Silicon Photomultiplier Tubes

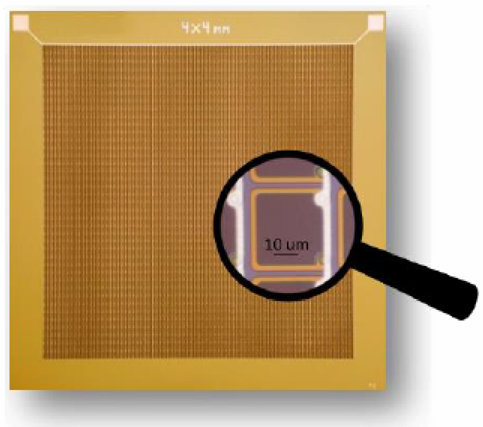


Fig. 1. Picture of a 4x4 mm^2 SiPM die. The SiPM consists of a matrix of micro-cells all connected in parallel. Each micro-cell is a GM-APD and it represents the basic sensitive element of the SiPM.

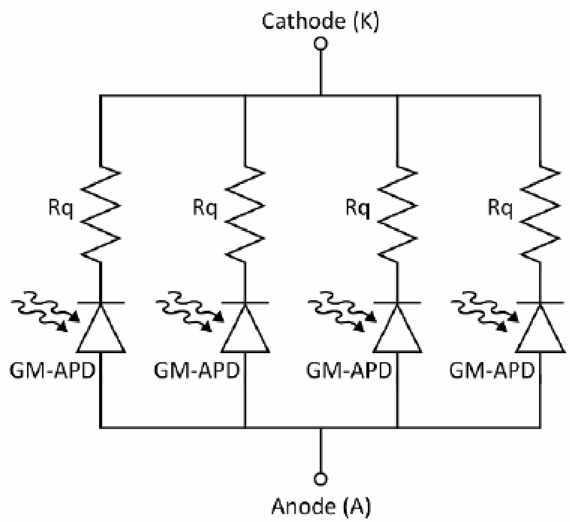


Fig. 2. The parallel arrangement of GM-APDs with series quenching resistor in a SiPM.

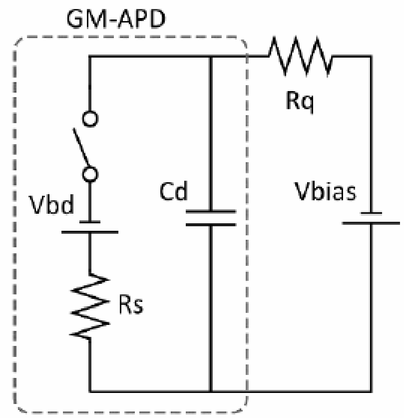
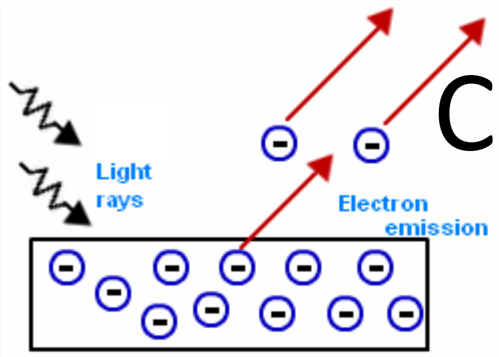


Fig. 3. The equivalent circuit of a GM-APD with series quenching resistor and external bias. The switch models the turn-on (photon absorption or dark event) and turn-off (quenching) probabilities.

http://advansid.com/attachment/get/up_89_1411030571.pdf

Xavier Garcia

Phys 575

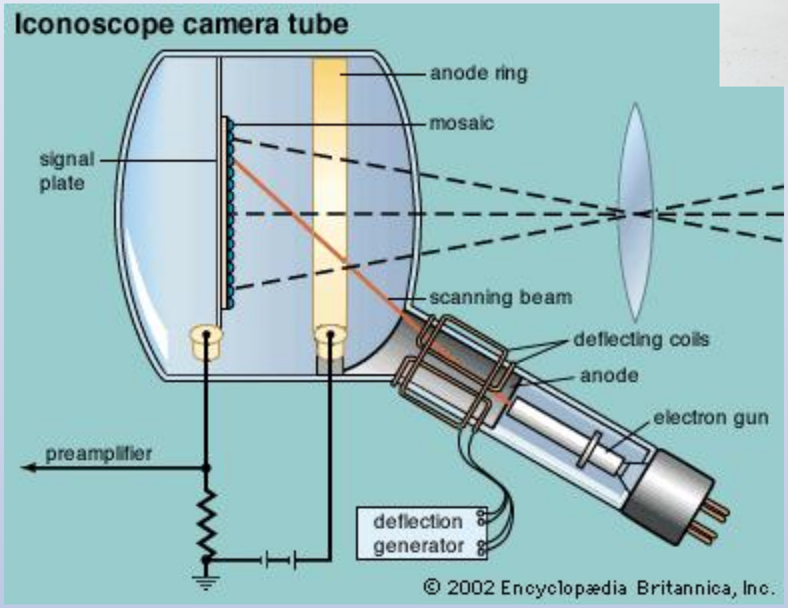


Conventional PMTs

Vladimir Zworykin – Inventor of first Multidynode PMT
http://russiapedia.rt.com/prominent-russians/science-and-technology/vladimir-zworykin/

http://www.grantfidelity.com/images/RZ/845T.jpg

- Photoelectric effect - 1887
- Vacuum Tubes -1904
- First conventional PMT produced - 1935-36



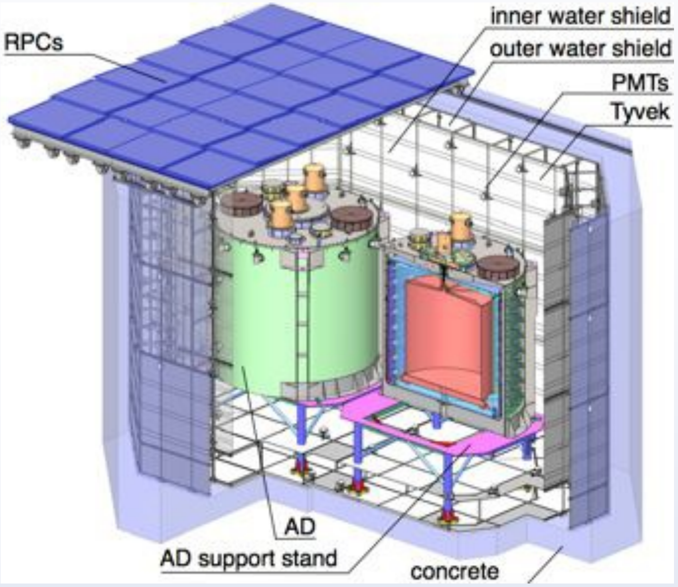
http://media-2.web.britannica.com/eb-media/88/6888-004-FE950420.jpg

Extremely Important

Mant, many many experiments from coincident photon counting to the Super-K

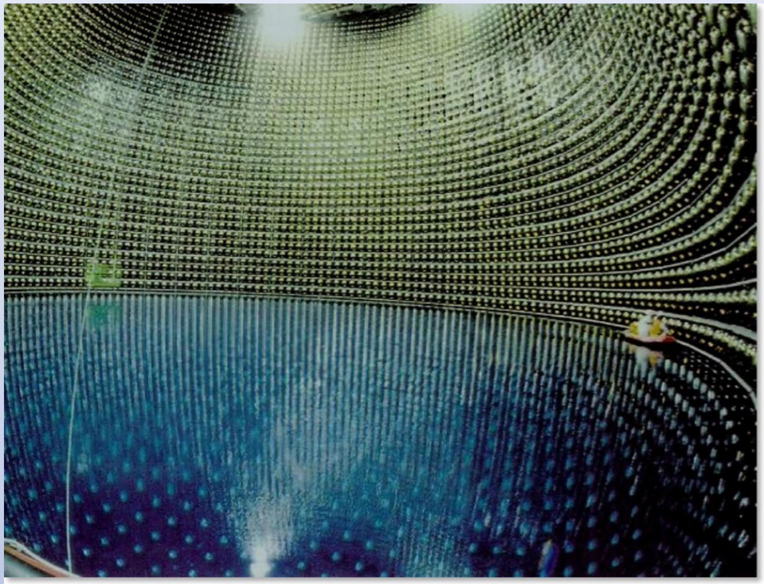
Time Measurement and Counting Lab, Physics 433

Daya Bay



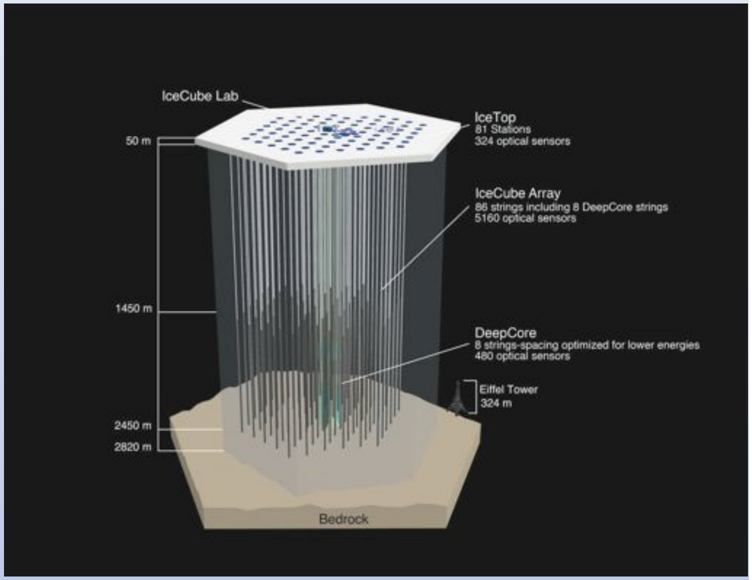
https://inspirehep.net/record/1283608/files/veto.png

Super Kamiokande



http://home.physics.ucla.edu/~arisaka/home/Detectors/files/superk.jpg

Ice Cube



http://depts.washington.edu/physcert/radcert/575website/slides/575-08-cosmicrays-smaller.pdf

- Large voltage
- Photocathode
- Multidynode
- Internal vs External Gain

$$\mu = \delta^n$$

$v^2_n = (2eI_{ph}BG_{int}^2R_L^2 + 4kTBR_L)A_{ext}^2$

$SNR^2 = I_{ph}/(2eB + 4kTB/R_L I_{ph}G_{int}^2)$

- Quantum Efficiencies

$$QE = \frac{S \times 1240}{\lambda} \times 100\%$$

S = radiant sensitivity in A/W

λ = wavelength in nanometers

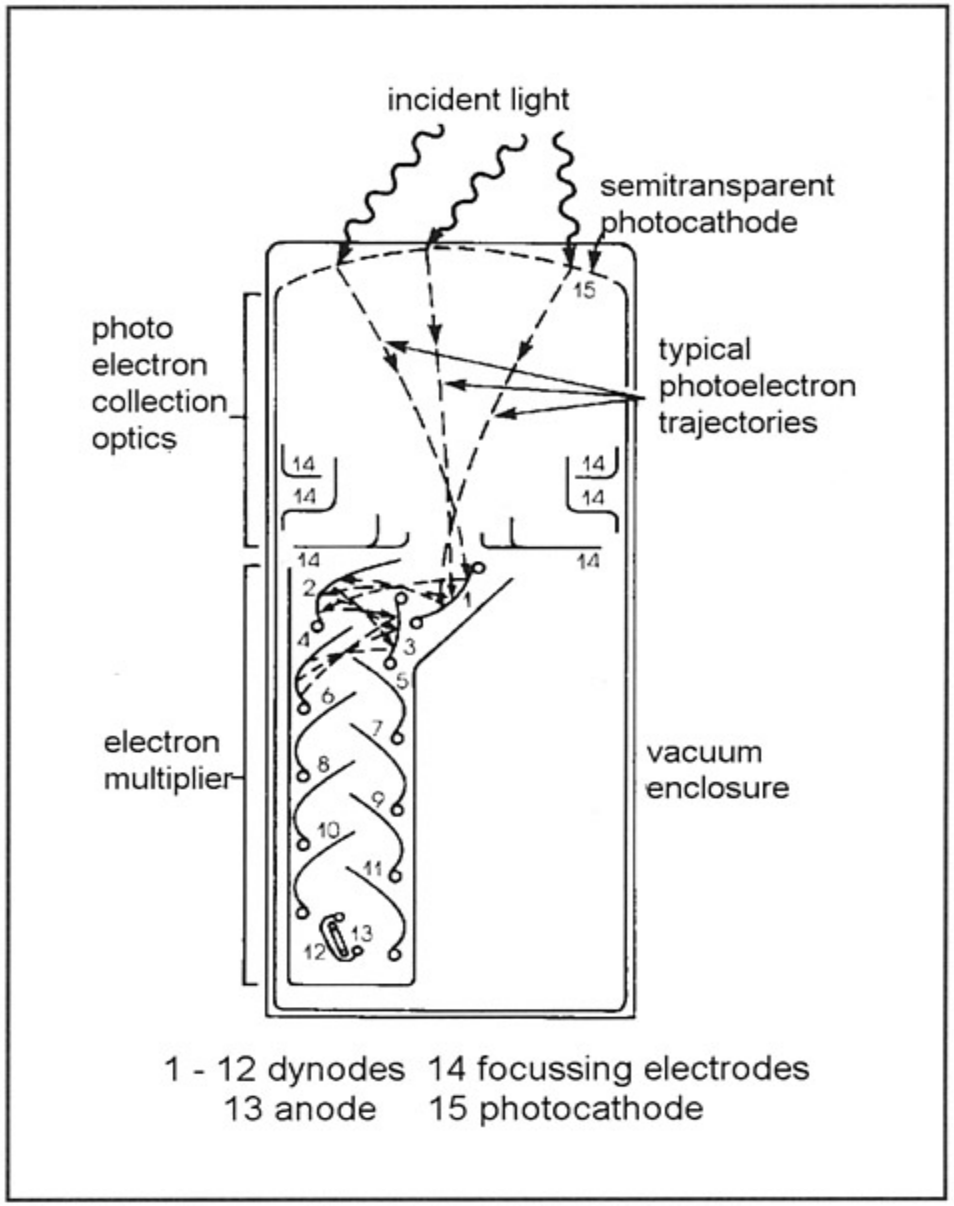


Fig. 4.1 Schematic of a photomultiplier tube.

http://www.hep2.fzu.cz/roznov/SiliconPhotomultiplier/Read%20Out%20of%20Scintillation%20Crystals_files/fig41.jpg

	PMT	APD	HPM	SiPM
Photon Detection Efficiency: Blue Green-yellow Red	 20% A few % <1%	 50% 60-70% 80%	 20% A few % <1%	 12% 15% 15%
Gain	10^6 - 10^7	100-200	10^3	10^6
Voltage Level	1-2 kV	100-500 V	20 kV	25 V
Operation in H-field	Problematic	OK	OK	OK
Threshhold Sensitivity S/N >>1	1 ph.e.	~10 ph.e.	1 ph.e.	1 ph.e.
Timing/10, ph.e.	~100 ps	A few ns	~100 ps	30 ps
Dynamic Range	~10^6	Large	Large	~10^3/mm^2
Complexity	High (vacuum, HV)	Medium (low noise electronics)	Very high (hybrid technology, very HV)	Relatively low

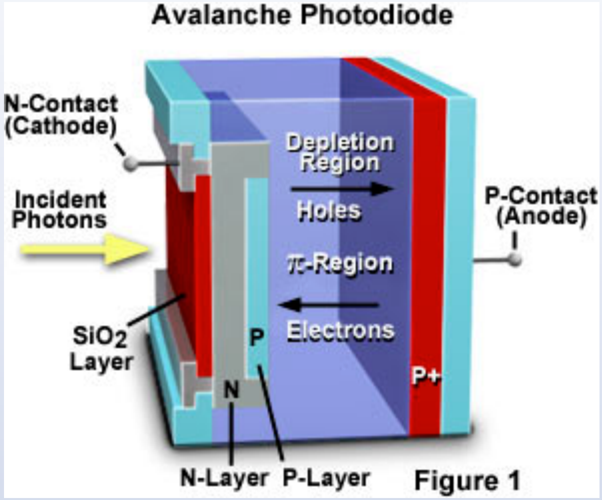
http://www.slac.stanford.edu/pubs/icfa/fall01/paper3/paper3.pdf

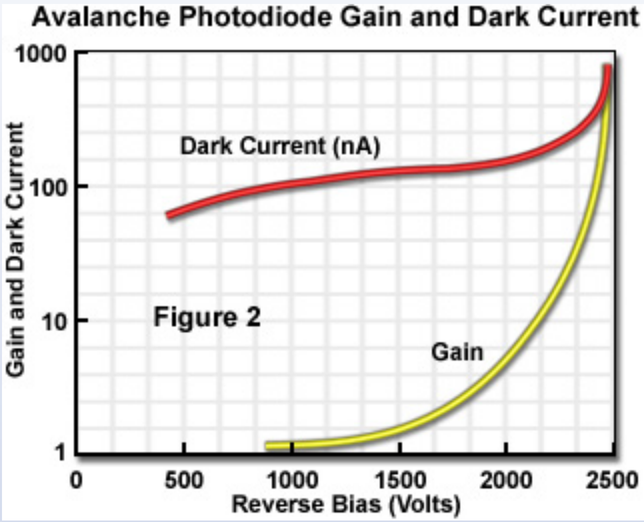
Semiconductor Industry

- Old Technology = BAD
  Semiconductor Technology = GOOD
- A semiconductor based PMT needed to have limited external gain, while having very high internal gain
- Bipolar and Unipolar Transistors have limited bandwidth, while photoconductors are not suitable for internal gain of $10^6 – 10^7$
- Solution discovered in late 60s

APD

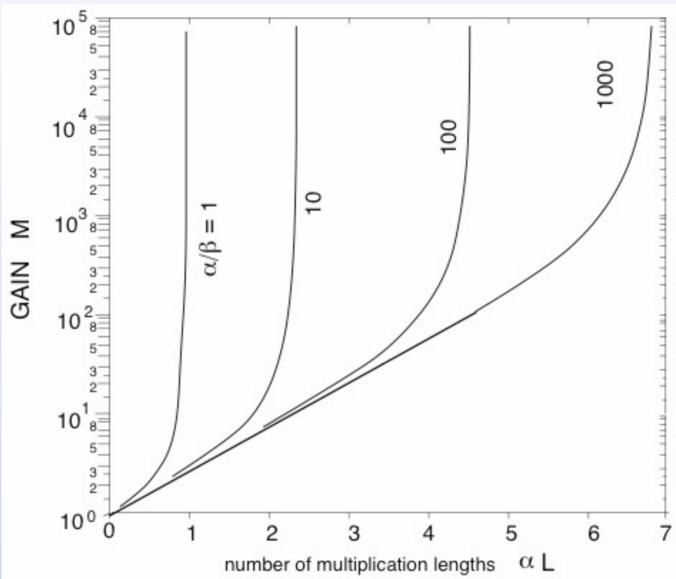
- Avalanche Photodiode





http://www.olympusmicro.com/primer/digitalimaging/concepts/avalanche.html

- With positive feedback internal gain is potentially infinite

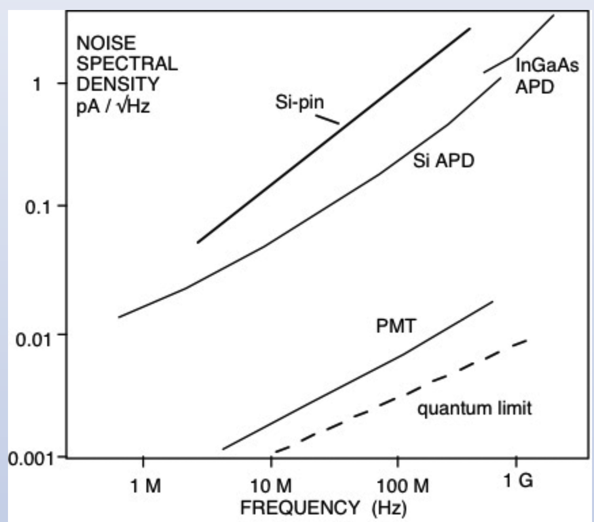


Optimum Gain determined by ratio of electron to hole ionization rates

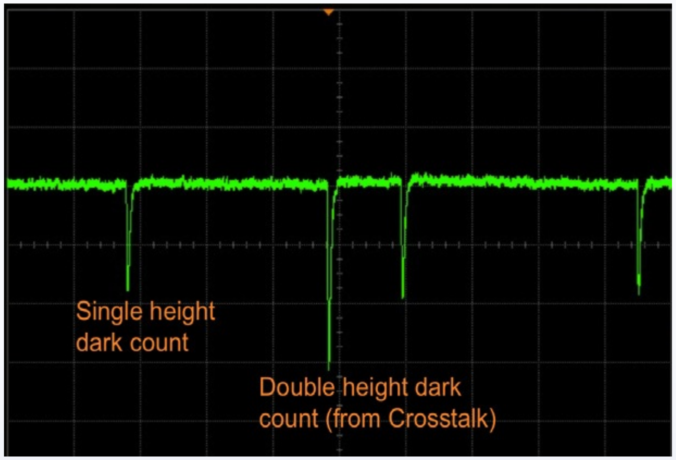
$G_{opt} = \alpha/\beta$.

Material with optimum natural path length turns out to be Silicon with a Gain of ~100. Even artificial materials are time consuming, difficult to make and the overall results are barely better than that of Silicon.

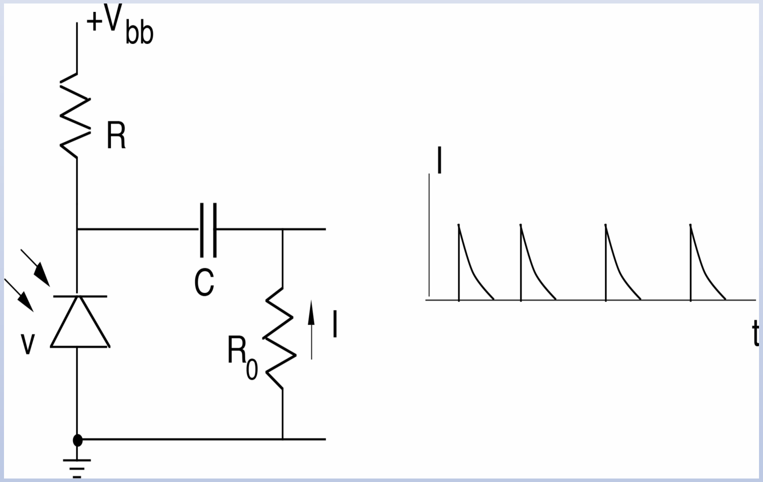
ADP still not ideal…



SPAD (Single Photon Avalanche Detector)



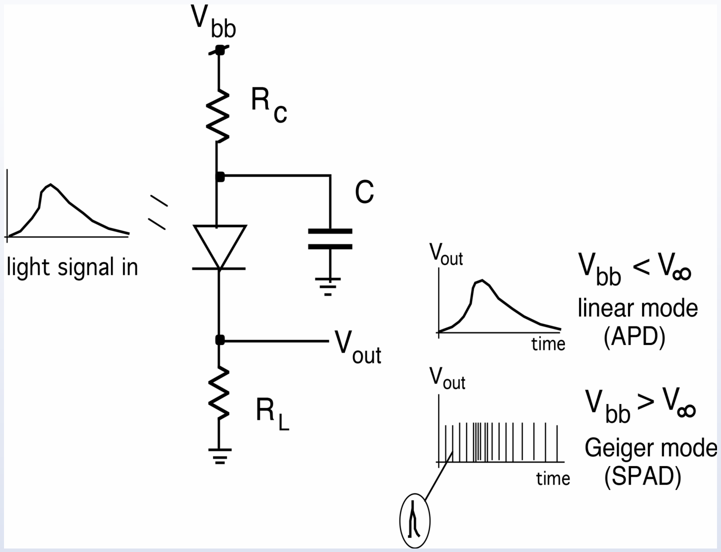
- Geiger Mode – One or more photons hit the photodiode, which produces a current sufficient to short this circuit. The circuit then has a recovery time proportional to the time constant of the RC circuit. Thus this method of detection is very analogous to that of a Geiger counter



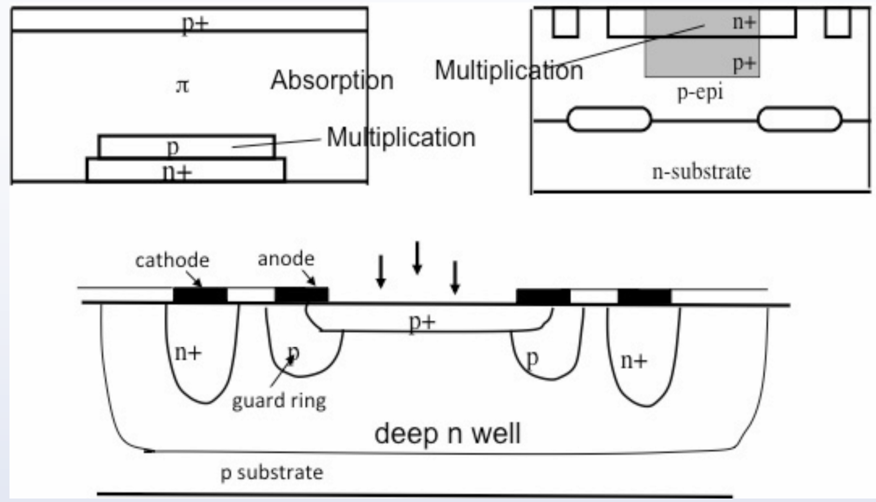
Therefore two important differences exist between the SPAD and the traditional PMT:

1. Dead Time – whereby the circuit must recharge before more detections are made.
2. Photon-at-a-time Counting – could be one photon could be millions the voltage produced will always be the same.

Dark currents also provide a problem; due to the charge/discharge times the maximum frequency of detection $f\text{max} \approx 1/T_R$, while due to dark currents the minimum frequency $f\text{min} = J_d A_d / e$, means that we must keep the total area of the detector low in order to adequately detect low frequency signals.

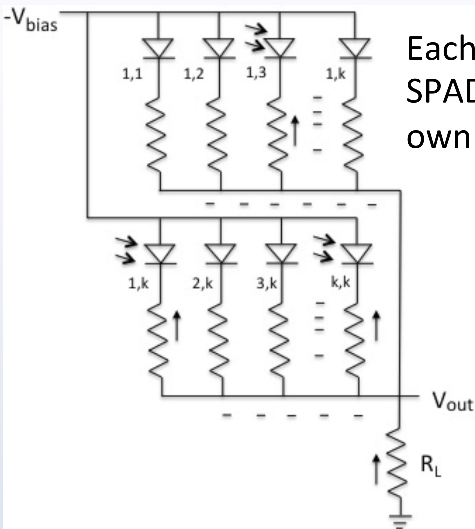


In the linear mode of operation (APD) the output signal waveform is a replica of the input, whereas in the Geiger mode of operation the SPAD supplies a series of pulses, all equal in waveform, whose rate is proportional to the input light power.



The early APDs (top left) featured a reach-through structure with a deep depletion layer for absorption, required high bias voltage and had long transit time, whereas the first SPADs (top right) used a much thinner absorption layer that reduces bias voltage and improves response time and dark current, at the expense of an earlier red λ-cutoff. Recent improvements (bottom), use a deep p-guard ring to control edge breakdown and n-trench to reduce diffusion and dark current, in an SPAD structure which is CMOS compatible.

Solid State Photomultiplier Tube



Each of these SPADs has its own RC circuit

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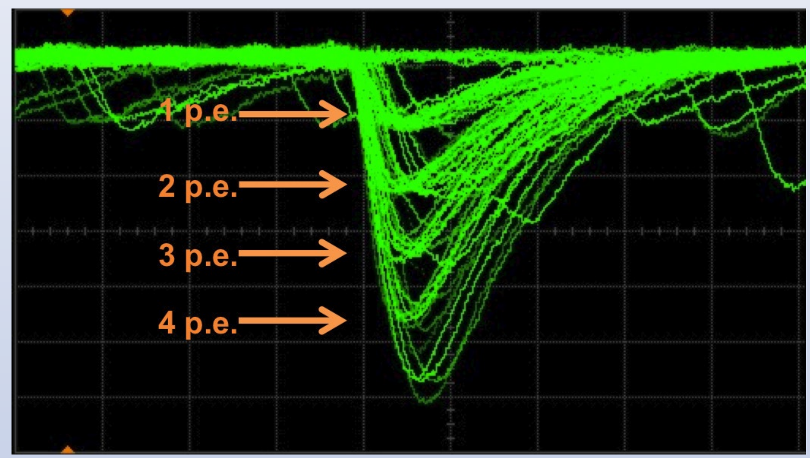
In an SSPM, the device is arrayed into a large number of individual pixels, each with an SPAD. Output currents are all summed up in a common load R_L. If three photons are received simultaneously, because of statistics they will hit separate pixels and trigger different SPADs, thus injecting into load R_L a current three times the single-pixel current. To allow separate quenching of each individual SPAD of the array, each pixel has its own ballast resistance.

Make a tight array of, for example 400 SPADs of area 50 X 50 μm^2 with all currents from individuals added together to produce a single output signal.

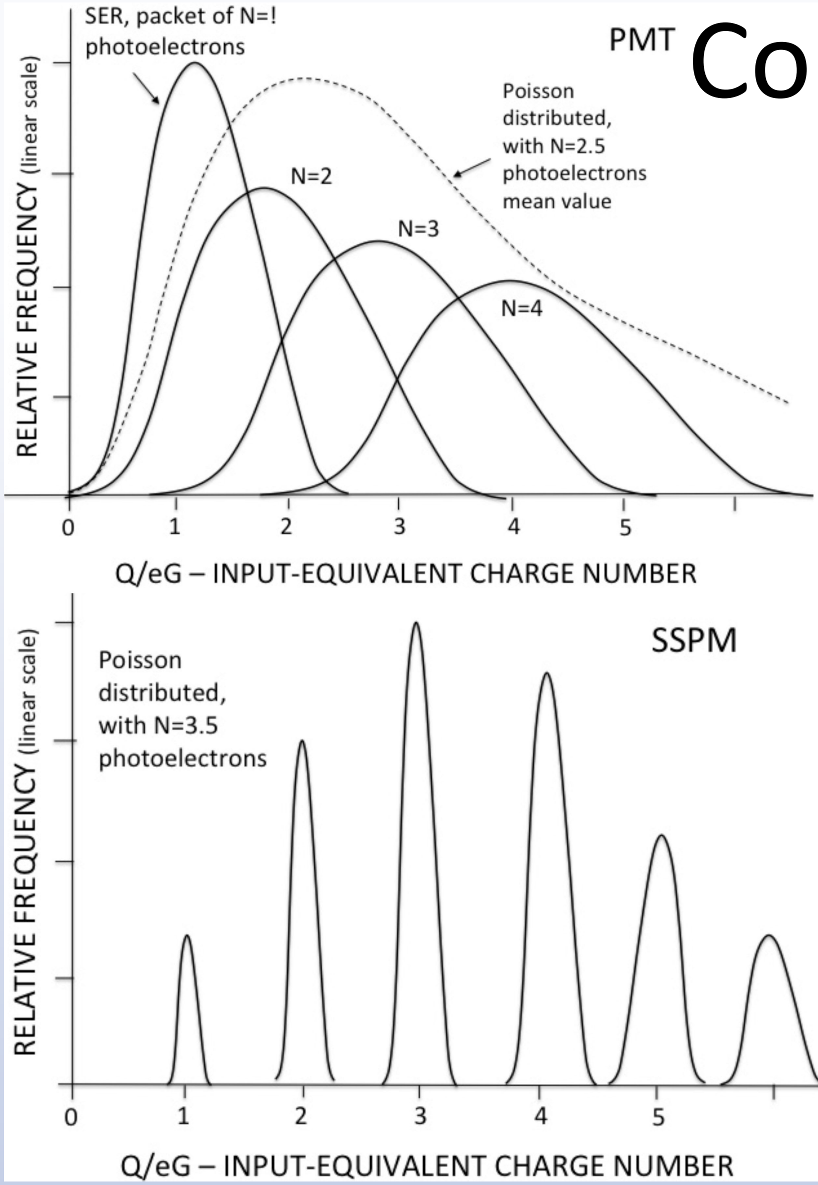


http://www.sensl.com/downloads/ds/TN%20-%20Intro%20to%20SPM%20Tech.pdf

Reliance on Statistics

- If you make the individual area of a pixel small enough, and increase the density of pixels, then the likelihood of problematic photon-at-a-time counting is limited
- As long as number of pixels is larger than the product of recovery time and photon rate, each pixel should have enough time to recover before another photon would come. In this way dead time is mitigated
- Densities of up to 4000/mm^2 are common

Comparisons



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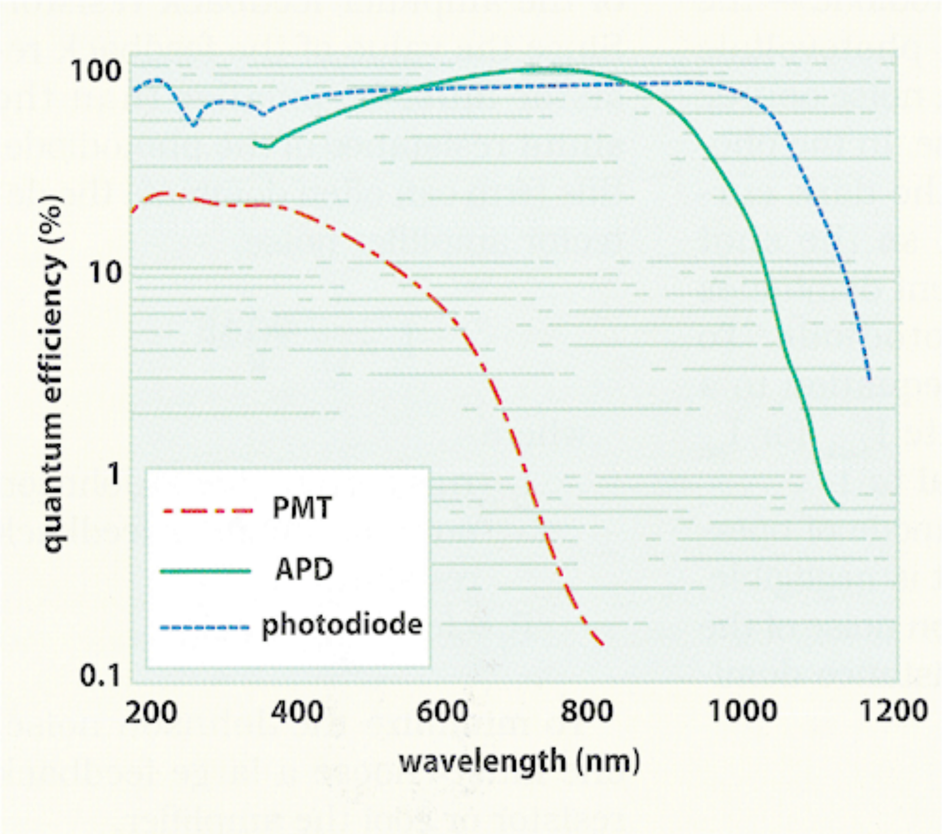
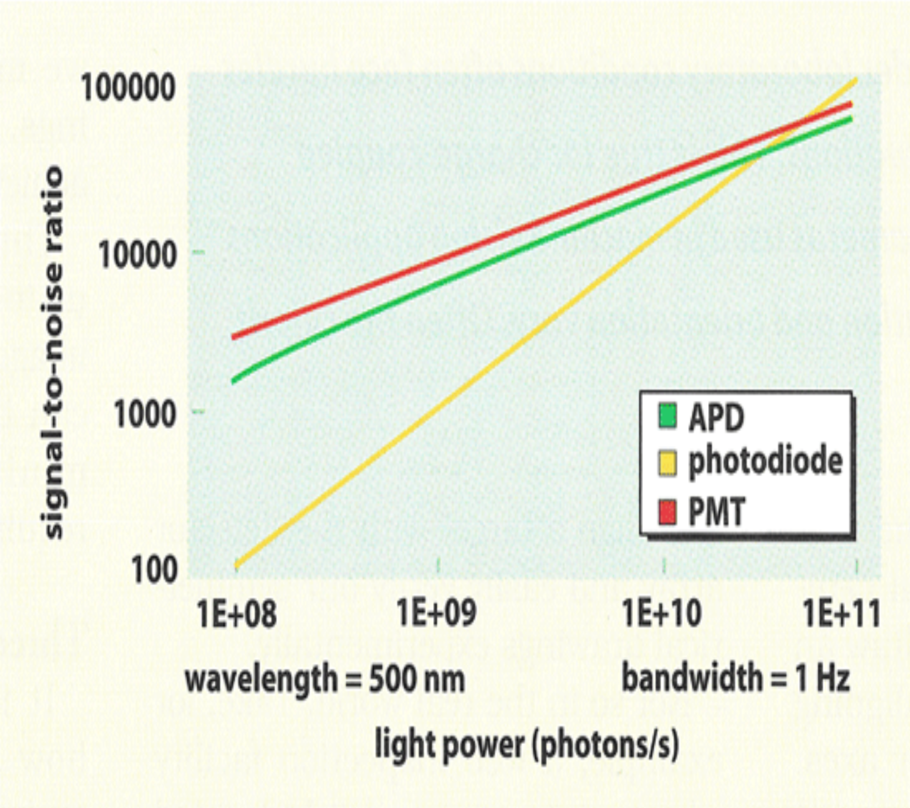
- SiPMTs are able to produce smaller jitter because of the ability to place processing equipment directly behind equipment with little penalty
- Power required is ~25 V compared to the ~2000V of a traditional PMT
- Complexity of a SiPMT is much reduced through use of photodiodes and solid-state devices as opposed to vacuum tubes, dynode chains, and photocathode.





Spectral response of a PMT, APD, and photodiode.

Signal-to-noise ratio vs. light power for a PMT, APD, and photodiode.

http://www.hamamatsu.com/us/en/community/optical_sensors/tutorials/guide_to_detector_selection/index.html

	PIN	APD	PMT	SPM
Gain	1	10^2	10^6	10^6
Operational Bias	Low	High	High	Low**
Temp. Sensitivity	Low	High	Low	Low
Mechanical Robustness	High	Medium	Low	High
Ambient light exposure?	OK	OK	NO	OK
Spectral range	Red	Red	Blue/UV	Green
Readout / Electronics	Complex	Complex	Simple	Simple
Form factor	Compact	Compact	Bulky	Compact
Large area available?	No	No	Yes	Yes
Sensitive to magnetic fields?	Yes*	Yes*	Yes	No
Noise	Low	Medium	Low	High
Rise time	Medium	Slow	Fast	Fast

** Due to the requirement for the external electronics to be located close to the detector*
*** SPM from SensL, having an operational bias of 30V, meet the requirements of the Extra Low Voltage directive*

http://www.sensl.com/downloads/ds/TN%20-%20Intro%20to%20SPM%20Tech.pdf

THE END

References

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- **Single-Photon Detectors: From Traditional PMT to Solid-State SPAD-Based Technology** Silvano Donati, Life Fellow, IEEE, and Tiziana Tambosso, Senior Member, IEEE
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- **Physics 575 2015 lectures** by Richard J. Wilkes
- **Physics 433 2014/2015 lectures** by Henry Lubatti
- **Introduction to SiPMs** by AdvanSiD