Detectors for microscopy - CCDs, APDs and PMTs

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Detectors/Sensors in general…

…are devices that detect events or changes in quantities (intensities) and provide a corresponding output, generally as an electrical or optical signal

- What do we expect of a sensor while taking an image?
  - speed – as fast as possible
  - work within a wide range of light levels
  - good dynamic range
  - work at different emission wavelength
  - enough resolution to see details
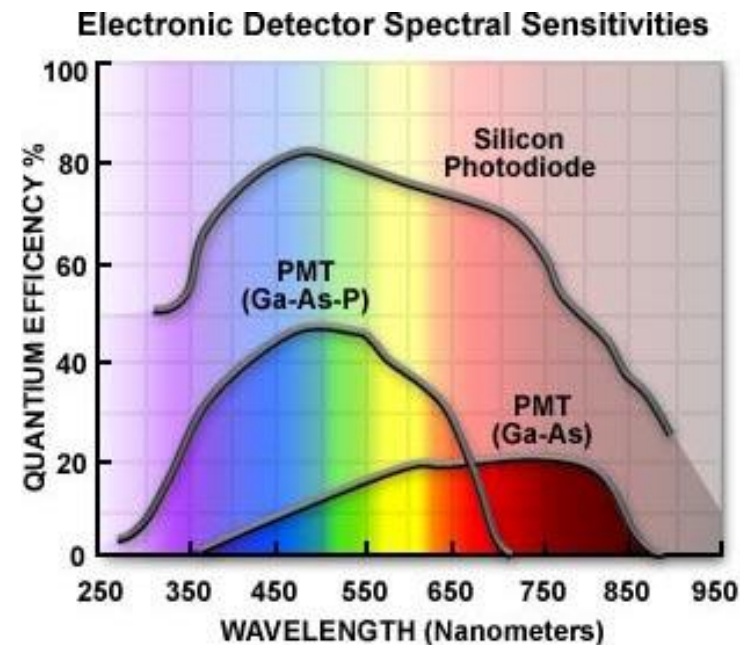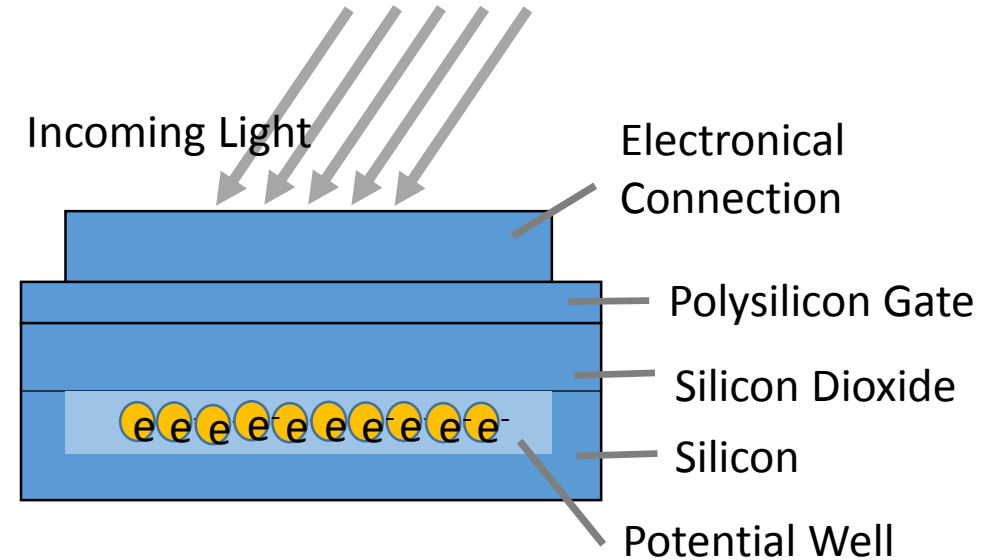 - low noise level (good signal-to-noise ratio)

Sensitivity

"A sensor's sensitivity indicates how much the sensor's output changes when the input quantity being measured changes (ratio between output signal and measured property)"

- Sensitivity is a horrible word which is often confused with **Quantum Efficiency**, **Pixel Size**, **Signal** and **Signal to Noise**

- some key facts:
  - Photons convert to electrons in sensors and they can then be measured – this conversion rate is defined as Quantum Efficiency
  - Sensors convert photons of some wavelengths better than others
  - The number of photons that interact with a pixel depend on the physical size of the pixel
  - We can have a sensitive sensor but if our signal to noise is low we get a noisy image with data we cannot decipher

Quantum Efficiency (QE)

- QE is a measure of the effectiveness of an imager to produce electronic charge from incident photons

- The wavelength of incoming light and photon absorption depth are directly related; the shorter the wavelength, the shorter the penetration depth into the silicon

Incoming Light

Electronical Connection

Polysilicon Gate

Silicon Dioxide

Silicon

Potential Well

Electronic Detector Spectral Sensitivities

Silicon Photodiode

PMT (Ga-As-P)

PMT (Ga-As)

QUANTIUM EFFICIENCY %

WAVELENGTH (Nanometers)

What is actually happening at each pixel?

1. Photon hits the CCD sensor
2. is then converted to an Electron
3. and digitised using an Analogue to Digital converter (ADC)
4. Electron value is now converted to a grey scale
5. User measures grey scale (ADU)
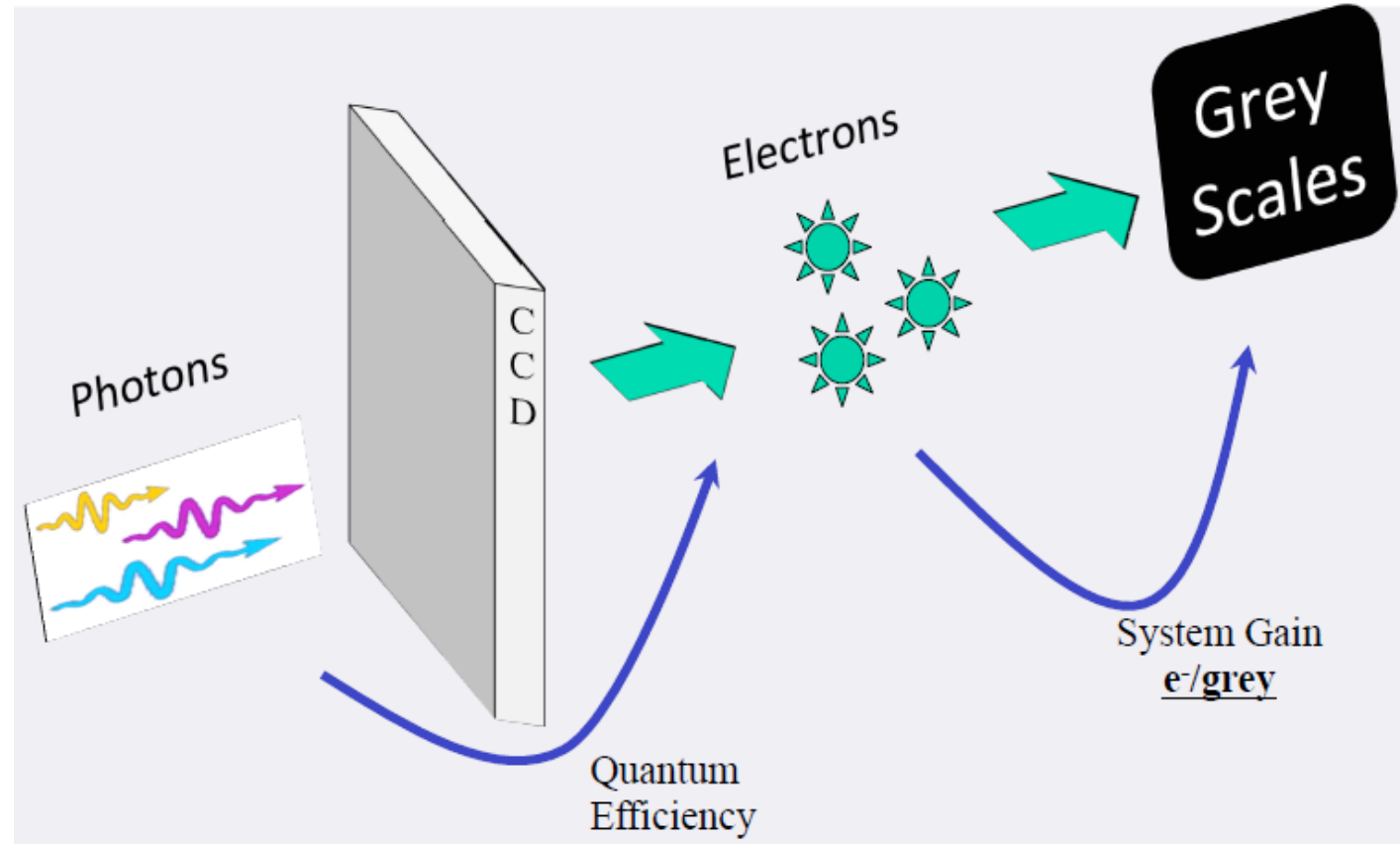
# Different Detector Types

- CCD – Charged Coupled Device

- EMCCD – Electron Multiplied CCD

- CMOS – Complementary Metal Oxide Semiconductor

- PMT – Photon Multiplier Tube

- APD – Avalanche Photodiode

CCD Fundamentals

- Invented in 1970 at Bell Labs
- A silicon chip that converts an image to an electrical signal
- Image is focused directly onto the silicon chip
- Widely used in TV cameras and consumer camcorders

CCD Sense Element (Pixel) Structure

Figure 3
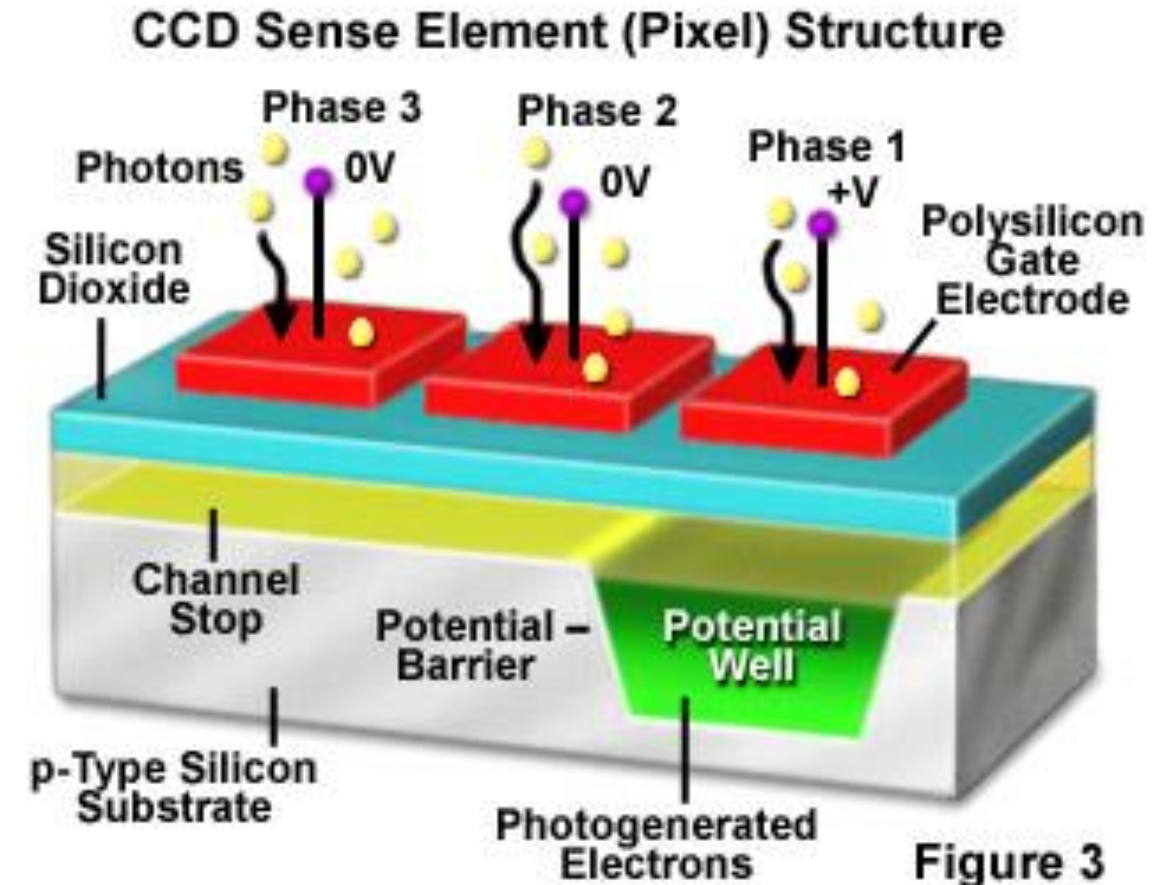
Bucket Brigade Rainfall Analogy

- rain intensity may vary from place to place

- parallel buckets on a conveyor belt transported stepwise to a row of empty serial buckets

- serial buckets move on a second conveyor oriented perpendicularly to the first

- accumulated rainwater in each bucket is transferred sequentially into a calibrated measuring container (= CCD output amplifier)

- process is repeated until all parallel buckets are shifted to the serials
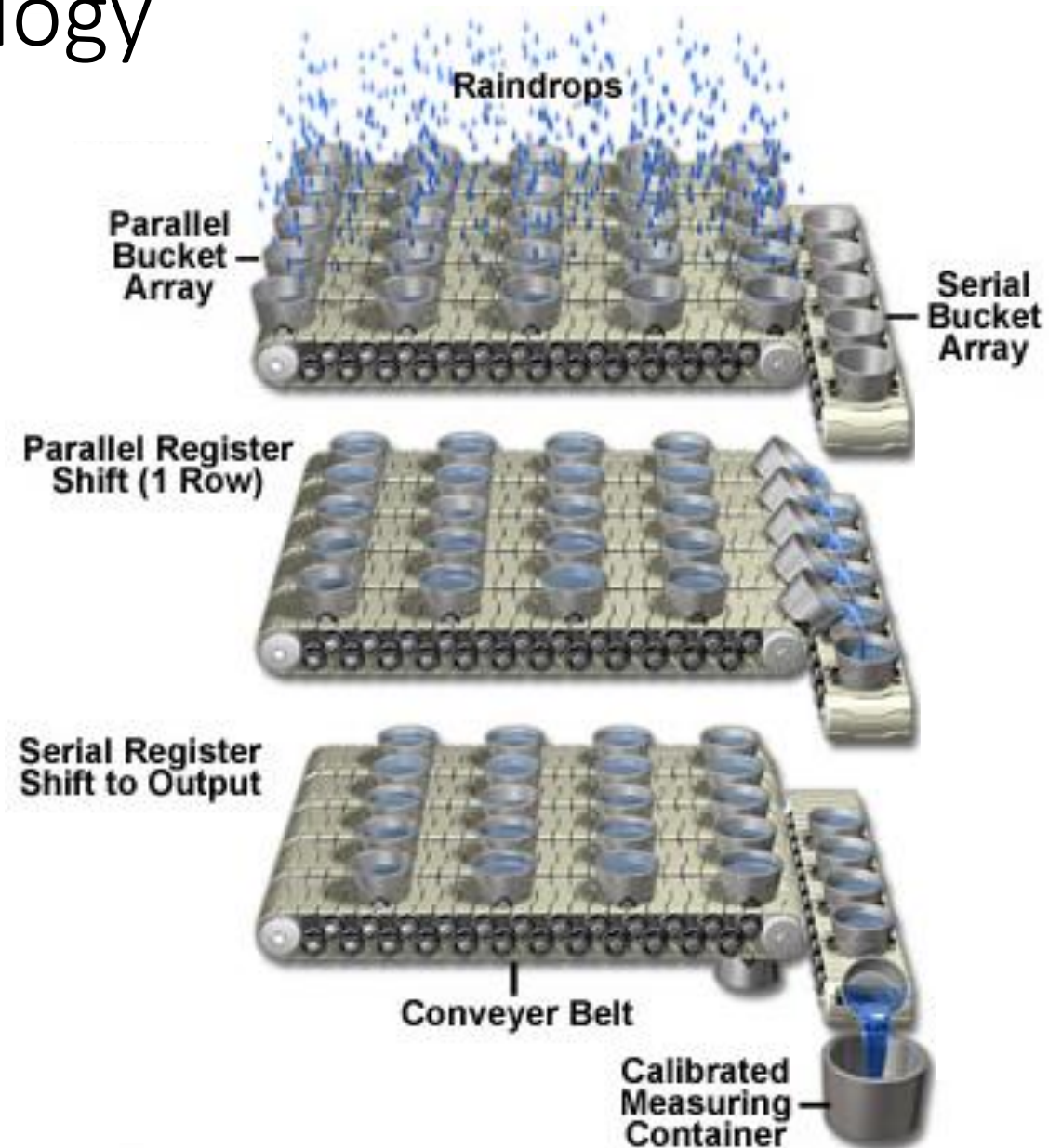
Readout of a CCD

- camera shutter is opened to begin accumulation of photoelectrons
- end of the integration period = shutter is closed
- accumulated charge is shifted row by row across the parallel register into the serial register
- charge contents of serial pixels are transferred into an output node to be read by an on-chip amplifier, which boosts the electron signal and converts it into an analog voltage output
- an ADC assigns digital value for each pixel according to its voltage
- each pixel value is stored in computer memory or camera frame buffer
- serial readout process is repeated until all pixel rows of the parallel register are emptied
- CCD is cleared of residual charge prior to the next exposure
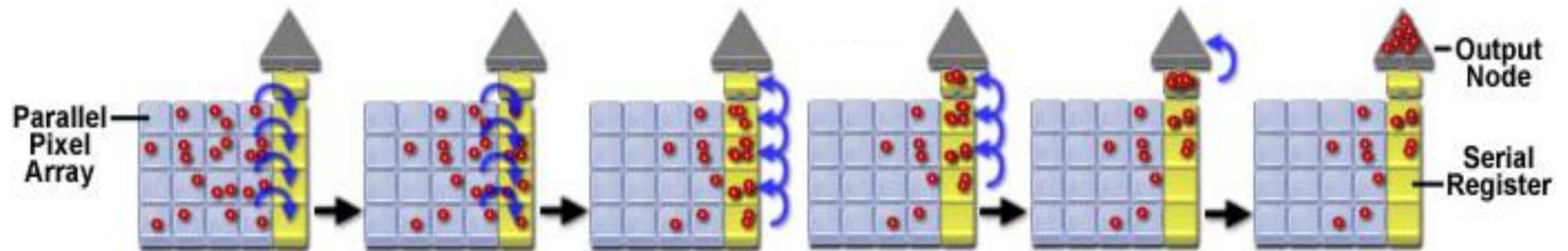
Camera Noise

- … is uncertainty

- … is plus or minus (not additive)

- … is driven by statistics

- … can be calculated

- … is not background

- standard deviation is an easy way for us to measure noise

- noise exists on every camera and in every measurement

- dependent on the image scale used you may or may not see it

- noise distorts measurements and increases the uncertainty in measurements.
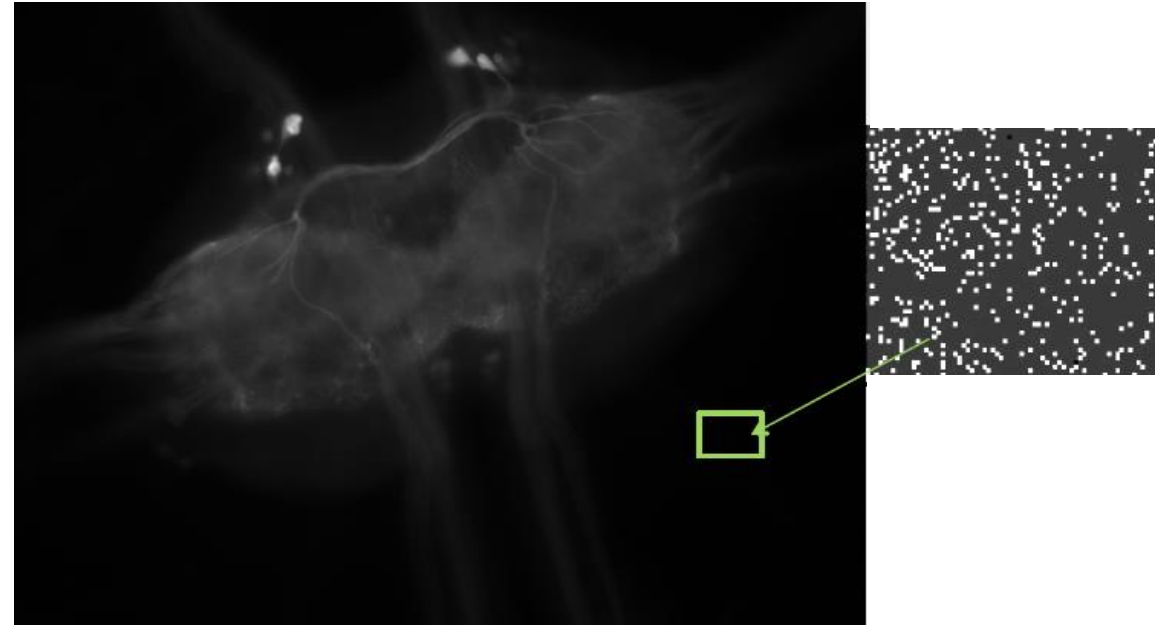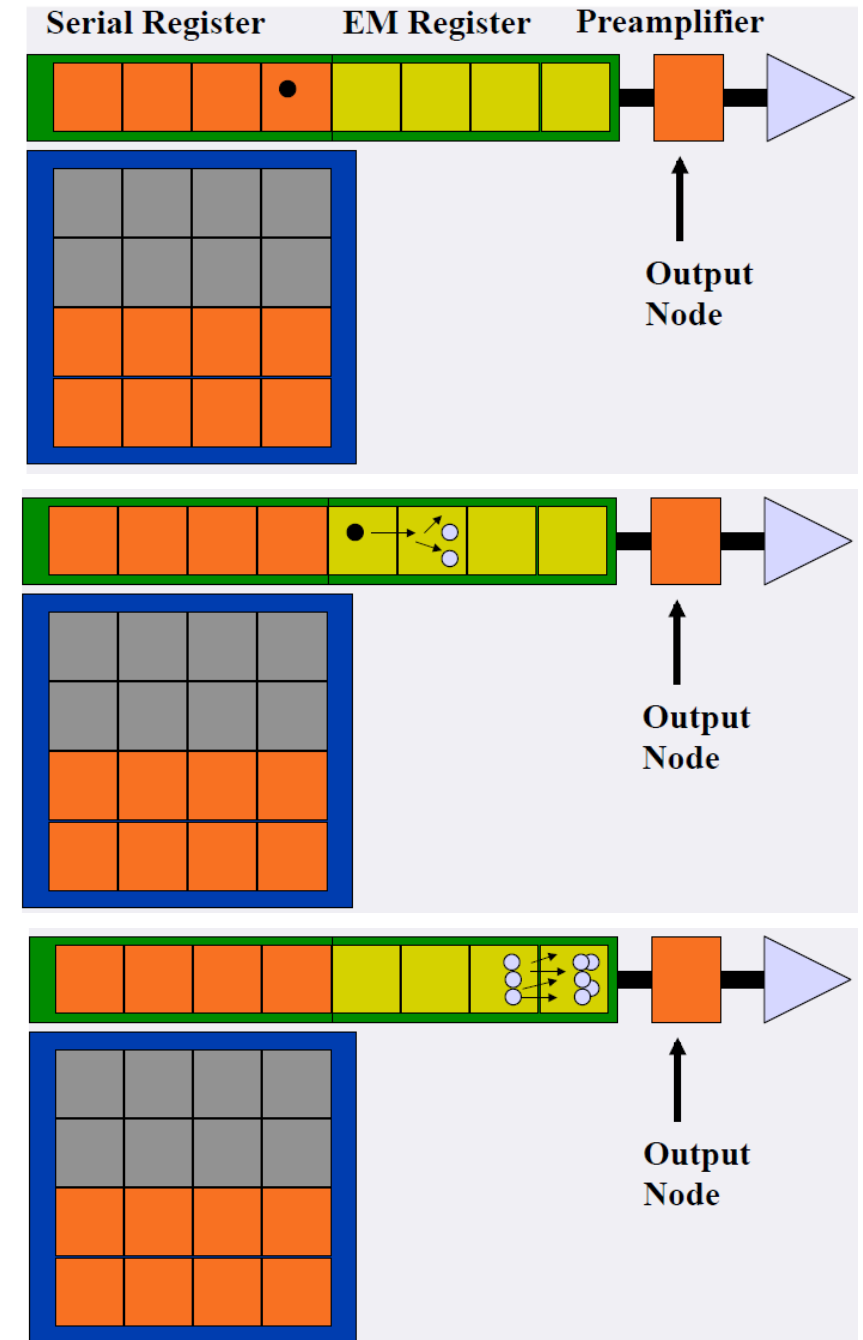
Noise Sources

1. ***Dark Current*** – noise from heat and cosmic noise – exposure dependent (less important)

2. ***Read Noise*** – noise of reading the signal – fixed

3. ***Photon Shot*** – square route of signal – signal dependent (Poission distributed)

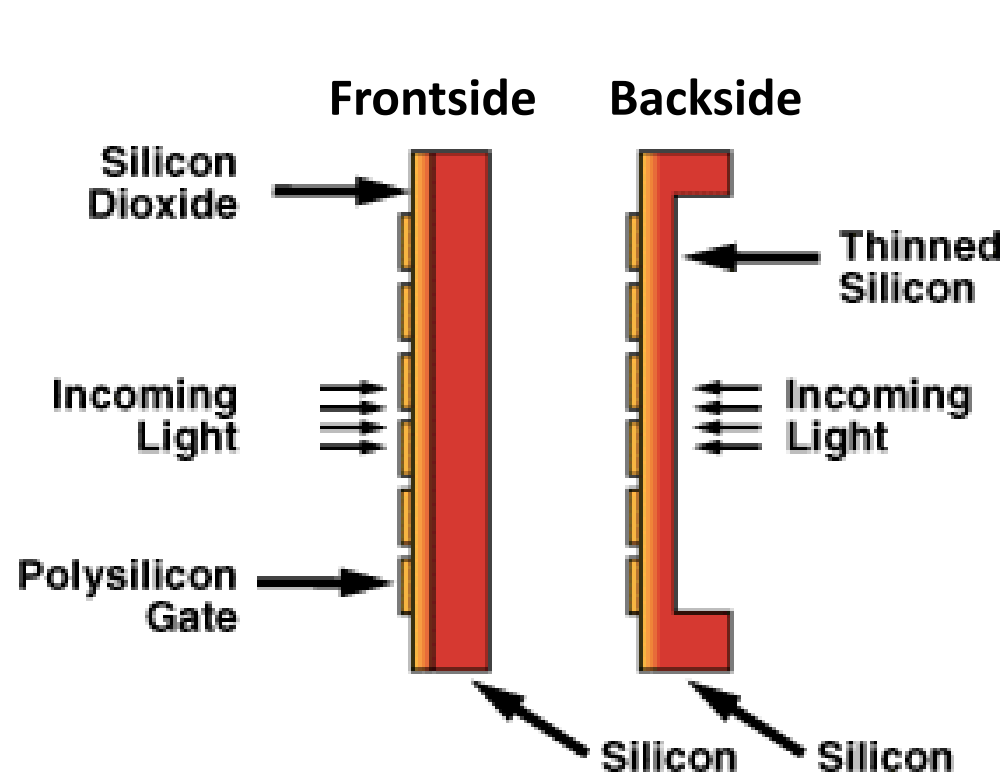$$SNR = \frac{S * QE}{\sqrt{(S * QE)^2 + DC + \sigma_R^2}}$$

- S =Signal in Photons (converted to electrons by * QE)
- QE = Quantum Efficiency of light at that emission
- D = Dark Current Noise = Dark Current * Exposure Squared
- σ_R = Read Noise

EMCCD- Electron Multiplied CCD

- based on CCD technology

- addition of an **Electron Multiplication register** ('gain register' between the usual serial shift register and the output amplifier)

- enabling higher signals relative to the fixed camera noise

- issues with EMCCDs
  - EM Gain decay
  - Bias Stability
  - EM Gain Stability (aging)
  - Back ground events – dark current
  - Excess Noise Factor (uncertainty due to unpredictable multiplication of electrons)

Front- and Backside-Illumination, Intensified CCD

Frontside   **Backside**

Silicon Dioxide

Thinned Silicon

Incoming Light

Incoming Light

Polysilicon Gate

Silicon   Silicon

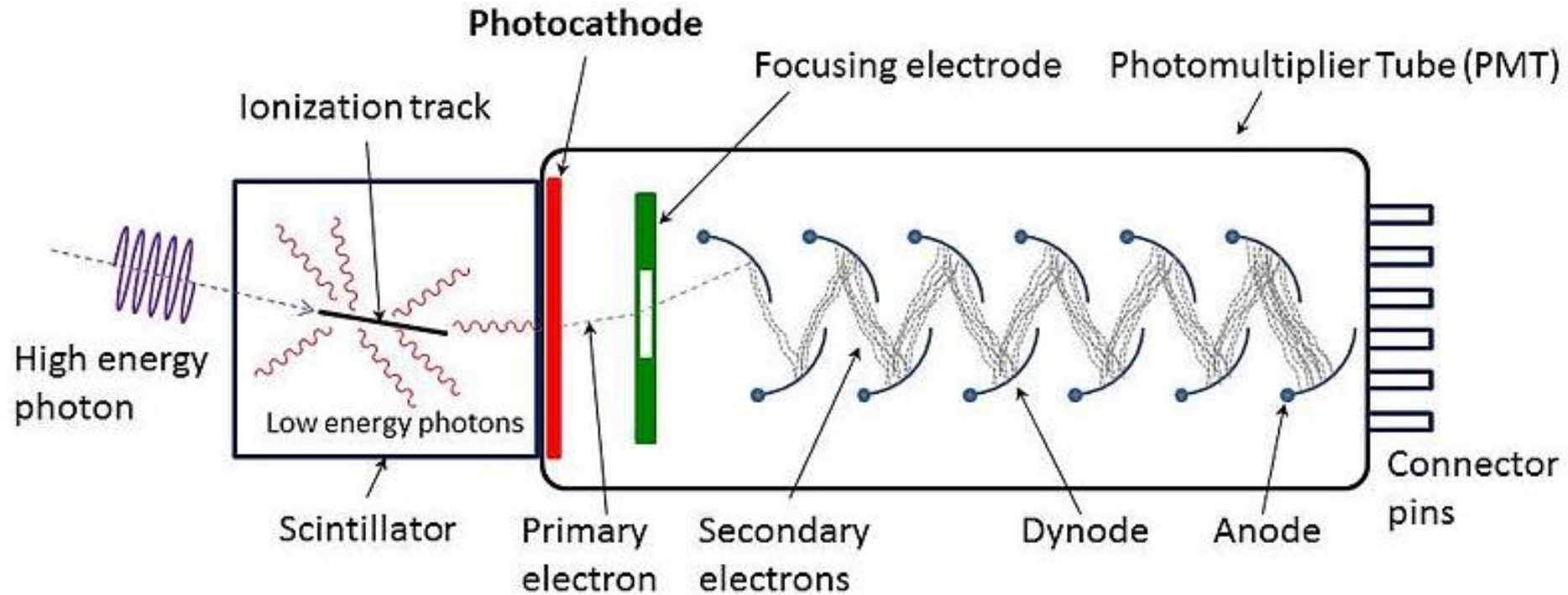**Photocathode   MCP   Phospher Screen   Fiber Optics**

A back-illuminated sensor orientates the wiring behind the photocathode which improves the chance of an input photon being captured from about 60% to over 90%.
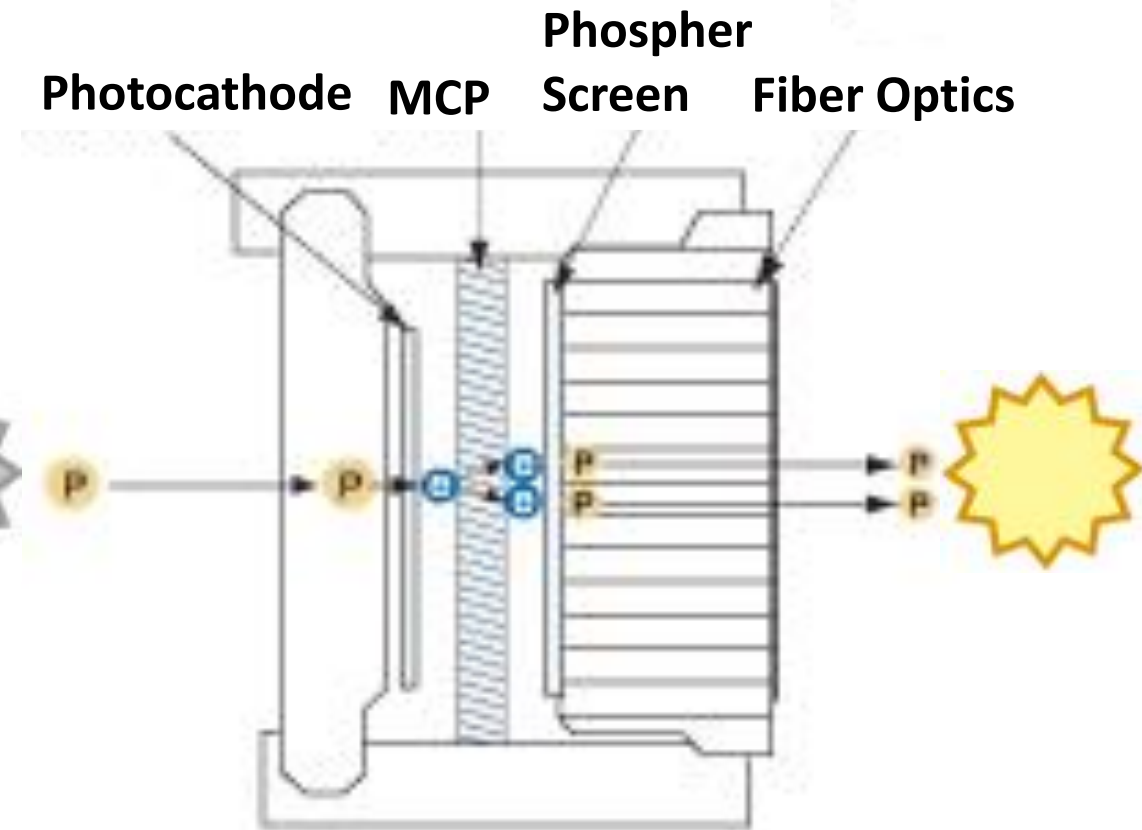
An ICCD is a CCD that is optically connected to an image intensifier sitting in front of the CCD

Excursus: Photomultiplier Tube (PMT)

Photocathode

Focusing electrode   Photomultiplier Tube (PMT)

Ionization track

High energy photon

Low energy photons

Scintillator   Primary electron   Secondary electrons   Dynode   Anode   Connector pins

- constructed from a glass envelope with a high vacuum inside, which houses a photocathode, several dynodes, and an anode

- photons produce electrons at the photocathode (photoelectric effect)

- electrons are multiplied by the process of secondary emission (amplification $\approx 10^8$)

MCP – Microchannel Plate

MCP

Channel

Incident Electron

Channel Wall

Output Electrons (thousands times)

VD
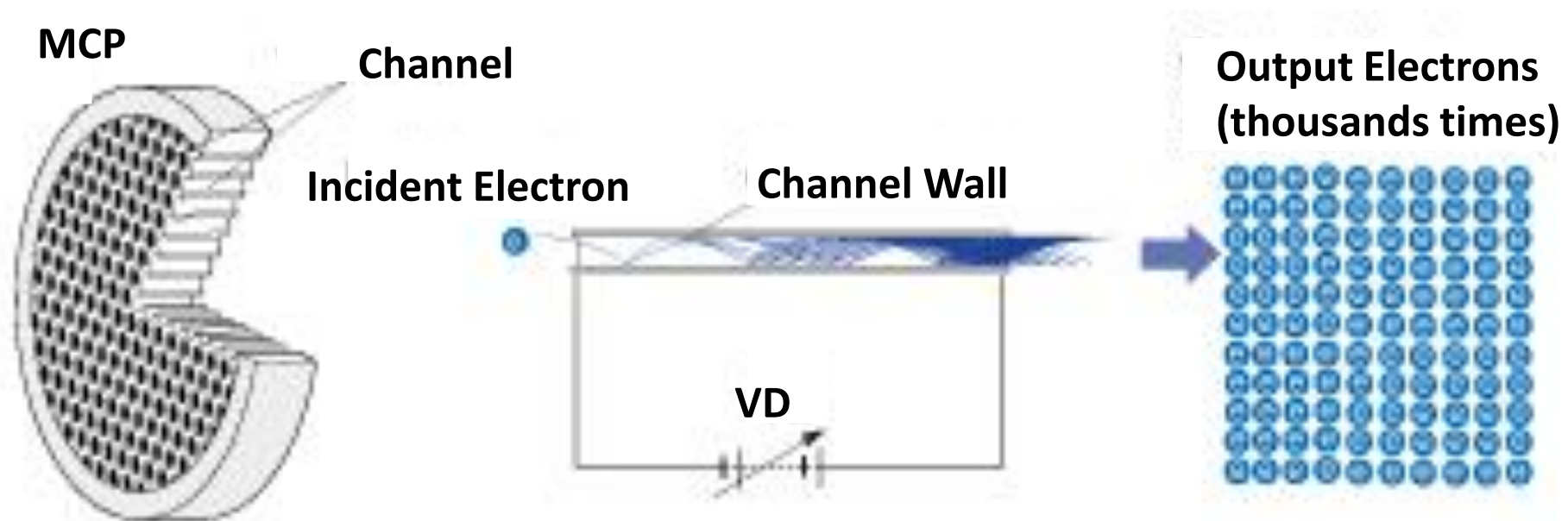
Each channel in the MCP is a secondary electron multiplier, multiplying electrons with each bounce off the channel wall

PMT

- release electrons with a peak quantum efficiency of about 40 %

- the photocathode active area ranges in size from a few millimeters to a half meter in diameter, depending upon the application.

- commonly used in applications without spatial resolution

- Photomultiplier tubes (**PMTs**) are widely used in confocal microscopes and high-end automatic exposure bodies for film cameras as well as in spectrometers

- because PMTs do not store charge and respond to changes in input light fluxes within a few nanoseconds, they can be used for the detection and recording of extremely fast events

- typically generate low noise values (and dark current) resulting in a huge dynamic range over which electrical current output still accurately reflects the photon flux

CMOS - Complementary metal-oxide-semiconductor

- CMOS technology, as CCD, uses an array of light sensitive pixels to collect full area image

- CMOS technology differs by completing all digitisation at the pixel point (faster)

- CMOS sensors require around 100x less power than CCD making them the perfect choice for camera phone sensors

- low costs

- disadvantages: small pixels so low dynamic range, high noise level, Rolling shutter, lower QE

CMOS goes Scientific (sCMOS)

- in 2009 manufacturers launched a camera technology called SCMOS (scientific CMOS)

- a new sensor type with
  - low noise – less than 2e read noise
  - high speed – 100 fps
  - high QE – 55-70%
 - high resolution – 2-5 million pixel
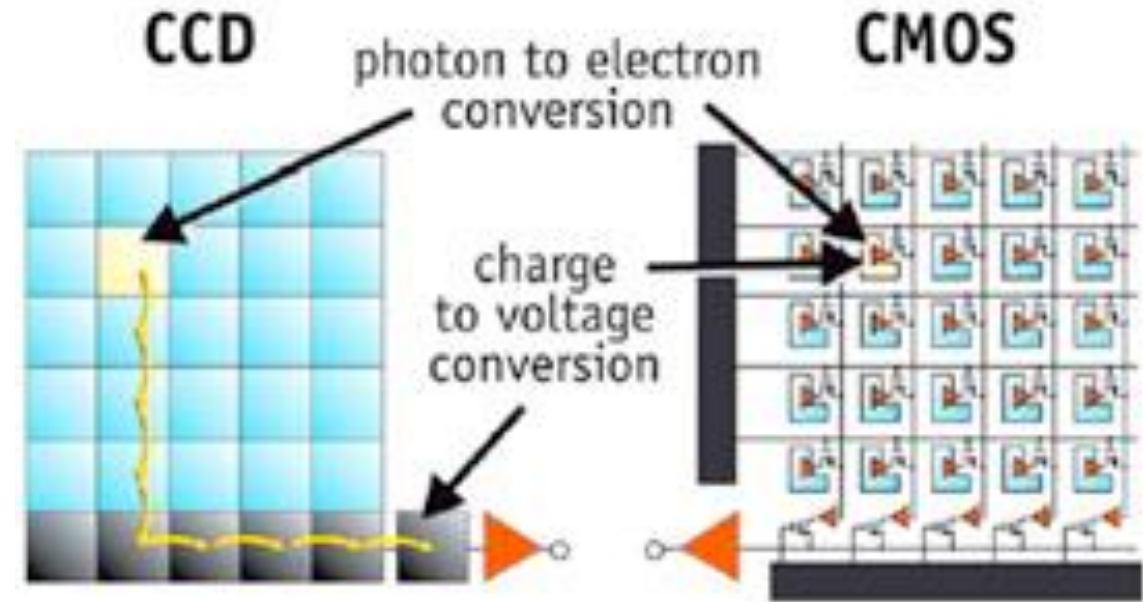
- **BUT**: Noise/Uncertainty occurs with the readout and digitization of each pixel's signal
- noise is not longer Gaussian distributed (random telegraph noise)
- rolling shutter (distortion of moving objects, poor synchronization with changing illumination experiments)

Summary

- **CCD** cameras have been the standard for general microscopy applications for many years and will continue to be the best choice for a variety of applications from colour imaging and fixed sample fluorescence to 'long stare applications'

- **EMCCD** cameras continue to offer the best solution when imaging at very low light levels with speed, for example single molecule fluorescence

- **SCMOS** is a new addition to the sensors available for microscopy when speed is key. Combining this with great sensitivity a large field of view and low noise. Well suited to applications such as SPIM.

PIN - Diode

- Incident photon creates an electron-hole pair (inner photoelectric effect)

- holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced. The total current through the photodiode is the sum of the dark current

- PIN = **high-level injection =** electric field extends deeply into this region
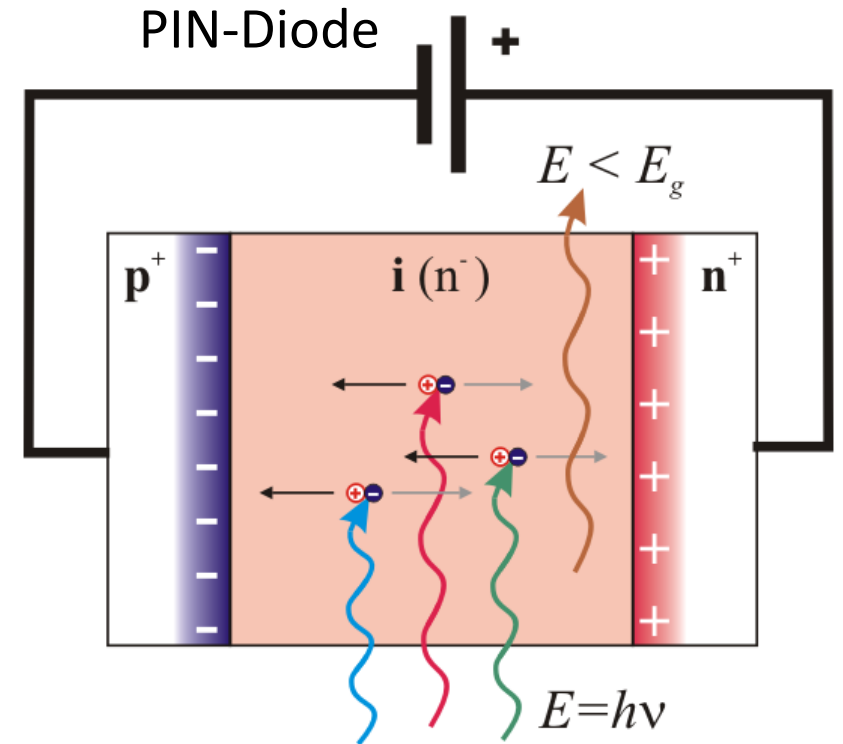
APD – Avalanche Photodiode

- APDs are similar to regular PIN diodes but operate with much higher revers bias

- have an additional heavily doped p- or n-region which allows an amplification (avalanche multiplication)

- acceleration of charge carriers in depletion region and generation of new secondary charge carriers via impact ionization (like PMTs)

- because of high revers voltage (close to breakdown voltage) of several 100V high magnifications of primary charge carriers

- for voltages bigger then the breakdown voltage = avalanche effect = amplification $\approx 10^6$
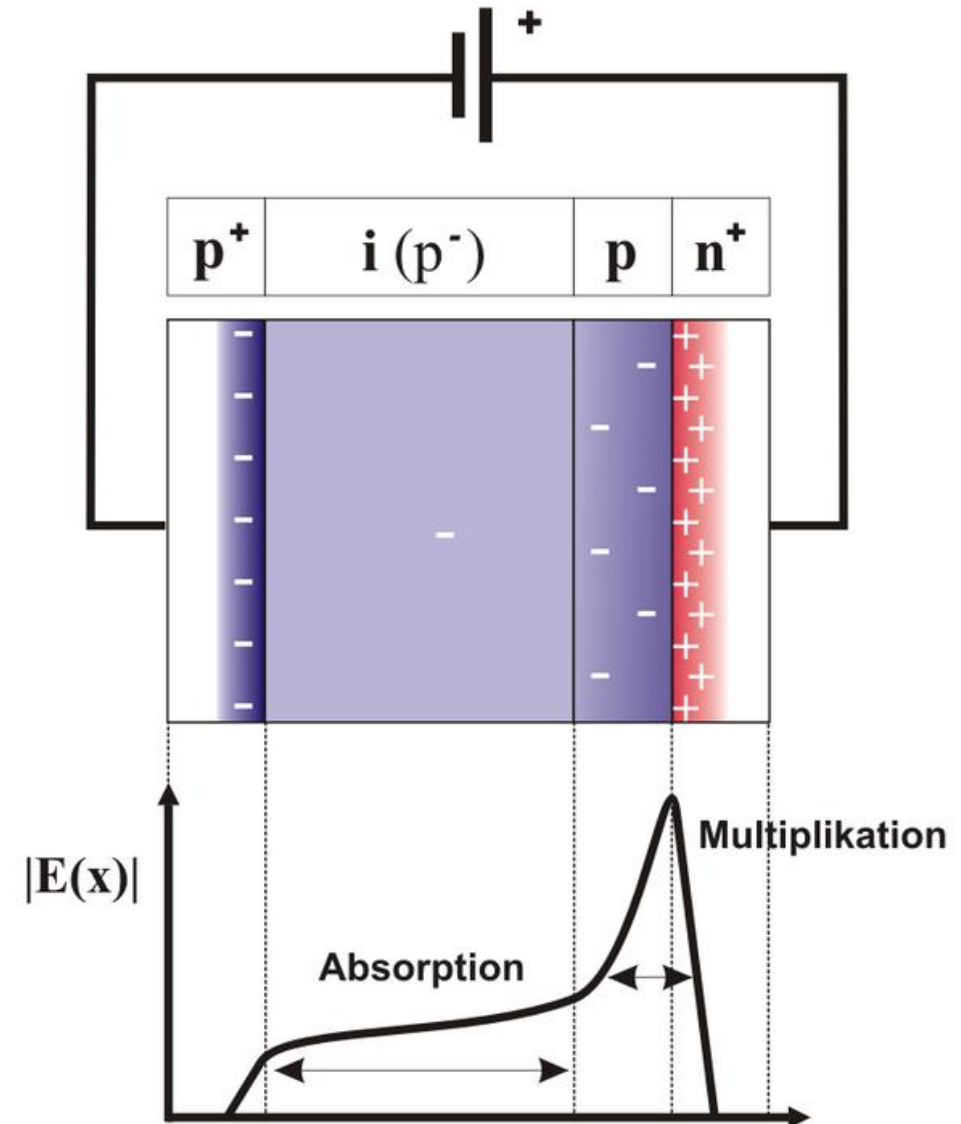
APD – Some Key Facts

- active area ≤ 1 mm^2 and ≤ 10 μm x 10 μm for a high-speed APD. It is therefore difficult to focus the fluorescence onto the APD, so the sensitivity is too low for most measurements.

- dead times of $\approx$ 100ns, wavelength dependent, event rates ca. 10MHz

- routinely used for TCSPC, especially in applications where the emission can be tightly focused, such as single-molecule detection (SMD) and fluorescence correlation spectroscopy (FCS)

- APDs have high quantum efficiencies at real wavelengths, and are the detector of choice for these applications.

The End!