CMOS Monolithic Active Pixel Sensors for Ionising Radiation

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- Overview
  - Introduction
  - UK HEP test structures
  - Star Tracker, 525x525 Space Science Prototype
  - Summary

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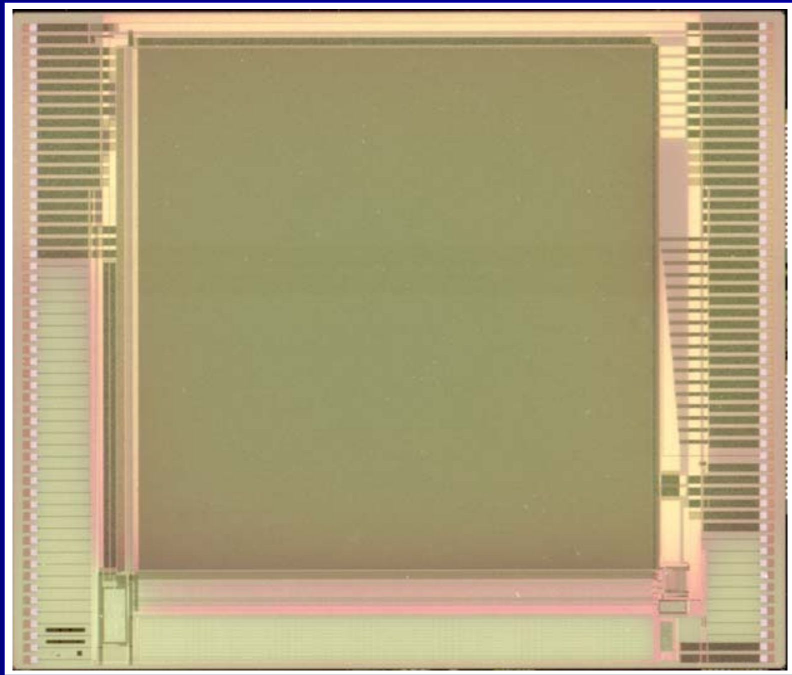
Introduction

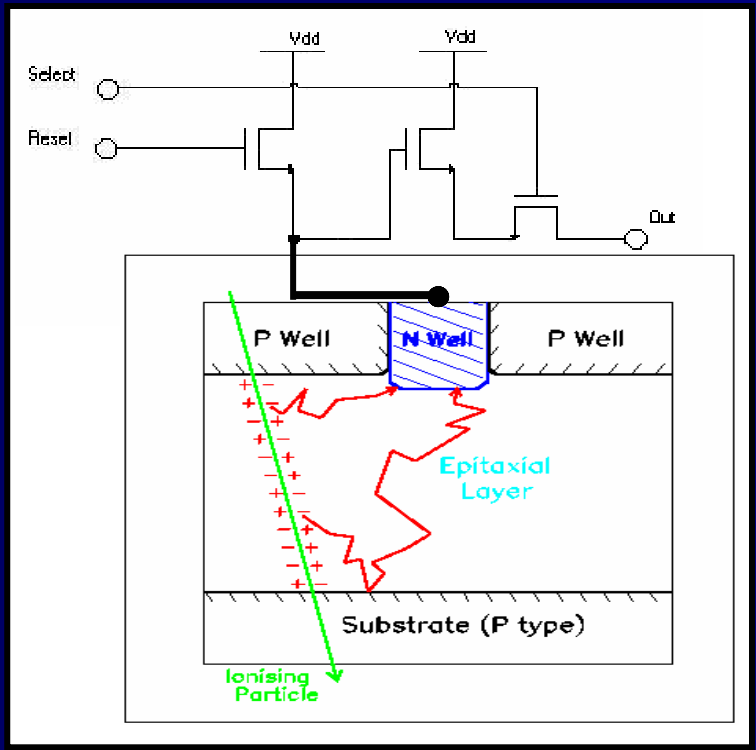
- Pixellated Detectors ~ 3 – 100 µm
- Standard VLSI CMOS technology
  - Low Power Consumption & Low Cost
- Industrial drive → Visual Light Imaging
  - Digital Cameras e.g. Mobile-phone, Video Cameras…
- Scientific Application
  - High Energy Physics, Space Science…
- Advantages
  - Radiation hardness
  - Readout speed
  - On chip & in pixel intelligence
  - Room temperature operation

Dimensions: 2cm*2cm

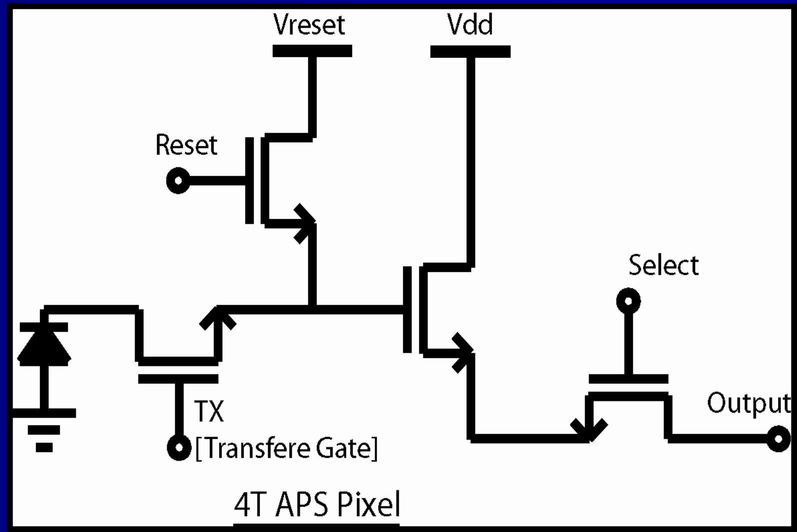


Star Tracker (525x525 → 25µm^2 pitch)

Operation Principle



Basic 3Transistor (3T) pixel



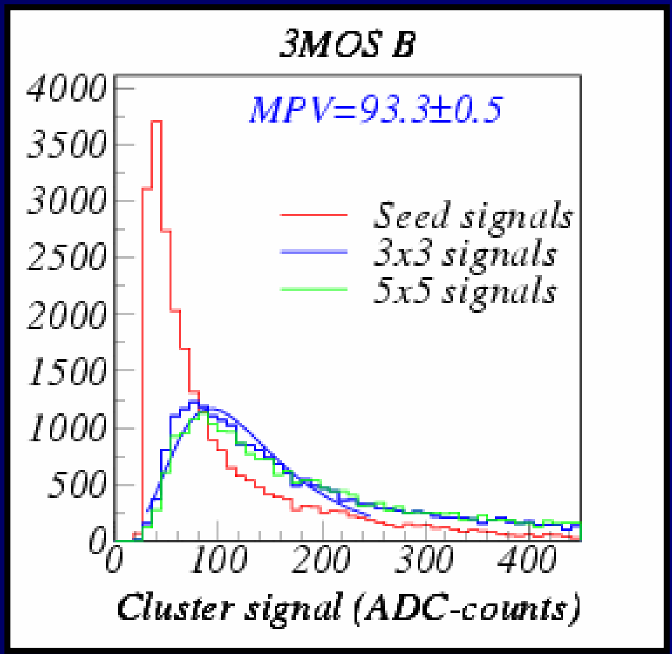
Basic 4Transistor (4T) pixel

UK HEP Test Structures

- APS1 (2001), IBM 0.25μm CMOS (2μm epi' layer)
  - Standard 3T & 4T pixels
  - Parametric Analysis
  - Radiation Hard, - 10^{12} protons/cm^2 [x10 requirement Linear Collider]
- APS2 (2003), TSMC 0.25μm CMOS (CIS) (8μm epi' layer)
  - Standard 3T & 4T pixels
  - FAPS, 10 memory cells, - burst readout 100ns
- APS3 (2004), TSMC 0.25μm CMOS (MS)
  - New pixel design – Deep N-well Diode

APS2

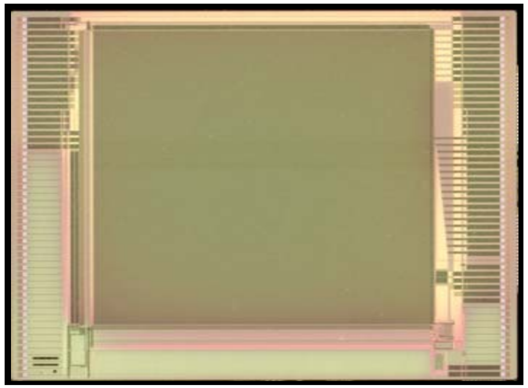
Source: Ru106 (Ruthenium)



Type	Signal (3x3)	Noise (3x3)	S/N
3T B	93.3+/-0.5	3.828 +/- 0.006	24.4+/-0.1
3T A	66.1+/-0.8	3.298 +/- 0.007	20.0+/-0.2
4T C	97.8+/-0.9	4.14 +/- 0.01	23.6+/-0.2
4T B	107.7+/-0.9	4.17 +/- 0.01	22.8+/-0.2
4T A	105+/-1	4.5 +/- 0.01	23.3+/-0.2

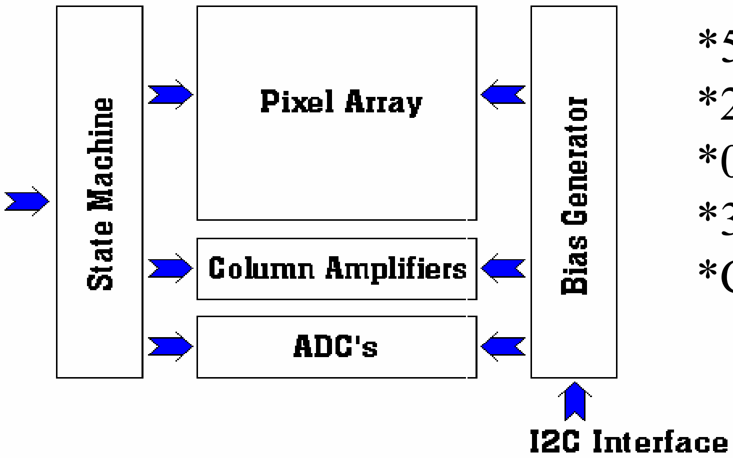
Cluster Algorithm - Seed Signal ≥ 6σ
- Area Signal ≥ 2σ

Star Tracker [Space Science Prototype]



Dimensions: 2cm*2cm

MAPS APS Block Diagram

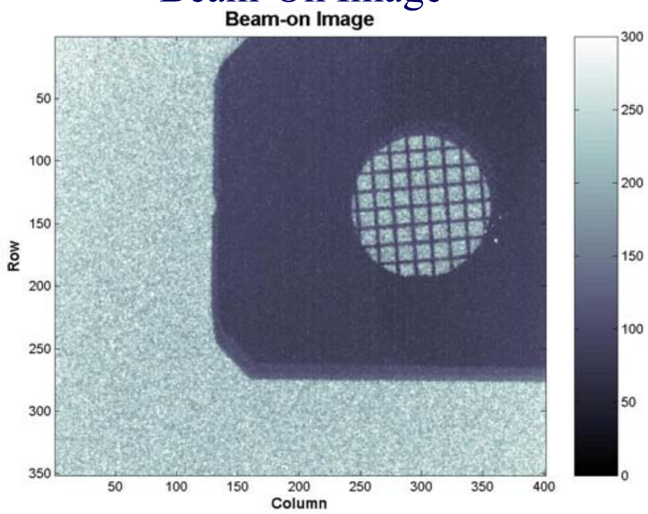


*525x525 array
*25μm pixels
*0.5μm CMOS
*3 – 4 μm epi'
*Camera on a chip

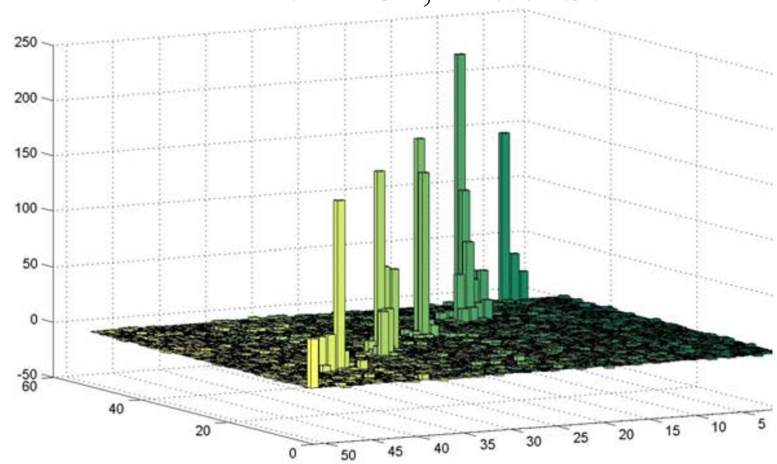
- Visual, Integrating Sphere (λ = 510nm)
- UV, Front etched and back-thinned
- Low Energy Electrons, 10keV → 120keV

120 keV Electron Microscope [LMB Cambridge]

•Beam-On Image



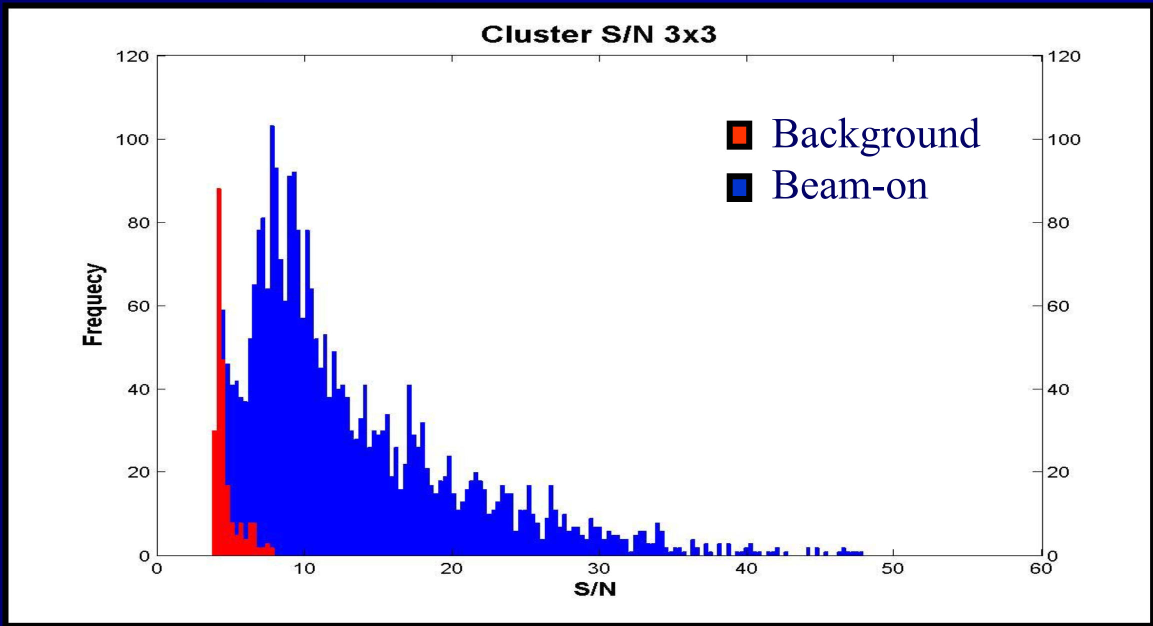
•Beam-On, Raster Scan



- Calibration
  - PTC, # of ADC units per e/h pair = 0.010 +/- 0.001
  - Noise floor = 1.2 +/- 0.1 ADC units
  - ETC, # of ADC's per incident 120keV electron = 23 +/- 2
  - S/N ~ 20

Single Electron Sensitivity
[120 keV E.M.]

- Low electron flat field illumination of ~ 6 electrons per 10 pixels
- Increased noise
  - Noise floor = 3.2 +/- 0.3 ADC units
  - Expected Signal Peak = 23 +/- 2 ADC units
  - Expected S/N Ratio ~ 7
- Cluster Algorithm
  - [Seed > 4σ, neighbours > 2σ]
- S/N Ratio = 8 +/- 2



Summary

- MAPS are a new and promising technology
- Detector for HEP experiments
  - MIP S/N = 24.4 +/- 0.1
- Star_Tracker, demonstrated direct detection of 120 keV electrons
  - 120 keV S/N = 8 +/- 2
- Results expected soon for
  - Flexible Active Pixel Sensors (10 memory cells per pixel)
  - Deep N_Well

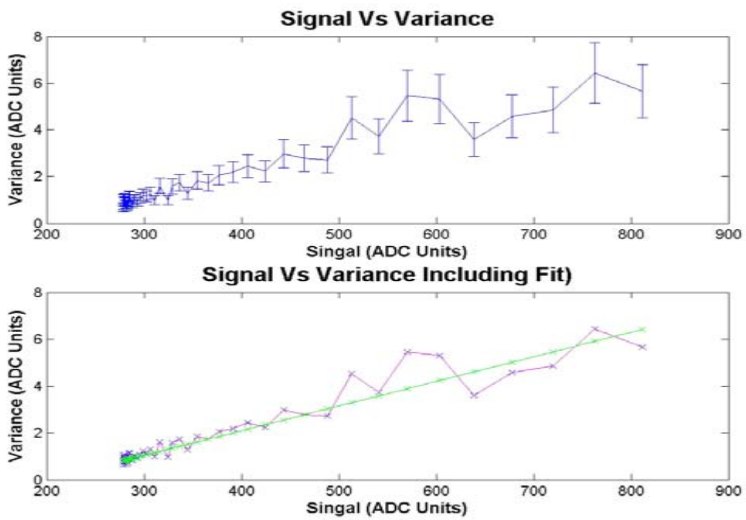
MAPS

•Star_Tracker, Characterisation:

• Uniform Light Source → Integrating sphere → PTC
510nm

PTC

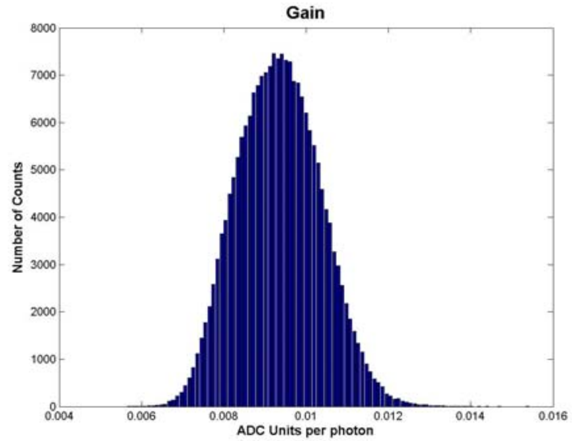
Variance (ADC Units)



Signal (ADC Units)

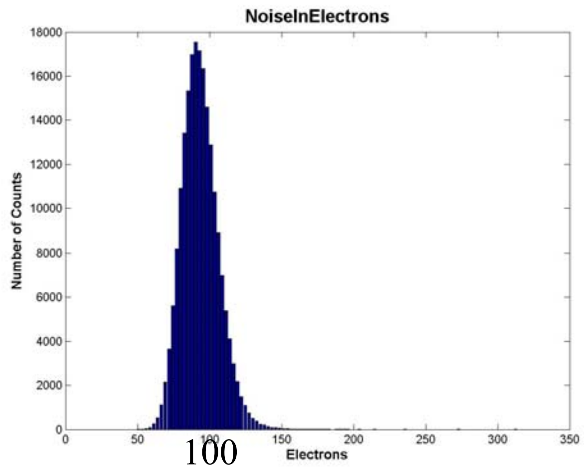
→ Full Well Capacity = 400k elec'
→ Signal Uniformity

Gain Distribution Photons



Gain = 0.01 +/- 0.0009 ADC/photon

Noise Distribution Electrons



Electrons

MAPS

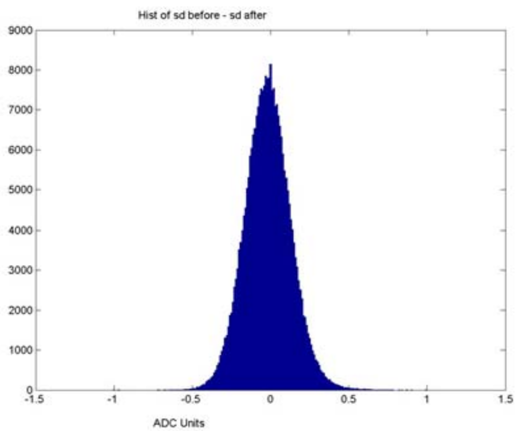
•Radiation Damage

- Dose: ~ 18krads
- Pedestal shift of ~ 21 ADC units
- Noise unchanged

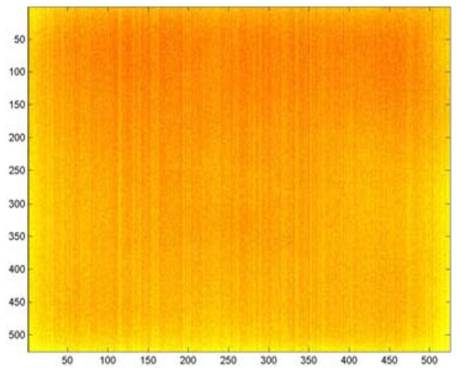
Main sources of pedestal change

- ➢ Increase in leakage current NO
- ➢ Transistor threshold voltage shift (V_{th}) YES, but can be corrected by DS or *design in deep submicron

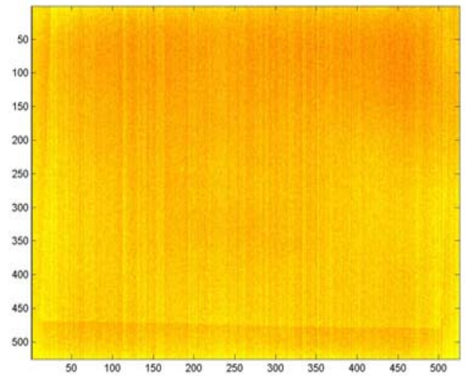
*Noise Histogram: Difference after-before



*Background Before Experiment

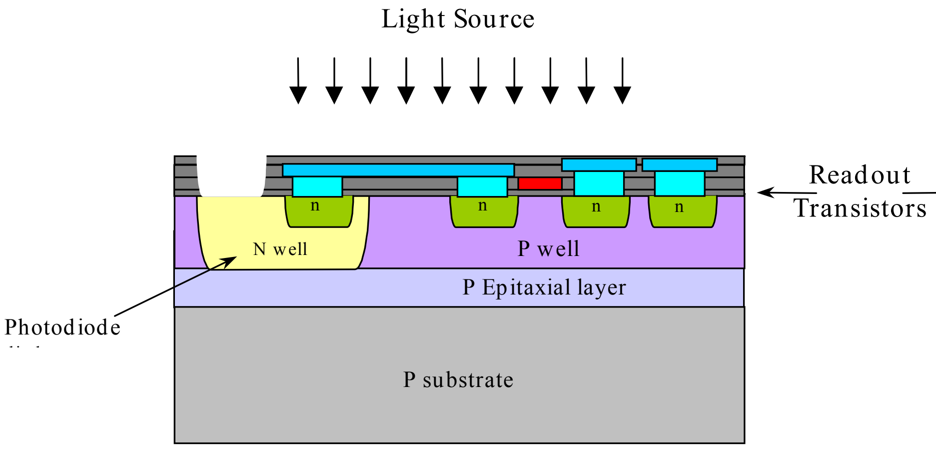


*Background After Experiment

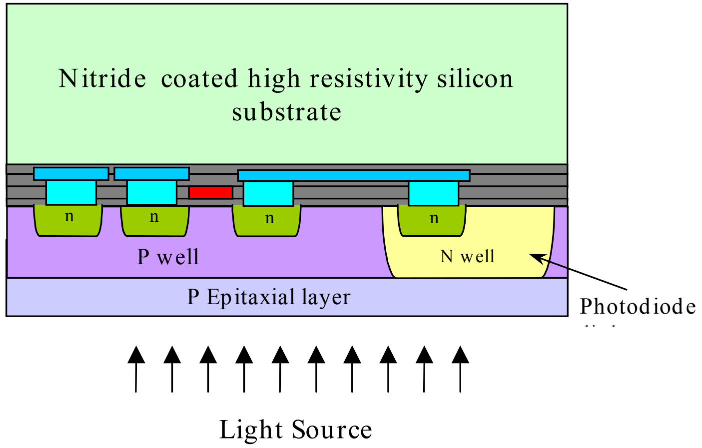


MAPS

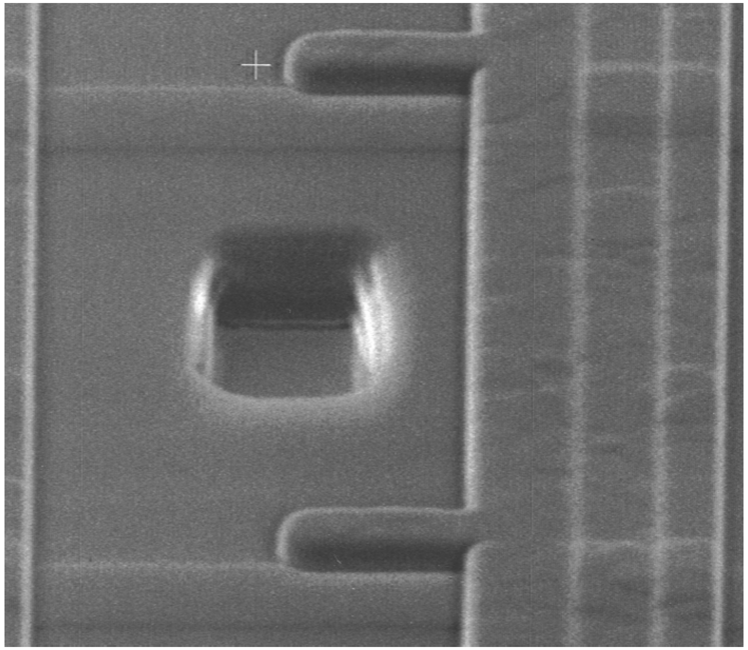
• **UV program**



Front illuminated approach

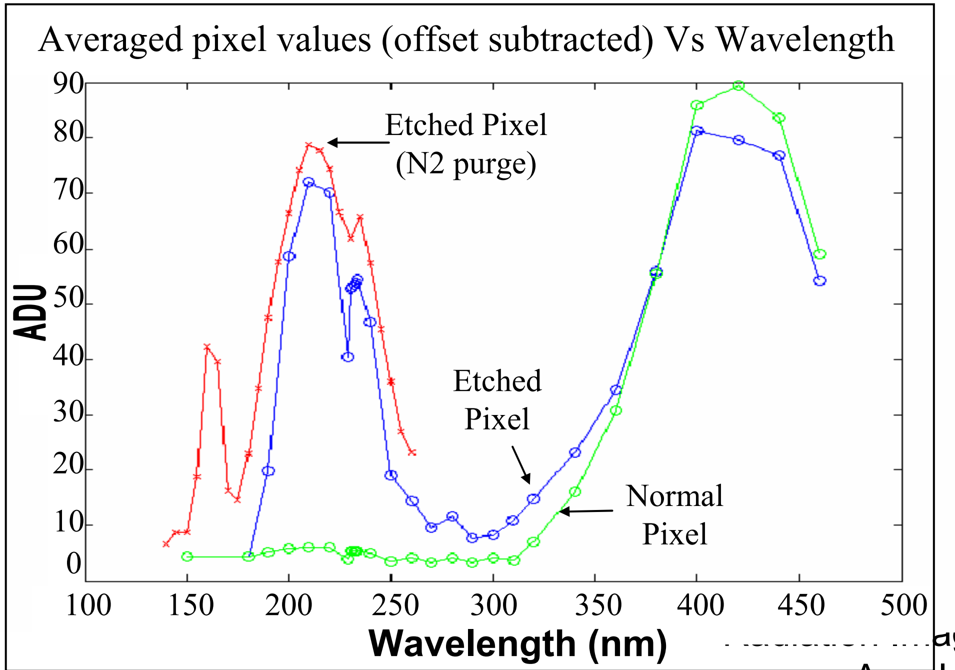


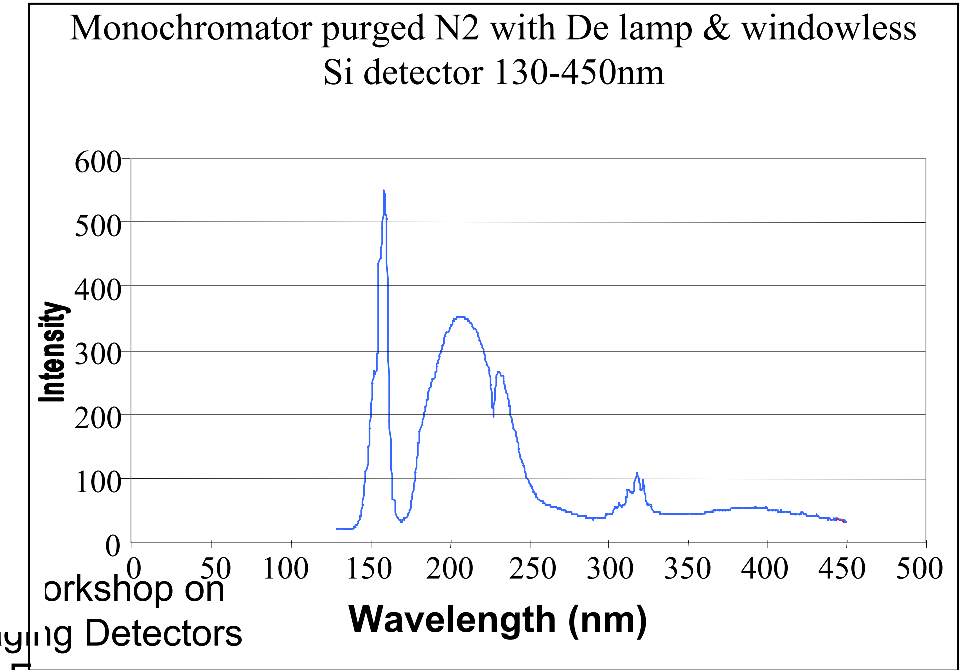
Back illuminated approach



- <u>Front Etched UV Response</u>

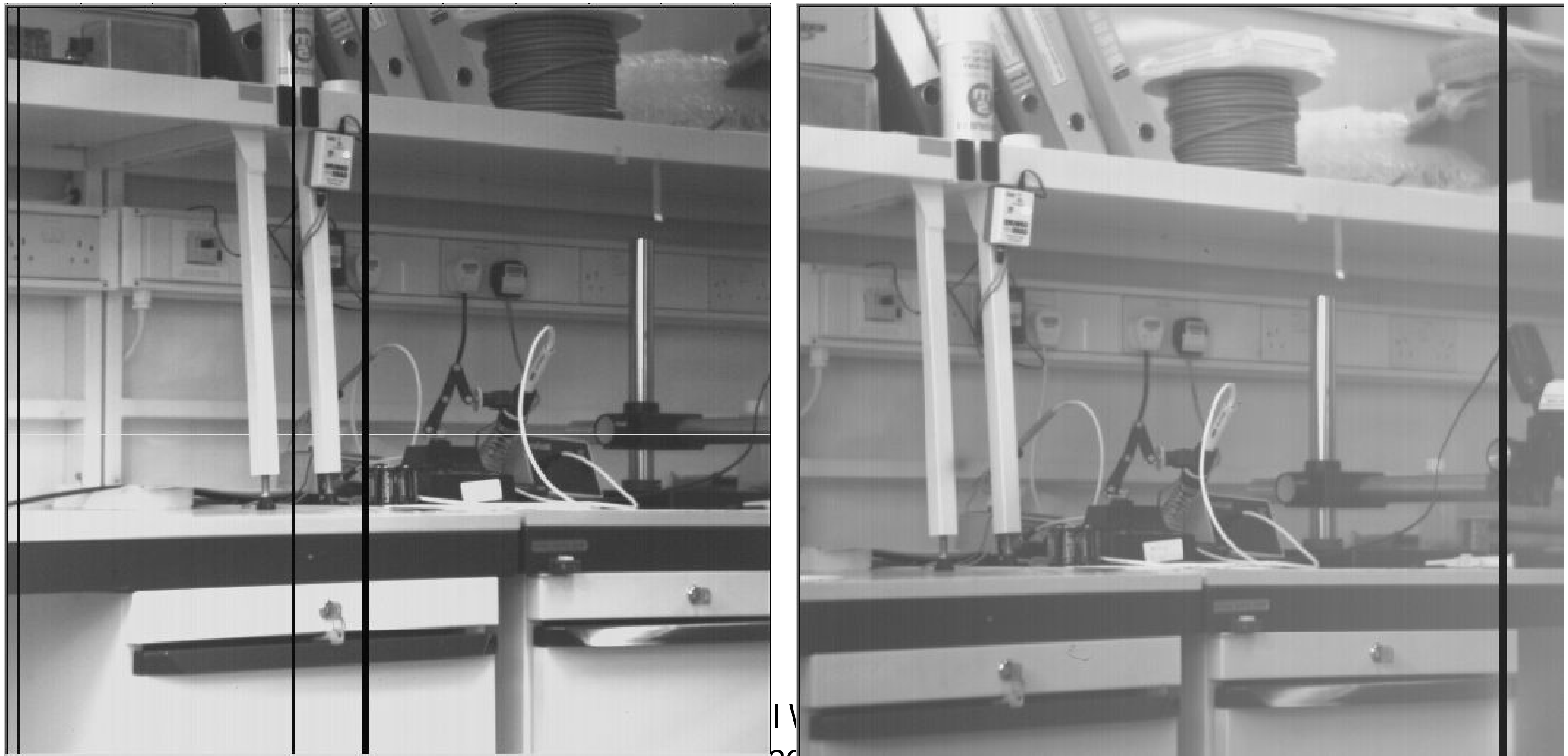
*Focused Ion Beam





MAPS

- <u>Back Thinning</u>
- Image from two back-thinned Star_Tracker sensors



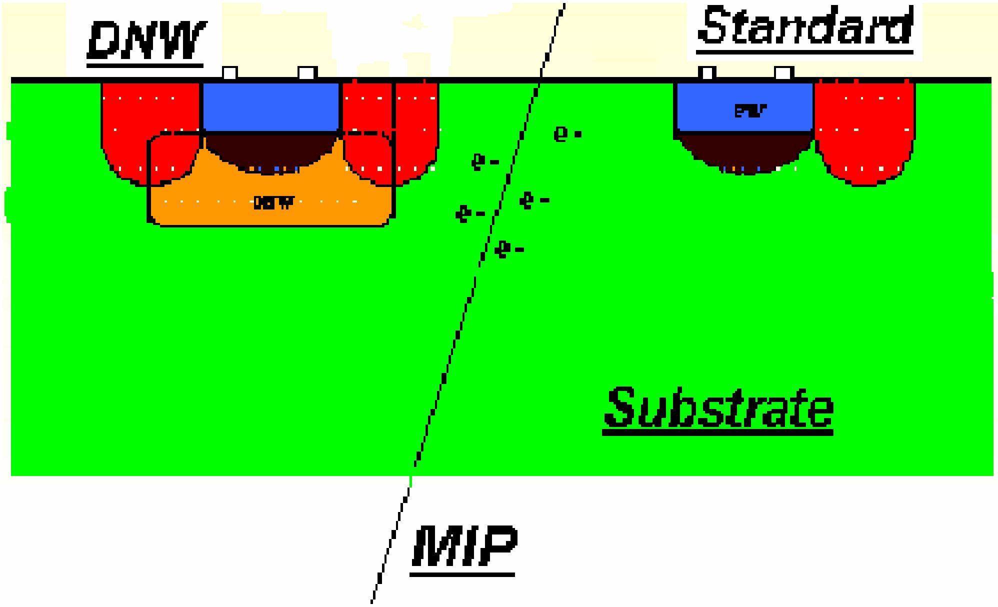
MAPS

•RalHepAPS 3

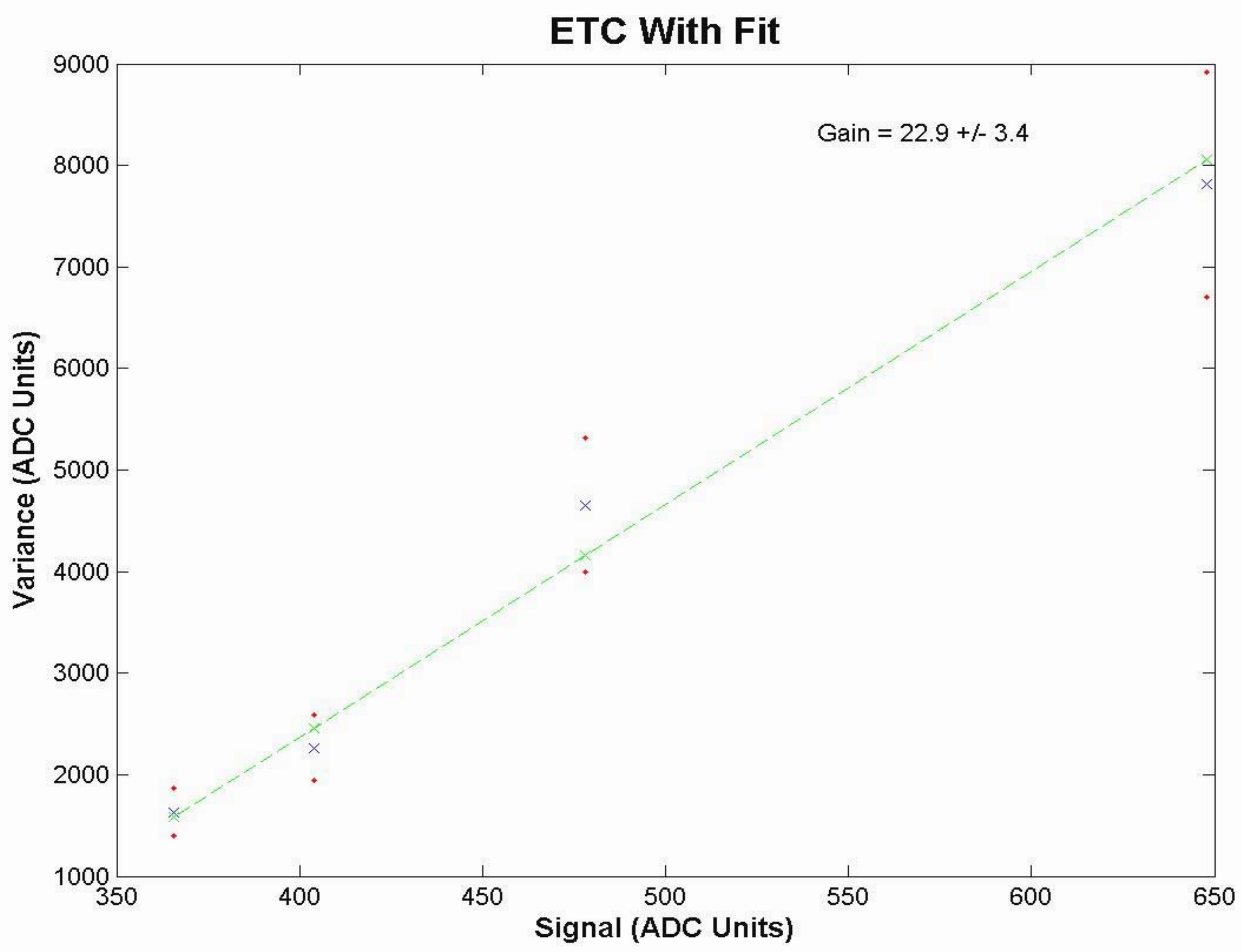
Deep N-Well Diode

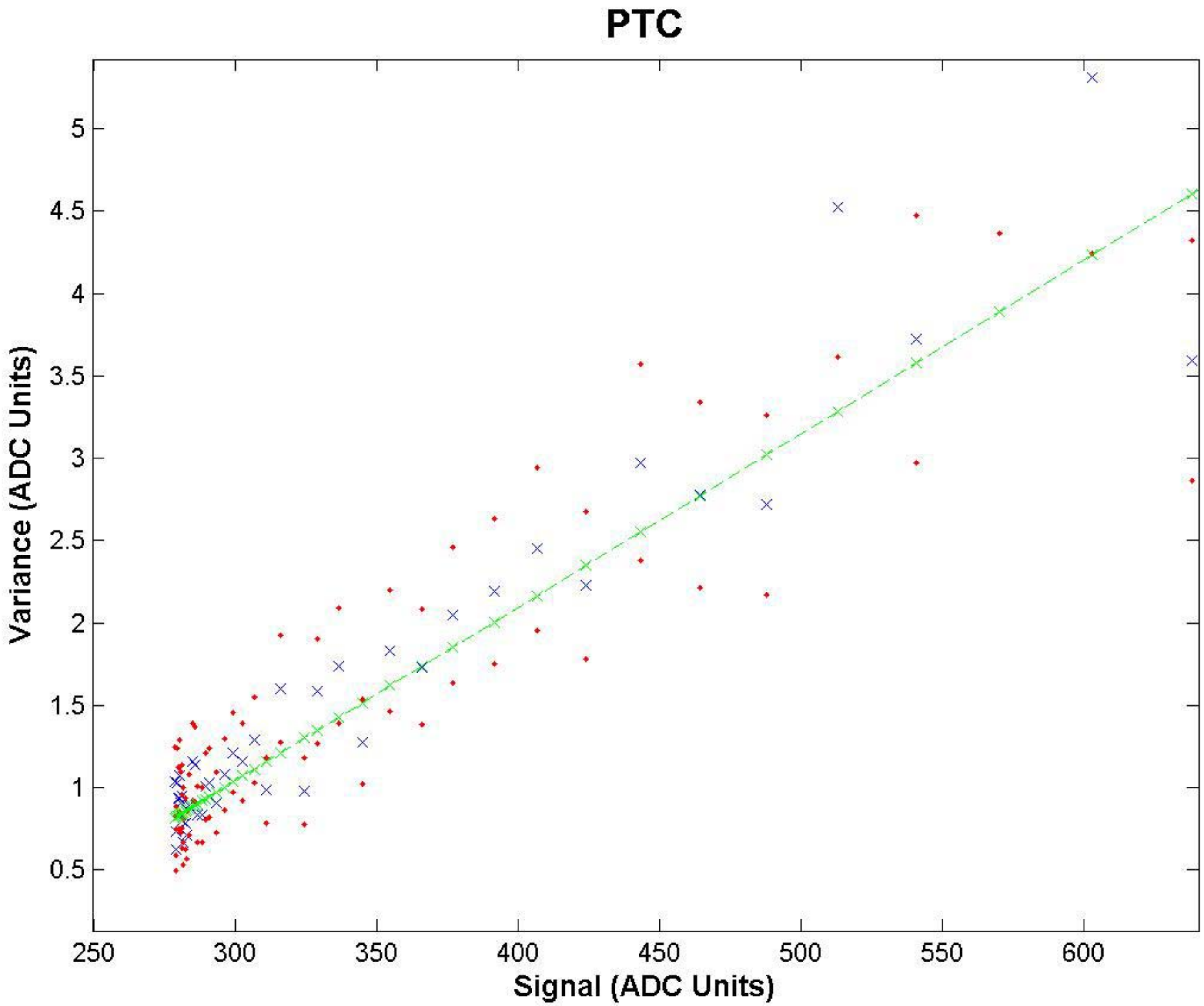
→Increased E-field - Charge Collection efficiency, Amount of Charge Collected & Charge Collection Speed

- Increased Radiation Hardness
- Negative Substrate Contact



*Designed by: Arwel Evans, Bruce Gallop, Renato Turchetta


ETC With Fit
Gain = 22.9 +/- 3.4
Variance (ADC Units)
Signal (ADC Units)
9000
8000
7000
6000
5000
4000
3000
2000
1000
350
400
450
500
550
600
650


PTC
Variance (ADC Units)
Signal (ADC Units)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
250
300
350
400
450
500
550
600