Science & Technology Facilities Council

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CMOS solutions for scientific imaging

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Outline

- Introduction
- Technology
  - Radiation hardness
  - In-pixel signal processing
- Applications
  - Transmission Electron Microscopy (TEM)
  - X-ray detection
  - Mass Spectroscopy (MS)
- Conclusions

Introduction

CMOS image sensors for scientific applications

- Low Noise
- High dynamic range
- Linearity
- Sensitivity
- Radiation hardness
- In-pixel processing
- Fast Readout
- Large Area
- Quantum efficiency

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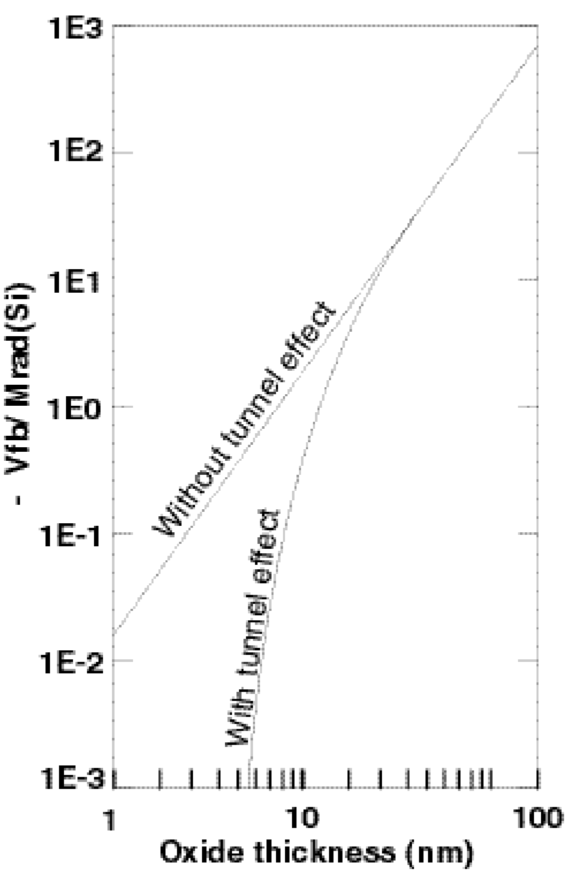
Technology

Radiation hardness

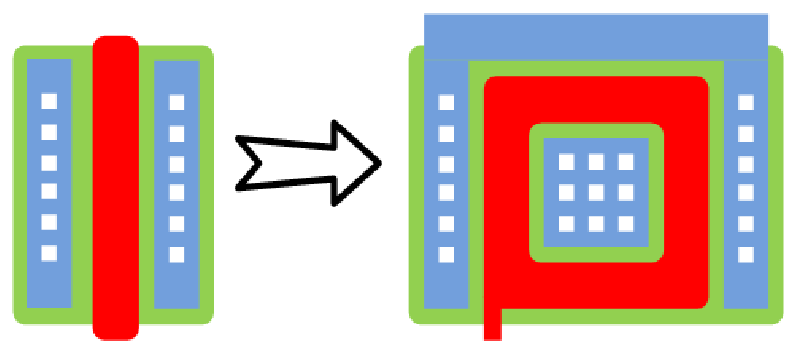
Threshold shift



From Saks, IEEE Trans. Nucl. Sci., vol. NS-31, p. 1249, 1984.

Radiation can create positive charge at the thin/thick oxide interface (bird's beak) that can short-circuit source and drain of the MOS transistors.

Enclosed geometry transistors (ELT) and guard-rings can be used in the entire layout to enhance the radiation resistance of the sensor.



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Technology

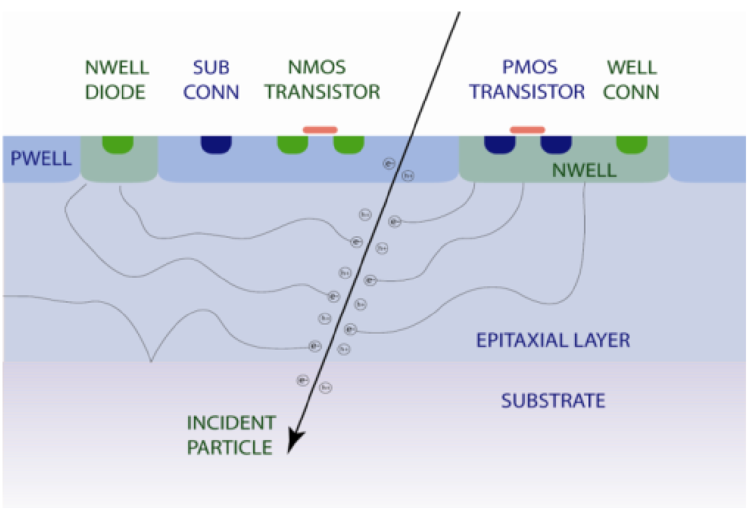
In-pixel signal processing

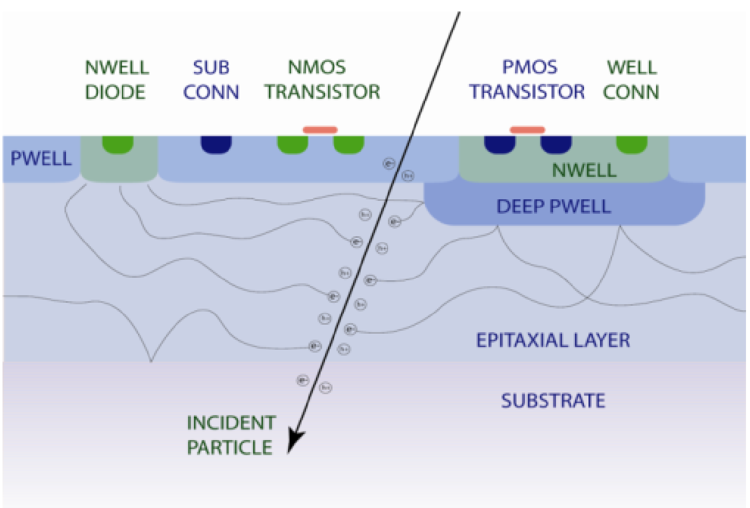
MAPS pixels generally *exclude* pMOS transistors

- Their N-well reduces charge collection efficiency
- Applies to light / particles

Regular imaging applications generally have no need for pMOS transistors in pixel

- Scientific applications sometimes do





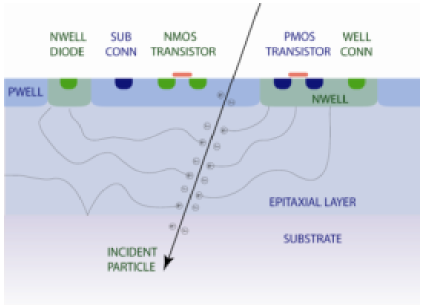
Technology

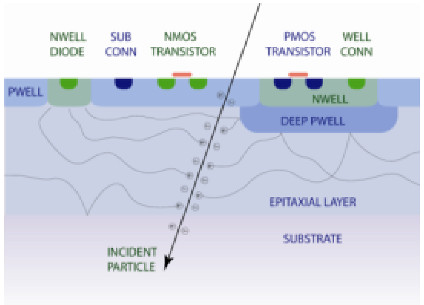
In-pixel signal processing

STFC-RAL CMOS Sensor Design Group has developed, in cooperation with a leading foundry, the **INMAPS** process, to allow in-pixel electronics.

INMAPS gives the opportunity to implement

- Analog pre-processing
- Threshold discrimination
- Logic - "intelligence"
- Per pixel trim/mask adjustment
- Data sparsification
- Image processing





- 0.18 μm commercial CMOS Image Sensor (CIS) process
- 4T pinned photodiodes
- Choice of epitaxial layer thickness
- Multi-project runs for prototyping

- Deep p-well
- High resistivity substrates
- Stitching

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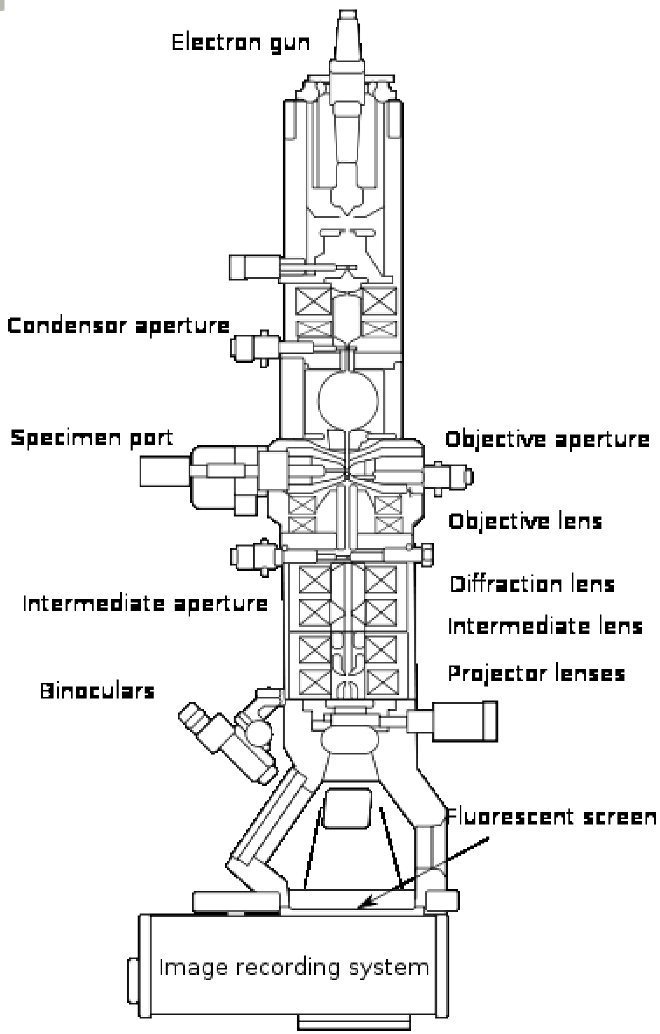
TEM

Transmission Electron Microscopy



In TEM (Transmission Electron Microscopy) a beam of electrons is transmitted through a very thin specimen.

Some electrons will pass though and are collected using an image recording system.

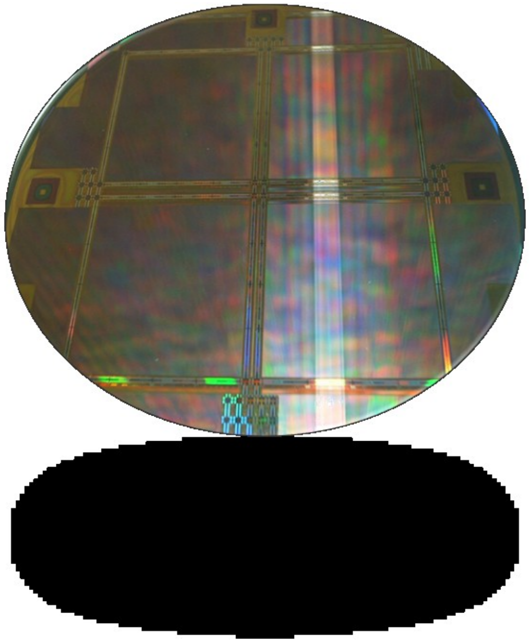
- Film: direct detection, very good resolution, non digital, needs time for development, poor S/N for weak exposure.

- CCD with phosphor: not direct detection (radiation hardness), phosphor ruins spatial resolution, good for tomography.

TEM

Transmission Electron Microscopy

CMOS sensors allow direct detection, good spatial resolution, good sensitivity (single electron detection).

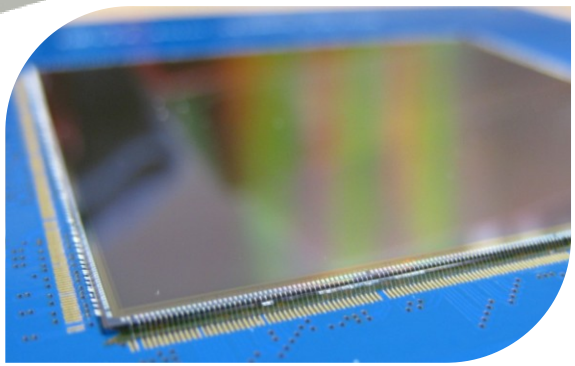


- 4k by 4k pixel array.
- Good spatial resolution.
- Good full well capacity (tens of primary electrons).
- Low Noise (enough for single electron detection).
- Radiation hardness. Lifetime up to $30*10^6$ primary electrons/pixel @300 keV

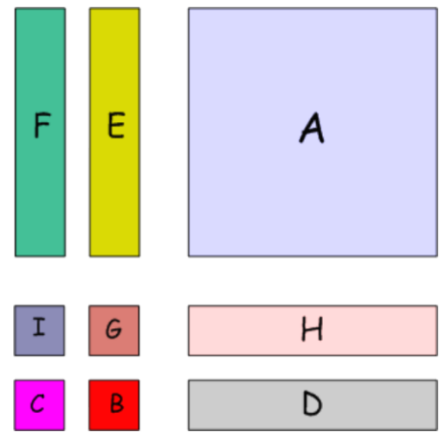
During the project development other features have been taken into account, like the use of a standard CMOS process, high readout rate, ROI readout, pixel binning, high yield.

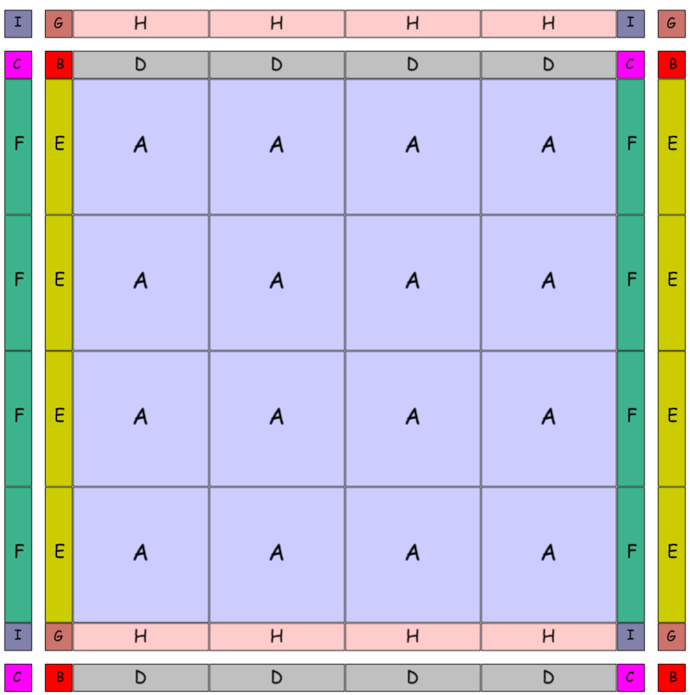
TEM

Transmission Electron Microscopy



The sensor is well beyond the reticle size and its fabrication is possible using a technique called **stitching**.



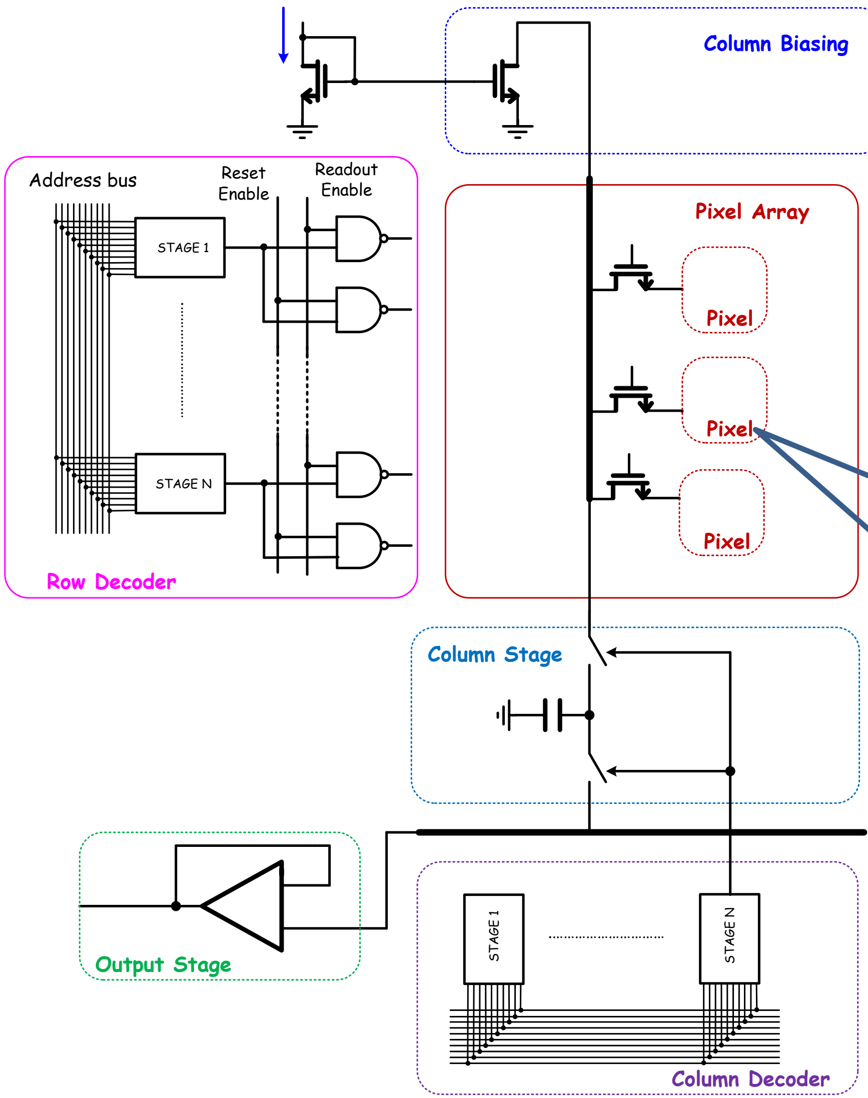


Above the reticle is shown and on the left the final result.

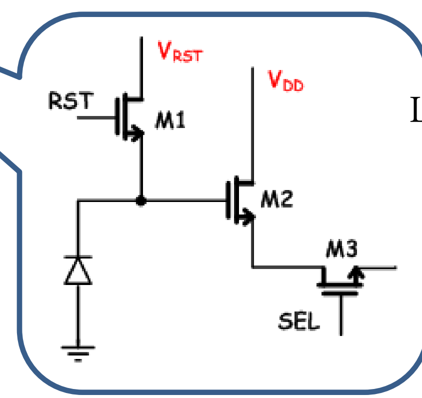
The fabricated sensor is obtained by stepping and repeating until the desired size is achieved.

TEM

Transmission Electron Microscopy



The sensor is based on a 4K by 4K pixel array fully addressable with the possibility of ROI readout. The ROI are controlled by two independent address buses and can be changed "on the fly".

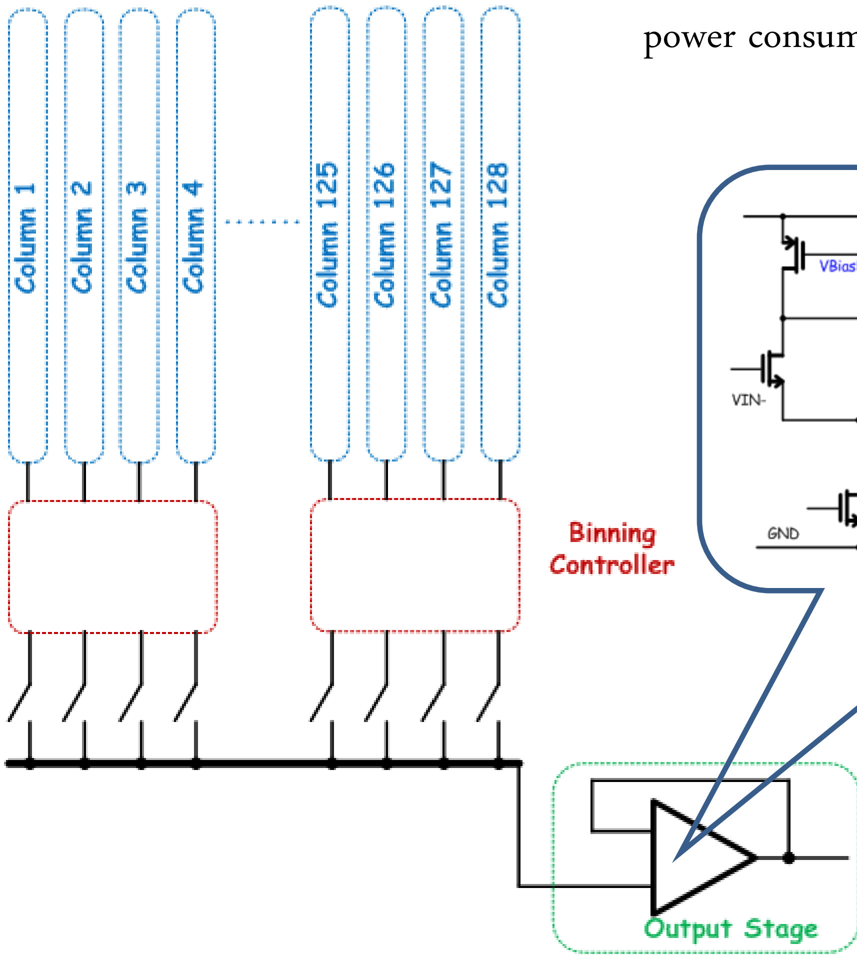


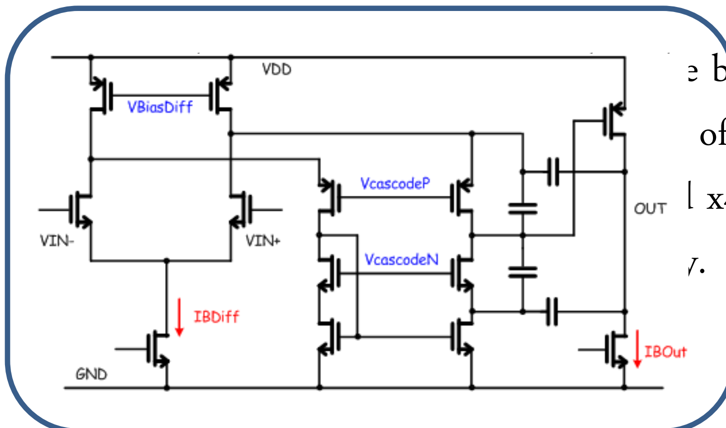
Pixel is a 3T one because of its radiation hardness.

Less transistors will improve also the yield.

Sampled data are stored at the bottom of the array.

Sensor architecture is based on a fully analogue readout chain to improve power consumption and the overall sensor yield.





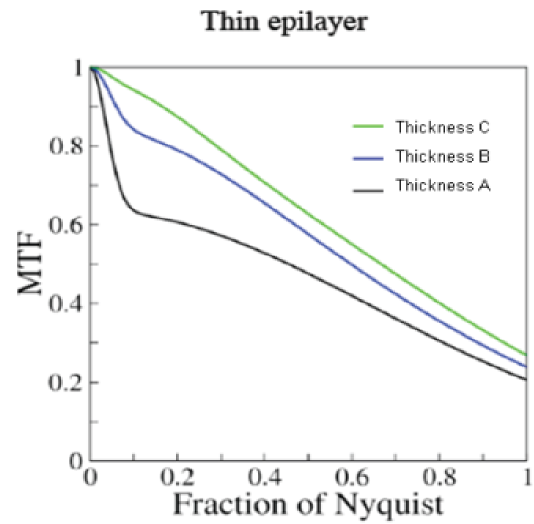
The analogue output is capable of driving a high capacitive load, hence direct connection to external ADC is possible.

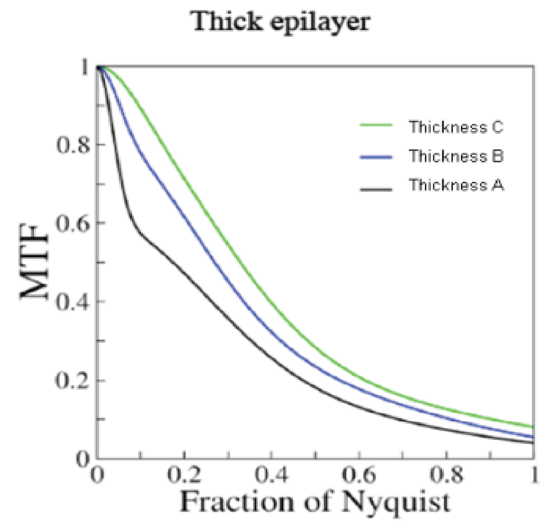
Having 4096 columns requires 32 parallel analogue outputs.

The sensor can operate with a maximum frame rate of 40fps.

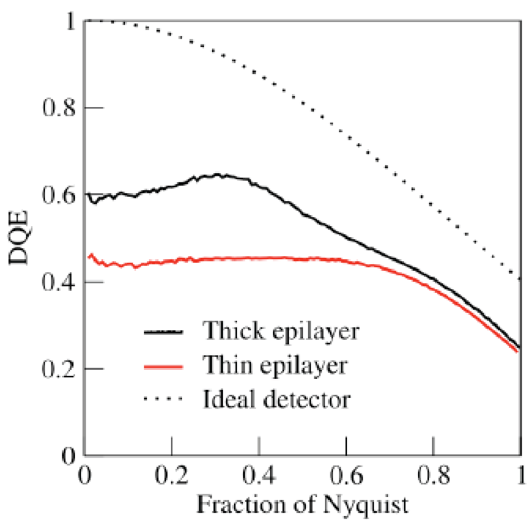
TEM

Transmission Electron Microscopy





The thickness of the detector plays also an important role in the MTF, hence there are some trade-off to be considered.

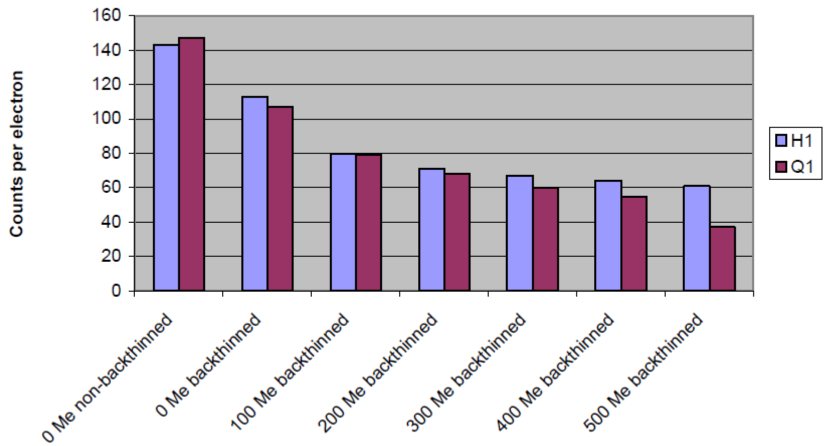


Charge generated , charge collection and crosstalk are related to the thickness of the epitaxial layer.

Pictures from Ultramicroscopy 109 (2009) 1144–1147

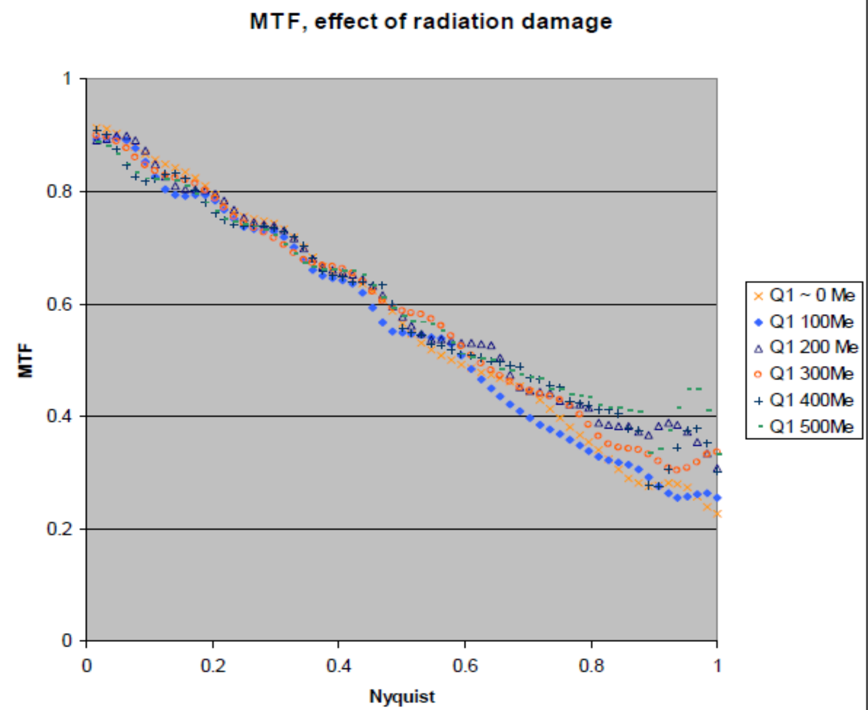
TEM

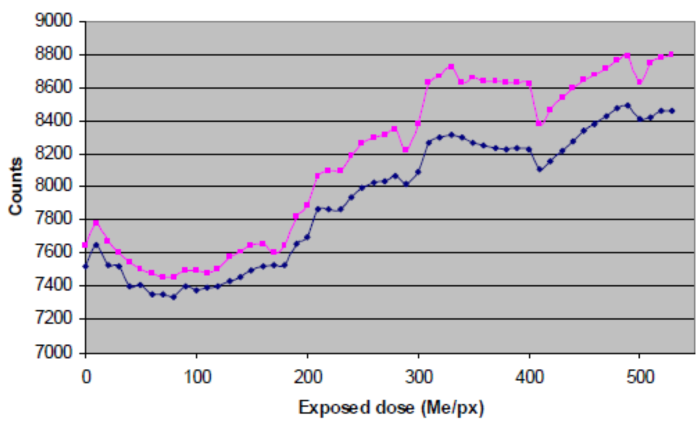
Transmission Electron Microscopy



Counts/electron vs. total dose

Radiation Hardness

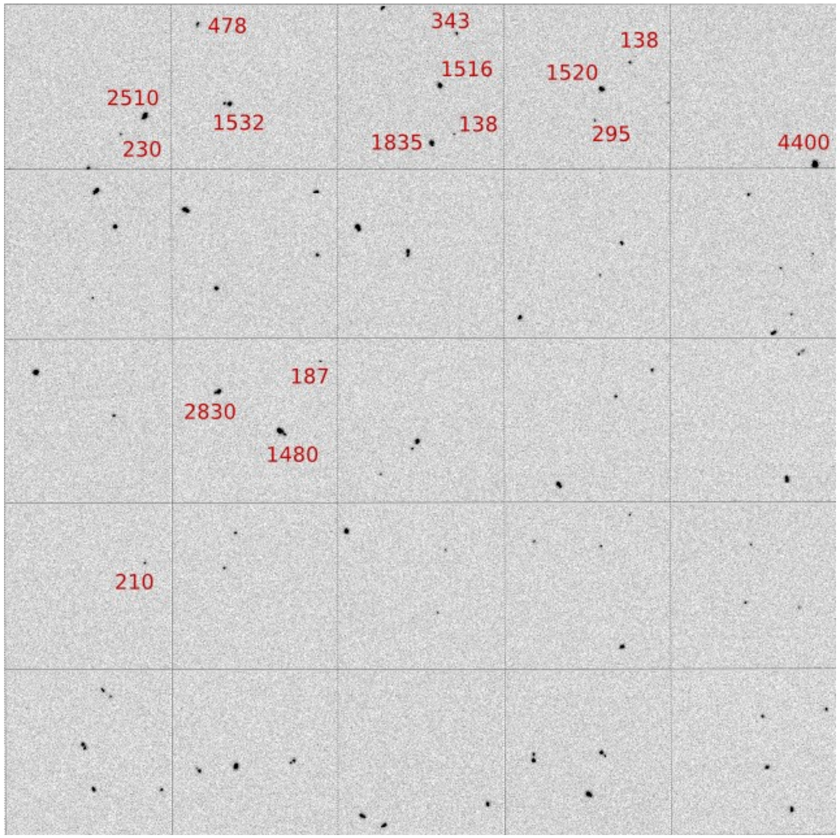




Dark counts vs. total dose

MTF vs. total dose

Single Electron Detection



Picture from Ultramicroscopy 109 (2009) 1144–1147

Some of the events consist of two adjacent energy deposits, one from the incident and one from the backscattered trajectories (in case of backscattering). Electrons passing in only one direction (not suffering any backscattering) appear as single events, usually with a relatively small amount of energy deposited.

Electrons slow down due to their interactions in the substrate, hence the second traversal through the epilayer leads to a greater energy deposition.

TEM

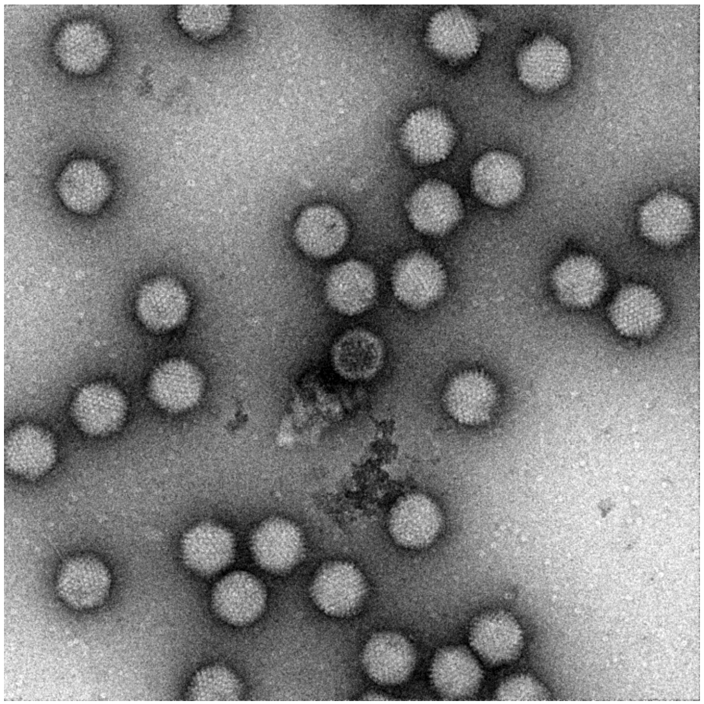
Transmission Electron Microscopy

The sensor here presented is the one used in the FEI Falcon™ Direct Electron Detector. The sensor main characteristics are summarised below:

- 4k by 4k pixel array, 16 Mpixel
- Pixel pitch 14 μm
- Focal plane 57.2x57.3mm
- Sensor size 61x63mm
- 32 analogue outputs
- Max frame rate 40fps
- Rad. Hardness >500Me- (20Mrad)
- Region of interest readout
- Pixel binning x1, x2, x4
- Power consumption 1.5W@full speed
- Gain 6.1μV/e-
- Noise 83e- without CDS
- Full well 75,000e- (120,000)
- Dynamic Range 59dB (63dB)
- QE 20% @ 546nm

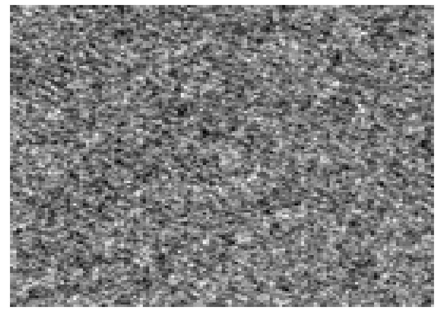
TEM

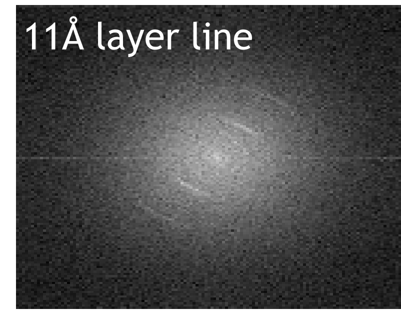
Transmission Electron Microscopy



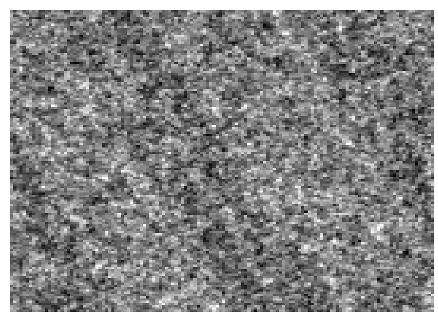
Courtesy of G. McMullan (LMB, Cambridge, UK)

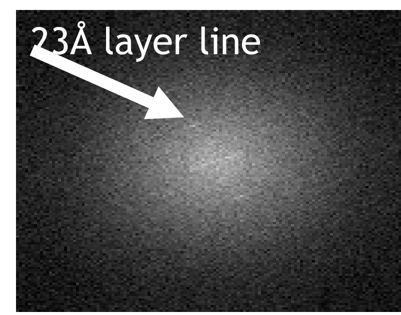
FEI Falcon™





4Kx4K CCD





Cryo TEM of TMV

Courtesy of G. Van Hoften (FEI, Eindhoven, The Netherlands)

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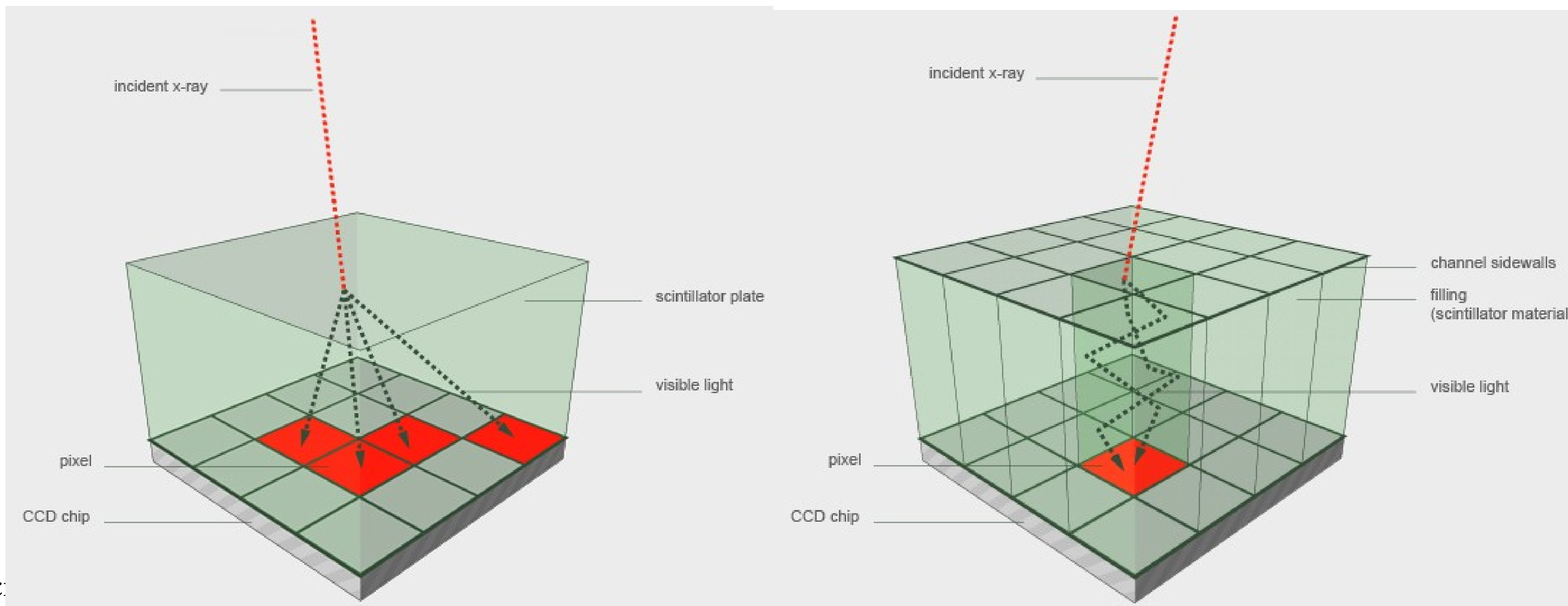
X-rays detection

The large area sensor just presented has been also successfully used in assembling a high spatial resolution X-RAY camera using a scintillator matrix technology.



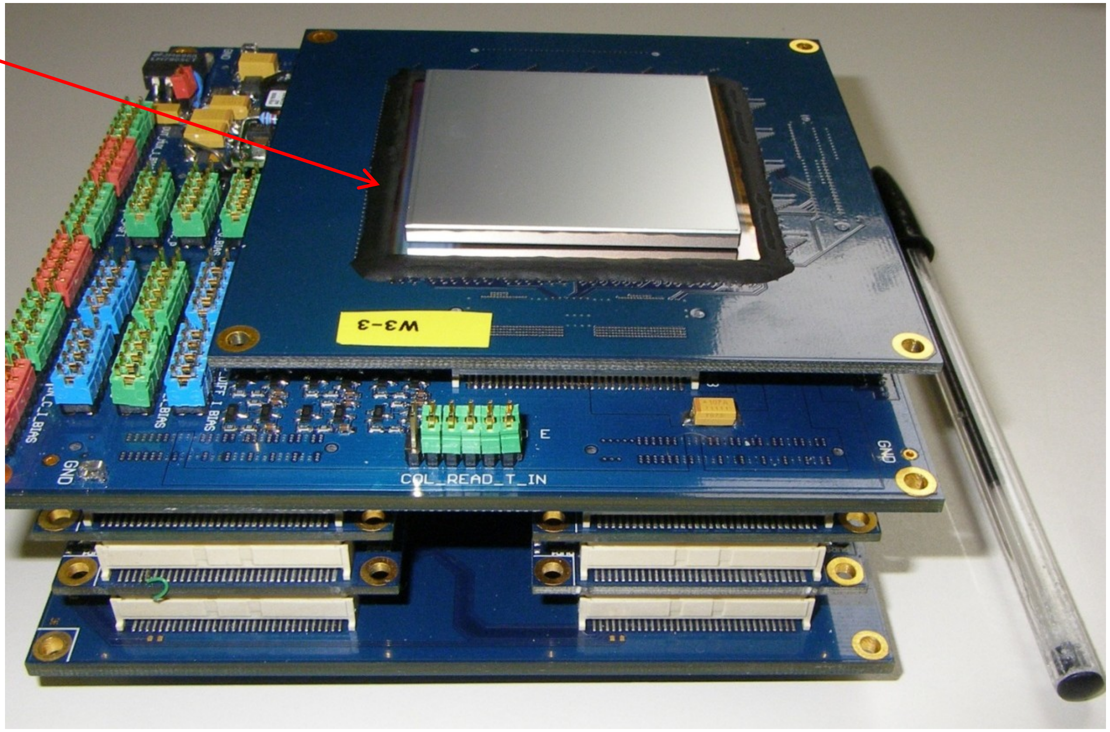
•Sc

•Matrix filled with monolithic CsI:Tl crystals

X-rays detection

Three 20x30mm[a] samples with matrix pitches of 15, 26 and 35μm were mounted on the CMOS sensor and tested in terms of relative light output and spatial resolution.

The spatial resolution was measured from the 10% level of the MTF, calculated by the edge method[b].

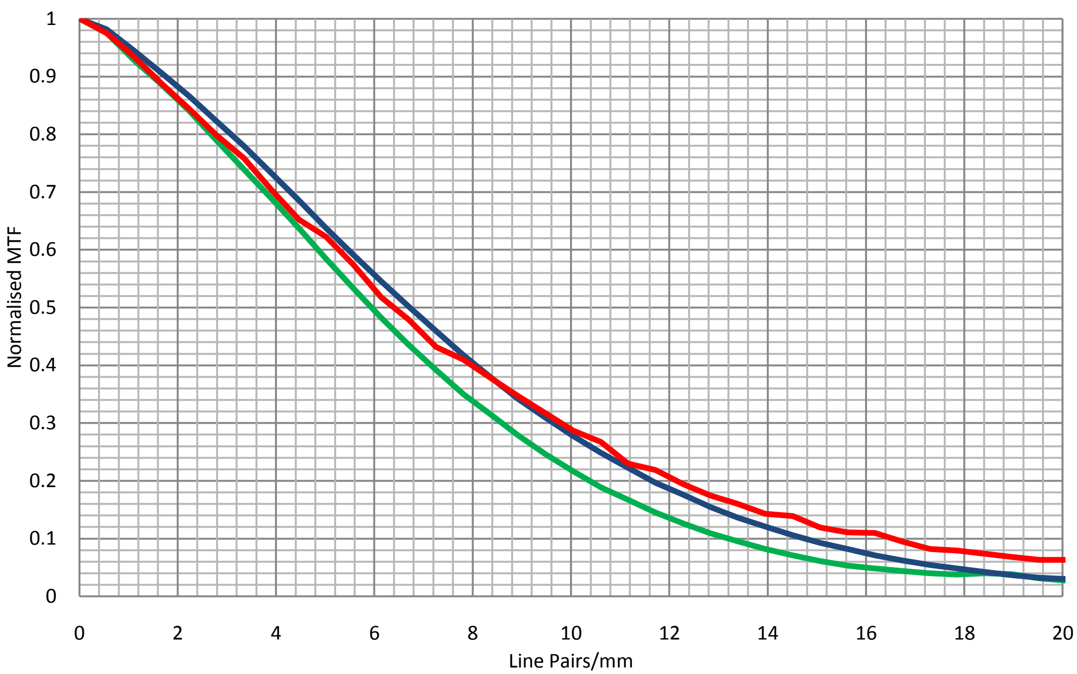


[a] Picture shows 50x50mm sample.

[b] H. Fujita et al. "*A simple method for determining the modulation transfer function in digital radiography*". 0278-0062/92 1992 IEEE, pages 34{39, 1992}.

X-rays detection

The relative light output was measured by exposing the three different pitch samples to a W X-ray tube at 20kV and incrementing the tube current. From these results it was decided that a matrix pitch of 26µm gave the best compromise of high spatial resolution and light output.



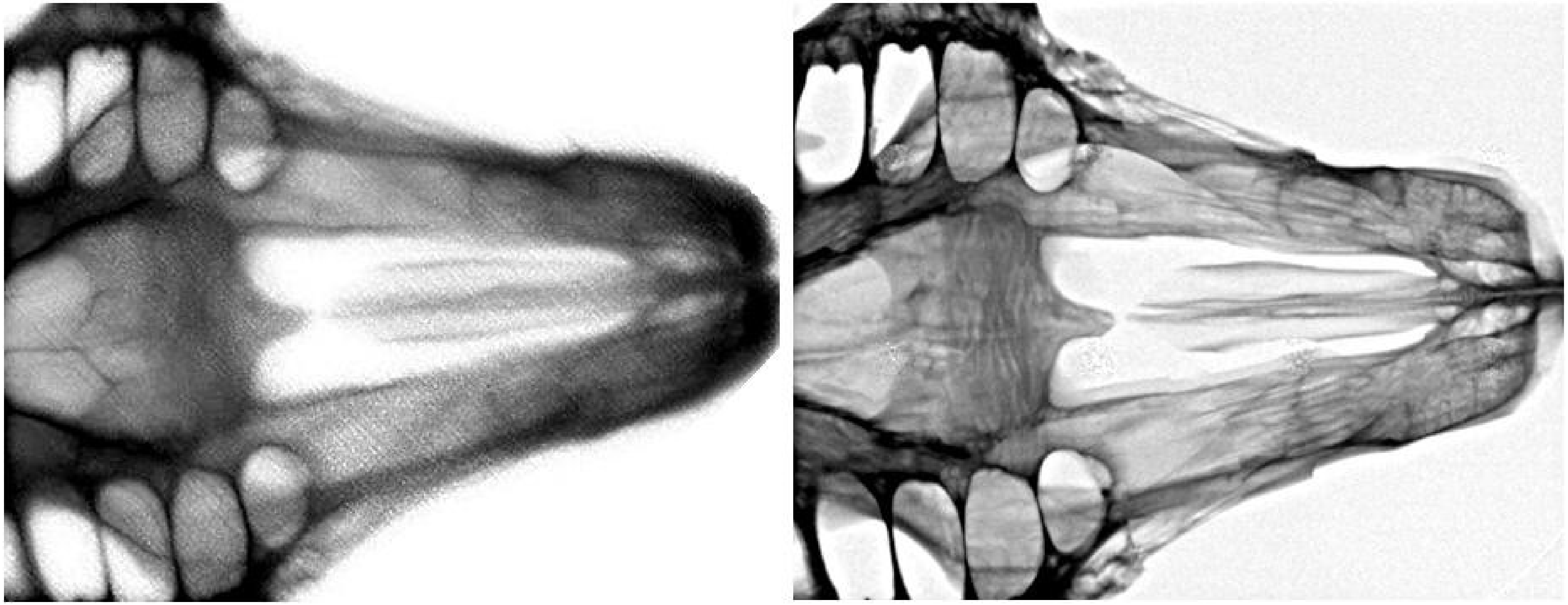
The MTF for the camera with a matrix pitch of
15µm (red)
26µm (blue)
30µm (green).

Courtesy of M. Wilson (STFC-RAL, Oxford, UK), submitted at IEEE NSS

X-rays detection

Spatial resolution improvements are shown in the images below.

An image of a small mammal skull taken with the CMOS sensor coupled to a conventional needle scintillator (left) and a 26µm pitch matrix scintillator (right).



Courtesy of M. Wilson (STFC-RAL, Oxford, UK)

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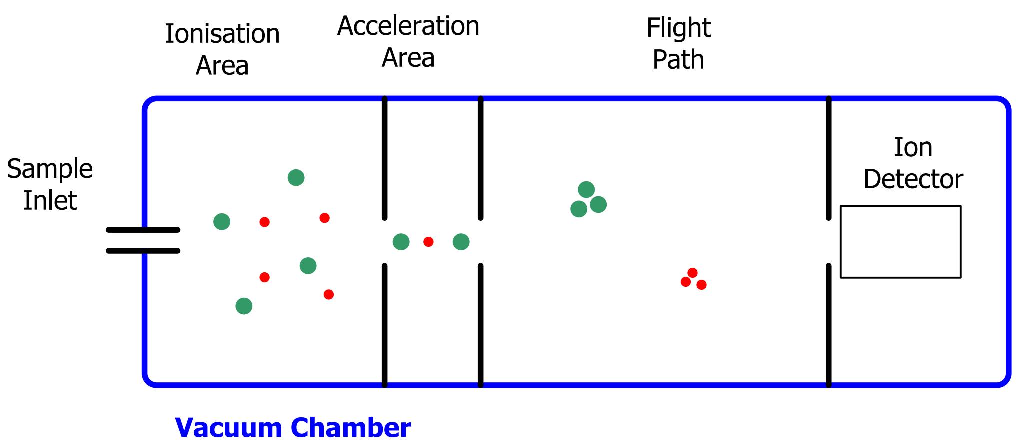
Mass Spectroscopy

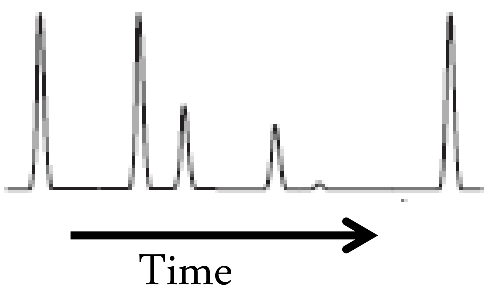
Mass spectroscopy (MS) is a powerful and sensitive technique used to identify chemical compounds and structure of molecules and it is widely used in many different fields:

- Pharmaceutical and healthcare industry
- Oil industry
- Security
- Biotech
- Forensics
- Materials

Time Of Flight Mass Spectroscopy is based on the principle that different masses will travel at different speeds.

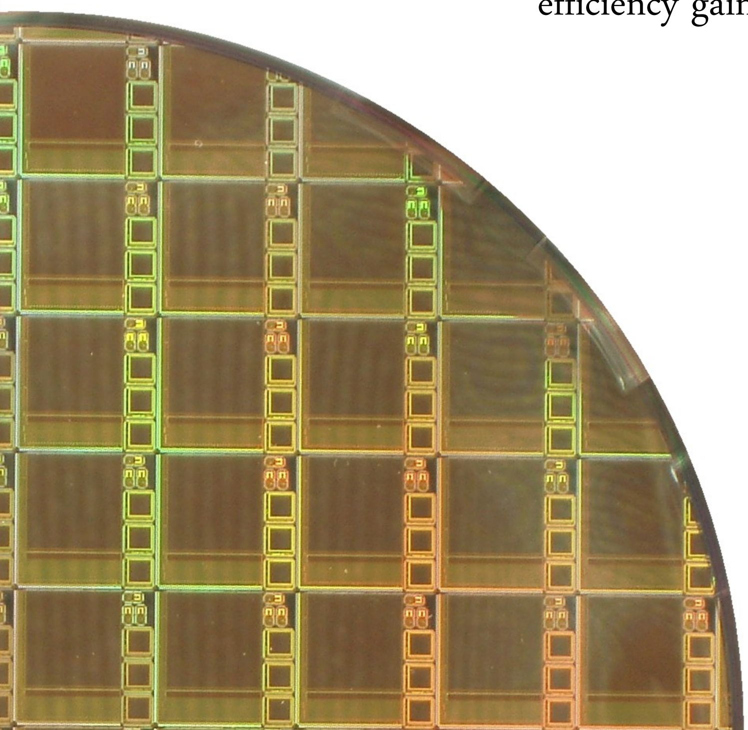


TOF Mass spectrum



Mass Spectroscopy

By combining traditional TOF Mass Spectroscopy techniques with a 2D pixelated detector it is possible to extract additional information about the spatial position or the velocity of the ions when generated.



- Process more samples in parallel, achieving a faster and more efficient use of MS, cost efficiency gains

“Single shot” molecular imaging of surfaces

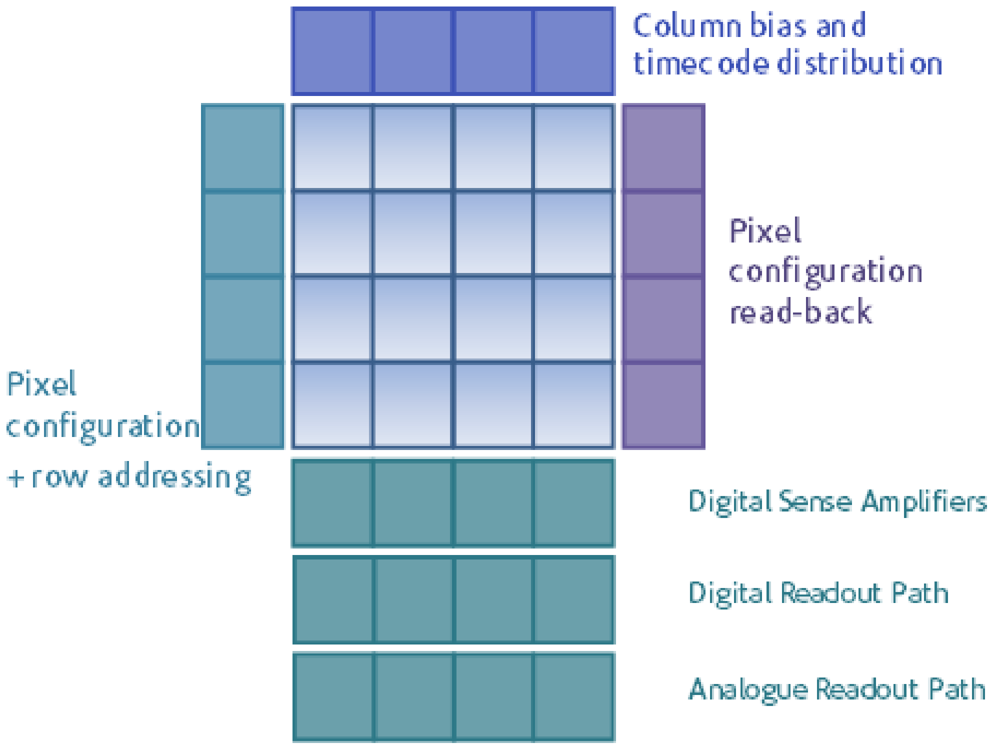
Provides structural information in addition to MS, helping understanding understand 3D structure of proteins

Has great potential to become new standard in TOF MS

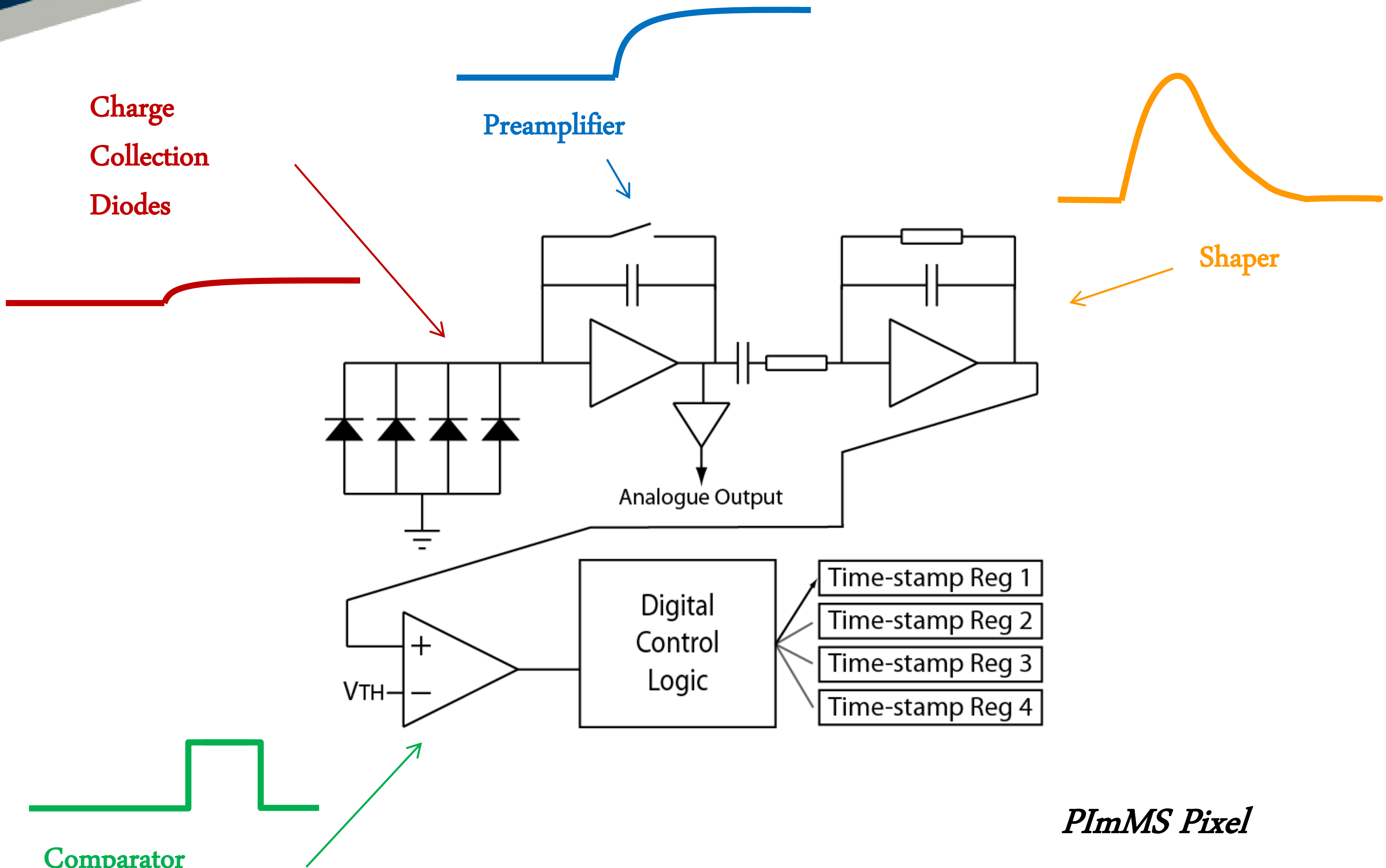
Mass Spectroscopy

The PImMS (**Pi**xel **Im**aging for **M**ass **S**pectroscopy) sensor is an event triggered time-stamp storing CMOS image sensor for Time Of Flight (TOF) Mass Spectroscopy.

- 72 by 72 pixel array
- 70 um by 70 um pixel
- 5 mm x 5 mm active area
- <50 ns timing resolution
- 12 bit time stamp storage
- 4 Memories per pixel
- > 1 ms maximum experimental period
- Programmable threshold and trim



Mass Spectroscopy



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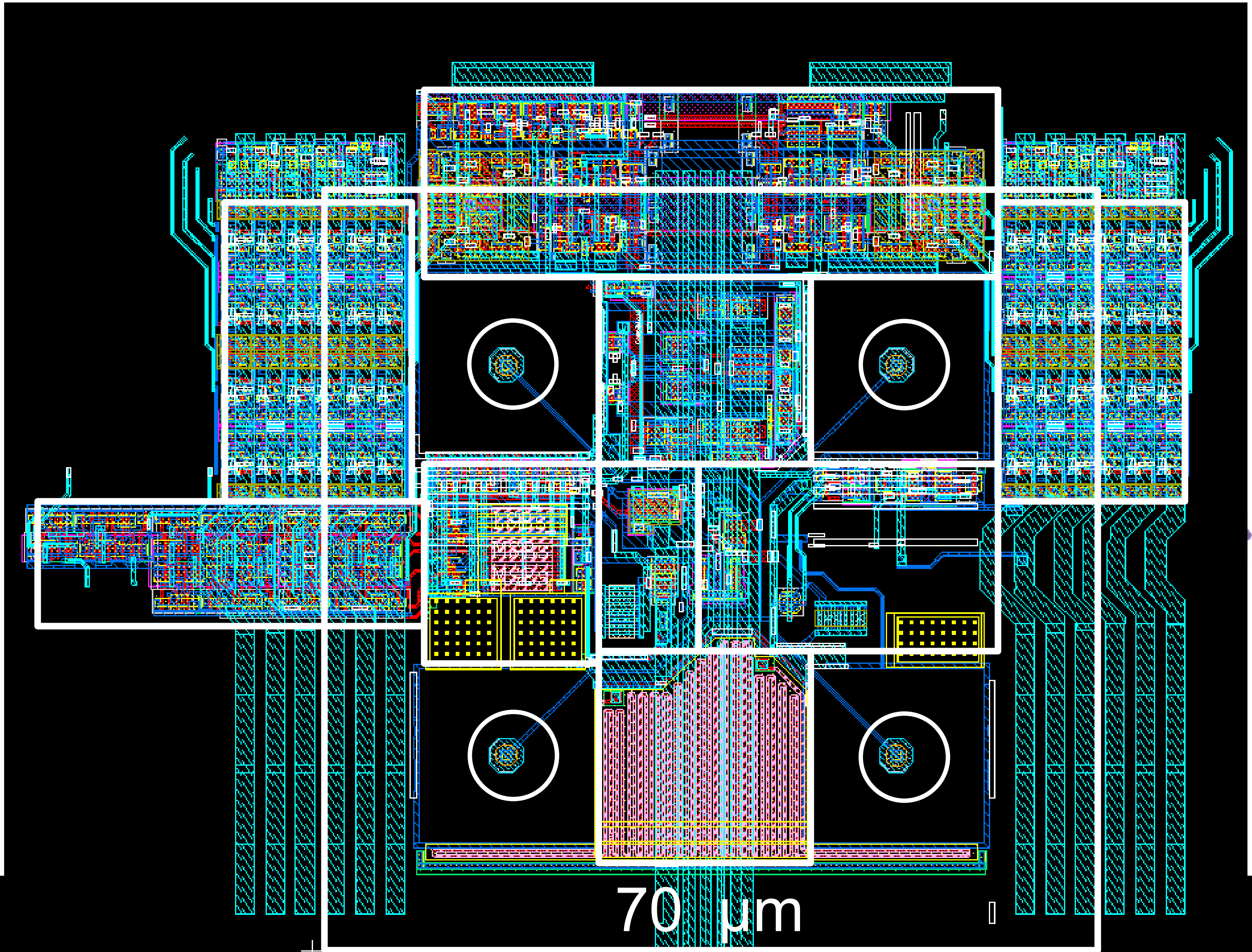
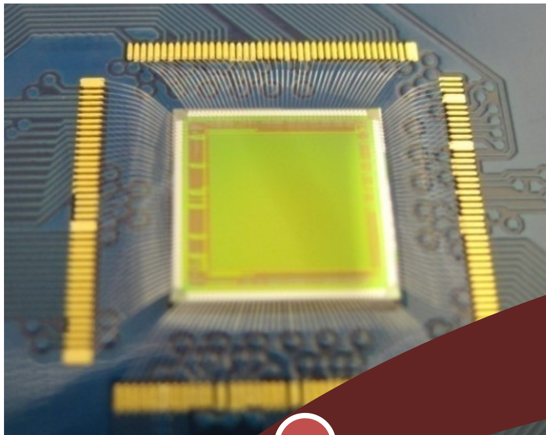
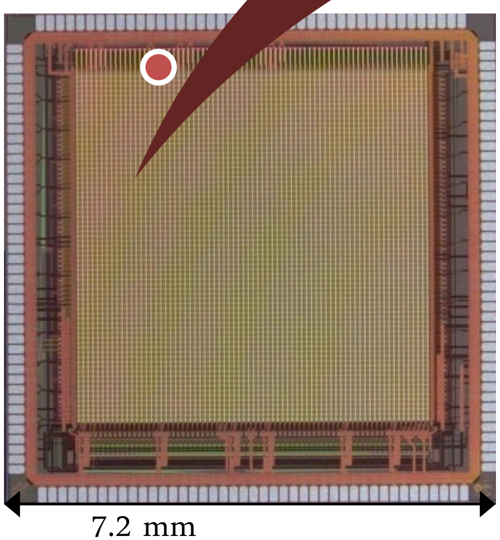
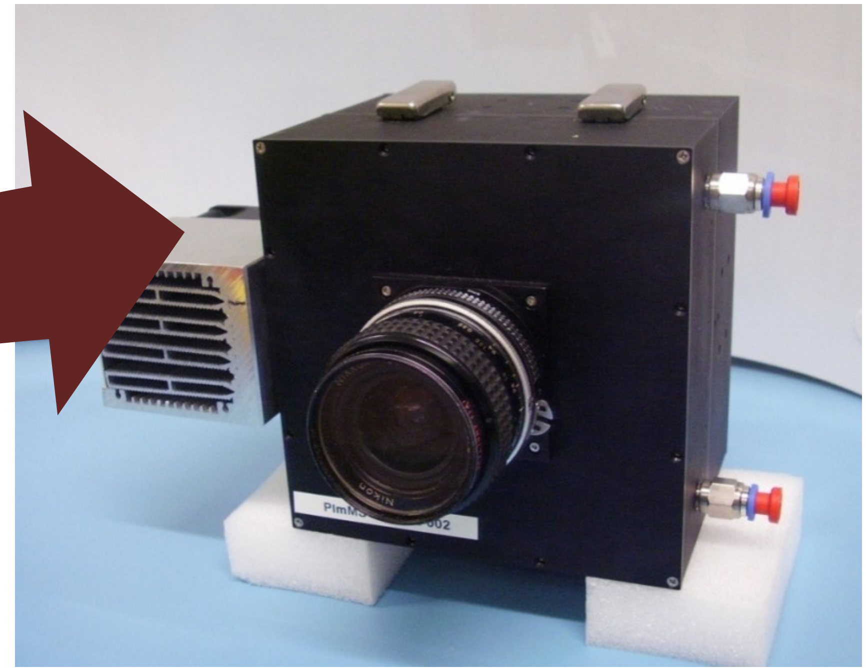
pectroscopy



Mass Spectroscopy





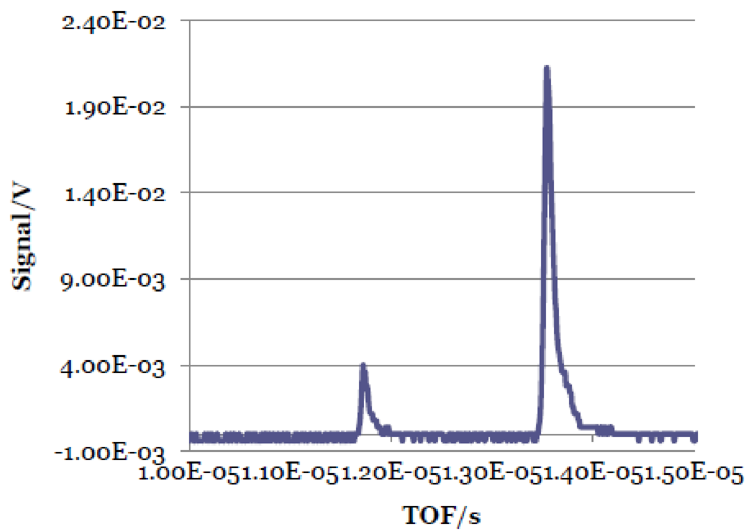


PImMS is built into a camera which is read by a computer over a USB cable.

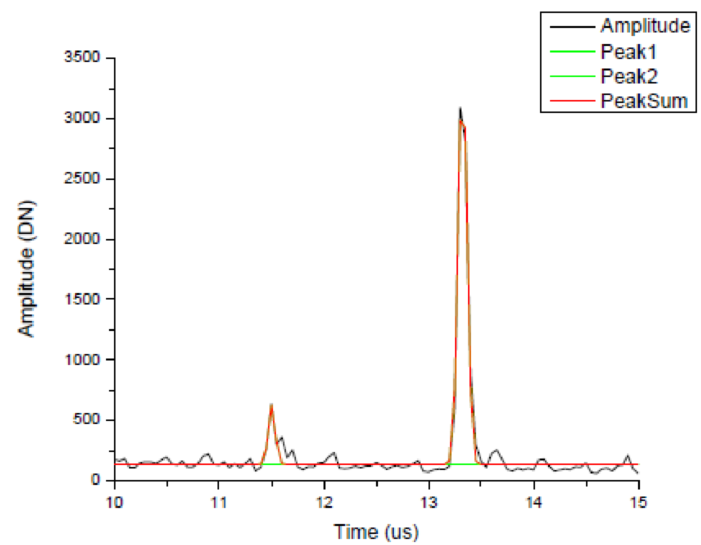
Mass Spectroscopy

Preliminary results comparing PImMs with a Photo Multiplier Tube (PMT) showed that the designed system is detecting the right peaks.

PMT signal



PImMS signal



W. Yuen et al.

Mass Spectroscopy

Complete characterisation for PImMs N.1 has to be completed

- Analogue readout noise
- Quantum efficiency at various wavelengths
- Spatial resolution (Modulation transfer function)
- Dark current
- Full well tests

- These will be done using a calibrated light source, generating a Photon Transfer Curve, from which the key measurements are derived

Second version (PImMs N.2) is currently under design.

- Larger Array 324 by 324 pixels
- 23 mm by 23 mm active area
- 47 fps (with existing camera)
- 380 fps (maximum)
- Reduced interface pin count
- Improved power supply and reference routing
- Increased on-chip control
- On-chip bias and reference generation
- Serial output

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Conclusions

CMOS image sensors for scientific applications

- Low Noise - > Single electron detection. Less than 4e- with 4T architecture.
- Fast readout - > Video rate on very large sensors.
- Large area - > With stitching 61x63 mm. Design almost completed for a wafer scale sensor
- In pixel processing (**INMAPS** process) - > Pixels with more than 600 transistors and 100% fill factor
- Radiation hardness - > More than 500Me- @ 300keV.

Acknowledgments

- Andy Clark
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- Ben Marsh

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- Mark Brouard
- Jaya John John

- Wasi Faruqi
- Richard Henderson
- Greg McMullan

- Gerald van Hoften

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Thanks!

www.dsc.stfc.ac.uk/cmossensors