CCLRC
Rutherford Appleton Laboratory

CMOS Image Sensors
for
non-HEP Applications

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Outline

- **Introduction**
- **CMOS for scientific applications**
  - **Visible light**
  - **UV**
  - **X-ray**
  - **Charged particles**
  - **Voltage**
- **Advanced pixels**
- **Conclusions**

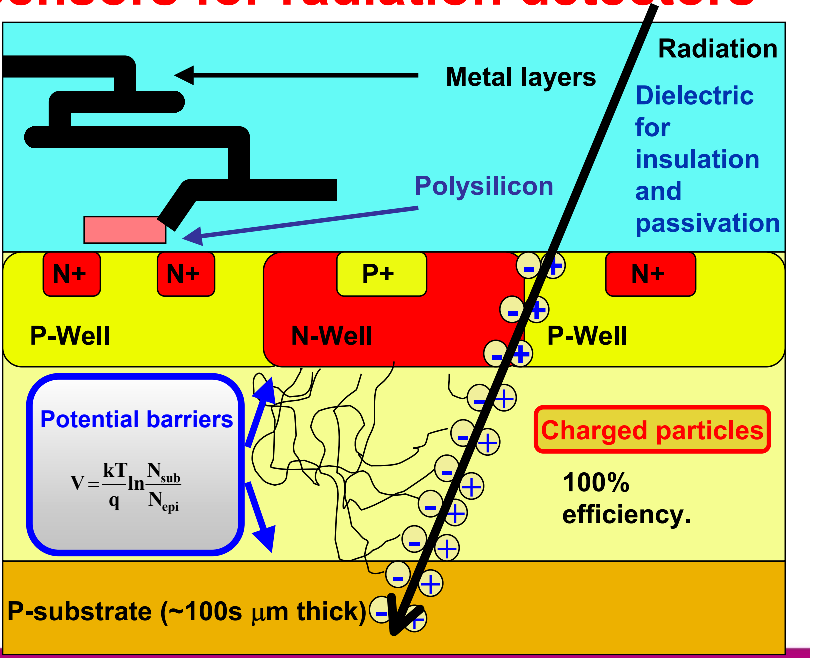
CMOS sensors for radiation detectors

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.



Charged particles

100% efficiency.

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 ?
- 4T transistor with pinned diode
- 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, …

CMOS sensors requirements. 2

- Images can be mainly dark with only a few bright spots
- 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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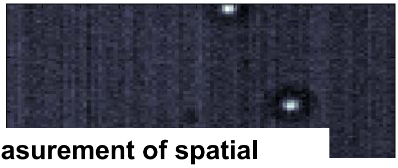
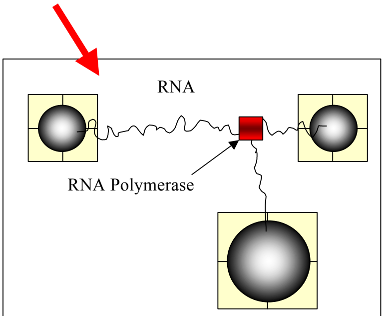
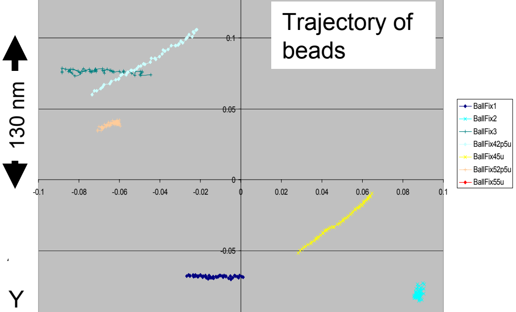
Optical tweezers

- 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.

- Designed within the UK-MI3 consortium
- 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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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

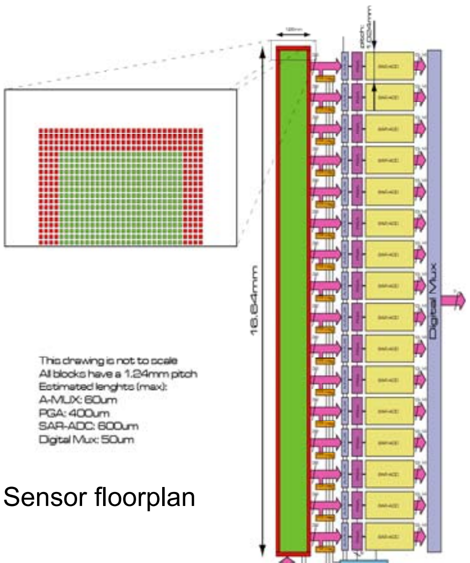
Image size: 5120x7680 = 40Mpixel/image @ 14 bits, ~70MBytes

Integration time per pixel: 10 ms

1.5 D CMOS sensor coupled to scintillator

1.5 D CMOS sensor

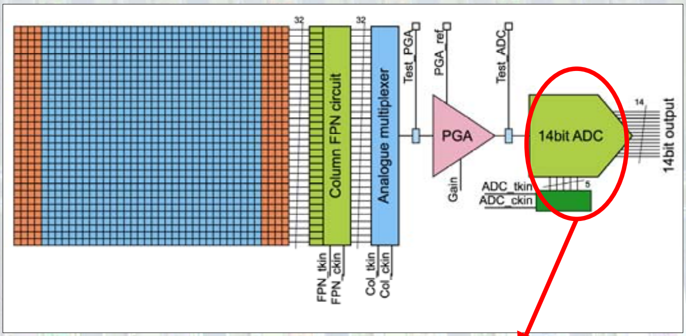
- Designed in 0.35 μm CMOS
- 512*32 pixels at 32 μm pitch plus 4 rows and columns on both sides for edge effects
- 200,000 e^- full well
- 33 to 48 e^- ENC depending on the pixel reset technique used
- more than 72dB S/N ratio at full well (equivalent to 12 bit dyn. range)
- possible to use hard, soft 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 =



This drawing is not to scale
All blocks have a 1.24mm pitch
Estimated lenghts (max):
A-MUX: 60um
PGA: 400um
SAR-ADC: 600um
Digital Mux: 50um

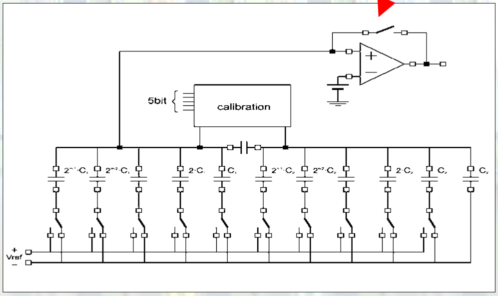
Sensor floorplan

1.5 D CMOS sensor. Architecture.



1 channel ↔ 32x32 pixel

14 bit successive approximation ADC
4 MSB on resistor string
20 MHz clock
16 cycles per conversion ↔ 1.25 MHz conversion rate



Photon Transfer Curve (PTC)

Basic tool for imaging sensors

At high level of illumination, the noise is dominated by the intrinsic source noise, i.e. photon shot noise

If N_{ph} photons are sensed, the output S is $\mathbf{S = G\ N_{ph}}$, where G is the gain, i.e. the response of the sensor to one input photon

The distribution of N_{ph} is Poisson with variance N_{ph}

The variance σ of the output signal is then $\sigma = \mathbf{G^2 \times N_{ph}}$

The ratio between the variance and the output signal is

$$R = \frac{G^2 \times N_{ph}}{G \times N} = G$$

Preliminary measurements

Test beam at
Unstructured (ation

PTC with scin version

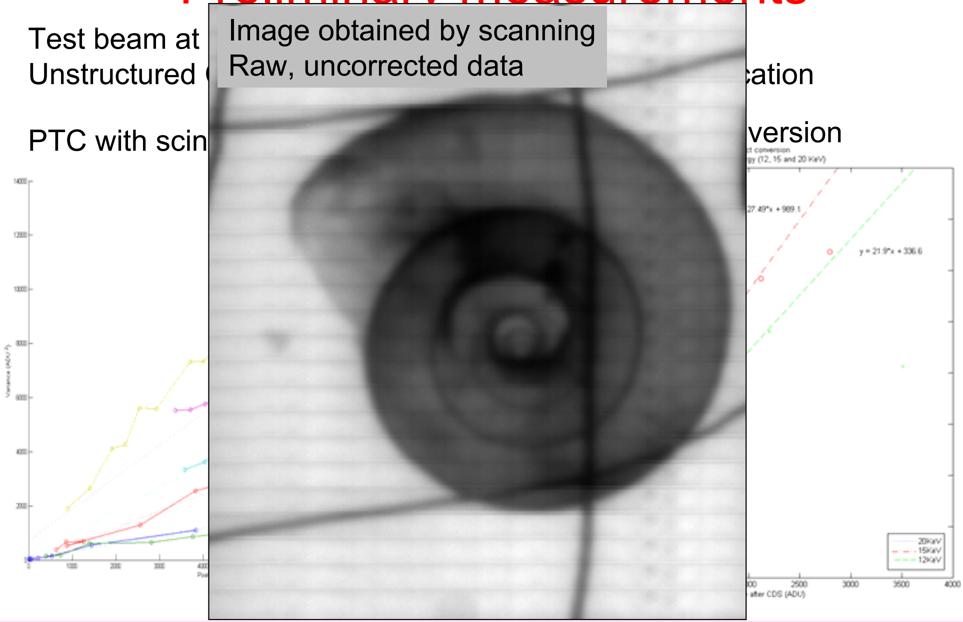


Image obtained by scanning
Raw, uncorrected data

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APS for Neuroscience (NAPS)

Goal of the project: study the spiking rate of a large number of neurons in parallel, each neuron being located with good spatial resolution across the surface of the visual cortex and with some depth discrimination.

Project involving the Universities of Birmingham, Oxford, Cambridge and Berkeley (US) and RAL.

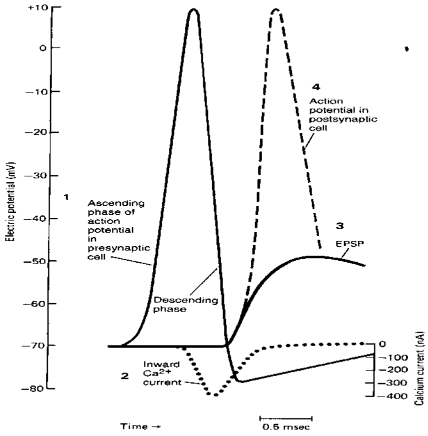


FIGURE 13–5
Time course of four events related to synaptic transmission. An action potential in the presynaptic cell (1) causes presynaptic Ca^{2+} channels to open and a Ca^{2+} current (2) to flow into the terminal leading to the release of neurotransmitter from the terminal. (Note that the Ca^{2+} current is turned on late during the falling phase of the presynaptic action potential.) The postsynaptic response to the transmitter (EPSP) begins soon afterward (3), and, if sufficiently large, will trigger an action potential in the postsynaptic cell (4). (Adapted from Llinás, 1982.)

The detecting principle

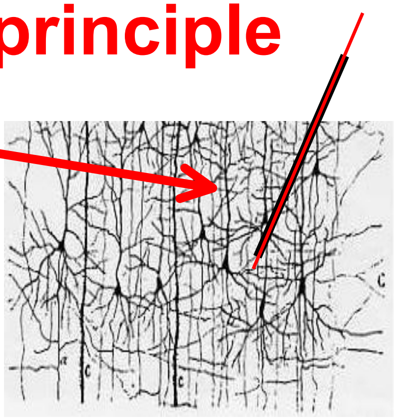
Present techniques:

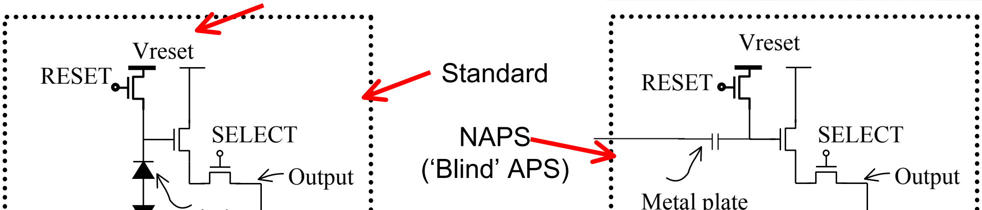
- Electrical: thin wires inserted in cortex
- Imaging: NMR and fluorescence.

Spatial and time resolution not good enough

What we propose:

Modified APS for contact imaging





Standard

NAPS
('Blind' APS)

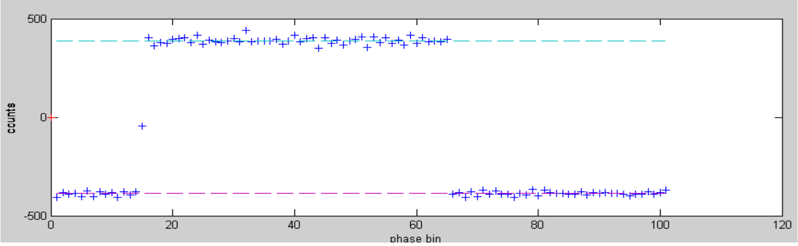
Proof of principle

Small test structure:

Small 8x8 test structure designed in 0.25 µm CIS. 15 µm pitch.

Detection of voltages. Good linearity.

300 Hz
square wave



What is next:

Target: 256x256 NAPS, 25 µm pitch, 100 µs frame rate, ROI, 12 bit resolution, low noise

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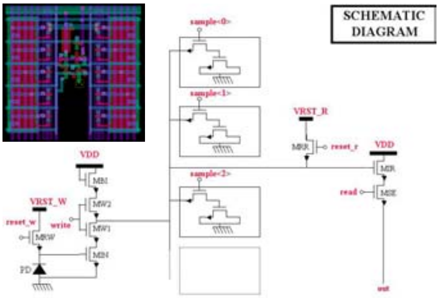
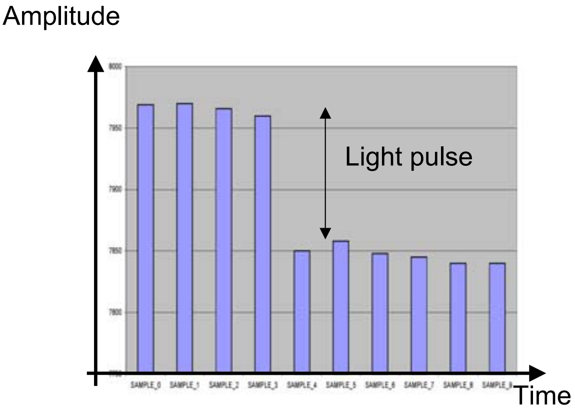
Flexible Active Pixel Sensor



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

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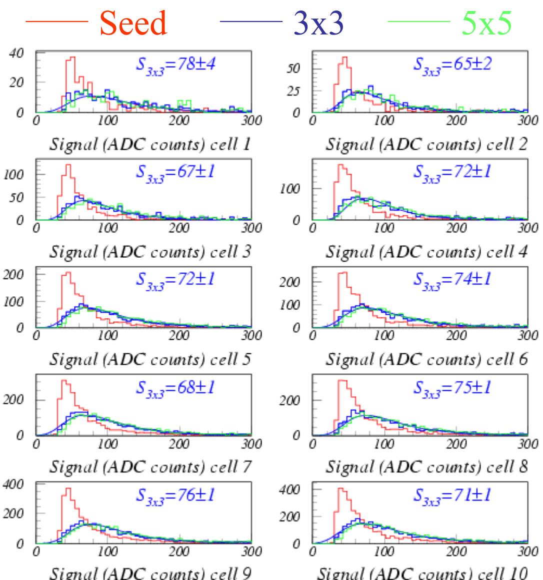
FAPS. Signal distribution

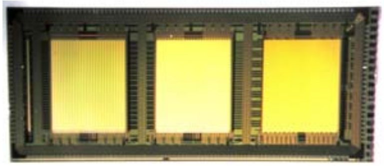
- Test with source
- Correlated Double Sampling readout (subtract $S_{cell\ 1}$)
- Correct remaining common mode and pedestal
- Calculate random noise
  - Sigma of pedestal and common mode corrected output
- Cluster definition
  - Signal >8σ seed
  - Signal >2σ next
- Note hit in cell *i* also present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

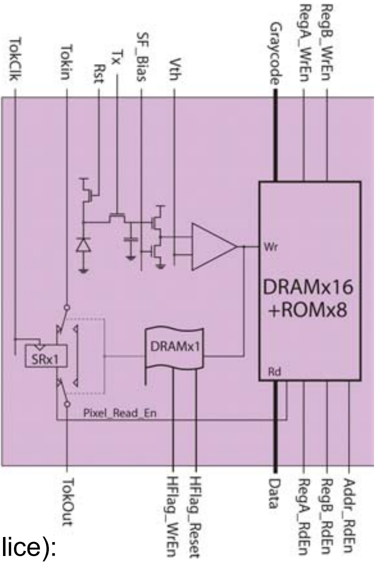


OPIC (On-Pixel Intelligent CMOS Sensor)

- 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 the ILC-ECAL (Calice): detection of MIPs + time stamps at 150 ns resolution over 2 ms

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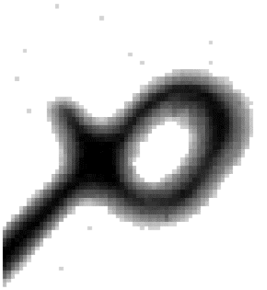
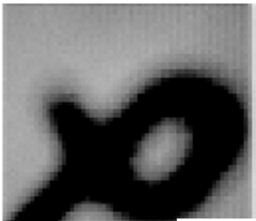
Experimental results

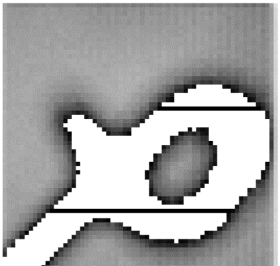
In-pixel ADC



Timing mode capture



In-pixel thresholding



Sparse data (timing mode)

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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

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