Beata Walasek-Höhne

# Overview of Video Cameras

# used in Beam Instrumentation

# Outline: Taking an Image

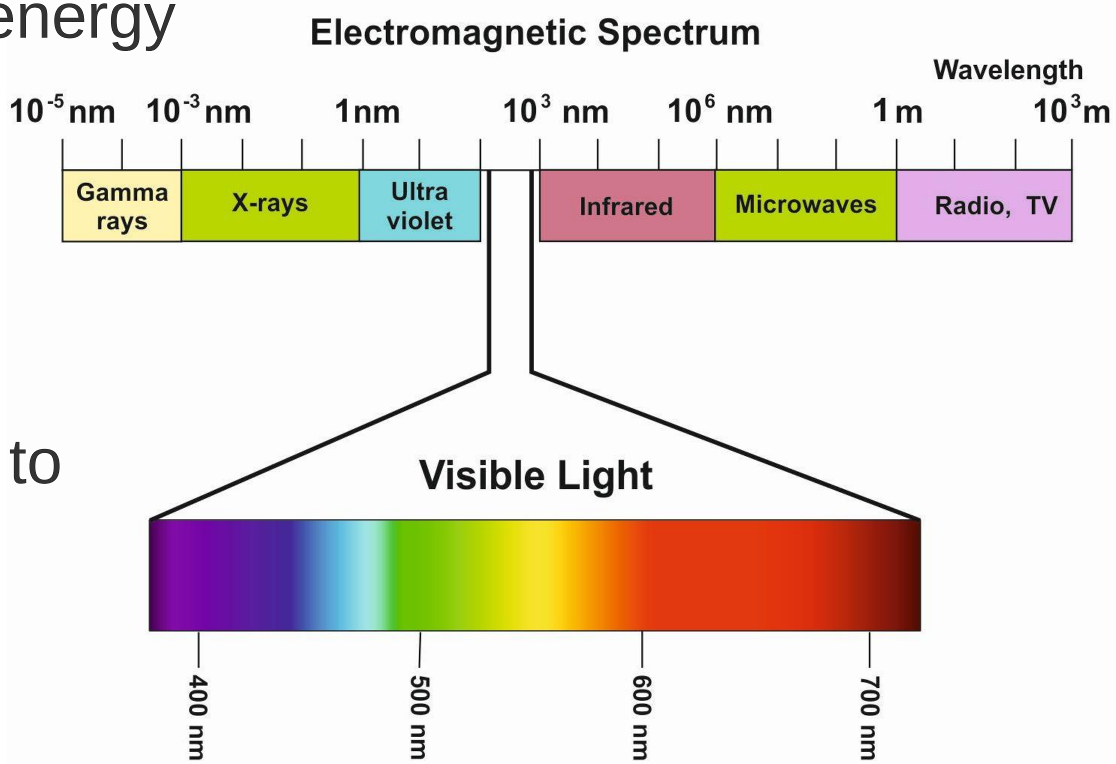
- Source of light — more details: talk of E. Bravin „Transverse Profile measurements“
- Optics — more details: talk of S. Gibson „Introduction to optics“
- Image sensors
  - Analog
    i. Video Tube
  - Solid state sensors
    i. CCD
    ii. CMOS
    iii. CID
- Radiation hardness
- Digitizer — more details: talk of M. Gasior „Analog Digital Conversion“
- Post processing

# Source of light

- light is represented as both a particle (photon) and electromagnetic wave
- photons have a defined energy
- energy correlates to wavelength

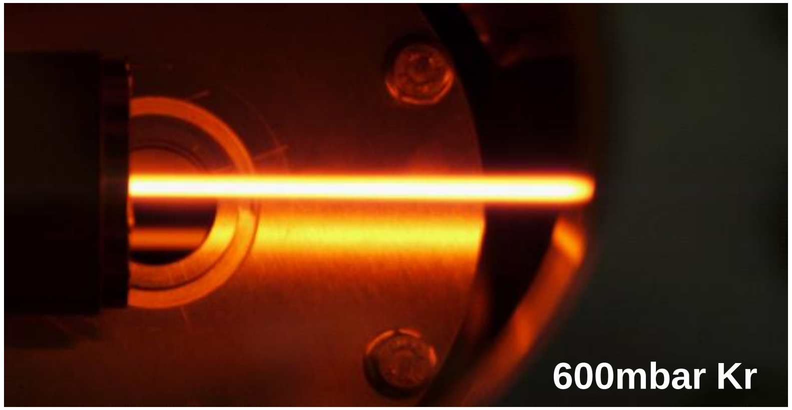
$$E = \frac{hc}{\lambda}$$

- wavelength corresponds to color
- number of the photons corresponds to intensity




- visible light is a very narrow band in the electromagnetic spectrum

# Source of light

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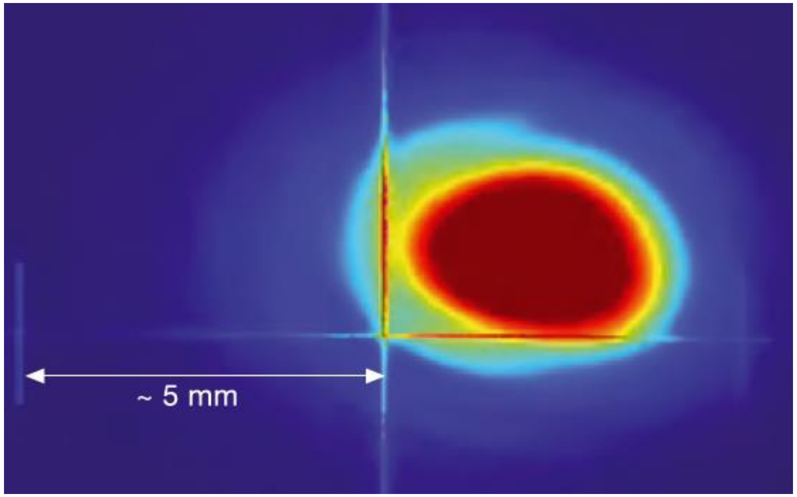


YAG:Ce at FLASH

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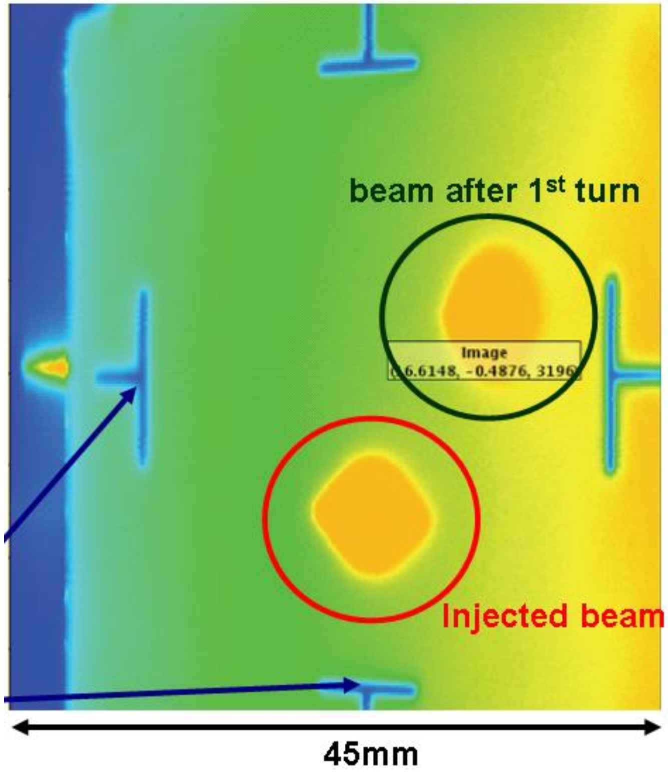
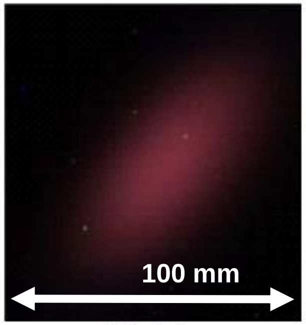


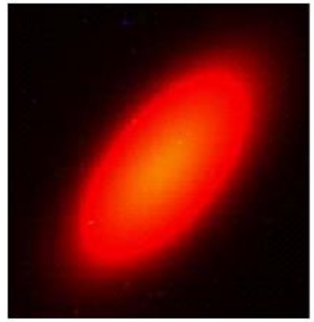

Ruby-Ceramics (Chromox) screen at LHC for injection and first turn, protons at 450 GeV

© CERN, www.cern.ch

# Source of light

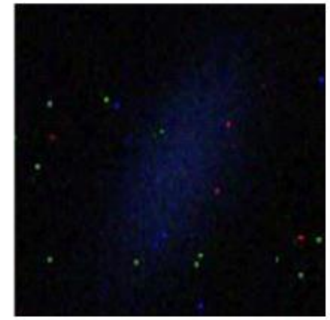



$Al_2O_3$

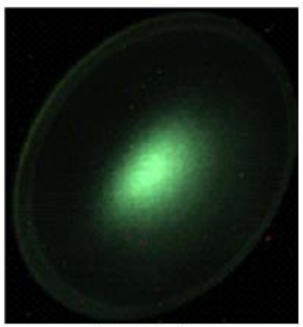


$Al_2O_3:Cr$

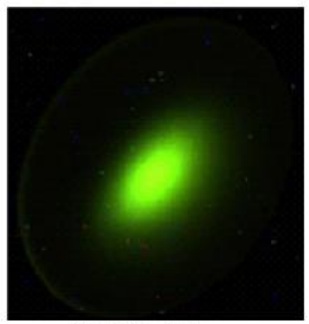
$ZrO_2:Mg$



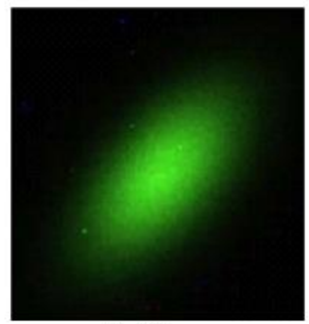
Herasil



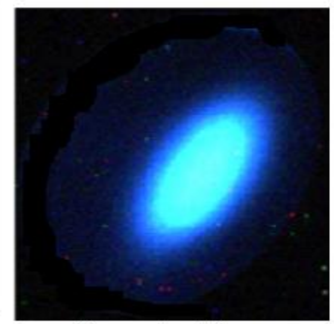
CsI:Tl



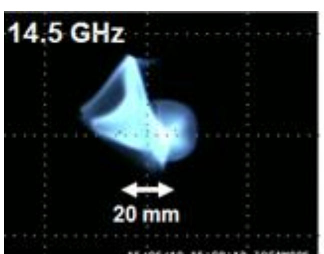
YAG:Ce

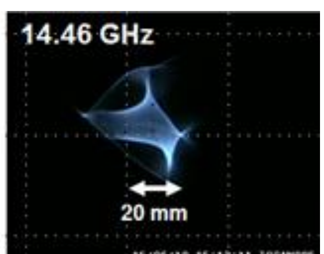


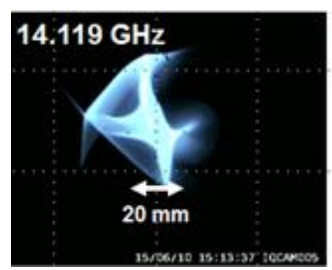
P43

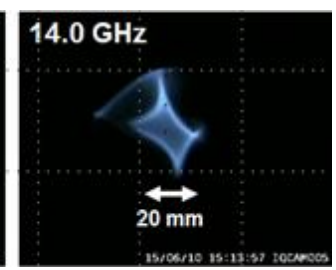


Quartz:Ce

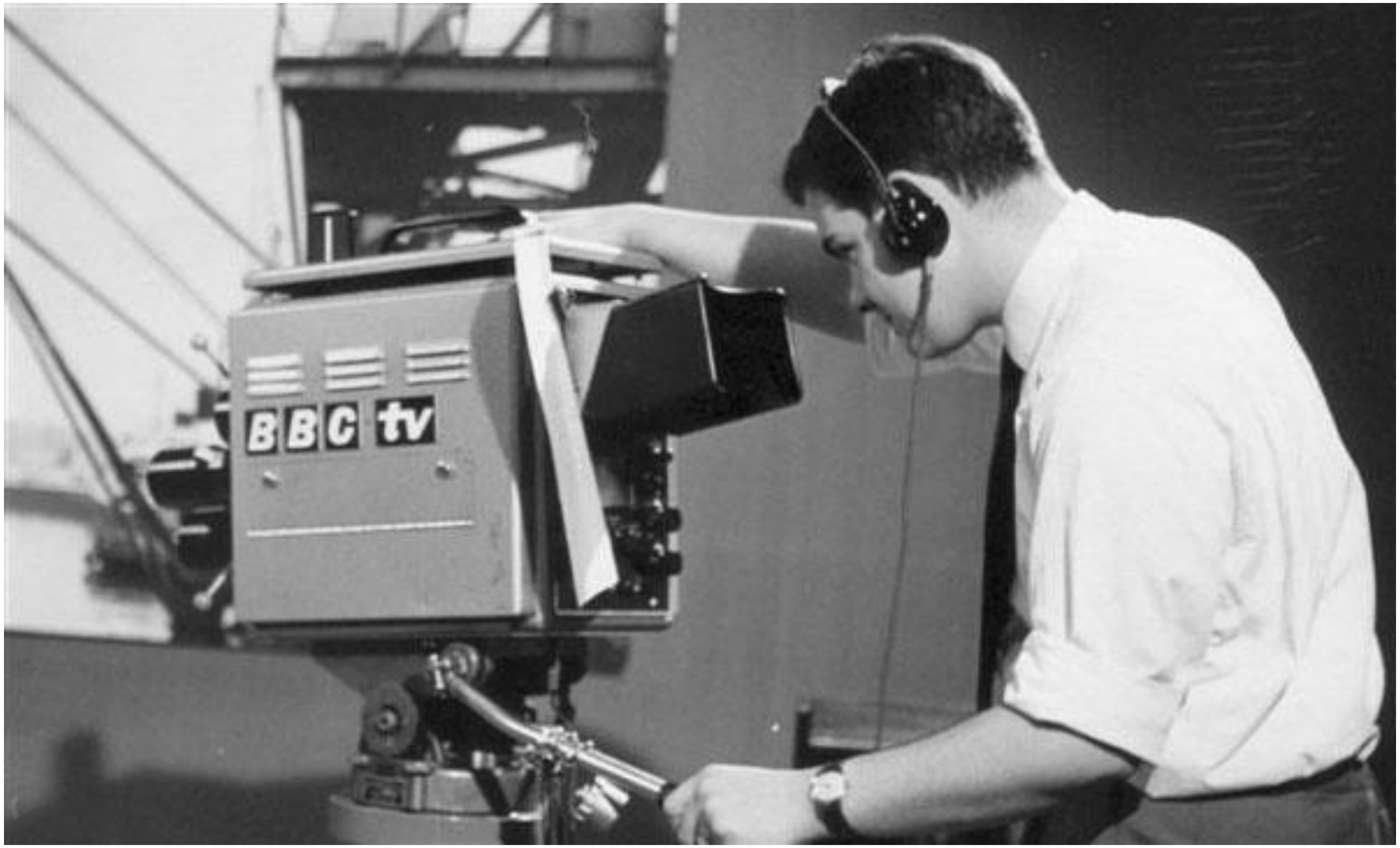


# Analog Video Cameras

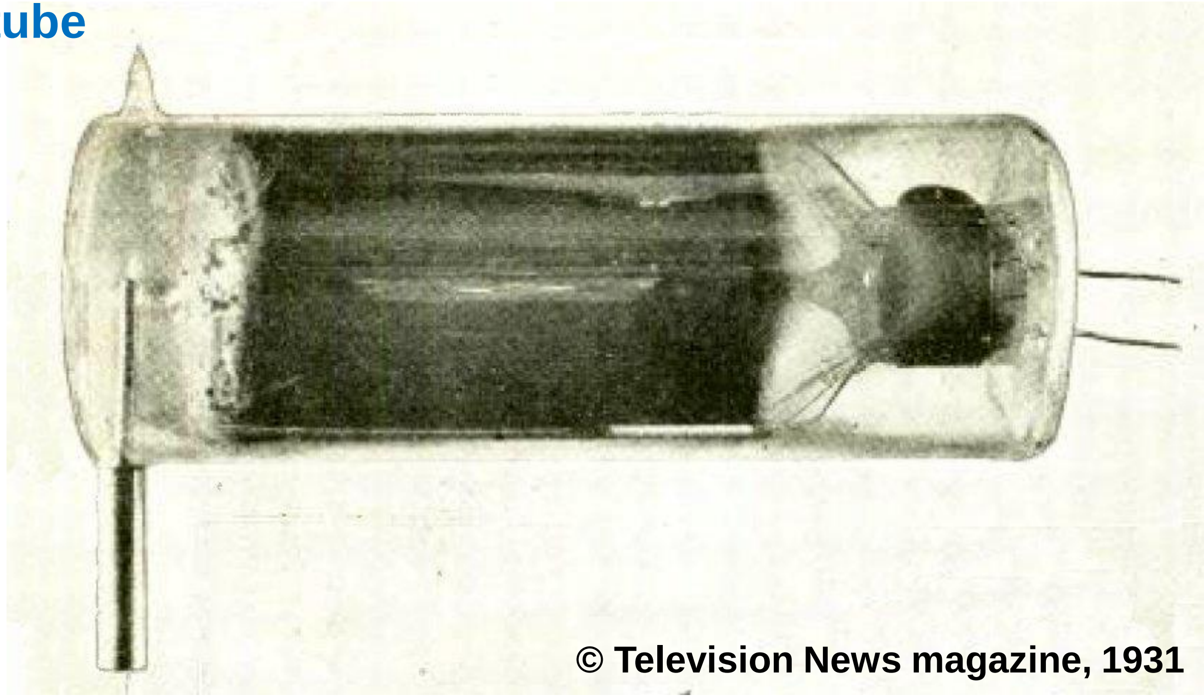



© Pete Simpkin, Marconi vidicon Camera www.bbceng.info

# **A**nalog Video Cameras

- early 1900s first experiment in image transmission
- in 1930s new electronic designs based on a cathode-ray video camera tube, including two versions dissector tube (Philo Farnsworth) and iconoscope (Vladimir Zsworykin)

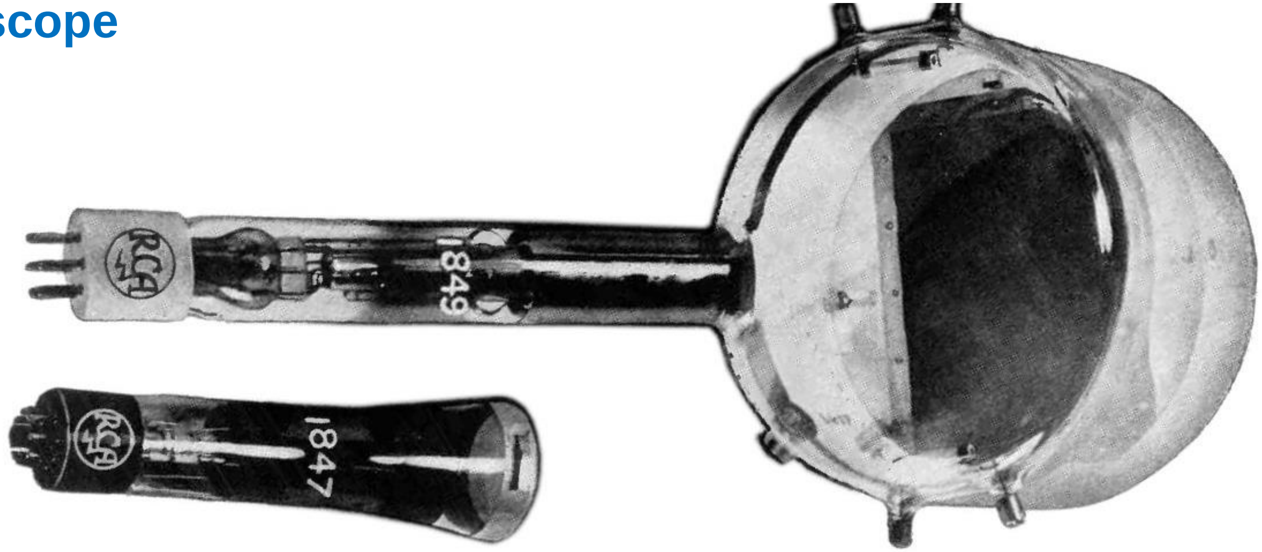
**Dissector tube**



# Analog Video Cameras

- analog system became the standard in the television industry and remained in wide use until the 1980s

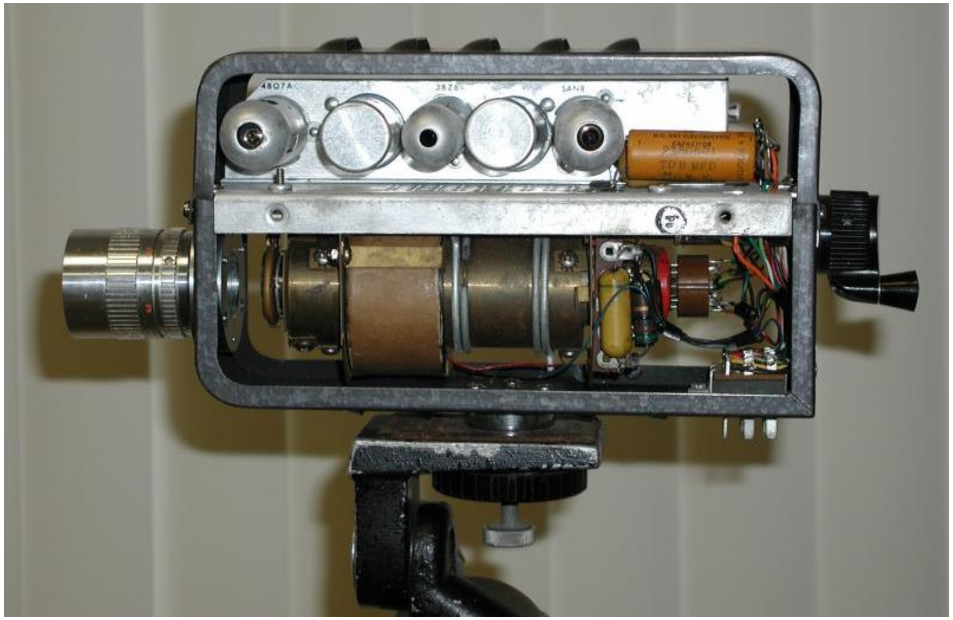
**Iconoscope**




**© Radio News magazine, 1945**

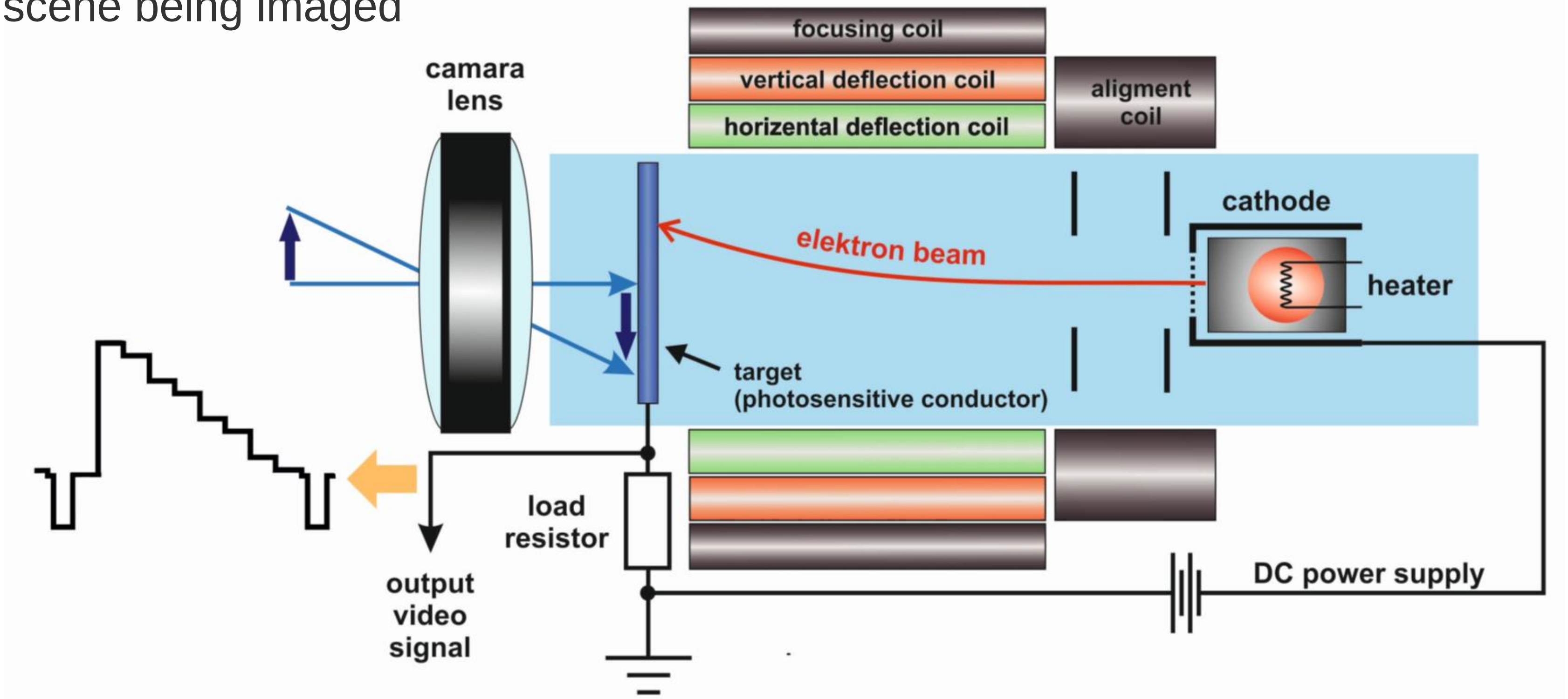
# Analog Video Cameras: Vidicon

- **developed in 1950** at Radio Corporation of America (RCA) by P. K. Weimer, S. V. Forgue and R. R. Goodrich

# **A**nalog Video Cameras: **V**idicon

- **storage type camera tube**
  - charge-density pattern is formed by the imaged scene radiation on a photoconductive surface which is then scanned by a beam of low-velocity electrons
  - fluctuating voltage coupled out to a video amplifier can be used to reproduce the scene being imaged



# Analog Video Cameras

- video tubes were popular till 1970s and 1980s after which they were rendered obsolete by modern sensors

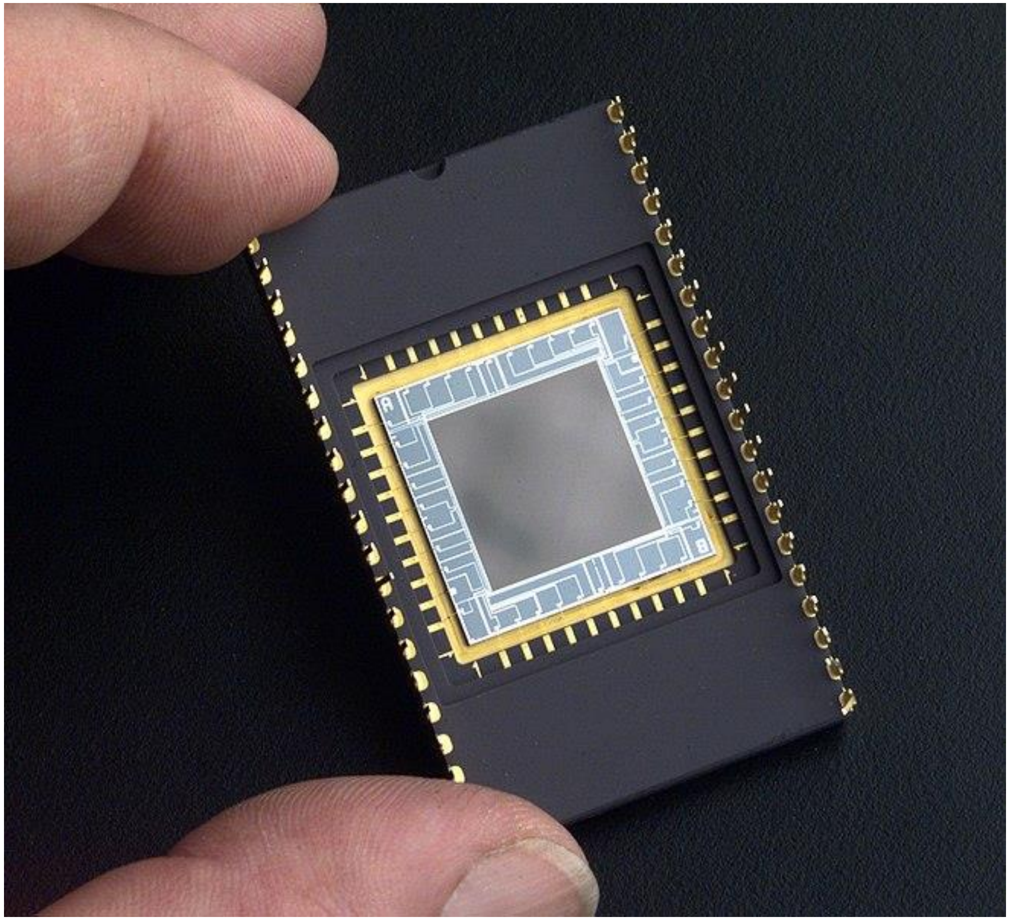
**The digitalisation starts!**

- modern cameras offer many advantages over tube
  - high overall picture quality
  - high light sensitivity and dynamic range
  - a better signal-to-noise ratio and significantly higher reliability
  - elimination of the respective high and low-voltage power supplies, no warm-up time and a significantly lower power consumption

**But: never seen a radiation damaged tube**

# Solid State Sensor: CCD

## Charge-Coupled Device



© Wikipedia

# Solid State Sensor: CCD

- invented in **1970** by Willard Boyle and George Smith (Bell Laboratories, USA)
- "[we] invented charge coupled device in one hour"
- huge range of products including fax machines, photocopiers, cameras, scanners etc.

**2009 Nobel Prize in Physics**


**© Y. Chae, Overview of Image Sensors**

# Solid State Sensor: CCD

- CCDs consist of thousands (or millions) of light sensitive cells called **pixels** that are able of produce an electrical charge proportional to the amount of light they receive

# Solid State Sensor: CCD

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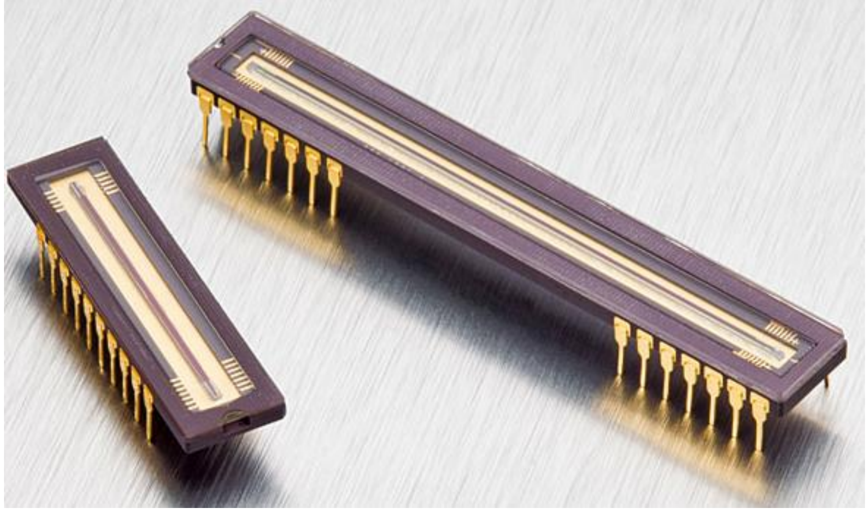
- pixels are arranged in a **single line** (**linear array** CCDs)



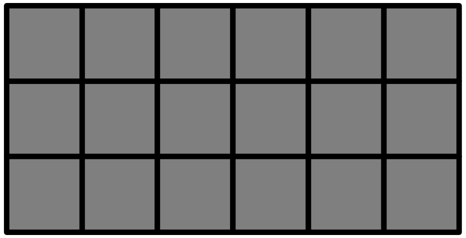
**© Warsash Scientific**

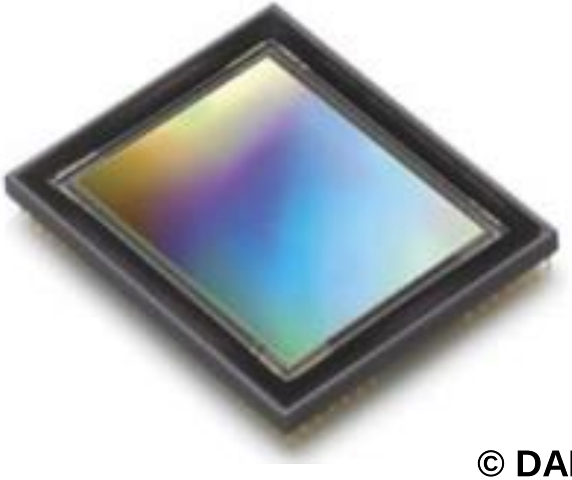
# Solid State Sensor: CCD

- CCDs consist of thousands (or millions) of light sensitive cells called **pixels** that are able of produce an electrical charge proportional to the amount of light they receive

- pixels are arranged in a **single line** (**linear array** CCDs)

- or in a **two-dimensional** grid (**area array** CCDs)





**© DALSA**

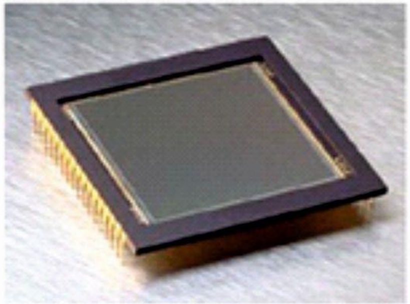
# Solid State Sensor: CCD

- one of the first area array CCDs, manufactured by Fairchild in 1974, 100x100 pixels

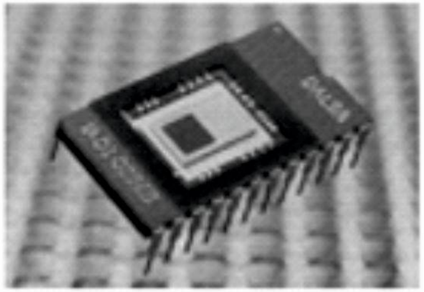
© Y. Chae, Overview of Image Sensors

# Solid State Sensor: CCD

- commercially available devices in different configurations



Manufacturer: Kodak
Typ: area array
Pixel count: 4096x4096
Transfer method: full frame transfer



Manufacturer: Dalsa
Typ: area array
Pixel count: 256x256
Transfer method: frame transfer

Manufacturer: Kodak
Typ: linear array
Pixel count: 5000
Transfer method: full frame transfer

# Solid State Sensor: CCD

- **160 million pixels** (Seitz), 7.500x21.250 (60mmx170mm)


© Seitz  Phototechnik AG


© LetsGoDigital

© D. Osborn, wwwbritishpanoramics.com

# Solid State Sensor: CCD

- CCDs are manufactured using **M**etal-**O**xide-**S**emiconductor (**MOS**) fabrication techniques
- each pixel can be thought of as a MOS capacitor that converts photons (light) into electrical charge
- two types of MOS capacitor (only small difference in fabrication)
  1. **surface channel**
  2. **buried channel** (nearly all CCDs use this structure)

# Solid State Sensor: CCD

- buried channel capacitor

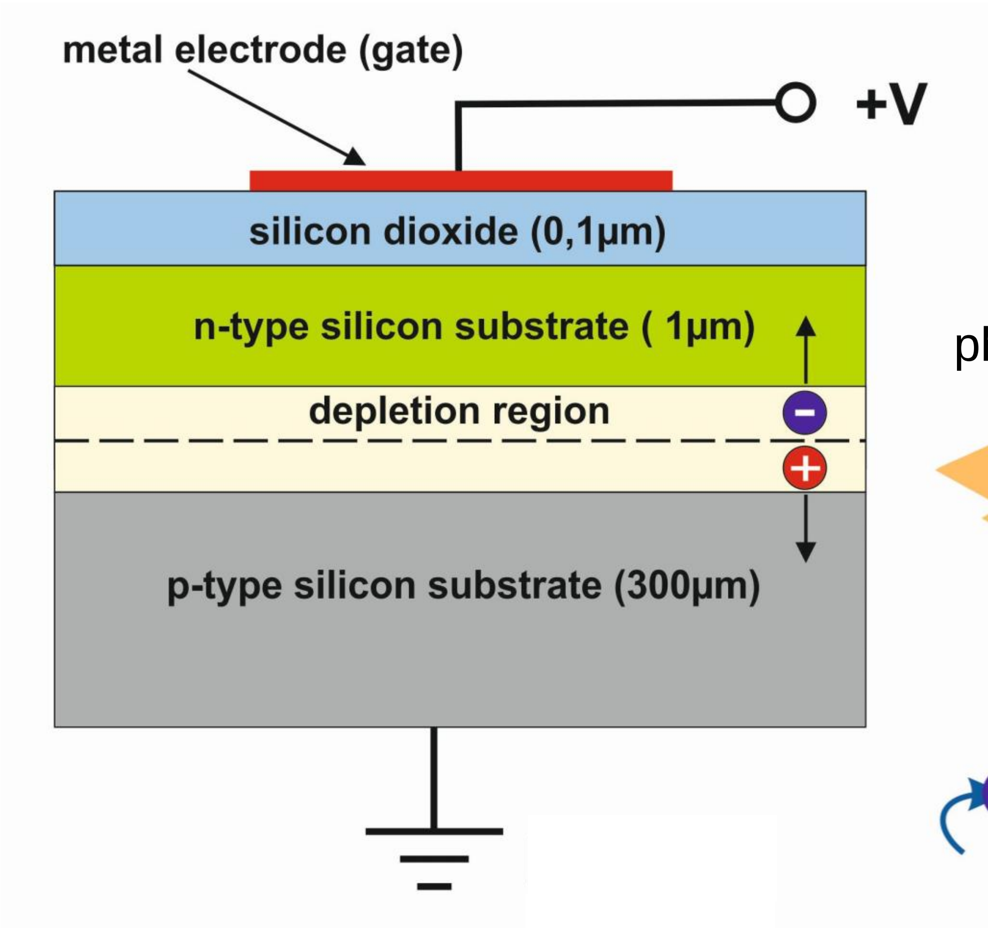
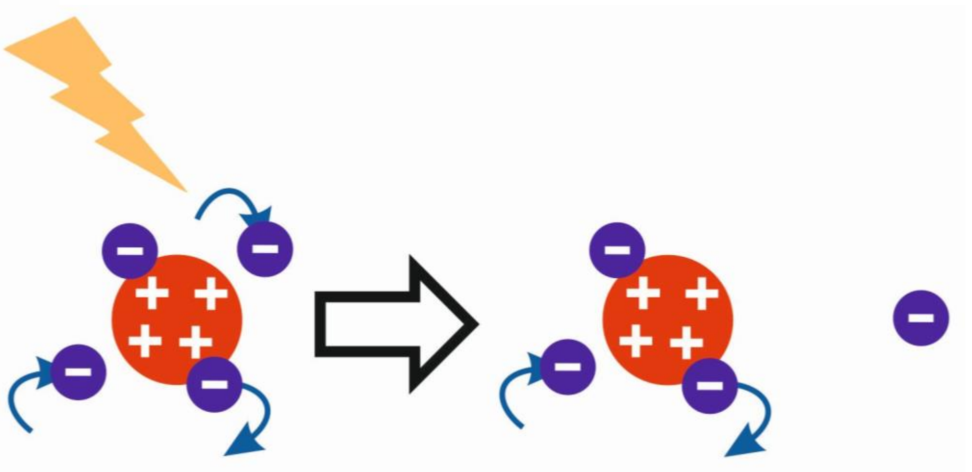
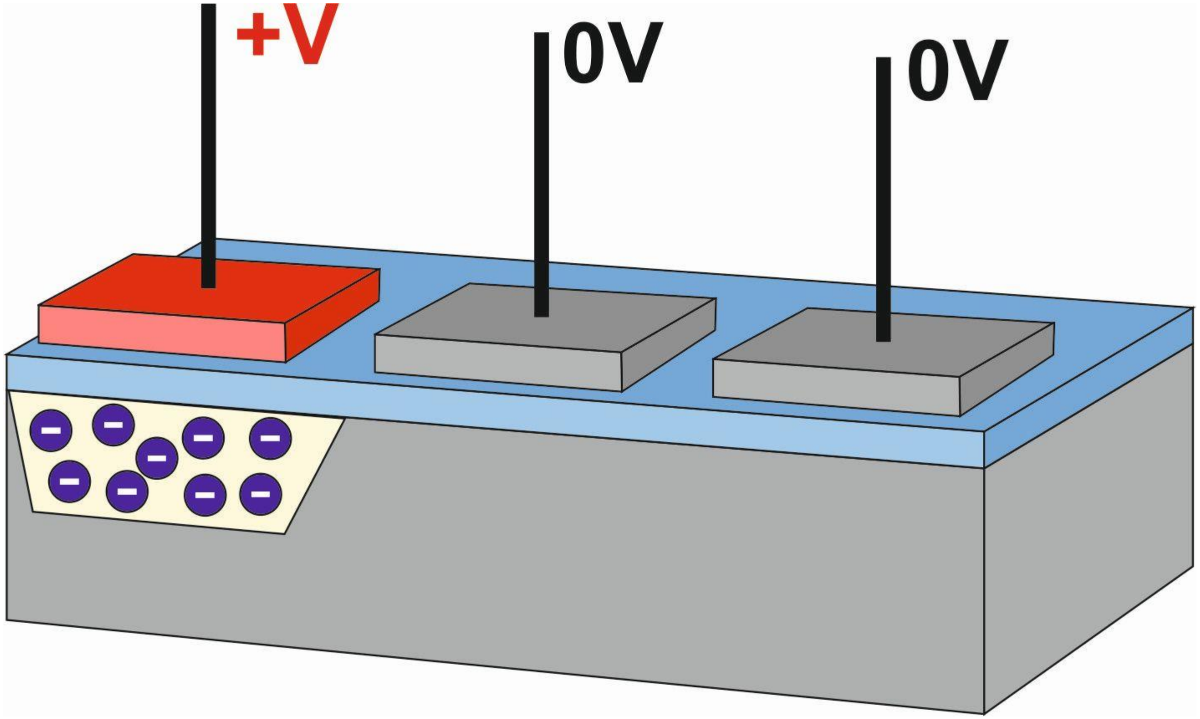



photo-generated electron-hole pairs



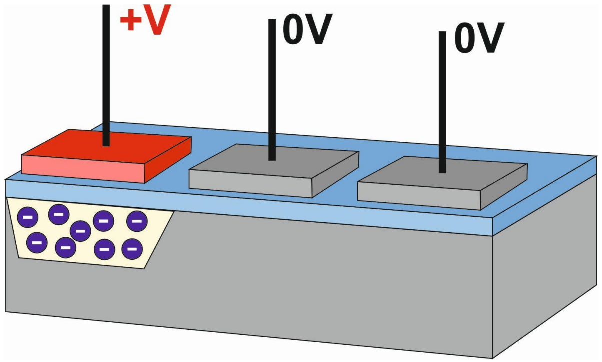
# Charge Readout Process

- takes place in two stages
  i. involves moving the pixel charges across the surface of the array
     - each pixel is divided into a number of distinct areas known as *phases* (3-phase sensor tend to be the most common)

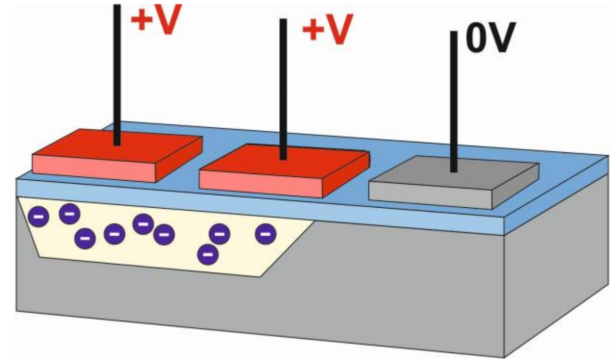


# Charge Readout Process

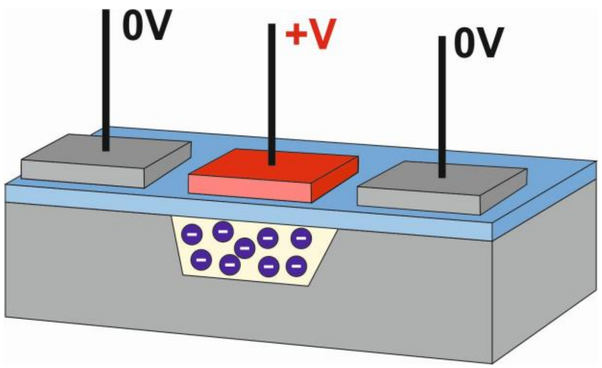
Part 1



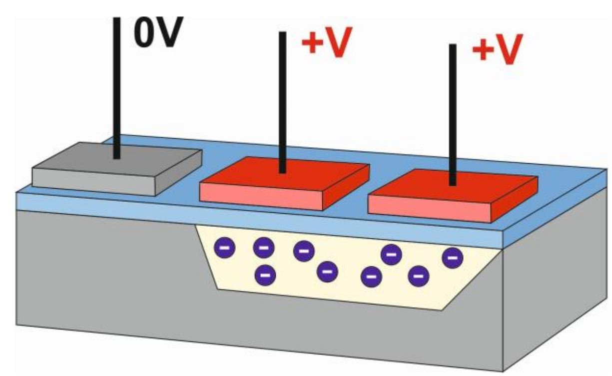

Part 2



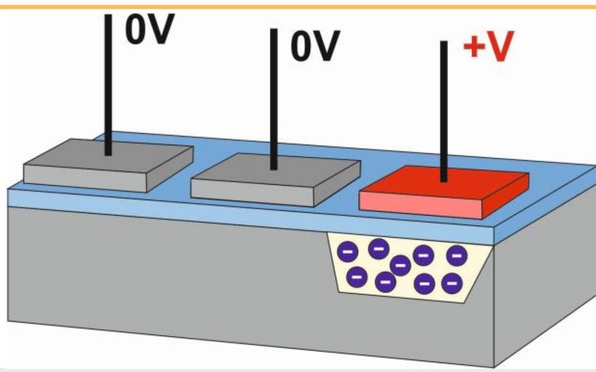

Part 3



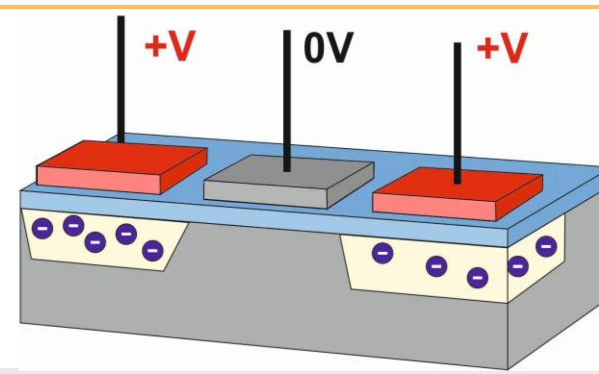

Part 4




Part 5

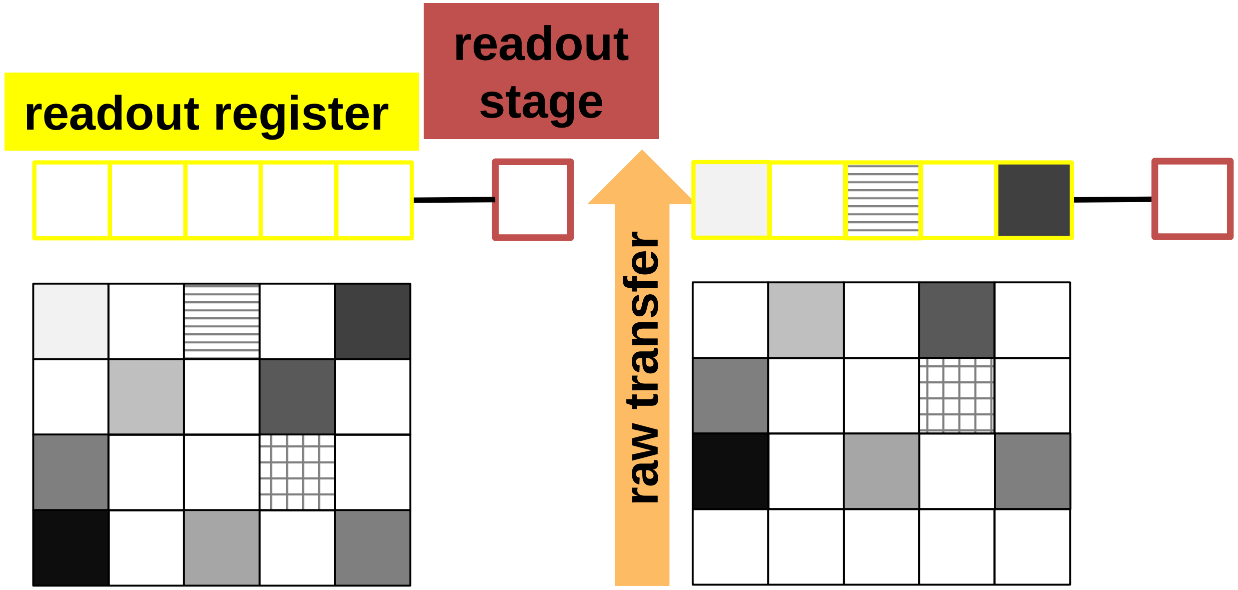



Part 6



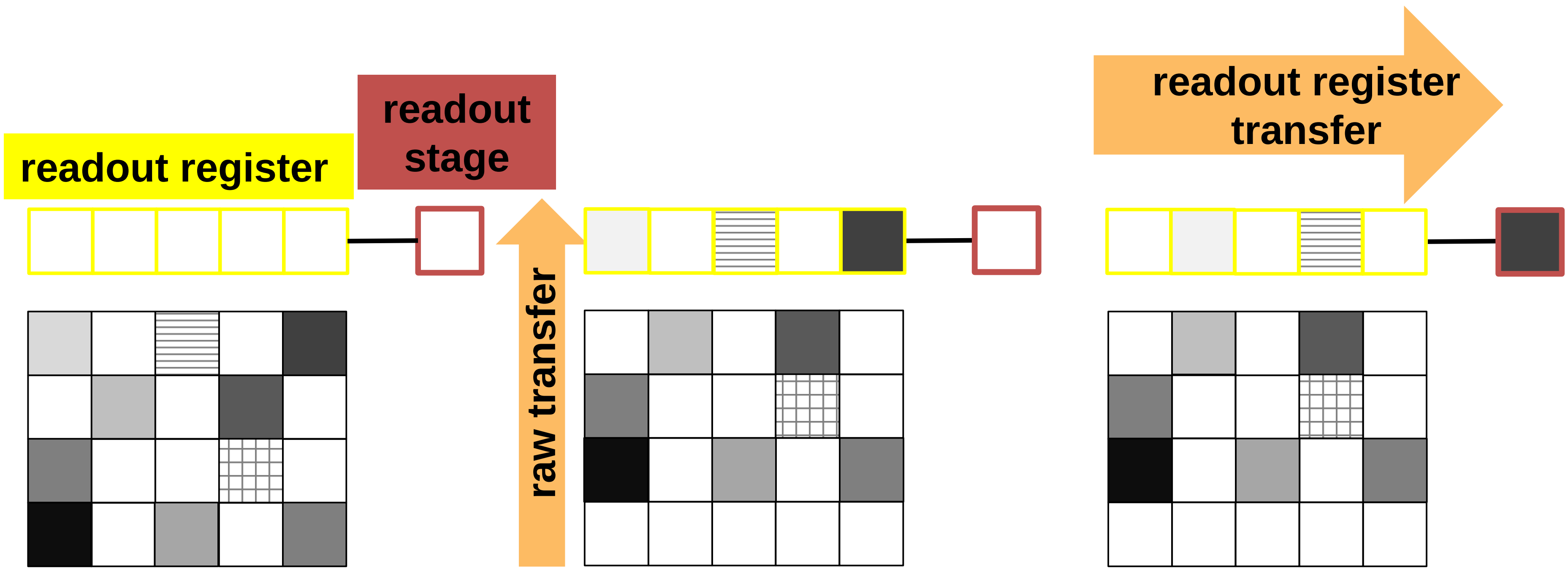
# CCD: Charge Readout Process

- takes place in two stages
  ii. reading out the pixel charges into a register prior to being digitized
    - as the charge from each row of pixels is moved up one row, the charge from the top row will be moved into the readout register

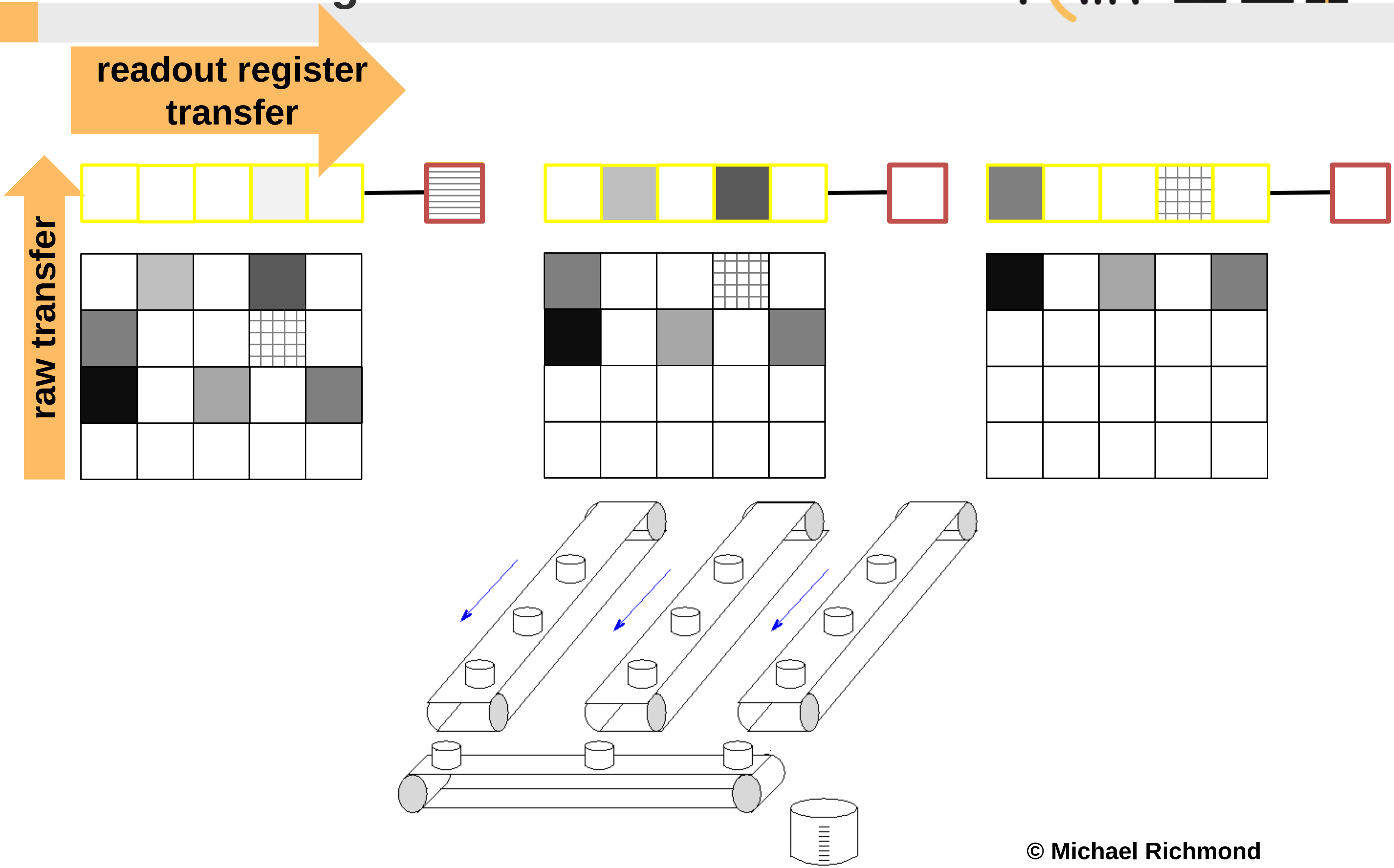


# CCD: Charge Readout Process

- takes place in two stages
  ii. reading out the pixel charges into a register prior to being digitized
    - charge values in the readout register are transferred horizontally into the readout stage



# CCD: Charge Readout Process



# Solid State Sensor: CCD

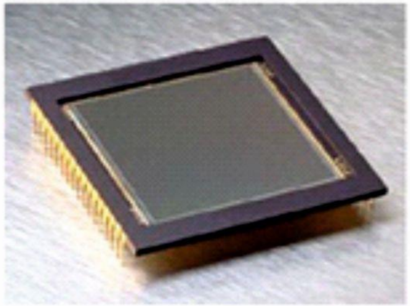
- the architecture of area array CCDs generally falls into one of four categories:
  - full frame
  - frame transfer
  - split frame transfer
  - interline transfer

# Solid State Sensor: CCD

- **full frame**
  i. image is transferred directly from the imaging region of the sensor to the readout register

  ii. since only a single row can be transferred to the readout register at a time, the rest of the imaging pixels must wait

  iii. pixels that have not yet been read out of the array are still capable of recording image information
    - imaged information will be offset from the original scene recorded: smearing and blurring
    - mechanical shutter required

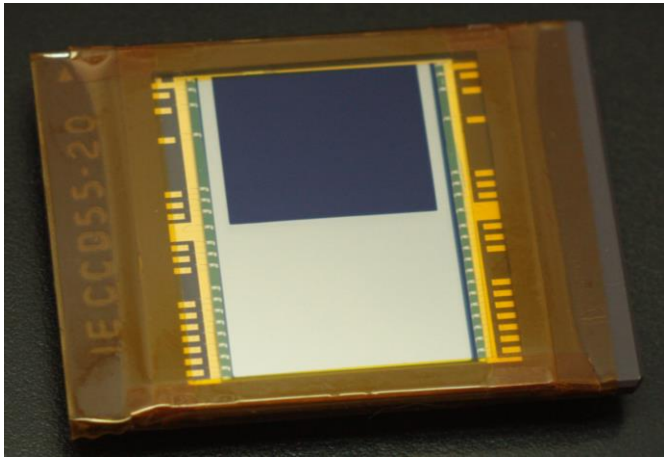
Manufacturer: Kodak
Typ: area array
Pixel count: 4096x4096
Transfer method: full frame transfer

# Solid State Sensor: CCD

- **frame transfer**
  i. captured image is quickly transferred to the adjacent storage section, both the image capture and readout processes to run in parallel

  ii. light shielded storage section of at least the same size as the imaging section of the array

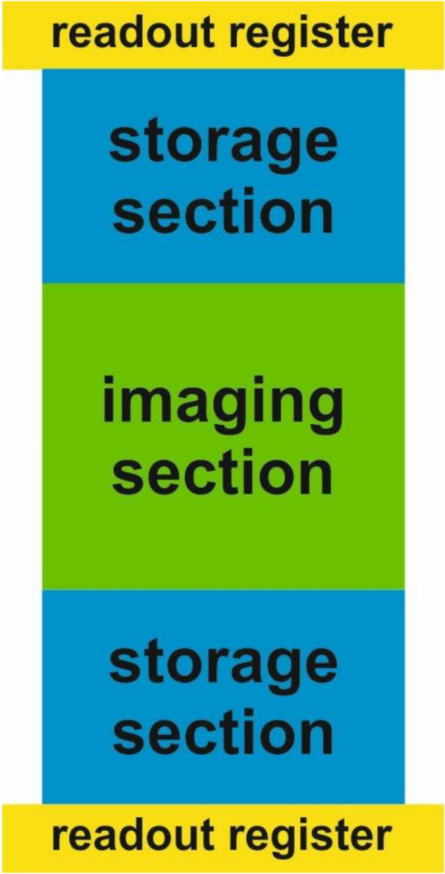
  iii. mechanical shutter may still be required

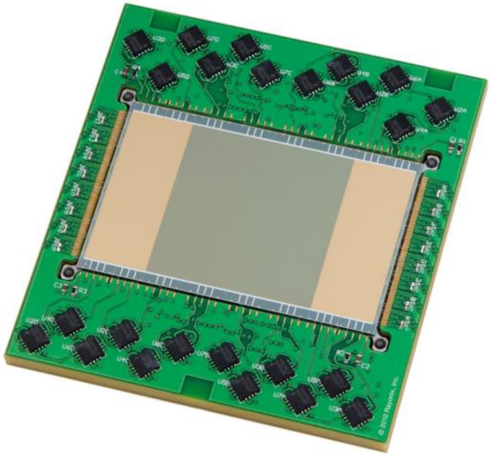



# Solid State Sensor: CCD

- **split frame transfer**
  i. the storage section is split in half, with each half being located above and below the imaging section

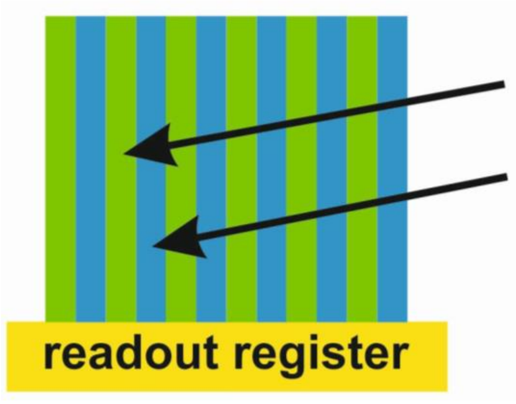
  ii. allows the image to be transferred out of the imaging section in half the time that is required for a frame transfer device

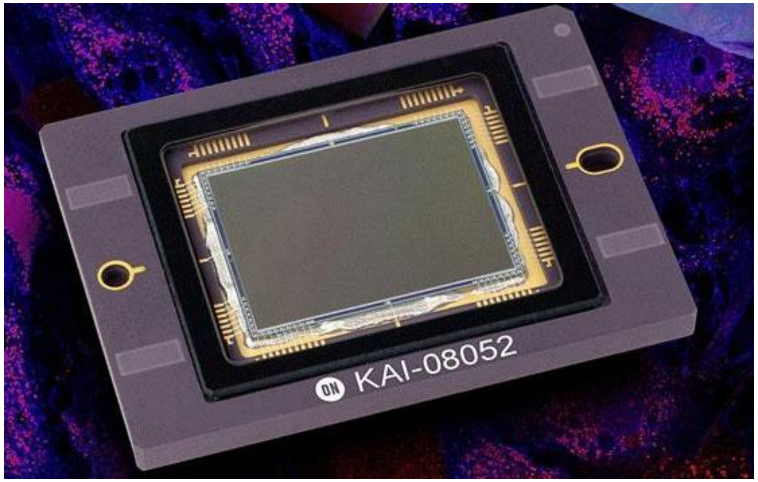


# Solid State Sensor: CCD

- **interline transfer**
  i. has columns of photosensitive elements separated by columns of light shielded registers
  ii. does not require a mechanical shutter
  iii. large proportion (typically 40%) of the imaging section is not sensitive to light, micro-lenses



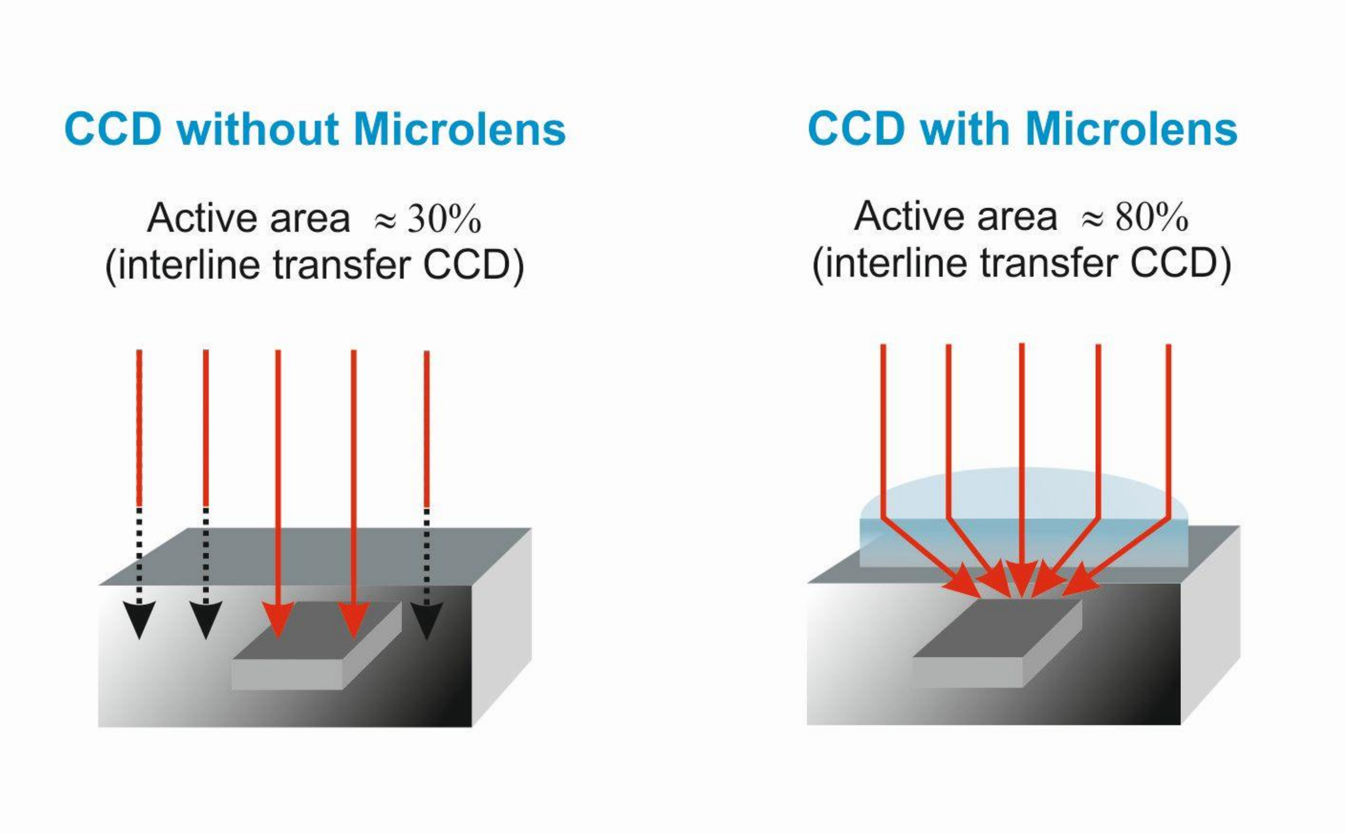



# Solid State Sensor: CCD

- **CCDs problems and limitations**:
  - fill factor
  - dark current noise
  - quantum efficiency
  - blooming
  - charge transfer efficiency

# Solid State Sensor: CCD

- **fill factor**
  i. the percentage of each pixel that is sensitive to light (ideally 100%)

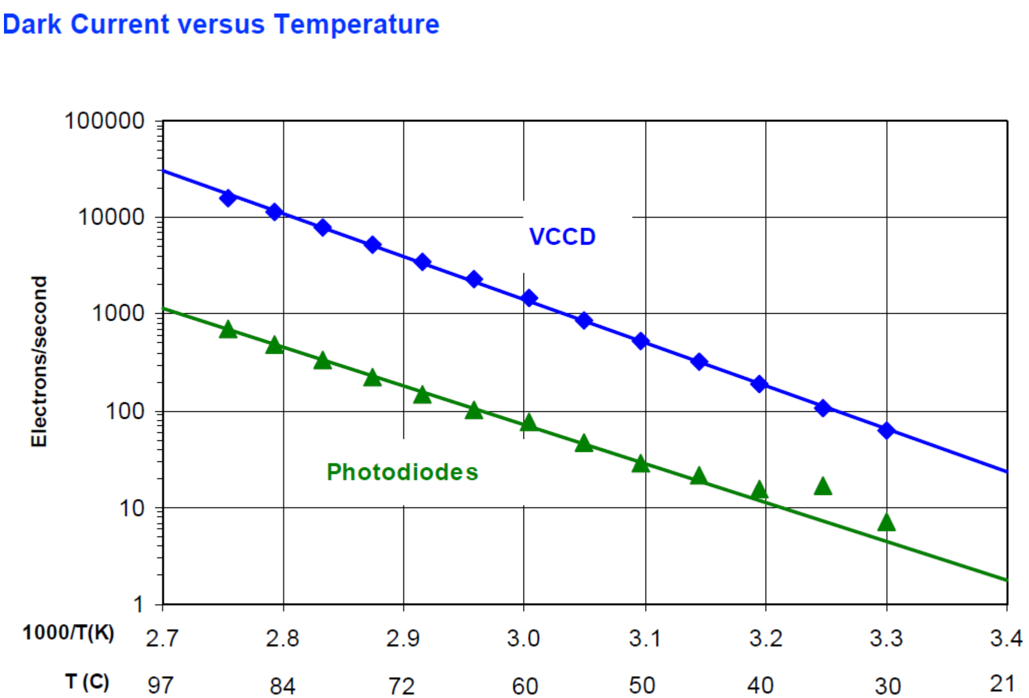


# Solid State Sensor: CCD

- **dark current noise**
  i. unwanted charge that accumulates in the CCD pixels due to natural thermal processes. Electron-hole pairs are randomly generated and recombine within the silicon and at the silicon-silicon dioxide interface

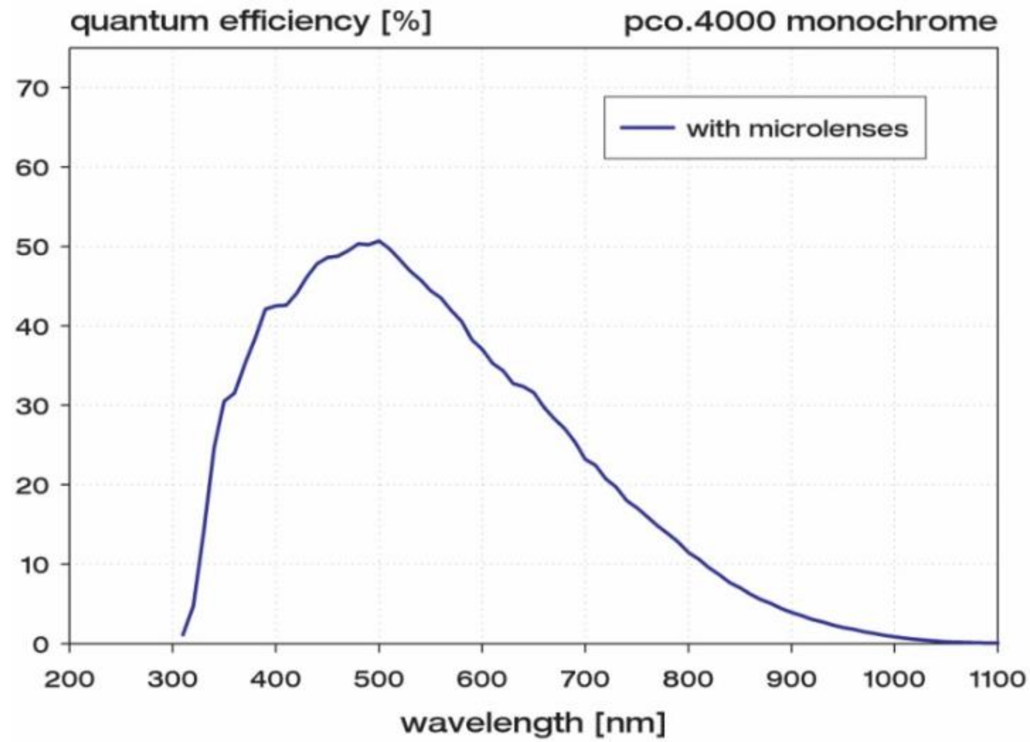
For applications requiring very low noise levels, for example astrophotography, dark current sources can be reduced by cooling the CCD since they are strongly temperature dependent

**Kodak, CCD Chip KAI-2001, Series Rev. 1.0 www.kodak.com/go/imagers**



# Solid State Sensor: CCD

- **quantum efficiency (QE)**
  i. the ratio of light that the sensor converts into charge
     - 60% QE: for every 10 photons hitting a pixel, 6 electrons are realized
     - QE depends on λ
     - QE is sensor specific

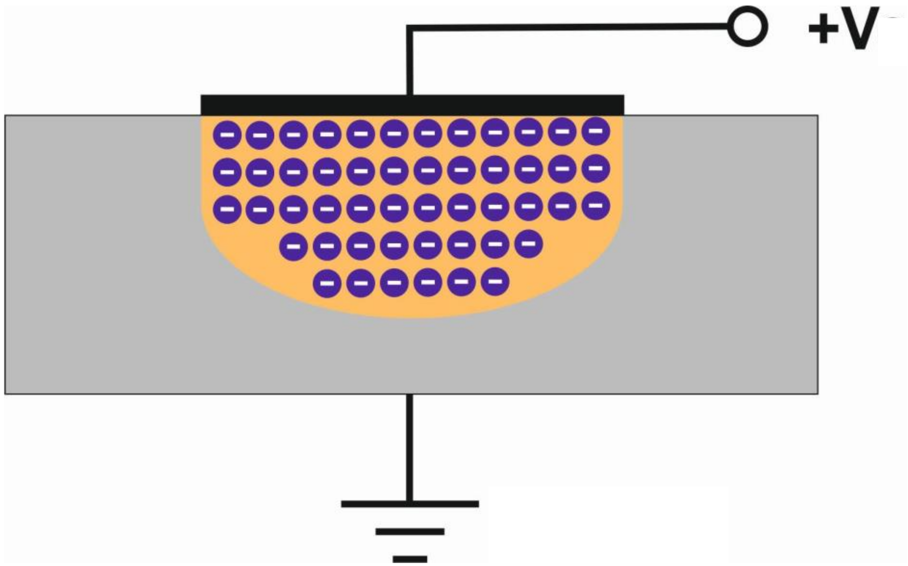


# Solid State Sensor: CCD

- **blooming**
  i. when a potential well overflows, the electrons flow into surrounding potential wells, thus creating an area of saturated pixels
     - caused by the presence of a bright object in the scene being imaged

# Solid State Sensor: CCD

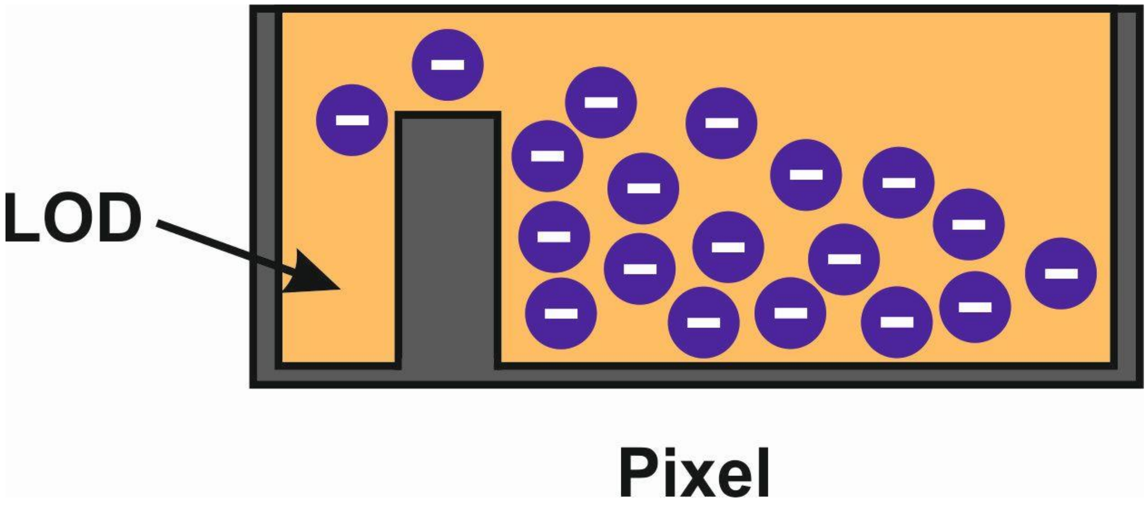
- **blooming**
  i. when a potential well overflows, the electrons flow into surrounding potential wells, thus creating an area of saturated pixels
     - **Full Well Capacity:** is the maximum number of electrons that a pixel can hold without overflow. Larger pixels have higher well capacity and better Signal to Noise Ratio (SNR), and increased dynamic range




**Typical Full Well Capacity**:
Small pixels: 4.000 electrons
Medium pixels: 10.000 electrons
Large pixels: 50.000 electrons

# Solid State Sensor: CCD

- **blooming**
  i. when a potential well overflows, the electrons flow into surrounding potential wells, thus creating an area of saturated pixels
     - **L**ateral **O**verflow **D**rains (LODs): work in a similar way to an overflow in a bathroom sink, when the potential well fills to a certain level, any further electrons that accumulate are allowed to drain away without affecting surrounding pixels



# Solid State Sensor: CCD

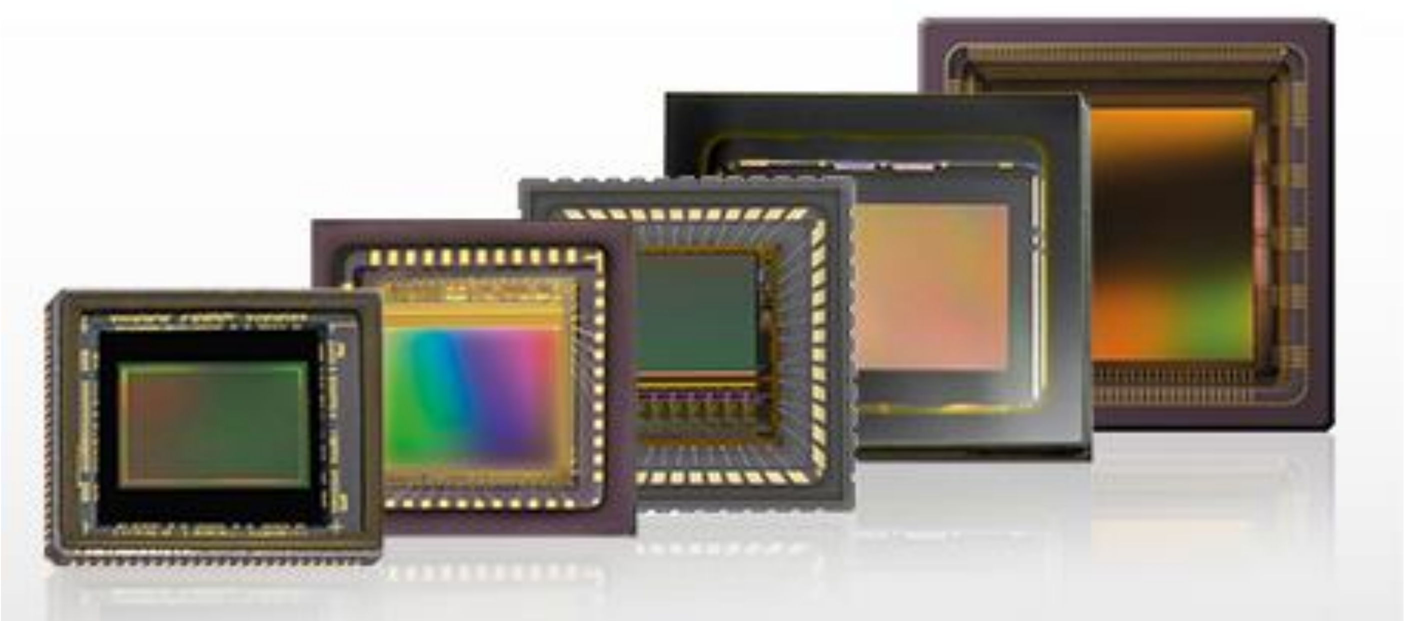
- **charge transfer efficiency (CTE)**
  i. measure of the percentage of electrons which are lost at each stage during the charge transfer process.
     - modern buried channel CCDs have CTE values in excess of 99.999%

# Solid State Sensor: CMOS

## Complementary Metal Oxide Semiconductor

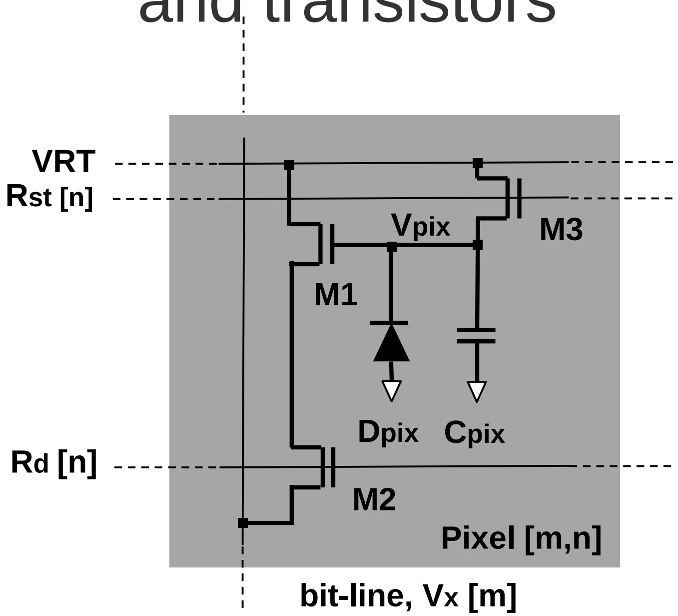
# Solid State Sensor: CMOS

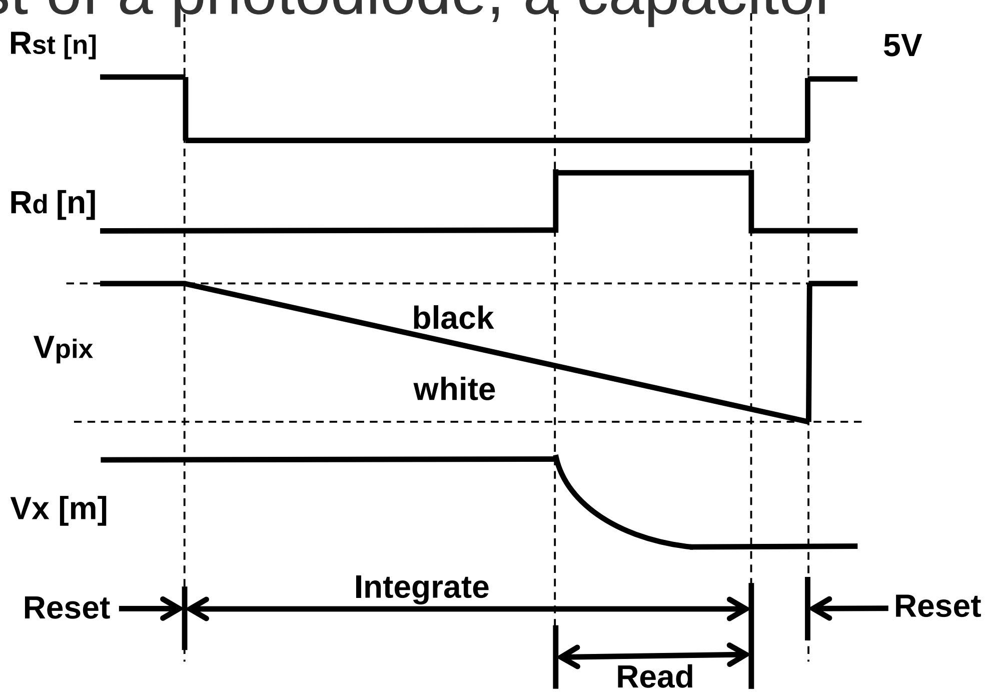
- CMOS image sensor have been around as long as CCDs
- 1993 Jet Propulsion Laboratory (JPL) produced CMOS sensor with performance comparable to scientific-grade CCD



# Solid State Sensor: CMOS

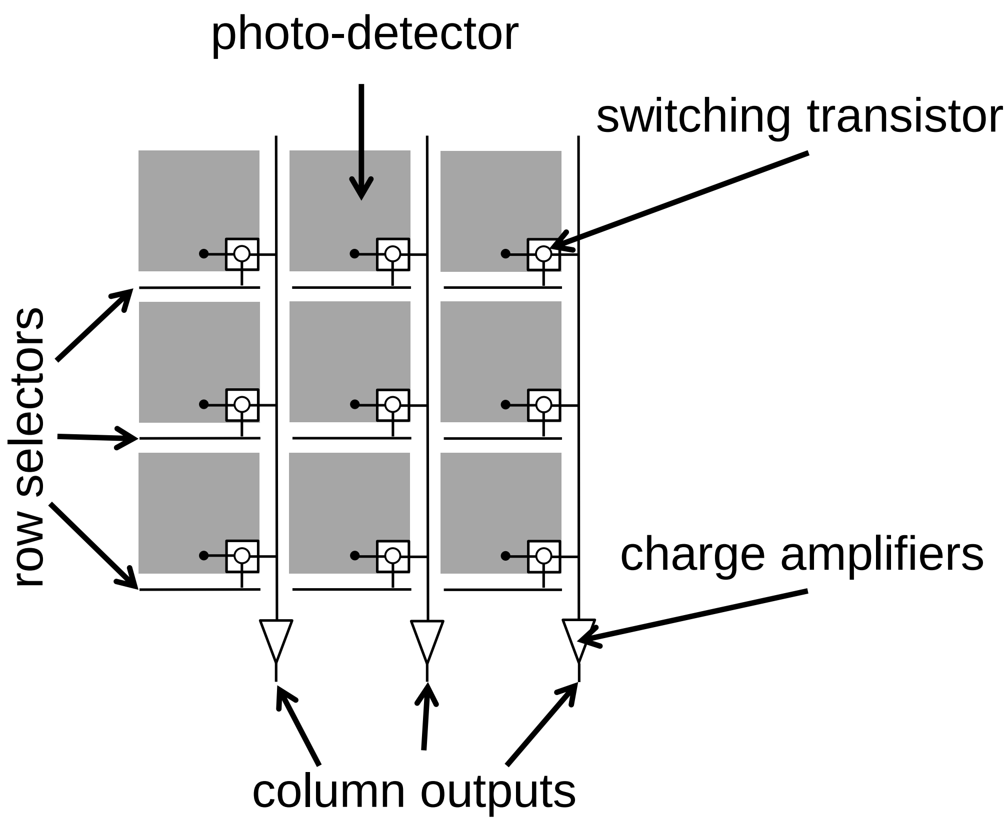
- CMOS sensors form a grid of light sensitive elements
- produce an electrical signal/charge proportional to the incident light
- each CMOS pixel consist of a photodiode, a capacitor and transistors



# Solid State Sensor: CMOS

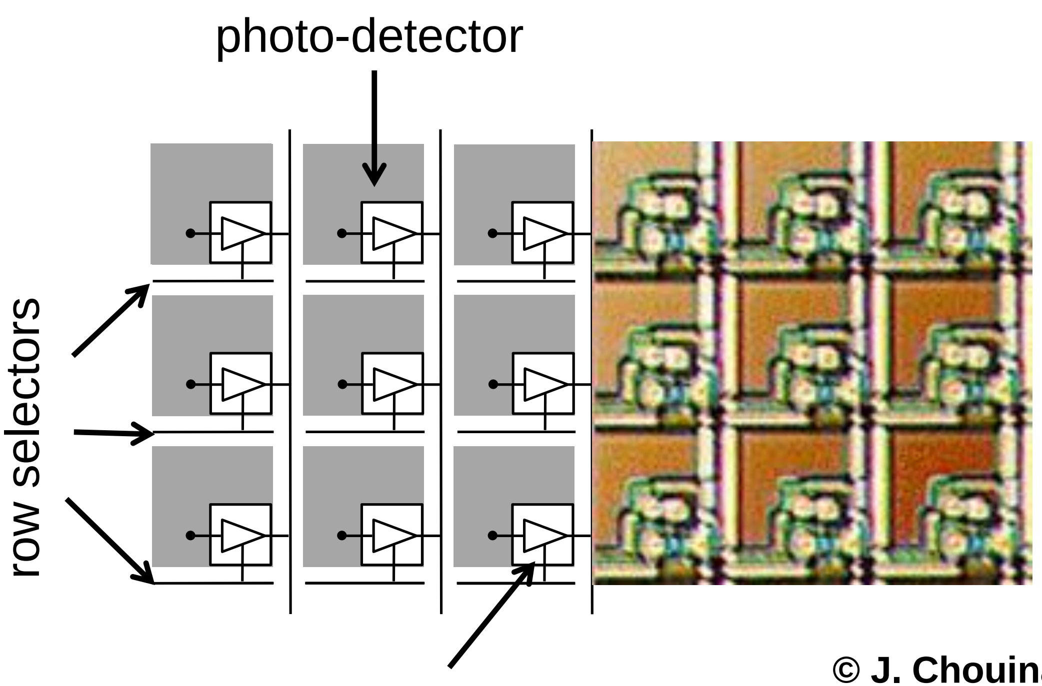
- CMOS image sensors come in two forms:
  i. **passive pixel**




i. single transistor (in addition to photodiode and capacitor) per pixel
ii. charge amplifier at the bottom of each column
iii. small pixel, large fill factor
iv. but slow, lower SNR

# Solid State Sensor: CMOS

- CMOS image sensors come in two forms:
  ii. **active pixel**




i. 3-4 transistors per pixel
ii. amplifier in every pixel
iii. larger pixel, lower fill factor
iv. fast, higher SNR

# CCD vs CMOS

| | CCD | CMOS |
|---|---|---|
| **pixel signal** | electron packet | voltage |
| **noise** | low | moderate |
| **fill factor** | high | moderate |
| **uniformity** | high | slightly lower “fixed pattern noise” |
| **speed** | moderate | high |
| **system complexity** | high | low |
| **power consumption** | moderate | low |
| **radiation** | sensitive | less susceptible to radiation |

**Global market leader Sony discontinues the production of CCD sensors in March 2017**

**CMOS is the future!**

# Solid State Sensor: CID

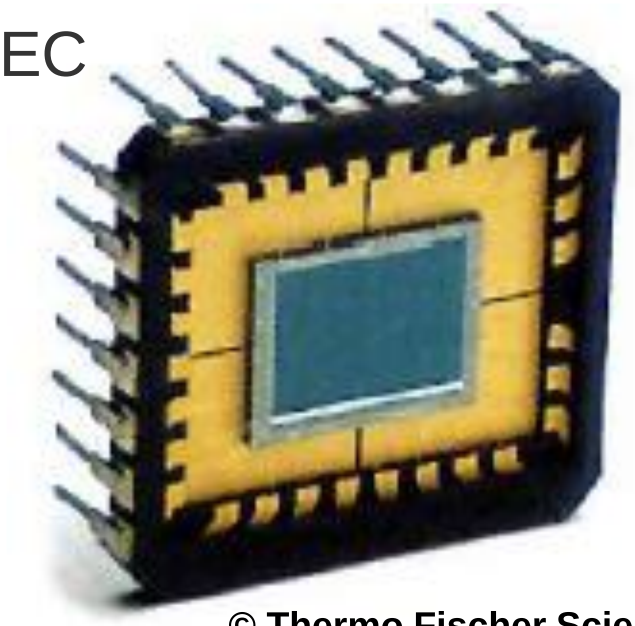
## Charge Injection Device

# **S**olid State Sensor: CID

- used from early 1970`s

- concept originated by H. Burke and G. Michon from General Electronic Company

- commercially developed by CIDTEC (today Thermo Fischer Scientific)

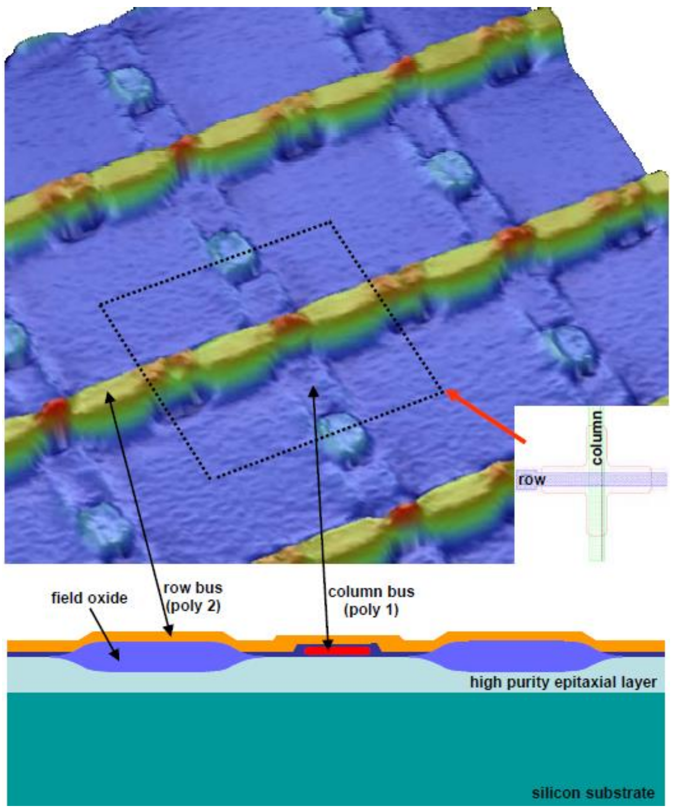


# Solid State Sensor: CID

- CID is a silicon MOS device
  - CID pixel built on low-doped epitaxial material
  - surface channel charge transfer device
- CID converts photons to an electrical charge
- each pixel has two photogates and a means of transferring charge between them („storage gate” for charge integration and “sense gate” for sensing the charge)
- unique ability to clear individual pixel sites by injecting its charge directly at the pixel site

# Solid State Sensor: CID

- CID image sensors come in two forms:
  i. **passive pixel**




i. “crossed-cell” design
   - ➢ all the photogates in the respective axis are electrically connected
   - ➢ large full well:
     100.000 - 2.000.000 electrons

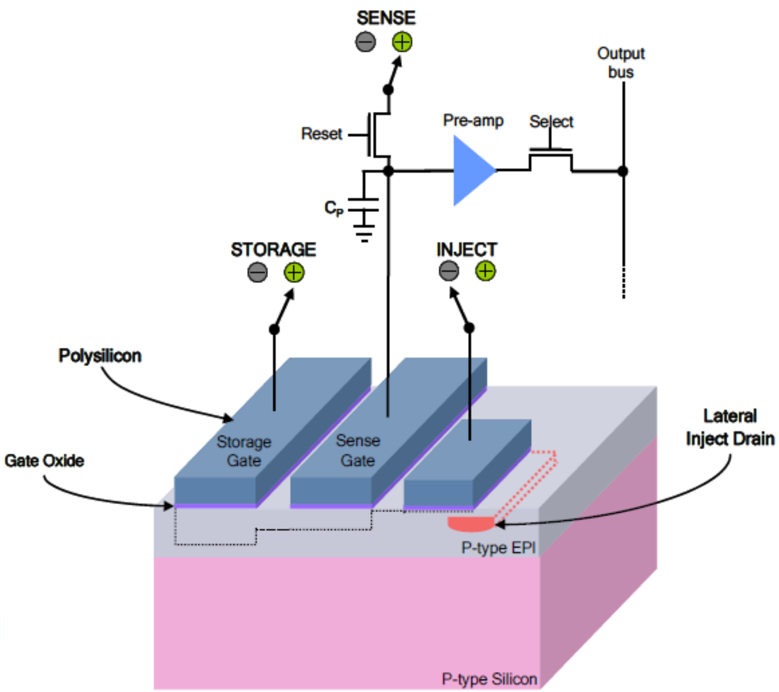
ii. high fill factor

iii. very high radiation hardness

**© Thermo Fischer Scientific**

# Solid State Sensor: CID

- CID image sensors come in two forms:
  ii. **active pixel**




i. "3 transistor" design
   - **storage**: non destructive readout feature maintained
   - **sense**: small sense node capacitance gives high conversion gain
   - **inject gate**: used to „skim" charge

ii. lateral drain for removing charge

iii. low noise

iv. improved sensitivity

**© Thermo Fischer Scientific**

# Active Pixel CID vs CMOS

| | CID | CMOS |
|---|---|---|
| **full well** | **high** | low |
| **fill factor** | **high** | low |
| **conversion gain** | low | **high** |
| **SNR** | low | **high** |
| **radiation tolerance** | **high** | low |

# Radiation Hardness

- Vidicon tubes “no” local electronics, CERN: good experience in the areas where integrated doses exceed 10kGy (10MRad)

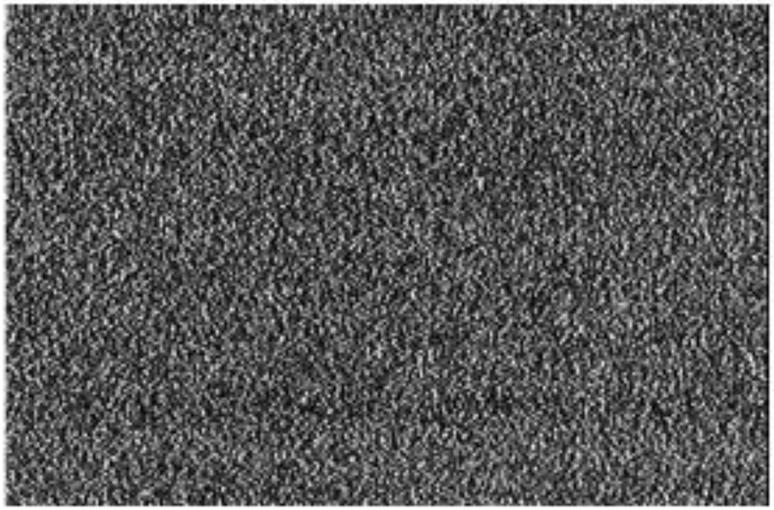
# Radiation Hardness

- Vidicon tubes “no” local electronics, CERN: good experience in the areas where integrated doses exceed 10kGy (10MRad)

- CCD and CMOS are typically not radiation hard ~100Gy (10kRad), CMOS is better than CCD (thinner oxides)

# Radiation Hardness

- CID up to 50kGy (5MRad)
  - in tests up to 14MRad a noticeable degradation in the image quality has been reported for MegaRAD3 by the manufacturer
  - use radiation tolerant devices BJT’s and JFET’s
  - signal processing electronics is located in a radiation-safe location

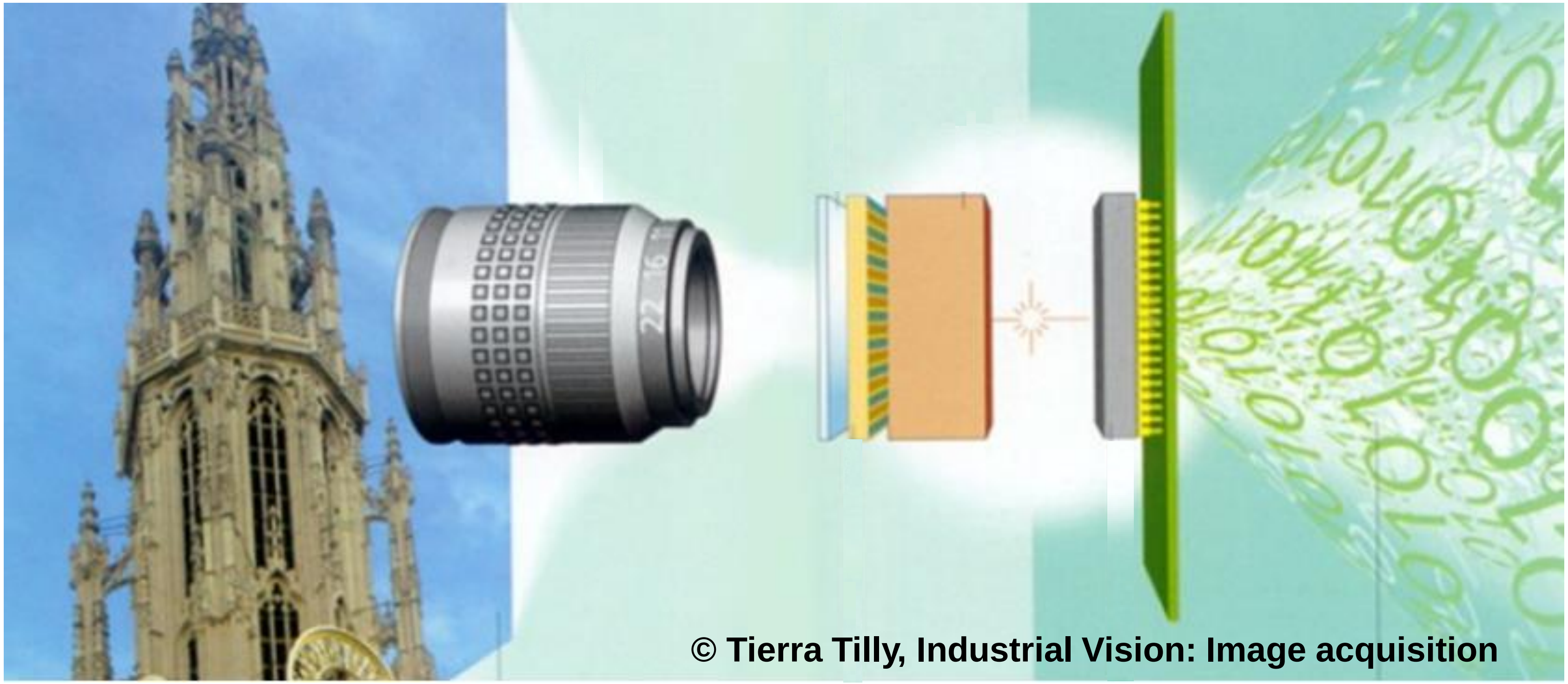


# Radiation Damages

- **cumulative effects:** gradual effect during complete lifetime of device; Total Ionising Dose (TID)
    - trapping of holes in the silicon oxide near the Si/$SiO_2$ interface
    - Si/$SiO_2$ interface traps producing inter-band gap states in the silicon
    i. threshold voltage shift of transistors
    ii. increase of leakage current

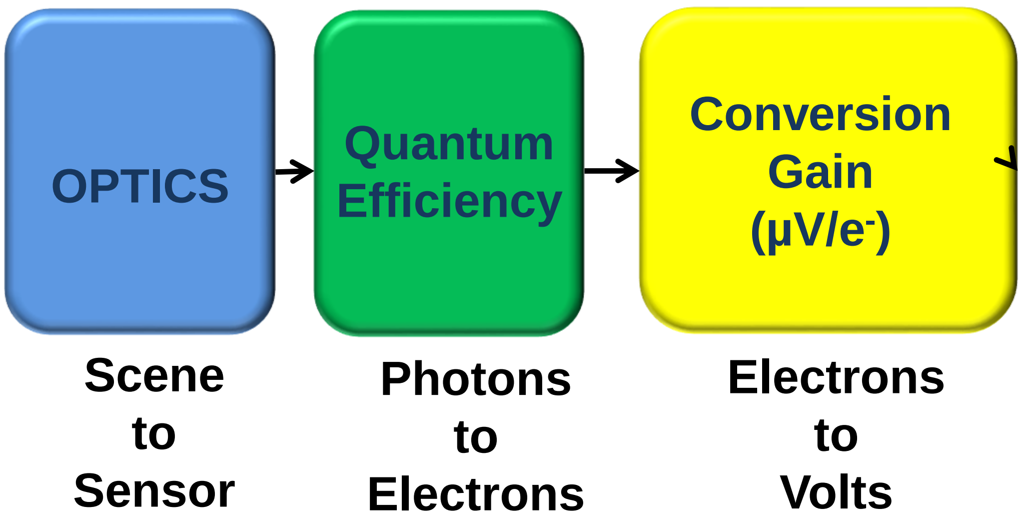
- **single event effects:** triggered by the crossing of ionizing particles
    - destructive effects (hard errors)
        - e.g. single event burnout: event in which a single particle strike induces a localized high-current state in a device that results in failure
    - non-destructive effects (soft errors)
        - e.g. single event upset: a change of state caused by one single ionizing particle

# Digitalisation – Photons to Bits



# Digitalisation – Electons to Volts

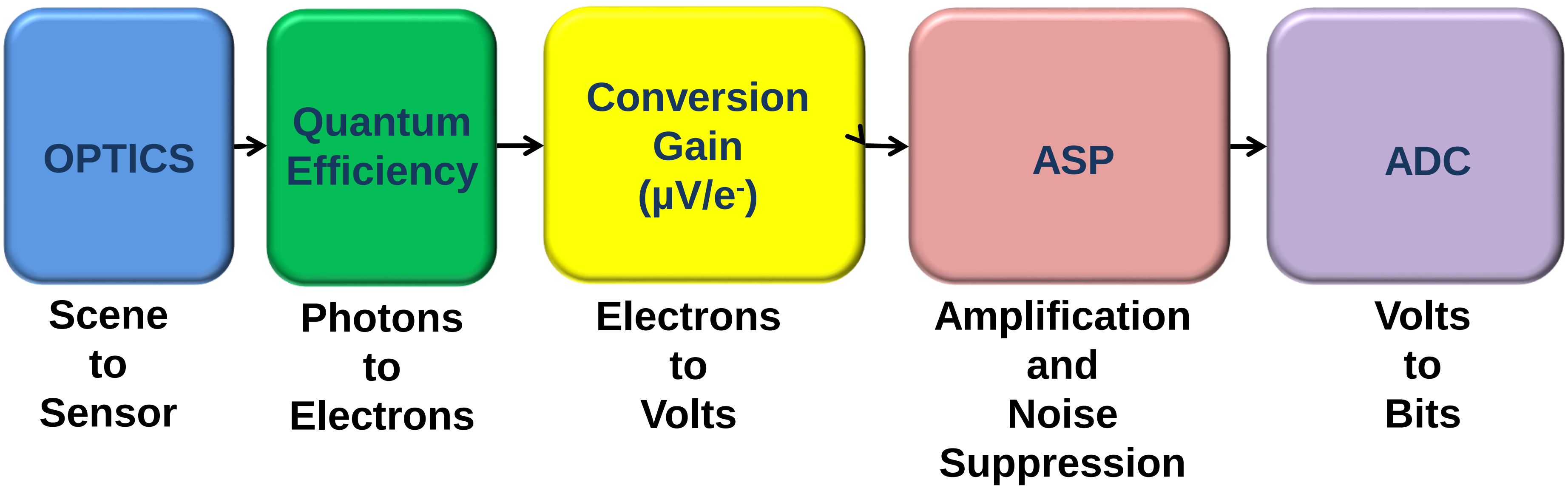
- charges from the pixels must be converted first to a voltage, done with a capacitor circuit




- **Conversion Gain** determinates the amount of Volts per electron for the pixels
  i. typical value range is 1 - 10µV/$e^-$
  ii. higher value is good but limits total signal that can be handled
     - at 10µV/$e^-$, 1$Volt_{max}$ = 100.000 electrons max

# Digitalisation – Volts to Bits

- then the voltage levels must be measured and converted to a number



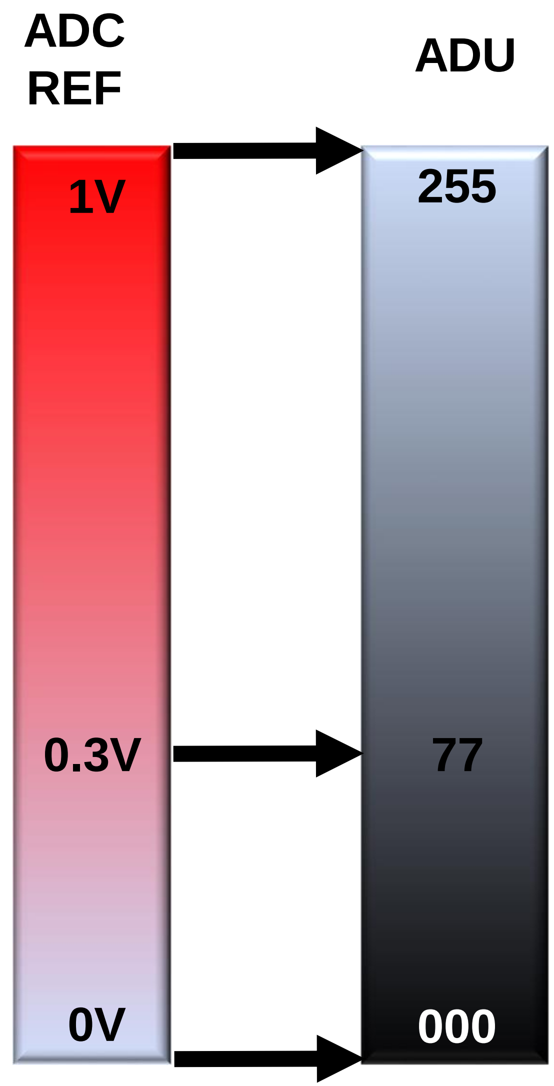

- **Analog to Digital Converter (ADC)** converts the Voltage from the pixel to a digital word

- ADC may have an **Analog Signal Processor (ASP)** to reduce noise and provide additional gain before conversion

# Digitalisation – Volts to Bits

- ADC has a reference Voltage, e.g. 1Volt, so that digital word is scaled against the reference voltage

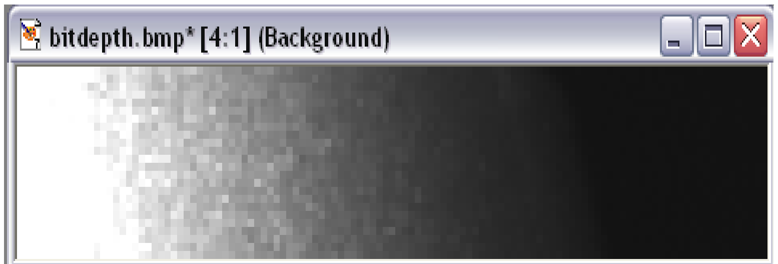
- on-chip ADCs trade power for resolution (number of bits)
  i. 8bits is enough for teleconferencing
  ii. 10-12bits is desired for digital cameras

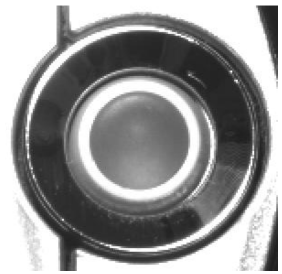


# Digitalisation – Volts to Bits

- more bits → more values to represent the light intensity from black to white (higher bit depth) → more data to transmit/process

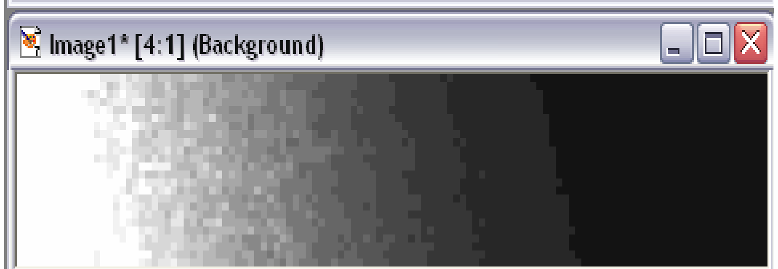
**8bit image**

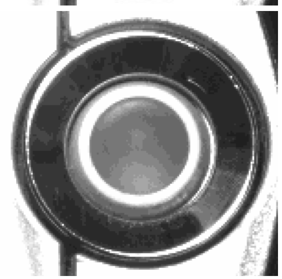


**256 pixel values available**
**88.2kB/image**

**4bit image**



**16 pixel values available**
**44.2kB/image**

**1bit image**


**2 pixel values available**
**11.3kB/image**

# Image Acquisition Options

- tree options available:
  - analog video camera and external framegrabber

# Image Acquisition Options

- tree options available:
  - analog video camera and external framegrabber
  - digital camera with dedicated protocol and external acquisition board like Camera Link

**© Leutron Vision, www.leutron.com**

# Image Acquisition Options

- tree options available:
  - analog video camera and external framegrabber
  - digital camera with dedicated protocol and external acquisition board like Camera Link
  - digital camera and standard bus like Gbit Ethernet, USB, FireWire,...

# Digital Interface Standards

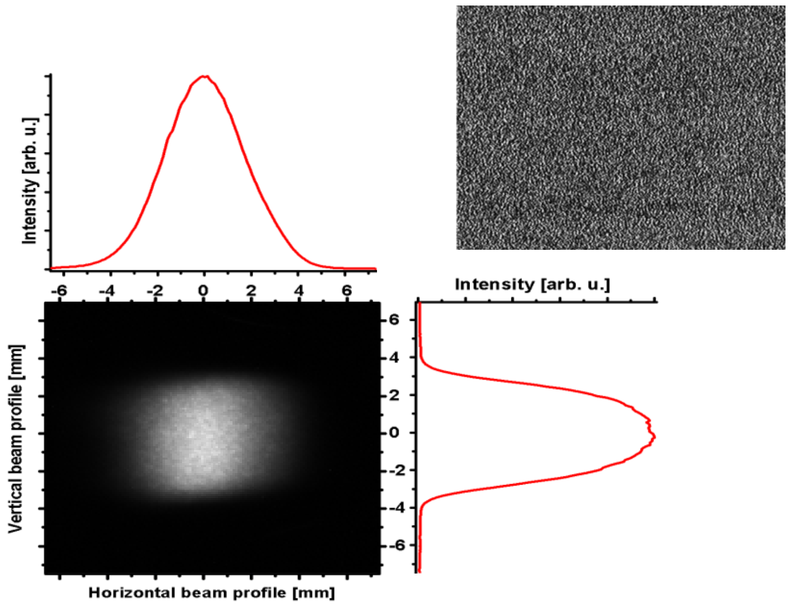
| Standard | | | Bandwidth | Cable length |
|---|---|---|---|---|
| **DCAM** | FireWire A - IEEE 1394a | | 400 Mbits/s | 10m |
| **DCAM** | FireWire B - IEEE 1394b | | 800 Mbits/s | 10m |
| **GigE Vision** | Gigabit Ethernet - GigE | | 1 Gbits/s | 100m |
| **10GigE Vision** | 10 Gigabit Ethernet - 10GigE | | 10 Gbits/s | 100m |
| **USB 2** | USB 2.0 –Speed USB | | 480 Mbits/s | 3 - 5m |
| **USB 3 Vision** | USB 3.0 – SuperSpeed USB | | 3.5 Gbits/s | 3 - 5m |
| **CoaX Press** | Framegrabber | | 6.25 Gbits/s | 100m |
| **Camera Link** | Framegrabber | | 6.8 Gbits/s | 10m |
| **Camera Link HS** | Framegrabber | | 16.8 Gbits/s | 10.000m |

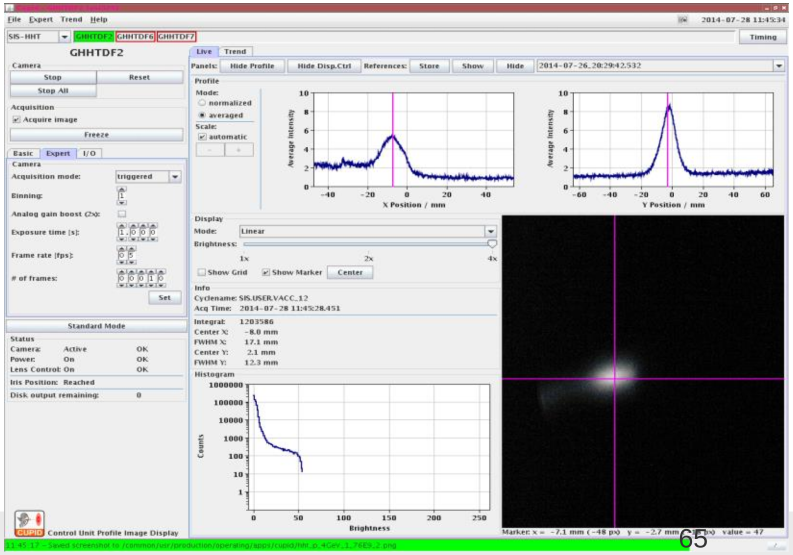
GEN<i>CAM

- generic programming interface for machine vision cameras. The goal is to decouple industrial camera interfaces technology from the user application programming interface (API)
- administered by the European Machine Vision Association (EMVA)

# Post Processing – Analysis Tools

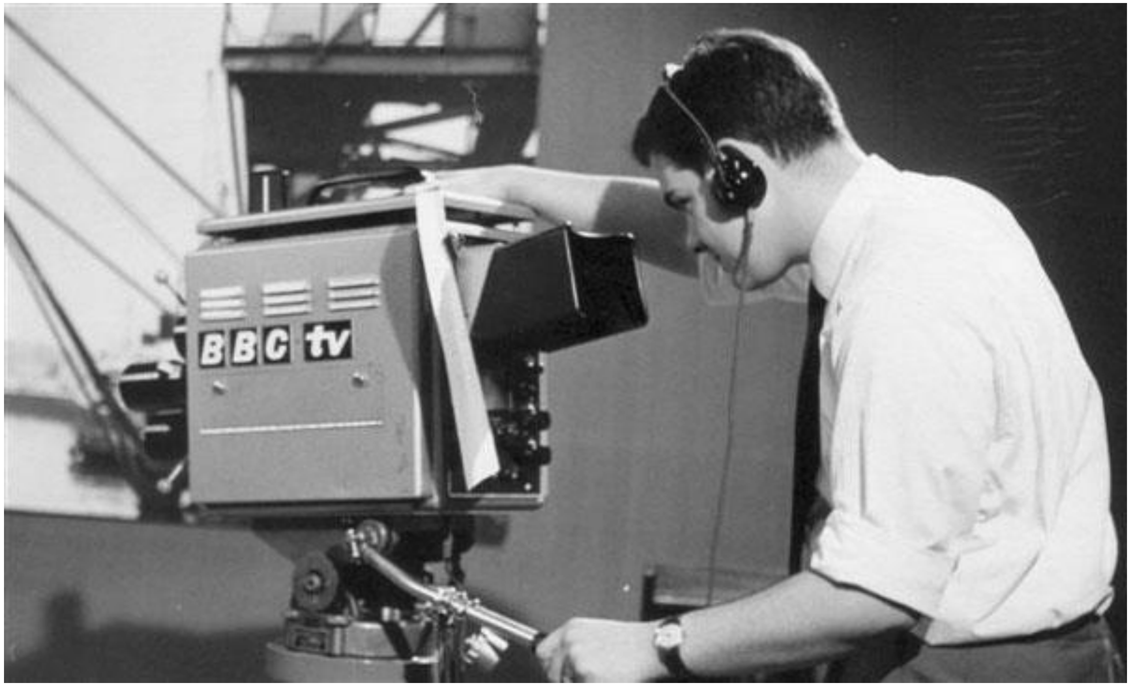
- camera provider offer tools
- usually we need to do:
  - background subtraction
  - geometrical corrections
  - projection and/or fitting
- most of the time we use in-house developed tools (JAVA, C/C++ etc.



# Summary

- technology is giving us a lot of possibilities in the imaging world
  - analog video cameras

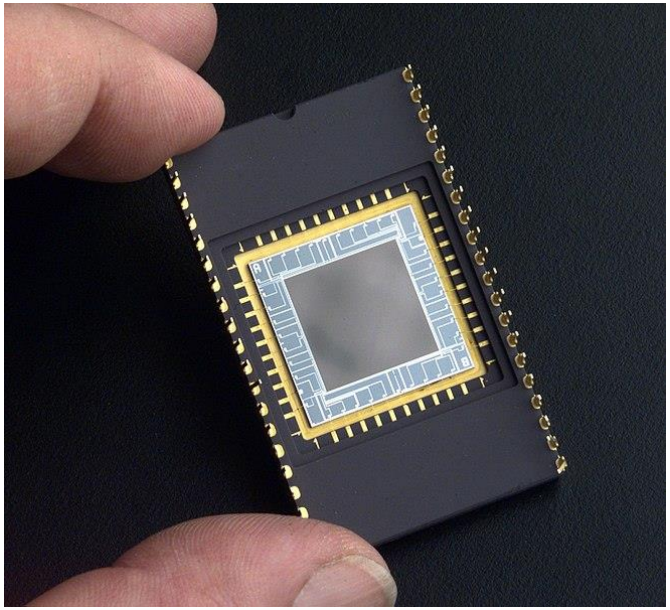



**© Pete Simpkin, Marconi vidicon Camera www.bbceng.info**

# Summary

- technology is giving us a lot of possibilities in the imaging world
  - CCD cameras


**© Seitz  Phototechnik AG**



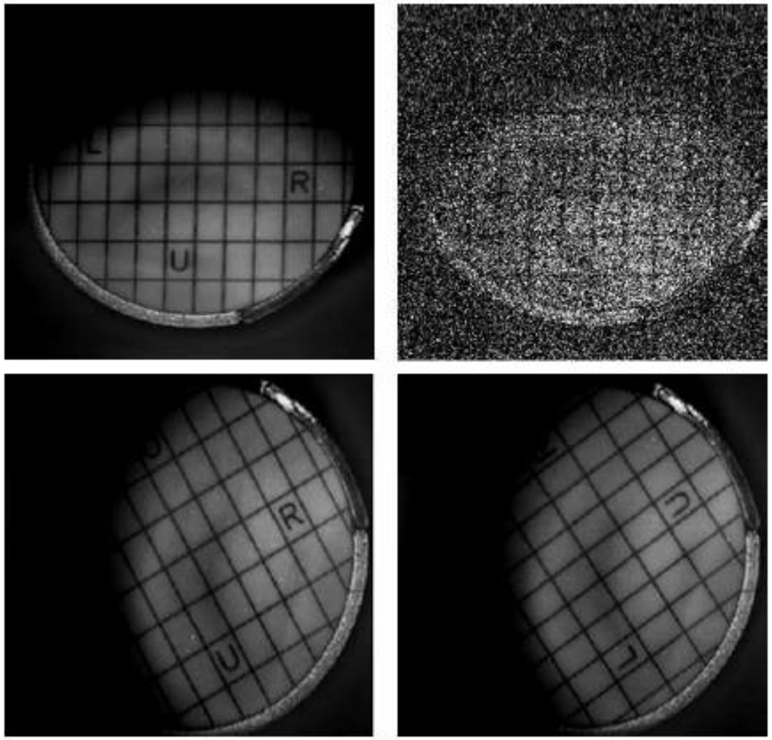
**© Wikipedia**

# Summary

- technology is giving us a lot of possibilities in the imaging world
  - CMOS cameras

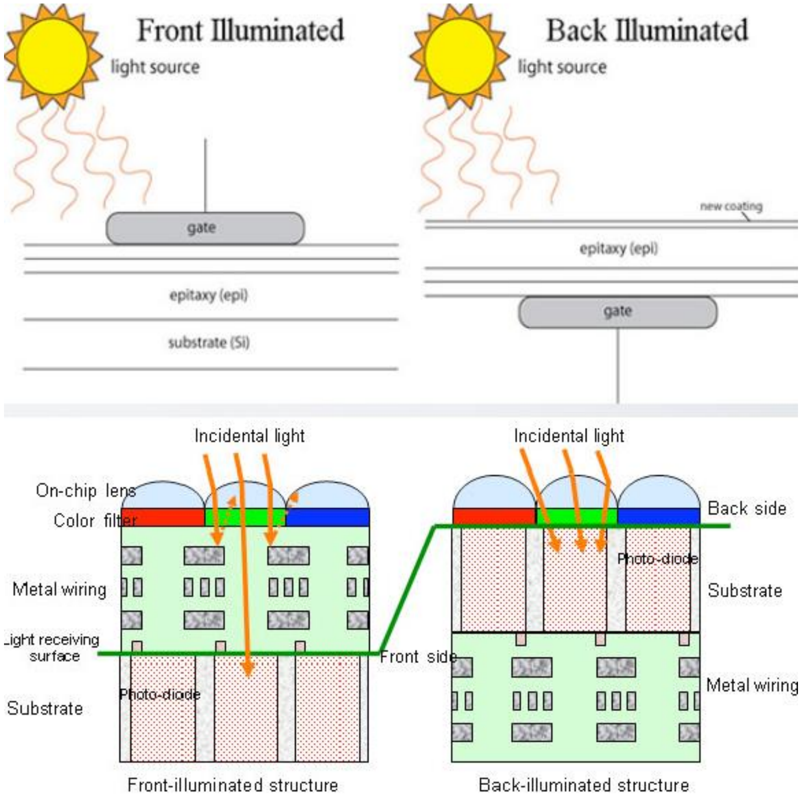
# Summary

- technology is giving us a lot of possibilities in the imaging world
  - CID cameras




# Summary

- technology is giving us a lot of possibilities in the imaging world
  - back illuminated cameras


© PCO www.pco-tech.com

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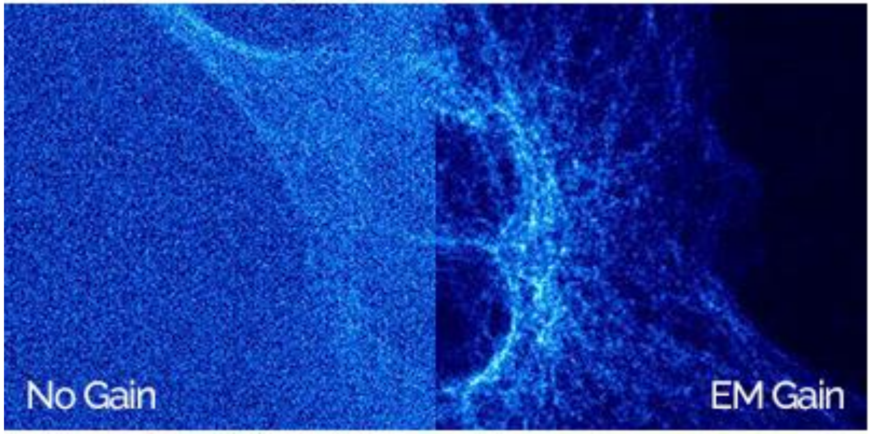
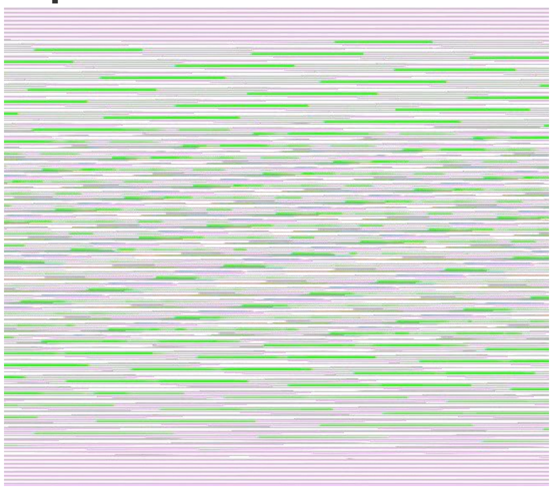
# Summary

- technology is giving us a lot of possibilities in the imaging world
  - electron multiplying CCD (EMCCD)

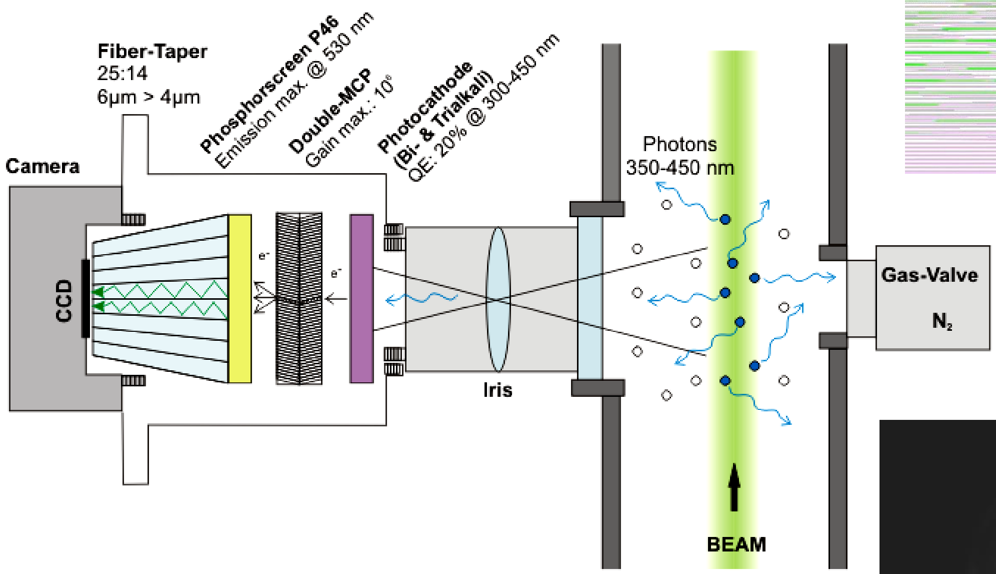



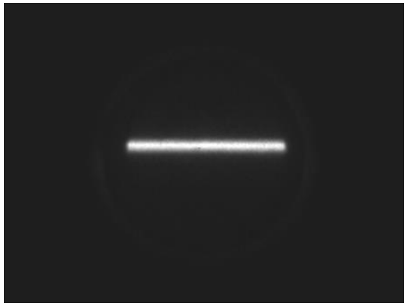
# Summary

- technology is giving us a lot of possibilities in the imaging world
  - image intensifier cameras







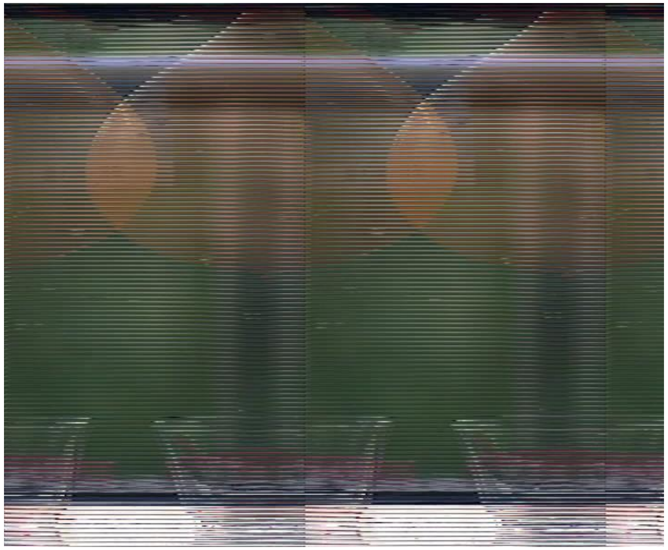



# Summary

- technology is giving us a lot of possibilities in the imaging world
  - high speed cameras

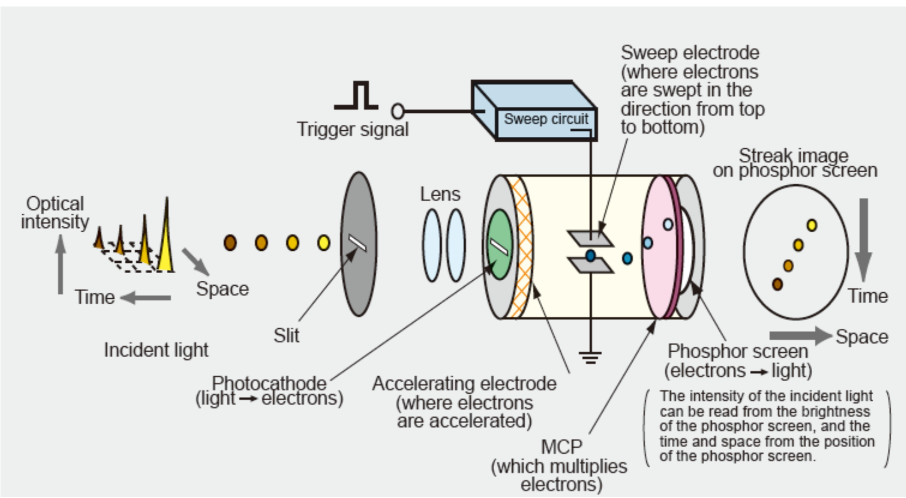


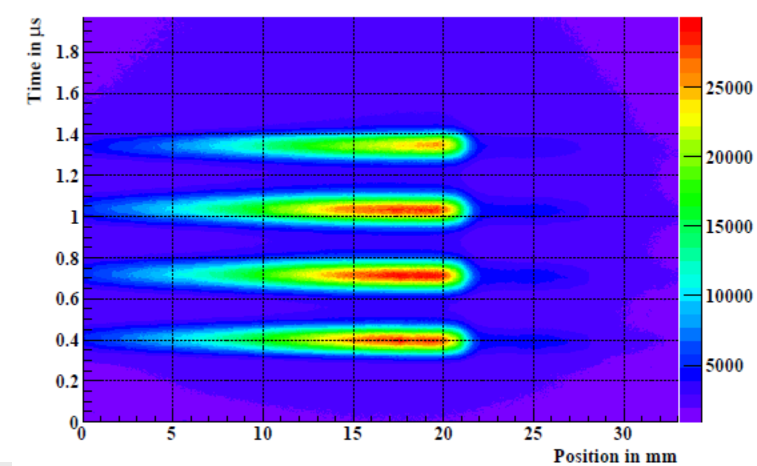

- 7039 fps @ 1 MPix resolution (1000 x 1000 pixel)
- excellent light sensitivity
- 12 bit dynamic range
- NO additional black reference calibration required
- 18 or 36 GB inbuilt image memory
- exposure time range 1.5 µs - 40 ms
- multiple trigger options
- master-slave camera synchronisation (up to 5 cameras)
- IRIG B timecode function
- Interfaces: USB 3.0, GigE/USB 2.0, CameraLink



# Summary

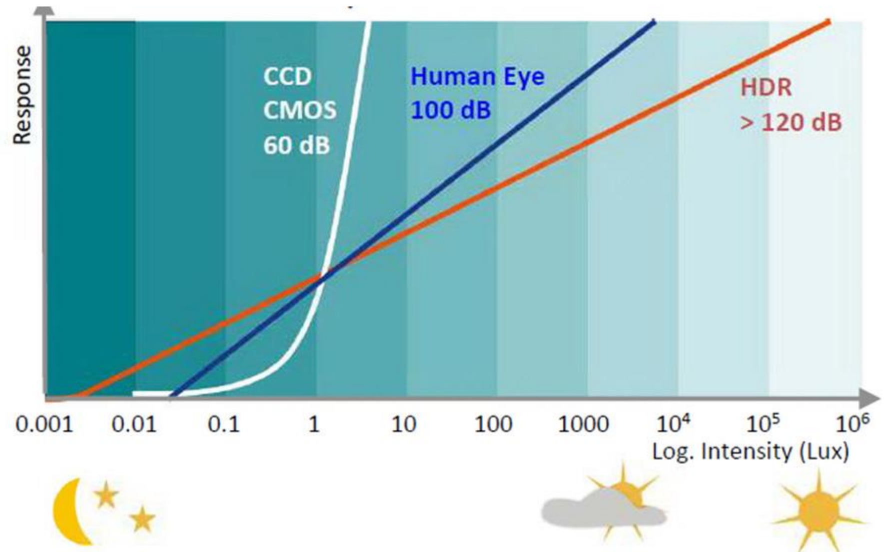
- technology is giving us a lot of possibilities in the imaging world
  - streak cameras

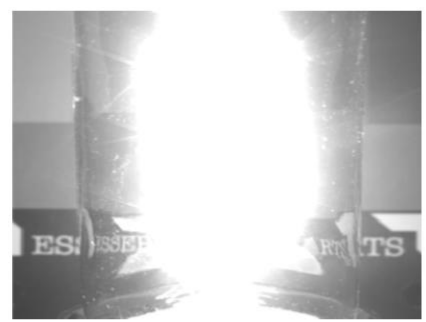


# Summary

- technology is giving us a lot of possibilities in the imaging world
  - high dynamic range camera



# Summary

- technology is giving us a lot of possibilities in the imaging world
  - analogue video cameras
  - CCD cameras
  - CMOS cameras
  - CID cameras
  - back illuminated cameras
  - electron multiplying CCD
  - image intensifier cameras
  - high speed cameras
  - streak cameras
  - high dynamic range cameras
- But, our needs often go opposite to the big market

# Summary

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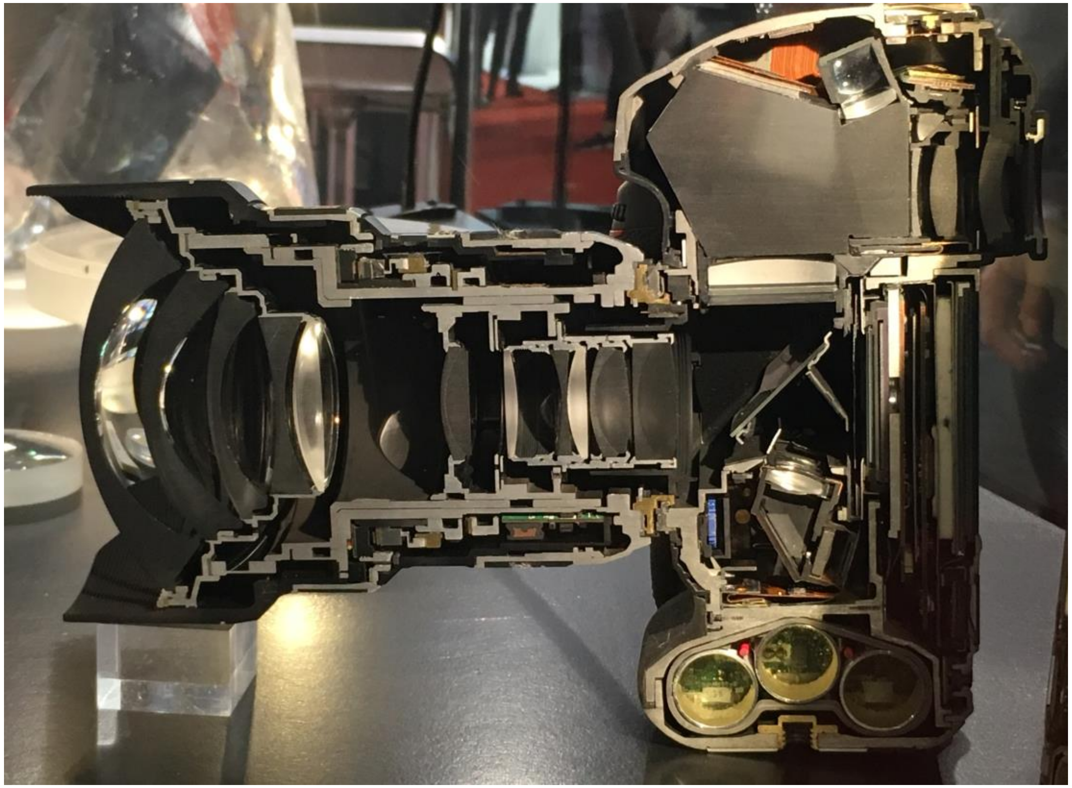
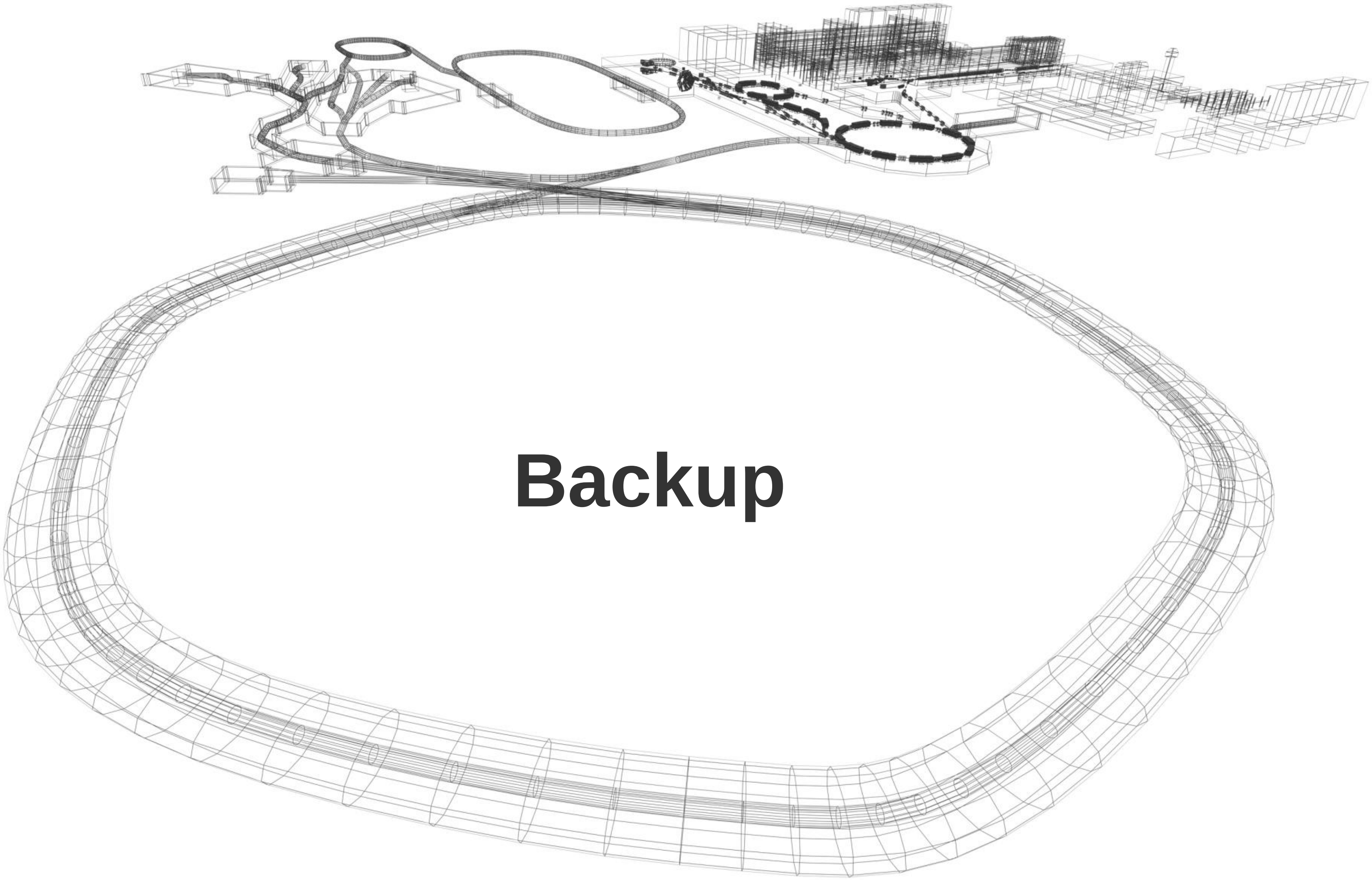
  - back illuminated cameras
  - electron multiplying CCD
  - image intensifier cameras
  - high speed cameras
  - streak cameras
  - high dynamic range cameras
- But, our needs often go opposite to the big market
- radiation is our enemy

# Thank You!



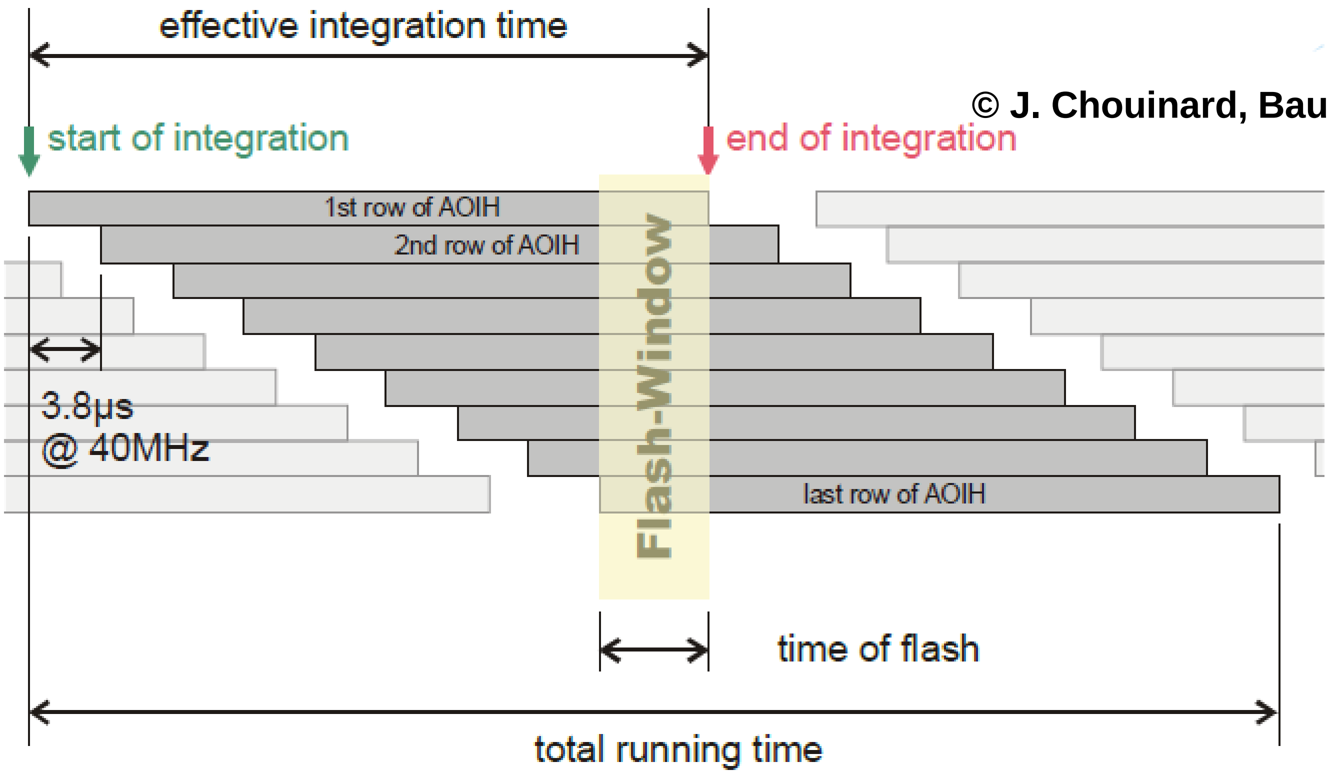
**I would like to express my special thanks to Harald Bräuning, Andre Petit, Rainer Haseitl, Hansi Rödl and Klaus Höhne who support me during preparation**



# Backup

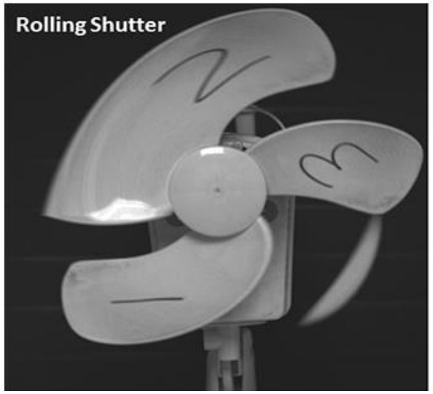
# CMOS Performance Characteristics

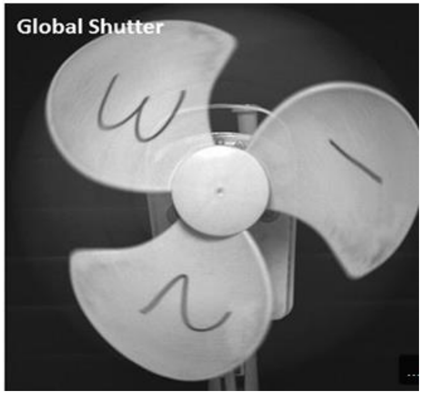
- **rolling shutter**
  - a method of image capture in which a picture is captured not by taking a snapshot of the entire scene at the same time but rather by scanning across the scene
    - not all parts of the image are recorded at exactly the same time



# **CMOS** Performance Characteristics

- **rolling shutter**
  - occurs when object/camera move faster that read out

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