HAMAMATSU
PHOTON IS OUR BUSINESS

MPPC & SPAD
Future of Photon Counting Detectors

Slawomir Piatek

New Jersey Institute of Technology &
Hamamatsu Photonics, Bridgewater, NJ, USA

10.1. 2019

HAMAMATSU
PHOTON IS OUR BUSINESS

Index

- Introduction
- Single-Photon Avalanche Photodiode (SPAD)
- Silicon Photomultiplier (SiPM)
- Concluding remarks

Introduction

Terminology

PD – Photodiode

APD – Avalanche photodiode

SPAD – Single-photon avalanche photodiode

SPPC – Single-pixel photon counter; another name for SPAD

} The same

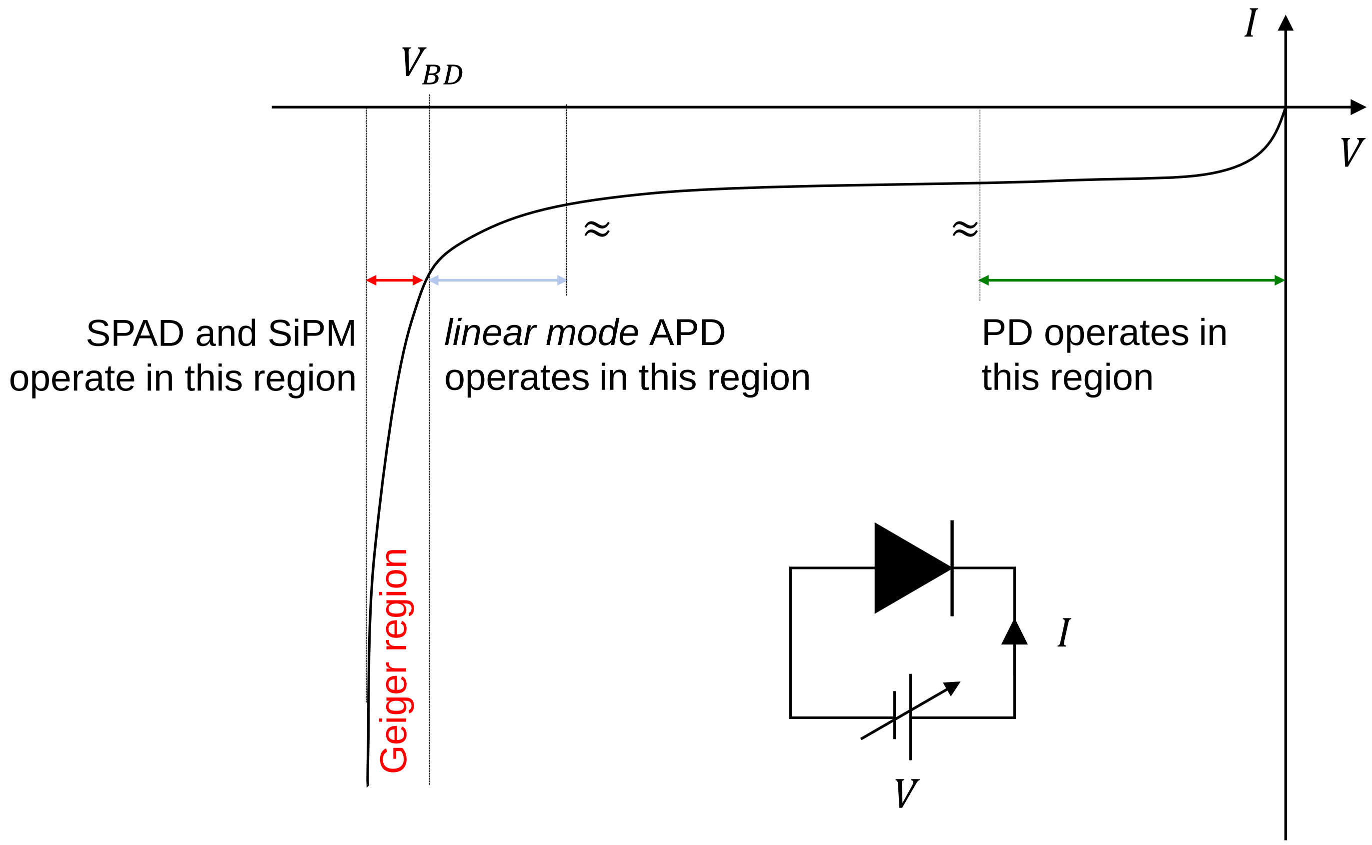
SiPM – Silicon photomultiplier

MPPC – Multi-pixel photon counter; another name for SiPM

} The same

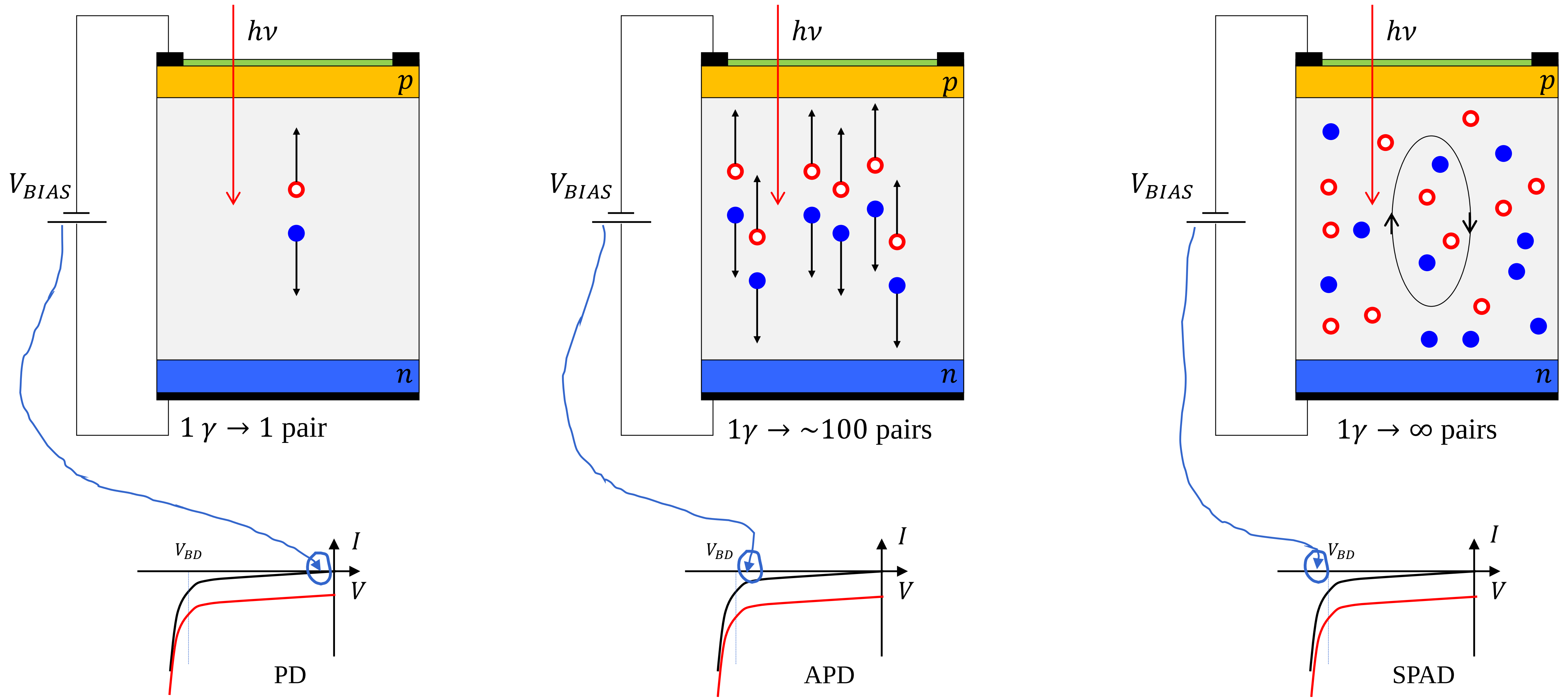
PMT – Photomultiplier tube

Generic PN junction: modes of operation



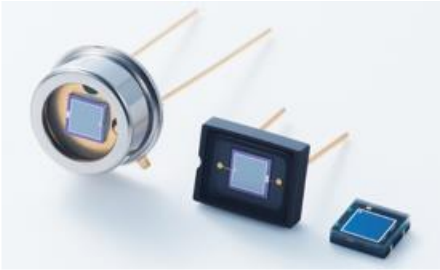
PN junction devices

HAMAMATSU
PHOTON IS OUR BUSINESS

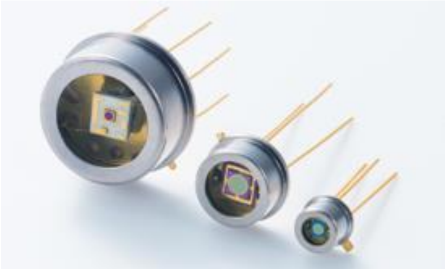


Attributes of a photodiode

1. Detector of choice for sufficiently high input light level
2. Wide spectral coverage (from UV to IR) for a family of photodiodes
3. Inexpensive and easy to use
4. Low intrinsic noise
5. Can be used in arrays and available in modules



Si PDs



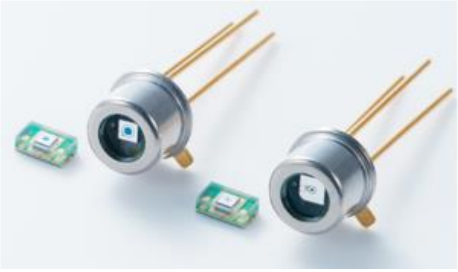
InGaAS PDs

PD arrays with amplifier

PD module

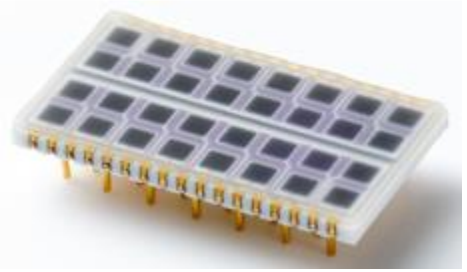
Attributes of an avalanche photodiode (linear mode)

1. Detector of choice for light levels too high for a PMT/SiPM but too low for a photodiode
2. Intrinsic gain up to ~ 100
3. Wide spectral coverage $(200\ nm\ - 1700\ nm)$ for a family of avalanche photodiodes
4. Can be used in arrays
5. Available as part of a module



Si APDs

InGaAs APDs

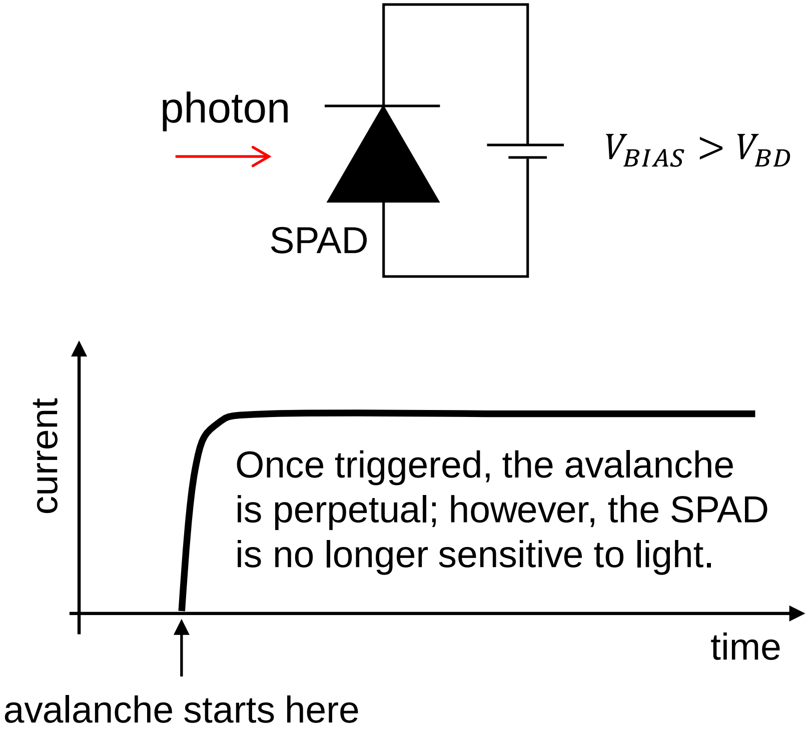


Si APD array

APD module

Single-Photon Avalanche Photodiode (SPAD)

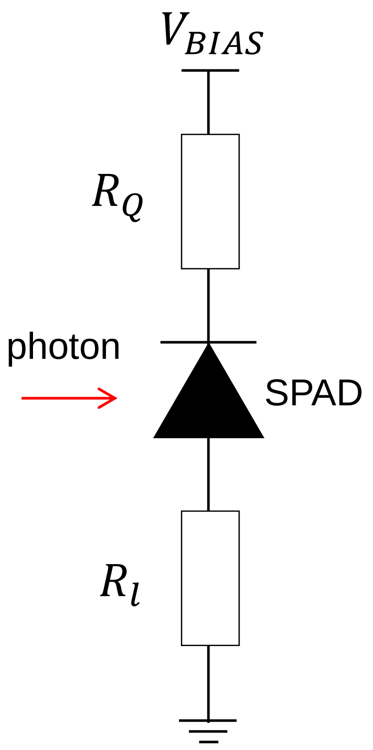
Operation of a SPAD

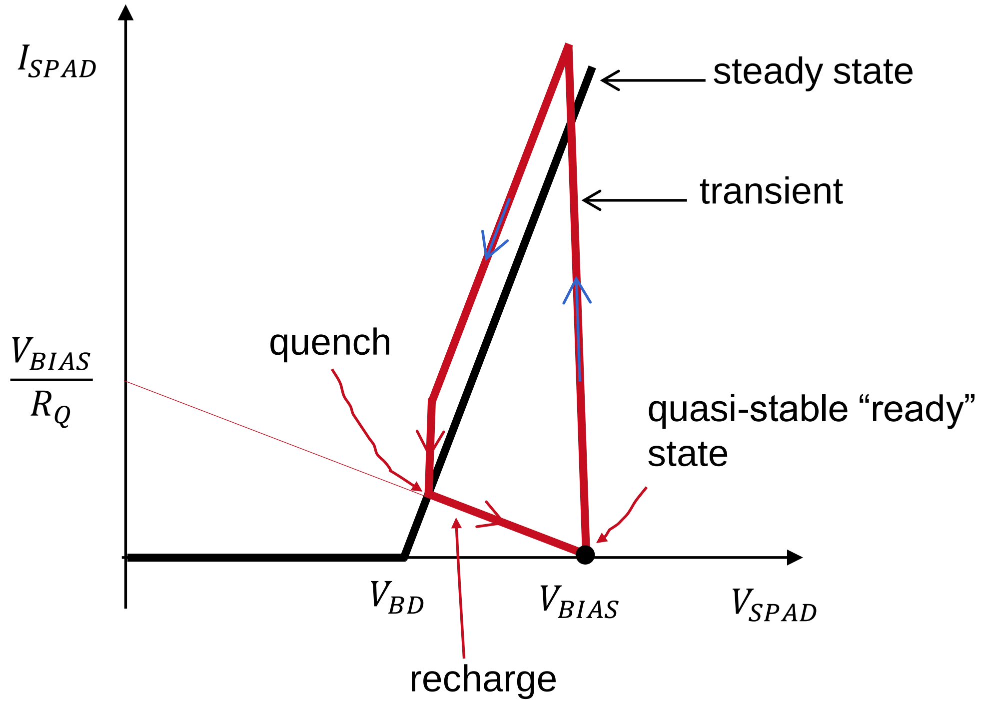


Without quenching, SPAD operates as a light switch.

Operation of a SPAD (passive quenching)

HAMAMATSU
PHOTON IS OUR BUSINESS





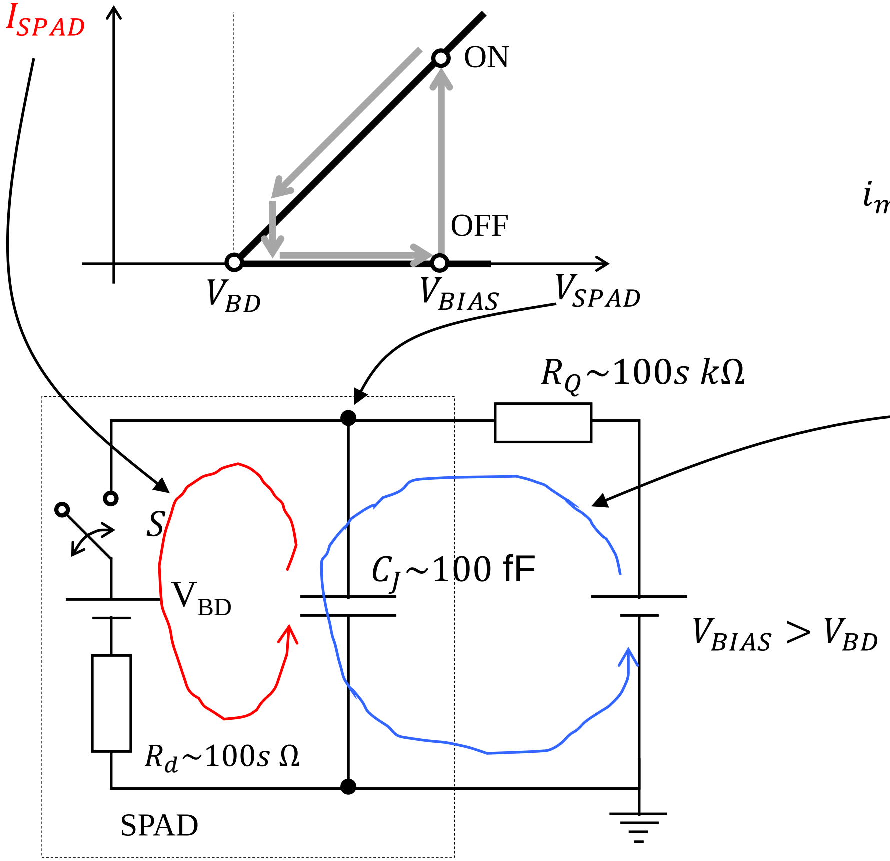
$R_Q \gg R_l$

R_Q must be large enough to ensure quenching.

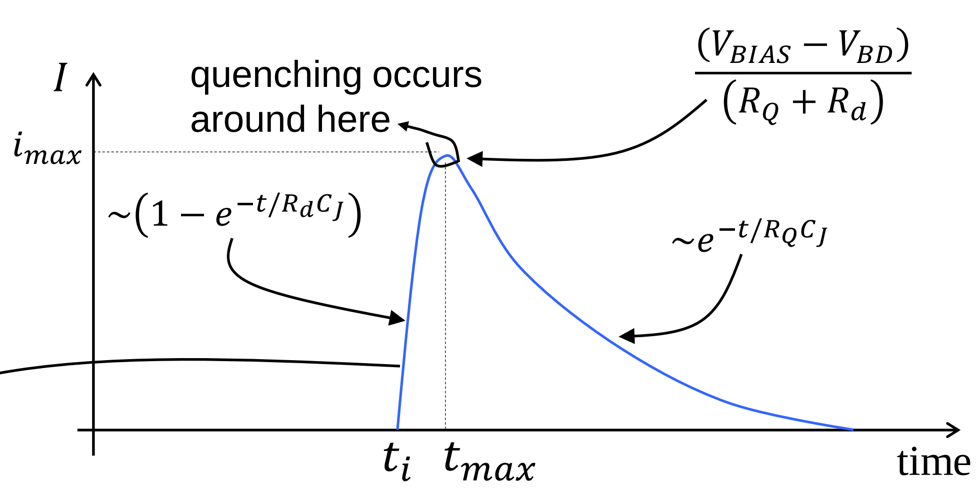
$\Delta V = V_{BIAS} - V_{BD}$ (overvoltage)

Operation of a SPAD (passive quenching)

HAMAMATSU
PHOTON IS OUR BUSINESS



Observed output current pulse



Rise time $\sim R_d C_J$ few ns

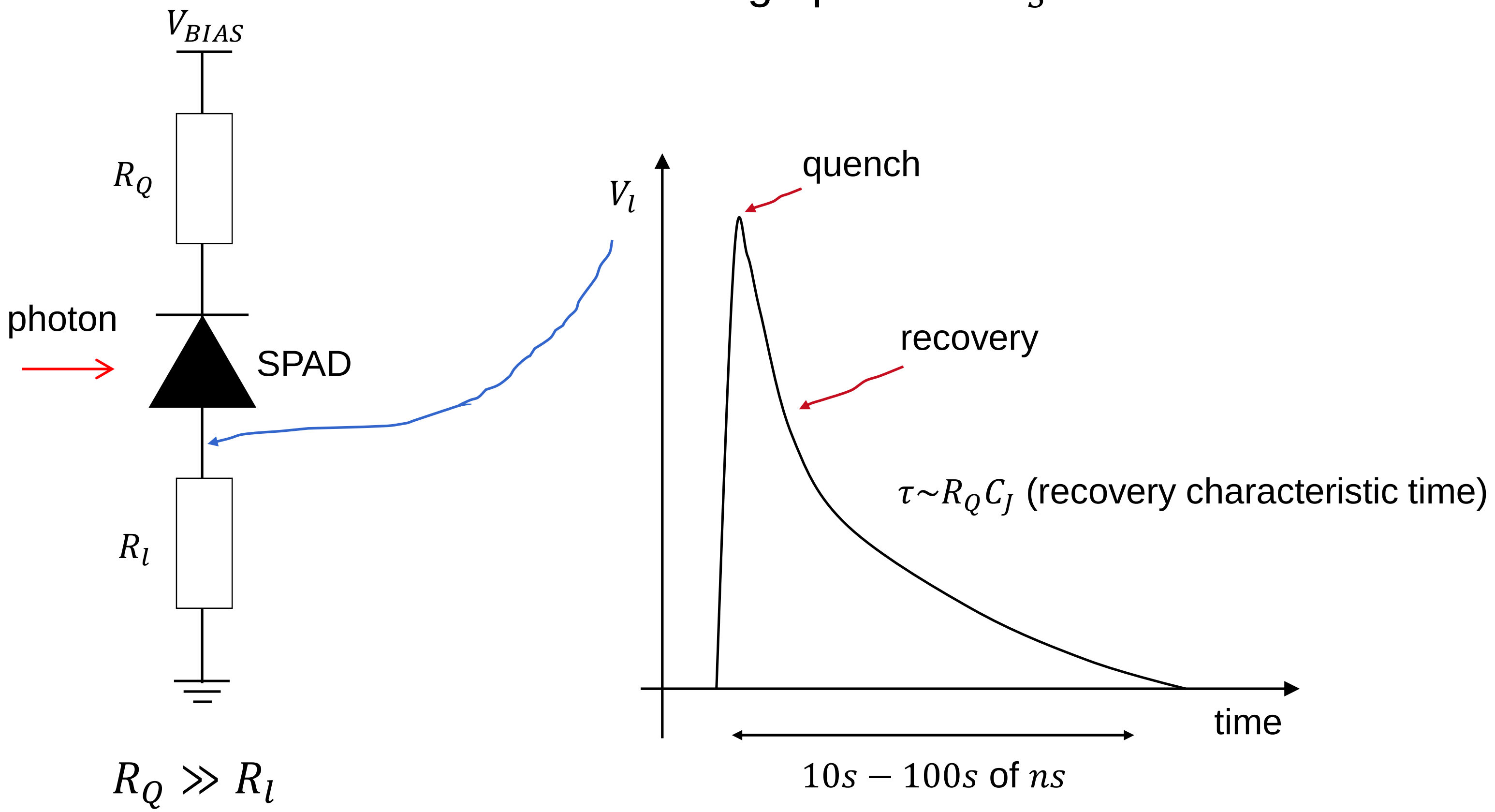
Fall time $\sim R_Q C_J$ tens of ns

$$\mu = \frac{i_{max} R_Q C_J}{e} = \frac{(V_{BIAS} - V_{BD}) R_Q C_J}{e(R_Q + R_d)} \approx \frac{(V_{BIAS} - V_{BD}) C_J}{e} = \boxed{\frac{\Delta V C_J}{e}}$$

(gain)

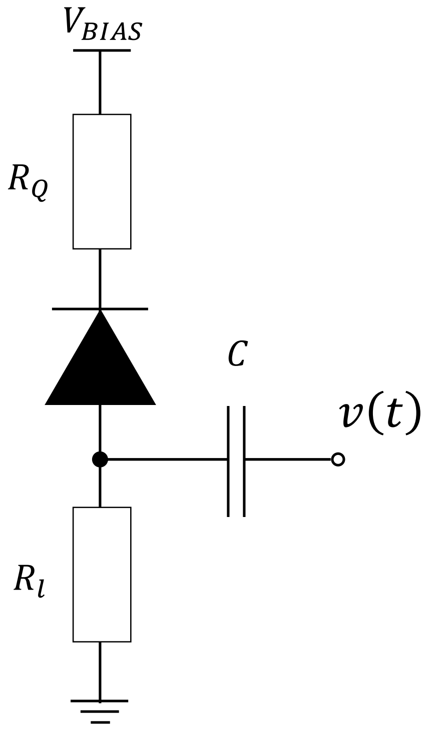
Operation of a SPAD (passive quenching)

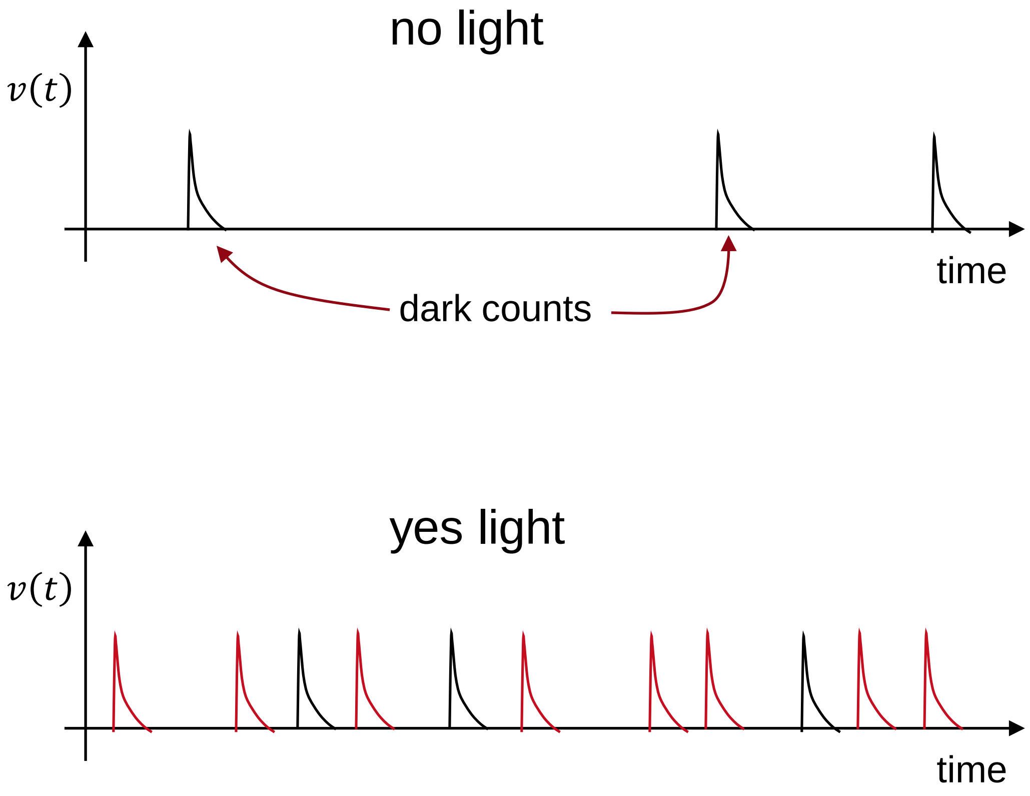
Voltage pulse on R_S due to avalanche



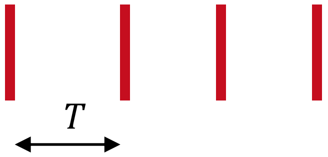
$R_Q \gg R_l$

Photon counting with SPAD

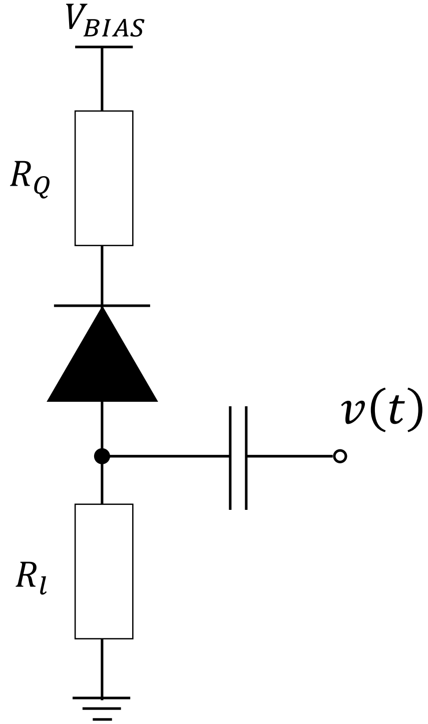


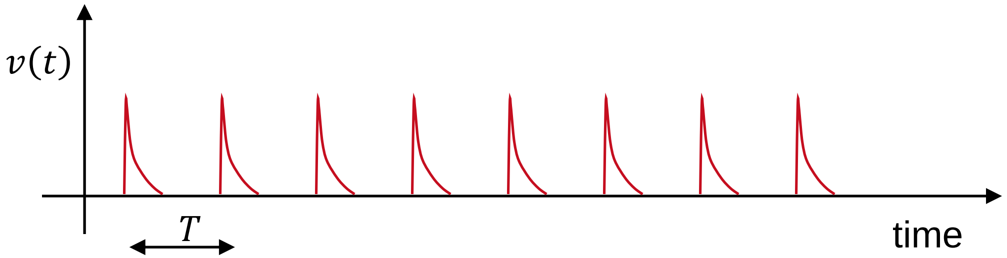


Photon counting with SPAD

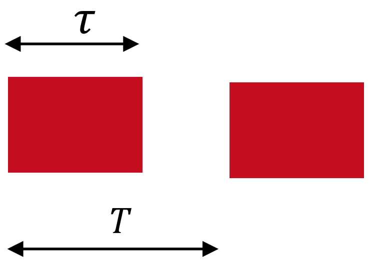


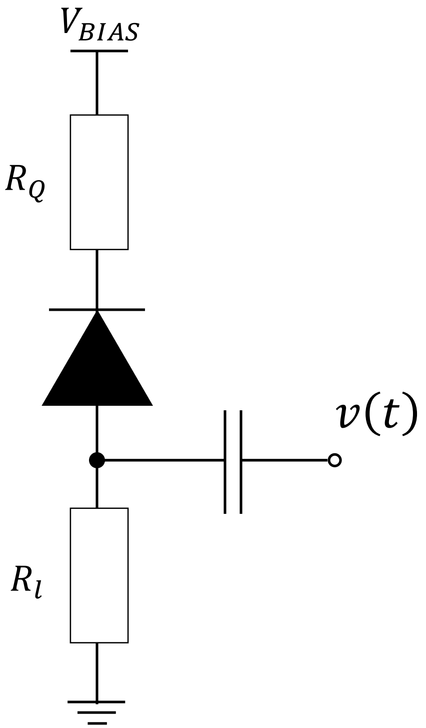
Pulses with a duration much shorter than the recovery time.



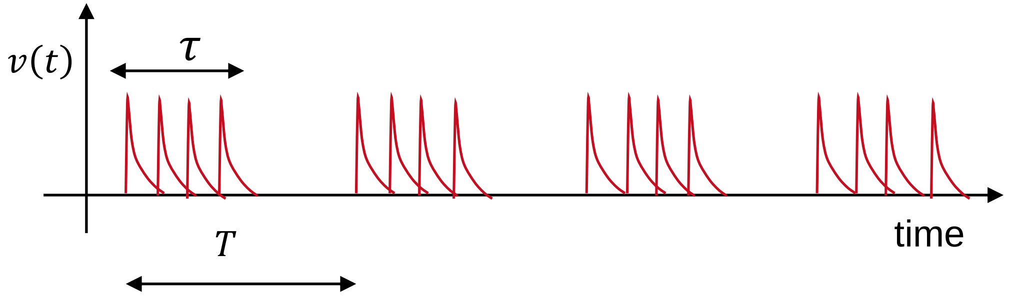


Photon counting with SPAD



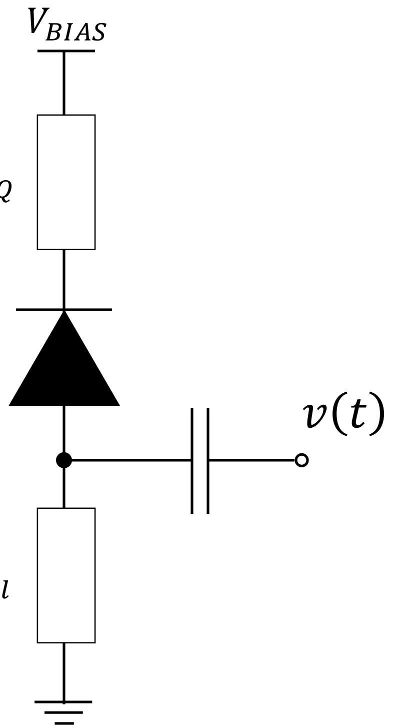


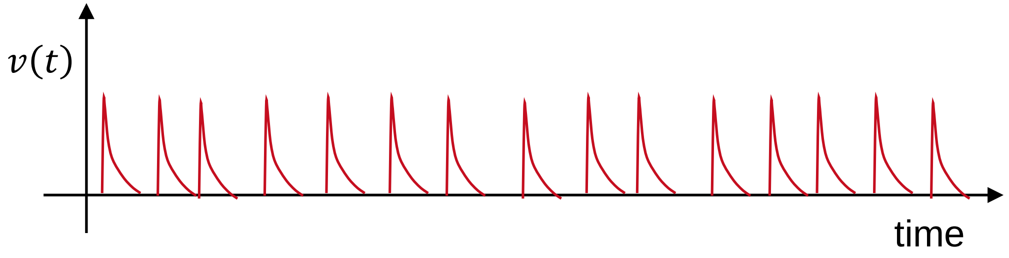
Pulses with a duration longer than the recovery time.



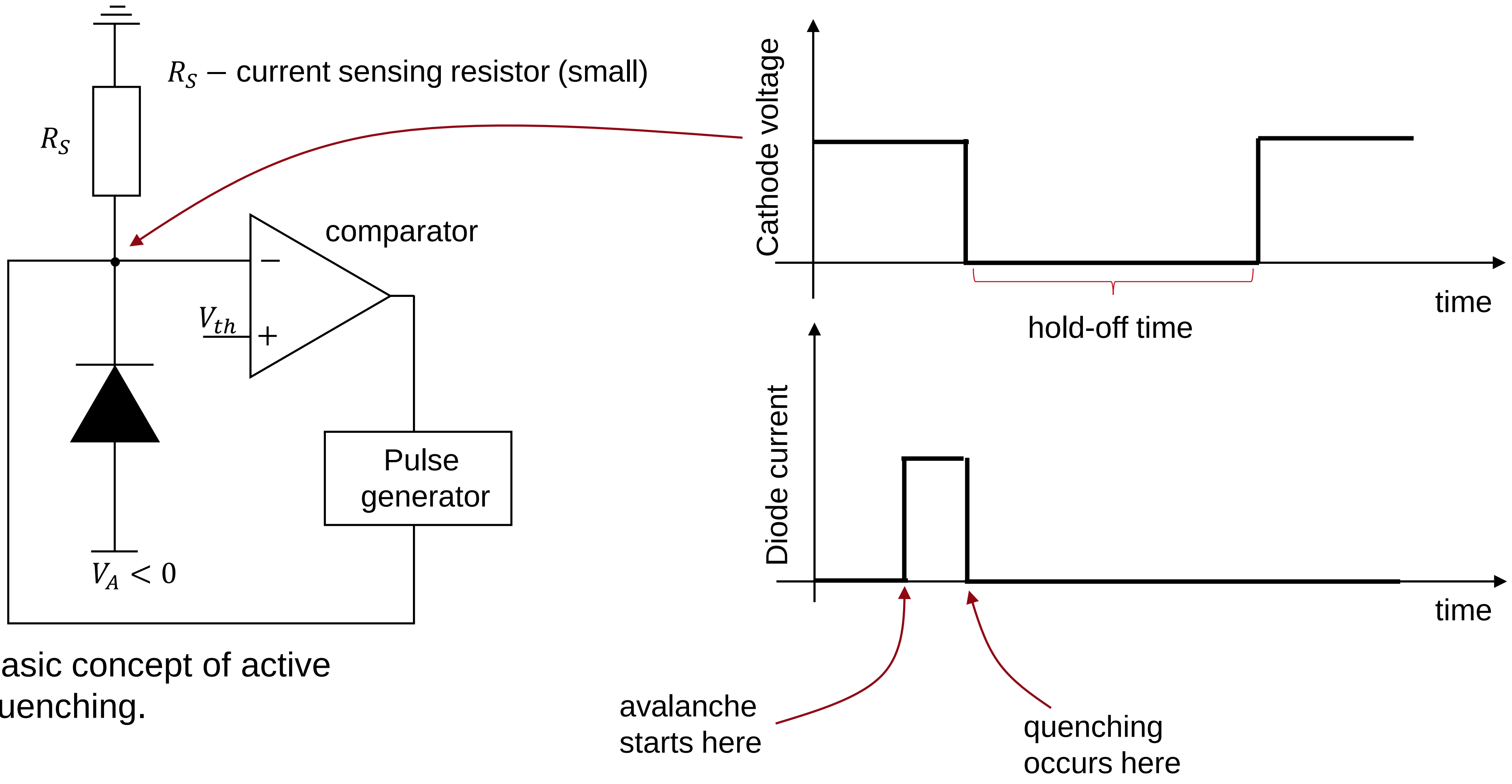
Photon counting with SPAD

DC





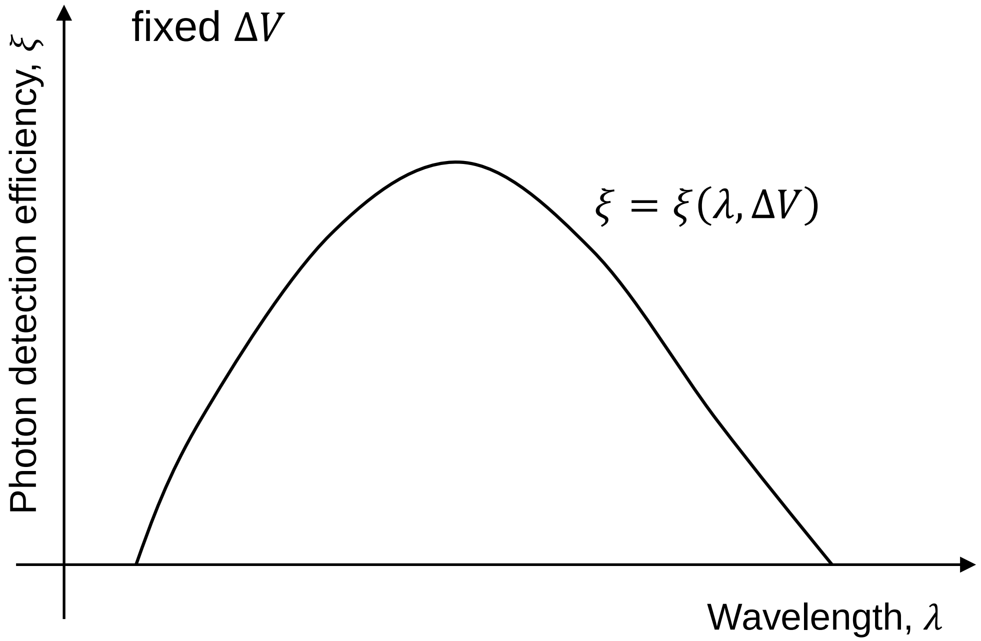
Active quenching



Basic concept of active quenching.

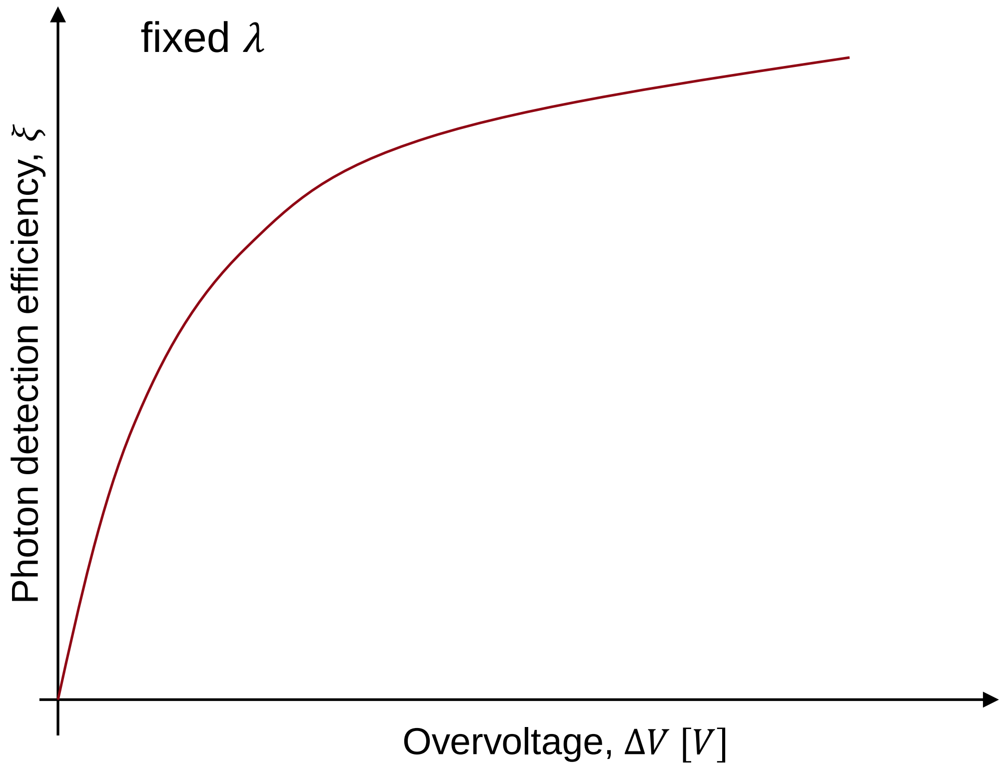
Reference: "Progress in Quenching Circuits for Single Photon Avalanche Diodes," Gallivanoni, A., Rech, I., & Ghioni, M., IEEE Transactions on Nuclear Science, Vol. 57, No. 6, December 2010

Photon Detection Efficiency



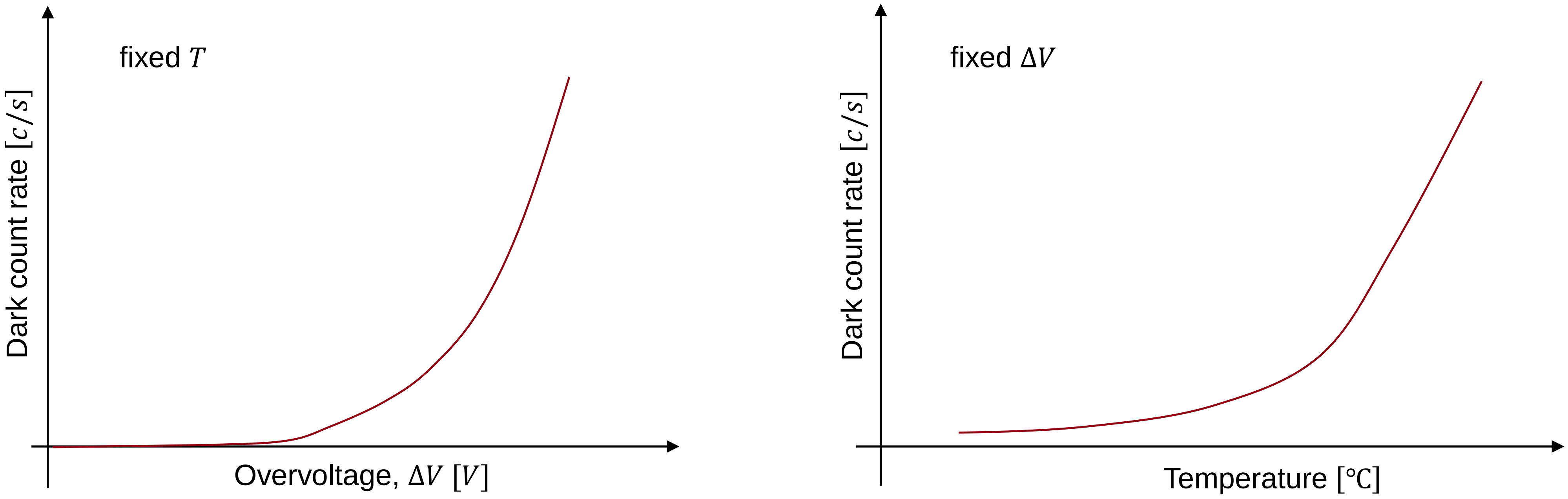
Photon detection efficiency is a probability that the incident photon is detected. It is a function of wavelength and overvoltage.

Photon Detection Efficiency



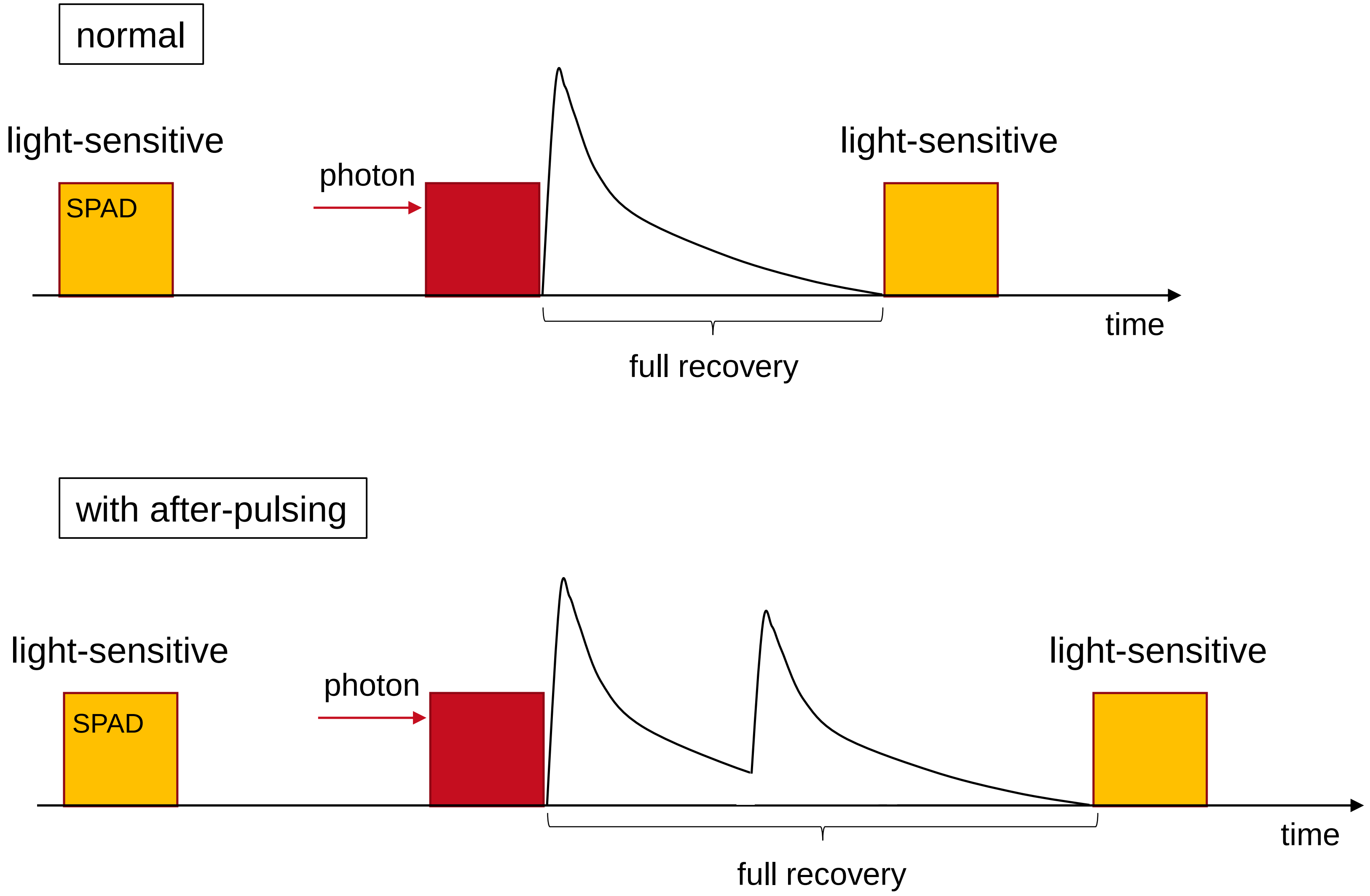
For a given wavelength, photon detection efficiency increases with overvoltage.

Dark count rates



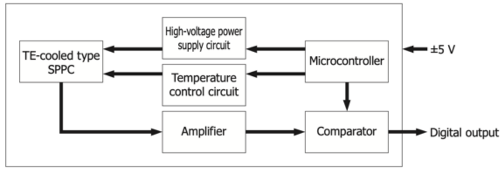
Dark count rate depends on temperature and overvoltage. Typical values at room temperature and recommended overvoltage are $10s - 100s\ c/s$, depending on the device design.

After-pulsing



Product example by Hamamatsu (C14463-050GD)

HAMAMATSU
PHOTON IS OUR BUSINESS

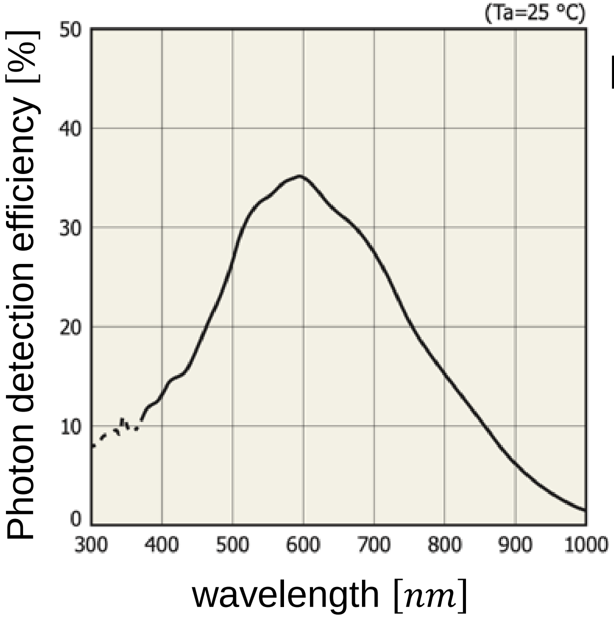


Photon counting module with SPAD (SPPC)

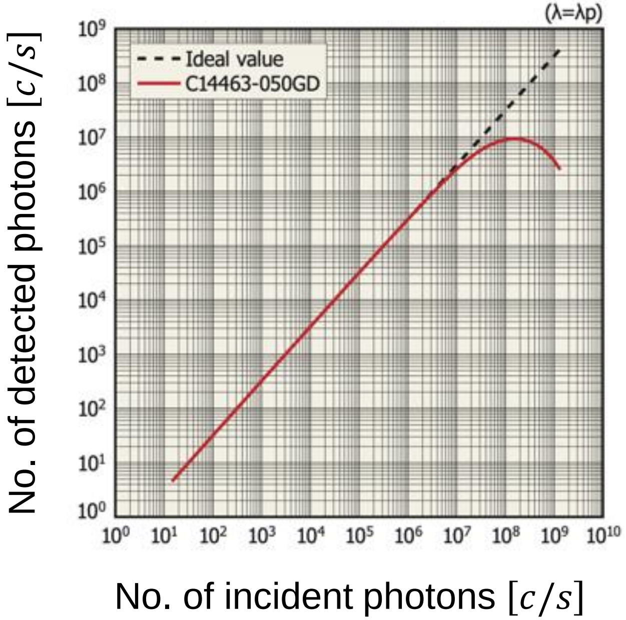
Electrical and optical characteristics (Ta=25 °C, λ=600 nm, Vs=±5 V, unless otherwise noted)

Parameter		Symbol	Condition	Min.	Typ.	Max.	Unit
Spectral response range		λ			370 to 1000		nm
Peak sensitivity wavelength		λp		-	600	-	nm
Fiber connector*3		-			FC type		-
Chip temperature (setting temperature)		Tchip		-	-20	-	°C
Photon detection efficiency		PDE		25	35	-	%
Dark count		CD		-	20	60	cps
Afterpulse probability		-	100 ns to 500 ns	-	0.1	-	%
Comparator output		-			TTL compatible		-
Current consumption	+5 V	Ic		-	+200	+1000	mA
	-5 V			-	-20	-40	

*3: Recommended fiber: GI 50/125 multimode fiber

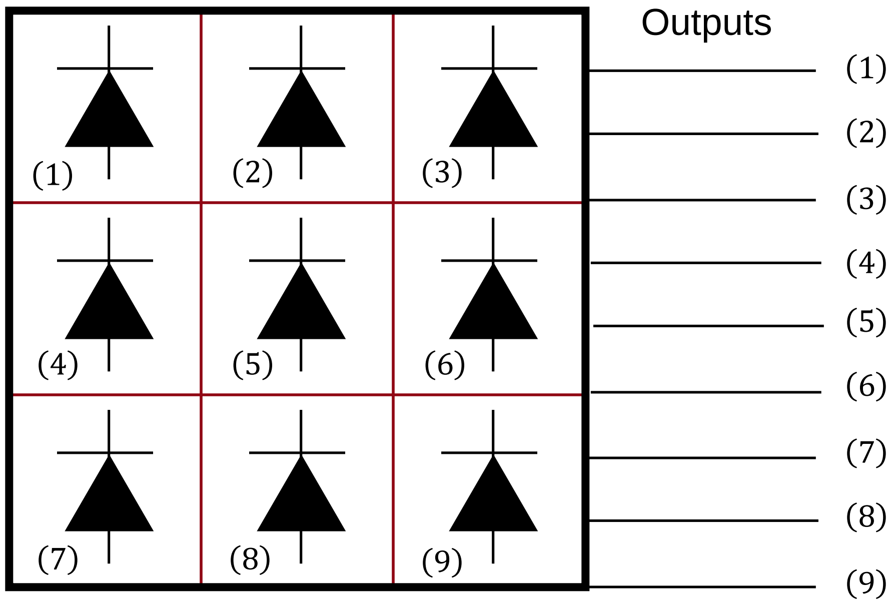


PDE



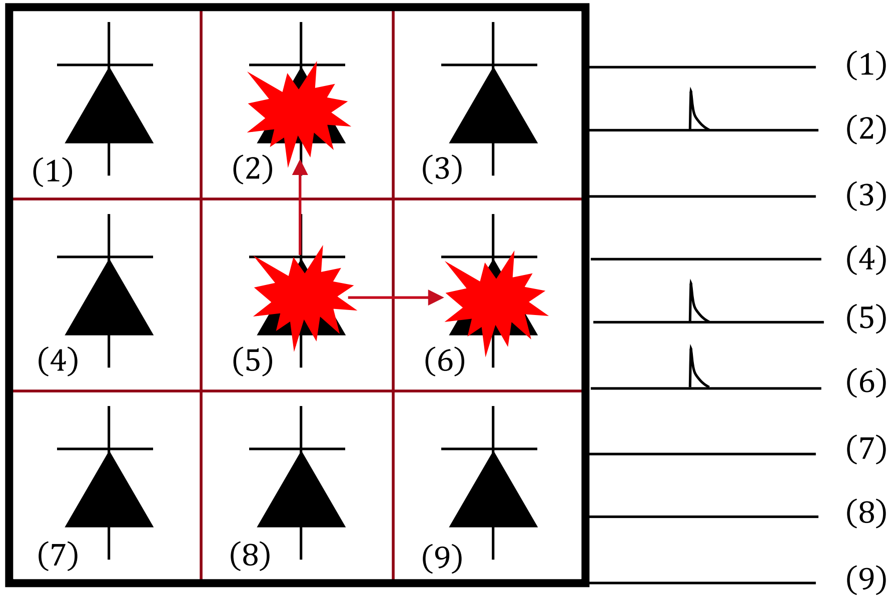
linearity

SPAD Array



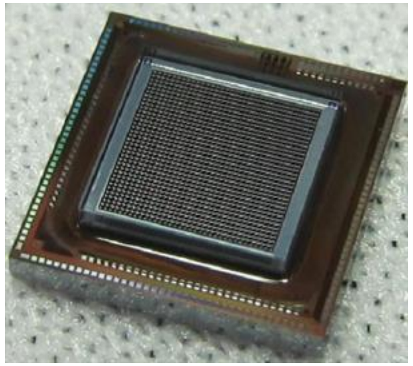
Each element of the array (pixel) has its own quenching circuitry (passive or active).

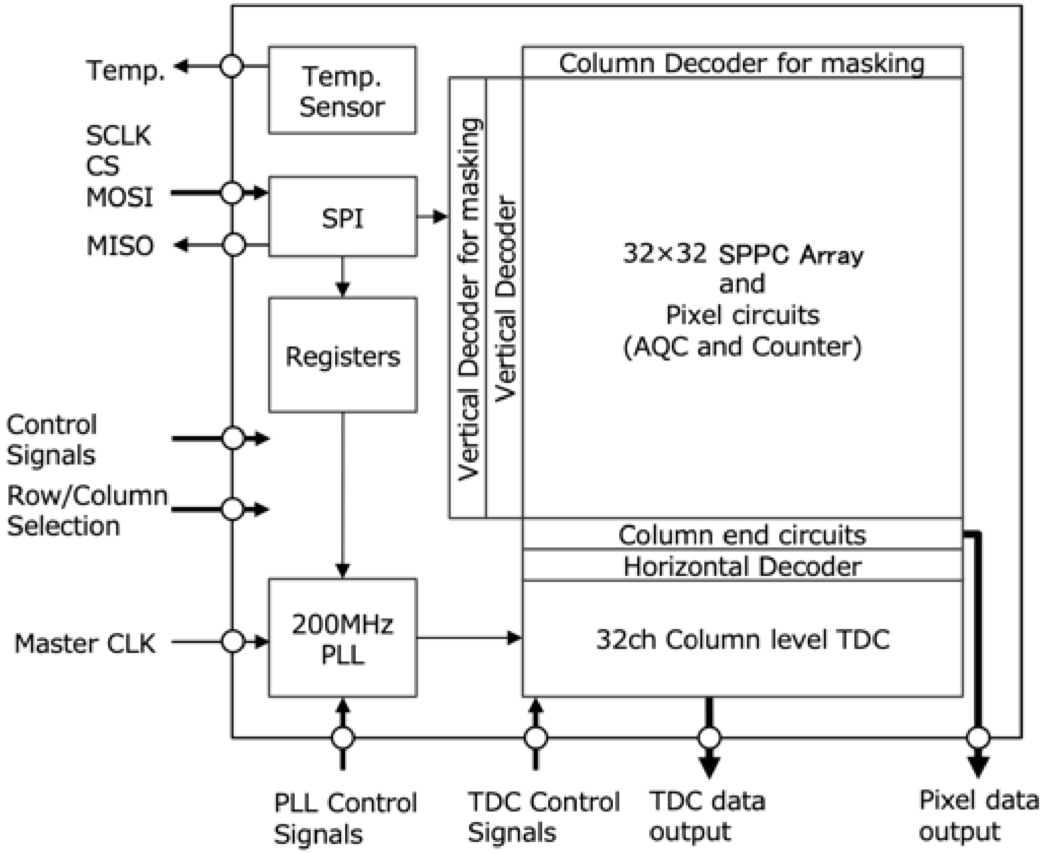
SPAD Array; Crosstalk



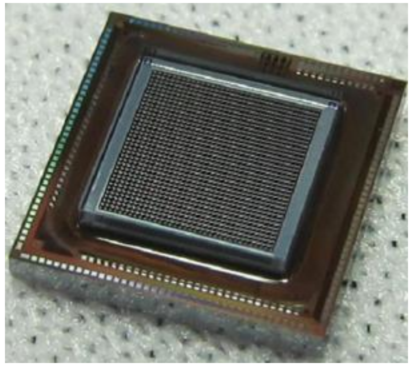
Each element of the array (pixel) has its own quenching circuitry (passive or active).

Product example by Hamamatsu (S15008-100NT-01)





Product example by Hamamatsu (S15008-100NT-01)



・SPPC Array Specification

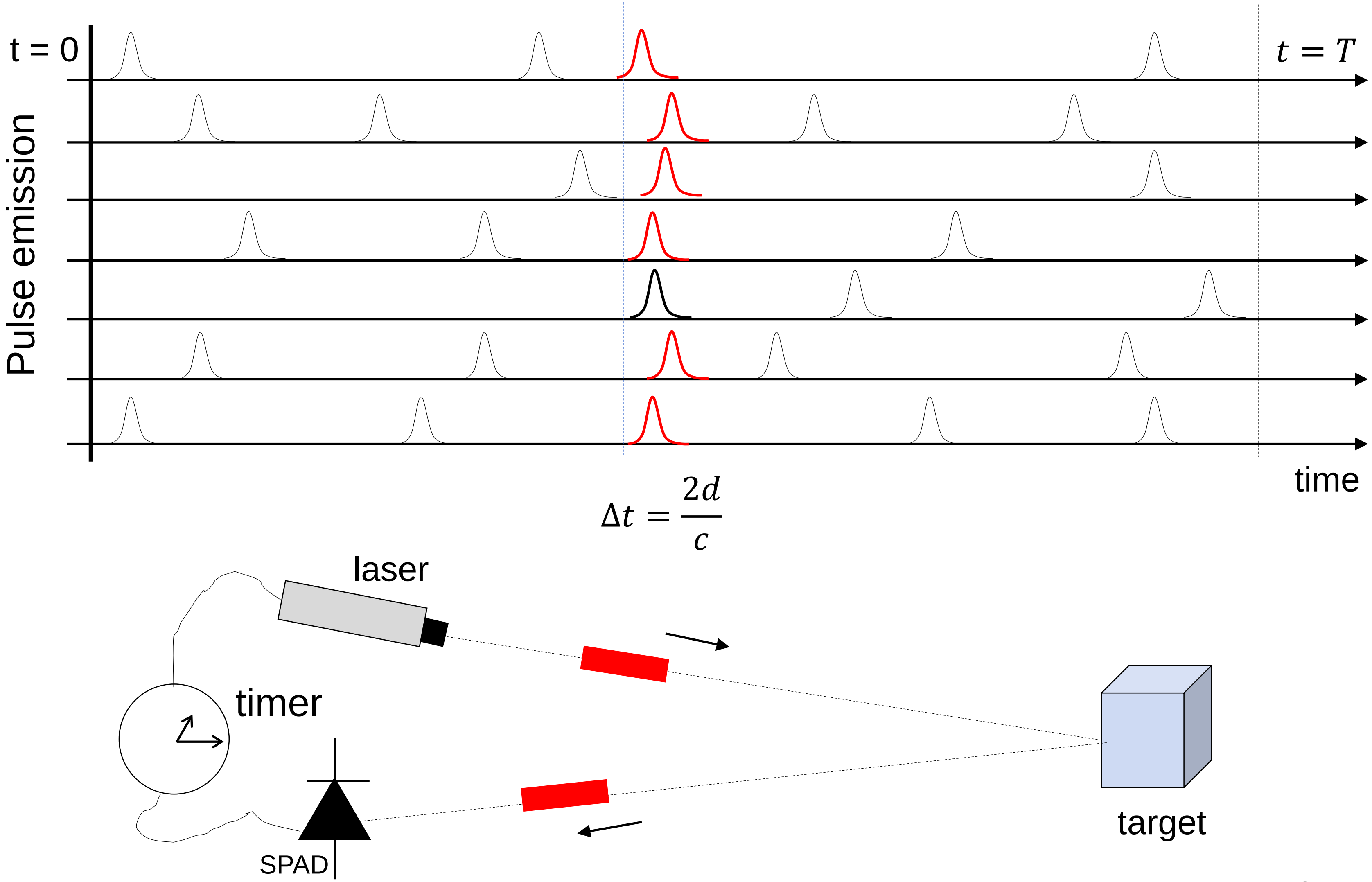
Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit
Pixel pitch			-	100	-	μm
Number of pixels			-	32×32	-	Ch
Diameter and shapes		Octagonal	-	75×75	-	μm
Geometrical fill-factor	FF		-	61	-	%
Peak sensitive wavelength	λ_P		450	500	550	nm
Spectral response region	λ	25℃	380		900	nm
Breakdown voltage	V_{BR}	25℃	50	52	54	V
Temperature coefficient of V_{BR}	ΔT_{VBR}	-20 ~ +30℃		56		mV/℃
Gain	M			1×10^6		-
Photon detection efficiency	PDE	λ=470 nm		30		%
		λ=525 nm		30		%
		λ=630 nm		20		%
Dark count rate	DCR	35℃, V_e=2.0V		20k		Hz
Cross talk probability	CT	35℃, V_e=2.0V		75		%
Afterpulse probability	AP	50 ns hold-off		3		%

Comments on SPAD arrays

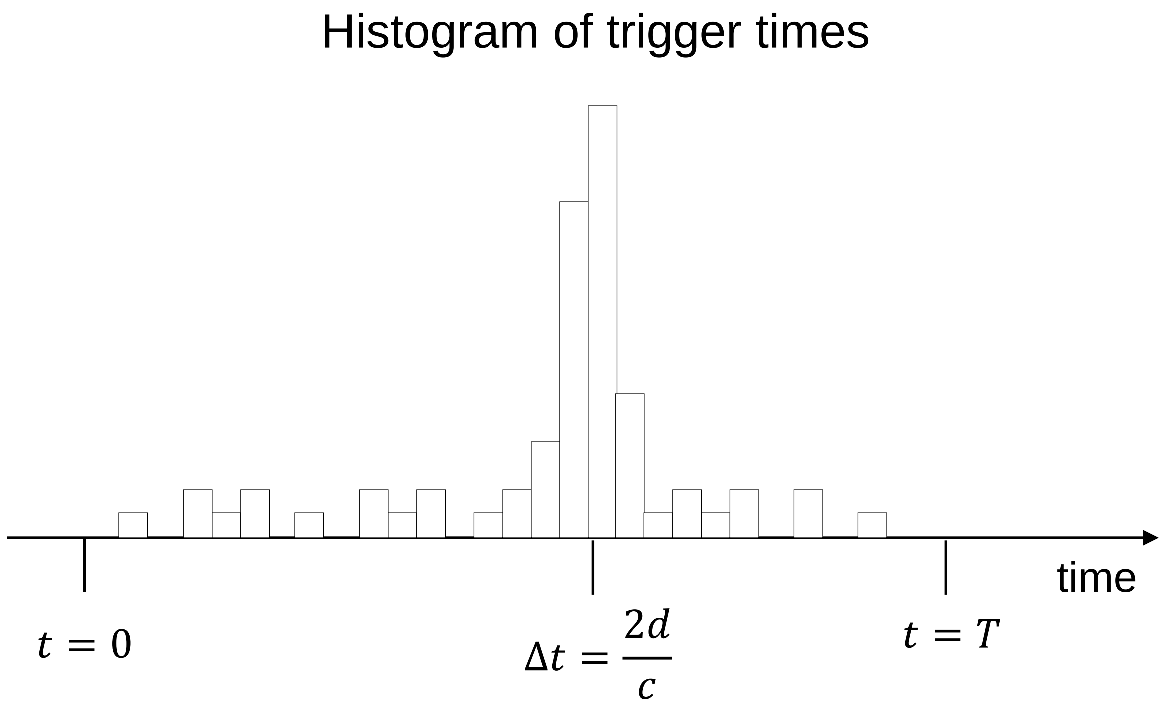
1. The array can be customized to specific user’s needs.
2. Hamamatsu is working on improving crosstalk.
3. Hamamatsu is working on higher resolution array (smaller pixels).
4. Hamamatsu is working on IR version of the array.
5. Hamamatsu will work with users on developing customized ASICs
6. Demos are available for evaluation.

Importance of ASIC (example)

Measuring distance with a SPAD



Importance of ASIC (example)



1. Multiple pulse illumination provides distance information to the target. The information comes from a histogram of trigger times.
2. An ASIC producing such histogram (per pixel) is part of the sensor.

Silicon Photomultiplier (SiPM)

Naming conventions

SiPM – Silicon Photomultiplier

MPPC – Multi-Pixel Photon Counter

} Most-commonly-used names

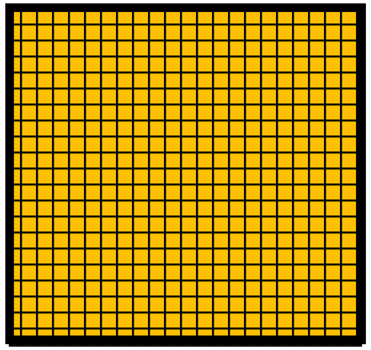
SSPM – Solid-State Photomultiplier

PMAD – Multi-Pixel Avalanche Photodiode

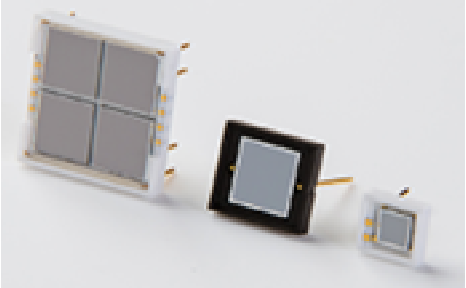
G-APD – Geiger Mode Avalanche Photodiode

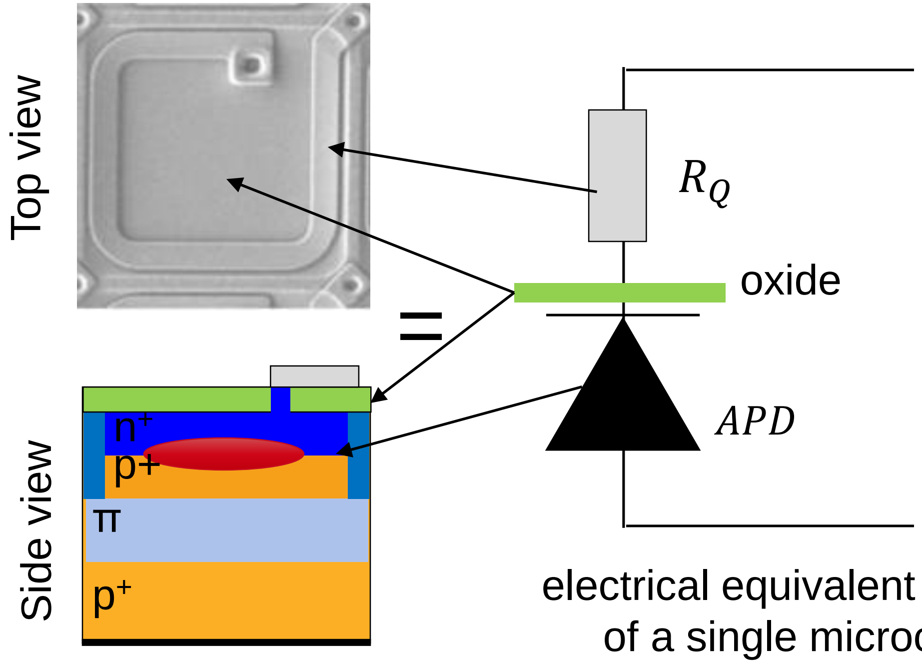
MPGM APDs – Multi-Pixel Geiger-Mode Avalanche Photodiodes

Structure



SiPM is an array of microcells



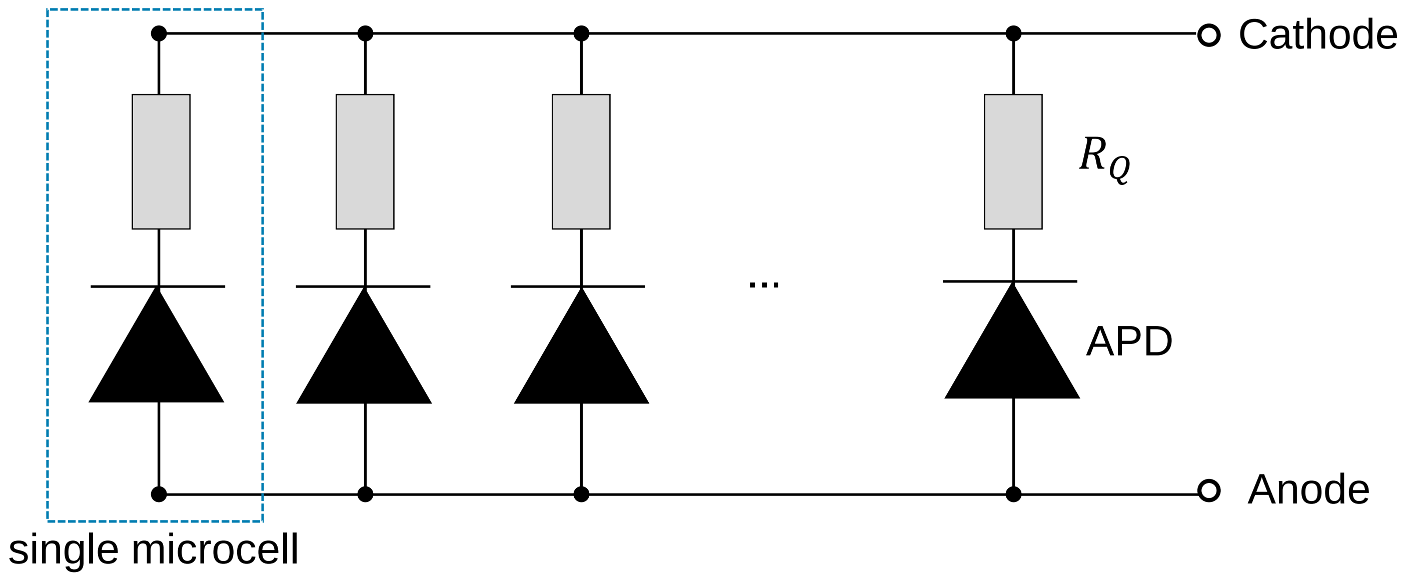


Single microcell

electrical equivalent circuit
of a single microcell

Also known as multi-pixel photon counter (MPPC)

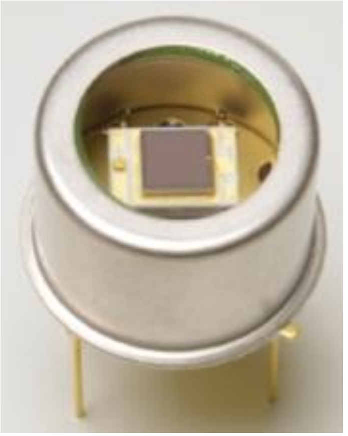
Structure



All of the microcells are connected in parallel.

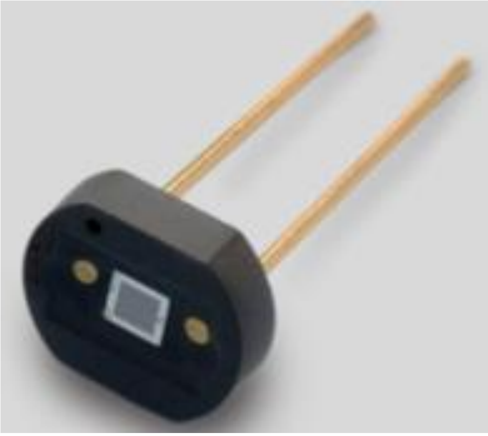
Example of models

S13360-3050DG



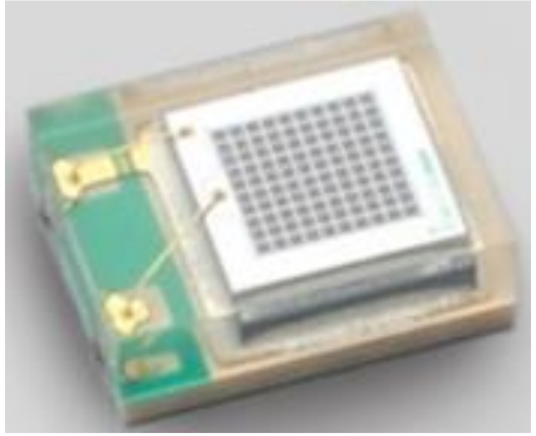
metal can, TE cooled, 3 × 3 mm^2, 3,600, 50 × 50 μm^2

S13360-1325CS



ceramic, 1.3 × 1.3 mm^2, 2,668, 25 × 25 μm^2

S13360-1375PE



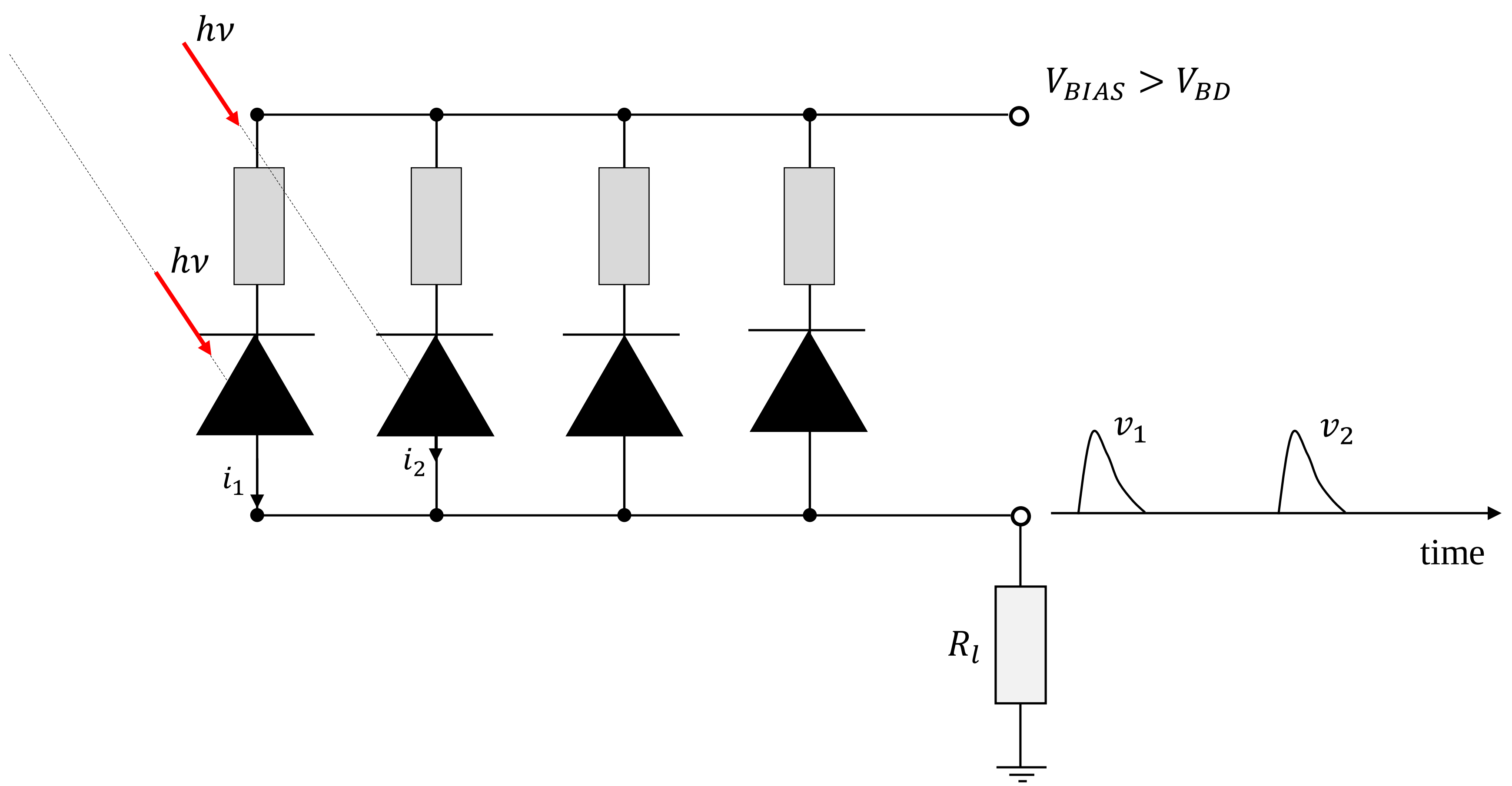
surface mount, 1.3 × 1.3 mm^2, 285, 75 × 75 μm^2

S13360-6050VE

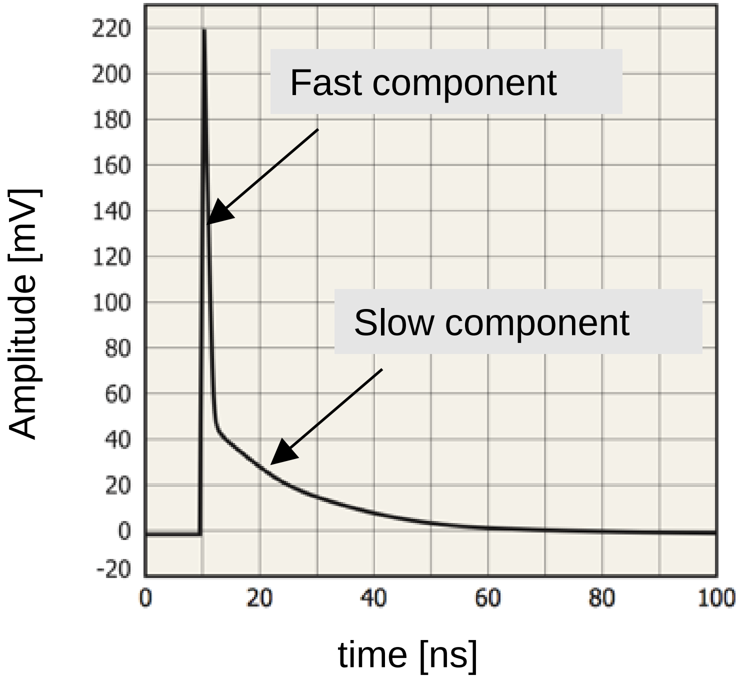
surface mount, 6 × 6 mm^2, 14,555, 50 × 50 μm^2

DG – metal can
CS – ceramic
PE – surface mount
VE – 4-side buttable (best for arrays)

Operation

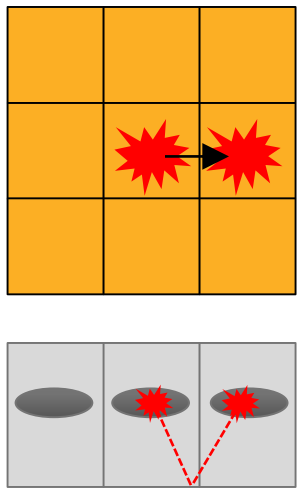


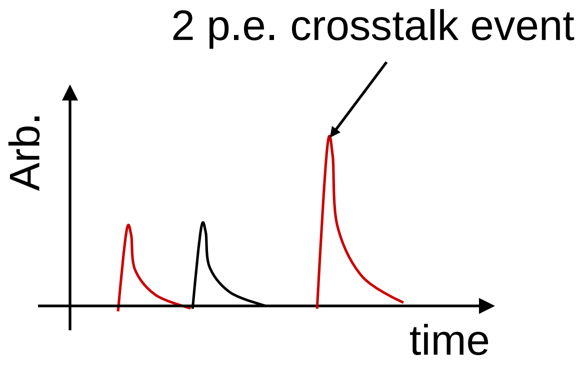
Anatomy of a pulse



- The RC time constant of the slow component depends on microcell size (all else being equal)
- The recovery time $t_r \approx 5 \times$ the RC time constant
- t_r is on the order of 10s to 100s of ns but in practical situations it is also a function of the detection bandwidth

Crosstalk





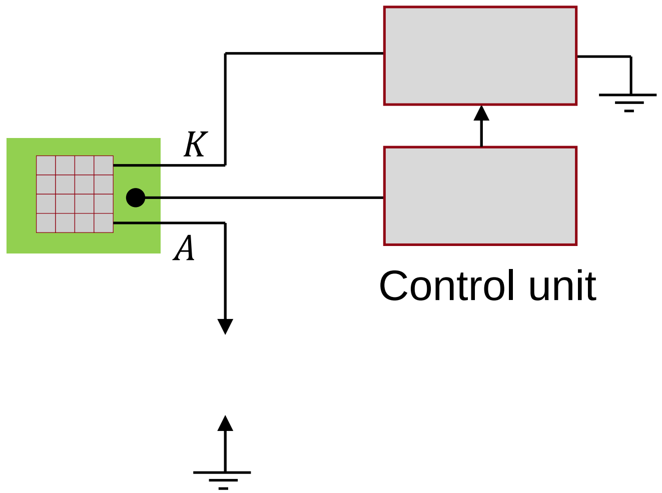
Primary discharge can trigger a secondary discharge in neighboring microcells. This is crosstalk.

Crosstalk probability depends on overvoltage.

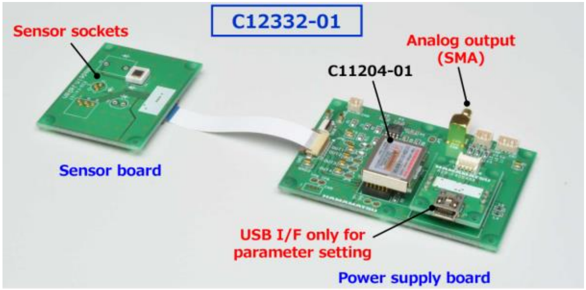
Temperature compensation

Temperature sensor $V_{BD}(T) = V_{BD}(T_0) + \beta(T - T_0)$ (breakdown voltage depends on temperature)

Variable power supply



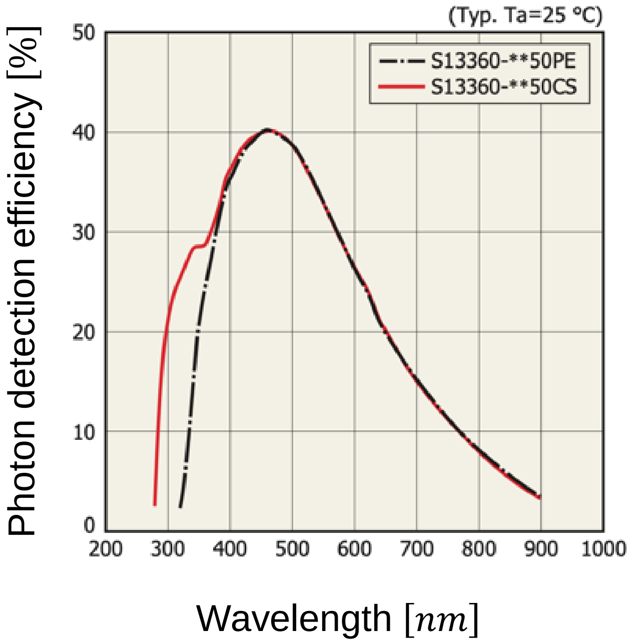
Control unit

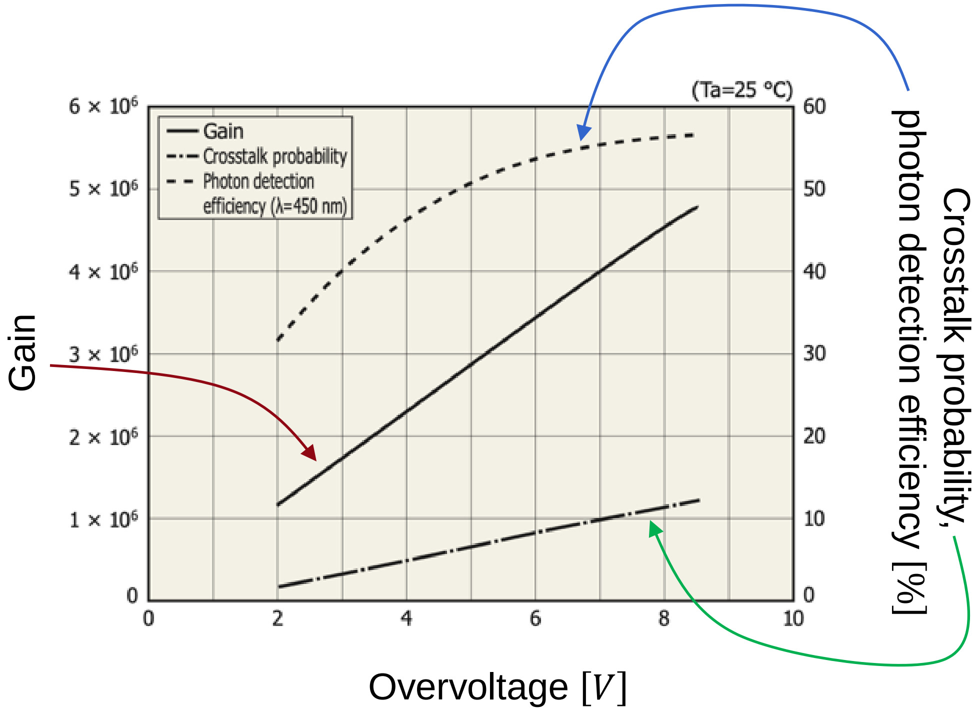


Example of SiPM (MPPC) module with temperature compensation

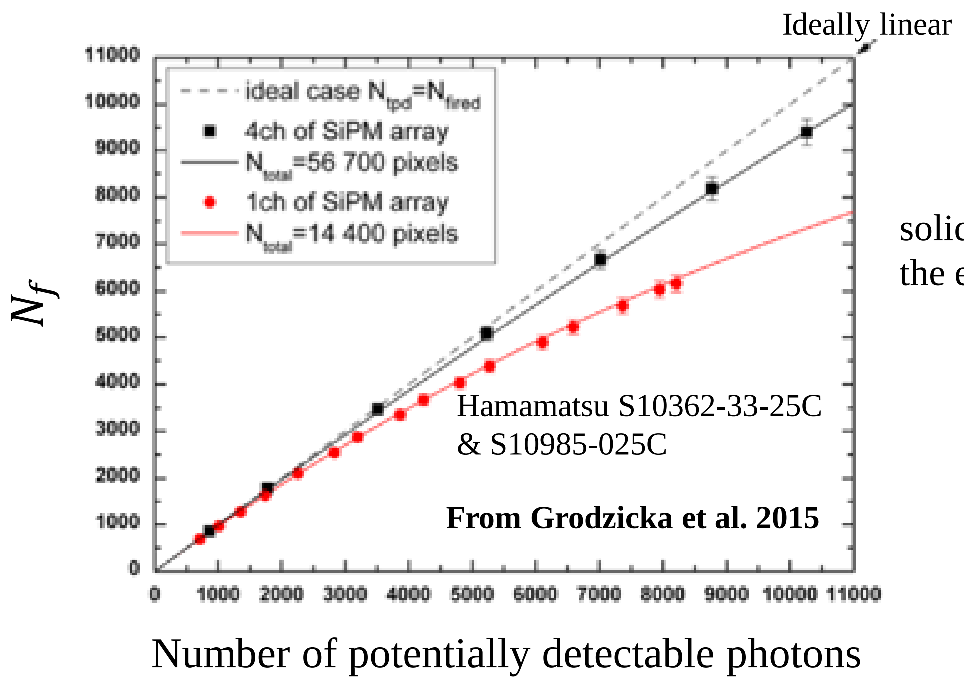
The role of the control unit is to adjust V_{BIAS} so that the overvoltage ΔV remains constant (and thus gain) as temperature changes.

Product example by Hamamatsu (S13360, 50 μm pitch)





Linearity and dynamic range (δ illumination)



solid lines fits to the equation

$$N_f = N_t\left(1 - e^{-N_\gamma \cdot PDE/N_t}\right)$$

N_t – Number of microcells

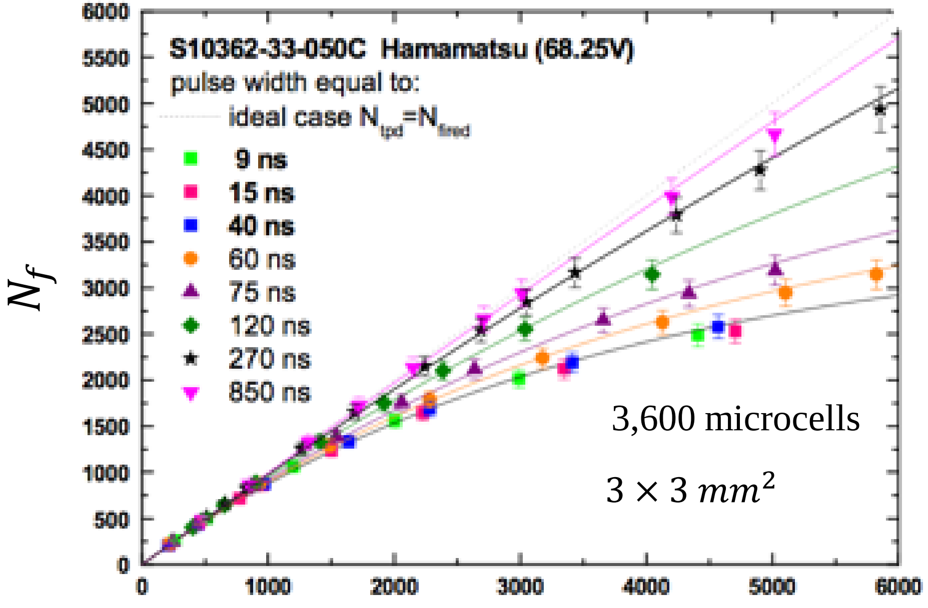
N_f – Average number of fired μ-cells

N_γ – Number of photons in a pulse

In the limit of δ –illumination, dynamic range and linearity depend on the number of microcells.

Linearity and dynamic range (finite-pulse illumination)

From Grodzicka et al. 2015



Number of potentially detectable photons

$$N_f = N_t \left(\frac{T_P}{t_r}\right)\left(1 - exp \frac{-N_\gamma \cdot PDE}{\left(\frac{T_P}{t_r}\right) N_t}\right)$$

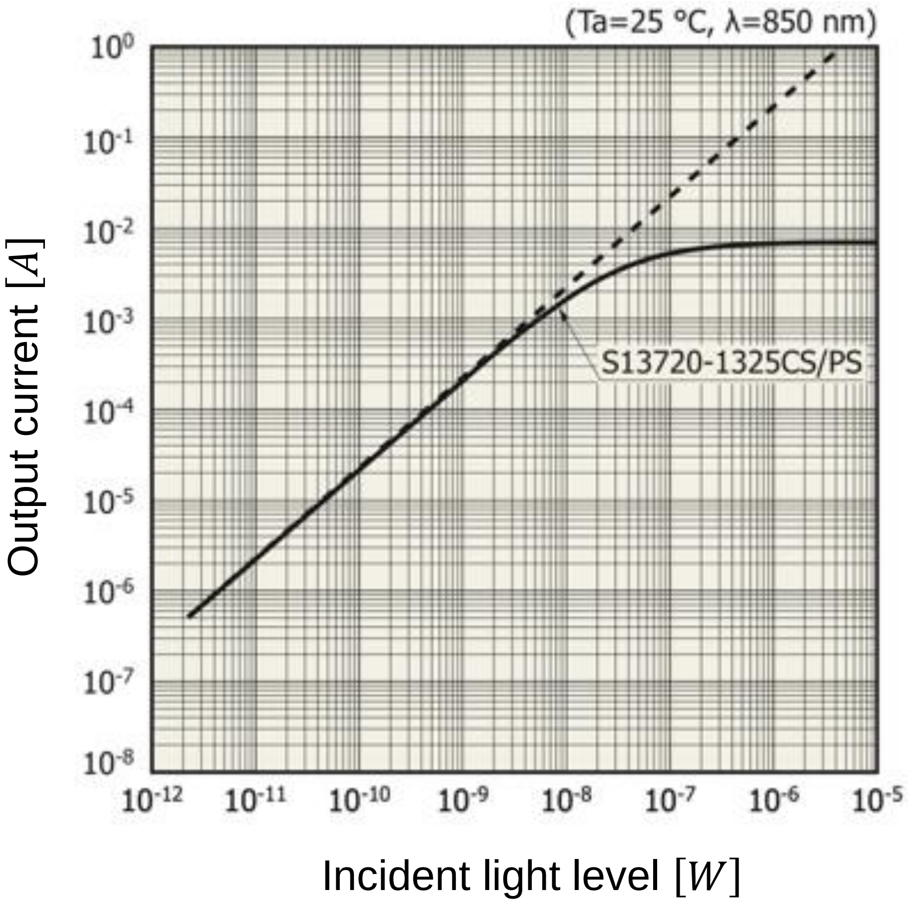
T_P – Pulse duration

t_r – Recovery time

For a given number of photons in a pulse, the number of effective fired microcells increases with the pulse duration.

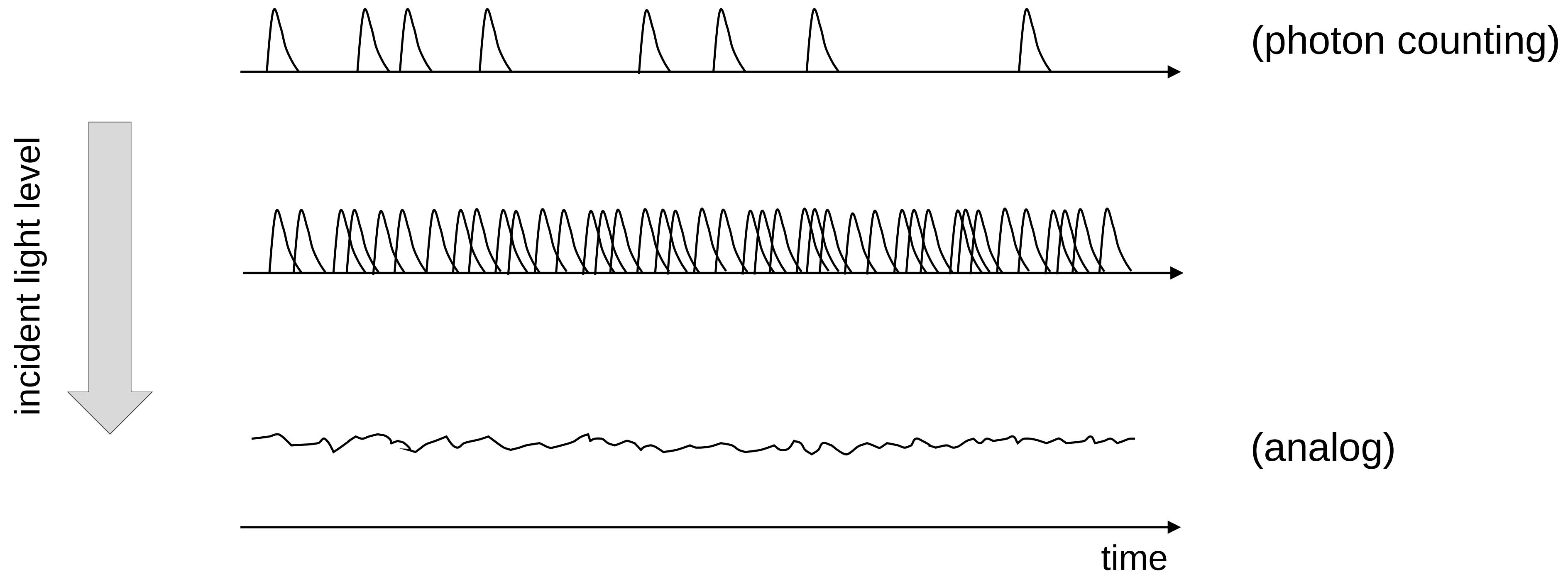
Linearity and dynamic range (DC)

HAMAMATSU
PHOTON IS OUR BUSINESS

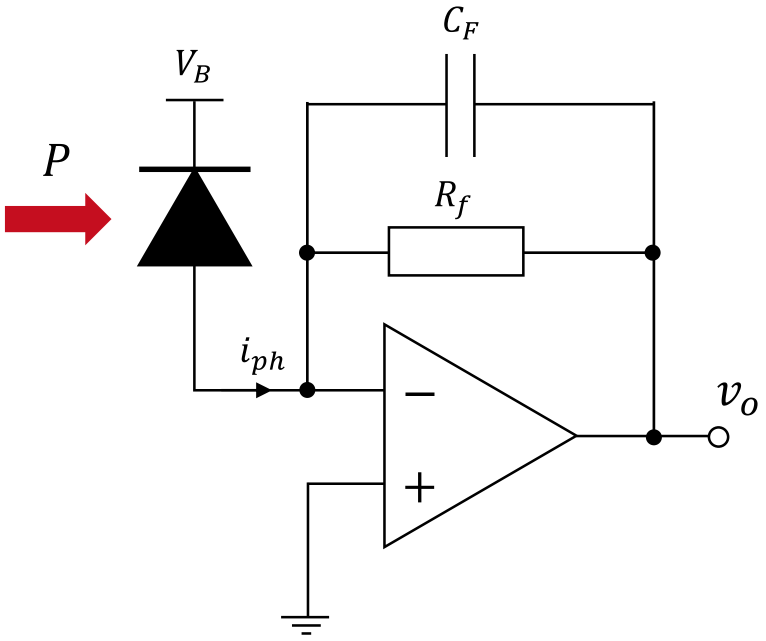


For some SiPMs Hamamatsu provides a linearity plot for DC illumination. This plot can be transcribed from $\lambda = 850\ nm$ to any other wavelength.

Modes of operation



Analog



$$i_{ph} = e\mu(1 + P_{ct})\frac{PDE \cdot P \cdot \lambda}{hc}$$

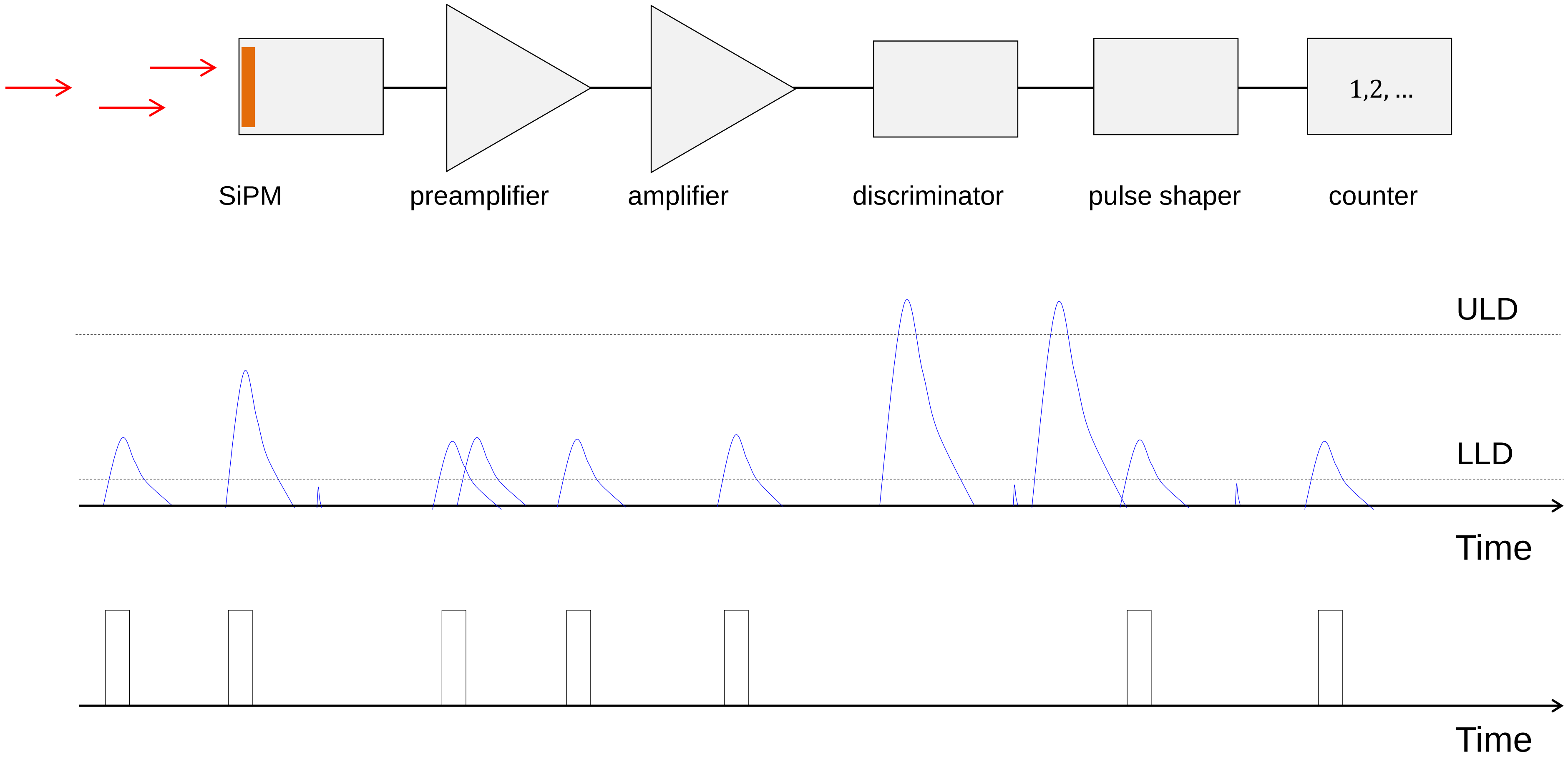
$$\frac{S}{N} = \frac{i_{ph}R_f}{\sqrt{i_{SS}^2 R_f^2 + i_{DS}^2 R_f^2 + \frac{4kT\Delta f}{R_f} R_f^2}}$$

$$i_{SS}^2 = 2ei_{ph}\mu F\Delta f$$ (signal photon shot noise)

$$i_{DS}^2 = 2ei_D\mu F\Delta f$$ (dark current shot noise)

$$i_J^2 = \frac{4kT\Delta f}{R_f}$$ (Johnson noise of the feedback resistor)

Photon counting



Photon counting

$$\frac{S}{N} = \frac{n_S\sqrt{T_{exp}}}{\sqrt{n_S + 2(n_B + n_D)}}$$

T_{exp} – measurement time

$n_S = n_{tot} - (n_B + n_D)$

n_{tot} – number of counts per unit time due to “science” light, background light, and dark counts

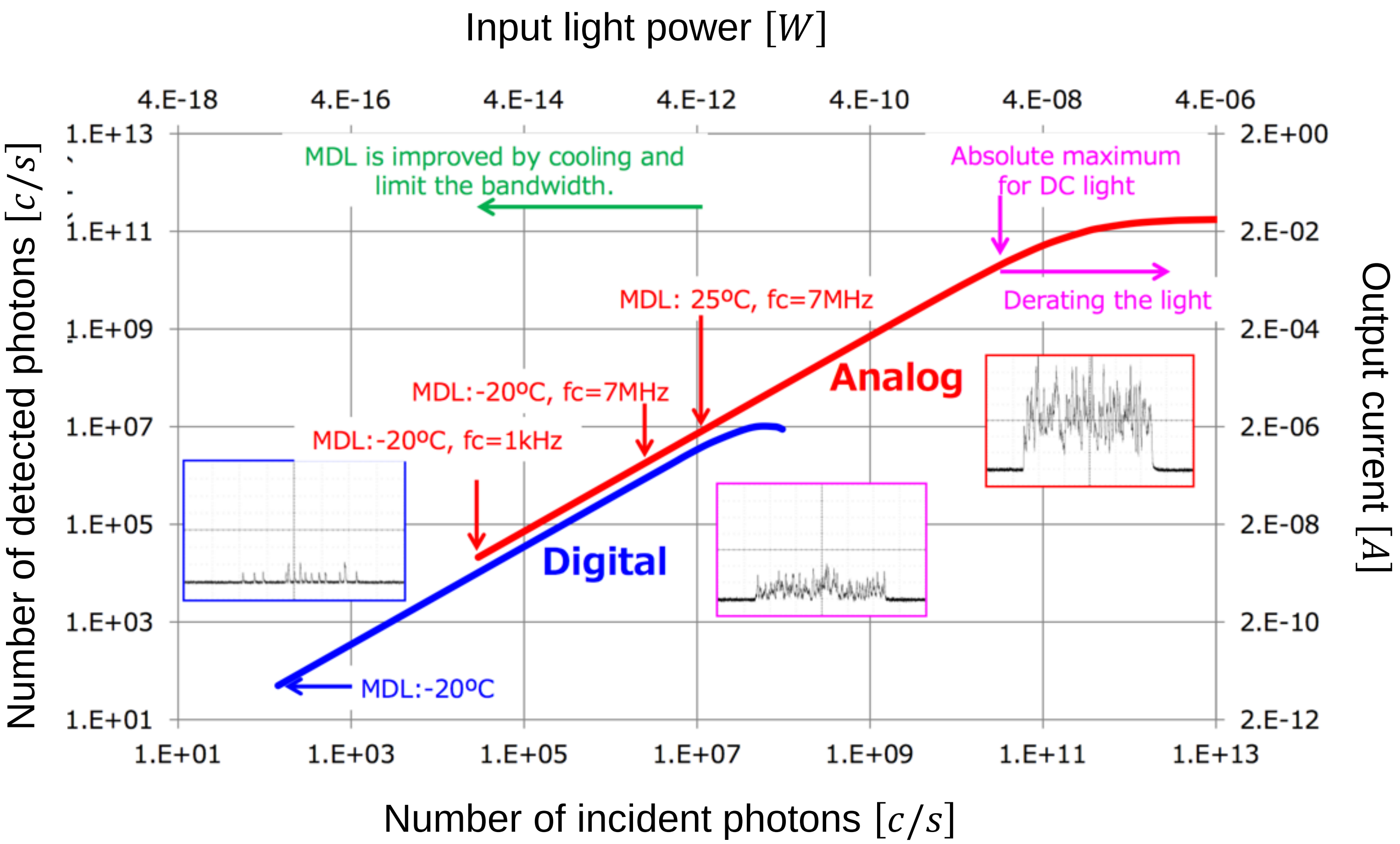
n_B – number of counts per unit time due to background light

n_D – number of counts per unit time due to dark current

All rates are measured with the same exposure time T_{exp}

Modes of operation

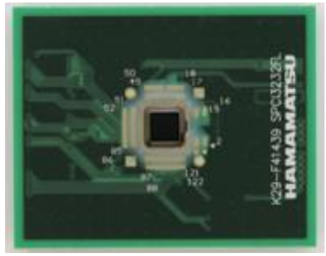
3 × 3 mm², 50 µm



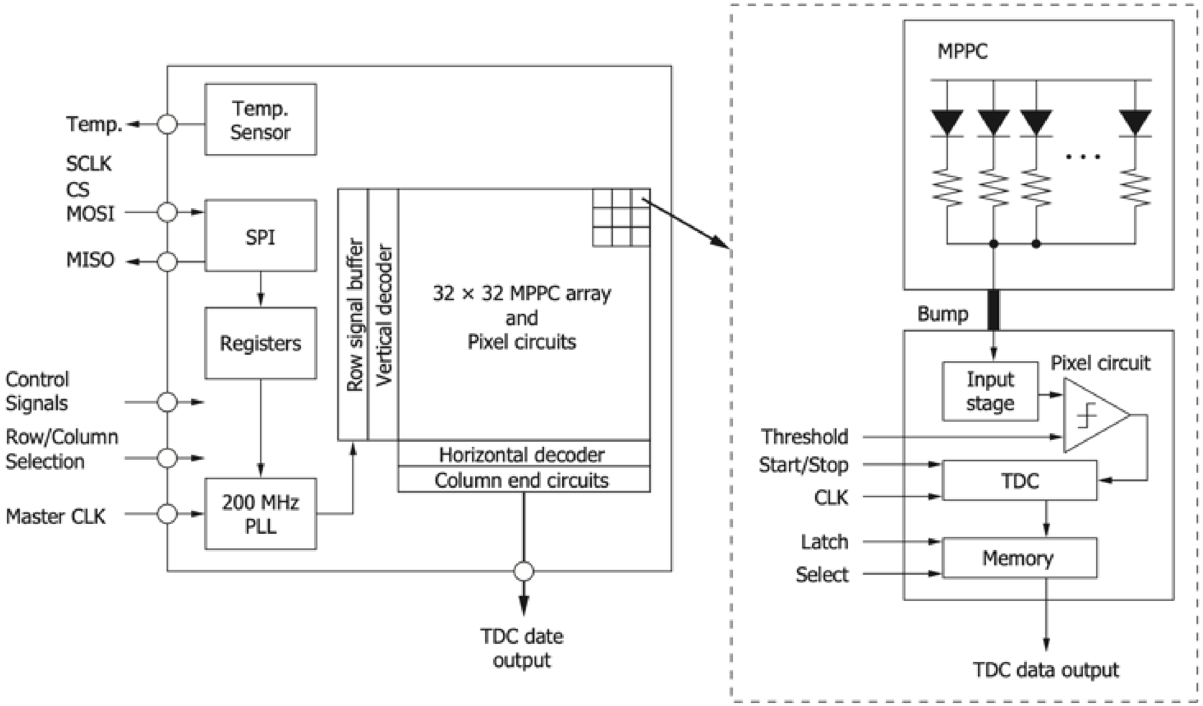
Minimum detection limit (MDL) can be lowered by cooling and limiting the detection bandwidth.

SiPM imaging array, product example by Hamamatsu

S15013-0125NP-01



2D MPPC photon counting image sensor



This array can be used for imaging and for ToF distance measurement (e.g., in flash LiDAR).

SiPM imaging array, product example by Hamamatsu

HAMAMATSU
PHOTON IS OUR BUSINESS

Structure

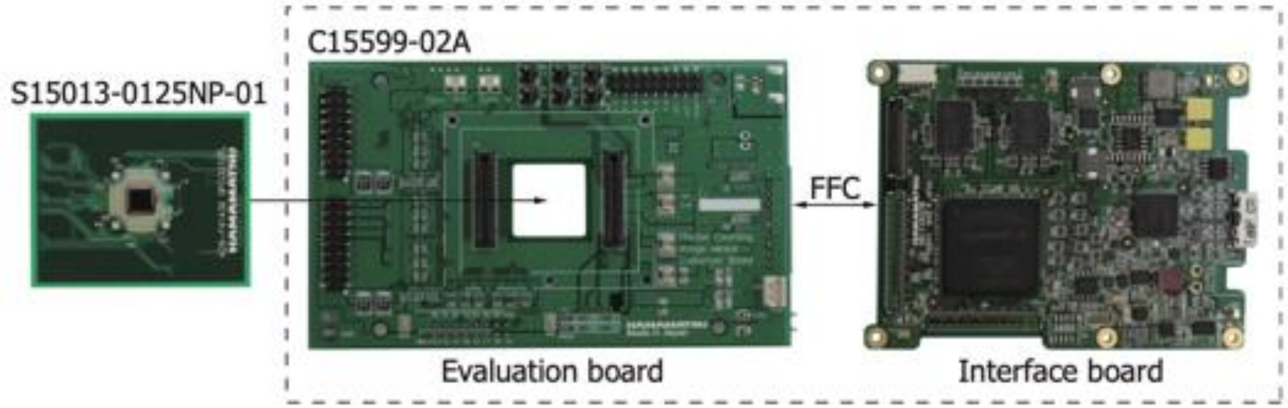
Parameter	Symbol	Value	Unit
MPPC type	-	Equivalent to S14420 series	-
Number of channels	-	32 × 32	ch
Effective photosensitive area / channel	-	100 × 100	μm
Pixel pitch	-	25	μm
Number of pixels / channel	-	12	-
Fill factor	-	36.4	%
Package type	-	Connector	-
Window	-	Borosilicate glass	-
Reflective index of window materials	-	1.51	-

Electrical and optical characteristics (Ta=25 °C)

Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit
Spectral response range	λ			550 to 1050		nm
Peak sensitivity wavelength	λp		-	840	-	nm
Photon detection efficiency*2	PDE	λ=910 nm	-	6	-	%
Dark count*3		Vop	-	2	-	kcps
Breakdown voltage	V_{BR}		-47.5	-42.5	-37.5	V
Recommended operating voltage	Vop		-	V_{BR} - 5	-	V
Gain	M	Vop	-	1.0×10^6	-	-
Temperature coefficient of V_{OP}	ΔTV_{OP}		-	47	-	mV/°C
Frame rate			-	10	-	kfps
PLL frequency	F_{PLL}		180	200	220	MHz
TDC full-scale range		F_{PLL}=200 MHz	-	-	10.24	μs
TDC resolution		F_{PLL}=200 MHz	-	312.5	-	ps
TDC jitter		FWHM, F_{PLL}=200 MHz	-	135	-	ps

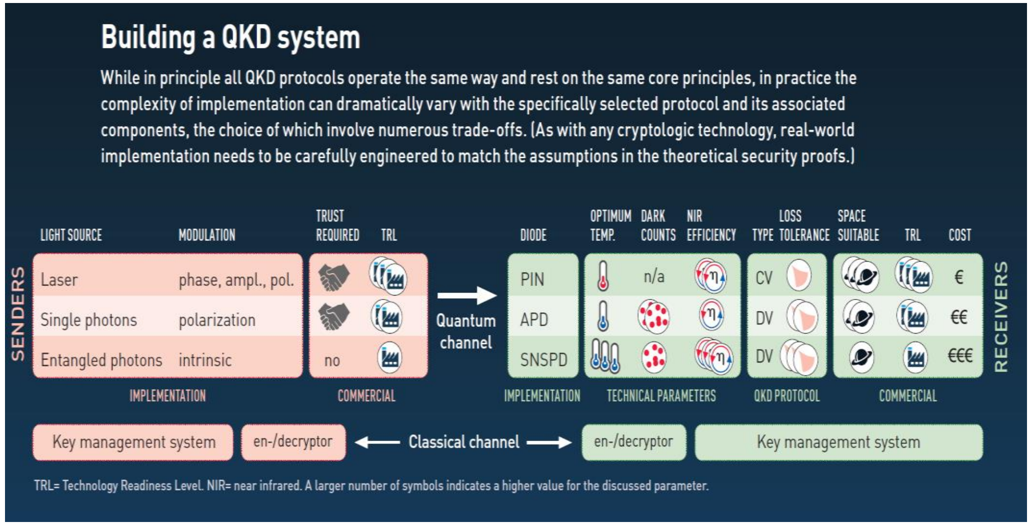
*2: Photon detection efficiency does not include crosstalk or afterpulses.
*3: Threshold=0.5 p.e.
Note: The above charactericties were measured the operating voltage that yields the listed gain in this catalog. (See the data attached to each product.)

SiPM imaging array, product example by Hamamatsu



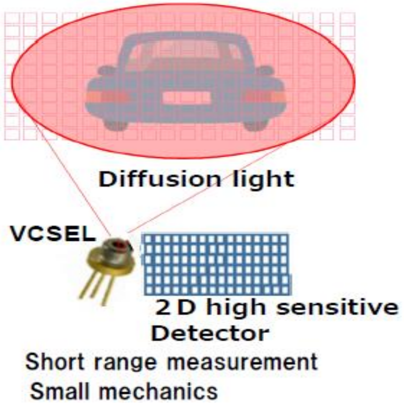
Demo units, together with evaluation and interface boards, are available to potential users.

Future Applications for SPAD Arrays



Quantum Technology – Quantum Key Distribution

Brain Activity Monitoring



Solid State Flash LiDAR

Closing remarks

1. Photon counting can be a preferred detection technique when the incident light level is low.
2. SPAD and SiPM are well-suited for photon counting.
3. SPAD and SiPM image sensors are being developed.
4. Research and development continues to extend the detection into the IR regime.
5. Integration of ASICs with the SPAD or SiPM imagers is the most cost-effective approach. Hamamatsu provides support and will work with individual customers to provide solutions.

Join Us for 10 Weeks of FREE Photonics Webinars (17 Topics)

HAMAMATSU
PHOTON IS OUR BUSINESS

Week #	Weekly Topics	# of Talks	Talk #1 Date	Talk #2 Date
1	Introduction to Photodetectors	2	26-May-20	28-May-20
2	Emerging Applications - LiDAR & Flow Cytometry	2	2-Jun-20	4-Jun-20
3	Understanding Spectrometer	2	9-Jun-20	11-Jun-20
1 Week Break				
4	Specialty Products – Introduction to Light Sources & X-Ray	2	23-Jun-20	25-Jun-20
5	Introduction to Image Sensors	2	30-Jun-20	02-Jul-20
1 Week Break				
6	Specialty Products – Laser Driven Light Sources	2	14-Jul-20	16-Jul-20
7	Image Sensor Circuits and Scientific Camera	2	21-Jul-20	23-Jul-20
8	Mid-Infrared (MIR) Technologies & Applications	2	28-Jul-20	30-Jul-20
1 Week Break				
9	Photon Counting Detectors – SiPM and SPAD	1	11-Aug-20	
10	Using SNR Simulation to Select a Photodetector	1	18-Aug-20	

To register for other webinars or hear previous webinar recordings, please visit link below:

https://www.hamamatsu.com/us/en/news/event/2020/20200526220000.html

Thank you

Thank you for listening.

Contact information:

piatek@njit.edu

HAMAMATSU
PHOTON IS OUR BUSINESS

www.hamamatsu.com