CMOS monolithic APS: Developments and future outlook

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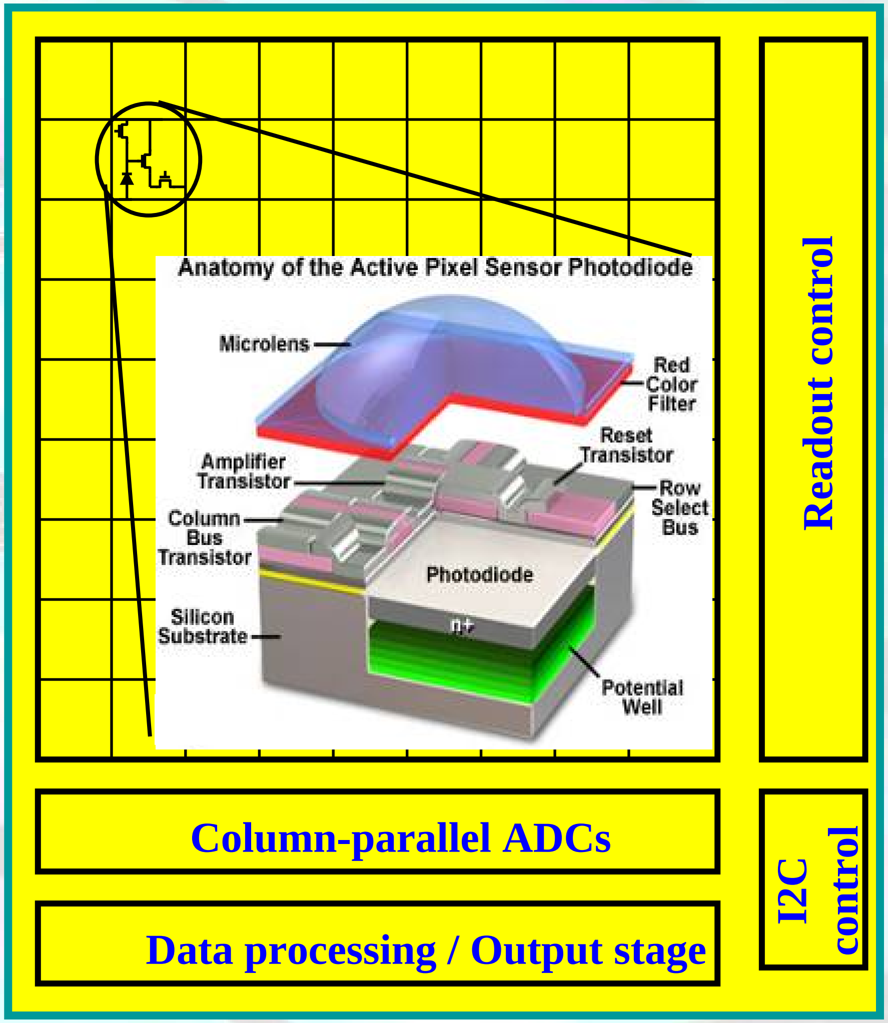
Outline

- Introduction.
- CMOS image sensors for science
  - Visible light
  - UV
  - X-ray
  - Charged particles
  - Voltages
- Future and conclusions

CMOS Monolithic Active Pixel Sensor (MAPS)

(Re)-invented at the beginning of '90s: JPL, IMEC, …

- **Standard CMOS technology**
- **all-in-one detector-connection-readout = *Monolithic***
- **small size / greater integration**
- **low power consumption**
- **radiation resistance**
- **system-level cost**
- **Increased functionality**
- **increased speed (column- or pixel- parallel processing)**
- **random access (Region-of-Interest ROI readout)**

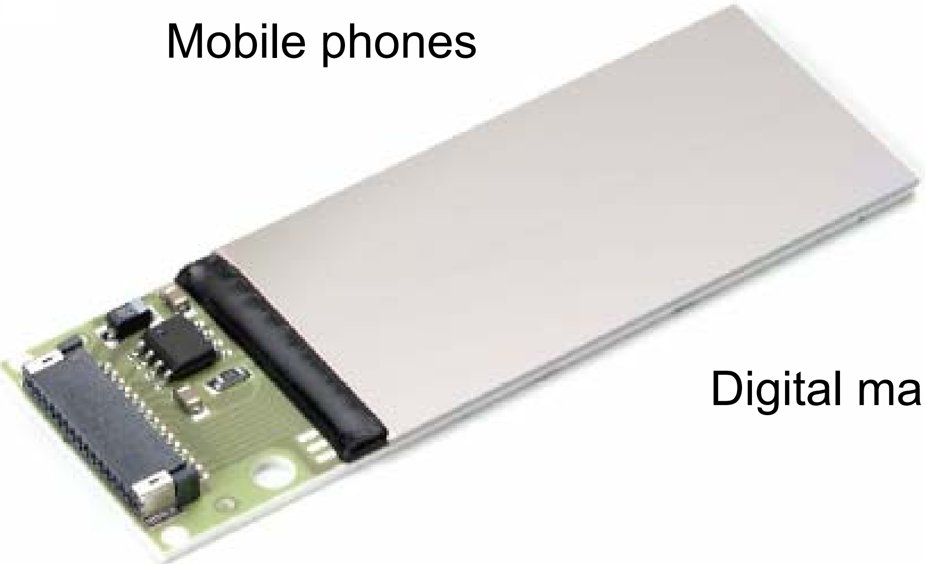


CMOS sensors in digital cameras

Consumer/prosumer
Digital cameras

Mobile phones

Digital intraoral imaging



Digital mammography

Web
cams

CMOS Image Sensor Technology. 1

In general, any CMOS process have different flavours.

The basic one is digital. Then MixedMode/RF, High Voltage, …, CIS (CMOS Image Sensor).

Transistors don't change. Modules added: high value resistors, linear capacitors, …

For CIS:

one/two masks/implants added to improve image quality / reduce leakage current

CMOS Image Sensor Technology. 2

Masks for colour filters, microlenses. Special BEOL for improved oxide transmission

Stitching for sensors larger than reticle is becoming more common due to push for 35mm film replacement

0.18μm available, 0.13μm starting this year in different places. Pixel transistors still at 0.35μm equivalent

Epitaxial wafers are generally used: better quality, reduced cross-talk

Thickness: depends on foundry, generally up to 20 μm thick epi layer

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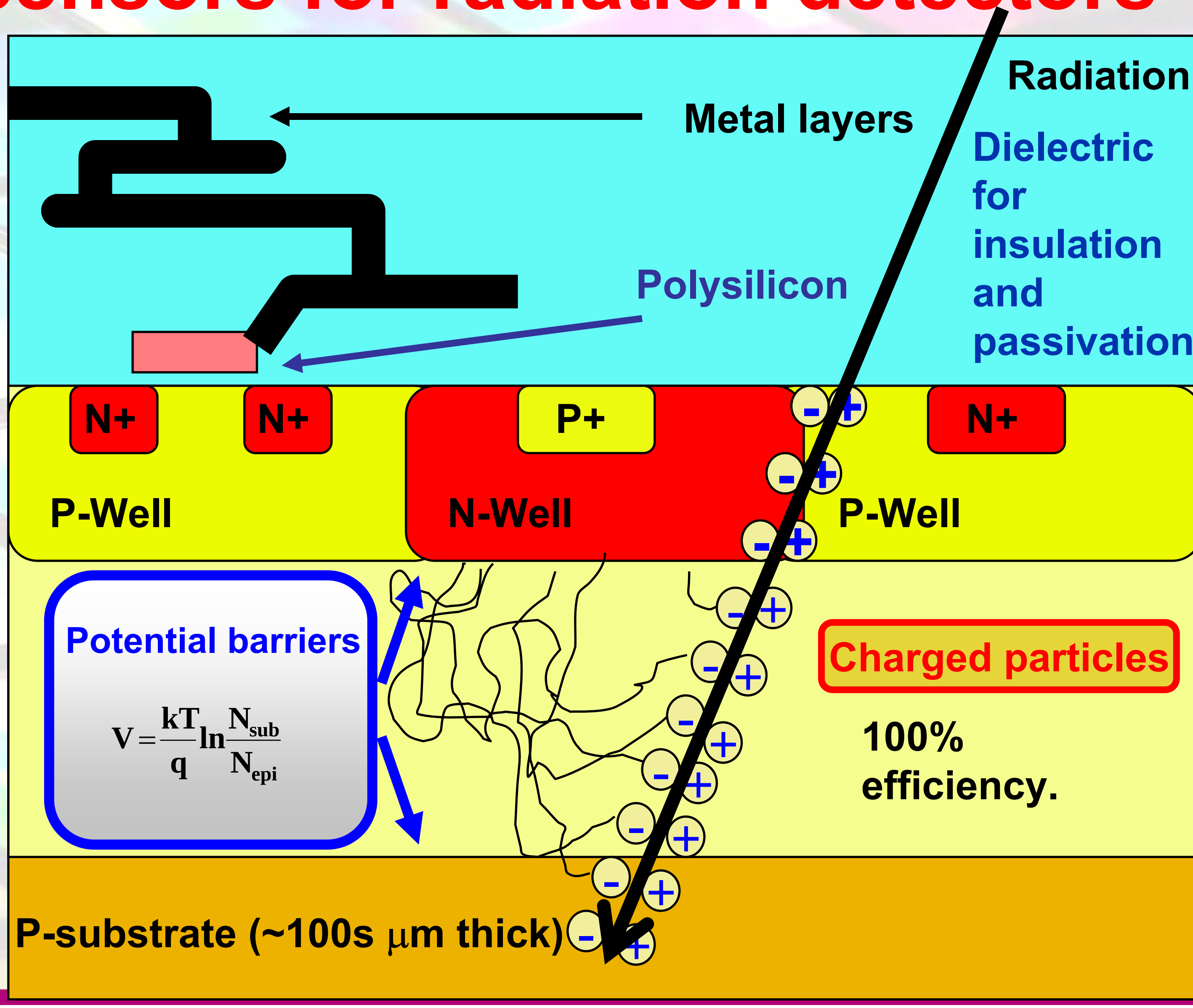
CMOS sensors for radiation detectors

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.



Applications for RAL CMOS MAPS

- 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, optical tweezers,
- Medicine: mammography, panoramic dental
- …

Detecting:

- Photons: visible, UV, EUV, X-ray (with scintillators), …
- Charged particles: MIPs, low/medium energy electrons (few keV up to 1 MeV)
- Voltages (!)

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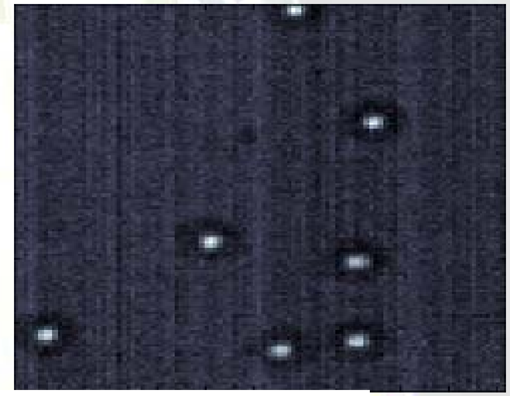
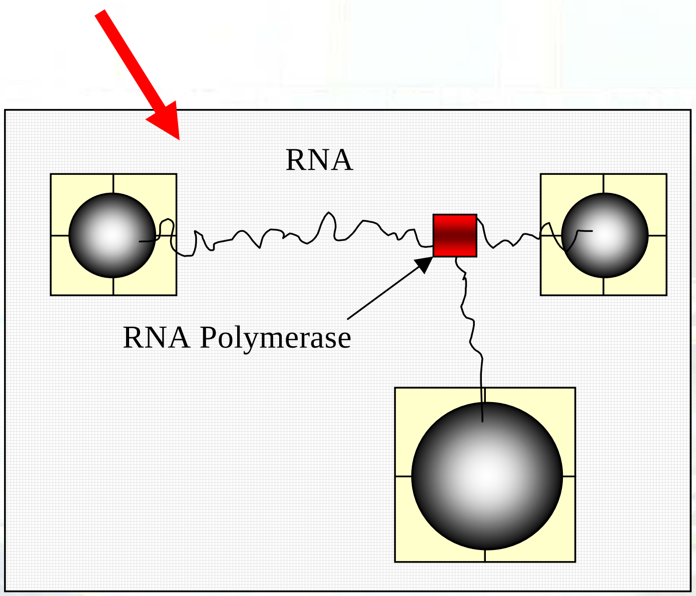
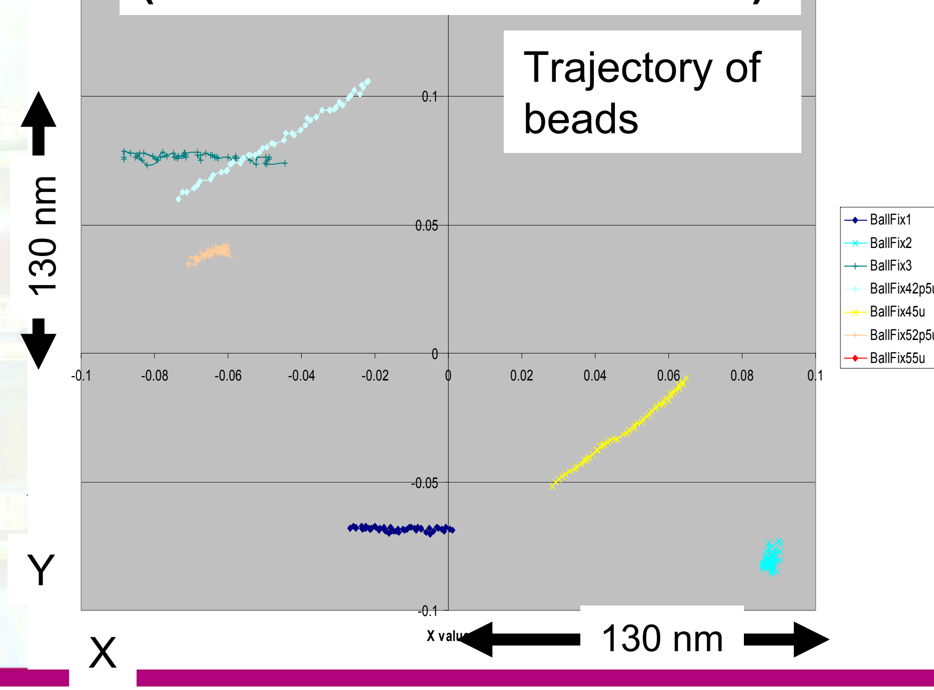
Optical tweezers



- 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. 1

- Designed within the UK-MI3 consortium (http://mi3.shef.ac.uk), aiming at developing novel CMOS APS
- Large pixels: 25 μm, design in 0.35 μm CMOS
- Epitaxial layer thickness: choice of 14 and 20 μm
- Backthinned version will be available end of this year
- Format 512x512 + black pixels (520x520 full format)
- 3T pixel with flushed reset
- Noise < 25 e- rms
- Full well capacity > 10^5 e-
- DR ~ 4000 ~ 12 bits
- On-chip SAR ADCs, one for 4 columns. Selectable resolution: 10 or 12. Adjustable range.

Vanilla sensor. 2

- Analogue output at 4.5 MHz
- Row and column address decoder
- *Full frame readout*: Frame rate > 100 fps.
- *Region-of-interest readout*: Fully programmable: any shape, any size
  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! It will be also tested for UV and electrons
- Data rate: > 40 MByte/sec in full frame mode
- Readout based around off-the-shelf FPGA development boards (VirtexII-Pro) plus optical link (Gbit at present but already testing 10Gbit)

Vanilla sensor.

- Sensor fully functional
- Already region-of-interest readout already tested at over 20 k fps
- Characterisation just started
- Preliminary results consistent with specifications

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Medical X-ray detection

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

Led by prof. R. Speller (University College London, UCL)

Application: mammography, dental (panoramic and cephalography)

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

Step-and-shoot, and double scan

Time for 1 image: a few seconds. Large pixels: 32 μm

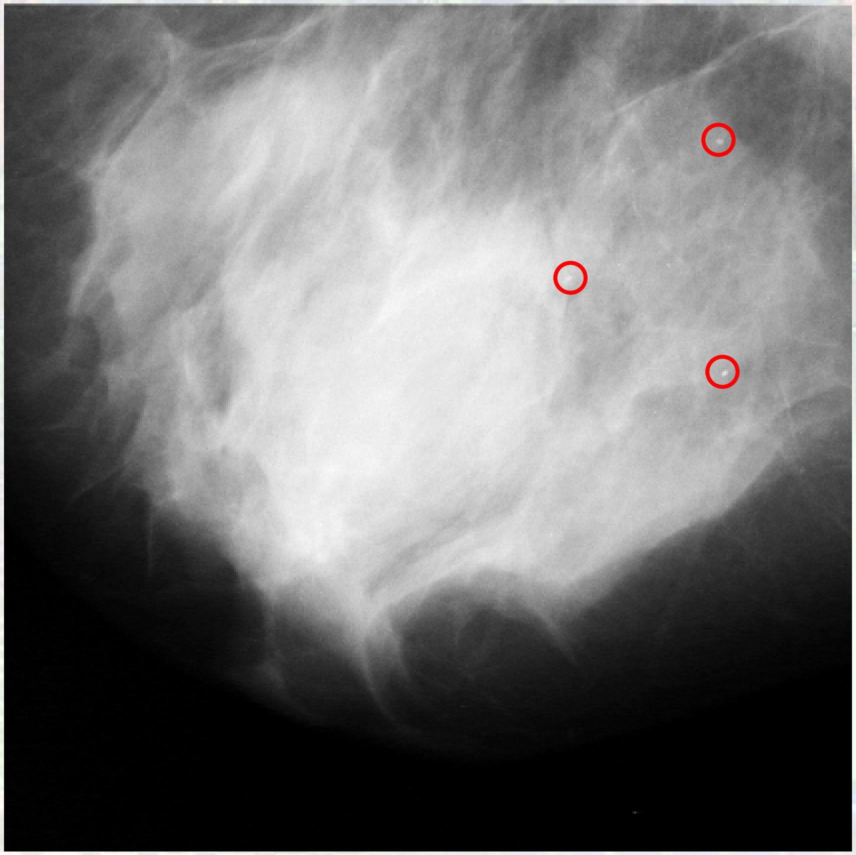
Image area: 18cmx24cm covered by several sensors in several steps

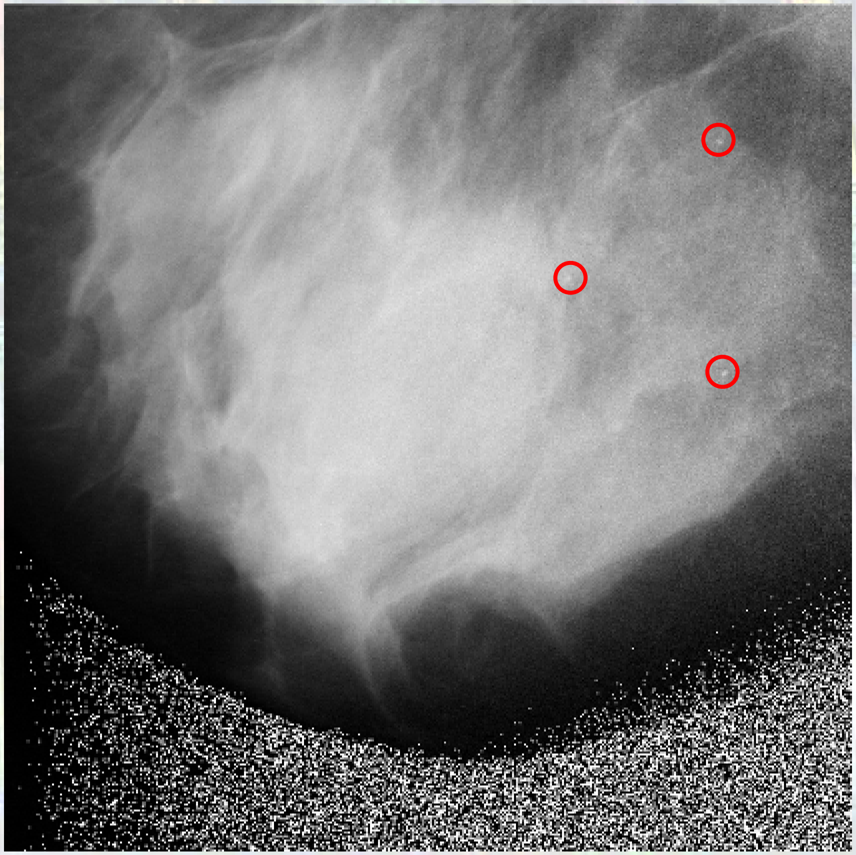
Image size: 5120x7680 = 40Mpixel/image @ 14 bits, ~70MBytes

Integration time per pixel: 10 ms

1½D CMOS sensor coupled to scintillator (structured CsI)

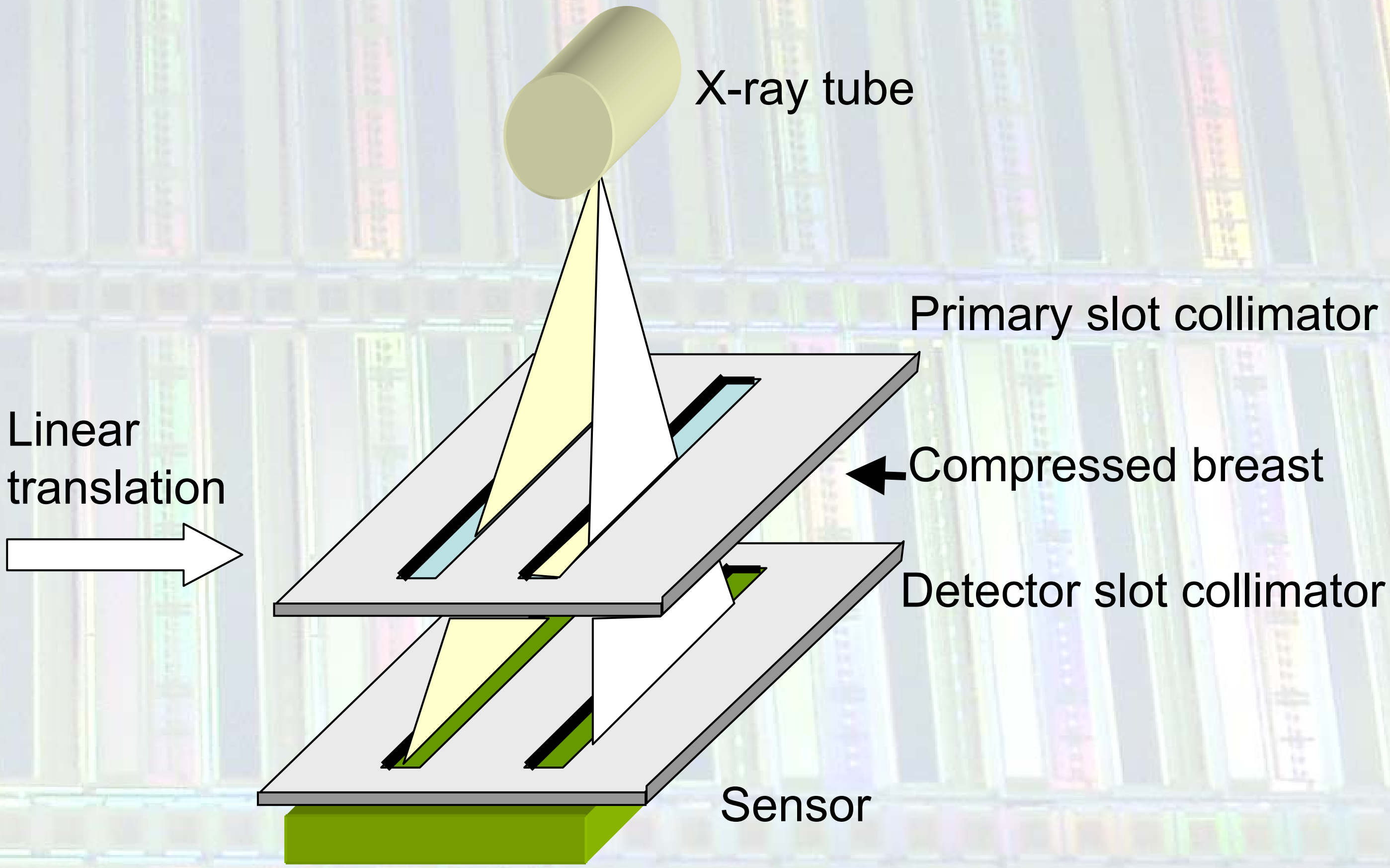
Expected results





Simulated mammography scan that uses 18% lower dose
(image courtesy of Prof. R.Speller - UCL)

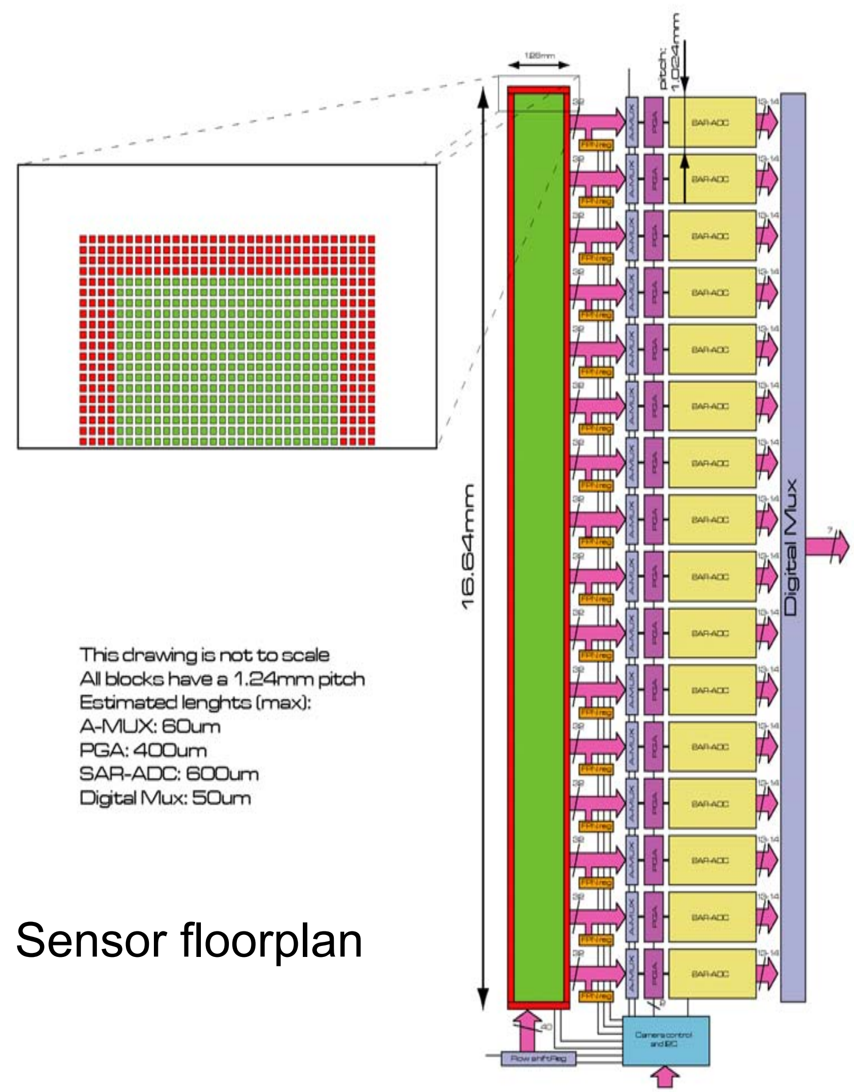
The X-ray camera



Example of mammography application
(image courtesy of Gary Royle - UCL)

1½D CMOS sensor

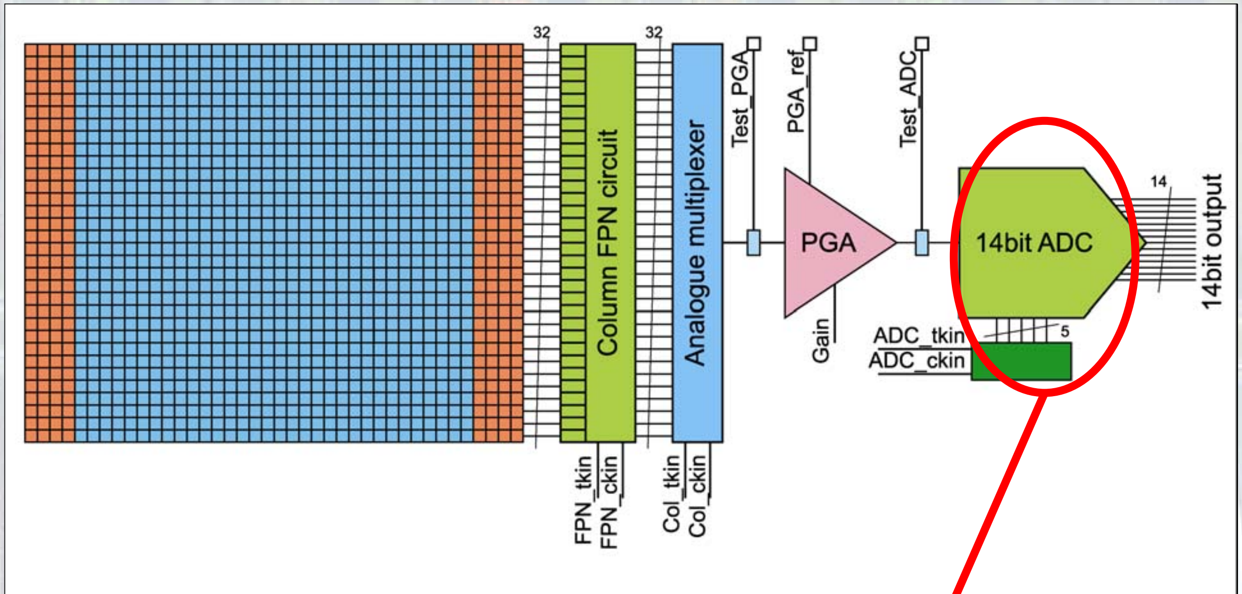
- Designed in 0.35 μm CMOS
- 512*32 pixels at 32 μm pitch plus 4 rows and columns on both sides for edge effects
- 200,000 e^- full well
- 33 to 48 e^- ENC depending on the pixel reset technique used
- more than 72dB S/N ratio at full well (equivalent to 12 bit dyn. range)
- possible to use hard, soft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



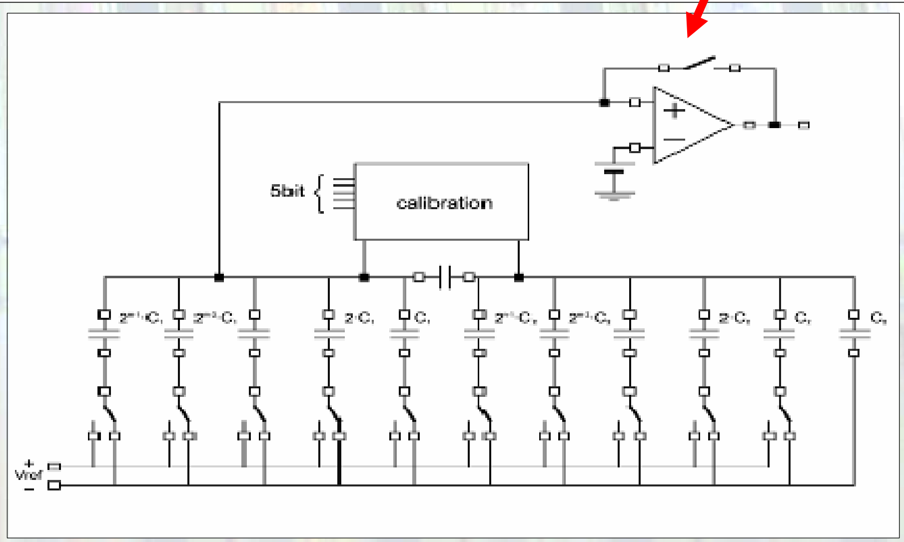
Sensor floorplan

1½D 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 σ $\mathbf{= G^2 \times N_{ph}}$

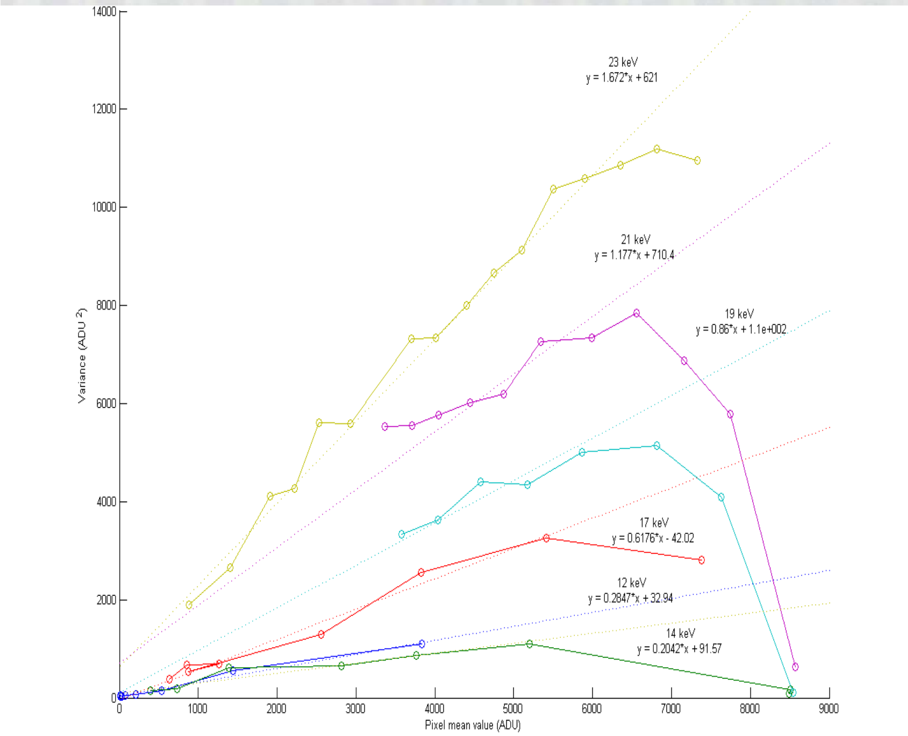
The ratio between the variance and the output signal is

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

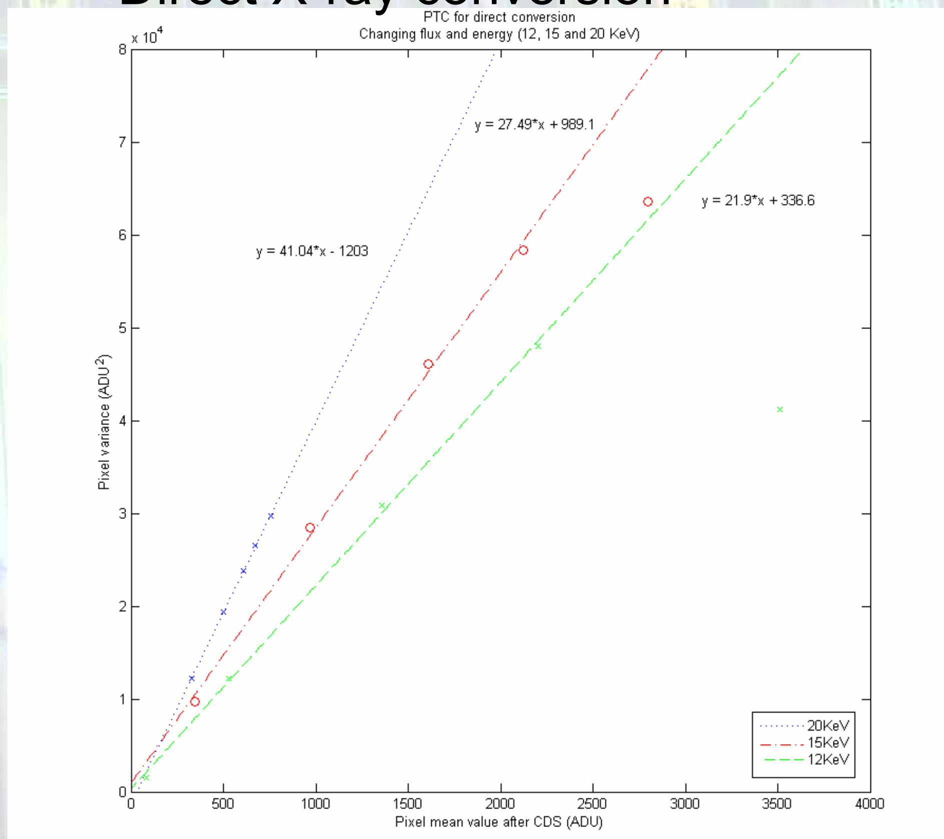
Preliminary measurements

Test beam at Elettra synchrotron, Trieste, Italy
Unstructured CsI scintillator, non optimum for the application

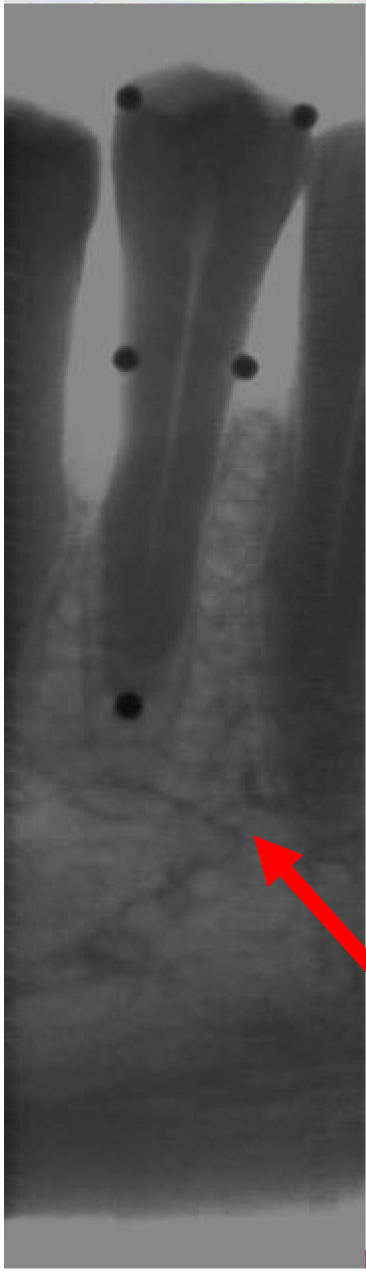
PTC with scintillator



Direct X-ray conversion



First preliminary images



Test at University College London (UCL). CsI scintillator on MAPS.

Images stitched with the correct overlap, corrected for dead pixel lines and, where possible, corrected for intensity variations both across the sensor and down the image (scan position). They were not fully corrected for dark noise nor using a true white field image, and so the final systems images will be superior to these.

Image of a tooth. Taken at 70 kVp, 6 mA

Image of the sensor PCB. Taken at 75 kVp, 4 mA

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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.

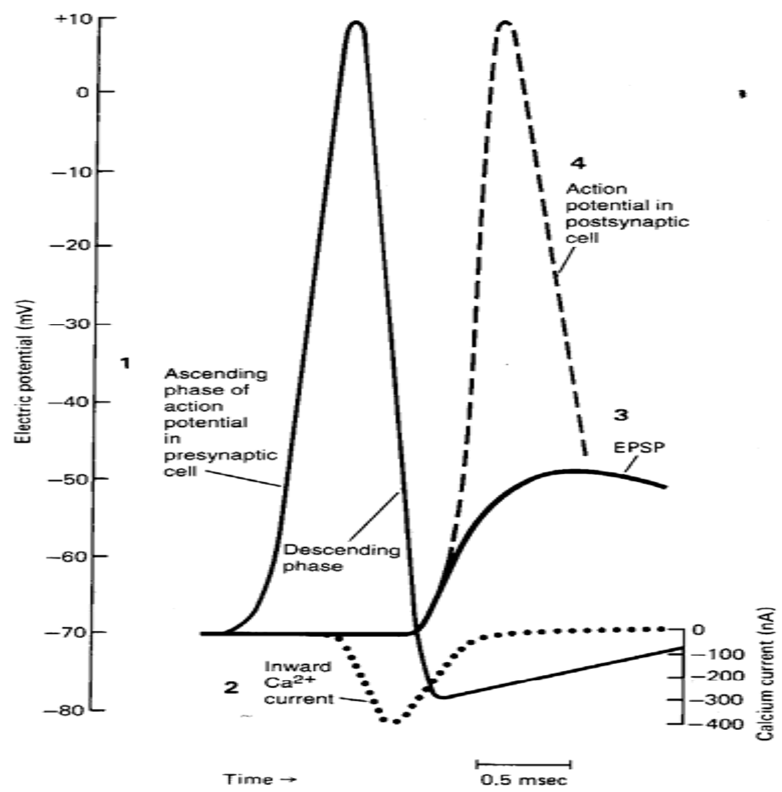


FIGURE 13–5
Time course of four events related to synaptic transmission. An action potential in the presynaptic cell **(1)** causes presynaptic Ca^{2+} channels to open and a Ca^{2+} current **(2)** to flow into the terminal leading to the release of neurotransmitter from the terminal. (Note that the 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

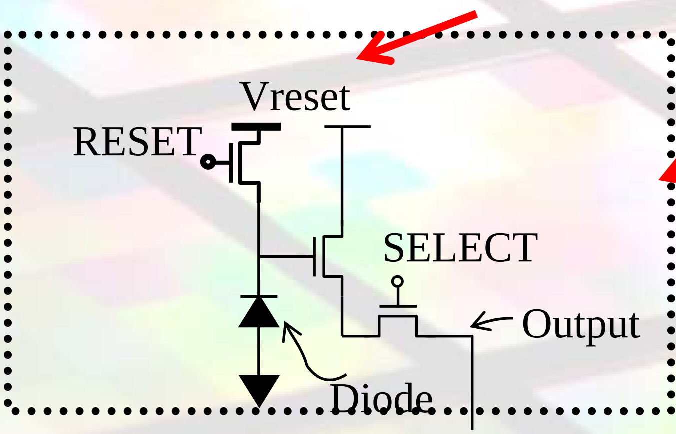
Present techniques:

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

Spatial and time resolution not good enough

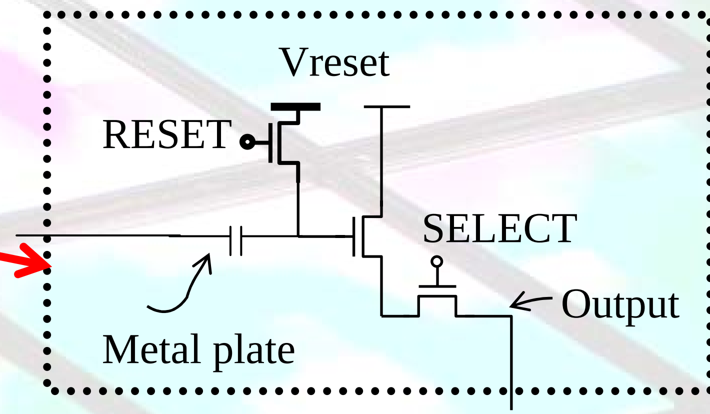
What we propose:

Modified APS for contact imaging



Standard

NAPS ('Blind' APS)



Proof of principle

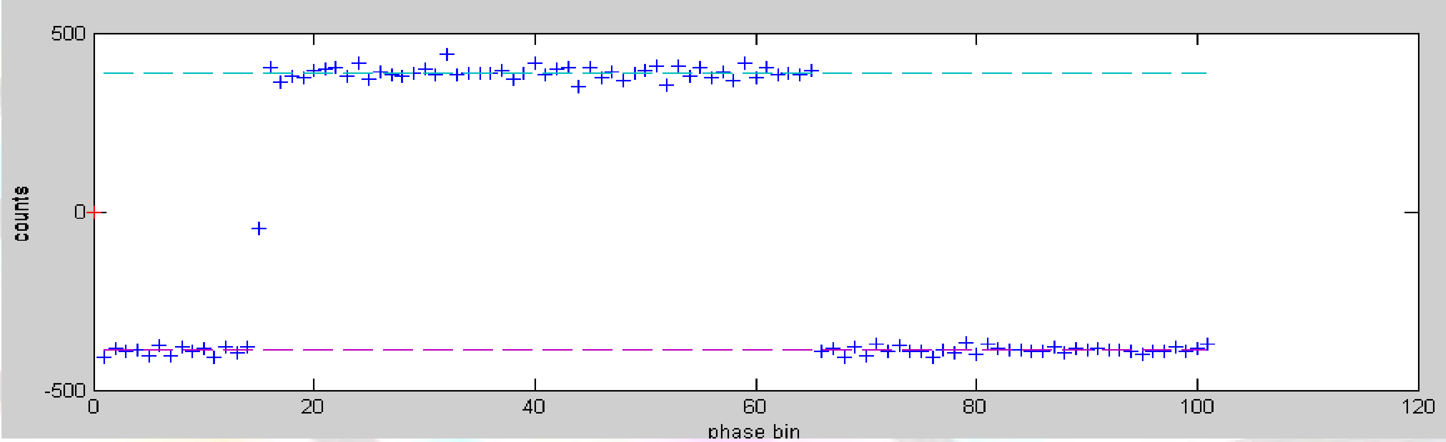
Small test structure:

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:

NAPS sensor designed for this application: 256x192 25-μm pixels, 4 differential ports, each @ >~ 10MHz, 50-100 μs frame rate, ROI, 12 bit resolution. Up to 160 MByte/sec for minutes/hours acquisition.

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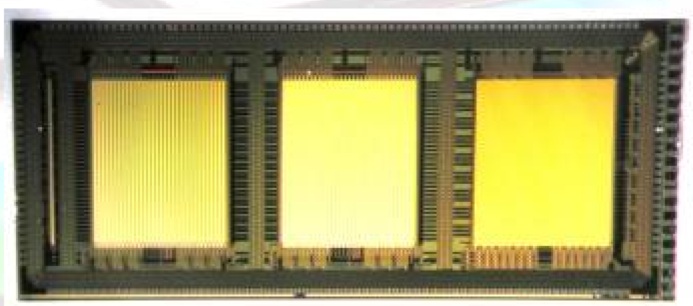
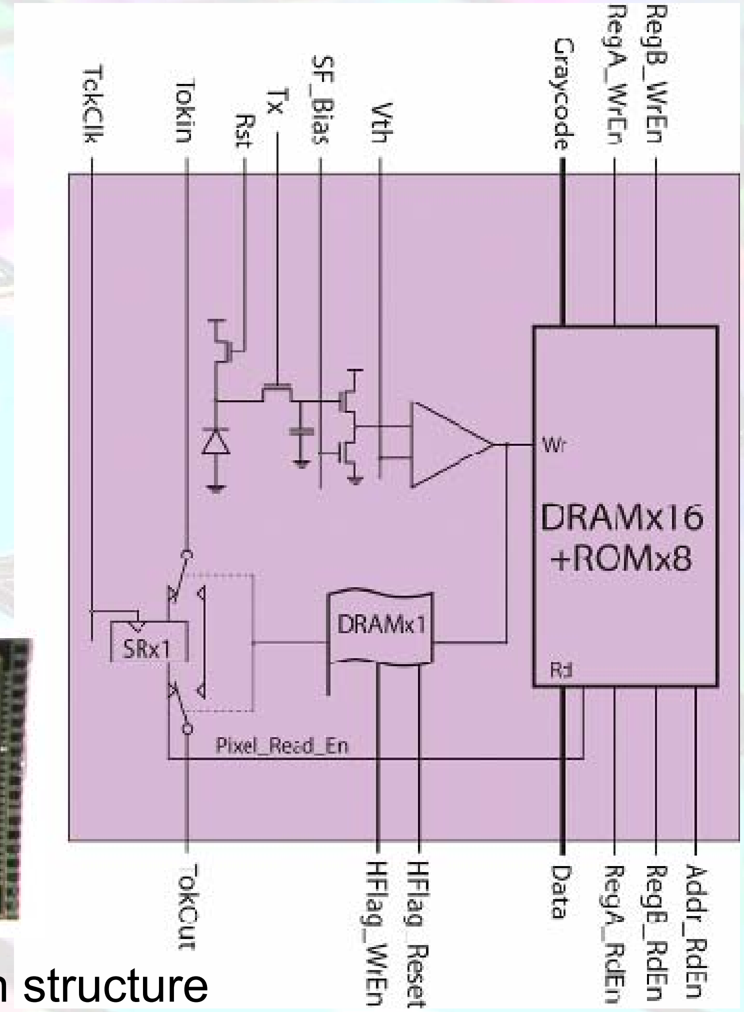
OPIC (On-Pixel Intelligent CMOS Sensor)

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

Test structure. Proof-of-principle.
3 arrays with different designs.
Each 64x72 pixels @ 30 μm pitch
Fabricated in 0.25 μm CMOS logic technology

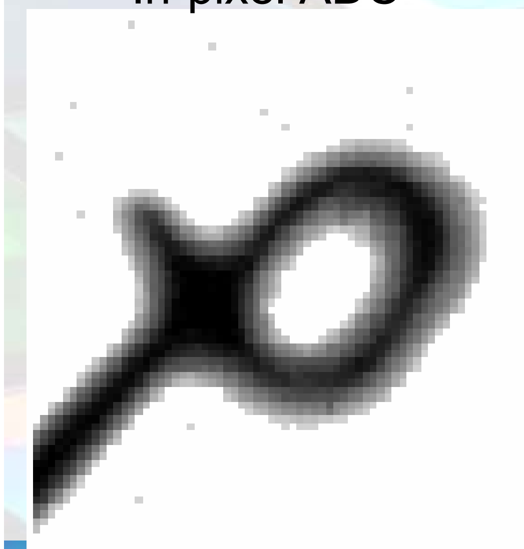




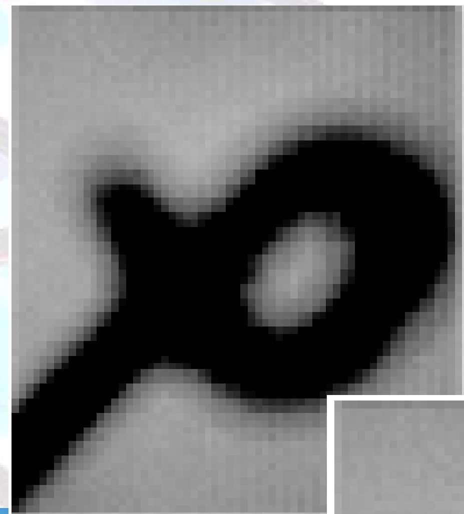
Measured noise floor: 40-60 e- rms depending on structure
(results from S. Bondiek-K. Arvanitis, UCL).

Modes of operation (experimental).

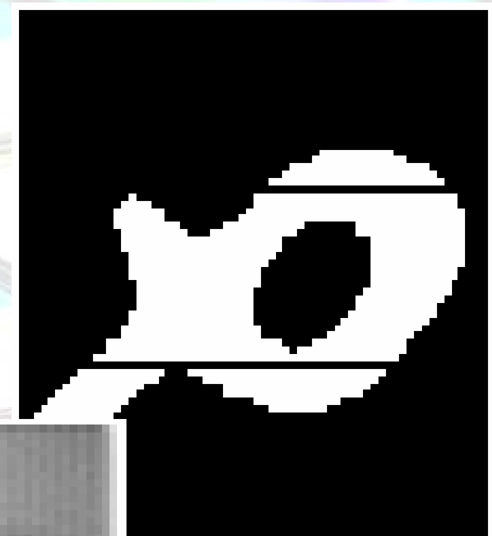
In-pixel ADC

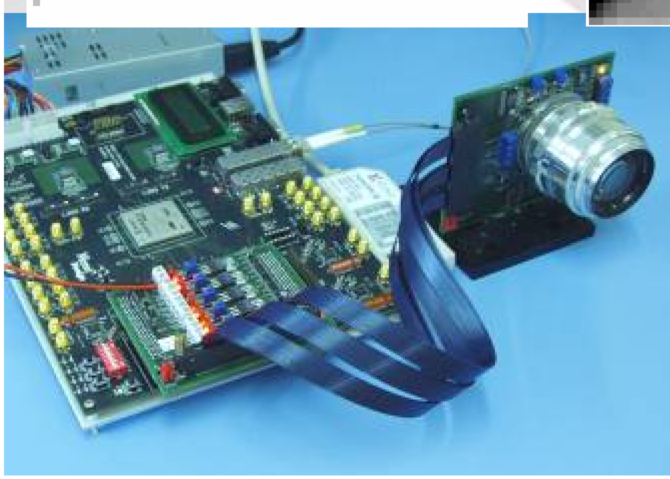


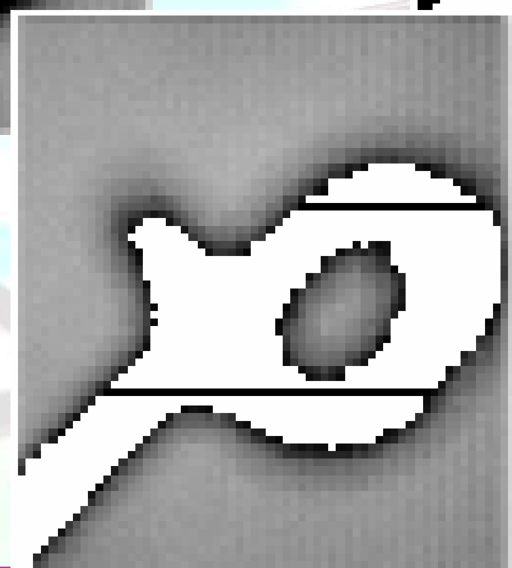
Timing mode capture



In-pixel thresholding







Sparse data
(timing mode)

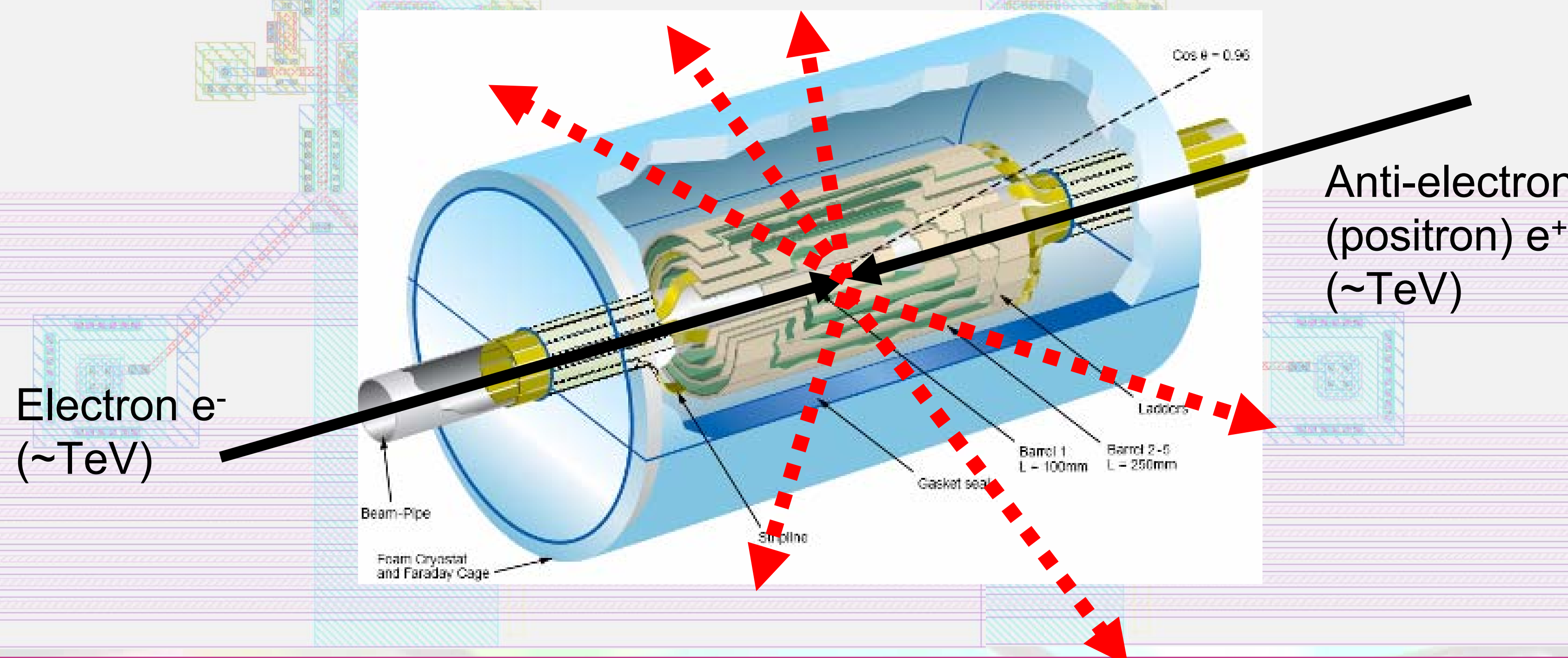
International Linear Collider

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: **~m^2** for Vertex (FAPS design), a few **10^3 m^2** for Electromagnetic calorimeter



Calorimeter for the Linear Collider Experiment (CALICE)

UK collaboration (Birmingham, Cambridge, Imperial College, Manchester, RAL, RHUL and UCL) is developping also a MAPS version of the calorimeter. Sensor designed by RAL.

Present specification: large (50x50 μm) pixels, measurement of hit timing with BCO precision (>~ 150 ns).

Present architecture: groups of pixels with 'common' digital area. Device simulation helps layout definition.

Designed in an advanced 0.18 μm CIS process, fully stitchable.

R&D just started. First test structures expected spring 2007.

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Future

CMOS Image Sensors (CIS) technology become more and more widespread. Continuous improvement in noise: reduced leakage current, in-pixel double correlated sampling (4T+pinned diodes)

More foundries proposing stitching

Continuous improvement in noise: reset noise reduction by design. New architectures and ways of modelling the reset noise.

Single figure (< 10 e- rms) noise achieved, approaching sub-electron noise (one group already declares it for a linear, non-cooled sensor!)

Conclusion

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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I. Thomson (Oxford University)

D. Tolhurst (Cambridge University)

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+ ... all the others I forgot to mention!