OVERVIEW OF IMAGING SENSORS AND SYSTEMS USED IN BEAM INSTRUMENTATION

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OUTLINE

- Introduction
- Image sensors
- Radiation effects
- Fast imaging/profiling
- Readout options

TAKING AN IMAGE

- Object / Source (illumination)
- Optics
- Sensor
- Digitizer
- Post processing

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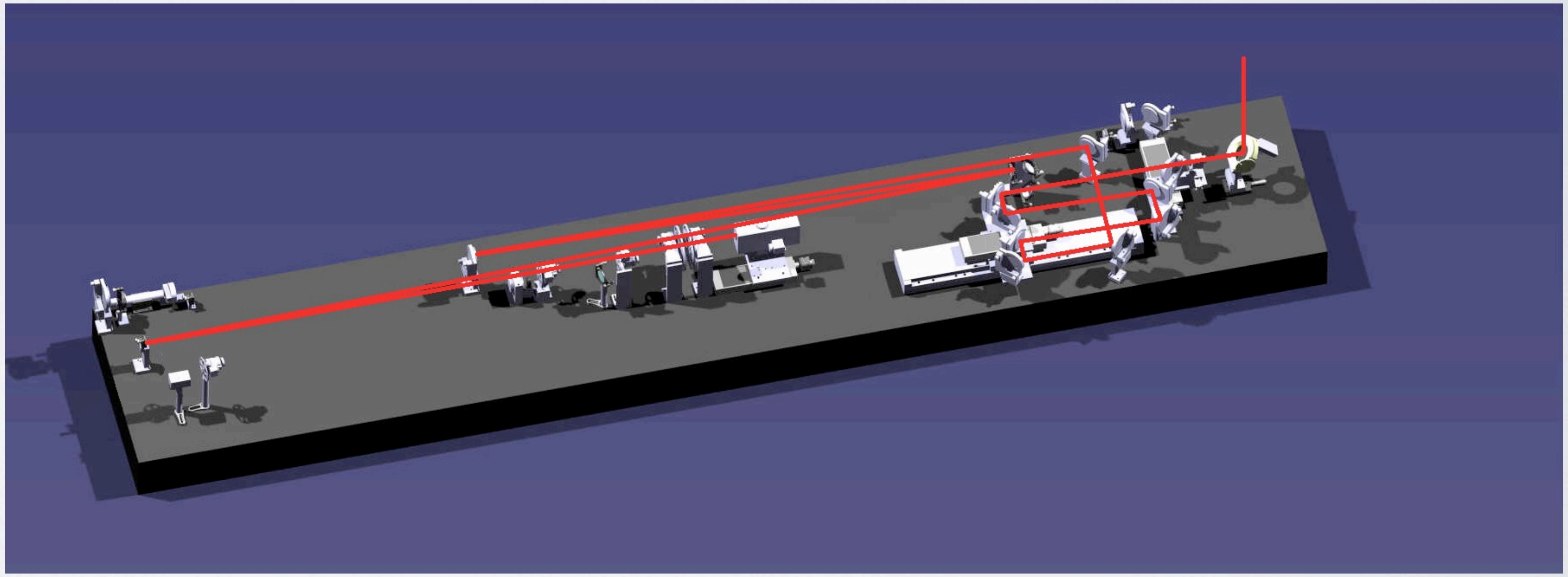

IMAGING FOR BEAM DIAGNOSTICS

- Difficult light conditions (intensity, angular distribution, reflections)
- IR / UV light
- Small objects (compared to object/sensor distance)
- Fast shutter speed (synchronized)
- High frame rate
- Radiation environment

IMAGE SENSORS

- Convert light into electric signals with a monotone and well defined relation between light intensity and output signal
- Provide information on the spatial distribution of light on image plane (eventually for different colors)

TYPES OF SENSOR

- CCD
- CMOS
- CID
- Video tube

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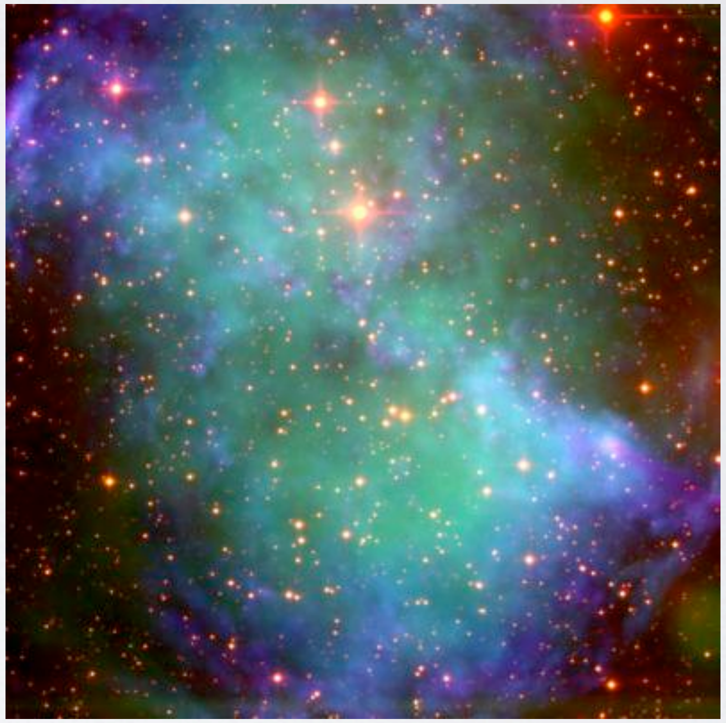

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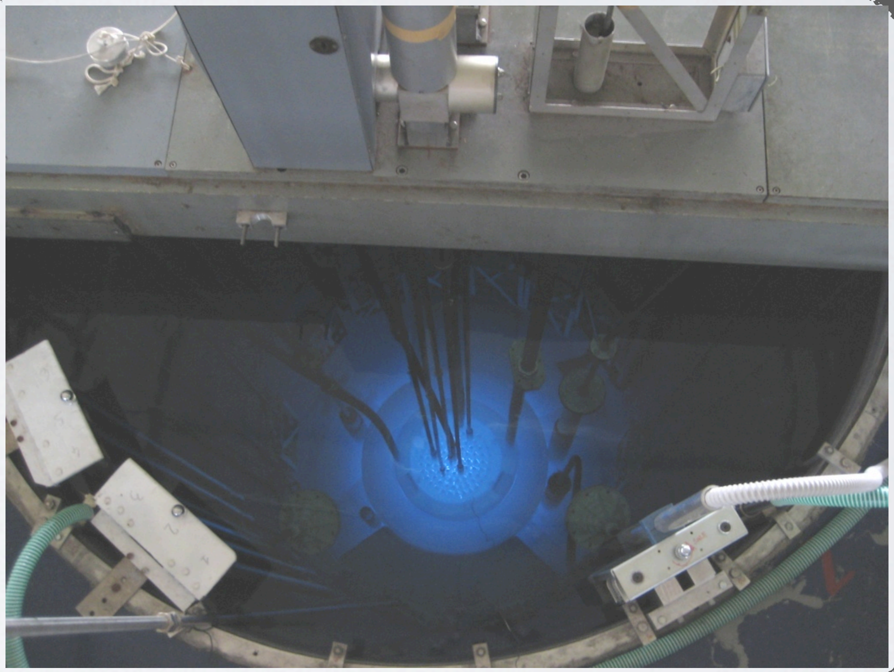

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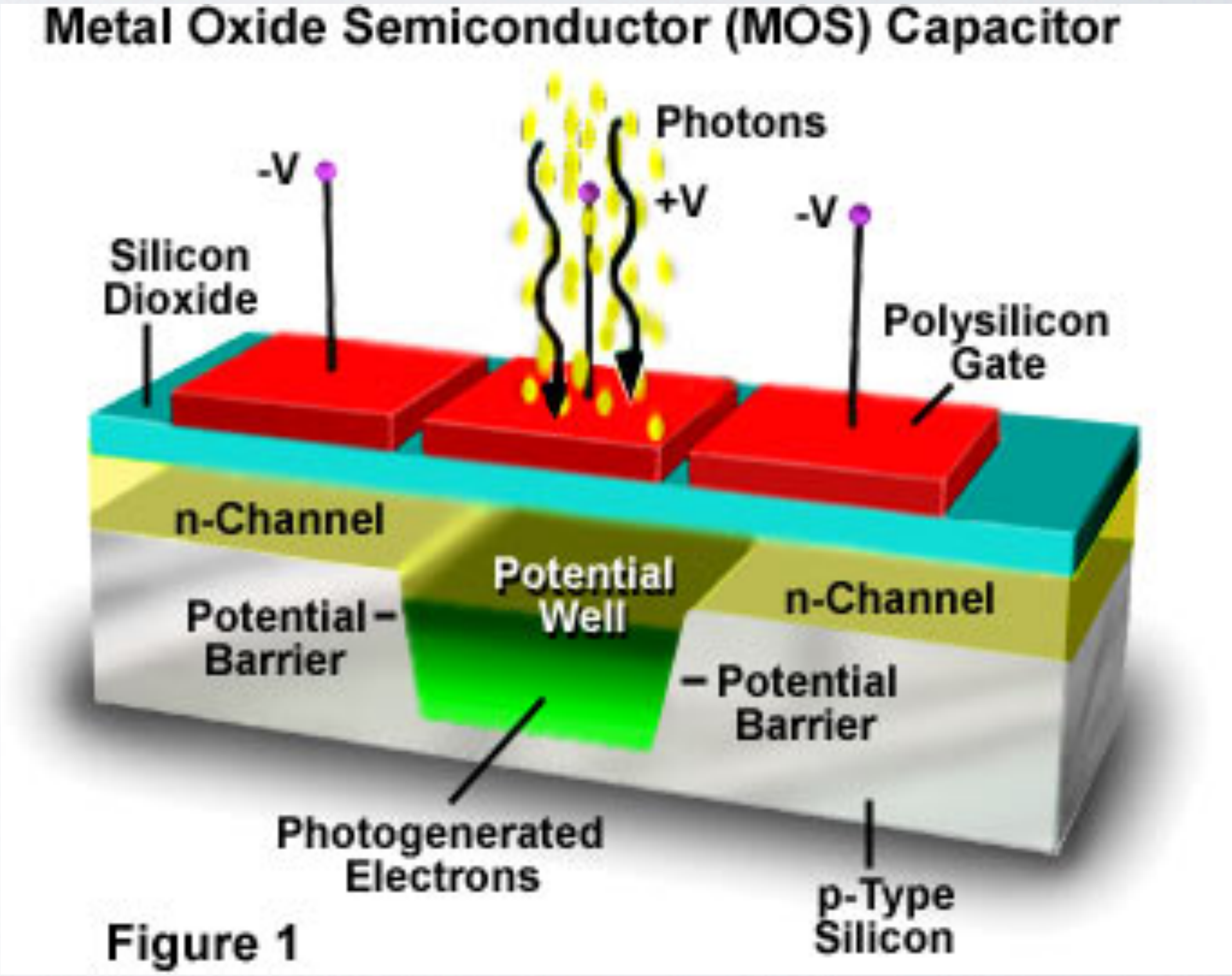
CCD

- Charge-Coupled Device
- Invented in 1969 by W.Boyle and E.Smith (AT&T Bell Labs) whom got a Nobel prize for it
- Based on Metal Oxide Semiconductor (MOS) capacitors
- Principle still the same, but technology refined a lot in the past 40 years

METAL OXIDE SEMICONDUCTOR (MOS) CAPACITOR

- The MOS capacitor is the base of CCD and CID image sensors
- Collects photo-generated charges (electrons) under a bias electrode
- Also known as photo-gate

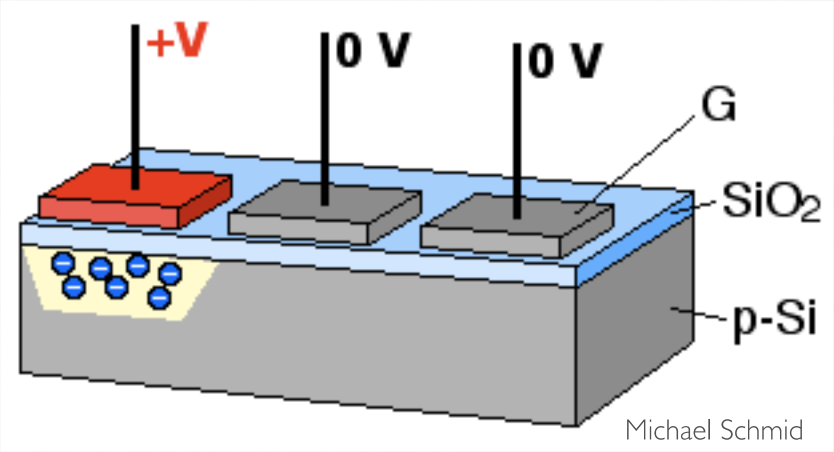


http://learn.hamamatsu.com/articles/moscapacitor.html

CCD PRINCIPLE

- Electrons are collected below the electrode

- The charge is shifted towards the readout by shifting the voltage on the electrodes (like in a linear motor)



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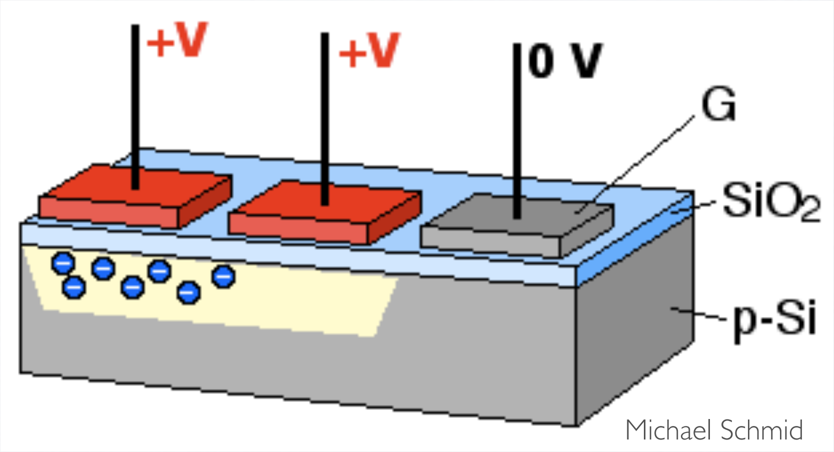

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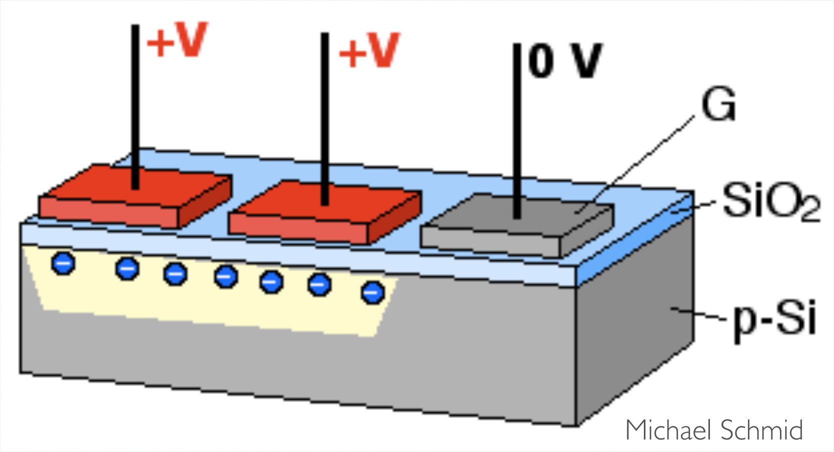

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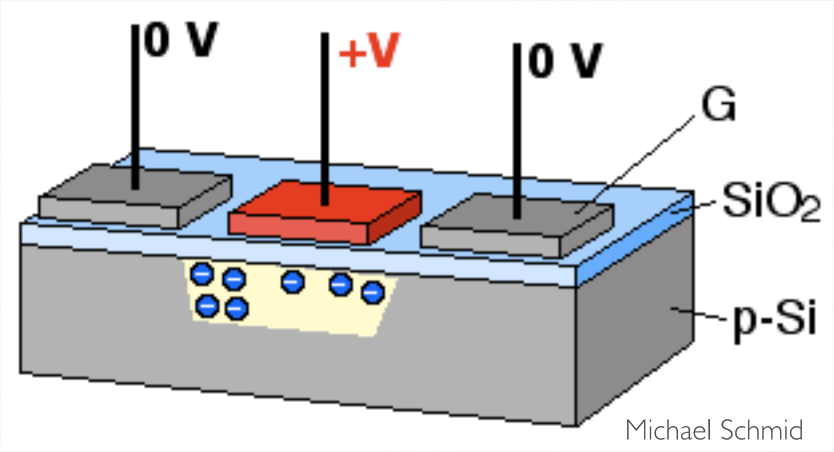

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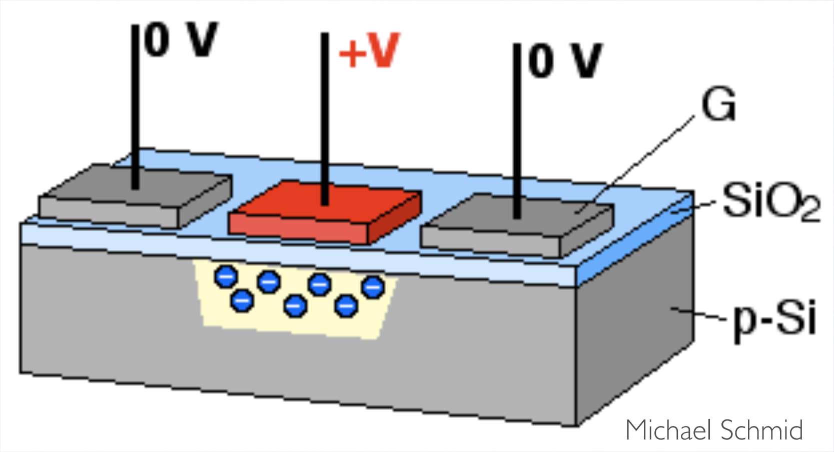

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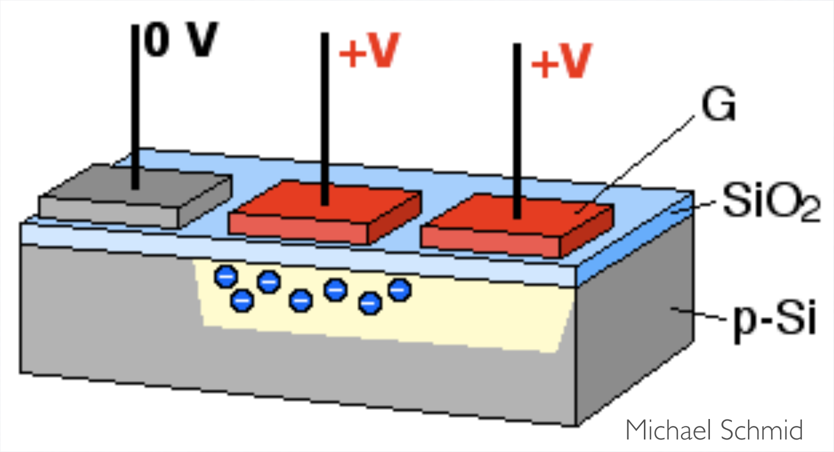

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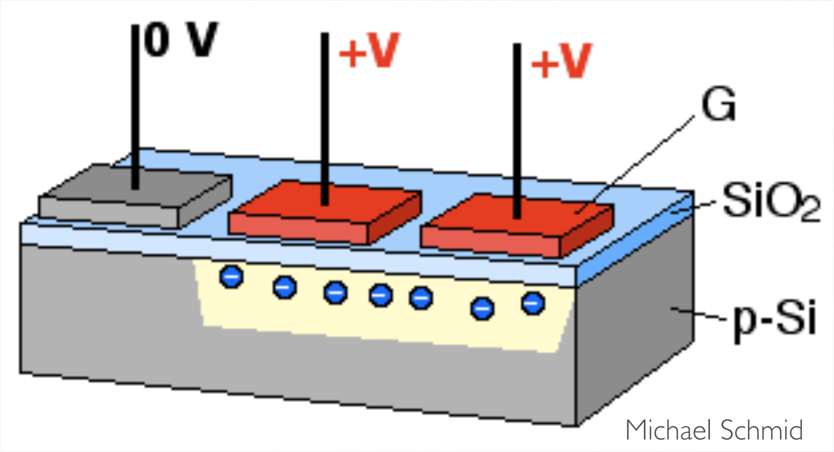

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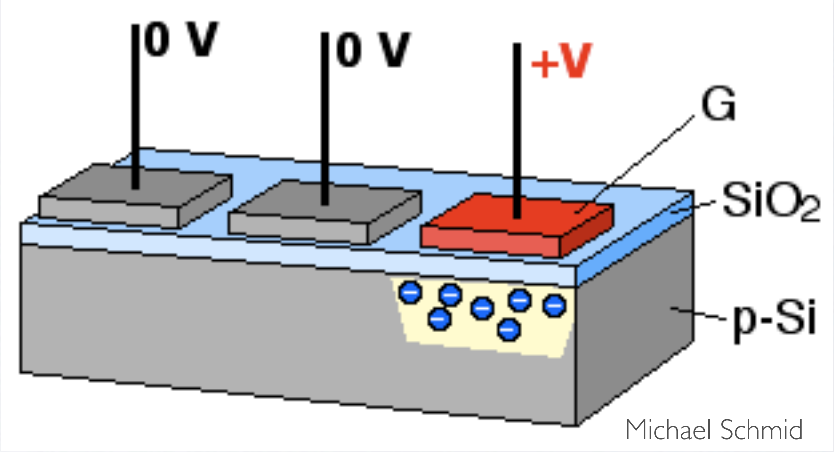

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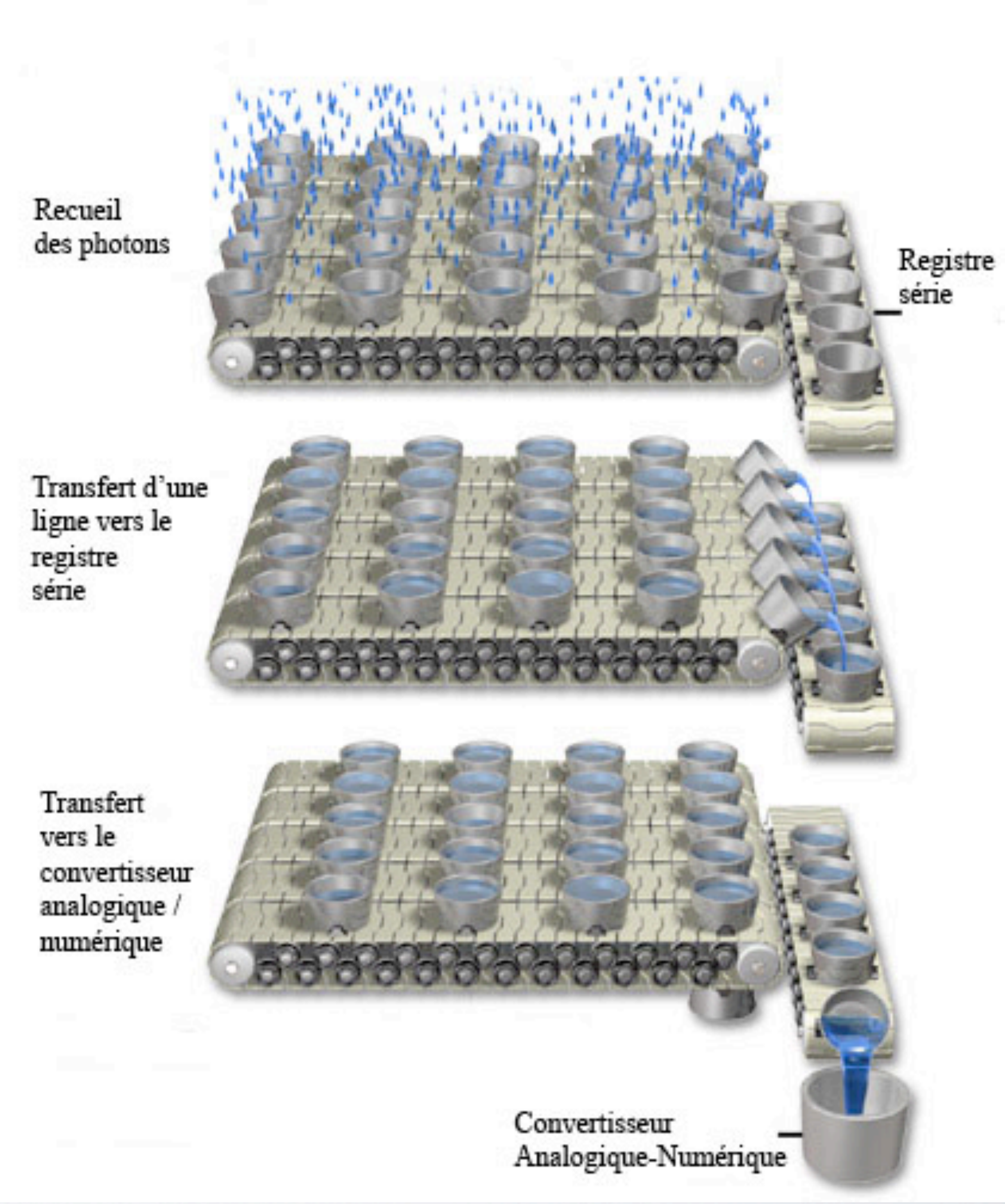
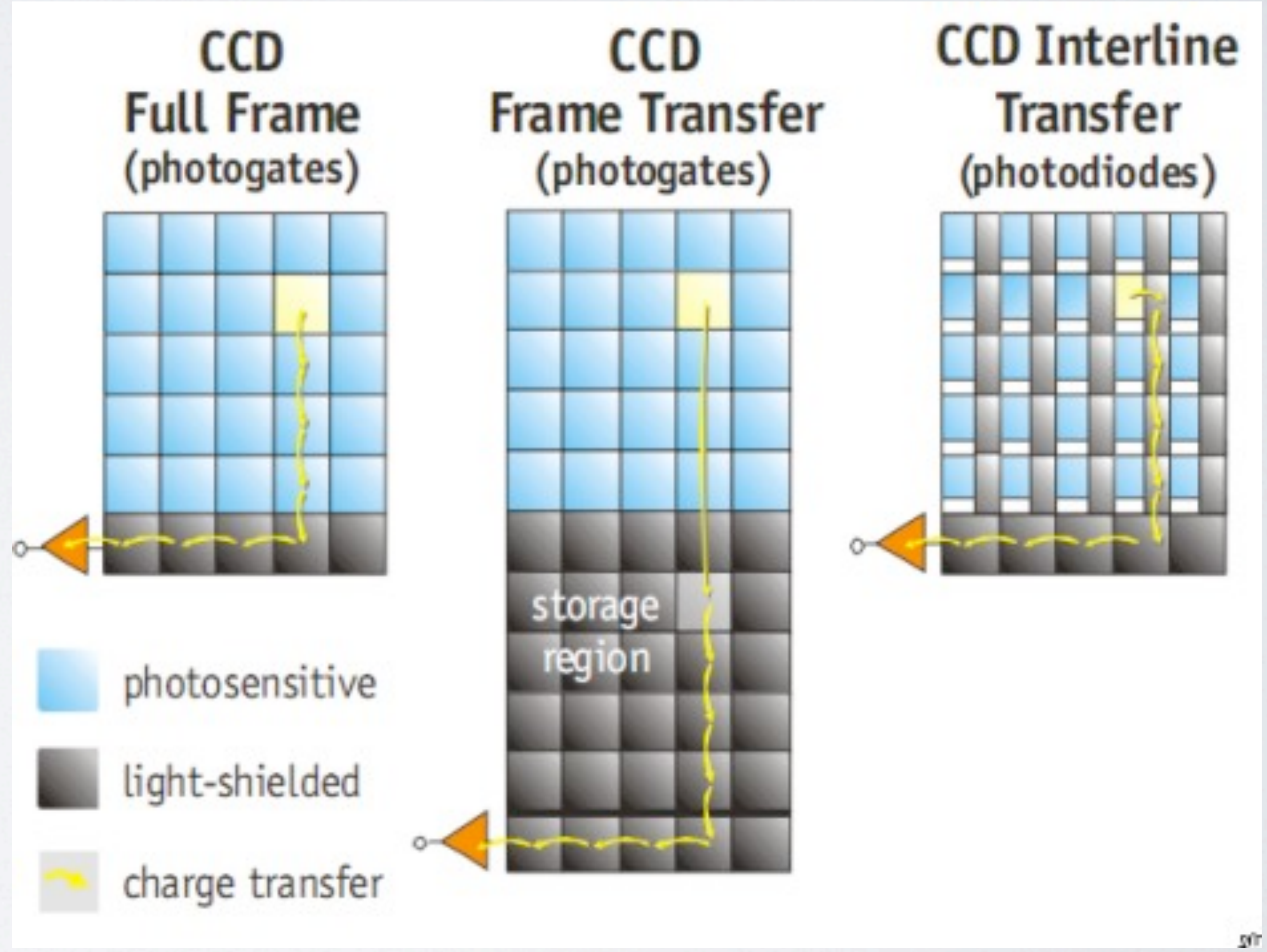


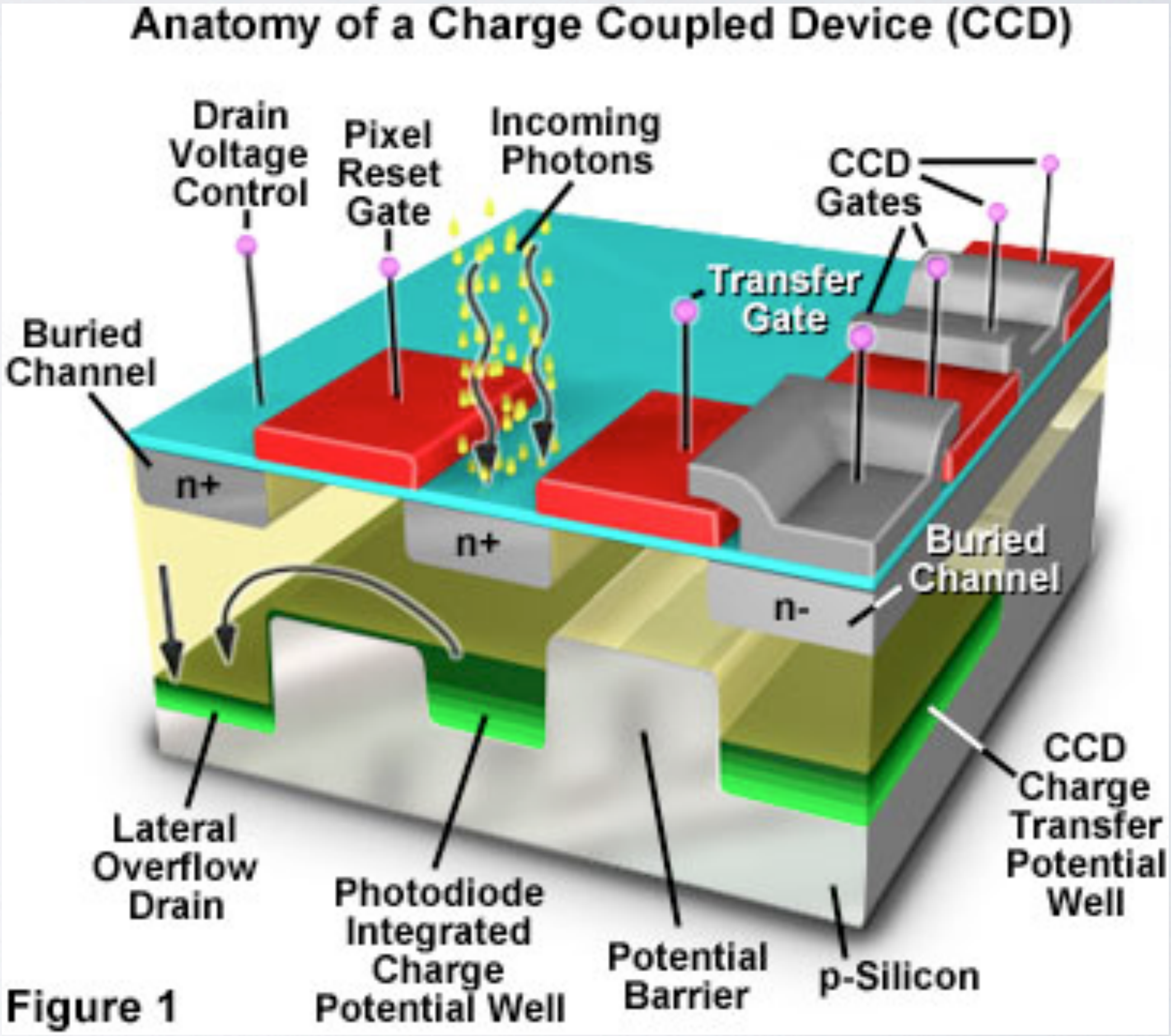
TYPES OF CCD

- Full frame requires an external shutter, strobed light or long integration times
- Interline CCD can provide electronic shutter down to few us
- (iCCD, EMCCD, EBCCD)



MODERN INTERLINE CCD

- Light is detected by a pinned photodiode (like C-MOS)
- Based on a n- buried channel (avoid defects in the Si-SiO_2 interface)

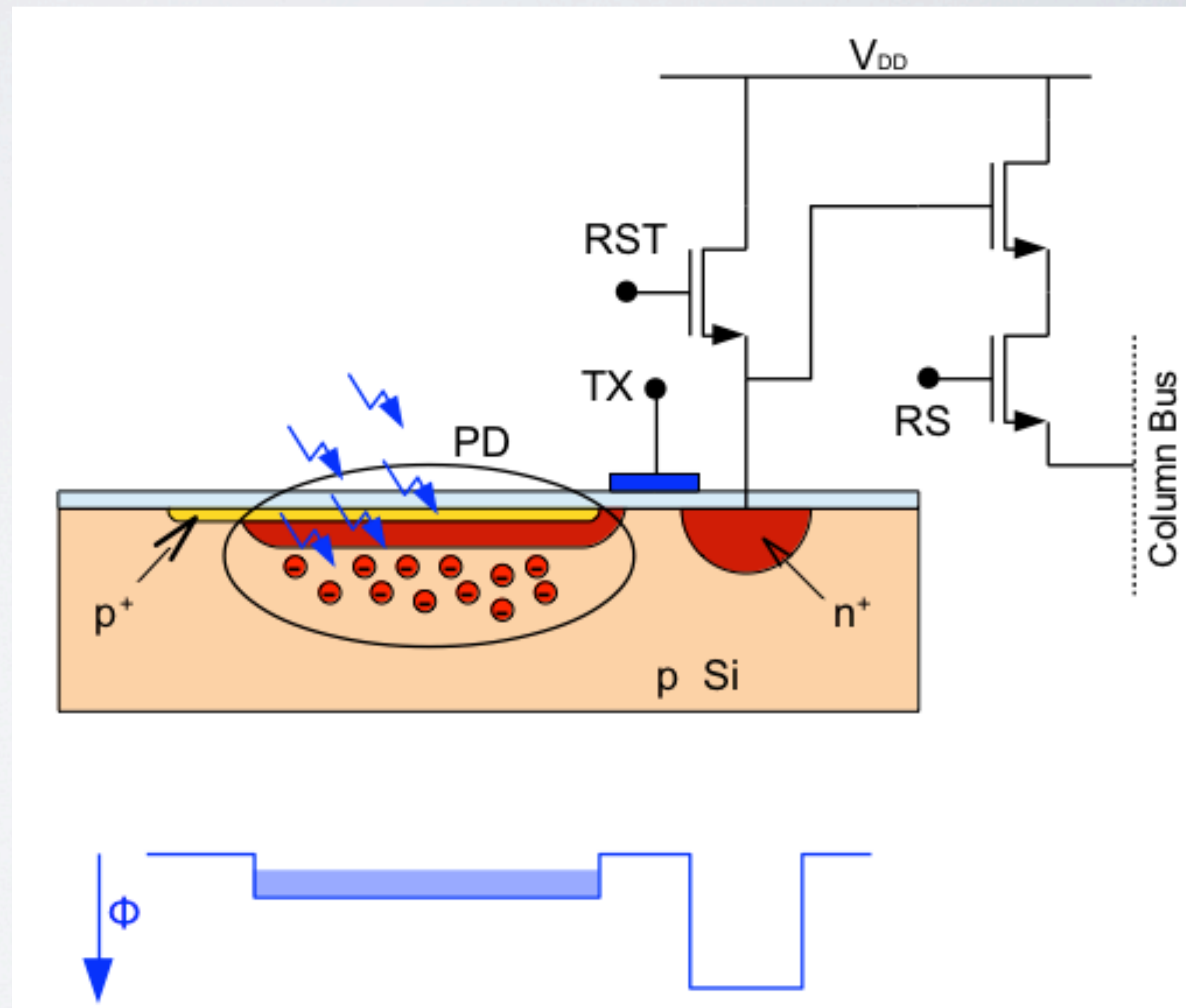


CMOS SENSORS

- Invented around 1968 by P. Noble
- Based on active pixels (CMOS transistors)
- Each pixel can be addressed separately (ROI, high speed)
- Not a match for CCDs until recent improvements in the CMOS technology (driven mainly by memory and CPUs)
- Replacing the CCD as the dominant type of sensors

CMOS APS

- The "modern" configuration of a CMOS pixel consist of a pinned photodiode and 4 CMOS transistors
- Large fraction of the pixel is (was) occupied by the transistors



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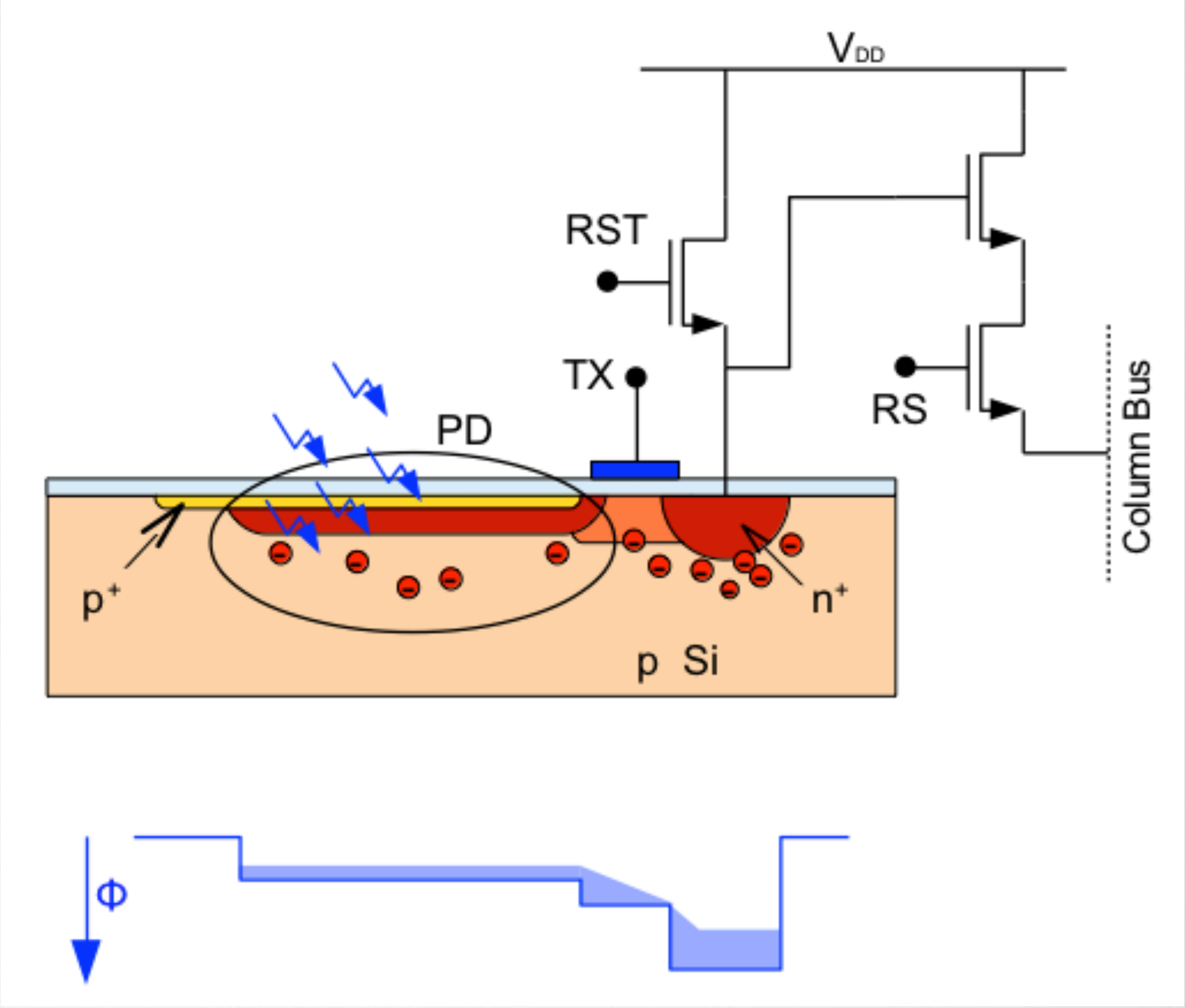

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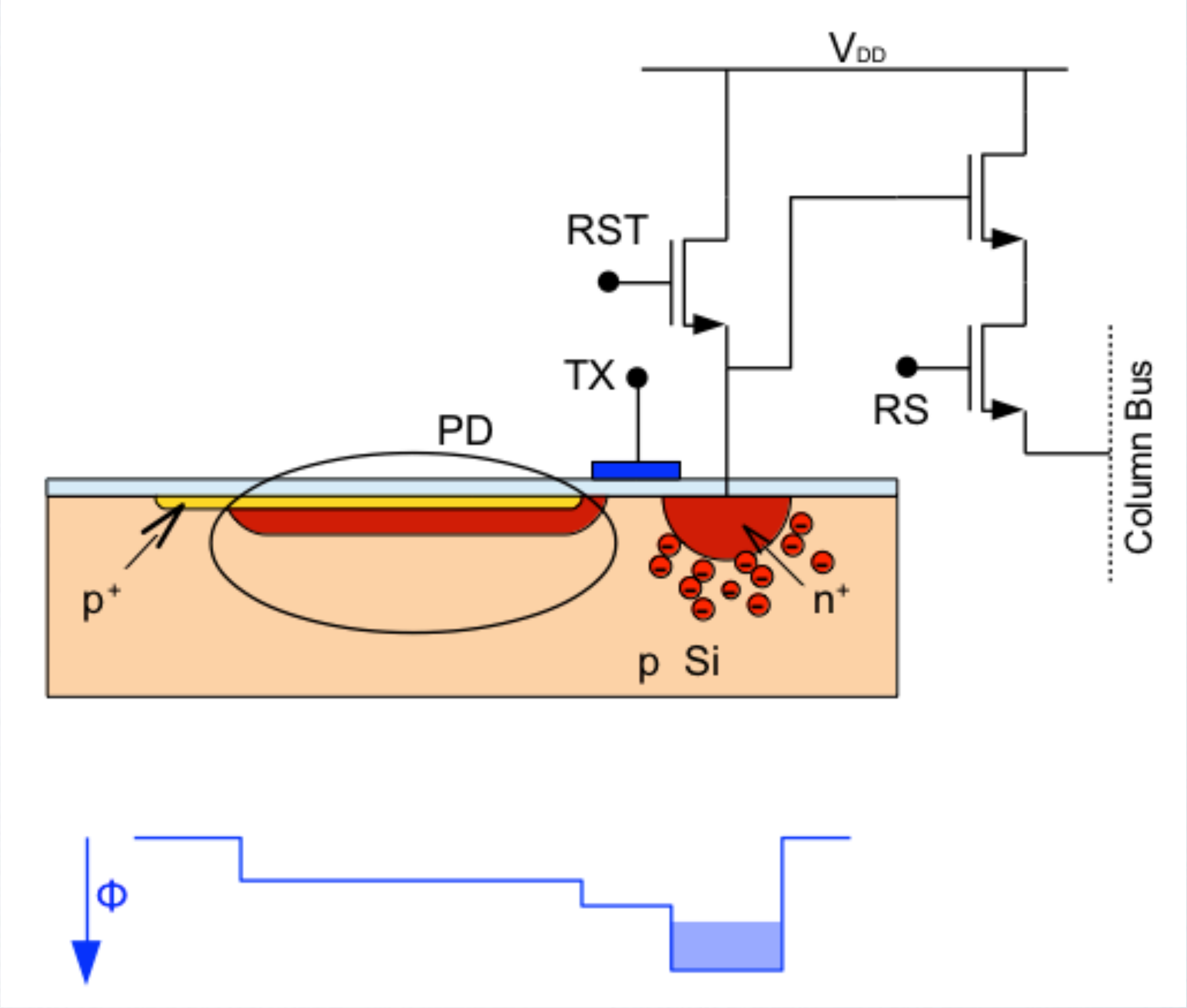

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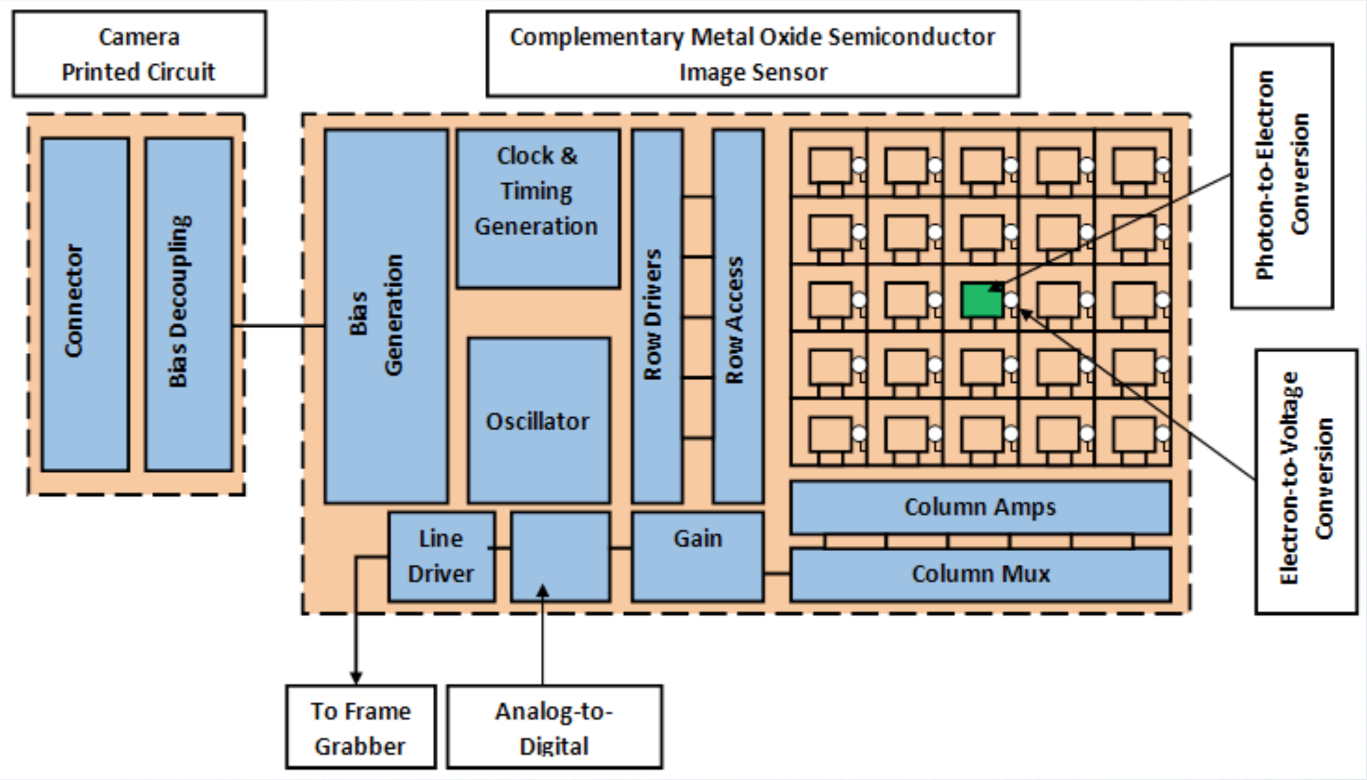
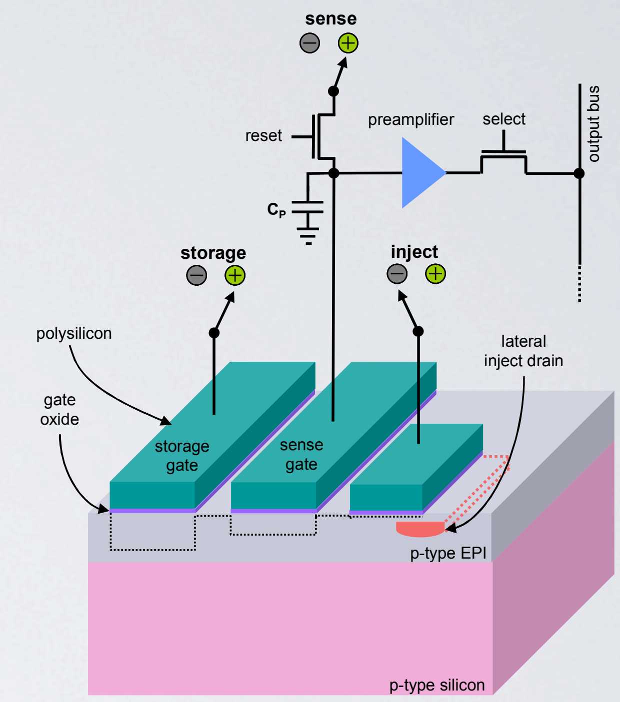


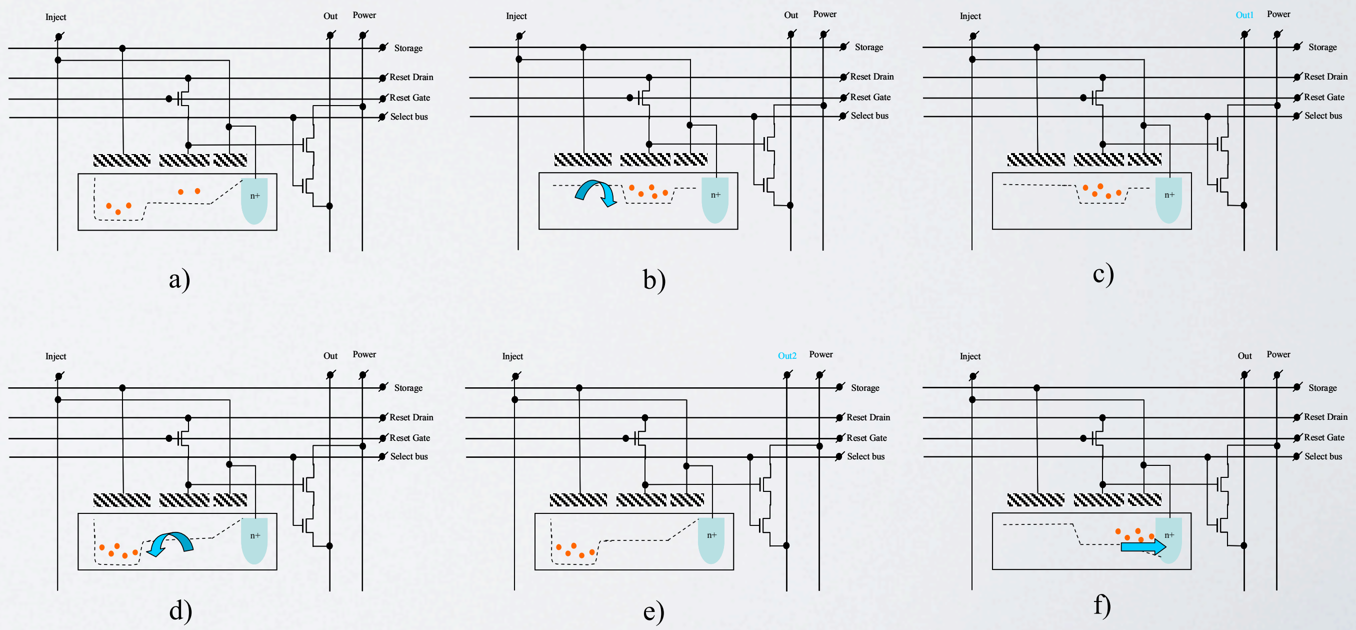
CID SENSORS

- Invented in 1973 by H.Burke and G. Michon of General Electric

- Commercially developed by CIDTEC (now Thermo Fisher Scientific)

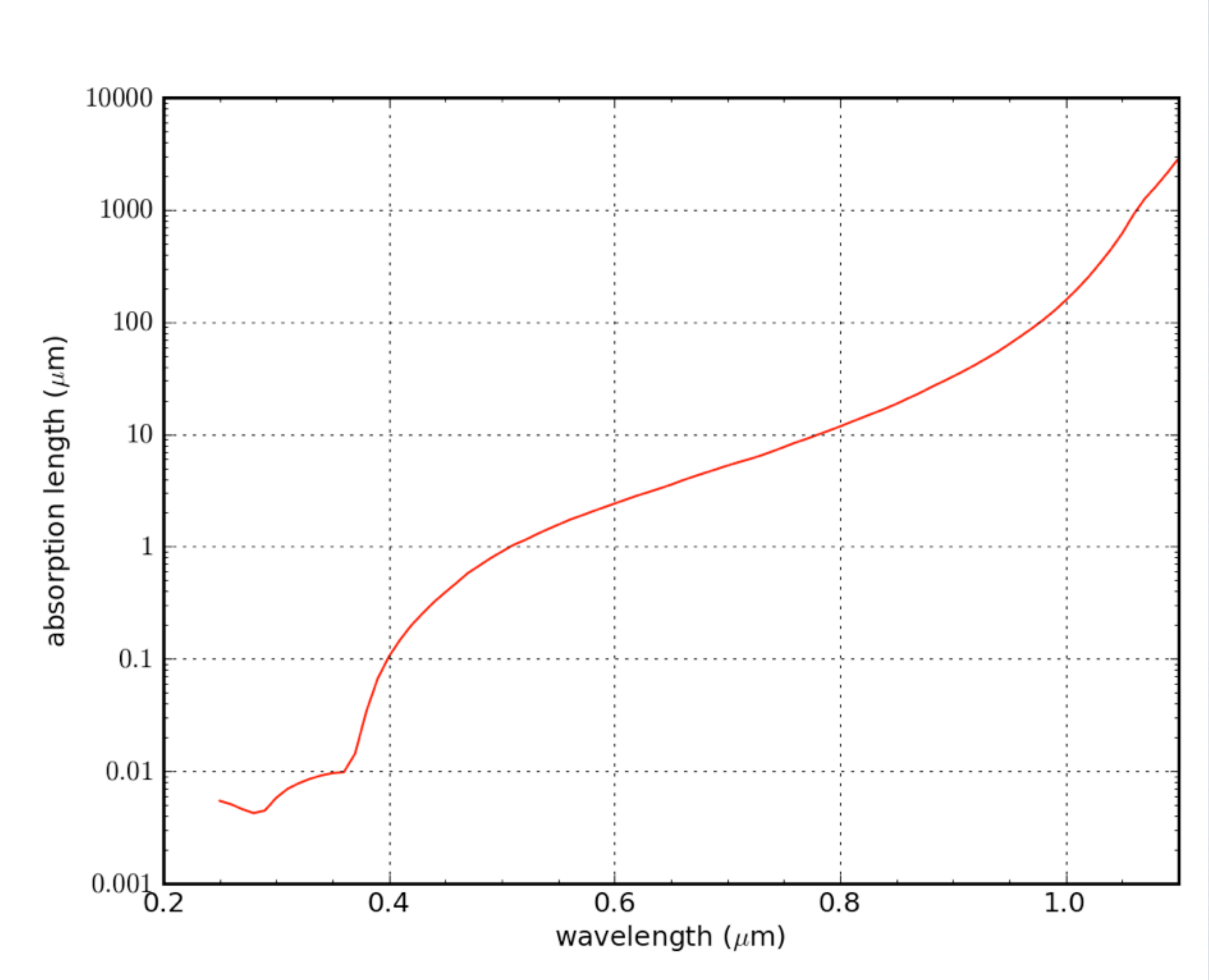
- Radiation hard (p type Si)





LIGHT ABSORPTION IN SILICON

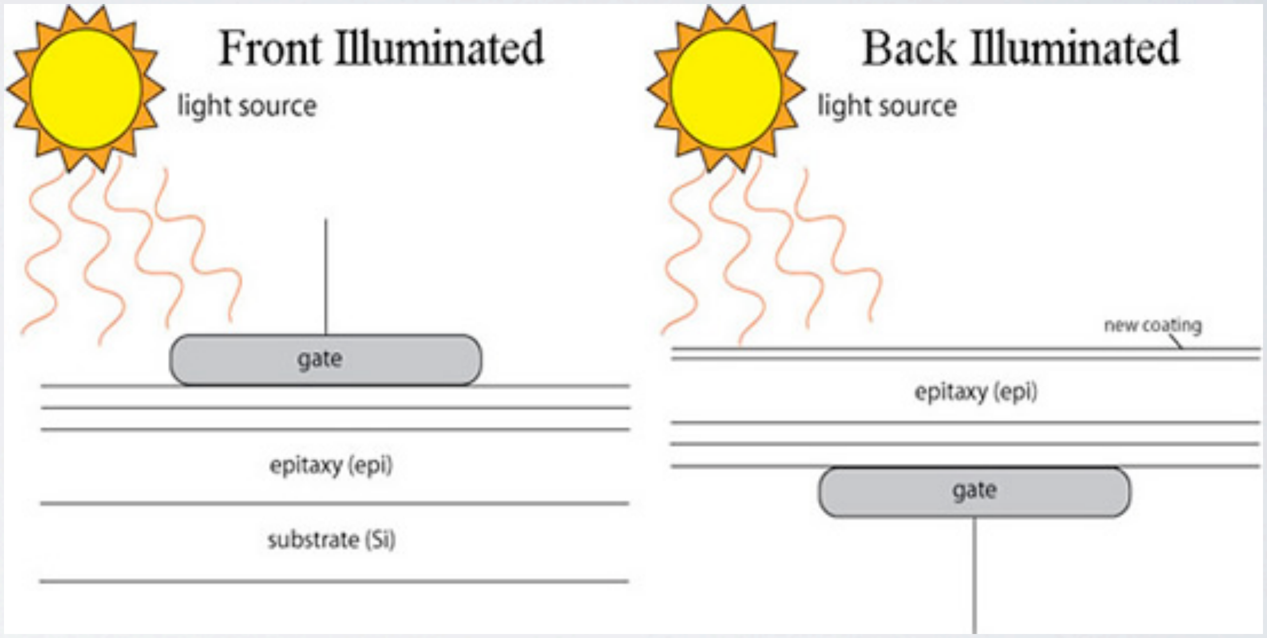
- Above 800nm light is not absorbed in the epitaxial layer
- Below 400nm the light is absorbed in the gates and oxides above the sensitive area

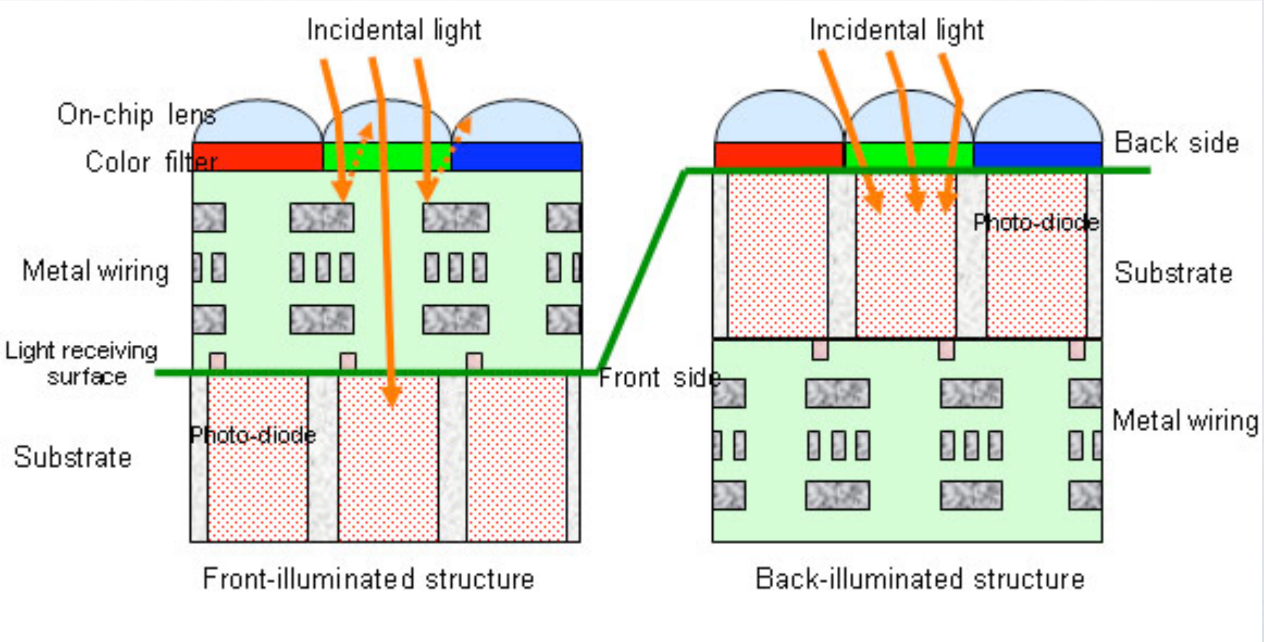


BACK THINNED SENSORS

- Back thinned CCD have been around for a while to extend sensitivity to above 1000nm and below 400nm

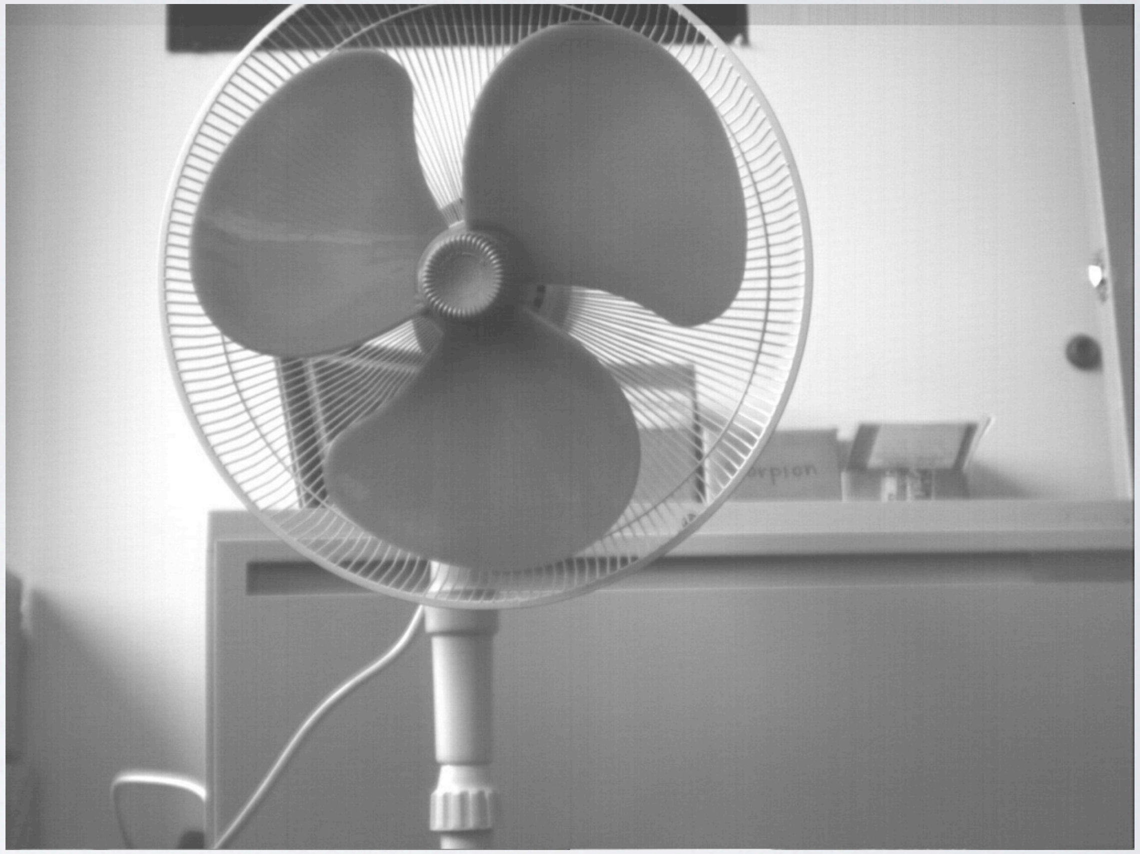
- Back thinned CMOS are quite recent and make up for the small fill factor





ROLLING SHUTTER

- Image integration delay differ from line to line
- Peculiarity of CMOS and CID (tube cameras as well)
- Problem for moving objects (or pulsed)
- Global shutter CMOS exist, but are more complex to make (loss of CDS)



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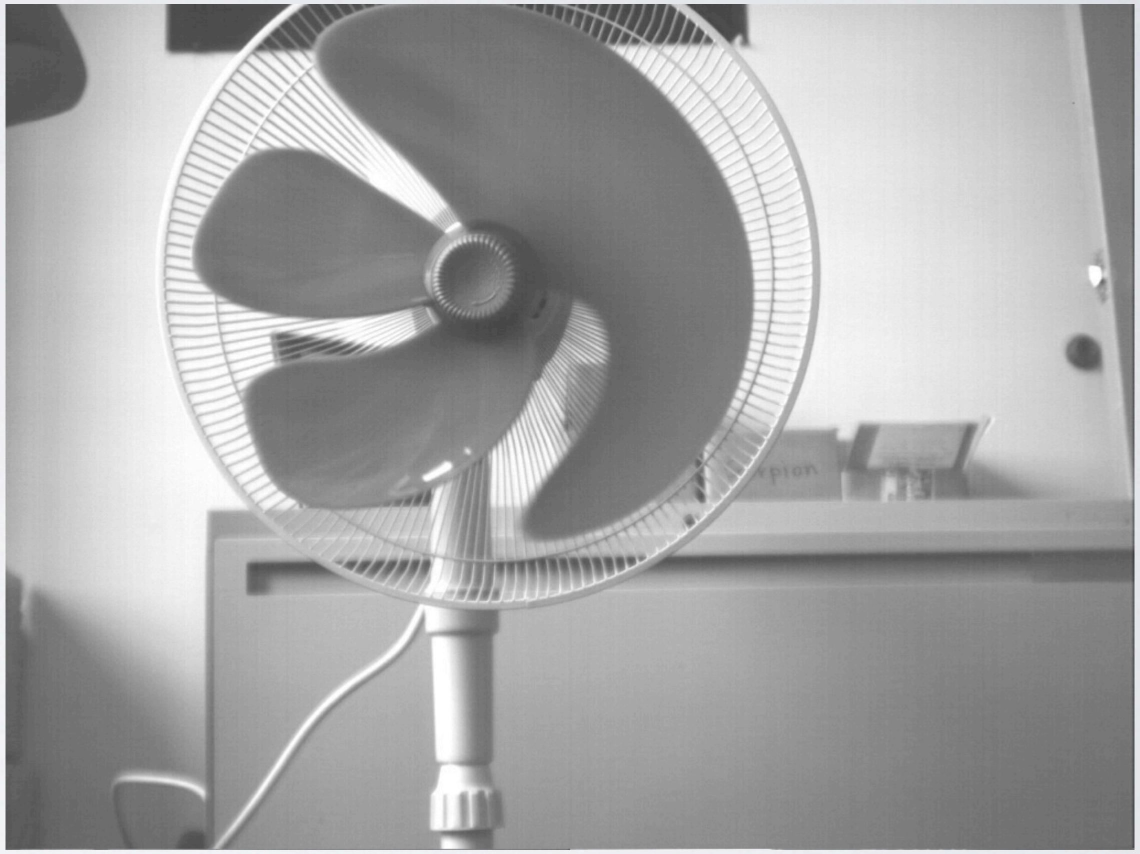


RADIATION IN MOS

- Charge creation in the oxide layer (flat band shift) $\Rightarrow$ reduce the oxide layer (CCD ~80nm CMOS <5nm)
- De-passivation of the interface layer
- Traps creation in the bulk, prominent for n type Si (due to phosphorus doping) $\Rightarrow$ p channel devices (collecting holes?) (LBNL, e2v)

RADIATION HARDNESS

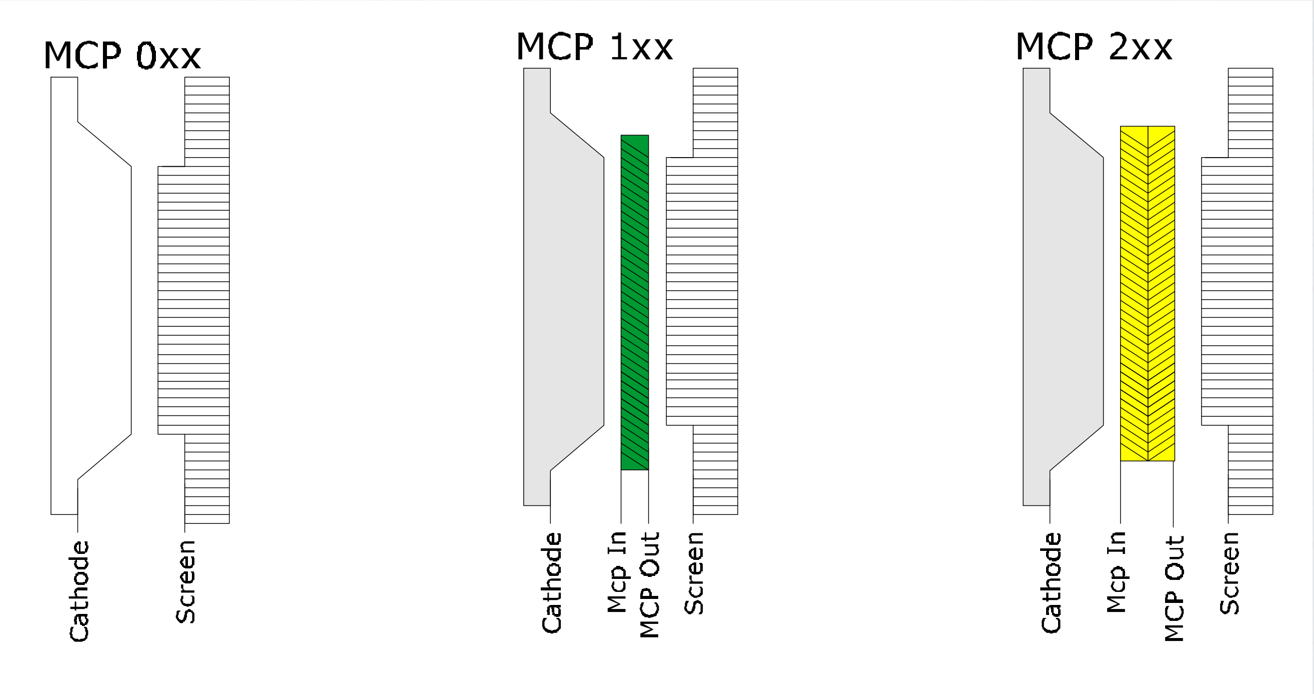
- CCD and CMOS typically not radiation hard ~100Gy (10kRad) max, can be improved with dedicated designs
- CMOS better than CCD (no CTE reduction, thinner oxides)
- CID up to 50kGy (5MRad)
- Vidicon tubes ? never seen a radiation damaged tube provided "no" local electronics

WHERE DO WE STAND

- Dramatic progress of CMOS and CCD in terms of pixels and sensitivity in the past 40 years (<10 e^- r.o.n., >10^7 pixels)
- Unfortunately radiation hardness has not improved much (often the opposite)
- CID recently improved in rad. hardness (>5MRad) and sensitivity (still ~5 times worse than consumer CCDs)
- Tubes are obsolete and difficult/impossible to procure

IMAGE INTENSIFIERS

- Modern intensifiers are based on MCPs
- Can amplify the light by more than 1000 times (single photons)
- Resolution is reduced by large amplification
- Can be gated to a few ns



ProxiVision GmbH

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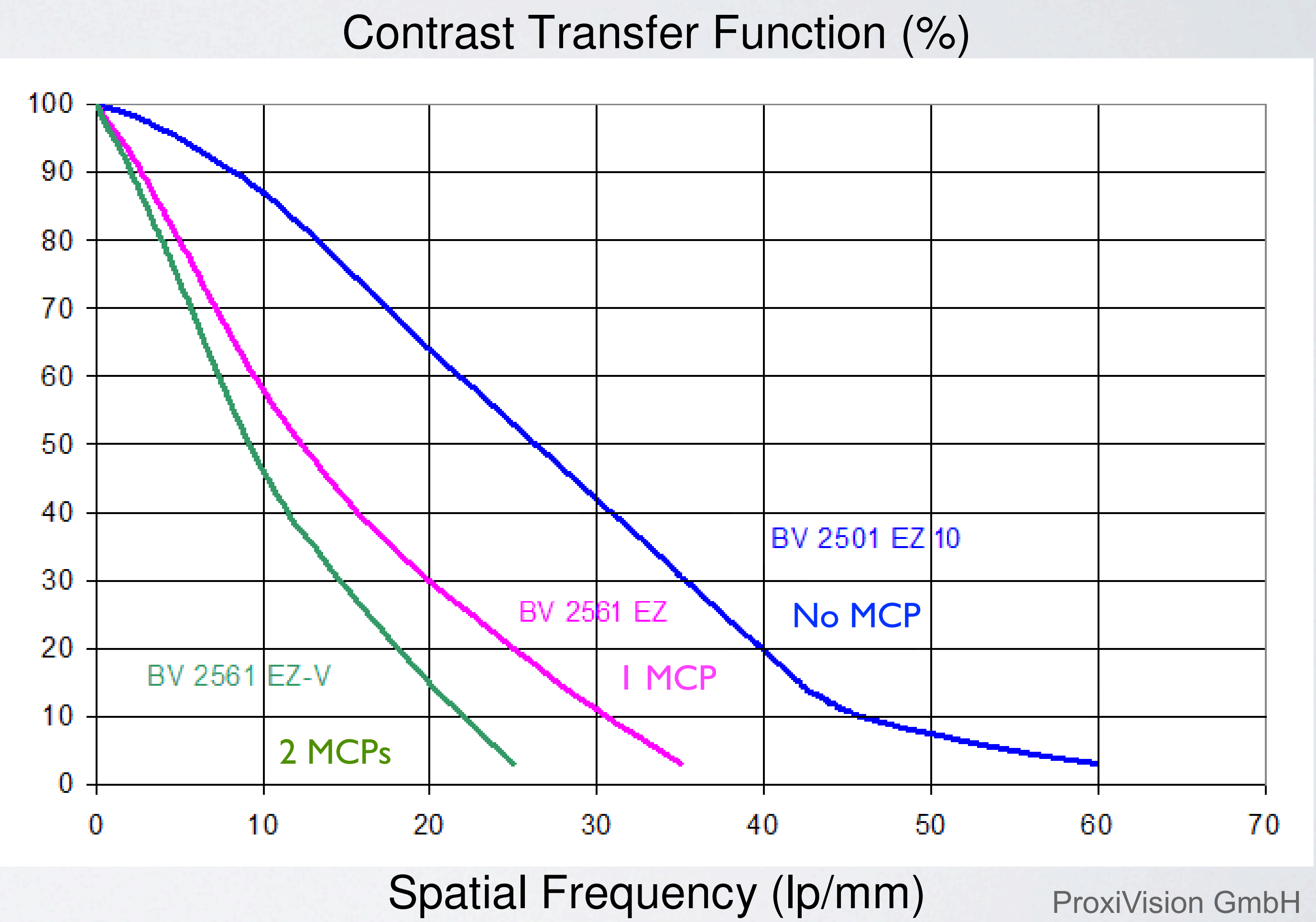

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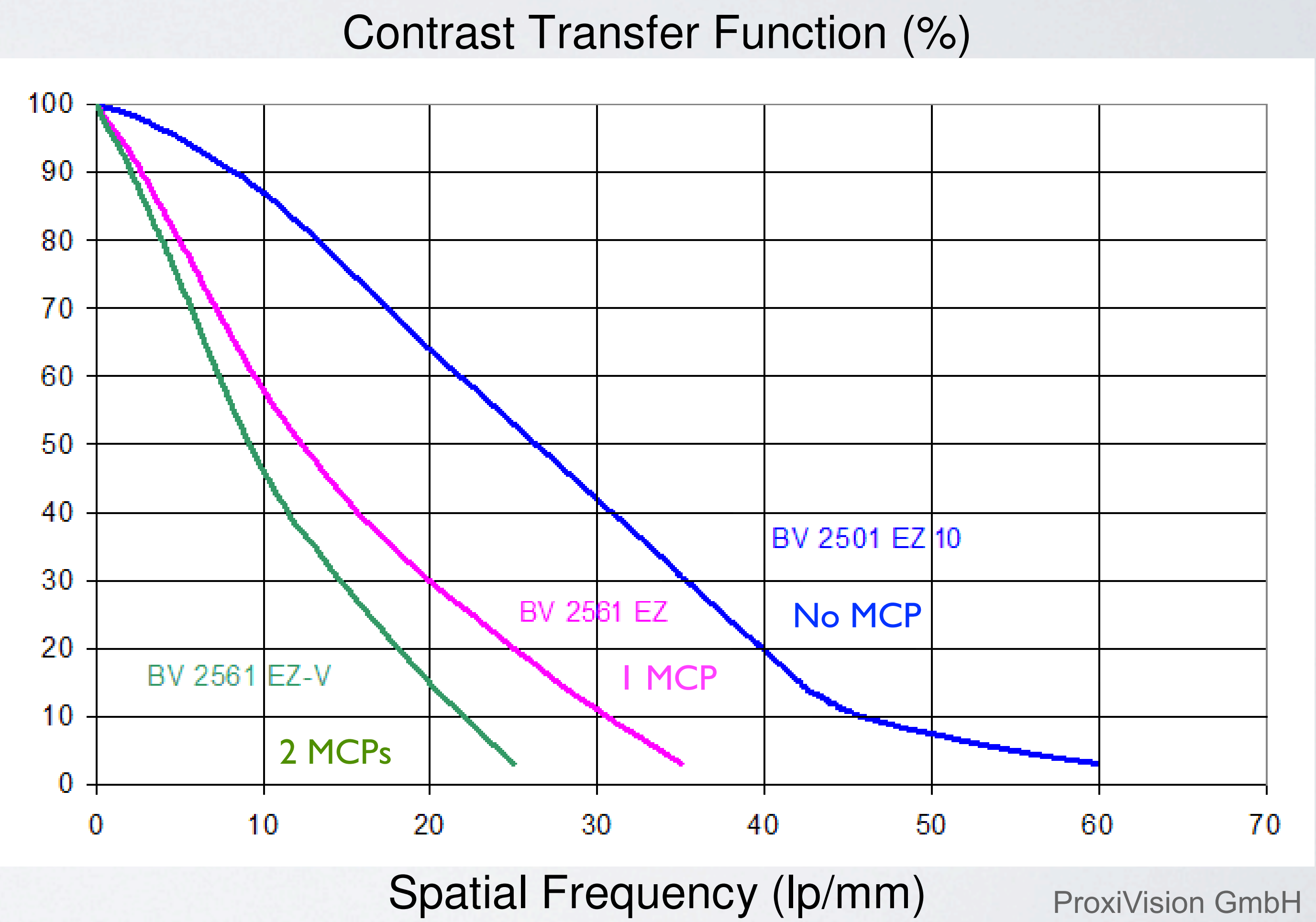

Wide range of photo-cathodes and phosphors available

FAST IMAGING

- Standard CMOS up to a few hundred frames/s (AOI)
- CCDs limited to ~ 50 frames/s (el. shutter ~1us)
- Specialized fast cameras up to 10^6 frames/s (small AOI) or 150k fr/s for AOI > 100x100 (Photron FASTCAM SA5)
- Fast profilers: Linear CCD/CMOS, segmented PMT, SiPM
- In most cases a fast shutter may be needed (Image Intensifier)

HIGH SPEED CAMERAS

- Based on CMOS sensors
- Can achieve > 100k frame/seconds with many GB storage memory (seconds long sequence)
- Expensive devices >50 kEuro
- Not suitable for a radiation environment
- Sensitivity ? specifications are not always clear
- Could be coupled to Img. Int. (using lenses)

HIGH SPEED CAMERAS

- Based on CMOS sensors

Could be coupled to img. int. (using lenses)

LINEAR ARRAYS

- Both CCD and CMOS versions exists
- Up to 50MHz readout clock possible (line rates of 100kHz possible)
- Using multi anode PMT or SiPM line rates up to 50MHz possible (parallel readout)
- Acquires just one line of given aspect ratio
- Need an asymmetric optics to get profiles
- External fast shutter ?

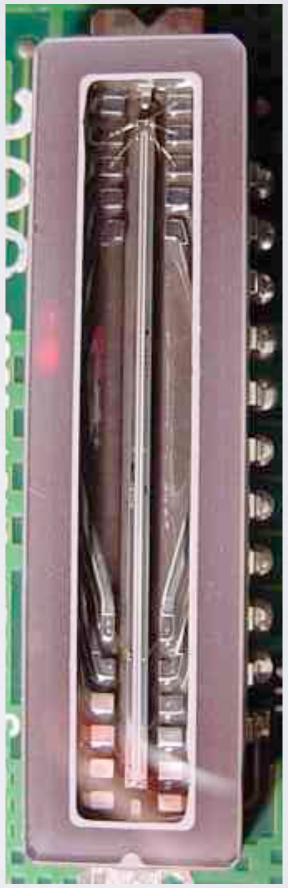

IMAGE ACQUISITION OPTIONS

- Three options available
  - Analog video camera and external frame grabber
  - Digital camera with dedicated protocol and external acquisition board (like camera link)
  - Digital camera and standard BUS (Gbit ethernet, USB, firewire...)

DIGITAL VS ANALOG

- In terms of performance (S/N, speed, cost, complication) digital wins hands down
- Analog still has an edge for the radiation problem, less electronics in radiation areas = less failures (... depends...)

ANALOG FRAME GRABBERS

- Typically used for CCIR (SD)
- Becoming obsolete as are analog cameras. We should probably expect a sharp end (like tube TVs and vinyl records)
- Since years "only" available for PCs (mainly WINDOWS, some support for Linux), not easy to integrate and maintain in large control systems
- Can be replaced by a mid-range ADC/FPGA board (~40MHz)

DIGITAL FRAME GRABBERS

- Getting obsolete as well. Will probably survive for very special applications (super high speed with multiple Gbit links)
- Same situation as for analog frame grabbers for the hardware choices, mainly PCs with WINDOWS or Linux

FIELD BUS CAMERAS

- Large choice, very fluid situation
- USB (1, 2, 3), Firewire (400, 800, S1600, S3200), Gigabit ethernet
- Transfer rates up to several G bits/s
- USB and Firewire only short cables (extension possible)
- Gbit Ethernet allows up to 100m (twisted pair)

BUS PROTOCOLS

- The physical layer is public (is or can be installed in any PC or crate)
- The data protocol is often proprietary and requires the use of binary only libraries/drivers, again with the same support as for the frame grabbers. Risk of lock-in to a product!
- Some open standard exists and is used by some company

ANALYSIS TOOLS

- Usually we need to do:
  - Background subtraction
  - geometric corrections
  - projection and or fitting
- Most of the time we use in-house developed tools (LabView, Java, C/C++...)

ANALYSIS TOOLS 2

- Scientific camera provider have some tools on their catalogues
  - Typically targeted at specific type of measurements
- Difficult to find a global, fit-all, solution.
- Our needs are a little off market
- Still it is possible to create collaborative tools

CONCLUSIONS

- Technology is giving us a lot of possibilities/opportunities in the imaging world
- Some times, unfortunately, our needs go opposite to the big market
- Radiation is our real enemy!
- A field where collaboration would help a lot!

THANKS!