Light Detection with *SiPMs*

by Dennis Cazar Ramírez

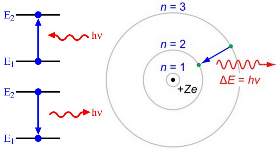
May 4, 2024

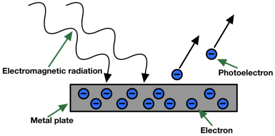
Contents

Light - Matter Interaction

Introduction

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



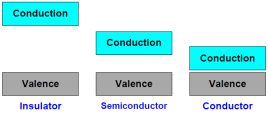


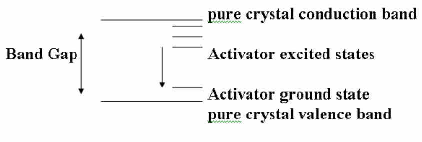
- Scintillation is light produced when a particle excites electrons from their fundamental levels.

Scintillation detectors

Inorganic scintillators

- Band structure for electron energies in solids (left), activated crystalline scintillator (right)



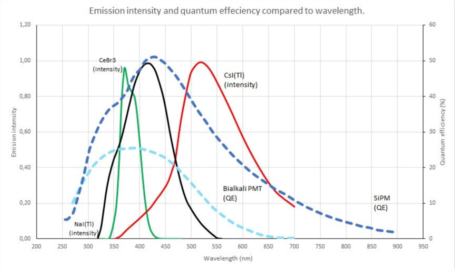


- In the **pure crystal**, Photon emission decay es very inefficient and band gap widths are such that the resulting emitted photon is too high to lie within the visible range
- Small amounts of impurities called **activators** create additional energy levels, the emission spectrum is shifted to longer wavelengths.

Scintillation detectors

Inorganic scintillators

- Types of inorganic scintillators:
    - Alkali halide: NaI(Tl), CsI(Tl), CsI(Na), LiI(Ei)
    - Other slow Inorganics: BGO, $CdWO_4$, ZnS(Ag)
    - Cerium-Activated Fast Inorganics: GSO, YAP, YAG, LSO, LuAP, $LaBr_3$

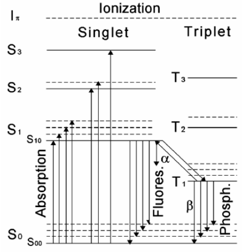


- The timing of the light output is dependent on the half-life of the state (typically 10^{-7} s).

Scintillation detectors

Organic scintillators

- The fluorescence mechanism in organic materials arises from transitions in the energy levels of a single molecule and therefore the fluorescence can be observed independently of the physical state.

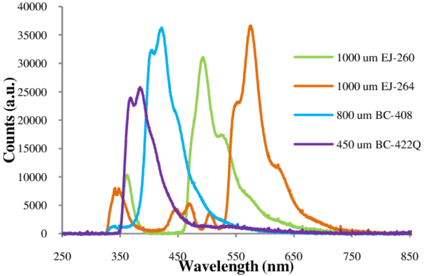


- Practical organic scintillators are organic molecules which have symmetry properties associated with the electron structure.

Scintillation detectors

Organic scintillators

- Scintillation light, prompt fluorescence, is emitted in transitions between S10 and the ground state.

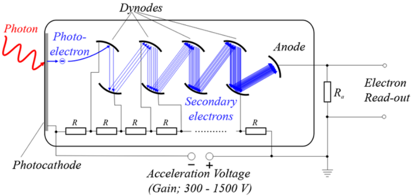


- Organic scintillators are very fast (≈ ns).
- Types of organic scintillators: Pure organic crystals: Anthracene, Stilbene, Liquid organic solutions: by dissolving an organic scintillator in a solvent, Plastic scintillators: dissolving & polymerizing

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

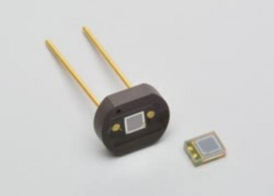
Cons

- 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

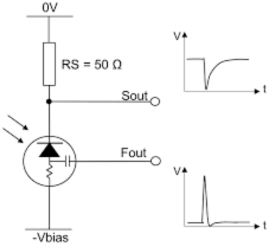


- When a photon travels through silicon, it may be absorbed and transfer energy to a bound electron. This absorbed energy causes the electron to move from the valence band into the conduction band, creating an electron-hole pair.

Silicon Photo-Multipliers

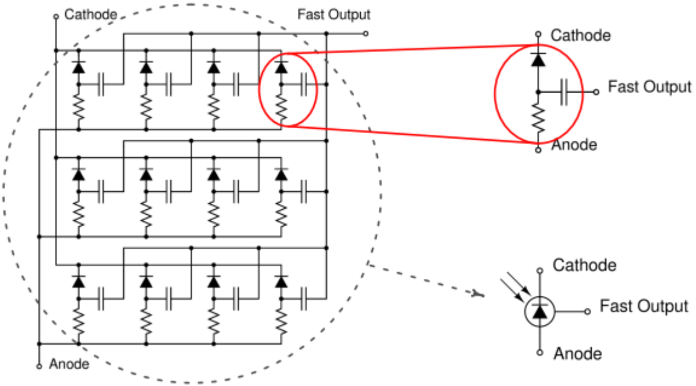
Photodiodes

- 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

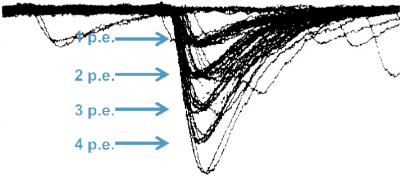


Simplified Circuit Schematic of a SiPM showing each Microcell which is Composed of the SPAD (Single Photon Avalanche Diode)

Silicon Photomultipliers

Pulse shape

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



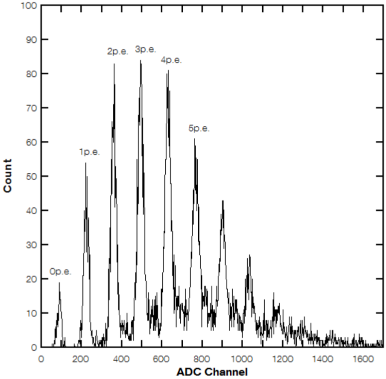
- The sensor output is a photocurrent, and the total charge Q generated from an event is given by,

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

- 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

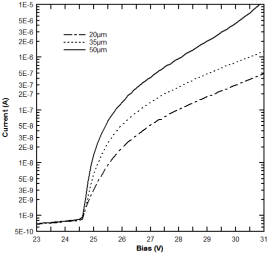


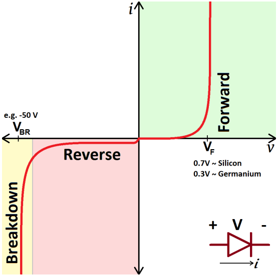
- Achieved using Brief, Low-level Light Pulses

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

Performance Parameters

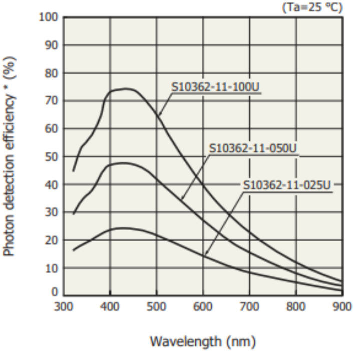
Gain

- 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:

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

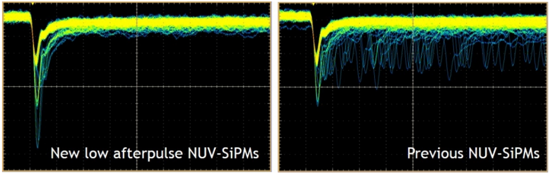
- where $\eta(\lambda)$ is the quantum efficiency of silicon, $\varepsilon(V)$ is the avalanche initiation probability and F is the fill factor of the device
- The quantum efficiency is a measure of the likelihood of an incident photon creating an electron-hole pair in the sensitive volume of the sensor.
- 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.

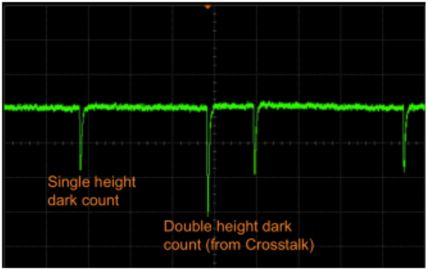


- Afterpulses with short delay that occur during the recovery time of the microcell tend to have negligible impact as the microcell is not fully charged. However, longer delay afterpulses can impact measurements with the SiPM if the rate is high

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

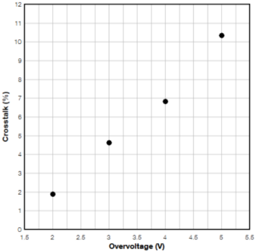


- Since the dark count is comprised of a series of pulses, its magnitude is quoted as a pulse rate (kHz)

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, γ) directly

References

- Hamamatsu PMTs
- Multi-Pixel Photon Counters
- On-semi SiPM application notes
- G.F. Knoll, Radiation Detection and Measurement - 3rd edition (Chapters 16 to 18), John Wiley & Sons, 1999.