16th Pisa Meeting on Advanced Detectors
La Biodola, Isola d'Elba
May 26 – June 1, 2024

imasenic

ICFA Instrumentation Award

Renato Turchetta
CEO and co-founder

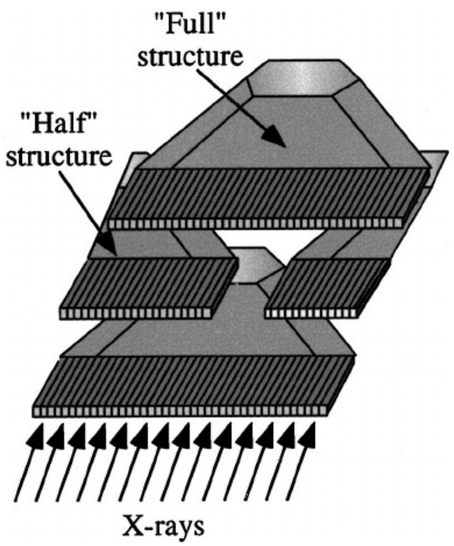
Pixel sensors

Presented at Pixel 1996, published NIMA 1997

Castor 1.0, a VLSI analog-digital circuit for pixel imaging applications

C. Colledani [a], G. Comes [a 1], W. Dulinski [a], Y. Hu [a], F. Loddo [a 2], R. Turchetta [a], V. Bonvicini [b], E. Castelli [b], D. Pontoni [b], M. Prest [b], A. Rashevsky [b], A. Vacchi [b]

Readout electronics for Edge-on silicon strip detectors for Syrmep



From: A. Olivo et al., A multilayer edge-on single photon counting silicon microstrip detector for innovative imaging techniques in diagnostic radiology, The Review of Scientific Instruments, July 2003

1996

Proceedings of the Third International Workshop on Semiconductor Pixel Detectors for Particles and X-ray

24-27 March 1996 • Bari, Italy

E.H.M. Heijne, S. Simone

Edited by E.H.M. Heijne, S. Simone
Volume 395, Issue 3,
Pages 291-473 (21 August 1997)

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Research article ○ Abstract only

Research article ○ Abstract only

CMOS active pixel image sensors

Eric R. Fossum

Pages 291-297

Article preview

Abstract

Abstract

CMOS active pixel sensors (APS) have performance competitive with CCD technology and offer advantages in on-chip functionality, system power reduction, cost and miniaturization. This paper briefly discusses recent advancements.

Active Pixel Sensors in imaging

Presentation at SPIE Symposium on Electronic Imaging, February 1993 by E. Fossum, Jet Propulsion Laboratory, Pasadena, USA

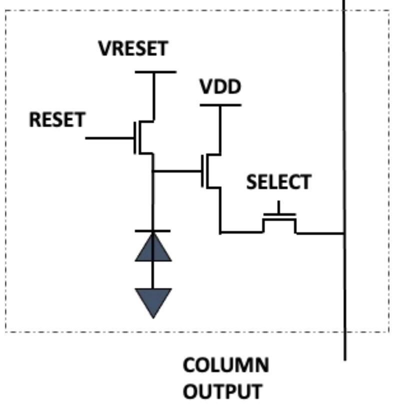
ACTIVE PIXEL SENSORS:

ARE CCD'S DINOSAURS?

CONCLUSIONS

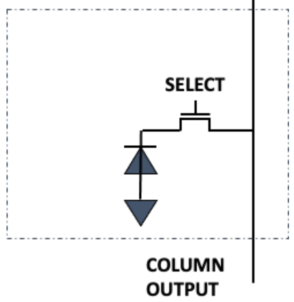
- Active Pixel Sensor technology in infancy compared to CCDs
- Performance already close to that of CCDs
- Eliminates many problems of CCD charge transfer
- Will likely supplant CCDs in future camera systems

(*The simplest*)
Active Pixel Sensors



Some definitions

Passive Pixel Sensors



I started working on CMOS image sensors for imaging application as well as particle detection

CCD = Charge Coupled Devices

Invented in 1970

Boyle WS, Smith GE (1970) Charge Coupled Semiconductor Devices. Bell Systems Technical Journal 49:587 593

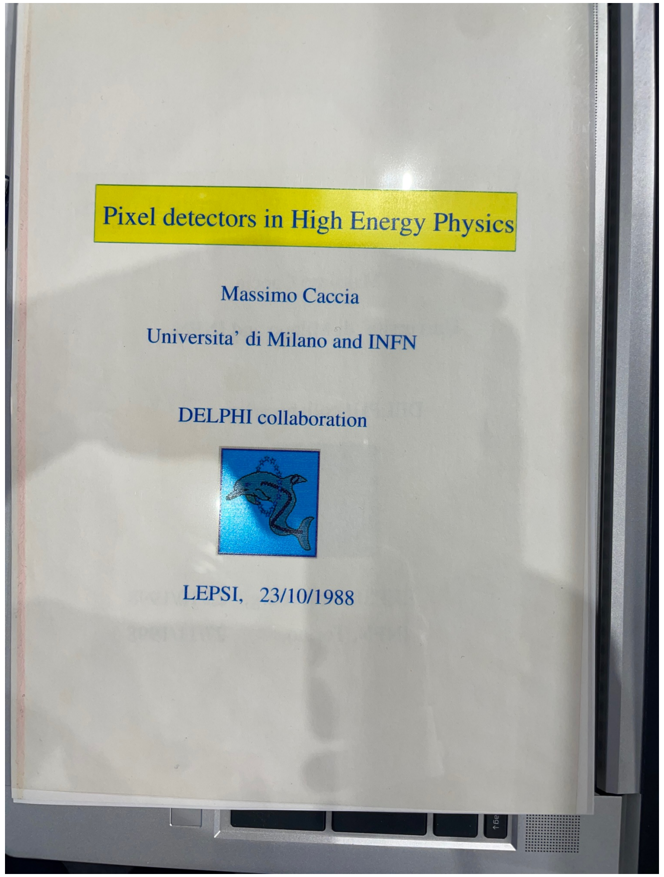
Nobel prize for Physics in 2009

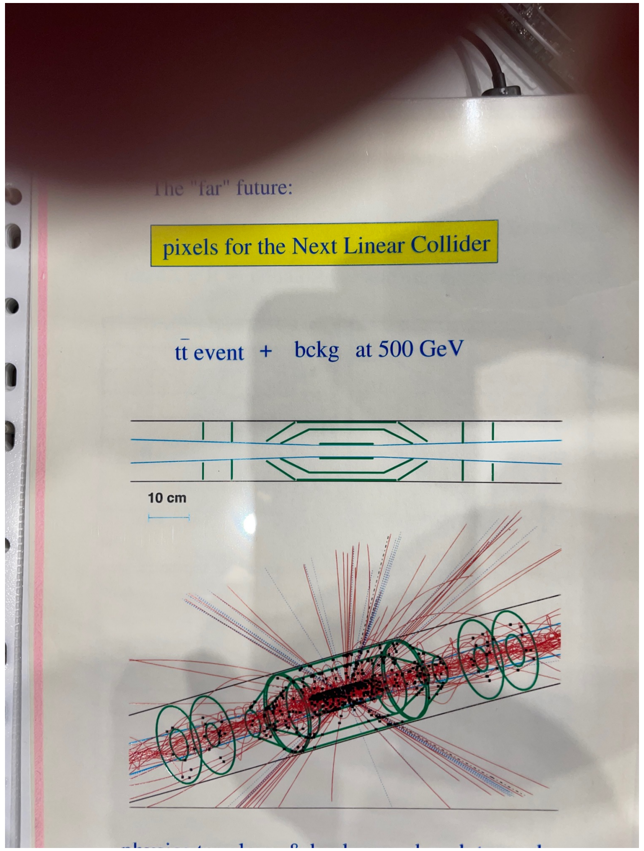
Towards MAPS

23-10-1998: Massimo Caccia (Milano Uni and INFN) came to LEPSI, Strasbourg, to give a seminar on his work on ”Pixel Detectors in High Energy Physics”

He spoke about the ”far” future: the Next Linear Collider.

Options for pixel detectors were hybrid pixels sensors or .. CCDs





I proposed that we should do it with CMOS image sensors as CCDs are dinosaurs!

100% sensitive ?

Imagers don't need to be sensitive over the entire surface.

Can we get 100% sensitivity?

How? Using magnetic field and tilting the sensor? Anything else?

Definitions again

When we start proposing CMOS Active Pixel Sensors, the "hybrid pixel" community started presenting their technology as Active Pixel Sensors.

I felt there was a need to differentiate, so I introduced the terms "Monolithic" Active Pixel Sensors (MAPS) to distinguish from "Hybrid" Active Pixel Sensors (HAPS)

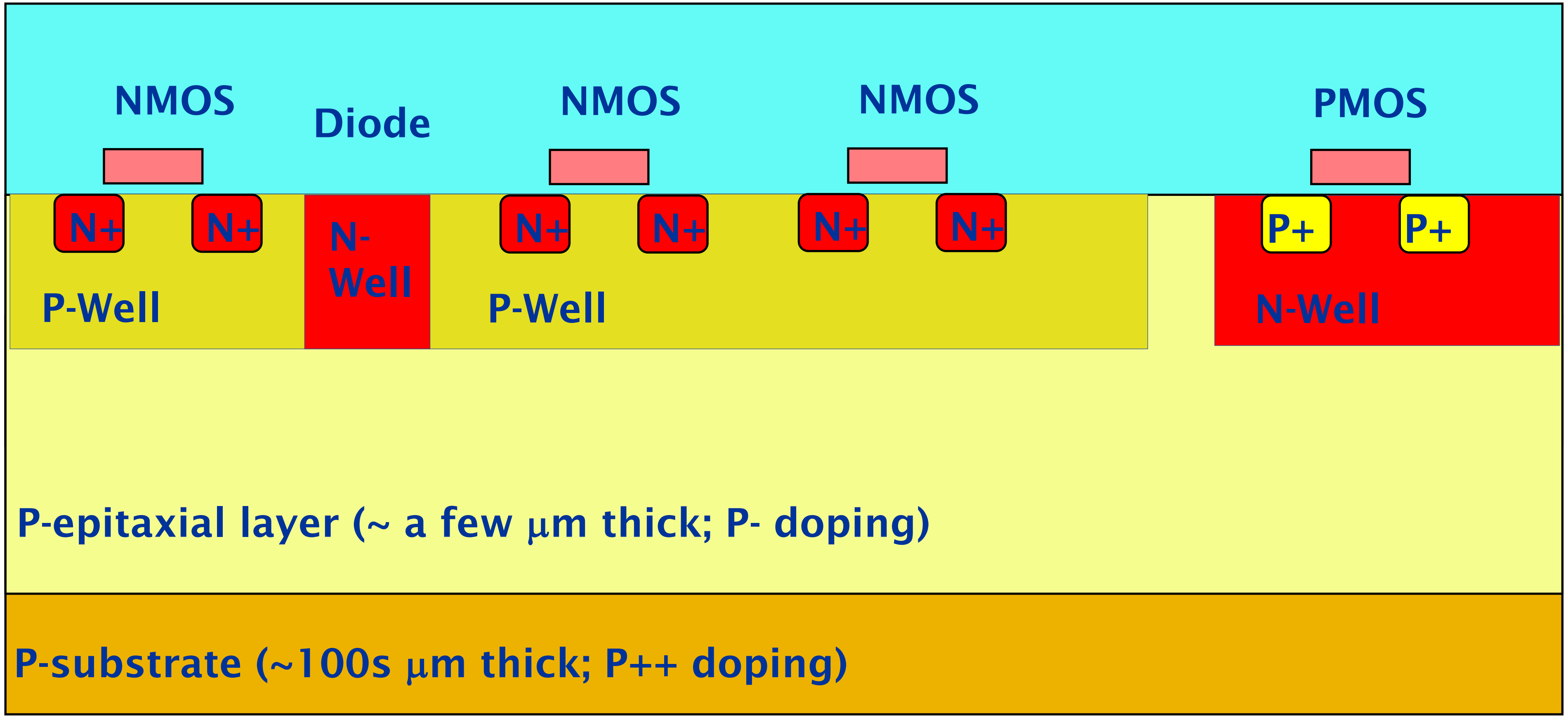
100% sensitive !!!

Metal routing not shown.

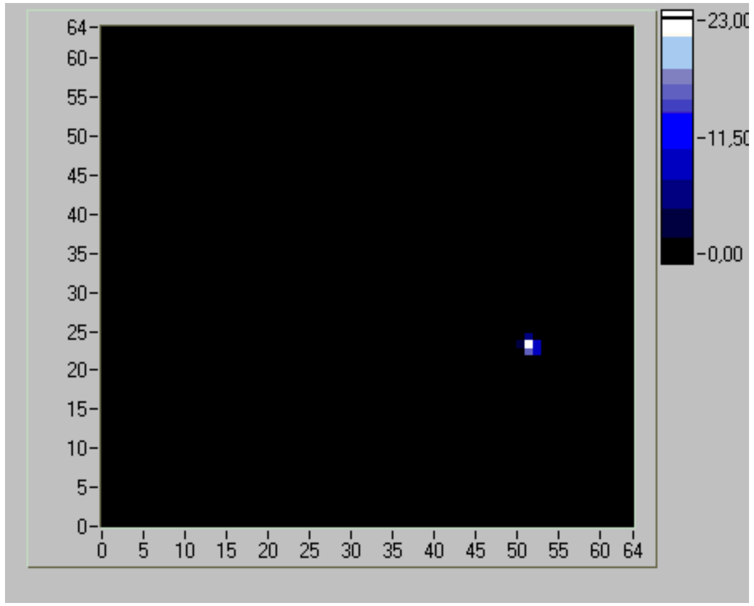
Most typical cross-section.

Deeper colour indicates higher doping. Red(ish) is N-doping; Yellow(ish) is P doping.

Note: Regions of same doping type but different concentration has different potential. E.g.: P-doping: there is a potential barrier keeping electrons in the region will lower doping



MAPS: proof of concept



First image of high energy electrons (~GeV) obtained with MAPS (beginning 2000)

MIMOSA1 was a 64x64 pixel sensor
Designed in 0.6 µm CMOS

ELSEVIER
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 458, Issue 3, 11 February 2001, Pages 677-689

A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI CMOS technology

R Turchetta [a], J.D Berst [a], B Casadei [a], G Claus [a], C Colledani [a], W Dulinski [a], Y Hu [a], D Husson [a], J.P Le Normand [a], J.L Riester [a], G Deptuch [1 b], U Goerlach [b], S Higueret [b], M Winter [b]

A novel Monolithic Active Pixel Sensor (MAPS) for charged particle tracking made in a standard CMOS technology is proposed. The sensor is a photodiode, which is readily available in a CMOS technology. The diode has a special structure, which allows the high detection efficiency required for tracking applications. The partially depleted thin

Because of these features, CMOS sensors are the favoured technology for demanding application, which are typically found in space science.

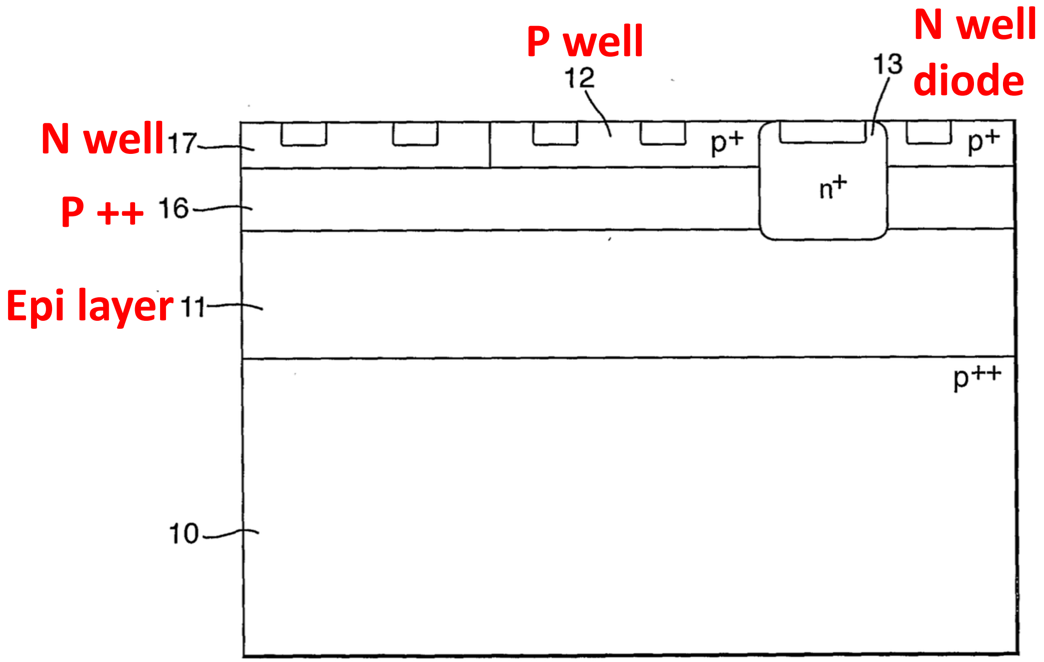
They also look attractive for tracking applications because of the following features:

- spatial resolution: the pixel size is usually between 10 and 20 times the Minimal Size Feature (MSF) of the fabrication process, which means that 10µm or smaller pitch is possible, and hence spatial resolution better than 3µm even with a binary readout. Taking advantage of possible analogue readout and natural charge spread between neighbouring pixels, for very demanding application the spatial resolution can possibly be pushed down to less than 1µm;
- very low multiple scattering: since the substrate can, in principle, be thinned down to a few tens of microns;
- radiation tolerance, taking advantage of the reduced radiation sensitivity offered by nowadays submicron VLSI processes.

How to make complex pixels in a MAPS ?

“CMOS” Image sensors only have NMOS in their pixels, .. and this is still true today for most imaging sensors!

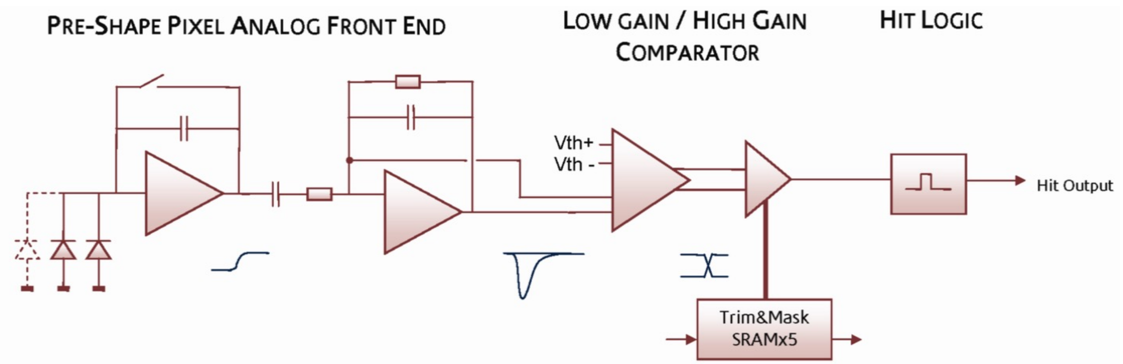
R. Turchetta, G. Villani, M. Prydderch, WO2004/099740, 8 May 2003



2004-5: Paul Dauncey, from Imperial College → Electromagnetic calorimeter CALICE, came to RAL with the requirements for a pixel detector with time stamping

Main requirements

- Pixel size 50 μm
- Time stamp @ beam crossing rate (150 ns)
- Total detector: 10^{12} pixels
- In-pixel Sparse readout



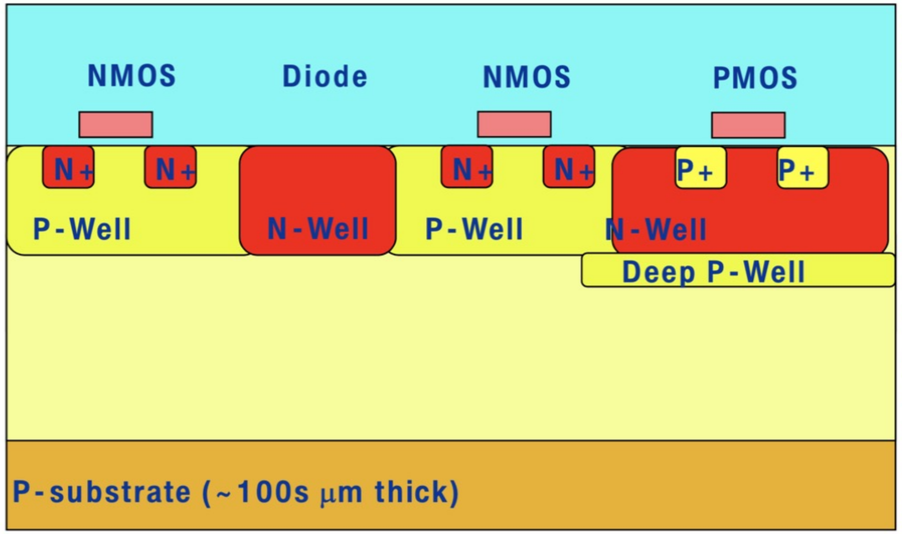
Pixel schematic: design started with NMOS only.

Quadruple well technology

We proposed an additional deep P-well layer to screen the PMOS's Nwell.

E. Toledano (Tower Semiconductor) accepted our challenge, at a time when it looked impossible to have any custom developed in a commercial CMOS foundry. The INMAPS process could become reality

INMAPS 0.18 μm
6 metal levels, linear capacitors, high-value resistors
Choice of diodes, including pinned diodes
Stiching up to wafer scale (200 mm diameter)
Choice of epi: 5 and 12 μm for first prototype than up to 20 μm

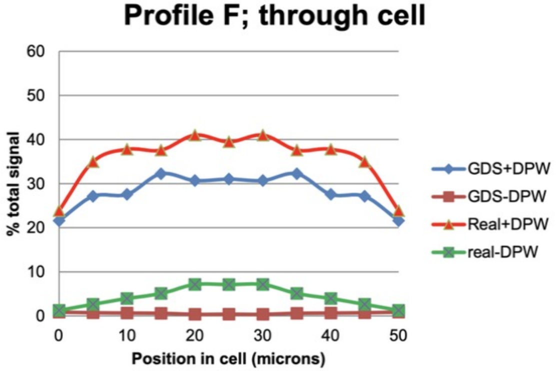


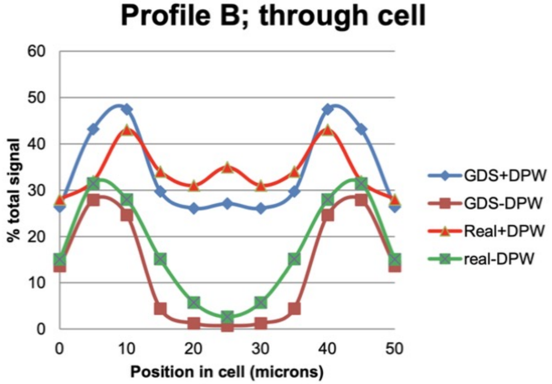
Standard CMOS with additional deep P-well implant. Quadruple well technology.

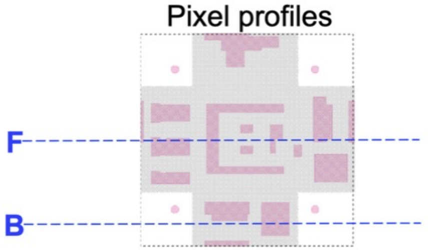
100% efficiency and CMOS electronics in the pixel.

Optimise charge collection and readout electronics separately!

- Amplitude results
  - With/without deep pwell
  - *Qualitative* comparison
    - Simulations "GDS"
    - Measurements "Real"







Two papers in 2007 IEEE NSS:

- M. Stanitzki et al.: A Tera-Pixel Calorimeter for the ILC
- J. Crooks et al.: A Novel CMOS Monolithic Active Pixel Sensor with Analog Signal Processing and 100% Fill Factor

Paper in Sensors in 2008:

- J.A. Balin et al.: MAPS in a quadruple Well technology for Nearly 100% Fill Factor and Full CMOS Pixels

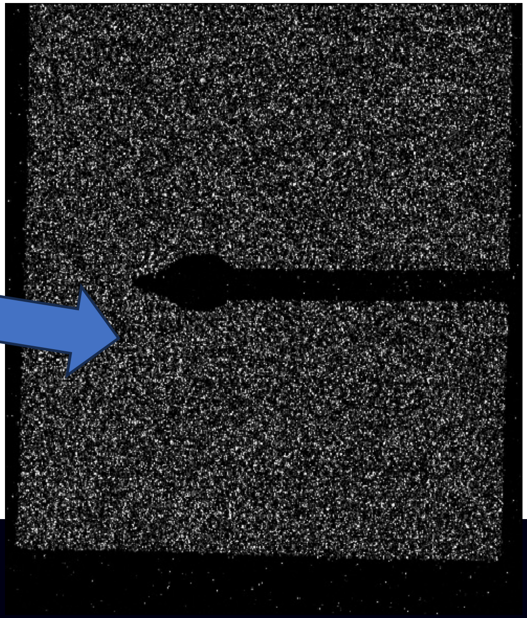
MAPS in Transmission Electron Microscopy (TEM)

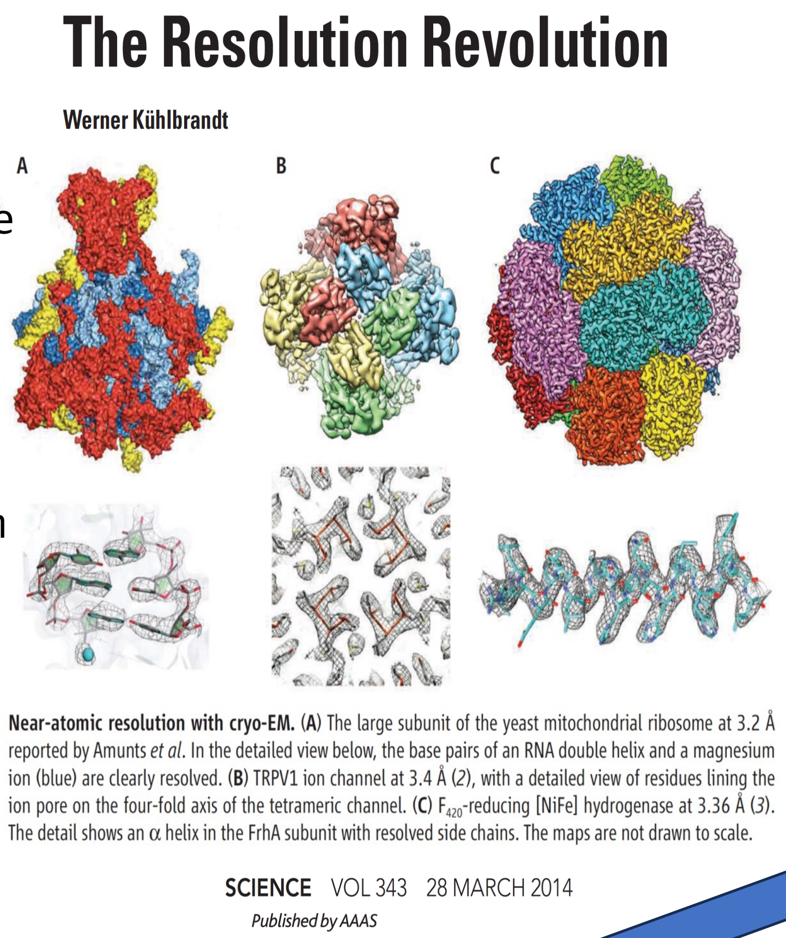
2001: meeting with Richard Henderson and Wasi Faruqi at MRC Laboratory of Molecular Biology, Cambridge, UK

2003: first test in a with a 512x512 CMOS image sensor, showing the good sensitivity of CMOS image sensors

2004: starts the development of a rad-hard, fast 16Mpixel, 4 dies per wafer CIS → they generated two family of products at FEI: Falcon and Ceta, for direct and indirect detection respectively

First direct detection image recorded with a CMOS Image Sensor 19 February 2003





The Resolution Revolution

Werner Kühlbrandt

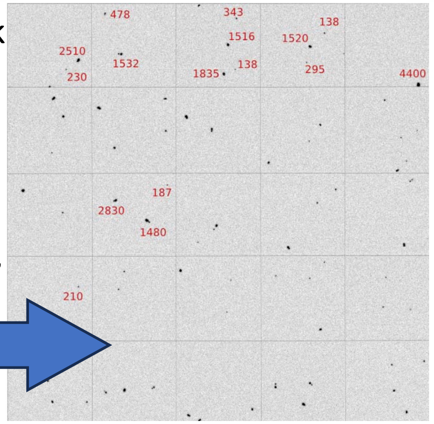
Near-atomic resolution with cryo-EM. **(A)** The large subunit of the yeast mitochondrial ribosome at 3.2 Å reported by Amunts *et al*. In the detailed view below, the base pairs of an RNA double helix and a magnesium ion (blue) are clearly resolved. **(B)** TRPV1 ion channel at 3.4 Å (*2*), with a detailed view of residues lining the ion pore on the four-fold axis of the tetrameric channel. **(C)** F_{420}-reducing [NiFe] hydrogenase at 3.36 Å (*3*). The detail shows an α helix in the FrhA subunit with resolved side chains. The maps are not drawn to scale.

SCIENCE VOL 343 28 MARCH 2014

Published by AAAS

R. Henderson, From electron crystallography to single particle cryoEM, Nobel lecture, 8 December 2017

Electron hits in a 1kx1k prototype of the 16Mpixel sensor, from McMullan, G., Faruqi, A. R., Henderson, R., Guerrini, N., Turchetta, R., Jacobs, A. & van Hoften, Ultramicroscopy, 2009



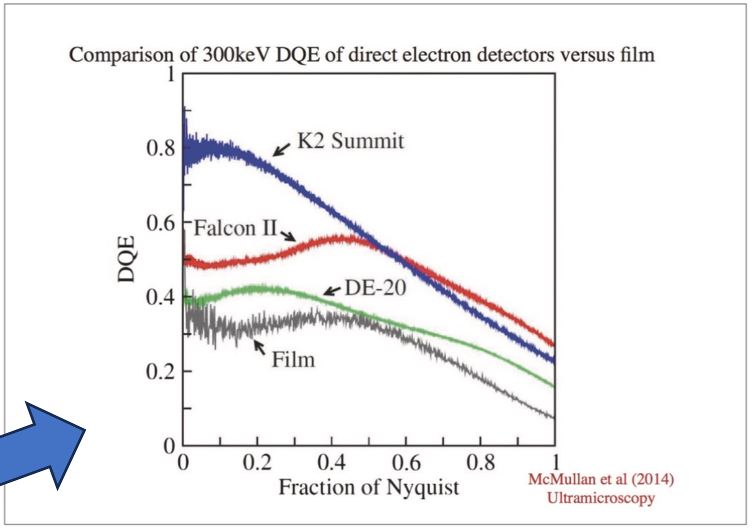
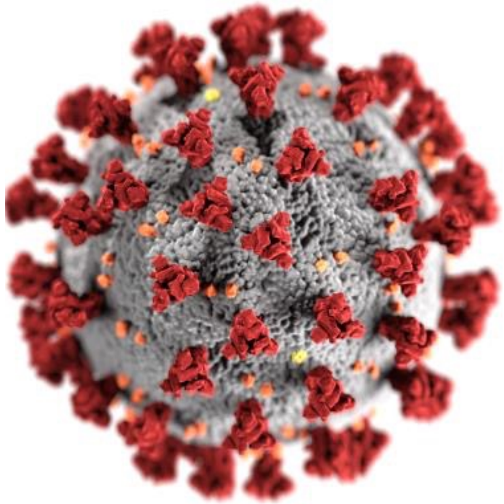


Figure 11. Comparison of performance of three direct electron detectors, reproduced from McMullan et al (2014). The DQE is measured as a function of spatial frequency for the DE-20 (green), Falcon-II (red) and K2 Summit (blue). The corresponding DQE of photographic film is shown in black.

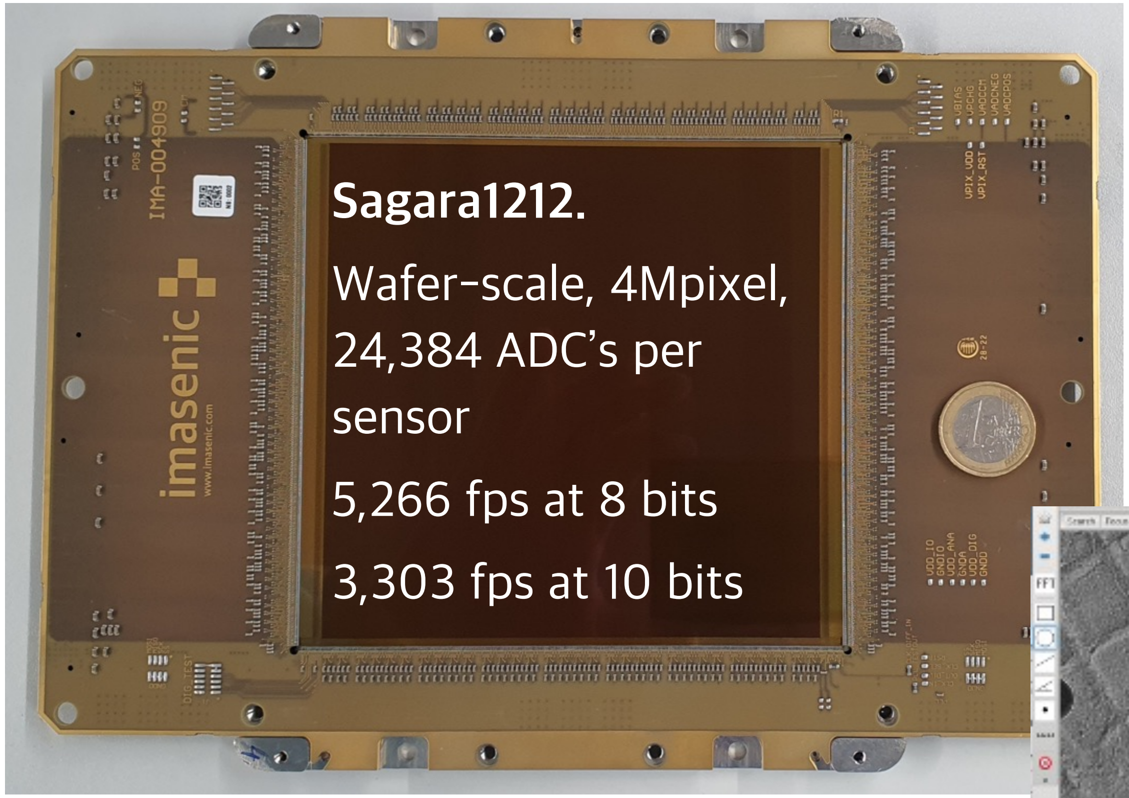
MAPS in TEM today

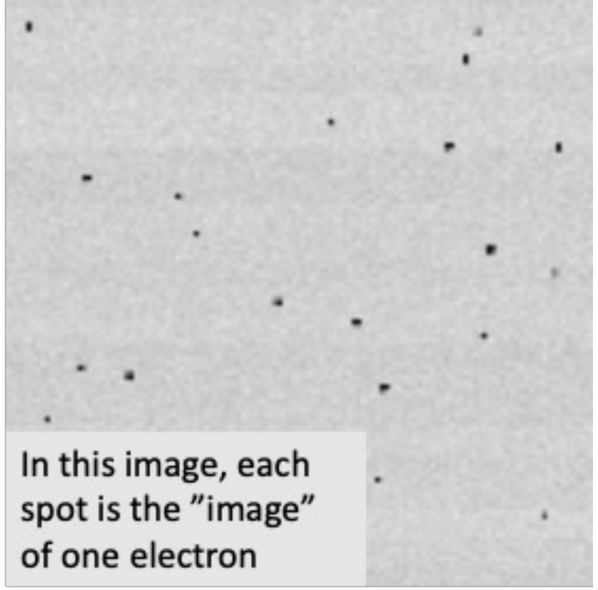


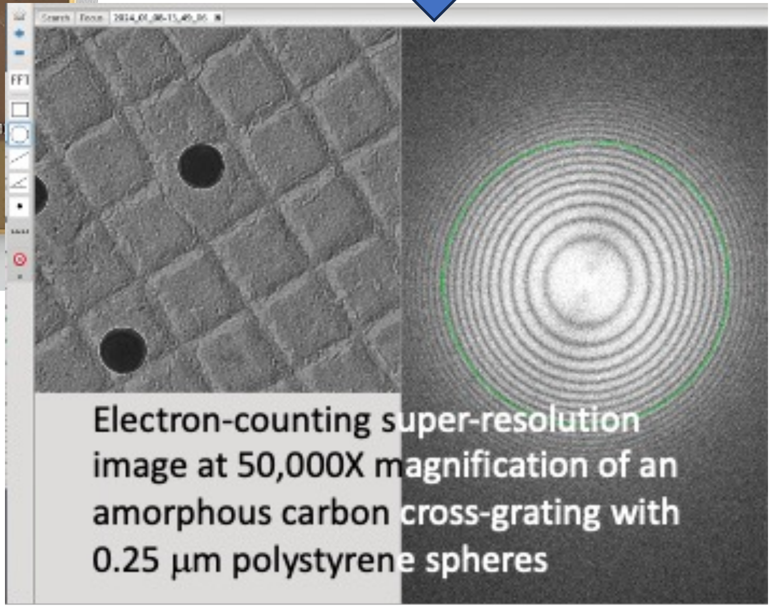
January 2020. First results on Covid-19 structure.

Within a few weeks, cryoEM researchers were able to determine the structure of SARS-CoV-2 spike protein and its cellular receptor during infection.

See https://www.thermofisher.com/blog/atomic-resolution/cryo-em-used-in-novel-coronavirus-research-to-support-vaccine-treatment-development/







Acknowledgment

My colleagues at LEPSI who worked on MIMOSA1: G. Deptuch, W. Dulinski, C. Colledani

My colleagues in Rutherford Appleton Laboratory: N. Guerrini, J. Crooks, I. Sedgwick, G. Villani, M. Stanitzki and all the other members of the CMOS Sensor design group

R. Henderson, W. Faruqi and G. McMullan at MRC-LMB

P. Dauncey at Imperial College

A. Bofill, M. Sannino, A. Scott, M. Giulioni, A. Mollà, C. Herrero, M. Gargallo and others at IMASENIC

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E. Toledano, Etesian / Tower Semiconductor

Thank you!

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