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Development of Counted Single Donor Devices using in-situ Single Ion Detectors on the SNL NanoImplanter

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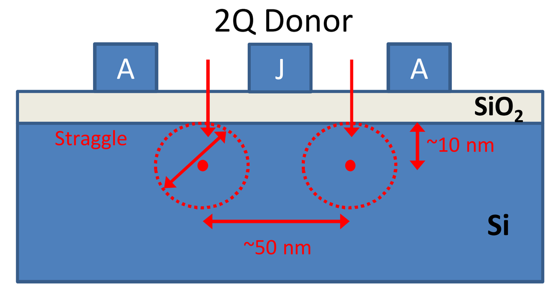
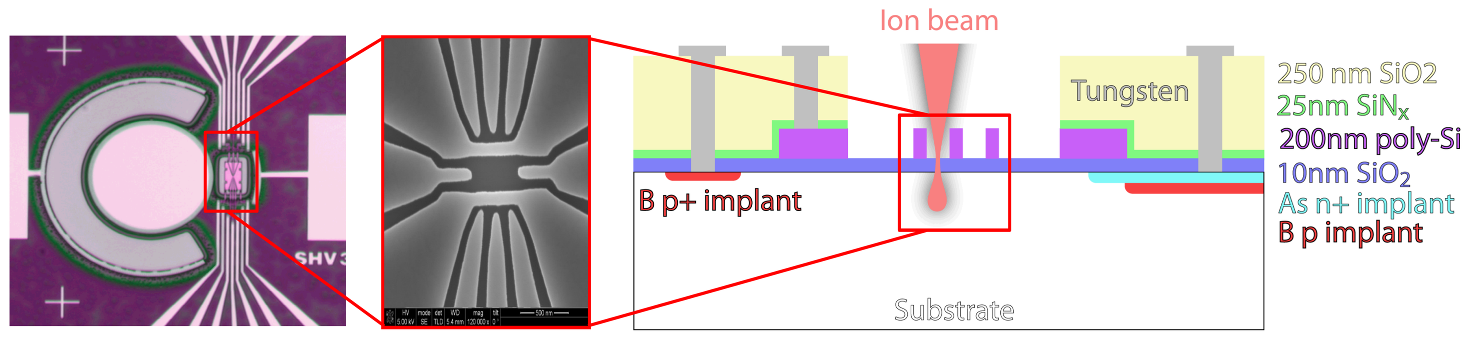
Realization of Single/Double Donor Devices

It is necessary to have

Accurate placement of P, Sb, or Bi donors

Deterministic verification that a single donor is in the targeted location



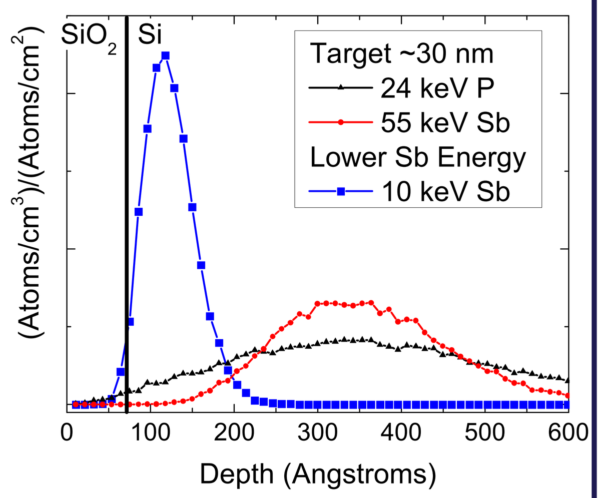


1Q donors: How deep?

- For 1Q, donor at ~29 nm below the surface

2Q donors: depth and separation?

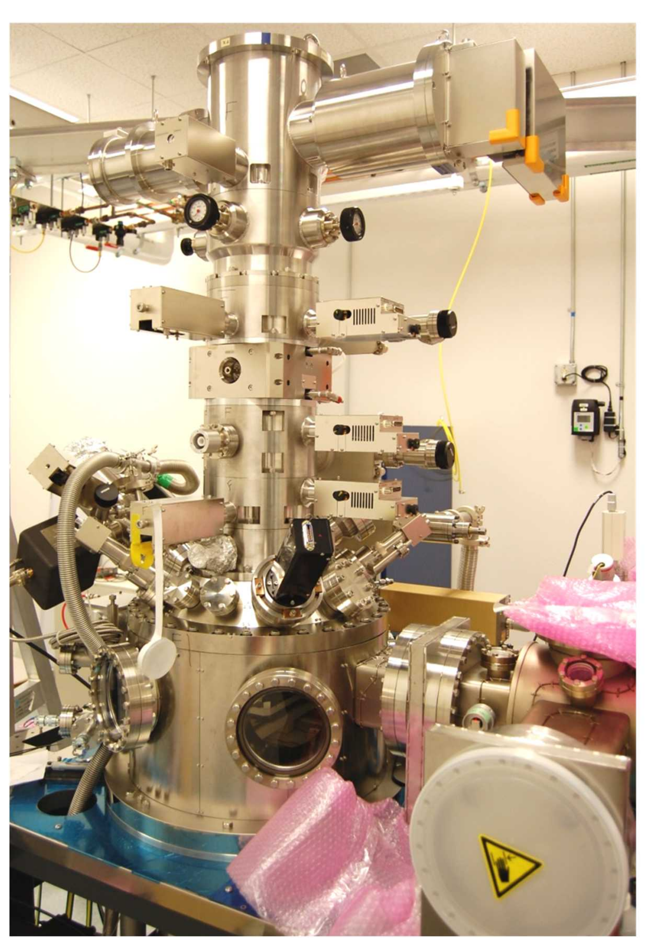
- For 2Q, 10-15 nm donor depth and 50-80 nm separation
- For accurate placement → Minimize Range and lateral straggle (low Energy)



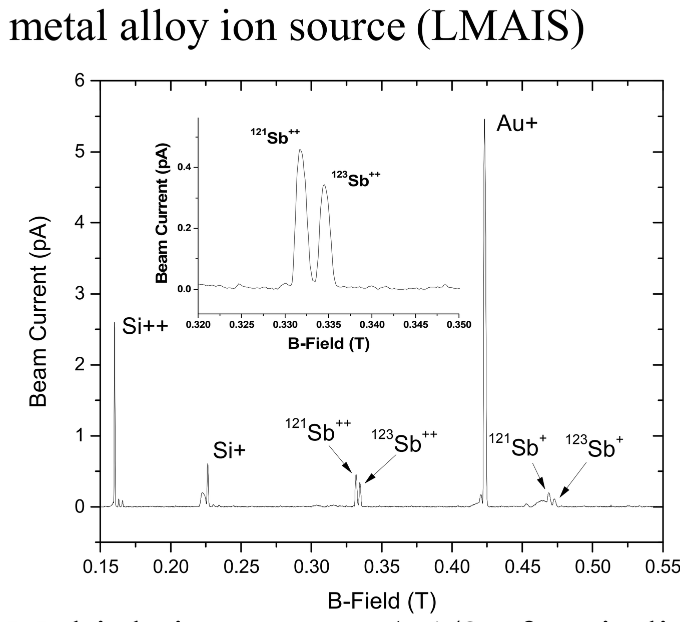
Approach

- Top Down FIB Ion implantation → Placement
- Single ion detectors in-situ → Verification of single donor implant.

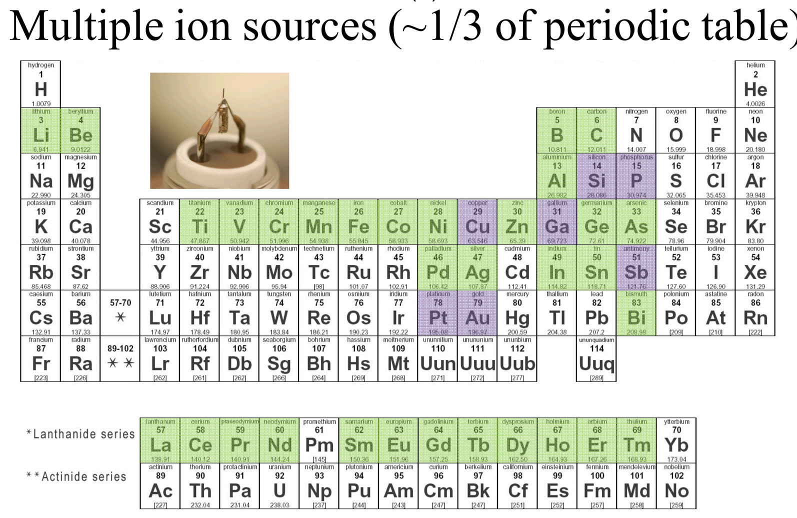
Top Down Single Ion Implantation with nm Resolution



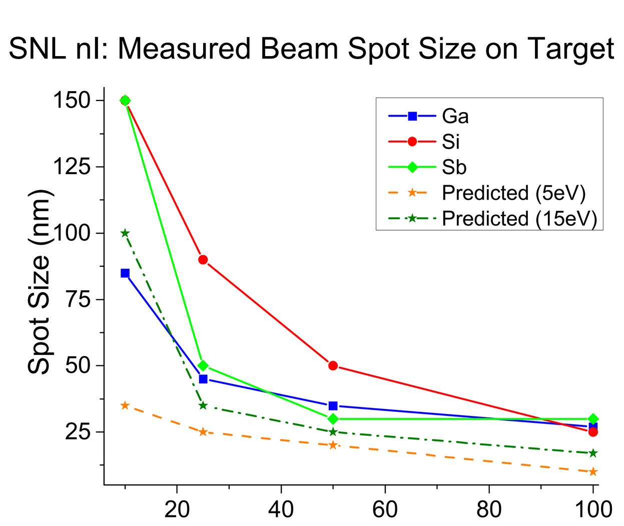
- 100 kV FIB with a Wein filter for liquid metal alloy ion source (LMAIS)



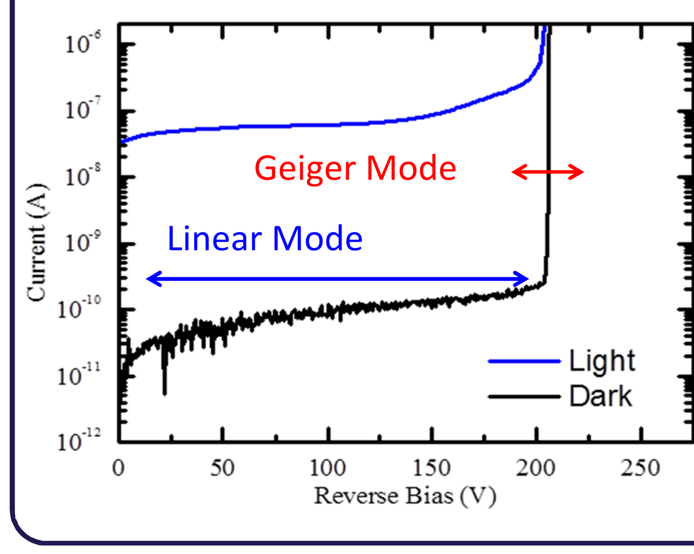
- Multiple ion sources (~1/3 of periodic table)



- Direct-write lithography platform
- High resolution beam deflectors
- Laser Interferometry-Driven Stage
- Capable of <10nm beam spot size on target (Ga)
- Fast Beam Blanking and Chopping for Single Ion Implantation



In-Situ Detector Operation



Geiger Mode Operation

- No Bias in Linear Response regime
- Signal proportional to No. of e-h pairs
- Limited Gain (~1)

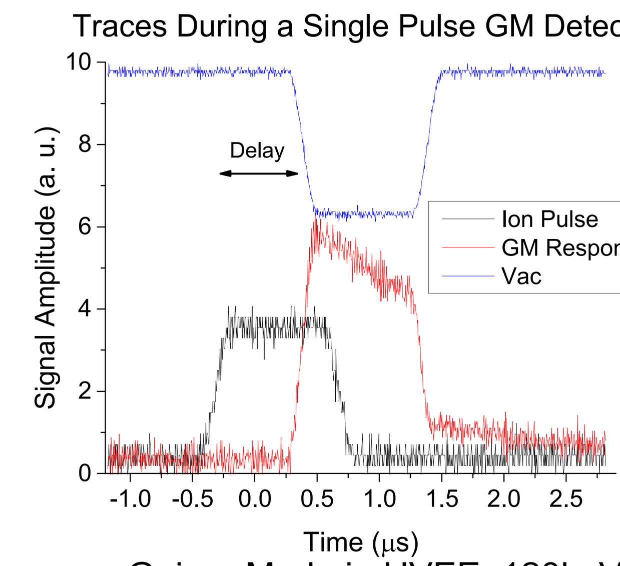
Linear Mode Operation

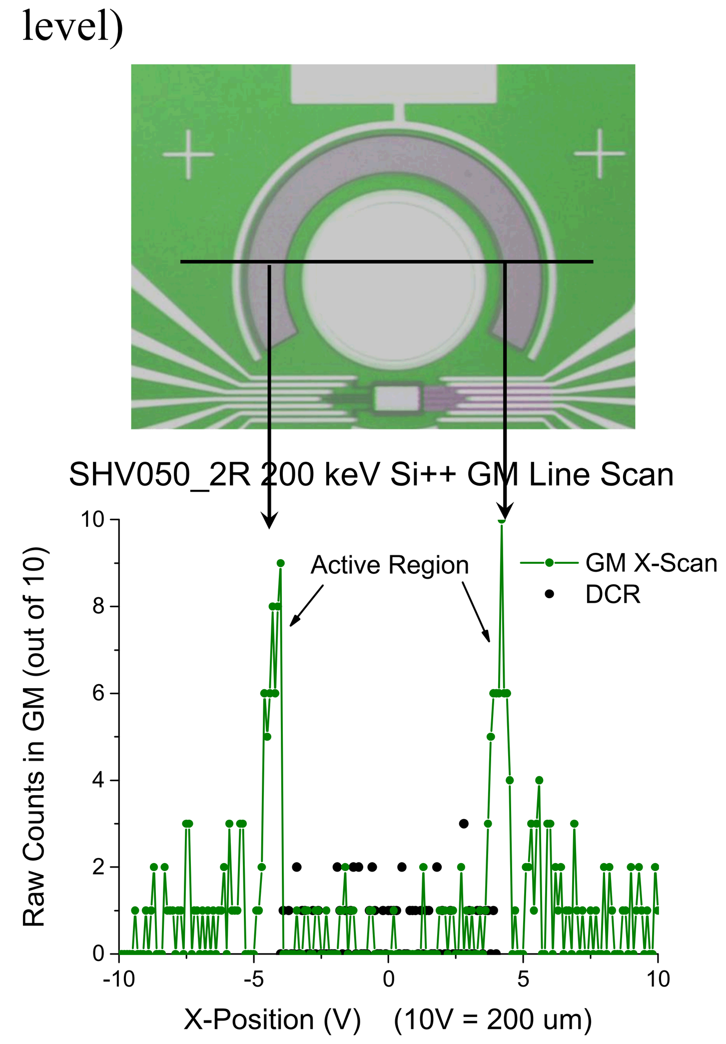
- Pulsed bias above breakdown
- Impact ionization → Large gain
- Gain meaningless (digital signal)

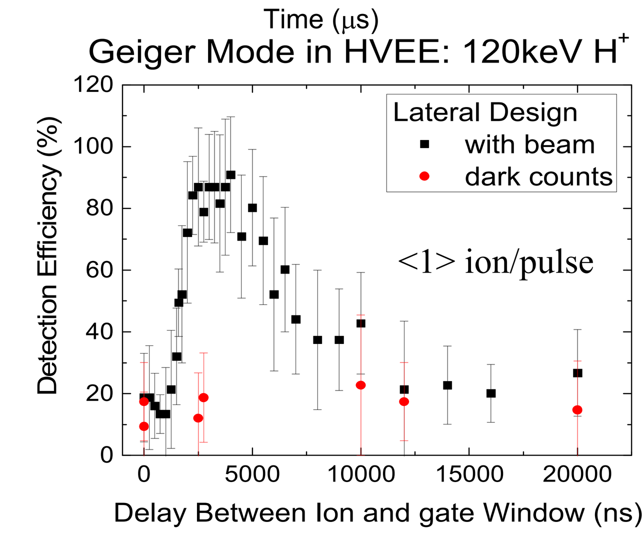
Single Ion Detection in Geiger Mode

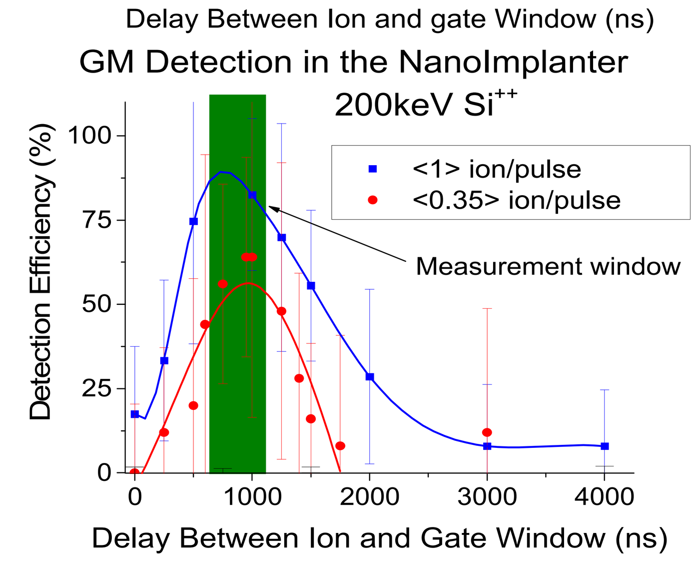
GM Detection Methodology:

- Expose Device to an Ion Pulse
- Account for Delay and momentarily bias above breakdown (Vac)
- If ion incident during Vac → e-h pair avalanche
- Discriminator gate (time and voltage level)



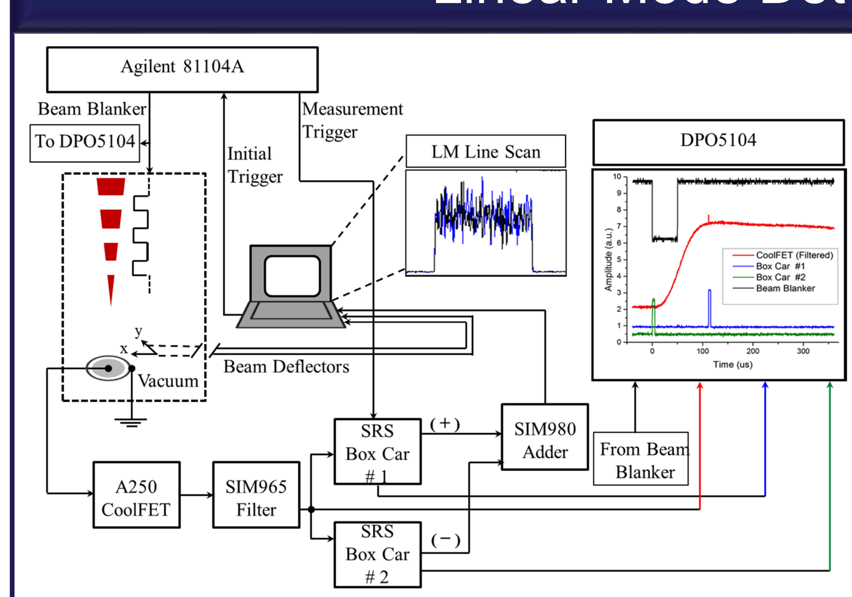


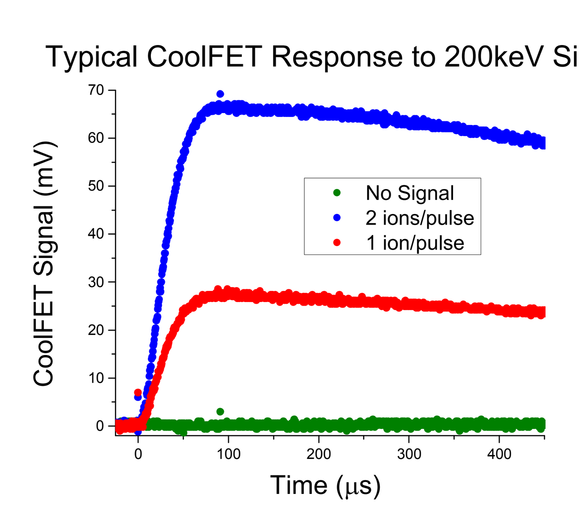




Currently investigating detector design to for detection of lower energy ions

Linear Mode Detection Setup



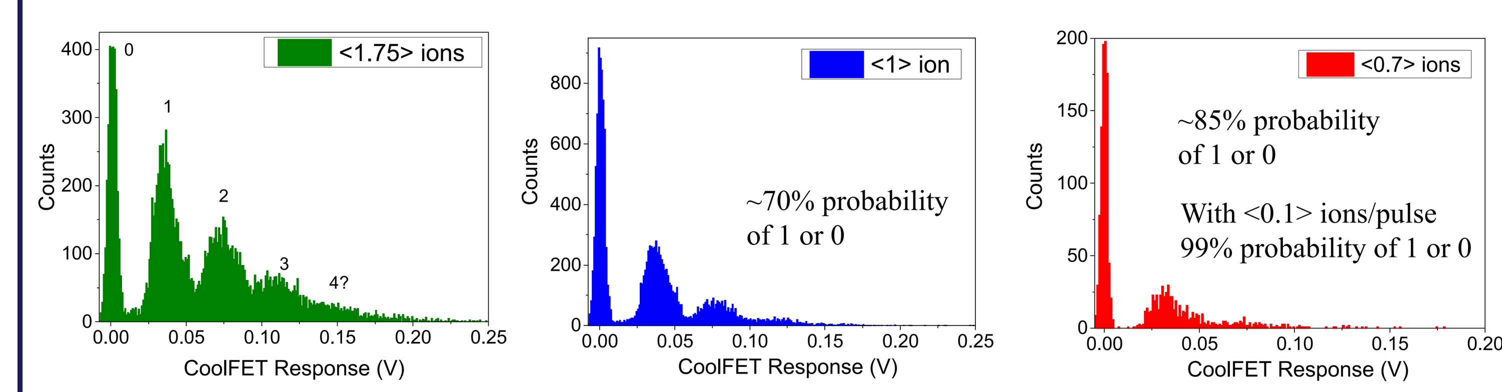


Procedure for Single Pulse-Single Ion implantation

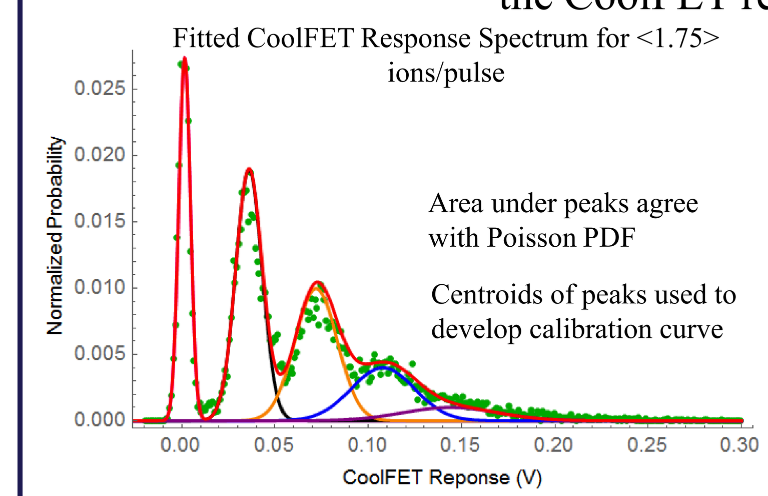
- Bin CoolFET response →Response distribution to a single ion
- Set routine to stop implantation when signal between a preset UL and LL discriminator

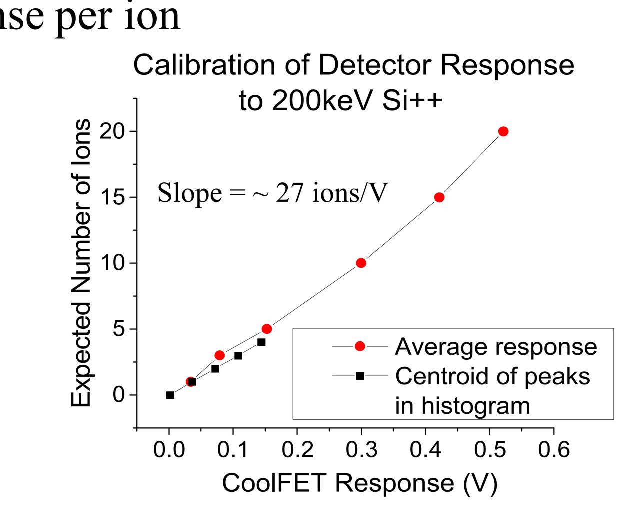
Linear Mode Single Pulse-Single Ion Detection

Histograms of coolFET response to determine the average # of ions in a pulse



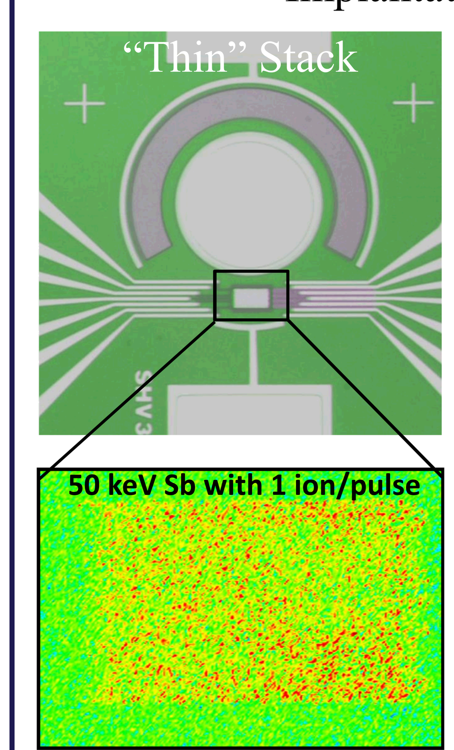
The quantization of ion number is clearly visible allowing for a determination of the CoolFET response per ion

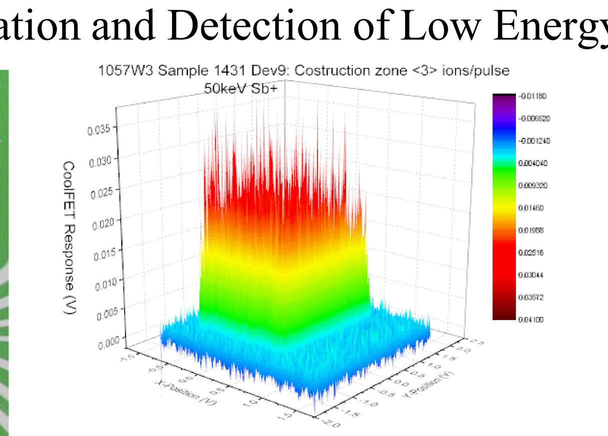


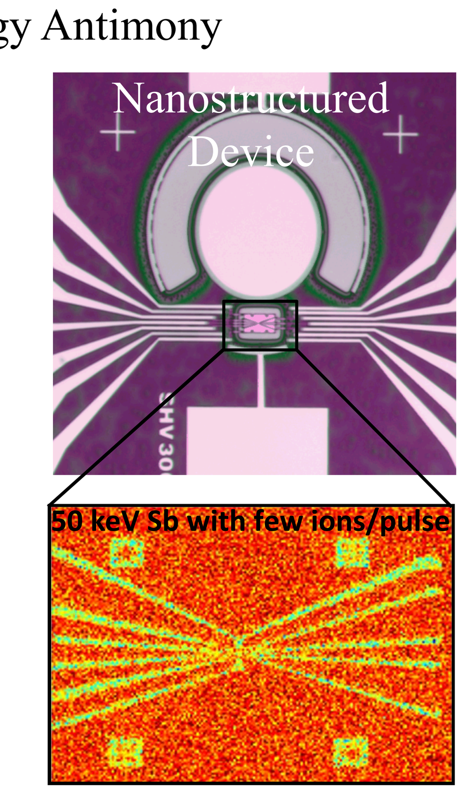


Path to deterministic implantation of single ions

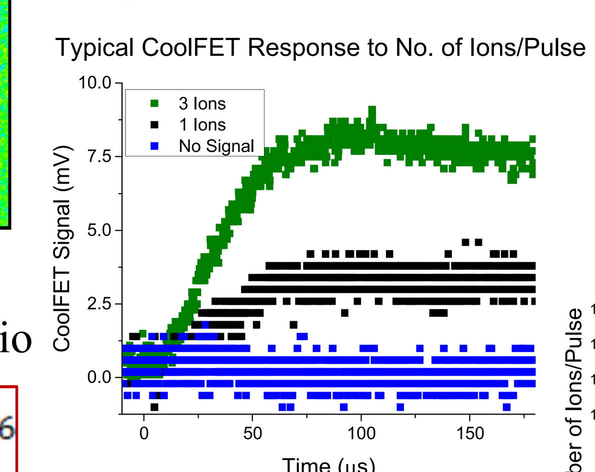
Implantation and Detection of Low Energy Antimony





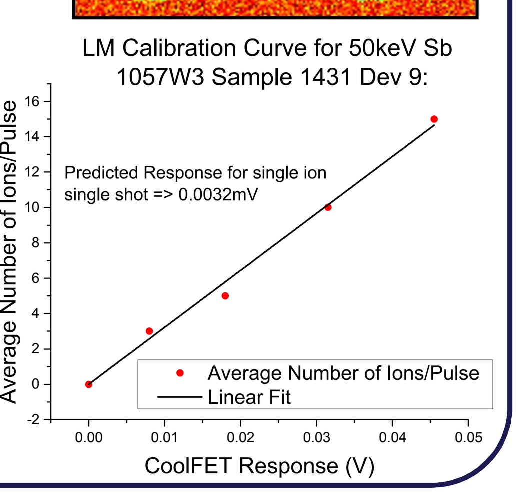


- 50 keV Sb → Single Pulse-Single Ion Detection



- Single Ion detection Signal-to-Noise Ratio

$$SNR = \frac{A_1}{\sigma_N} = \frac{3mV}{0.5mV} = 6$$



- Achieved SNR for Single Pulse-Single Ion Detection → Single Ion Implant with High Fidelity

Conclusion

- We have further developed two techniques to ensure deterministic implantation of single donors
  - LM → yields information about the number of ions implanted (but no gain thus far)
  - GM →high gain but provides digital signal (ion strike or no ion strike)
- Combined with the nI capabilities → Deterministic Single Ion Implantation with nm spatial accuracy
- Lower beam energy → Tighter implantation (decreased straggle) → Stronger donor coupling
- Current detection limit: 30 keV Sb (20keV Si)
- Exploring possibilities to detect ions with lower energies

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