SiPM
a short introduction

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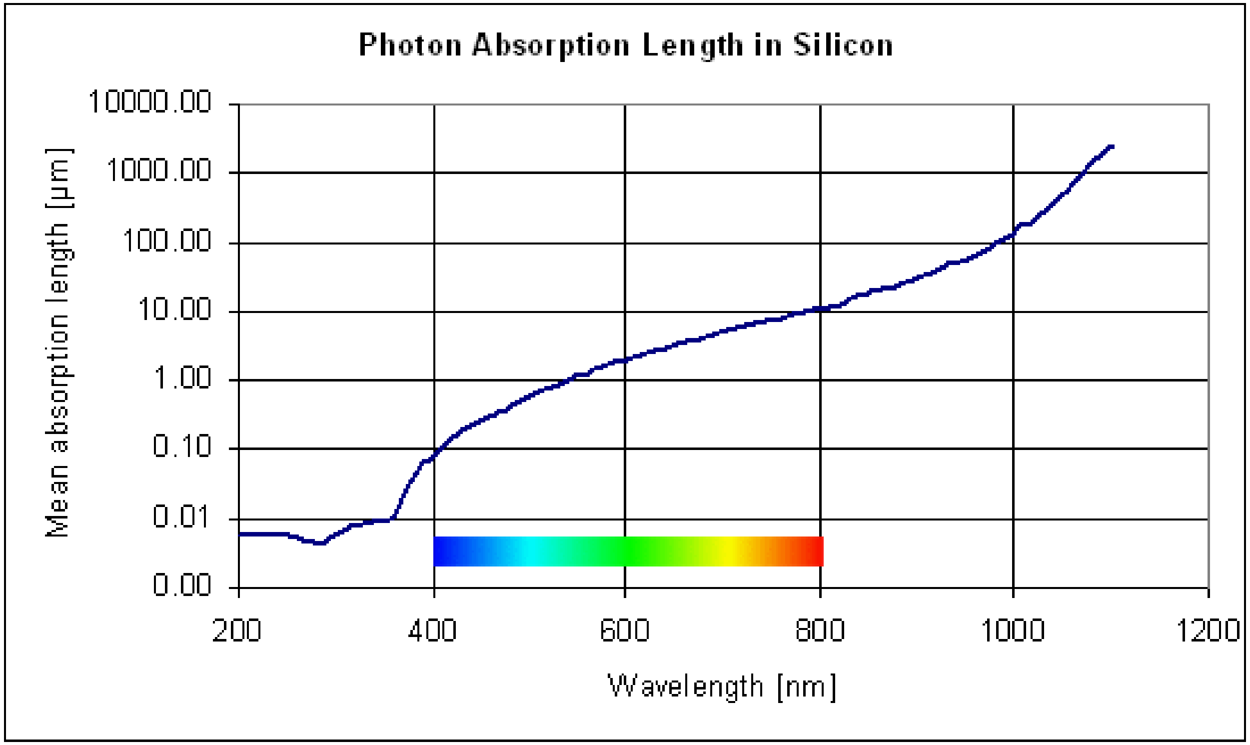
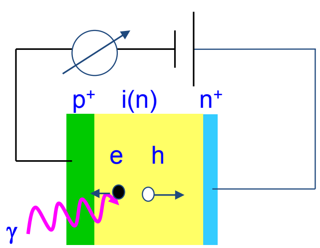
PHOTON ABSORPTION LENGTH IN SI

- Photon crossing silicon slice can transfer its energy to a valence electron generating an electron-hole pair
- The photon absorption length is function of the photon wavelength (or energy)
- Silicon is a good photo detector material for 400 nm < λ < 800 nm (above 1000 nm the silicon detector would be too bulky, below 350 nm the silicon would be too thin)



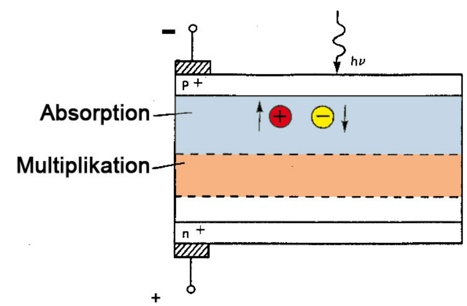
PIN & APD

- Diode reverse biased → depletion region
- Electrons-holes generated by absorbed photons results in a current (electrons → n-type, holes → p-type)
- Different behavior according to the doping profile and applied voltage



PHOTODIODE (PIN DIODE)

- P(I)N type
- P layer < 1 μ
- High QE (80% @ λ= 700 nm)
- Gain=1

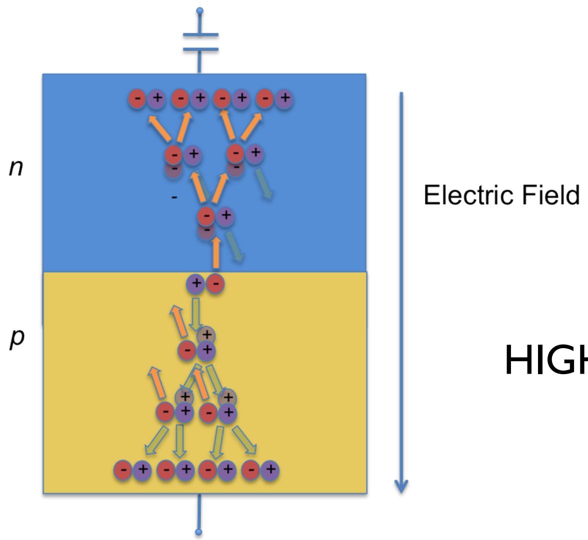


AVALANCHE PHOTODIODE (APD)

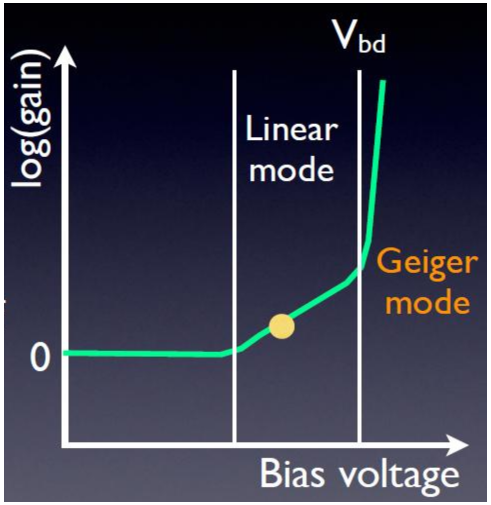
- High reverse bias voltage (few hundred of volt)
- Special doping profile → high internal Field (> 10^5 V/cm) → avalanche multiplication
- Typical gain ≈ 100
- Gain fluctuations due to avalanche process
- High sensitivity on temp and bias voltage (ΔG ≈ 3%/V – ΔG ≈ 2.5%/K)

THE GEIGER MODE IN SILICON (I)

- High electric field (> 5 x 10^5 V/cm) in the depletion region accelerates charge carriers
- Charge carriers acquire enough kinetic energy to create secondary charge pairs (impact ionization process)
- Single photoelectron can generate self-sustaining cascade through the silicon
- The original photoelectron is amplified into a current flow
- Because the analogy of ionization discharge in gases (Geiger Muller Tube) the process is called Geiger discharge

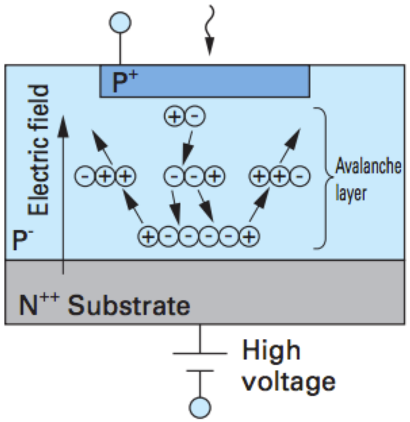


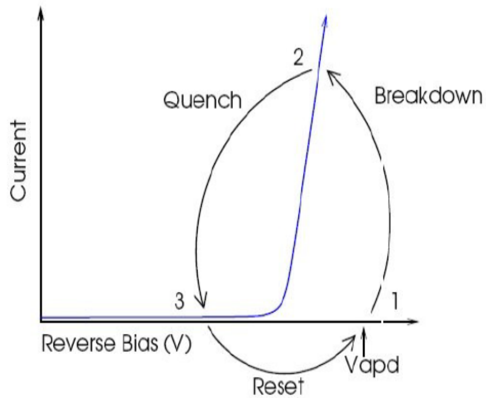
HIGH ELECTRIC FIELD

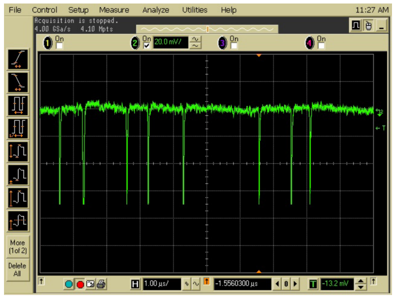


THE GEIGER MODE IN SILICON (II)

- p-n region designed to sustain reverse bias besides his nominal breakdown voltage
- Flowing current is stopped through a passive quencing circuit (resistors)



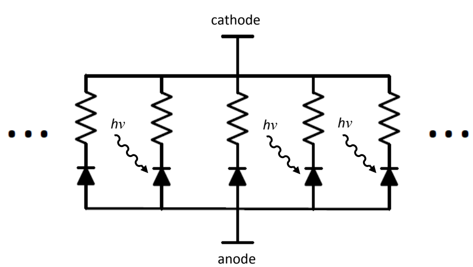


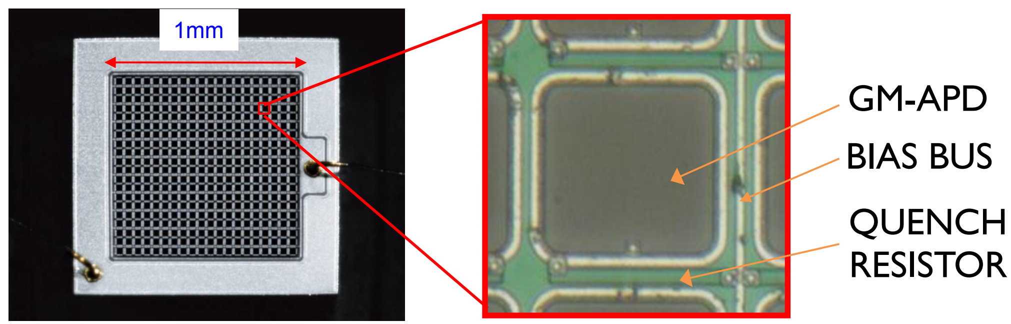


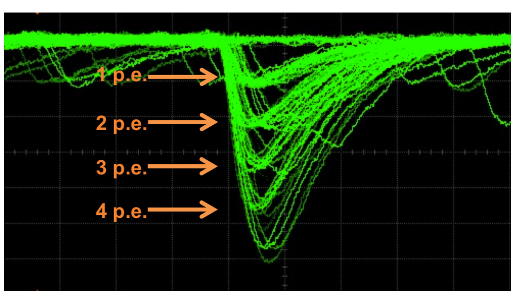
- A single photodiode acts as a photon-triggered switch
- The photodiode can not provide proportional magnitude information (i.e. if 1 or more photons hit the same cell produce the same signal)

THE SILICON PHOTO MULTIPLIER (SIPM)

- To mitigate the lack of proportionality an array of optical isolated Geiger-mode photodiodes has been built each one with his own quencing resistor
- The number of photodiodes range from 100 and 1000 per mm^2
- The signals of all photodiodes are then summed

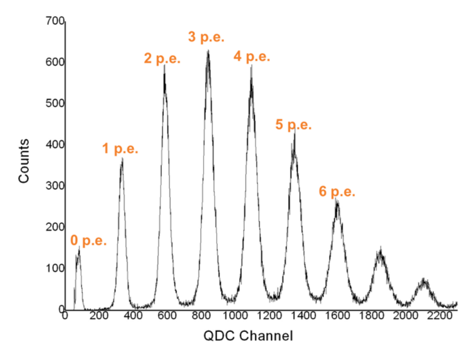






SPECTRUM →

← OSCILLOSCOPE



THE SIPM GAIN

- Matrix of Nmicro-cells ("pixels") in parallel, connected to a common output node
- Each micro-cell: GM-APD+$R_{QUENCING}$
- V.M. Golovin and A.Sadygov (Russian patents1996-2002)

A single GM-APD do not produce information about the light intensity. In a SiPM the output charge is proportional to the number of triggered cells or, assuming a CONVERSION EFFICIENCY =1, to the number of photons hitting different cells.

GAIN: number of carriers produced by an absorbed photon. Collected charge correspond to the area of the output signal and can be estimated according to the circuit element and bias

$$I_{MAX} \cdot \frac{\tau_Q}{q} = \frac{(V_{BIAS} - V_{BD})}{R_Q} \cdot \frac{\tau_Q}{q} = \frac{(V_{BIAS} - V_{BD}) \cdot C_D}{q}$$

- V_{BIAS} = Supply voltage
- V_{BD} = Breakdown Voltage
- C_D = Device Capacitance
- R_Q = Quencing resistor

SIPM NOISE & PHOTO DETECTION EFFICIENCY (PDE)

NOISE

- **Primary dark count**: current pulses triggered by non-photogenerated carriers (main source of dark carriers: thermal generation in the depleted region)
- **After-pulsing**: secondary current pulse caused by a carrier trapped during the primary avalanche and released after a certain time
- **Optical cross-talk**: excitation of neighboring cells due to photoemission during avalanche discharges

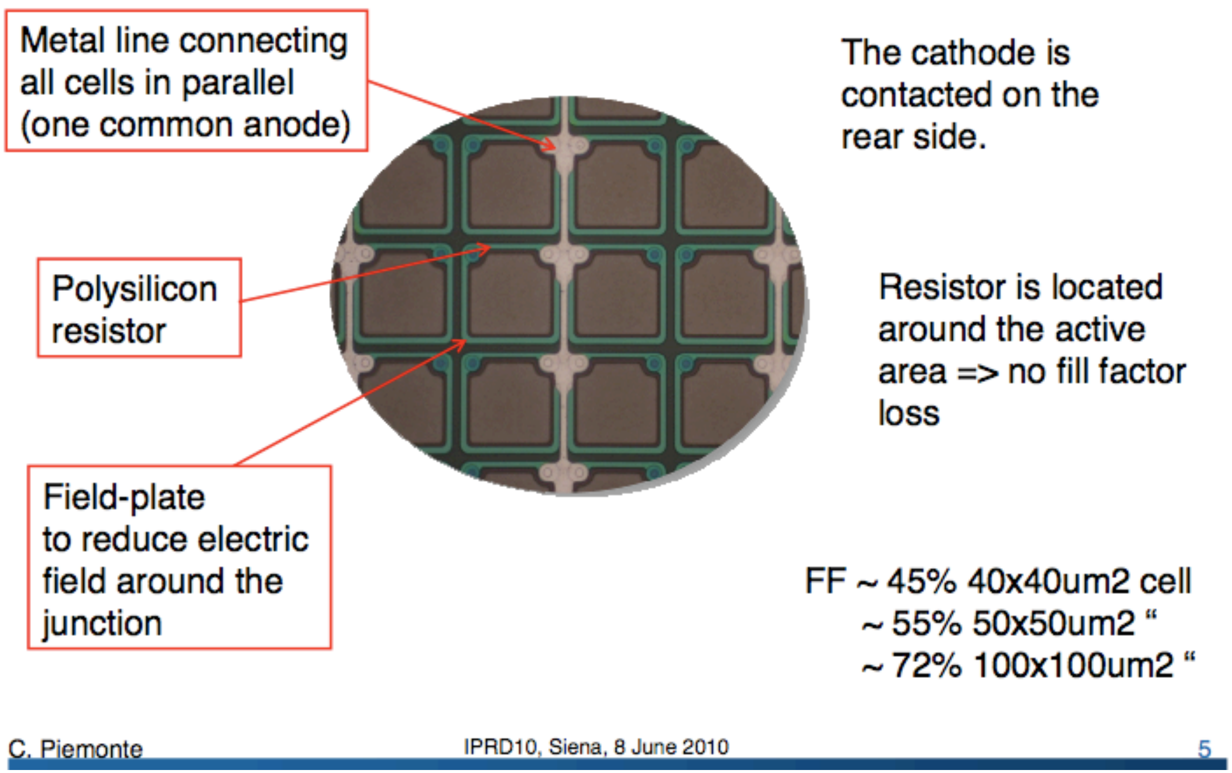
PDE: $N_{PULSES}/N_{PHOTONS} = QE \times A_{TP} \times FF$

- QE = Quantum Efficiency ≈ 1 in the blue-green region
- A_{TP} = Geiger-APD Avalanche Trigger Probability > 0.95 when $(V_{BIAS}-V_{BD})$/VBIAS > 0.15
- FF = Fill Factor = 0.2 - 0.8

Producer	SiPM ID	No. μcells	μcell size (μm)	ε_{geom} (%)
Photonique	SSPM-0701-BG	556	43 × 43	70
FBK-irst	W20-B10-T3V2PD/I run	625	40 × 40	20
FBK-irst	W3-B3-T6V1PD/II run	625	40 × 40	16
SensL	SPM-20	848	29 × 32	43
SensL	SPM-35	400	44 × 47	59
SensL	SPM-50	216	59 × 62	68
HPK	S10362-11-25	1600	25 × 25	31
HPK	S10362-11-50	400	50 × 50	61.6
HPK	S10362-11-100	100	100 × 100	78.5

SIPM PDE - FILL FACTOR

- Metal lines connecting the cells, poly-silicon resistors, thrences and implantation profile reduce the sensitive area
- Fill Factor increase with increasing cell size (up to 70/80%)



SUMMARIZING

TYPE	GAIN	MIN DETECT SIGNAL (PE)	BANDWIDTH (order of)	MAX SIZE (order of)
PIN	NO	200-300	100 kHz	10 cm^2
APD	LINEAR (50-200)	10-20	100 MHz	2.5 cm^2
SIPM	GEIGER (10^5-10^6)	1	100 MHz	< 1 cm^2

SiPM PROS

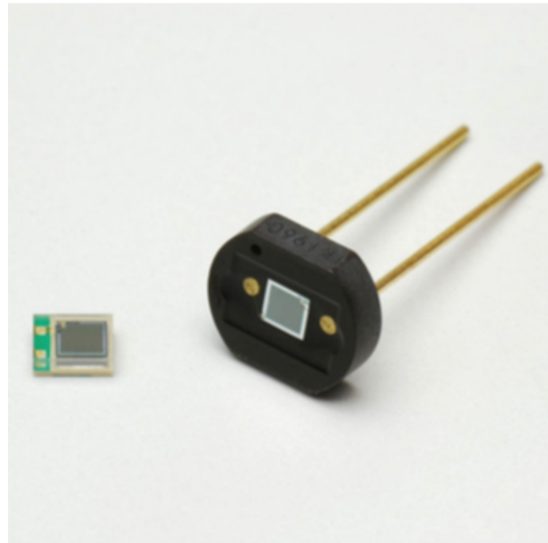
- High photo detection efficiency
- High gain (10^5-10^6)
- Single photo-detection sensitivity
- Fast (≈ 1 ns rise time)
- Good time resolution (< 100 ps)
- Lov bias voltages (< 100 V)
- B field insensitivity

SiPM CONS

- Limited linearity
- Dark count
- Surface Area
- Temperature dependence

S18825 HAMAMATSU MPPC

Multi-Pixel Photon Counter



Structure

Parameters	Symbol	S12825-050C	S12825-050P	Unit
Effective photosensitive area	-	1.3 x 1.3		mm^2
Pixel pitch	-	50		μm
Number of pixels / channel	-	667		-
Geometrical fill factor	-	62		%
Package	-	Ceramic	Surface mount type	-
Window	-	Silicone resin	Epoxy resin	-
Window refractive index	-	1.41	1.55	-

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S18825 HAMAMATSU MPPC

Multi-Pixel Photon Counter

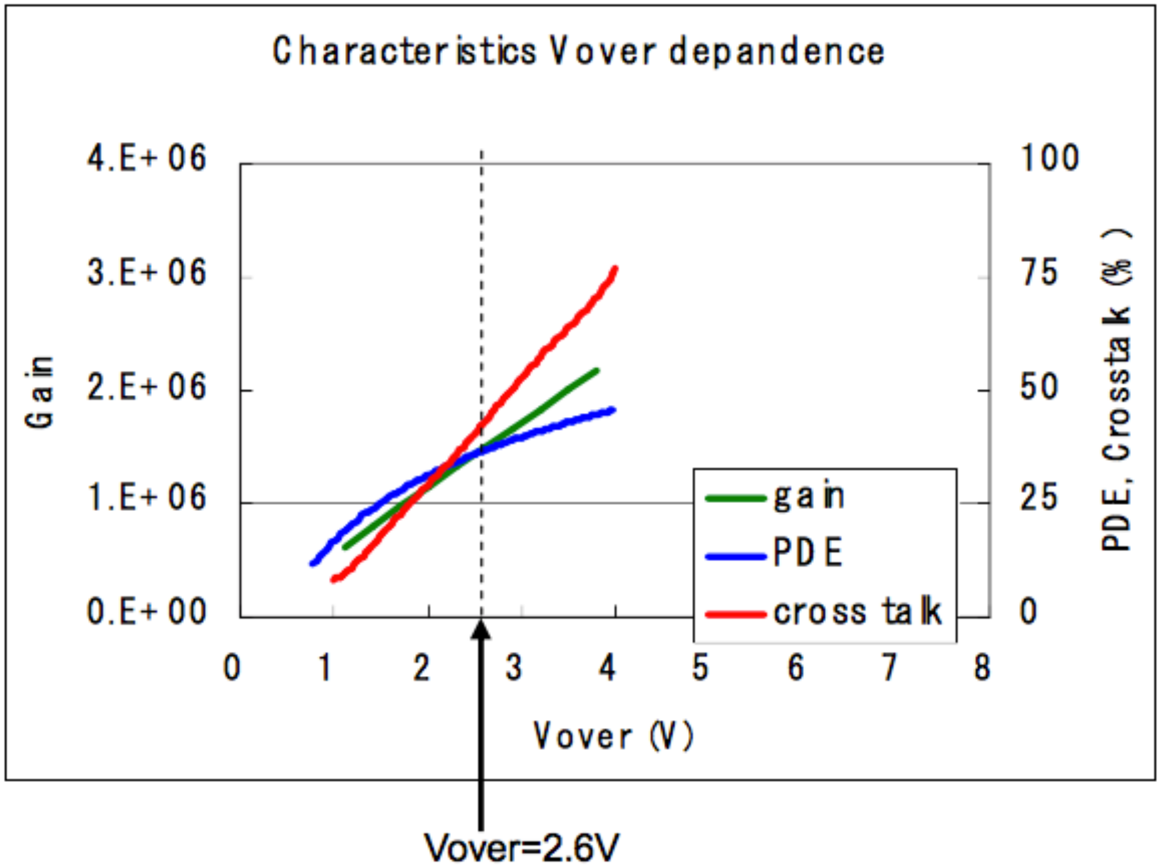
Electrical and optical characteristics
(Typ. Ta=25 deg C, Vover=2.6 [*1] Unless otherwise noted)

Parameters		Symbol	S12825-050C, S12825-050P	Unit
Spectral response range		λ	320 to 900	nm
Peak sensitivity wavelength		λp	450	nm
Photon detection efficiency at λp [*4]		PDE	35	%
Dark count	Typ.	-	170	kcps
	Max		350	kcps
Terminal capacitance		Ct	60	pF
Gain [*5]		M	1.25×10^6	
Breakdown voltage		V_{BR}	65±10V	
Recommended operating voltage [*6]		Vop	V_{BR} +2.6	V
Temperature coefficient of recommended reverse voltage		ΔTVop	60	mV/ ºC

S18825 HAMAMATSU MPPC

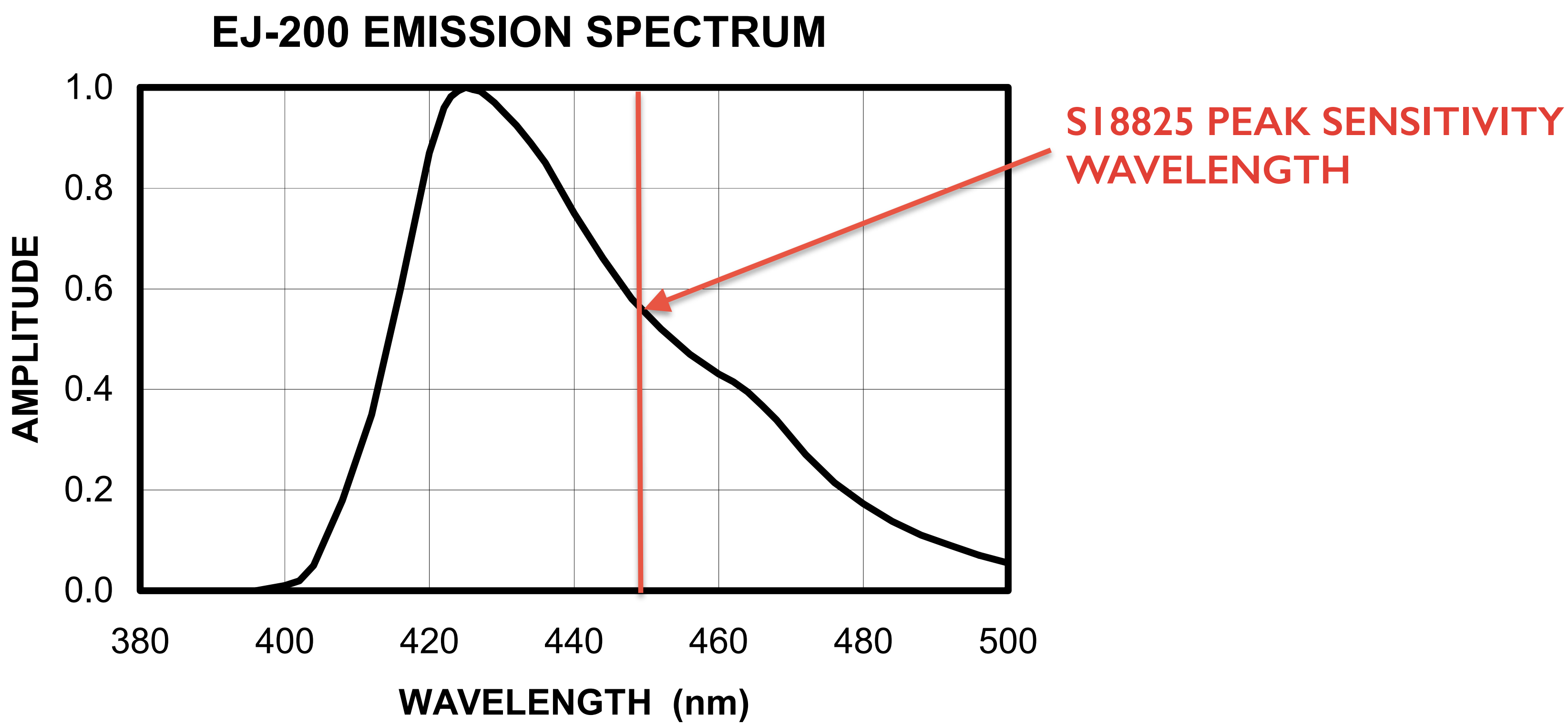
Multi-Pixel Photon Counter

Operation voltage dependence



PDE: measured at λ=408nm
(not including cross talk and after pulse)

S18825 HAMAMATSU PEAK SENSITIVITY vs EJ200 PEAK EMISSION SPECTRUM



SCINTILLATOR PEAK EMISSION AND
SiPM PEAK SENSITIVITY DO NOT MATCH → WLS REQUIRED

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