV P	13.0±9.3±7.8 nm	~1100
10 keV Sb	5.5±3.0±2.9 nm	~500
7 keV P	5.7±6.1±5.1 nm	~500

2.) Need to detect low energy ions

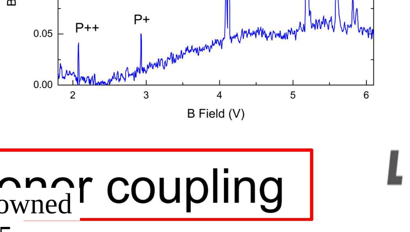


20 keV Sb detected, if need low energies, we will:

- improve noise floor, in vacuum preamps, etc…
- improve gain – Geiger mode operation, sensitive to <100 e-h pairs!

3.) For any experiments that require nuclear spin ½ P implants

Mass spectrum PtPSb



Estimated Spot Size
- 20 keV Sb <50 nm
- 12 keV P ~100 nm

Can be reduced by ~40% with negative PS for OL lens (installing)

→ Immediate path forward to donor-donor coupling

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