Introduction to Image Sensors

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- CCD, CMOS, and distance sensor
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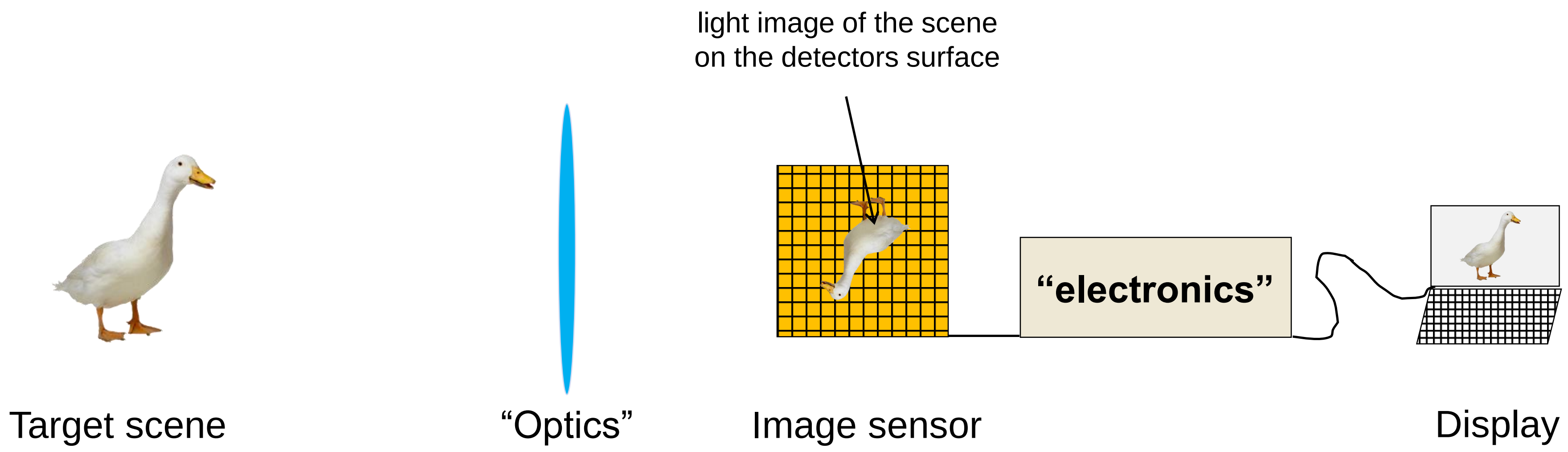
Opto-electronic characteristics of image sensors

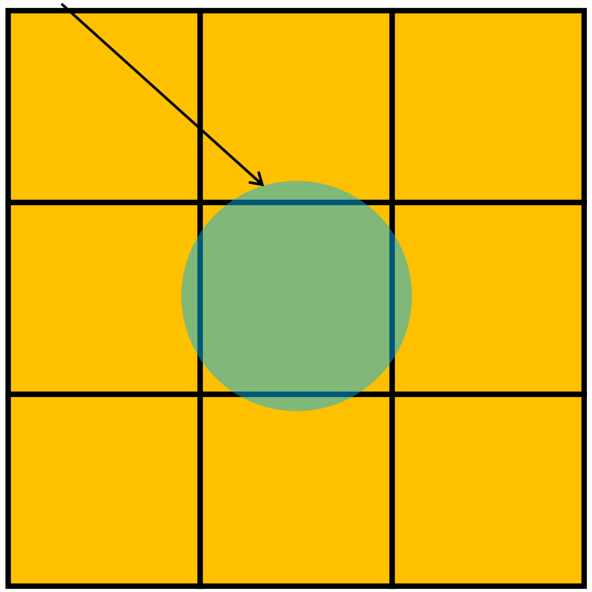
The idea of imaging



1. The role of an image sensor is to convert the imaged light scene to an electronic image
2. The conversion of light's energy to electrical signal occurs in a pixel
3. Pixel is the smallest imaging element in an image sensor

From photons to electrons

imaged element of
the scene



3 × 3 array of pixels

no electrical signal	little electrical signal	no electrical signal
little electrical signal	a lot of electrical signal	little electrical signal
no electrical signal	little electrical signal	no electrical signal

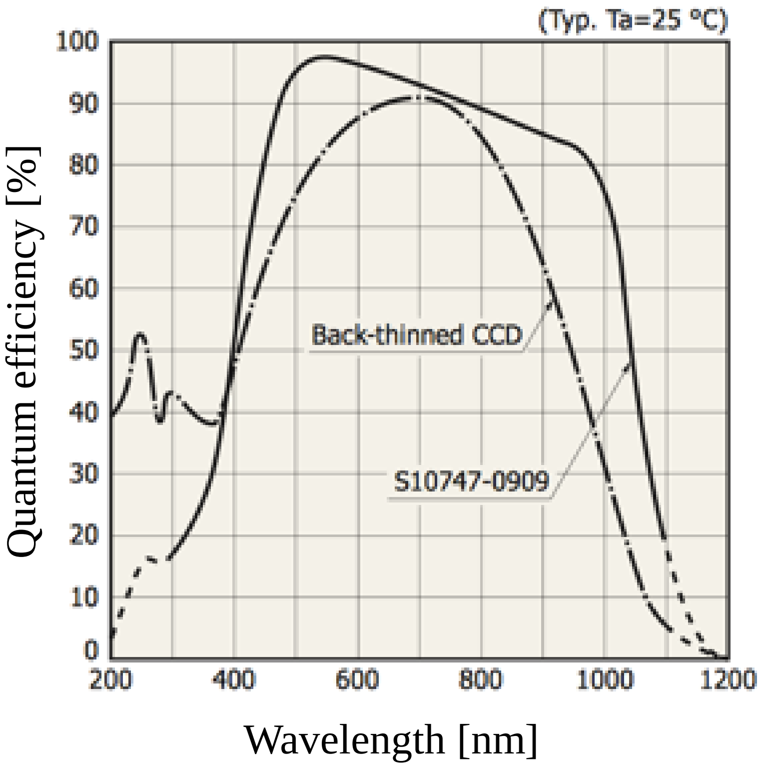
$$S[e^-] = \eta n T_{exp} \quad \text{(signal)}$$

η – quantum efficiency

n – photon irradiance per pixel

T_{exp} – Exposure time

Quantum efficiency

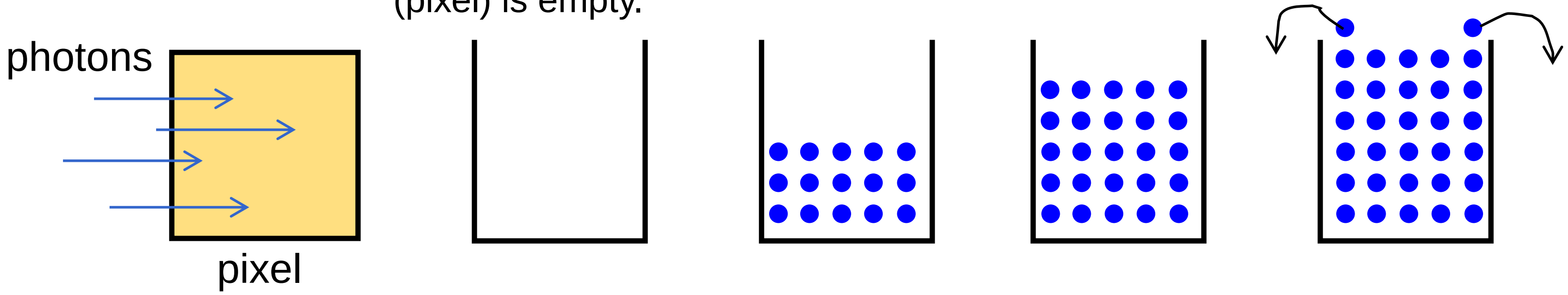


Example of a quantum efficiency curve for an image sensor (back-illuminated CCD).

1. Quantum efficiency is a ratio of the number of electrons produced in a pixel (signal) to the number of photons that struck the pixel during the integration time.
2. It is a function of wavelength
3. It depends on the architecture of the sensor and the construction material (e.g., silicon)

Pixel as a charge bucket: full well capacity

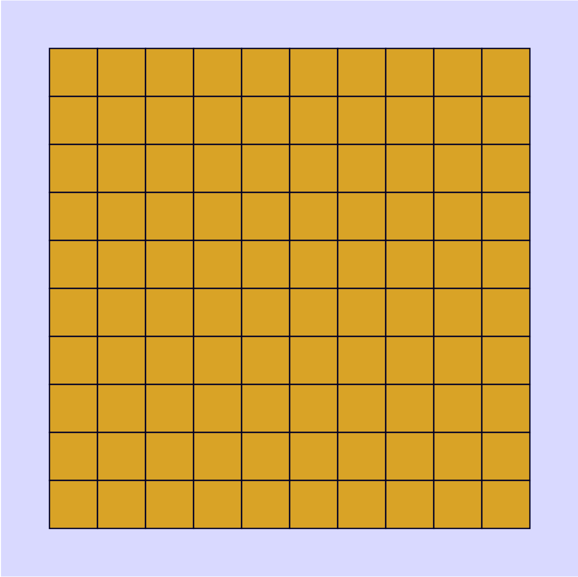
At the beginning of the integration, the bucket (pixel) is empty.



A CCD image showing blooming. CMOS imagers do not exhibit blooming.

The bucket has a finite capacity (Full Well Capacity, FWC). FWC is expressed in electrons (e.g., 300,000 e^-). If the amount of the generated charge exceeds the full-well capacity, the charge may flow to the neighboring pixels - a phenomenon known as **blooming**.

Uniformity



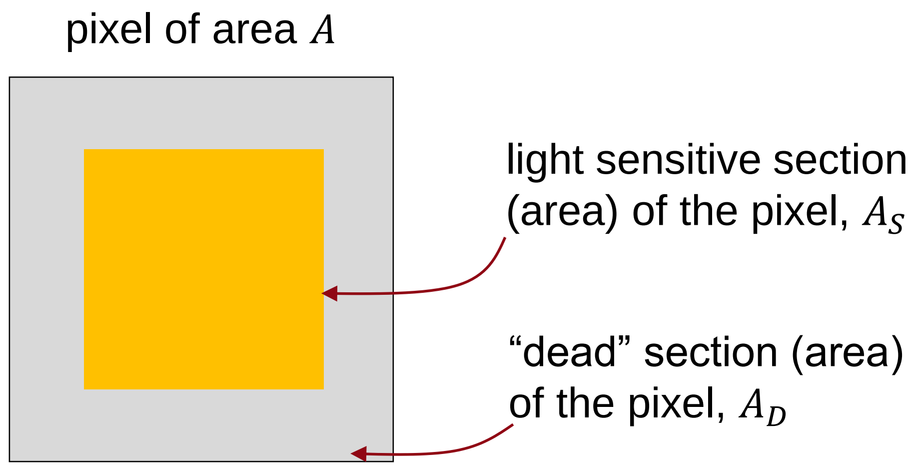
Uniformly illuminated image sensor

The resulting displayed image is not uniform.

Factors affecting uniformity

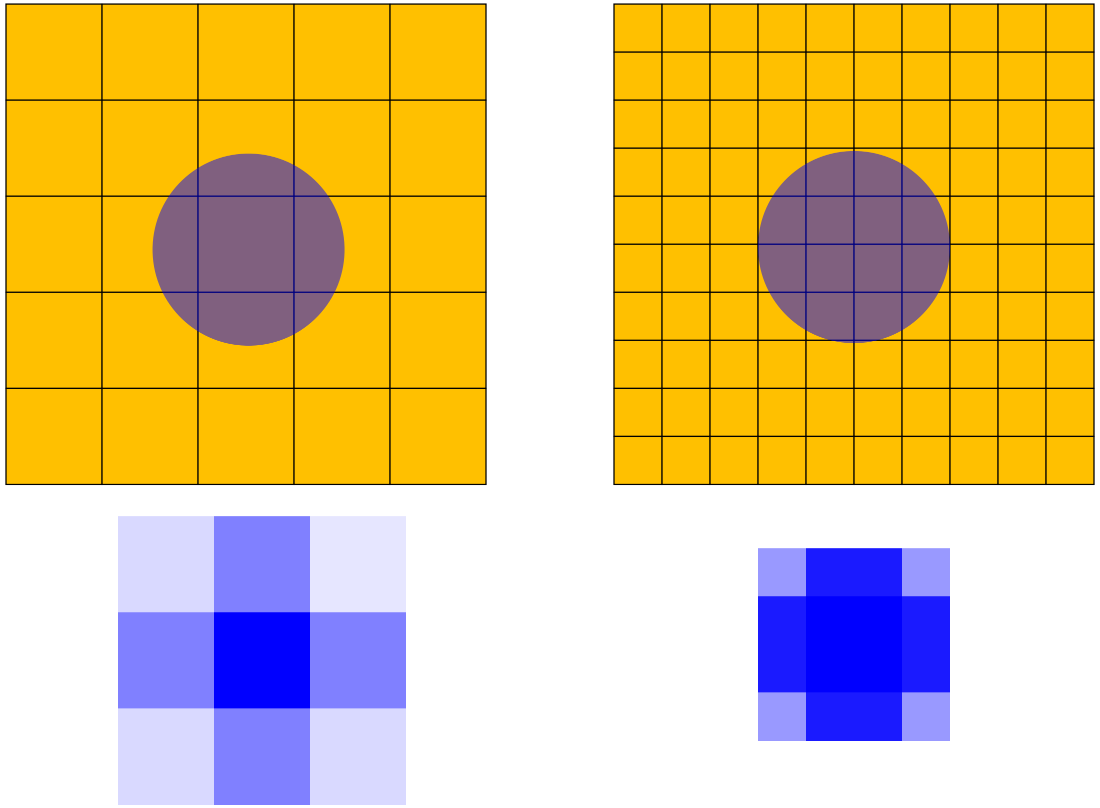
1. Spatially varying quantum efficiency
2. Pixel defects
3. Optics (e.g., vignetting)
4. Foreign objects on the sensor/optics

Fill factor



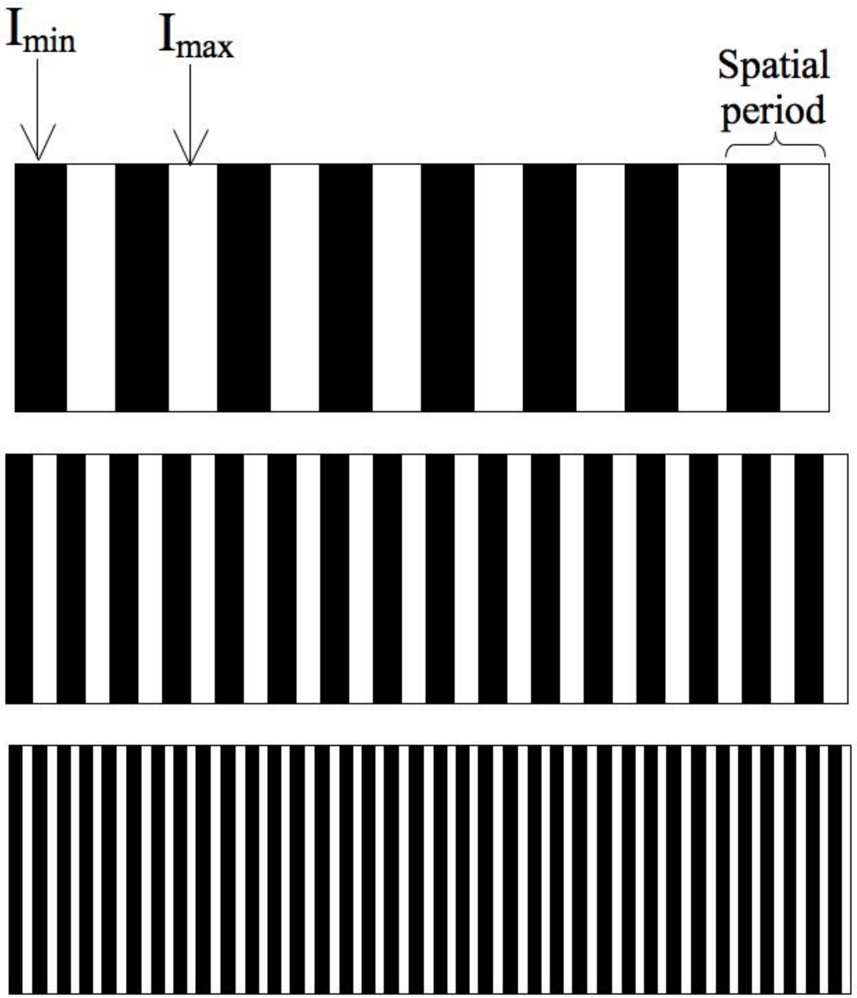
$$f = \frac{A_S}{A} = \frac{A_S}{A_S + A_D}$$ (fill factor f)

Resolution



For a smaller pixel size, the displayed image better resembles the object

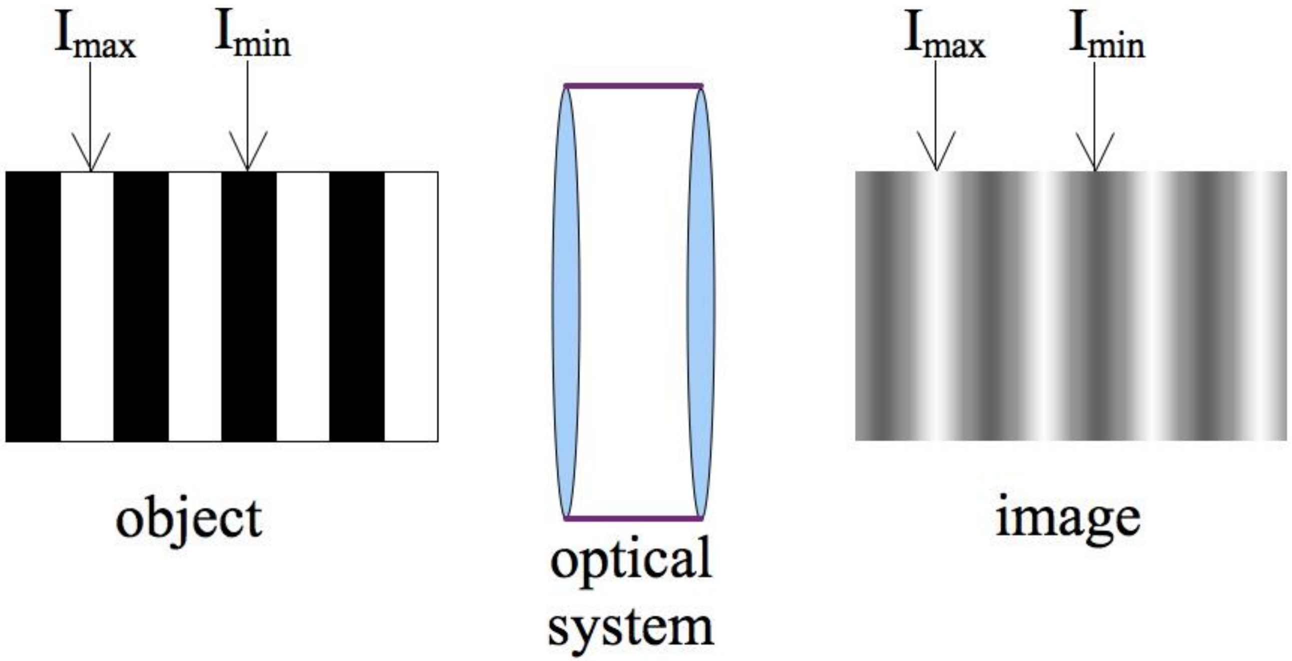
Line frequency and modulation



$$M = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

(Modulation)

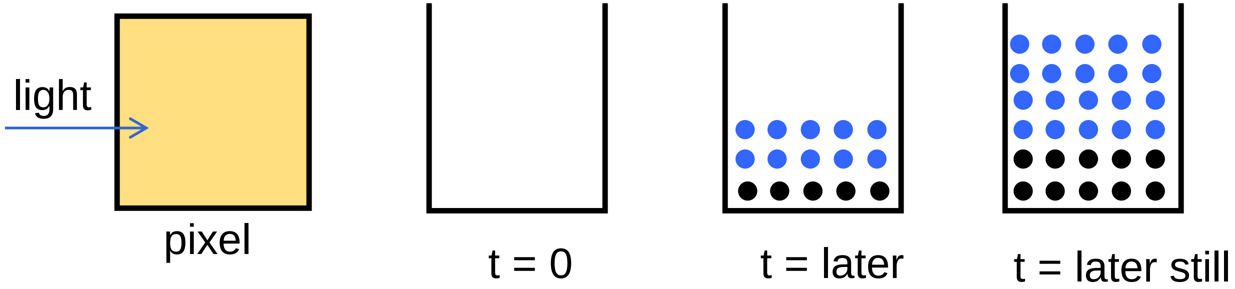
Modulation transfer function

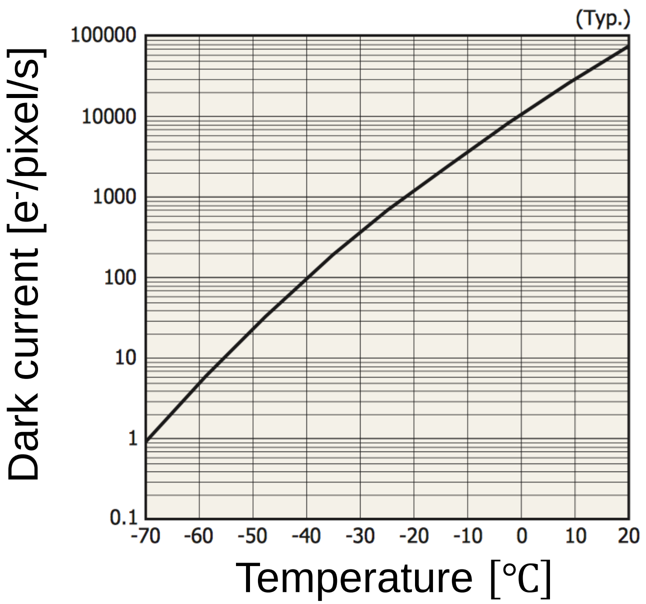


$$MTF = \frac{M_i}{M_o}$$

Modulation Transfer Function (MTF) is a measurement of the camera’s ability to transfer contrast from the object to the image plane at a specific resolution.

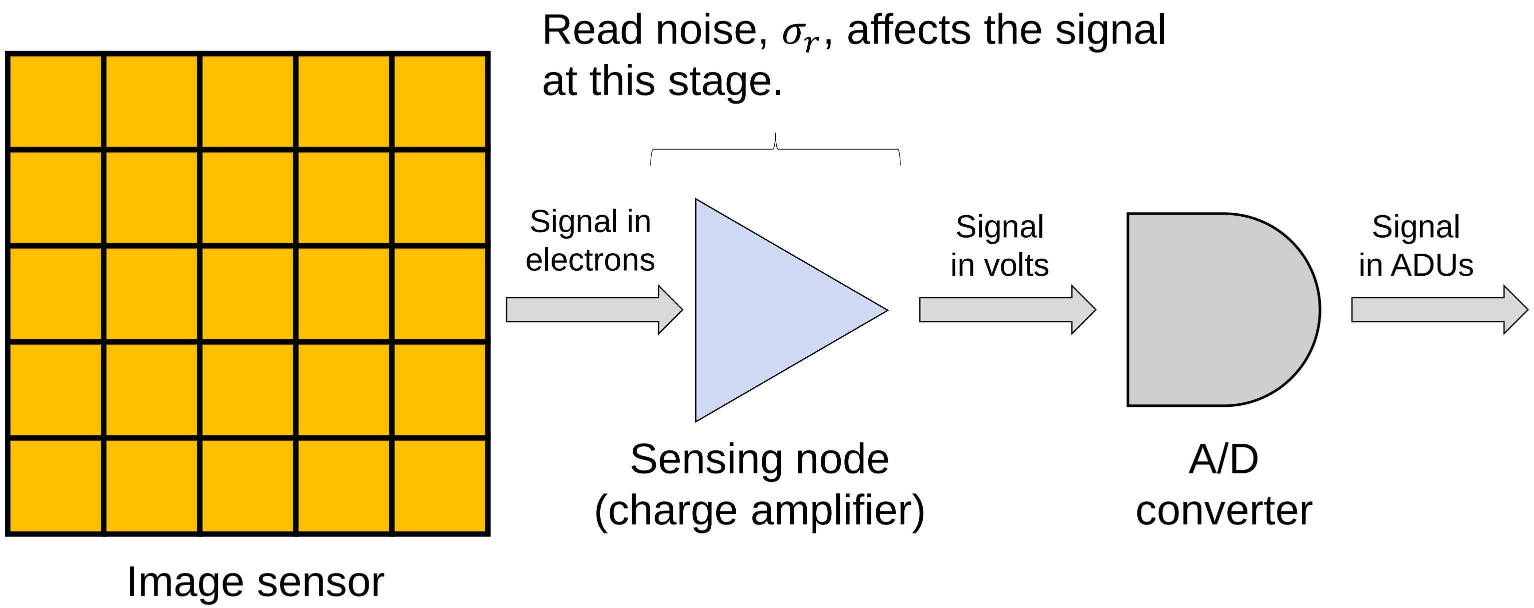
Dark current





Example of dark current as a function of temperature plot.

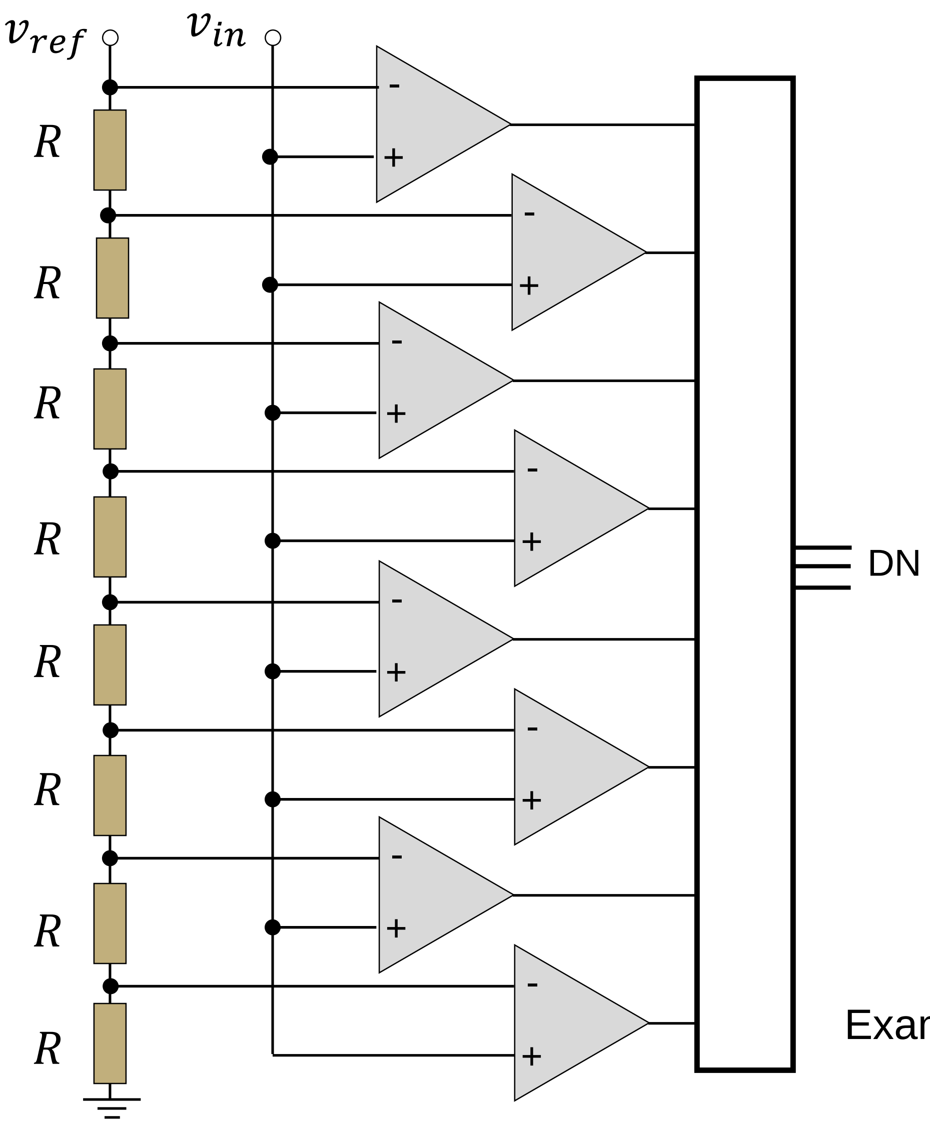
Read noise


Read noise, σ_r, affects the signal at this stage.
Signal in electrons
Signal in volts
Signal in ADUs
Sensing node (charge amplifier)
A/D converter
Image sensor

Read noise comments

1. Read noise is often expressed in electrons (e^-). Its value can range from few e^- to hundreds of e^-.
2. The mean value of the read noise is 0. If read noise is, for example, 10 e^-, the value expresses a standard deviation around the mean. Read noise has a Gaussian distribution.
3. In a CCD, all of the pixels are read with the same charge amplifier (well…., not always), thus the read noise is the same for all of the pixels.
4. In a CMOS, each pixel may have its own charge amplifier, thus read noise may be different for different pixels.
5. Read noise represents the noise floor of an image sensor.
6. Read noise depends on temperature and readout speed.

Analog to digital converter



N – number of bits

Number of gray levels $= 2^N$

Example of a 3-bit A/D converter

Camera gain

$$S[e^-] = K[e^-/ADU] \times S[ADU]$$

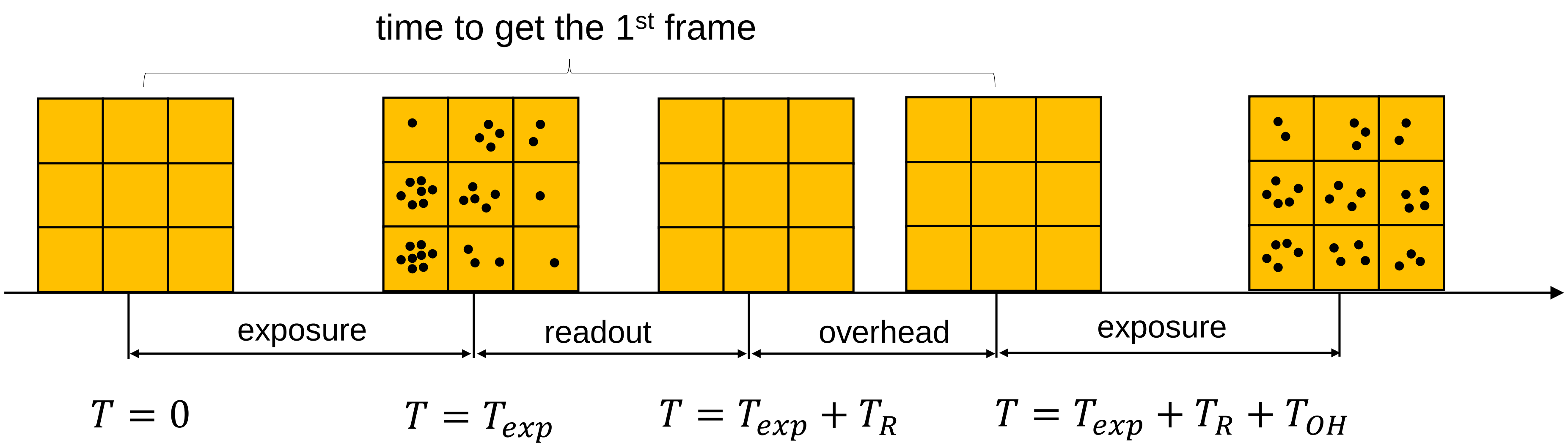
K – Camera gain (really a conversion factor) is determined by the A/D converter. K provides a conversion from ADUs to e^-. All noise calculations should be performed in e^-.

Dynamic range

$$DR = \frac{FWC}{\sigma_r}$$

DR – Dynamic range, a ratio of full well capacity and read noise. High dynamic range is desirable. DR determines the smallest detectable signal changes.

Frame rate (for CCD)



$$\text{frame rate [frames/s]} = 1/(T_{exp} + T_R + T_{OH})$$

Major noises in image sensors

1. Read noise, σ_r. This noise is independent of the signal.
2. Signal photon shot noise, $\sigma_S = \sqrt{S} = \sqrt{\eta n_\gamma T_{exp}}$
3. Dark current shot noise, $\sigma_D = \sqrt{D} = \sqrt{i_D T_{exp}}$
4. Background shot noise, $\sigma_B = \sqrt{B} = \sqrt{\eta n_B T_{exp}}$
5. Multiplication noise; excess noise figure F in EMCCD
6. Fixed pattern noise. This noise is corrected for by ”flat fielding.”

Signal to noise ratio (per pixel)

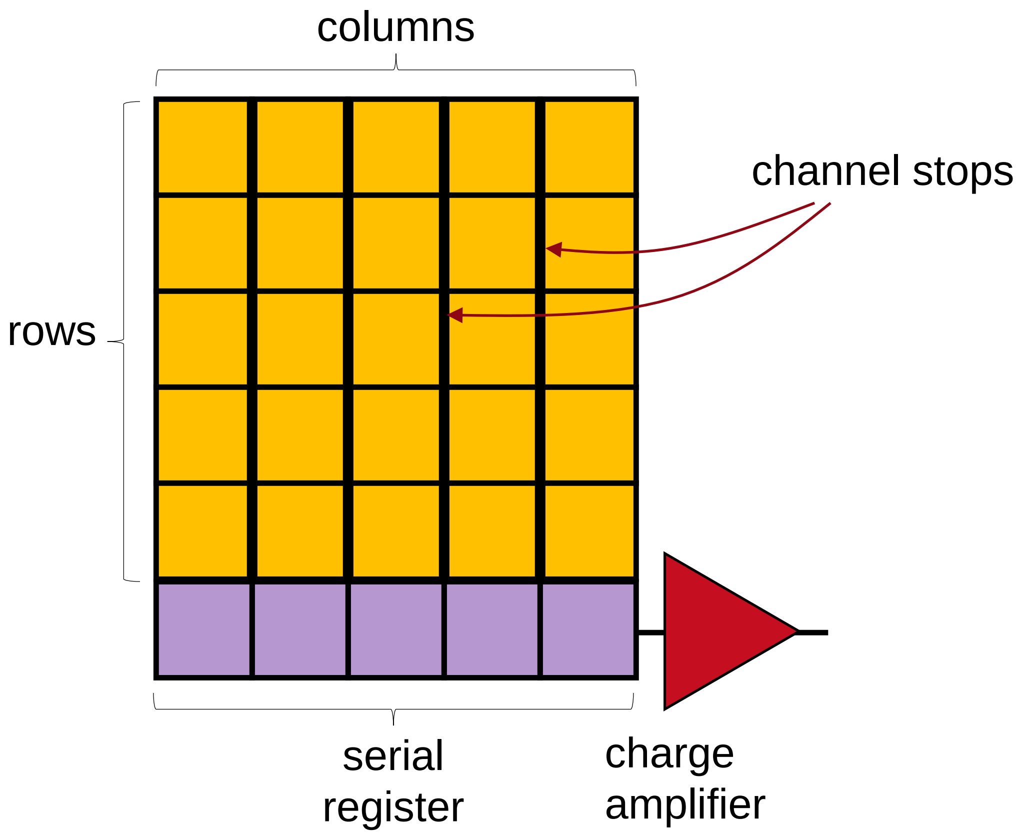
$$\frac{S}{N} = \frac{\eta n_\gamma T_{exp}}{\sqrt{F^2 \eta T_{exp}(n_\gamma + n_B) + F^2 T_{exp} i_D + \left(\frac{\sigma_r}{M}\right)^2}}$$

M – gain ($M = 1$ for CCD and CMOS) and > 1 for EMCCD

σ_r is the same for all pixels in a CCD bit not in a CMOS

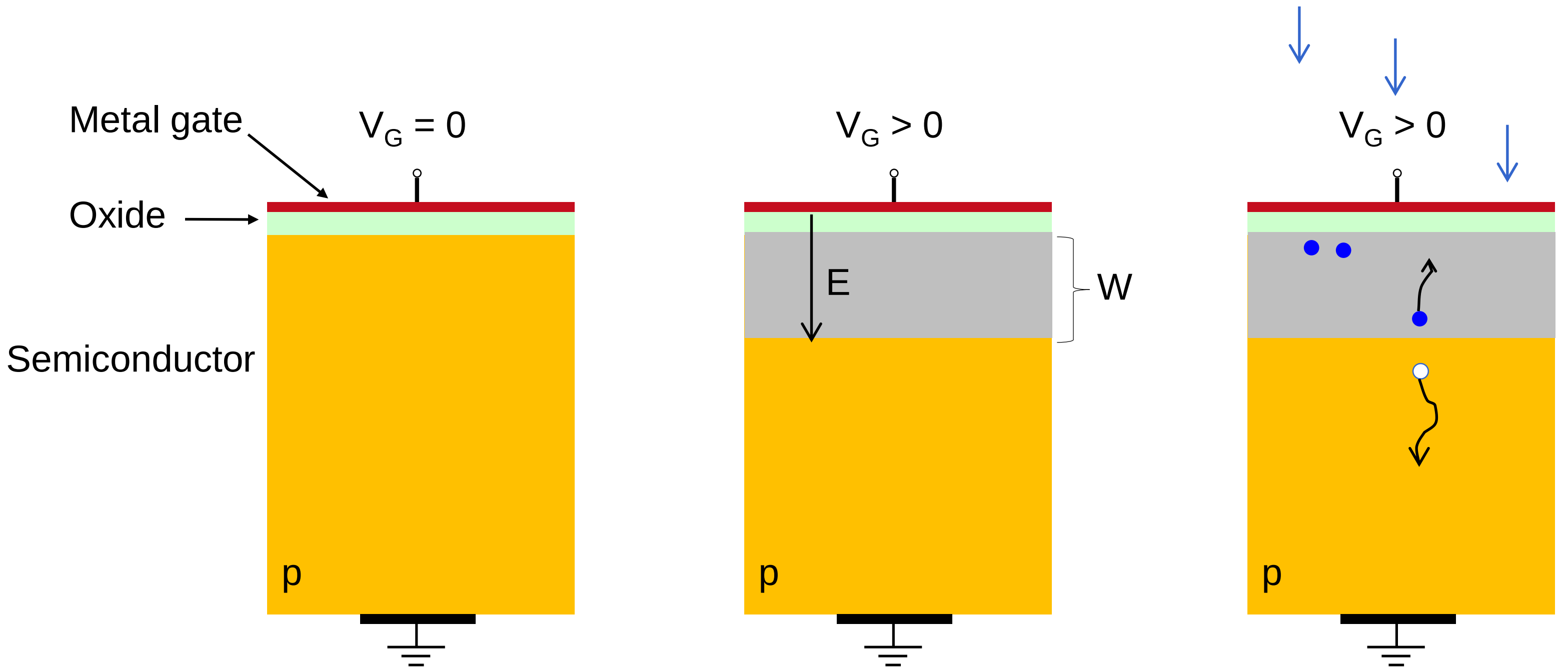
CCD, CMOS, and distance sensor

CCD structure



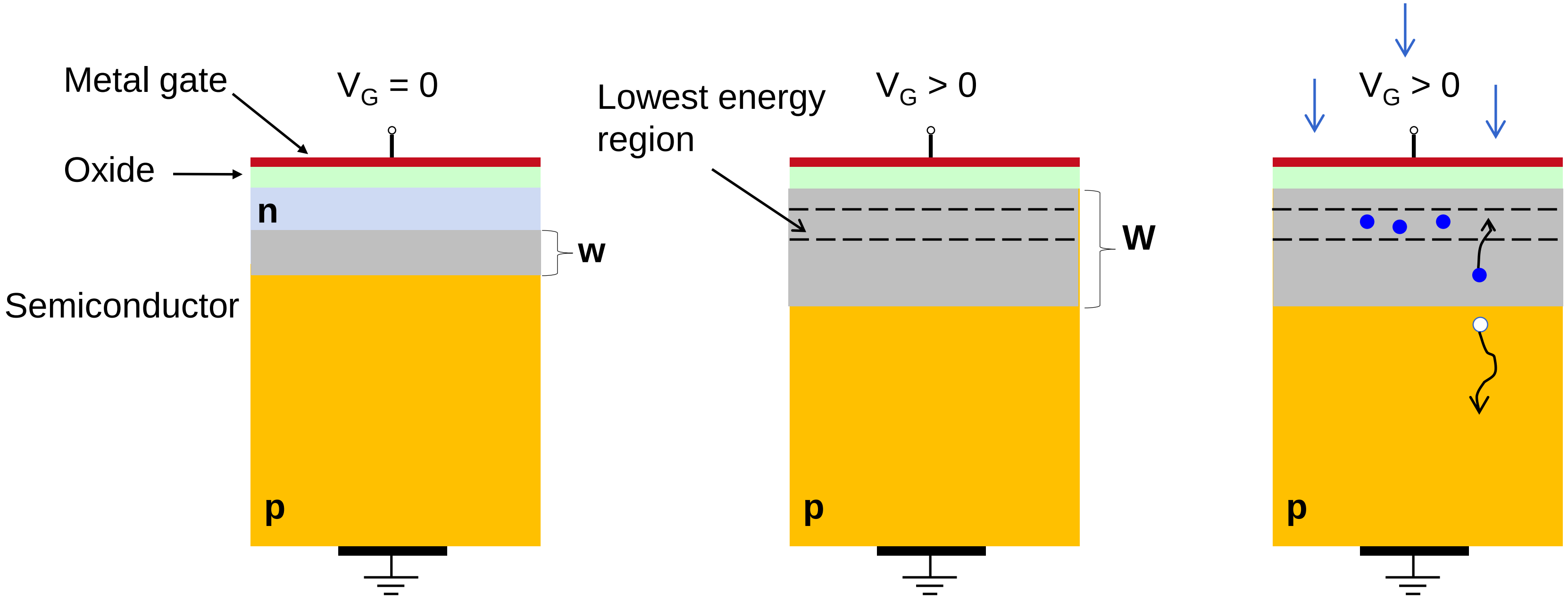
The most basic (highly simplified) structure of a CCD image sensor. Other architectures exist.

MOS Capacitor (surface channel)



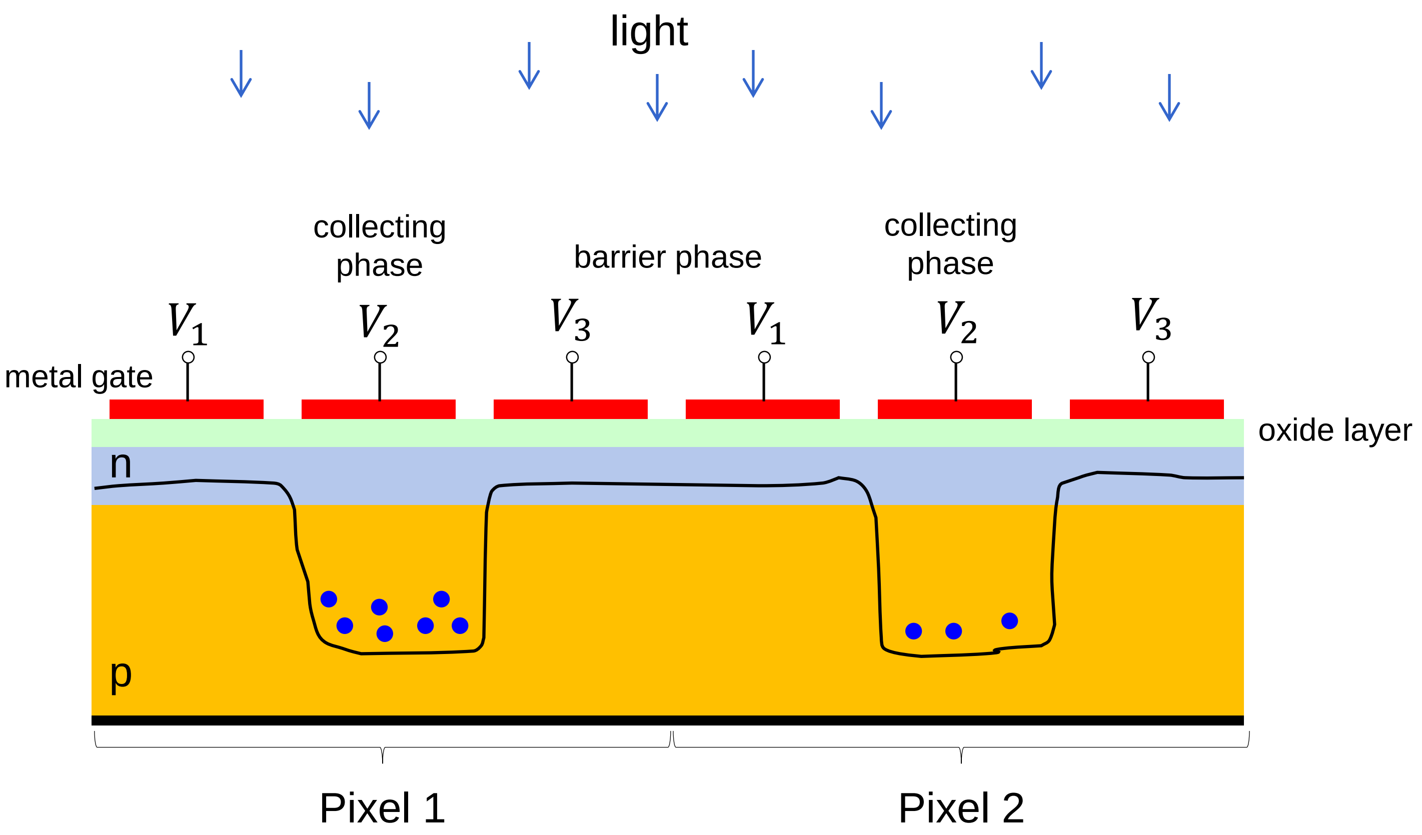
CCD pixels are MOS capacitors. However, modern CCDs do not use the above structures (surface channel) because of poor charge transfer efficiency. Instead, the “buried channel” structures, discussed on the next slide, are used.

MOS capacitor (buried channel)



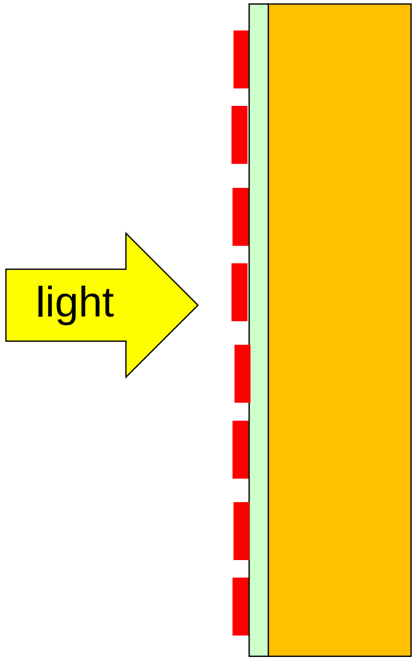
Buried channel MOS capacitor. All modern CCDs use this structure.

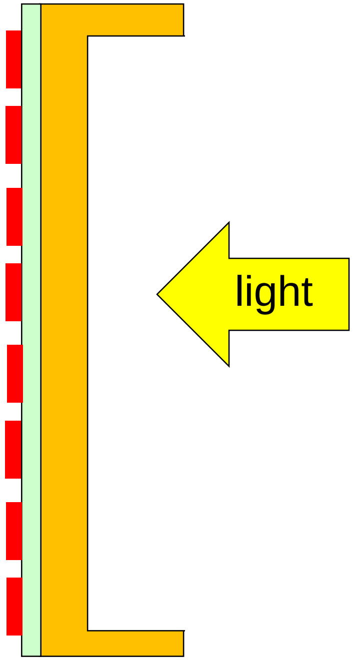
CCD pixel (front illuminated, buried channel, three phase)

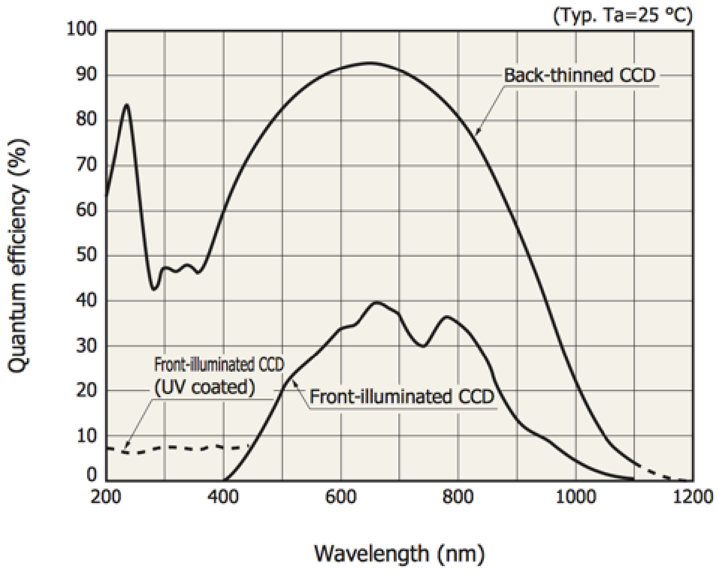


The values of V_1, V_2, and V_3 can be manipulated so that the charge packet can move from one location to another.

Front and back illuminated CCD







Front-side illuminated CCD

Back-illuminated or back-thinned CCD

Charge transfer (full frame transfer readout)

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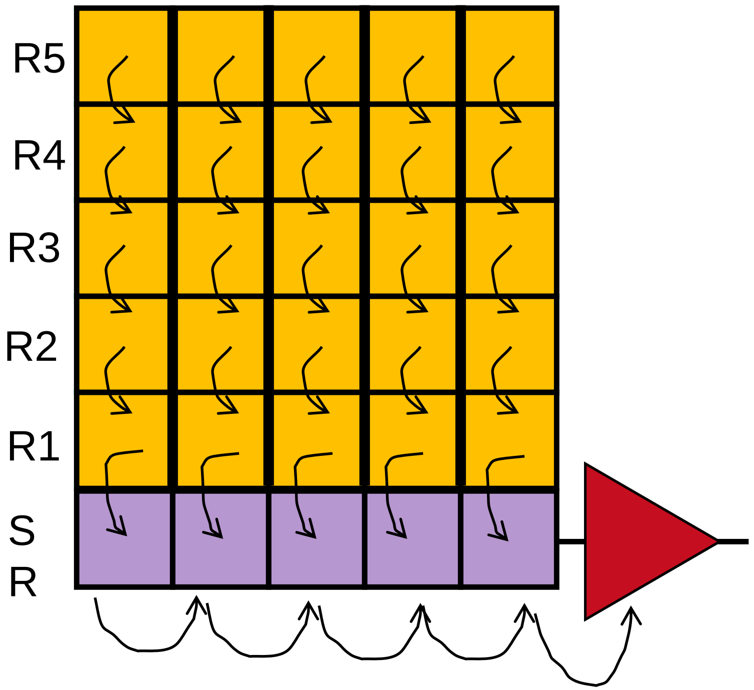
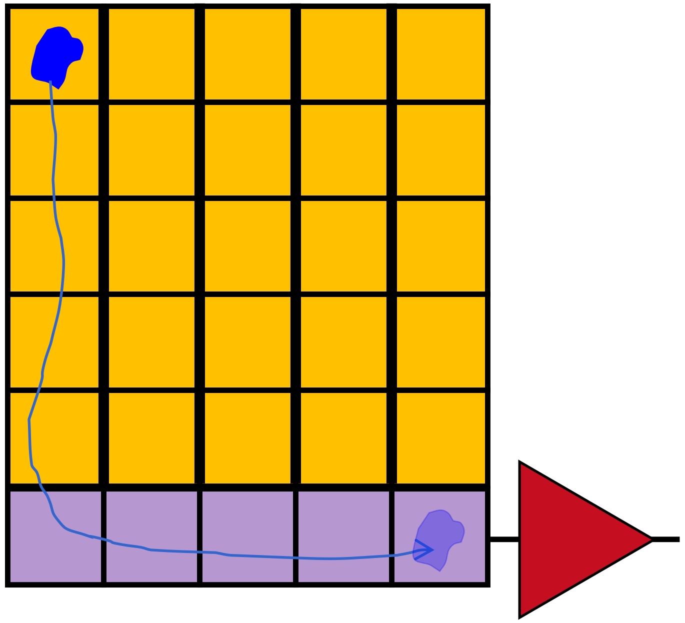


1. Charge in the pixels of the bottom row (R1) is transferred (clocked) to the corresponding pixels of the serial (horizontal) register (SR).
2. Charge in the pixels of the serial register is sequentially clocked towards the charge amplifier. Each charge packet is read individually be the charge amplifier.
3. While charge is read in the SR, R2 is clocked to R1, R3 to R2, R4 to R3, and R5 to R2.
4. Once reading in the SR is completed, the charge packets in R1 are clocked into SR and the process repeats as described above.

Time to read the entire array = Number of pixels × time to read a single pixel + overhead

Charge transfer efficiency

charge packet



the same charge packet with fewer electrons

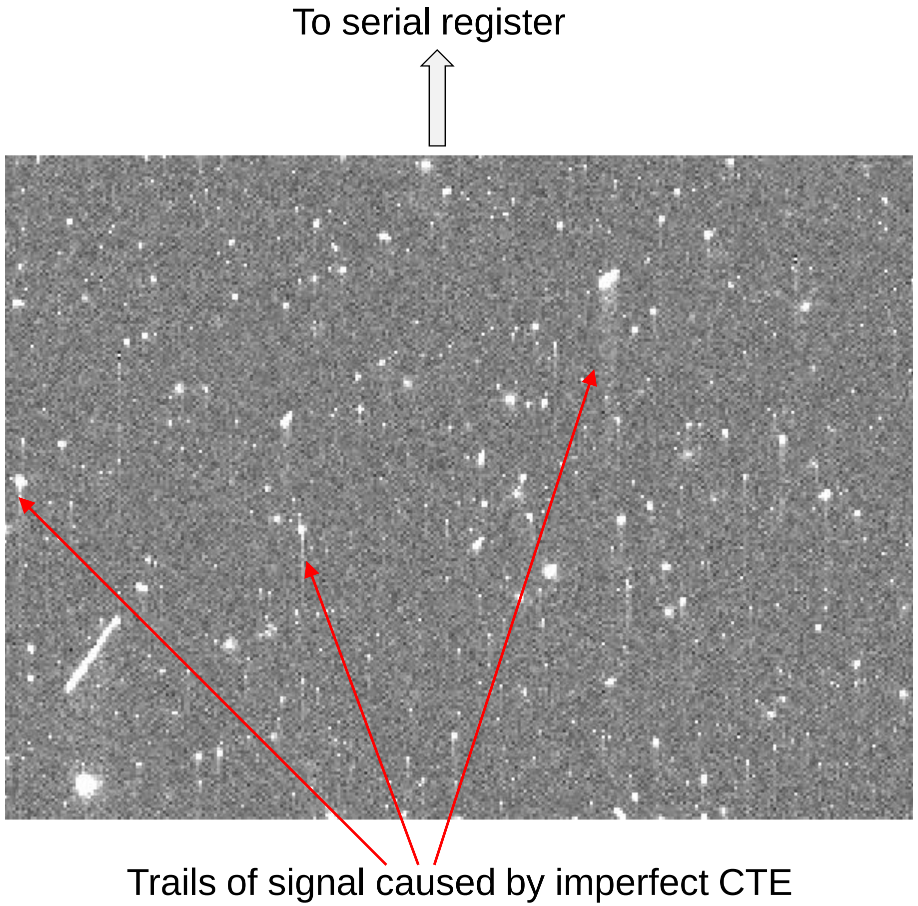
CTE – charge transfer efficiency (for example, CTE = 0.99999)

TTE – total transfer efficiency, the fraction of the original charge packet that remains after p transfers. TTE = $(CTE)^p$

For example, if CTE = 0.99999 (five nines) and p = 2048, then TTE = 0.98 or 2% of charge is lost.

However, if CTE = 0.9999 (four nines) and p = 2048, then TTE = 0.81 or 19% of charge is lost.

Charge transfer efficiency



1. Imperfect CTE reduces the brightness of an image detail (star, cell, etc.). This effect depends on the location of the detail with respect to the serial register
2. Imperfect CTE affects the x, y location of an image detail. This effect depends on the brightness of the detail and its location with respect to the serial register.
3. Correcting images for imperfect CTE is very hard. It is impossible to have an exact correction.

Frame transfer CCD

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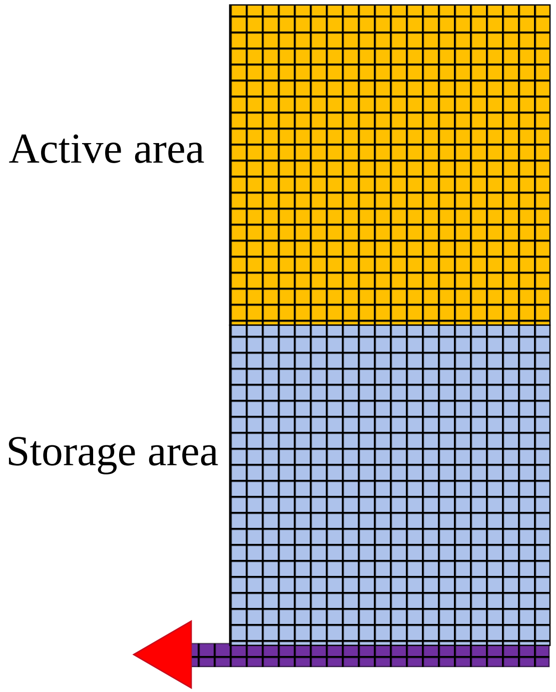
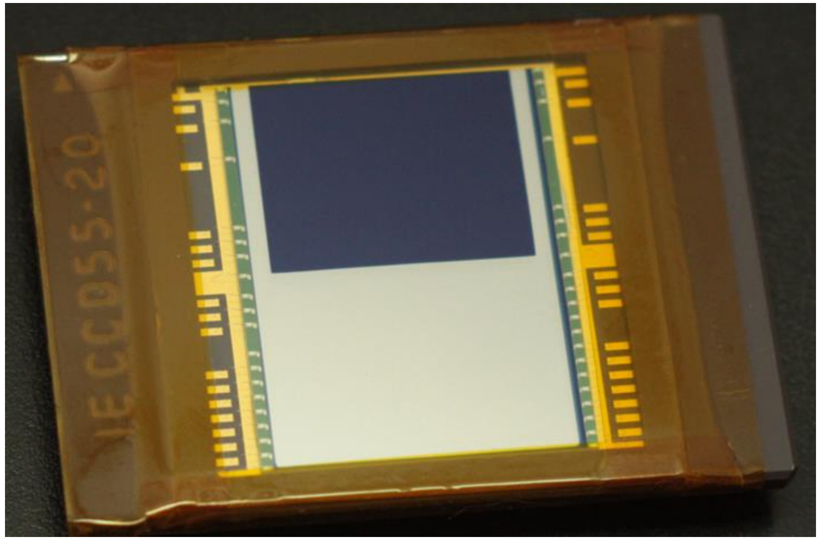
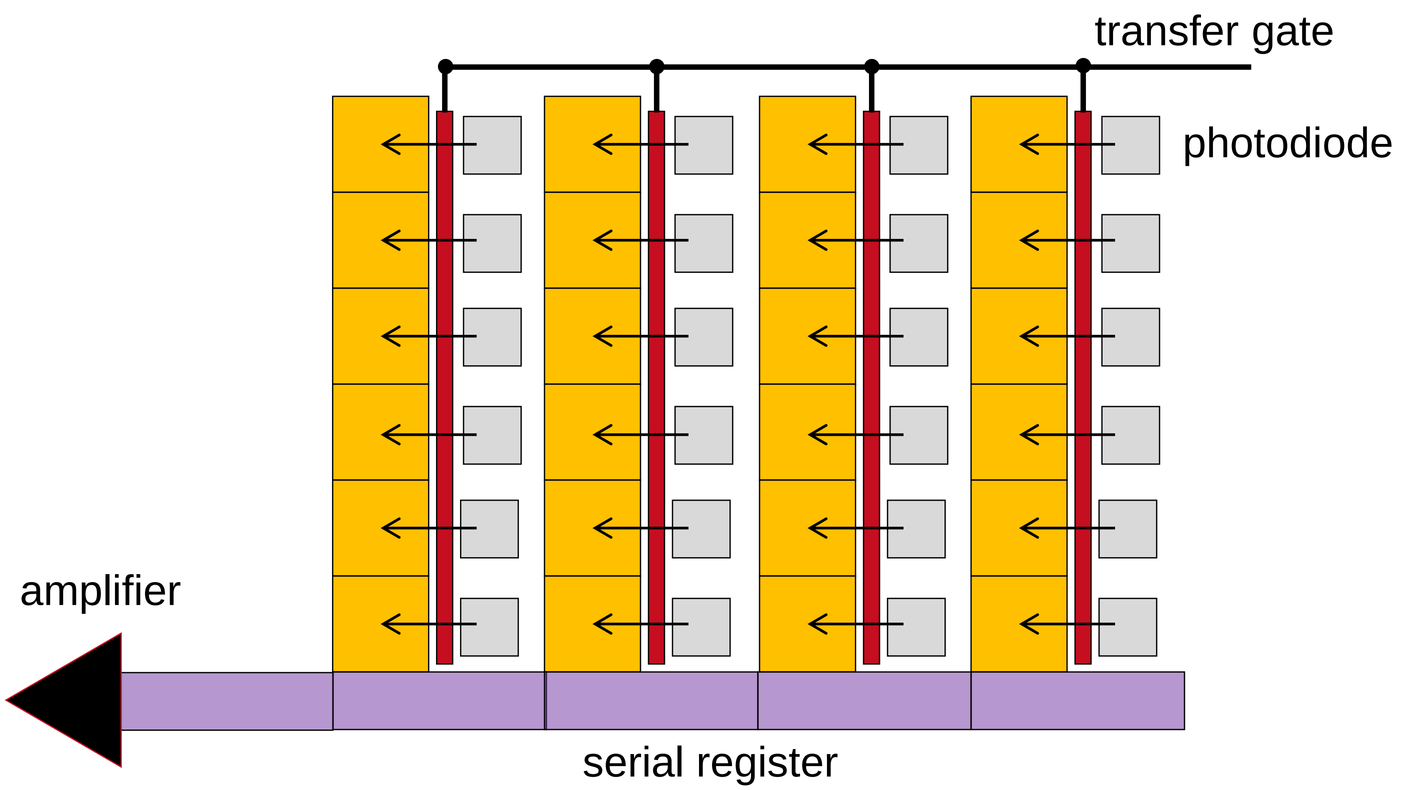




- \+ Allows continuous light collection
- \+ Readout and light collection simultaneous
- \+ Mechanical shutter not needed
- \- Some smearing possible
- \- Detection area smaller than conventional CCD

Interline Transfer CCD

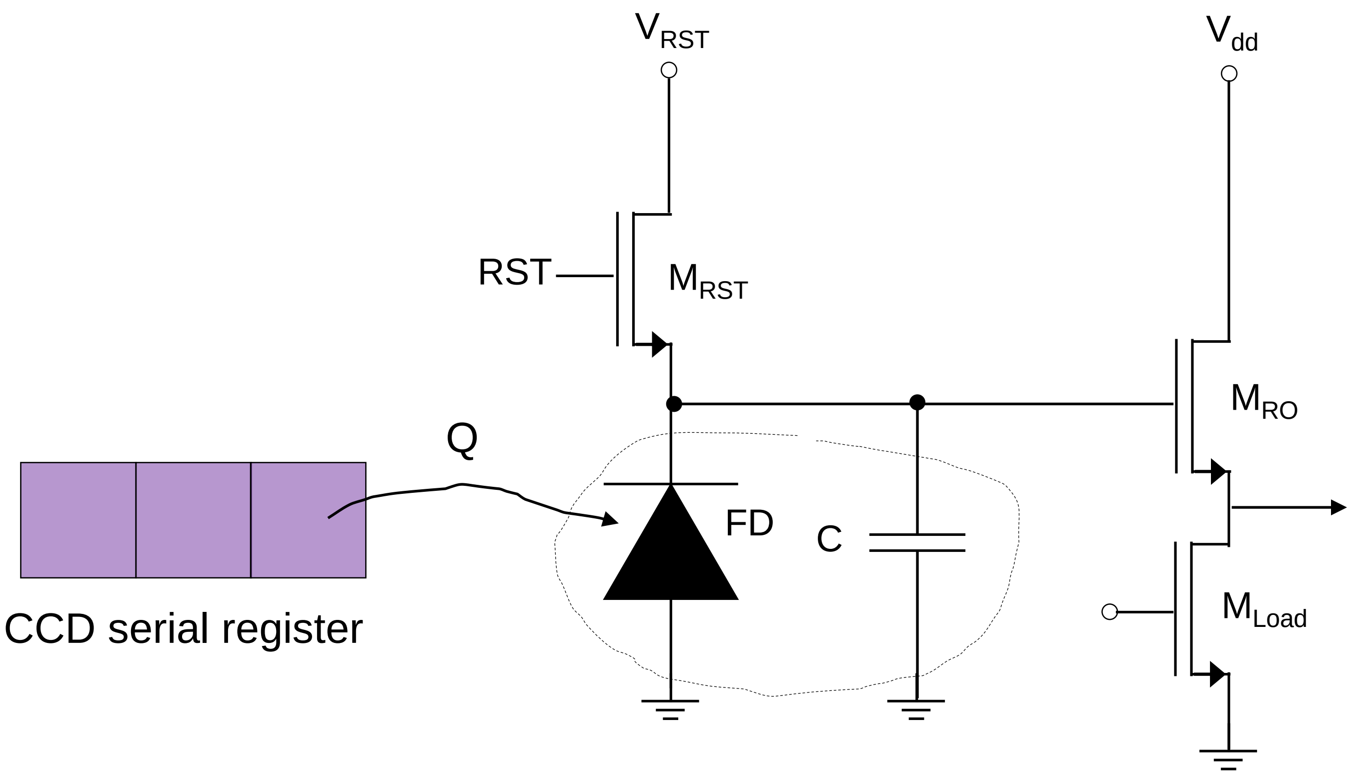


+ Very rapid image transfer
+ No smear
+ No need for a shutter

- Reduced quantum efficiency

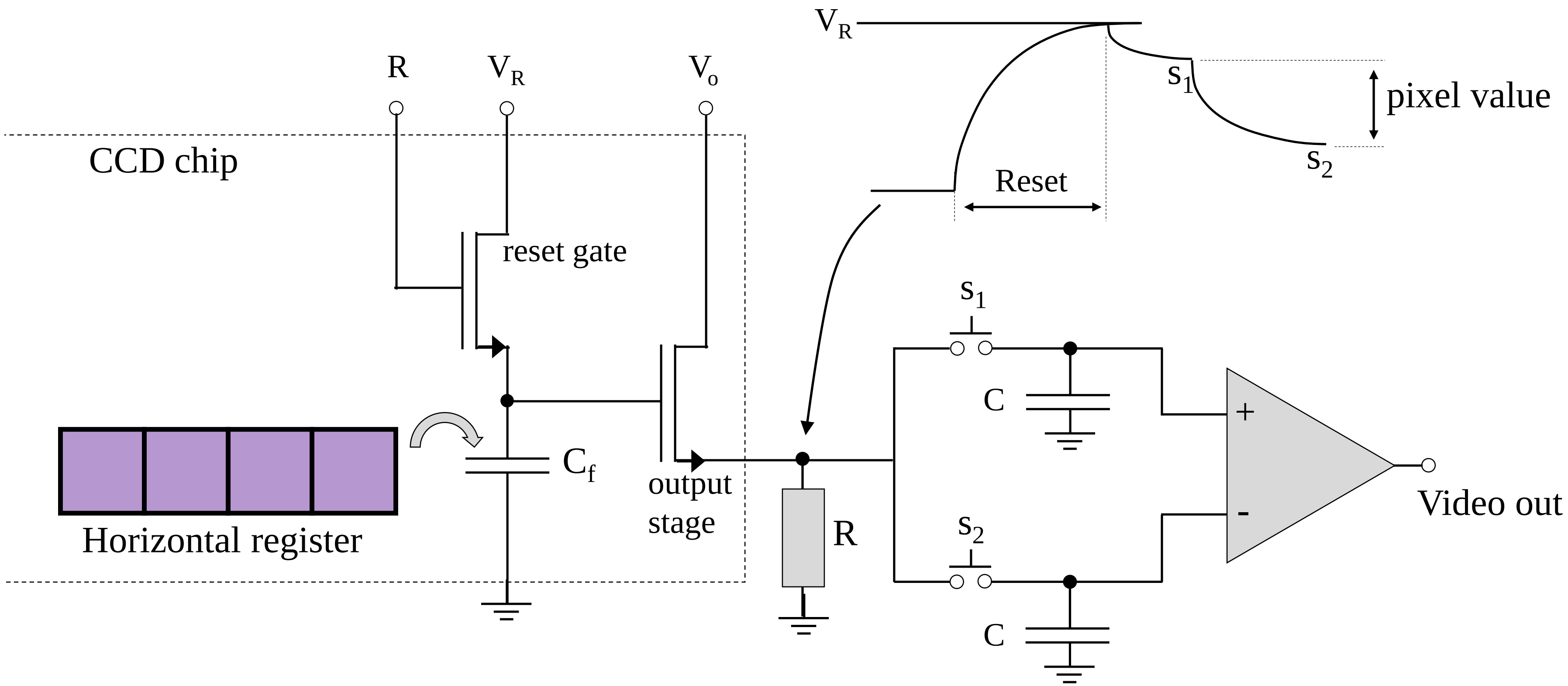
The reduction in quantum efficiency can be compensated by using micro lenses.

Charge readout (destructive)



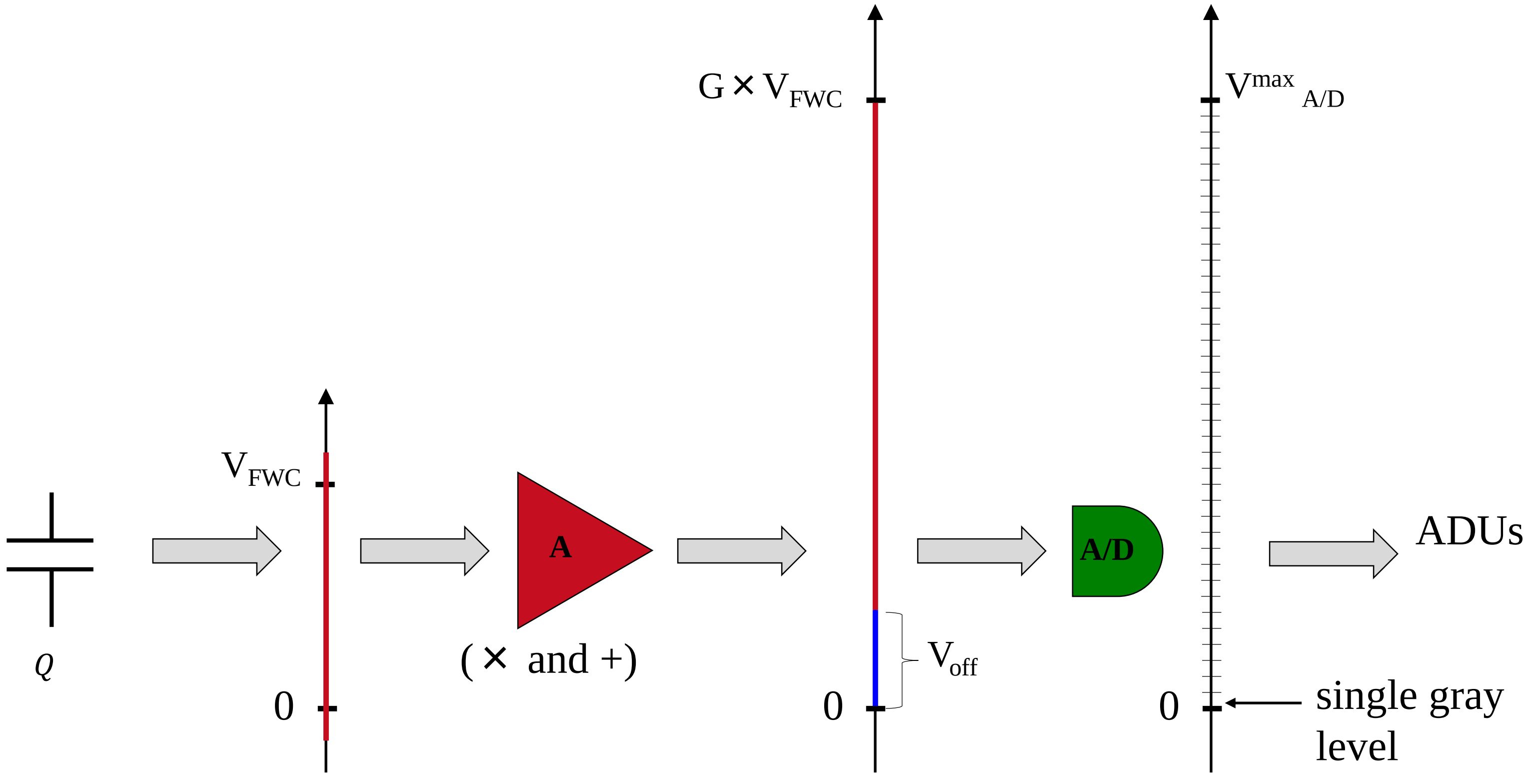
$\Delta V = Q/C$

Correlated double sampling



The figure shows the waveform resulting from the CDS. Sampling is done at point S_1 right after reset and then again at S_2 near the end the charge transfer. The two sample values are held in capacitors and subtracted in the video amplifier as shown to obtain the output video without the reset noise.

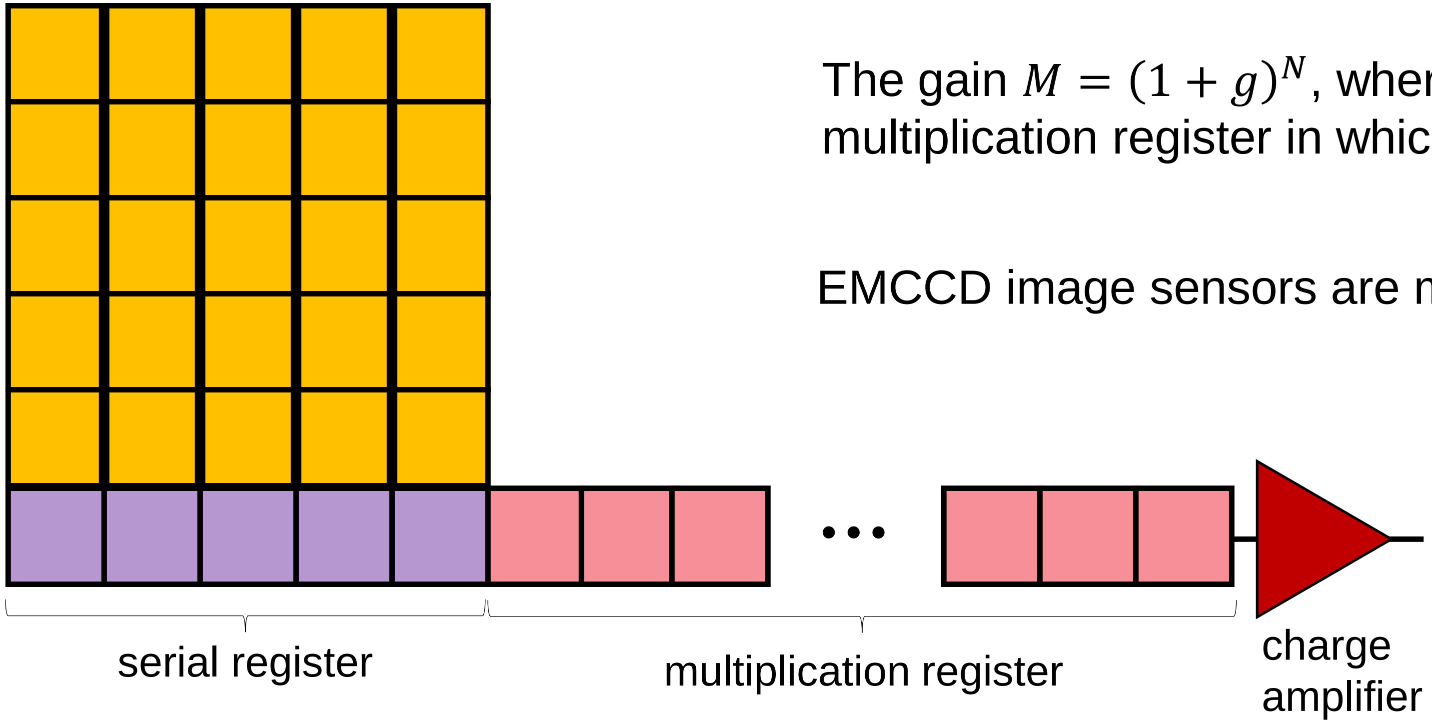
Understanding offset



Because of the read noise, the output voltage from the charge amplifier (Q) **can be negative**. To prevent negative values, the amplifier A amplifies the voltage and adds an offset voltage V_{off}. The maximum possible voltage at the output of the amplifier should match the maximum convertible A/D voltage, $V^{max}{}_{A/D}$. The number of gray levels is 2^N, where N is the bit number of the ADC.

EMCCD

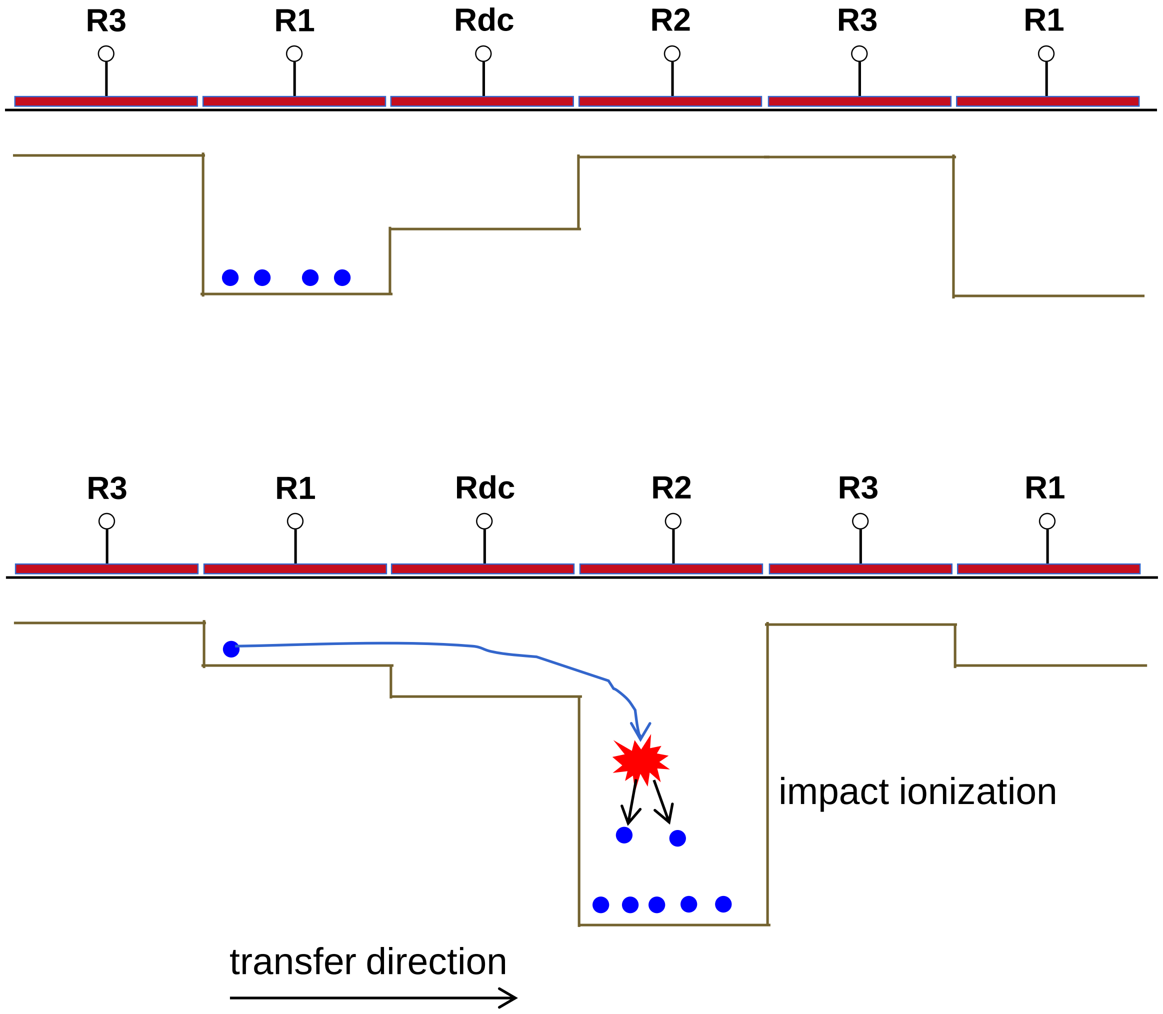
As the charge is clocked through the multiplication register, the amount of charge in a packet increases due to impact ionization. The probability of impact ionization, g, is on the order of 1%.



The gain $M = (1 + g)^N$, where N is the number of pixels in the multiplication register in which impact ionization occurs.

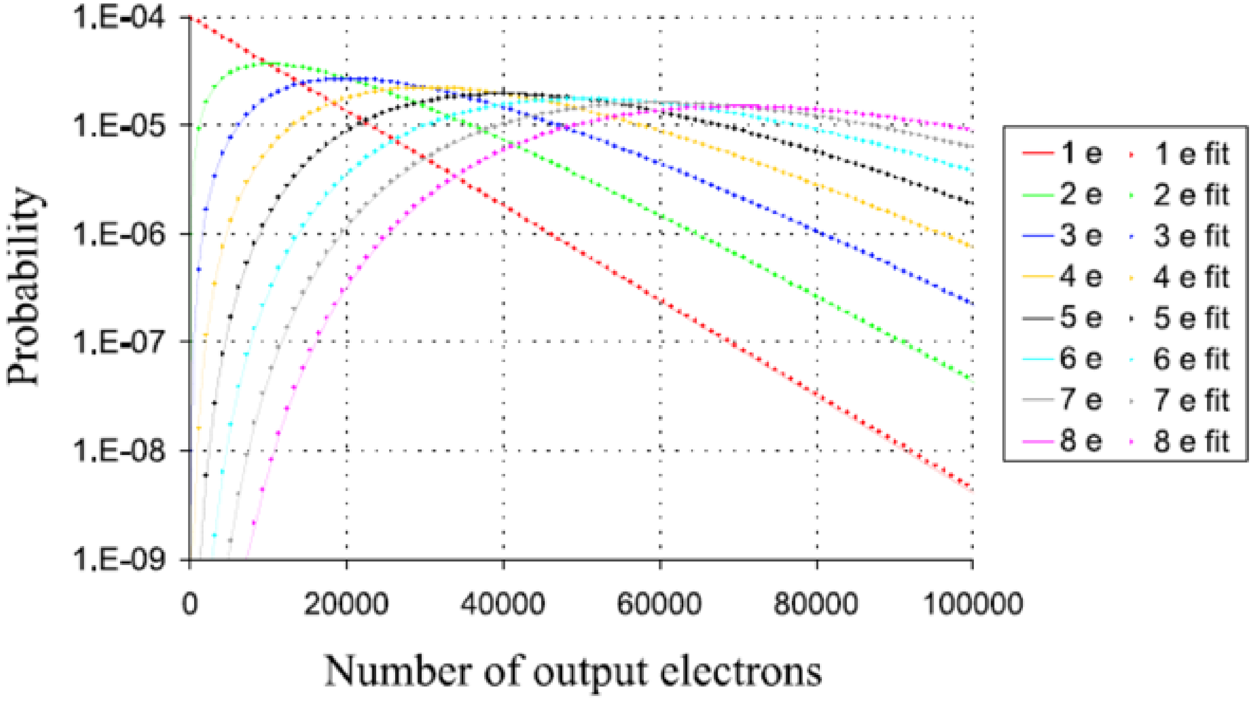
EMCCD image sensors are meant for very-low-light-level application.

Gain Mechanism



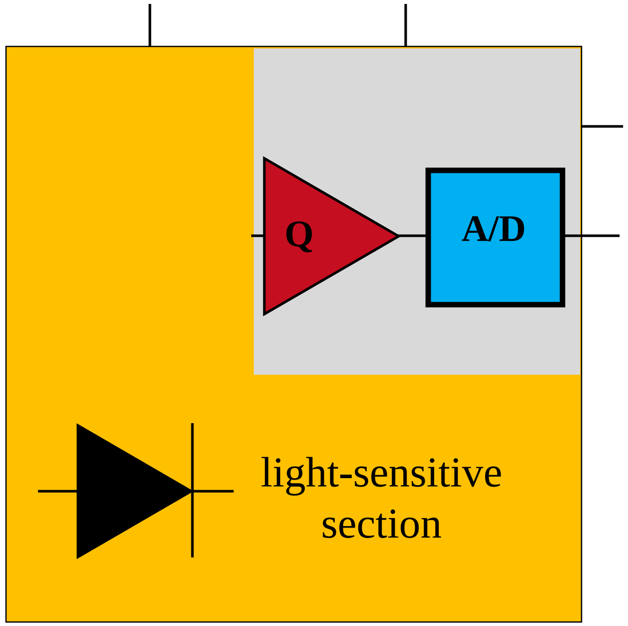
1. Gain M is a function of clock R2 potential and temperature.
2. The same input of electrons can produce different number of output electrons. **Multiplication noise.**
3. Noise figure F expresses the effect of multiplication noise in S/N calculations.
4. EMCCD can be used for photon counting. Here, the output is binary (yes photon, no photon) regardless of the number of output of electrons.

Excess Noise



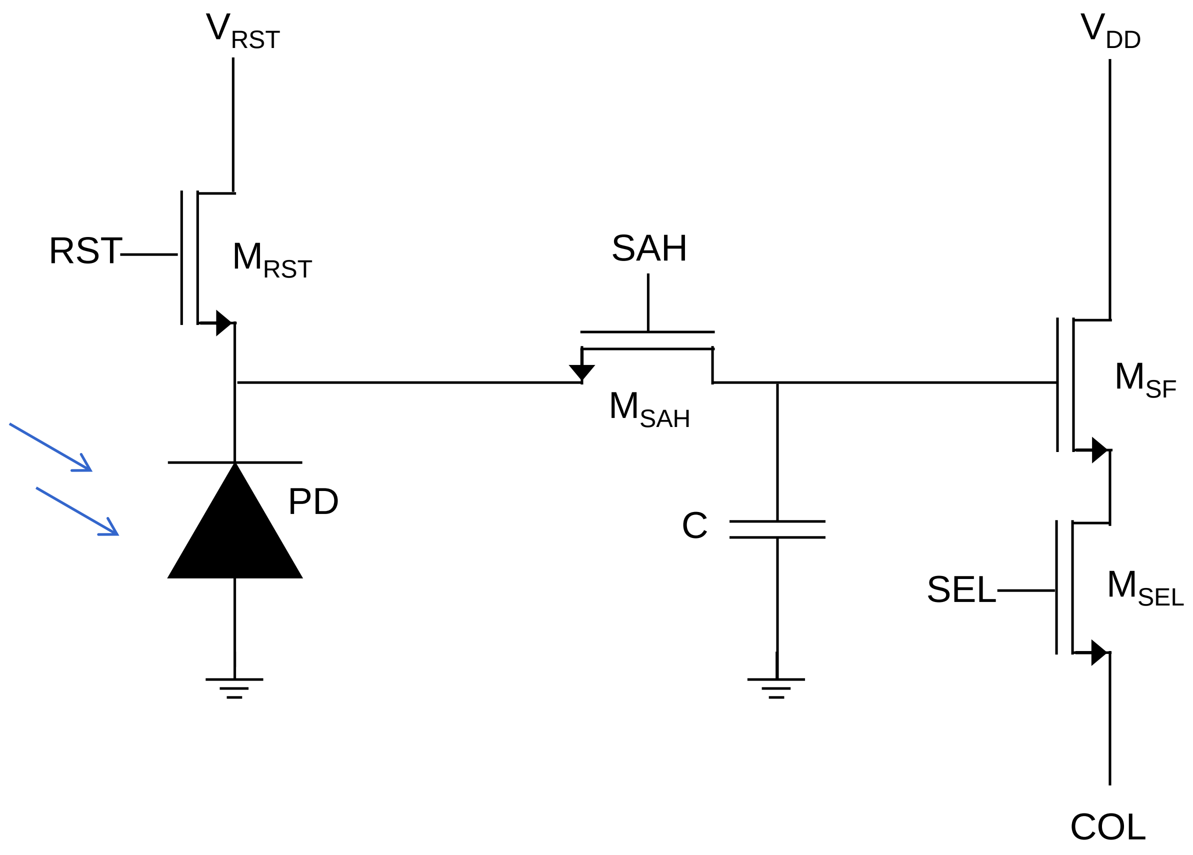
For a given number of output electrons, the figure gives probability functions for the input number of electrons. Since no single number of input electrons can be stated with certainty, the multiplication process introduces noise. This noise is represented by a multiplicative factor, F, that is typically close to $\sqrt{2}$.

CMOS Pixel (Digital)



1. CMOS – complementary metal oxide semiconductor
2. Signal generation in a pixel is fundamentally different from that in a CCD pixel, though many concepts such as quantum efficiency, FWC, dark current, etc. still apply.
3. Unlike in a CCD pixel, it is possible to create electronic circuitry in CMOS pixel including charge amplifier, A/D converters, and more.
4. There is no pixel to pixel charge transfer in CMOS image sensor. In principle, pixels are individually addressable.
5. A wide variety of CMOS pixels designs exists and more are likely to be developed.

CMOS pixel (4T design)



SAH – sample and hold. This MOSFET transfers the signal from the PD onto the capacitor C. This design allows a global electronic shutter.

Cartoon depiction of a CMOS readout

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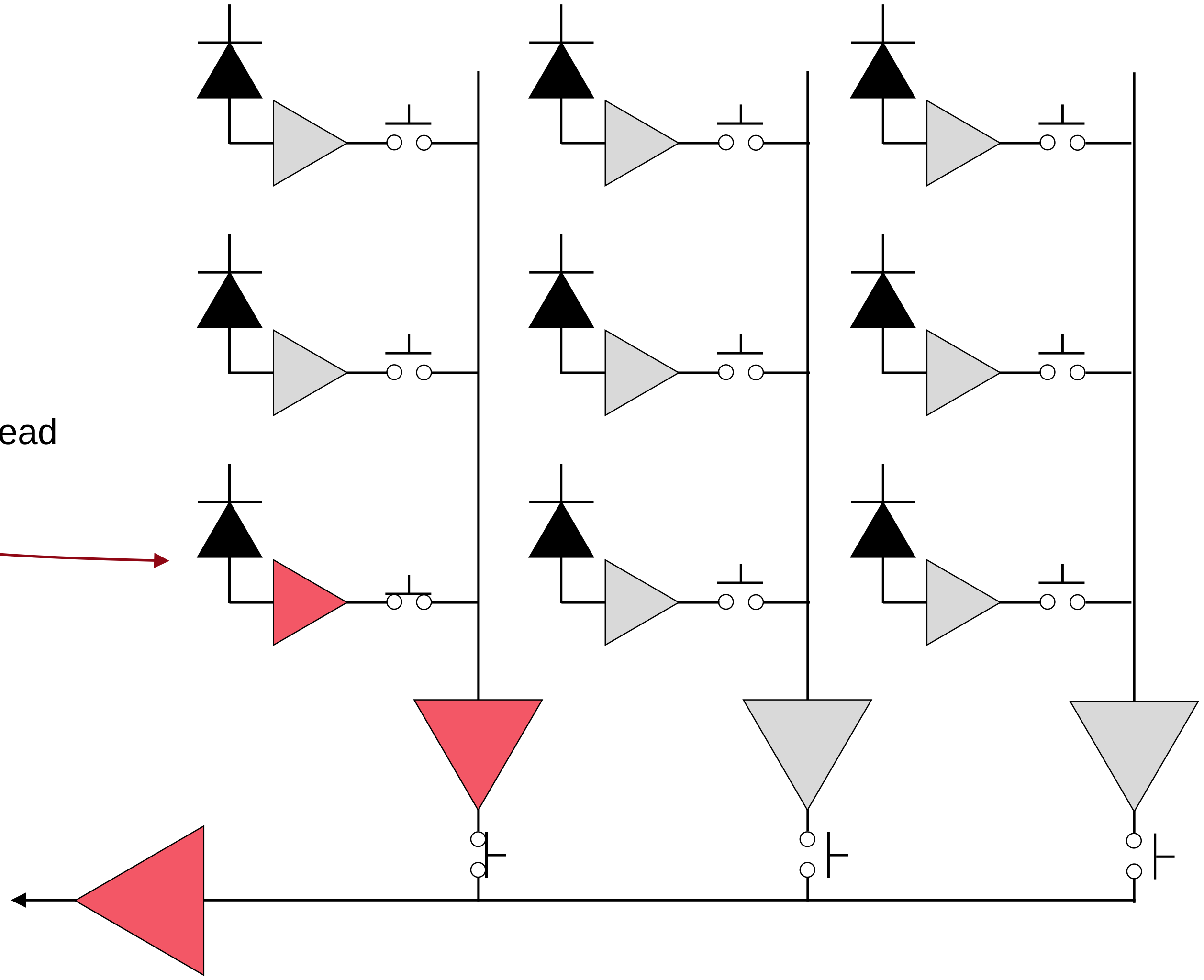
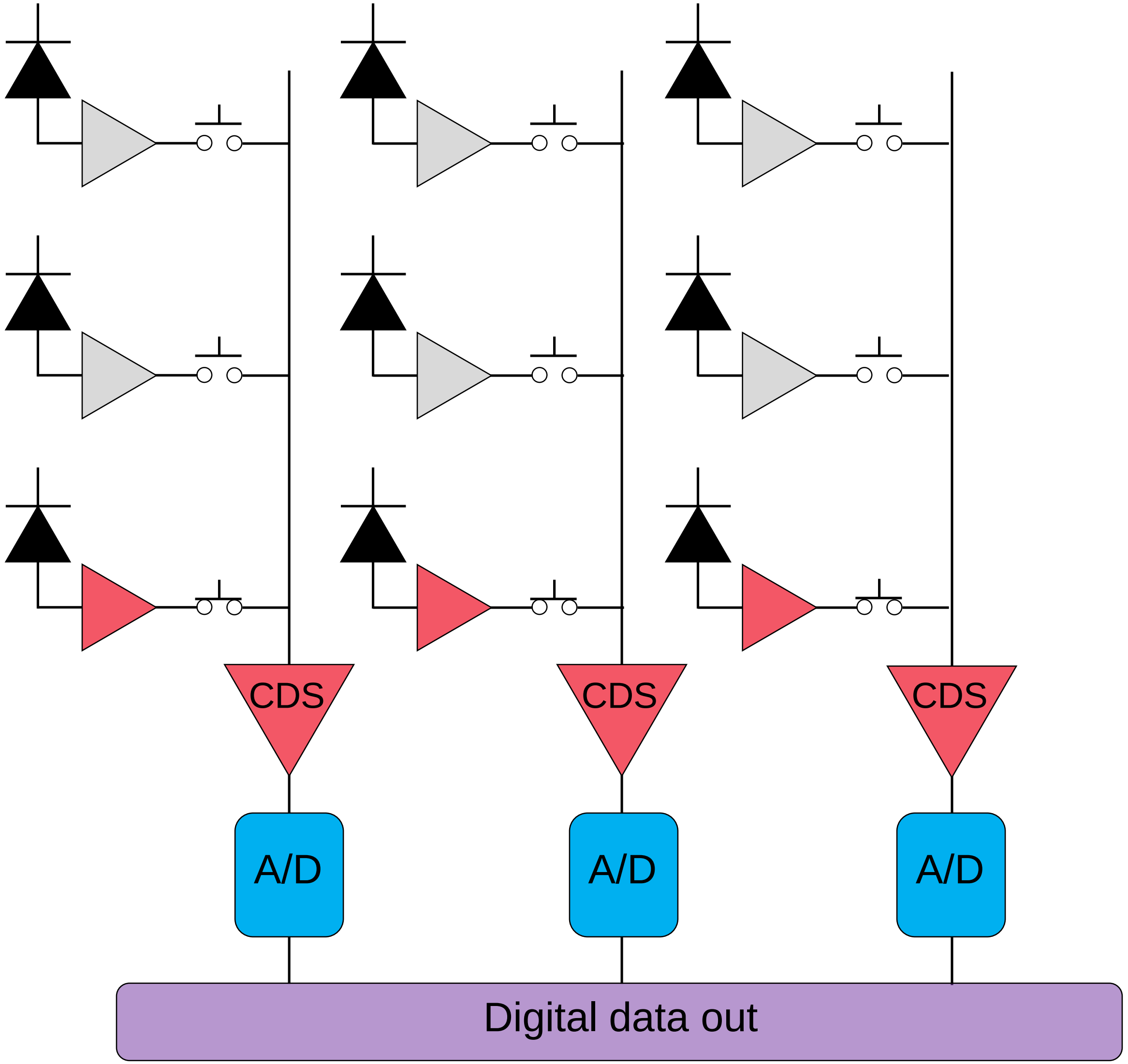
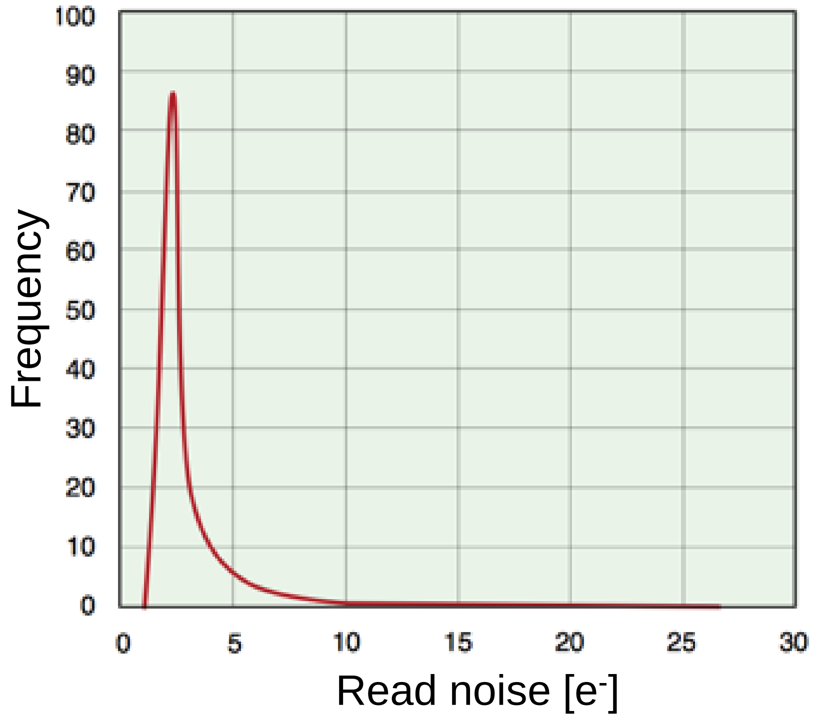
This pixel is being read



CMOS Structure in Flash 2.8 Hamamatsu Camera

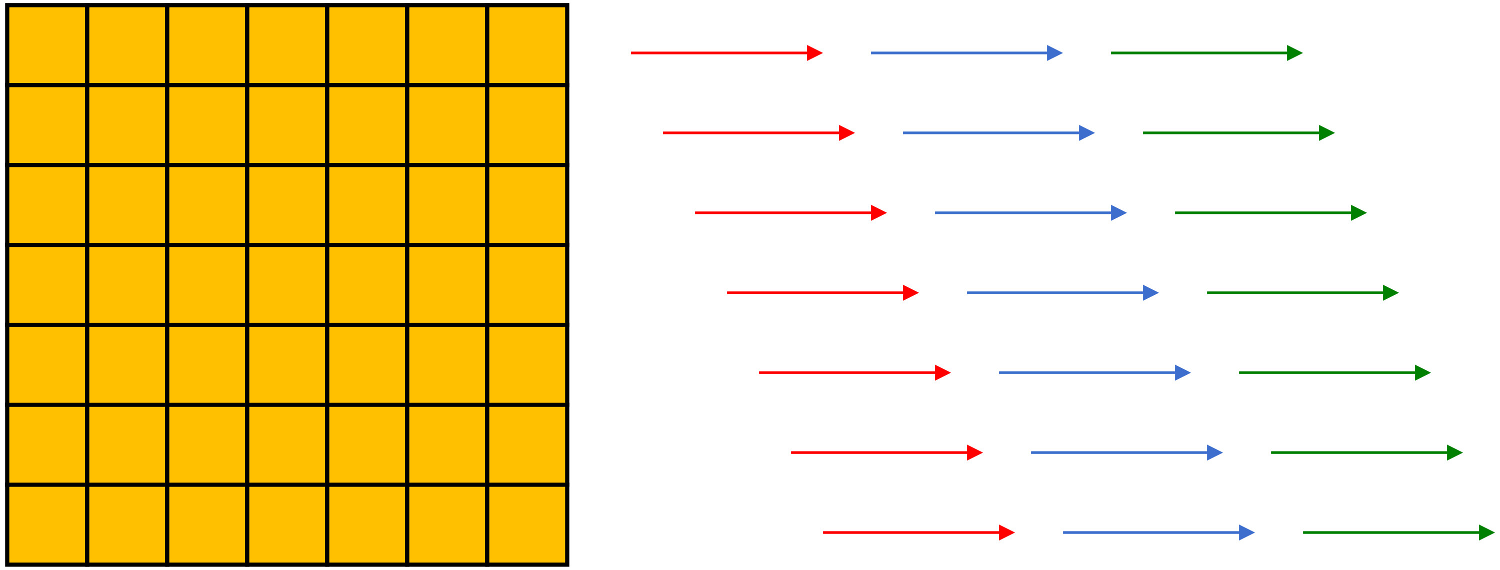


Read noise in CMOS



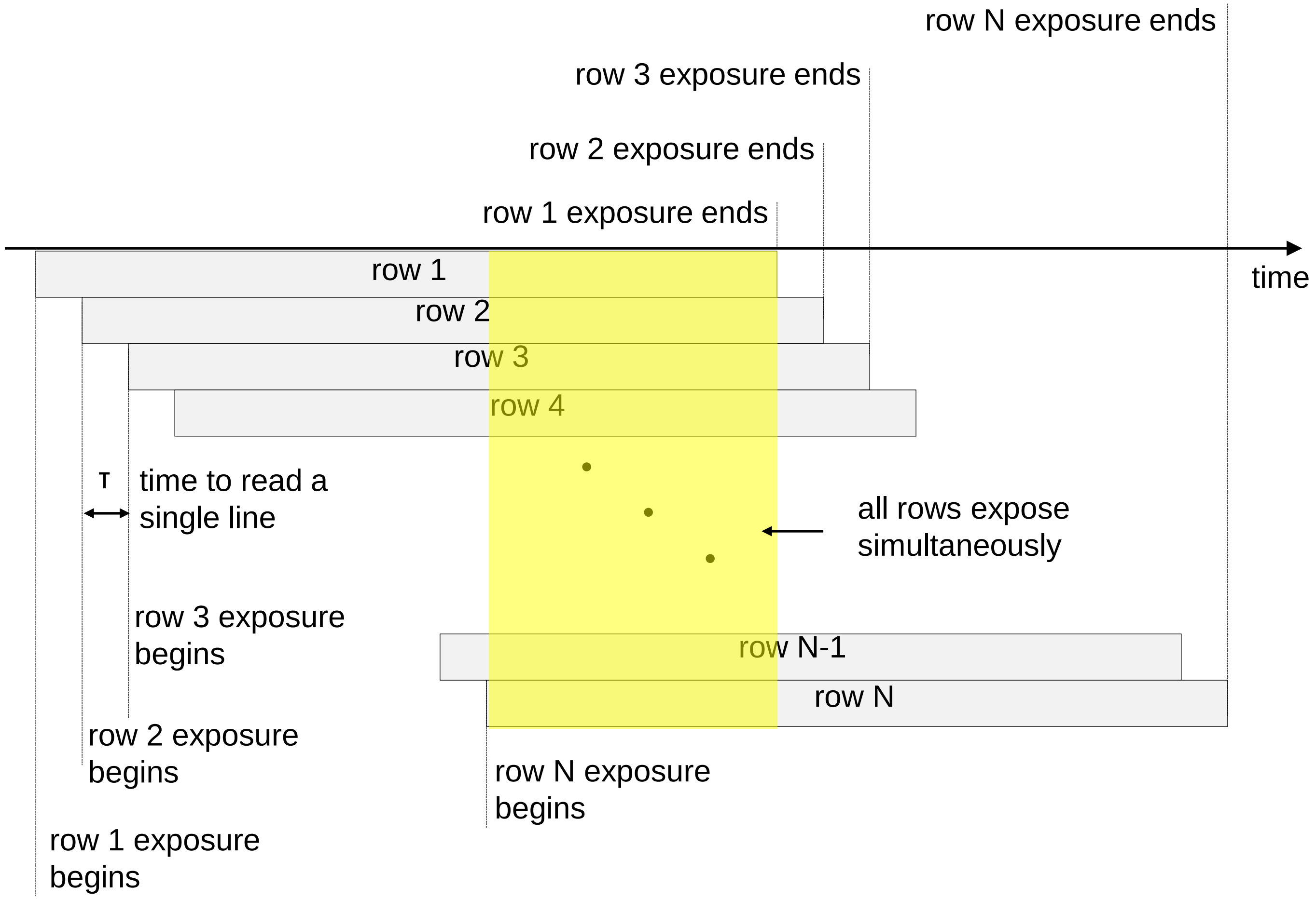
Unlike CCD, each pixel in CMOS has its own charge amplifier. Therefore, **there is no single read noise for the detector.** Instead, each pixel has its own read noise. The plot above shows read noise histogram for a CMOS detector.

Readout in CMOS (rolling shutter)

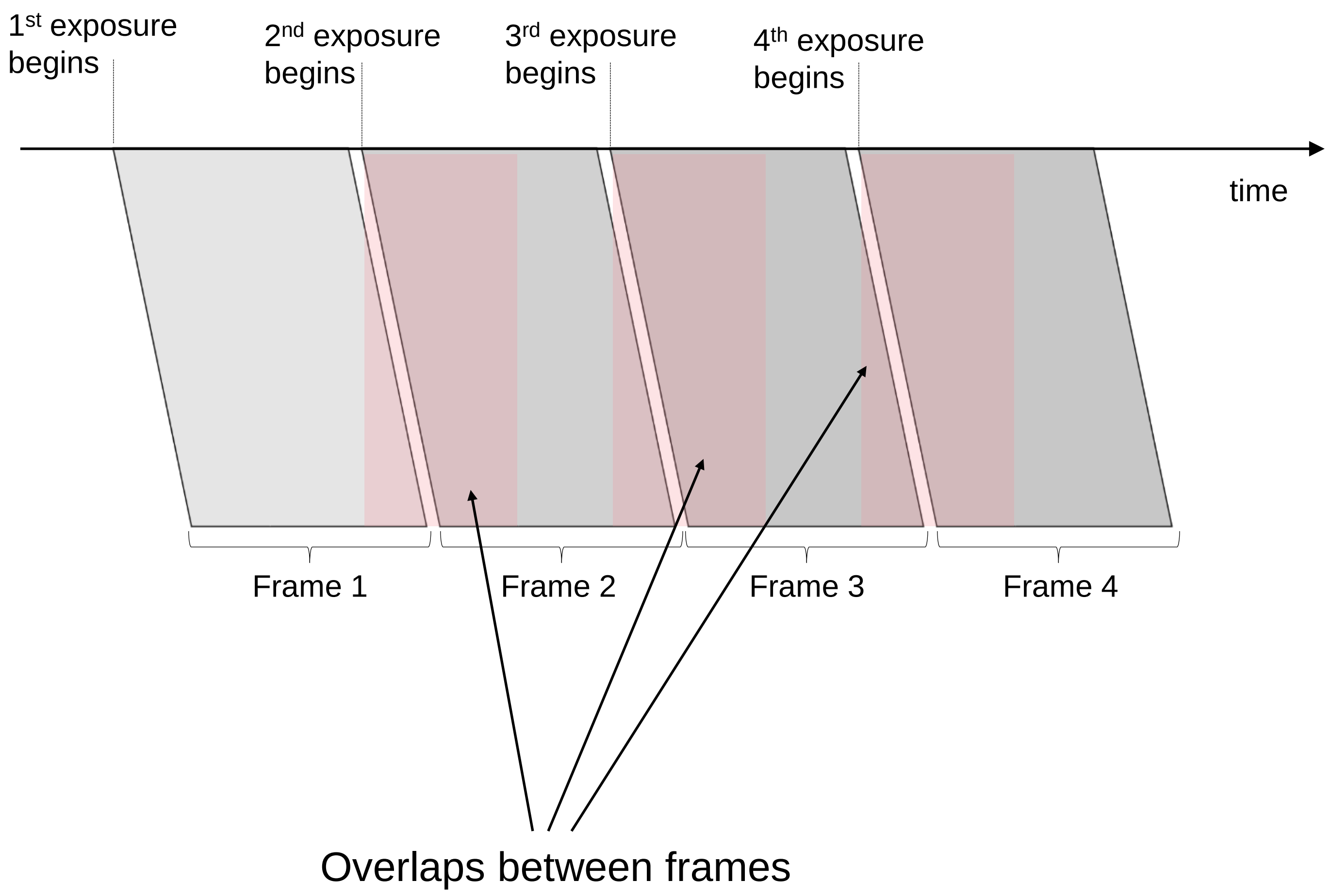


- Exposure length is the same for all lines
- Pixels in a given row read at the same time

Closer Look At Rolling Shutter: Single Exposure



Closer Look At Rolling Shutter: Multiple Exposures



Readout in CMOS (global shutter)

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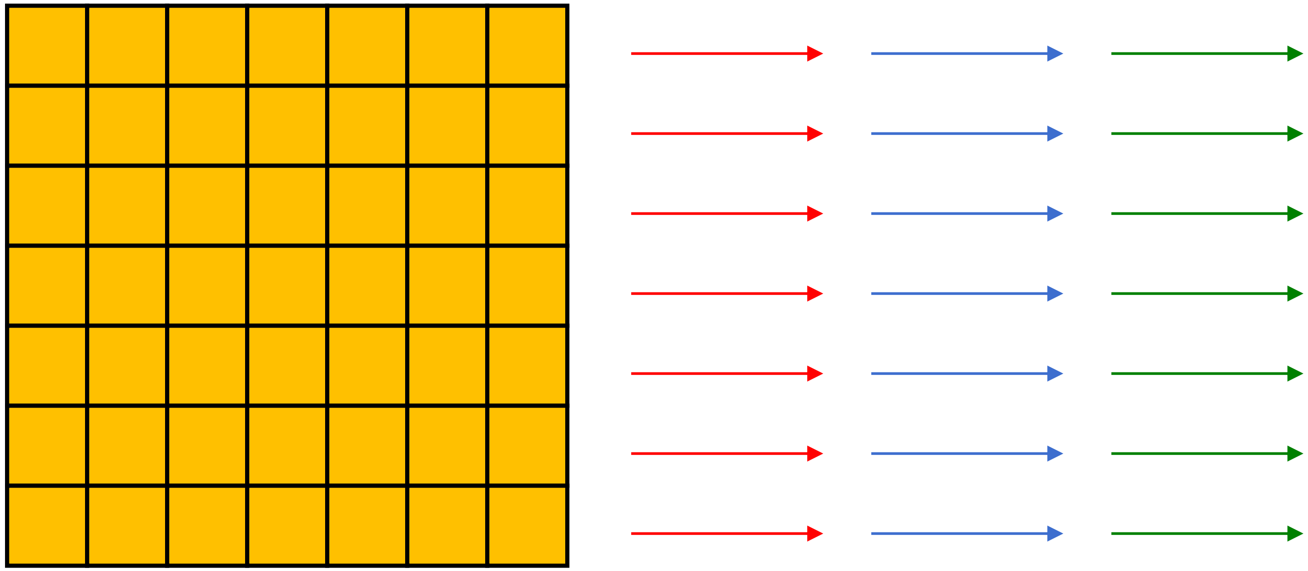
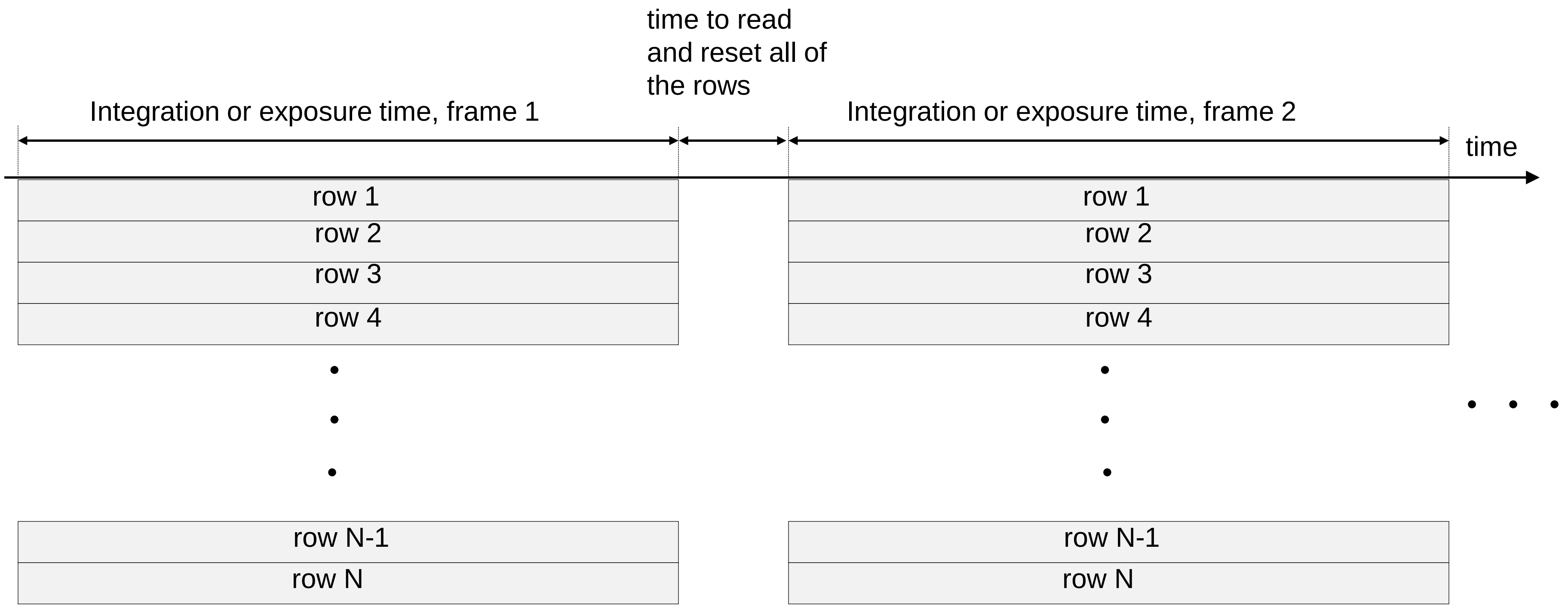
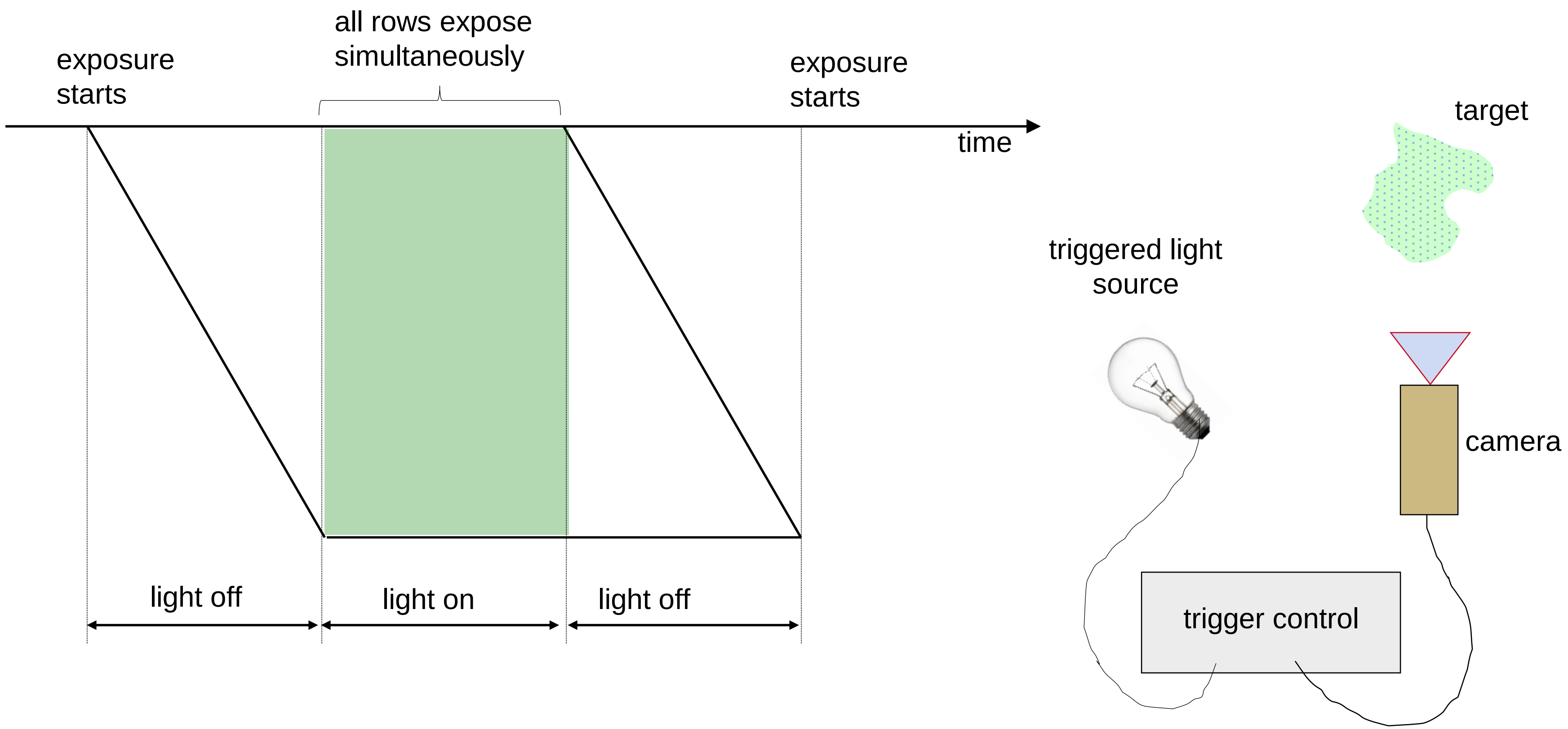


Closer Look At Rolling Global Shutter



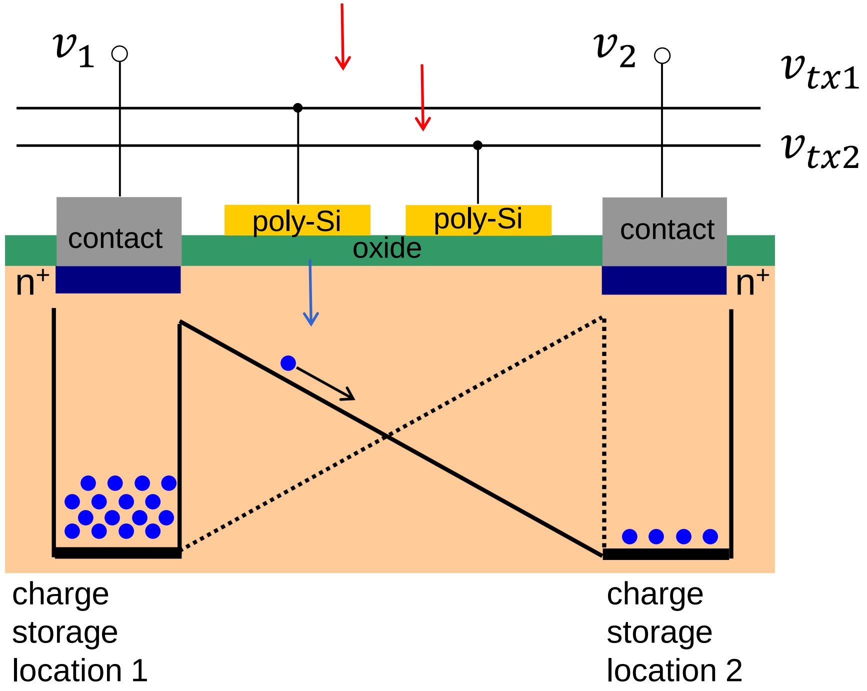
Although conceptually simple and desirable in some application, the global shutter mode readout has lower frame rate, and generally higher read noise and dark current.

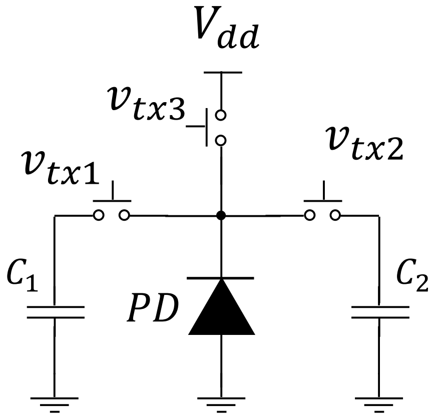
Triggered Exposure



In this example, even though the readout is rolling shutter, all of the rows were illuminated and at the same time. This has been achieved with triggered illumination synchronized with the camera readout.

Distance sensor: structure

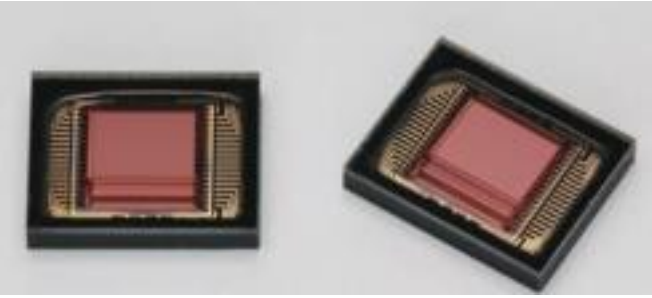




equivalent circuit

$$R = \frac{1}{2} c T_0 \frac{v_2}{v_1 + v_2}$$ (range)

$$\delta_R \sim \frac{\frac{1}{2} c T_0}{\sqrt{S/N}}$$ (uncertainty)



actual chip made by Hamamatsu

Distance sensor: operation

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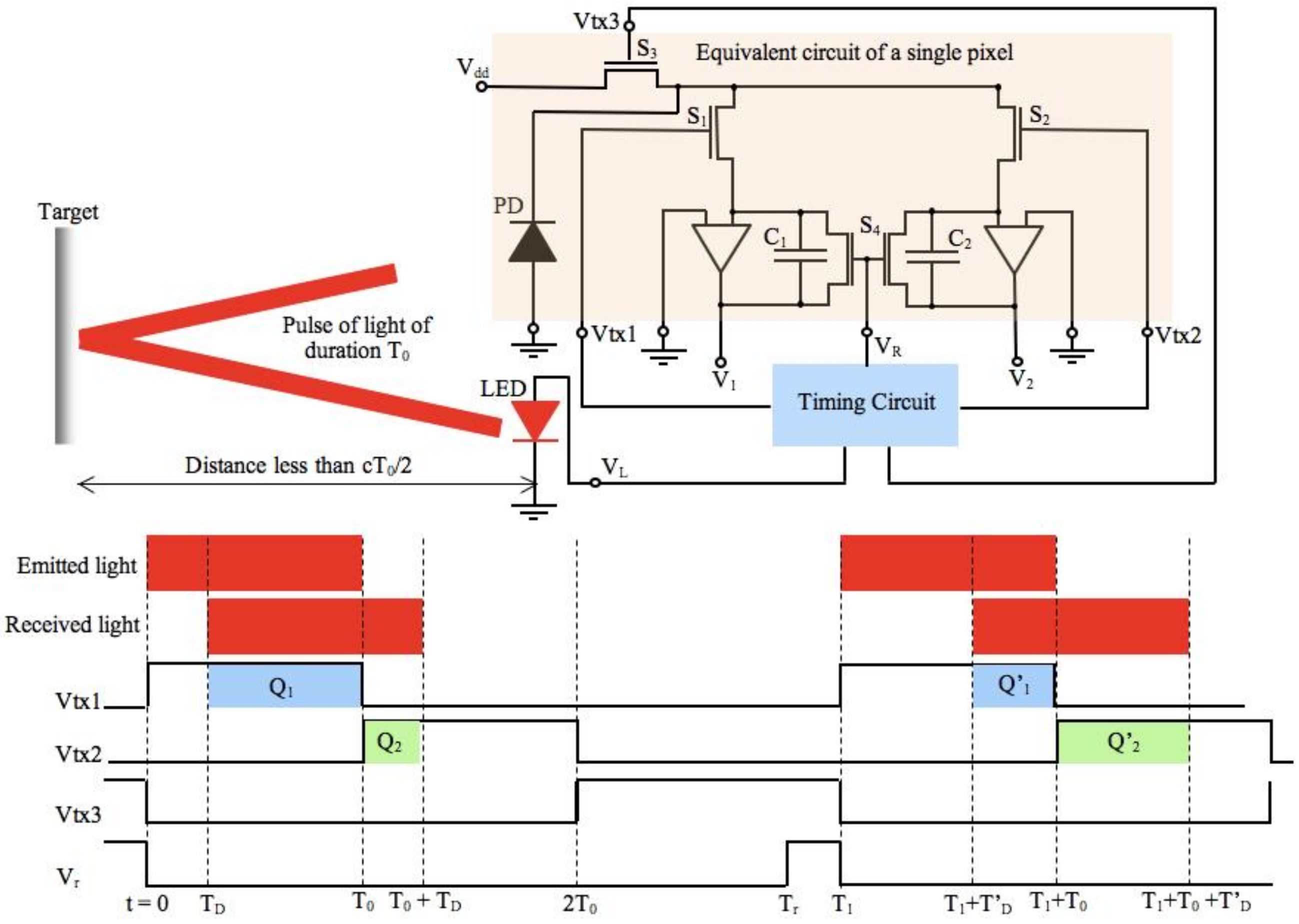
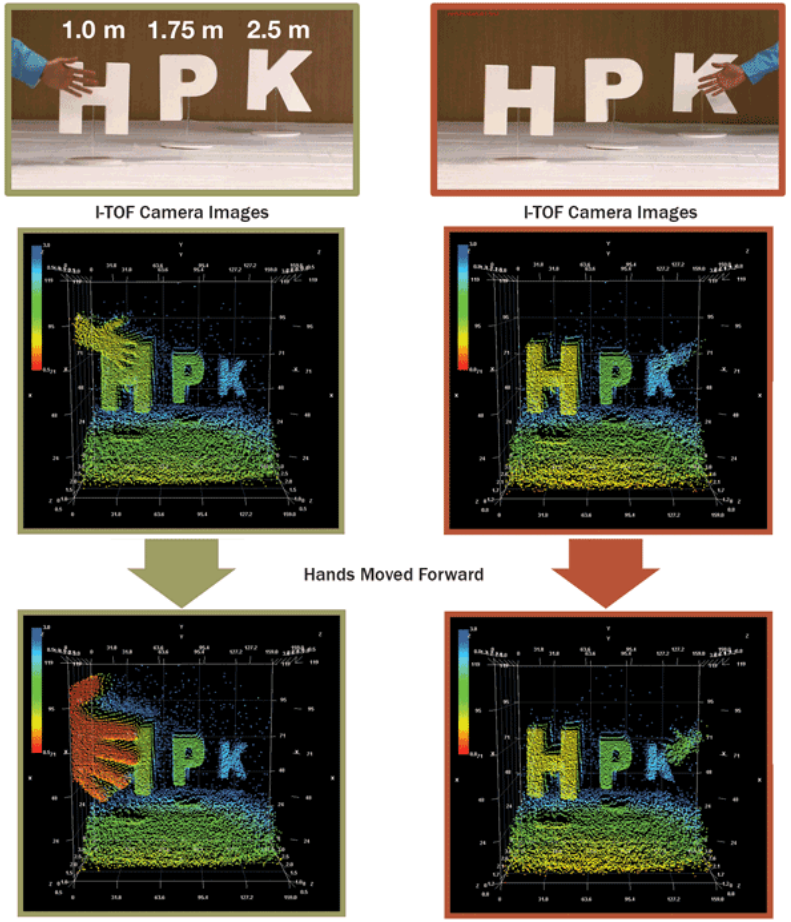


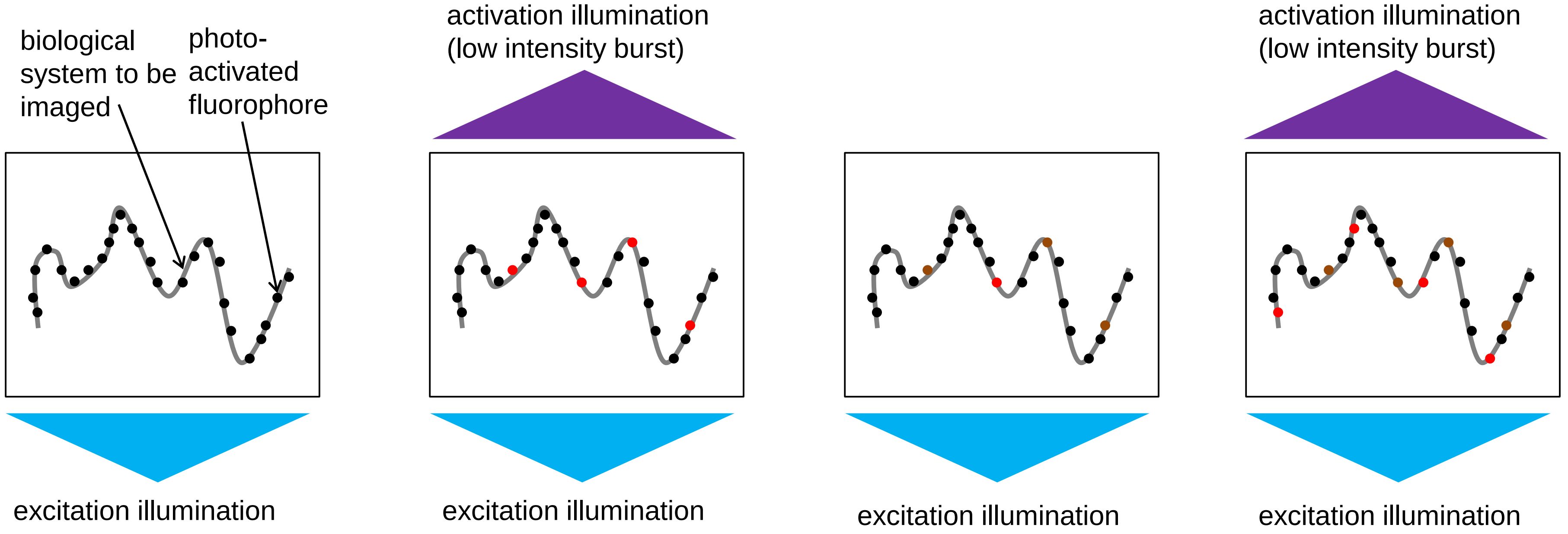
3D imaging



1. The maximum distance that can be measured is $\frac{1}{2}cT_0$.
2. There are no moveable parts
3. Yields information about distance, shape, and size in real time
4. Needs a stable pulsed source of light (LEDs or lasers)

Applications

EMCCD: Photoactivated Localization Microscopy (PALM)



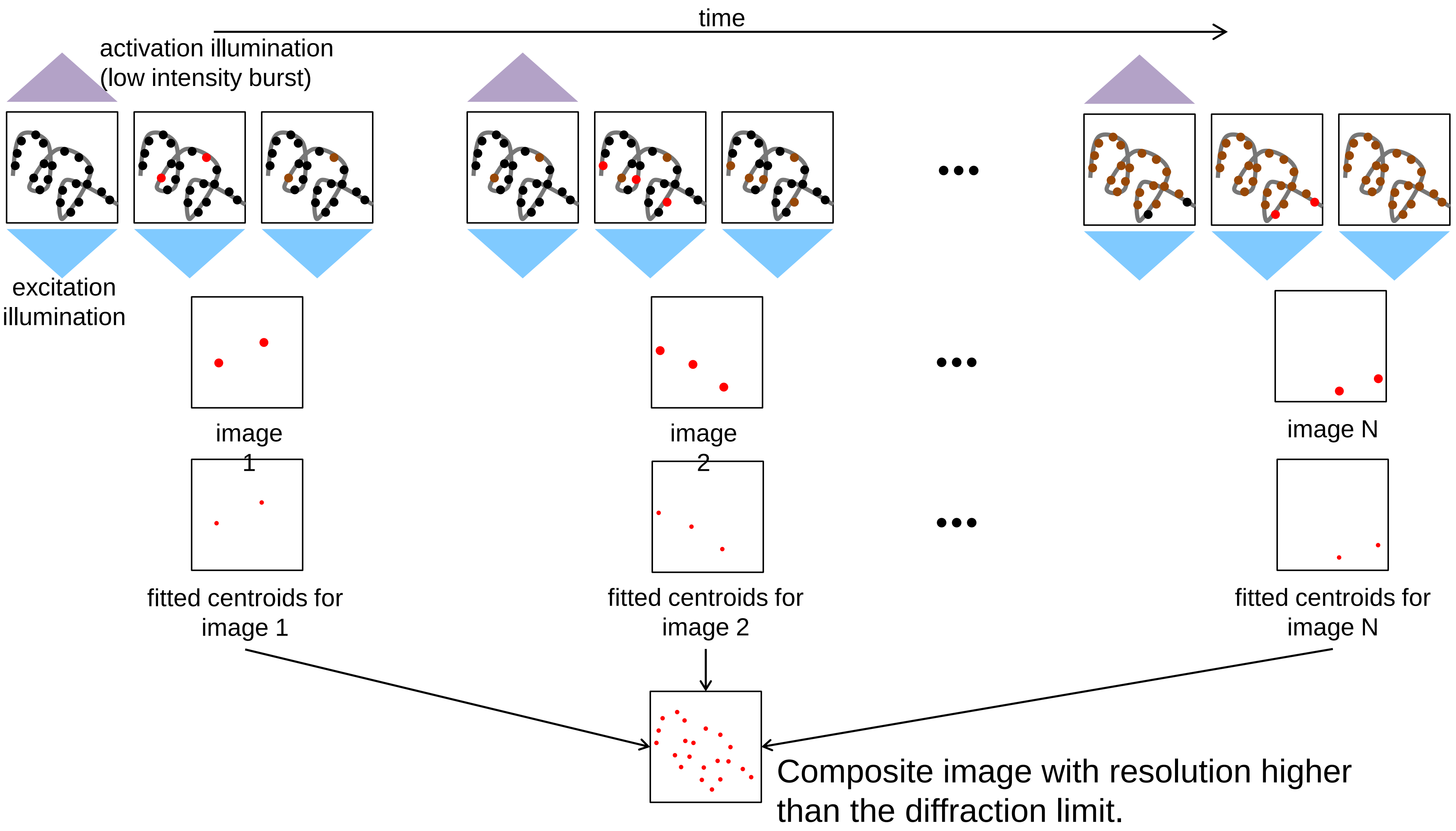
The scene is illuminated with *excitation* light but the fluorophores do not fluoresce because they are in the off state.

The scene is now illuminated with a low-intensity burst of *activation* on top of *excitation* illumination. The activation light turns some fluorophores into a fluorescent state causing them to fluoresce (red) in response to excitation light

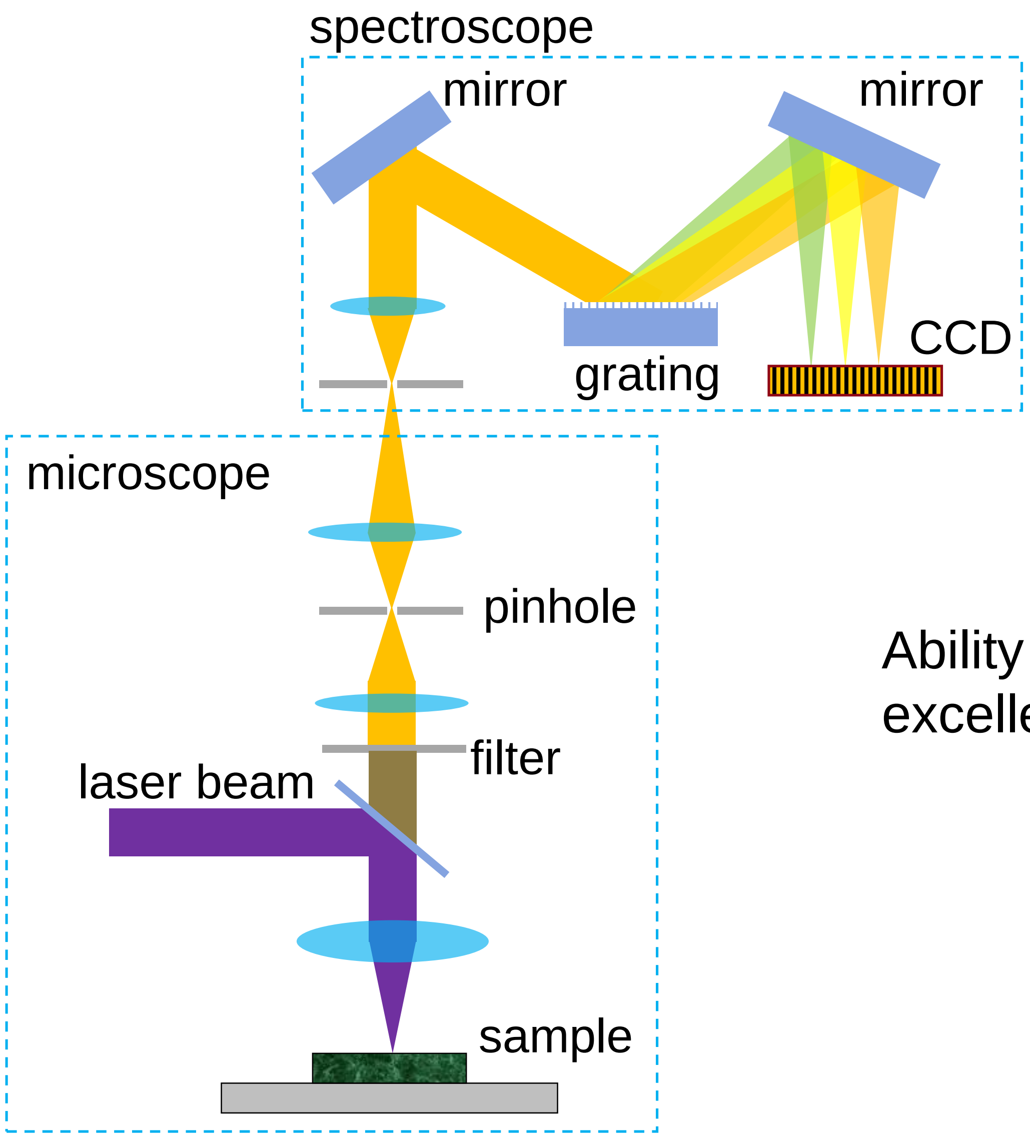
The scene continues to be illuminated with excitation illumination. However, due to **photobleaching** only one molecule continues to fluoresce before eventually it also is photobleached. If photobleaching is irreversible, the photobleached molecules will not fluoresce again.

The scene is again illuminated with activation light causing a new set of fluorophores to turn into a fluorescent state.

EMCCD: Photoactivated Localization Microscopy (PALM)



CCD: Raman Spectroscopy Microscope



Ability of line binning makes a CCD an excellent choice for spectroscopy.

CMOS: Cellphone cameras!

Thank you

Thank you for listening

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