Focused Ion Beam Development for Single Ion Implantation

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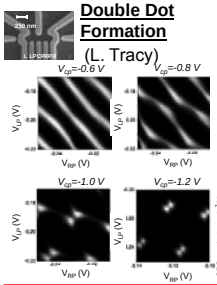
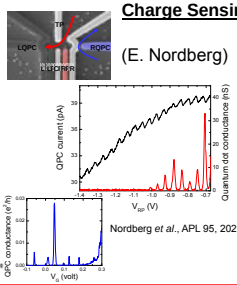
Status of Standard MOS Double Dot Structure

Double Dot Formation (L. Tracy)



Charge Sensing (E. Nordberg)



Nordberg *et al*., APL 95, 202102

Recent success with Si-MOS devices (stable Coulomb blockade and charge sensing) mean we can build use the existing platform as a starting point for more advanced designs.

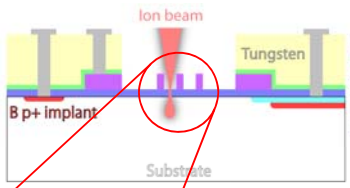
Potential challenges in the Si-MOS system:

1. Dangling bonds and other defects at the Silicon-SiO_2 interface leading to short T^*_2
2. Difficulty reaching single electron occupation due to interface disorder.

Solutions:

1. Move electrons away from the Si-SiO_2 interface using donors.
2. Replace SiO_2 dielectric with a cleaner system, such as SiGe.

Focused Ion Beam Implantation of a Single Donor



Contacts to device not shown in this figure.

Top view of device.

High yield fabrication of implanted devices or large scale integration requires implanting exactly one donor with sub-10 nanometer resolution.

Single ion implants require on-chip ion detectors with 100% detector efficiency for low energy implants (10 to 100keV) integrated with the DQD electronics.

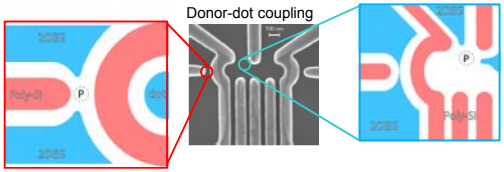
Our design is based on silicon avalanche photodiodes (SPADs), which respond to the electron-hole pairs produced by the ion. We have achieved 100% detector efficiency and are currently working on integration, beam spot size, and ion sources.

Single Donors for Spin Storage or Interaction

Advantage of using electrons localized on donors:

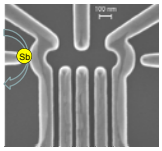
1. Electron held farther away from interface and potential charge or spin decoherence centers.
2. Valley degeneracy naturally broken by donor potential, eliminating another decoherence mode. Spin-orbit coupling is also negligible for donor-bound electrons. (Calderon et al, PRB 2008).

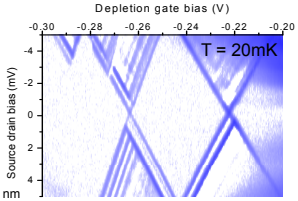
Donor-dot coupling



While we develop single ion implant capability, we have already started device processing with implants done by CORE systems.

Initial Timed Donor Devices: 100 keV Sb Implants



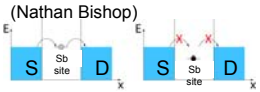


- Designed opening ~80 x 80 nm
- Defines the ion spot size required for localized position dependence, <100 nm

(Nathan Bishop)

Transport through donor:
Implant single/few donors into a QPC.

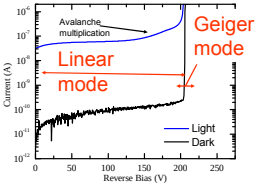
The presence of a donor impurity in the QPC has a clear signature in transport.



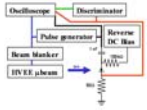
Conduction through donor state below pinch-off in a QPC.

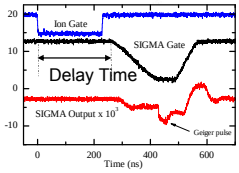
Single Ion Geiger Mode Avalanche (SIGMA) Detector

APD operation



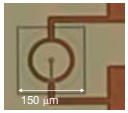
I-V response of an APD with both linear and Geiger mode operations indicated.



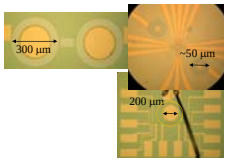


APD Structures

Discrete SIGMA Detectors (Mark-0)



Integrated SIGMA Detectors (Mark-1)

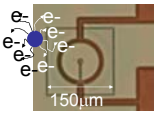


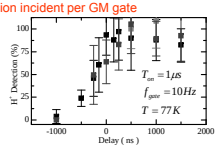
Designed for integration with Si DQD platform

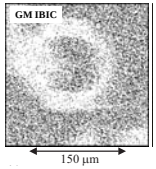
- Reduce oxide thickness to 10 or 35 nm
- Reduce background doping
- Change the APD doping profile
- Both active and diffused carrier detection

Initial Results – Discrete APD Devices

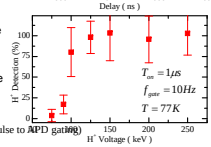
Single 250 keV H^+ ion incident per GM gate



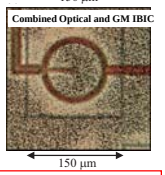




- Detector efficiency falls off with decreasing energy as the H^+ ions no-longer penetrate through the over-layers
- With 125 keV H^+ we produce ~10^4 e-h pairs per ion strike only ~ **1,000 in Si body**



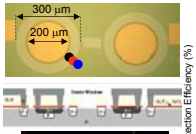
(Delay time is the time from ion pulse to APD gating)

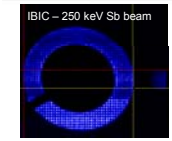


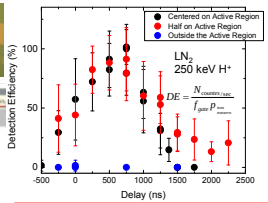
Single ion detection with ~1,000 e-h pairs produced in the Si body

IBIC of SIGMA in Geiger Mode, showing diffused carrier collection

Initial Results – Integrated APD Devices

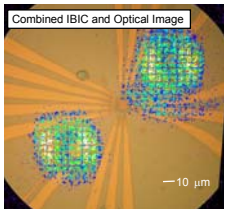






Preliminary results are encouraging and additional testing/redesign is on-going – reduced background doping leads an increased DCR, lower DE

Single Donor 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!

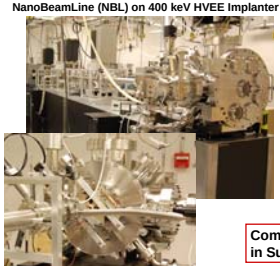
Diffused carrier detection

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!

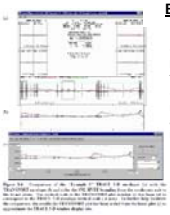
Focused Ion Beam-line Development

NanoBeamLine (NBL) on 400 keV HVEE Implanter



- 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 of <100 nm

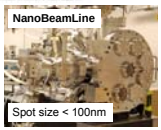
Completion expected in Summer 2010



Beam-line Modeling Results using PBOLabs Software

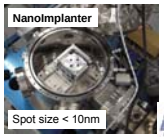
- Complete model of the beam-line from source to target.
- New electrostatic quadruple model added to TRANSPORT and TURTLE modules to improve fidelity of models.

- 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



NanoBeamLine (NBL) on 400 keV HVEE Implanter

- Attached to the 400 keV HVEE implanter with sources for P, Sb, B, etc… readily available from 20 to 400 keV
- New 4K QIST sample stage with 100 mm of travel will allow for large scale implantation
- We have ordered a new set of micro-manipulators to probe the wafer level devices – set of four will allow for simultaneously connect to two APD detectors for single ion implantation



NanoImplanter (nl) 100 keV FIB

- New 100 keV FIB with ExB filter for multiple species usage. Liquid metal ion sources (LMIS) for Sb and P under development.
- New nl sample stage 100 mm of travel with 2.5 nm resolution will allow for large scale implantation.

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