CMOS Image Sensors
for
Scientific Applications

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Outline

- **Introduction.**
- **CMOS for radiation detection in scientific applications**
  - **Visible light** **UV**
  - **X-ray** **Charged particles**
- **Advanced pixels**
- **Conclusions**

CCLRC-RAL

CCLRC is one of Europe's largest multidisciplinary research organisations. It owns and operates three laboratories.

Rutherford Appleton Laboratory (RAL) is the largest one.

Technology department providing engineering solutions for UK, European and world-wide research institutes and large facilities: CERN, ESRF, ESA, NASA, …

Main activity on radiation detectors and readout electronics: CCD, hybrid active pixel sensors, CMOS image sensors.

CMOS Image sensors started in 1999 with the design of a StarTracker.

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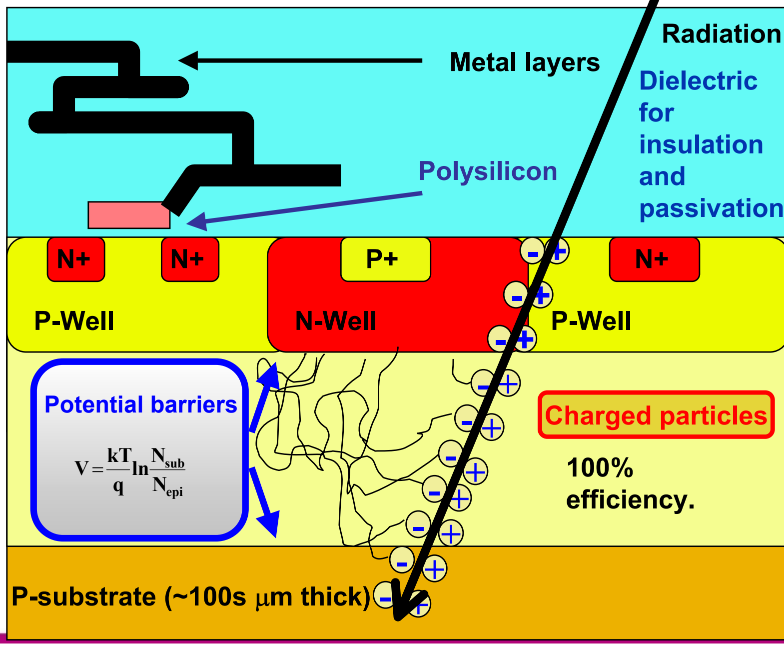
CMOS sensors for radiation detectors

Photons

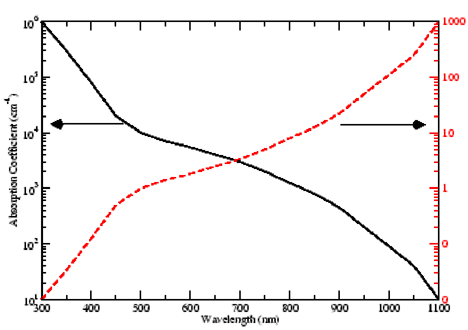
Silicon band-gap of 1.1 eV ↔ cut-off at 1100 nm.

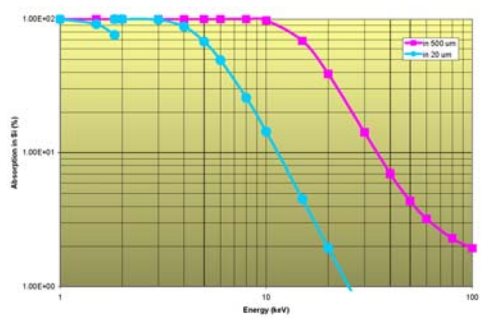
Good efficiency up to 'low' energy X-rays. For higher energy (or neutrons), add scintillator or other material.

Need removal of substrate for detection of UV, low energy electrons.



Photon absorption





For higher energy photons, number of N electron-hole pairs generated is proportional to absorbed energy ΔE with proportionality constant W = 3.6 eV / pair

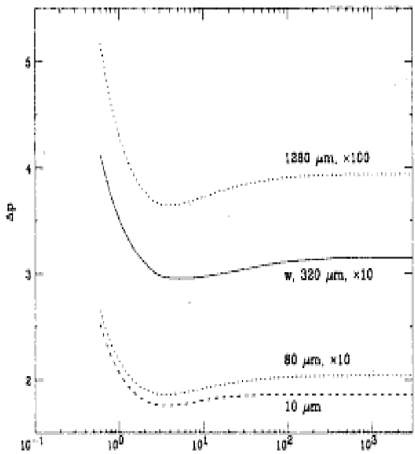
$$N = \Delta E / W$$

Higher absorption by adding absorber (scintillator) or hybrid solution (detector bump-bonded to electronics)

Charged particles in silicon

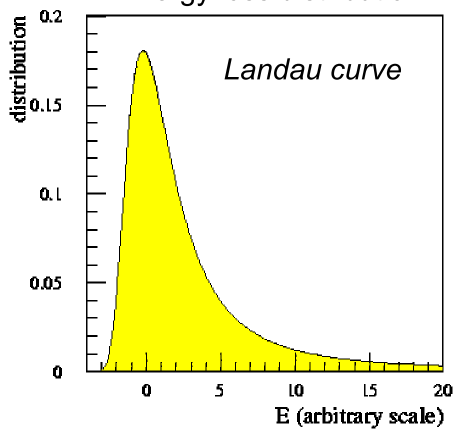
Energy loss vs particle energy in silicon

Most probable value



(from H. Bichsel)

Energy loss distribution



N = ΔE / W, again!
N = ~ 80 / μm in silicon

Applications for RAL CMOS APS

- Space science: Star Tracker, ESA Solar Orbiter, …
- Earth Observation: 3 μm pixel linear sensors, ..
- Particle Physics: ILC, vertex and calorimeter (CALICE), SLHC, …
- Biology: electron microscopy, neuron imaging
- Medicine: mammography, panoramic dental
- …

Detecting:

- Photons
- Charged particles
- Voltages (!)

CMOS sensors requirements. 1

- Wide dynamic range: → 16 bits and beyond
- Low noise: <~ 10 e- rms → < 1 e- rms ?
- Radiation hardness: Mrad and beyond
- Speed: data rate in excess of 50 MB/sec → 500 MB/sec and beyond

  Short integration time and gating → ns
- Large pixels: >10 μm → 50 μm
- No data compression or lossless compression
- Large volume of data: 100s MB/sec for minutes, hours, …
- Images can be mainly dark with only a few bright spots

CMOS sensors requirements. 2

- Requires advanced pixel designs
- In-pixel data reduction
- Only NMOS in pixel if 100% efficiency for charged particle detection is required
- Large area: side ~ cm's; no focusing possible for X-ray or charged particles
- SOI on high resistivity handle wafers → full CMOS
- Semiconductor deposition

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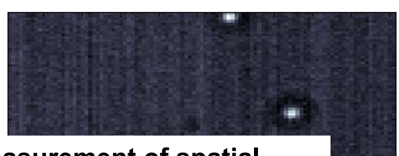
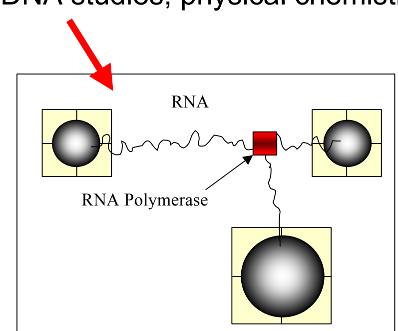
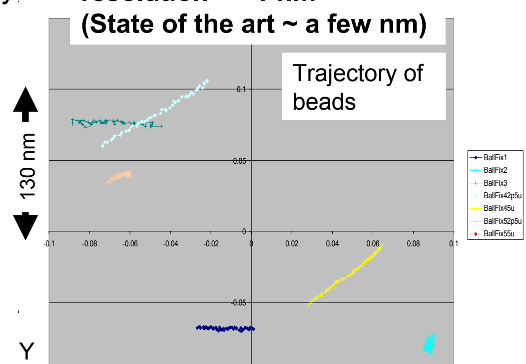
Optical tweezers

- Particles are optically trapped and controlled → molecular forces at picoNewton level and position resolution <~ 1 nm
- Applications in medicine, cell biology, DNA studies, physical chemistry, …





Measurement of spatial resolution <~ 1 nm
(State of the art ~ a few nm)



Vanilla sensor.

- Large pixels: 25 μm, design in 0.35 μm CMOS
- Format 512x512 (→ StarTracker) + black pixels
- 3T pixel with flushed reset
- Noise < 25 e-   Full well capacity > 10^5 e-   DR ~ 4000 ~ 12 bits
- On-chip SAR ADCs, one for 4 columns with column-FPN control.

Selectable resolution: 10 or 12. Adjustable range.

- Analogue output at 4.5 MHz
- Row and column address decoder
- *Full frame readout*: Frame rate > 100 fps.
- *Region-of-interest readout*: Fully programmable.

Example speed: six 6x6 regions of interest @ 20k fps

- Two-sided buttable for 2x2 mosaic
- Design for backthinning
- Detecting capability not limited to visible light!

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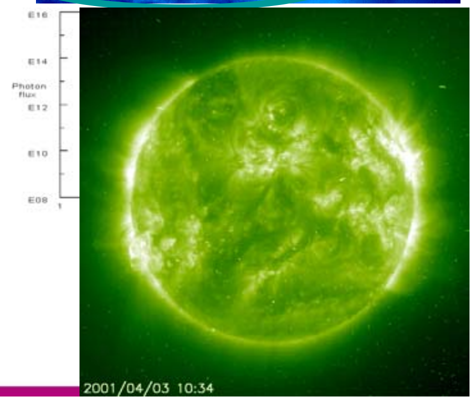
ESA Solar Orbiter

Study of the Sun's atmosphere and heliosphere

- ➢ Study the Sun from close up (45 solar radii or 0.21 AU) → pixel size of 35 km on the Sun or 0.05 arcsec from Earth
- ➢ Launch in 2015, mission completed in 2024
- ➢ Among the objective: observation of the sun into the EUV band (down to 170 nm)
- ➢ High radiation environment
- ➢ High resolution → large format (4kx4k or 2k * 2k)
- ➢ linearity
- ➢ 14-bit dynamic range
- ➢ low noise
- ➢ good uniformity
- ➢ low power

Lead technology scientist: Dr. N. Waltham



CMOS Sensors for Solar Orbiter

Design of sensors

- ➢ 2002: 4k x 3k, 5 μm pixels in 0.25 μm CMOS, 8 μm epitaxial wafers
- ➢ 2005: 1.5k x 0.5k, 10 μm pixels in 0.35 μm CMOS, 14 and 20 μm epitaxial wafers

Enhancing EUV sensitivity

Backthinning (collaboration with e2v)

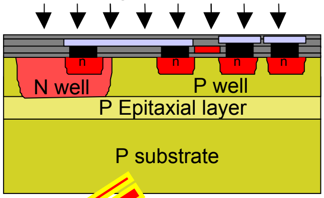
- ➢ 2002: on 512x512 StarTracker, 4 μm epitaxial wafers
- ➢ 2004/5: on 4kx3k

Front etching

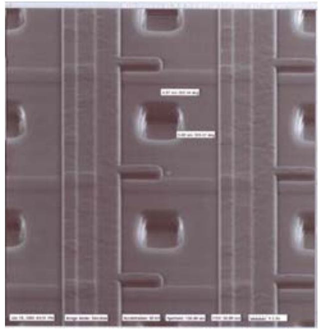
- ➢ 2002: on 512x512 StarTracker, 4 μm epitaxial wafers, by Focused Ion Beam (FIB)

Enhancing UV sensitivity

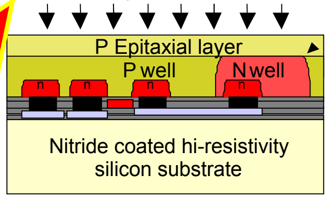
Front-illuminated



Front-etched Front-illuminated

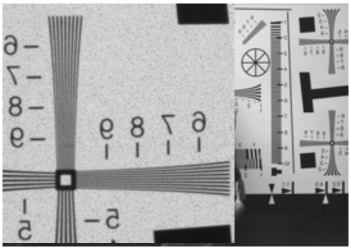


Back-thinned Back-illuminated

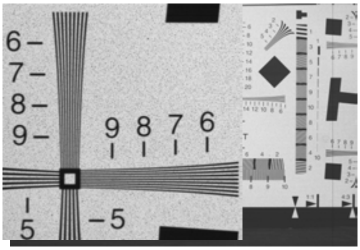


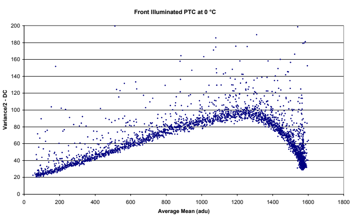
4kx3k sensor

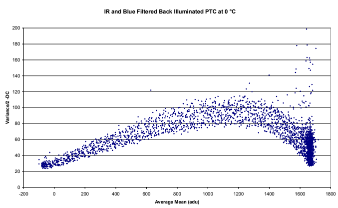
Front-illuminated



Back-illuminated







Fill factor better than 75% achieved on a 5 μm pixel (1 PMOS transistor + back-illumination)

QE better than 20% at 200 nm

No AR coating used

Back-illuminated image was taken through a 50nm filter at 350nm

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Medical X-ray detection

Project I-ImaS (http://www.i-imas.ucl.ac.uk) funded by EU

Application: mammography, dental (panoramic and cephalography)

Scanning system with real-time data analysis to optimised dose uptake

Step-and-shoot, not TDI

Time for 1 image: a few seconds

Large pixels: 32 μm

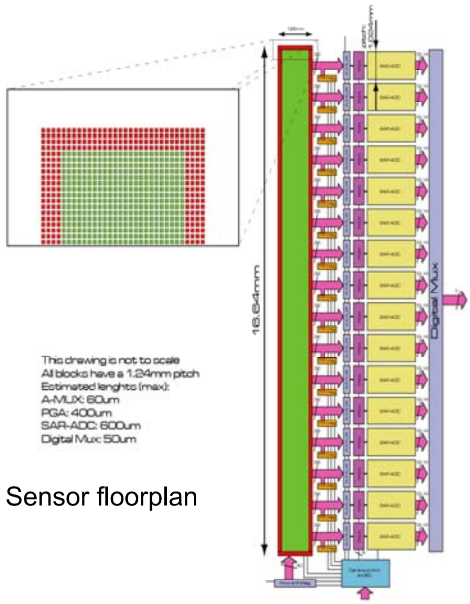
Image area: 18cmx24cm covered by several sensors in several steps

Image size: 5120x7680 = 40Mpixel/image @ 14 bits, ~70MBytes

Integration time per pixel: 10 ms

1.5 D CMOS sensor

- Designed in 0.35 μm CMOS
- 512*32 pixels at 32 μm pitch plus 4 rows and columns on both sides for edge effects
- 200,000 e^- full well
- 33 to 48 e^- ENC depending on the pixel reset technique used
- more than 72dB S/N ratio at full well (equivalent to 12 bit dyn. range)
- possible to use hard, soft or flushed reset schemes
- 14 bit digital output; one 14-bit SAR ADC every 32 channel
- 20 MHz internal clock; 40 MHz digital data rate
- data throughput: 40MHz·7bit = 280Mbit/s = 35 MB/sec

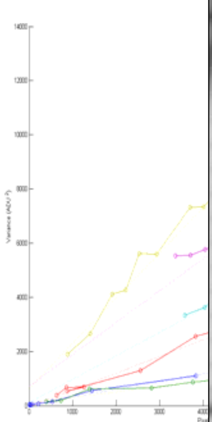
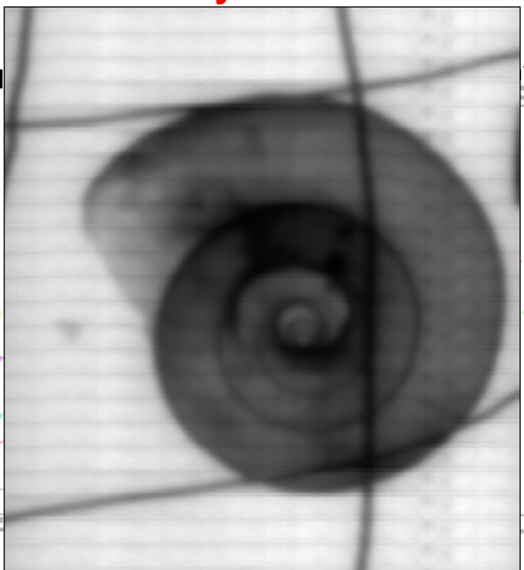
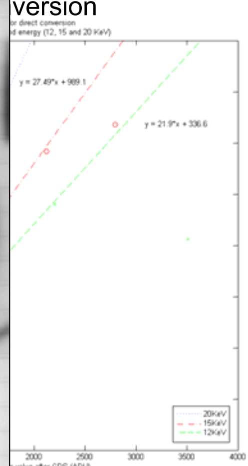


Sensor floorplan

Preliminary measurements

PTC with scintil

version

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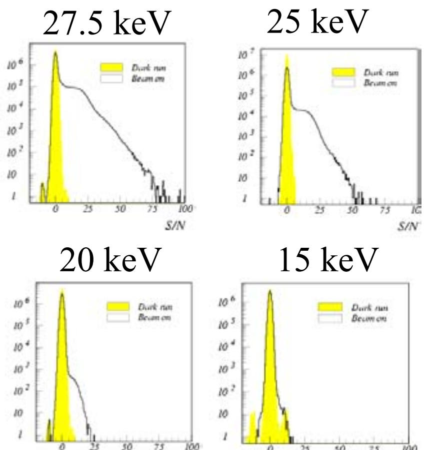
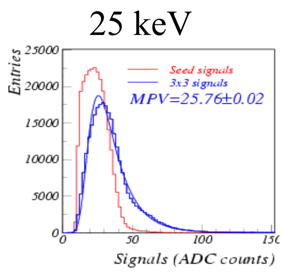
Detection of charged particles

Low energy particles, e.g. a few keV electrons, requires backthinning and backillumination.

High energy traverses front layers of passivation. See examples below

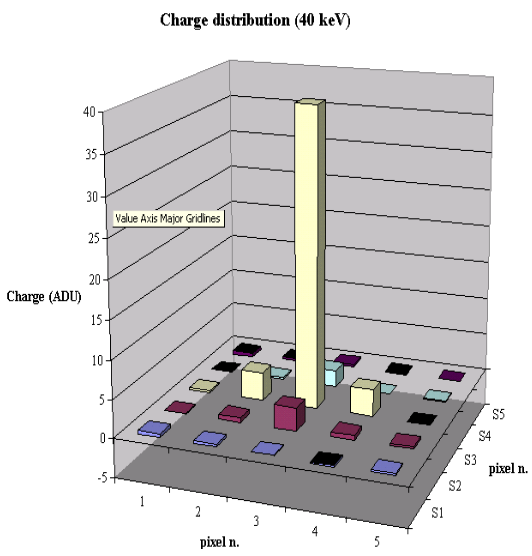


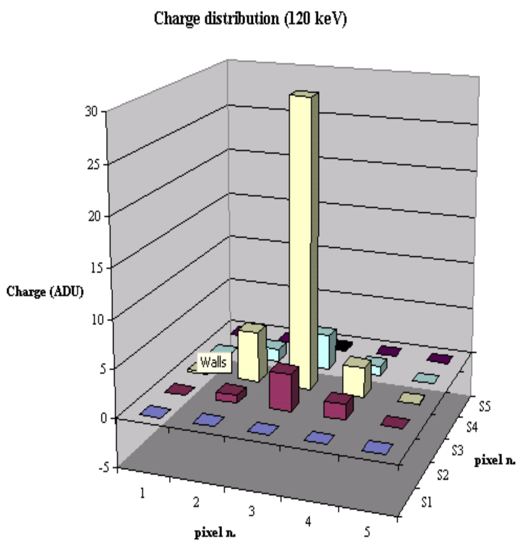
Energy loss distribution



Intermediate energy electron detection

StarTracker 512x512 pixels, 25 μm pitch, 0.5 μm CMOS, 4 μm epitaxial layer





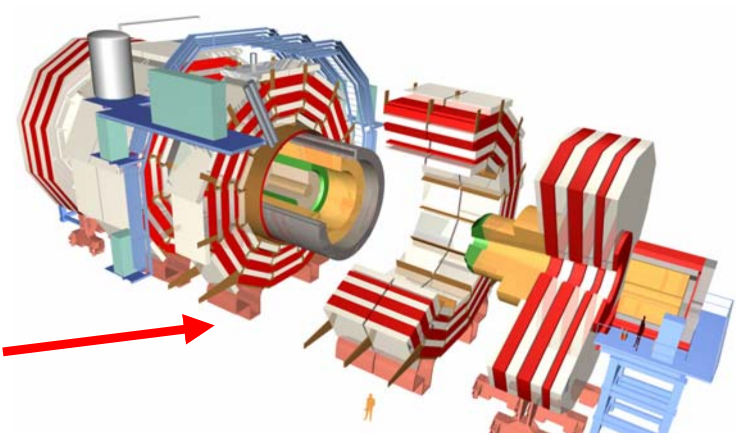
Particle, or High-Energy, Physics

'Big science' projects: large particle accelerators (Ø km), large international (world-wide) collaborations.

High-energy particles (↑ TeV) collide → new particles are created → insight into ultimate structure of matter.

Detectors are large apparatus (size ~m) with cylindrical symmetry and several sub-detectors.

Example of CMS at the Large Hadron Collider



CMOS Image Sensors for Particle Physics

First proposed end of 1999

Low noise detection of MIPs first demonstrated in 2001 with a 3T pixel

Since then, with a number of technologies/epi thickness:

AMS 0.6/14, 0.35/∞, 0.35/14, 0.35/20, AMIS (former MIETEC) 0.35/4, IBM 0.25/2, TSMC 0.35/10, 0.25/8, 0.25/∞, UMC 0.18/∞

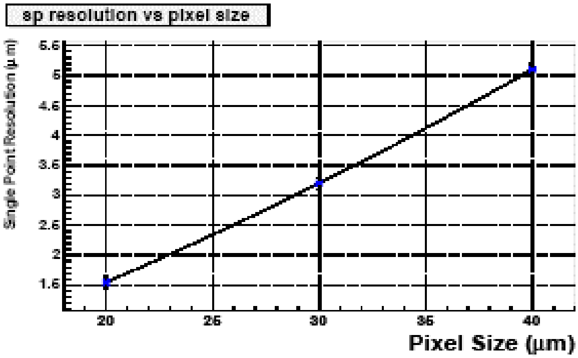
Noise <~ 10 e- rms with off-chip, off-line CDS

Spatial resolution 1.5 μm @ 20 μm pitch, with full analogue readout

Good radiation hardness

Low power

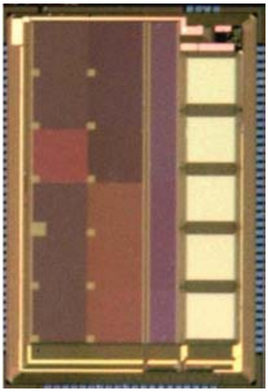
Speed: rolling shutter can be a limit



RAL Sensors for Particle Physics

Parametric test sensor: RAL_HEPAPS family

RAL_HEPAPS2: 0.25 μm CIS, 8 μm epitaxial layer, 384*224 pixels, 15 μm pitch: 3MOS, 4MOS, ChargePreAmplifier (CPA), Flexible APS (FAPS, 20 μm pitch)

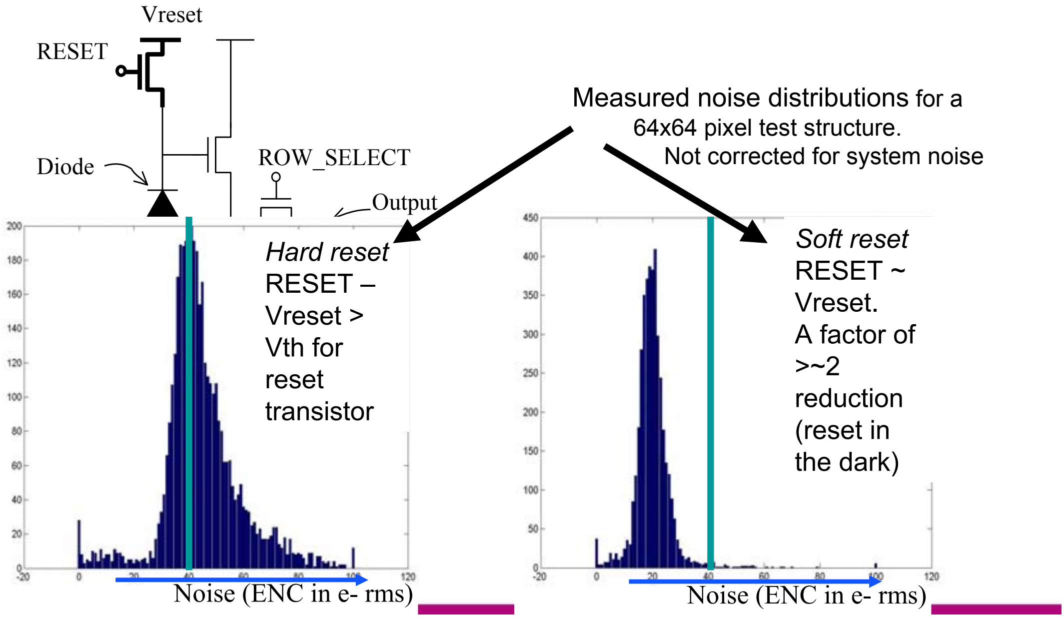


RAL_HEPAPS3: 0.25 μm MM, no epitaxial layer, 192*192 pixels, 15 μm pitch: 3MOS, 4MOS, Deep N-well diodes

Test sensors

RAL_HEPAPS4: 0.35 μm CIS, 20 μm epitaxial layer, 1026*384 pixels, 15 μm pitch. 3 versions: 1, 2 or 4 diodes per pixel. Rad-hard, 5MHz row rate (now in manufacturing)

Soft and *hard* reset



Radiation hardness

Transistors.

Threshold shift: reduces with shrinking feature size

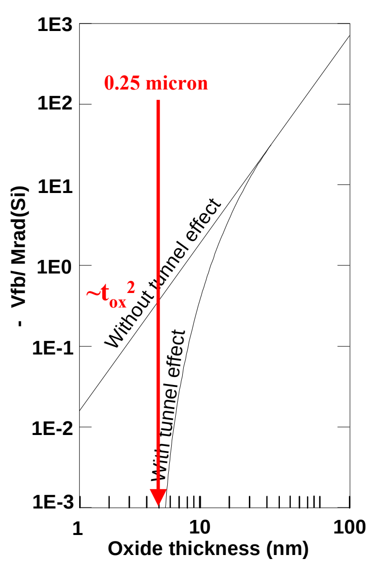
Bird's beak effect: use enclosed geometry transistors

Transistor leakage current: use guard-rings to separate transistors

Diodes.

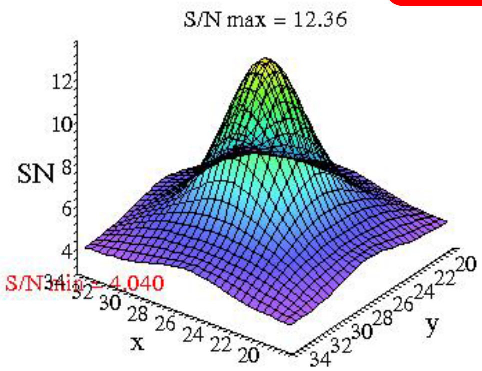
Radiation damage increases leakage current

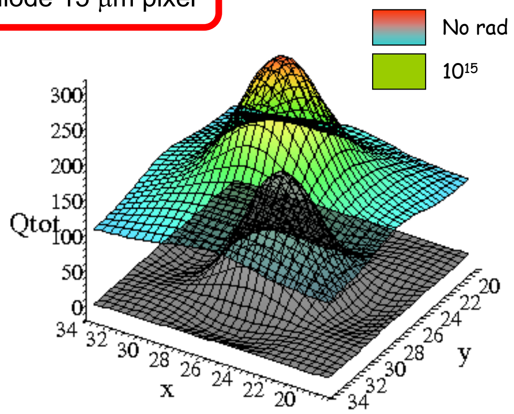
Radiation damage reduces minority carrier lifetime → diffusion distance is reduced



Single pixel S/N dependence on impact point. 1

Device simulation.
Single diode 15 µm pixel





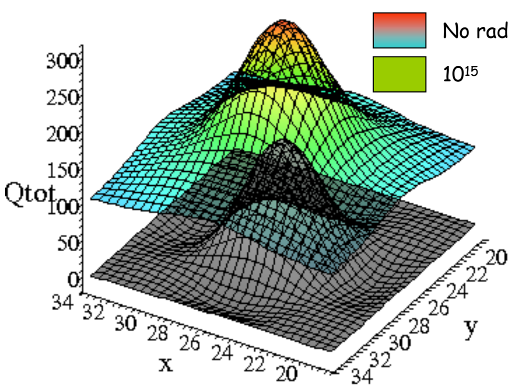
- S/N varies over pixel between 12 and 4 before irradiation.
- S drops to zero at edges after 10^{14} p/cm^2.

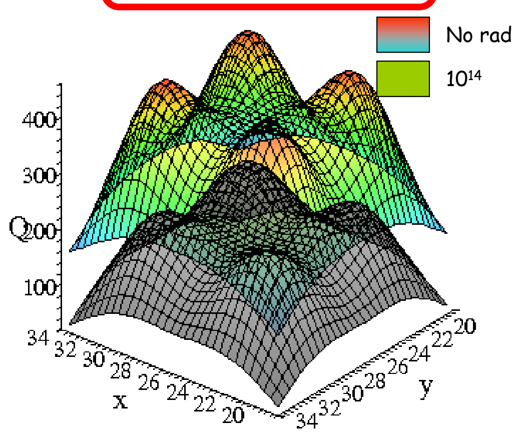
G. Villani (RAL)

Single pixel S/N dependence on impact point. 2

Device simulation.
Single diode 15 µm pixel

Device simulation.
4-diode 15 µm pixel



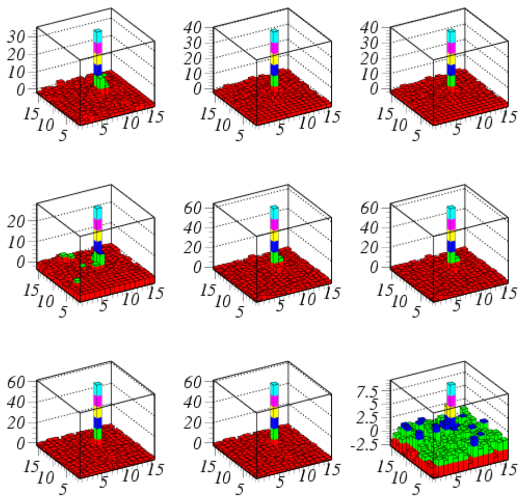


- Less variation in S/N varies over pixel before and after irradiation.

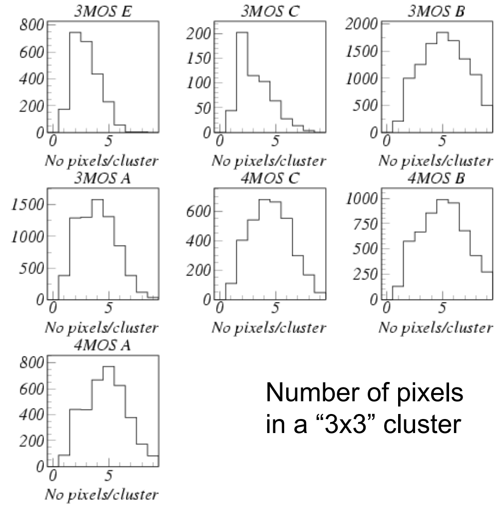
Signal from individual particles

Beta source (Ru106) test results. Sensors HEPAPS2.

Cluster in S/N



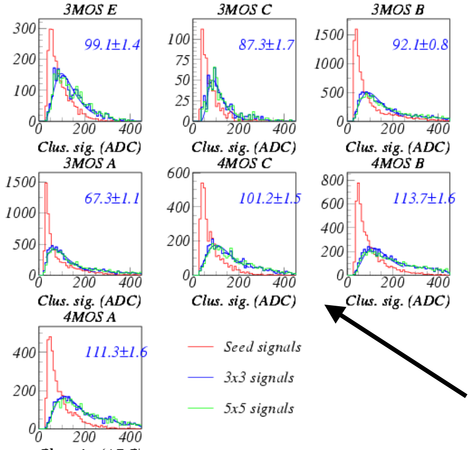
Signal spread



Number of pixels in a “3x3” cluster

Distribution of signals

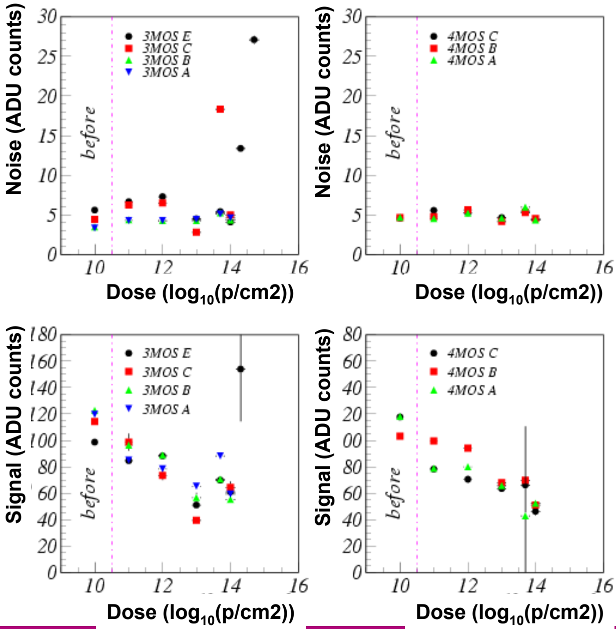
From different types of pixels.
HEPAPS2



Type	Specs	S	N	S/N
3MOS E	4 diodes	99	4.94	20.1
3MOS C	GAA	87	4.85	18.0
3MOS B	Diode 1.2x1.2	92	3.87	23.8
3MOS A	Diode 3x3	67	3.31	20.3
4MOS C	Lower V_T	101	4.14	24.4
4MOS B	Higher V_T	114	4.70	24.2
4MOS A	Reference	111	4.45	25.0

Typical ‘Landau distribution

Radiation test. Source results

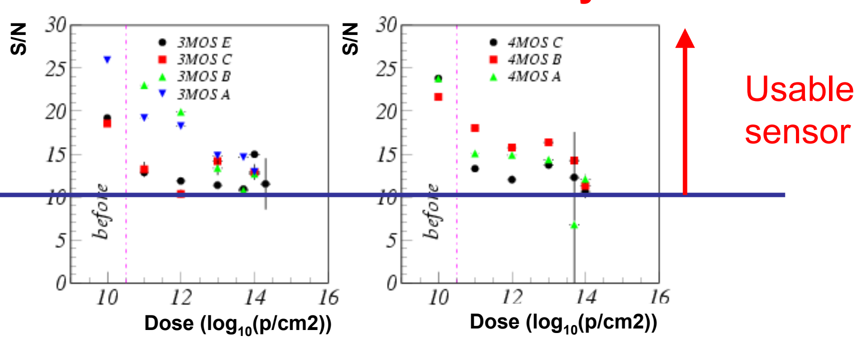


- Noise seems to increase slightly with dose.
- Signal decreases with dose.

3MOSA	3x3 μm^2
3MOSB	1.2x1.2 μm^2
3MOSC	GAA
3MOSE	4 diodes
4MOSA	Reference
4MOSB	Higher V_T
4MOSC	Lower V_T

J. Velthuis (Liv)

Radiation test. Summary



- Sensors yield reasonable S/N up to 10^{14} p/cm^2
- 0.35 μm technology in the pixel transistors. Enclosed layout in 3MOS_E
- S/N reduction seems to be dominated by charge collection
- Especially 3MOS_E (4 diodes) looks interesting
  - (-) Larger capacitance yields larger noise
  - (+) Four diodes: less dependence of S/N on impact point
  - After irradiation remains a larger "sensitive area"

HEPAPS 4

- 1026x384 pixels
- 3 versions: 1 diode; 2 diodes; 4 diodes
- 15 μm pitch
- ENC <~ 15 e- rms (reset-less)
- 5 MHz line rate
- Rad-hard: > Mrad
- Designed in 0.35 μm CMOS technology
- Epi thickness 20 μm
- Simple shift-register control
- Odd-even rows output in parallel; Left-right symmetry
- Single-ended and differential output

International Linear Collider

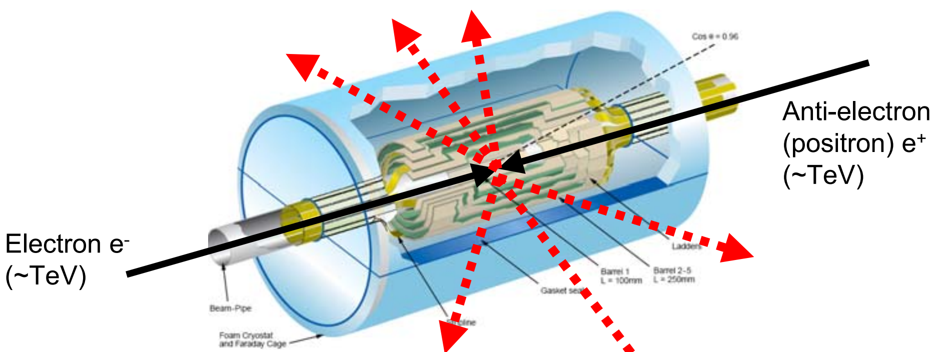
International Linear Collider: CMOS sensors proposed for Vertex and Electromagnetic calorimeter.

Radiation hardness: moderate (~100s kRad, 10^{12} n/cm^2)

Large area (stitched) sensor required in both cases.

Total covered area: **~m²** for Vertex, a few **10³ m²** for Electromagnetic calorimeter

They both call for advanced APS



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- **Advanced pixels**
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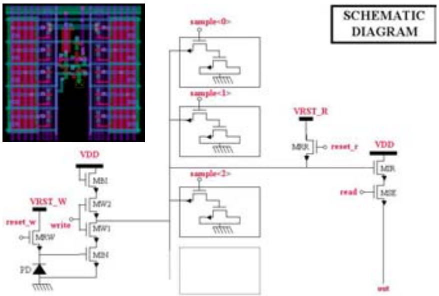
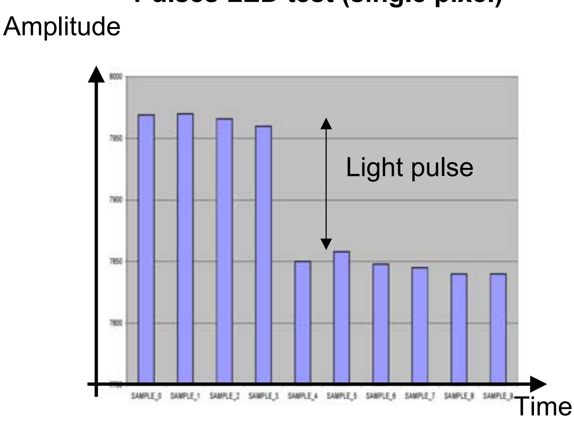
Flexible Active Pixel Sensor



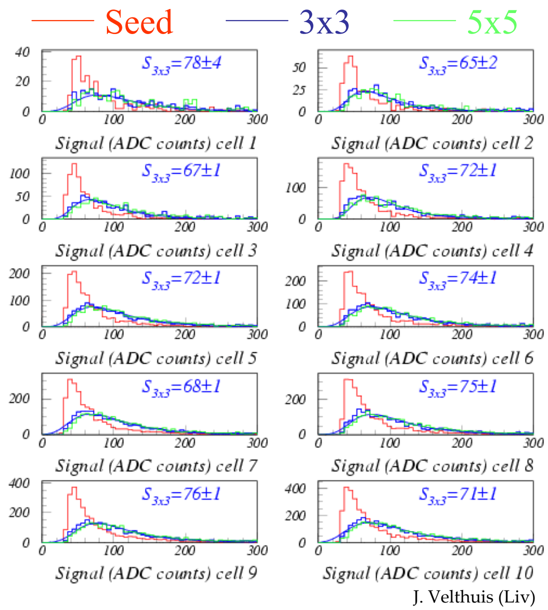
Pulses LED test (single pixel)



10 memory cell per pixel
28 transistors per pixel
20 μm pitch
40x40 arrays
Design for the Vertex detector at the International Linear Collider

FAPS. Signal distribution

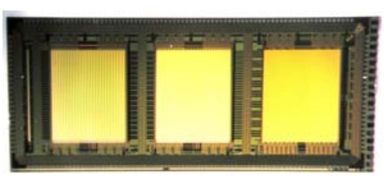
- Test with source
- Correlated Double Sampling readout (subtract $S_{cell\ 1}$)
- Correct remaining common mode and pedestal
- Calculate random noise
  - Sigma of pedestal and common mode corrected output
- Cluster definition
  - Signal >8σ seed
  - Signal >2σ next
- Note hit in cell *i* also present in cell *i+1*.
- **S/N$_{cell}$ between 14.7±0.4 and 17.0±0.3**

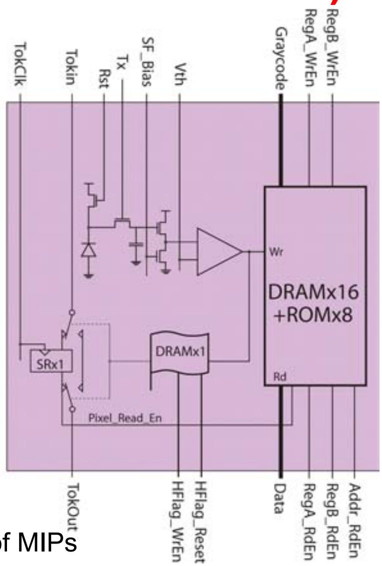


OPIC (On-Pixel Intelligent CMOS Sensor)

- In-pixel ADC
- In-pixel TDC
- Data sparsification

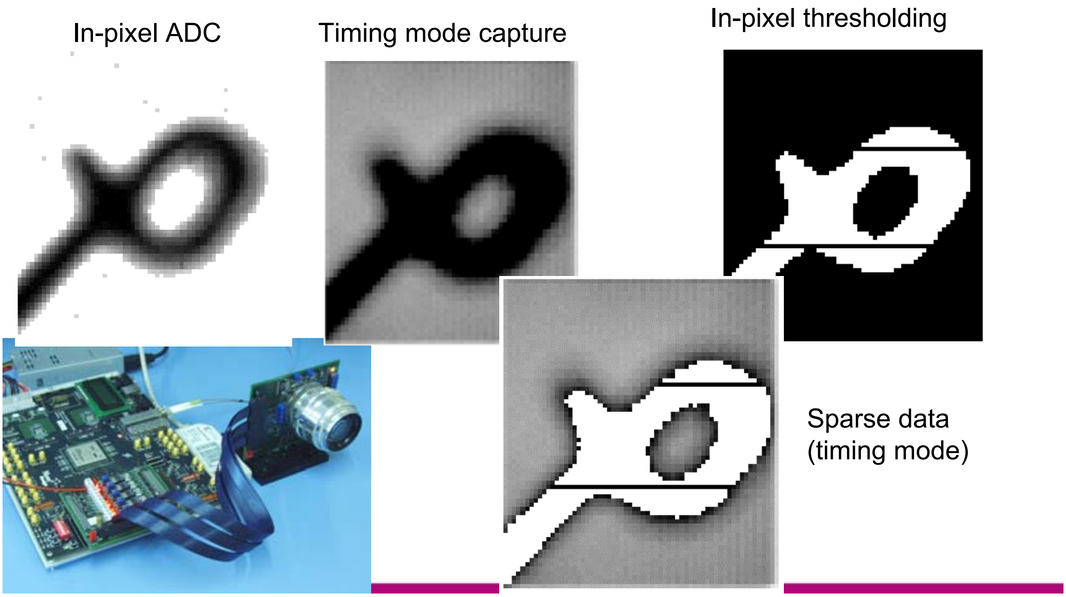
Test structure. 3 arrays of 64x72 pixels @ 30 μm pitch
Fabricated in 0.25 μm CMOS technology





This design is the starting point for Calice: detection of MIPs

Experimental results



Outline

- Introduction.
- CMOS for radiation detection in scientific applications

  Visible light UV

  X-ray Charged particles
- Advanced pixels
- Conclusions

Conclusions

CMOS Image Sensors can be used to detect photons from IR down to low energy X-rays (direct detection), X-rays (indirect detection) and charged particles (direct detection with 100% efficiency) (… and voltages)

Demonstrators built

For some applications, large sensors already built

Working towards delivery of CMOS Image Sensors-based for scientific instruments for space-science, particle physics and bio-medical applications

And last but not least …

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