POLITECNICO
MILANO 1863

Image Sensors

SENSOR SYSTEMS

Federica Villa
federica.villa@polimi.it

for scientific purposes

- Charge Coupled Device (CCD)

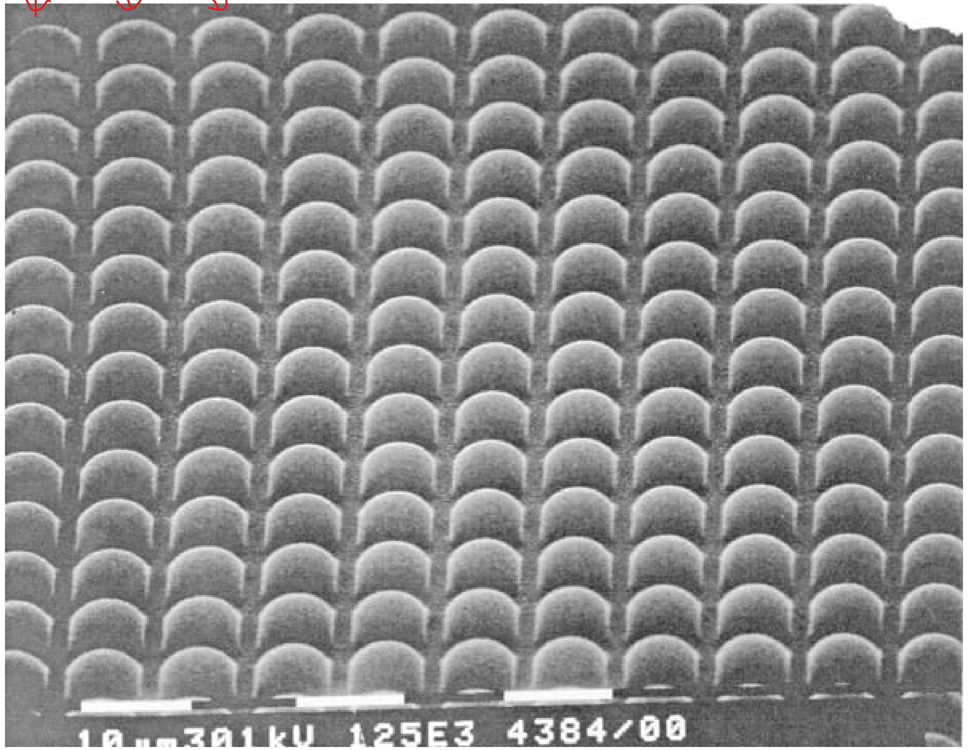
cameras of smartphones

- CMOS active pixel image sensor

two main technologies

- CCD vs. CMOS

Pixels

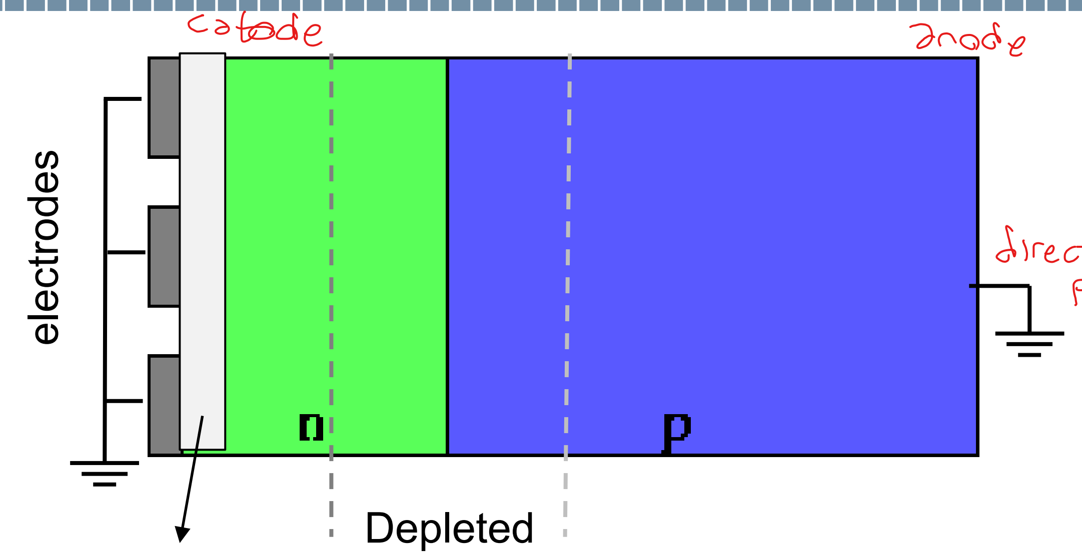


Charge Coupled Device (CCD)

used for a microscope

CCD pixel: MOS capacitor

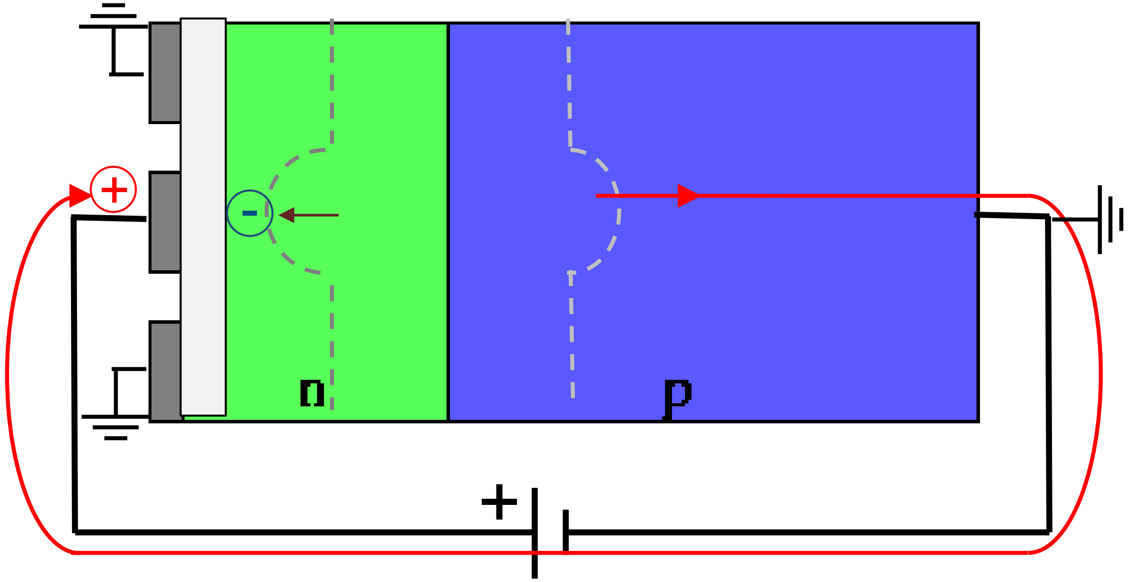
similar to photodiode
PN junction, depleted region
region that absorbs photons



Unbiased

(no current flow
→ free carriers recombination)

N region can't be directly contacted, there is an insulator (like a capacitance)

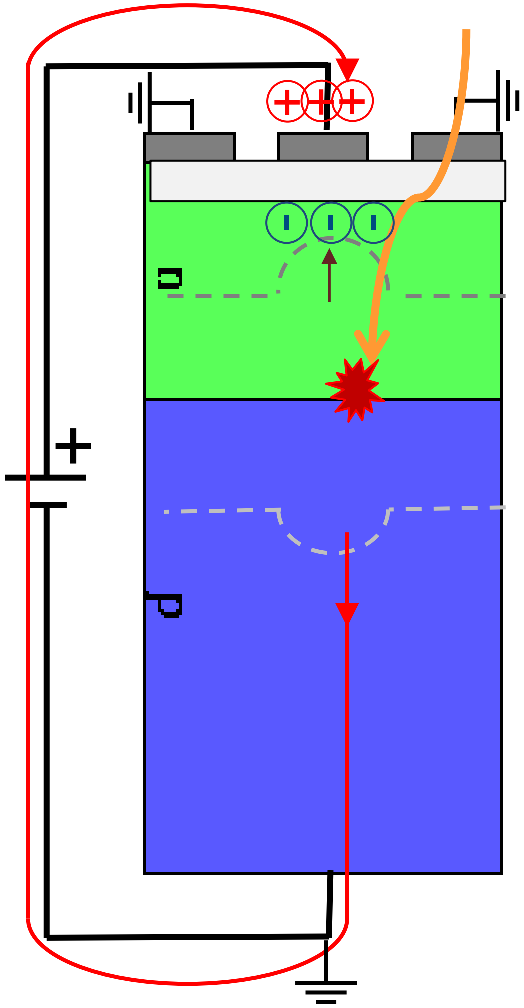


Biased

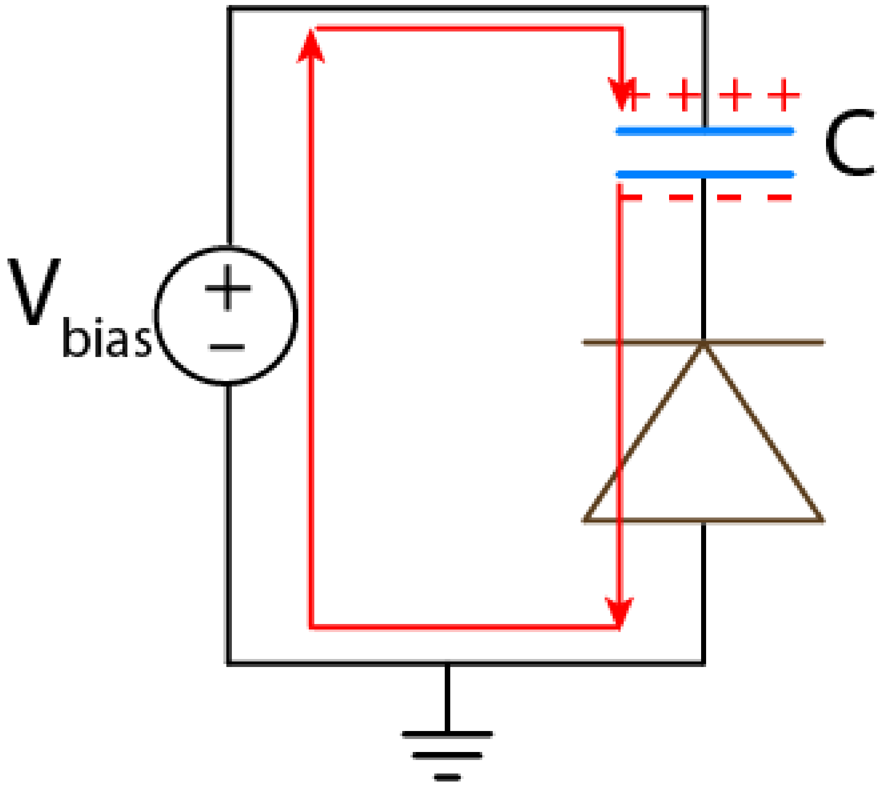
(free carriers generates a current
similarly to a photodiode)

all electrons collected in pixel are in central electrode
(separate charges of pixels)

Photon absorption



Equivalent model



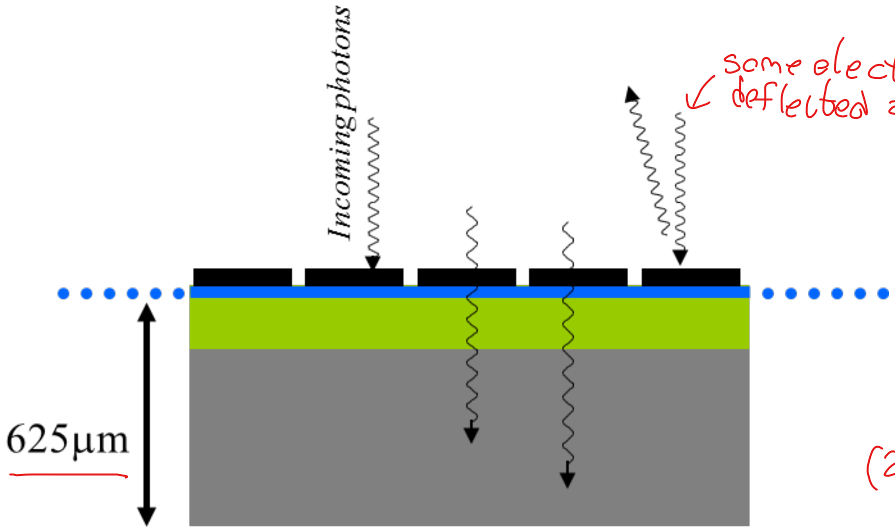
When a photon is absorbed, it generates an electron-hole pair → photocurrent

Differently from photodiodes, electrons are stopped by the insulator at the n-doped side

Front / Back side illumination

FSI

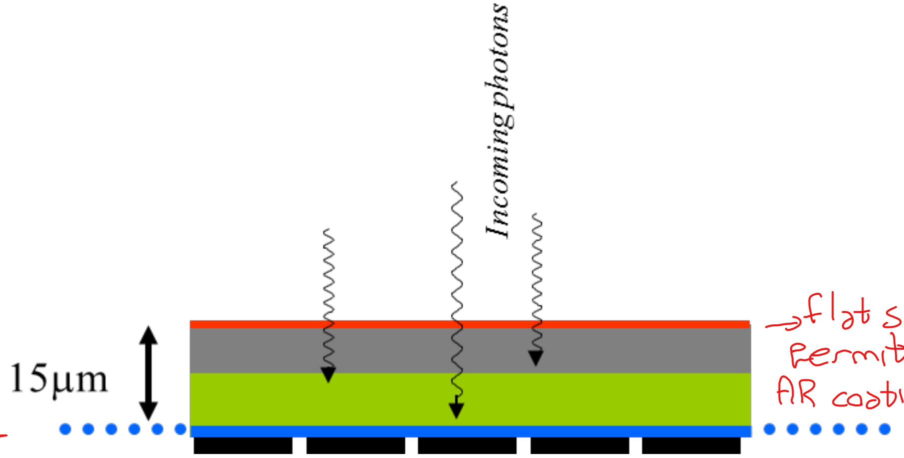
Front side illuminated (Standard Wafer)



if too wide Photons absorbed before deplated region (and not readout)

Back side illuminated (Thinned Wafer)

BSI



mechanical sustain and can contain some electronics for readout

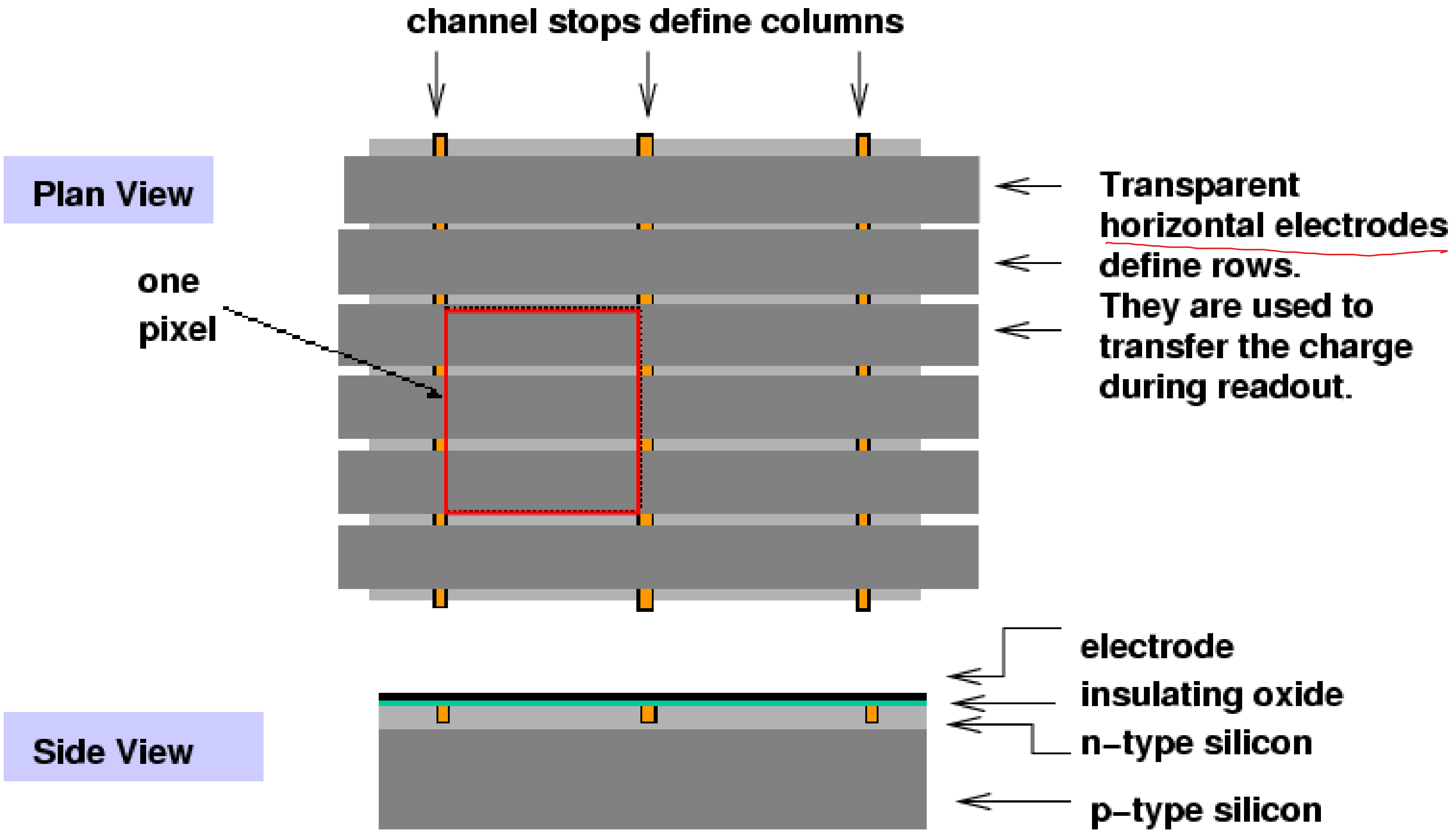
- p-type silicon
- n-type silicon
- Silicon dioxide insulating layer
- Polysilicon electrodes (transparent to light)

- Anti-reflective (AR) coating
- p-type silicon
- n-type silicon
- Silicon dioxide insulating layer
- Polysilicon electrodes

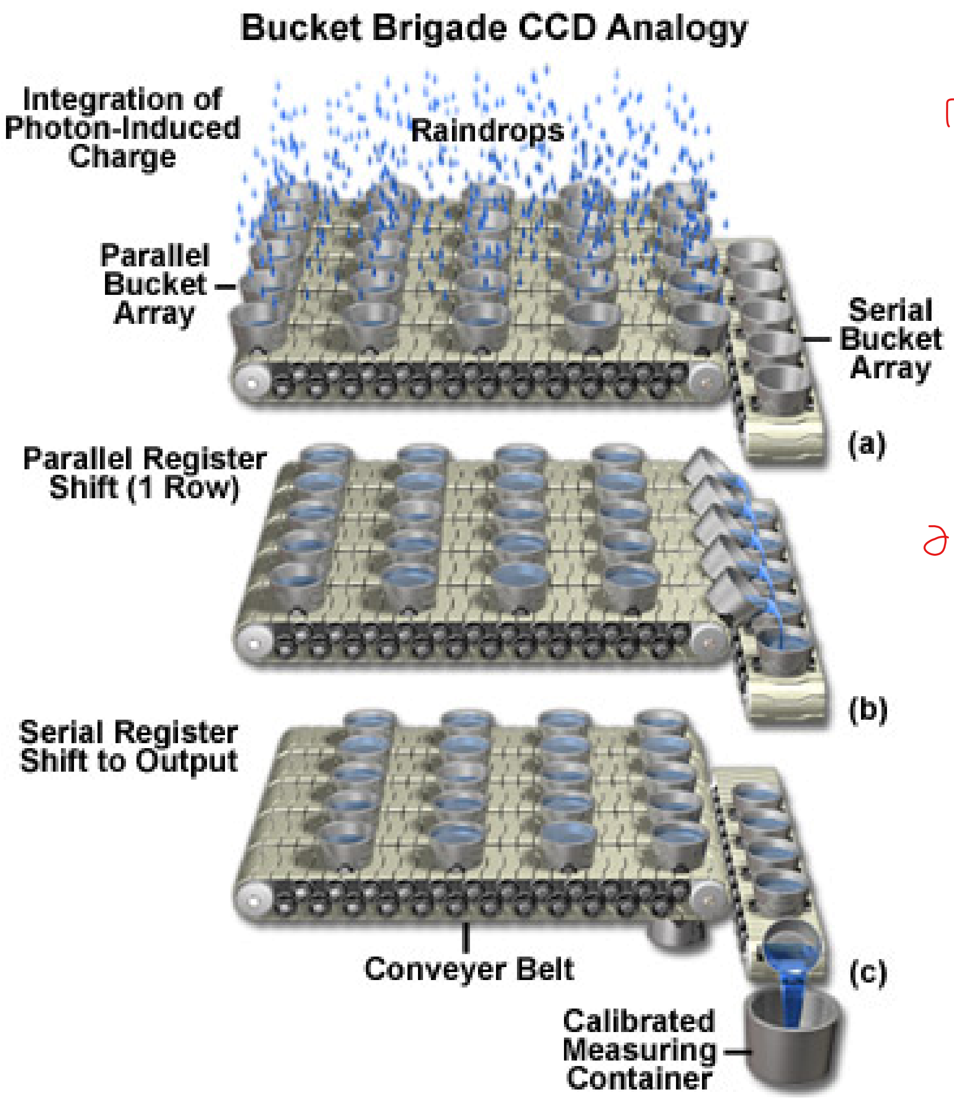
→ 3D vertical integration

anti-reflective coating

CCD structure

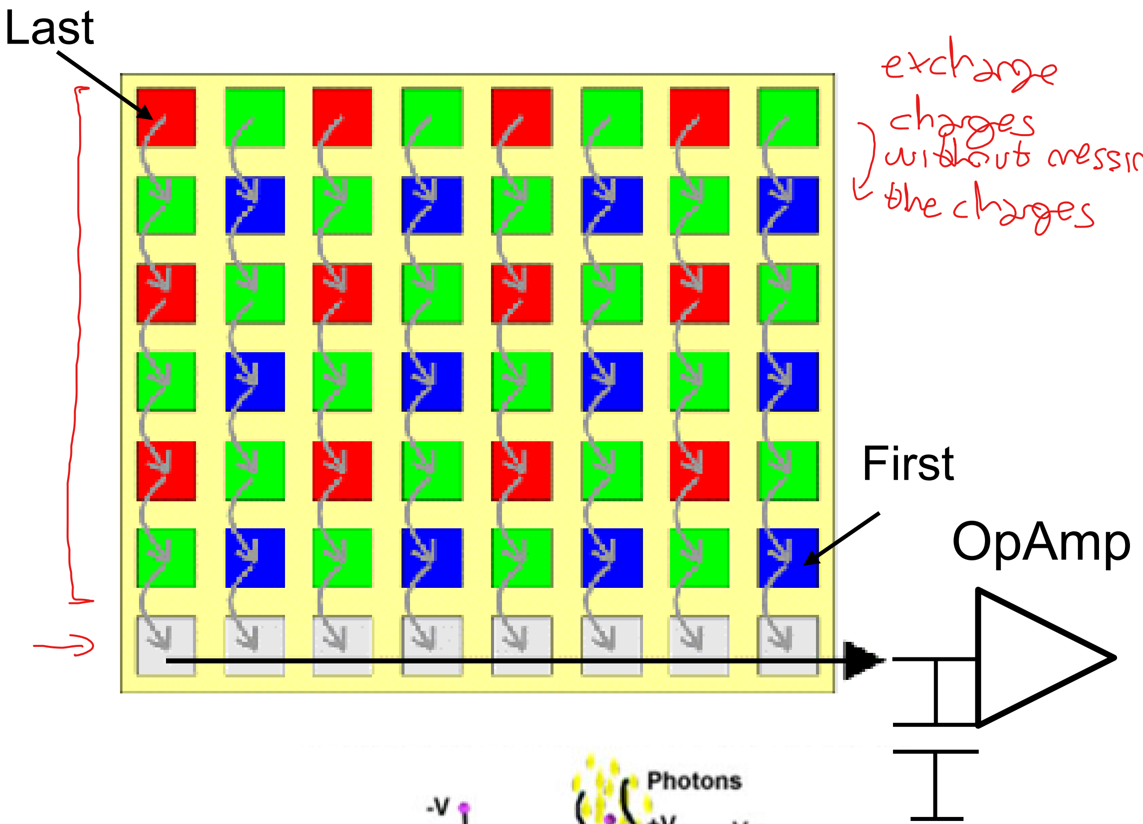


CCD readout

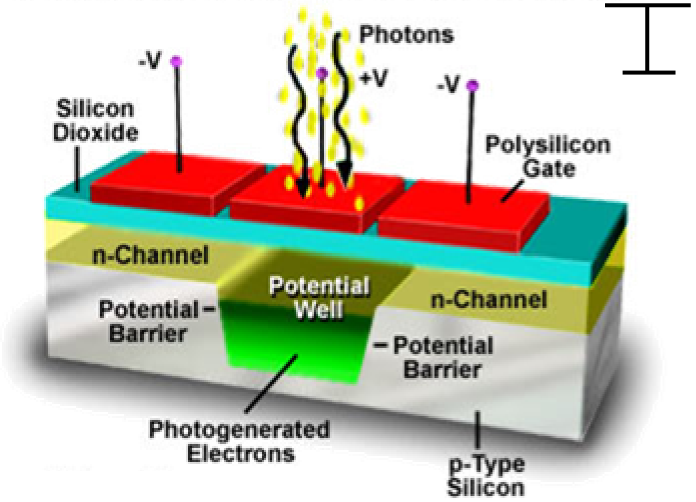


real CCD

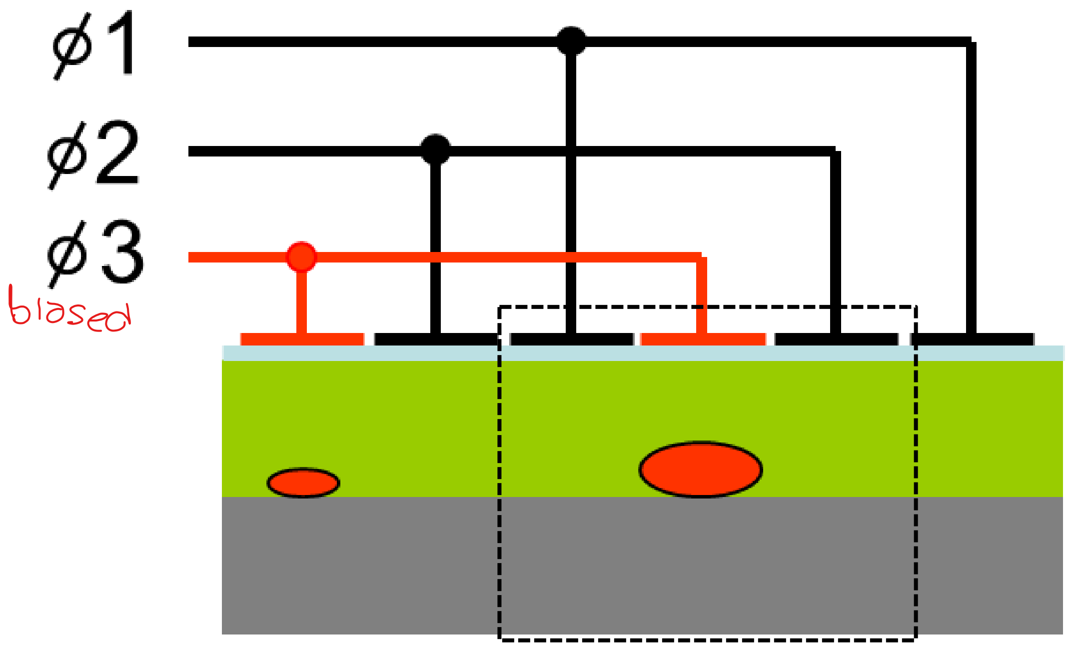
auxillary

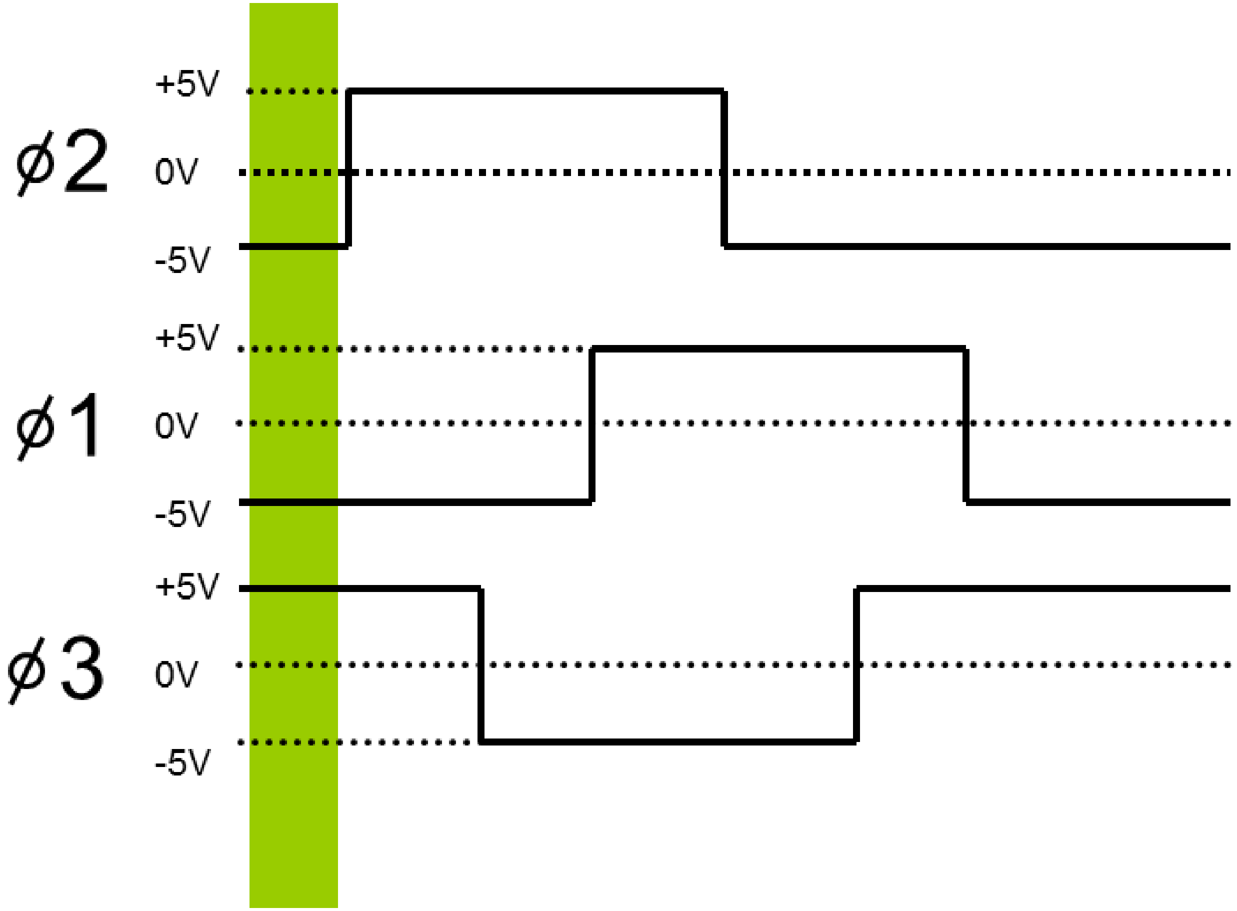


exchange charges without messing up the charges

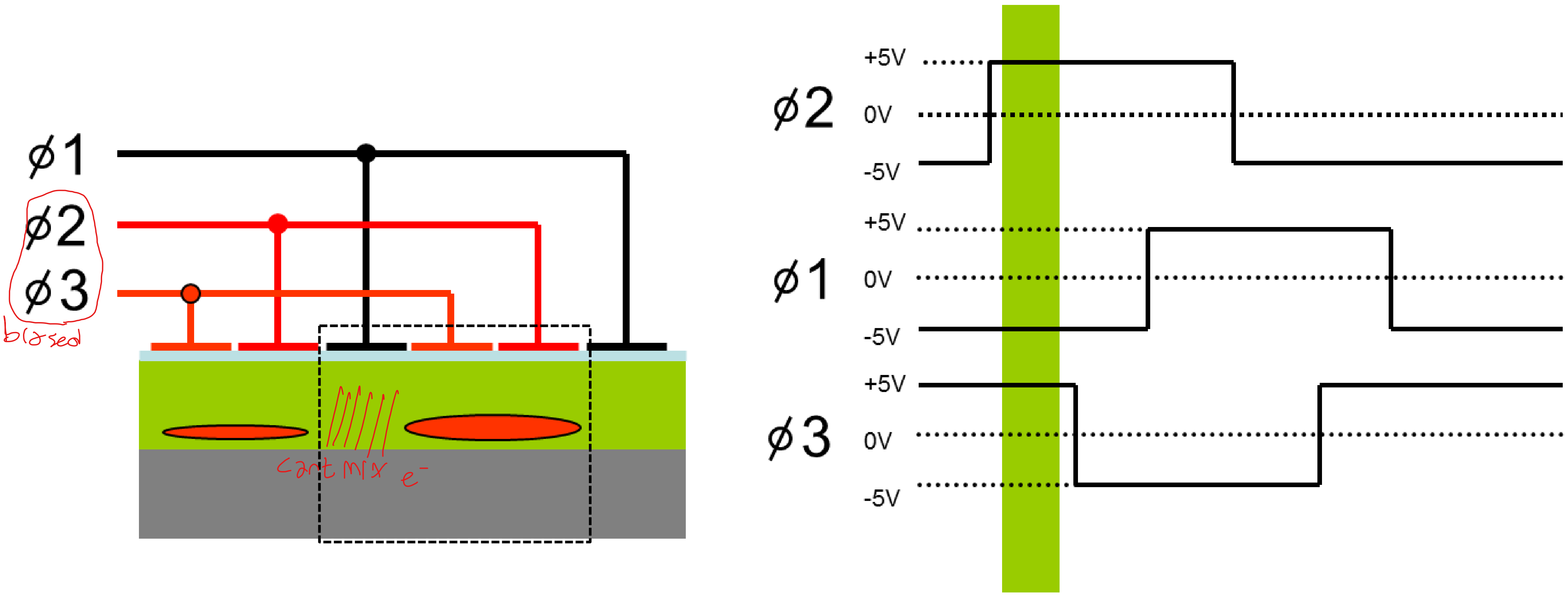


Readout – step 1

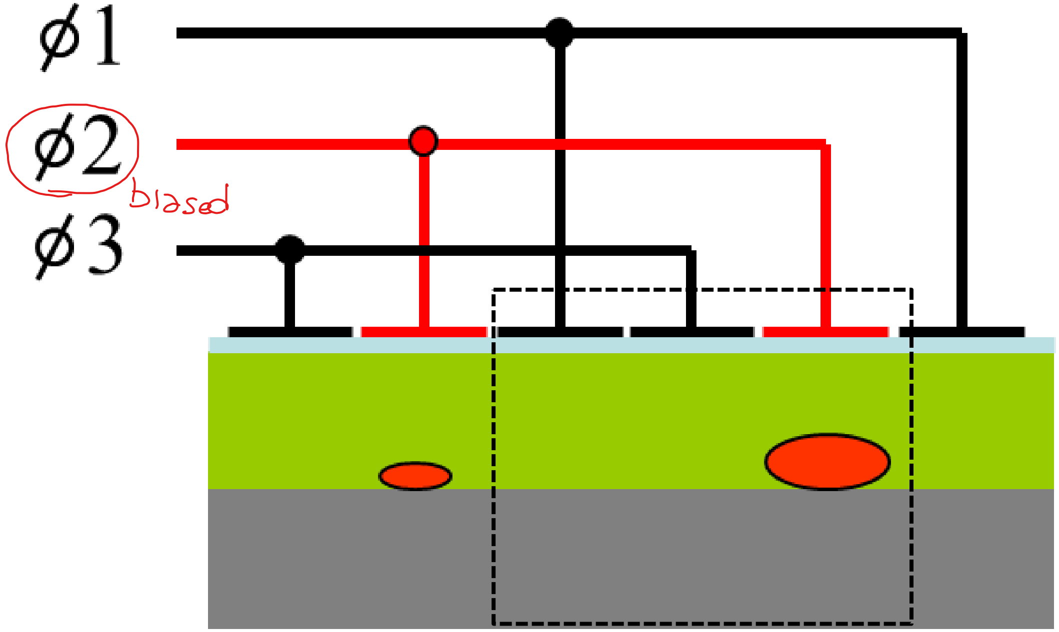


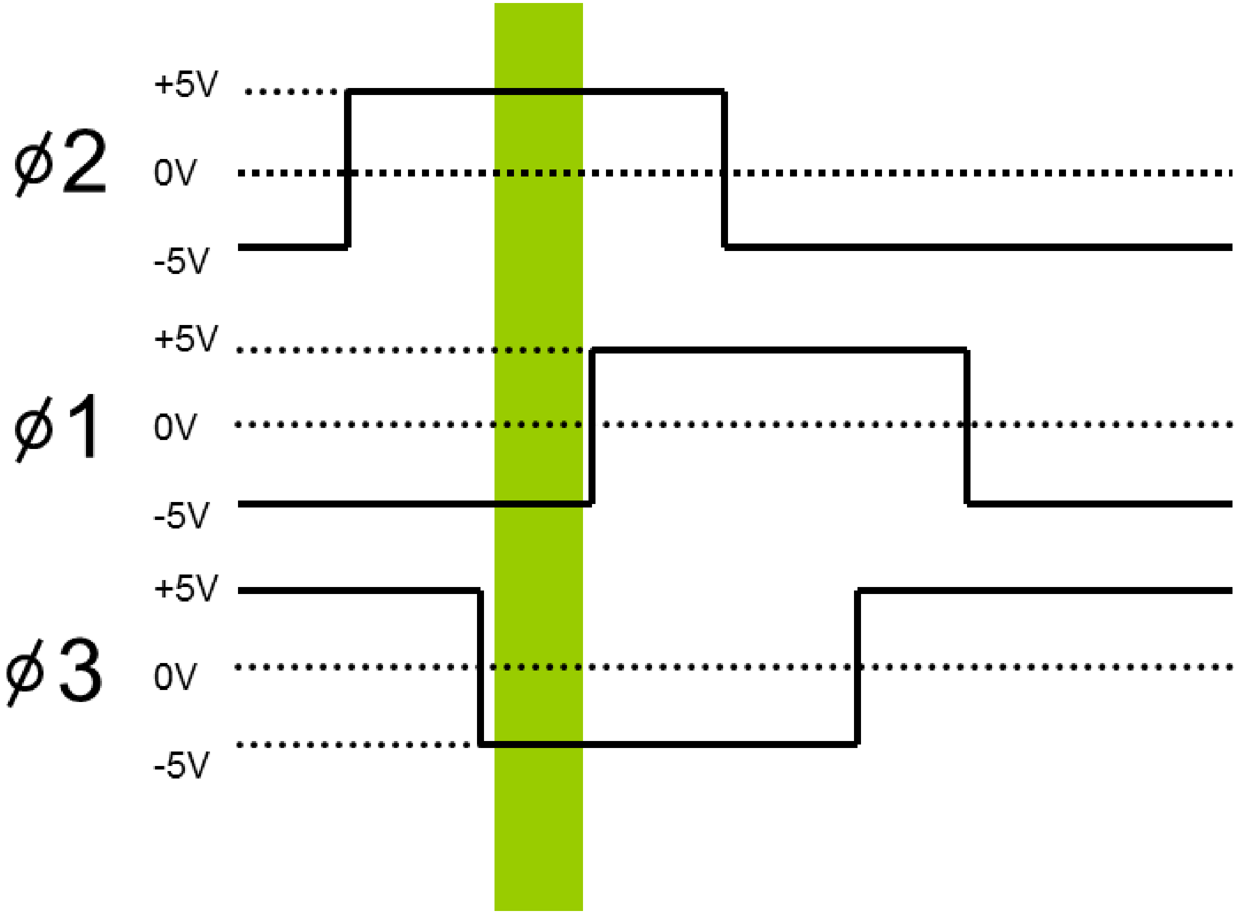


Readout – step 2

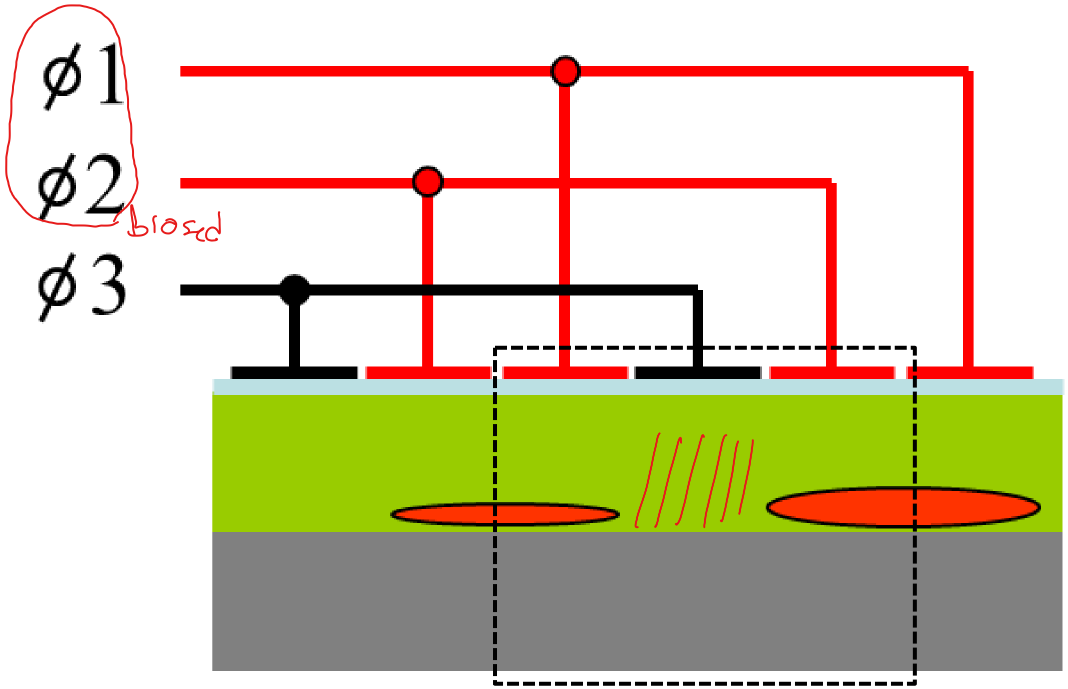


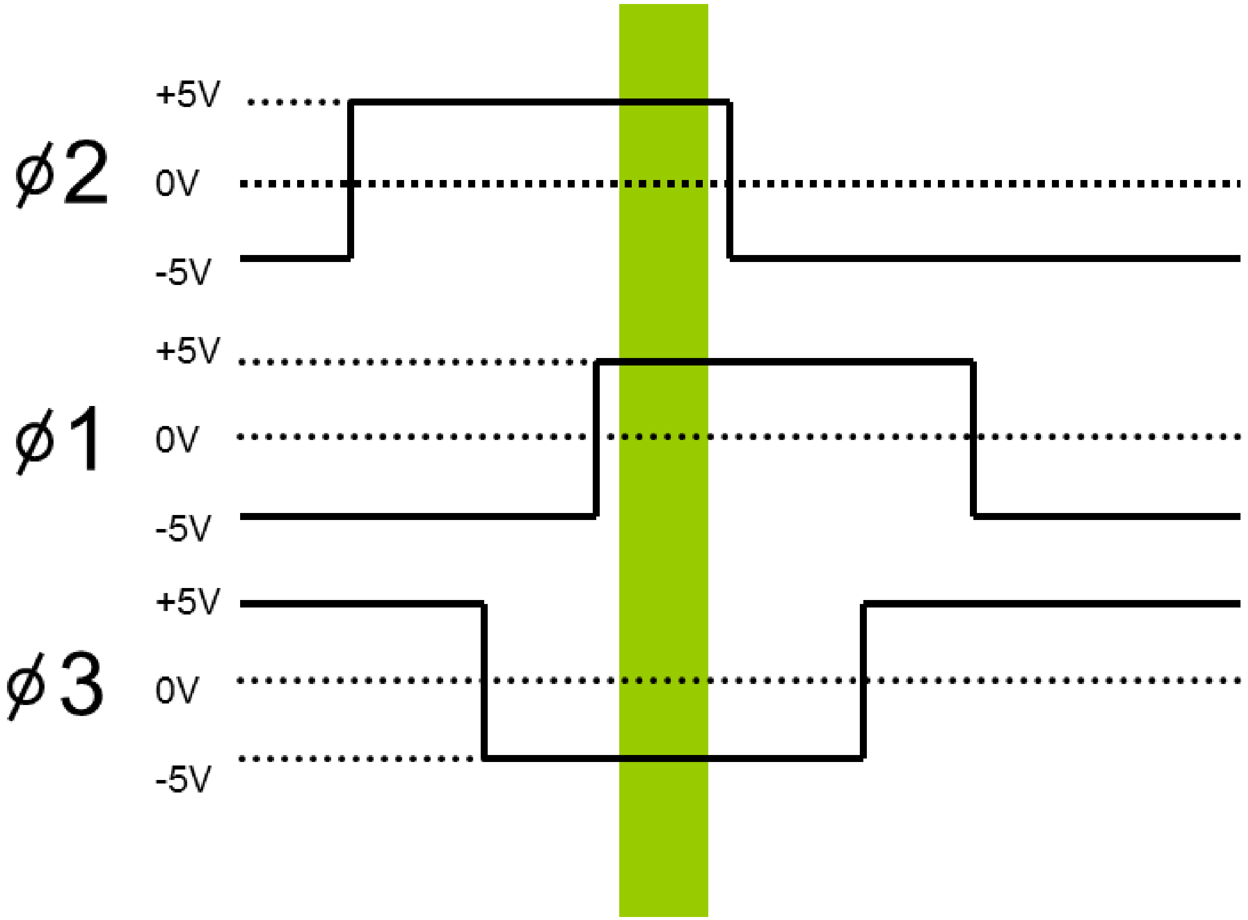
Readout – step 3



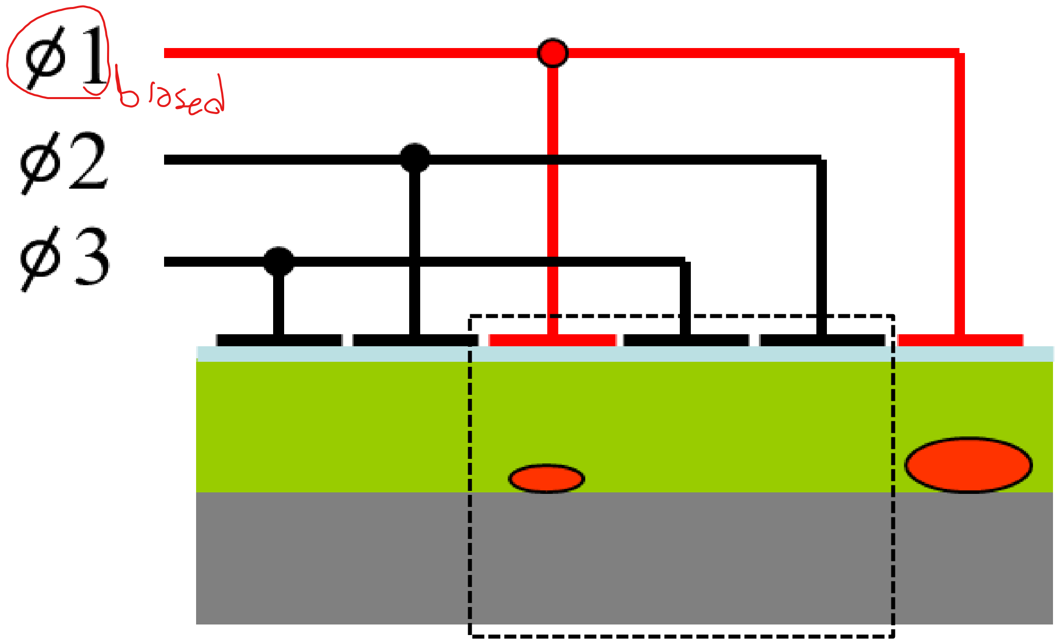


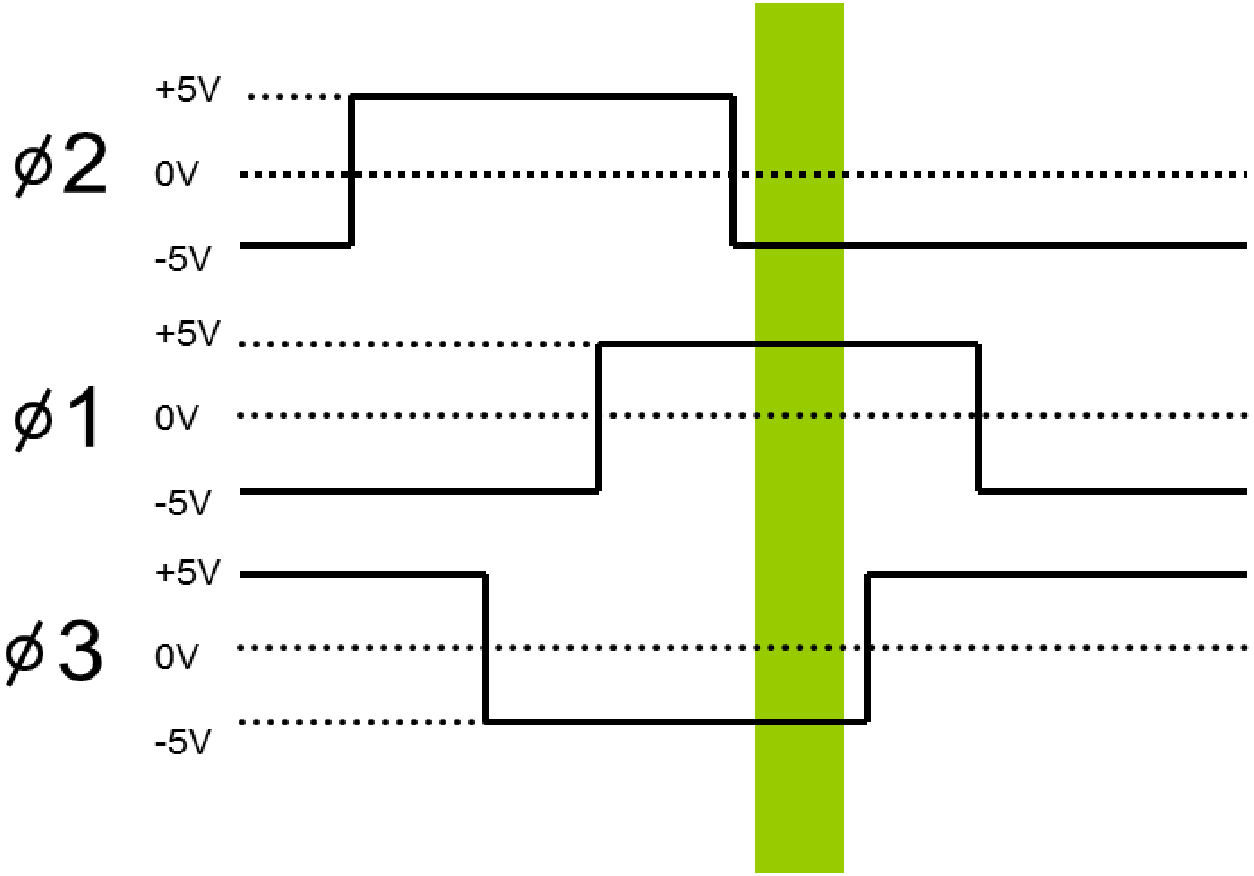
Readout – step 4



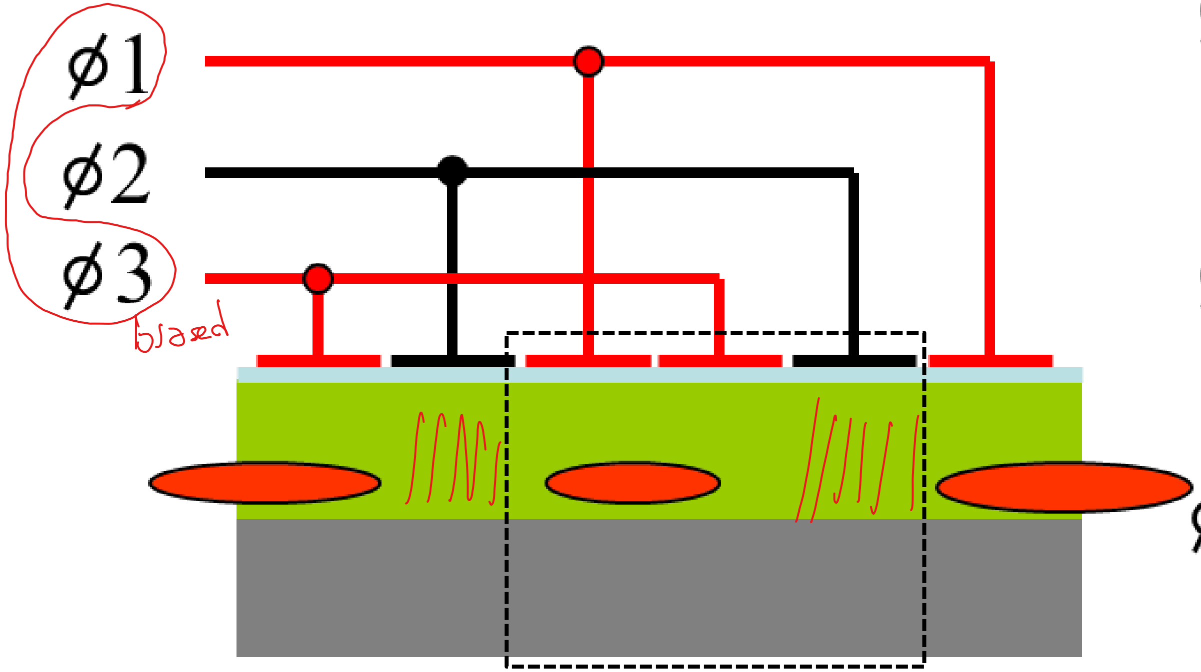


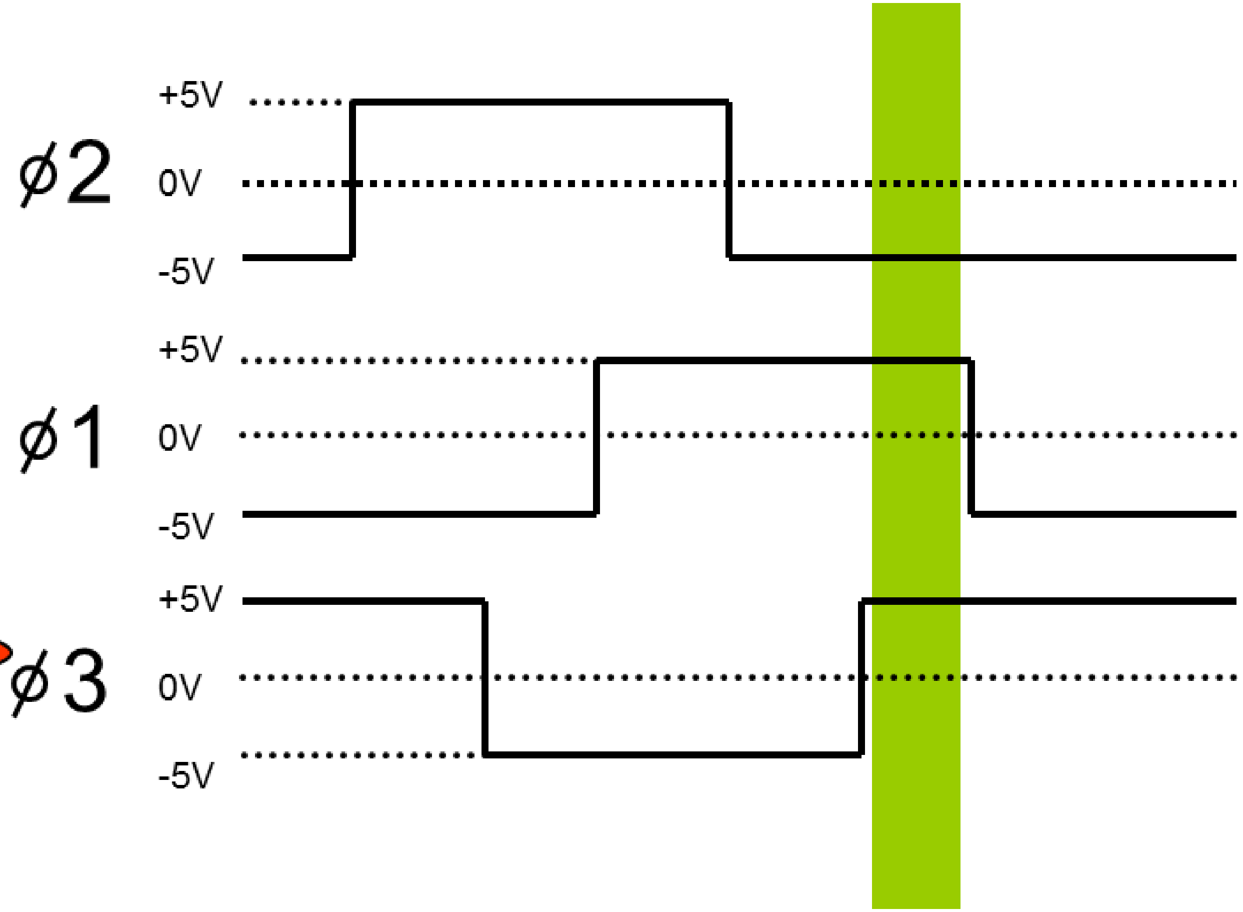
Readout – step 5





Readout – step 6





ability to detect and not detect light appropriately

Charge generation

Quantum Efficiency (QE), Dark Current

detection efficiency and dark current

Charge collection

Well Capacity, Pixels Size, Linearity, Blooming, Pixel Uniformity

Charge transfer

Charge Transfer Efficiency (CTE), Defects

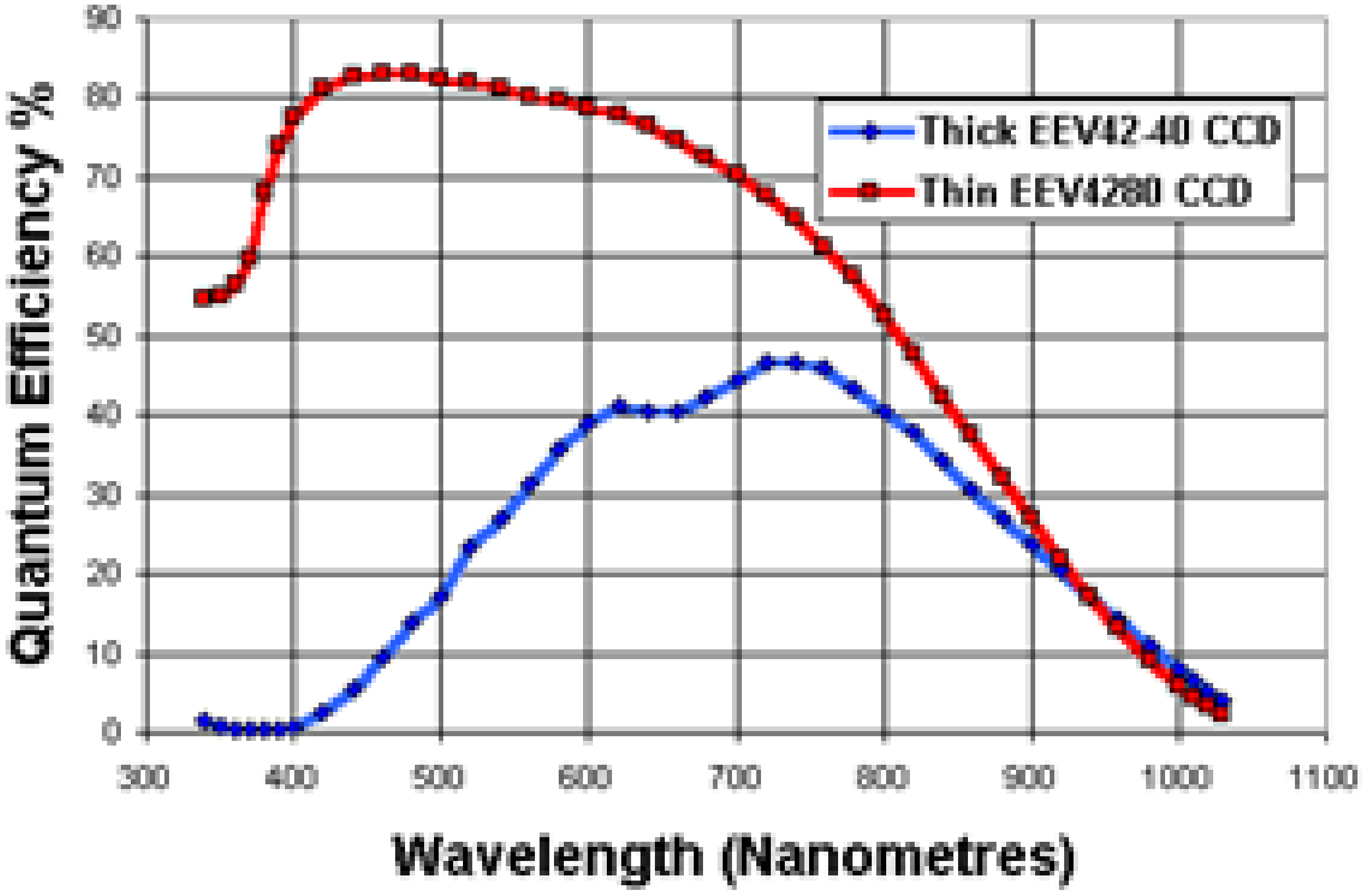
and Inefficiency

Charge readout

Readout Noise

Charge generation: Quantum Efficiency

responsivity of the sensor: $\frac{\#\text{ detected photons}}{\#\text{ incident photons}}$



$$QE = \frac{detected\ photons}{incident\ photons}$$

Probability that
a photoelectron will be released
for each incident photon

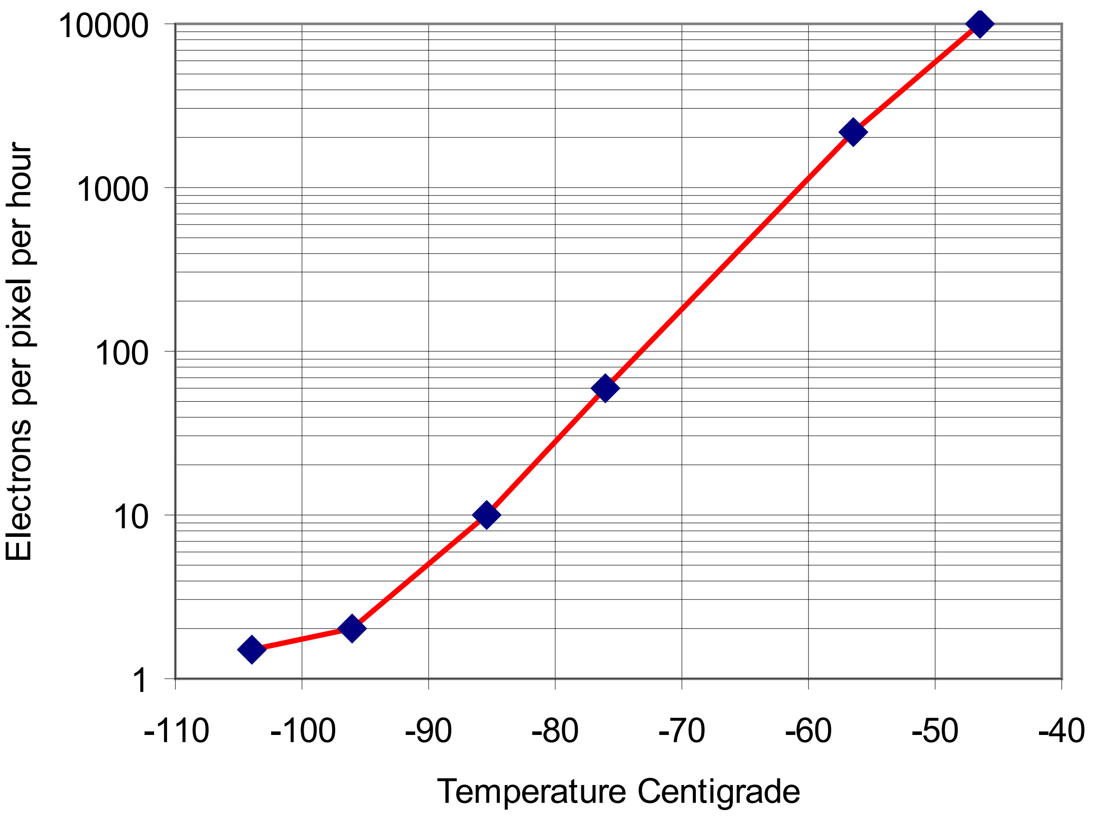
Mechanisms which hamper
photon collection:

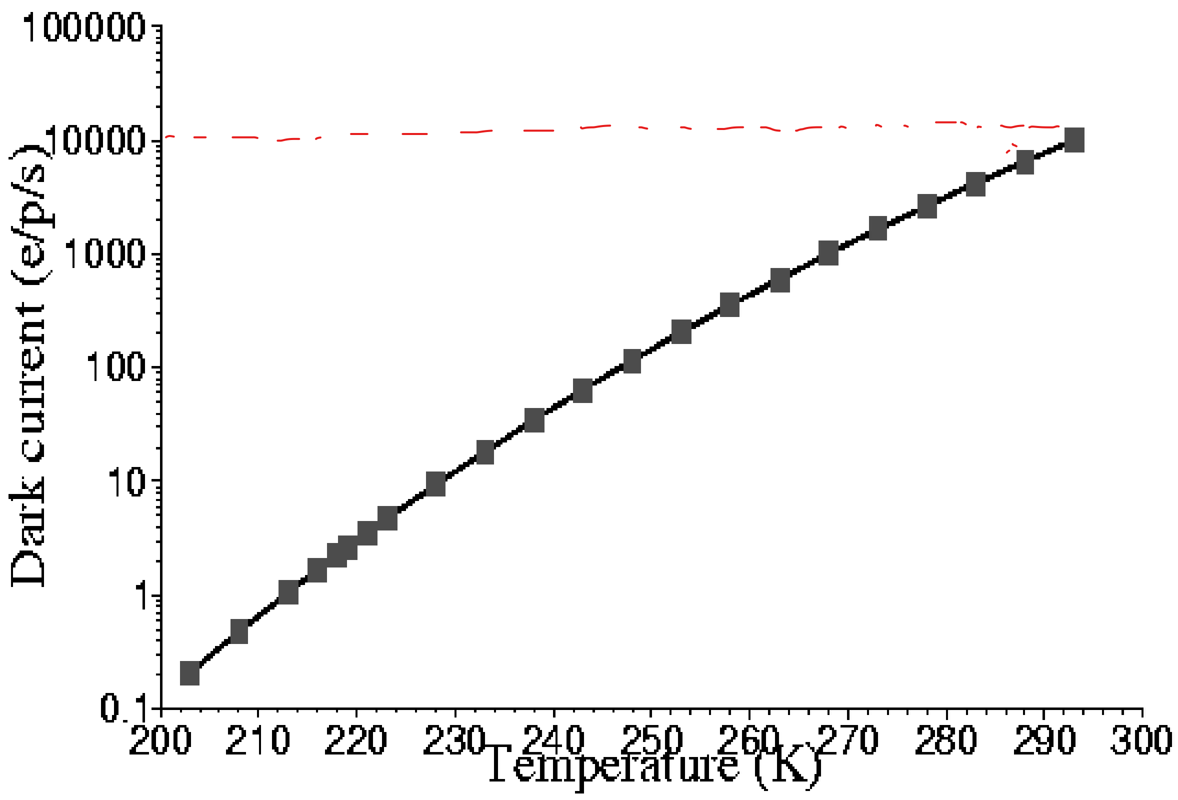
QE depends on:

- Reflection
- Absorption before depleted region
- Transmission not absorbed by depleted region

Charge generation: Dark Current

→ caused by temperature





Thermal effects cause an electron to move from the valence band to the conduction band.

The majority of dark current is created near the interface between the Si and the SiO_2, where interface states at energy between the valence and conduction bands act as a stepping stone for electrons.

Well capacity = maximum charge that can be held in a pixel.

Typically, it is about 10,000 electrons/μm^2 → a few hundred thousand electrons per pixel

Example: V_{cell} = 5V, pixel size = 5µm× 5µm, C_{OX}/A = 35nF/cm^2

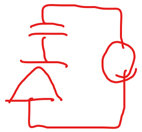
$$\frac{Q}{A} = \frac{C_{ox}}{A} \cdot V_{cell} = 35\mathrm{nF}/cm^2 \cdot 5V \approx 175nC/cm^2 \approx 11{,}000\, {}^{e}/_{\mu m^2}$$

$$\rightarrow Q \approx 300{,}000e$$

⇩

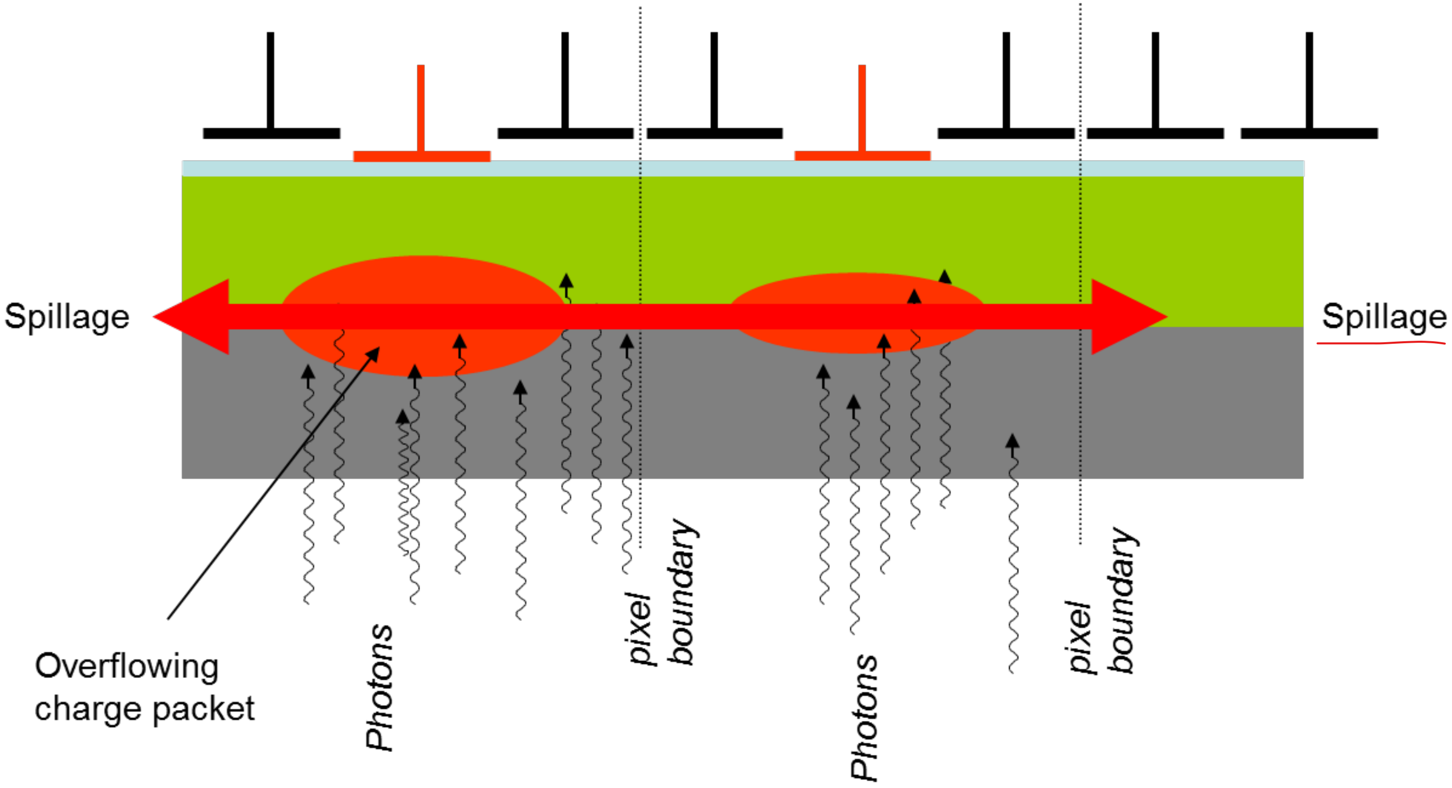
Saturation = when a pixel has accumulated the maximum amount of charge that it can hold.

>80% → non-linear response → biasing voltage decreases

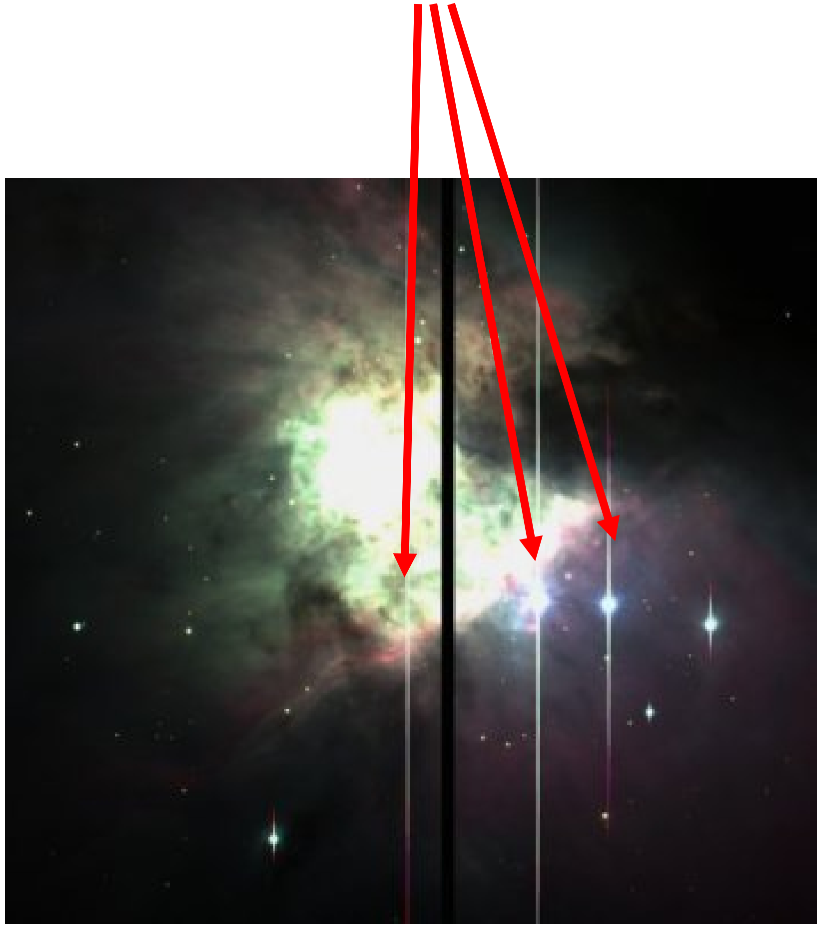


>100% → blooming

Charge collection: Blooming



Bloomed star images



Blooming occurs mainly vertically, as there is little horizontal bleeding because of the permanent doped channel stops.

Charge collection: pixel uniformity

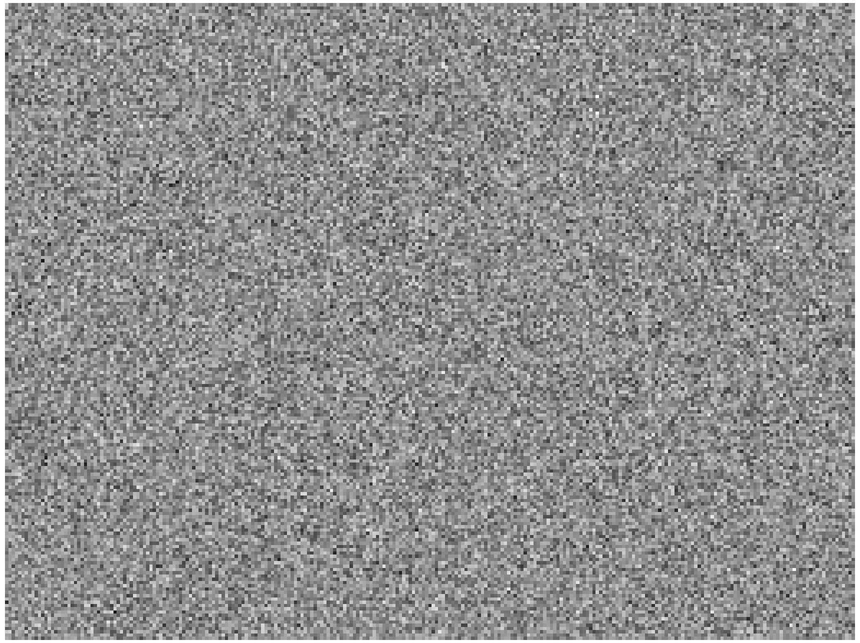
Fixed pattern noise

every pixel has a slightly different sensitivity

The sensitivity of pixels is not the same, for reasons such as differences in thickness, area of electrodes, doping, bias.

↓

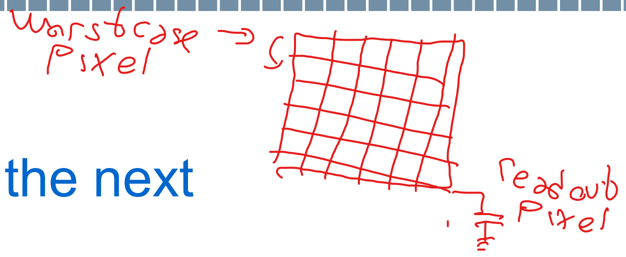
However these differences do not change, and can be calibrated out by dividing by a flat field, which is an exposure of a uniform light source.

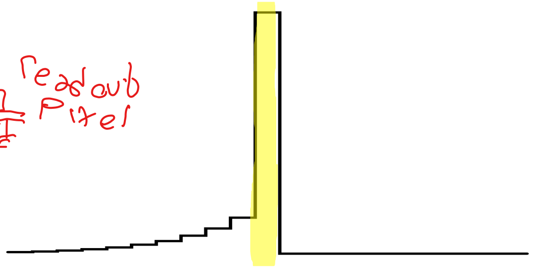


flat fielding

↳ stored and used to compensate

Charge transfer efficiency





Charge Transfer Efficiency (CTE)

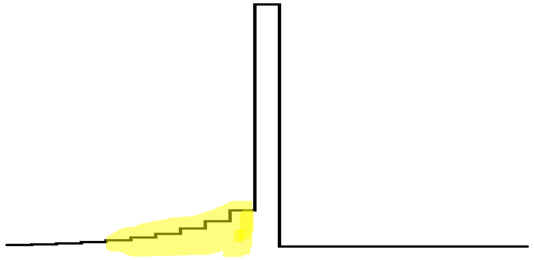
= fraction of electrons transferred from one pixel to the next
(typically 0.9999 to 0.999999)

Charge Transfer Inefficiency (CTI)

= fraction of electrons deferred by one pixel Part of "pixel" leaved on a "pixel" during transfer

CTI = 1 – CTE (typically 10^{-6} to 10^{-4})

→ charges are trapped by defects in the silicon crystal lattice



Example: CTE = 0.99999, 12Mpixel (about 3.5 kpixel × 3.5 kpixel)

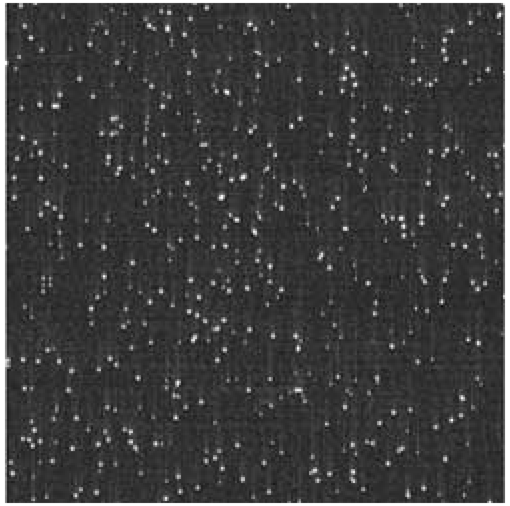
CTI in the worst case (about 7,000 transfers):

$$CTI = 1 - \left(0.99999^{7,000}\right) = 6.7\%$$

Increase efficiency: slow down readout

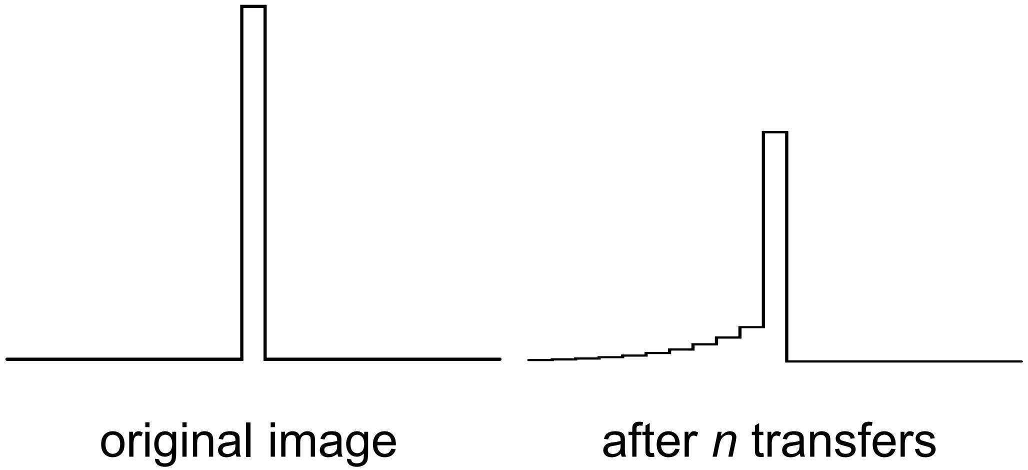
Charge transfer efficiency

good CTE

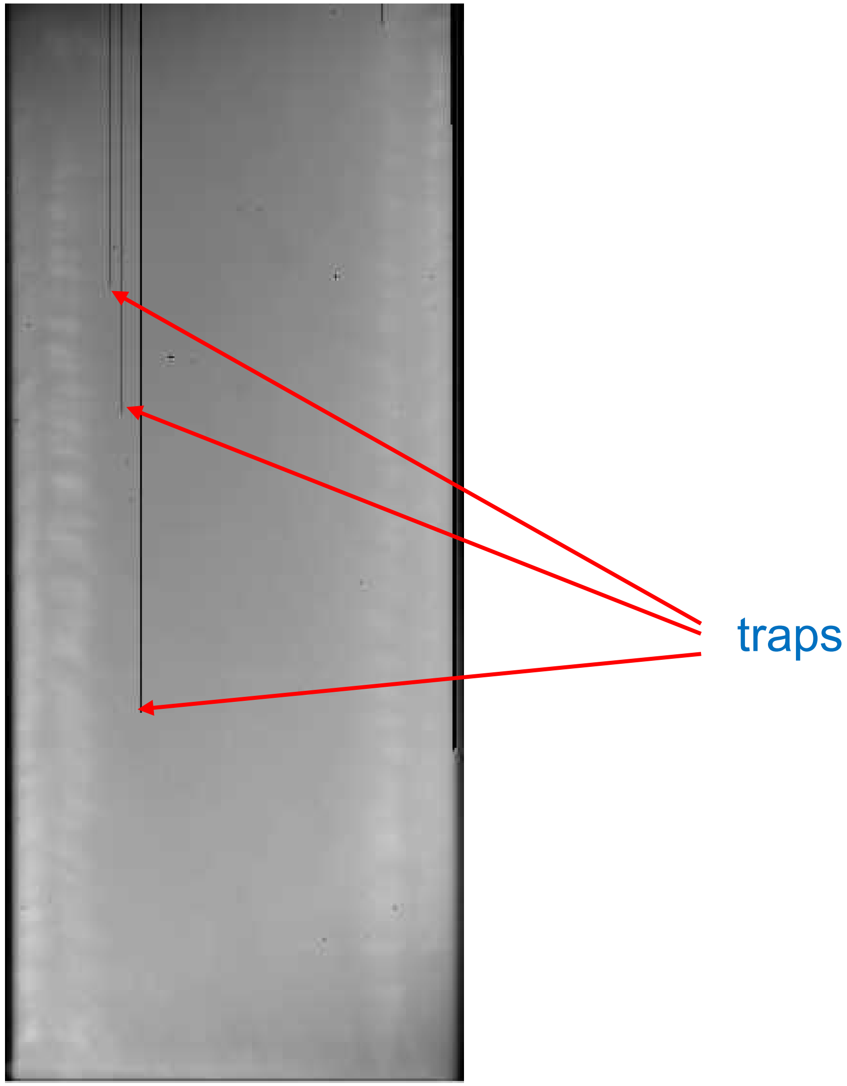


bad CTE

Part of the original image is smeared with an exponential decay function, producing “tails”:



Defects: dark columns

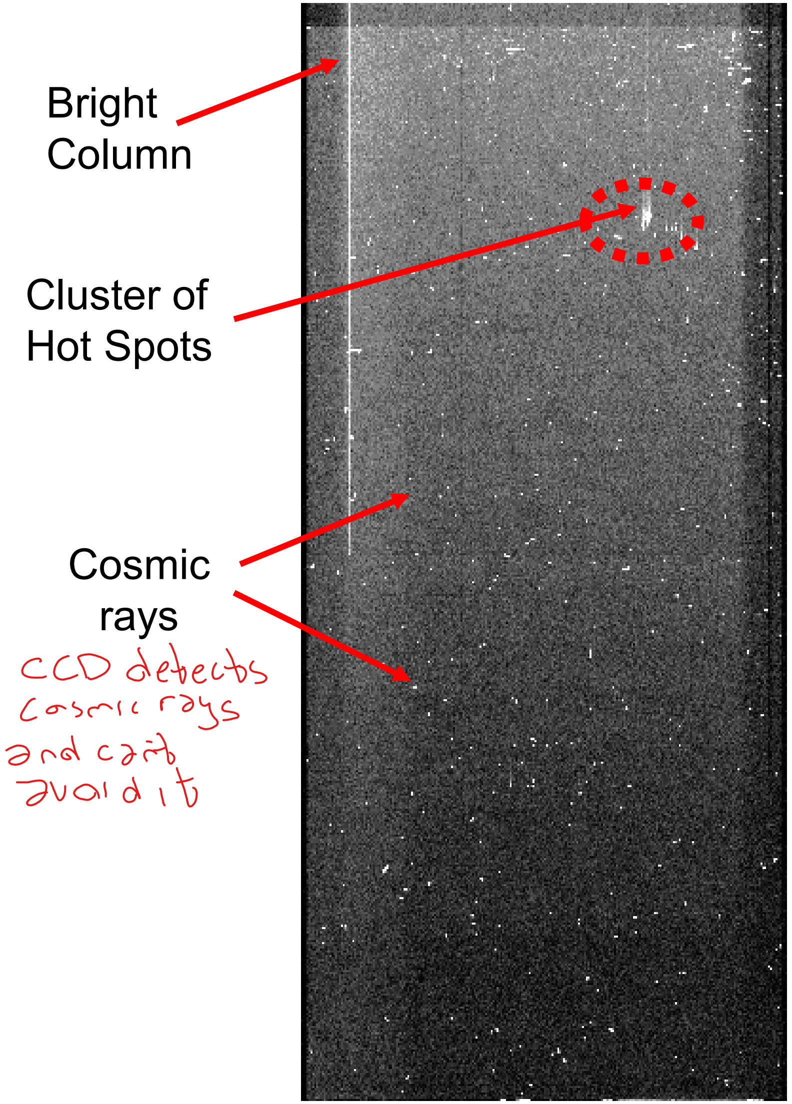


Dark columns

caused by “traps” that block the vertical **transfer** of charge during image readout.

Dark columns are removed by calibration.

Other defects



CCD defects
cosmic rays
and can't
avoid it

Bright columns

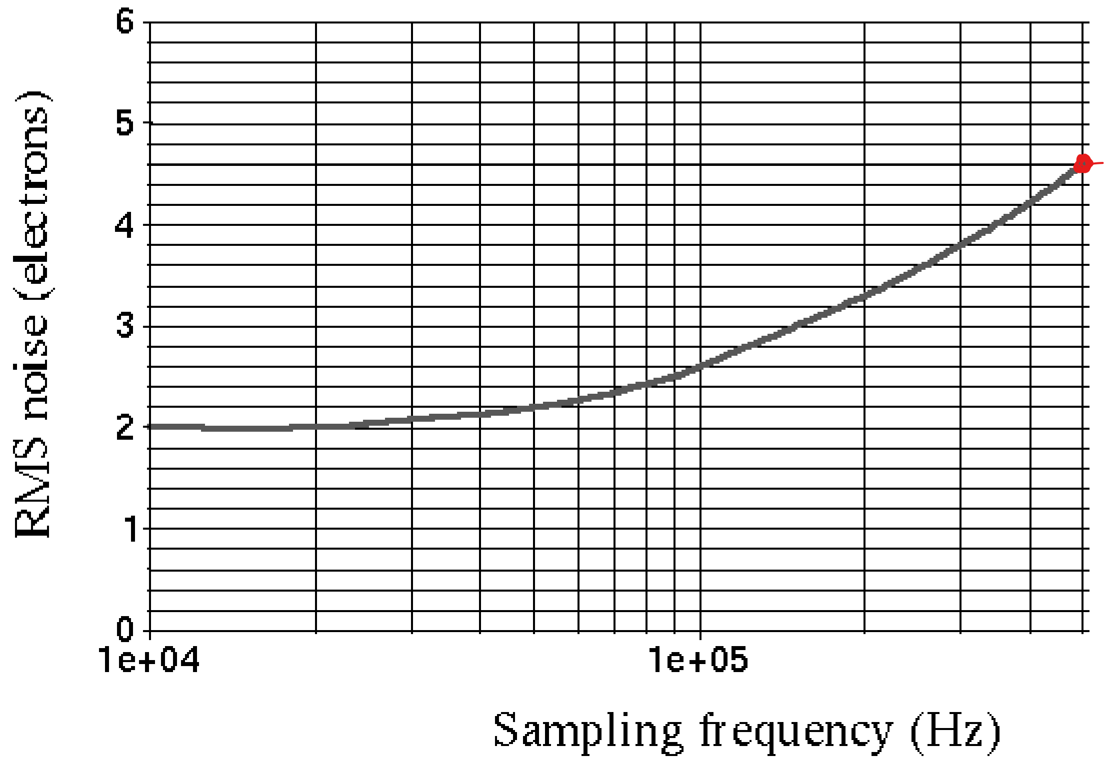
Caused by traps. Electrons contained in such traps can leak out during **transfer** causing a vertical streak.

Hot Spots

Pixels with higher than normal **dark current**. Their brightness increases linearly with exposure times.

Somewhat rarer are light-emitting defects which are hot spots that act as tiny LEDs and cause a halo of light on the chip.

Readout noise (1/3)



$V_n = \sqrt{S_v \cdot \Delta f}$ → sampling freq

variance noise read

spectral density

Mainly due to amplifier noise.

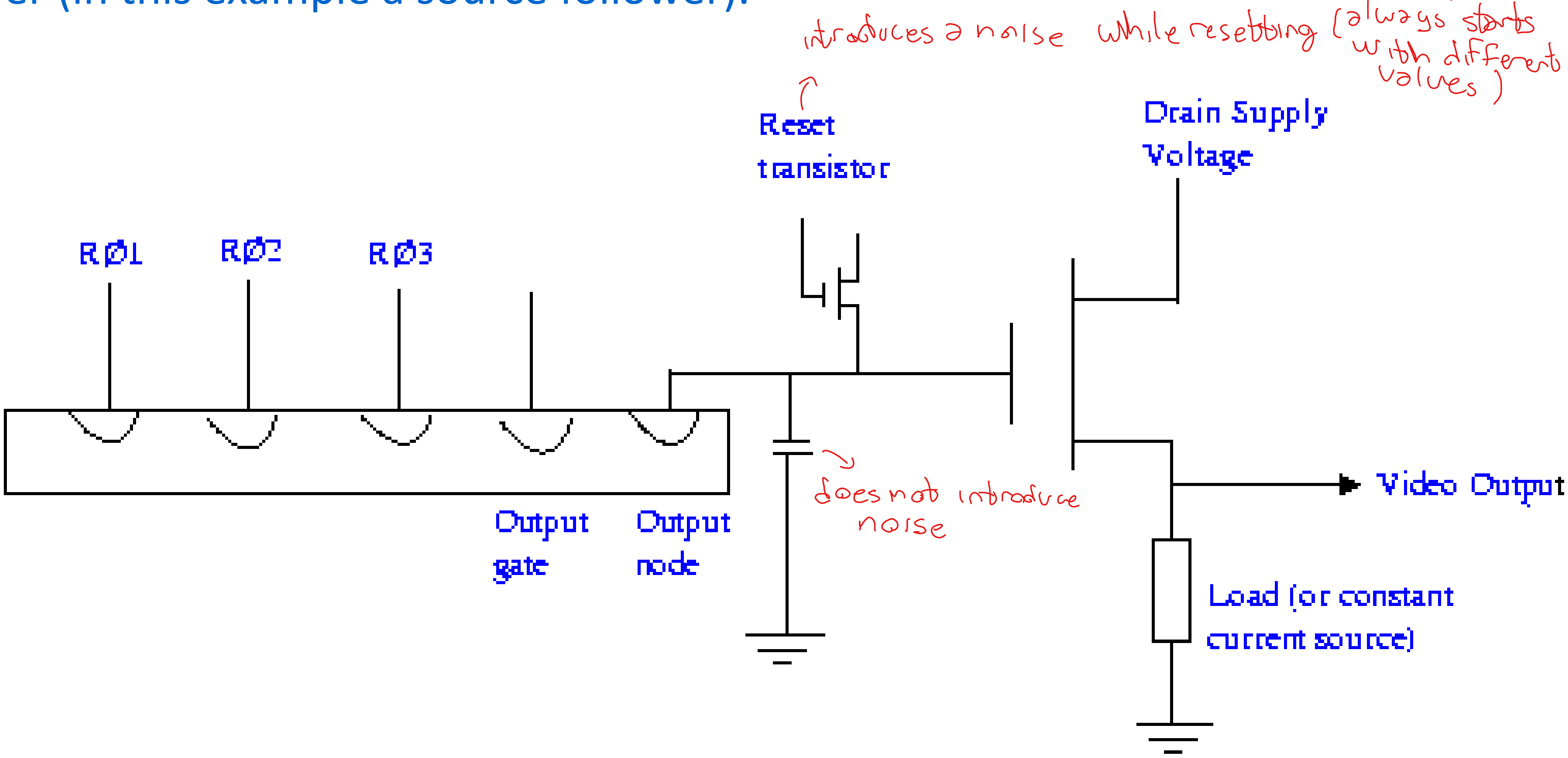
It can be reduced by reducing the bandwidth (slower readout).

= rate at which each pixel is read by the CCD

f_s = 500kHz → T_s = 2µs

Assuming 12Mpx → $T_{readout}$ = 2µs × 12Mpx = 24s !!

The readout circuit consists of a storage capacitor, a rest transistor and a voltage amplifier or buffer (in this example a source follower).



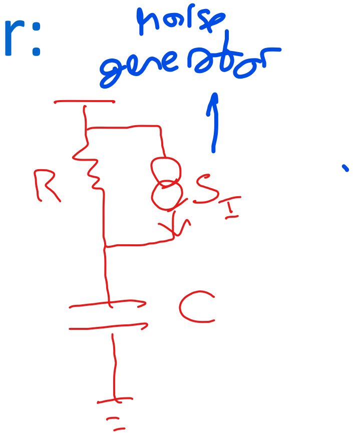
Reset noise

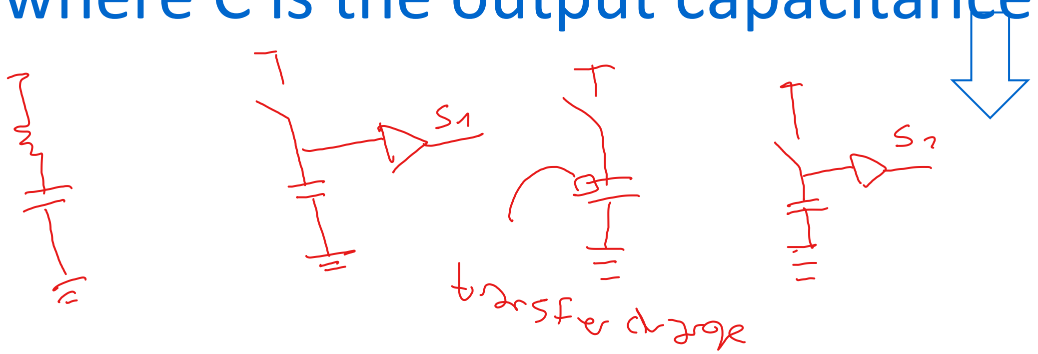
Noise associated with recharging the output storage capacitor:

$$\sigma Q_{reset} = \sqrt{kTC}$$

where C is the output capacitance.

$\sigma_{noise} = \sqrt{S_n \Delta f}$



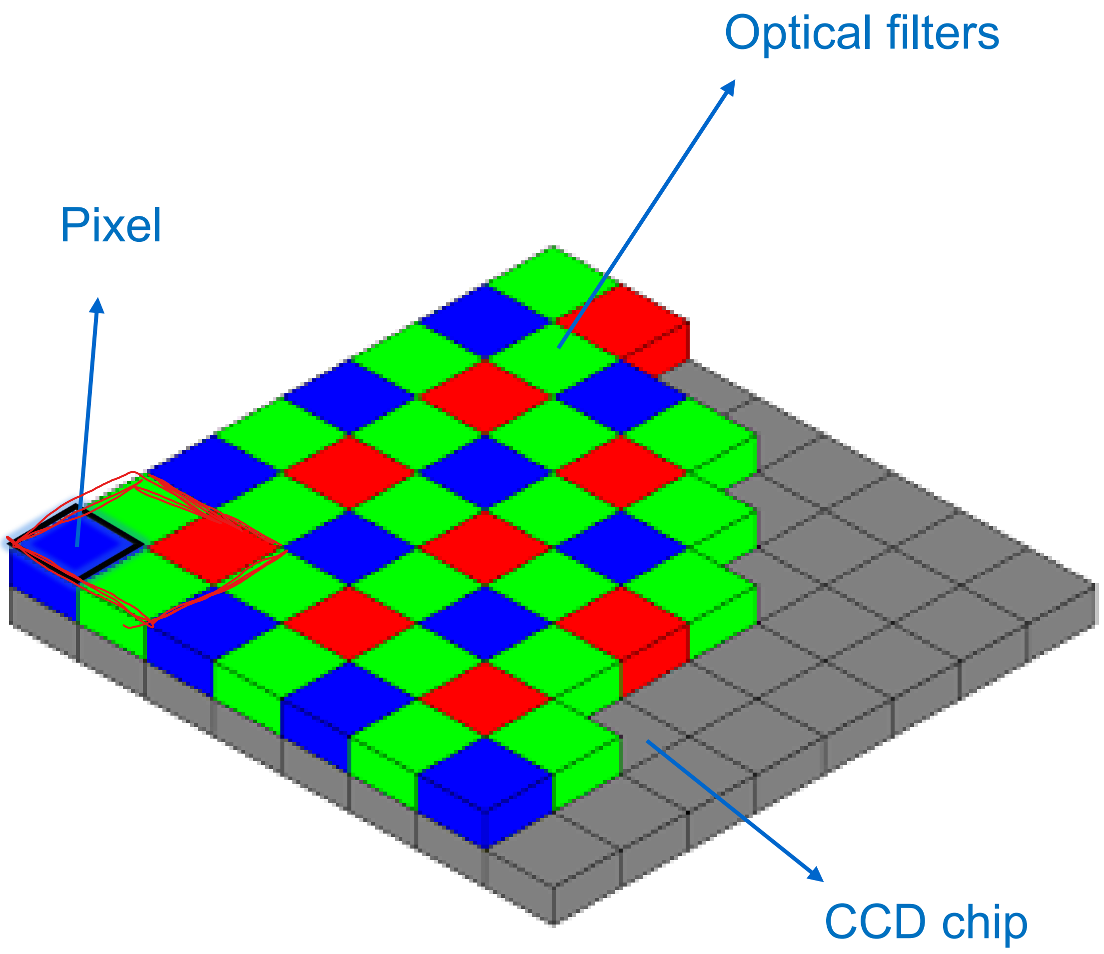


start resetting, sample noise, transfer charge, sample noise

This is removed by correlated double sampling

→ The output voltage is measured after reset and again after readout. The first value is subtracted from the second.

Color filtering



Bayer array

= most common RGB color filter

Since the human eye is more sensitive to green than to the other two colors, the Bayer array has twice as many green color filters.

This also means that with the Bayer array, the human eye can detect more detail than if the three colors were used in equal measures in the filter.

Demosaicing algorithm are used to “fill in” missing color information for each pixel

Types of CCD

we don't want the CCD to register light during readout

Full frame entire chip exposed to light

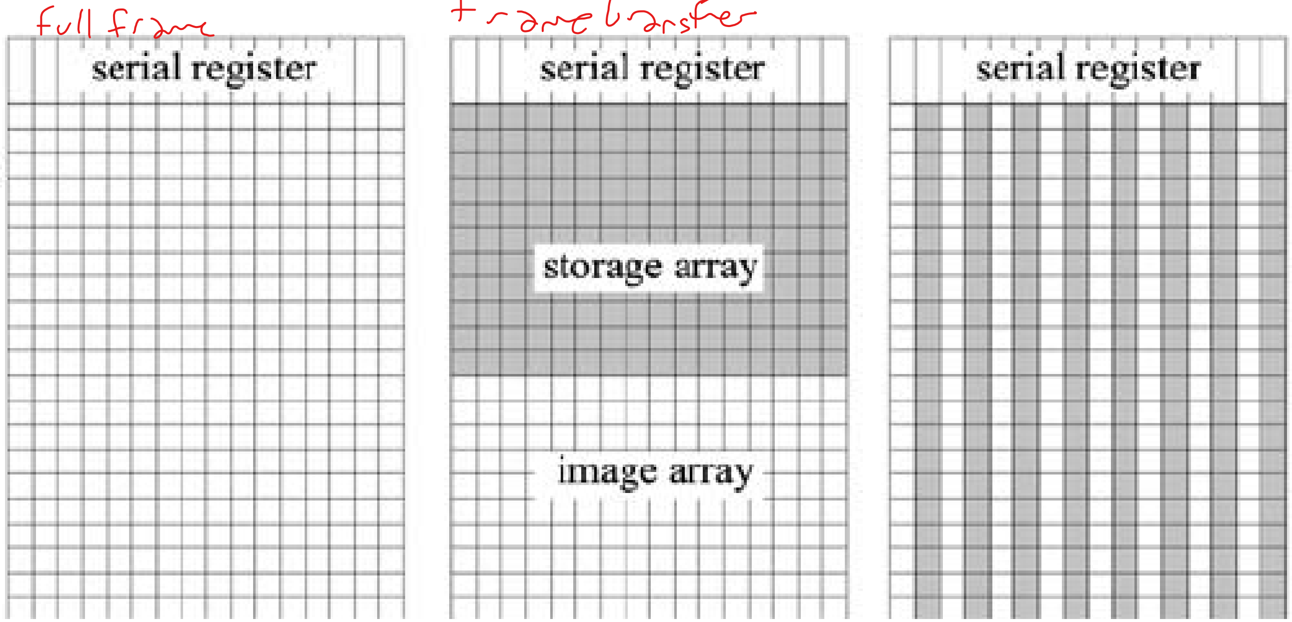
→ long readout time, signal corrupted during readout (shutter is needed) mechanically covering CCD

Frame transfer the chip upper (or lower) part is protected against light and the image is only made in the lower part of the chip.

Fast transfer from uncovered to masked region + slow readout from masked region.

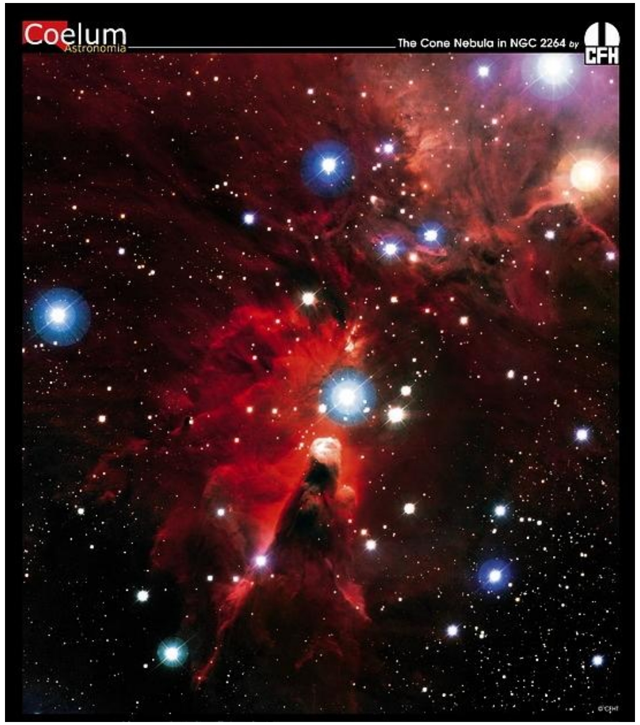
Interline transfer every other line is protected from light.

Uncovered line is transferred to masked line for readout.



CCD applications

- Digital cameras
- Optical scanners
- Microscopy and biology
- Astrophotography (galaxies, nebulae)
- Infrared photography (night vision, VLSI testing)



CMOS active pixel image sensor

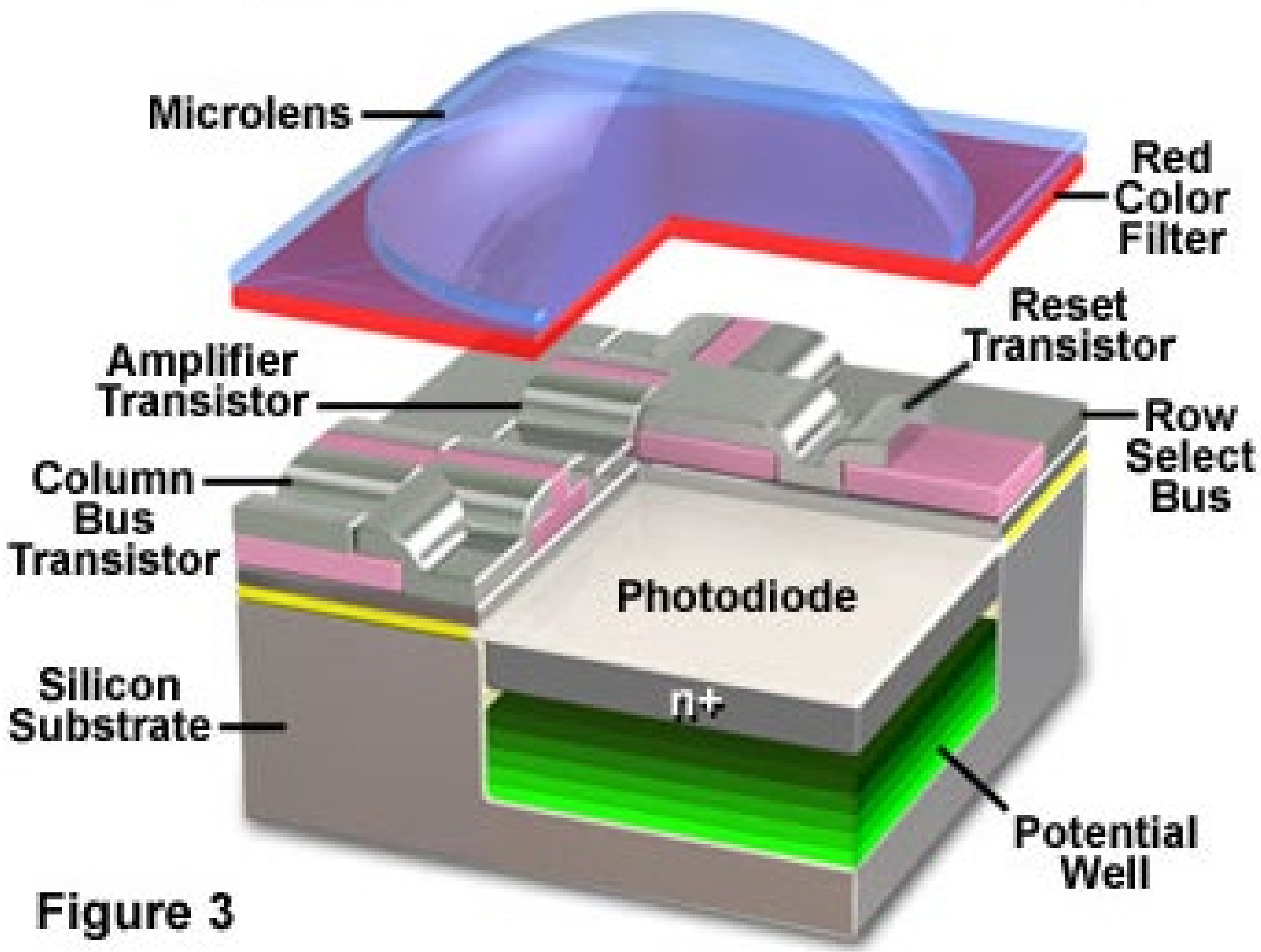
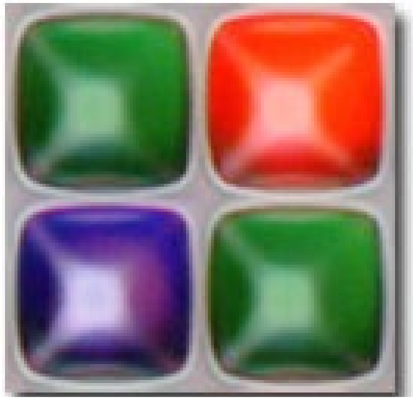
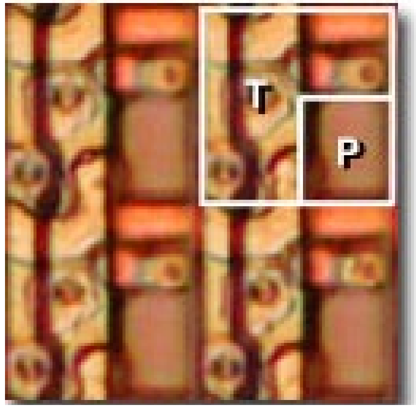


Figure 3





T ≈ 70%

P ≈ 30%

fill factor

FF ≈ 30%

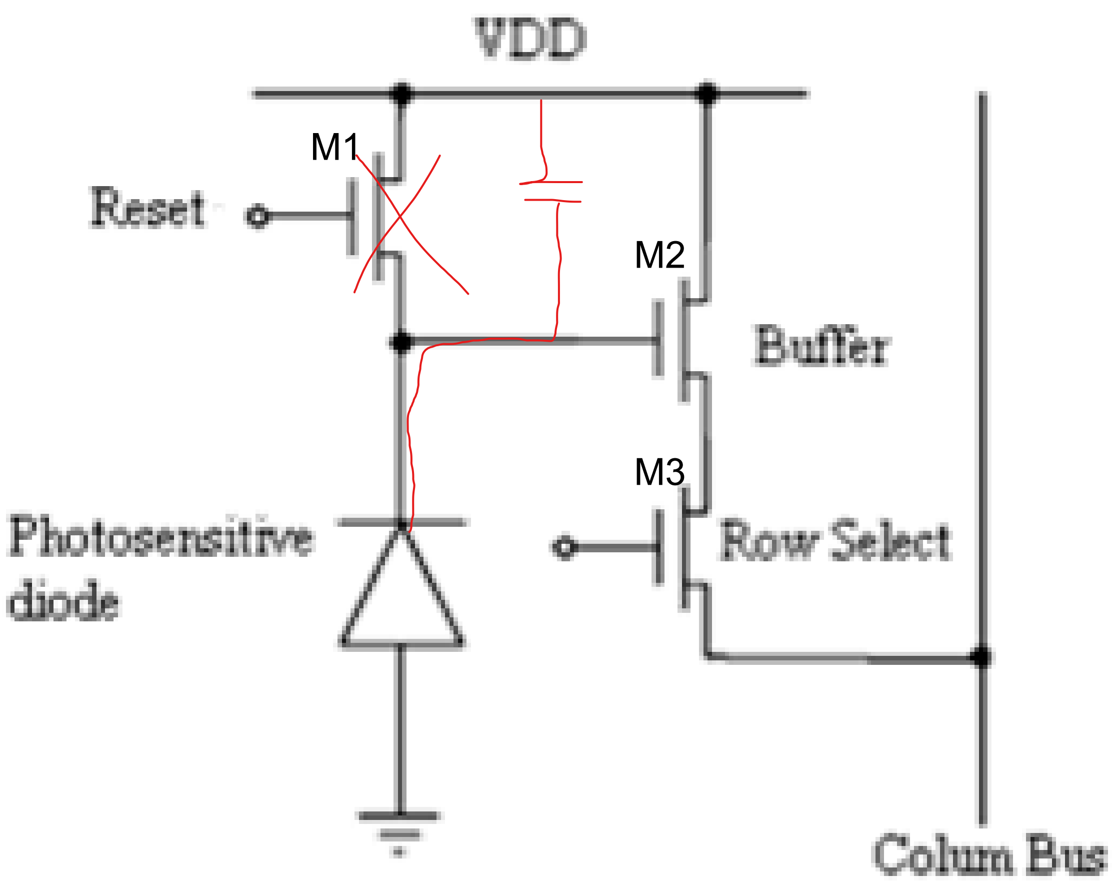
Both the **photodiode** and **readout amplifier** are incorporated into each pixel

This enables the charge accumulated by the photodiode to be converted into an amplified voltage inside the pixel and then transferred in sequential rows and columns to the analog signal-processing portion of the chip.

Main components of pixels:

- Photodiode
- 3 transistors
- Busses → metal lines to let signals travel
- Bayer filter
- Micro-lens

3 transistors APS



M1

Reset Transistor

to restore initial condition before exposure.

M2

Amplifier transistor - source follower.

The load being common to all the pixels in a column.

M3

Row-select transistor

It connects the pixel output to the column bus for readout.

All of the pixels in a particular column connect to a column amplifier.

- Fixed Pattern Noise (FPN) caused by:
  - Variation in photodiode efficiency and noise
  - Mismatches in source follower transistor performance

  FPN is constant and reproducible

  → flat field correction (= on chip subtraction of an image with constant illumination)

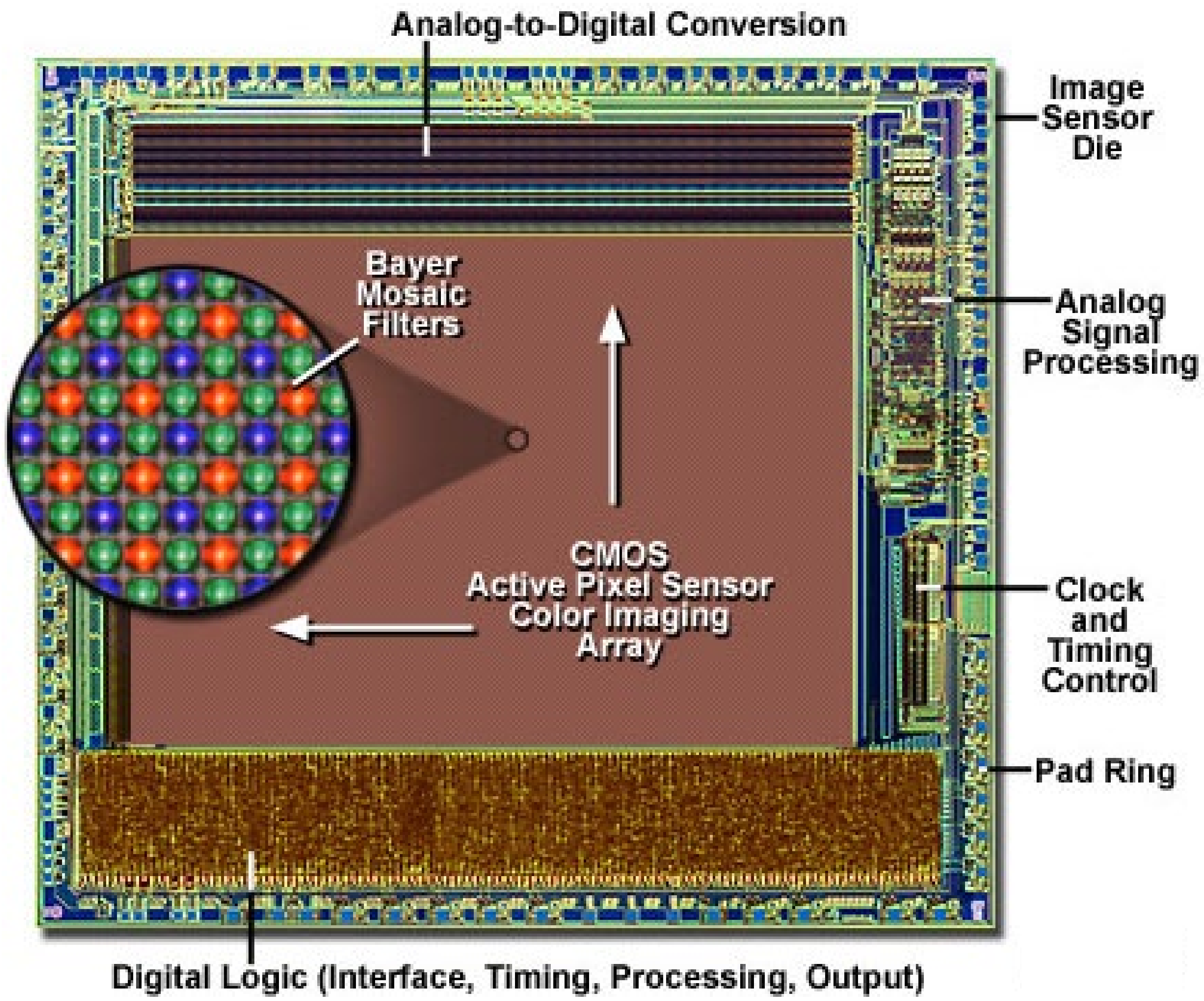
- Reset noise (kTC noise)

$$v_n = \sqrt{\frac{KT}{C}}$$

- Amplifier noise (1/f noise)

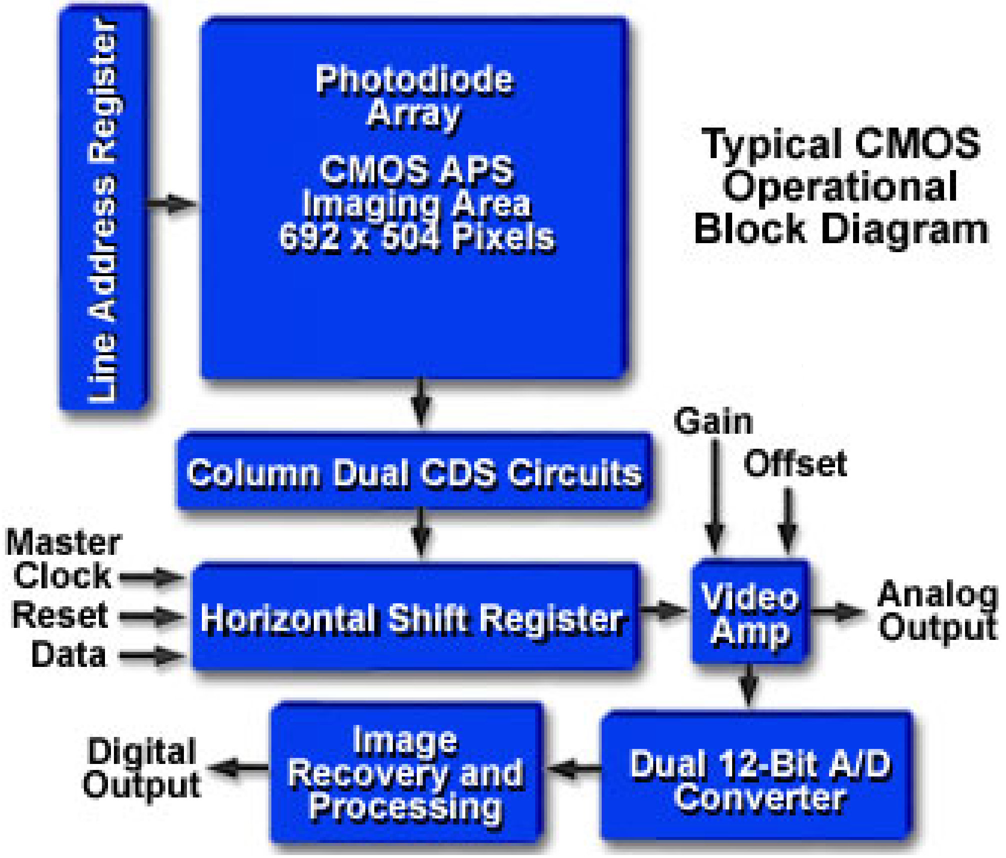
- Photodiode shot noise

CMOS sensor general structure



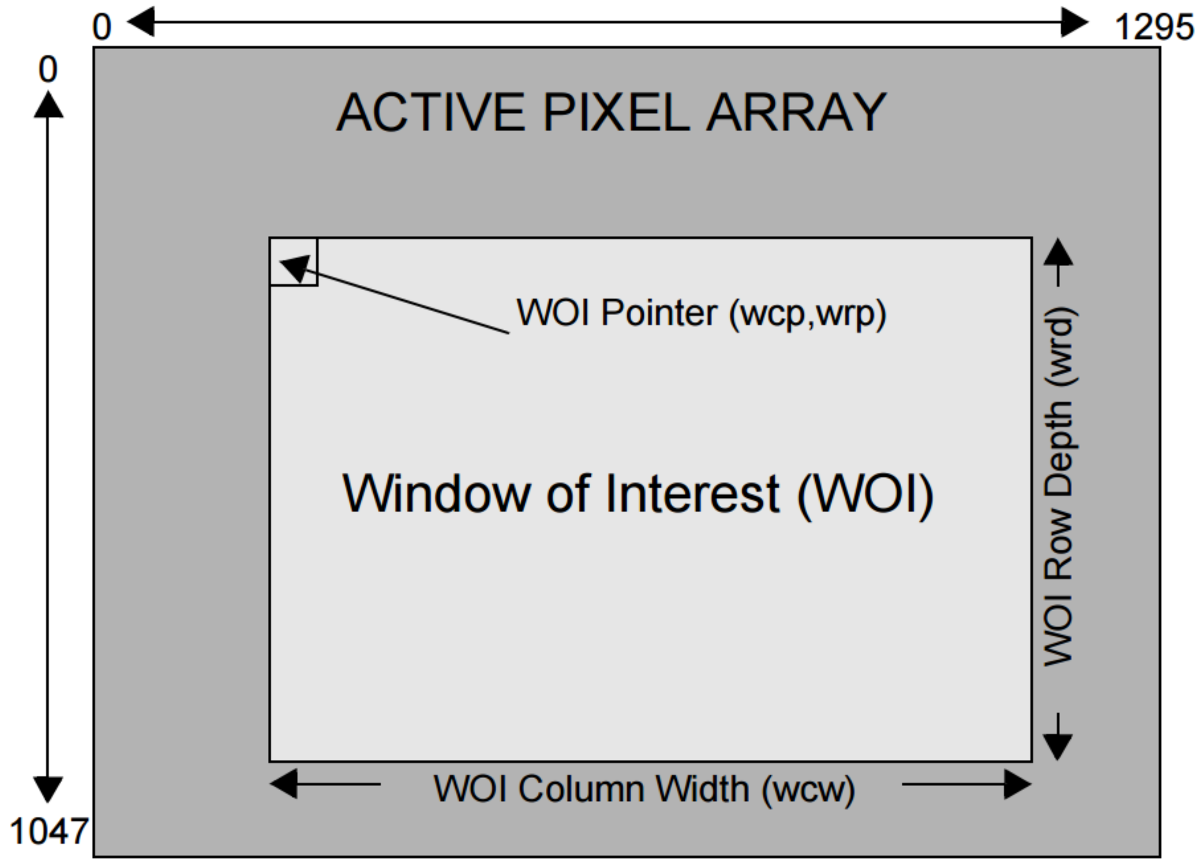
CMOS sensor functional blocks

- VGA resolution (640x480)
  + shielded pixels for black level compensation
- Line address register for readout
- Correlated Double Sampling circuit
  to reduce the pixel reset noise
- Horizontal Shift Register
- Video Amplifier with adjustable gain and offset
- ADC converter
- Image processing
  (interpolation, smoothing, white and black balancing…)

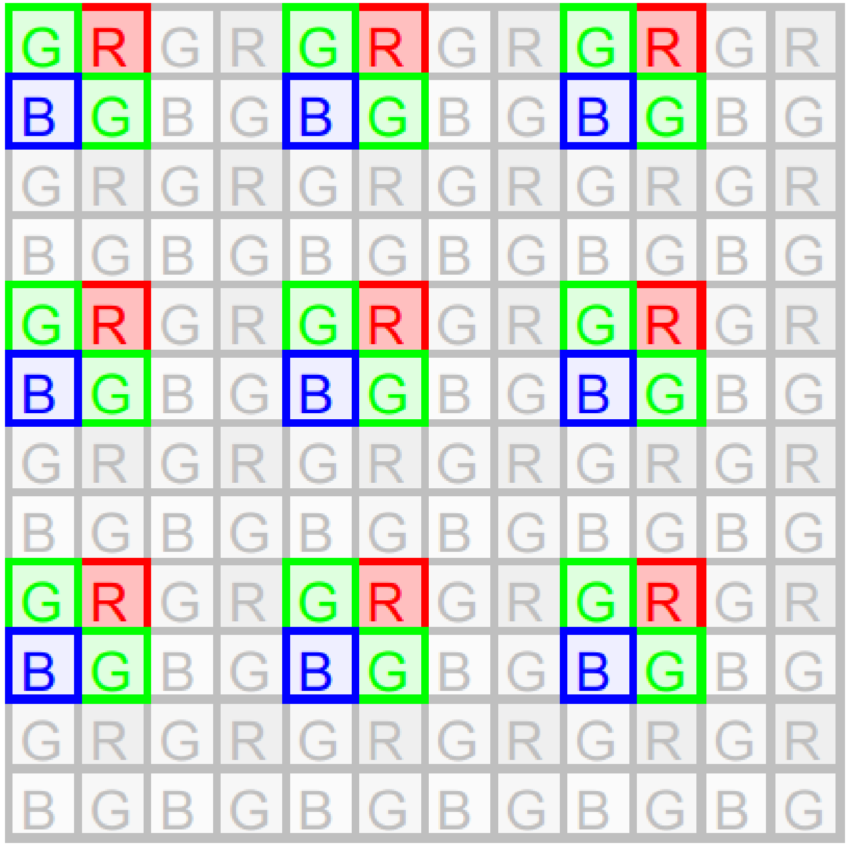


Alternative:
One Video Amp + ADC for each column
(high frame rate)

Window of interest



Window subsampling

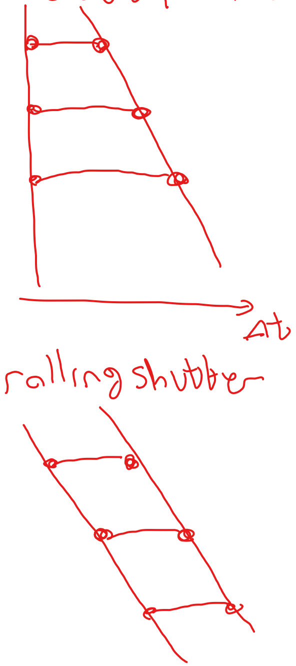


→ speed up the readout

Rolling shutter

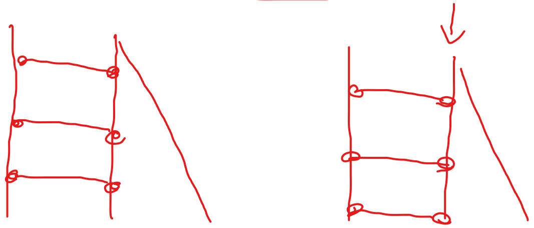
each frame is captured by scanning rows across the scene rapidly, so not all parts of the image of the scene are recorded at the same instant. This produces predictable distortions of fast-moving objects or rapid flashes of light.

readout problem

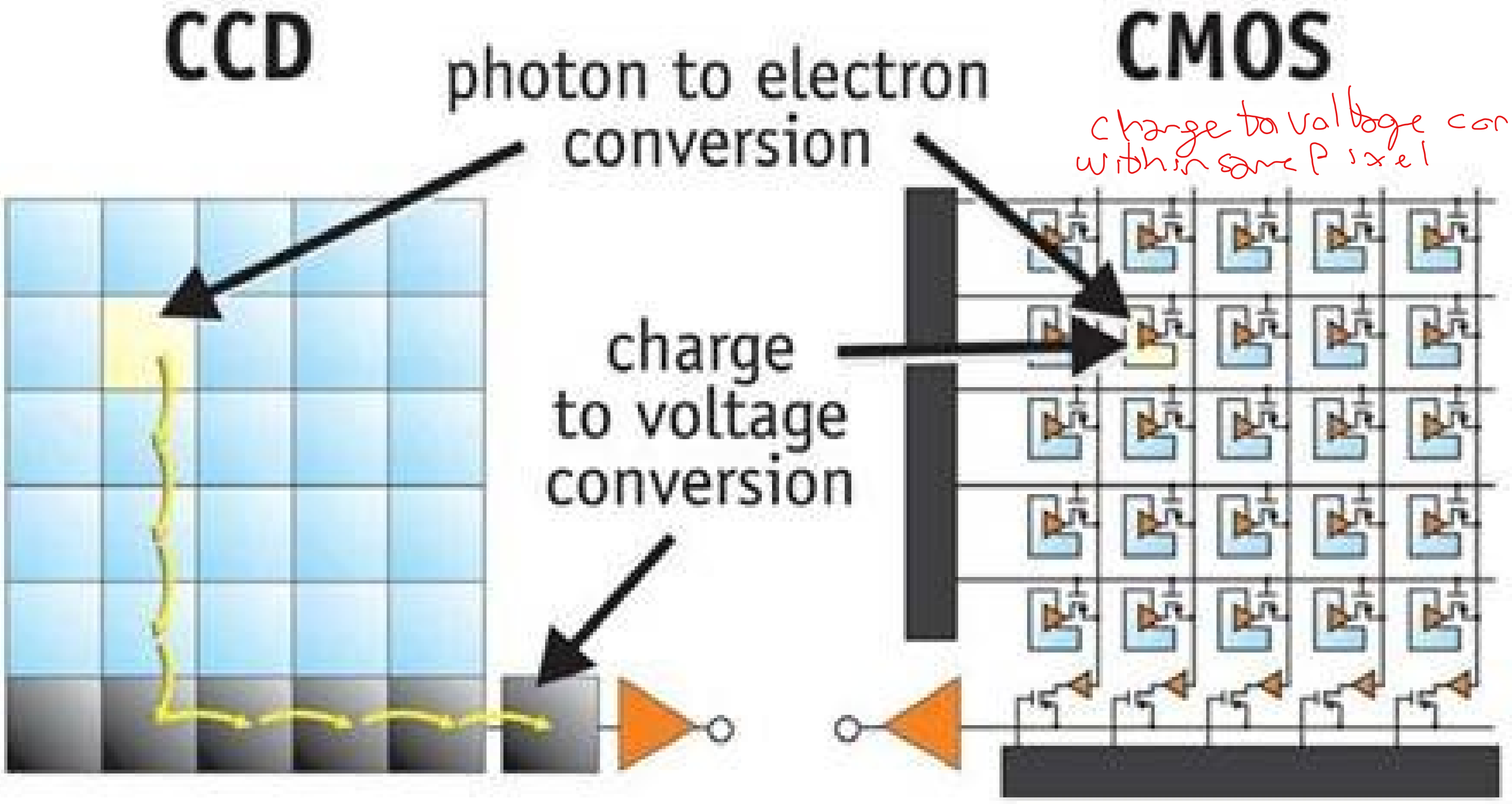


Global shutter

the entire frame is captured at the same instant.



- High Volume Imagers for Consumer Applications (e.g., camera-phones)
- WebCams
- Imagers for Machine Vision (area and line scan)
- High Speed Motion Capture Cameras
- Digital Radiography
- Endoscopy (pill) Cameras
- DSLRs (Digital Single-Lens Reflex) camera


CCD
photon to electron conversion
CMOS
charge to voltage conversion within same pixel
charge to voltage conversion

CCD advantages:

- Uniformity (less structured noise)
- Higher Fill-Factor
- Almost all chip area devoted to light capture
- Higher sensitivity in the Near Infra-Red (NIR)

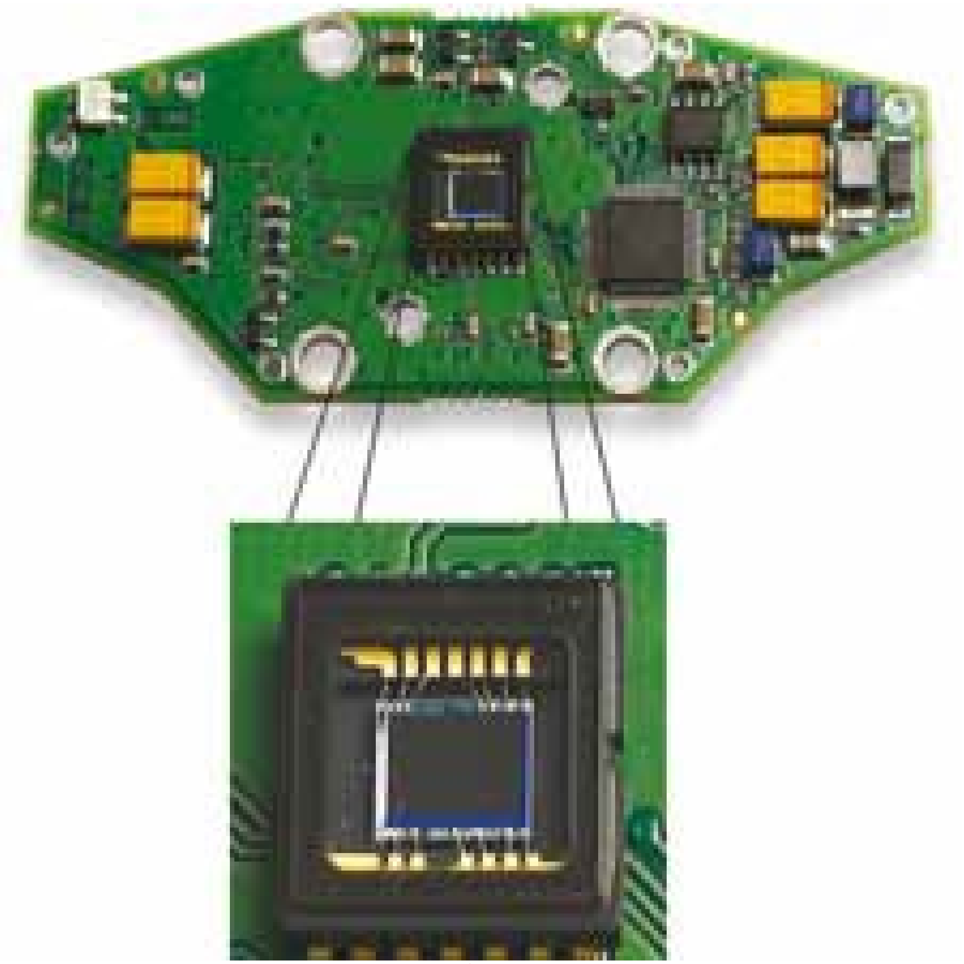
CMOS advantages:

- Faster readout
  (one charge to voltage converter per pixel)
- Selectable active window (for higher frame rate)
- Digital output
- Less electronics outside sensor
  (internal Amplifier, ADC, processing…)
- Less power (→ lower temperature)

Cost considerations

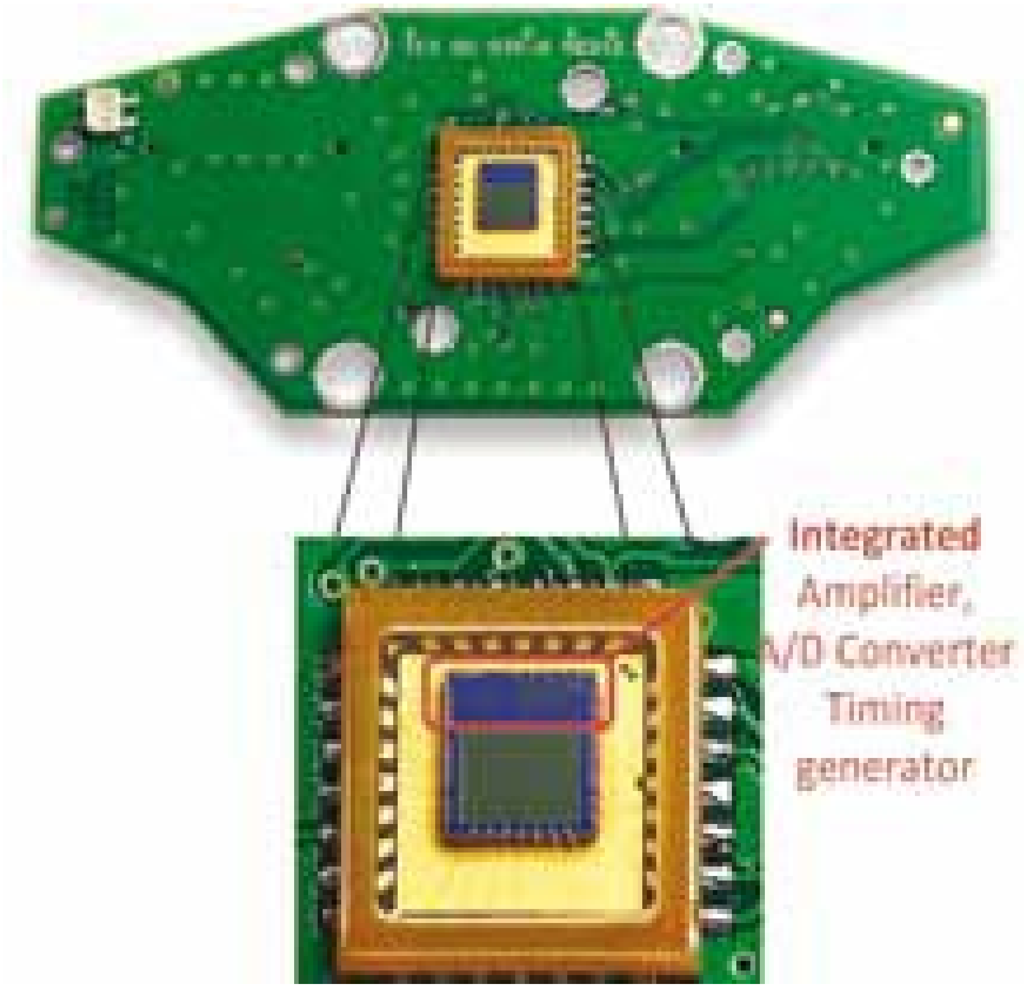
- Custom imager → CCD
- Large scale economy → CMOS

Comparison CCD vs CMOS



a lot of external electronics

CCD sensor



CMOS sensor