Development of VUV light detection solutions

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Motivation

- Search for Neutrinoless double beta decay $^{0\nu\beta\beta}$ of $^{136}$Xe
- TPC with 5 tons of LXe
- LXe: decaying nucleus and detection medium
- Silicon Photomultipliers for the detection of VUV scint. light
- Simultaneous collection of light and charge

Targeted Energy resolution

1% Energy resolution in $^{0\nu\beta\beta}$ decay of $^{136}$Xe

SiPM photon detection efficiency drives “light” energy resolution

What is then a SiPM?
Introduction to SiPM

- Main Characteristics:
  - SPADs connected in parallel
  - Operated in reverse bias mode
  - Incoming photon triggers charge avalanche
  - Single pixel is discharged

- Advantages:
  - High gain at low bias voltage
  - Single photon detection resolution
  - High radio purity possible
  - Suitable at cryogenic temperature
Crosstalk suppression: a road throw the idea detector

- Uncorrelated Noise
- Dark Noise (thermal and voltage assisted noise)
- Correlated Noise:
  - After Pulse (almost suppressed)
- Cross Talk

Excess Noise Factor:

\[ F_{APD} \propto 1 + \frac{\sigma_M^2}{M_{APD}^2} \]

\[ F_{SiPM} \propto 1 + P_{CT} \]
## SiPM Requirement for nEXO

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photo-detection efficiency at 175-178nm in liquid Xenon (PDE)</td>
<td>≥ 15%</td>
</tr>
<tr>
<td>Radio purity: contribution of photo-detectors on the overall background</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Dark noise rate at -100°C</td>
<td>≤ 50 Hz/mm²</td>
</tr>
<tr>
<td>Average number of correlated avalanches per parent avalanche at -110°C</td>
<td>≤ 0.2</td>
</tr>
<tr>
<td>Single photo-detector active area</td>
<td>≥ 1cm²</td>
</tr>
<tr>
<td>Capacitance per area</td>
<td>&lt; 50 pF/mm²</td>
</tr>
<tr>
<td>Gain fluctuations + electronics noise</td>
<td>&lt; 0.1 PE</td>
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</tbody>
</table>
Correlated Avalanche (CA) in 1us for nEXO

Correlated avalanche Noise: “Sum of AP and CT events”

The nEXO DAQ acquisition window has a post trigger of 1us

**nEXO Requirement:** $CA < 0.2$
nEXO Requirement: PDE $\geq 15\%$

VUV4 is close to meet nEXO requirements

FBK LF meets nEXO requirements
The TRIUMF SiPM: overview

Goal: develop a new generation of SiPMs with high VUV sensitivity and low correlated noise

Stage 1 (This talk)

- Understand what drives the efficiency and optimisation parameters to obtain the best detector
- SiPM Characterisation
- Junction Modellization
- More to come …

Stage 2

SiPM design: Expected Results in 2020

Initial goal: Can we achieve a SiPM with no Correlated avalanche noise?

\[ F_{SiPM} \propto 1 + P_{CT} \]

Design optimised for Cross talk Suppression and Avalanche Triggering Probability Saturation
What Drives the Efficiency?

Understanding the over voltage dependence of the PDE is crucial to achieve high PDE in few OV.

- PDE saturates at different OV
- Same wavelength but probability saturates at a different OV
- Why the FBK saturates faster?
What Drives the Efficiency?

Understanding the over voltage dependence of the PDE is crucial to achieve high PDE in few OV.

We started building a simplified 1D model

$$\text{PDE} \sim \epsilon_0 \cdot \int_{d_p^*}^{d_w^*} \frac{1}{\mu} \exp\left(-\frac{x}{\mu}\right) \cdot P_P(x, V) \, dx$$

**Optical Efficiency:**
Transmission in the Silicon
$$\epsilon_0(\lambda) \sim \left[\text{FF} \times \left(1 - R(\lambda, \theta)\right)\right]$$

**Absorption in an effective volume**
$$W^* = (d_w^* - d_p^*)$$

**Avalanche triggering Probability**

Electric Field

PDE \sim \varepsilon_0 \cdot \int_0^{d_p^*} \frac{1}{\mu} \exp\left(-\frac{x}{\mu}\right) \cdot P_p(x, V) \, dx

Optical Efficiency:
Transmission in the Silicon

\varepsilon_0(\lambda) \sim \left[ \text{FF} \times (1 - R(\lambda, \theta)) \right]

Absorption in an effective volume

W^* = (d_W^* - d_p^*)

Avalanche triggering Probability

The FIELD is not zero outside the junction!
Diffusion drives part of the total efficiency
Junction Efficiency

\[ \text{PDE} \sim \epsilon_0 \cdot \int_{d_p^*}^{d_W^*} \frac{1}{\mu} \exp \left( -\frac{x}{\mu} \right) \cdot P_p(x, V) \, dx \]

From SPAD simulation a direct Num. Integration is preferable but a simplification is possible

\[ \text{PDE} = \text{PDE}_{\text{MAX}} \cdot \left( P_e(d_p) \cdot f^*_e + P_h(d_w) \cdot (1 - f^*_e) \right) \]

- \( P_e(d_p) = \) electron ATP measurable from UV light
- \( P_h(d_w) = \left[ 1 - \left( 1 - P_e(d_p) \right) \right]^k \) \( P_h(d_w) = \) hole ATP

\( k = \) Effective Ratio of ionization coefficients

conditional ATP = \frac{PDE}{PDE_{MAX}}

Probability to trigger an avalanche IF the photon is transmitted in the sensitive area of the detector

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

The ATP is not changing what is changing is the absorption position

EDA: Electron Driven Avalanches

The ATP is not changing what is changing is the absorption position
Three devices analysed

VUV4 and FBK LF

EDA: Electron Driven Avalanches
Diffusion is important!

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

<table>
<thead>
<tr>
<th>Device</th>
<th>((x_{PN} - d_P^*)) [(\mu\text{m})]</th>
<th>(W^*) [(\mu\text{m})]</th>
<th>C [fF]</th>
<th>(W) [(\mu\text{m})]</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamamatsu H2017 [22]</td>
<td>1.8 ± 0.1</td>
<td>4.1 ± 0.4</td>
<td>163 ± 1</td>
<td>1.54 ± 0.01</td>
<td>0.25 ± 0.06</td>
</tr>
<tr>
<td>Hamamatsu VUV4 [3]</td>
<td>0.8 ± 0.2</td>
<td>3.9 ± 0.8</td>
<td>116 ± 6</td>
<td>1.01 ± 0.05</td>
<td>0.07 ± 0.06</td>
</tr>
<tr>
<td>FBK LF [23]</td>
<td>0.145 ± 0.01</td>
<td>2.2 ± 0.1</td>
<td>83 ± 5</td>
<td>0.92 ± 0.06</td>
<td>0.05 ± 0.01</td>
</tr>
</tbody>
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\((x_{PN} - d_P^*)\) represents the length of the region in which avalanches are triggered by an electron. \(W^*\) is the length of the effective region in which an absorbed photon can initialize an avalanche process. \(W\) is the physical junction length derived using: (i) the pixel size and the fill factor provided by each manufacturer, (ii) the single cell capacitance \(C\) extrapolated from the SiPM gain [18]. \(k\) is an effective ratio of the impact-ionization-coefficients as reported in [10].

The junction length is not enough to justify the measured PDE!
The diffusion mechanism will be subject of analysis
Understand diffusion is crucial to predict sensitivity in a certain range of wavelength

\[ P_e(d_P) = \text{electron ATP measurable from UV light} \]

\[ P_h(d_W) = \left[ 1 - \left( 1 - P_e(d_P) \right) \right]^k \]
Extrapolation of e-h Boundaries probabilities

Pe and Ph give a figure of merit of your detector both for the NOISE and for the light detection efficiency.

Why the probabilities are different?

The ratio of the ionisation coefficient is changing.

The three SiPMs have different fields.

The FBK with lower field ionises in a better way!

This can be seen looking at the total number of carriers created along its path.
The TRIUMF SiPM: Overview of the project

To have a PDE that saturates faster a low field is needed!

Weighted number of electron-hole pair created by the incoming photon due to impact ionisation along particle path

\[
\delta = \text{Weighted number of electron-hole pair}
\]

conditional ATP = \[\frac{\text{PDE}}{\text{PDE}_{\text{MAX}}}\] Probability to trigger an avalanche IF the photon is absorbed in the effective region.

![Graph showing conditional ATP vs. \(\delta\) and over voltage for different materials. The graph indicates that lower over voltages are achieved with lower \(\delta\) values for all materials, with a notable difference between VUV4 and FBK-LF.](image)

Preliminary
Parameter | FBK LF | HPK VUV4 | 3DdSiPM
---|---|---|---
Next steps | New production from FBK is at TRIUMF | VUV4 reflectivity in LXe is now under testing | VUV sensitivity

**Summary of the first part**

** FBK LF significantly exceeds nEXO requirements**

**Hamamatsu VUV4 is marginally close to meet nEXO requirements**

**Next Steps :**

TRIUMF is working to develop a new generation of VUV SiPMs for low light level detection in Liquid Argon and Liquid Xenon
Thank you
TRIUMF Setup
Optical Efficiency

Optical Efficiency: Probability to be transmitted in the silicon

\[ \varepsilon_0(\lambda) \sim \left[ \text{FF} \times \left( 1 - R(\lambda, \theta) \right) \right] \]

FF: Fill Factor

R: Reflectivity

ARC is important!