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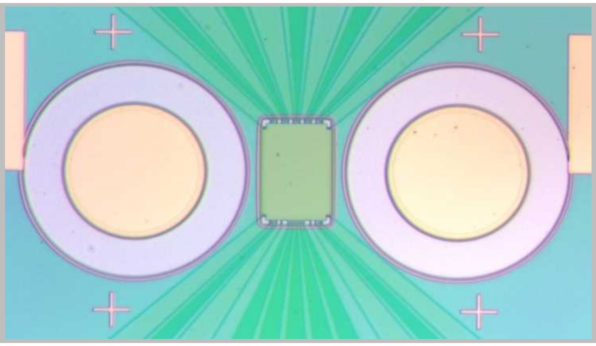

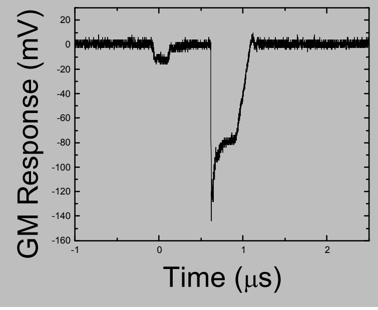

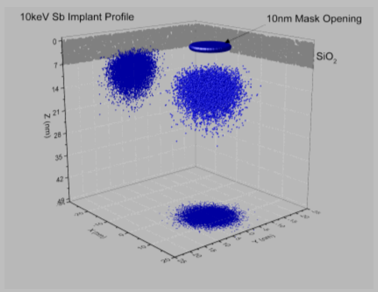

Optimization of avalanche photodiodes for the detection of subsurface single ion implants in Silicon

J. Abraham, P. A. Sharma, J. L. Pacheco,
E. Bielejec and M. S. Carroll

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

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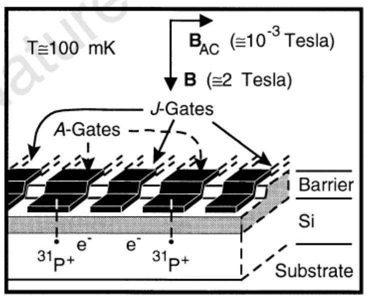
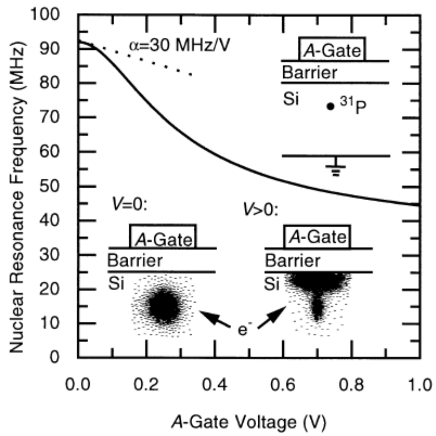
Outline

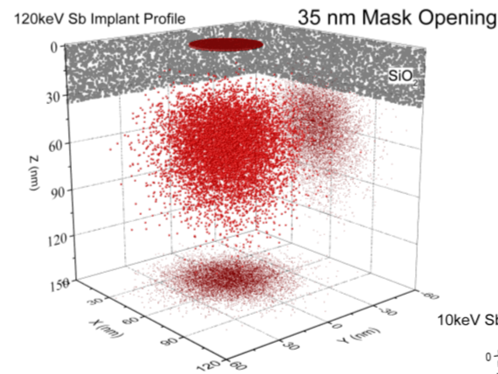
- Deterministic Implants for Quantum devices
- Avalanche Photodiode (APD) Design, Performance and Characterization
- Laser Testing
- Conclusion/Outlook

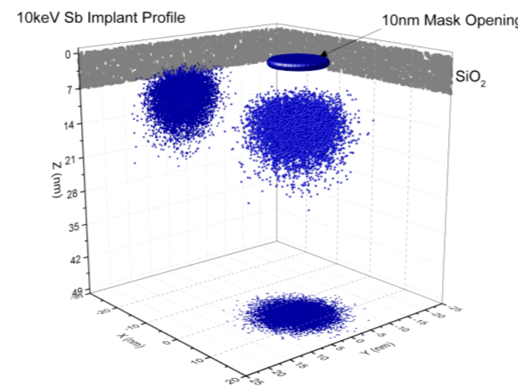
Deterministic Implantation





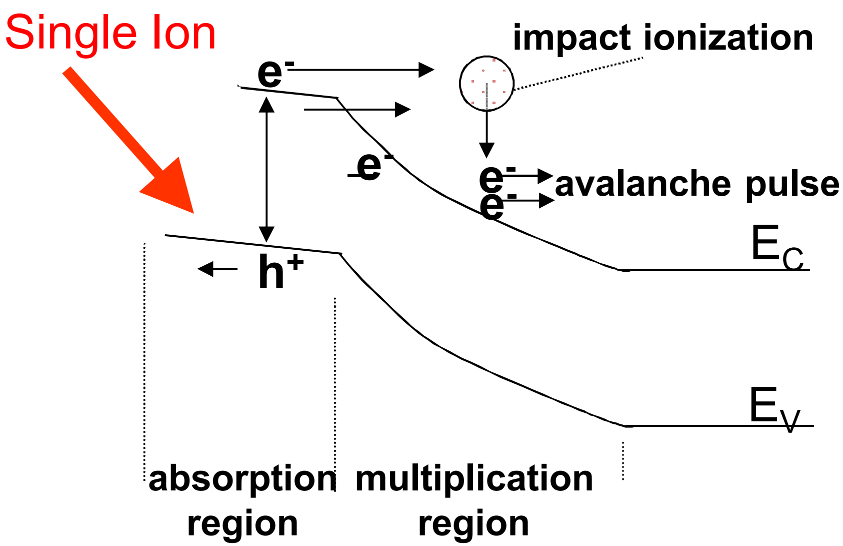
B. E. Kane, Nature **393**, 1998

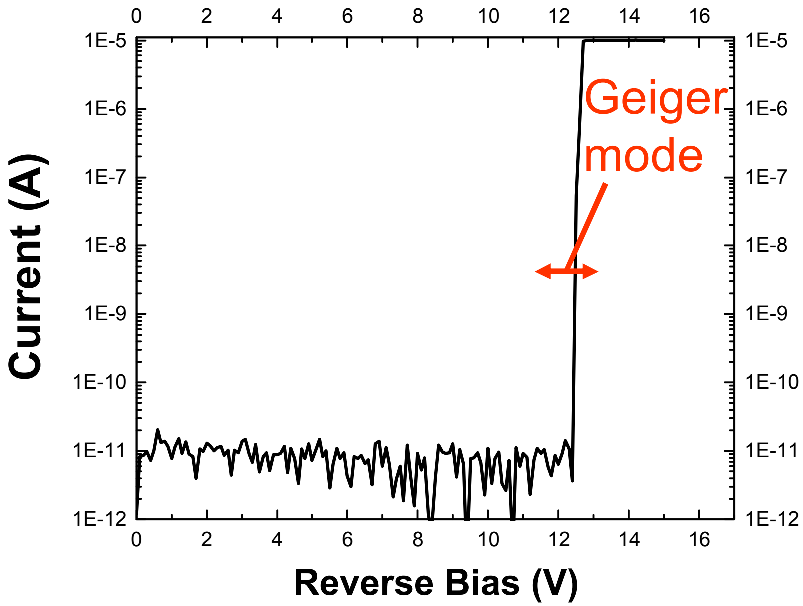




- Coupling to an electron?
- Deterministic implants for quantum devices – to overcome the limitation of Poisson Statistics
- Monte Carlo simulation illustrates the challenge of straggle

APD Introduction





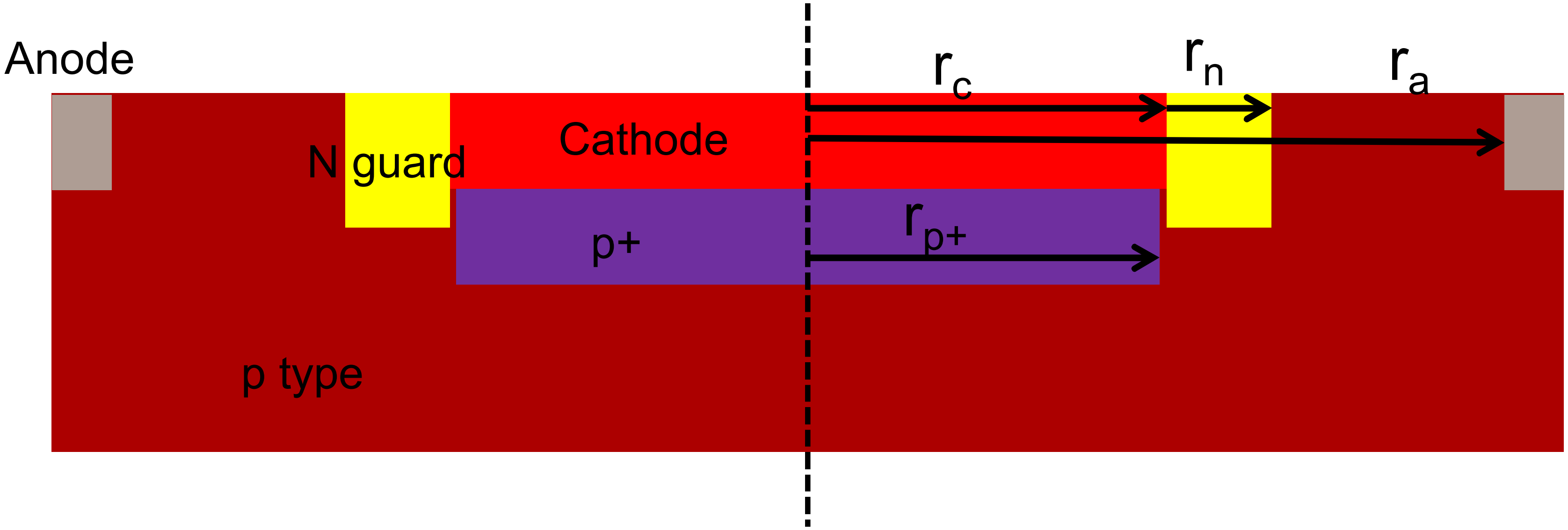
•Reverse bias pn junction

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

Geiger Mode Operation

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

APD Geometry



- Schematic of the device design
- Experiments varying rp+, ra, rn/rc are performed to understand how to optimize eh pair detection for detection in the guard ring vicinity.

APD modeling with TCAD

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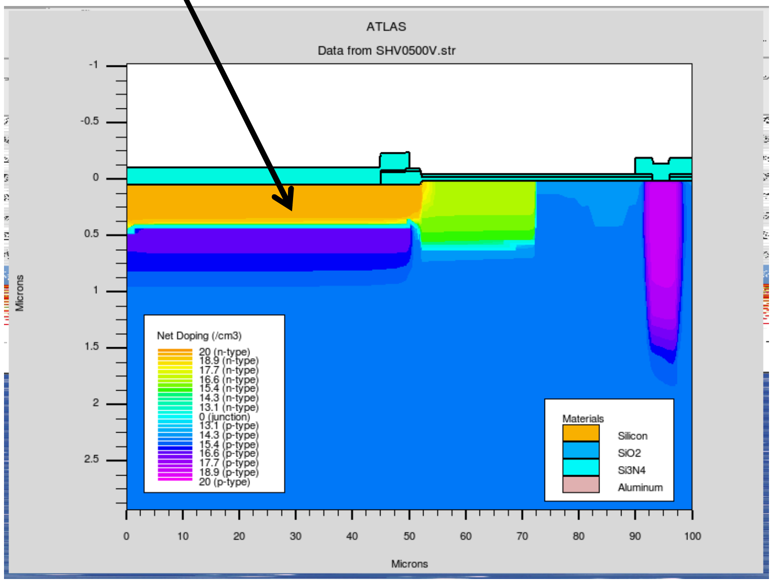
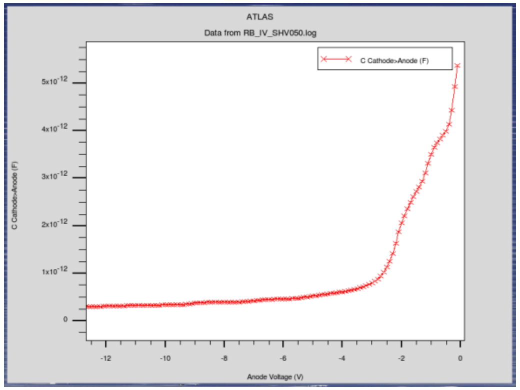
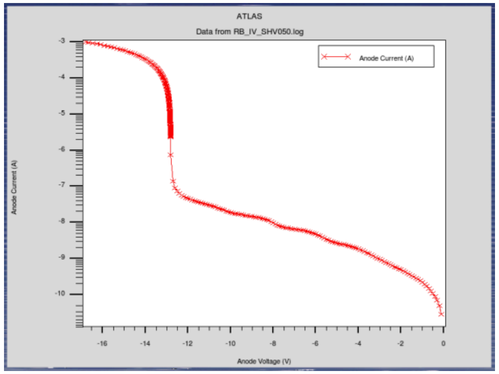
Junction depth:
400 nm





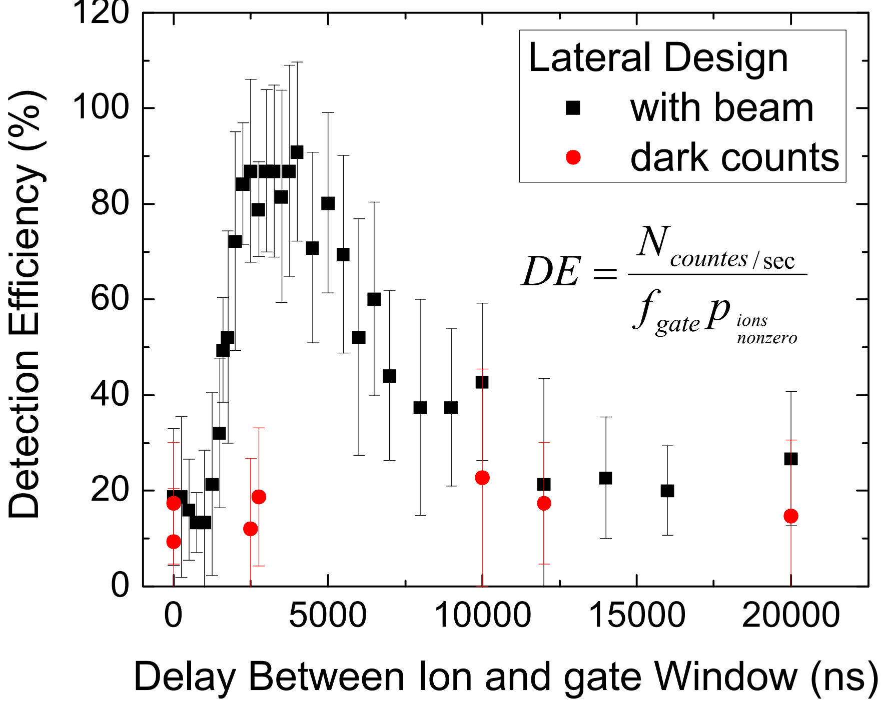


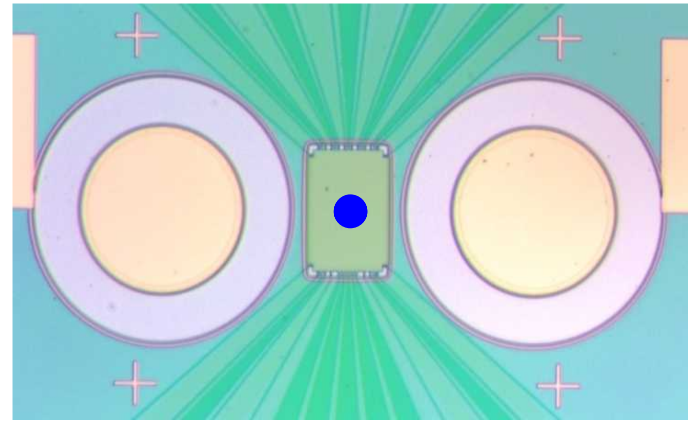
TCAD Modeling for junction depth characterization in order to understand the length scales and sensitive volumes of the device.

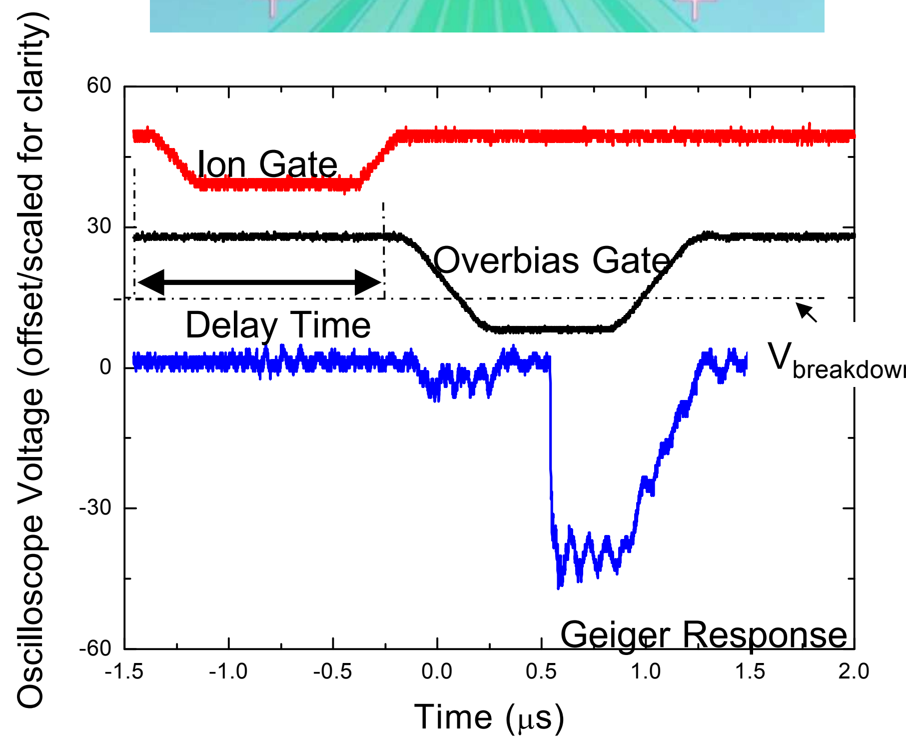
Fidelity check with IV and CV characterization

APD Ion Response

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

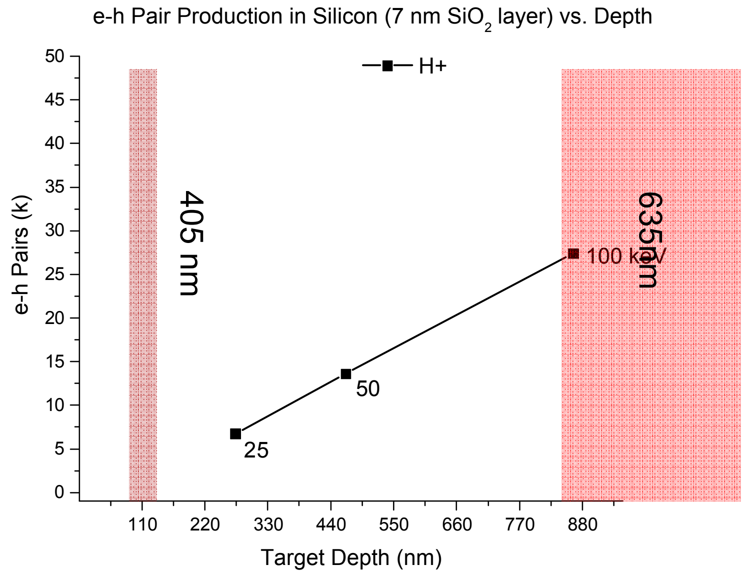


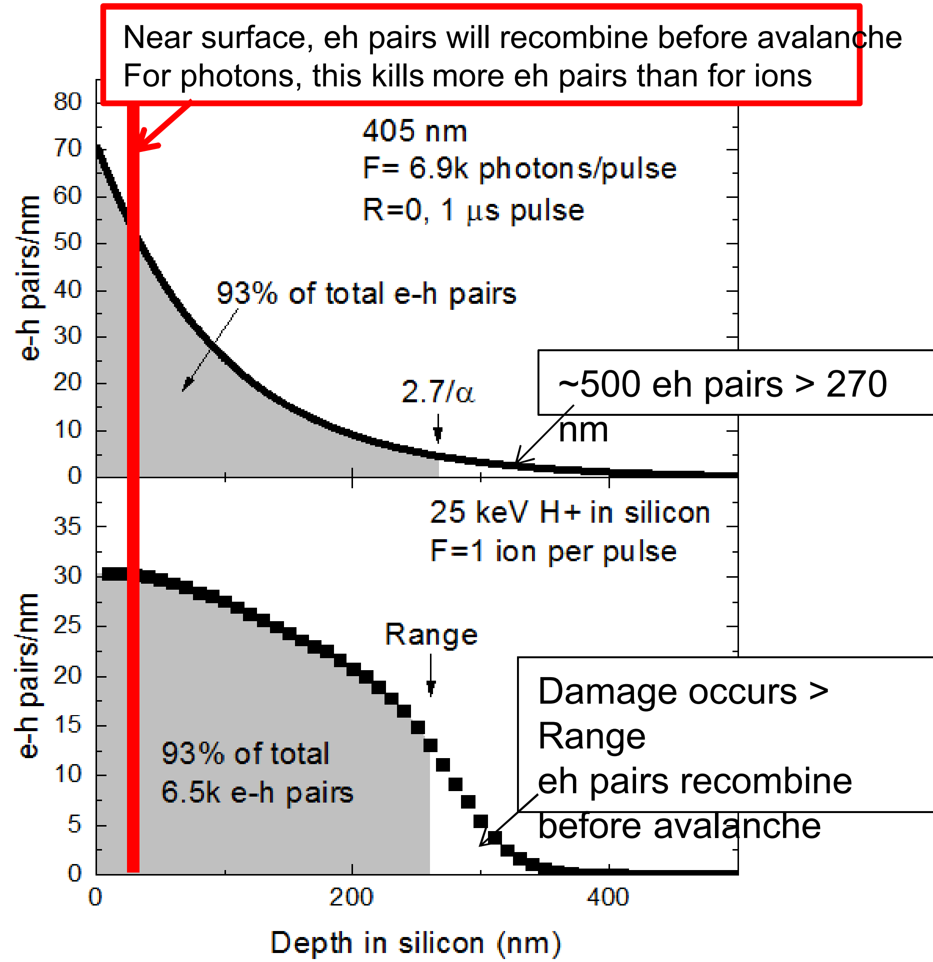




Detect single ions with detection efficiency approaching ~100% for diffused carriers

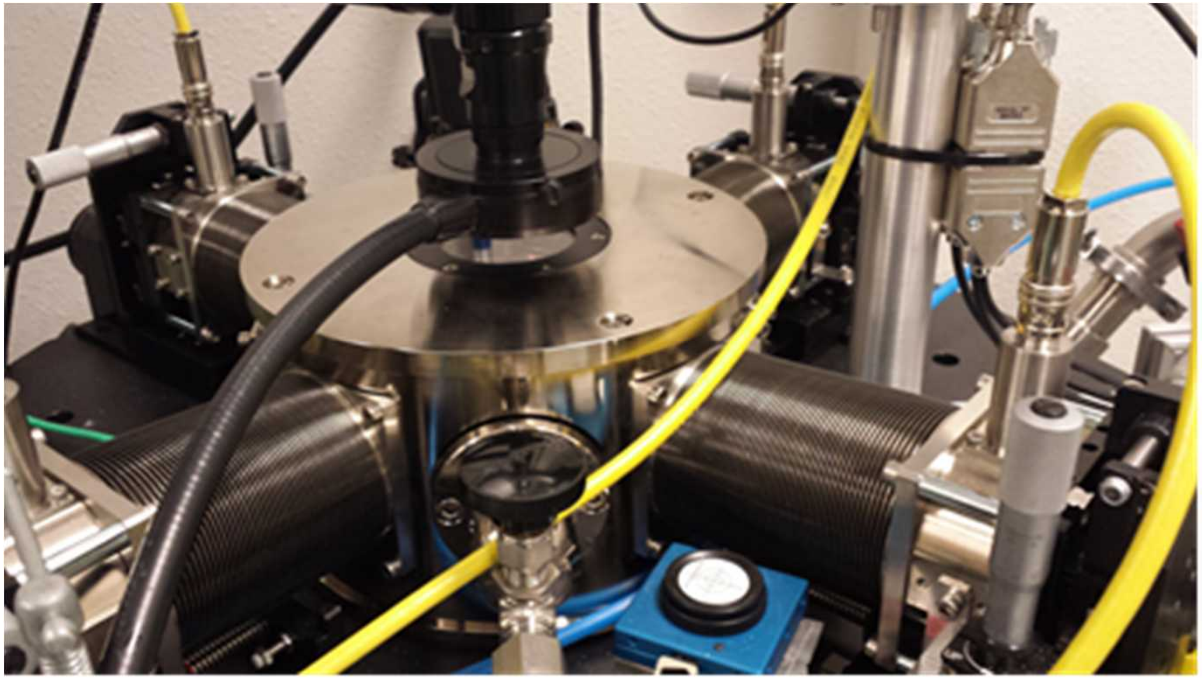
Ion vs. Photon Response

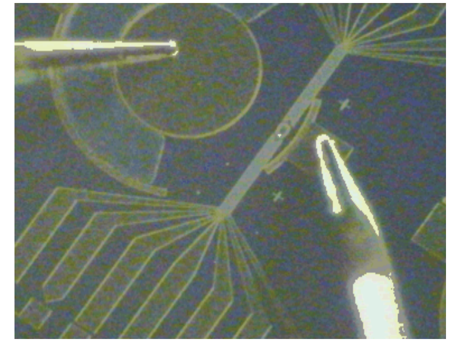


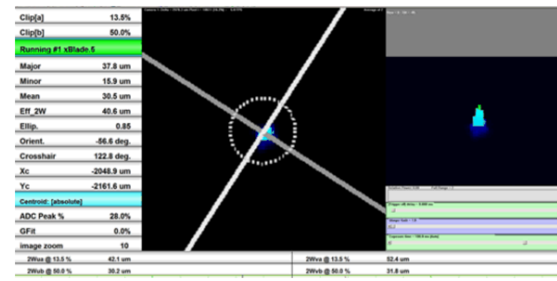


Use photon response to characterize
Bound ion response response.

Testing Chamber







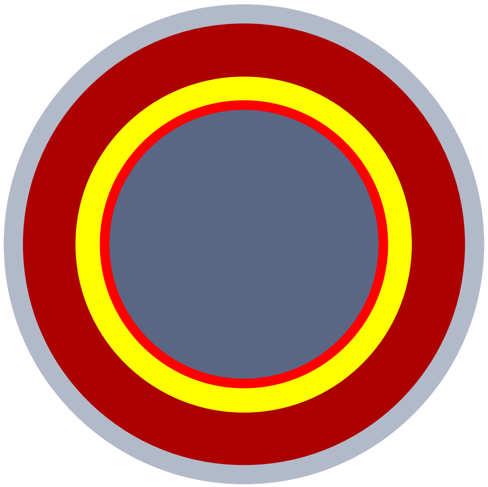
Laser/Microscope/CCD Column

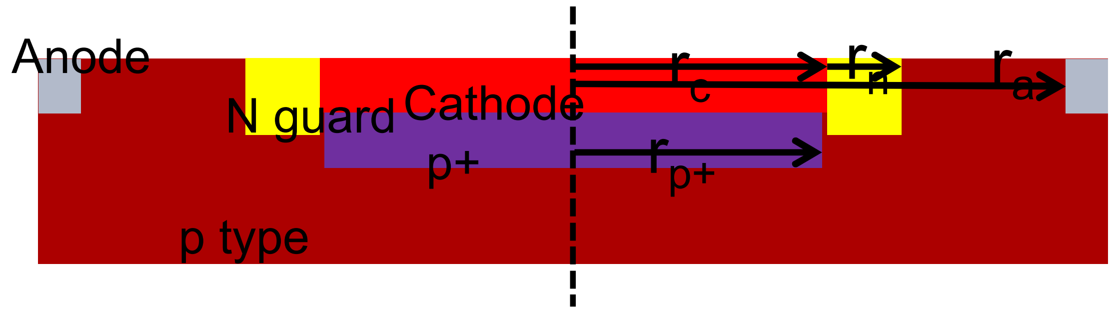
XYZ stage

4 point probe station

Can cool device – work at 77 K

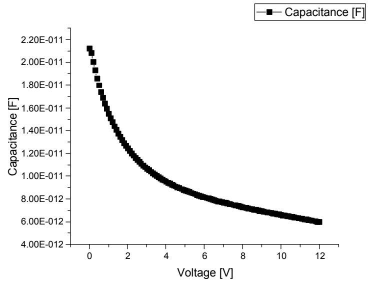
Experimental Scheme

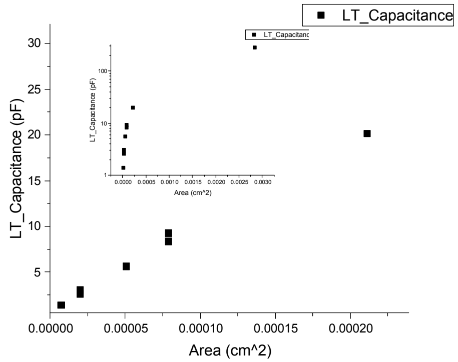


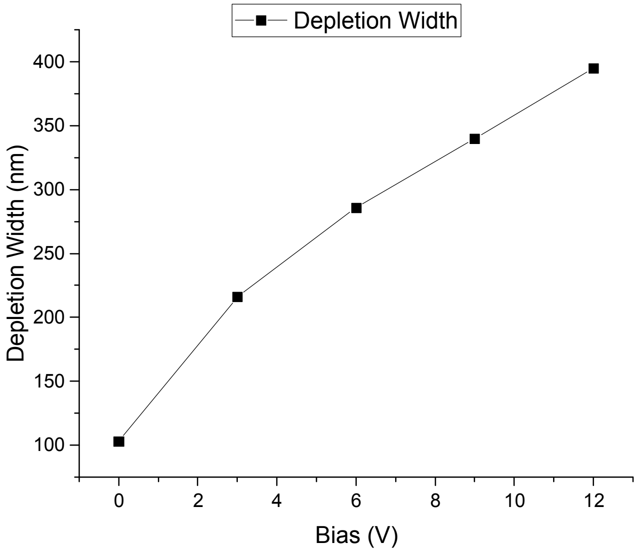


- Three Experimental Arms:
  - Anode radius
  - P+ radius
  - N guard radius

CV measurements

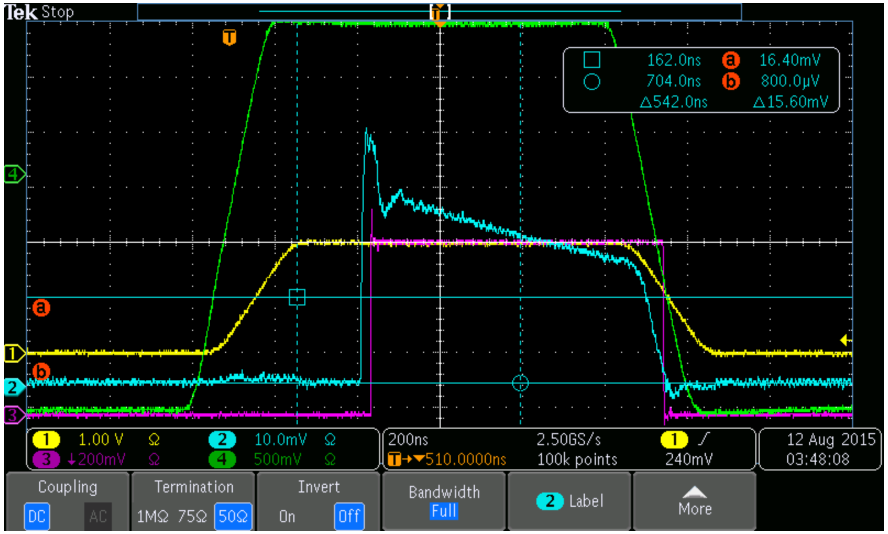






- All devices fit on curve of C versus Area of Cathode/p+ junction
- Can extract depletion width from CV data

Detection Efficiency



Device is gated with GM pulse

Laser illuminates device

SR400 photon counter detects pulses above threshold

Experiment is repeated at 100 Hz.

80%DE -> 80 pulses above threshold for 100 experiments

Anode Series

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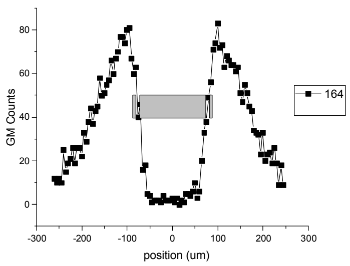
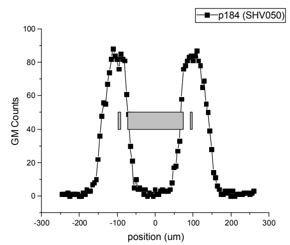
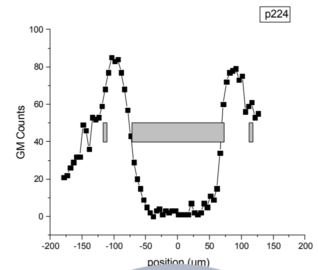
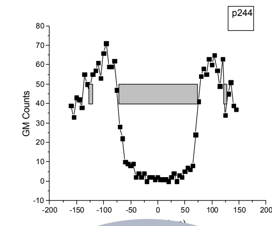
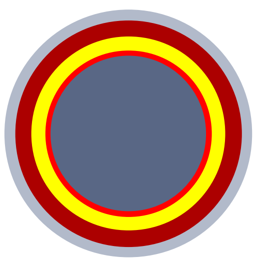
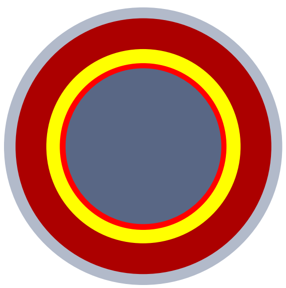


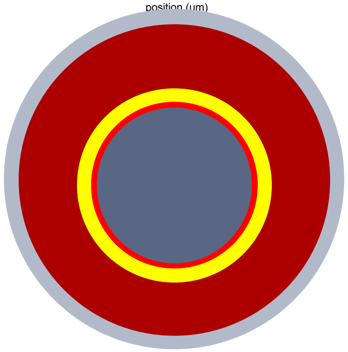


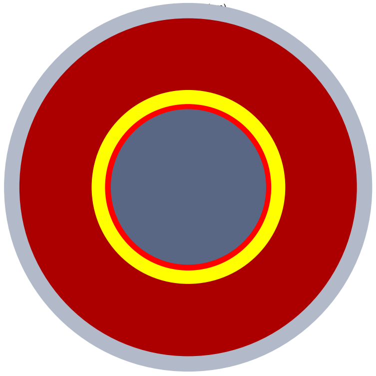




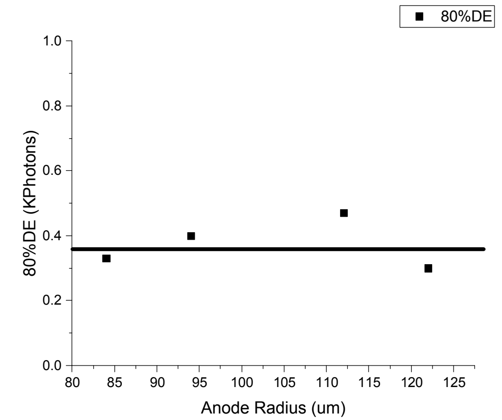




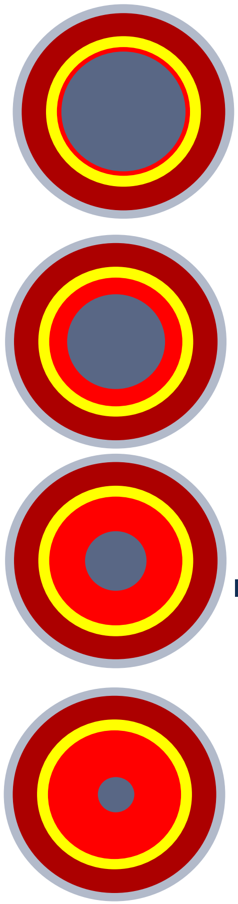


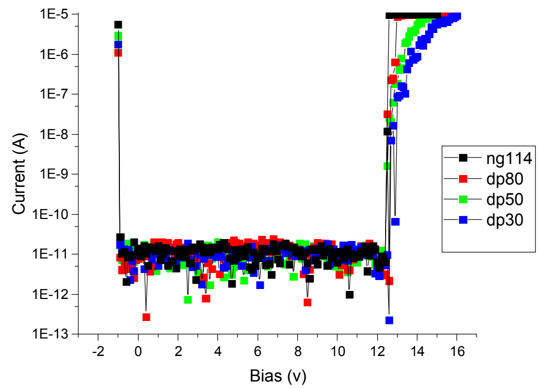


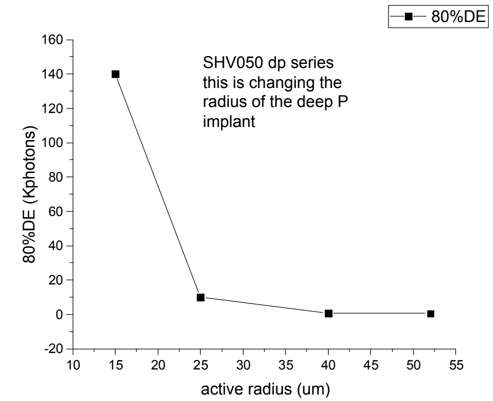
- Anode position is not a significant factor for DE
- Thermal velocity >> drift velocity, expect diffusion length to dominate



p+ Series (IV measurements)

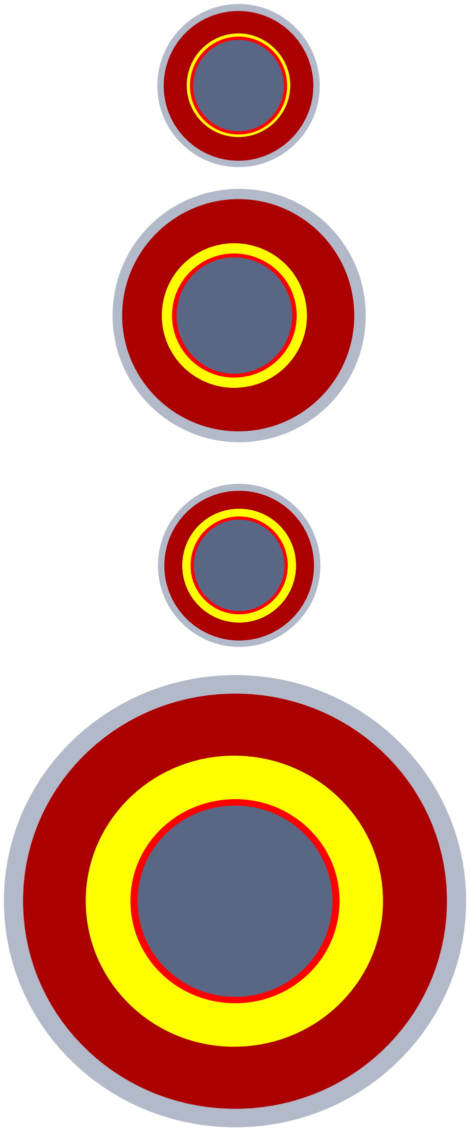


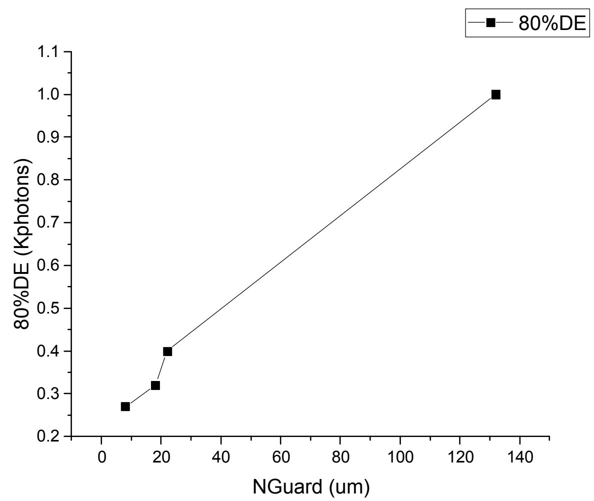


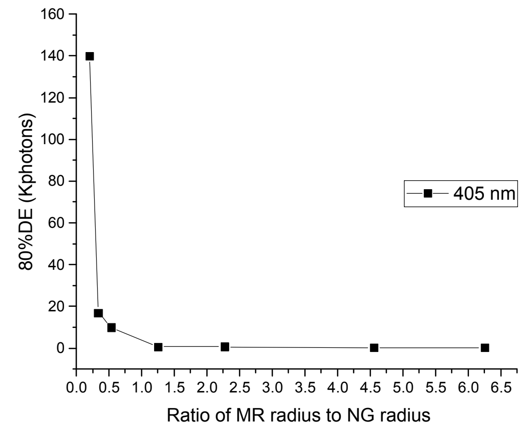


- Larger active radius improves Sensitivity- to a point – it improves the leak E field value in the multiplication region -> improving the probability of impact ionization

SHV Series (nguard issue)



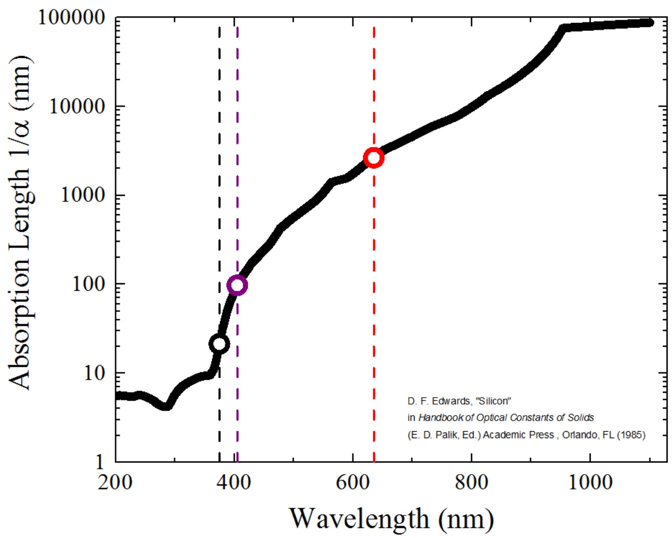


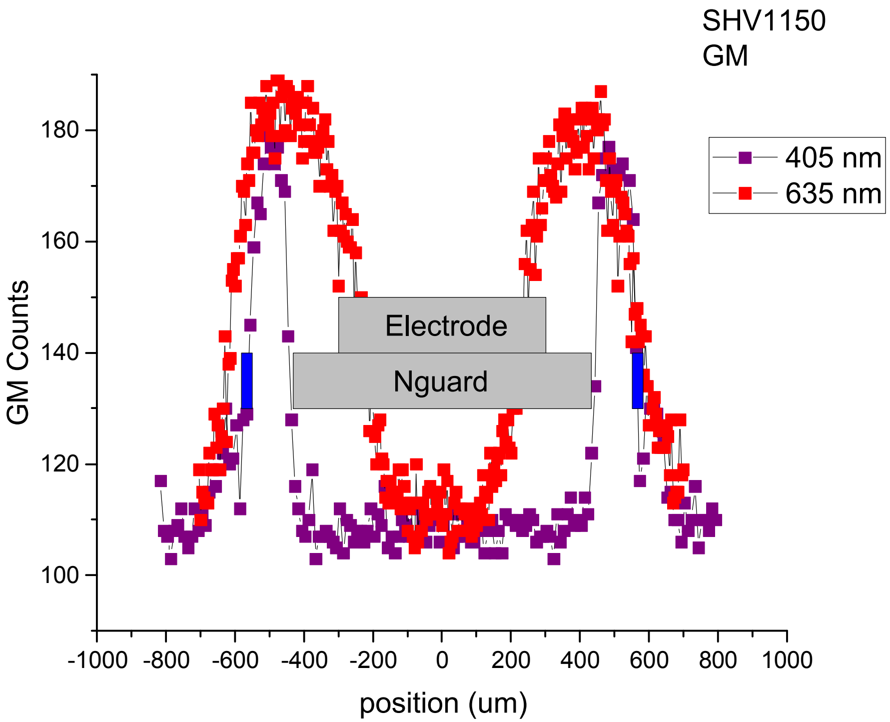


- Larger guard ring is an issue for DE
- Can combine the results from the SHV series and guard ring series

635 nm Confirmation

$$GR(z) = F(1 - R)\alpha e^{-\alpha z}$$





- For 405 need to keep a large MR to Nguard ratio.
- Diffusion dominates the collection, we are far from the junction – (need to compare thermal velocity to the field – drift velocity) so the N-guard pushes us further from the multiplication region.

Conclusion/Outlook

- Laser testing can provide insight to APD performance with Ion detection
- The Guard ring looks to be problematic for shallower implants
  - UV tests will confirm
  - A device redesign may be required for subsurface detection