# Light Detection with *SiPMs*

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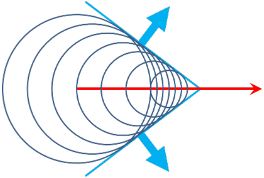
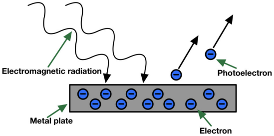
## Contents

# Light - Matter Interaction

## Introduction

- Let´s focus in two scenarios:
  - **Charged particles vs matter:** Ionization, Cherenkov Effect, Bremsstrahlung
  - **Photons vs matter:** Photoelectric Effect, Compton effect, pair production



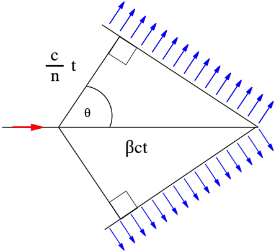


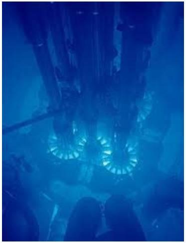
- Cherenkov effect produces light (UV photons) while Photoelectric effect produces photo-electrons

# Cherenkov Effect

## Basic Concepts

- Cherenkov radiation is electromagnetic radiation emitted when a charged particle (such as a muon) passes through a dielectric medium at a speed greater than the speed of light in that medium.



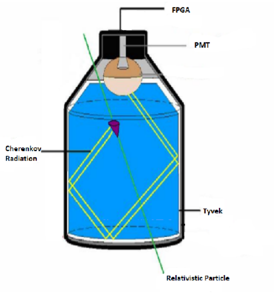


- Its cause is similar to the cause of a sonic boom, the sharp sound heard when faster-than-sound movement occurs.
  - $\beta$ the ratio between the speed of the particle and the speed of light
  - The emitted light waves travel at speed $v_e = c/n$
  - the emission angle results in $cos\theta = 1/n\beta$

# Cherenkov Effect

## Applications

- A Water Cherenkov Detector WCD is used to detect relativistic particles (muons, electrons even neutrinos)

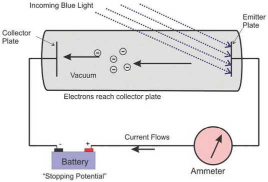


- Cherenkov radiation is detected by a Photomultiplier PMT and converted into electric current
- This signal is digitized and processed by an FPGA

# Photoelectric effect

## Basic Concepts

- The photoelectric effect is the emission of electrons when electromagnetic radiation, such as light, hits a material. Electrons emitted in this manner are called photo-electrons.
- In 1905, Einstein proposed a theory of the photoelectric effect using a concept first put forward by Max Planck that light consists of tiny packets of energy known as photons or light quanta.

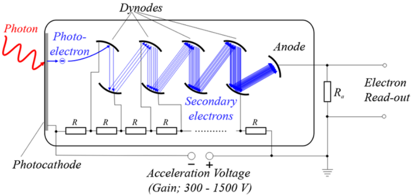


- Kinetic energy of the emitted photo-electron is $K = h(f - f_o$
- The emitted photo-electron can be accelerated by an external electric field

# Photomultipliers

## Basic Concepts

- These are extremely light-sensitive vacuum tubes with a coated photocathode inside the envelope.
- By means of a series of electrodes (dynodes) at ever-higher potentials, these electrons are accelerated and substantially increased in number through secondary emission to provide a readily detectable output current.



- Photomultipliers are still commonly used wherever low levels of light must be detected

# Photomultipliers

## Pros and Cons

Pros

- PMTs are extremely sensitive detectors of light (UV, visible, and near-IR)
- PMTs amplification is as much as $10^8$ (i.e. 160 dB!!!)
- They have low noise and fast response

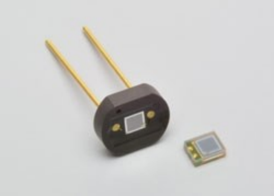
Cons

- PMTs need High Voltage HV (300 to 2000 V) sources to operate.
- PMTs are sensitive to Magnetic Fields
- Very expensive and delicate

# Silicon Photo-multipliers

## Basic concepts

- The Silicon Photomultiplier (SiPM) is a sensor that addresses the challenge of sensing, timing and quantifying low-light signals down to the single-photon level
- The SiPM features low-voltage operation, insensitivity to magnetic fields, mechanical robustness and excellent uniformity of response

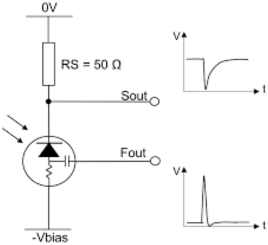


- When a photon travels through silicon, it may be absorbed and transfer energy to a bound electron. This absorbed energy causes the electron to move from the valence band into the conduction band, creating an electron-hole pair.

# Silicon Photo-Multipliers

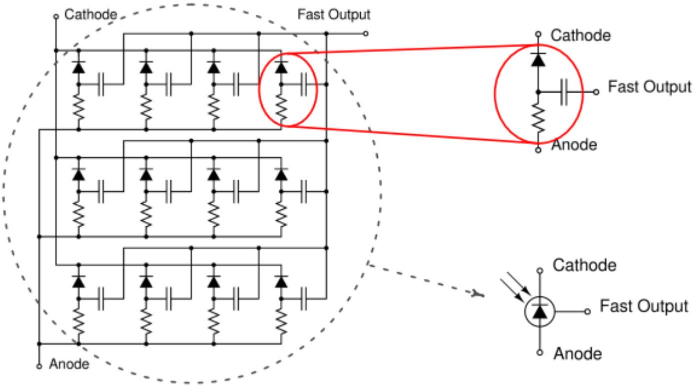
## Photodiodes

- A photodiode is formed by a silicon *p-n* junction that creates a depletion region that is free of mobile charge carriers.
- When a photon is absorbed in silicon it will create an electron-hole pair.
- Applying a reverse bias to a photodiode sets up an electric field across the depletion region that will cause these charge carriers to be accelerated towards the anode (holes), or cathode (electrons).



# Silicon Photomultipliers

## Schematic

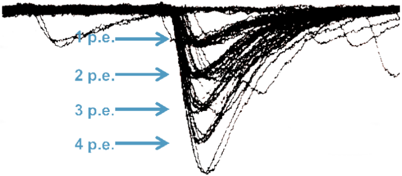


Simplified Circuit Schematic of a SiPM showing each Microcell which is Composed of the SPAD (Single Photon Avalanche Diode)

# Silicon Photomultipliers

## Pulse shape

- The response to low-level light pulses of an reverse biased SiPM is



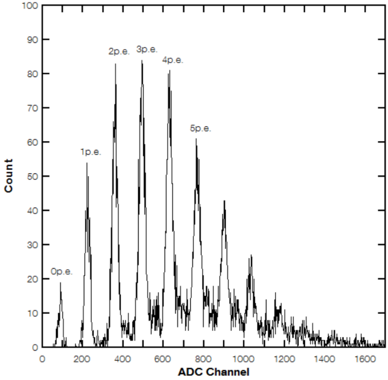
- The sensor output is a photocurrent, and the total charge $Q$ generated from an event is given by,

$$Q = N_{fired} \cdot G \cdot q$$

- Where $G$ is the gain and $q$ is the electron charge

# Photo-electron Spectrum

- The total charge is also equal to the integral of the photo-current pulse

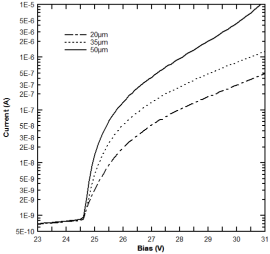


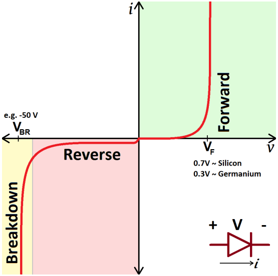
- Achieved using Brief, Low-level Light Pulses

# Performance Parameters

## Breakdown Voltage and Overvoltage

- The breakdown voltage ($V_{br}$) is the bias point at which the electric field strength generated in the depletion region is sufficient to create a Geiger discharge.





- Bias Voltage is $V_{bias} = V_{br} + \Delta V$
- $\Delta V$ is the Overvoltage
- $V_{br}$ and $\Delta V$ are given in product's datasheet

# Performance Parameters

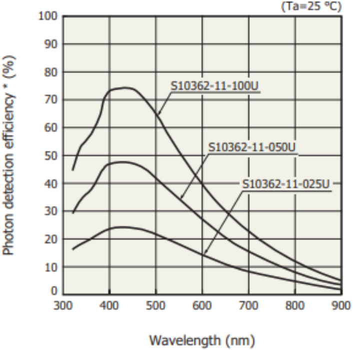
## Gain

- The gain of an SiPM sensor is defined as the amount of charge created for each detected photon, and is a function of overvoltage and microcell size
$$G = \frac{C \cdot \Delta V}{q}$$
- If the charge from each pulse is integrated and a charge spectrum is formed, the peaks due to successive numbers of detected photons will be clearly visible
- The separation between each pair of adjacent peaks (in $pC$) is constant and corresponds to the charge generated from a single fired microcell.
- This can therefore be used to accurately calculate the gain, using the equation above.

# Performance Parameters

## Photon Detection Efficiency and Responsivity

- The photon detection efficiency (PDE) is a measure of the sensitivity of an SiPM and is a function of wavelength of the incident light, the applied overvoltage and microcell fill factor



- The PDE differs slightly from the quantum efficiency (QE) that is quoted for a PMT or APD

# Performance Parameters

## Photon Detection Efficiency and Responsivity

- The PDE is the statistical probability that an incident photon interacts with a microcell to produce an avalanche, and is defined as:

$$PDE(\lambda, V) = \eta(\lambda) \cdot \varepsilon(V) \cdot F$$

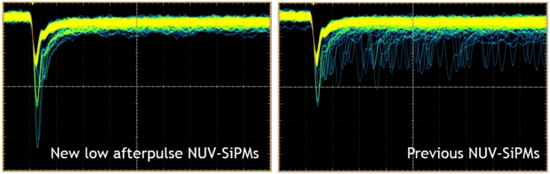
- where $\eta(\lambda)$ is the quantum efficiency of silicon, $\varepsilon(V)$ is the avalanche initiation probability and $F$ is the fill factor of the device
- The quantum efficiency is a measure of the likelihood of an incident photon creating an electron-hole pair in the sensitive volume of the sensor.
- The responsivity is defined as the average photocurrent produced per unit optical power and is given by:

$$R = \frac{I_p}{P_{op}}$$

- where $I_p$ is the measured photocurrent and $P_{op}$ is the incident optical power at a particular wavelength over the sensor area.

# Afterpulsing

- During breakdown, carriers can become trapped in defects in the silicon.
- After a delay of up to several *ns*, the trapped carriers are released, potentially initiating an avalanche and creating an afterpulse in the same microcell.

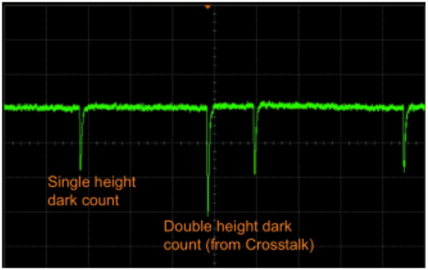


- Afterpulses with short delay that occur during the recovery time of the microcell tend to have negligible impact as the microcell is not fully charged. However, longer delay afterpulses can impact measurements with the SiPM if the rate is high

# Dark Count Rate

## Noise in SiPMs

- The main source of noise in an SiPM is the dark count rate (DCR), which is primarily due to thermal electrons generated in the active volume. The DCR is a function of active area, overvoltage and temperature

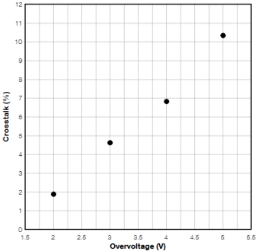


- Since the dark count is comprised of a series of pulses, its magnitude is quoted as a pulse rate (kHz)

# Optical Crosstalk

## Noise in SiPMs

- During avalanche, accelerated carriers in the high field region will emit photons that can initiate a secondary avalanche in a neighboring microcell.
- These secondary photons tend to be in the near infrared (NIR) region and can travel substantial distances through the silicon



- Optical Crosstalk increases with overvoltage

# SiPM advantages

- The SiPM has high gain ($10^6$) and PDE ($> 50\%$) combined with the physical benefits of compactness, ruggedness and magnetic insensitivity.
- In addition, the SiPM achieves its high gain with very low bias voltage ( $50V$) and the noise is almost entirely at the single photon level.
- Because of the high degree of uniformity between the microcells the SiPM is capable of discriminating the precise number of photons detected as distinct, discrete levels at the output node
- The ability to measure a well resolved photoelectron spectrum is a feature of the SiPM which is generally not possible with PMTs due to the variability in the gain, or excess noise
- Some SiPM models can detect radiation (X, $\gamma$) directly

# References

- Hamamatsu PMTs
- Multi-Pixel Photon Counters
- On-semi SiPM application notes