Characterization of SiPM Avalanche triggering probabilities

Giacomo Gallina
Fabrice Retiere

giacomo@triumf.ca
Outline

- Introduction / Motivation.
- Avalanche Triggering Probability Modelling
- Dark Noise Modelling
- Conclusions
Introduction / Motivation
Our work is primarily targeted towards low-background liquid noble experiments (Dark Matter & Neutrino) but other experiments can be considered in the future.
Commercial Applications

**LXe PET Scanner (Medical Imaging)**

**Challenge:** Pulse Timing $< 15$ [ps]

**LiDAR Sensors with SiPM (3D Imaging)**

**Challenge:** Good PDE ($>30\%$) from 200-800 [nm]

**Early-Fire Gas Analyzer:** Use both Visible and UV light for particle studies in areas where fires are a considerable yearly problem (west-coast US, Canada).

**Goal of this talk:** Infer design parameters for future photodetector developments!
Avalanche triggering probability modelling
The Photo-Detection-Efficiency (PDE) is defined as the probability for a photon (of a given wavelength) to be detected and produce a measurable signal in the SiPM.

Usually PDE is defined as

\[
PDE = FF \cdot QE(\lambda) \cdot T_p(V, \lambda)
\]

1) lack of formal separation between the different processes that define the total PDE.
2) lack of an analytical expression
How Do SiPMs Work? Solid-State Approach

p-n junctions micro-cells operated in Geiger-mode, with an added quenching resistor. Each SiPM is composed by multiple micro-cells.
How Do SiPMs Work? Solid-State Approach

p-n junctions micro-cells operated in Geiger-mode, with an added quenching resistor. Each SiPM is composed by multiple micro-cells.
How Do SiPMs Work? Solid-State Approach

An incoming photon enters the junction and it is absorbed (wavelength dependent process).
The absorbed photons generate an electron-hole pair.

The diagram shows a single micro-cell with a silicon oxide layer (SiO₂) on the left, a positive (P⁺) region in the middle, and a negative (N) region on the right. The excess charges are indicated by white and black circles within the P⁺ region, representing electrons and holes, respectively. The graph on the right side illustrates the carrier concentration and electric field distribution within the cell, with depth in micrometers [μm] on the x-axis and carrier concentration on the y-axis in units of cm⁻³.
How Do SiPMs Work? Solid-State Approach

The internal field of the junction brings the generated carrier (e/h) to the avalanche region.

The e-h pair can be created or not in the depleted region.
How Do SiPMs Work? Solid-State Approach

This triggers an avalanche, with gain $\sim 10^6-10^7$, which produces a readable signal.
PDE needs to account for the fact that if the photon is absorbed outside of the active region, it will not be observed.

\[ PDE = \epsilon_0 \cdot \int_{d_p}^{d_w} \frac{1}{\mu} \exp \left( -\frac{x}{\mu} \right) \cdot P_P(x, V) \, dx \]

The Total Avalanche Triggering Probability has both an electron-driven and a hole-driven component

\[ P_P(x, V) \equiv \left( P_e(x, V) + P_h(x, V) - P_e(x, V) \cdot P_h(x, V) \right) \]

The probability to have an electron-driven avalanche is defined as

\[ P_e(d_P) = \left[ 1 - \left( k_e \cdot V \cdot \exp \left( -\frac{k_{e2}}{\sqrt{V}} \right) \right) \right]^{-2} \]

The probability to undergo a hole-driven avalanche is dependent on \( P_e(d_P) \) and the field-strength factor in the junction \( k \).

\[ P_h(d_W) = \left[ 1 - \left( 1 - P_e(d_P) \right) \right]^k \]

\( W^* \) effective junction length
Avalanche Triggering Probability

We redefined the PDE to include the avalanche triggering probabilities for electron and hole driven avalanches.

\[
PDE = PDE_{\text{MAX}} \cdot \left( P_e(d_P) \cdot f_e^* + P_h(d_W) \cdot (1 - f_e^*) \right)
\]

where \( f_e^* \) is the fraction of avalanche electron driven

\[
f_e^* \equiv \left[ \frac{1 - \exp \left( -\frac{(x_{PN} - d_P^*)}{\mu} \right)}{1 - \exp \left( -\frac{W^*}{\mu} \right)} \right] \in [0 \ldots 1]
\]
Avalanche Triggering Probability

\[
PDE = PDE_{\text{MAX}} \cdot \left( P_e(d_P) \cdot f_e^* + P_h(d_W) \cdot (1 - f_e^*) \right)
\]

\[
f_e^* = \frac{1 - \exp \left( -\frac{x_{PN} - d_P^*}{\mu} \right)}{1 - \exp \left( -\frac{W^*}{\mu} \right)} \in [0, 1]
\]
Precise estimation of junction quantities can also be achieved and different devices can be compared.
Dark Noise Modelling
Dark Noise Characterisation

Can we infer the source of the Geiger mode Dark Noise?

- Is hole or electron dominated?
- Is SRH field enhanced or not?
- Band to band tunnelling is important?

To reduce the noise we need to understand its source.

Example using the Hamamatsu VUV4 data.

Graph showing dark noise vs over voltage with different temperatures.
It includes 3 main noise sources

- Band to Band tunneling
- Trap assisted tunnelling
- SRH recombination
- Diffusion

Finally the corrected slope can be predicted!
Conclusions
Conclusions

- New technologies and ideas are fundamental for precision physics to search beyond the standard model of particle physics.
- SiPMs already provide a great option (compared to PMTs) for experiments dominated by scintillation and Cherenkov light detection.
- SiPMs challenges include: size scalability, radiopurity, good timing, overall noise reduction.
- We have introduced a novel physics-driven method to characterize and fully understand SiPMs, including avalanche-triggering-probability (ArXiv:1904.05977).
- We are working on new models to precisely infer the source of the noise and optimise future SiPM development.
- We are commissioning new set-up to better understand and design new generation of SiPMs! Strongly interested in collaborations.
Thank you

www.triumf.ca
Backup
Photo-Detection-Efficiency

arXiv:1903.03663
Correlated Avalanches (CAs)

Temperature: 
- 233 [K]
- 163 [K]

Temperature: 
- 233 [K]
- 163 [K]

ArXiv: 1705.10183
Pulse Shape Fitting

Rise Time: \( \tau_r \propto \left( R_d \cdot C_j \right) \)

Parasitic Spike: \( \tau_S \propto \left( R_{tot} \cdot C_{tot} \right) \)

Recovery Time: \( \tau_L \propto \left( R_q \cdot C_j \right) \)

\( k \): relative contribution of \( t_S \) and \( t_L \).

![Schematic diagram of pulse shape fitting](image)

\[
V(t) = A \cdot \left( \frac{1 - k}{\tau_S} \right) \cdot \left( e^{-t/(\tau_S + \tau_r)} - e^{-t/\tau_r} \right) + \left( \frac{k}{\tau_L} \right) \cdot \left( e^{-t/(\tau_L + \tau_r)} - e^{-t/\tau_r} \right)
\]
New Setup at TRIUMF
VUV Optics and SiPM Characterization Setup
Boosting SiPM VUV Efficiency

**Photo Detection Efficiency:**
- Transmittance
- Reflectivity

**VUV Optics Game**

**VUV Setup Design:**
- Reflectance, Transmission, Fluorescence and more.
- Deuterium Lamp 100-400 nm continuous source spectrum.
- Advanced monochromator for precision wavelength selection.
- Ability to cool the sample to cryogenics temperatures.
- Ability to control the sample and readout position and tilt-angle.
- Reference PMT capable of sampling the beam via a parabolic mirror.
- Cryogenic sample holder with the ability to operate cold Diode/SiPM/PMTs.
AR Surface coating is critical for the ultimate VUV sensitive SiPM. (Issue: Si reflectivity at ~175 nm is ~50%) (SiO2 has poor transmission ~128 nm).

Important to balance transmission and reflectivity to identify the most optimal AR surface coating for 3DSiPM.

**Optical Material Selection Campaign:**
Currently Under Investigation:

- Al₂O₃
- MgF₂
- LiF
- LaF₃
- Pure Al
AR Surface coating is critical for the ultimate VUV sensitive SiPM.
(Issue: Si reflectivity at ~175 nm is ~50%)
(SiO2 has poor transmission ~128 nm).

Important to balance transmission and reflectivity to identify the most optimal AR surface coating for 3DSiPM.

Optical Material Selection Campaign:
Currently Under Investigation:

- Al₂O₃
- MgF₂
- LiF
- LaF₃
- Pure Al

We are interested in your samples !!!