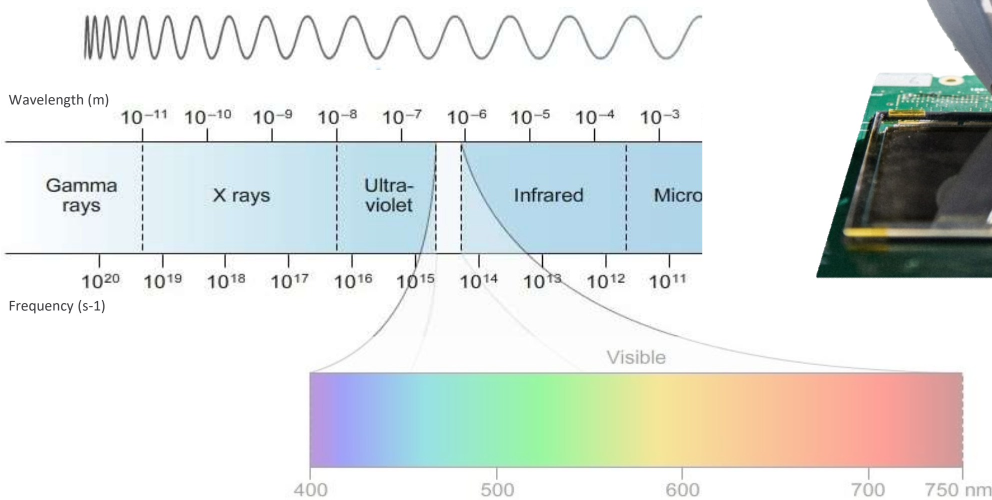
CCD and CMOS:
A journey through the past and the future

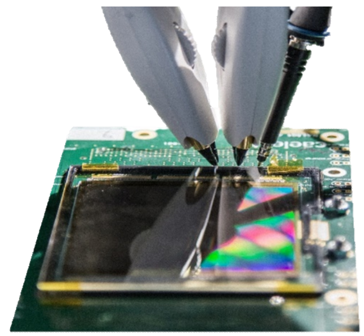
Ben De Brabanter, Jeroen Hoet, Jan Vermeiren

Caeleste, Belgium

- Caeleste company introduction
- The Historical track: towards CCD
- The Present and the future: CMOS and the application broadening

Caeleste's mission

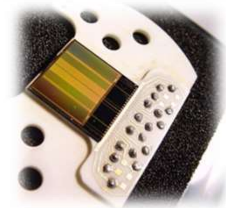




Be the supplier of beyond state-of-the-art

custom-designed CMOS image sensors

Imaging the …

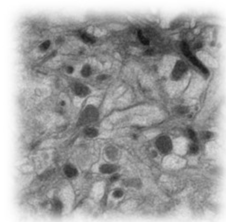


… very far away

Mass spectrometer of the ROSINA/DFMS
Today resting on the surface of Comet 67P/Churyumov-Gerasimenko

… very large

4096 x 4096 pixels
70mm sensor diagonal



… very small

Fly neuron
8k x 8k TEM

… invisible

Color X-ray of breast cancer

Expertise through people and collaboration

Stable growth

Founded in 2006

Owned by founders & employees

20% $CAGR_{15\text{-}20}$

Expertise

45+ Employees

13+ nationalities

12+ tape-outs per year

Collaboration

University collaboration

100+ peer reviewed publications

Caeleste University

Technology

15 patents granted

2 patents pending

Expertise in different applications

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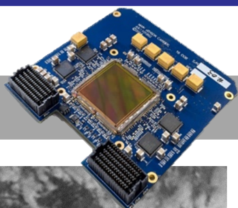
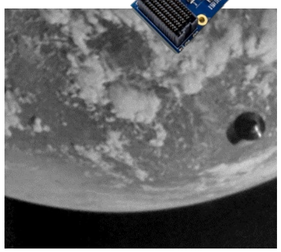
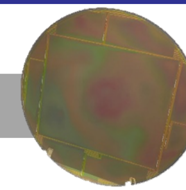
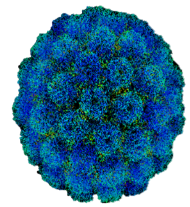
Scientific & Space



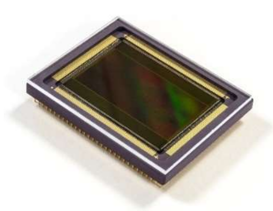
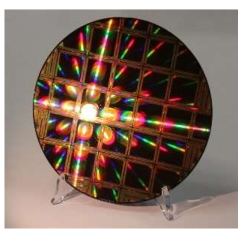



Medical & Life science

Caeleste's
Unique custom-design
Experience

Industrial applications

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Paradromics

+ many more

- Caeleste company introduction

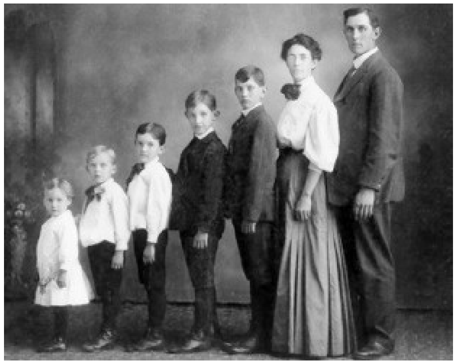
- The Historical track: towards CCD
  - Why imaging
  - The CCD precursors
  - The CCD era
  - The CCD limitations

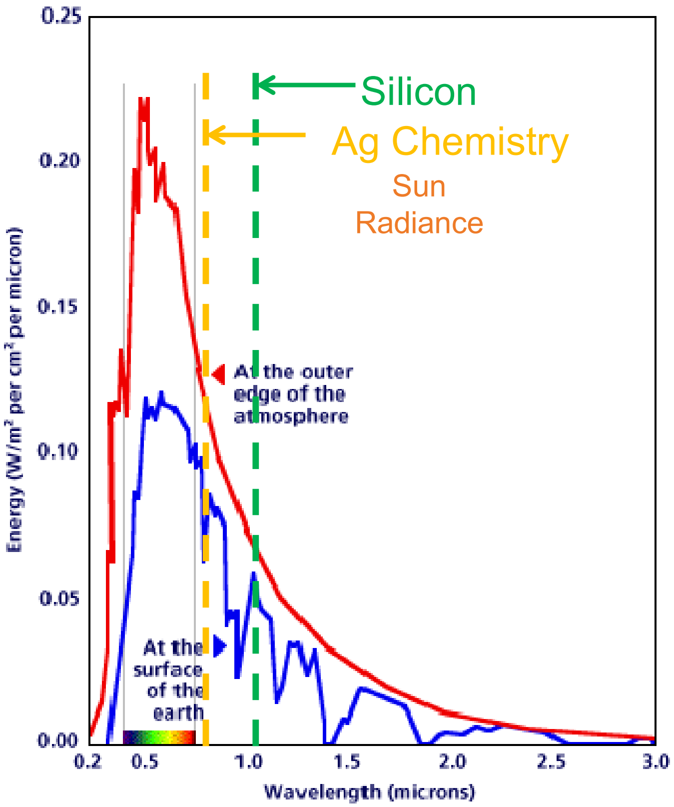
- The Present and the future: CMOS and the application broadening

Humans want to preserve

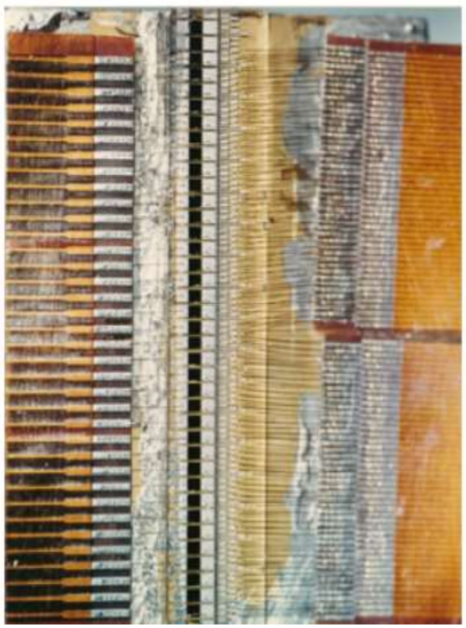
Imaging in the Visible range

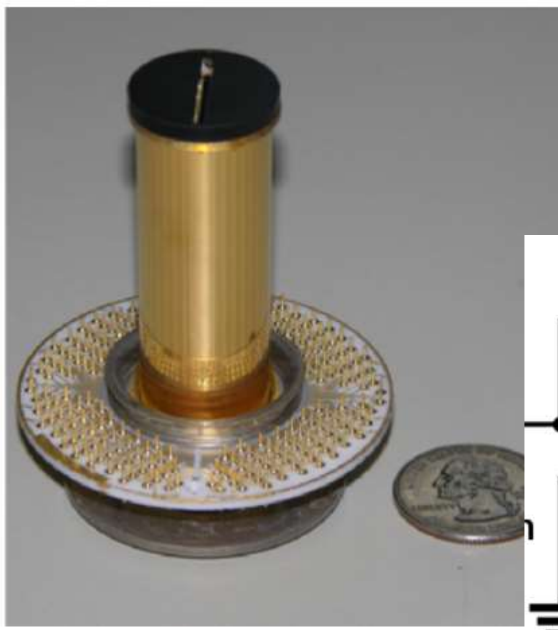
- **Very common**
  - Our eye is nicely matched to the emitted radiation of the sun
- **Imaging reflected sunlight**
  - Camera's can readily capture light and make images

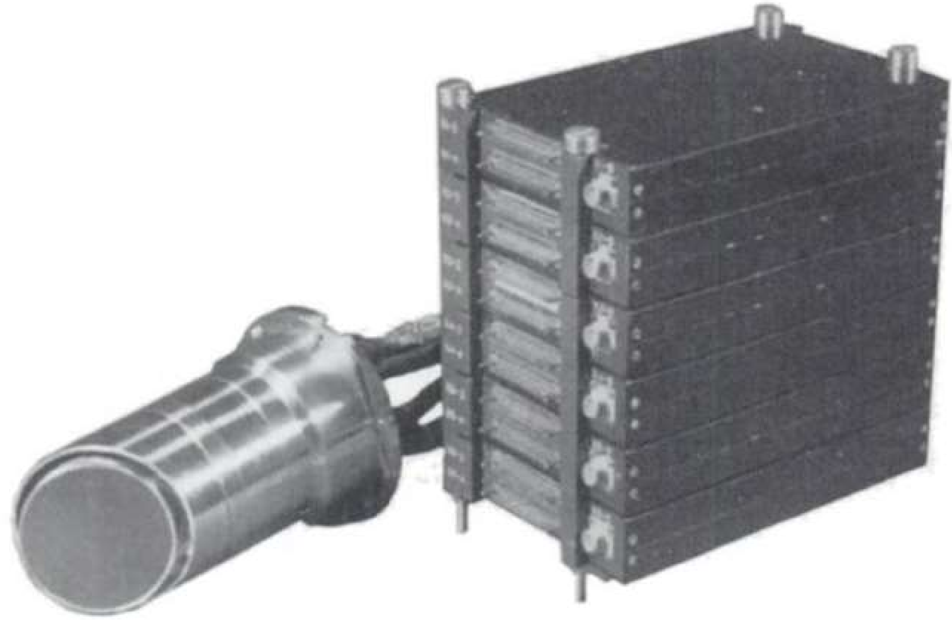


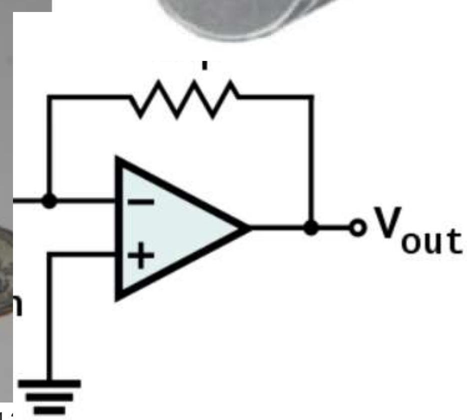


The very start of electronic imaging









The onsets of integration: the MOS capacitor

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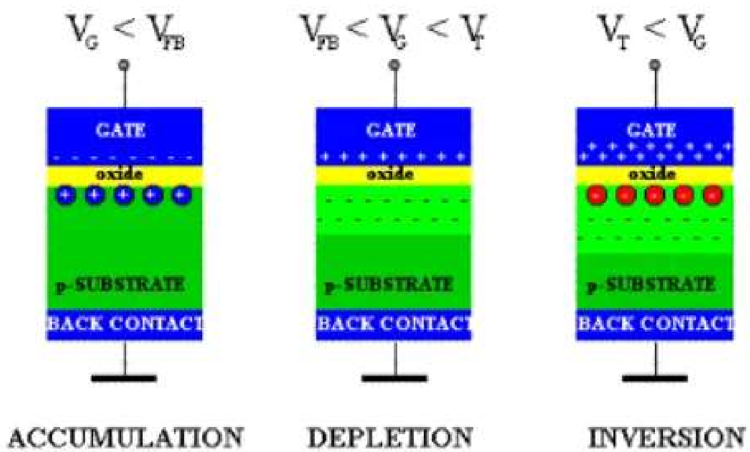
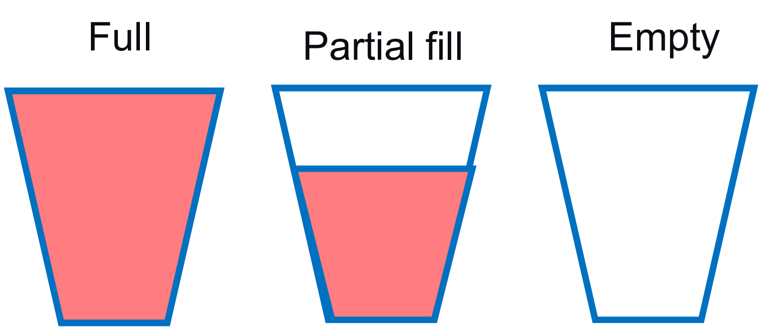
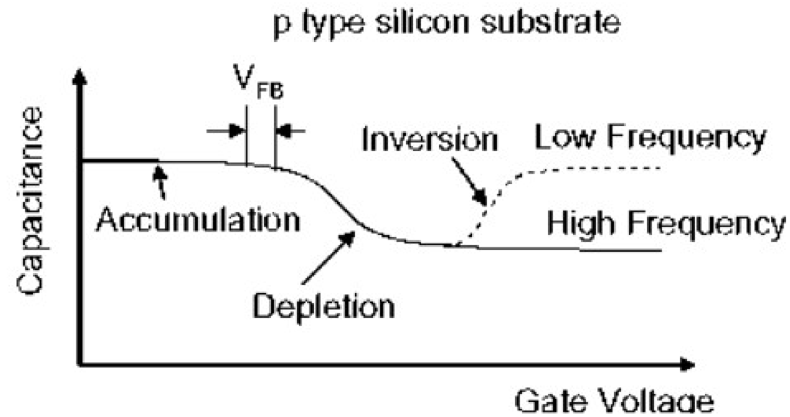
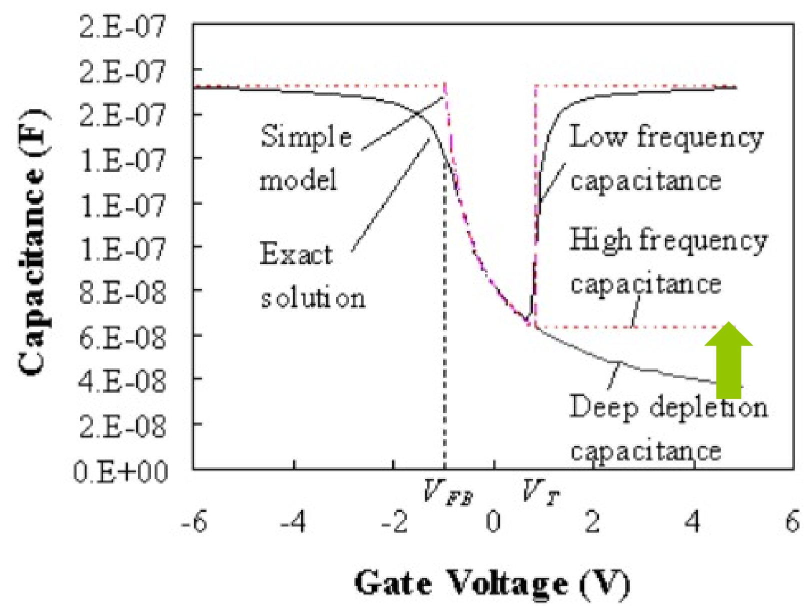








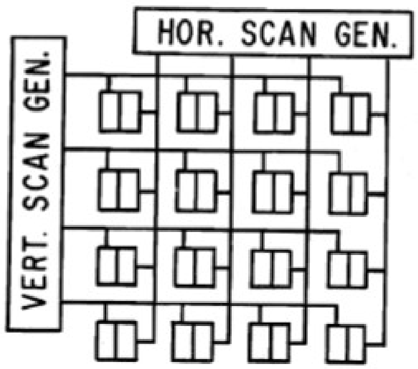
The CID device

CHARGE COUPLED AND CHARGE INJECTION DEVICE PERFORMANCE TRADEOFFS

R. D. Baertsch*

1976

2022: still used by Thermofisher for camera's in a high radiation environment



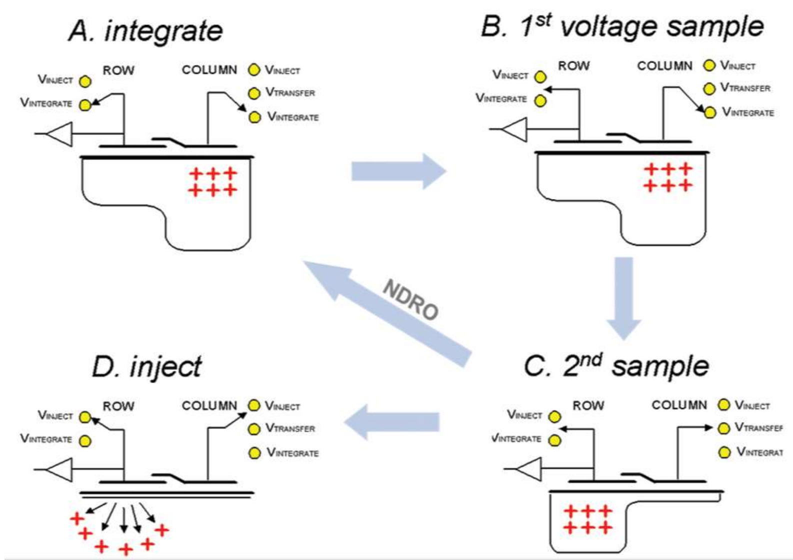


Fig. 4 - Further evaluation is required with this 244 x 248 CID imager.

The Bucket Brigade Device

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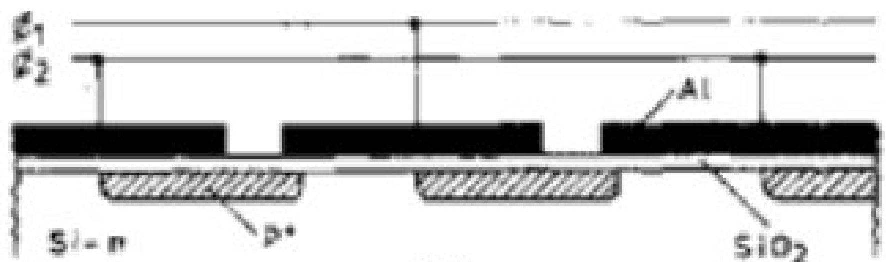
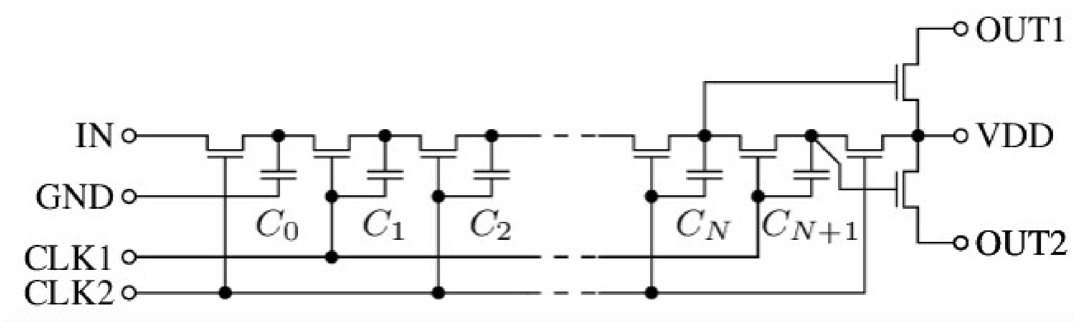


(a)



Advantages:
- Single poly gate
- Simple process

Disadvantages
- Not self-aligned
- Transfer losses (charge retention)

Used as delay lines:

Topics

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  - The CCD precursors
  - The CCD era
  - The CCD limitations
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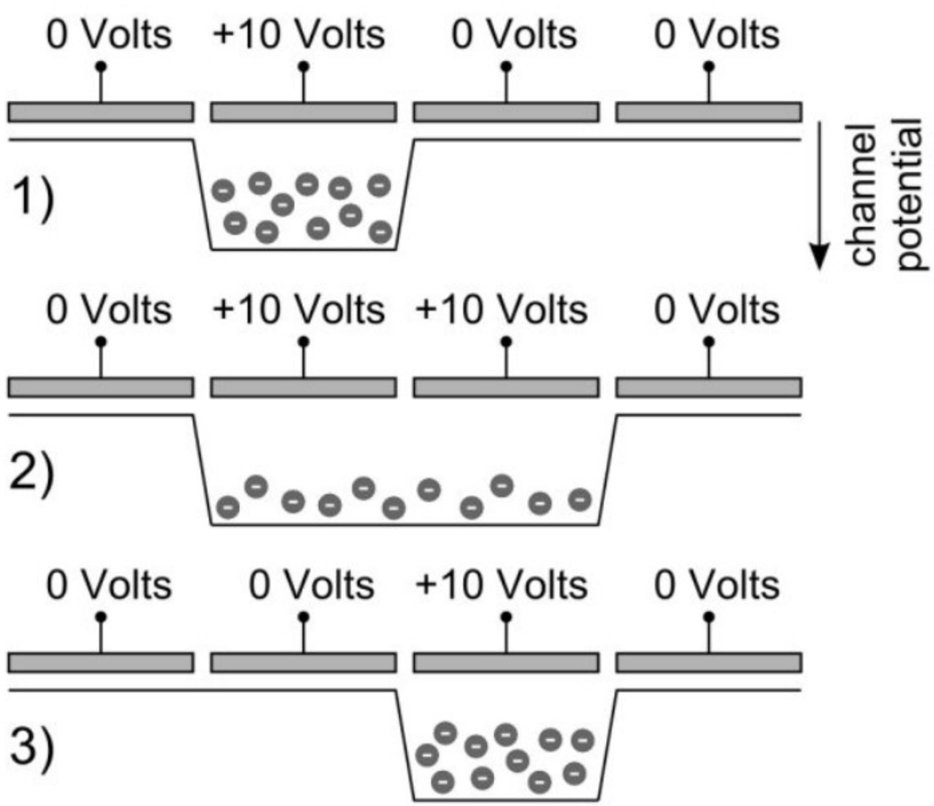
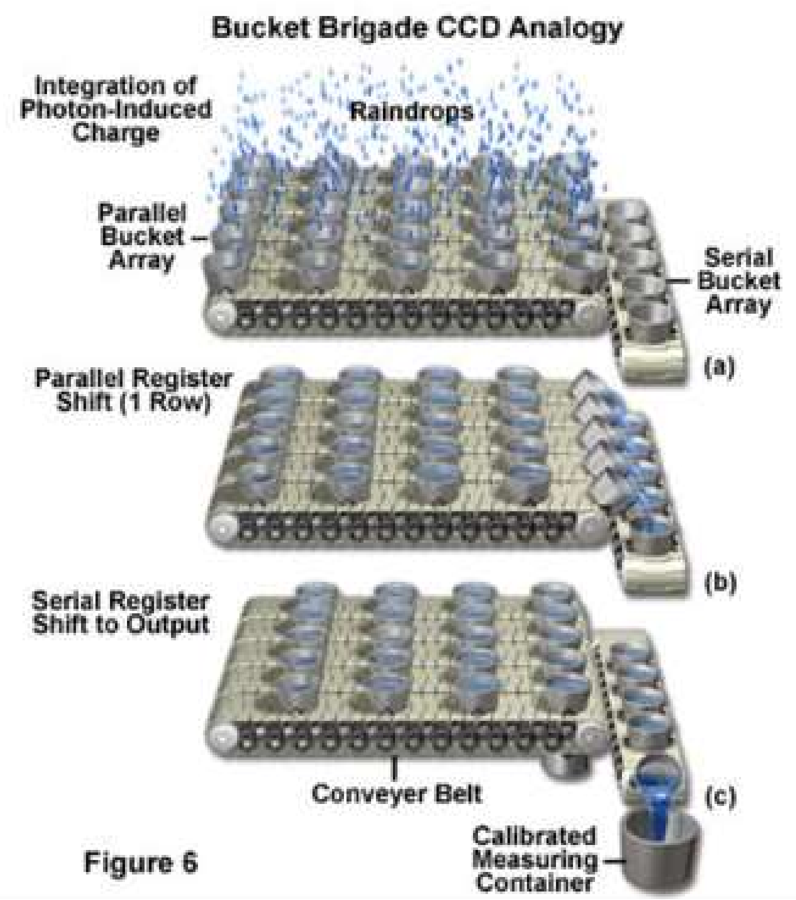
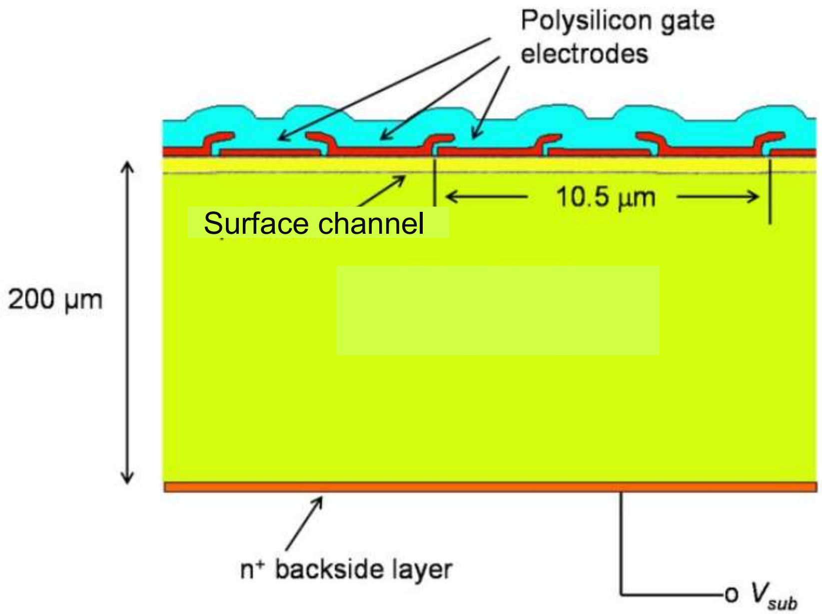
The introduction of the CCD

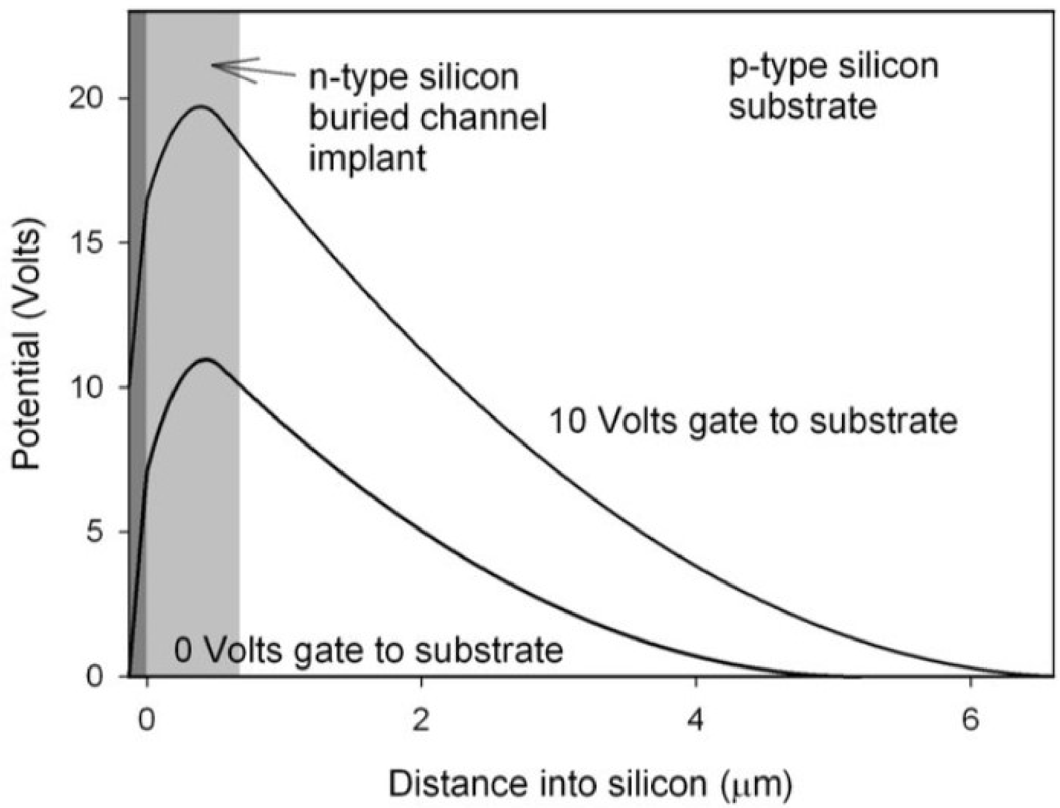




1969: Boyle & Smith: CCD principle
1970 – 1972: Michael Tompsett: 1 st image sensors
1975: 1st commercial product by Eastman Kodak

From surface channel to Buried channel





Advantages:
- Lower dark current
- Better charge transfer
- Higher fringe fields

Disadvantages
- Lower charge storage

CCD architectures

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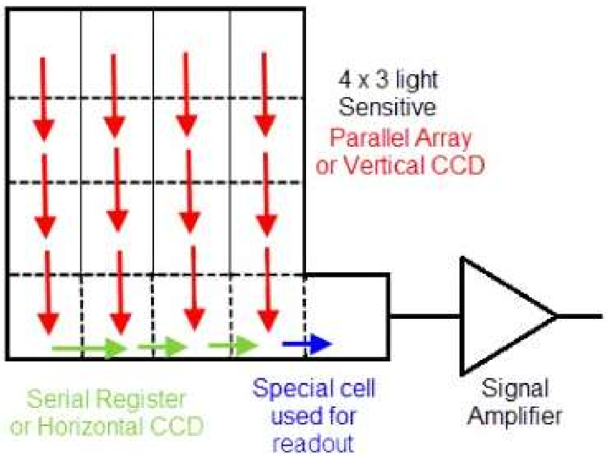
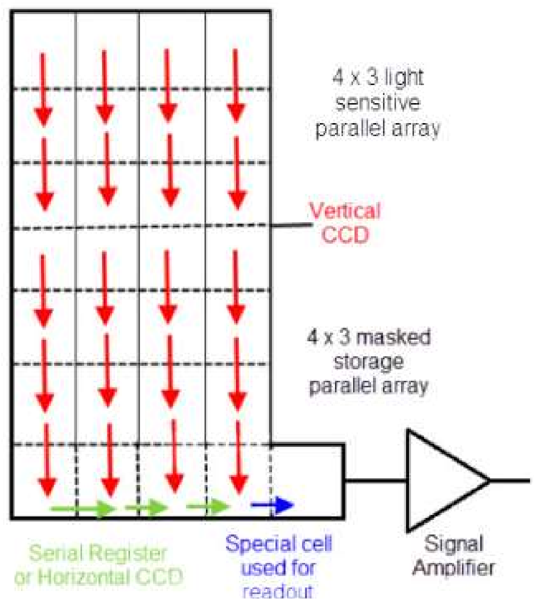


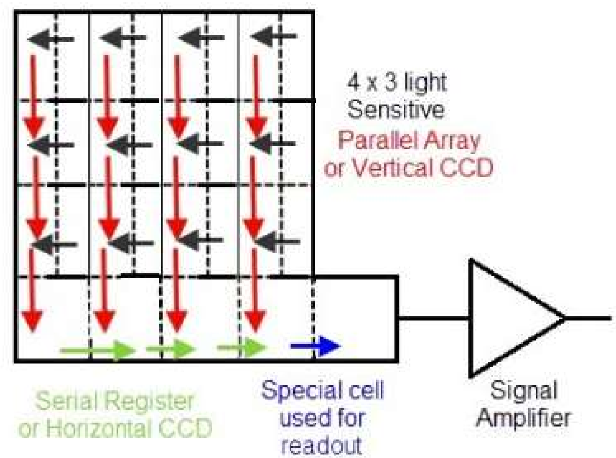
Full Frame CCD

- Astronomy
- Slow scan applications
- Shuttered applications
  - Still picture



Frame transfer CCD

- Life recording
- Easiest architecture
- Some motion blur
- Bright spot impact



Interline transfer CCD

- Life recording
- More complicated architecture
- Real global shutter
- No bright spot impact

It is all about performance

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- **When considering an image sensor, the following performance parameters are key:**
  - Spectral response: collected electrons / incident photons or [A/W]
  - Full well charge: related issue: photon shot noise – Signal to Noise ratio close to saturation
  - Noise in dark: or Dynamic range – what is the minimal visible signal?
  - Dark current: how long can we integrate before we influence Full well or noise
  - Power – Current – Voltage
- **Some derivative parameters:**
  - Driving voltage – signal height
  - Voltage + oxide / stack thickness: charge density
  - Charge to voltage conversion gain

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Some calculation examples

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Buried Channel CCD

- Implant condition: [1.E+12 – 2. E+12 cm-2]
- Useful “dose” = 20 %: [0.2 – 0.4E+12 cm-2] or [2000 – 4000 e-/µm2]
- Pixel size: 15 µm → storage area = 100 µm2 → [200 – 400 ke-] full well → shot noise: 447 e-rms → 9 bit
- Pixel size: 5 µm → storage area = 7.5 µm2 → [15 – 30 ke-] full well → shot noise: 112 e-rms → 7 bit
- Pixel size: 3 µm → storage area = 3.0 µm2 → [6 – 12 ke-] full well → shot noise: 77 e-rms → 6 bit

Type	Pixel	Full well	Noise	Format	Frame rate	Type
KAF-16803	9*9 µm2	100 ke-	9e-rms	4k * 4k	1.6 Fps	Full frame
KAF-08051	5.5*5.5 µm2	20 ke-	10 e-rms	3k*2k	16 Fps	Interline
KAF-50140	4.5*4.5 µm2	13 ke-	13 e-rms	10k*4k	4 Fps	Interline
ICX829AL	8.2*8.4 µm2	50 ke-	10 e-rms	750*580	50Fps	Interline
ICX445	3.75*3.75 µm2			1.4*1k	20 Fps	Interline

Transition to CMOS image sensors

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CCD	CMOS
Dedicated process - expensive	Mainstream process – Low-cost

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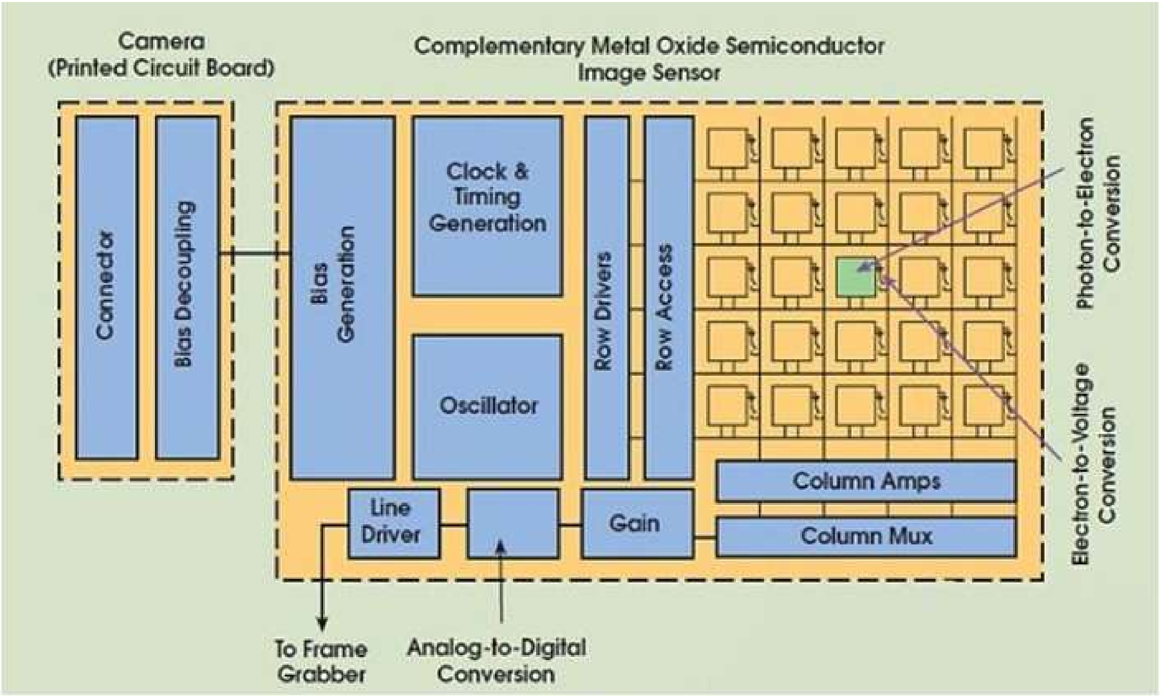
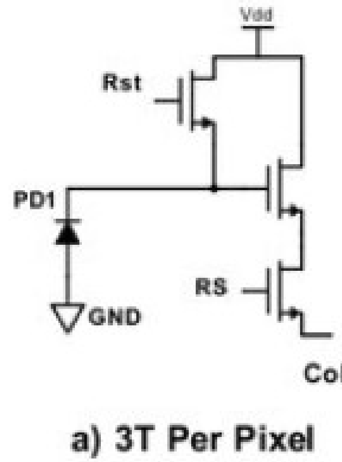
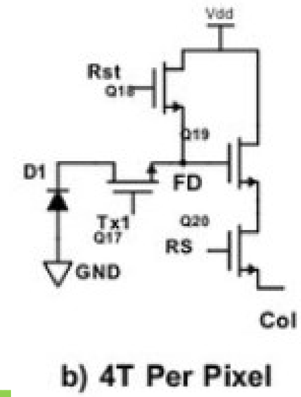
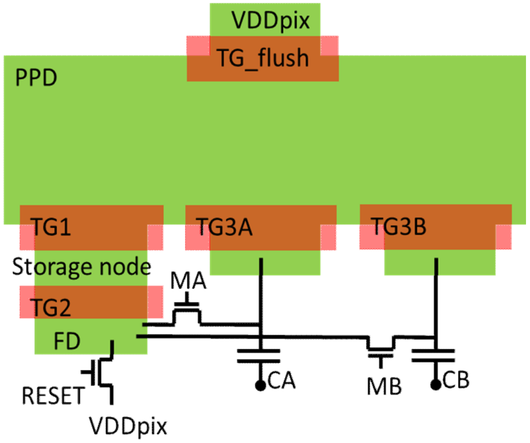
- The Present and the future: CMOS and the application broadening
  - Basic CMOS architectures and HDR
  - CMOS tendencies and diversification
  - Non-visible imaging

CMOS sensor basics

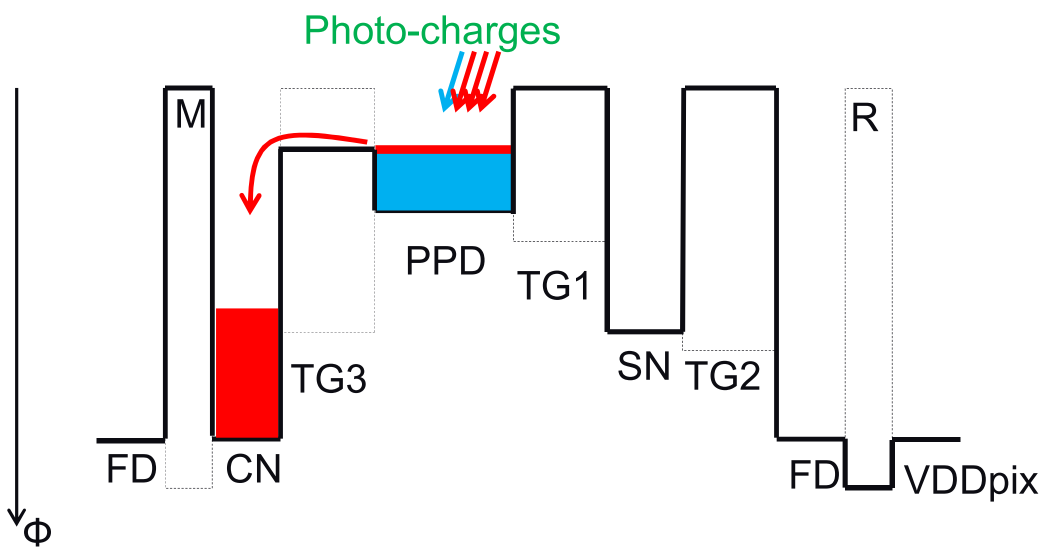


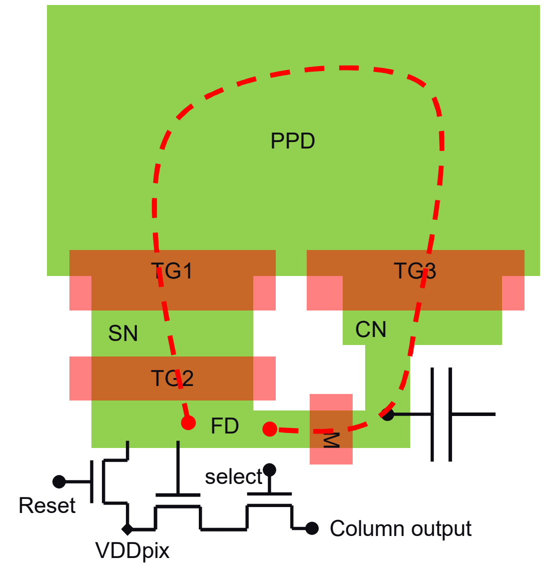




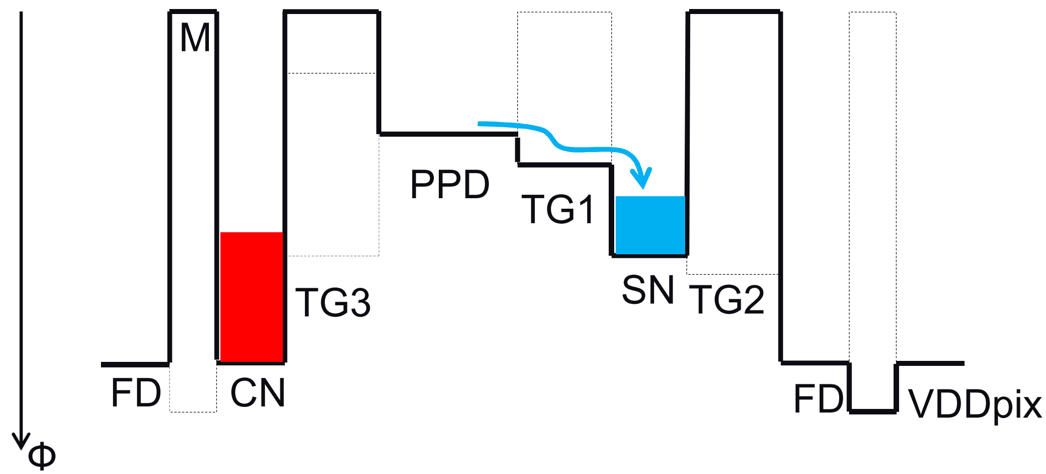


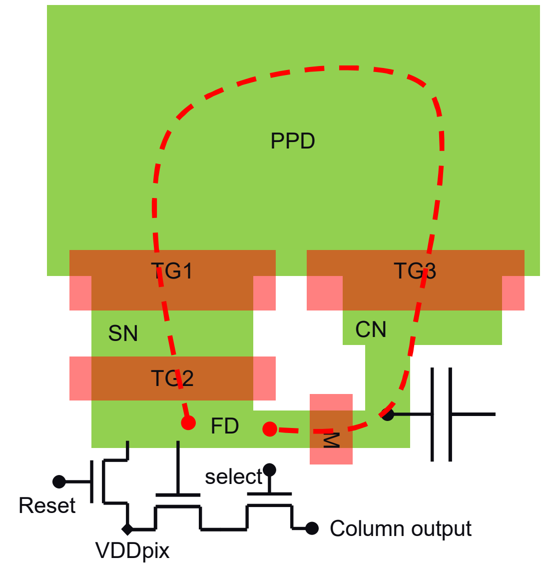
During integration photocharge is accumulated in the photodiode.
The TG3 gate voltage is set to the intermediate "overflow barrier" operation point.
When the photodiode is too full, charge overflows to the capacitor node
blue: charge fitting in the PPD
red: charge overflowing into the capacitor node.



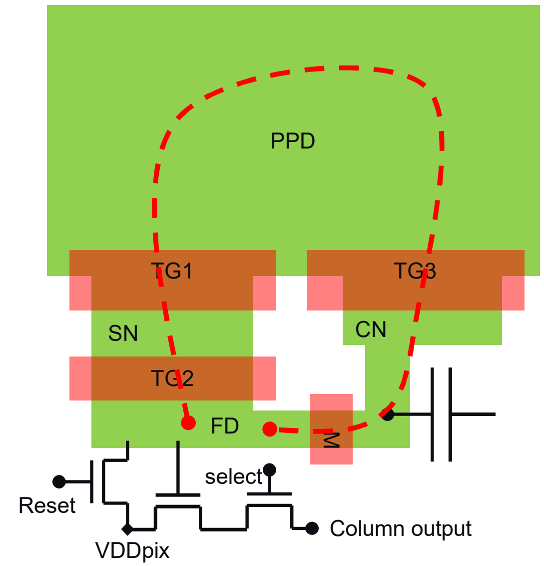


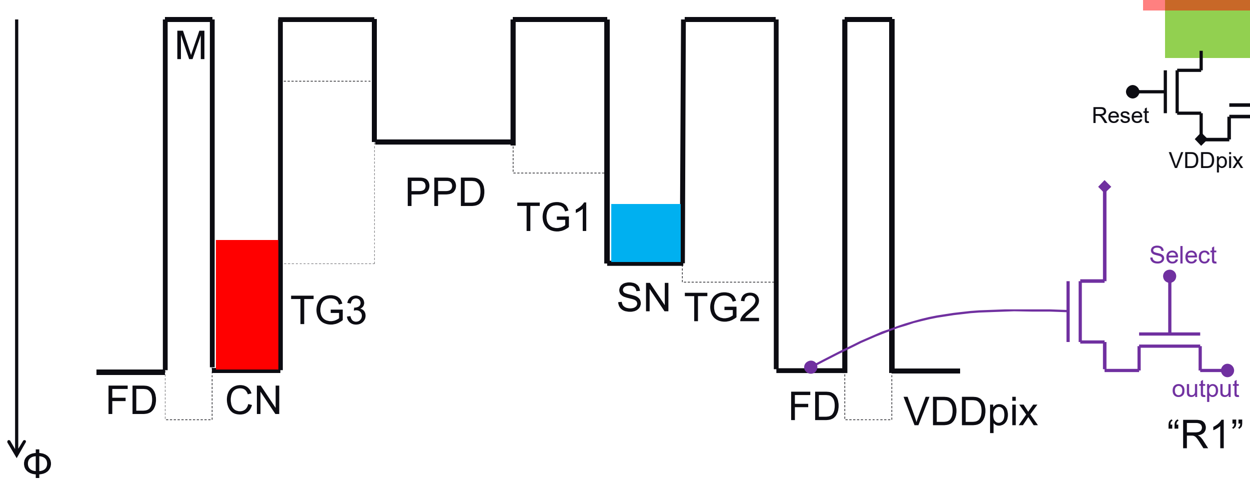
End of integration time:
1) stop overflow over TG3
2) transfer PPD (blue) charge to the SN using TG1



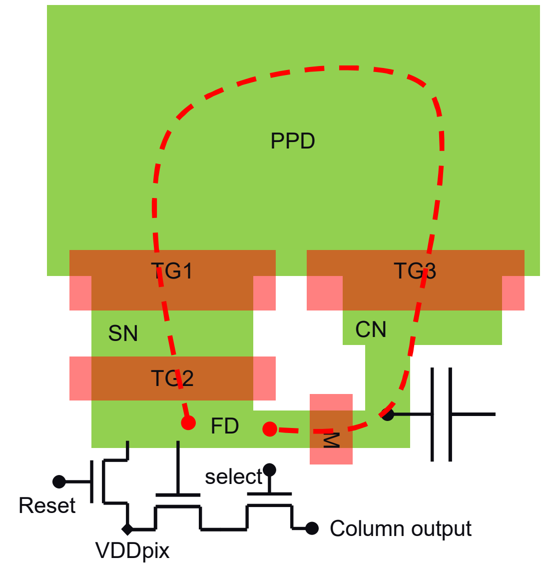


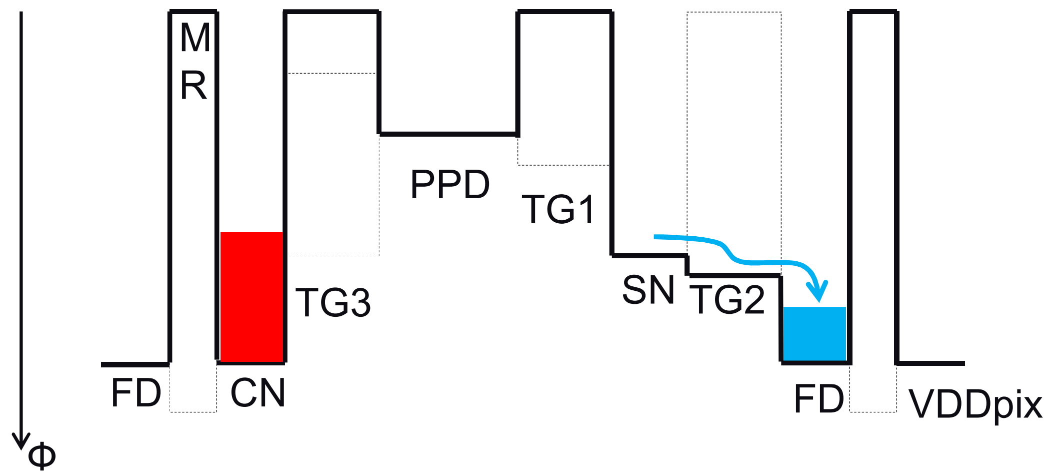
As the photocharge of the previous integration time is now in available in the SN and the CN, if can be read out. The readout of the imager happens row-by-row or in "rolling readout". The select transistors of the rows to be read out are activated, the reset transistors are turned off, and then three voltage levels are put on the column bus: "R1", "S1" and "S2".
"R1" is reset level as present on the FD immediatedly after releasign the reset.





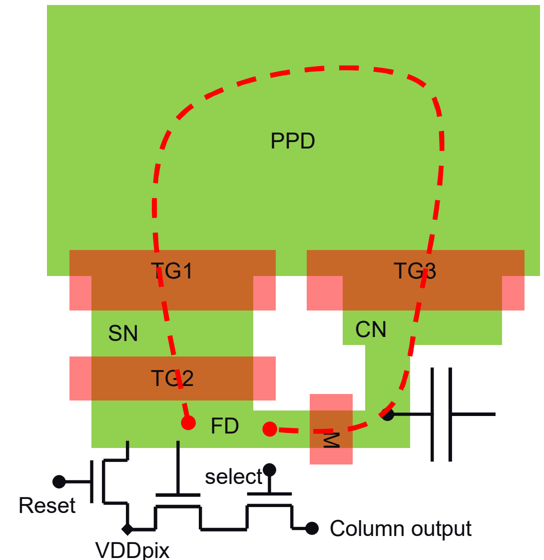
Then the gate TG2 toggled off-on-off, allowing the charge in the SN to transfer to the FD.
This is the “S1” signal level, representing the “blue” charge.

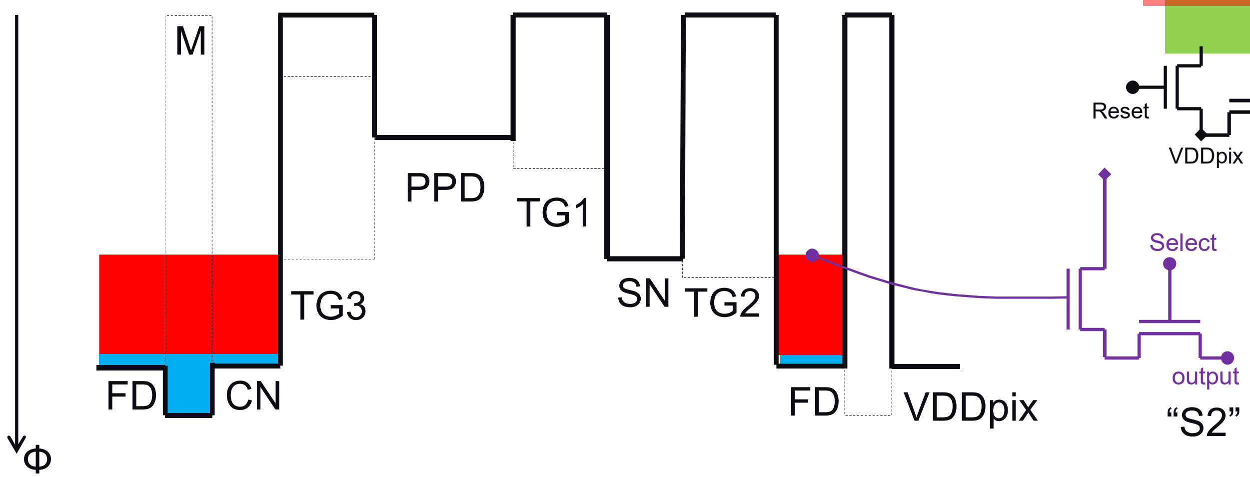




Expertise in different applications

Then the Merge transistor is closed, shunting the FD and the CN. All photocharge, previously divided over the SN (blue) and the CN (red) is now reunited.
This signal is "S2", being the LG or high Q_{FW} signal level. We do not apply CDS on S2; still S2 is readout differentially as (S2-ref)&(ref-S2).





HDR by combining two “normal” DR ranges

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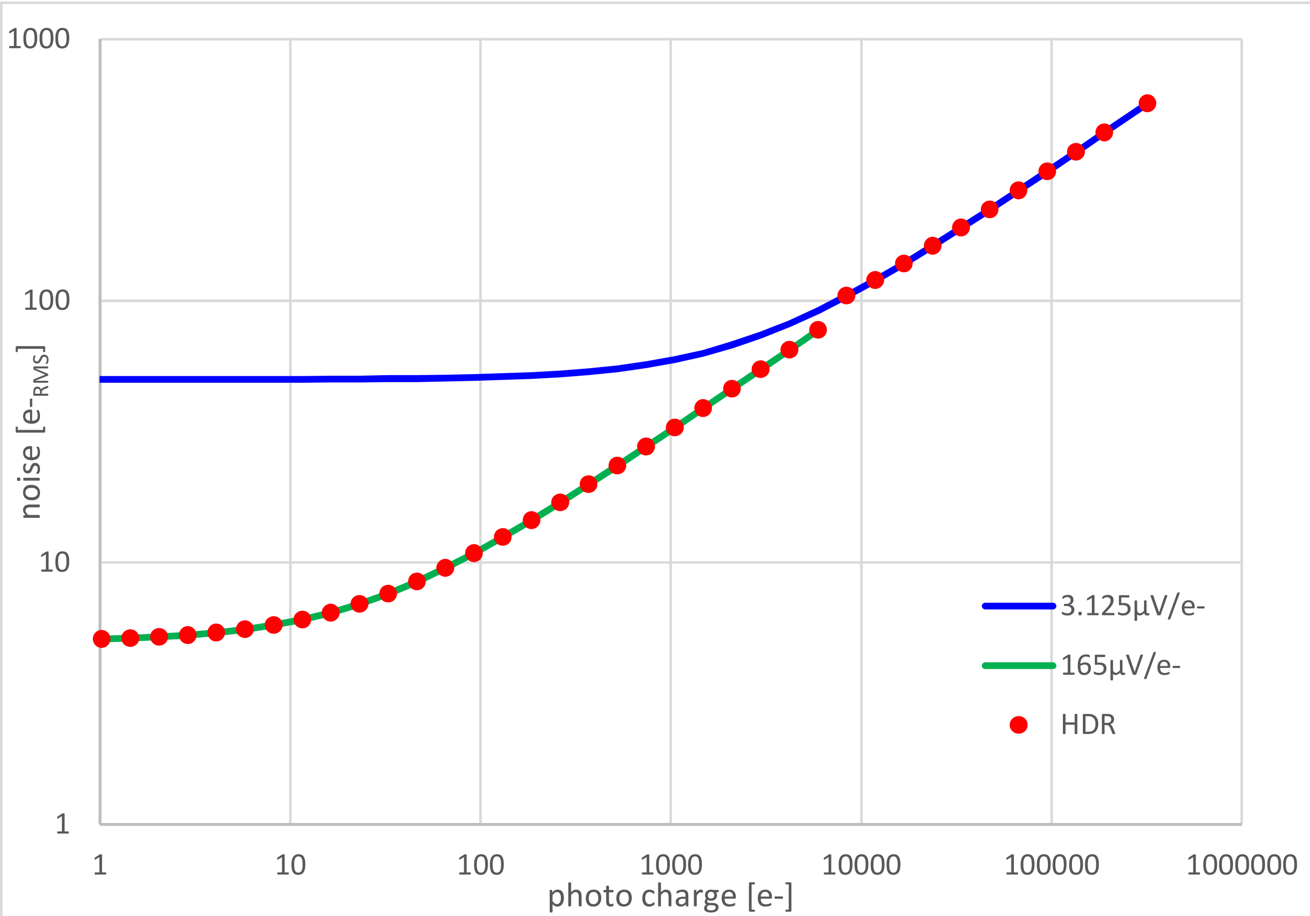

This graph is the “Noise versus Signal” relation of a two range image sensor pixel, i.c. the ELFIS pixel.
Each Q_{FW} range on its own has such relation. The dynamic range (DR) is defined as the ratio of the largest, near saturation, photocharge (Q_{FW}) and the noise equivalent photocharge (Q_{noise}) in the dark. When the two signals are combined into one “HDR” signal, it has such relation as well, and an overall dynamic range that is equal to the LG Q_{FW} divided by the HG Q_{noise}.

High Q_{FW} range:
DR=320000/50≈6400:1

Low Q_{FW} range:
DR=6000/6,5 ≈ 1000:1

Combination
DR=320000/6,5 ≈ **93,8dB**

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- The Present and the future: CMOS and the application broadening
  - Basic CMOS architectures and HDR
  - CMOS tendencies and diversification
  - Non-visible imaging

Image sensors: general evolution

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CITIUS, ALTIUS, FORTIUS

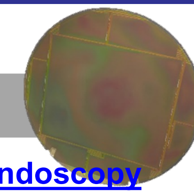
- **Key specifications**
  - Frame rate → Faster
  - Number of pixels → More pixels
  - Pixel size → Smaller pixels
  - Noise → Lower noise floor
  - Spectral response → Better colour / NIR /UV reproduction
  - Quantum efficiency → Higher quantum efficiency
  - Full well → Higher (but following the pixel size)
- **Resulting specifications**
  - Light sensitivity → Higher sensitivity
  - Dynamic range → Higher dynamic range
  - Bit depth → Mainly following dynamic range

Expertise in different applications

Scientific & Space

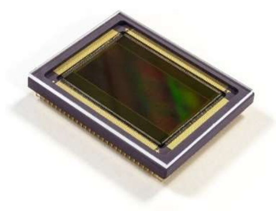
High sensitivity devices
Medium – large pixels: 5.5 … 9 … 12 … 15 µm
Larger formats
high cost
FW: up to 400 000 e-
Noise: 1 - 2 e-rms
Long Tint = lower power

Medical & Life science



Xray	**Endoscopy**
Large pixels: 100 µm	small pixels: 1.12 µm
Up to Wafer scale	1..3 mm size
Low cost	1 wafer lot = life time
FW: ± 100 000 e-	FW: 10 000 e-
Noise: ± 10 e-rms	Noise: ± 2 e-rms

CMOS
Image sensor
Diversity



Industrial applications

High Speed devices

Medium large pixels: 5.5 … 9 … 12 … 15 µm
Larger formats
Medium cost – high speed
FW: up to 400 000 e-
Noise: 1 - 2 e-rms
Short Tint = higher power

Consumer

Mobile phone – Security

Smaller pixels: 2.5 … 1.4 … 1.12 … 0.8 µm
Smaller outline
Low cost
FW: 5 000 – 10 000 e-
Noise: 2 -5 e-rms

Image sensors: specific evolution for scientific & Industrial

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- **Key specifications**
  - Frame rate → **Faster**
  - Number of pixels → **More pixels**
  - Pixel size → Smaller pixels
  - Noise → **Lower noise floor**
  - Spectral response → Better colour / **NIR /UV / Xray / Low cost IR**
  - Quantum efficiency → Higher quantum efficiency
  - Full well → **Higher** ← → **Higher gain**
- **Resulting specifications**
  - Light sensitivity → Higher sensitivity
  - Dynamic range → Higher dynamic range
  - Bit depth → Mainly following dynamic range
  - Large format → **Stitched designs**
  - Temperature range → **Cooled Operation**

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Where is the light absorbed

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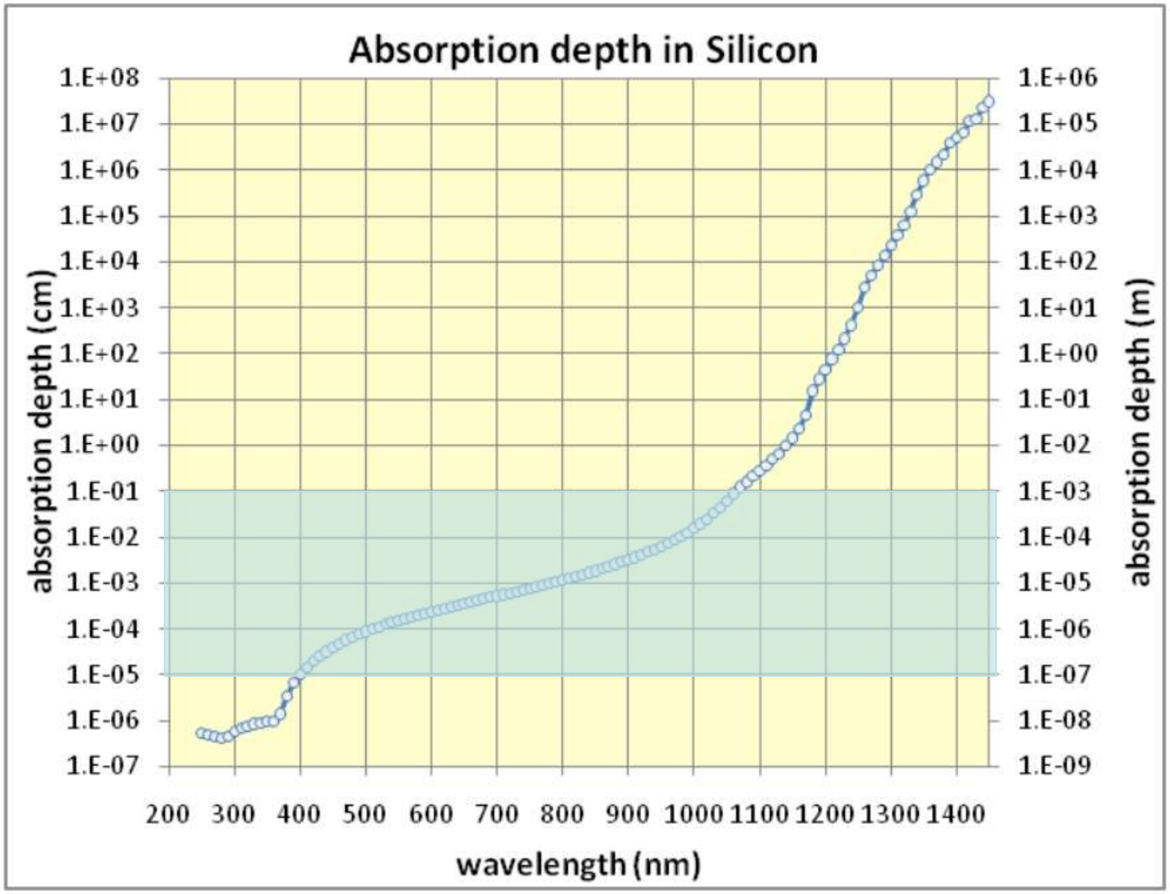
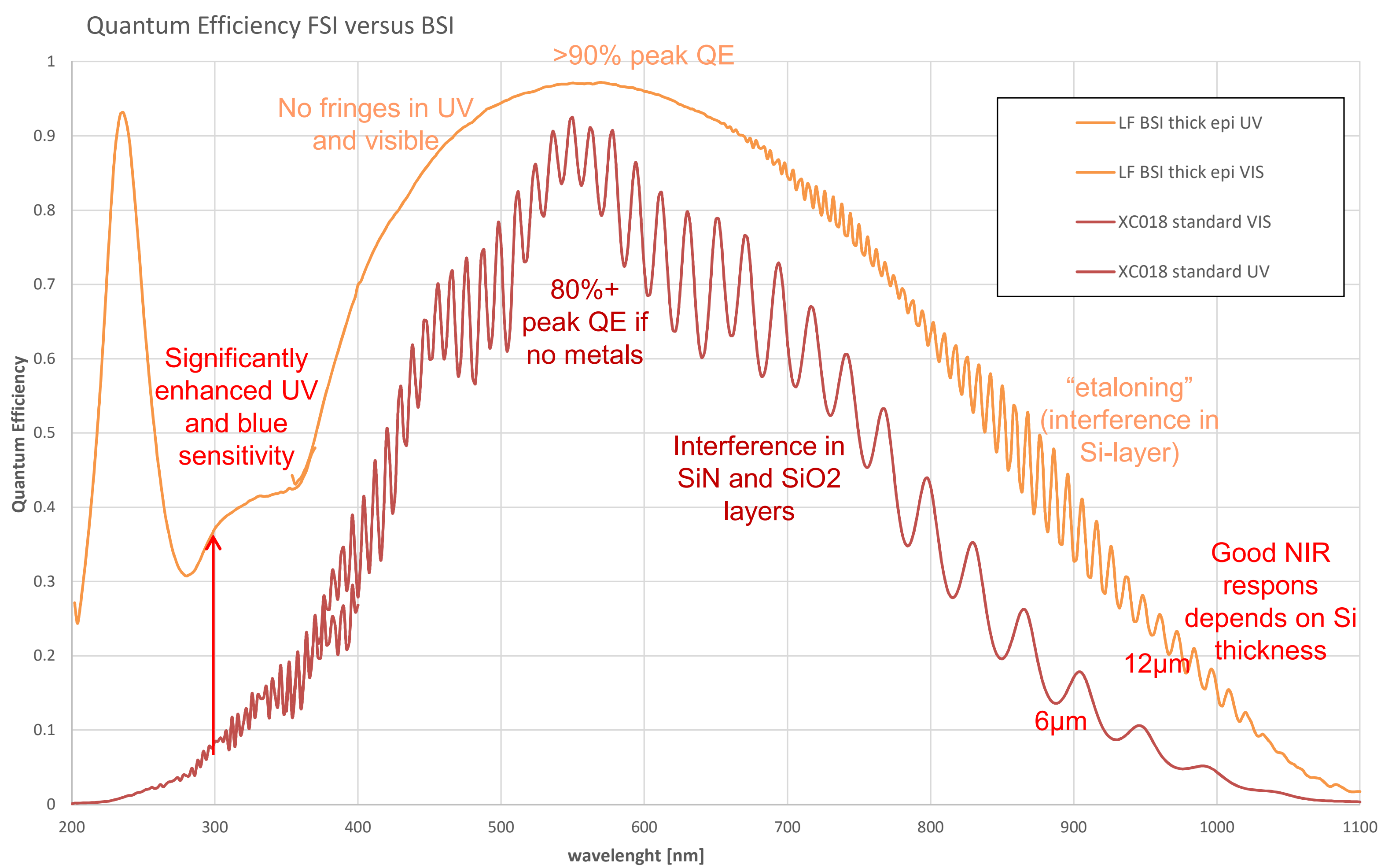


BSI versus FSI: QE

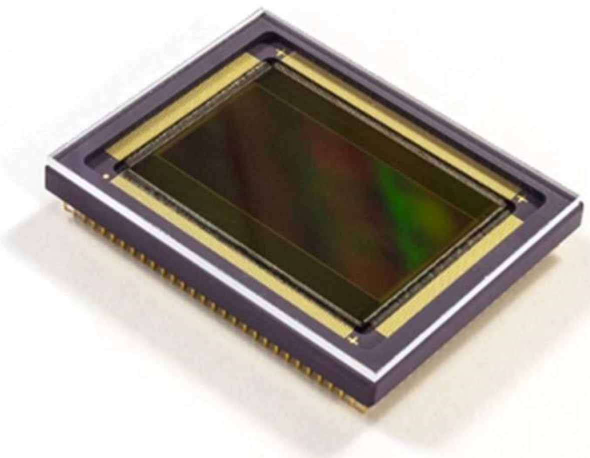


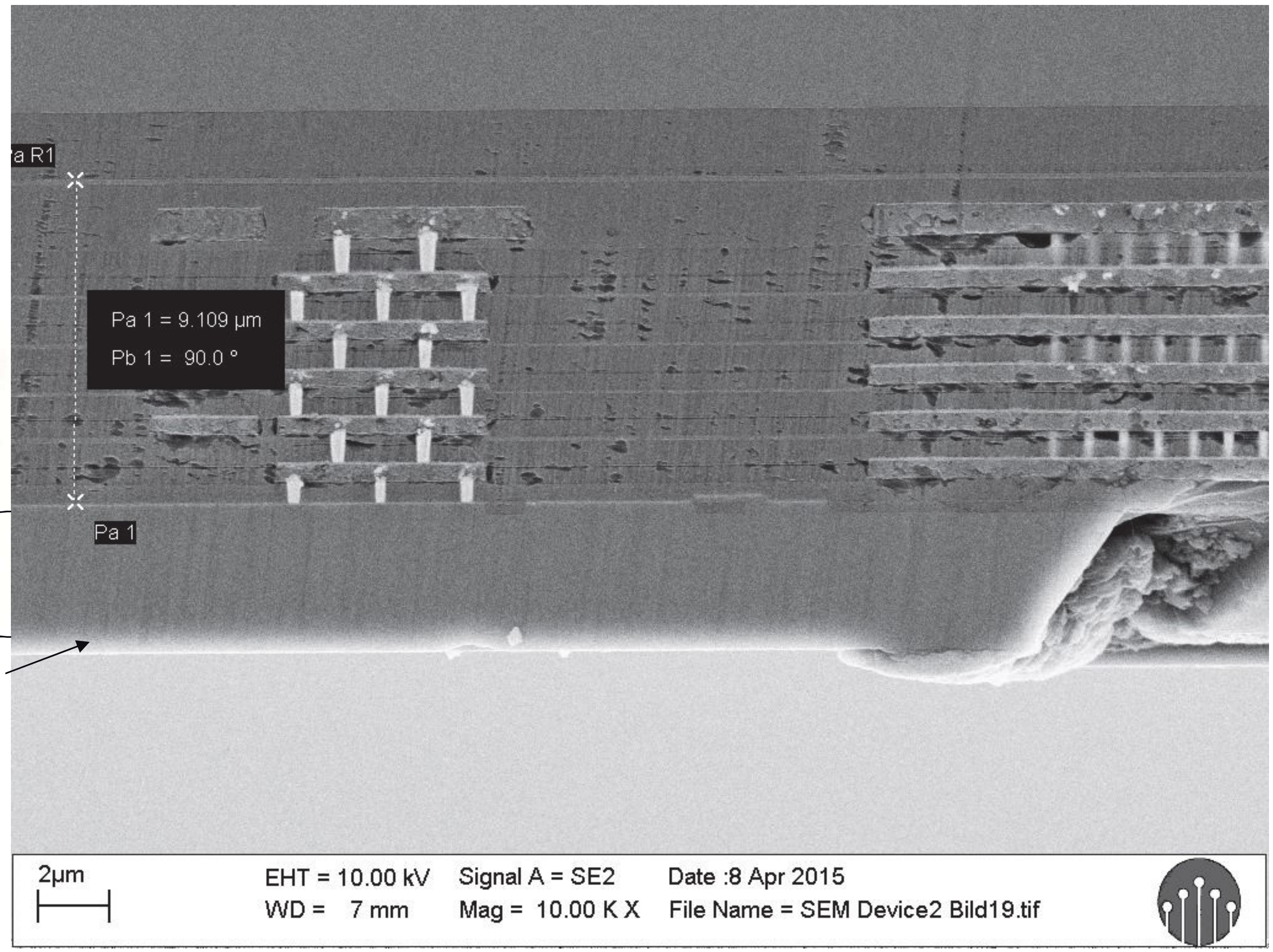
BSI example

caeleste

SEM Cross Section

Carrier Wafer



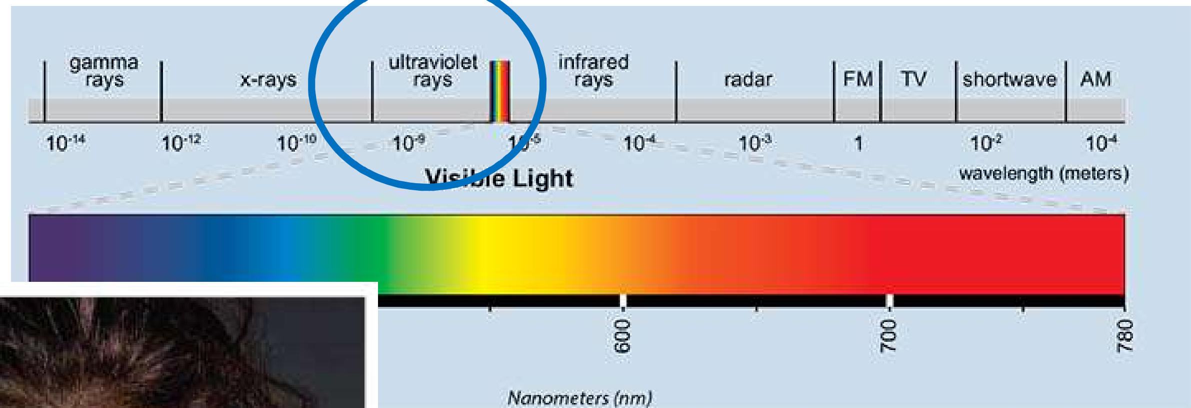


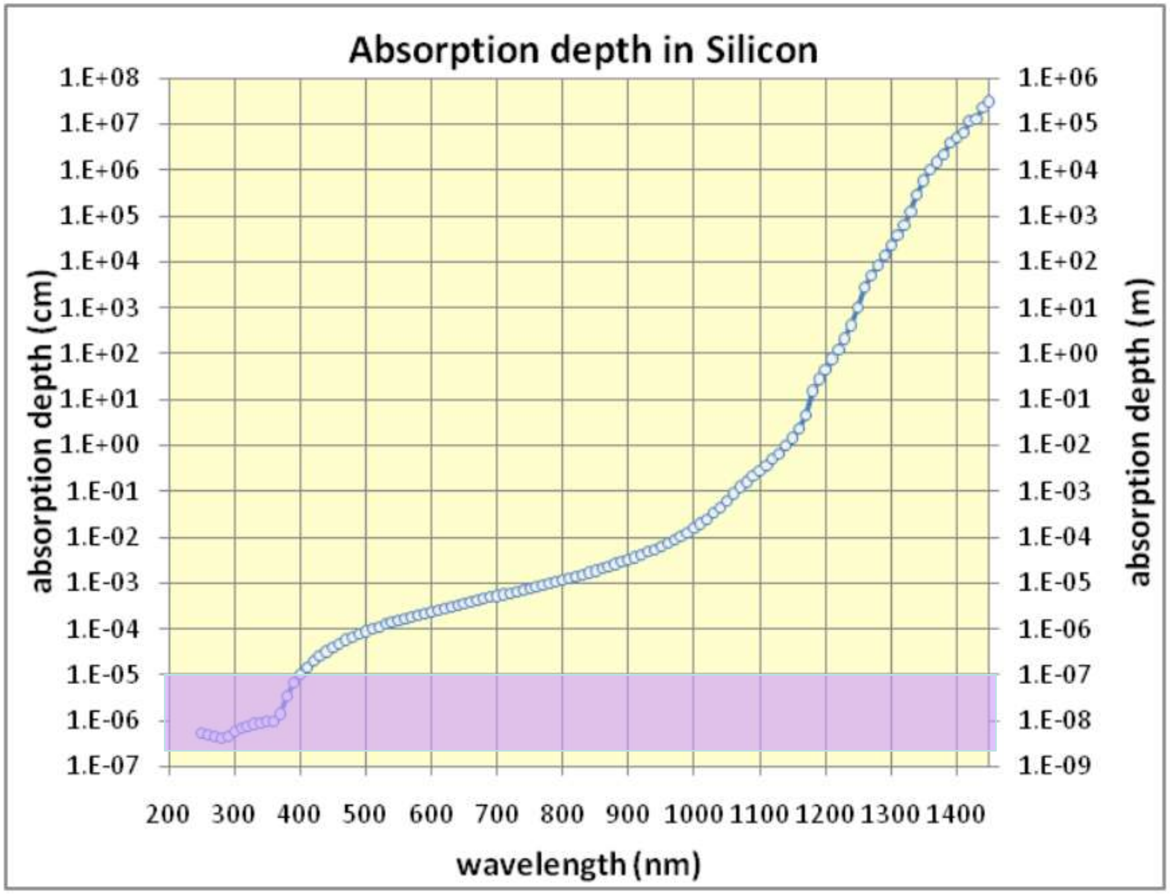
4µm EPI

AR Coating

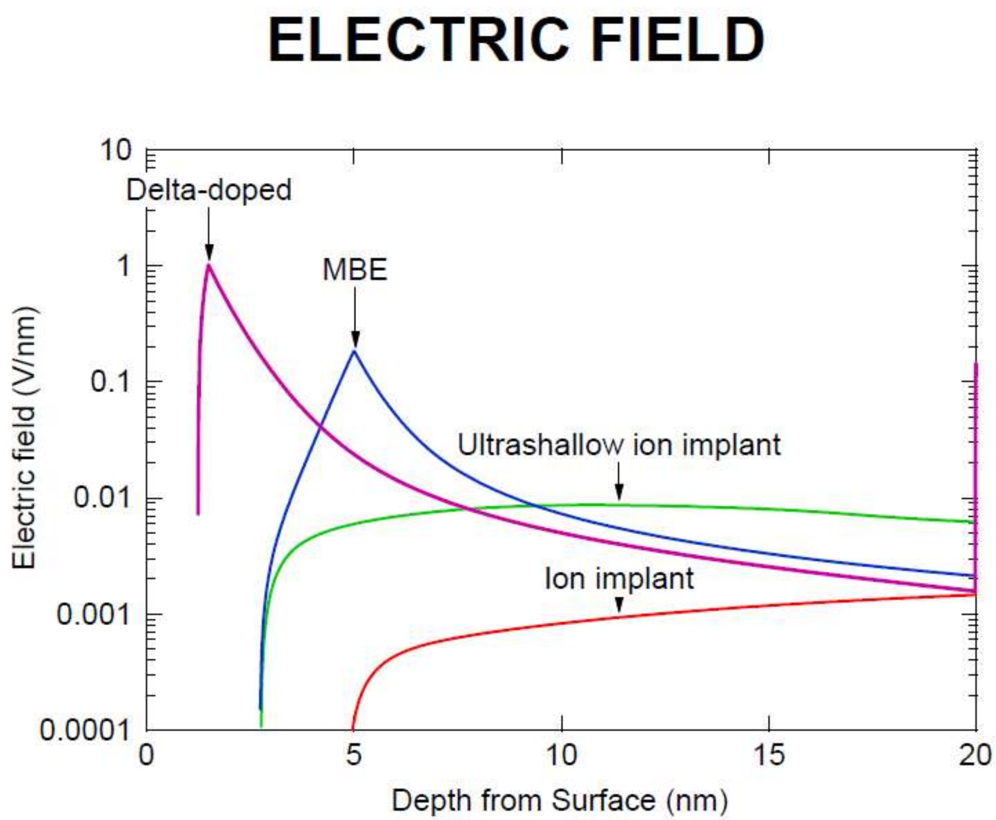
Why using other wavelengths

- Different view on objects
- Skin inspection




Absorption depth in Silicon
absorption depth (cm)
absorption depth (m)
wavelength (nm)
1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400

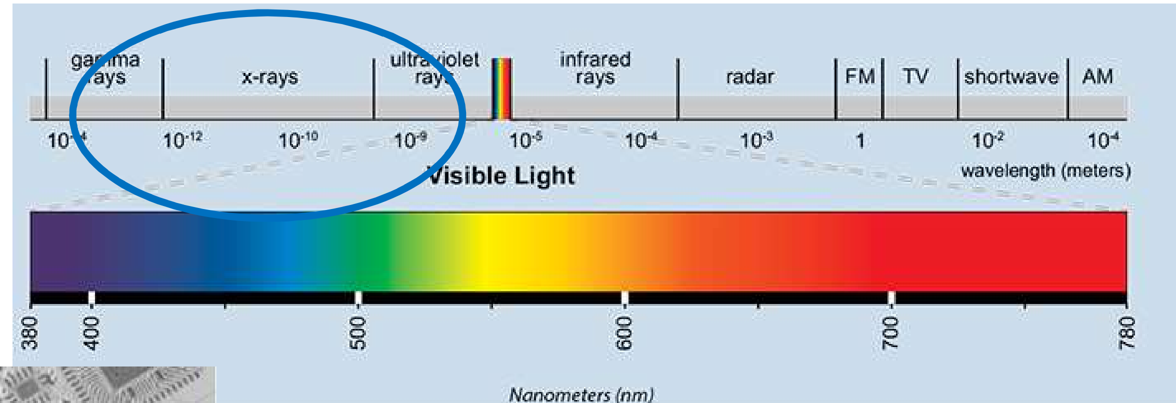
Special backside treatments for shallow absorption

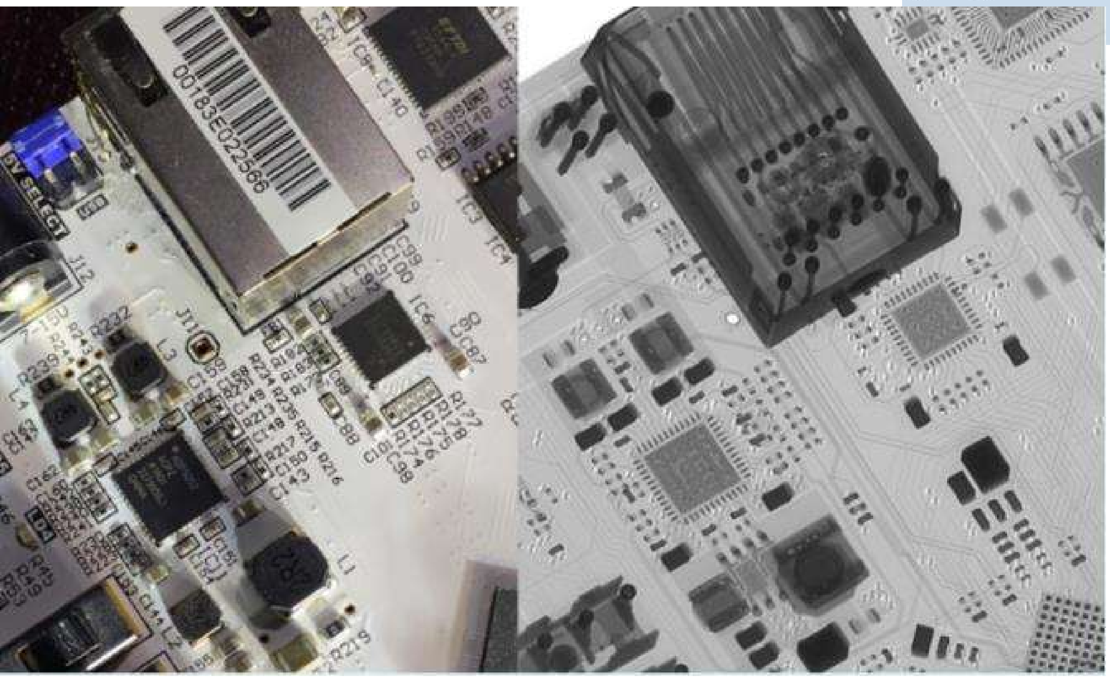


Good surface uniformity
Low scattering
Very shallow back-surface field

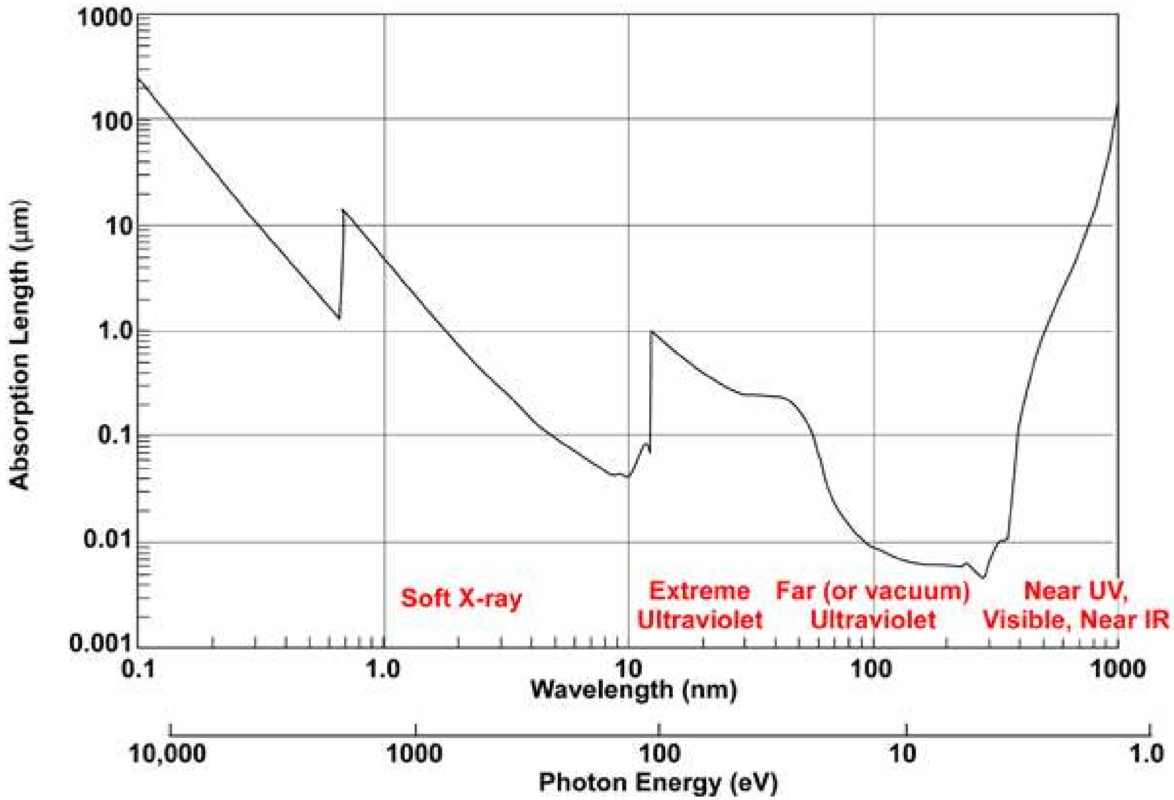
Why using other wavelengths

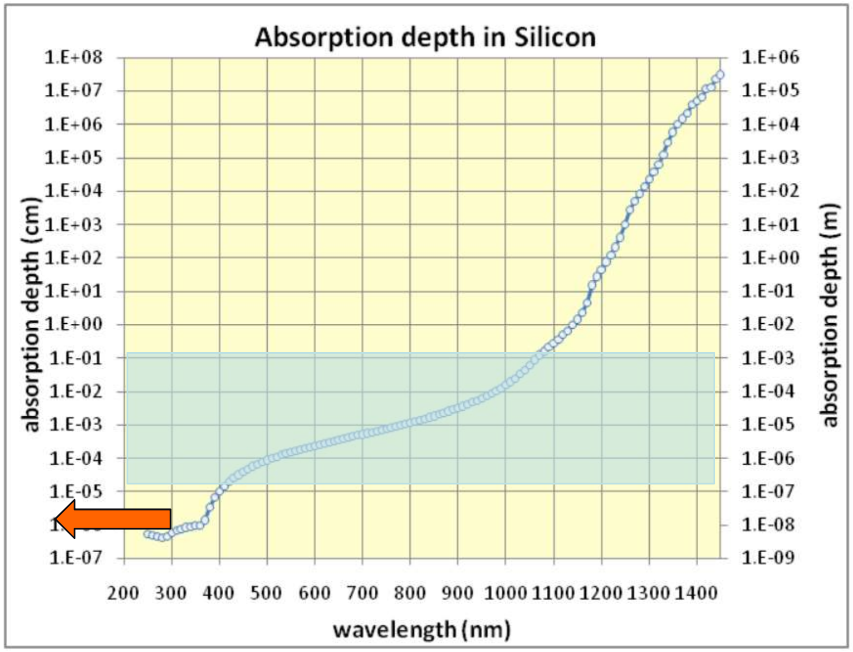
- Different view on objects
- Xray PCB inspection





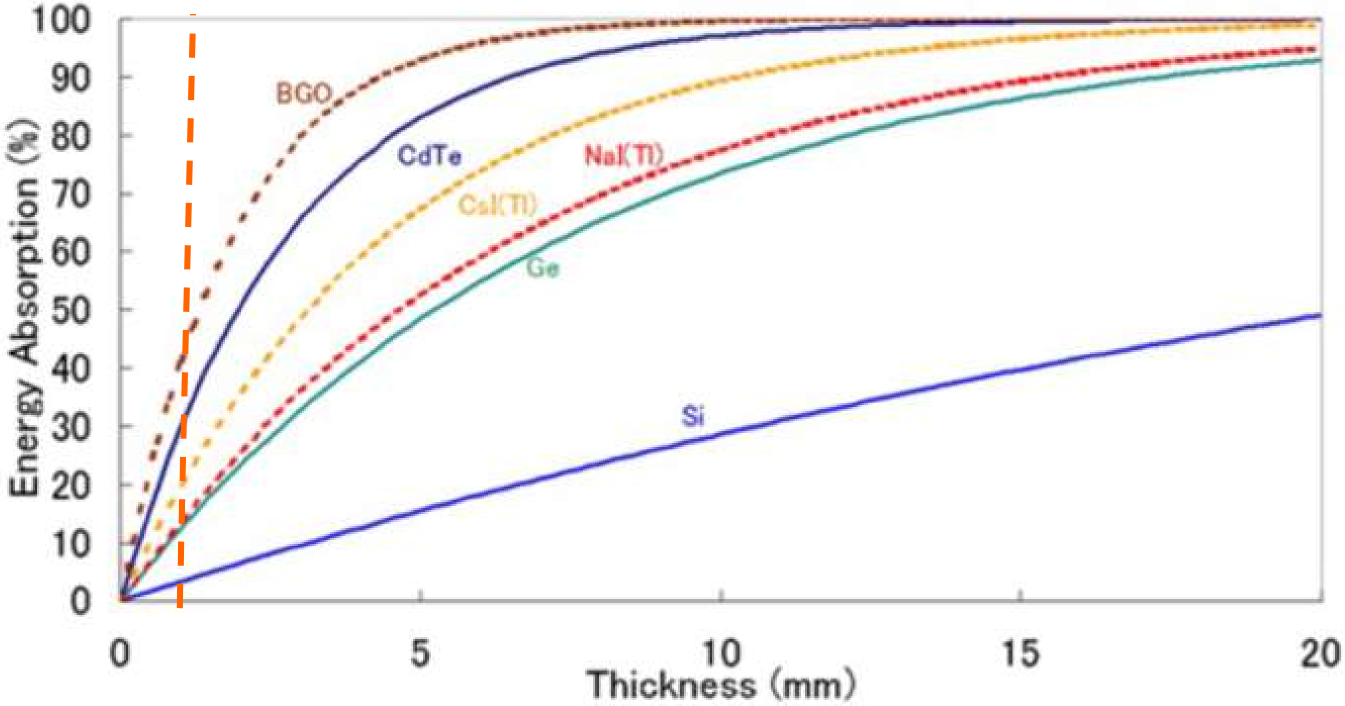
Absorption of X-rays





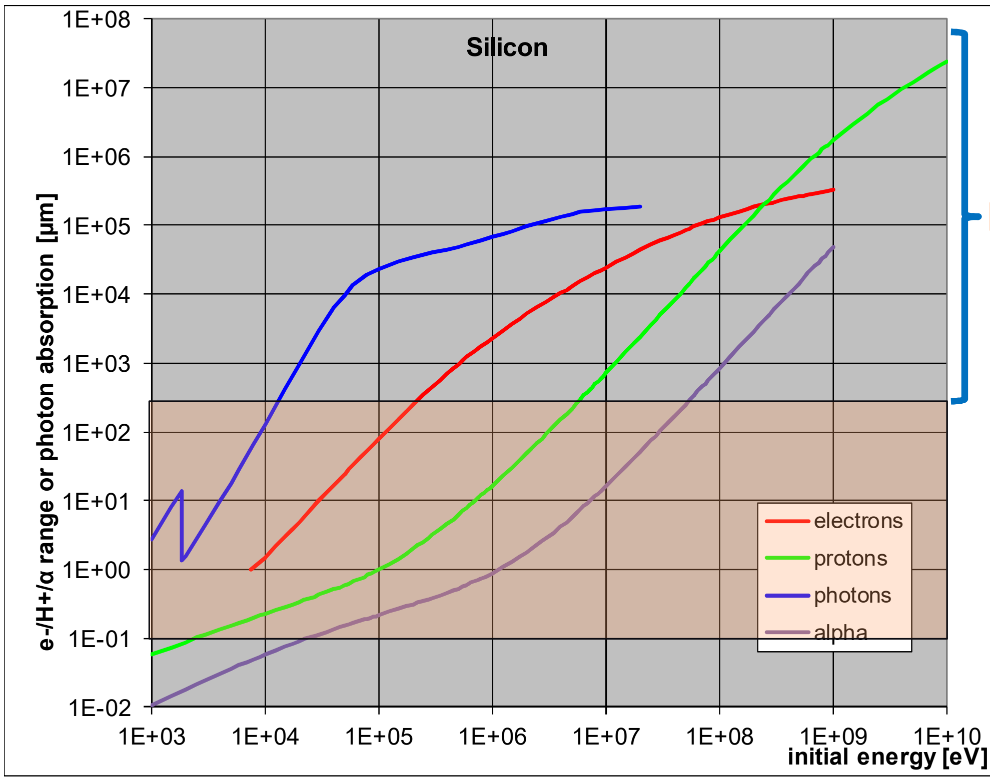
X-ray require heavy materials

(source Acrorad)



Use of scintilators

Particle absorption depth

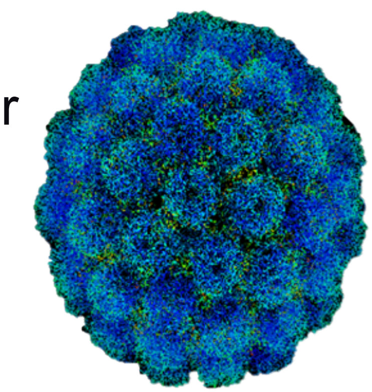


Energy resolving

- Use of scintillator
- On Fiber-optic faceplate
- Directly on surface

Trajectory

- Only presence detection
- No scintillator necessary



Take-home messages

- **CCD have seen an incredible growth between 1980 – 2010**
- **CCD will be gradually phased out**
  - Small community
  - Technology (un)availability
  - Pixel size
  - Performance
  - Last buys are ongoing at various places
  - Last bastion: scientific imaging

- **CMOS images are (becoming) mainstream**
  - Large Community
  - Open foundry model
  - High degree of integration, even 3D integration potential
  - Faster read-out, lower noise
  - Uniformity is becoming better