SiPM and SPAD:
Emerging Applications for Single-Photon Detection

Slawomir S. Piatek, Ph.D.
Senior University Lecturer of Physics
New Jersey Institute of Technology

HAMAMATSU
PHOTON IS OUR BUSINESS

PHOTONICS MEDIA
photonics.com

SiPM and SPAD: emerging applications

Slawomir Piatek
NJIT/Hamamatsu

Outline

- Introduction to PN junction devices
- Fundamentals of single-photon avalanche photodiode (SPAD)
- Fundamentals of silicon photomultiplier (SiPM)
- Key opto-electronic characteristics of SiPMs
- Applications of SiPMs and SPADs
- Summary and conclusions

Introduction to PN junction devices

Terminology

PD – Photodiode

APD – Avalanche photodiode

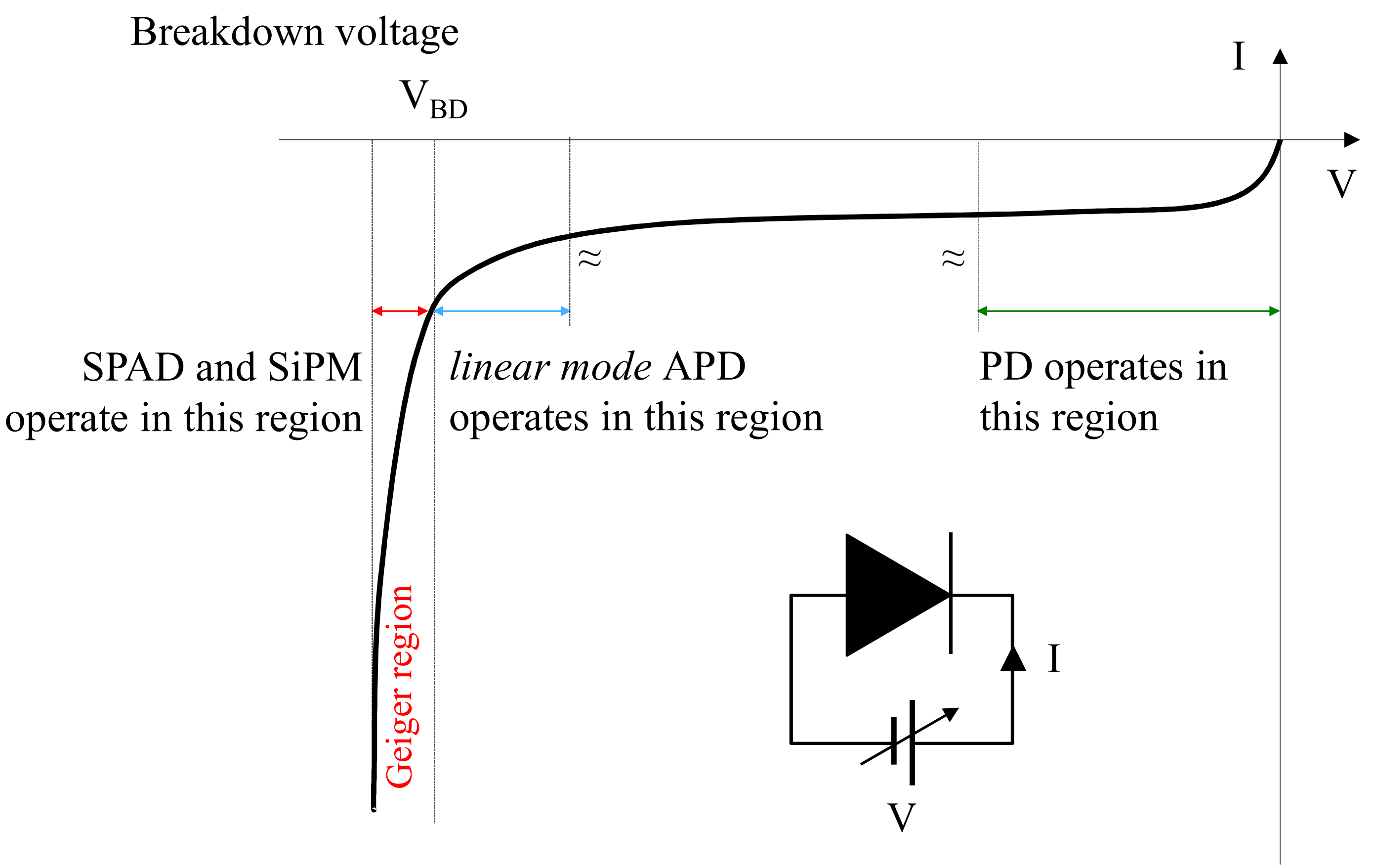
SPAD – Single-photon avalanche photodiode
SPPC – Single-pixel photon counter; another name for SPAD
} The same

SiPM – Silicon photomultiplier
MPPC – Multi-pixel photon counter; another name for SiPM
} The same

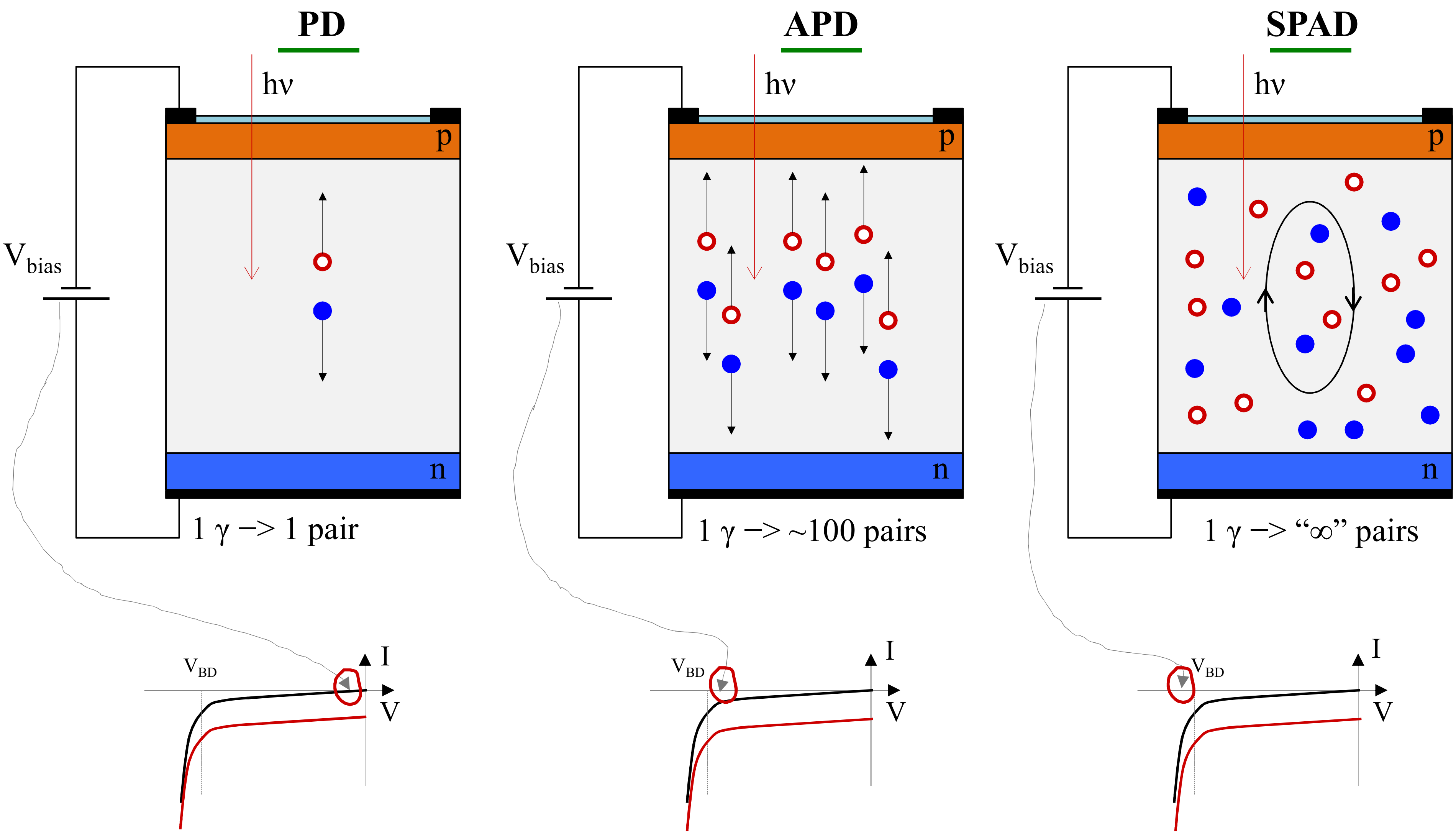
PMT – Photomultiplier tube

Generic PN junction: modes of operation

Dark current versus bias voltage

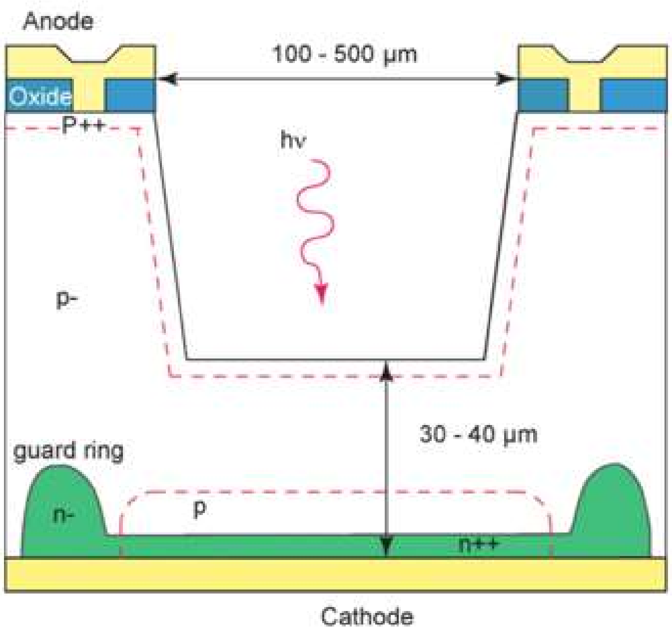


PD, APD, and SPAD

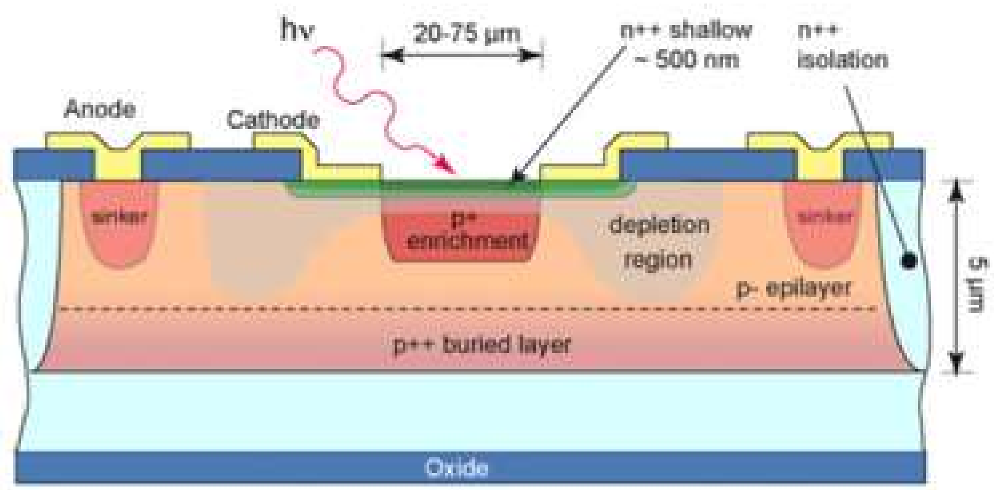


Single-photon avalanche photodiode (SPAD)

Structure of a SPAD



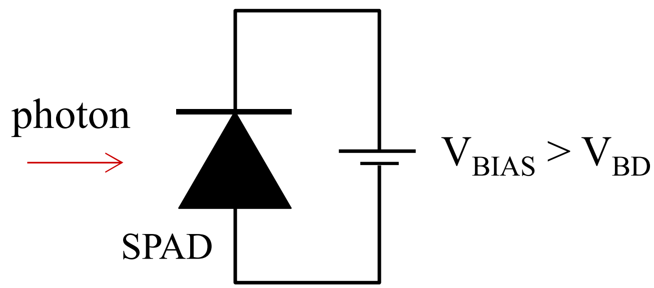
Structure of a *thick* SPAD

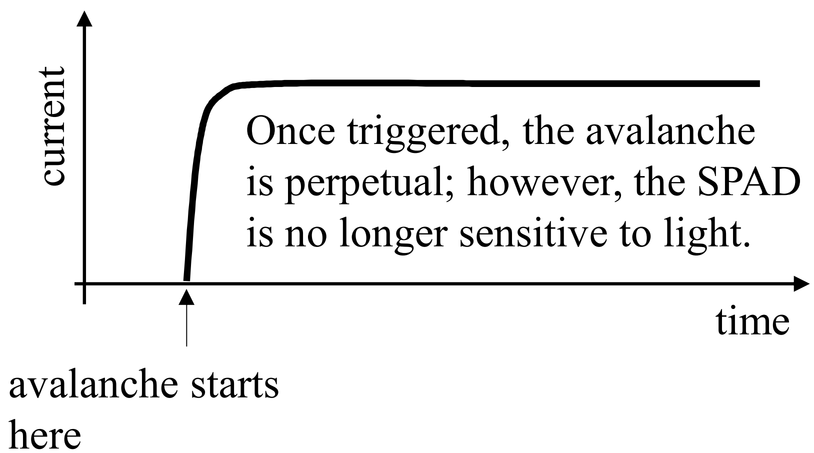


Structure of a *thin* SPAD. This structure is used in SPAD arrays.

Figures from Zappa et al. 2007

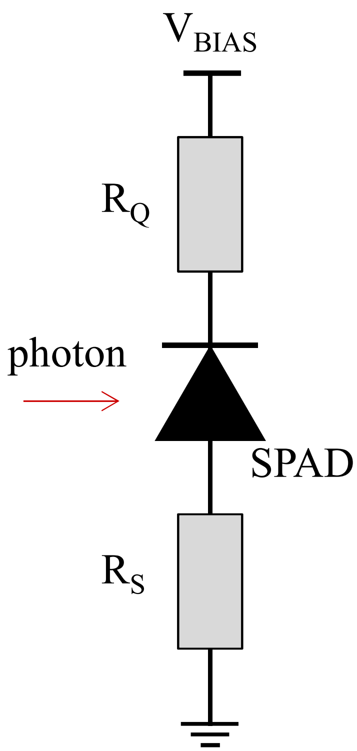
Operation of a SPAD



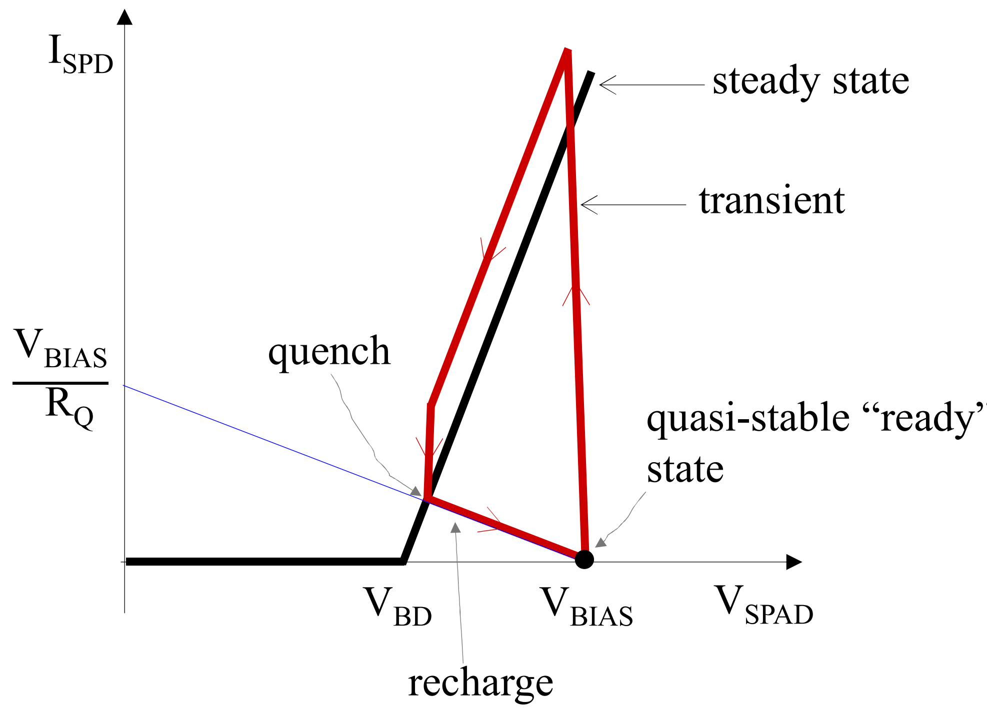


Without quenching, SPAD operates as a light switch.

Operation of a SPAD (passive quenching)

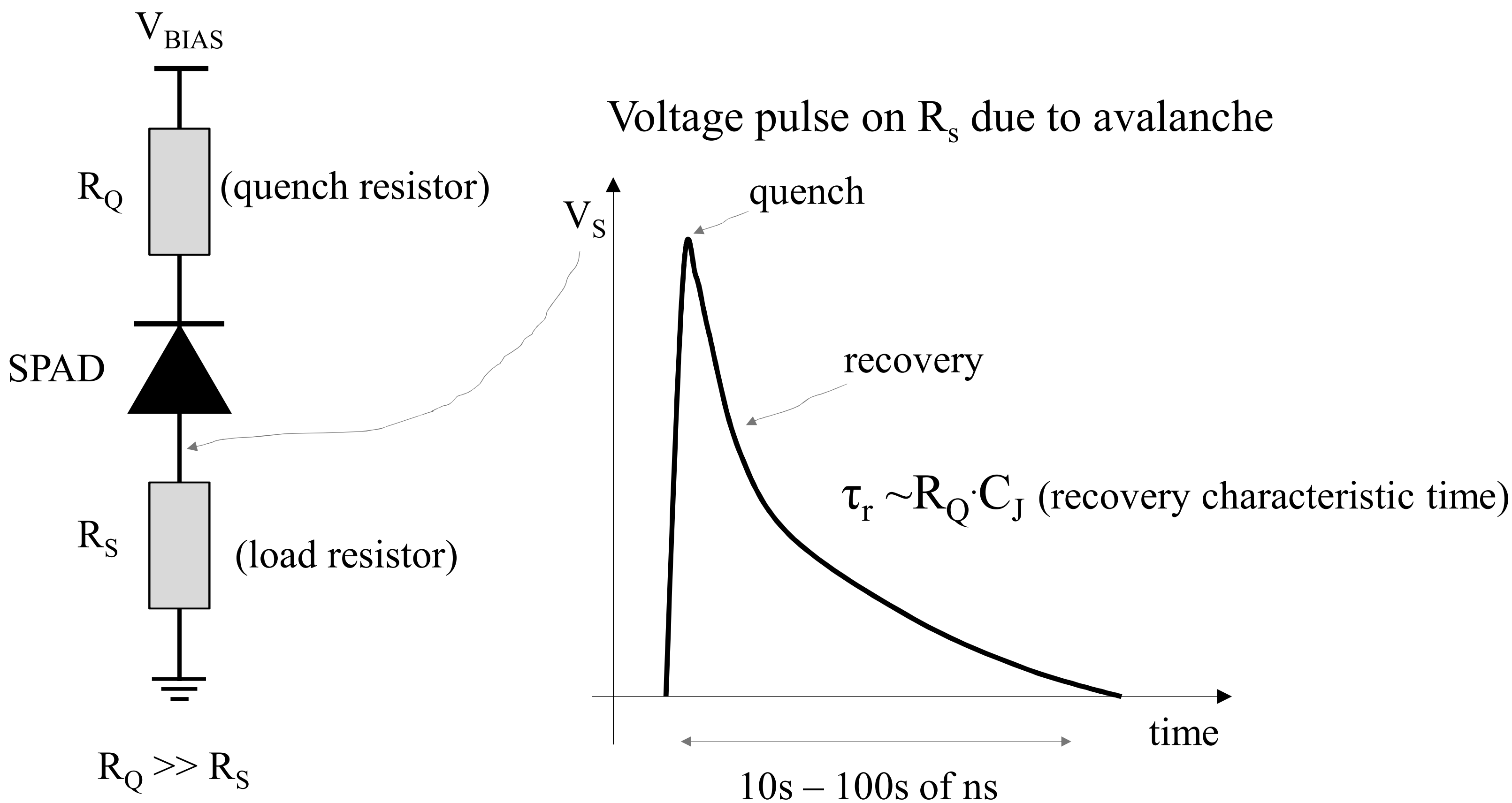


$R_Q >> R_S$



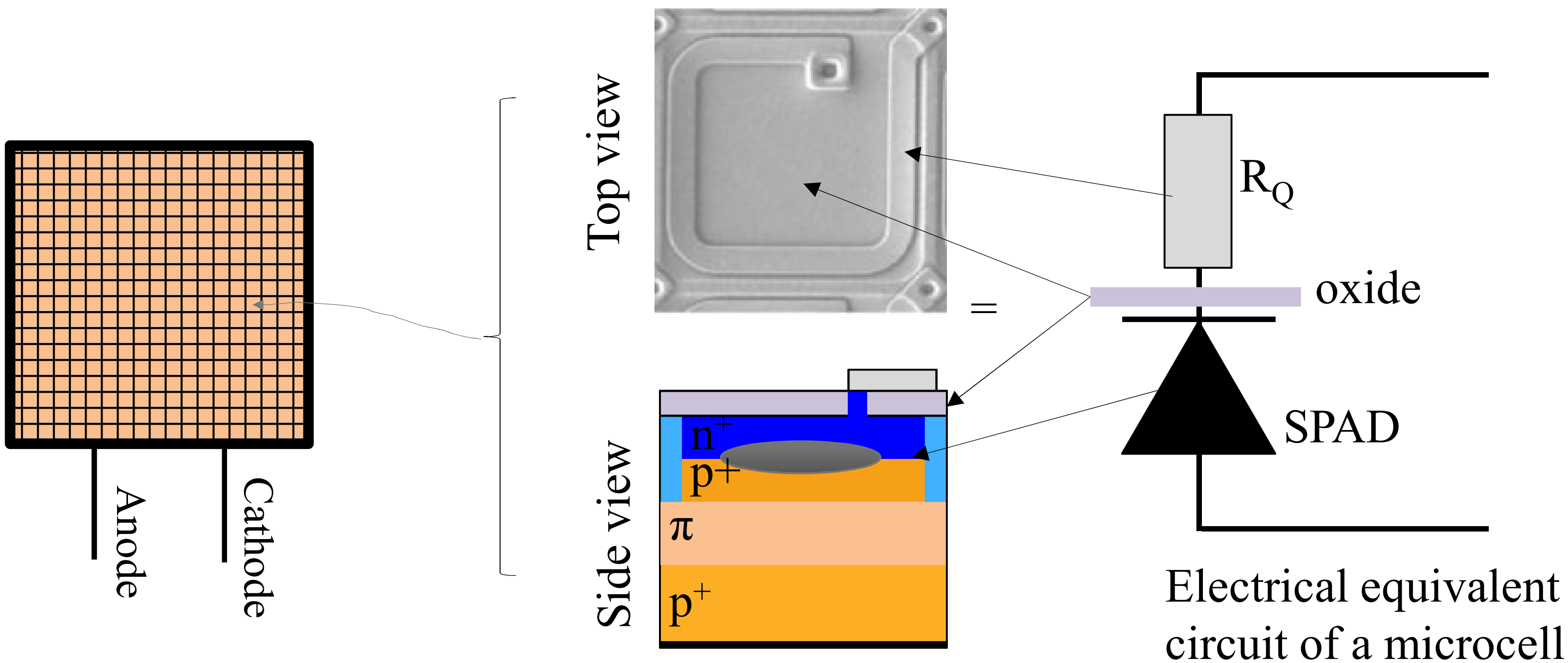
R_Q must be large enough to ensure quenching.

Operation of SPAD (passive quenching)



Silicon photomultiplier (SiPM)

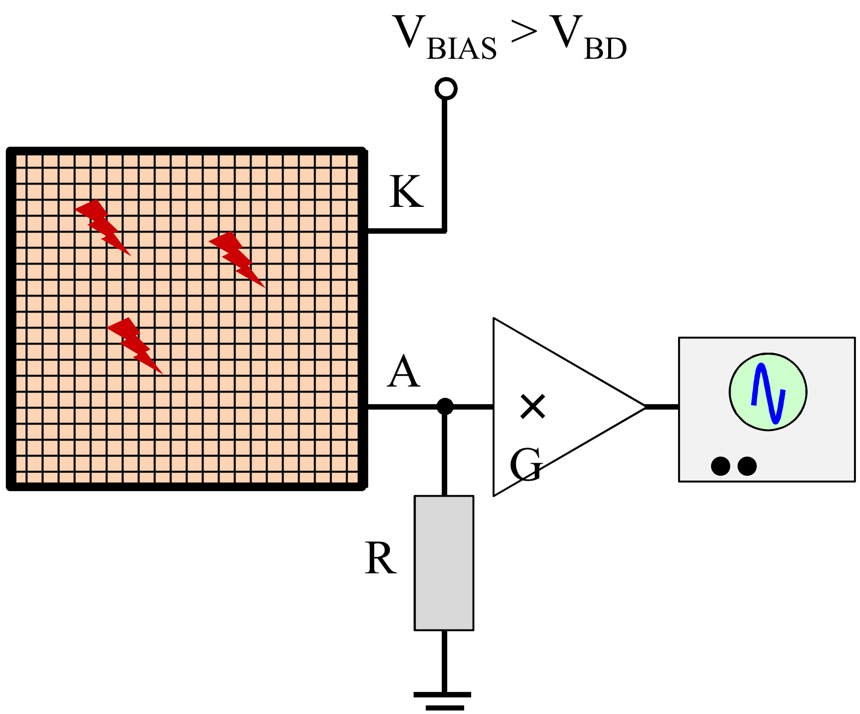
Silicon photomultiplier: structure

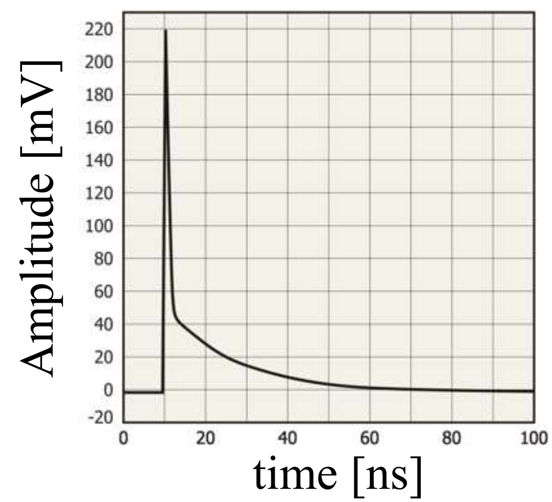


Single microcell

Each microcell is a SPAD in series with a quench resistor. All microcells are connected in parallel. SiPM is **not** an imaging device because all microcells share a common current summing node.

Silicon photomultiplier: operation



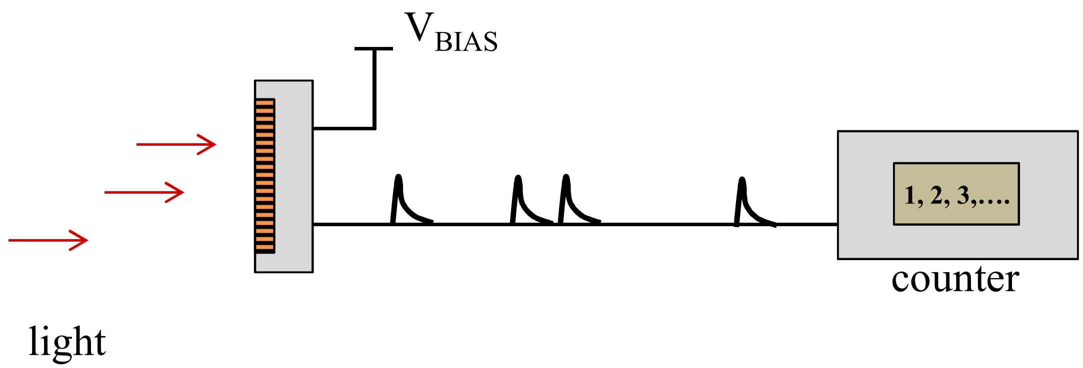


Example of single-photoelectron waveform (1 p.e.)

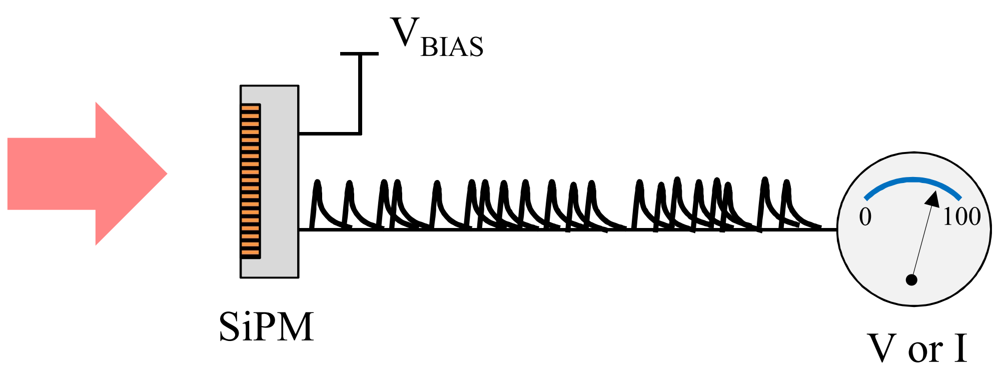
Gain = area under the curve in electrons

Overvoltage, $\Delta V = V_{BIAS} - V_{BD}$

Silicon photomultiplier: modes of operation



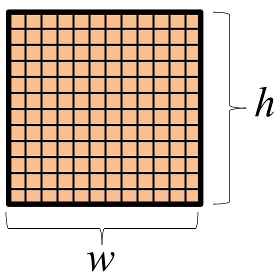
If the pulses are distinguishable, SiPM can be operated in a **photon counting** mode.



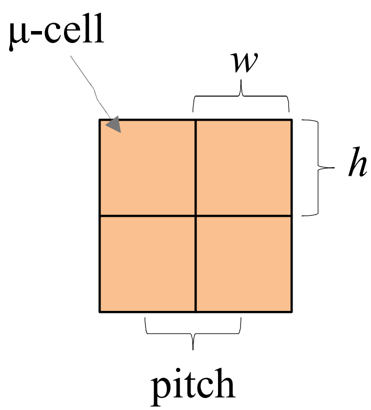
If the pulses overlap, the SiPM can be operated in an **analog mode**. The measured output is voltage or current.

Key opto-electronic characteristics of SiPMs

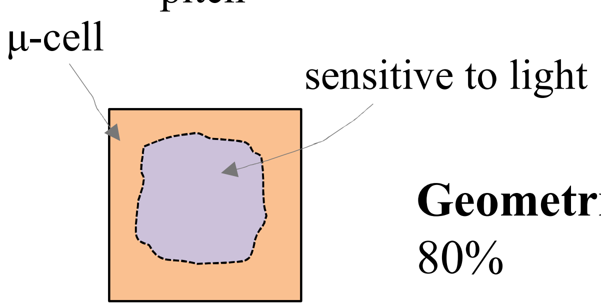
Structural and geometrical considerations



Active area: $w \times h$; ranges from 1×1 mm^2 to 6×6 mm^2



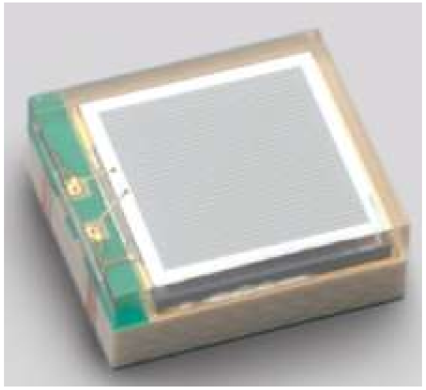
Microcell area: ranges from 10×10 µm^2 to 100×100 µm^2
Pitch: center-to-center distance



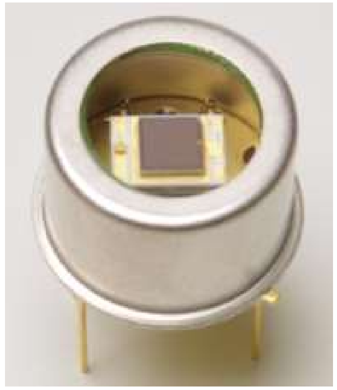
Geometrical fill factor: fraction of a µ-cell sensitive to light, ~30% to ~ 80%

Packaging

Ceramic



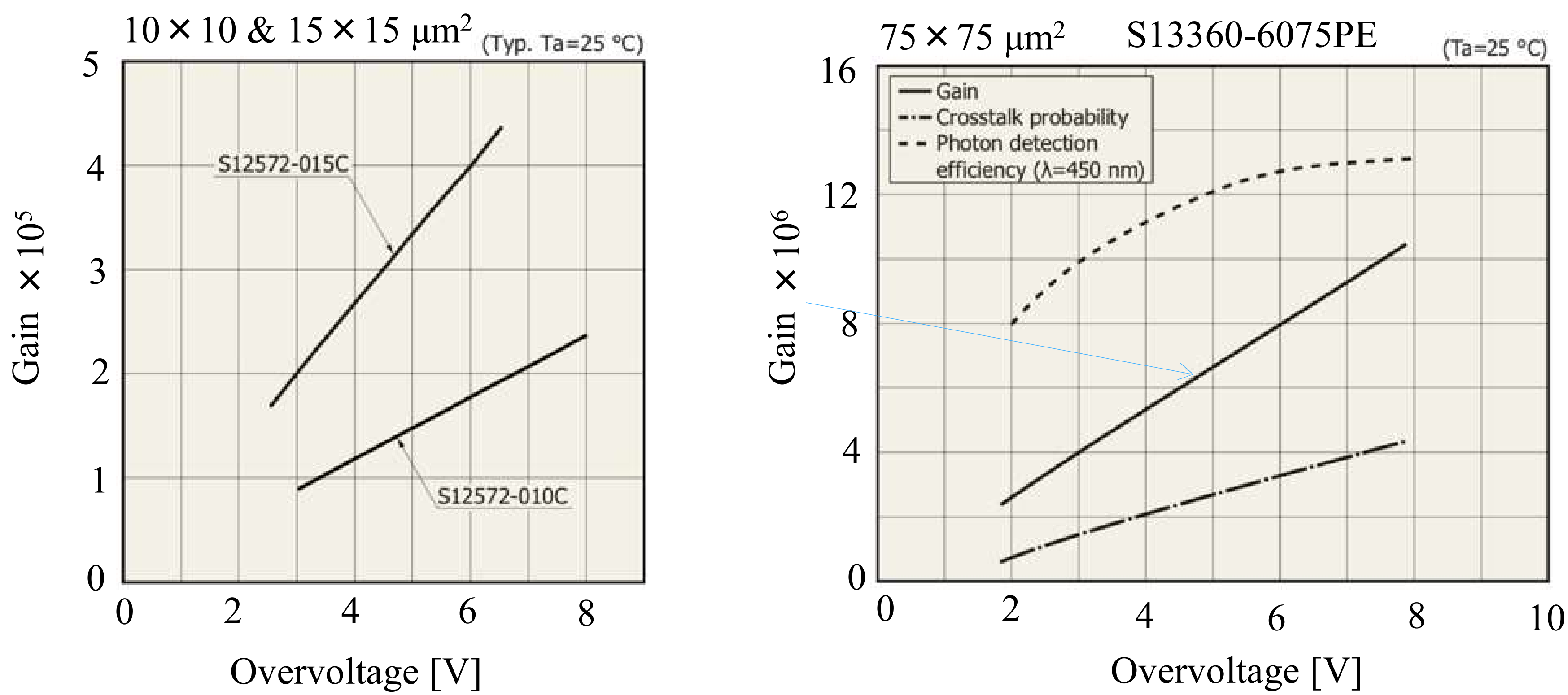
Surface mount



Metal, TE-cooled

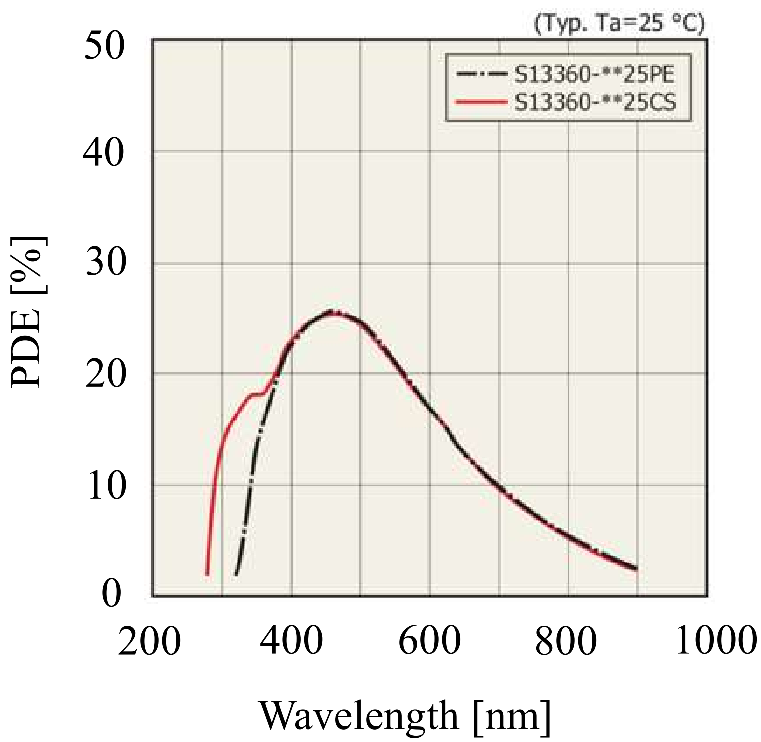
Array of SiPMs

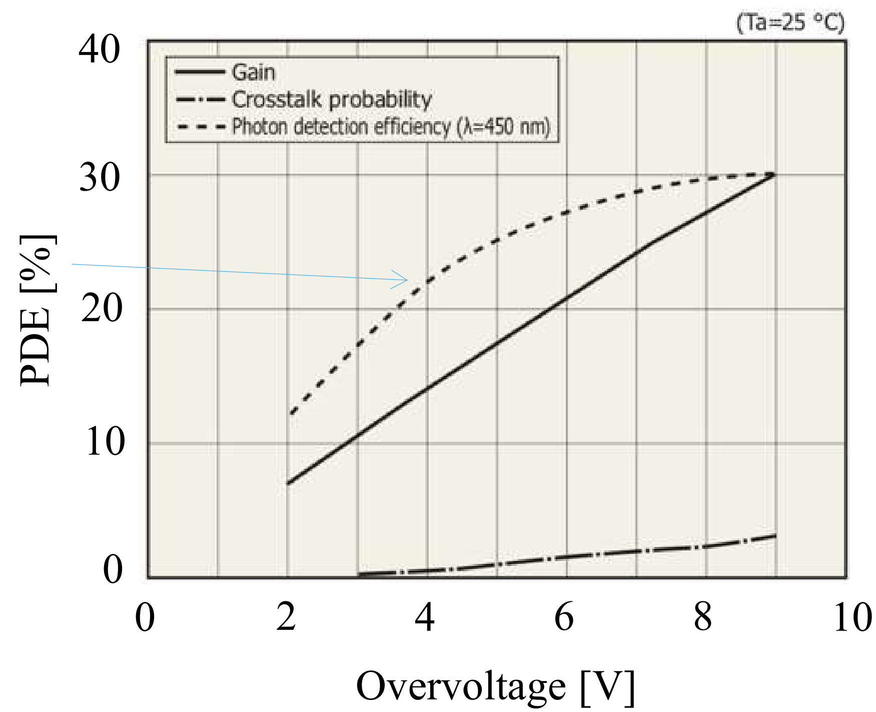
Gain



Gain depends linearly on overvoltage. For a given overvoltage, gain depends on the μ-cell size.

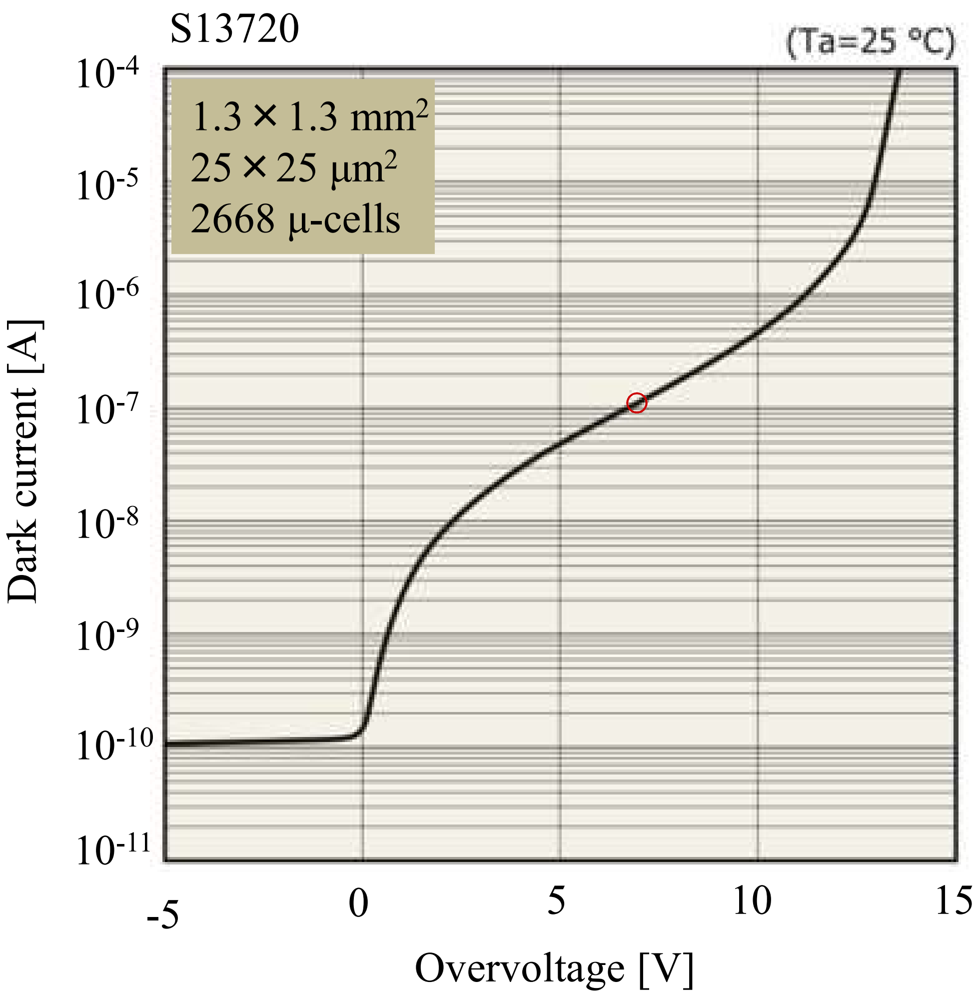
Photon detection efficiency (PDE)





Probability that the incident photon is detected. PDE is a function of wavelength and overvoltage. For a given overvoltage, PDE depends on the μ-cell area.

Dark current and dark count rate



Recommended overvoltage: 7 V

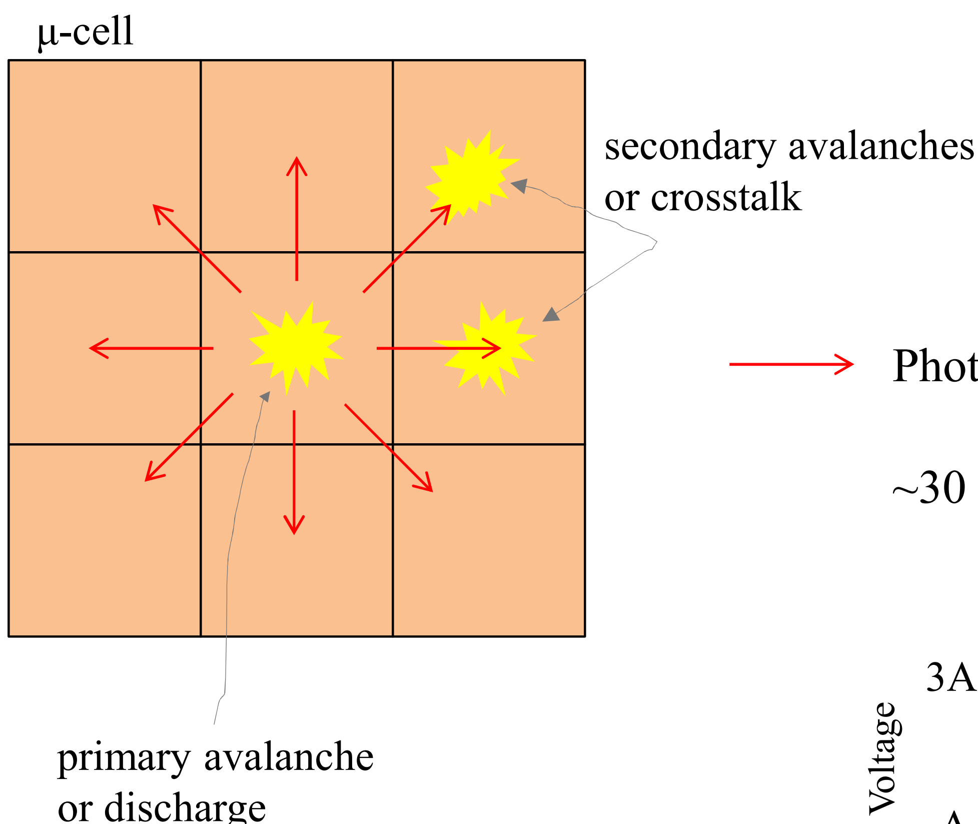
Gain (μ) = 1.1×10^6

$I_D = 10^{-7}$ A

DCR = $I_D/(\mu e) \approx$ 570,000 cps

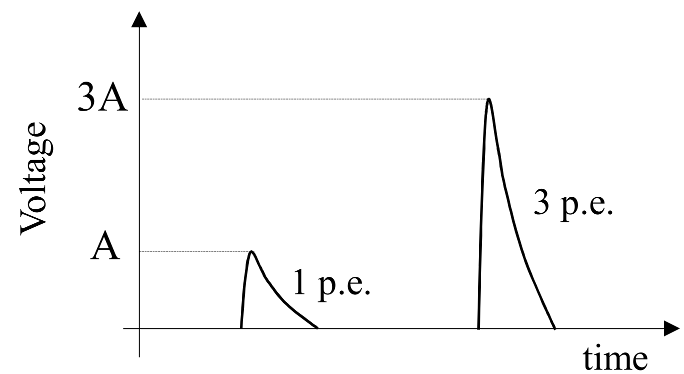
DCR/μ-cell = 213 cps

Crosstalk

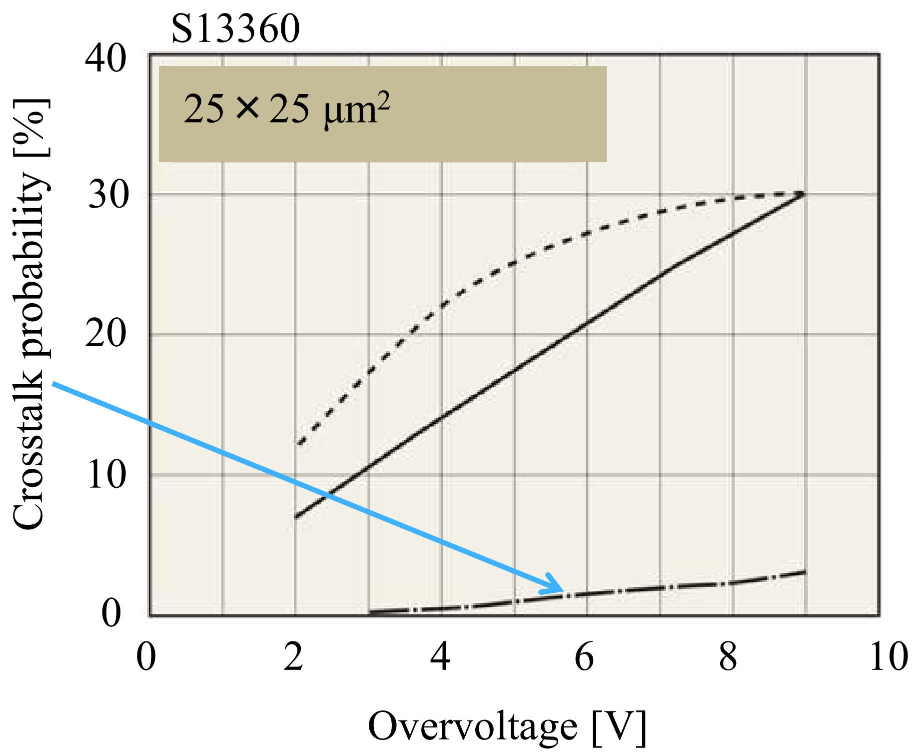


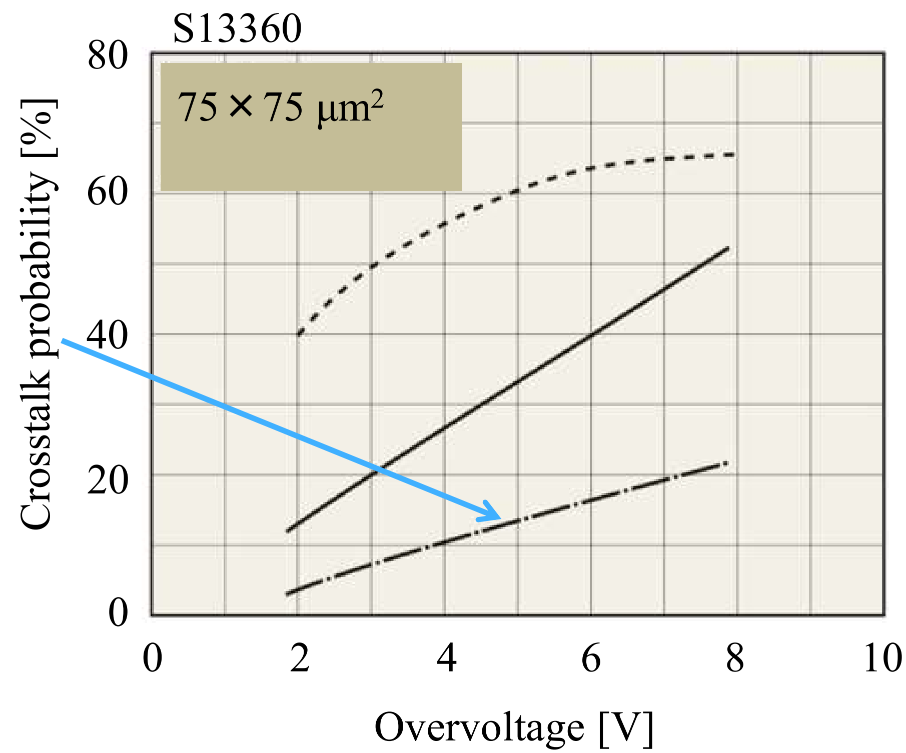
→ Photon emitted during an avalanche.

~30 photons with $E_{\gamma} > 1.14$ eV ($\mu=10^6$)



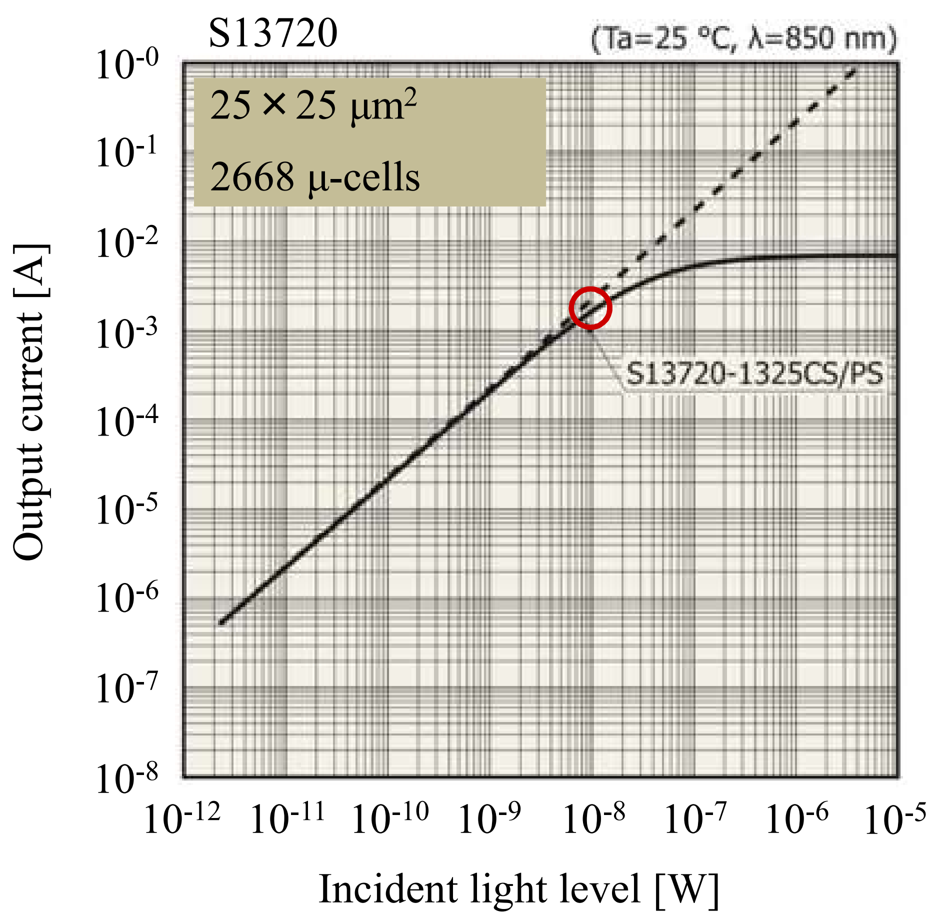
Crosstalk probability





Crosstalk probability depends on overvoltage and microcell size (gain).

Linearity and dynamic range



10^{-8} W implies 3.7×10^{-12} W per μ-cell

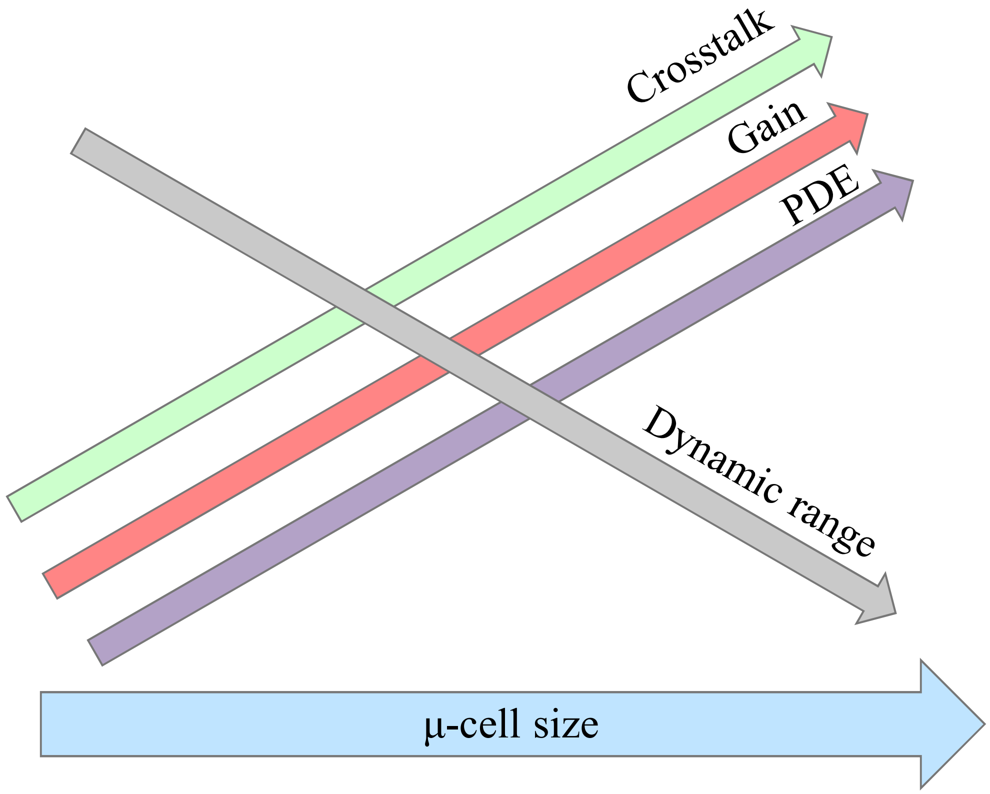
which is ~16×10^{6} photons per second per μ-cell

which is ~1 photon per 63 ns

For a given active area, the number of μ-cells determines the upper limit of the dynamic range.

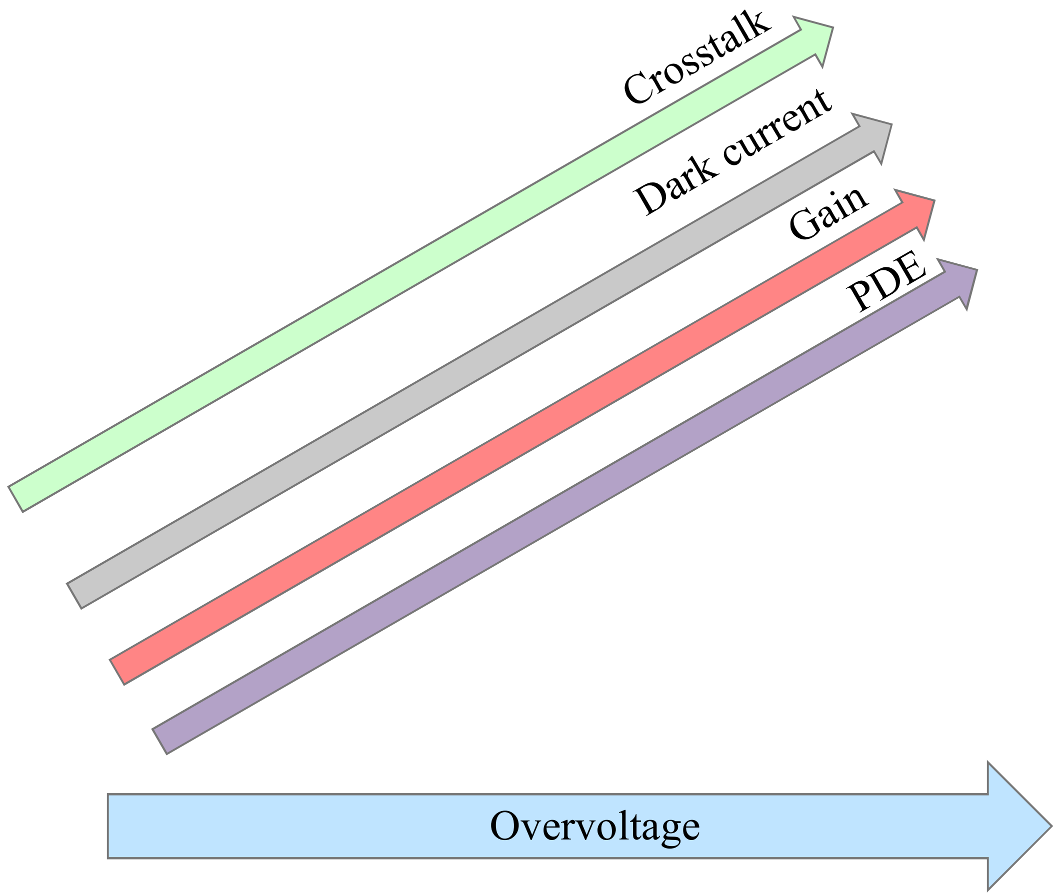
Tradeoffs

Fixed: active area & overvoltage; change μ-cell size



Tradeoffs

Fixed: active area & μ-cell size; change overvoltage



Applications

- Dark matter detection
- Flow cytometry
- Bio- and chemiluminescence
- Time-of-flight LiDAR
- Flash LiDAR

HAMAMATSU
PHOTON IS OUR BUSINESS

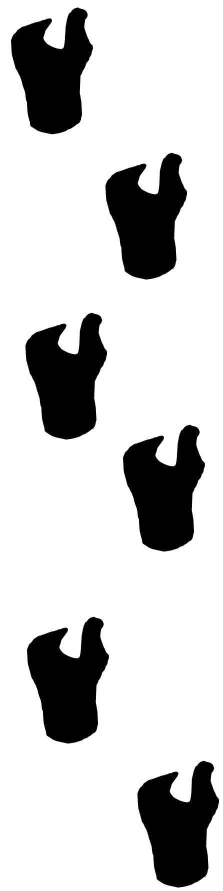
Photodetector comparison

	PMT	APD	SiPM
Quantum efficiency	Up to ~40%	Up to ~85%	Up to ~50%
Gain	10^5 - 10^7	Up to ~100	10^5 - 10^6
Excess noise	~1.2	3 – 4	~1.1 – 1.2
Minimum detectable power	Best	Good	Better
Dynamic range	Dependent on the voltage divider	Largest (high saturation level)	Dependent on the number of microcells
Temperature effects	Weak	Strong	Strong

Additional attributes of SiPMs

- Operation immune to electric and magnetic fields
- Low bias voltage (10s of volts)
- No damage or lasting effects when exposed to full light
- Simple biasing circuit
- Ability to make arrays and to mount on a circuit board
- Ruggedness

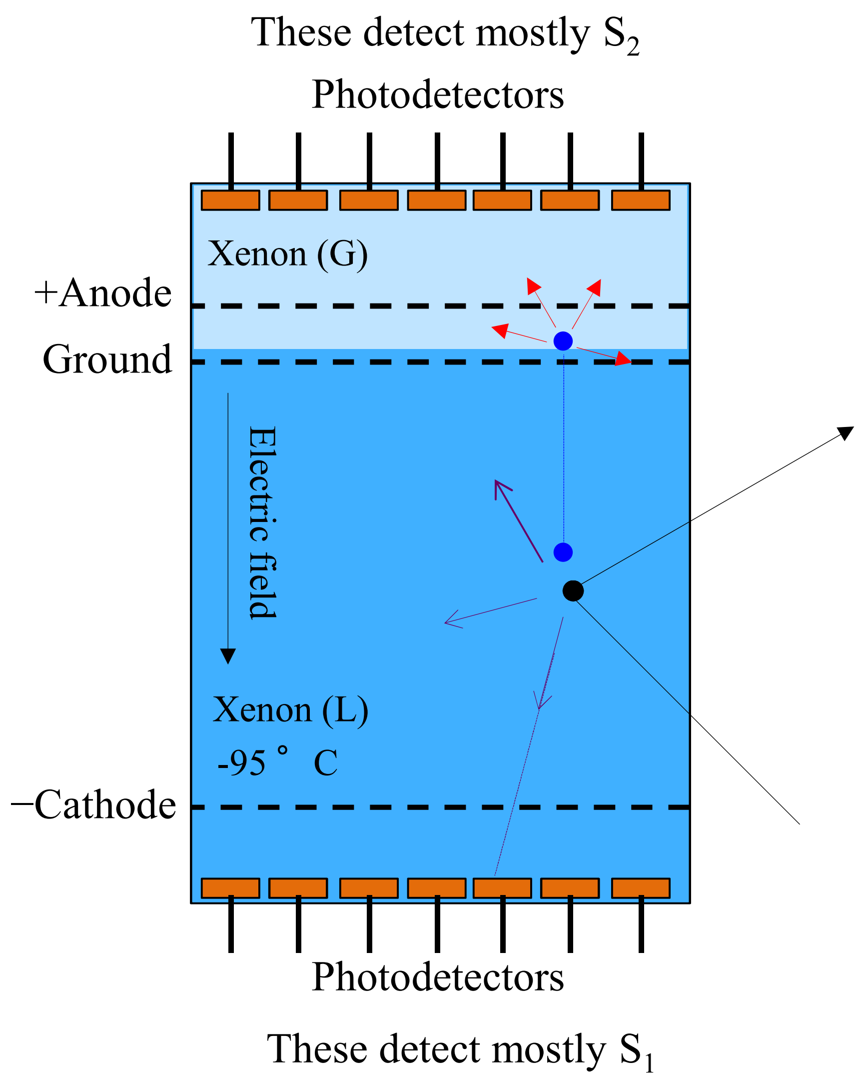
Dark matter detection



Background

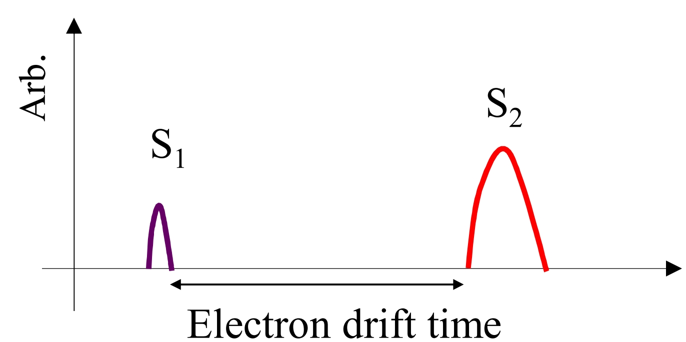
- A galactic mass deduced from stellar kinematics is much larger than that implied by its luminous matter. The difference is known as ***dark matter***.
- Dark matter interacts gravitationally but emits little or no light.
- The nature of dark matter is still not known.
- Among a number of possibilities, dark matter could be in the form of particles that can interact with "ordinary" matter.
- Active research exists in identifying the nature of dark matter.

Detection concept for WIMPs



Legend:

- ● Dark matter particle (WIMP)
- → 175-nm light from liquid Xenon scintillation
- ● Electron
- → Light from ionized Xenon gas



Characteristics of received light

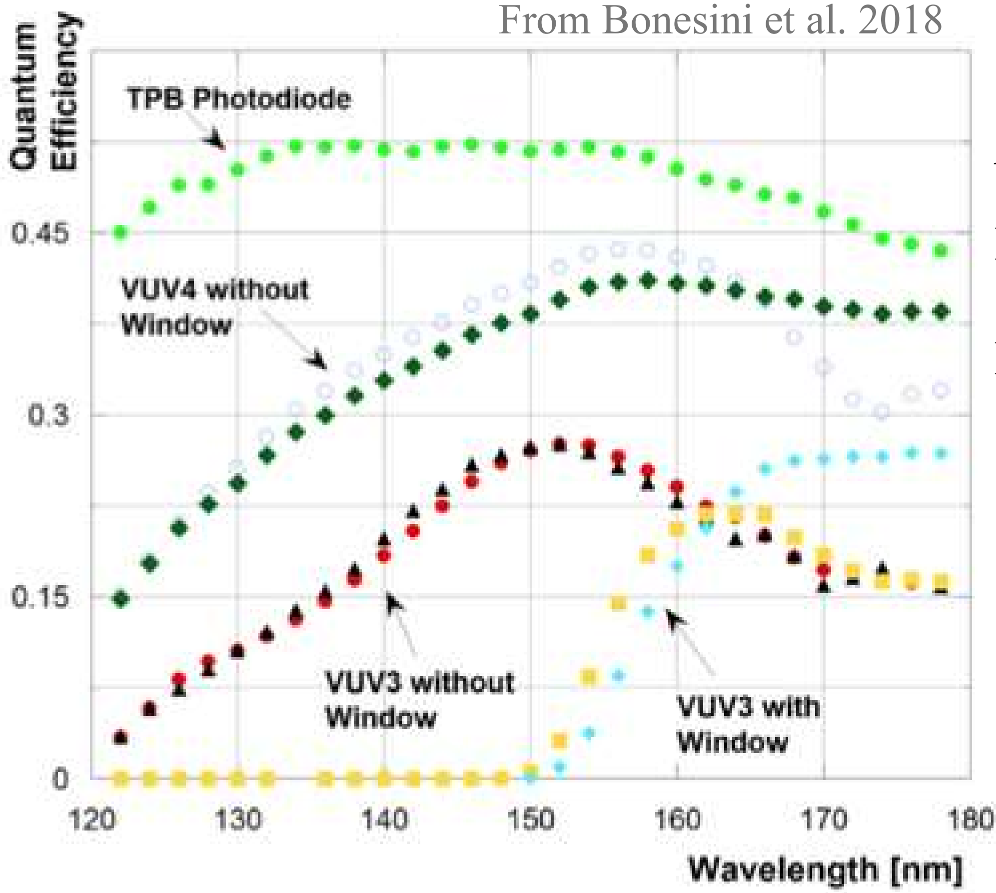
- Two pulses of light: S_1 contains ~few tens of photons, while S_2 ~few thousand
- Wavelength: UV and V
- Pulse duration: ~ns for S_1 and ~µs for S_2

Photodetector requirements

- Photosensitivity in UV and V range
- High intrinsic gain (suppresses importance of electronic noise)
- High bandwidth (to avoid distortion of S_1 pulse)
- Able to operate at low temperature (- 95 ° C or 178 K)

Product recommendation for liquid Xenon detection

From Bonesini et al. 2018



VUV3 and VUV4

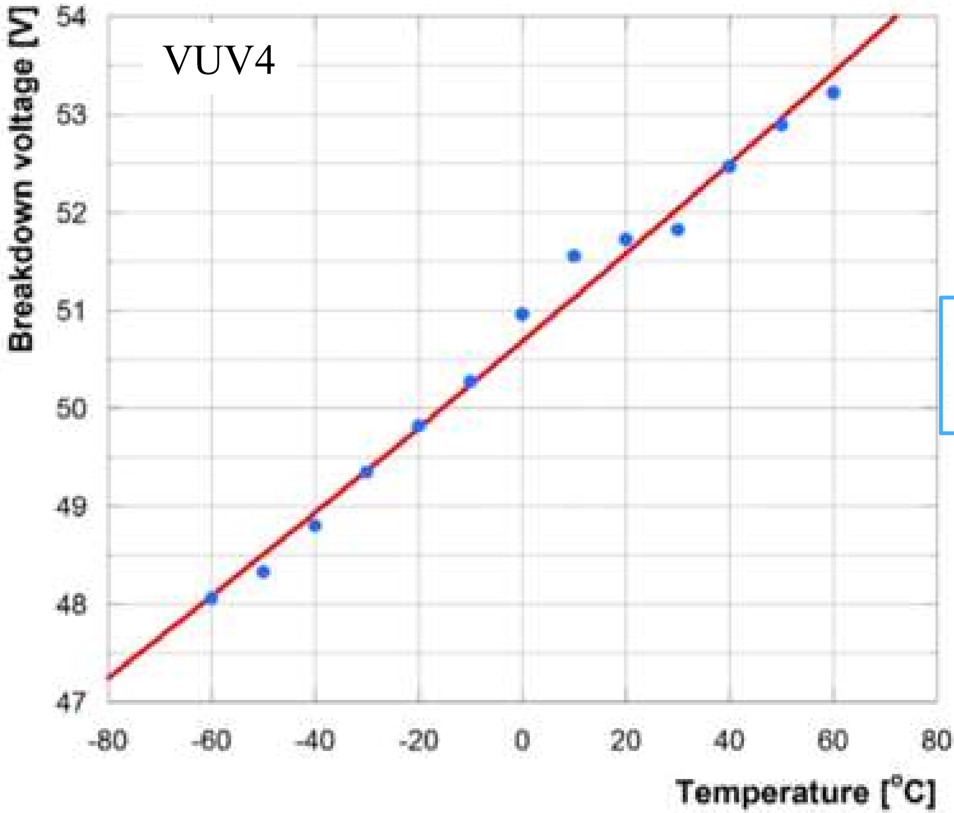
Array: Four 5.95 × 5.85 mm^2 SiPMs

Each SiPM has 13,923 μ-cells, 50 μm pitch

Fill factor: 60%

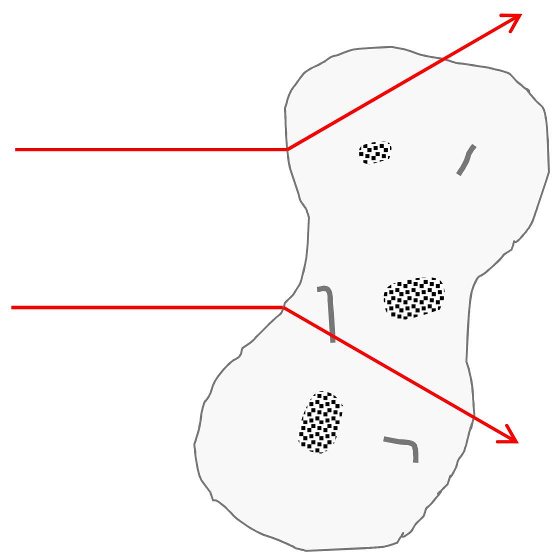
Effect of temperature on the gain

From Bonesini et al. 2018

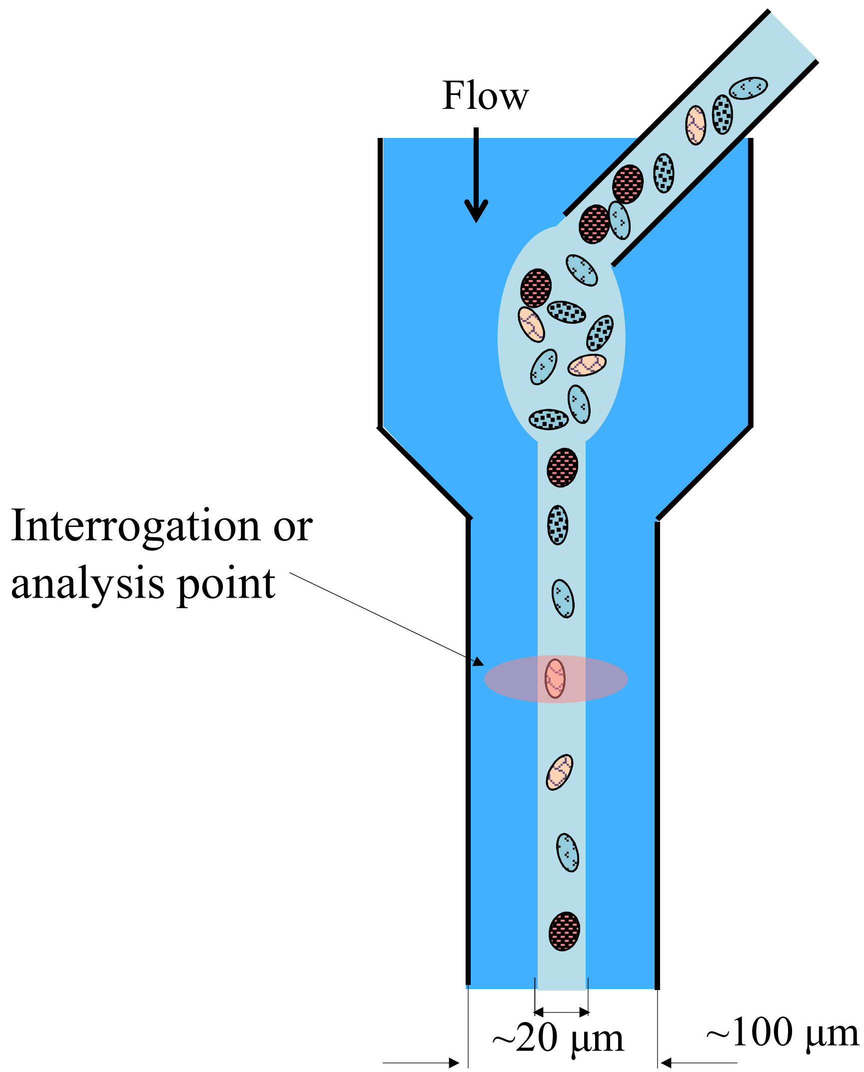


- Breakdown voltage decreases with decreasing temperature.
- Gain depends on V_{BIAS} - V_{BD}
- If $V_{BIAS} - V_{BD}$ is held constant, **the gain is constant too.**

Flow cytometry

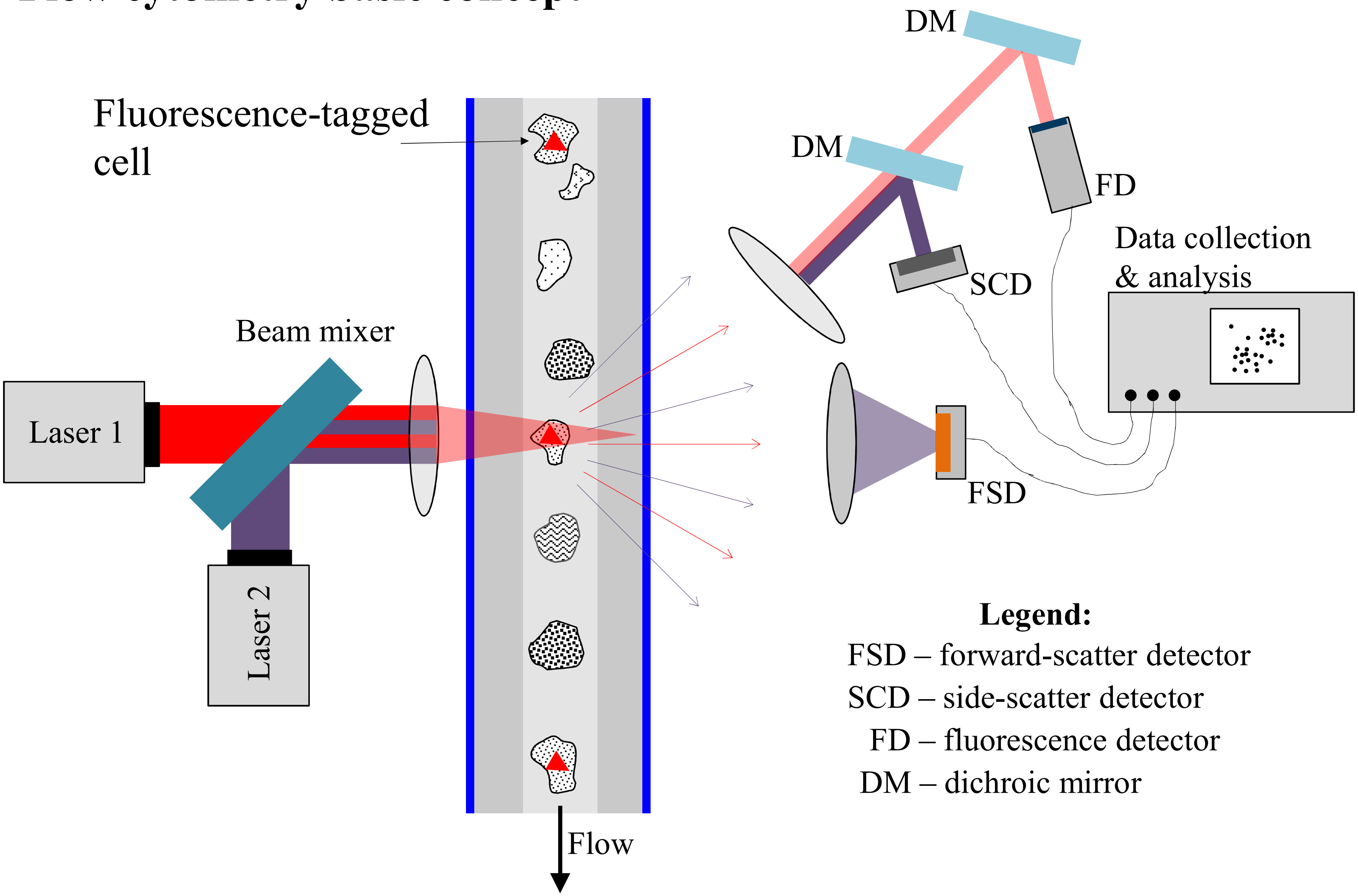


Flow cytometry: study of cells and micro-particles



- Used in medicine, biology, and engineering to study and sort cells and micro-particles
- Cells scatter interrogation light. The manner of scatter depends on the cell properties.
- The rate of interrogation is on the order of 1,000 cells per second or more.

Flow cytometry basic concept



Legend:

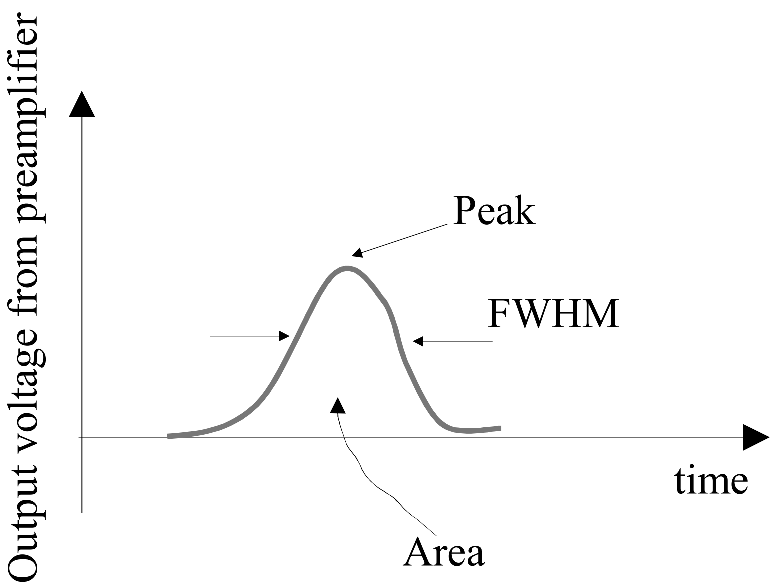
FSD – forward-scatter detector

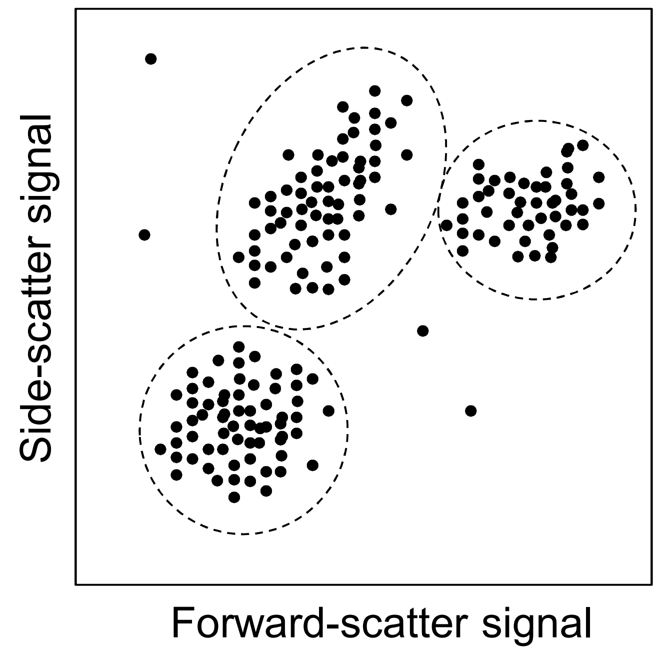
SCD – side-scatter detector

FD – fluorescence detector

DM – dichroic mirror

Flow cytometer: what is measured?





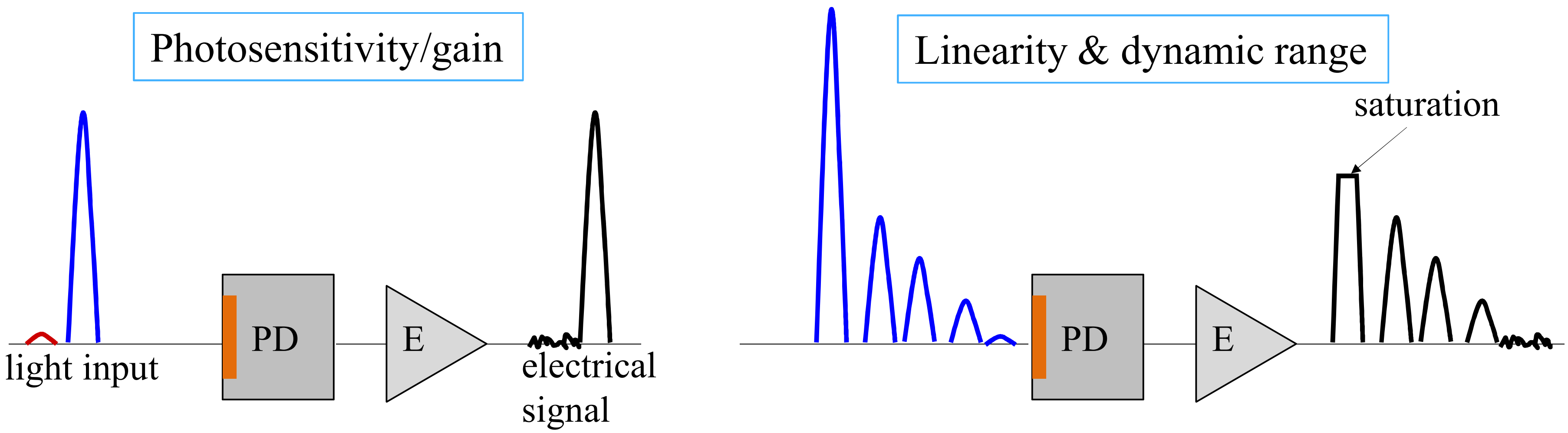
The front-end electronics can be set up to measure the peak value of the pulse, its FWHM, and/or area under the curve. These different measurements provide specific information about the cell.

HAMAMATSU
PHOTON IS OUR BUSINESS

Characteristics of received light

- Wavelength: can be selected depending on cell sizes and fluorescence
- Pulses: duration dependent on the sheath flow speed and cell size and is on the order of μs
- Number of photons per pulse varies from a few to thousands
- Rate of pulses is in kHz

Photodetector requirement

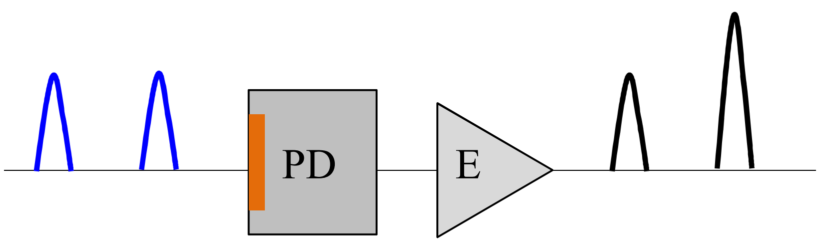


Can we detect the red pulse?

Is the output proportional to the input?

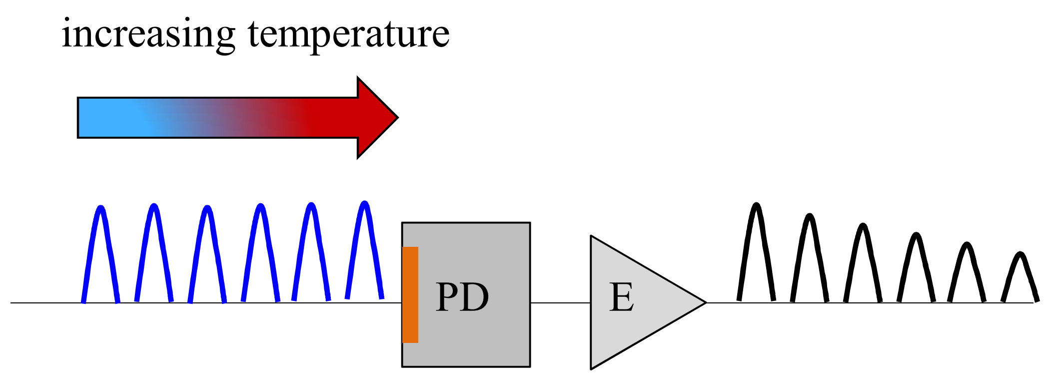
Photodetector requirement

Gain variation



How much *excess noise* is there?

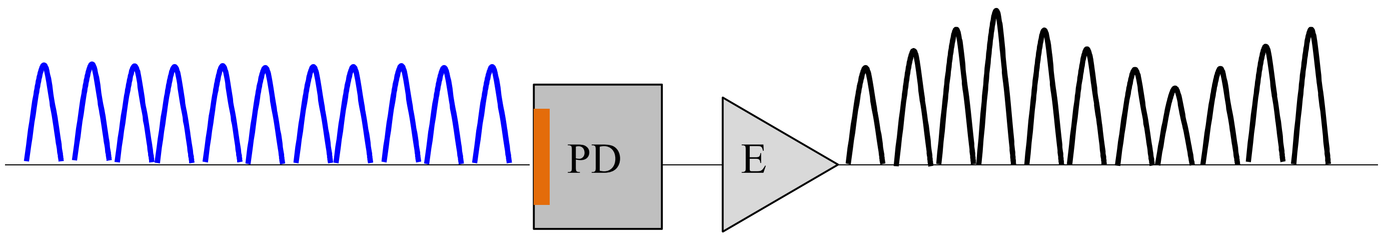
Temperature drift



Does the gain depend on temperature?

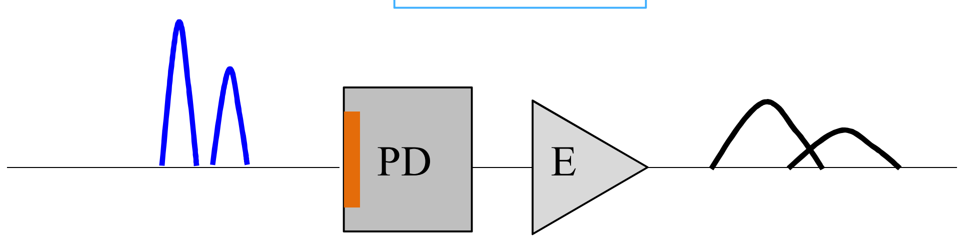
Photodetector requirement

Stability



How stable are the photodetector's characteristics such as gain?

Bandwidth



Does the photodetector and detection electronics have enough bandwidth?

HAMAMATSU
PHOTON IS OUR BUSINESS

Product recommendation for flow cytometry

Hamamatsu S14420 SiPM (MPPC) series

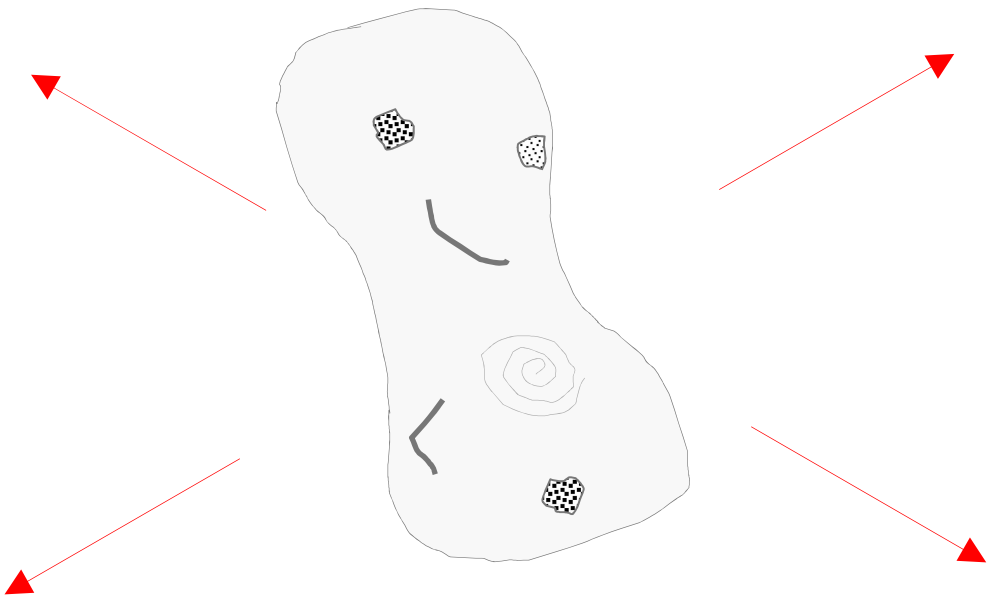
Structure / Absolute maximum ratings

Type no.	Pixel pitch (μm)	Photosensitive area (mm)	Number of pixels	Fill factor (%)	Package	Window material	Window refractive index
S14420-1525MG	25	ϕ1.5	2876	63	Metal (TO-5)	Borosilicate glass	1.49
S14420-1550MG	50		724	81			
S14420-3025MG	25	ϕ3.0	11344	63			
S14420-3050MG	50		2836	81			

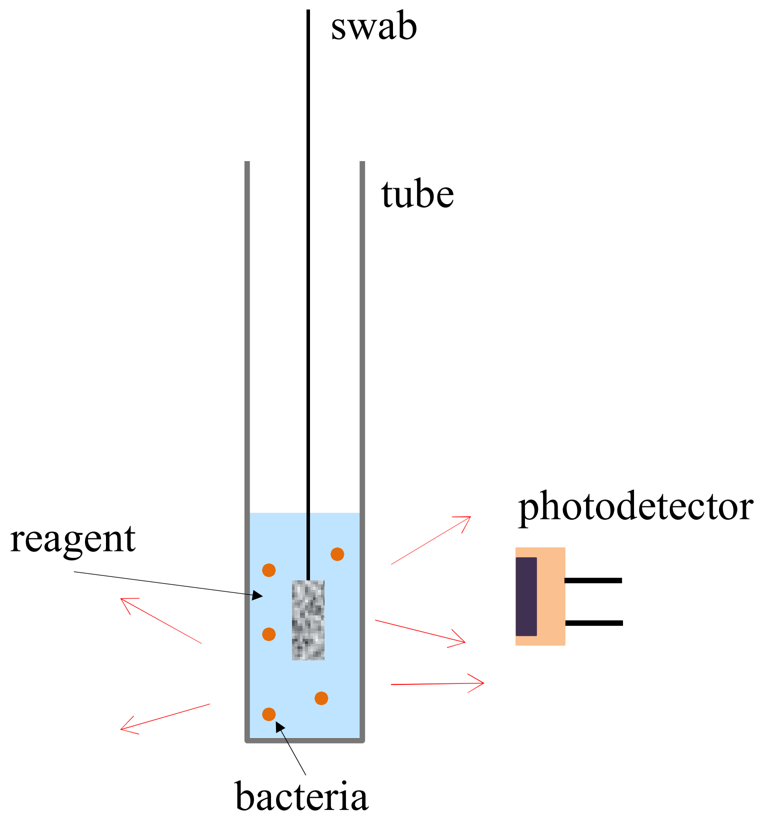
Electrical and optical characteristics

Type no.	Spectral response range λ (nm)	Peak sensitivity wavelength λp (nm)	Photon detection efficiency*3 PDE λ=λp (%)	Dark count Typ. (kcps)	Dark count Max. (kcps)	Terminal capacitance Ct (pF)	Gain M	Breakdown voltage VBR (V)	Crosstalk probability (%)	Recommended operating voltage*4 Vop (V)	Temperature coefficient of recommended operating voltage ΔTVop (mV/°C)
S14420-1525MG	350 to 1000	600	30	380	1000	90	0.9×10^6	42 ± 5	1.5	VBR + 5	47
S14420-1550MG			40				3.6×10^6		5		
S14420-3025MG			30	1600	4000	350	0.9×10^6		1.5		
S14420-3050MG			40				3.6×10^6		5		

Bio- and chemiluminescence luminometer



Basic concept of a luminometer



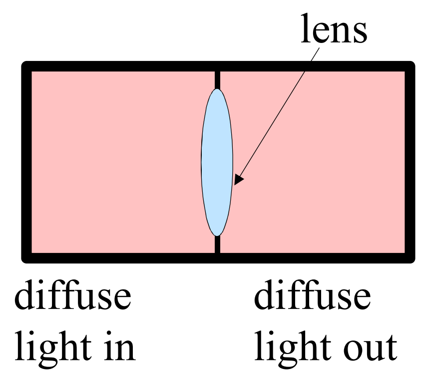
- Used to measure surface cleanliness
- The reagent reacts with the bacteria ATP, causing emission of light.
- The amount of light is proportional to the amount of ATP.

Legend:

ATP – adenosine triphosphate

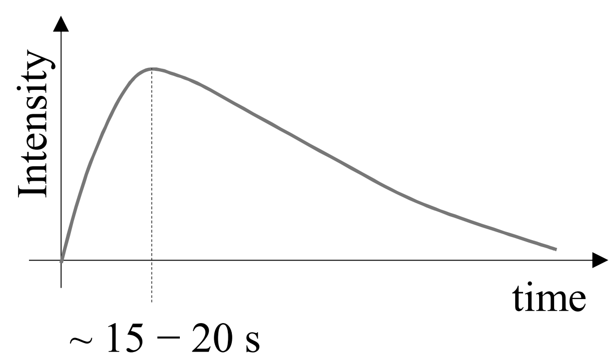
Characteristics of the received light

1. Wavelength in the 500 nm – 550 nm range



2. Diffuse (diffuse light cannot be focused)

3. Weak and slowly varying



Photodetector requirement

1. Large active area

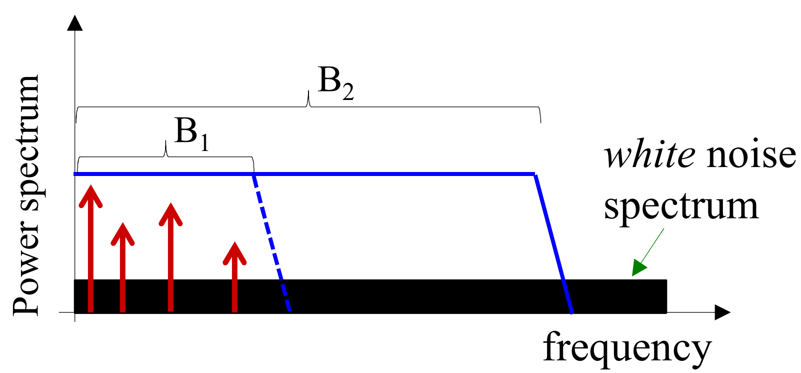
Signal ~ A   Noise ~ √A   so S/N ~ √A

2. Photosensitivity in 500 – 550 nm range

3. Gain

4. Low dark current

5. Small detection bandwidth (limited by the amplifier)



Wider bandwidth reduces S/N

Product recommendation for luminescence

Hamamatsu S14420 SiPM (MPPC) series

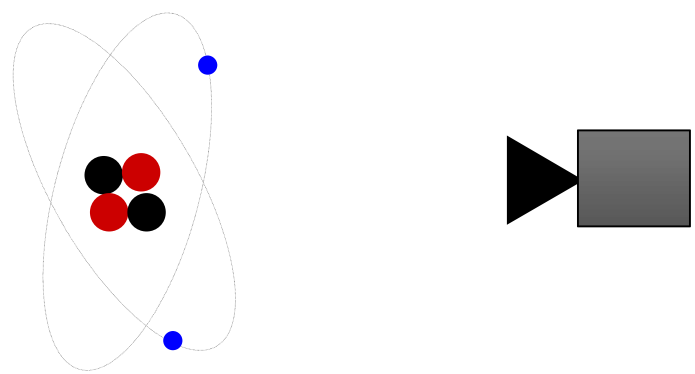
Structure / Absolute maximum ratings

Type no.	Pixel pitch (μm)	Photosensitive area (mm)	Number of pixels	Fill factor (%)	Package	Window material	Window refractive index	Absolute maximum ratings: Operating temperature[*1] Topr (°C)	Absolute maximum ratings: Storage temperature[*1] Tstg (°C)	Absolute maximum ratings: Soldering conditions[*2]
S14420-1525MG	25	ϕ1.5	2876	63	Metal (TO-5)	Borosilicate glass	1.49	-40 to +85	-40 to +105	Peak temperature: 350 °C, once, 3 s max.
S14420-1550MG	50		724	81						
S14420-3025MG	25	ϕ3.0	11344	63						
S14420-3050MG	50		2836	81						

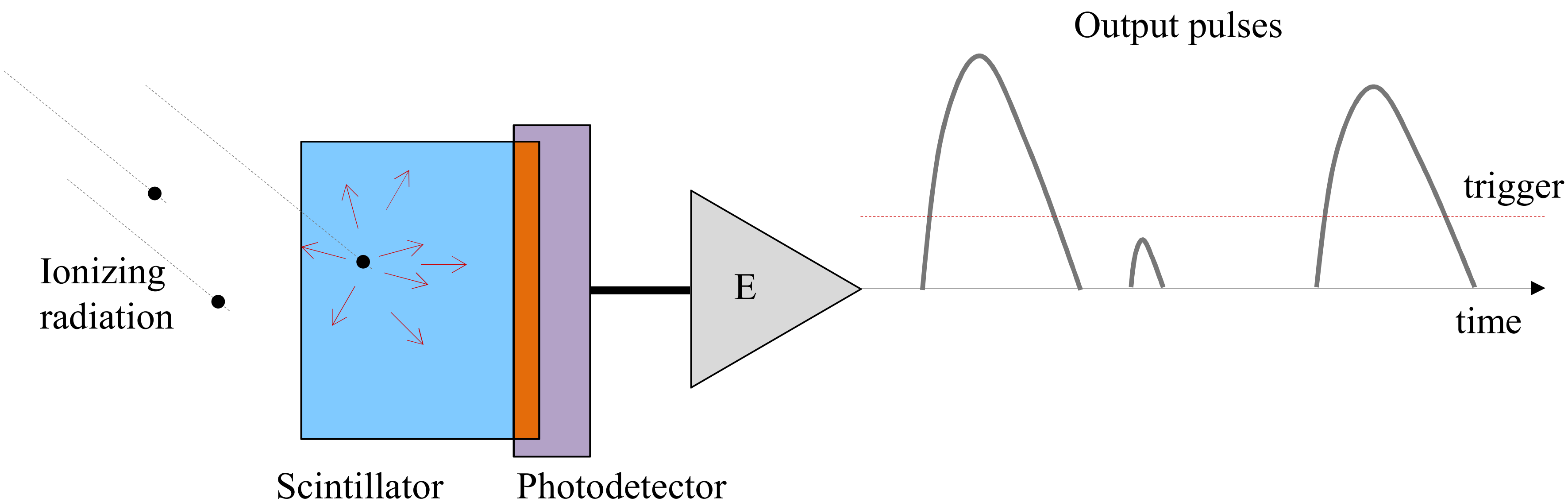
Electrical and optical characteristics

Type no.	Spectral response range λ (nm)	Peak sensitivity wavelength λp (nm)	Photon detection efficiency[*3] PDE λ=λp (%)	Dark count Typ. (kcps)	Dark count Max. (kcps)	Terminal capacitance Ct (pF)	Gain M	Breakdown voltage VBR (V)	Crosstalk probability (%)	Recommended operating voltage[*4] Vop (V)	Temperature coefficient of recommended operating voltage ΔTVop (mV/°C)
S14420-1525MG	350 to 1000	600	30	380	1000	90	0.9×10^6	42 ± 5	1.5	VBR + 5	47
S14420-1550MG			40				3.6×10^6		5		
S14420-3025MG			30	1600	4000	350	0.9×10^6		1.5		
S14420-3050MG			40				3.6×10^6		5		

Radiation monitoring



Radiation monitoring basic concept



Detection of radiation such as α, β, γ, and others. Applications in, for example, environmental monitoring, radiation safety, or security.

Characteristics of received light

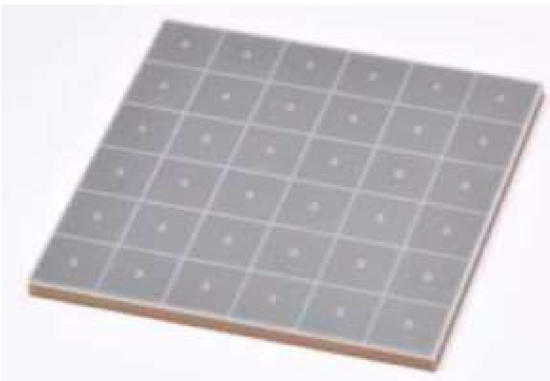
- Pulses
- Number of photons per pulse depends on energy of the ionizing radiation and type of scintillator
- Duration of the pulse depends on the size and type of the scintillator (decay time constants range from ns to µs)
- Frequency of pulses depends on the rate of incoming radiation

Photodetector requirements

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

Product recommendation for radiation detection

S14160 series



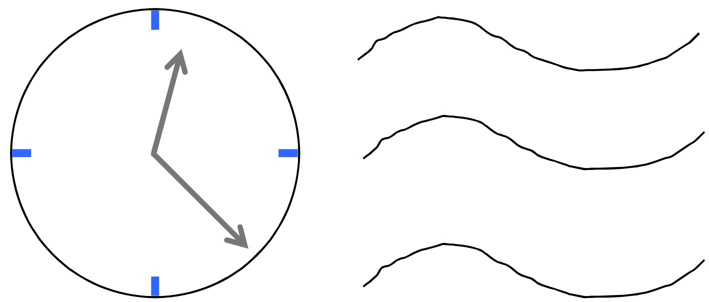
■ **Structure**

Parameters	S14160/S14161 -3050HS(-04,-08)	S14160/S14161 -4050HS(-06)	S14160/S14161 -6050HS(-04)	unit
Effective photosensitive area/channel	3.0 x 3.0	4.0 x 4.0	6.0 x 6.0	mm^2
Pixel pitch	50			μm
Number of pixels / channel	3531	6331	14331	-
Geometrical fill factor	74			%
Package	Chip on board surface mount type			-
Window	Silicone			-
Window refractive index	1.57			-

■ **Electrical and optical characteristics**
(Typ. Ta=25 deg C, Over voltage=2.7V Unless otherwise noted)

Parameters		Symbol	S14160/S14161 -3050HS(-04,-08)	S14160/S14161 -4050HS(-06)	S14160/S14161 -6050HS(-04)	unit
Spectral response range		λ	270 to 900			nm
peak sensitivity wavelength		λp	450			nm
Photon detection efficiency at λp*3		PDE	50			%
Break down Voltage		VBR	Typ. 38			V
Recommended operating voltage *4		Vop	VBR + 2.7			V
Vop variation Between channels(+/-) in one array *5	typ.		0.05			V
	max.		0.1			V
Dark current	typ.		0.6	1.1	2.5	μA
	max.		1.8	3.3	7.5	μA
Crosstalk probability		-	7			%
Terminal capacitance		Ct	500	900	2000	pF
Gain		M	2.5×10^6			-
Temperature coefficient of recommended reverse voltage		ΔTVop	34			mV/℃

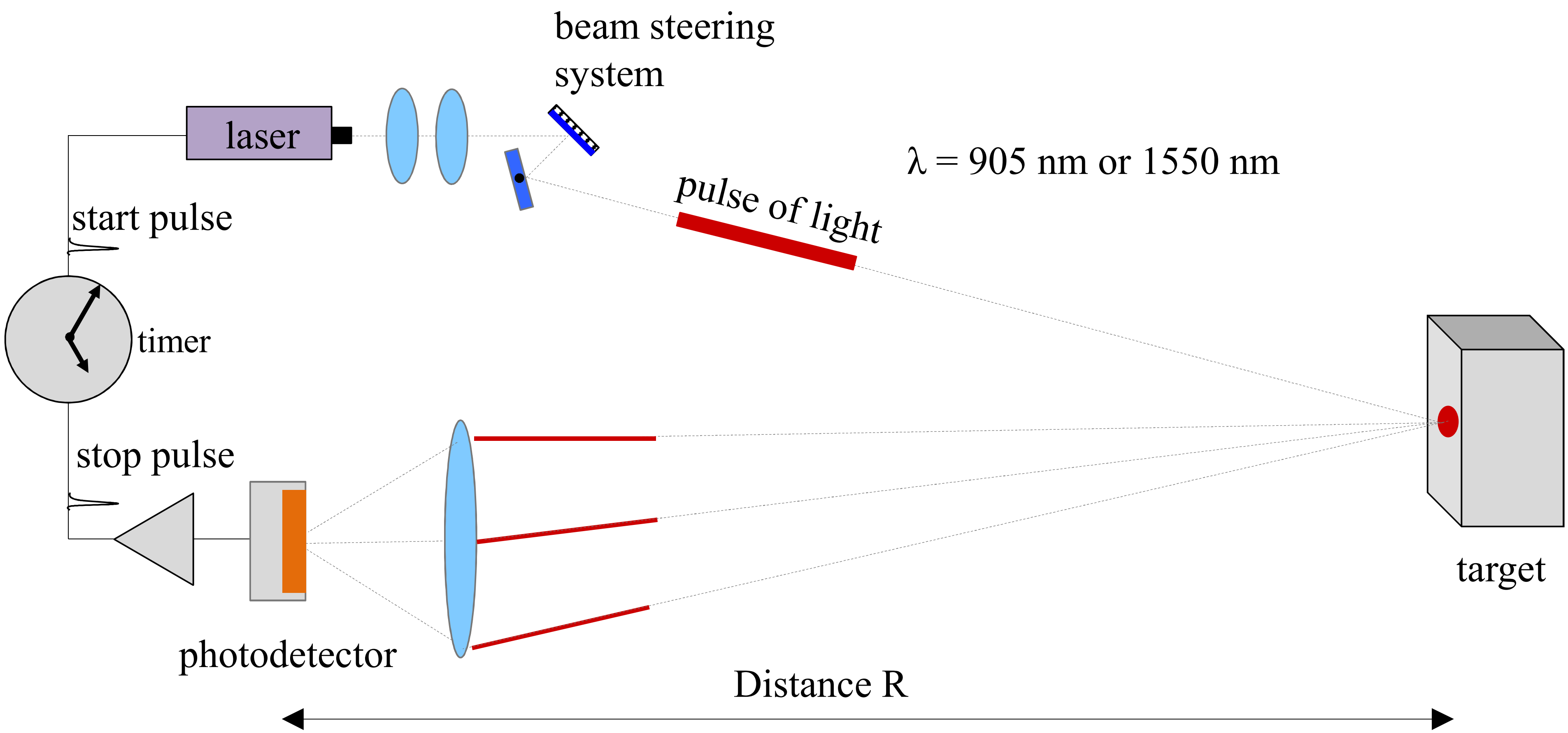
Time-of-flight LiDAR



Time-of-flight (ToF) automotive LiDAR

- There is a great interest in developing self-driving cars.
- Automotive LiDAR is likely needed on a self-driving car to provide high-resolution 3D imaging of its surroundings.
- Photodetection and beam-steering are two most outstanding challenges in the development of an automotive LiDAR.

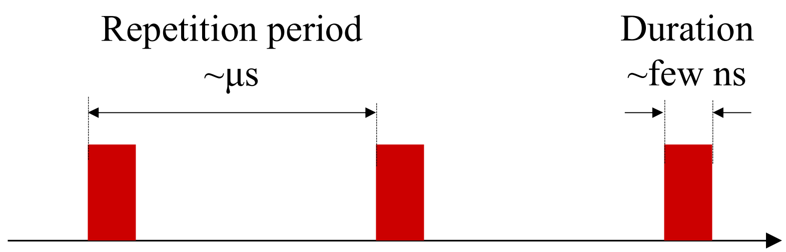
Time-of-flight (ToF) LiDAR



Measure time of flight Δt $R = c\Delta t/2$

Characteristics of the received light

Pulses



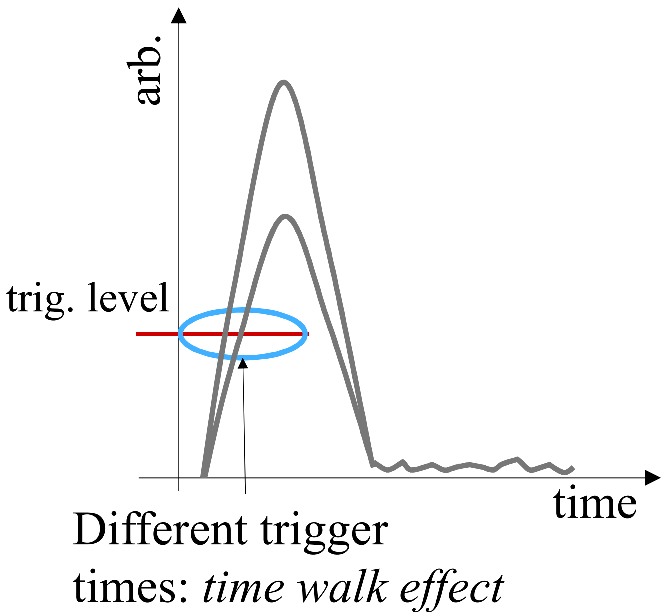
Wavelength – 905 nm or 1550 nm

Peak power – few to 100's of nW

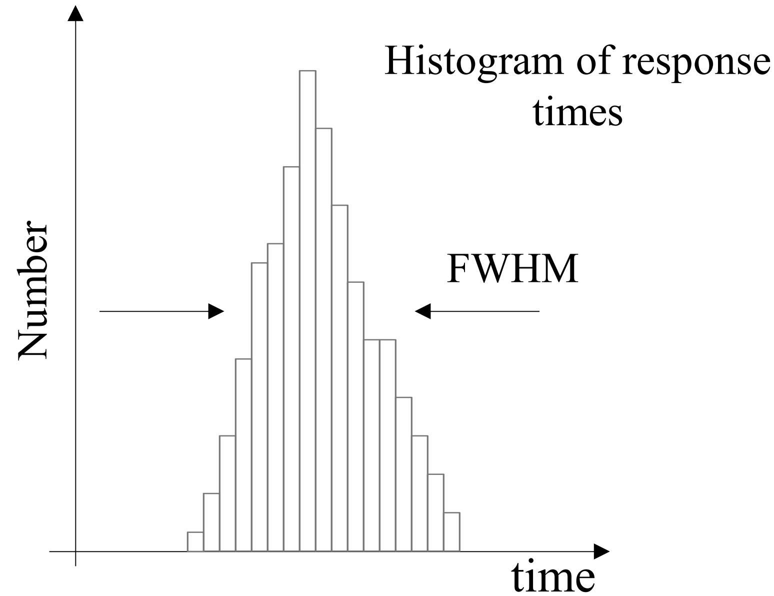
Photodetector requirements

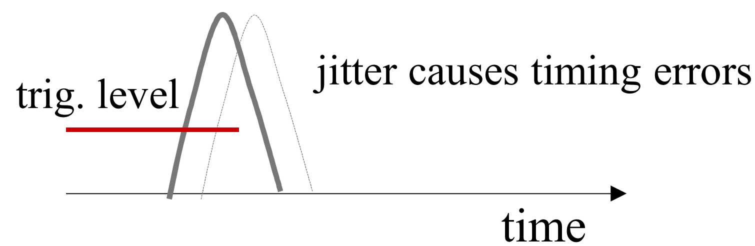
- High quantum efficiency at 905 nm and/or 1550 nm (affects detection range)
- High detector (intrinsic) gain (reduces importance of electronic noise)
- Small excess noise (affects timing error)
- Small time jitter (affects distance error)
- High dynamic range

Importance of excess noise

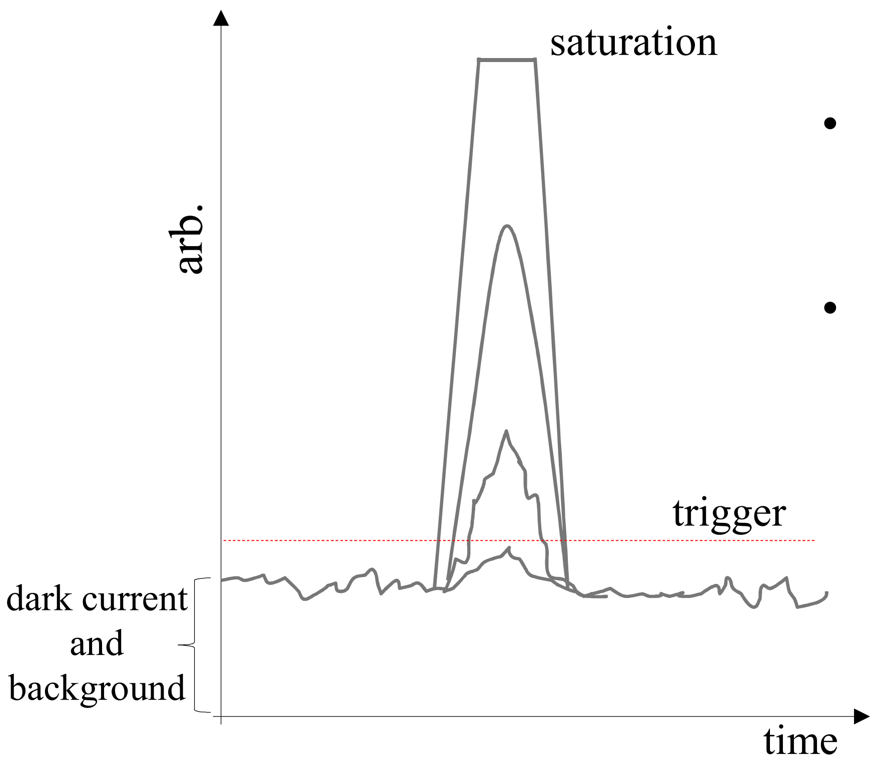


Importance of photodetector jitter



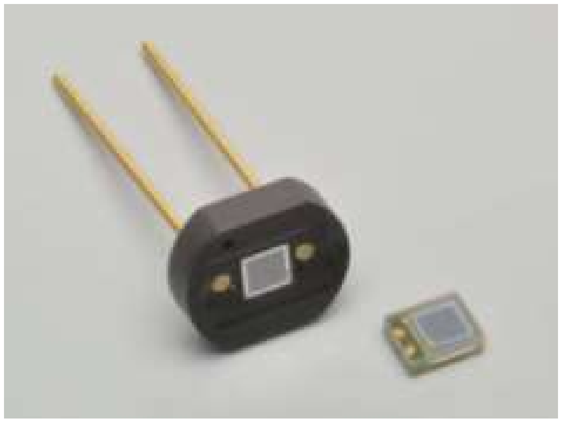


Importance of dynamic range



- If fixed trigger is used, the changing background will affect timing.
- If constant fraction trigger is used, saturation will affect timing.

Product recommendation for ToF LiDAR

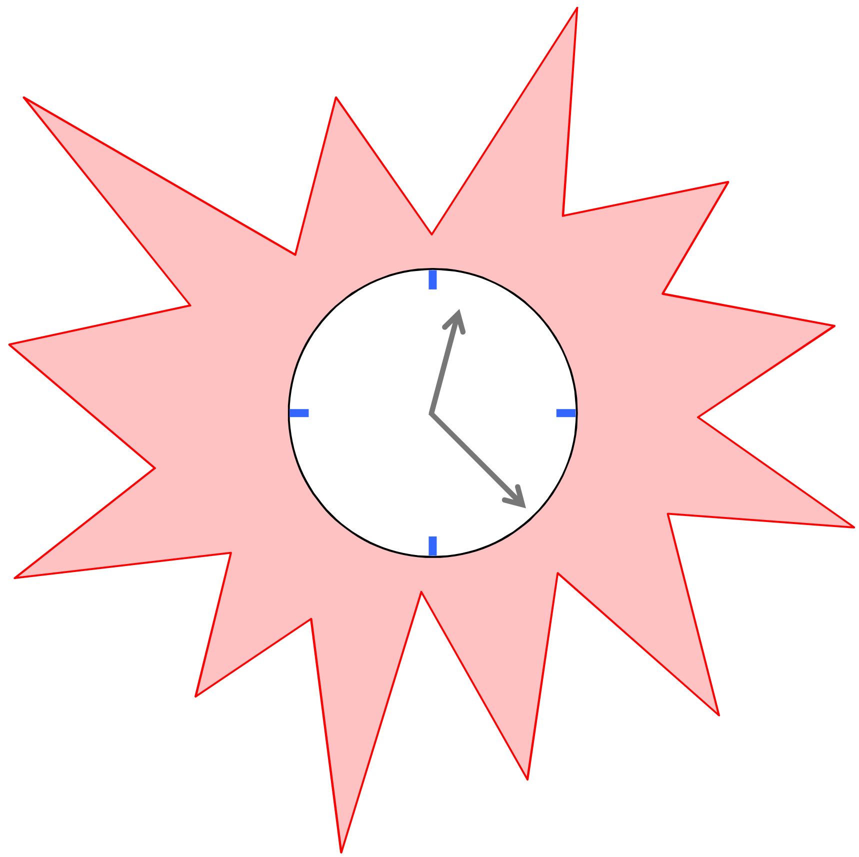


Hamamatsu S13720 SiPM (MPPC) series

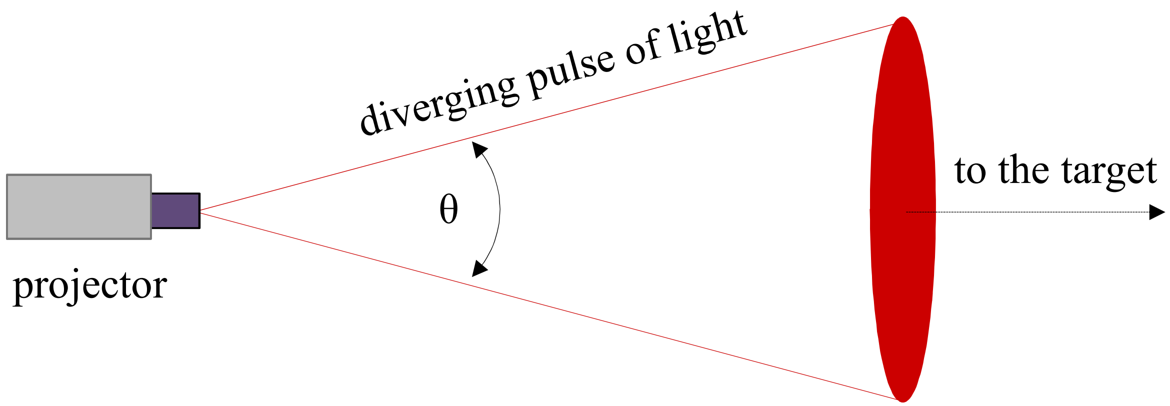
Electrical and optical characteristics (Typ. Ta=25 °C, overvoltage=7 V, unless otherwise noted)

Parameter	Condition	Symbol	Min.	Typ.	Max.	Unit
Spectral response range		λ	-	350 to 1000	-	nm
Peak sensitivity wavelength		λp	-	660	-	nm
Photon detection efficiency*3	λ=λp	PDE	-	22	-	%
	λ=905 nm		-	7	-	
Breakdown voltage		V_{BR}	52	57	62	V
Recommended operating voltage*4		Vop	-	V_{BR} + 7	-	V
Dark count		-	-	500	1500	kcps
Crosstalk probability		-	-	6	-	%
Terminal capacitance		Ct	-	65	-	pF
Gain		M	-	1.1×10^6	-	-
Temperature coefficient of reverse voltage		ΔTVop	-	54	-	mV/°C

Flash LiDAR

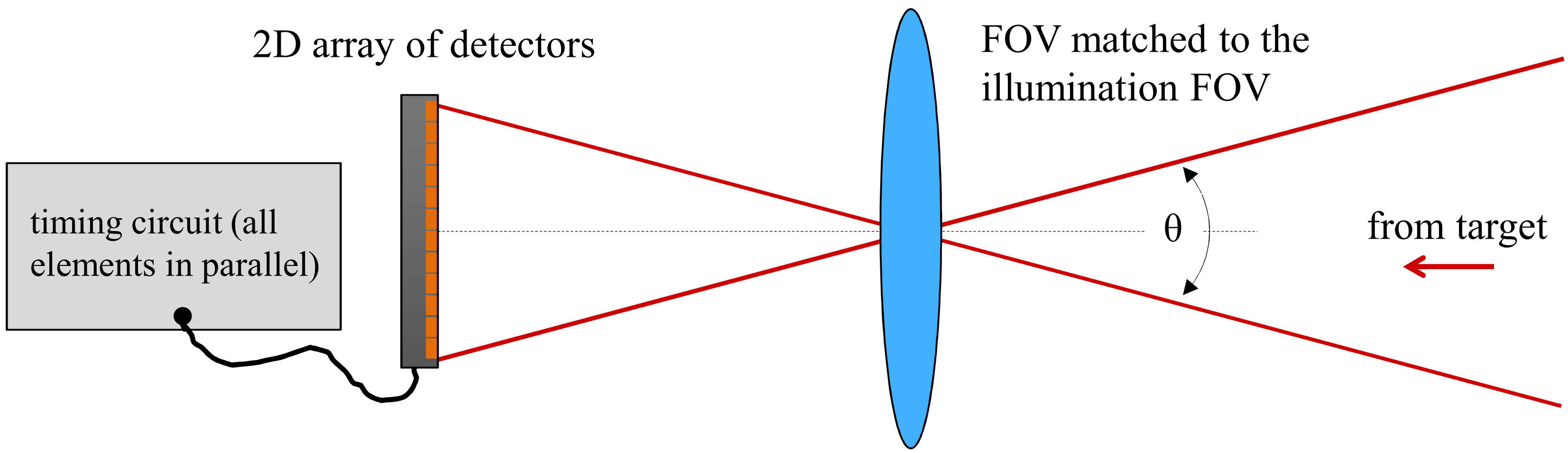


Flash LiDAR



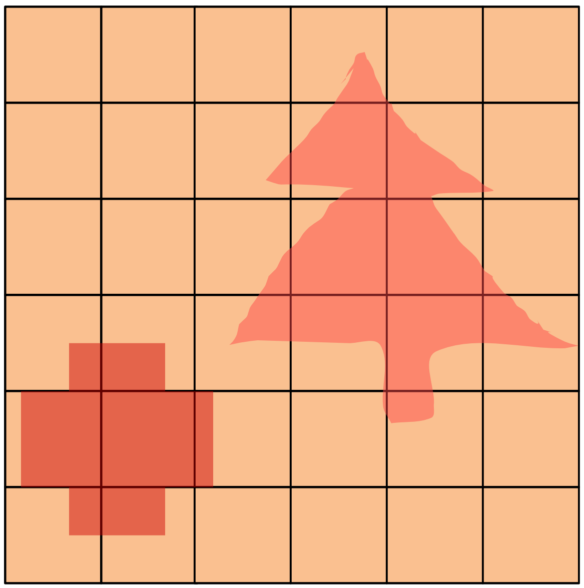
The projector illuminates the scene with multiple divergent pulses of short duration (few ns).

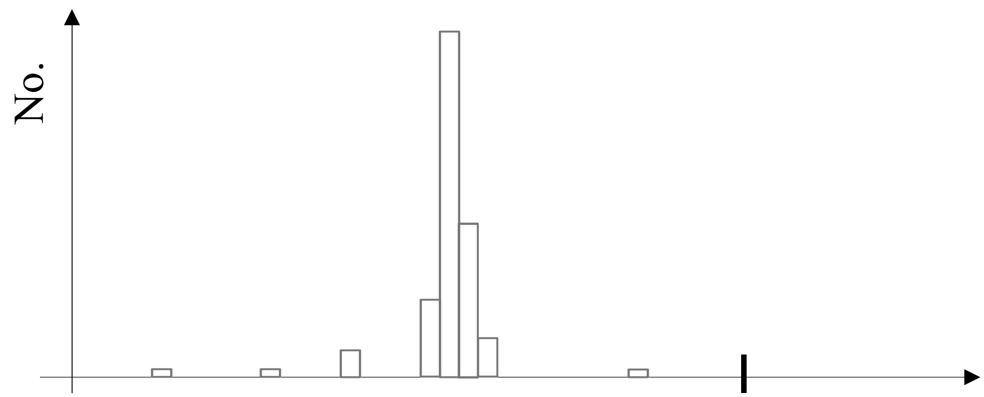
Flash LiDAR



The returned light is imaged on an array of sensors. Each pixel measures distance to the imaged element of the scene.

Flash LiDAR



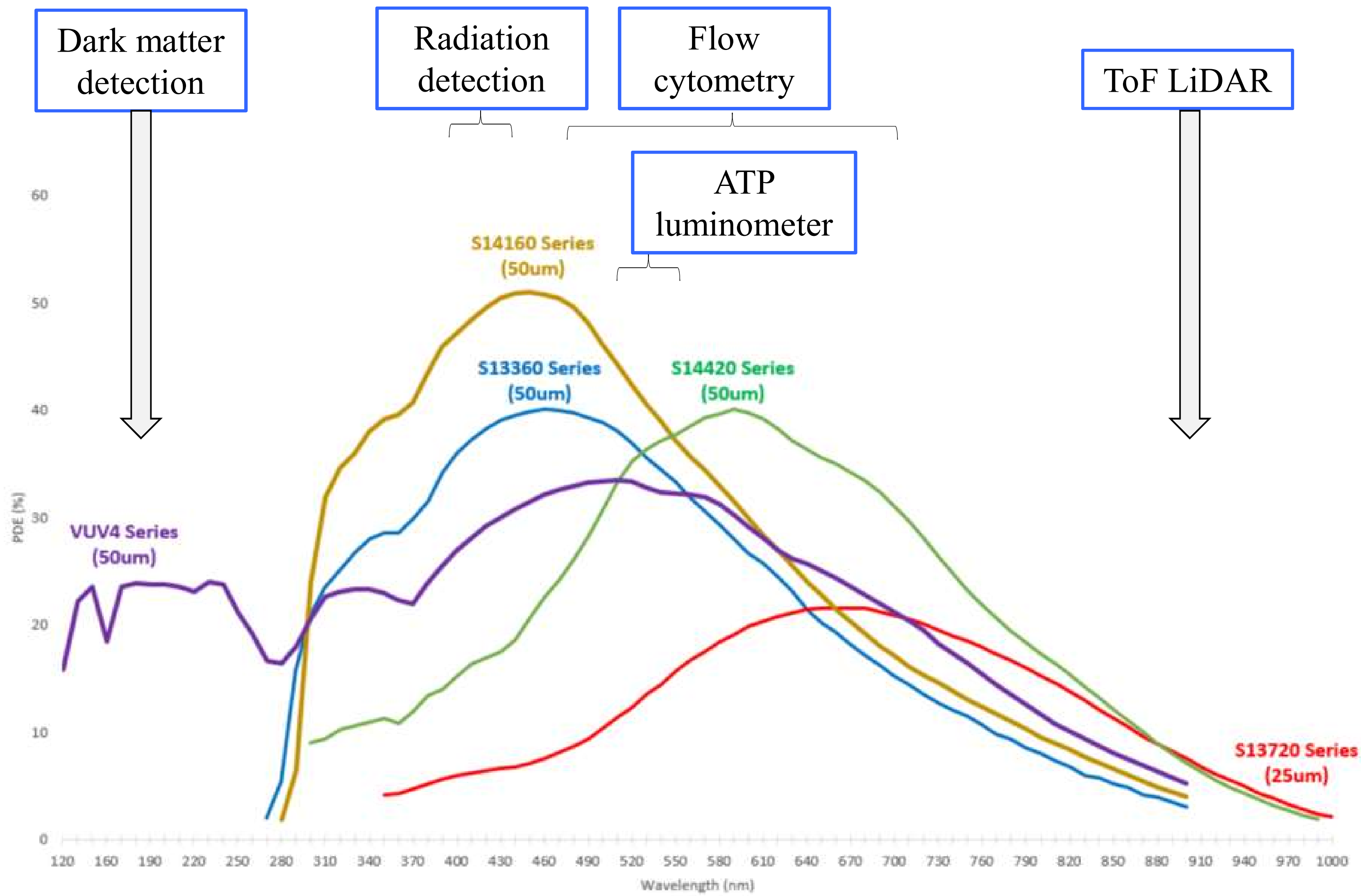


A histogram like the one above must be obtained for each pixel.

SPAD array by Hamamatsu is being developed. More information will be released at the Photonics West 2019 meeting.

HAMAMATSU
PHOTON IS OUR BUSINESS

Summary and conclusions



Summary and conclusions

- SiPMs as a family have a spectral response in the 120 nm – 1000 nm range.
- SiPM has an intrinsic gain comparable to that of a PMT, and on the order of 10^6.
- SiPMs enjoy an ever increasing adoption as the detector of choice in a wide range of applications.
- SPAD arrays open the possibility of single-photon imaging and may resolve engineering challenges in designing automotive LiDAR.

Upcoming Hamamatsu Promotional Activities:

SPIE Photonics West 2019 (San Francisco), Wednesday, February 6, 2019 (8 hours)
Mr. Koei Yamamoto (Director of Solid State and Laser Division from HQ Japan) is presenting two key topics highlighted in red:

- Part 1 (8:10 AM – 10:00 AM) – "Introduction to Photodetectors" (Slawomir Piatek)
- **Part 2 (10:15 AM − 11:45 AM) – "Evolution of Geiger Mode APD Technologies – SiPM & SPAD" (Mr. Koei Yamamoto)**
- Part 3A (1:00 PM – 2:15 PM) – "Spectroscopy and Spectrometer Concepts" (Slawomir Piatek)
- Part 3B (2:15 PM – 3:00 PM) – "Spectroscopy and Spectrometer – What's Next" (John Gilmore)
- Part 4A (3:15 PM – 4:00 PM) – "Automotive LiDAR: Design Concepts and Challenges" (Jake Li)
- **Part 4B (4:00 PM – 5:00 PM) – "Photonics Technology Improvements that Drive the Future of LiDAR Designs" (Mr. Koei Yamamoto)**

Thank you for listening!

For more info, see our past SiPM webinars linked below.

SiPM: Operation, performance, and possible applications
https://www.youtube.com/watch?v=HHS1qYfMDfk&t=430s

Low light detection: PMT vs. SiPM
https://www.youtube.com/watch?v=I5dUB6LT4T4&t=2s

Contact: Slawomir Piatek
piatek@njit.edu