

caeleste



Human eye 2.0

IEEE Student Branch Gent

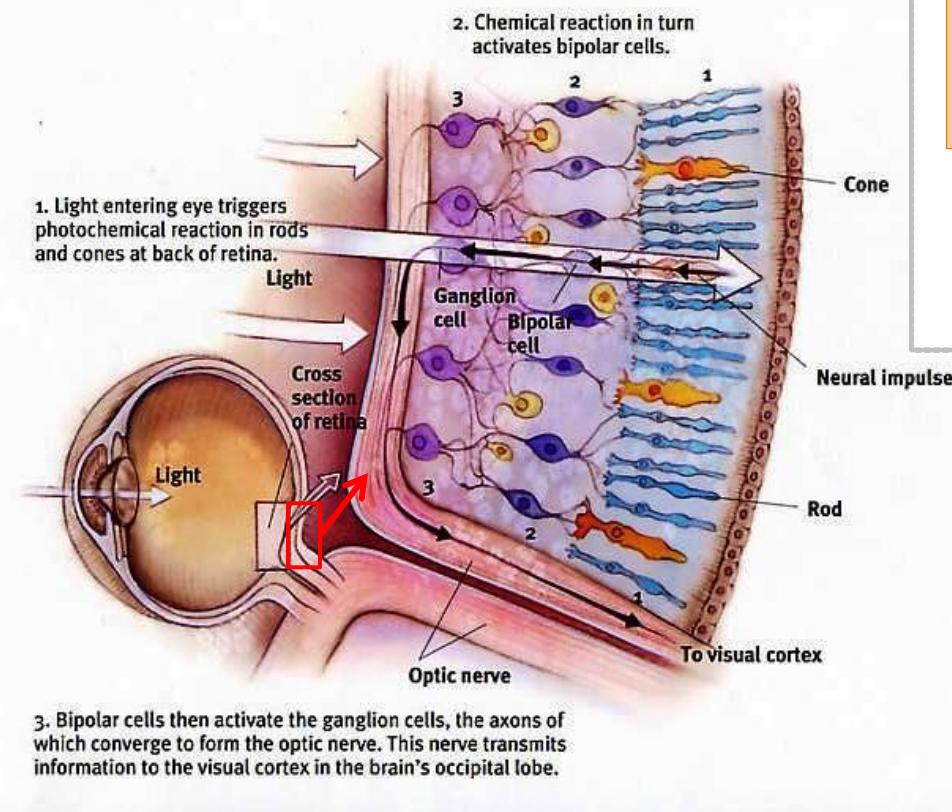
8 oktober 2013

Bart Dierickx

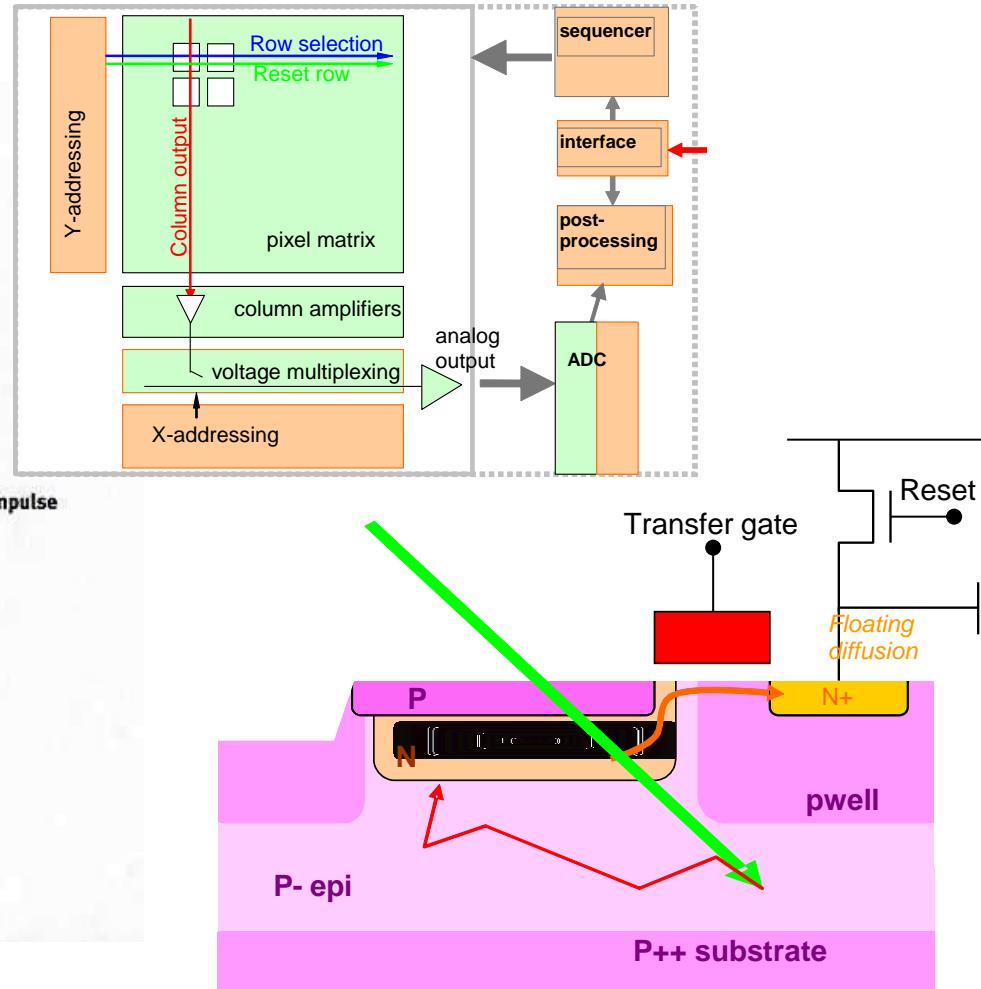
Founder & Chief Technical Officer
Caeleste CVBA, Berchem-Antwerpen

EYE versus Silicon

EYE



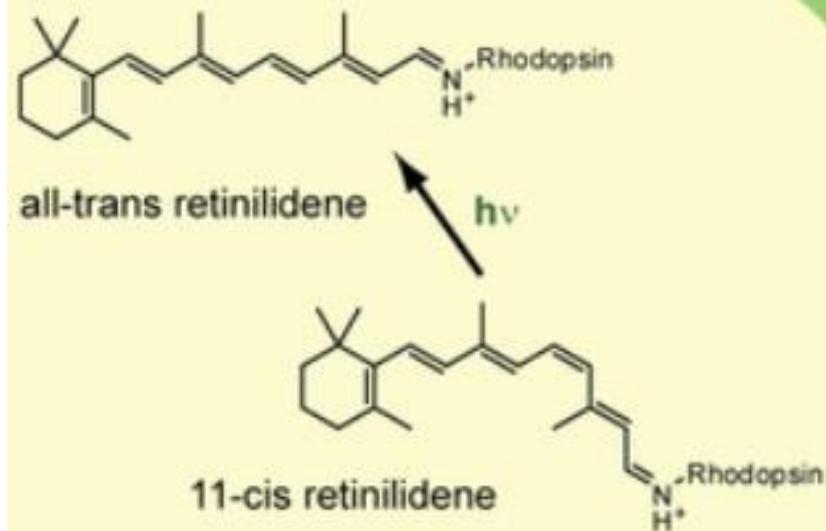
Silicon



EYE versus Silicon

EYE

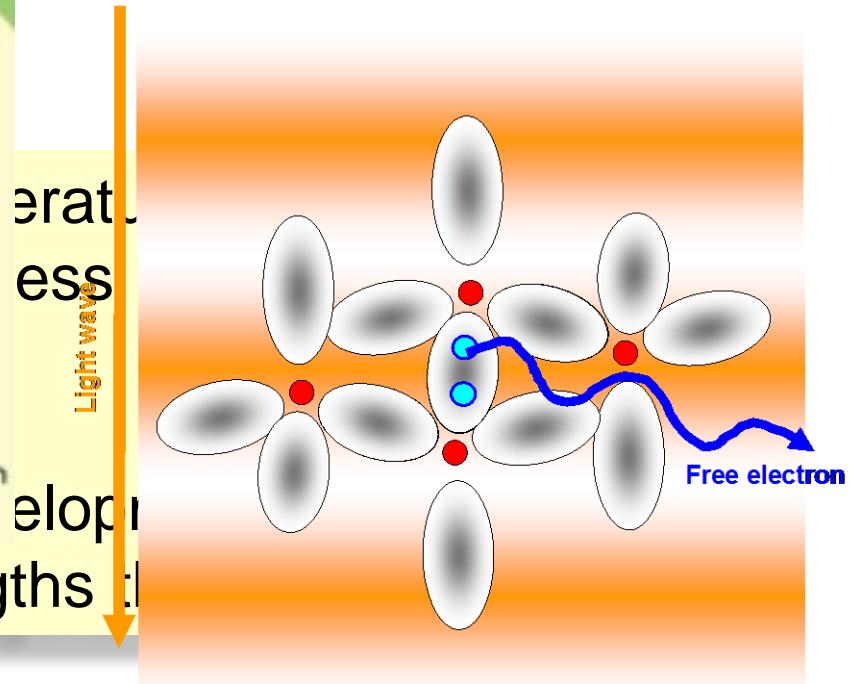
- Photo-electric effect



Other wavelengths

Silicon

- Photo-electric effect



The sky is not blue

- Human eye ~5% NEC (noise equivalent contrast)
- Si Imager <0.1% NEC

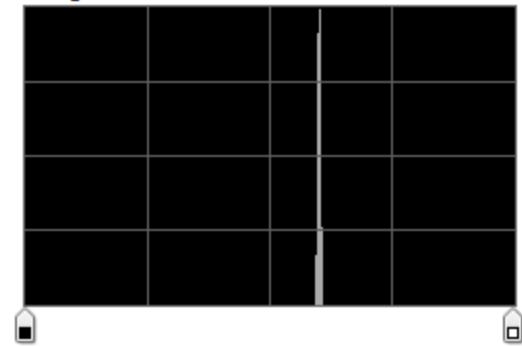
april, 12h00

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blauwe lucht boven Mechelen

**Gemiddelde van 1000 beelden
Belicht gedurende 1 minuut**

Histogram

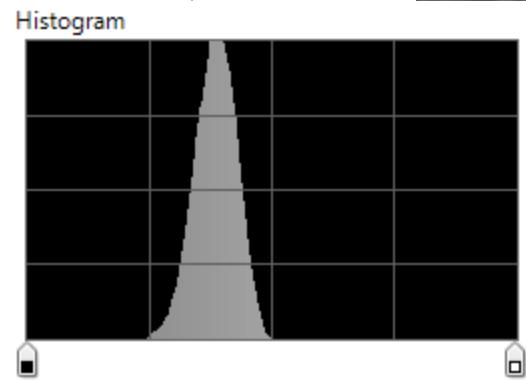
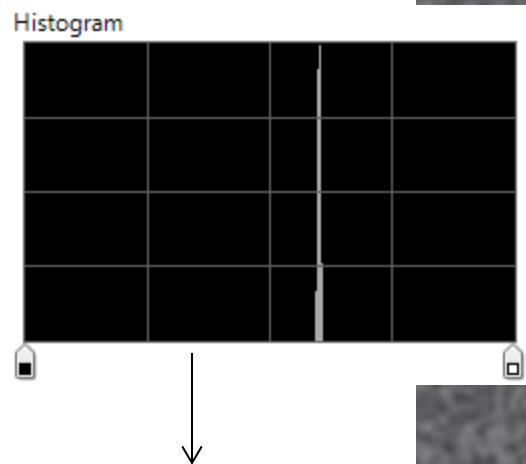


april, 12h00

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blauwe lucht boven Mechelen

Gemiddelde van 1000 beelden
Belicht gedurende 1 minuut
Contrast -> x100



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Eye versus Silicon and Film

EYE	Silicon	Film
<ul style="list-style-type: none">• $11\text{CR} + h\nu \rightarrow \text{ATR}$• 400-700nm• QE ~10%• DR ~140dB• NEC ~5%• 0.01 lux // 1 lux• ~10 fps• 120^{000000} cones+rods	<ul style="list-style-type: none">• $\text{Si} + h\nu \rightarrow \text{Si}^+ + e^-$• 350-1000nm• QE > 50%• DR > ~70dB• NEC < ~0.1%• < 0.0001 lux• > 100000 fps• 1...100 Mpixels	<ul style="list-style-type: none">• $\text{Ag} + h\nu \rightarrow \text{Ag}^+ + e^-$• $> 1^{000000}$ grains

Who we are

- Caeleste CVBA founded on 18 Dec 2006
- Team of 15
- The specialist for custom designed high-end image sensors
- Market: Space, Medical, Science
- Wavelengths: visible, X, γ , UV, IR, μ , e-, H+, α ...



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9

Mission

- Caeleste makes the photon sensor that helps develop the cancer cure of tomorrow
- Caeleste's sensors enable the world's largest telescope in its search to distant earth-like planets
- Caeleste creates the true color medical X-ray, by counting and weighting individual photons

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Beyond State of the Art Custom Image Sensors

Scientific imaging:
High speed, high QE, sub electron noise image sensors
CMOS Avalanche photodiodes
Visible light photon counting

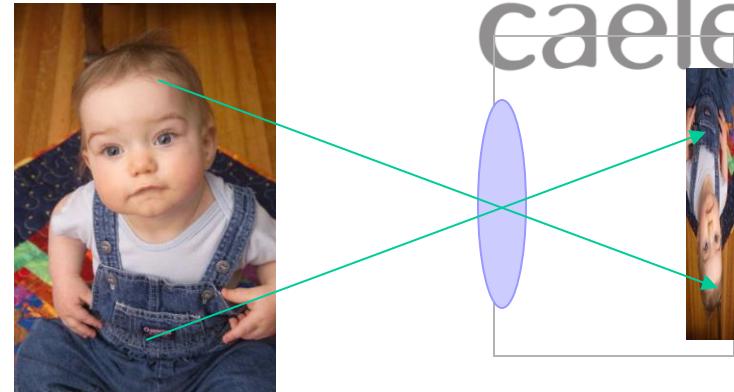
Space imaging:
From sensors to ROICs and companion chips
Gamma+proton TID and SE/SEU/SEL radiation hardness
Best in class TID hard Dark Current

Industrial Vision:
High Speed, High sensitivity image sensor,
From NIR to UV monolithic image sensors
3D imaging

Medical Imaging:
X-ray detectors,
Integration and/or photon counting
Color X-ray, ultra low dose X-ray

www.caeleste.be
www.eureca.de

Image sensing is



- Light sensing
 - photo-electric effect
 - photo diode
 - pixels

Large pixels
High sensitivity
High S/N ratio

- Focal plane readout
 - multiplexing pixels
 - scanning
 - solid state scanning

Many pixels
High resolution

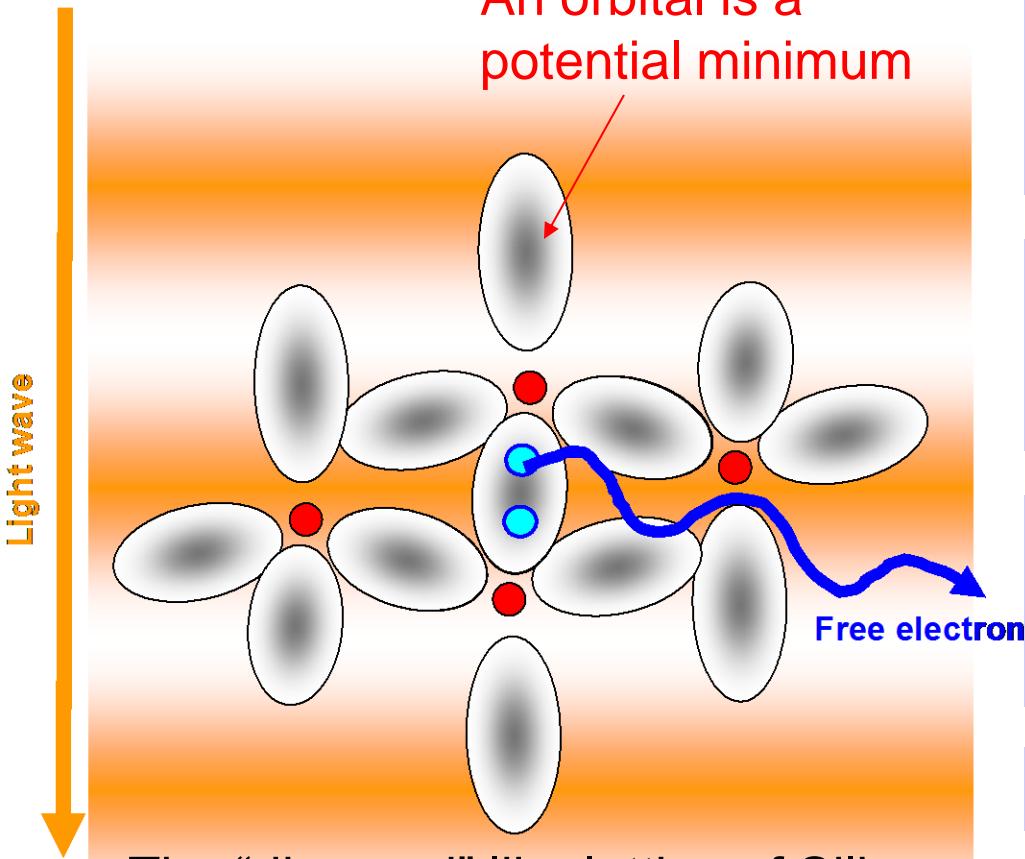
A technology of previous century

Solid state image sensing has roots that go back more than a century.
Basic concepts turn out to be nearly as old as photography

Photography	1827 (Niepce)
Flexible "film"	1884 (Eastman of Kodak)
Color film	1936 (Koslowsky of AGFA)

Rectifying metal/crystal contact	1876 (Braun)
Wireless optical transmission with Se photo resistor	1880 (Bell & Tainter)
Rectifying tube ("diode")	1883 (Edison) -1904 (Fleming)
The FET principle	1928 (Julius Lilienfeld)
First image tube "iconoscope"	1931 (Zworykin)
Integrated circuit	1959 (Kilby and Noyce)
Planar technology	1960
→ MOS image sensor	1967 (Weckler & Noble)
→ CCD	1970 (Boyle & Smith)

Photon to electron conversion: the photo-electric effect



Si outer electrons mediate the chemical binding in atom-atom “orbitals”. Binding energy is 1.12 eV.

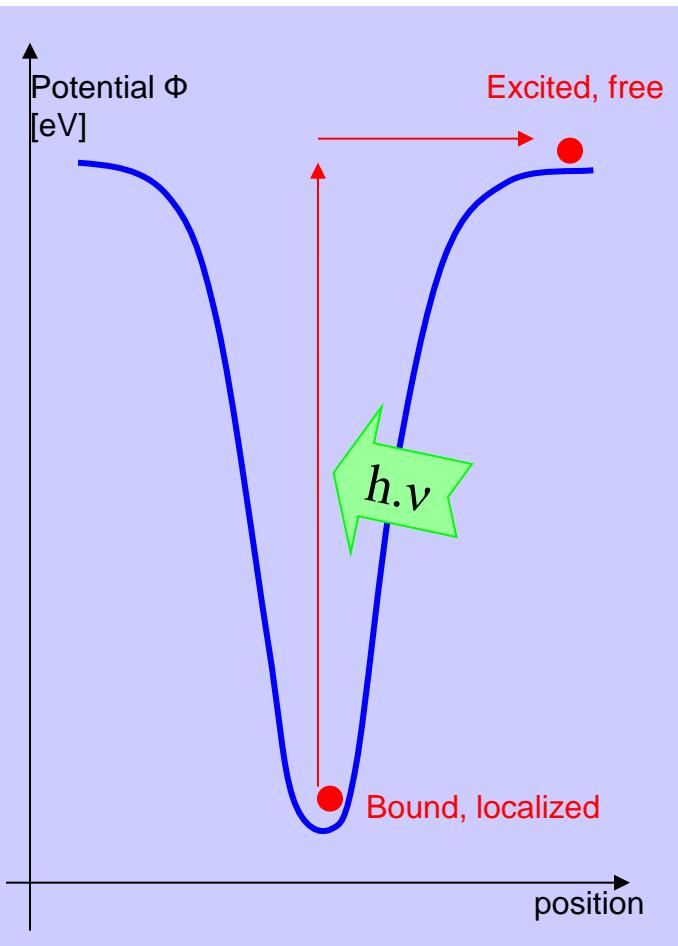
Photo-electric effect:
Electromagnetic wave excites bound electrons

Exactly one electron is excited by exactly one quantum of energy $h\nu$ (>1.12 eV)

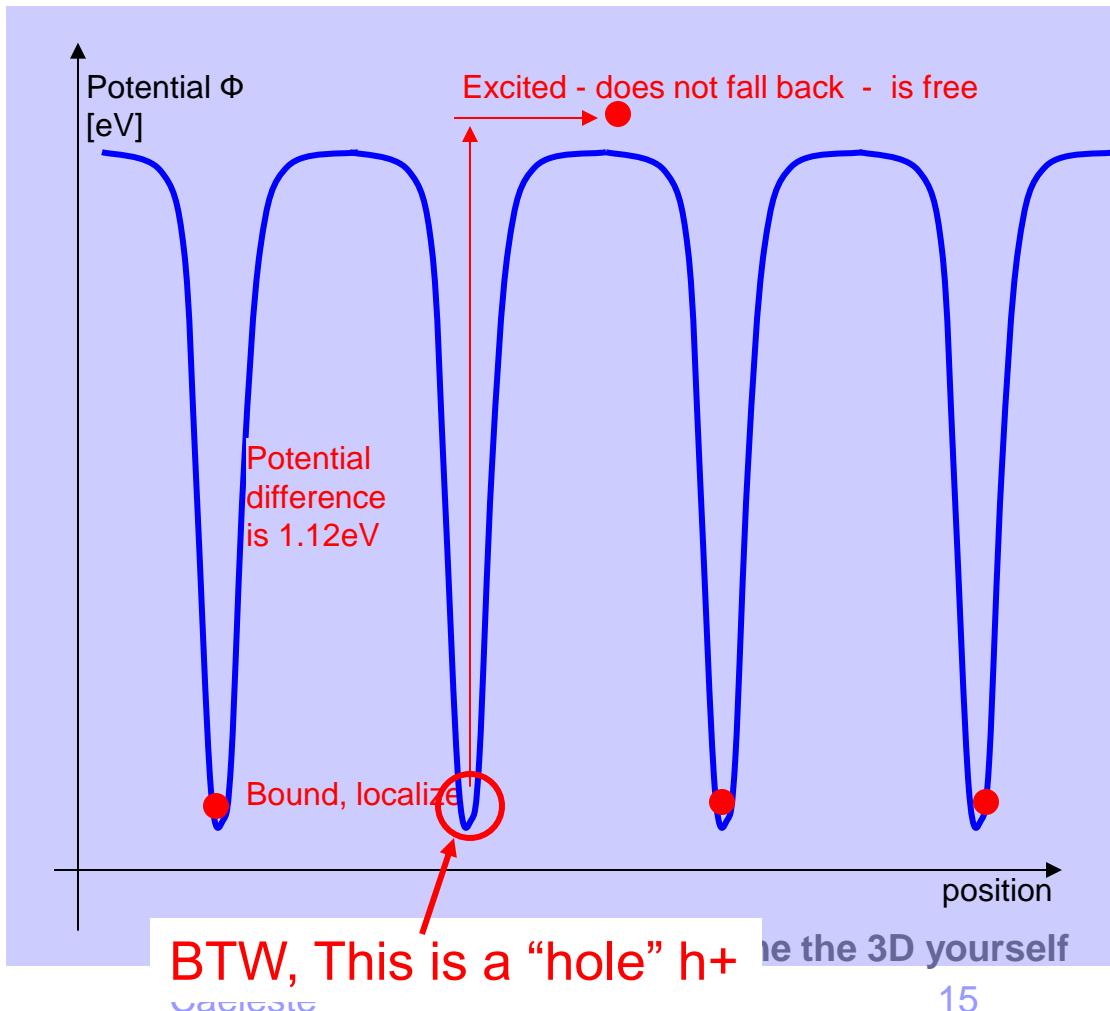
This quantum is called “photon”

Bandgap, huh?

Pseudo-classical interpretation: the electrostatic potential seen by one electron in:
one binding orbital in an array of such orbitals



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vacuum

15

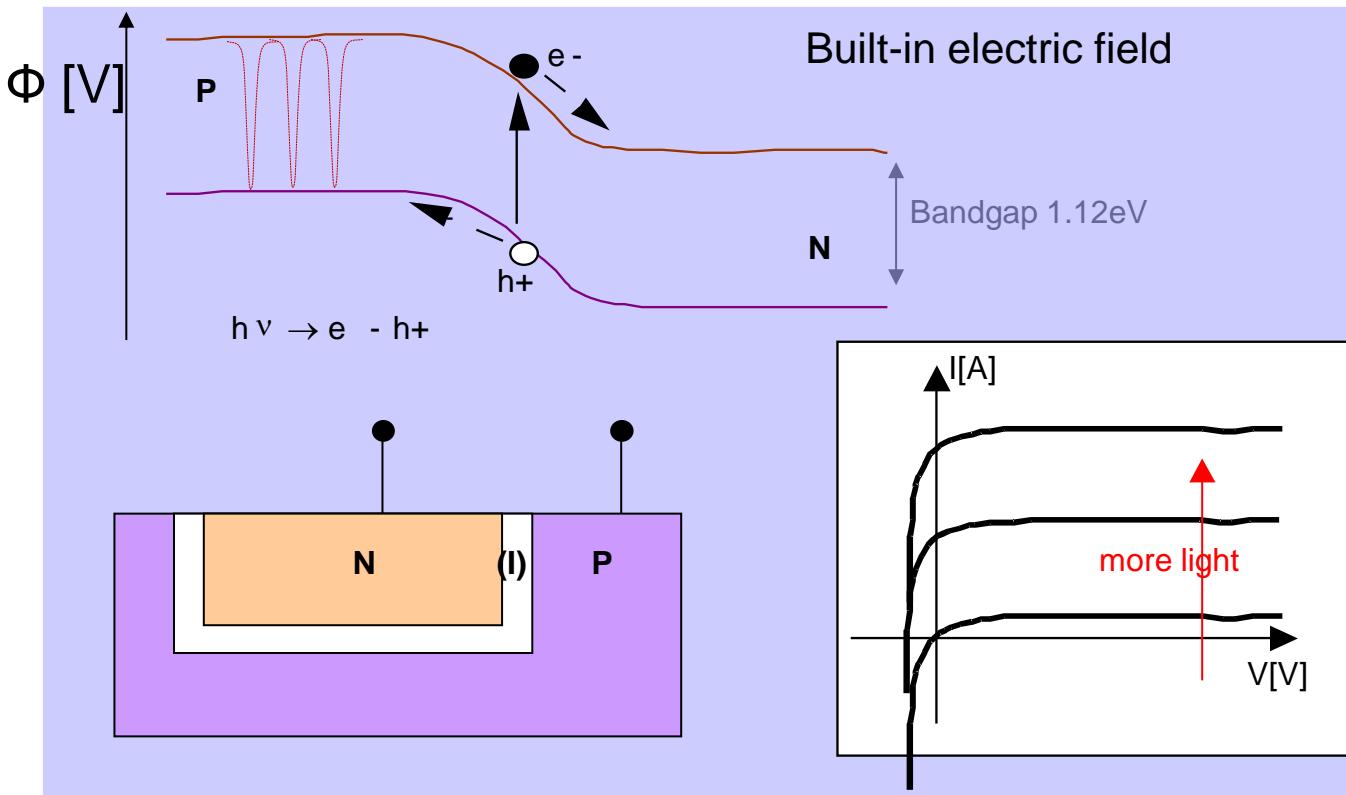
So, you have a free electron...

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What can you do with it?

Electric field affects drift speed of the free electron: $v_d = \mu \cdot E$ and $E = \frac{\partial \Phi}{\partial x}$

Photo-voltaic diode



$I = f(\text{light power})$
Current source

Consequence

- ANY material is light sensitive
 - The photo-electric principle applies to all bound electrons
 - Yet: the excited electron must be free (**no insulators!**)
 - Yet: the excited electron must not drown in a sea of free electrons (**no metals!**)
- The excited electron must be detected
 - As a current, as a charge packet

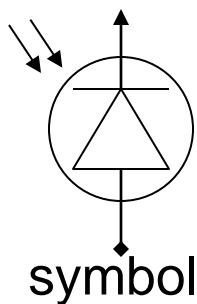
Typically one speaks of photocharge

Photo current \sim light power

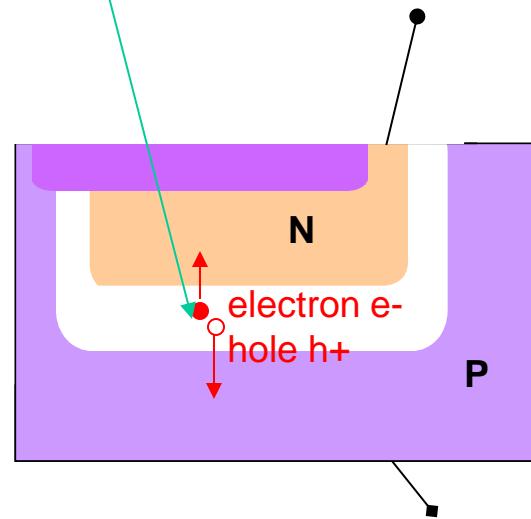
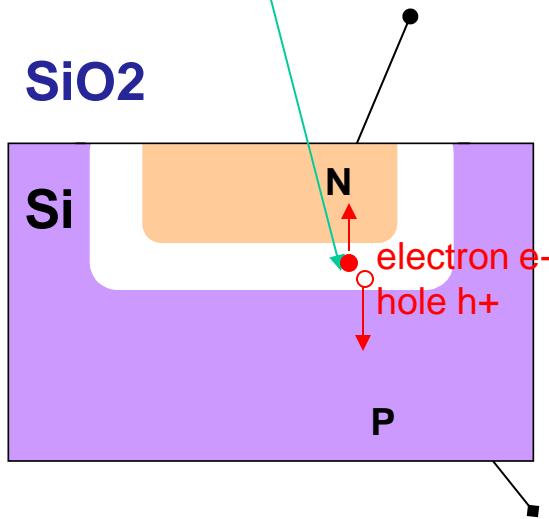


Integral over time ("integration time" == shutter time)

Photo charge \sim light energy



The Photodiode

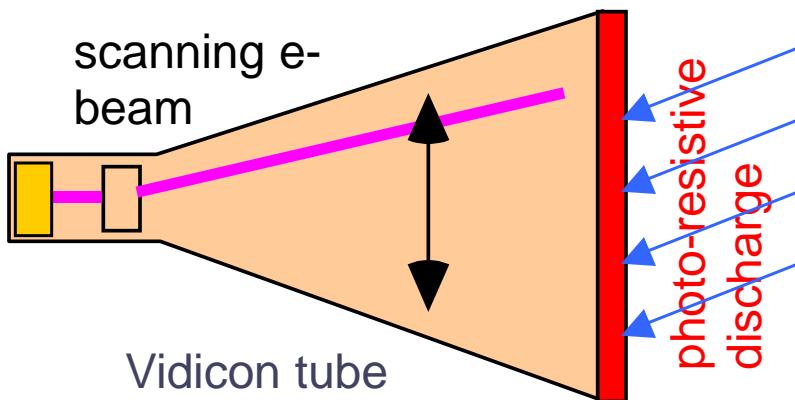


Photodiode	Buried (pinned) photodiode
<u>ANY</u> p-n junction is a photodiode	Shield junction from Si-SiO ₂ interface to decrease leakage (dark current)
Most basic	Most used today

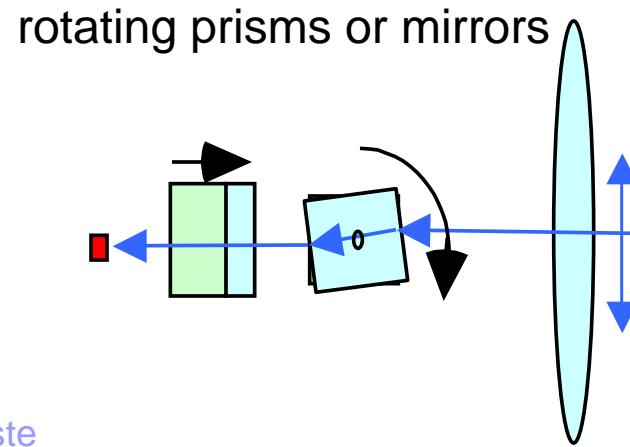
Imaging = light detection + focal plane readout

Methods for scanning the focal plane

Non solid state scanning	Solid state scanning
<ul style="list-style-type: none"> •image tubes (Vidicon): scanning by an electron beam •opto-mechanical scanning (flatbed scanners, barcode scanners) •photographic emulsion: chemical memory •biological systems: parallel processing 	<ul style="list-style-type: none"> •Diode array or passive pixel: <u>current multiplexing</u> •CCD (CID, CSD): <u>charge multiplexing</u> •Active pixel CMOS: <u>voltage multiplexing</u>



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Silicon pixel & array concepts

Pixel:

Picture element

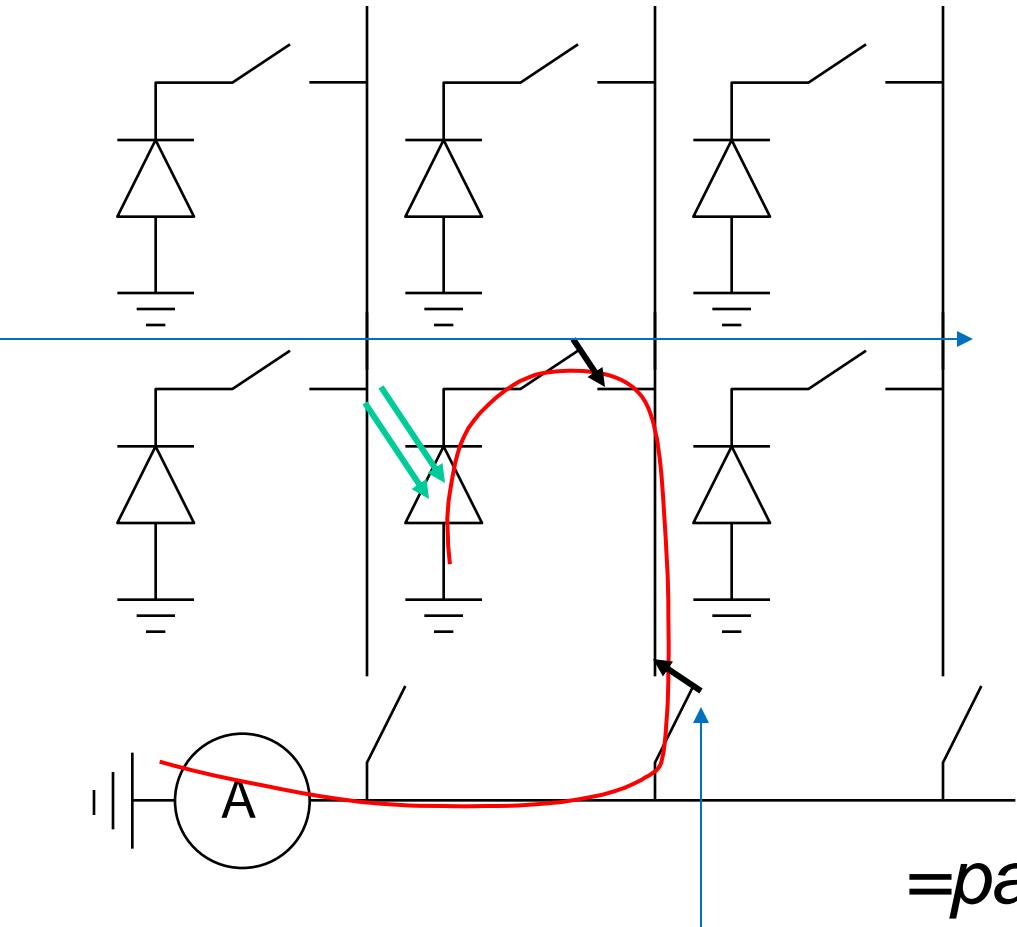
In an image sensor: photodiode + local readout electronics

Imager = Image sensor

= pixel array + peripheral electronic circuits

1. Passive pixel sensor
2. CCD (charge coupled device)
3. Active pixel sensor

Quiz: let's make a simple image sensor



+
Decent photo diodes and
decent multiplexing

+
Direct measurement of
photocurrent

-
Photocurrent is measured
only when pixel is accessed
Information of not accessed
pixel is lost

=passive pixel image sensor

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Let's make a better
passive pixel image sensor?

no

Out of the blue came the

CCD (charge coupled device)

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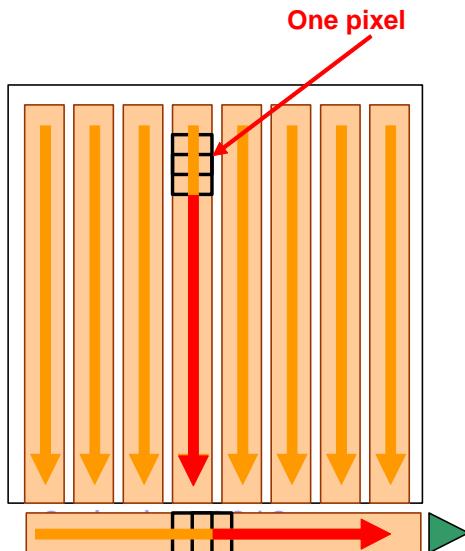
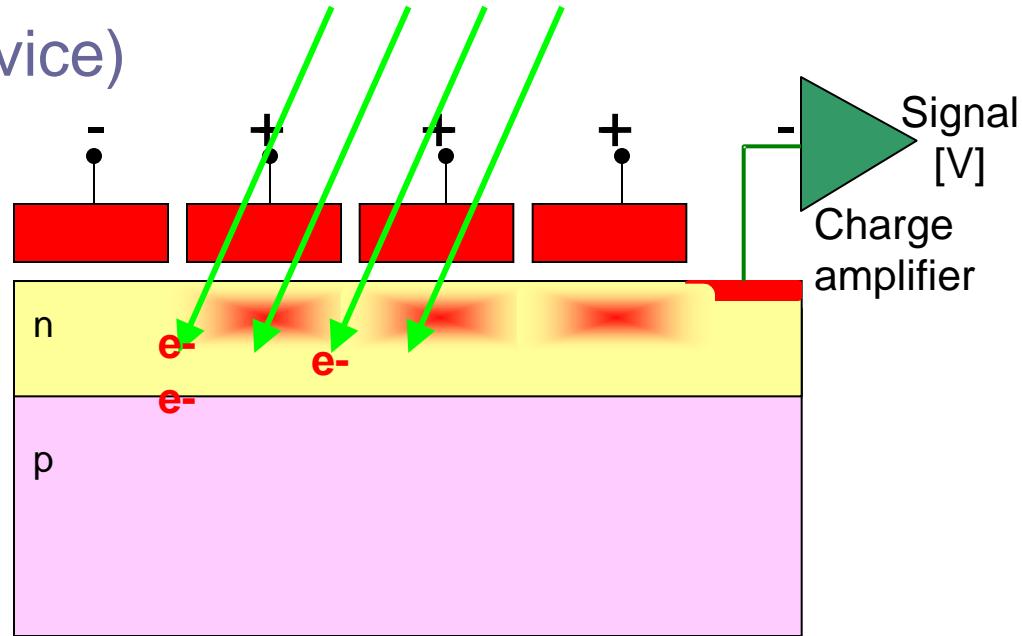
Short history:

MOS passive pixel: 1967

CCD invented in 1970

→ and quickly became the
preferred image sensor technology

First reason: litho density

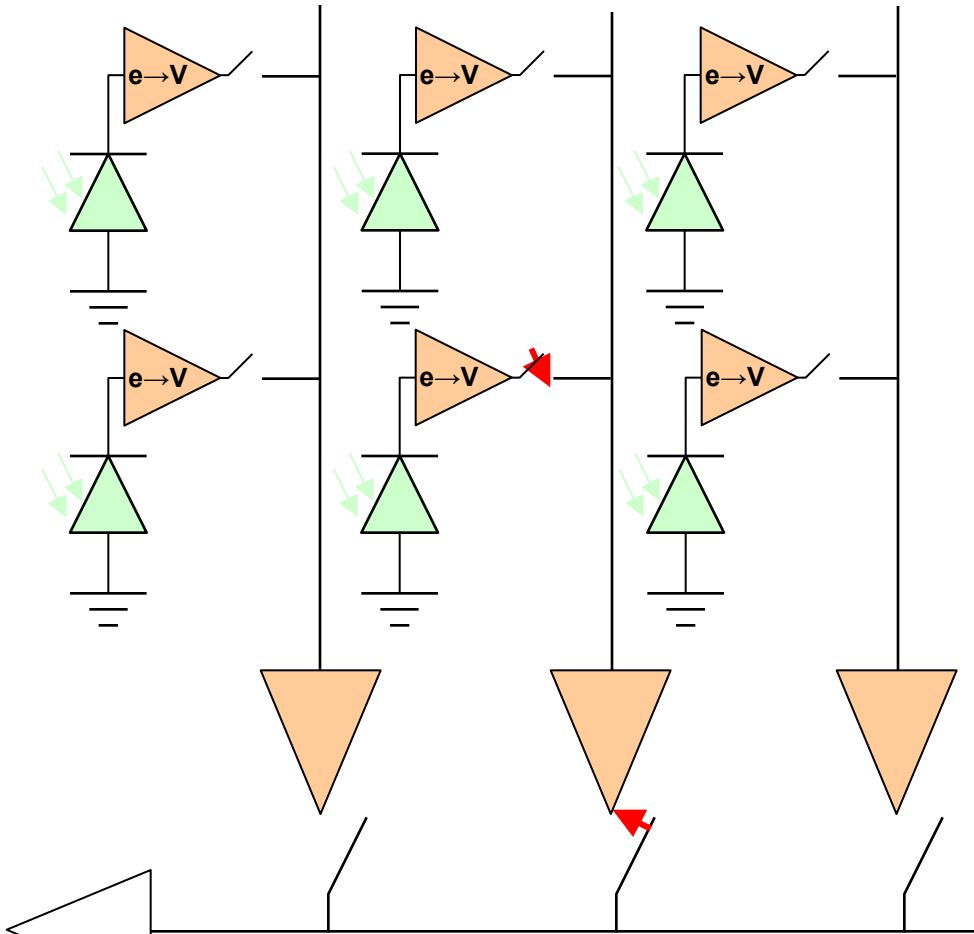


CCD Technology:

- Photo detection in distributed *buried photo-diode*
- Electron cloud attracted and confined by electro potentials
- *Buried channel* charge transfer
- Closely spaced electrodes
- Originally based on Silicon nMOS
- Historically optimized for optical detection

Next Improvement ~1980: **caelest**

Active Pixel Sensor: [charge] amplifier inside each pixel



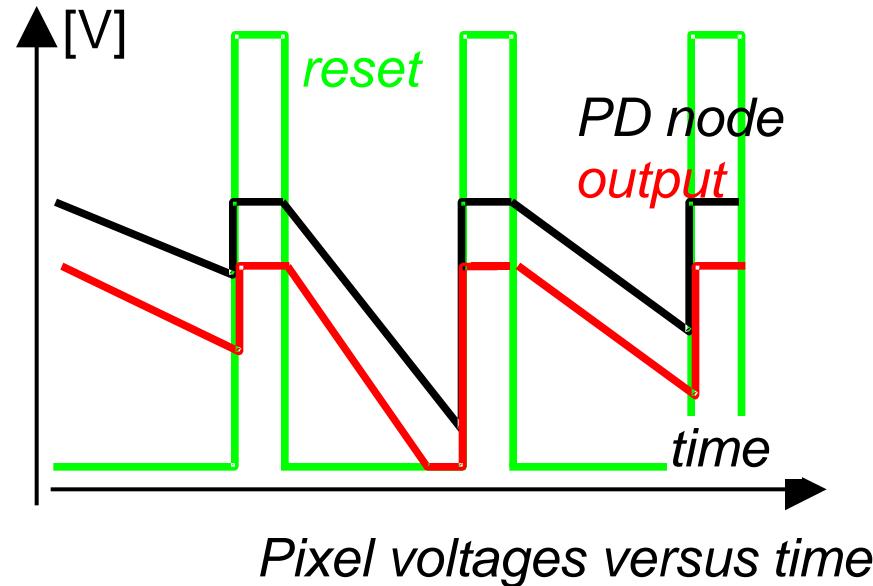
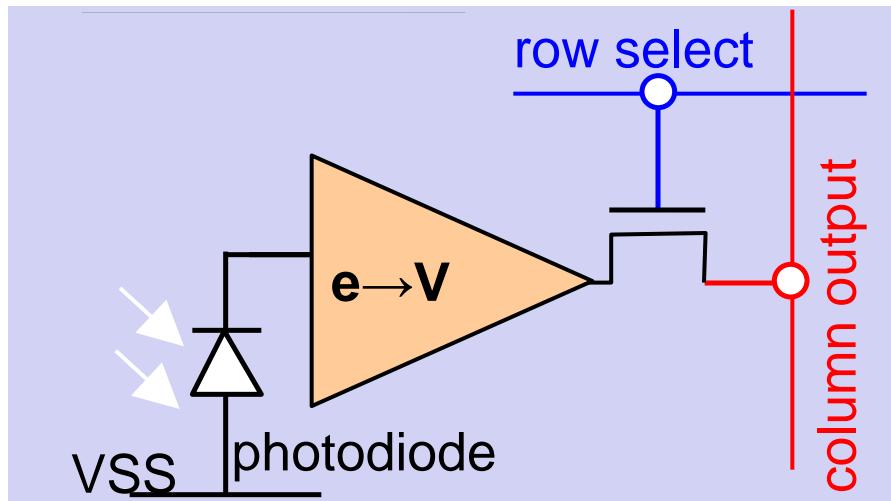
+

- charge integration
- low parasitic capacitance on sense node
- voltage multiplexing

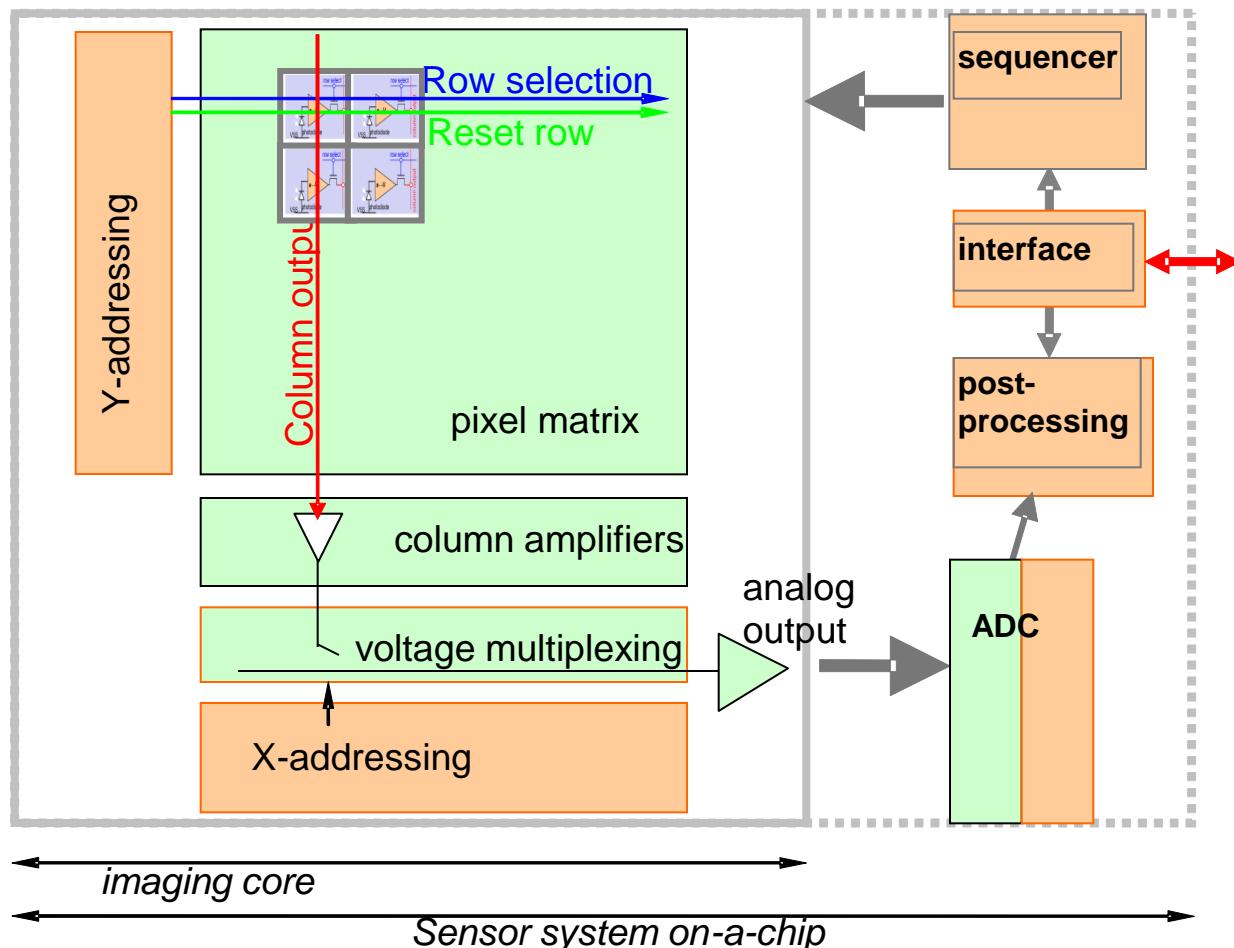
-

- pixel-to-pixel non-uniformity
- low fill factor
- several transistors per pixel

The most straightforward active pixel: The 3 Transistor (3T) active pixel



Floor plan of a typical CMOS image sensor SoC



Worth remembering

- Image sensing means:
 - Light sensitive pixels
 - Scanning or multiplexing the information
- All materials are light sensitive due to the photo-electric effect
 - why is not every material suitable as detector?
- There are three major image sensor families
 - Current multiplexing: passive pixel sensor
 - Charge multiplexing: CCD
 - Voltage multiplexing: active pixel sensor

Examples of image sensor design and applications

Adaptive Optics (AO)

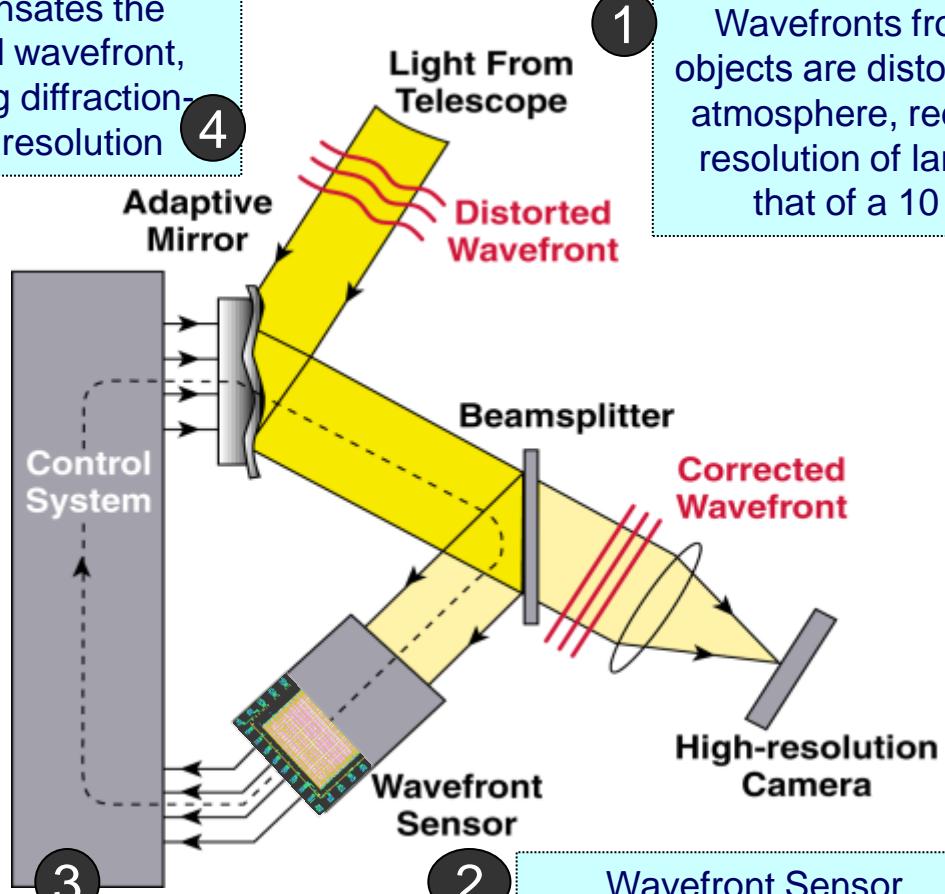
removing the twinkle of the stars

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Deformable mirror compensates the distorted wavefront, achieving diffraction-limited resolution



ESO
European Organisation
for Astronomical
Research in the
Southern Hemisphere



1

Wavefronts from astronomical objects are distorted by the Earth's atmosphere, reducing the spatial resolution of large telescopes to that of a 10 cm telescope

2

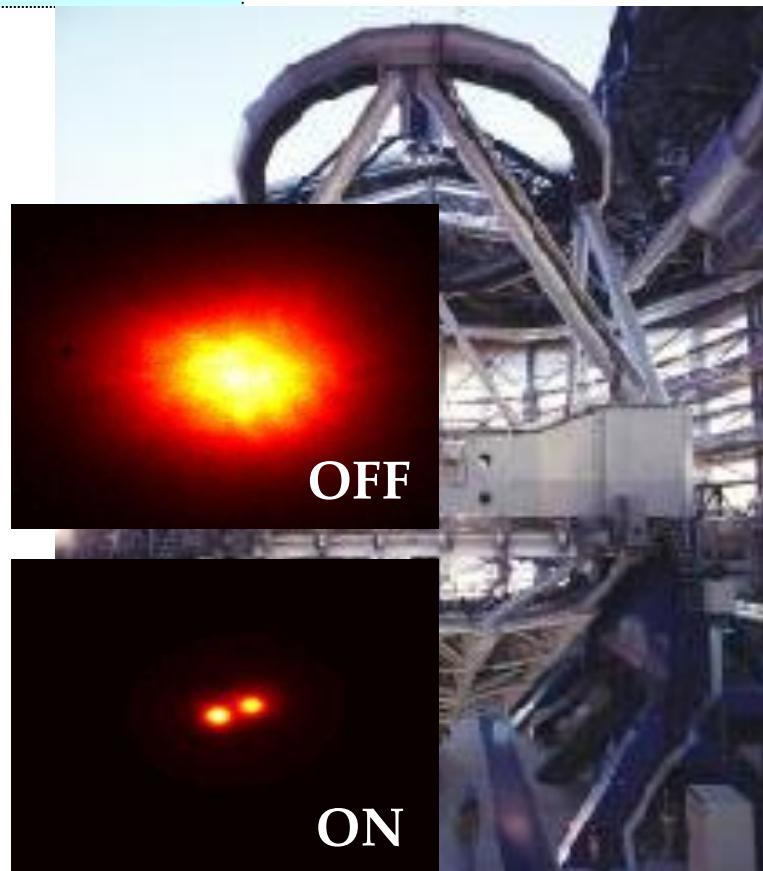
Wavefront Sensor measures deviation of wavefront from a flat (undistorted) wave

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3

Control System computes commands for the deformable mirror(s)

4



Wavefront sensor

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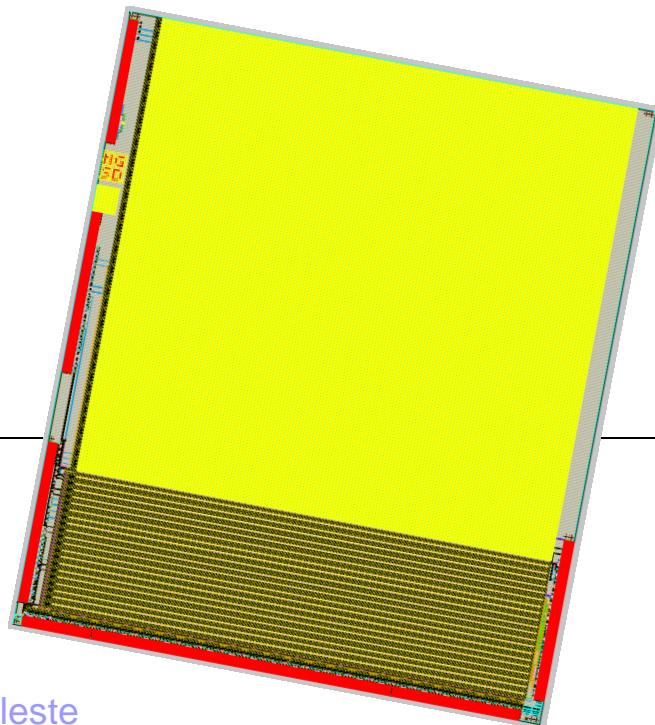
Low noise **x** high QE **x** high speed

Geometrical

- Pixel size: 24 μm
- Pixel Array: 1760 x 1760 (4x4cm)
- Frame rate: 700(...1000) fps
- Pixel rate: 40 MHz/channel
- 88 LVDS channels
- 4T pinned photo diode pixel
- 40x1760 10bit ramp/column ADCs

Electro-optical

- Full well charge 4000 e-
- Read noise: $\sim 2.5 \text{ e}^-_{RMS}$
- QE 95% visible range backside illuminated



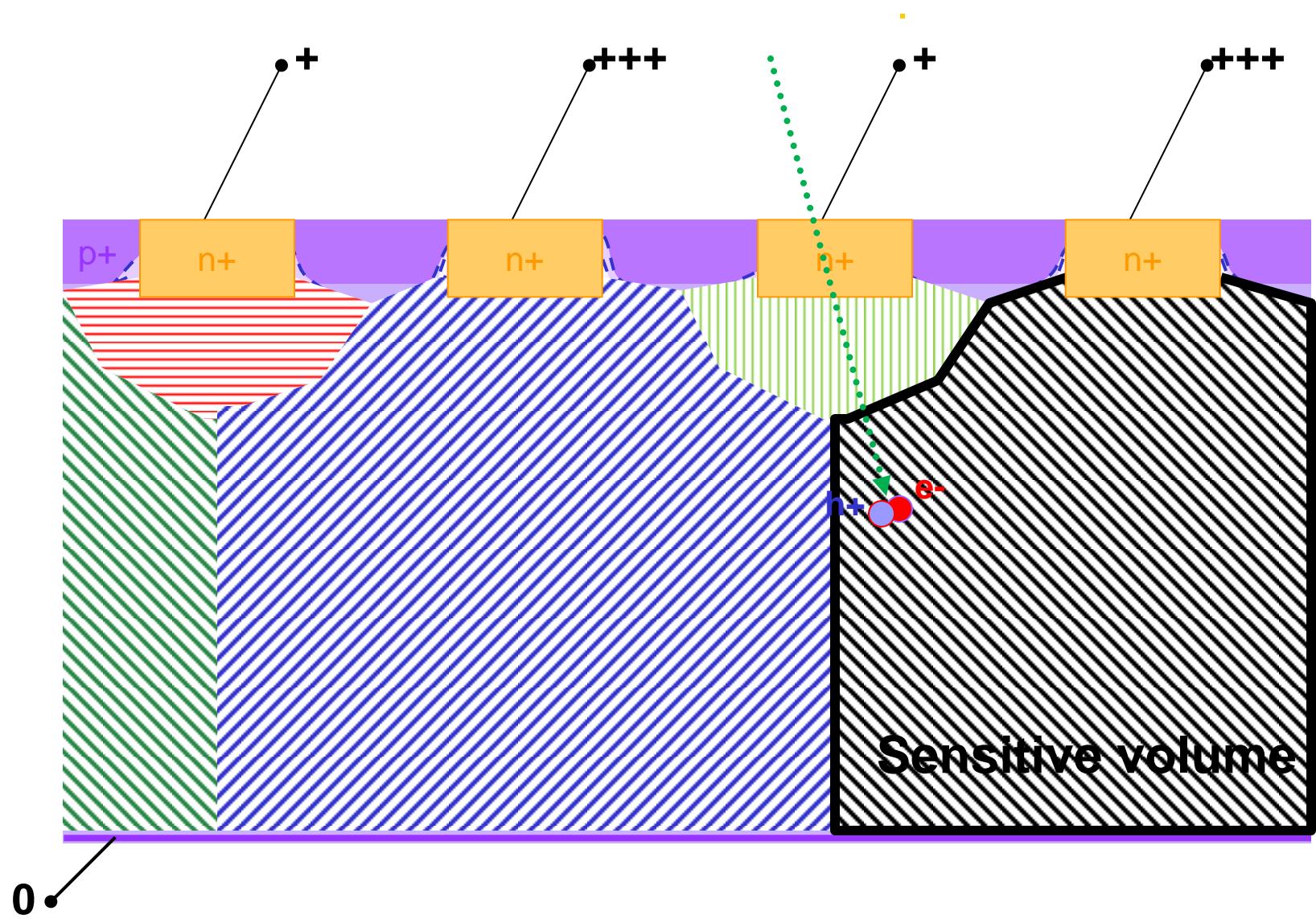
B Dierickx, A Defernez, B Dupont, M Fryer, P Jorden, A Walker, A Pike, P Jerram, J Pratlong, "Backside thinned, 2.5 e $^-_{RMS}$, BSI, 700fps, 1760x1760 pixels wave-front imager read out over 88 parallel LVDS channels", IISW, Hokkaido Japan, June 2011

TOF 3D ranging

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time gating based

US patent US7564022

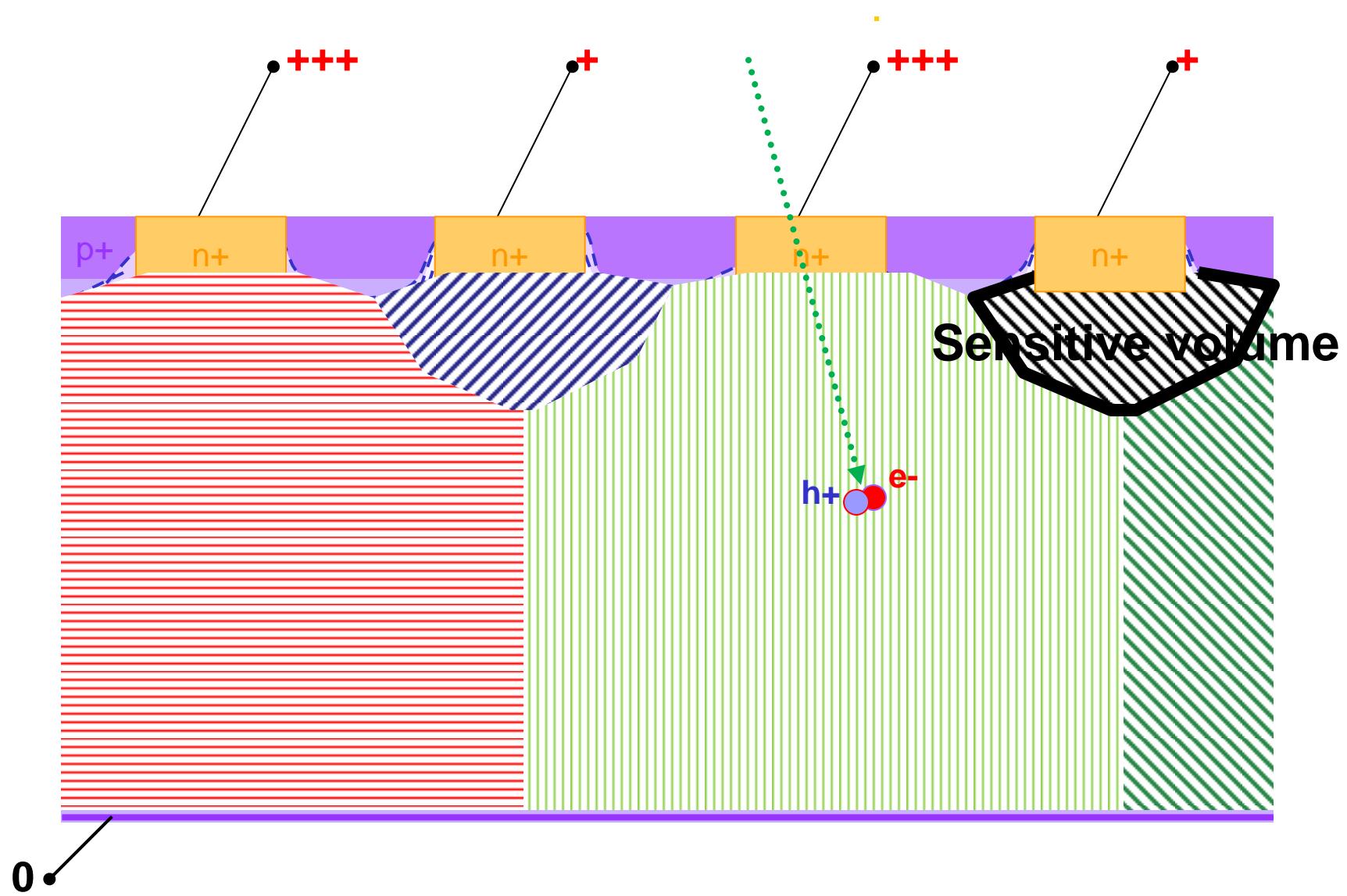


TOF 3D ranging

caelest

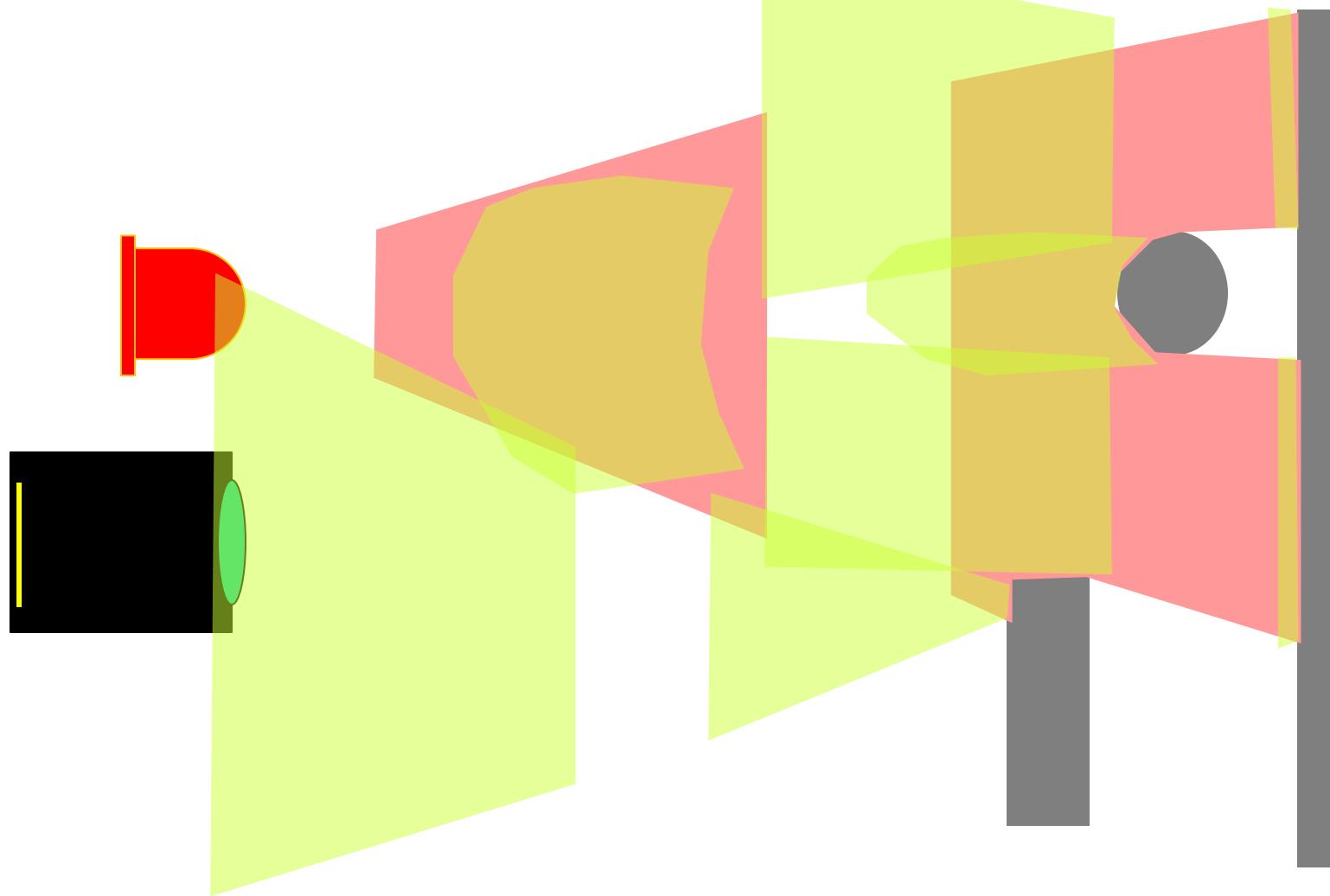
time gating based

US patent US7564022



TOF?

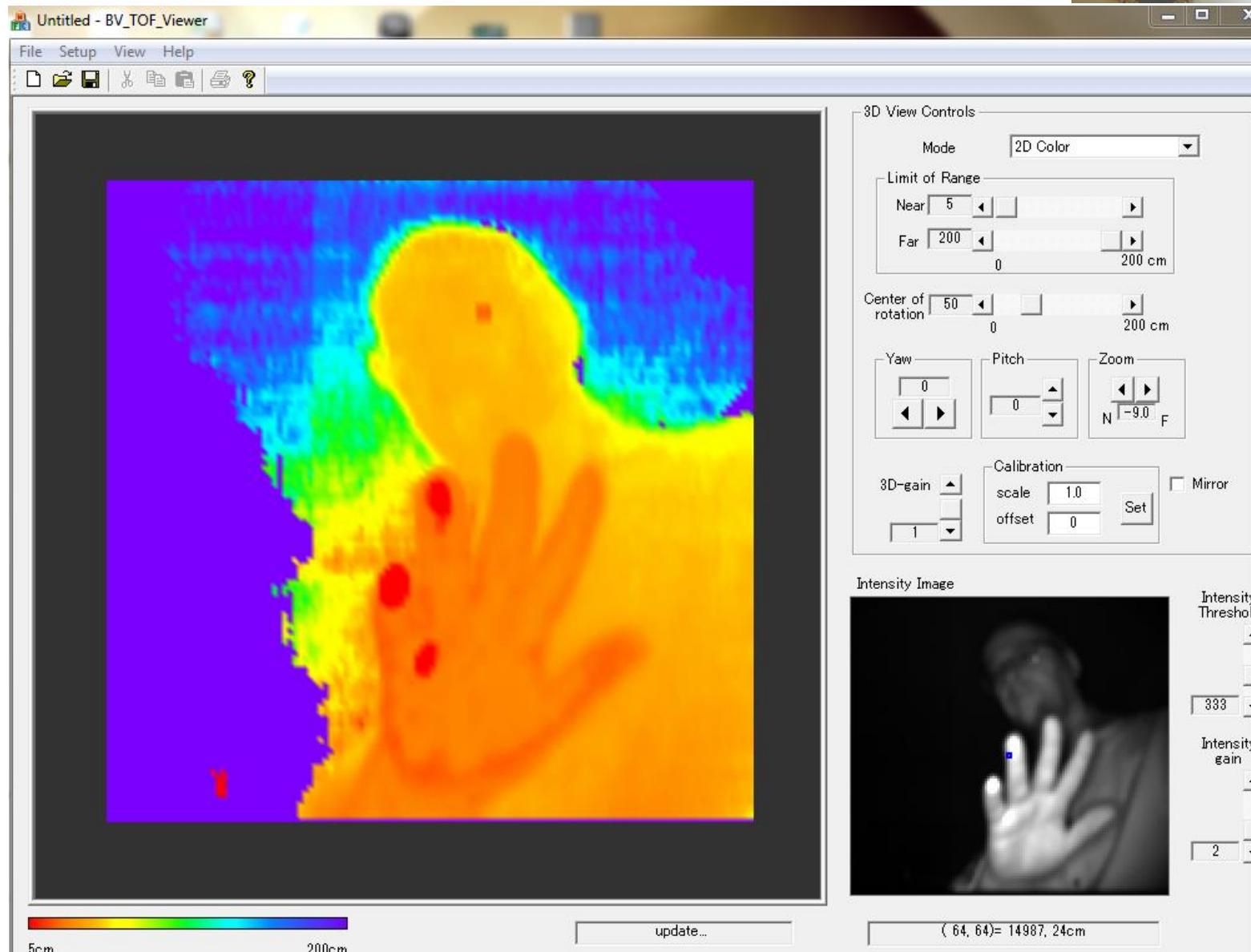
Time of flight



TOF 3D ranging

time gating based

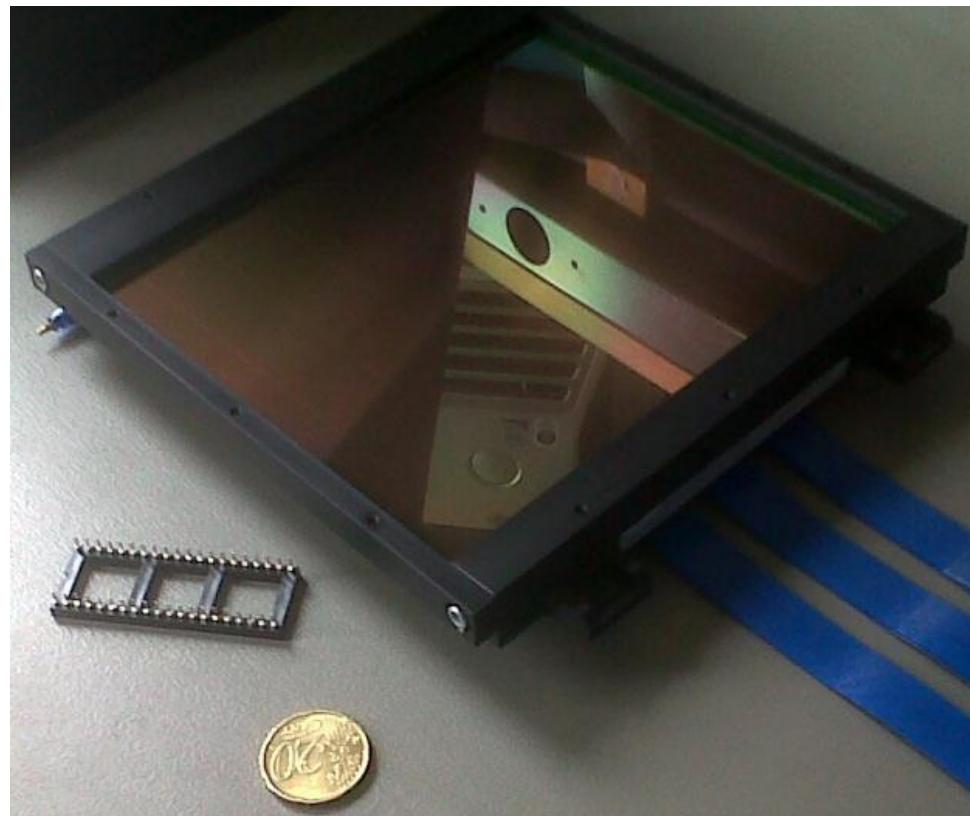
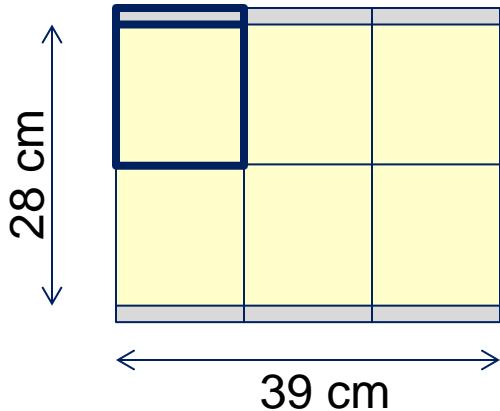
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BrainVision



SotA (state of the art) X-ray imagers

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- Classic integrating 4T pixels
- Indirect detection CMOS imager below scintillator
- Classic “Black&White”
- **Wafer scale 13*14 cm**
- High yield
- 3-side abutable:



“Color” X-ray

10cm

Breast carcinoma specimen

“Poorly differentiated invasive duct” type.

B. Dierickx, N. Buls, C. Bourgain,
C. Breucq, J. Demey, B. Dupont, A.
Defernez, “Multi-energy X-ray
imaging for mammography”, BHPA
symposium, Brussels, 5-6 feb 2010

I.Willekens, B.Dierickx, N.Buls,
C.Breucq, A.Schiettecatte, J.de
Mey, C.Bourgain, “Superiority of
multi-energy color X-ray for breast
specimen radiography”, European
Society for Radiography, Vienna,
March 2011

C Bourgain, B Dierickx, I Willekens,
N Buls, C Breucq, A Schiettecatte, J
de Mey, “A new technique for
enhanced radiological-pathological
correlation in breast cancer: multi-
energy color X-ray”, RSNA,
Chicago, Nov 2011

Courtesy of and in
collaboration with



Universitair
Ziekenhuis
Brussel

the tumor is degenerated
because the blood supply,
though increased, still
insufficient to maintain the
whole cancer mass alive.

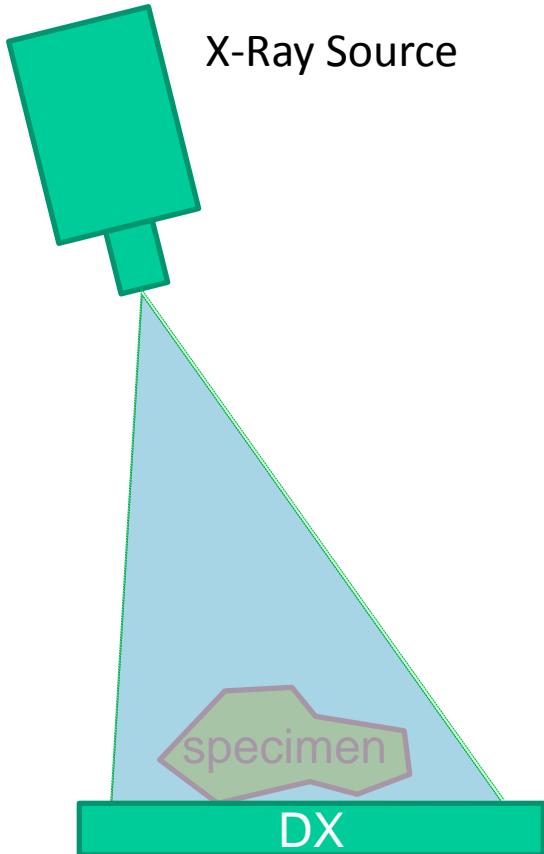
The center consists of dead
cells and calcifications
(yellowish dots).

blue arrows: normal fat
tissue (“lobules”)

Red arrows: increased
blood vessel density
around the tumor

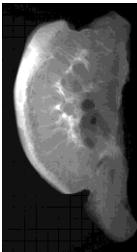
3-exposure color X-ray caeleste

Specimen X-ray

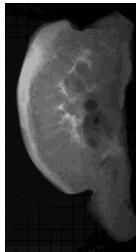


X-Ray Source

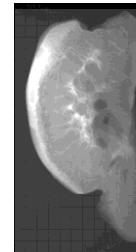
22kVp



30kVp



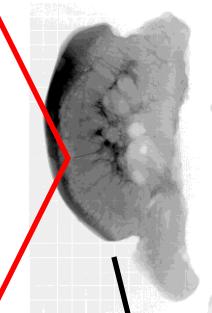
40kVp



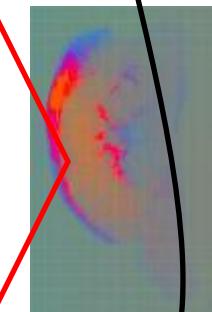
empirical white balance
Oxygen/Carbon ratio codes as
magenta/green or red/green/blue

Compensation of absorption
(inverse Beer's law)

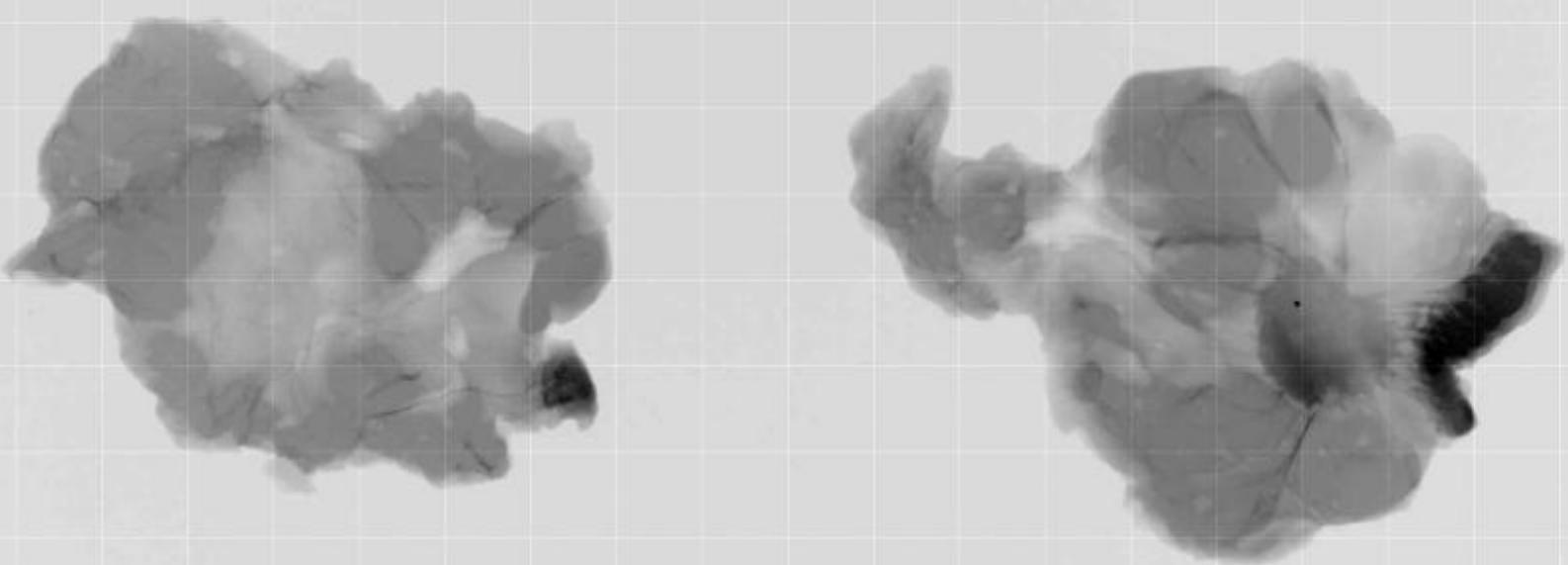
Luminance
= average



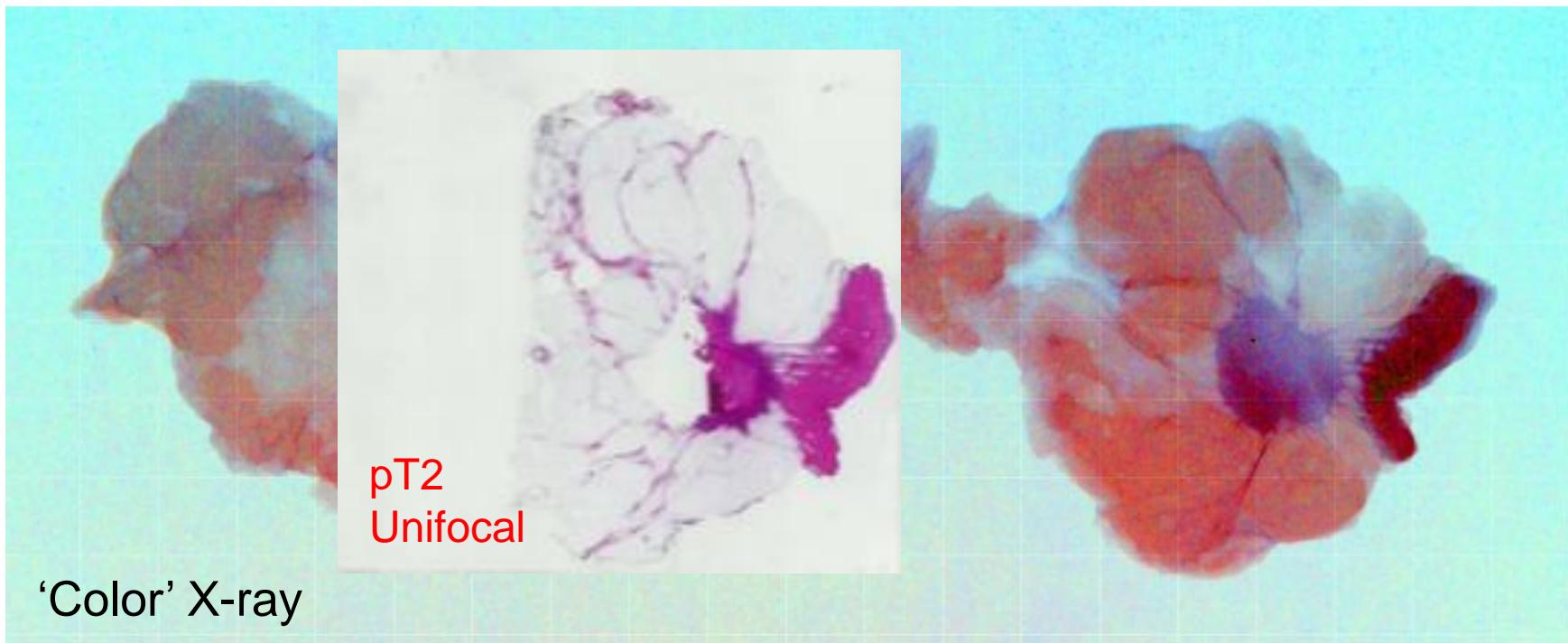
Chrominance
= differences



+



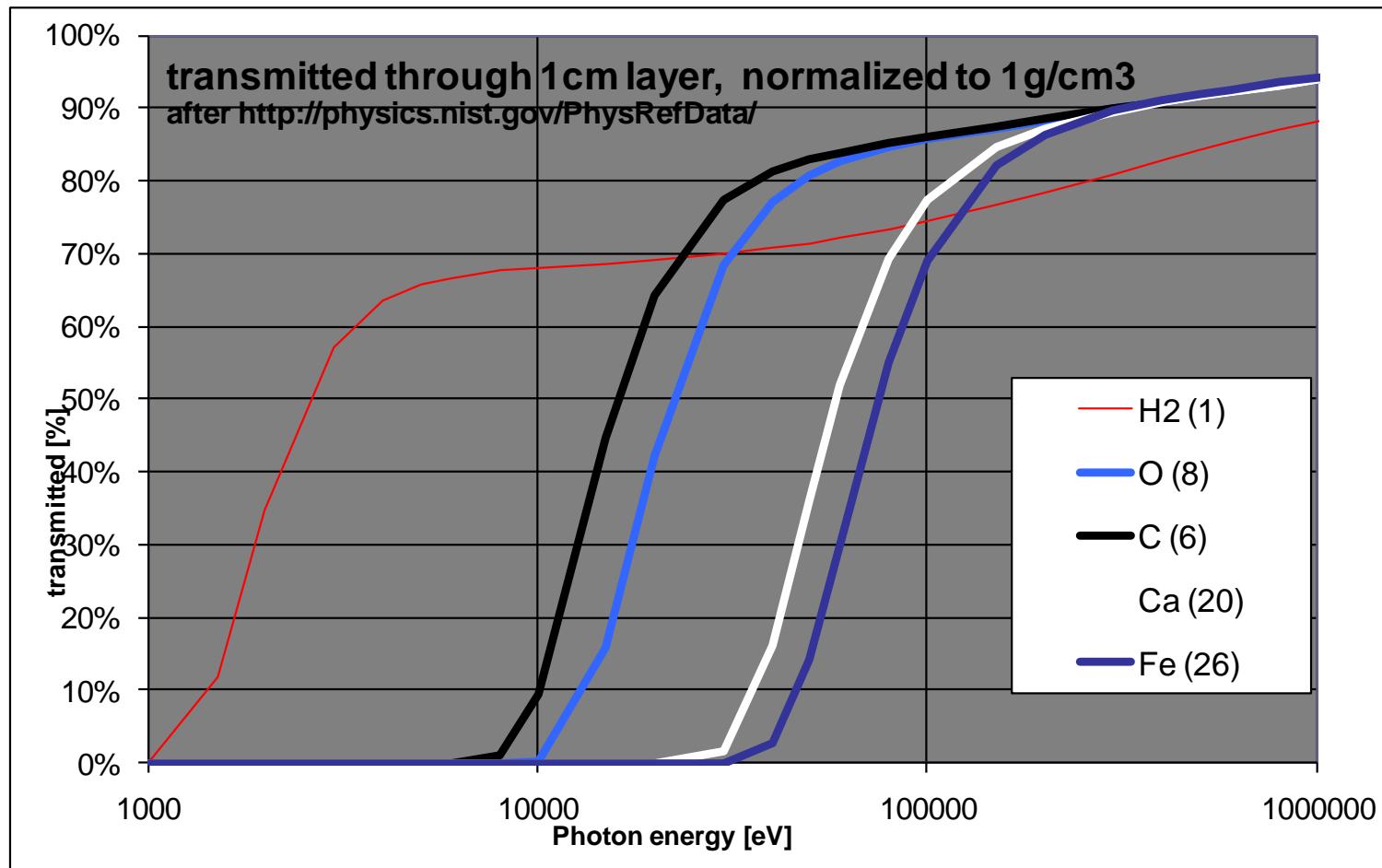
Specimen X-ray



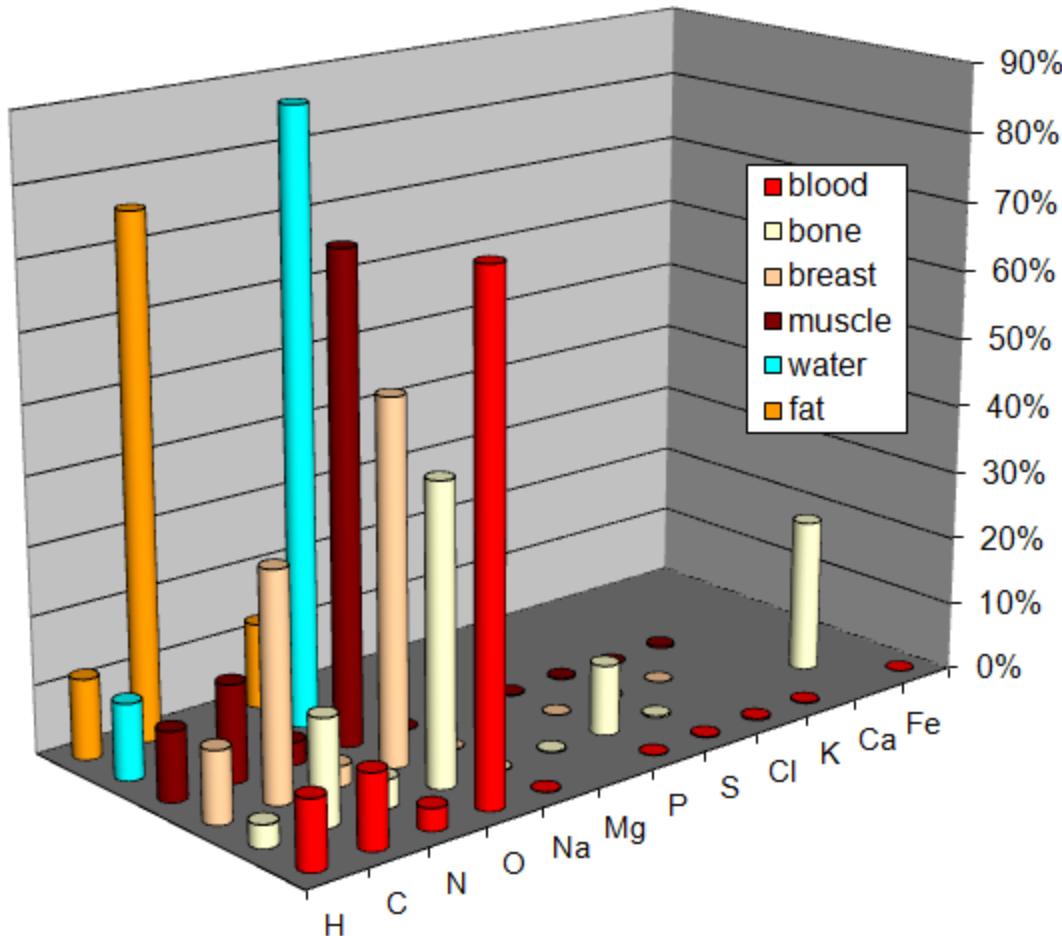
pT2
Unifocal

'Color' X-ray

The absorption of X-rays tells the atomic composition



The absorption of X-rays tells the atomic composition



C:

- fat

C+O:

- Collagen
- Proteins
- DNA

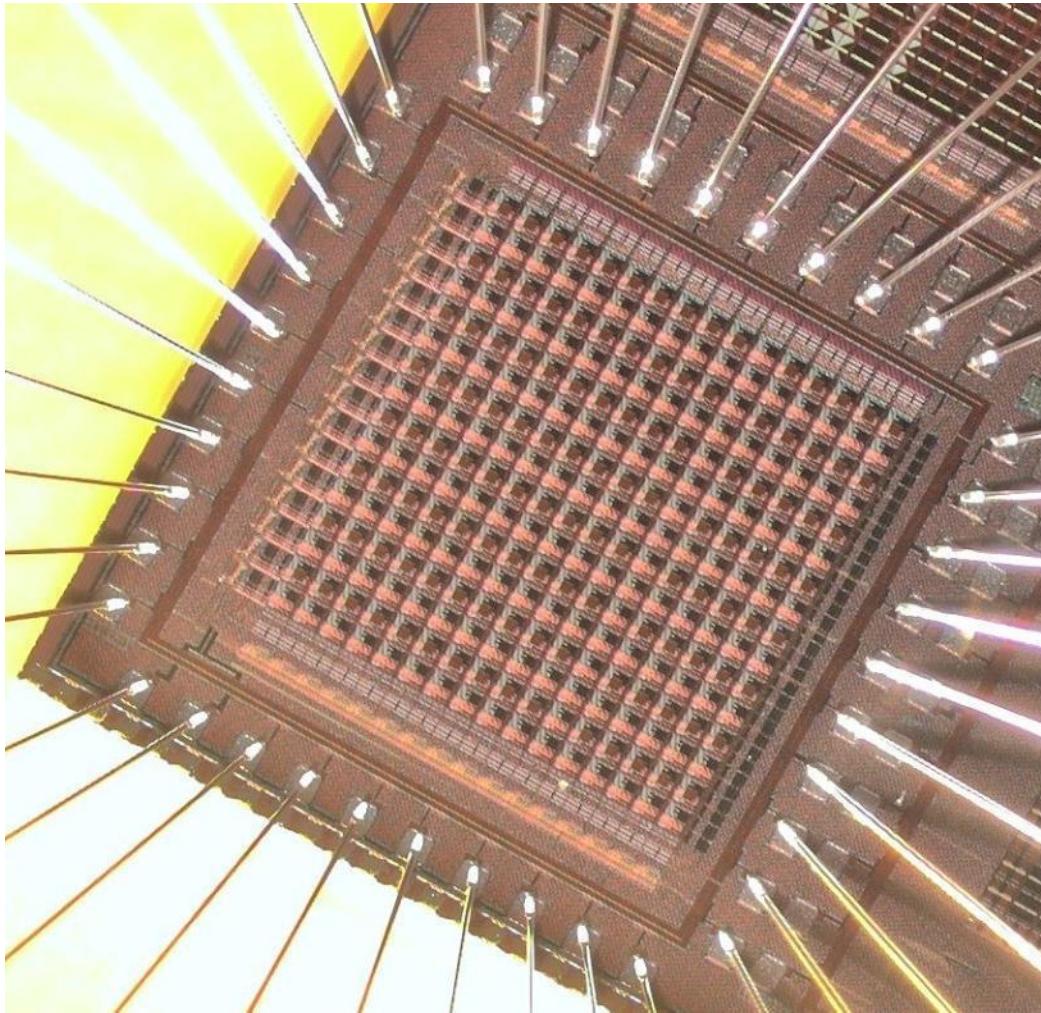
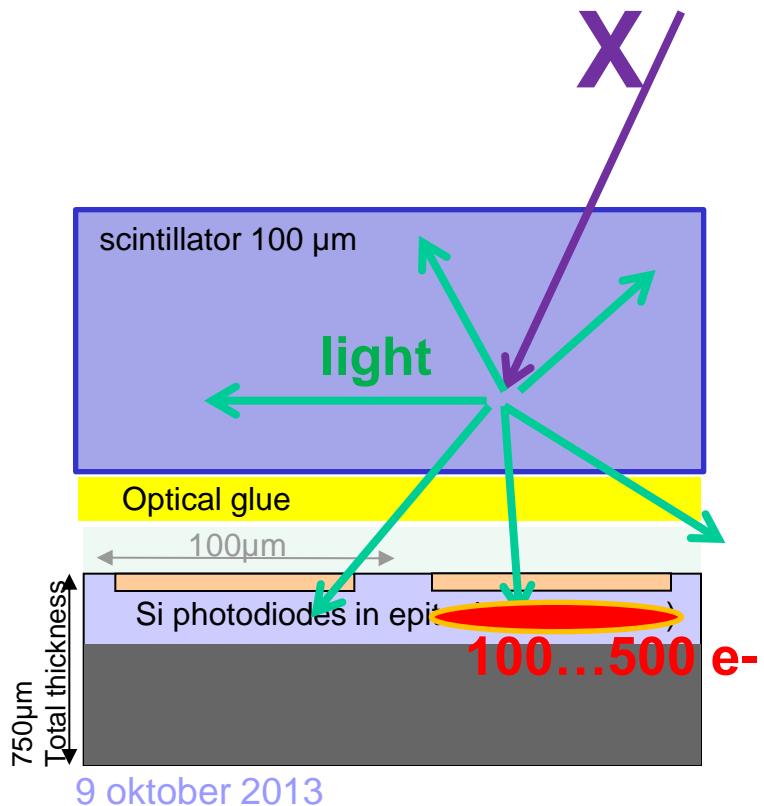
O:

- Water
- blood

Ca:

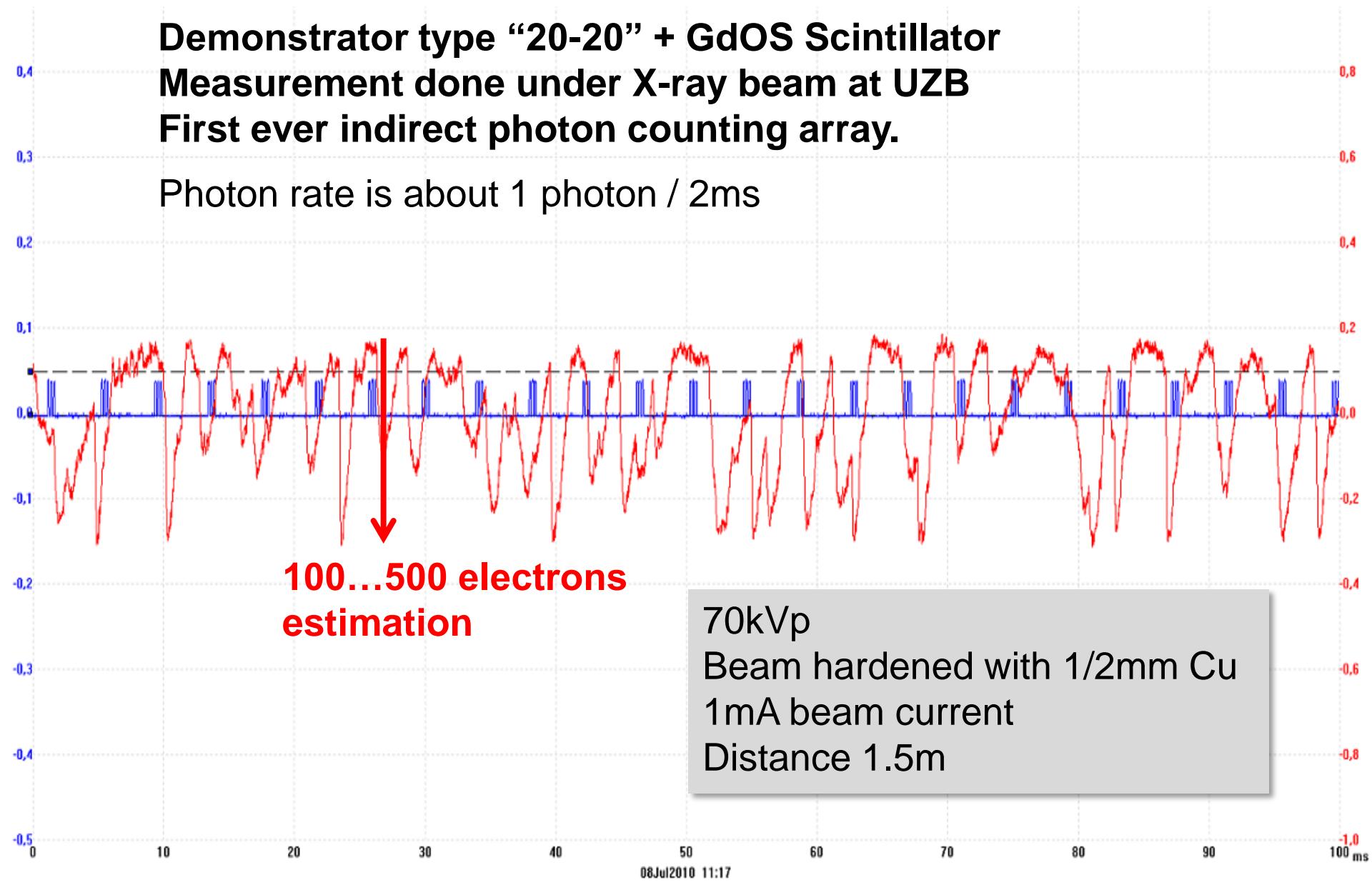
- Bone
- Calcifications
- Degenerate tumors

X-ray Photon counting

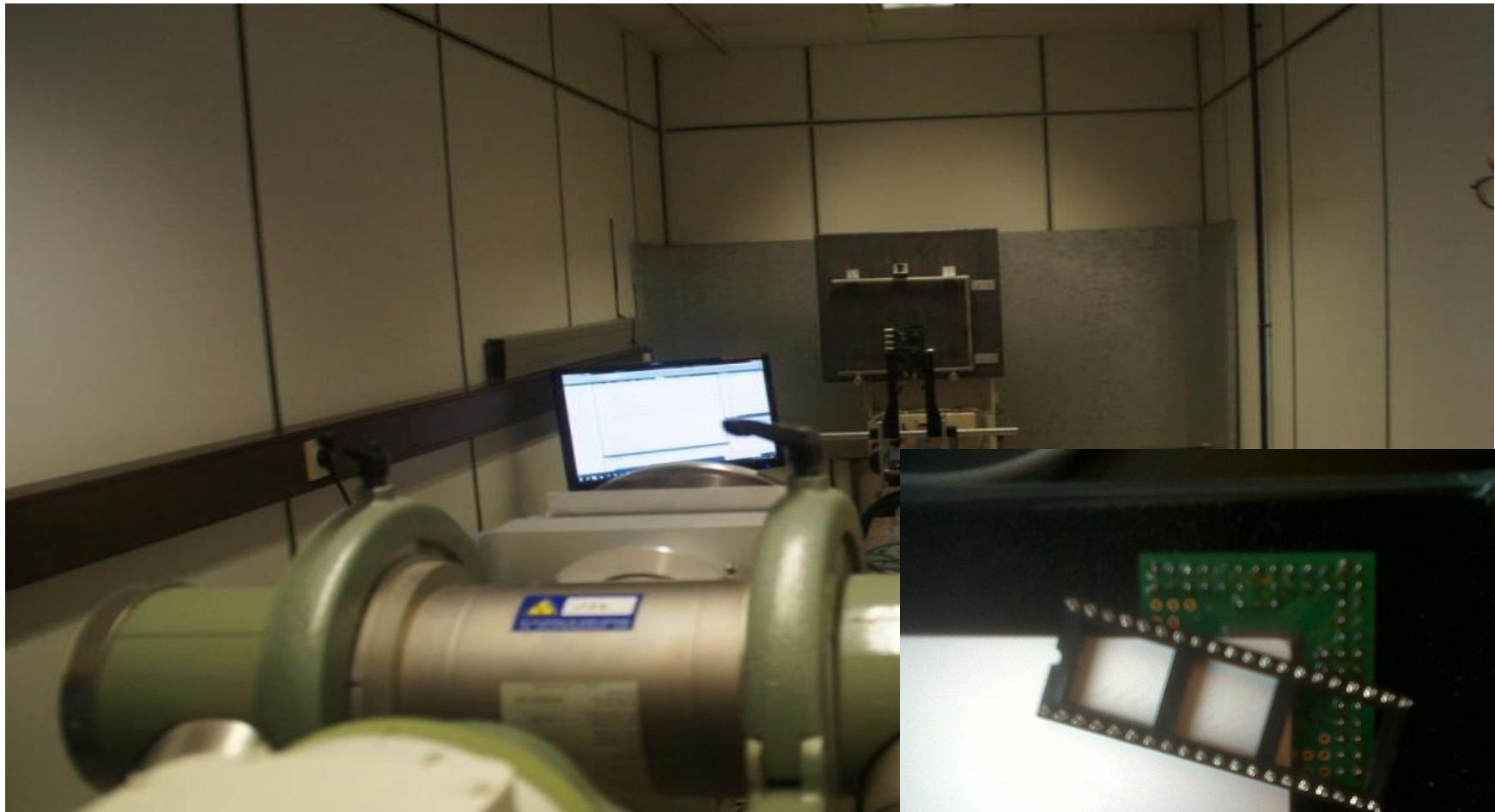


**Demonstrator type “20-20” + GdOS Scintillator
Measurement done under X-ray beam at UZB
First ever indirect photon counting array.**

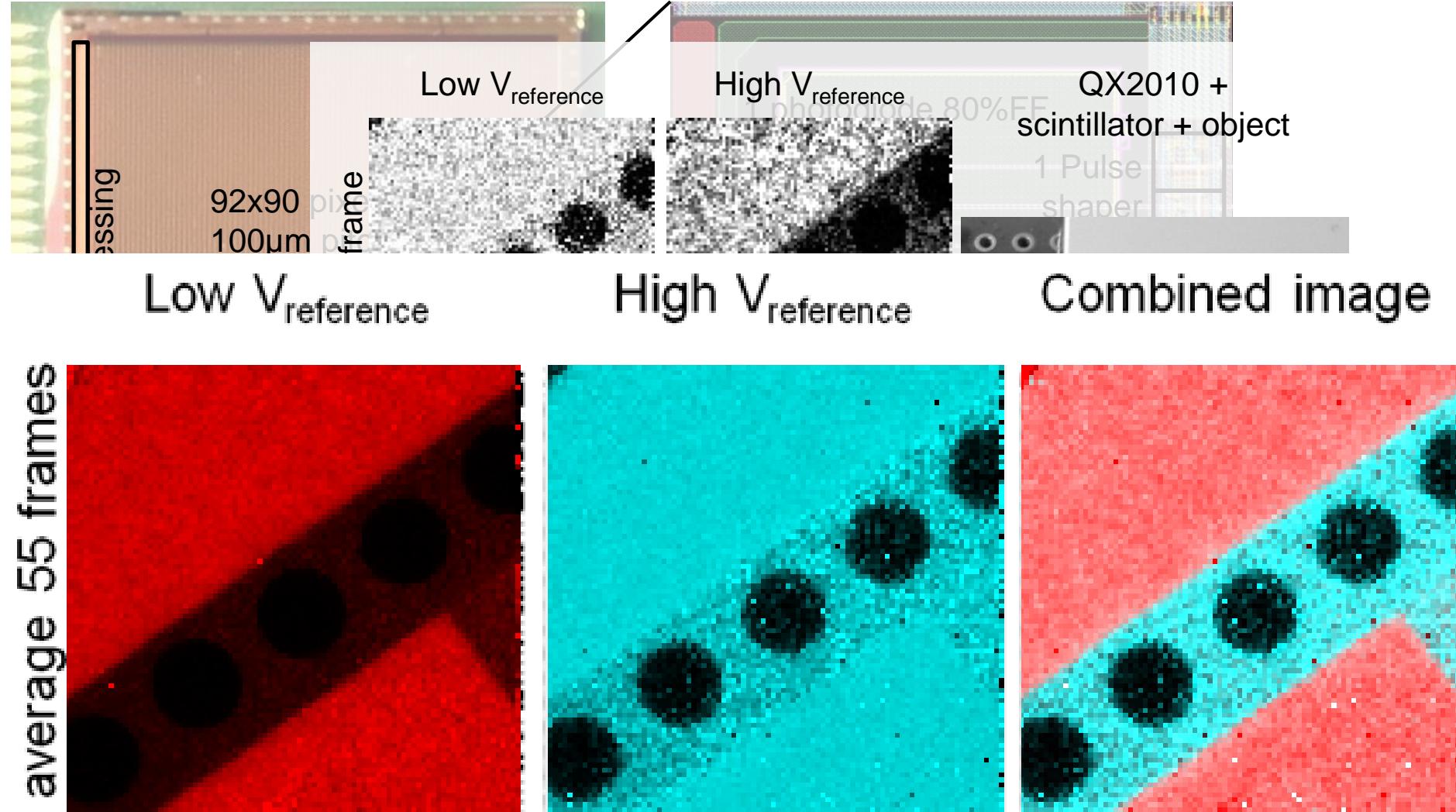
Photon rate is about 1 photon / 2ms



Example X-ray setup



QX2010 demonstration



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10 jaar vooruit

op de vlaamse researchinstituten

Tja, *zij* zijn begonnen met die onnozele slogans