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Silicon Photomultiplier

Operation, Performance & Possible Applications

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Introduction

Very high intrinsic gain together with minimal excess noise make silicon photomultiplier (SiPM) a possible choice of a photodetector in those applications where the input light is in the photon-counting range.

Introduction

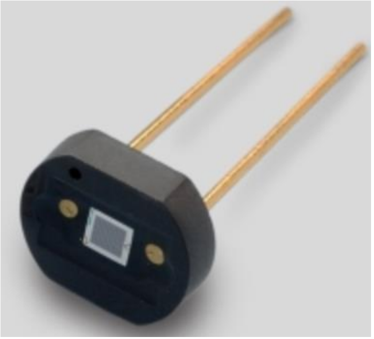
This webinar is a high-level review of SiPM's structure, operation, and opto-electronic characteristics, followed by a discussion of some possible applications.

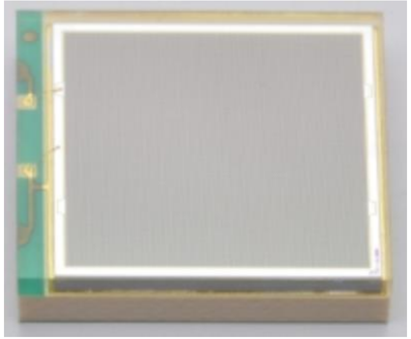
Outline

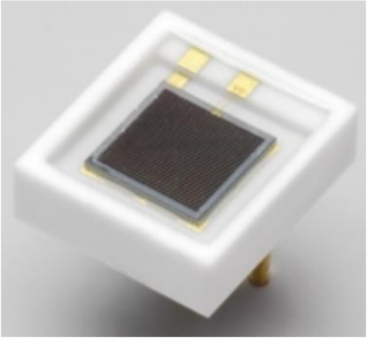
- Structure and operation
- Opto-electronic characteristics
- Applications
  + Automotive ToF LiDAR
  + Flow cytometry
  + Radiation detection and monitoring
- Summary and conclusions

SiPM

Structure and Operation of a SiPM

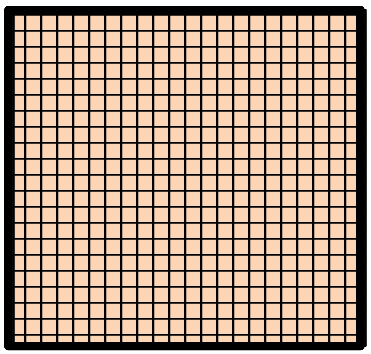




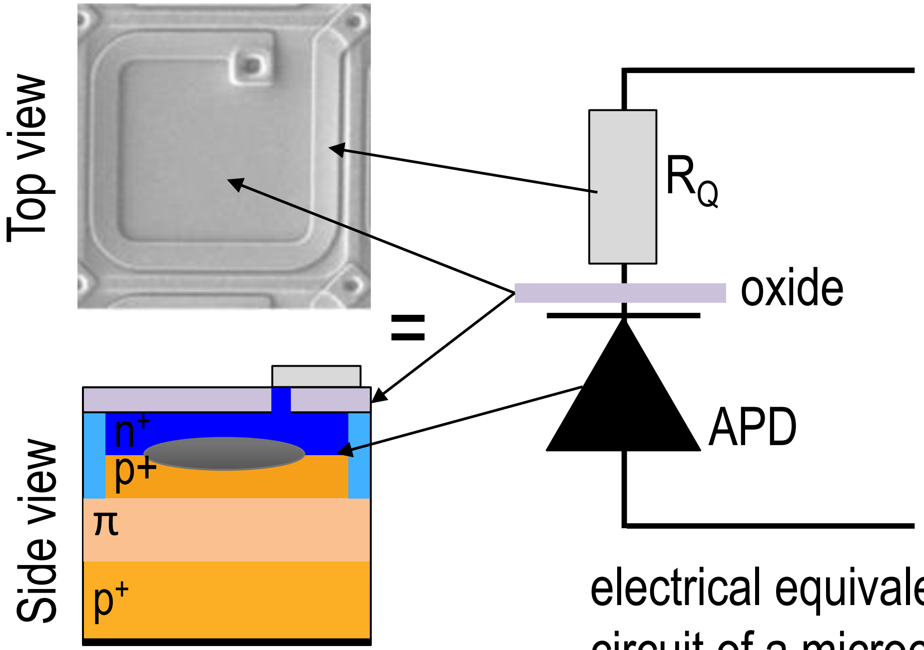


Portraits of SiPMs (images not to scale)

SiPM structure



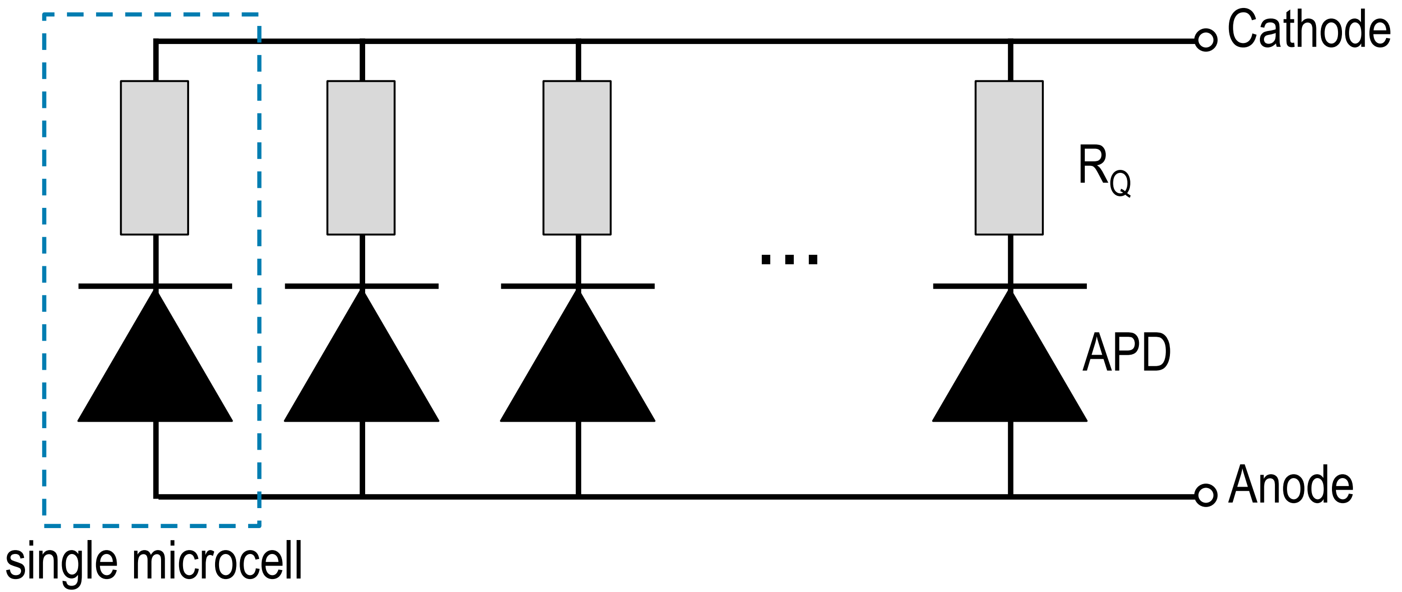
SiPM is an array of microcells



Single microcell

electrical equivalent circuit of a microcell

SiPM structure



All of the microcells are connected in parallel

SiPM specifications

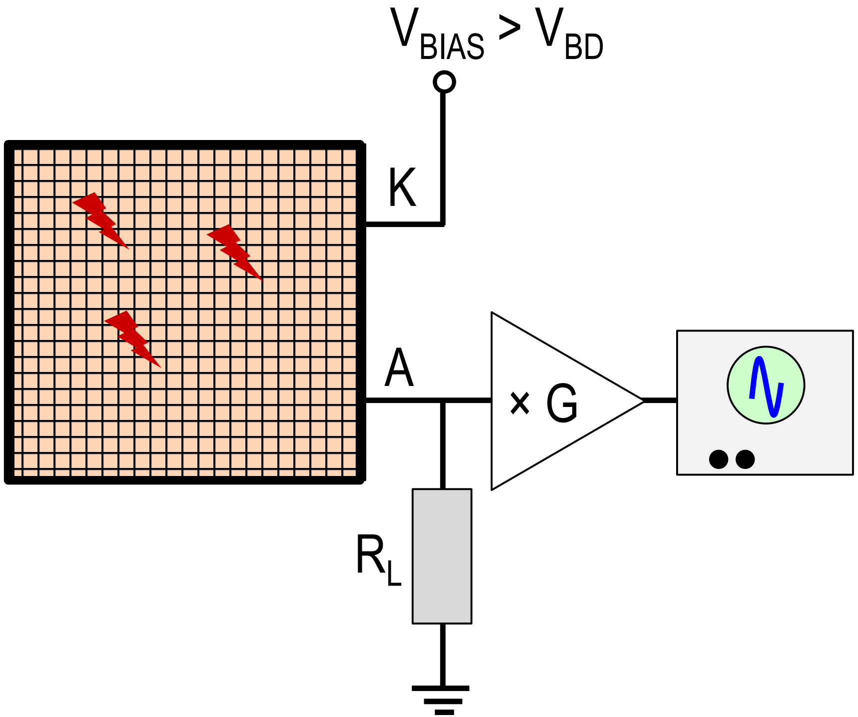
Active area: 1.3×1.3 – 6×6 mm^2

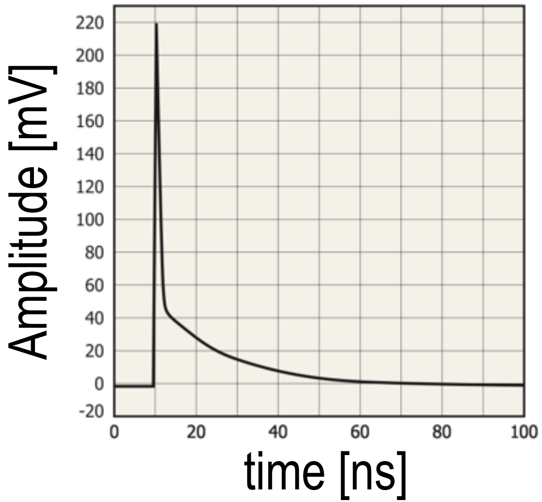
Microcell size (pitch): 10×10, 15×15, 25×25, 50×50, 75×75 μm^2

Number of microcells: (active area)/(microcell size), from 100’s to 10,000’s

Overvoltage: $\Delta V = V_{BIAS} - V_{BD}$; recommended by the manufacturer

SiPM operation

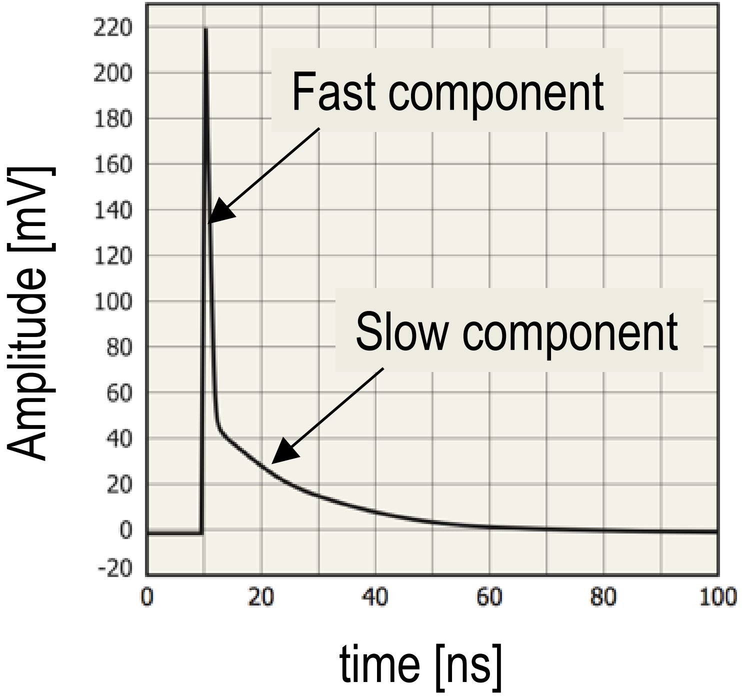




Example of single-photoelectron waveform (1 p.e.)

Gain = area under the curve in electrons

SiPM operation

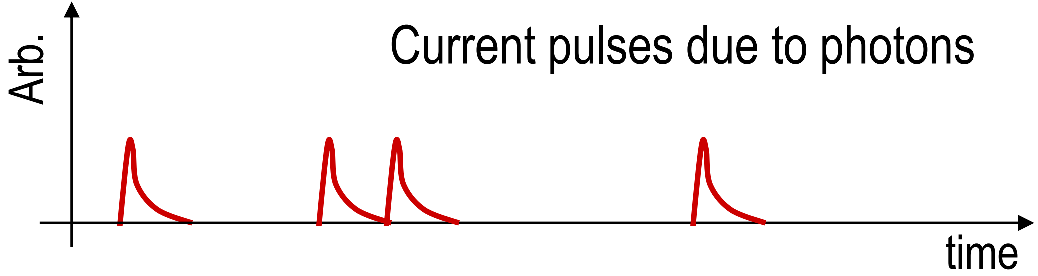


RC time constant of the slow component depends on microcell size (all else being equal)

Recovery time $t_R \approx$ 5 times the RC time constant

t_R is on the order of 10's to 100's ns but in practical situations, it is also a function of detection bandwidth

SiPM operation

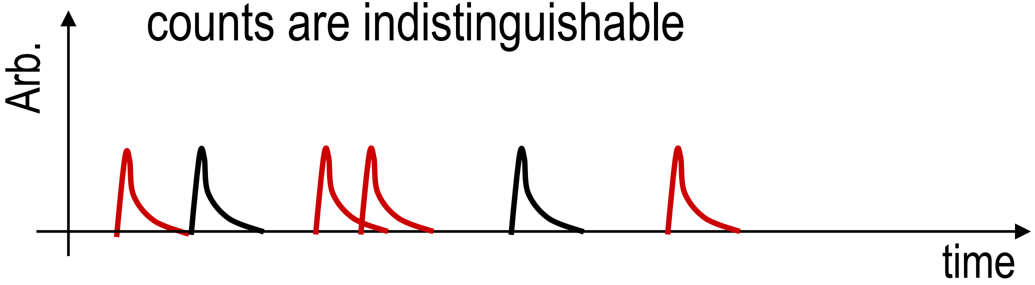


The output of an SiPM is a chronological superposition of current pulses

SiPM also outputs current pulses even in absence of light: dark counts (dark current)

Dark Counts

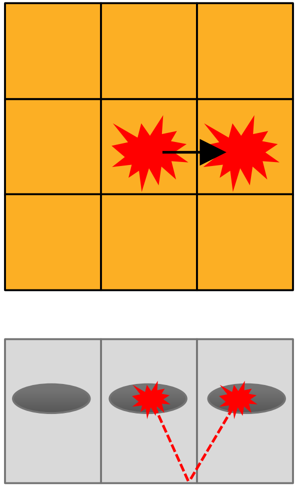
Current pulses due to photons and dark counts are indistinguishable



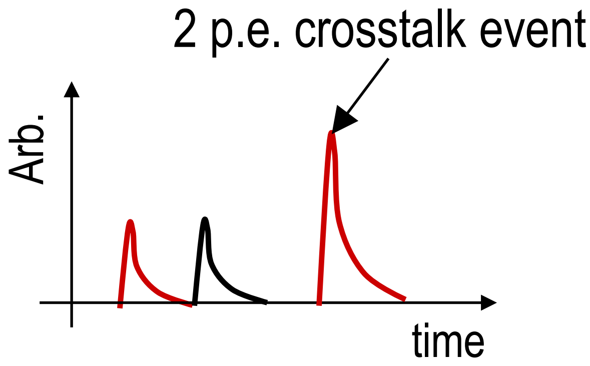
Dark-count pulses are indistinguishable from those due to photons

The rate of dark counts depends on overvoltage, temperature, and size of the active area

Crosstalk

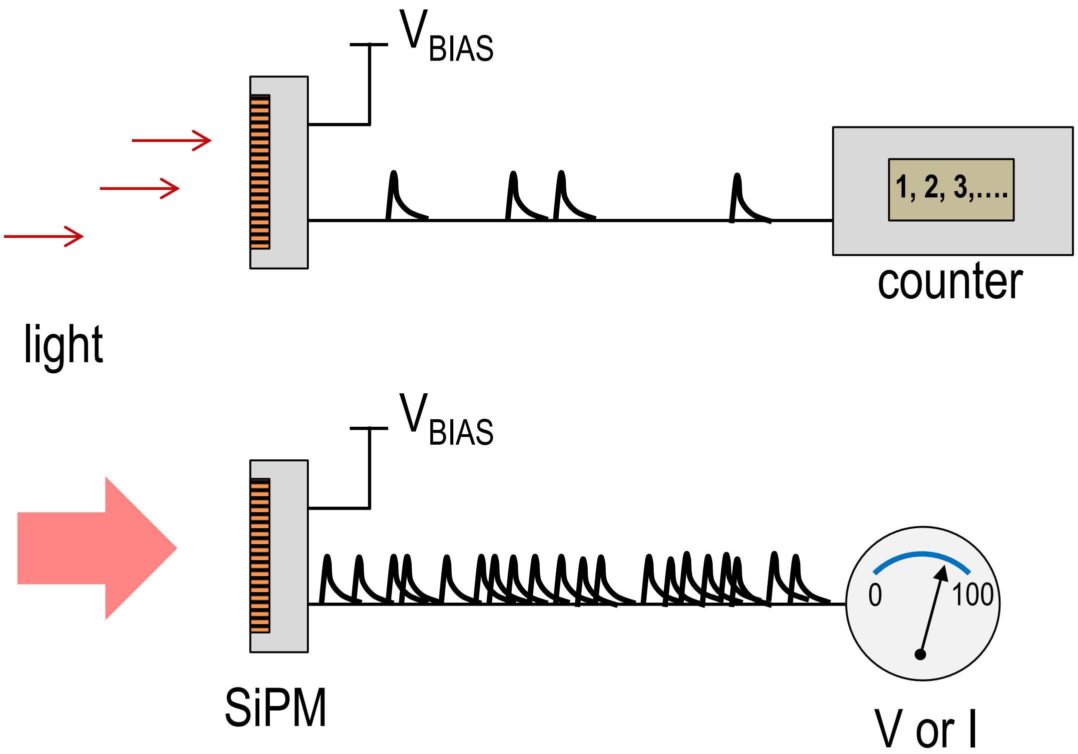


Primary discharge can trigger a secondary discharge in neighboring microcells. This is crosstalk.



Crosstalk probability depends on overvoltage

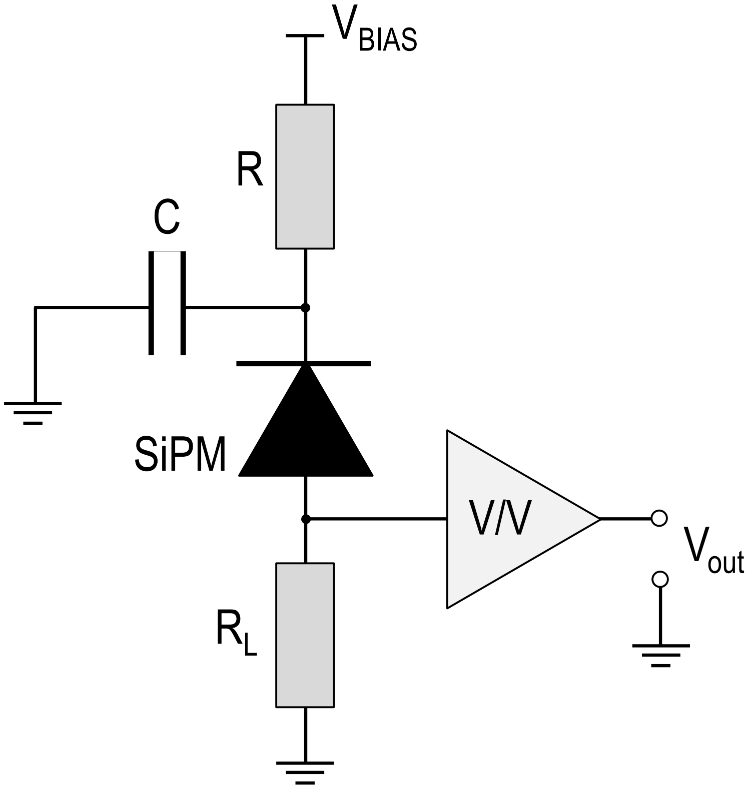
Operation

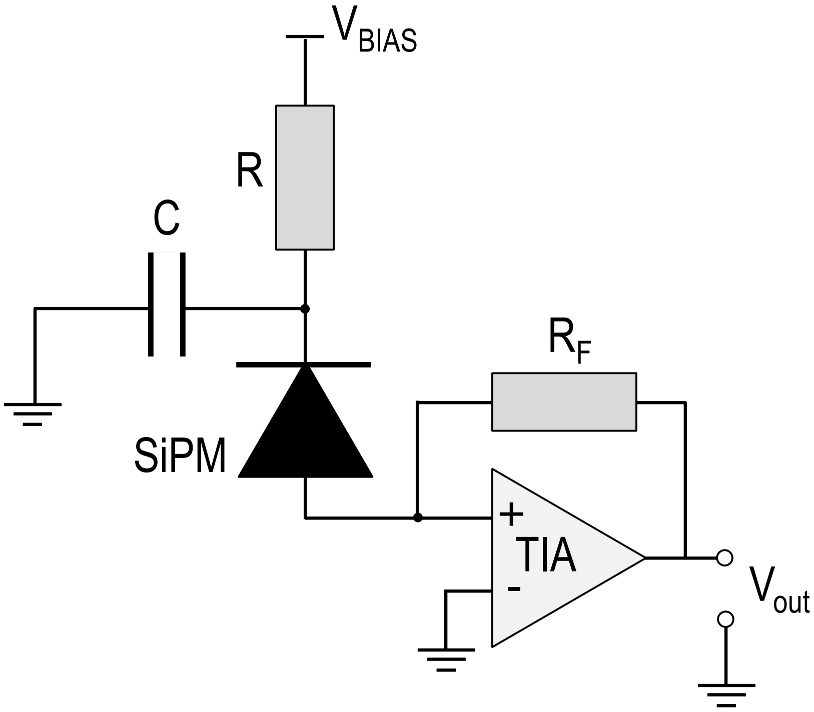


If the pulses are distinguishable, SiPM can be operated in a **photon counting** mode.

If the pulses overlap, the SiPM can be operated in an **analog mode**. The measured output is voltage or current.

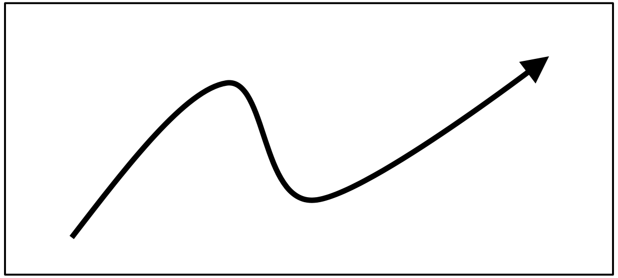
SiPM *detection circuits*





SiPM

Performance and characteristics



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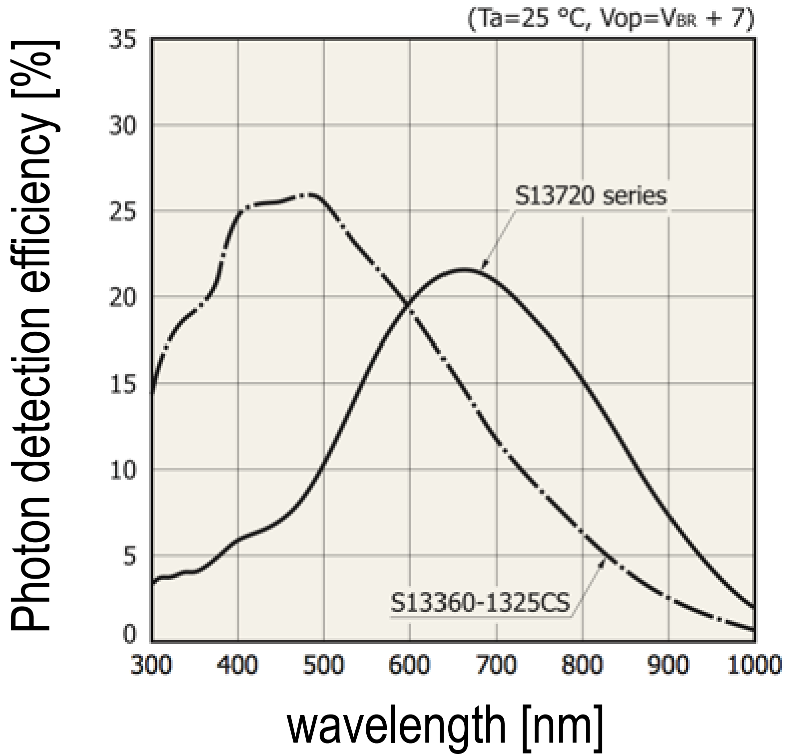
Characteristics of a SiPM

- Photon detection efficiency
- Gain
- Temperature effects
- Crosstalk probability
- Dark current & dark counts
- Linearity & dynamic range

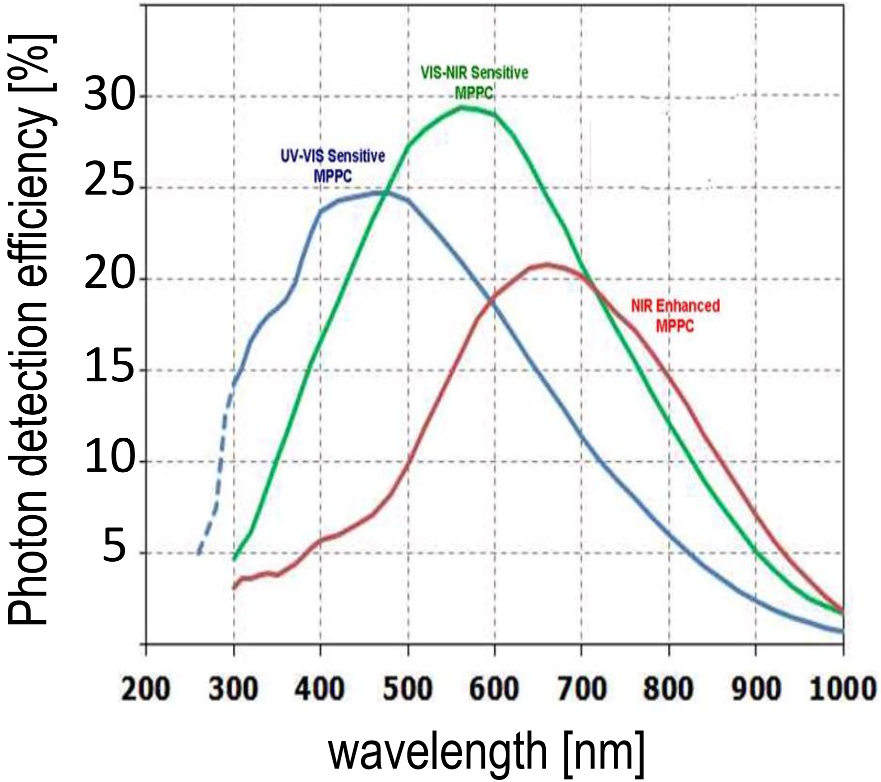
Photon detection efficiency



- Photon detection efficiency (PDE) is a probability that an incident photon is detected. It depends on:
  - wavelength
  - overvoltage
  - microcell size

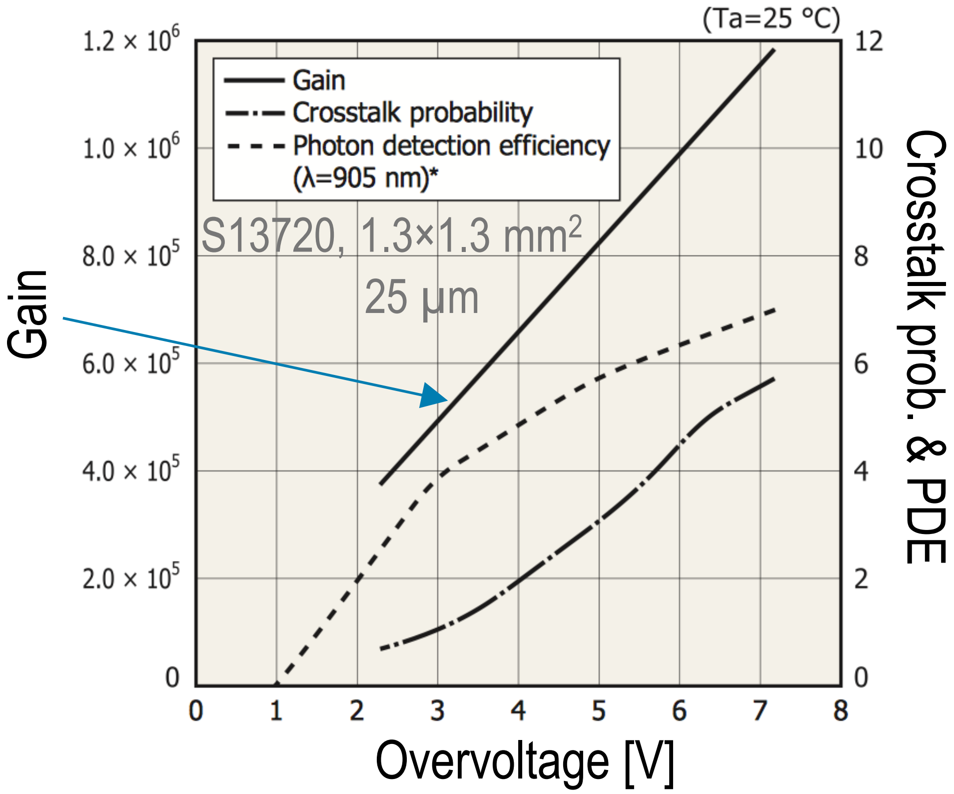
Peak PDE 20% – 50%

Photon detection efficiency



Examples of PDE curves for SiPMs optimized for NIR, VIS, and UV response.

Gain



- Gain of SiPM is comparable to that of a PMT.

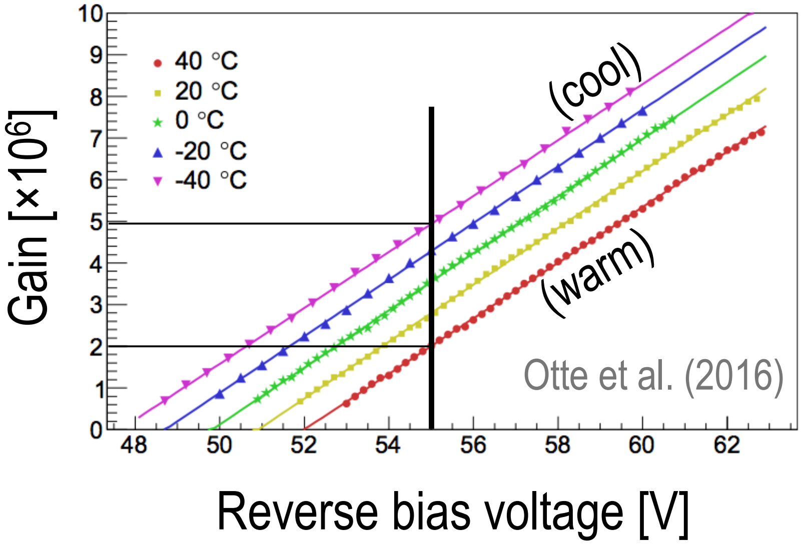
  Excess noise very low:
  F ~ 1.1, mostly due to crosstalk

- Gain depends linearly on overvoltage

Gain *versus* temperature

Does gain of an SiPM depend on temperature?

Yes – if the bias voltage is fixed



Gain *versus* temperature

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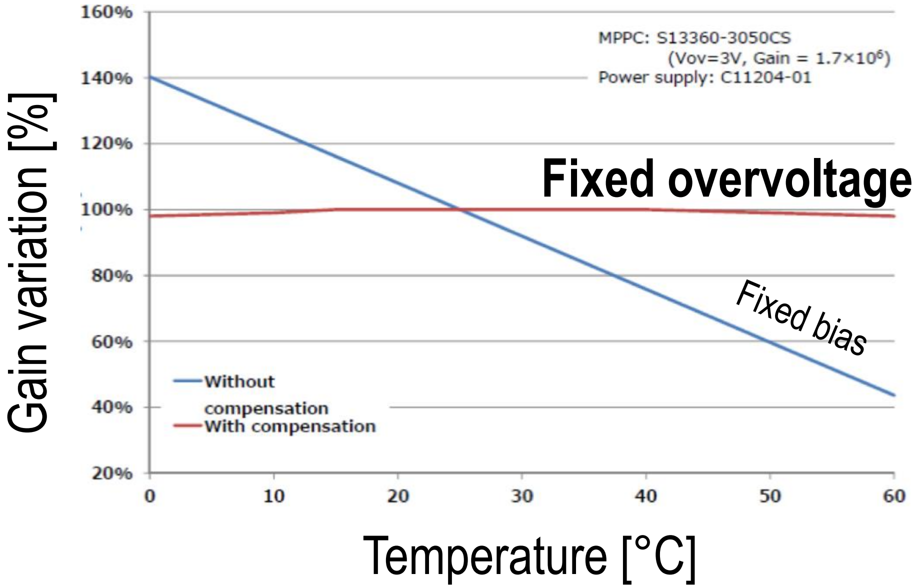
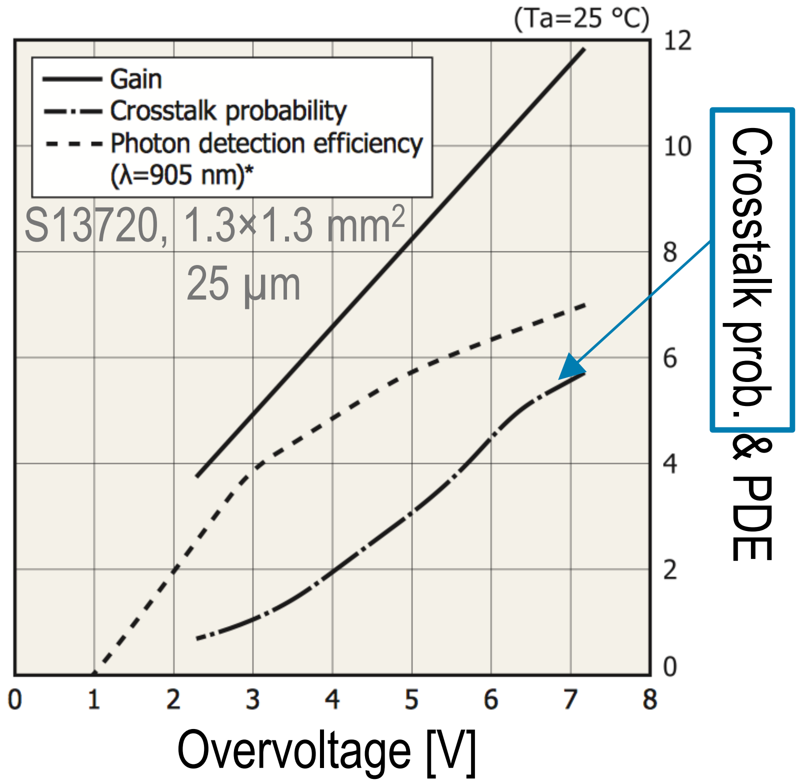


Crosstalk

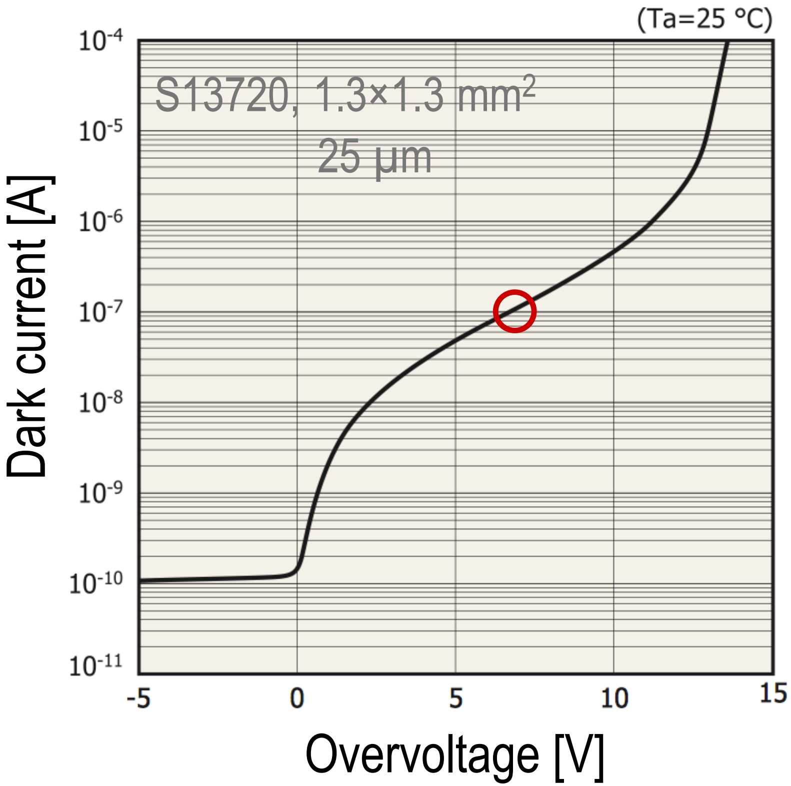


P_{CT} increases with overvoltage

Crosstalk is the main contributor to excess noise

$$F \approx (1+P_{CT})$$

Dark Current



Example of dark current versus overvoltage

$$DCR = I_D / e\mu$$

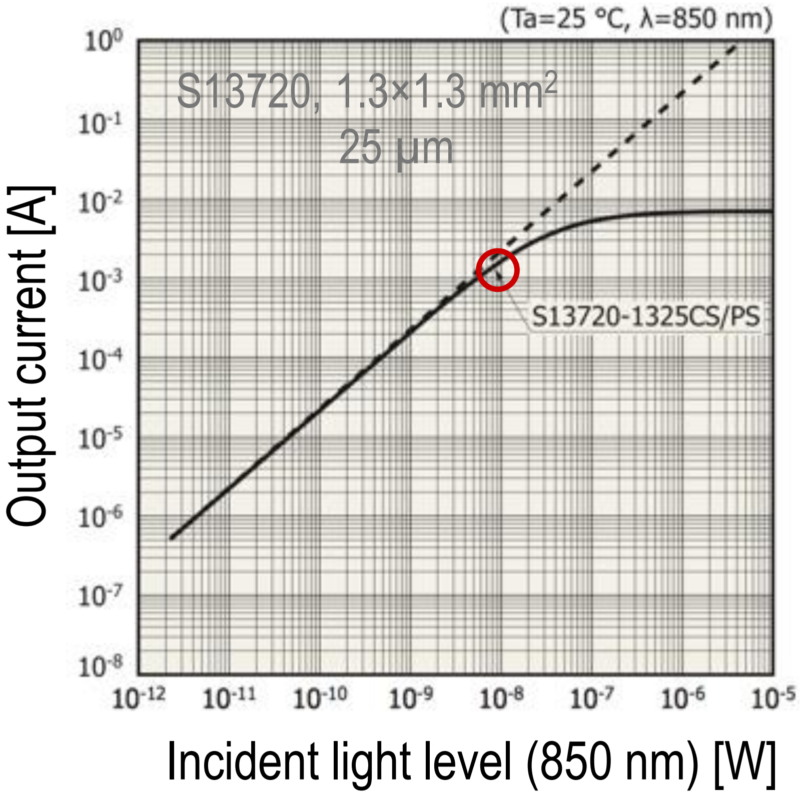
$I_D = 1\times10^{-7}$ A (at 7 V)

$\mu = 1.2\times10^{6}$ (at 7 V)

-> DCR ≈ 520 kHz

or once per about 2 µs

Linearity and dynamic range



Example of output current versus incident light level.

Photon irradiance (at 850 nm) = $4.3\times10^{18}\times$ P[W]

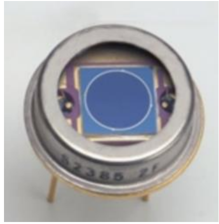
P = 10^{-8} W –> 4.3×10^{10} photons per second

Linearity depends on the number of microcells for a given active area

SiPM, PMT & APD

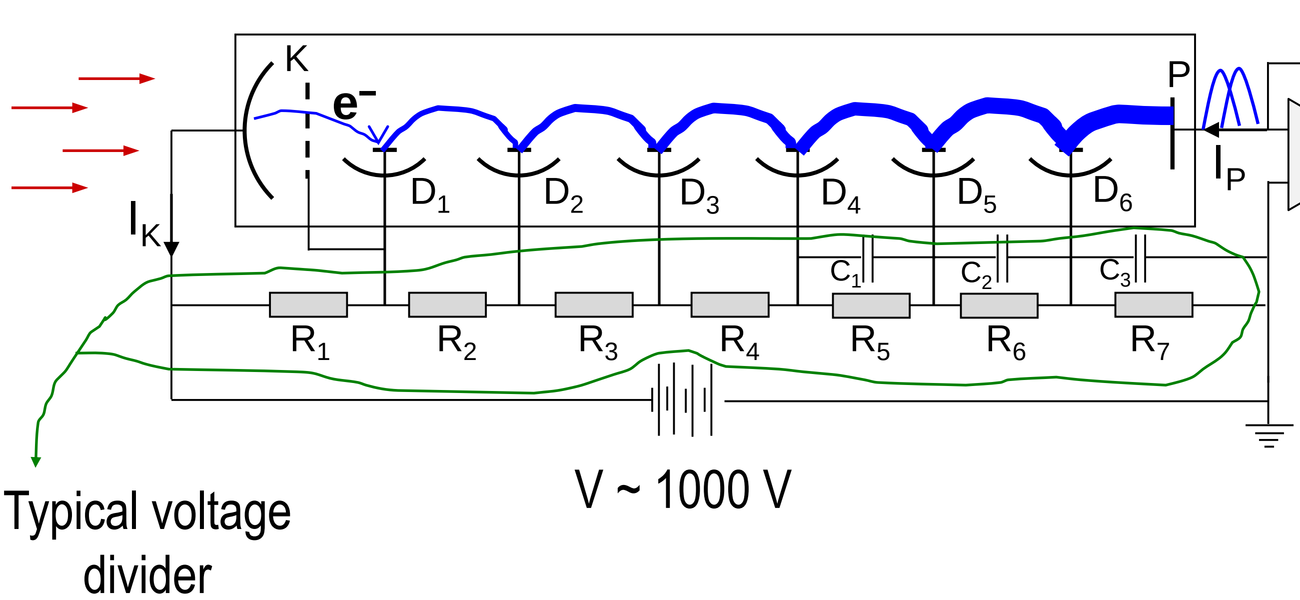
This webinar will compare and contrast SiPM with a photomultiplier tube (PMT) and APD.

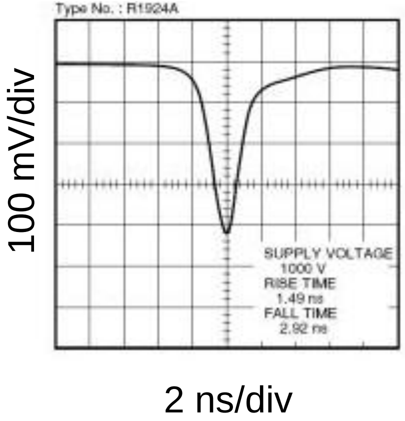
Let’s briefly review the operation of a PMT and APD



Examples of a PMT (left) and APD (right).

Operation of a PMT

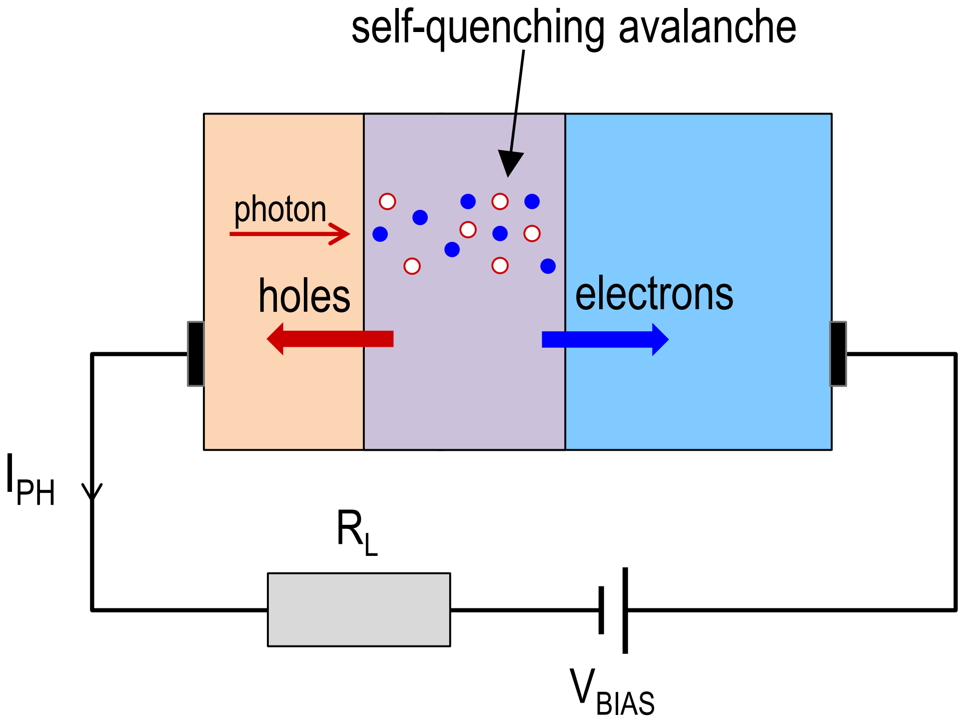




SiPM *versus* PMT

- Solid state *versus* vacuum tube technology
- Comparable gains
- Comparable excess noise
- Dark count rate per unit active area larger in SiPM
- E & B field immunity in SiPM
- Comparable photosensitivity in the spectral overlap region
- Greater optimization for PMTs

Operation of an APD



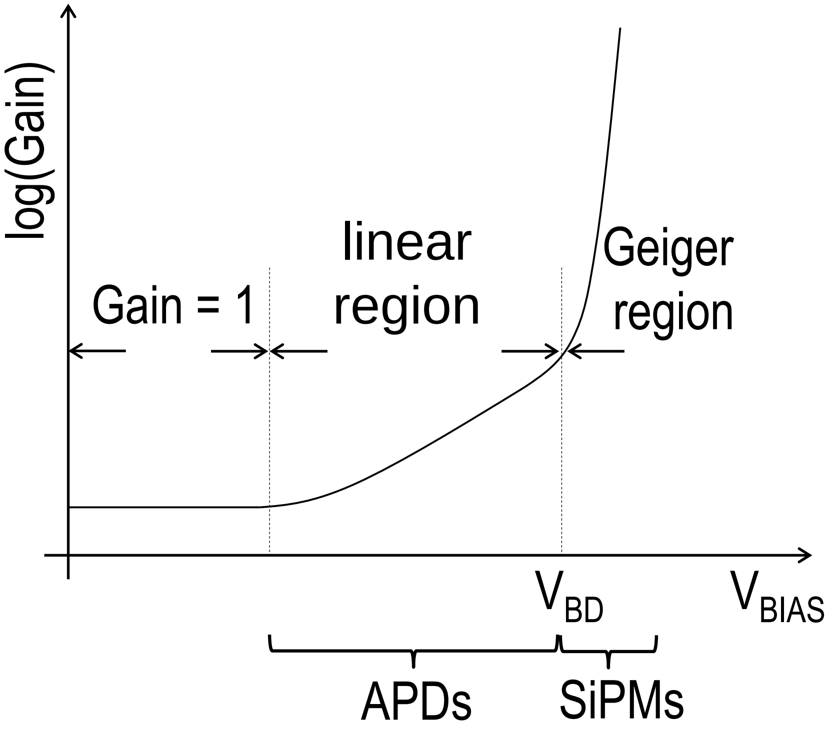
APD biased below breakdown voltage

Single photon can lead up to about 100 of electron-hole pairs

Thus gain up to ~100

Avalanche is self-quenching

SiPM *versus* APD

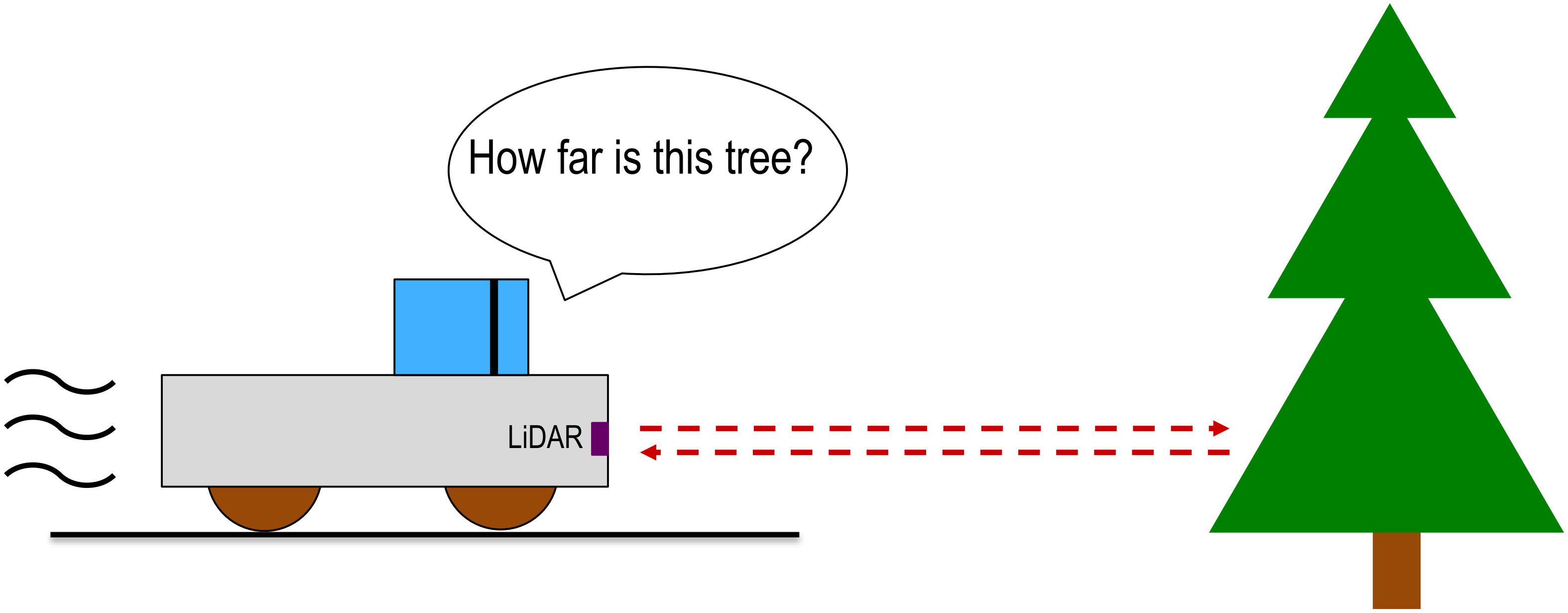


- Differ in construction
- $Gain_{SiPM} >> Gain_{APD}$
- $F_{SiPM} << F_{APD}$

Possible applications of SiPMs

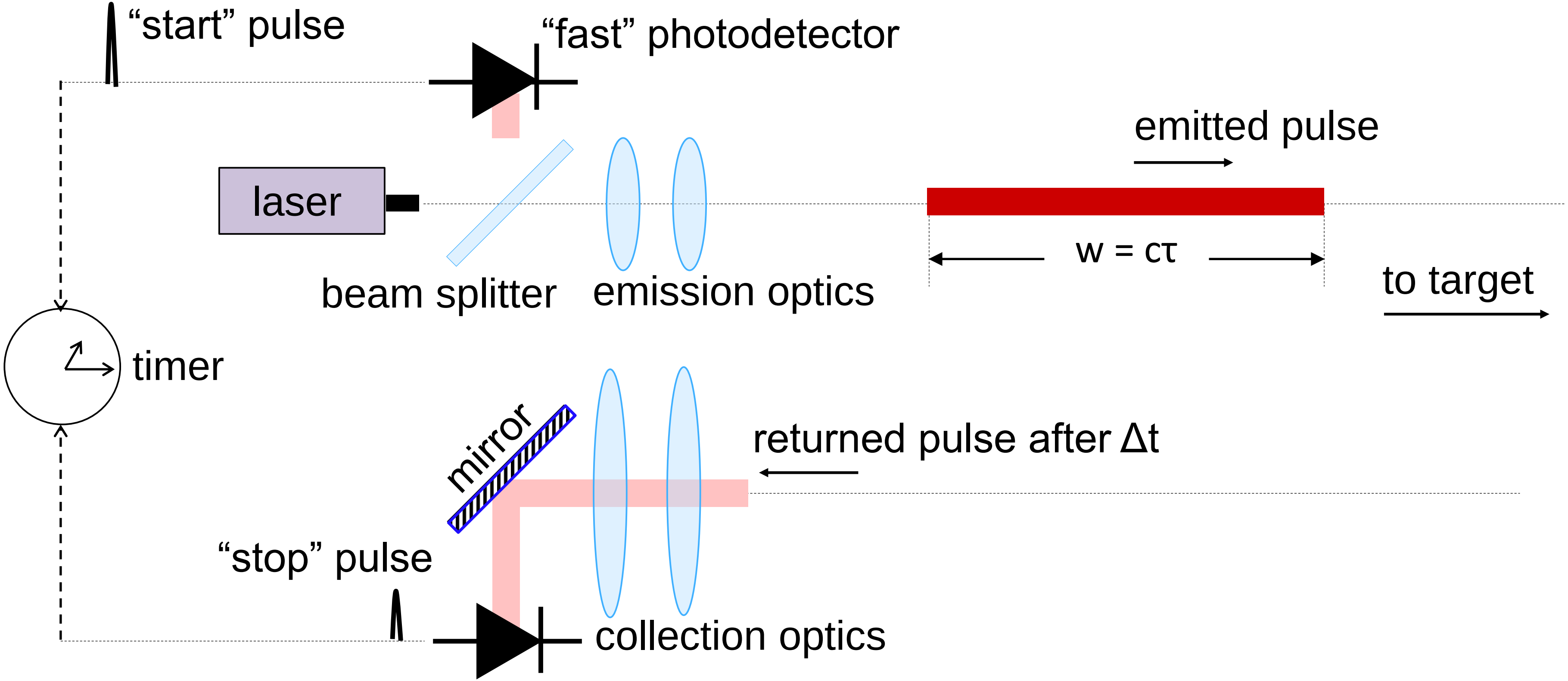
- Automotive time-of-flight LiDAR
- Flow cytometry
- Radiation detection and monitoring

Automotive time-of-flight LiDAR



LiDAR = Light Detection and Ranging

Automotive ToF LiDAR: basic concept



Automotive ToF LiDAR: basic concept

Measure round-trip time-of-flight Δt

Range (distance to the reflection point) = $c\Delta t/2$; here c is the speed of light

By scanning the surroundings, a 3D map can be constructed

Characteristics of received light

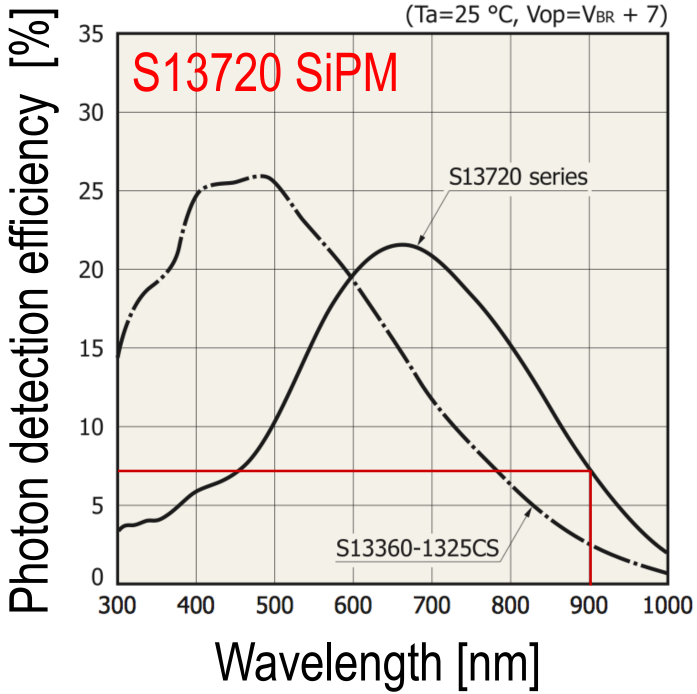
- Wavelength: 905 nm or 1550 nm
- Pulse: duration 2 – 5 ns
- No. of photons per returned pulse: 100’s – 10,000’s on detector’s active area
- Repetition frequency: kHz - MHz
- DC photon background

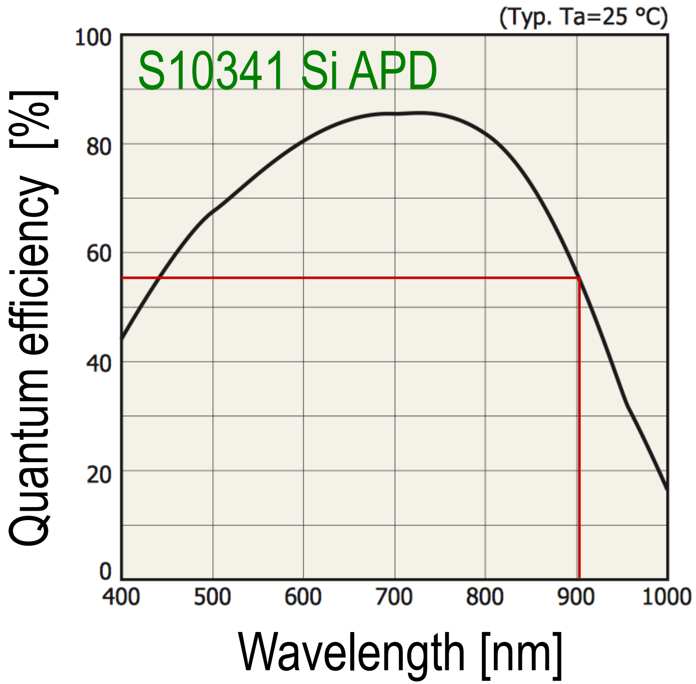
Photodetector requirements

- High quantum efficiency at 905 nm and/or 1550 nm (affects detection range)
- High detector (intrinsic) gain (reduces importance of electronic noise)
- Small excess noise (affects timing error)
- Small time jitter (affects distance resolution)

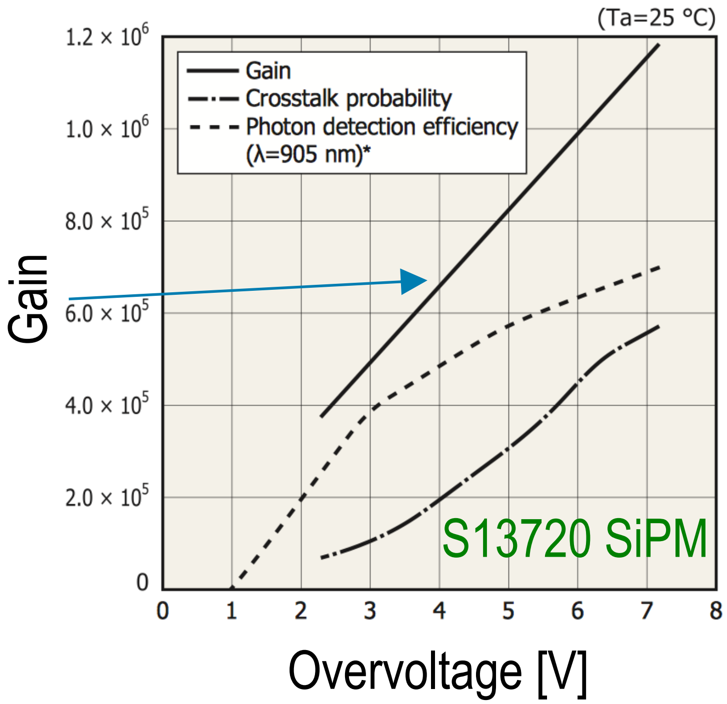
APD has been a default detector. Could SiPM be a better choice?

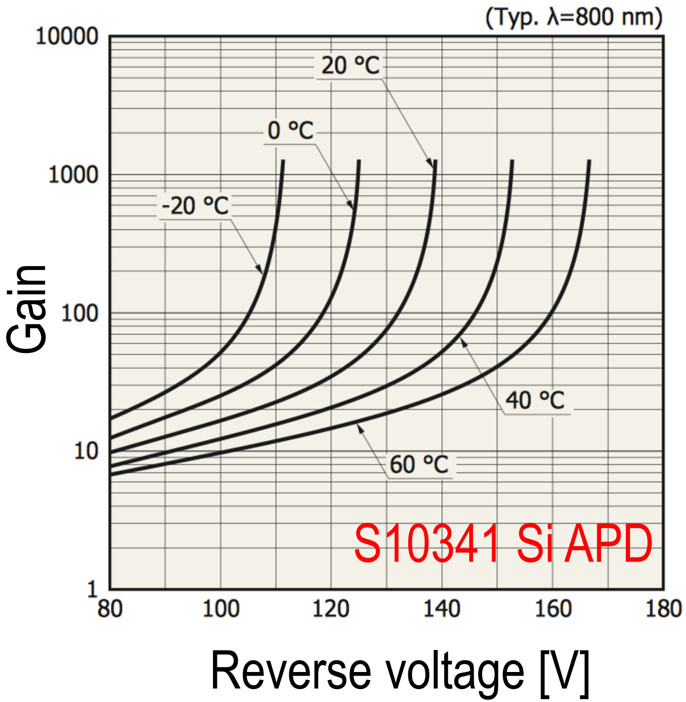
Photosensitivity



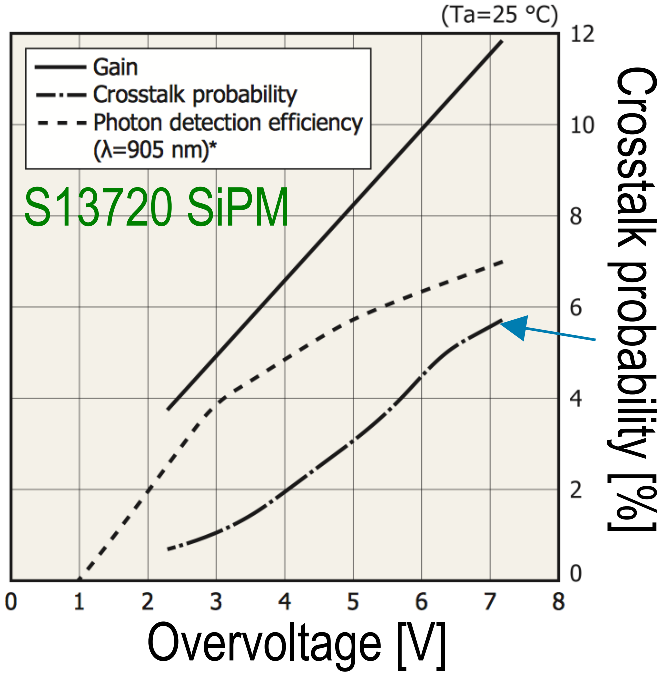


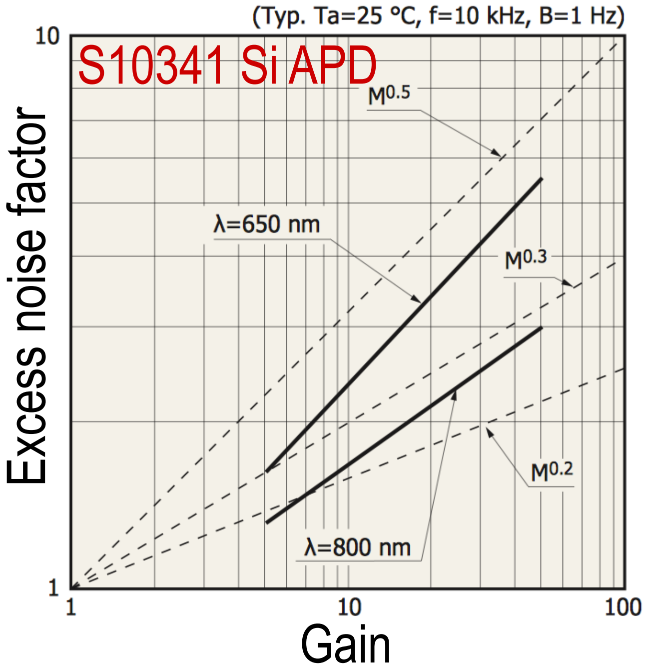
Intrinsic gain





Excess noise





$F \approx 1+P_{CT} = 1.06$

$F \approx (\text{Gain})^{0.3} = 3.2$ for gain = 50

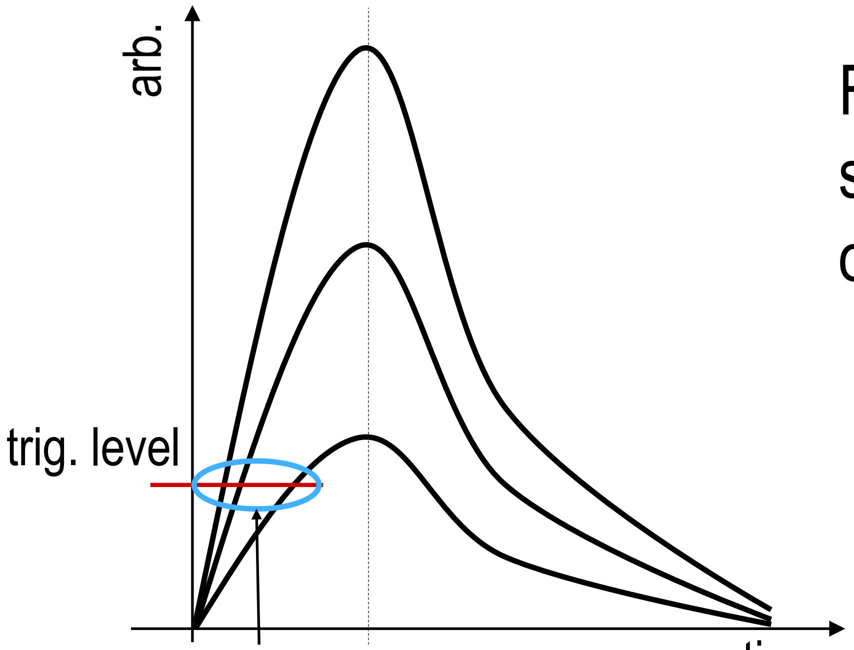
Time jitter

There are two contributions to timing jitter:

1. "Classical" jitter – variation in response time, often reported for a single photon illumination. This contribution is on the order of 100 ps for SiPMs and APDs

2. Time-walk effect. For a constant trigger level, timing depends gain variation and signal intensity.

Time jitter



Different trigger times:
time walk effect

For a given light level SiPM has smaller time-walk effect because of its lower excess noise.

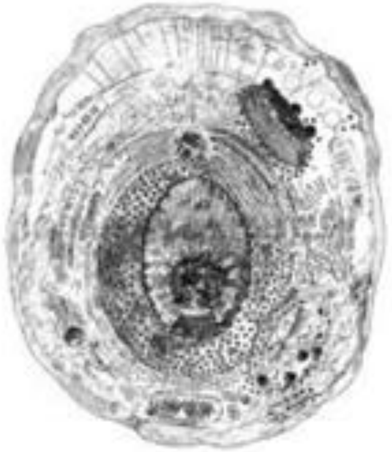
Take-away points

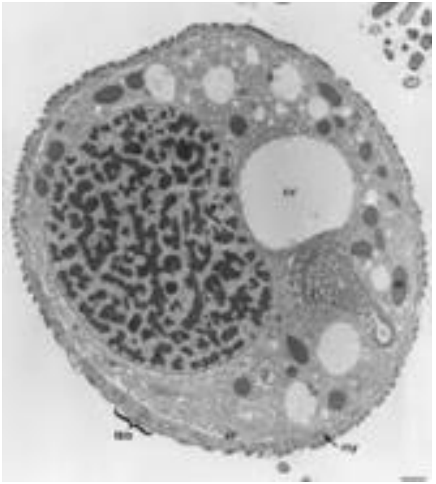
1. SiPMs are likely to compete successfully with APDs at 905 nm because of their higher gain and much lower excess noise. Empirical evidence is forthcoming.

2. Sensitivity at 905 nm will improve in a new generation SiPMs

3. SiPMs with sensitivity at 1550 nm are being developed.

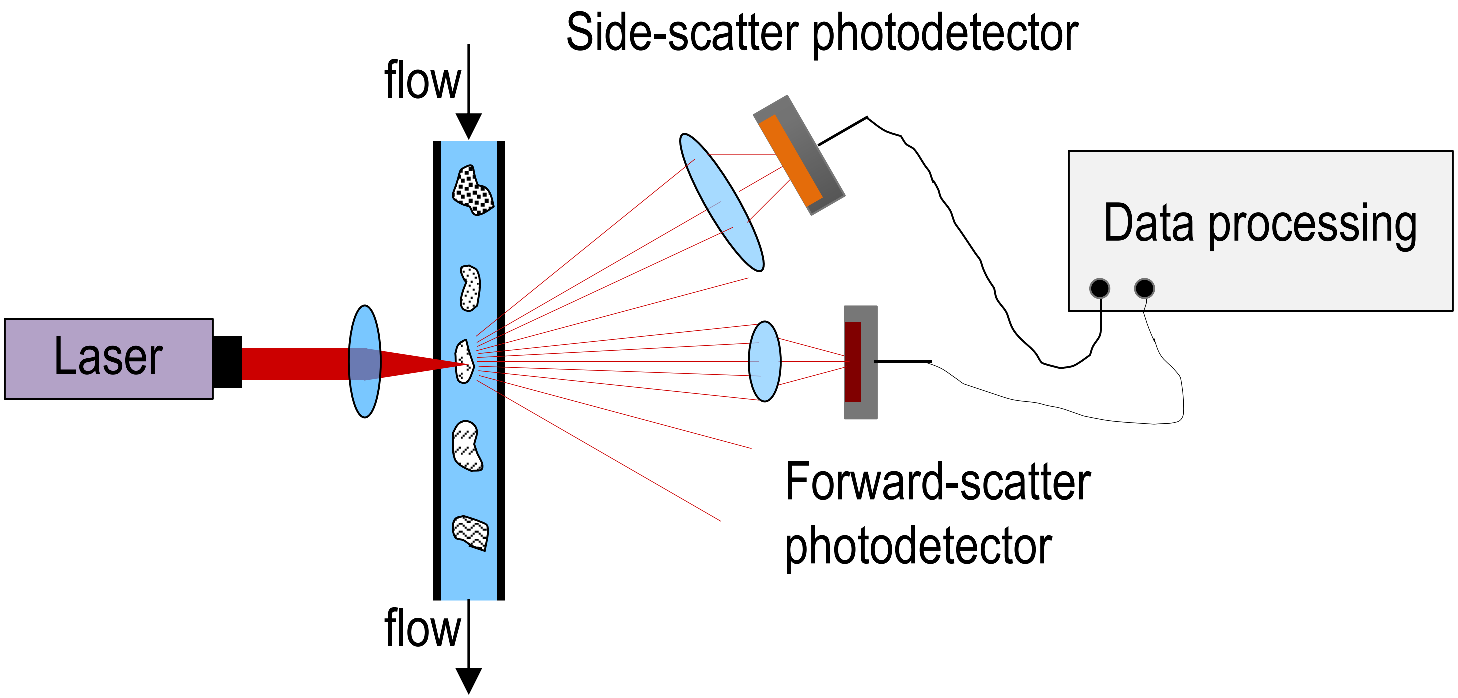
Flow cytometry



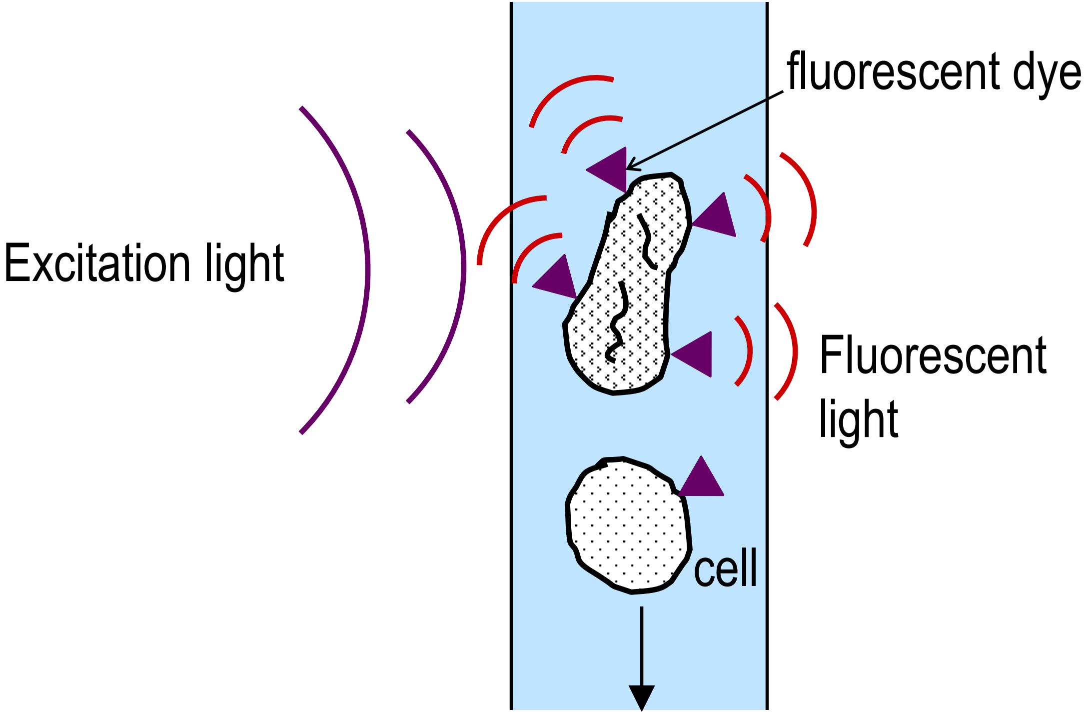


Studying biological cells with light

Flow cytometry (basic concept)



Flow cytometry

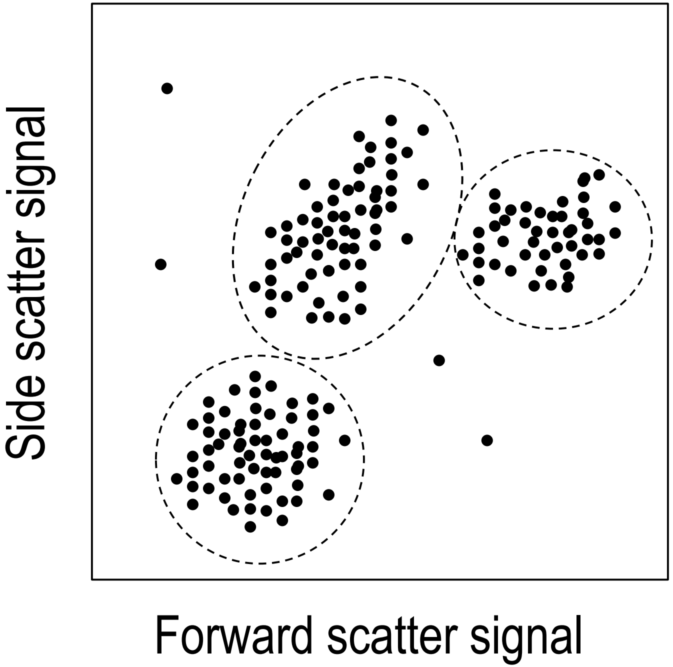


Flow cytometry also uses fluorescence tagging to study cells

Flow cytometry

- Used to study and sort biological cells
- Side-scatter signal vs. forward scatter signal depends on cell properties
- Fluorescence is also employed (dyes attached to cells) to produce a variety of plots using fluorescence signal(s)
- The optical system employs a combination of lasers (different wavelengths), optical filters, and photodetectors

Flow cytometry data



Side scatter vs. forward scatter plot – the most fundamental in flow cytometry

Cell's characteristics such as size, complexity, or refractive index affect the relative strengths of side scatter and forward scatter signals

Characteristics of received light

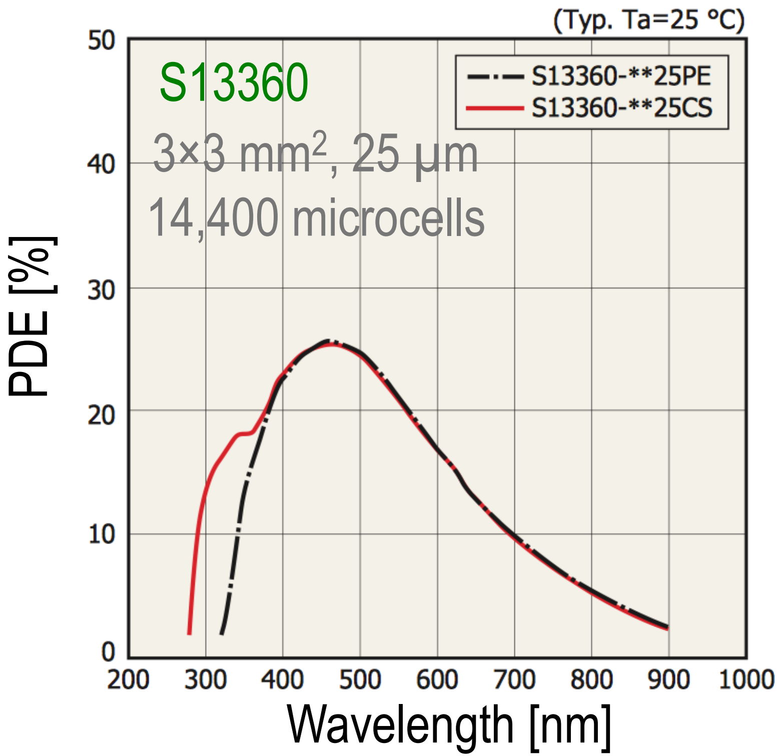
- Wavelength: can be selected depending on cell sizes and fluoresce
- Pulses – duration dependent on sheath flow speed and cell size and is on the order of μs.
- No. of photons per pulse varies from few to thousands
- Rate of pulses in kHz

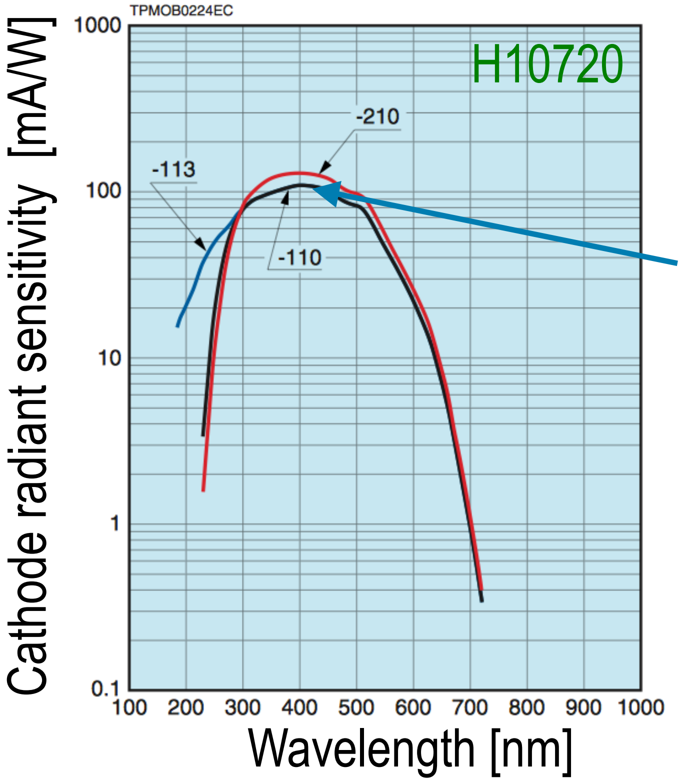
Side-scatter photodetector requirements

- High photodetection efficiency (affects S/N of detection)
- High intrinsic gain (reduces importance of electronic noise)
- Minimal excess noise (affects accuracy of the scatter plots; random noise)
- High linearity (affects accuracy of the scatter plot; systematic errors)
- High dynamic range (affects accuracy of the scatter plot; systematic errors)

PMT is commonly used. Could SiPM be a better choice?

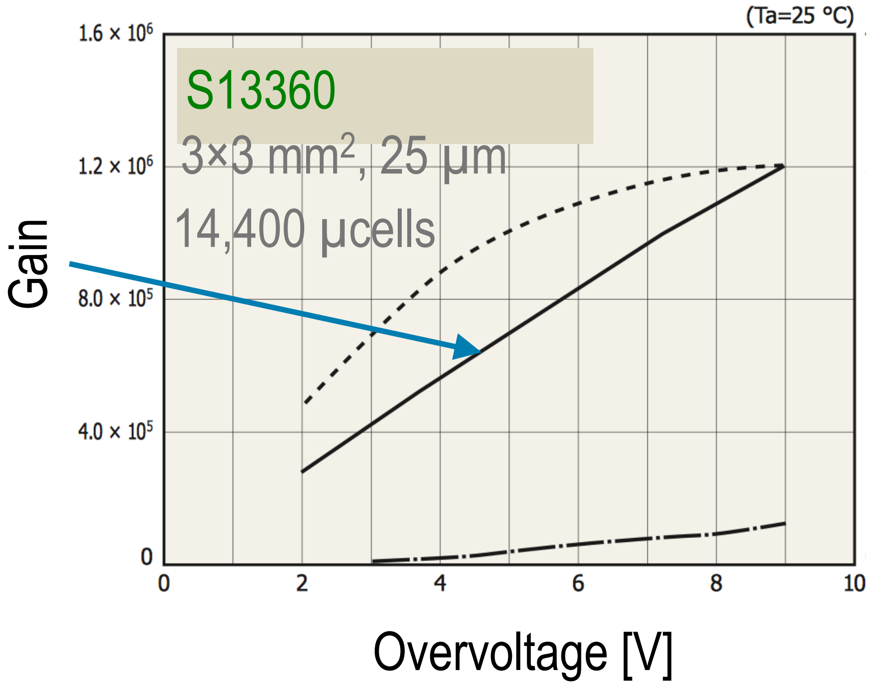
Photosensitivity

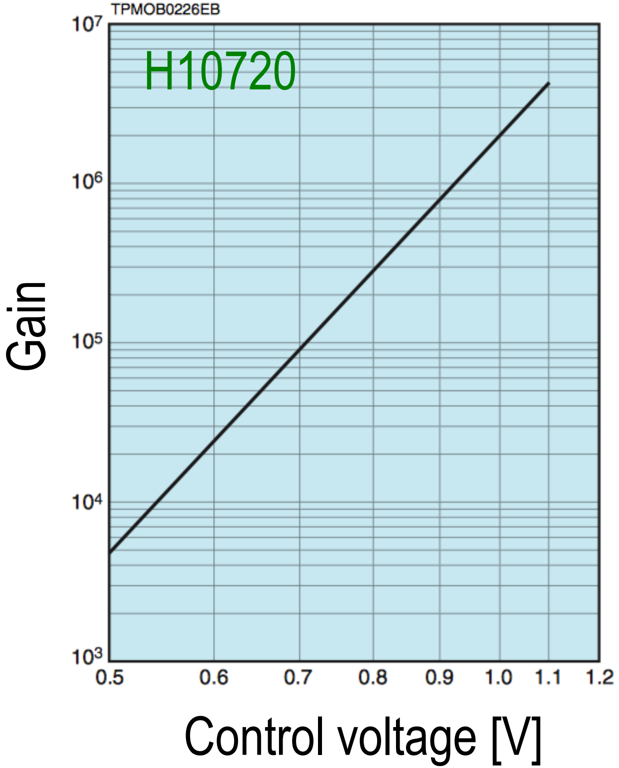




QE ≈ 28%
at 450 nm

Gain


(Ta=25 °C)
S13360
3×3 mm², 25 µm
14,400 µcells
Gain
1.6 × 10⁶
1.2 × 10⁶
8.0 × 10⁵
4.0 × 10⁵
0
0
2
4
6
8
10
Overvoltage [V]


TPMOB0226EB
H10720
Gain
10⁷
10⁶
10⁵
10⁴
10³
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
Control voltage [V]

Excess Noise

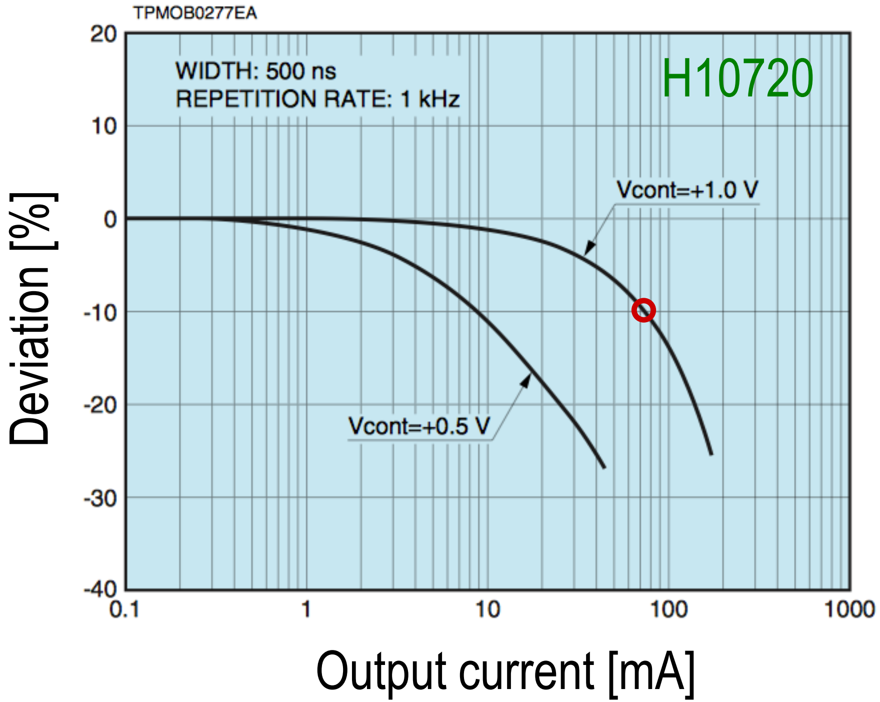
$F \approx 1+P_{CT}$ (SiPM)

Excess noise **increases** with gain

$F \approx \delta/(\delta - 1)$ (PMT; δ – gain of the first dynode)

Excess noise **decreases** with gain

Linearity/dynamic range (PMT)



10% nonlinearity: 75 mA, T_P = 500 ns

Gain = 2×10^6, QE = 28%

No. of incident photons at 450 nm:

4.2×10^5

Linearity/dynamic range (SiPM)

$$\overline{N}_{\text{fired}} = N_{\text{tot}} \left(\frac{T_P}{t_r}\right) \left(1 - \exp \frac{-N_\gamma PDE}{\left(\frac{T_P}{t_r}\right) N_{\text{tot}}}\right)$$

N_{tot} = 14,400; PDE = 25%, t_r = 50 ns

$N_\gamma \cdot PDE = 1.1 \times 10^5$ (ideal response)

N_{fired} = **0.75×10^5 or 32%** below an ideal response

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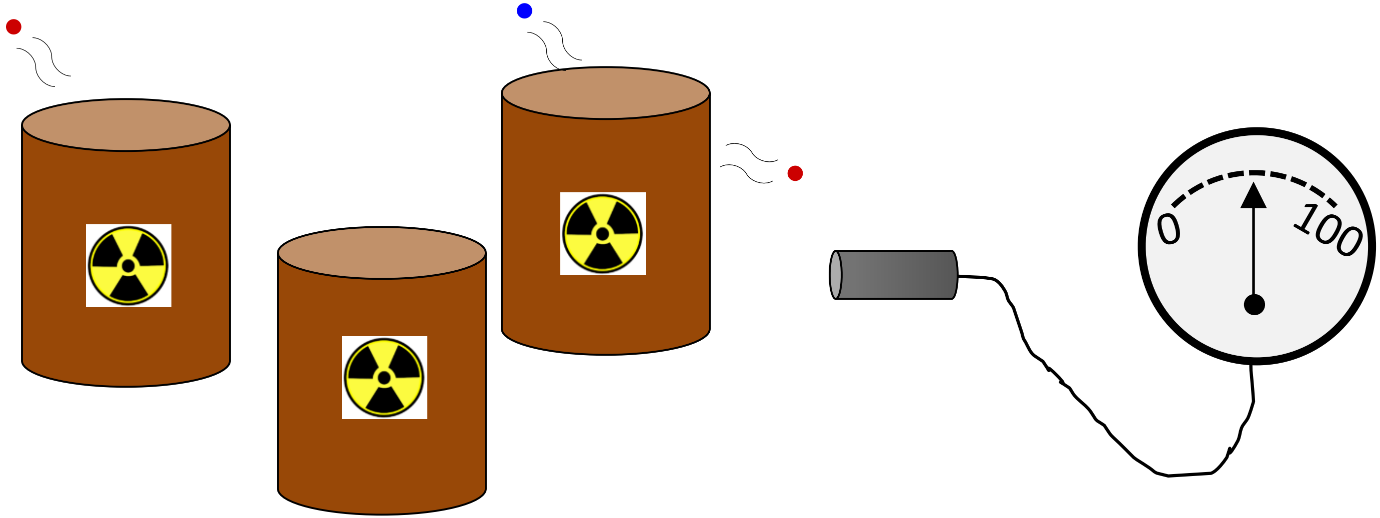
Take-away points

1. The major weakness of SiPMs in flow cytometry is limited dynamic range and linearity

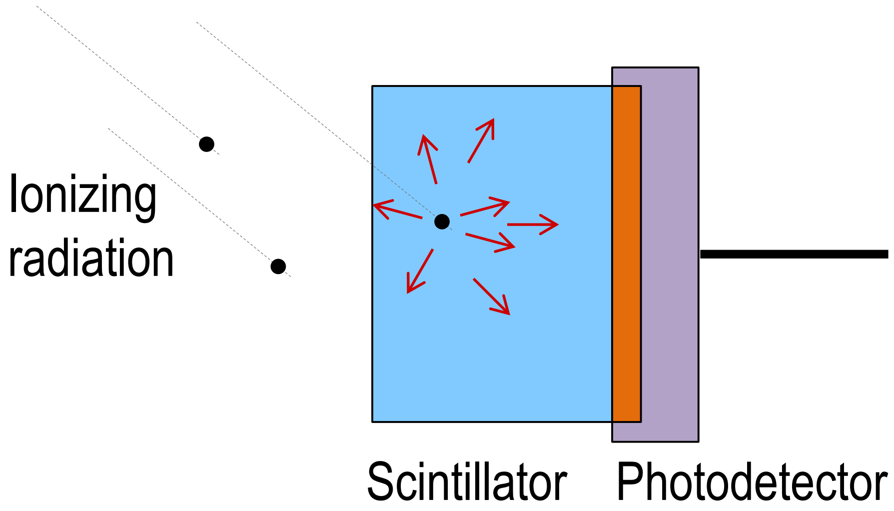
2. However, out of dozens of optical channels in a flow cytometer, SIPM can be suitable for some

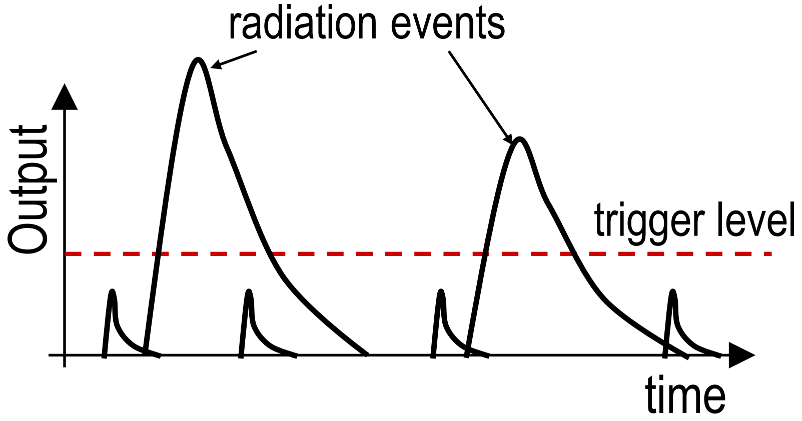
3. There is a great interest in using SiPMs in flow cytometry but little published work on this subject exists

Radiation monitoring and spectroscopy



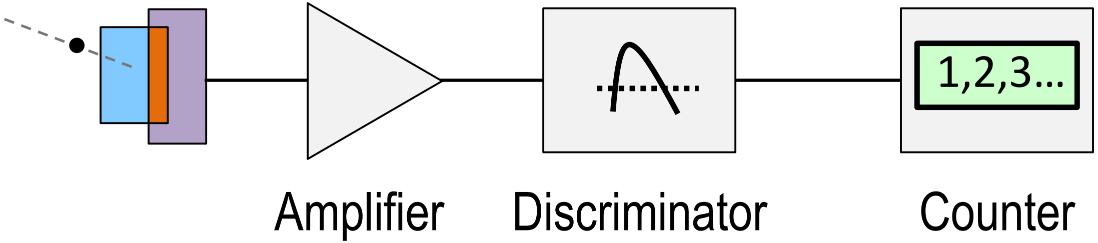
Radiation monitoring (basic idea)





An event is registered if the output signal exceeds the threshold level.

Radiation monitoring (basic idea)



- Used to detect the presence of specific radiation
- Monitoring devices are often portable and hand-held.
- Information provided: radiation rate (flux can be derived)

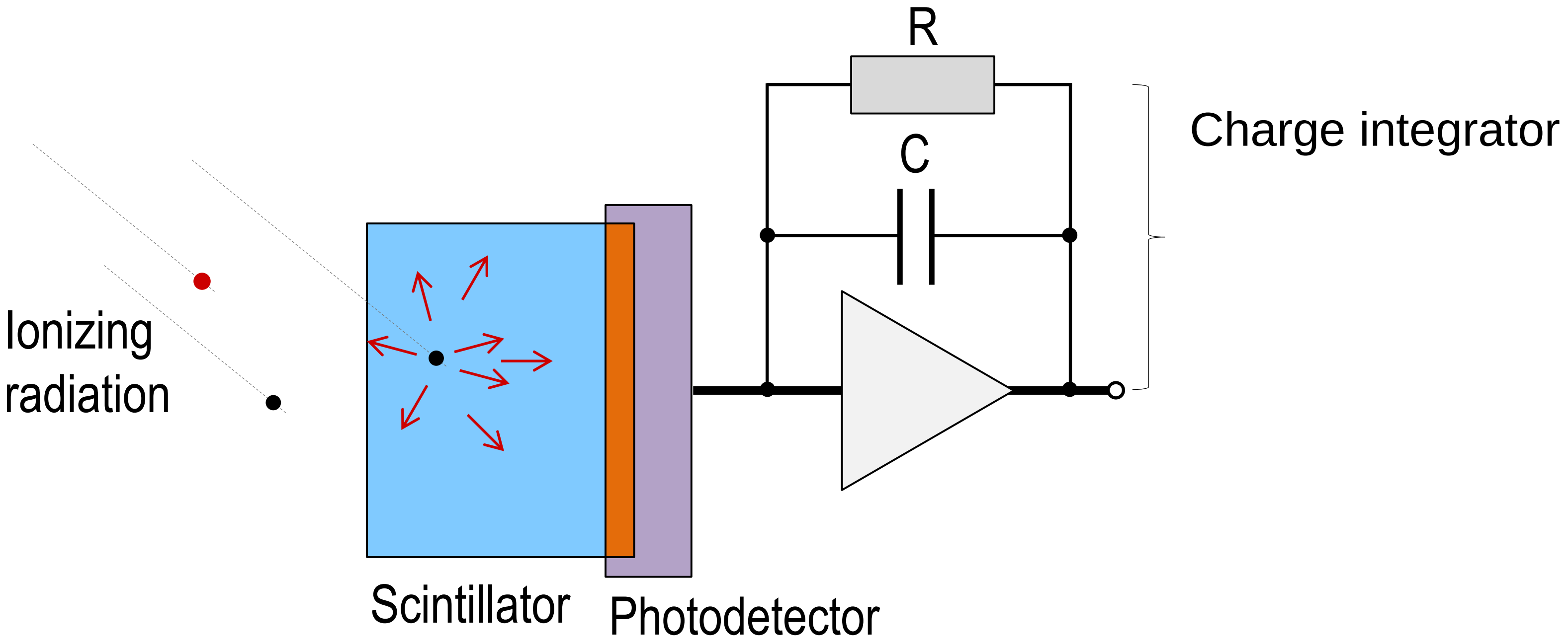
Characteristics of received light

- Wavelength dependent on the choice of scintillator often in the 300 nm – 500 nm range
- Pulses
- Number of photons per pulse depends on energy of ionizing radiation and type of scintillator
- Duration of the pulse depends on the size and type of the scintillator (decay time constants range from ns to µs)
- Frequency of pulses depends on the rate of incoming radiation

Photodetector requirements

- High photodetection efficiency
- High intrinsic gain
- Large active area
- Ability to couple to a scintillator
- Suitable for portable hand-held devices

Radiation spectroscopy



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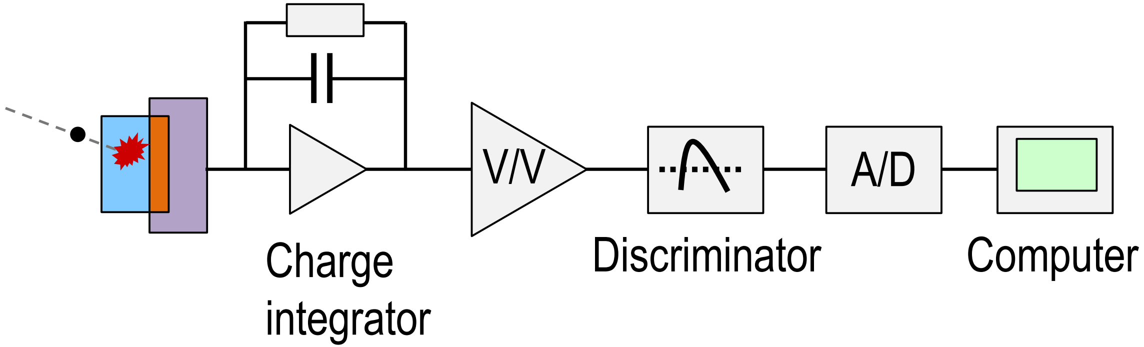
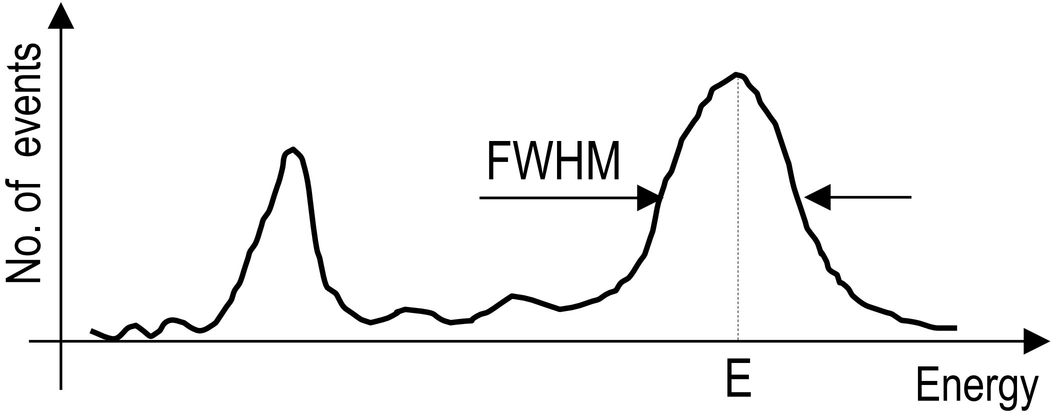
Radiation spectroscopy (basic idea)





$$\text{Resolution} = \frac{\text{FWHM}}{\text{E}}$$

Resolution is affected by the properties of the photodetector and the scintillator.

Photodetector requirements

- High photodetection efficiency (affects S/N of the detection and thus resolution)
- High intrinsic gain (reduces the importance of electronic noise and, thus, better count rate and measurable lower energy levels)
- Low excess noise (affects energy resolution)
- High linearity (affects systematic errors and energy range)
- Ability to couple to a scintillator

Radiation detection photodetectors

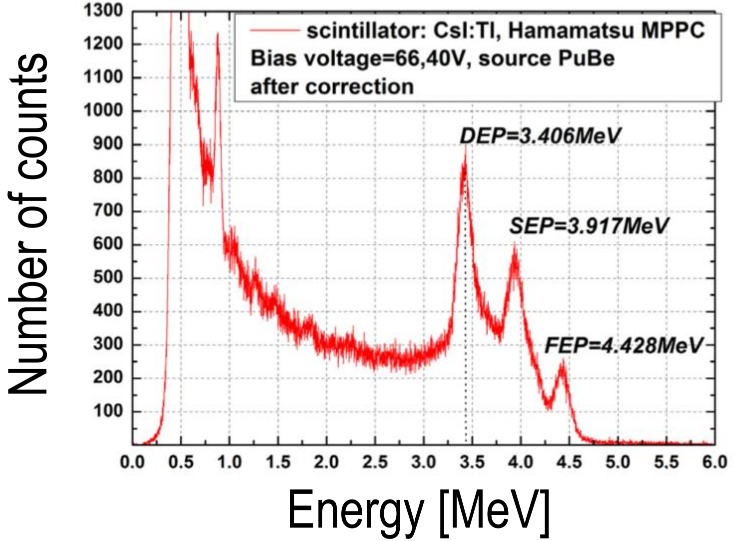
PMTs used to dominate the detector choice in radiation detection, monitoring, and spectroscopy.

SiPMs are becoming a viable alternative.

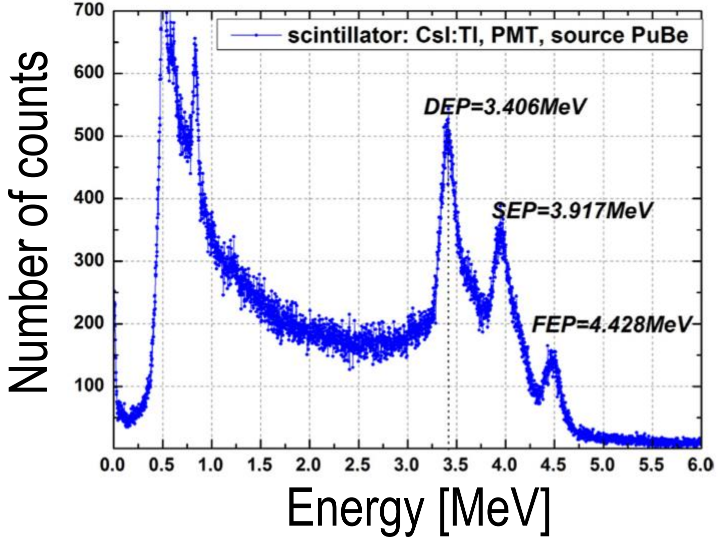
Due to a multitude of possible detection scenarios, it is best to perform a side-by-side comparison between an SiPM and a PMT.

SiPM vs. PMT in γ-ray detection

SiPM



PMT



Example of energy spectra from Grodzicka et al. 2017 [Nuclear Inst. and Methods in Physics Research, A 874 (2017) 137–148]

SiPM vs. PMT in γ-ray detection

Source	Energy [keV]	$CeBr_3$			NaI:Tl			CsI:Tl		
		MPPC		PMT	MPPC		PMT	MPPC		PMT
		FWHM/centroid, [%]	Energy resolution after correction	Energy resolution [%]	FWHM/centroid, [%]	Energy resolution after correction	Energy resolution [%]	FWHM/centroid, [%]	Energy resolution after correction	Energy resolution [%]
^{22}Na	511	7.1 ± 0.4	7.6 ± 0.4	5.6 ± 0.2	9.1 ± 0.5	9.6 ± 0.5	7.1 ± 0.2	7±0.4	7.2 ± 0.4	7.9 ± 0.3
^{137}Cs	662	5.9 ± 0.3	6.4 ± 0.3	4.9 ± 0.2	8.1 ± 0.4	8.7 ± 0.4	6.3 ± 0.2	6.1 ± 0.3	6.4 ± 0.3	6.3 ± 0.2
^{22}Na	1275	4.2 ± 0.2	5.1 ± 0.3	3.7 ± 0.1	5.8 ± 0.3	6.5 ± 0.4	4.8 ± 0.2	4.5 ± 0.3	4.9 ± 0.3	4.7 ± 0.2
PuBe	3416	3.4 ± 0.2	4.9 ± 0.3	3.8 ± 0.1	5±0.3	5.9 ± 0.3	4.5 ± 0.2	4.1 ± 0.2	4.7 ± 0.2	4.6 ± 0.2
PuC	5116	2.1 ± 0.1	3.5 ± 0.2	2.3 ± 0.1	3.9 ± 0.2	4.7 ± 0.3	2.8 ± 0.1	2.9±2	3.6 ± 0.2	3.9 ± 0.1

SiPM – PMT comparison for different energies and scintillators from Grodzicka et al. 2017 [Nuclear Inst. and Methods in Physics Research, A 874 (2017) 137–148]

Take-away points

1. SiPMs provide comparable performance to PMTs in radiation monitoring and spectroscopy

2. It is likely that the majority of hand-held devices will employ SiPMs

3. Side-by-side comparison is the best approach in deciding if an SiPM or a PMT should be used for a given detection application

Summary and conclusions

- High gain, low excess noise, magnetic immunity, and ease of use are some of the highly desirable characteristics of SiPMs
- There is a great interest in using SiPMs instead of APDs and PMTs in a variety of applications
- New generation SiPMs will have improved characteristics making the transition more likely

Visit Booth #521 & Presentations at PW18

Development of an InGaAs SPAD 2D array for Flash LIDAR

Presentation by Takashi Baba, January 29, 2018 (11:00 AM - 11:30 AM)

Development of an InGaAs MPPC for NIR photon counting applications

Presentation by Yusei Tamura, January 30, 2018 (5:50 PM - 6:10 PM)

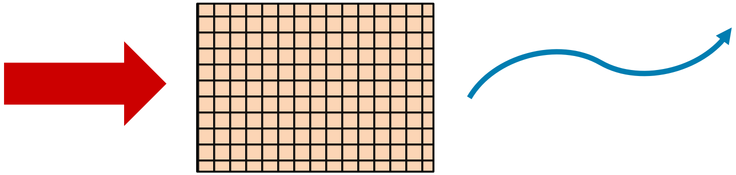
Photodetectors, Raman Spectroscopy, and SiPMs versus PMTs

One-day Workshop with Slawomir Piatek, January 31, 2018 (8:30 AM - 5:30 PM) – Free Registration Needed

Development of a Silicon hybrid SPAD 1D array for LIDAR and spectrometers

Poster session with Shunsuke Adachi, January 31, 2018 (6:00 PM - 8:00 PM)

Thank you for listening!



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