Silicon S&T Quantum Computing 4th Annual Workshop

Quantum Information S&T

Silicon S&T Quantum Computing 4th Annual Workshop,
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On-Chip Avalanche Detectors for Deterministic Doping of Silicon Nano-Devices with sub-10 keV single ion implantation

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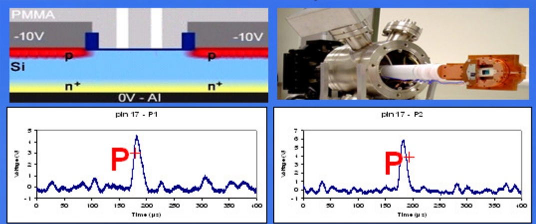
Single ion implantation: bulky silicon versus epi-Si

Bulky silicon devices:

- Single ion → ionization →e-h pairs
- Charge carrier diffusing/drifting in bulky Si
- Charge trapping loss negligible
- 100% charge collection (**PIN**)
- >>100% charge collection (**APD**)

PIN linear charge measurement:

Jamieson and et al, APL 2005 (Univ of Mel)



APD Geiger-mode: non-linear

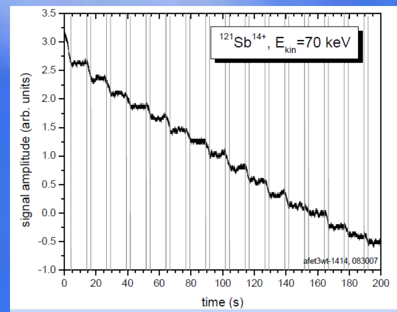
Sensitivity: 1 e-h pair;

J. A. Seamons and et al., APL2008 (SNL).

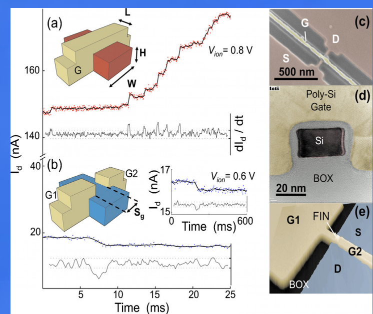
Epi-Si/SiO_2 , nano-device:

- Single ion → D-S current modulation
- As a method to control single ion doping

A. Batra and et al., APL 2007 (LBNL)



Johnson and et al., APL 2010 (Univ of Melb)

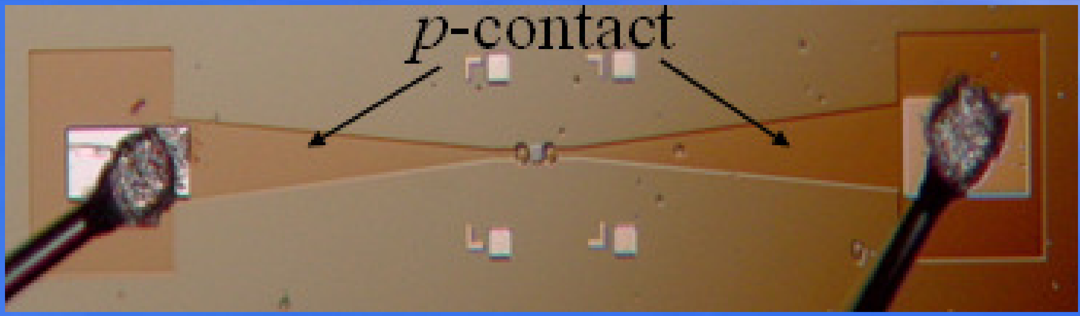


Single ion induced secondary electron emission

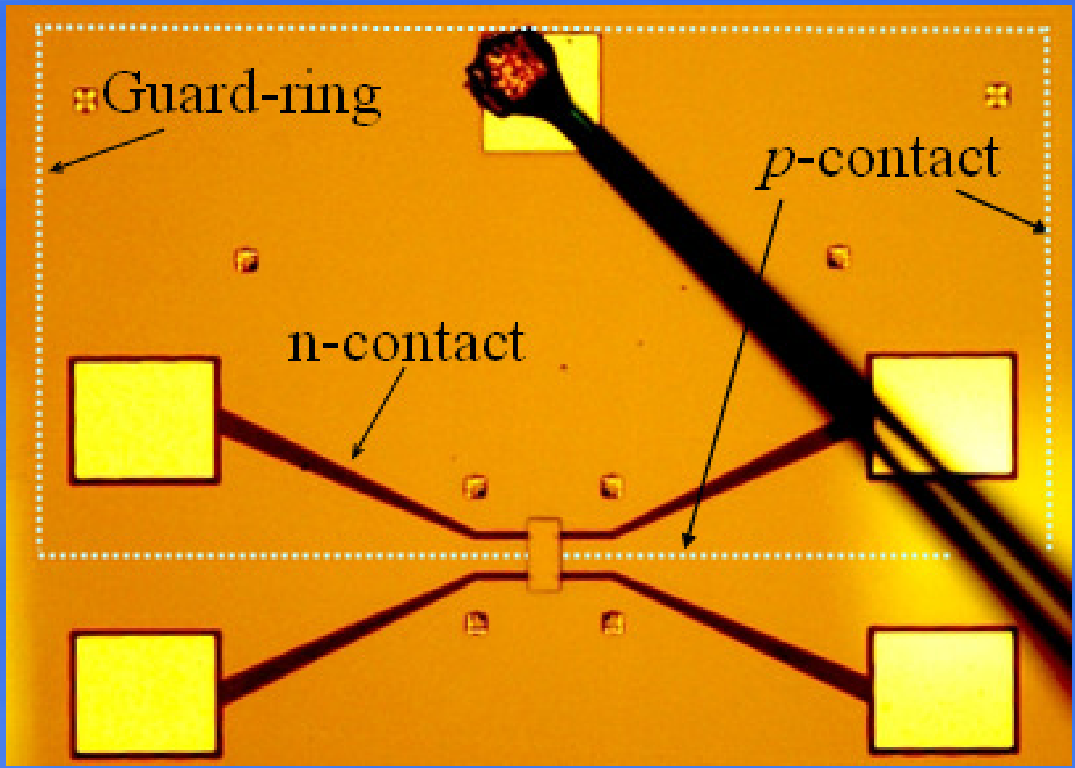
A. Persaud and et al., J. Vac. Sci. Technol. B 23, 2798 (2005). Nano Letters 2005. (LBNL).

T. Shinada and et al., Nature 2005 (Waseda Univ.)

PIN detectors with different structure of surface electrodes



- Simple design
- Good performance
- Acceptable detection limit:
  ~ 1 keV (300 e-h pairs)

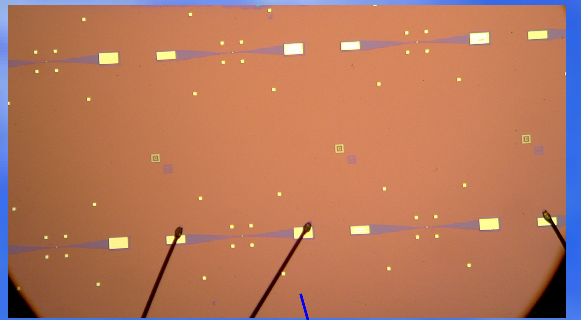


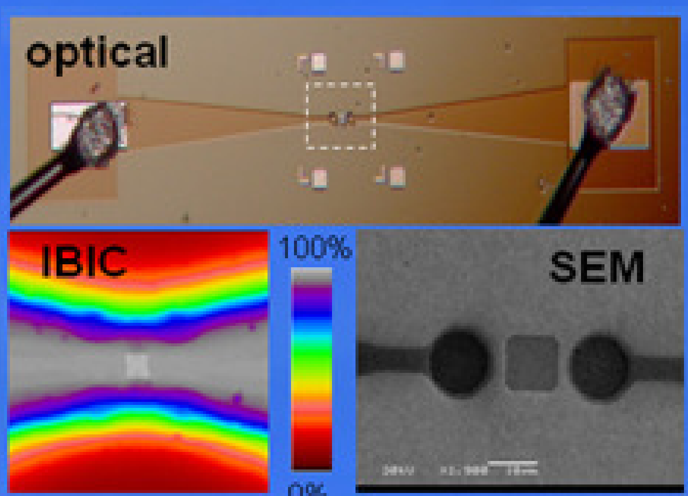
- Electrodes integration
- Larger capacitance
- Higher noise threshold
- Poorer detection limit:
  ~ 1.5-2.5 keV

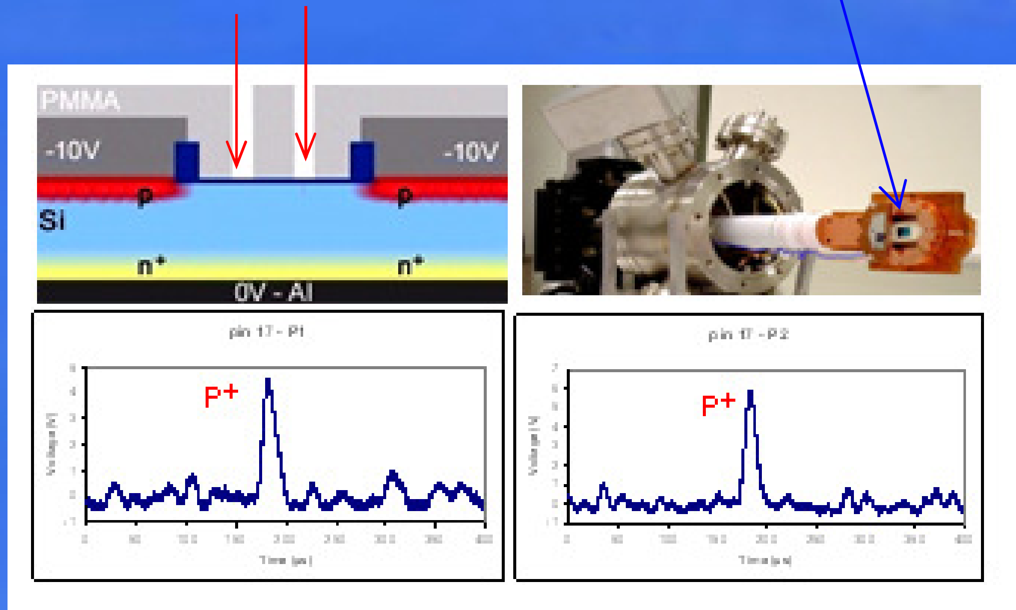
Detector performance: simple electrodes at surface

Summary on the PIN detector performance:

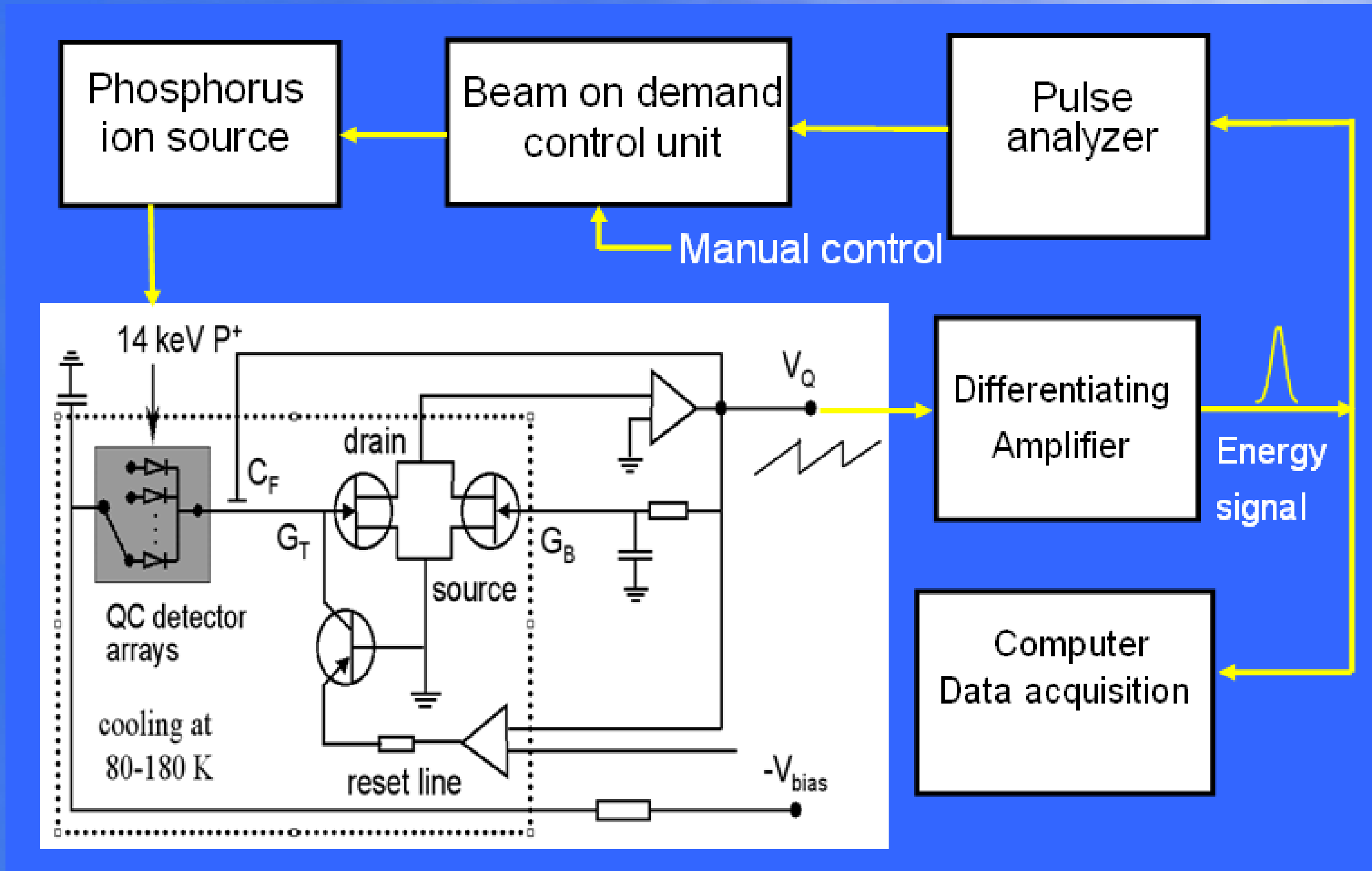
- Smaller active detector area
- Small capacitance
- Easy control of leakage current
- Lower numbers of trapping defects
- Detection limit 1keV (~ 300 e-h pair charge)







Control of single ion implantation and on-line detection



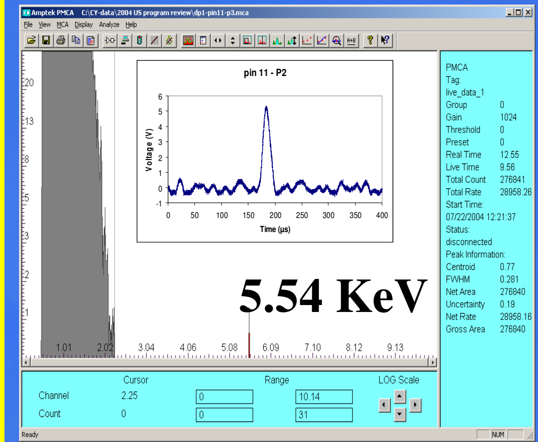
- Numbers of *e-h* pair per single 14 keV P^+ ion excitation:

$$N=E_{ioniz}(eV)/3.62(eV)\ [e\text{-}h \text{ pair}] \sim \mathbf{1000}\ [e\text{-}h \text{ pair}].$$

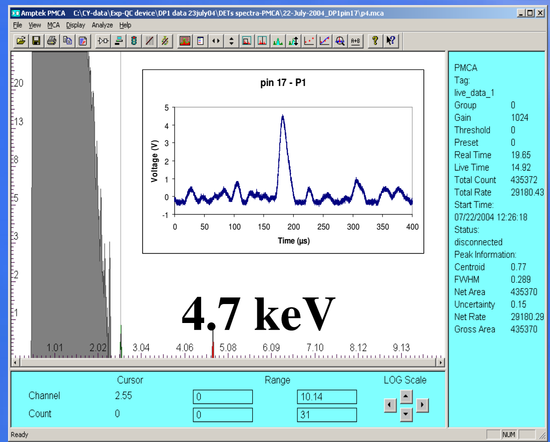
- Charge carriers have a very long life time in a high quality indirect band-gap silicon.

14 keV P^+ implantation – single event identification

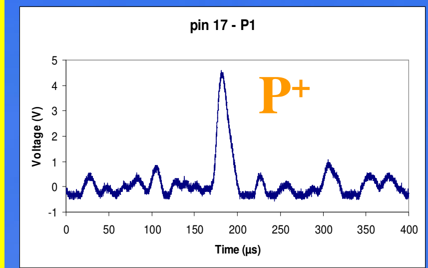
DP1-pin11,single P^+

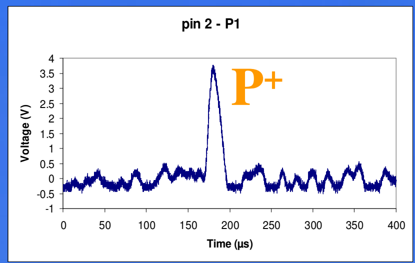


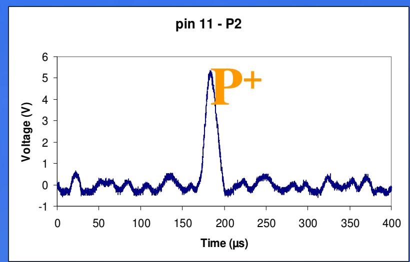
DP1-Pin17,single P^+

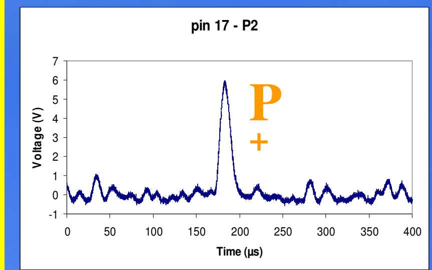


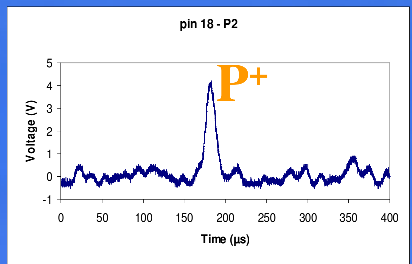
1. Count no any event at energy threshold 2.4 keV when beam blanked.
2. Use Gaussian pulse shape to screen against noise events.
3. Implant 14 keV 1.5 pA P+ beam into QC devices for an average time period of 10-30 seconds for each single P+ ion.

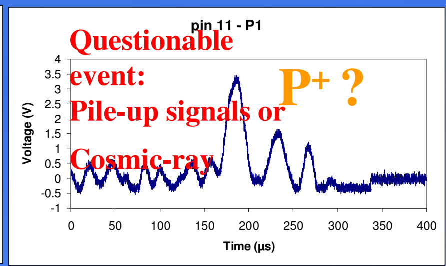






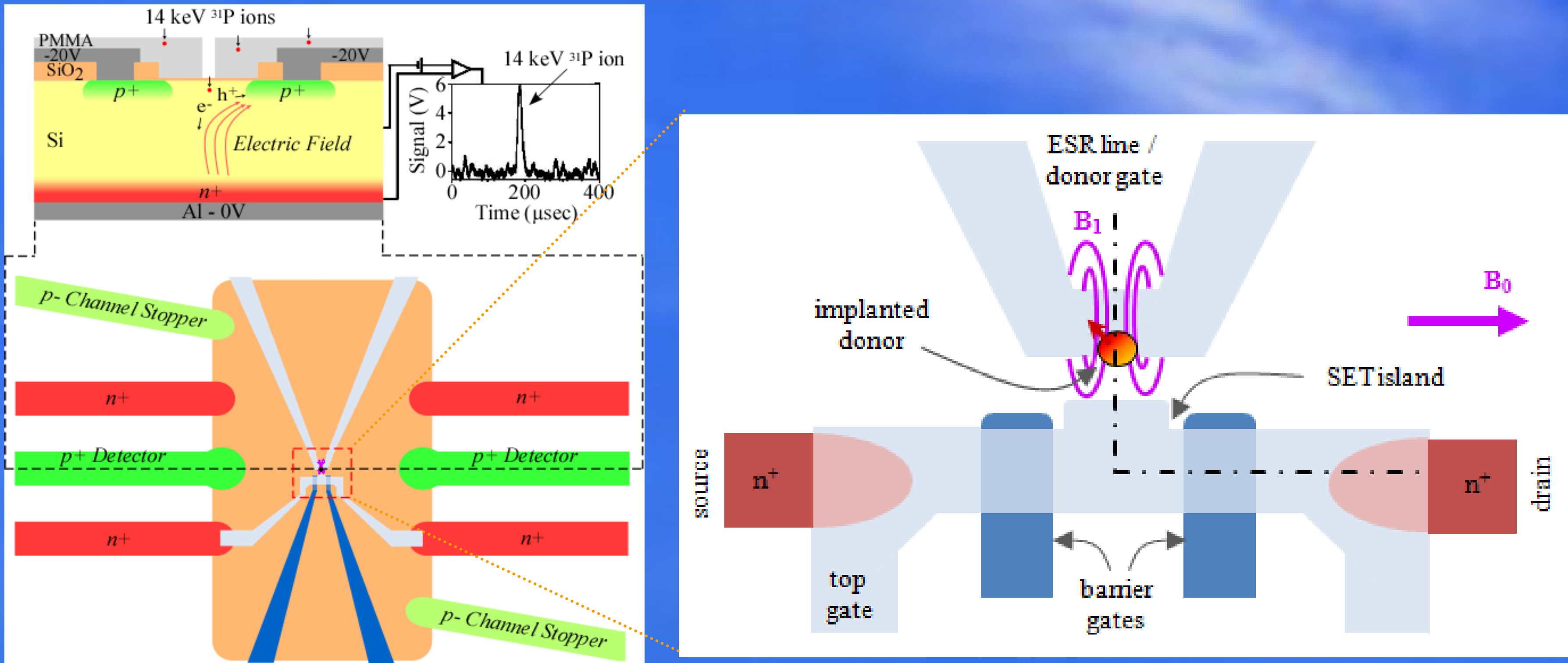






- Real single P+ events can can be clearly identified.
- There is a small chance of events pile-ups or a disturbance of cosmic-ray may introduce a P+ event like signals.

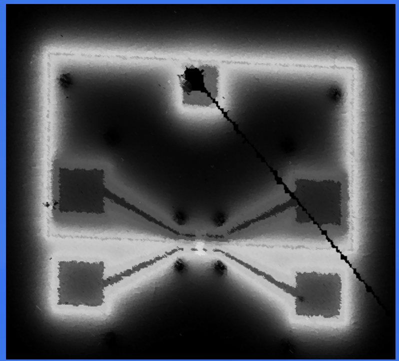
Integrated devices with additional surface structure



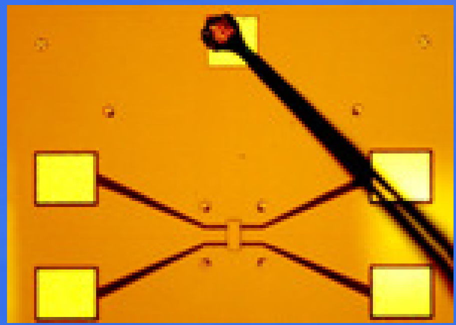
N.S. Lai and et al., IEEE Nano2009

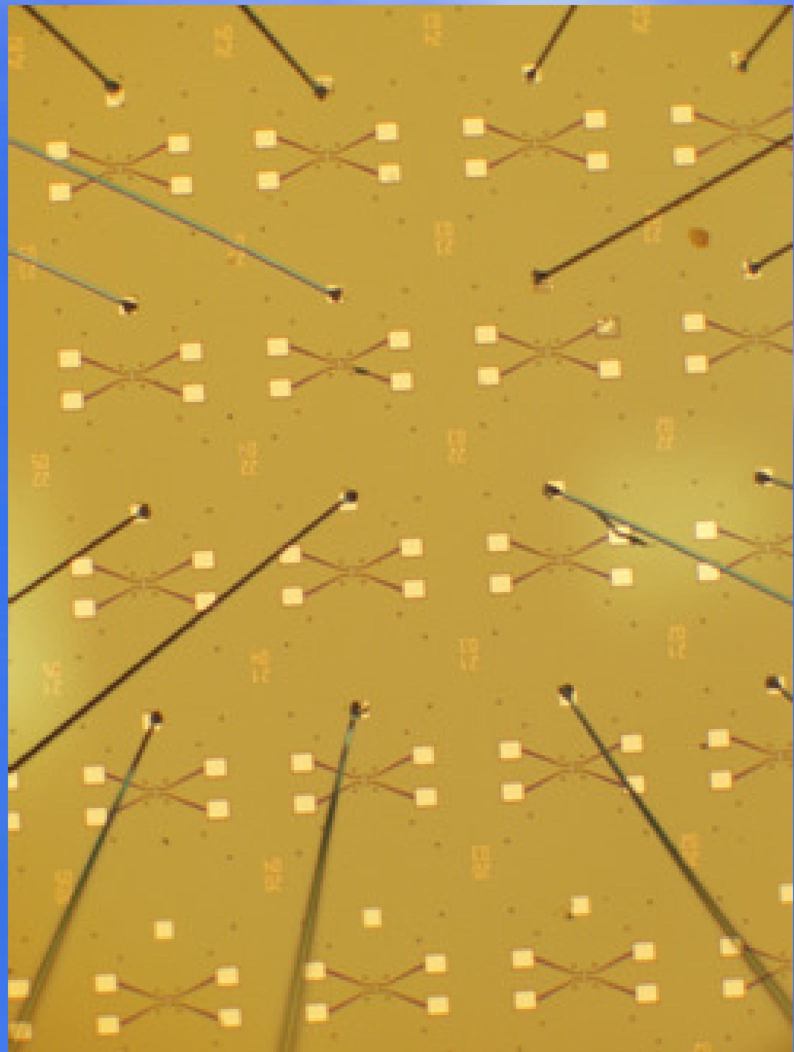
New detector architecture with guard ring and channels stoppers

IBIC (0.5 MeV He^{+})



Optical image





PIN versus APD detector

PIN detector:

- Noise threshold: 1.0 keV → 2.5 keV
- Signal-to-noise ratio 3.5 → 1.4
- Successful application in single 14 keV P^+ ion implantation and nano-fabrication of QC devices

Avalanche detector:

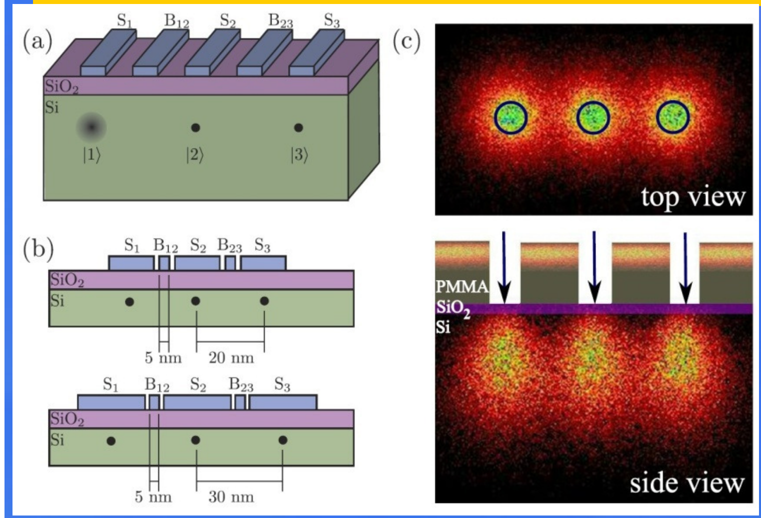
- Noise threshold: ~ far less than 1 keV
- Signal-to-noise-ratio: very high
- Improvement of the detection limit of the ionization energy for the low-energy- heavy ion implantation:

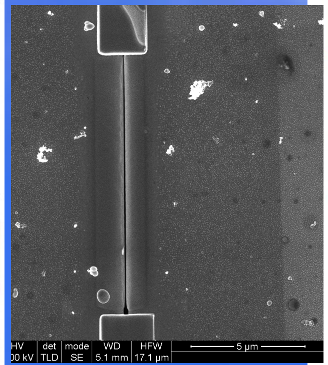
  14 keV P^+ ionization energy ~ 3.5 keV
  7 keV P^+ ionization energy ~1.5 keV

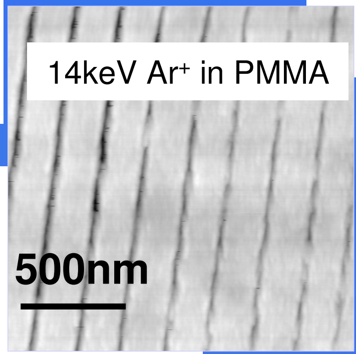
- Shallower depth & Improving position accuracy:

  - Shallower implantation depth: 20 nm → 15 nm
  - Less straggling:
    14 keV P^+: 10 nm uncertainty
    7 keV P^+: 6 nm uncertainty

Fabrication Precision: CTAP with 7 keV P^+ doping







New Journal of Physics
The open-access journal for physics

Top-down pathways to devices with few and single atoms placed to high precision

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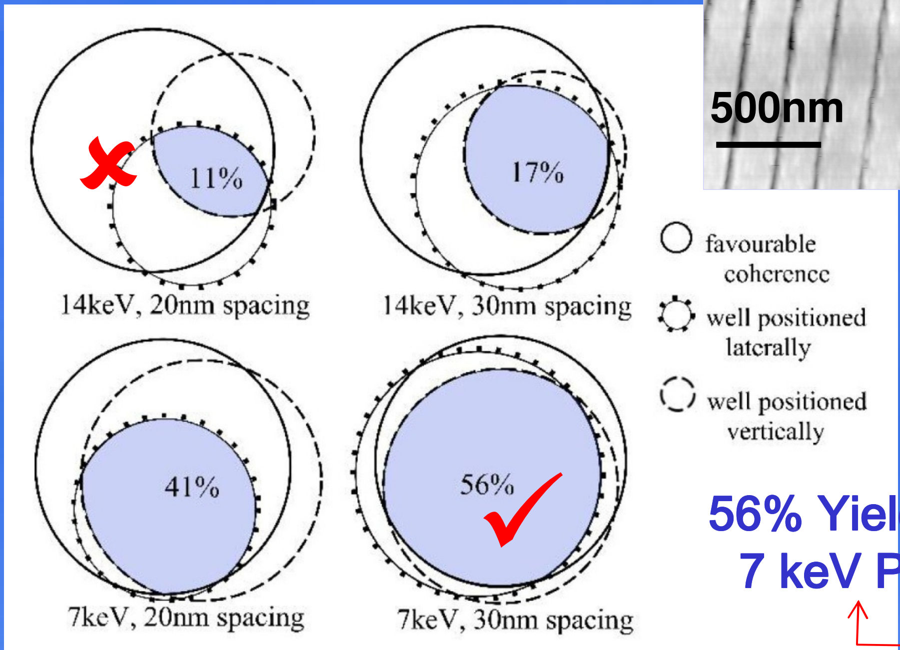
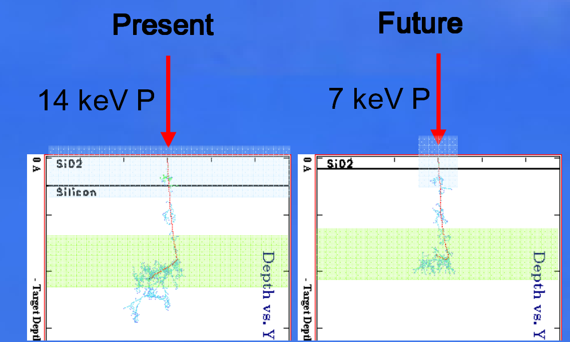


56% Yield for 7 keV P:Si

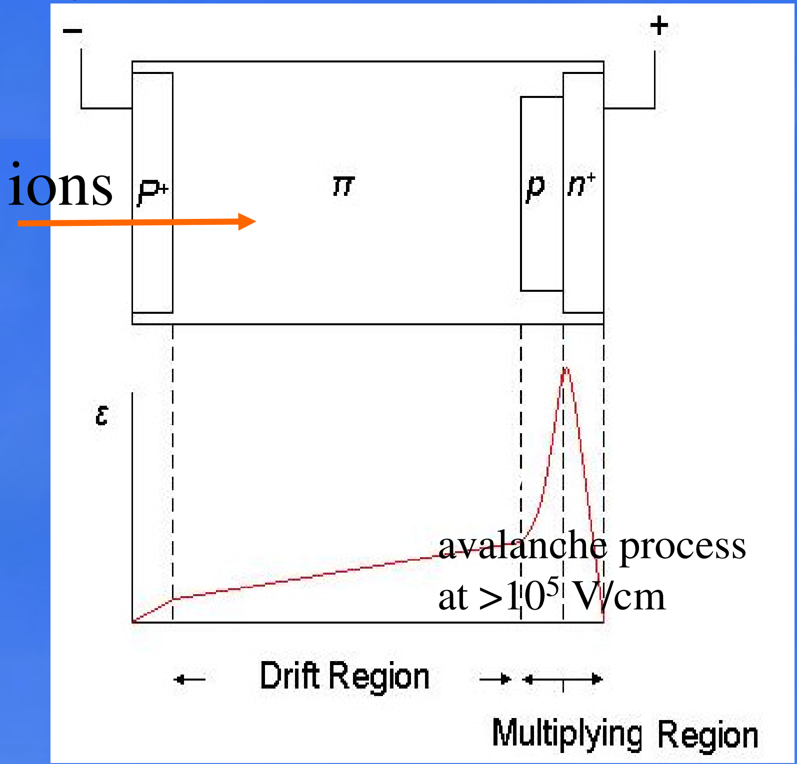


SRIM	Present	Future
Oxide thickness	5 nm	2 nm
Beam Energy	14 keV	7 keV
Range and straggle	22 ± 10 nm	13 ± 6 nm
Energy to ionization	3.5 keV	1.5 keV
Noise threshold	1.1 keV	< 1 keV

Investigation of Avalanche detector for linear mode operation

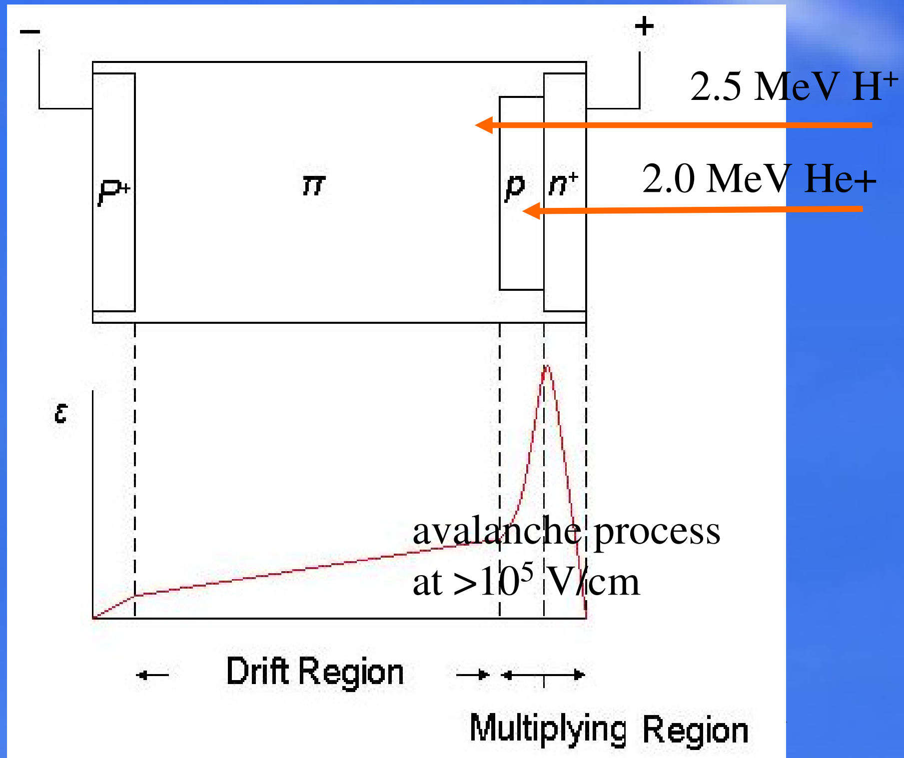
Uniform charge gain:

- ❑ Ions incident in drift zone
- ❑ The e-carrier reaches a high saturation velocity in drift zone
- ❑ The e-carrier gains a high velocity in avalanche zone and make a large ionization impact.



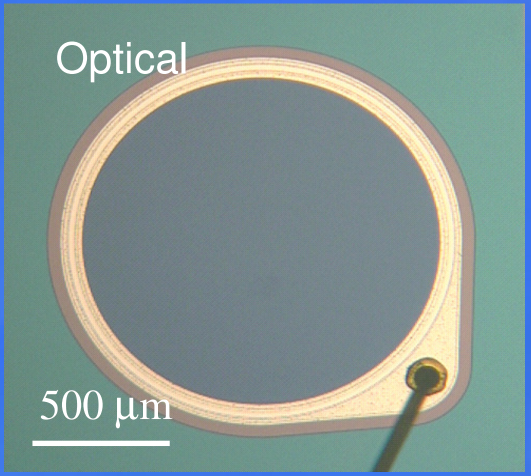
Charge gain not uniform:

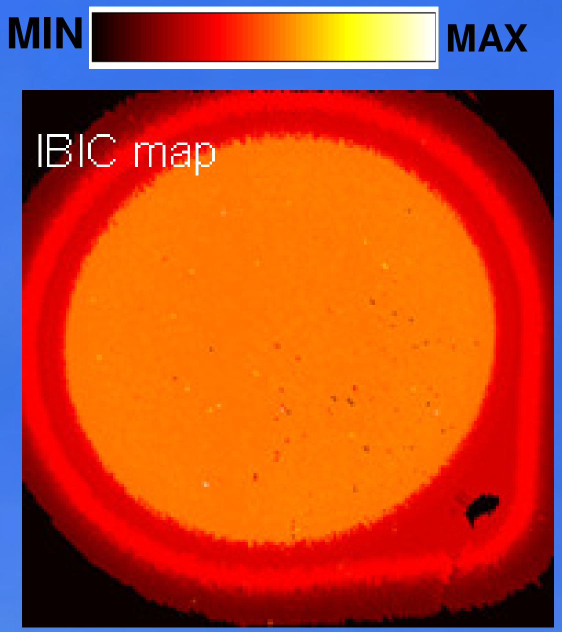
- ❑ Ions incident in avalanche zone
- ❑ The e-carrier never experience a full drifting process.
- ❑ The e-carrier may not gain a sufficient velocity in avalanche zone before ending the ionization process.

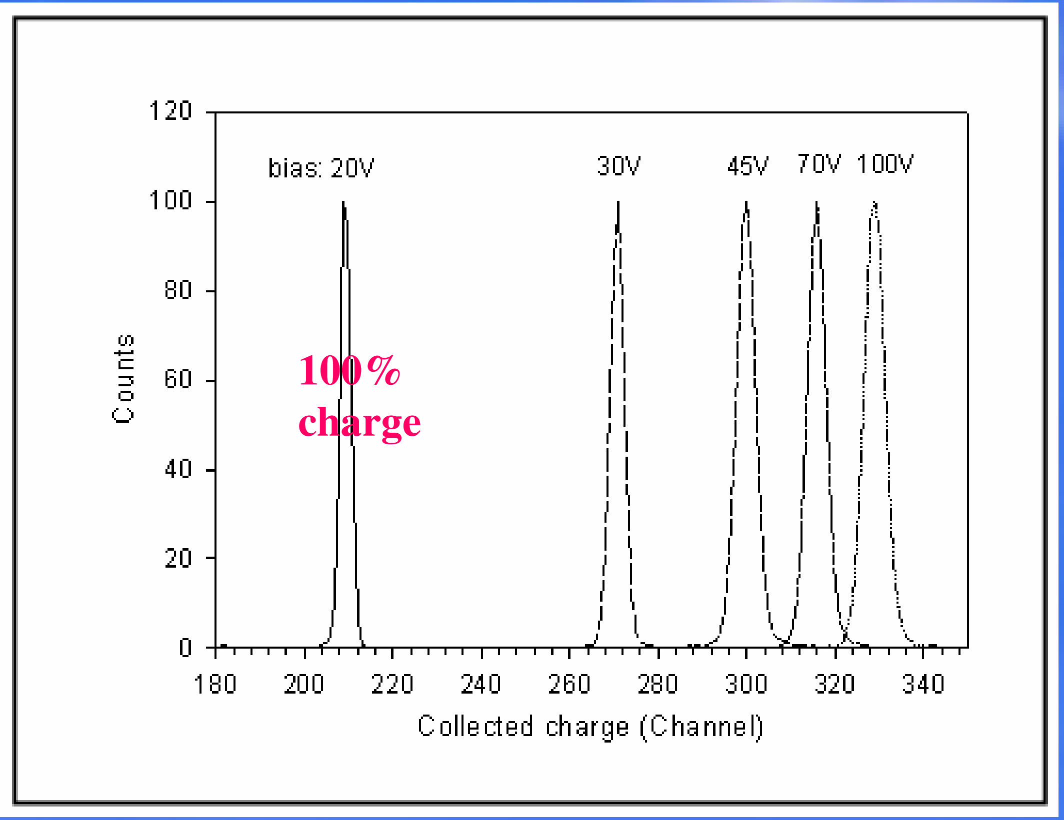


Avalanche detector: linear internal charge gain

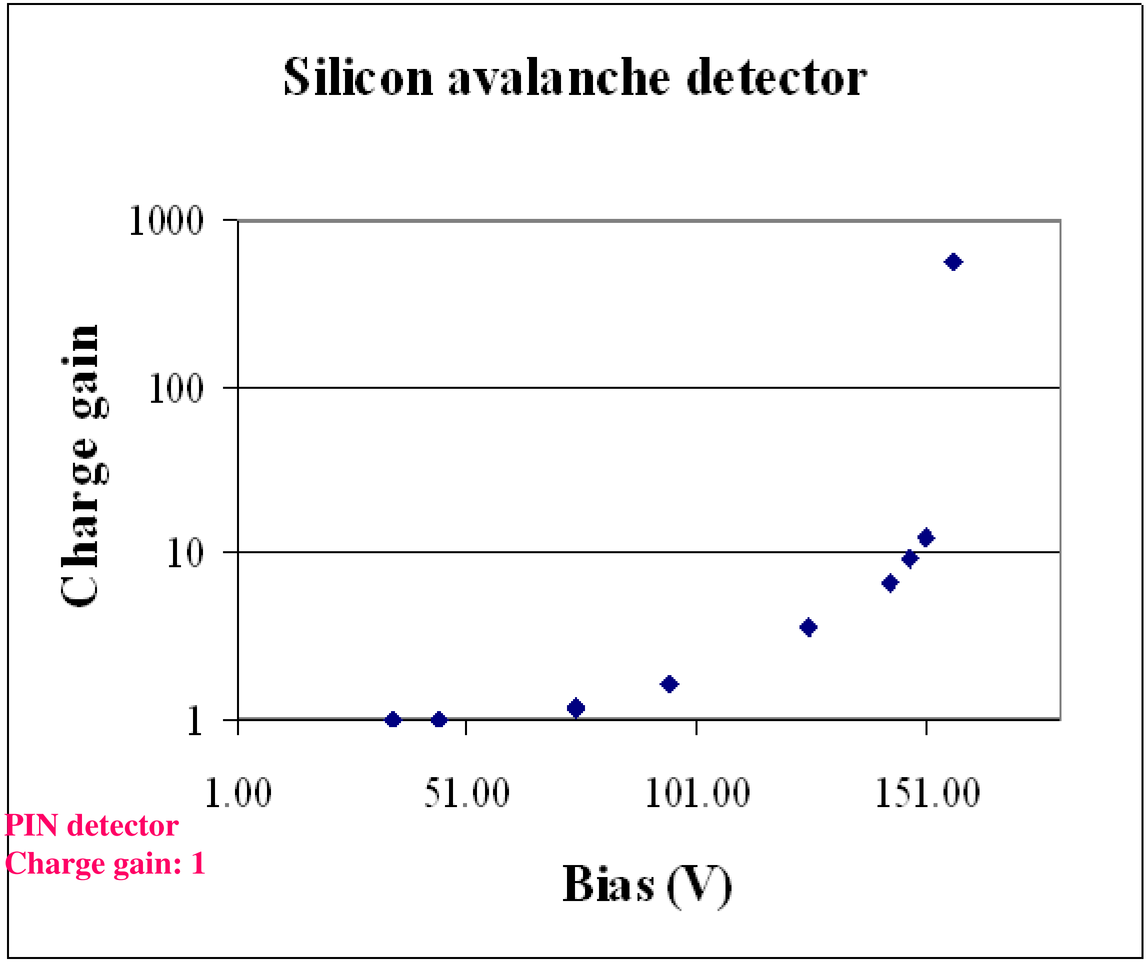
- Increase the signal out put using internal charge gain
- IBIC analysis: relative charge collection efficiency
- 2.0 MeV He^{+} ions generate 0.55×10^{6} *e-h* pairs
- A high charge gain can be achieved.





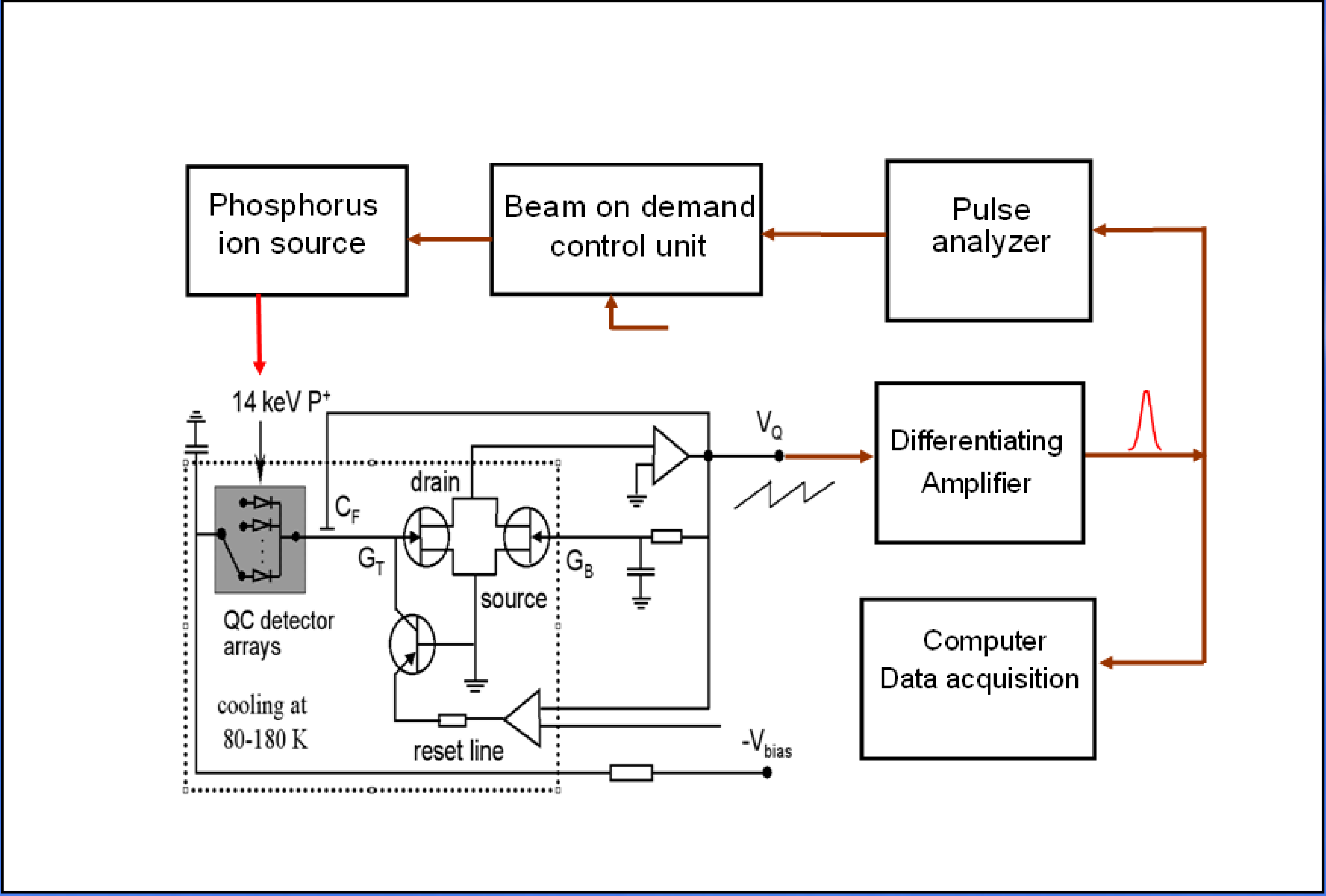


Avalanche detector: charge gain VS bias voltage



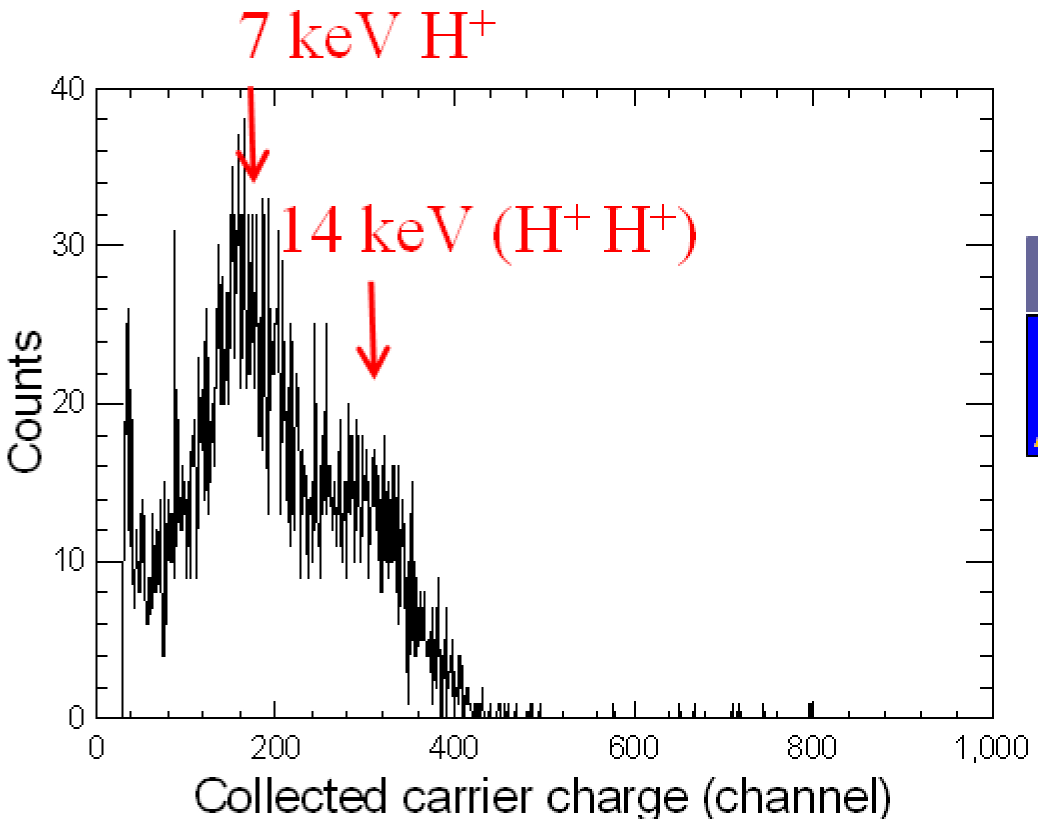
PIN detector
Charge gain: 1

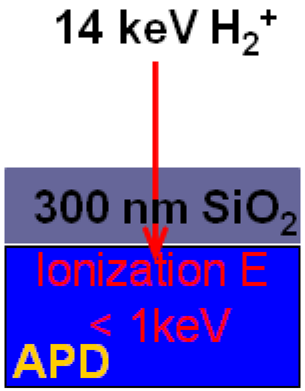
Linear mode avalanche detector operation



Linear mode APD: Readout of energy spectrum

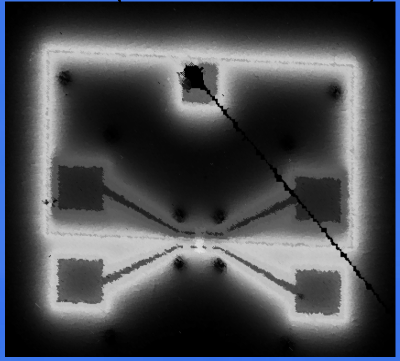
14 keV H_2^+ ions into a commercial APD device with 300 nm SiO_2 dead-layer, **residual ionization energy ~ 1 keV.**



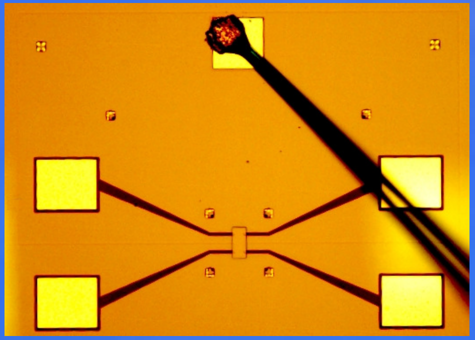


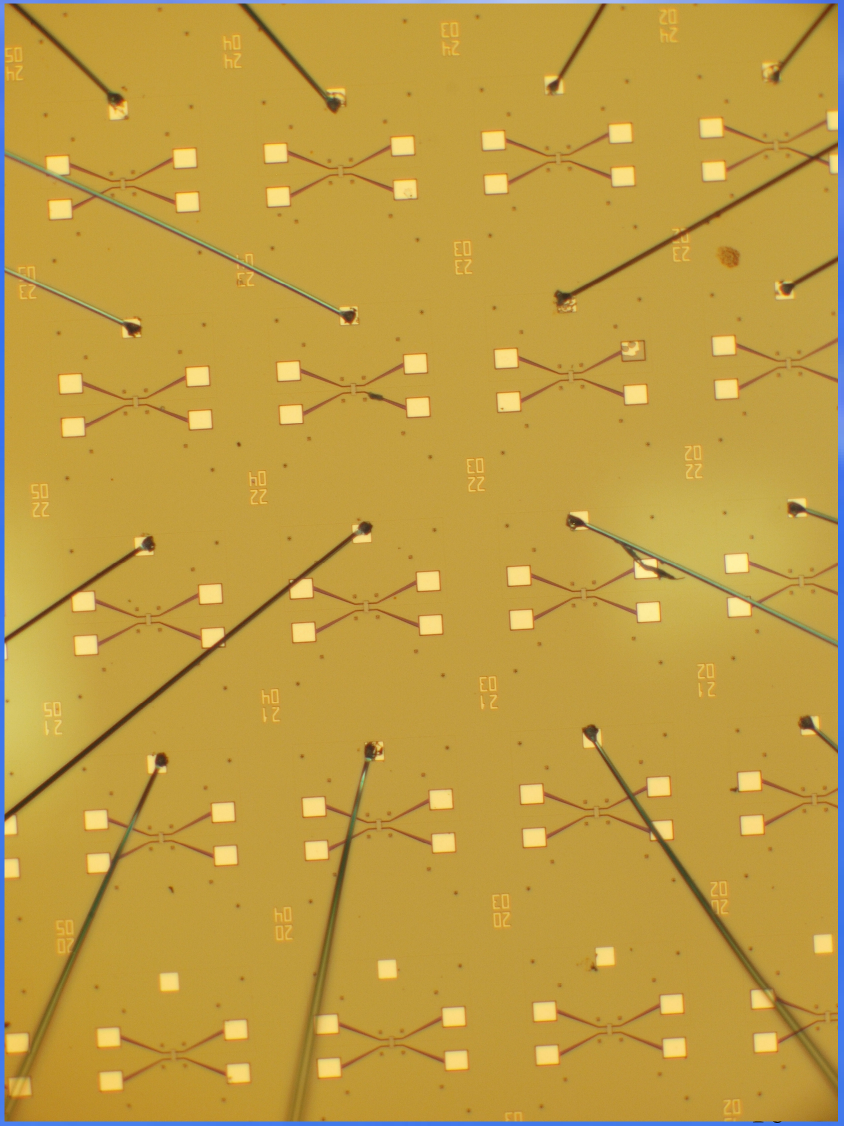
PIN detector arrays

IBIC (0.5 MeV He$^+$)



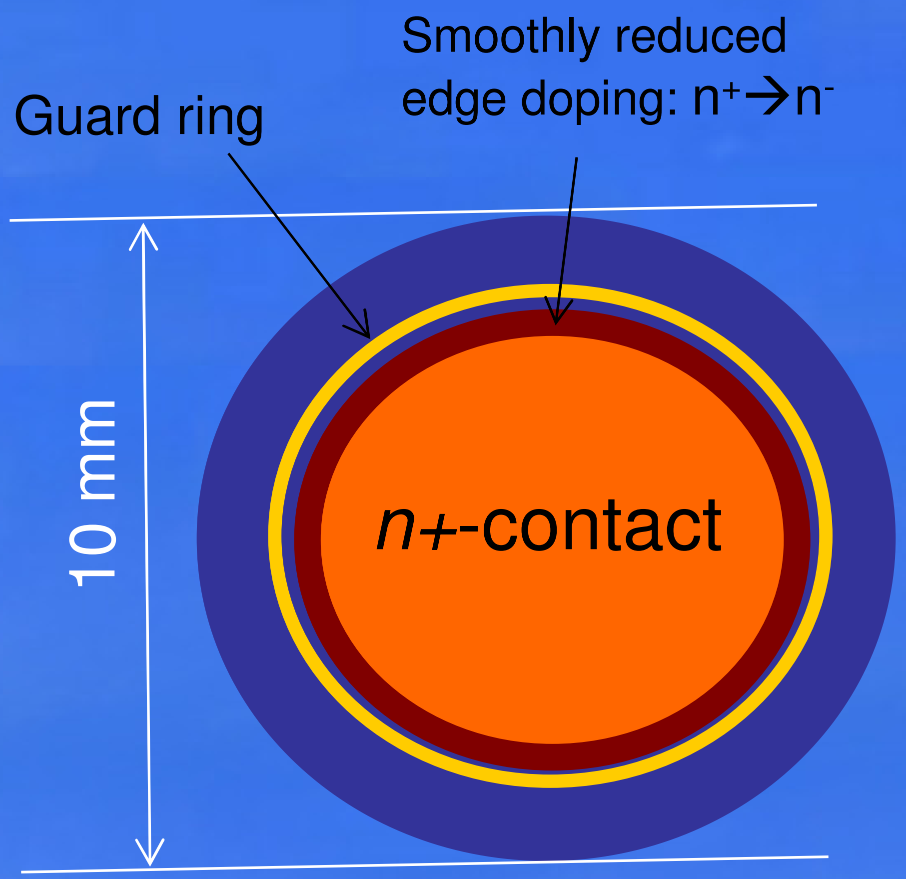
Optical image





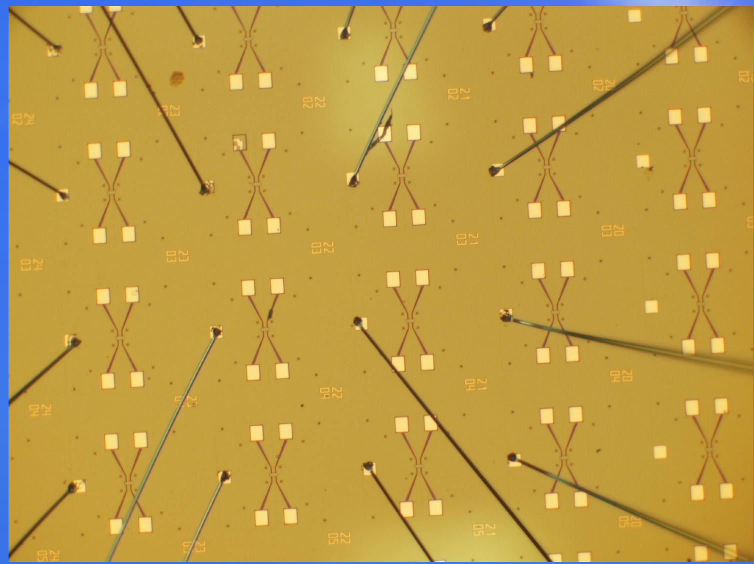
Integrating avalanche zone in the existing detector structure

Backside of the wafer

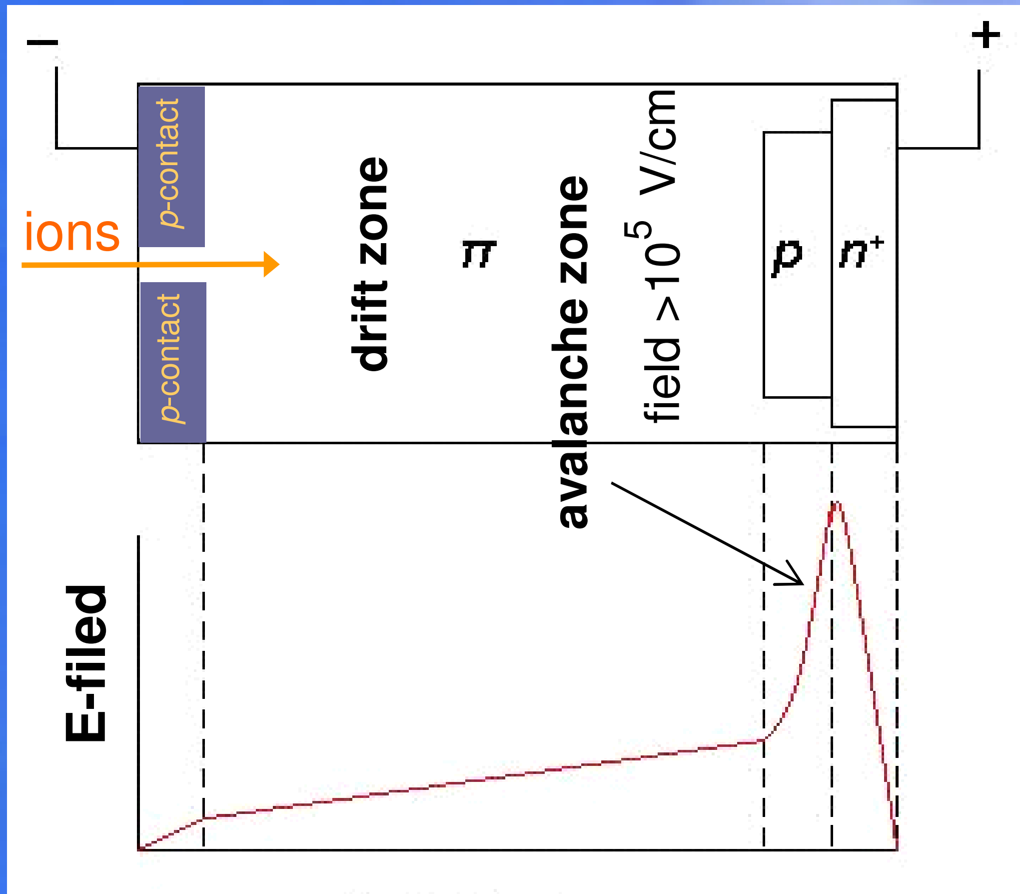


Front side wafer
(allowing ion entrance)

Detector *p*-contact arrays



Linear mode APD: E-field profile

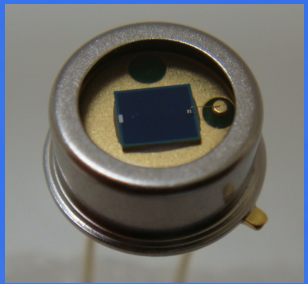


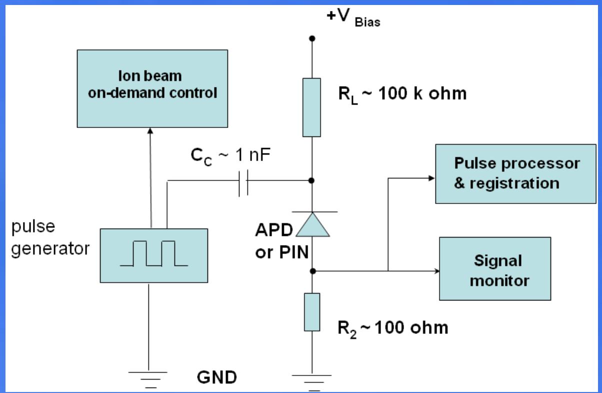
Geiger mode: Testing a commercial PIN detector as APD device

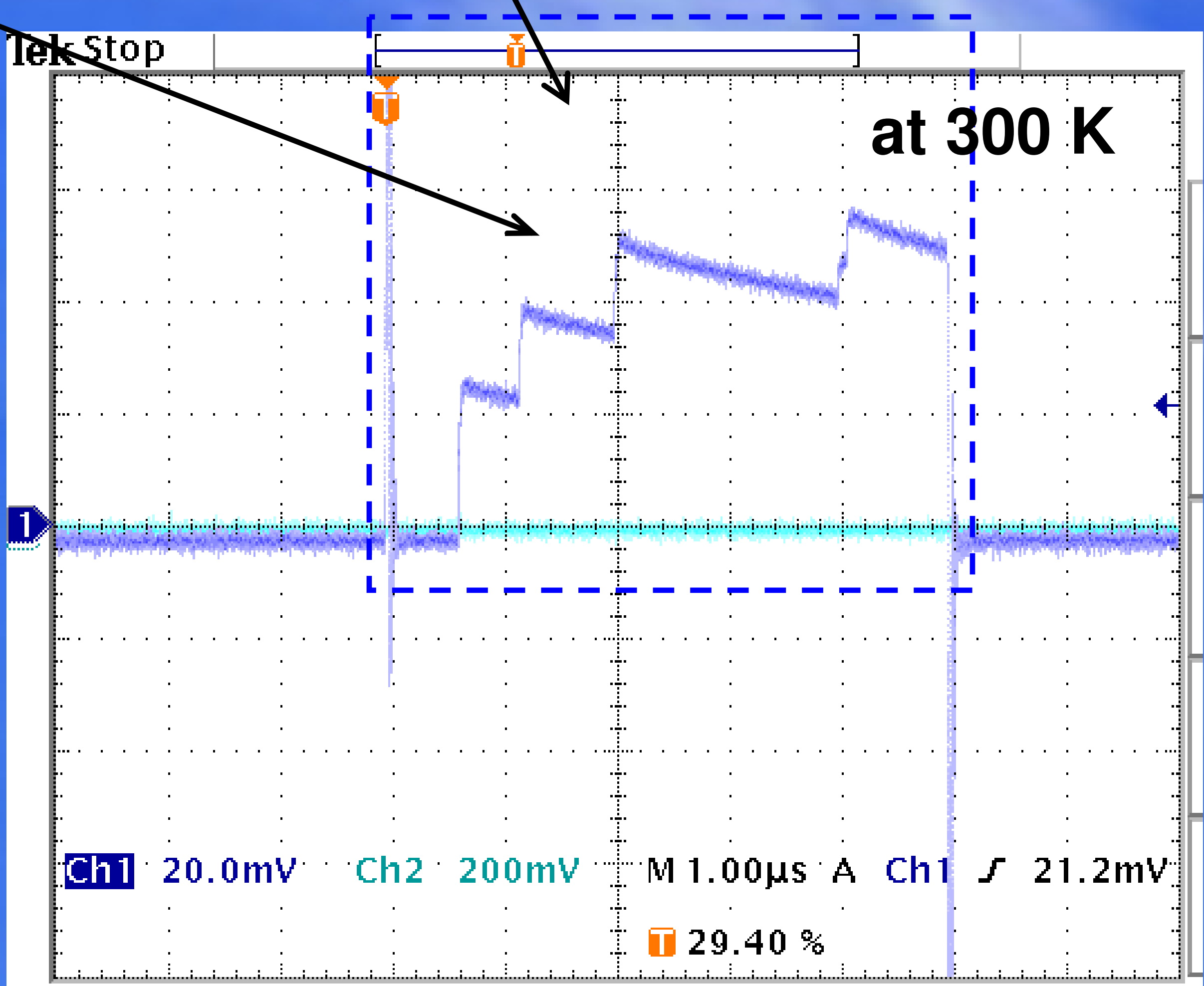
4 events observed from Geiger mode avalanche operation per 5 ms pulse

Gated bias time window: 5 microseconds

The PIN device has a terminal capacitance ~ 20 pF

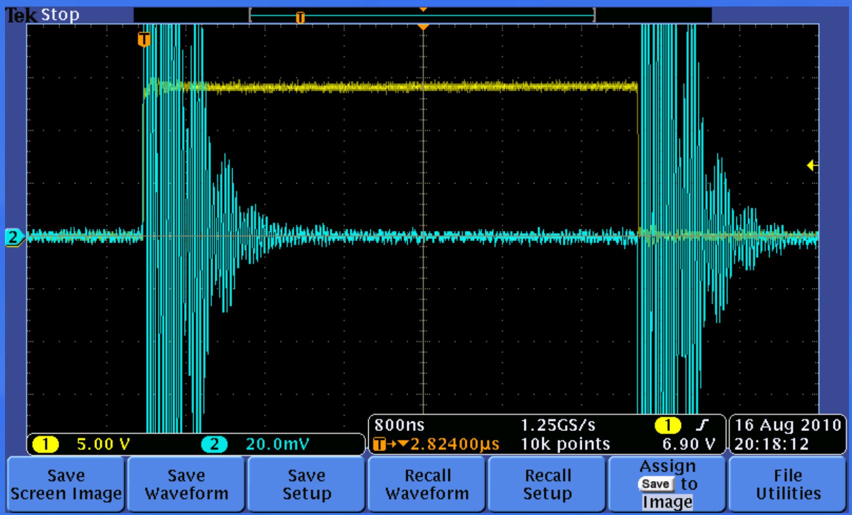




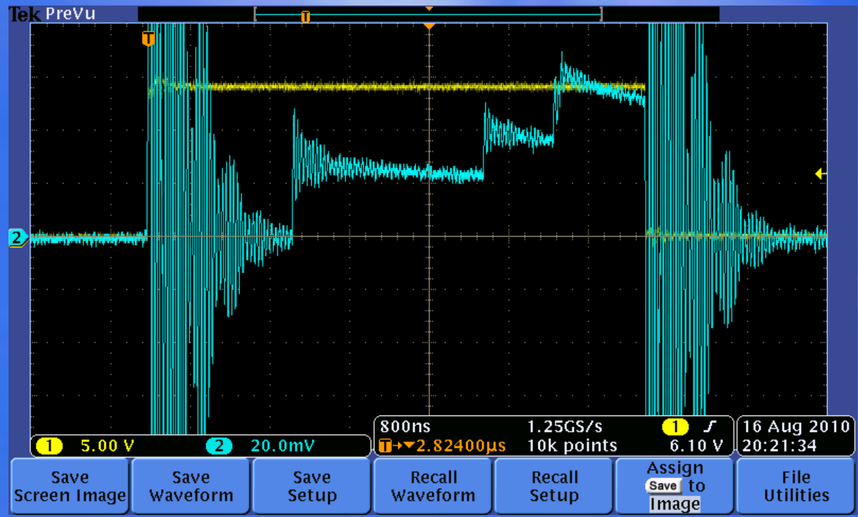


Geiger mode avalanche operation on a PIN diode

Switch-off light
Dark count at room T (77K)

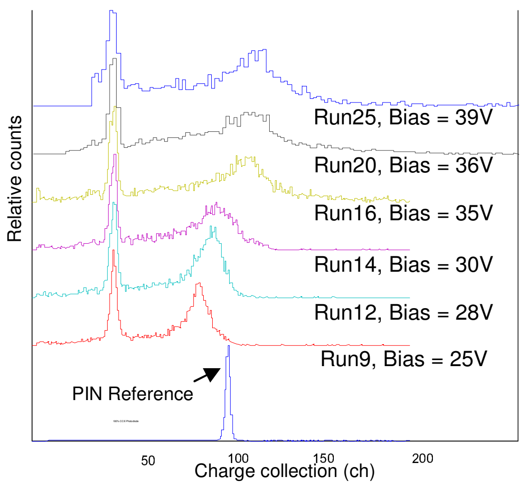


Switch-on light
With very weak light at near 77K

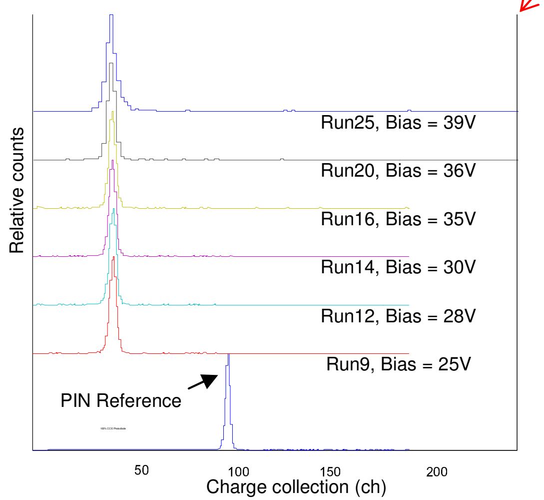


SNL Geiger mode detectors in Melbourne

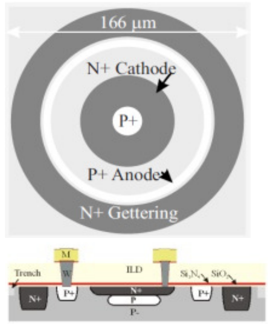
IBIC near the n^{+} contact: Avalanche onset



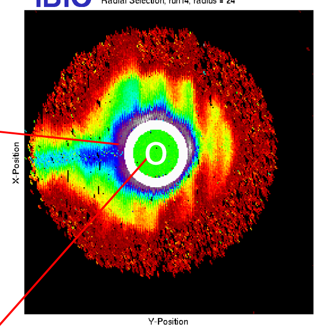
IBIC p^{+} contact area: No avalanche



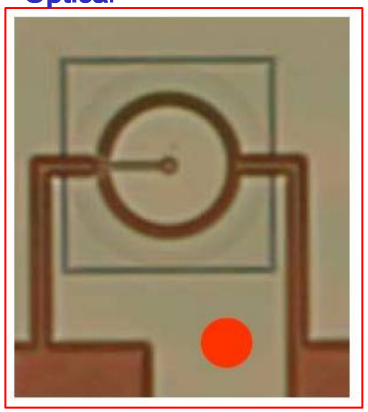
Schematic



IBIC



Optical



- Designed to be operated in Geiger mode
- IBIC mapping with 2 MeV He in P-i-N mode (not expected to avalanche)
  - Measure internal electric field distribution and charge collection efficiency
- Next steps:
  - Develop device control electronics in Melbourne to allow devices to be tested in full Geiger mode.
  - Develop new device architecture with **sub-5 nm oxides** to allow for tests with **sub-20 keV P ions**.
  - Identify potential **device architectures** that will allow integration of Geiger mode detectors into the CQCT process flow – ensure **compatibility** with new channel stopper electrode structure.

Summary

- PIN detector does not provide enough detection limit for single ion implantation operation in the new device design.
- APD linear and Geiger mode operation are promising for lower energy (sub-10 keV) ion doping with more accurate positioning control (the uncertainty can be reduced from current 10 nm to less than 6 nm).
- APD design can be made compatible with nano-fabrication strategy in the existing PIN structure.