Recent developments in photodetection for Astroparticle Physics

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Outline

- The Physics behind silicon photomultipliers
- Geometry and principle of operation
- A SiPM for every need: from vacuum-ultra-violet to near-infrared, to extreme environments
- SiPMs for astroparticle physics
The Nobel Prize in Physics 1921 was awarded to Albert Einstein

a) «for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect»
b) «for his services to Theoretical Physics, and especially for his theory of special relativity, reconciling Newton’s laws of motion with electromagnetism»
c) «for his services to Theoretical Physics, and especially for his theory of gravitation*»

*a.k.a.: «general relativity»
The Nobel Prize in Physics 1921 was awarded to Albert Einstein "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect."

Albert Einstein received his Nobel Prize one year later, in 1922. During the selection process in 1921, the Nobel Committee for Physics decided that none of the year's nominations met the criteria as outlined in the will of Alfred Nobel. According to the Nobel Foundation's statutes, the Nobel Prize can in such a case be reserved until the following year, and this statute was then applied. Albert Einstein therefore received his Nobel Prize for 1921 one year later, in 1922.

https://www.nobelprize.org/prizes/physics/1921/summary/
Photoelectric absorption is a **threshold** process: $E_b$ is the minimum amount of energy a photon must carry to extract the electron.

\[
\gamma (E_\gamma = h\nu) \quad \rightarrow \quad E_{e^-} = h\nu - E_b
\]
Detectors that exploit the photoelectric effect: Photomultiplier tubes

http://www-sk.icrr.u-tokyo.ac.jp/~sk/index-e.html

https://icecube.wisc.edu/science/icecube/
Detectors that exploit the photoelectric effect: Solid-state sensors

**Photodiodes**

![Photodiode schematic](image1)

*Figure 3.12: Schematic of a Si photodiode cross section.*

**APD**

![APD schematic](image2)

*Figure 3.13: Effect of a photon impinging on a photodiode.*

**GM-APD**

- p/n junction is biased above the breakdown voltage → single hole-electron pair can trigger a self-sustaining avalanche.

- gain factor: $10^4$-$10^7$, even with relatively low applied voltages (few tens of volts).

Hamamatsu Photonics Handbook. Si Photodiodes
Silicon photomultipliers (SiPMs): an array of GM-APDs

SiPMs: array of reverse-biased Single Photon avalanche Diodes (SPADs) connected in parallel, each with integrated quenching resistor

SiPM size: from 1x1mm$^2$ to 10x10mm$^2$

SPAD size: from 5µm to 40µm (typical)

http://advansid.com/resources/the-silicon-photomultiplier
SiPMs: 3D view

SiPMs I-V curves

Forward and reverse I-V characteristics of a NUV 1x1mm² SiPM with 40µm cell at different temperatures. (M. Capasso, «Development of a NUV camera for Cherenkov telescopes applications»)
A single-photon counter in action

The output signal is proportional to the impinging number of photons (in the linear regime)
SiPMs: Fill Factor

\[ FF = \frac{A_{\text{eff}}}{A_{\text{total}}} \]

- All SiPMs belonging to a given technology lie on the same curve
- Smaller pixels → higher dynamic range and faster recovery
- Larger pixels → higher efficiency

The optimal compromise varies from application to application (figure of merit)

A. Gola et al., https://doi.org/10.3390/s19020308
SiPMs in a snapshot: why we like them

High PDE

- High PDE

Single p.e. resolution

- Ruggedness
- Insensitivity to magnetic fields
- ...

Gola et. al. https://www.mdpi.com/1424-8220/19/2/308

https://webstockreview.net/explore/thumb-clipart-hand/
Compactness, ruggedness, insensitivity to magnetic fields, wide sensitivity spectrum: a perfect mix for scientific and industrial applications!!!

LIDAR (light detection and ranging)

fNIRS (functional NIR Spectroscopy)

Rare-event experiments

Liquid Argon emission, wavelength-shifted (~400-450nm)

2 light readout planes: ~20 m²
SiPMs at FBK: technological roadmap

https://www.fbk.eu/it/

- RGB
- NUV
  - Electric field engineering for green and UV response
- RGB-HD
- NUV-HD
  - High density cells with deep trench isolation
- Position Sensitive
  - Position sensitive with xy spatial resolution
- NUV-HD-LF
  - Optimized for oxygen applications
- VUV-HD
  - ARC optimizer for detection in VUV (~175nm)
- RGB-UHD
  - Ultra-high density, very small cells
- NIR-HD
  - Thick epitaxial for improved detector-1000nm RQE

2012
2013
2014
2015

Today
INFN and FBK, a long, fruitful partnership (a.k.a.: an undergraduate story)


- 2013-2014: M. Capasso first internship at FBK and Master’s thesis on SiPM for Cherenkov telescopes applications

- …
Some SiPM recent developments

SiPMs for «extreme» environments: cryogenic applications

SiPMs for short (VUV) or long (NIR) wavelengths
NUV-HD go “cool”: cryogenic challenges

Tunneling is the primary DCR generation mechanism

Increase of release time constant of trapping centers increases AP probability (LF is not enough).


A. Gola et al., *Sensors* 19, no. 2, (2019), 308
Reverse IV curves at 77K (LN), under light

A. Gola et al., *Sensors* 19, no. 2, (2019), 308

Full operational range recovered
In some specific applications direct detection of VUV light is required → NUV-HD technologies have 2 main limiting factors

Typical ARC is a multi-layer stack of $\text{SiO}_2$ (absorbs $\lambda < 150\text{nm}$), $\text{Si}_3\text{N}_4$ (absorbs $\lambda < 250\text{nm}$) → external QE is affected

Ultra-shallow absorption of UV light → generated e-h pairs have high recombination probability → internal QE is affected

R&D focused on ARC optimization:
• $\text{Si}_3\text{N}_4$ removal
• Preservation of surface passivation quality

Current R&D has been conducted in collaboration with TRIUMF

Gallina et. al, 2019
https://doi.org/10.1016/j.nima.2019.05.006
Near-infrared detection with SiPMs: technical challenges

RGB-HD’s cross-section

Acerbi et al, 2018 10.1109/JQE.2018.2802542

Absorption depth in silicon

Absorption depth in silicon:
- ~5 μm
- ~12 μm
- ~33 μm

Longer absorption depth → thicker epitaxial layer

Border effects may limit the effective area, reducing the PDE despite the thicker epi

Dedicated electric-field engineering partially reduced lateral depletion and extended high-field region

TCAD simulation at BD

Dedicated electric-field engineering
Future challenges

- **Go denser**: some applications might require higher pixel density for higher dynamic range
  - Push pixel design to the limit in order to keep satisfactory fill-factor
- **Go harder**: required in high-energy-physics experiments and space applications
- **Go longer**: better performance in the NIR of interest for e.g.: LIDAR applications
SiPMs for Cherenkov astronomy

The Schwarzschild-Couder Telescope at the Fred Lawrence Whipple Observatory (Arizona)
The motivation

The milestone

The inauguration

Photo: M. Capasso

Credit: CTA/SCT consortium
The CTA SCT Project

- ~30 institutions [https://cta-psct.physics.ucla.edu/institutions.html](https://cta-psct.physics.ucla.edu/institutions.html)

Milestones:
- 1st construction: 06-23-2015
- Inauguration: 01-17-2019
- 1st light: 01-23-2019
- December 2019: optical alignment achieving pre-construction estimated PSF
- May 2020: significant detection of the Crab Nebula (presented at 236th AAS) – published paper
- Endorsement by the CTA Consortium for supporting the development and construction of SCTs to add to the array and complement single-mirror MSTs

Next steps:
- Ongoing (funded MRI): population of the focal plane to ~11k channels with upgraded SiPMs and electronics
The SCT SiPM camera

- Full camera = 9 sub-fields
- 177 modules
- 11,328 image pixels

1 sub-field = 25 modules

Module of 64 image pixels

4 image pixels = 1 trigger pixel

~2.7° FOV

INFN modules
Preamplifier+FEE upgrade

- **Testing Setup:**
  - **Full chain** from SiPMs to FEE assembled
  - Laser source + moving stage to illuminate one pixel at a time
Full-chain testing: current vs. upgrade

Preamps and current sensors

FPM and preamps

Separate trigger and digitizer

FPM + preamps and current sensors (SMART)

(C)T5TEA + (C)TC

Charge Spectrum

Charge (ADC-ns)

Counts

Entries 7944
Mean 67.64
RMS 49.64

F. Giordano, M. Capasso
15/07/21
SiPMs are nowadays a mature technology that can replace PMTs in a wide variety of applications requiring single-photon sensitivity
- There is a SiPM for every need and every spectral response from VUV to NIR

SiPMs in ground-based Cherenkov astronomy: the SCT
- A milestone pathfinder for dual-mirror telescope technology + solid-state sensors
- New SiPMs, new electronics and a fully-populated focal plane to come! (The upgrade is ongoing)

STAY TUNED!!!