MICRO-428: Metrology

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MICRO-428: METROLOGY

WEEK THREE: OPTICAL IMAGE SENSORS

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EPFL at Microcity, Neuchâtel, Switzerland

EPFL

Reference Books

- A. Theuwissen, “Solid-State Imaging with CCDs”, SSS&T Library, 1995
- P. R. Gray, P. J. Hurst, S. H. Lewis, R. G. Meyer, “Analysis and Design of Analog Integrated Circuits (4th ed.)”, Wiley, 2001
- P. E. Allen, D. R. Holberg, “CMOS Analog Circuit Design (2nd ed.)”, Oxford University Press, 2002

Outline

3.1 Abbe’s Limit and sub-resolution pixels – Review of Sampling Theory

3.2 Microlenses and vignetting

3.3 Single-photon detectors and their metrology

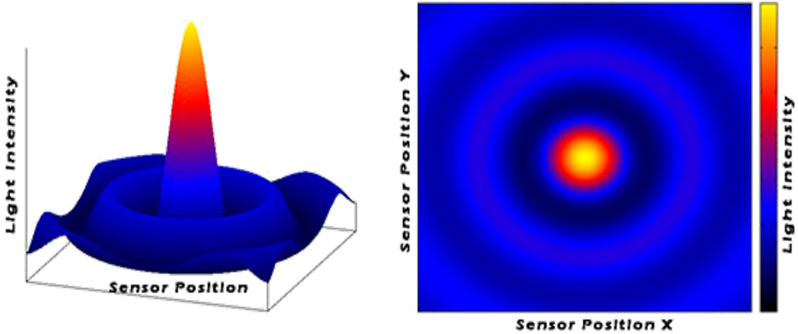
3.1.1 Abbe's Limit

- The Rayleigh criterion says that the minimum spatial resolution behind a lens is the radius of the Airy disk

$$r_a = 1.22\lambda F\#$$

where λ is the wavelength of light and $F\#$ is the F-number of the lens, defined as f/D, where f is the focal length and D the diameter of the entrance pupil.

- Image of the Airy rings projected onto a screen:



3.1.2 Sub-resolution Pixels – The Gigavision Approach

- In conventional pixels, the number of photons detected is proportional to the number of accumulated charges, and thus the voltage across a capacitance
- If the pixel is sub-divided in smaller (ideally infinitesimal) cells, each detecting a single photon, then the pixel would look like this:

3.1.2 Sub-resolution Pixels – The Gigavision Approach

- Thus, photosensitive cells smaller than r_a will capture a uniform light and will show no additional details of the scene!
- However, we can imagine them as receiving a low-pass filtered image where r_a is the equivalent of the Nyquist bandwidth (but in space-, not in time-domain) and the cells are operating a sort of oversampling, the OSR being defined as

$$OSR = \frac{X \cdot Y}{x \cdot y},$$

where x,y and X,Y are the pitch of the cells and of the pixel.

3.1.2 Nyquist-Shannon sampling theorem

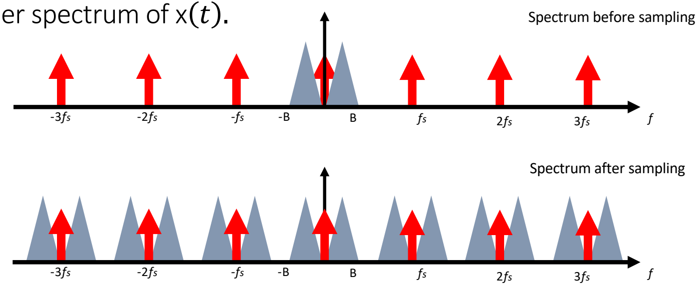
- Given a band-limited continuous function x(t), sampled with a rate (sampling rate) $f_S = 1/T_S$, into a function x_S

$$x_S(t) = \sum_{k=-\infty}^{+\infty} x(t - kT_S).$$

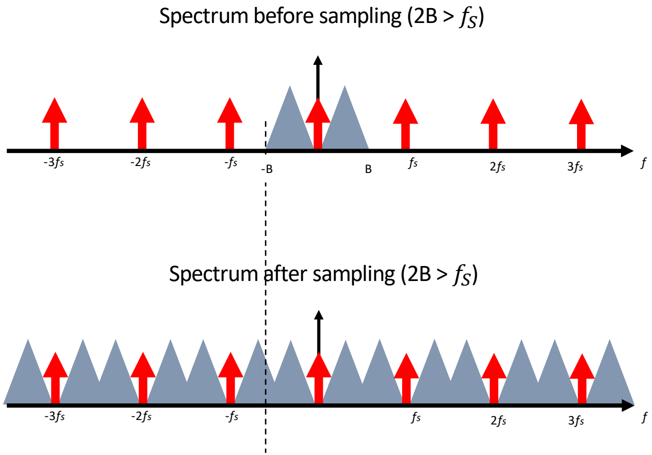
- $x(t)$ can be reconstructed with perfect fidelity iff f_S>2B, where B is the bandwidth of $x(t)$. The resulting Fourier spectrum $X_S(\omega)$ is

$$X_S(\omega) = \sum_{k=-\infty}^{+\infty} X(\omega - kf_S),$$

where $X(\omega)$ is the Fourier spectrum of x(t).

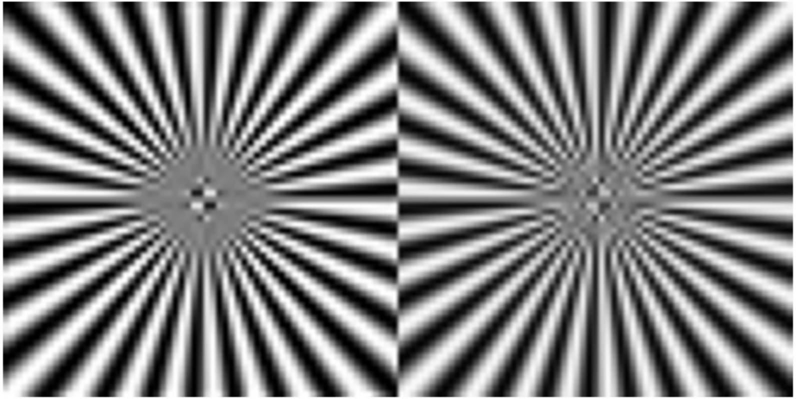


3.1.2 Nyquist-Shannon sampling theorem => Aliasing



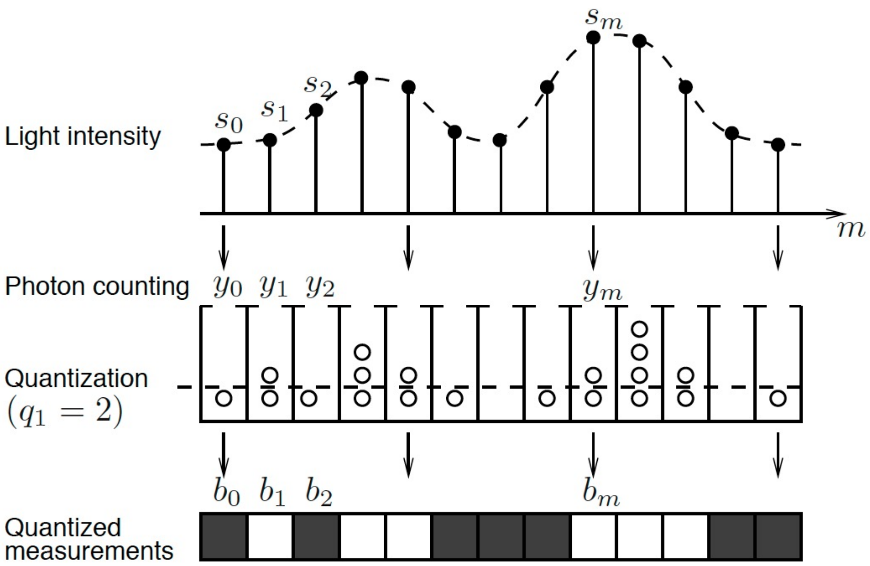
3.1.2 Nyquist-Shannon sampling theorem in space

- The same is true when we sample in space, where sampling in x-, y-direction results in aliasing if the x- and y-spatial spectrum have a bandwidth that is higher than the sampling distance (or, in our case, the pitch of the pixels)
- Examples of aliasing in cameras



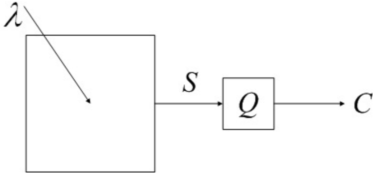
Source: Bart Wronski

3.1.2 Sub-resolution Pixels – The Gigavision Approach

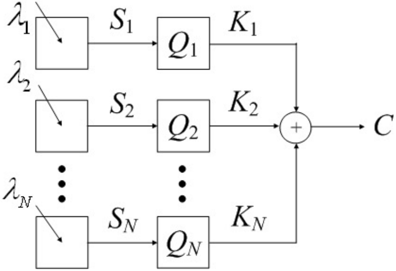


3.1.2 Sub-resolution Pixels – The Gigavision Approach

Conventional Pixels:



Gigavision Pixels:

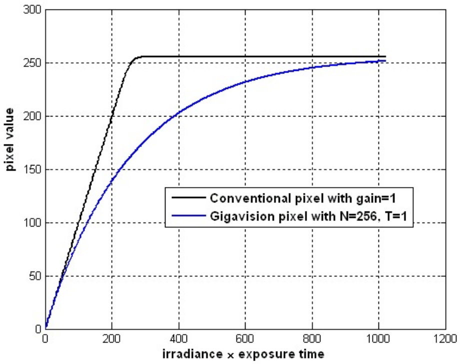


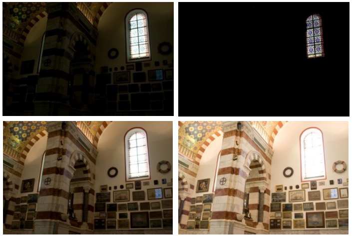
$$p_\lambda = \mathbb{P}[S_i \geq T] = \sum_{k=T}^{\infty} e^{(-\lambda/N)} \frac{(\lambda/N)^k}{k!}.$$

$$\lambda = -N log\left(1 - \frac{\mathbb{E}[C]}{N}\right)$$

3.1.2 Sub-resolution Pixels – The Gigavision Approach

- Logarithmic response given by statistics, thus no PVT variability are present!





Conventional Cameras: multiple exposures

Gigavision Camera: single exposure

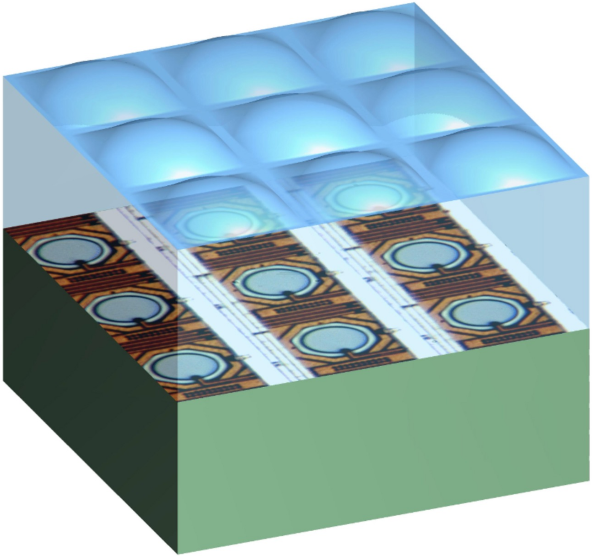
3.1.2 Sub-resolution Pixels – Color Example

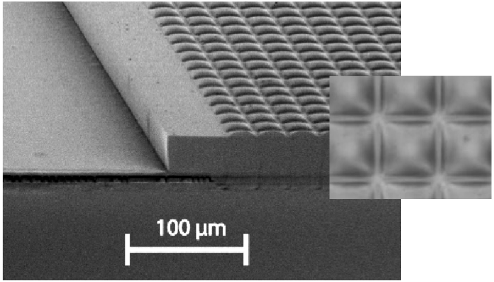
original image

1 binary image, oversampling factor 8 by 8

255 binary images, oversampling factor 8 by 8

3.2.1 Microlenses





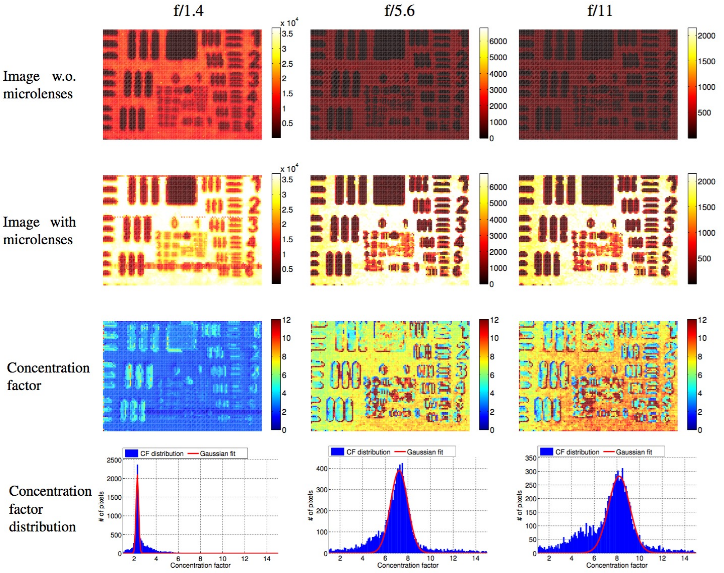
J. Mata Pavia et al., Optics Express 2014

3.2.1 Microlens Metrology – Practical characterization

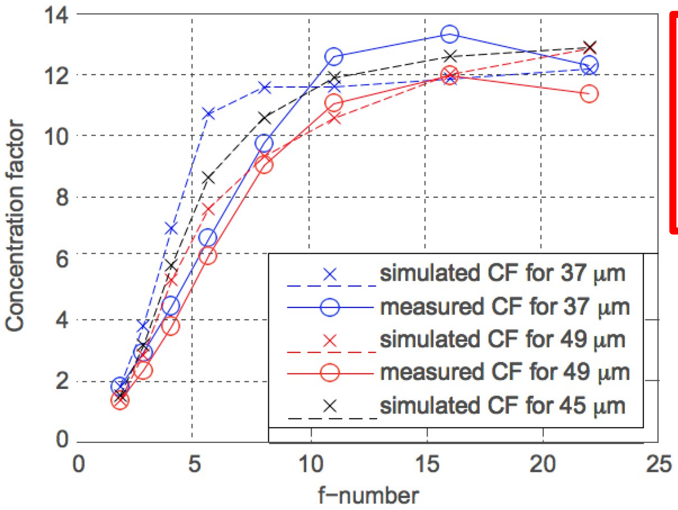
- Goal: Concentration factor (CF) characterization
- CF definition:

$$CF = \frac{\text{Photon count with microlens}}{\text{Photon count without microlens}}$$

- Use different f-numbers
- Normalize for infinite or 1
- At an f-number of 1, the concentration factor will approach 1
- Perform relative measurement



3.2.1 Microlens Metrology – Concentration Factor vs. f-number



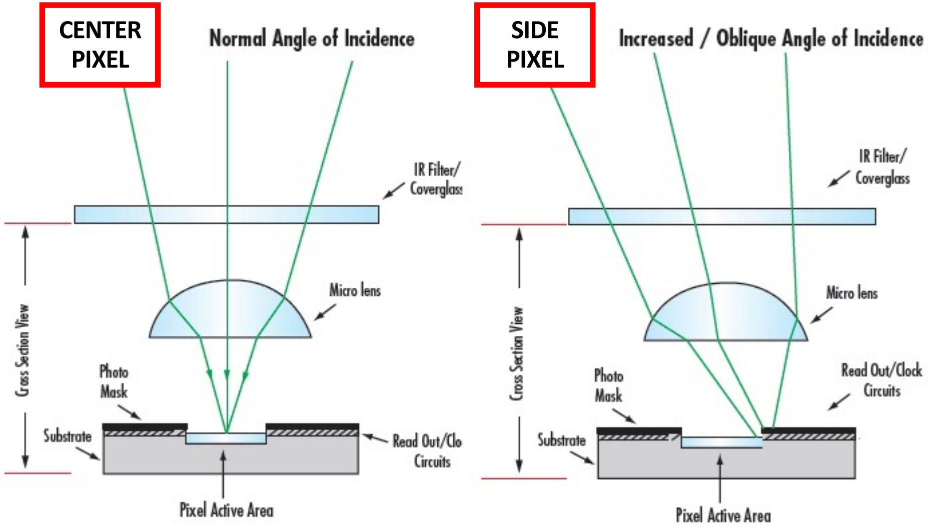
J. Mata Pavia et al., Optics Express 2014

F-number = f/D

D = *aperture (diameter of entrance pupil)*

f = *focal length*

3.2.2 Vignetting

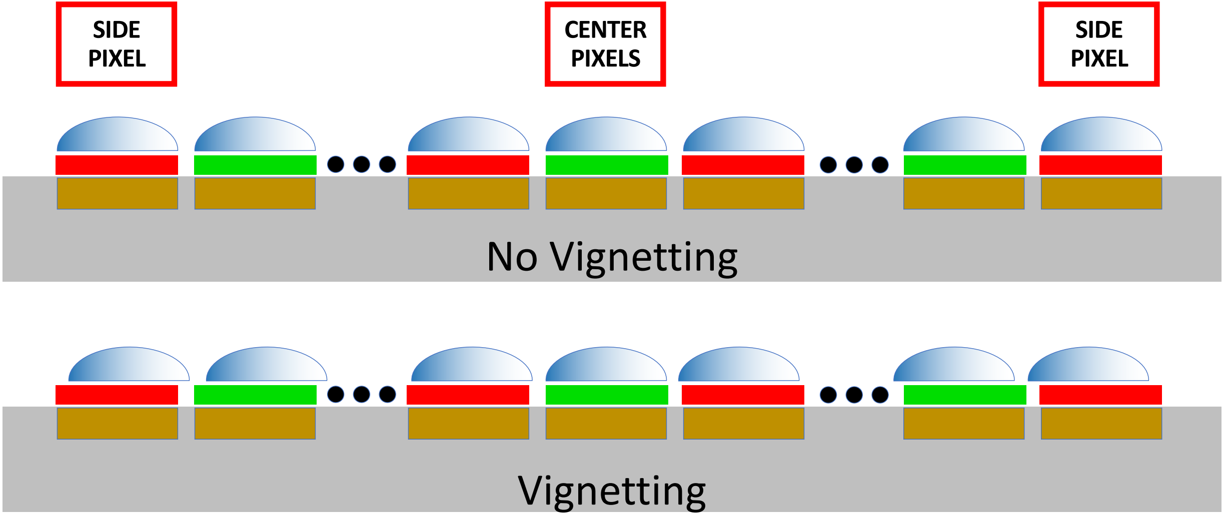


Source: Edmund Optics Ltd.

3.2.2 Vignetting – Example

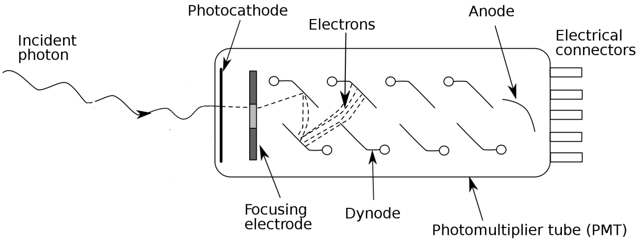
Source: Wikipedia.

3.2.2 Vignetting – Solution



3.3.1 Single-photon Detectors

- Electron multiplication in vacuum
  - **Photomultiplier tube (PMT)**
  - **Microchannel plate (MCP)**
- Electron multiplied charge-coupled device (EMCCD)
- Avalanche photodiode (APD)
- Geiger-mode APD (GAPD) or Single-photon avalanche diode (SPAD)
- Silicon photomultiplier (SiPM)

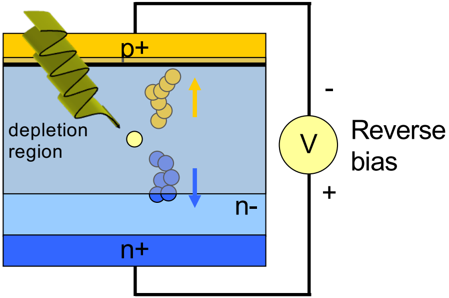


Source: Hamamatsu

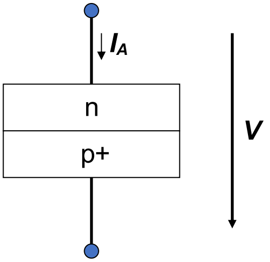
3.3.1 Single-photon Detectors – CMOS SPDs

- Suppose one can perform *impact ionization* in a solid, thereby achieving *very large gain* in an area of a *few tens of μm²* (thus at pixel level)

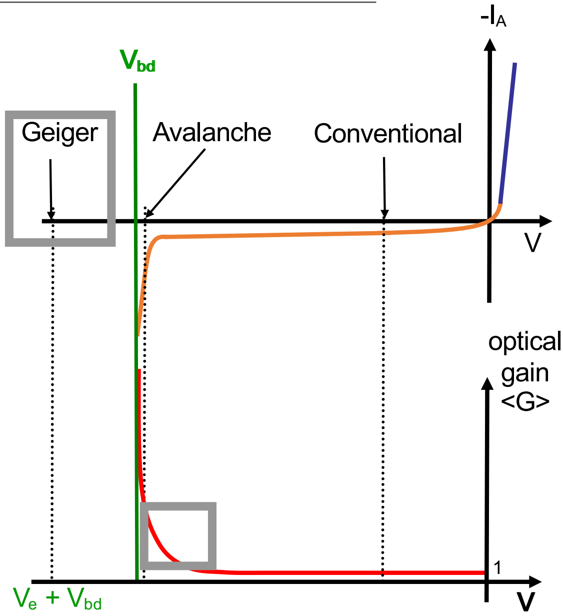
- This can be achieved in an abrupt one-sided junction



3.3.1 Single-photon Detectors – Single-photon Avalanche Diode (SPAD)

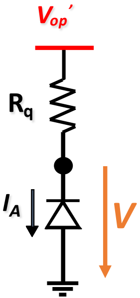


- One can achieve a current gain of 2-10,000…
  but G varies exp. with bias!

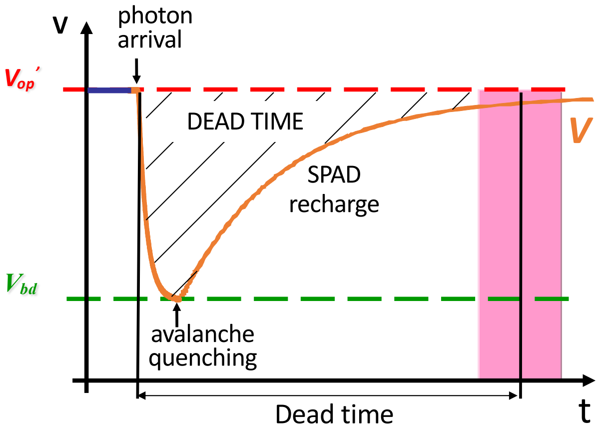


3.3.1 Single-photon Detectors – Single-photon Avalanche Diode (SPAD)

Passive quenching:

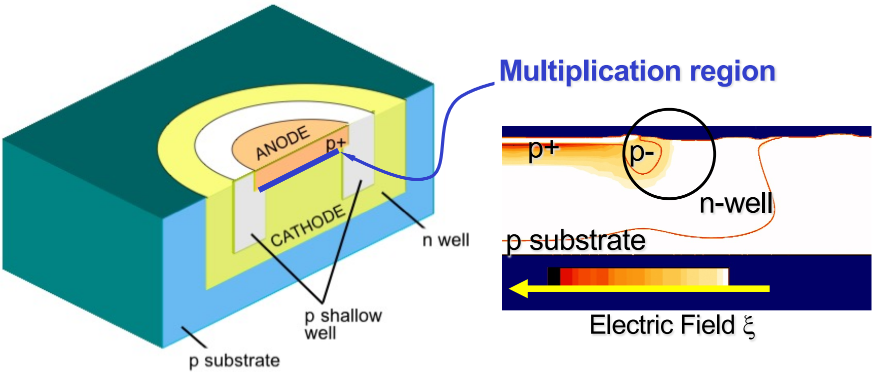


Operation cycle:



3.3.1 Single-photon Detectors – Single-photon Avalanche Diode (SPAD)

- Implemented entirely using standard layers and conventional process steps!



3.3.2 SPAD Metrology

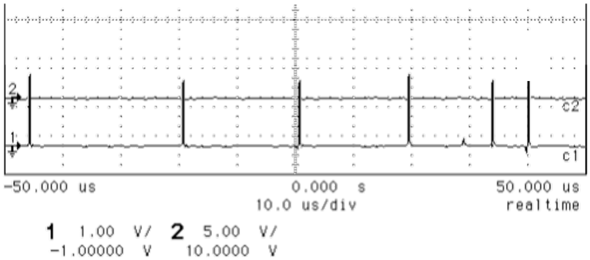
- *Dead time*
- Dark counts
- Photon detection probability (PDP)
- Timing resolution
- *Afterpulsing*

… and in SPAD matrices

- Crosstalk
- PDP Uniformity
- DCR Uniformity

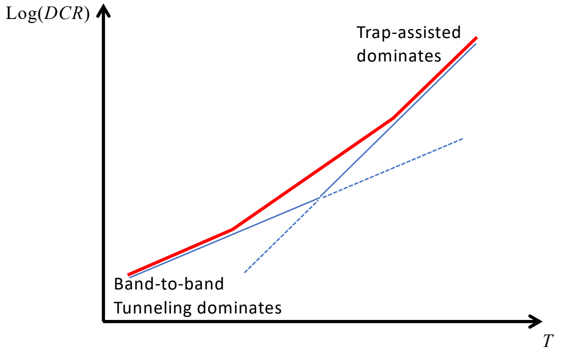
3.3.2 SPAD Metrology – Dark Counts

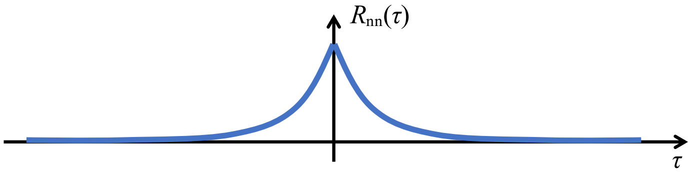
- Measure dark count rate (DCR)
  - Count events in fixed time Δt
    - tradeoff btw. timing resolution and DCR error
  - Counter resolution
  - Averaging
  - Area of detector proportional to DCR
- Due to statistical behavior use:
  - Mean
  - Median
  - Cumulative
- State-of-the-art SPADs in dedicated technology:
  - 0.04~1Hz/μm^2
- State-of-the-art CMOS SPADs:
  - 0.1~10Hz/μm^2



3.3.2 SPAD Metrology – Dark Counts

- Physical mechanisms
  - Band-to-band tunneling generation
  - Trap-assisted thermal generation
  - Trap/tunneling assisted generation
- DCR statistics is Poisson, just like photon arrivals, so it is indistinguisheable from the signal (and thus it cannot be removed from it)
- Consequently, the autocorrelation function $R_{nn}(\tau)$ is a double exponential:





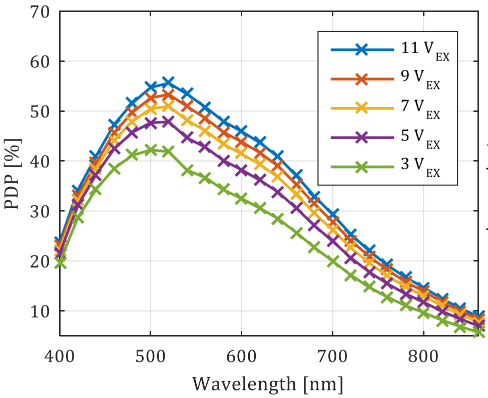
3.3.2 SPAD Metrology – Photon Detection Probability

- Measure photon response in a monochromator
  - As a function of excess bias
  - As a function of wavelength and temperature
- Measure count rate subtracting DCR
- Check time-varying behavior, it should have a Poisson distribution

$$PDP = QE \cdot \Pr(\text{Avalanche} \mid E)$$

QE : Quantum Efficiency

$\Pr(\text{Avalanche} \mid E) =$ Probability an avalanche is triggered from photon event E



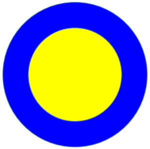
Antolovic et al., Optics Express 2018

$$PDE = FF \cdot PDP$$

$$FF : \text{fill factor} = \frac{\text{Active Area}}{\text{Total Sensor Area}}$$

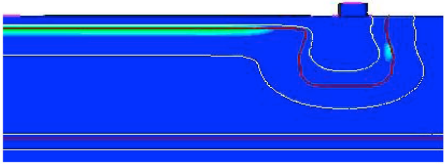
3.3.2 SPAD Metrology – Fill Factor

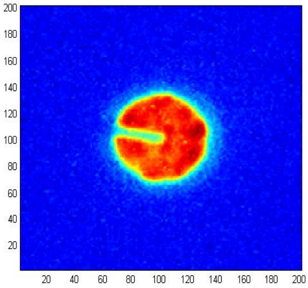
- Drawn fill factor
  - Easy to compute
- Effective fill factor
  - Needs simulations to find it
  - Needs light emission tests



Drawn multiplication region (p+ region) in yellow

Simulation of electric field distribution; see where critical field is exceeded





Light emission during multiple avalanches

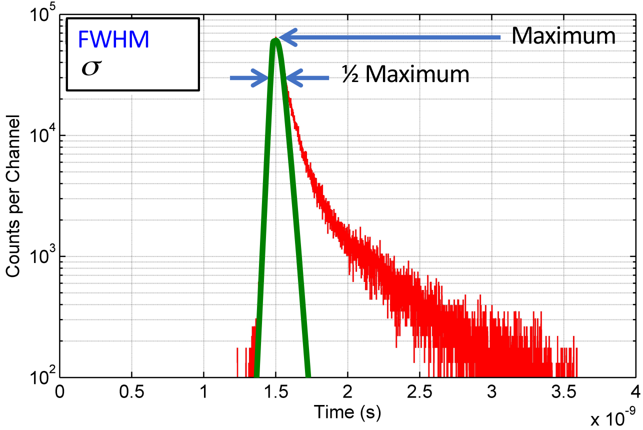
3.3.2 SPAD Metrology – Photon Detection Efficiency (PDE)

- PDE
  Measure count rate at given excess bias and temperature
  Normalize to a reference detector with known PDE
- PDP
  Compute effective sensitive area
  PDP = PDE/FF
- Pr(Avalanche $|E$)
  Pr(Avalanche $|E$) = PDP/QE
- Proportionalities
  PDE linear (active area); PDP ~constant (active area)
  PDP&PDE linear (excess bias voltage)
  PDP&PDE ~constant (temperature)

3.3.2 SPAD Metrology – Jitter or Timing Resolution

- Measure timing resolution, i.e. timing uncertainty of a response given an optical pulse excitation

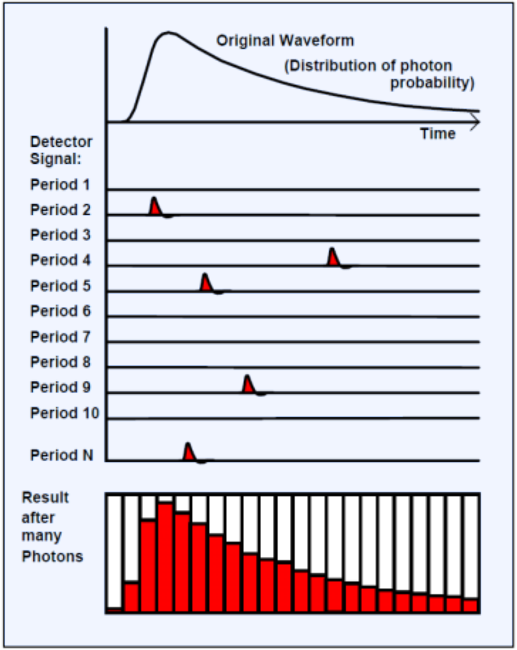
  Assuming a Gaussian response, it is the std dev or full-width-at-half-maximum (FWHM)
- This measurement is usually obtained by time-correlated single-photon counting (TCSPC)
- When the detector is fomed by multiple SPADs we talk about single-photon time resolution (SPTR) vs. multi-photon time resolution (MPTR)
- With multiple detectors we talk about coincidence time resolution (CTR) or coincidence resolving time (CRT)



3.3.2 SPAD Metrology – TCSPC (Review)

- Goal: measure the photo response *h(t)* of a detector
- Synchronize a pulsed laser source with a chronometer (TDC or TAC)
- Use a SPAD as a detector
- Repeat a measurement of the time response *N* times and record the result into a histogram

$$\hat{h}(t) \rightarrow h(t) \text{ for } N \rightarrow \infty$$

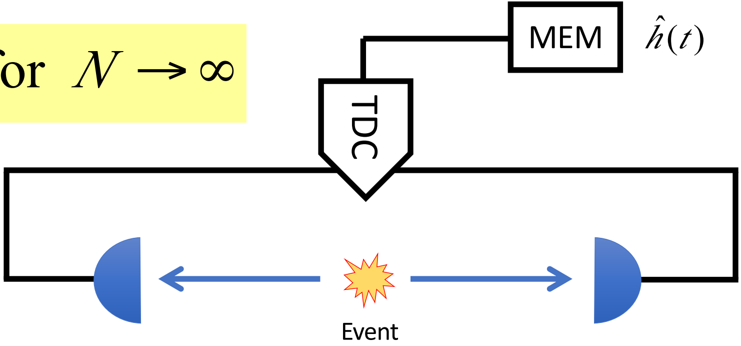


Source: Becker and Hickl

3.3.2 SPAD Metrology – CTR/CRT

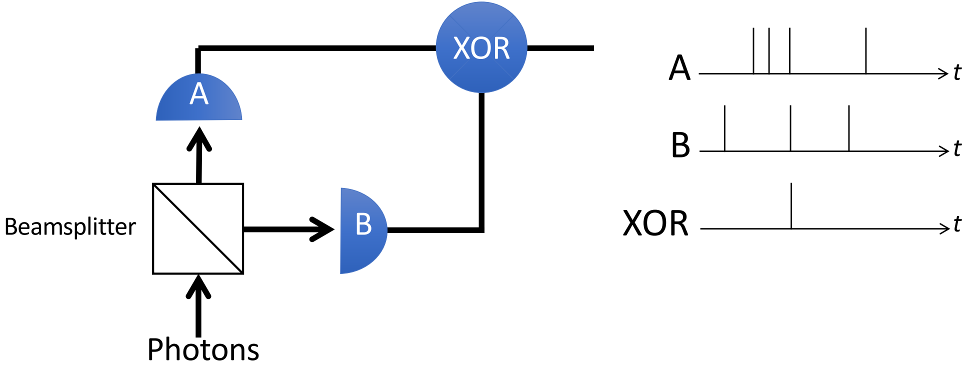
- Goal: measure coincidence of an event between multiple detectors
- Use one detector to start a TAC or TDC and the other to stop it
- Repeat a measurement of the time response *N* times and record the result into a histogram
- *This method does NOT require a known event occurrence!*
- Again:

$$\hat{h}(t) \rightarrow h(t) \text{ for } N \rightarrow \infty$$



3.3.2 SPAD Metrology – DCR Suppression

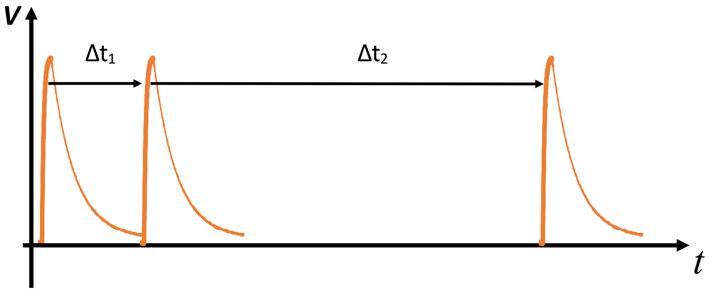
- Coincidence is a technique use routinely to reduce the effects of DCR in low photon flux measurements
- When two pulses are measured in coincidence, they are assumed to be originated by the same source.
- Otherwise 'singles' are assumed to be DCR, thus ignored

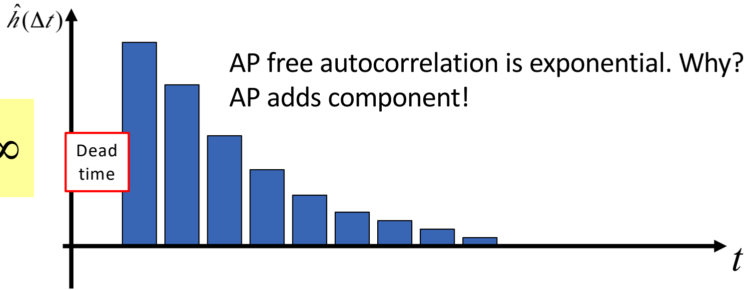


3.3.2 SPAD Metrology – Afterpulsing

- Measure afterpulsing probability, i.e. the probability that an avalanche is triggered by an event that is related to a previous event
- Free-running TCSPC
- Compute histogram **of inter-arrival times**
- Again:

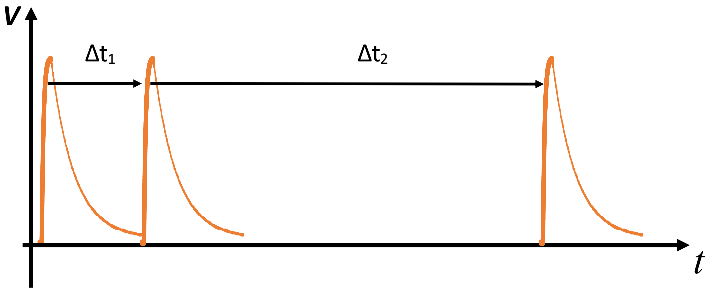
$$\hat{h}(\Delta t) \to h(\Delta t) \text{ for } N \to \infty$$





3.3.2 SPAD Metrology – Afterpulsing

- Four methods, of which these are the most used:
  1. Sample counts at fixed times in the presence of light and compute the autocorrelation function
  2. Measure inter-arrival times in the presence of light and compute autocorrelation function



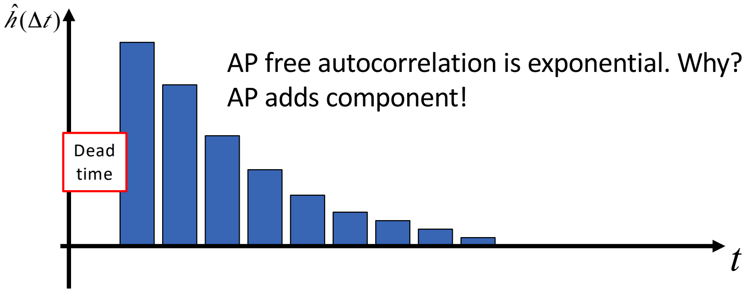
- Proportionalities:

  Linear (charge involved in an avalanche)

  Exponential (inter-arrival time & dead time)

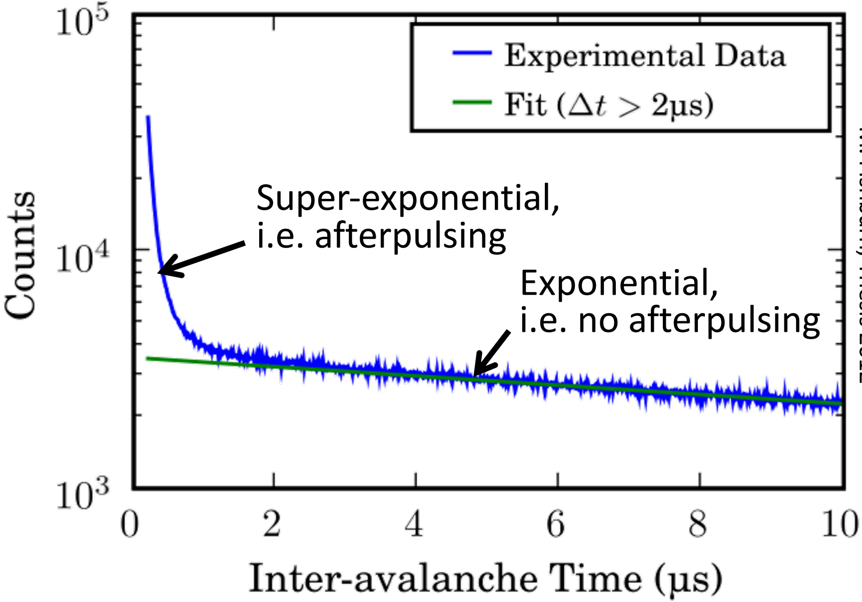
  Complex dependency (excess bias voltage)

  Complex dependency (temperature)



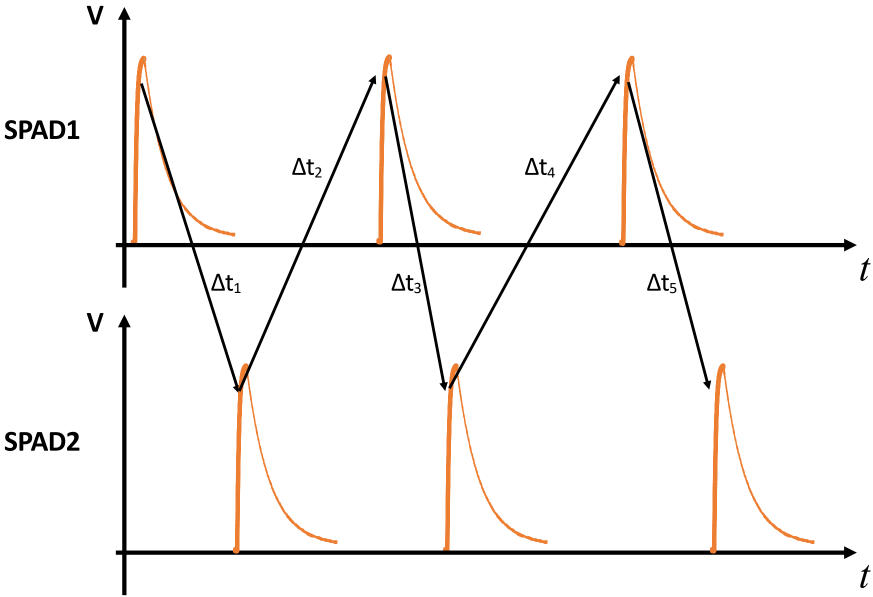
AP free autocorrelation is exponential. Why?
AP adds component!

3.3.2 SPAD Metrology – Afterpulsing Example

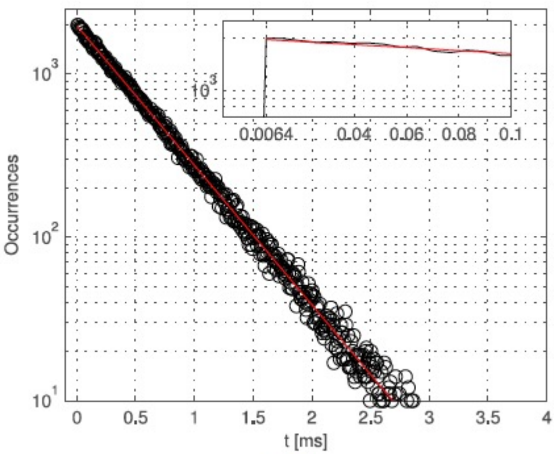


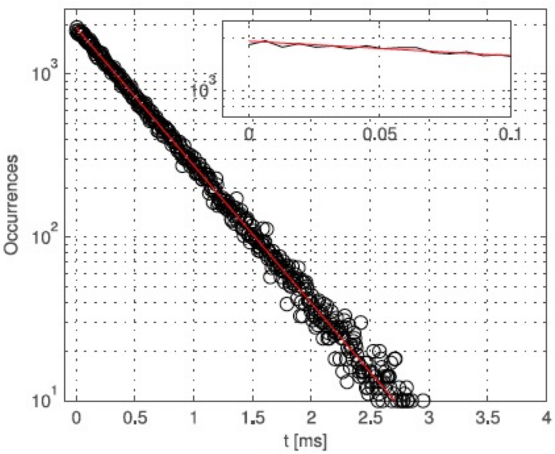
M. Fishburn, Thesis 2012

3.3.2 SPAD Metrology – Crosstalk: Cross-inter-arrivals



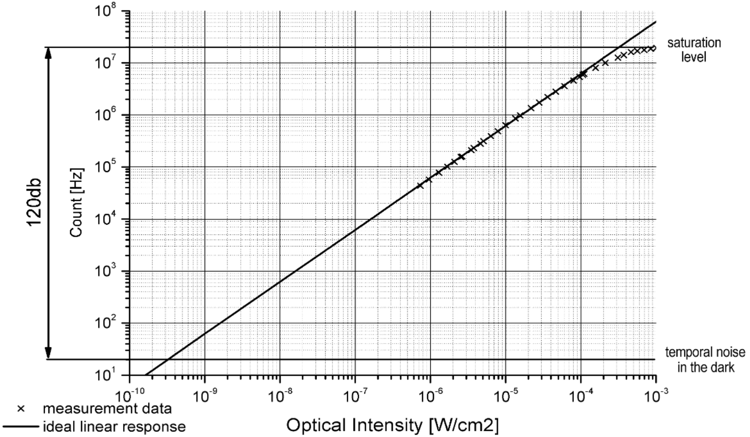
3.3.2 SPAD Metrology – Crosstalk: Cross-inter-arrivals

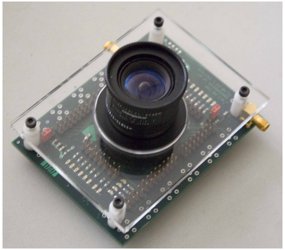


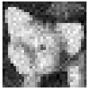


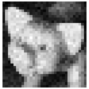
I.M. Antolovic, S. Burri, R. Hoebe, Y. Maruyama, C. Bruschini, E. Charbon, MDPI Sensors, **16**, 1005, 2016

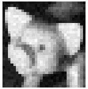
3.3.2 SPAD Metrology – Dynamic Range



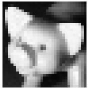



4μs

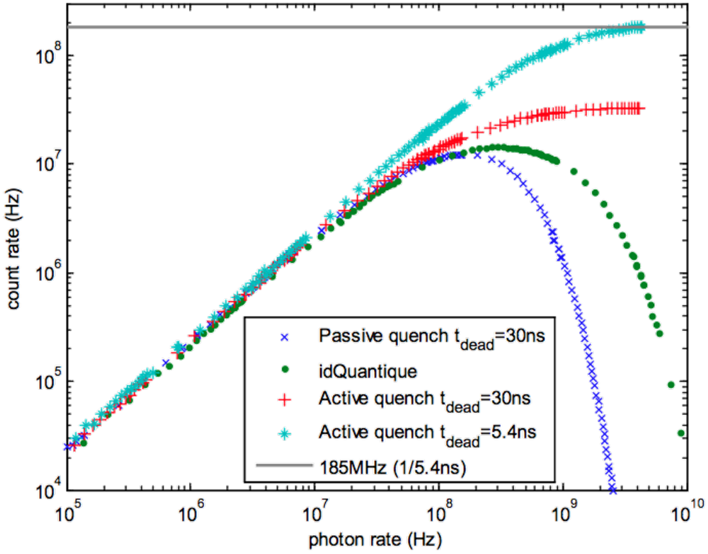

10μs


25μs


100μs


1ms

3.3.2 SPAD Metrology – Dynamic Range: Active vs. Passive Recharge



$$f_{MAX} \cong \frac{1}{t_{DEAD}} \quad \text{for active quenching}$$

$$f_{MAX} \cong \frac{1/e}{t_{DEAD}} \quad \text{for passive quenching}$$