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Do you plan to submit this publication to a DOE sponsored laboratory for classification reviews?	Yes, a DOE sponsored laboratory will review this.
Name of Laboratory:	Sandia National Laboratories
Do you plan to request fellowship funding for travel associated with this submission?	Yes
Please explain the relevance of this submission to International Nuclear Security Safeguards (please link research to IAEA research plan):	This research contributes directly to the advancement of radiation detection technology, which is crucial for enhancing nuclear security and safeguarding. Silicon photomultipliers (SiPMs) are a promising technology in radiation detection due to their compact size, low power consumption, and high photon detection efficiency, making them ideal for applications in environments like nuclear material monitoring and verification under international safeguards. By improving the understanding of how SiPMs perform in various temperature conditions, this work supports the IAEA's ongoing efforts to improve safeguards technologies. This research is aligned with the IAEA's research plan on enhancing verification methods to ensure the non-proliferation of nuclear materials. Understanding the noise mechanisms of SiPMs can help improve the accuracy and reliability of detection systems, which are vital for the successful implementation of global nuclear safeguards protocols.

Please explain why this work is being performed, what the practical applications are, what problems will be solved, what objectives will be achieved, etc.	This work addresses the performance challenges of SiPMs, particularly their susceptibility to increased dark count rates (DCR) and optical crosstalk (OCT), which degrade their performance in harsh environments. These issues are critical because SiPMs are increasingly used in nuclear safeguards where accurate and reliable radiation detection is essential. The objective of this research is to compare different SiPM technologies (Advansid, Broadcom, and Onsemi) across varying temperatures to assess their noise characteristics, temperature sensitivity, and suitability for use in nuclear safeguards systems. The practical application of this research lies in improving the design and deployment of radiation detectors for nuclear safeguards. By identifying the SiPM technologies with optimal performance (low noise, high gain, minimal temperature sensitivity), this study aims to enhance the detection capabilities of safeguards equipment, thereby contributing to more effective monitoring of nuclear materials. The results will inform the selection of SiPMs for environments where temperature variations are a factor, ultimately leading to more robust radiation detection systems that can operate reliably under varying conditions.

Characterization of High-Temperature SiPM Noise

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Introduction

- **Background**: Silicon photomultipliers (**SiPMs**) are compact, low-power, and high-efficiency detectors that are increasingly used in radiation detection applications like medical imaging and nuclear safeguards. The have **advantages of PMTs** because they are smaller, operate at lower voltages, and offer high photon detection efficiency.
- **Challenges:** SiPMs suffer from increased **dark count rate (DCR)** and **optical crosstalk (OCT)**, which degrades performance.
- **Purpose of study:** This study compares the **Advansid ASD-NUV3S-P-40, Broadcom AFBR-S4K33C0147L,** and **Onsemi MicroFJ-30035-TSV-TR** under four different temperatures to compare their performance in harsh environments.

	SiPMs	PMTs
Power Requirements	Low-voltage	High-voltage
Size	Small form factor	Large form factor
Photon detection efficiency	Up to ~50%	Up to ~40%
Timing resolution	~100ps	~100ps

Table 1: Comparison of SiPM and PMT characteristics.

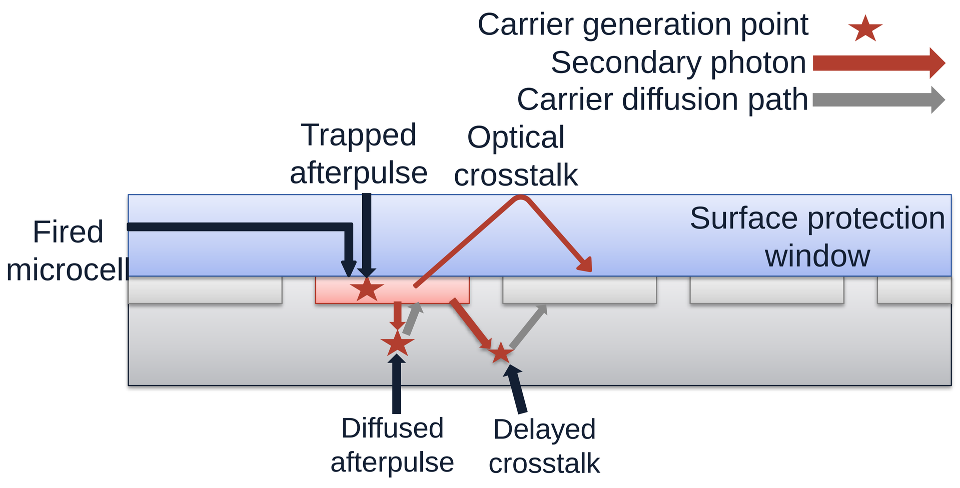

Figure 1: Illustration of noise mechanisms in SiPMs

Methods

- **Measurement range:** We measured the dark counts of the SiPMs at **19°C, 22°C, 30°C, 40°C, and 50°C**.

Parameter	Advansid	Broadcom	Onsemi
Active area (mm²)	3 × 3	3 × 3	3.07 × 3.07
PDE (%)	43	47	50
DCR (kHz/mm²)	100	85	150
Breakdown Voltage (V)	26	28.75–30.25	24.2–24.7
Gain	3.6×10^6	7×10^6	6.3×10^6
Microcell count	5520	4096	5676
Fill factor (%)	60	82	75

Table 2: Performance parameters of SiPM technologies from manufacturer datasheets.

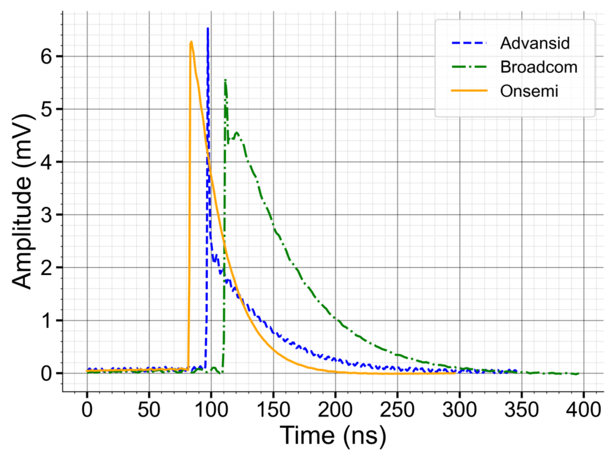

Figure 3: Comparison of pulse shapes from the three technologies.

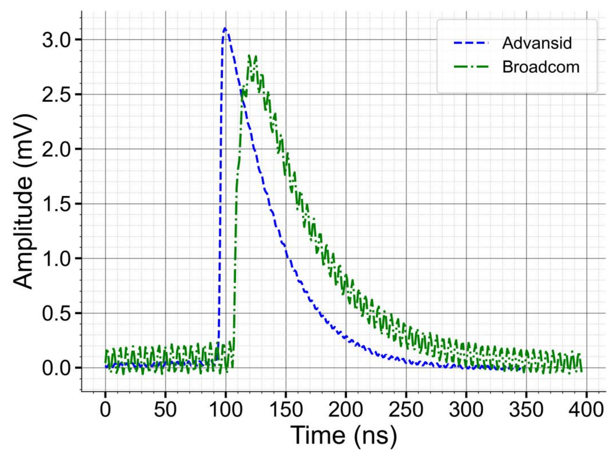

Figure 4: Effect of Ortec 113 preamplifier on pulse shapes.

Experimental Setup

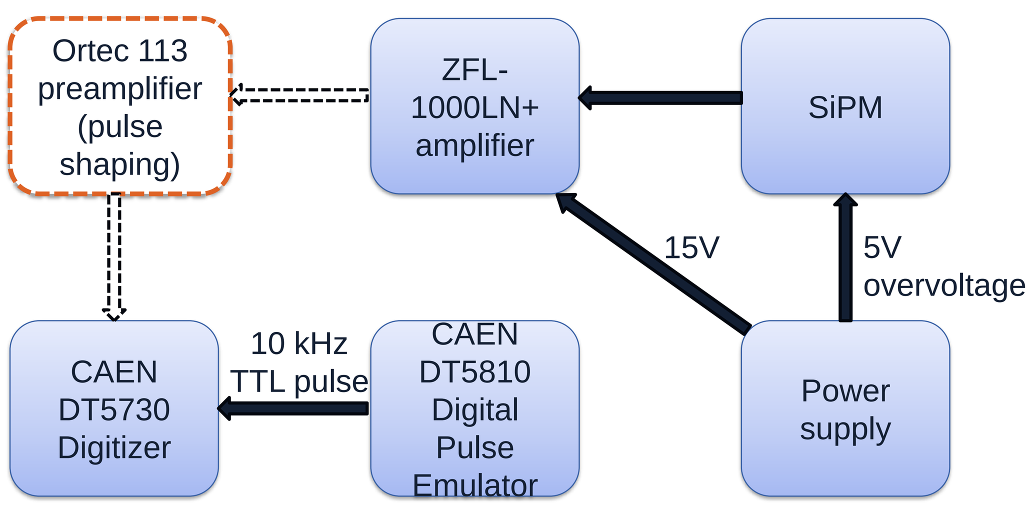

Figure 2: Acquisition chain for SiPM analysis. The measurements were taken with and without the Ortec 113 preamplifier. The measurements took place in dark conditions.

Equation 1: Decay removal model

$$V_i = V_{0_i} + \frac{1}{\tau}\sum_{j=1}^{i} V_{0_j} \times (t_j - t_{j-1})$$

where $t_{j-1} = 0$

and $V_0 = V - V_{min}$

t=time in nanoseconds V= volts in millivolts

τ= microcell recharge time

i represents the current sample and j represents the previous samples

Data Analysis

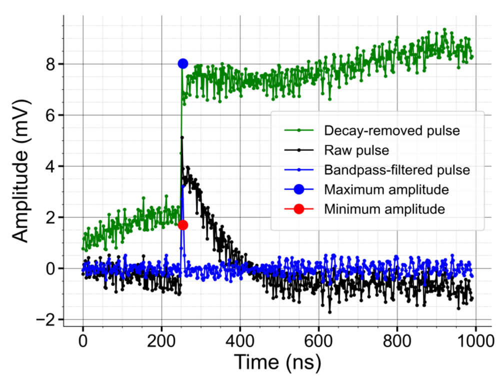

Figure 5: Pulse height calculation after decay removal.

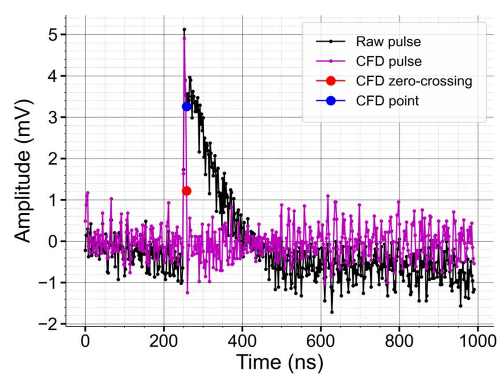

Figure 6: Constant fraction discrimination-like method used to calculate pulse height.

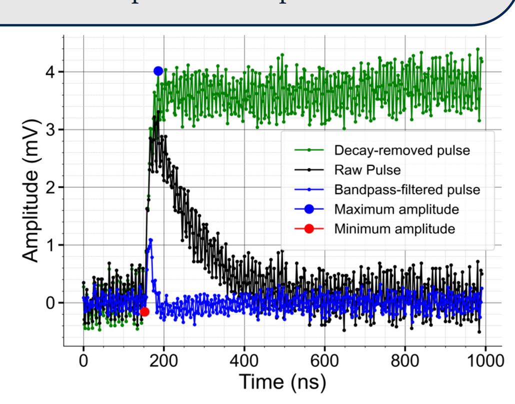

Figure 7: Pulse height calculation from the preamplified acquisition chain signal.

Equation 2: Constant Fraction Discrimination (CFD)

$CFD(i) = F \times S(i) - S(i - \Delta)$

where $S(i)$ is the value of the signal at index i, F is a constant between 0 and 1, and Δ is delay time

Results

Equation 3: Pulse height spectrum fitting function

$$Y(x) = A\sum_{n=1}^{\infty} \frac{p_n}{\sqrt{2\pi(\sigma_e^2 + n\sigma_a^2)}} \exp\left(\frac{-(x - nx_g - x_o)^2}{2(\sigma_e^2 + n\sigma_a^2)}\right)$$

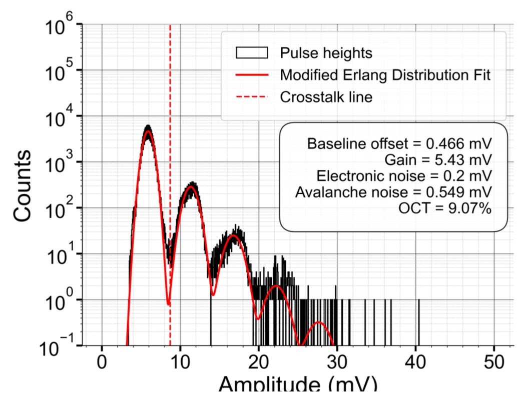

Figure 8: Broadcom pulse height spectrum for decayless removal method.

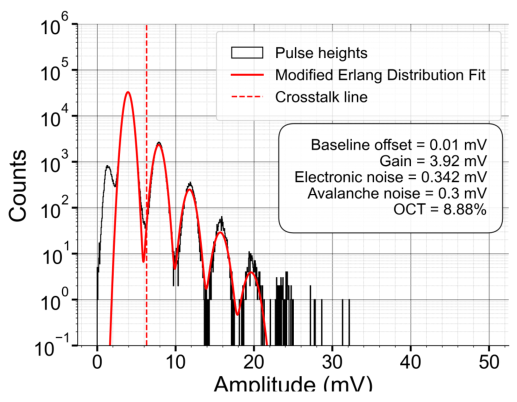

Figure 9: Broadcom pulse height spectrum for CFD method.

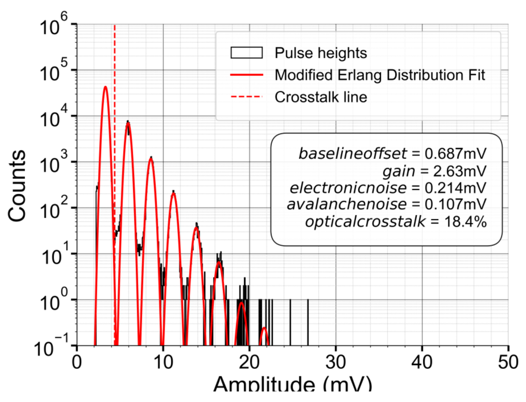

Figure 10: Broadcom pulse height spectrum for preamplifier acquisition chain.

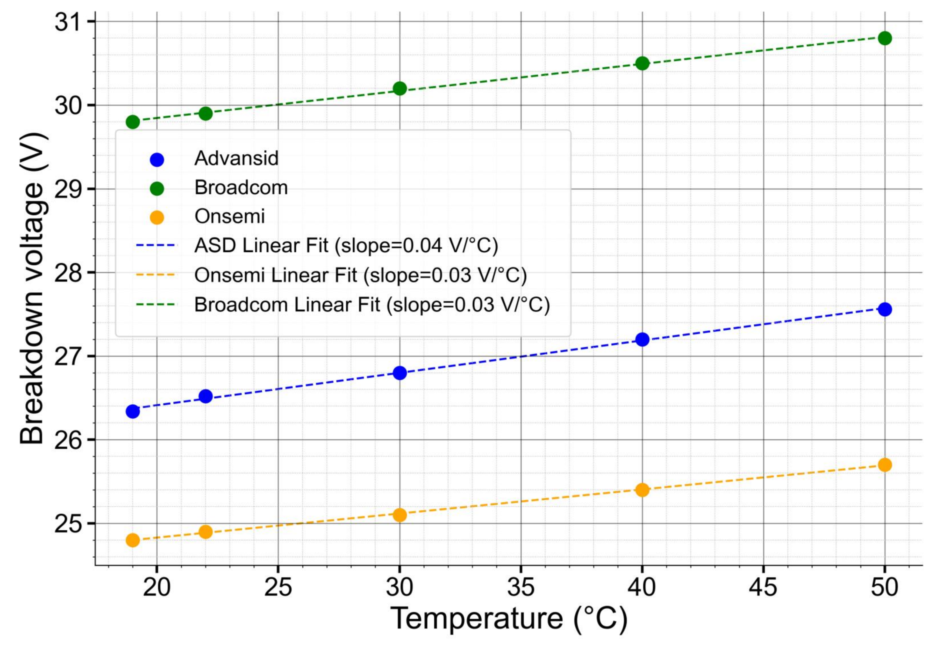

Figure 11: Breakdown voltage as a function of temperature for Advansid, Broadcom, and Onsemi SiPMs. The error bars are smaller than the data markers. The Advansid is most sensitive to temperature.

Table 3: Comparison of performance parameters of three SiPM technologies at room temperature.

Technology	Temperature (°C)	DCR (kHz/mm²)	Gain (mV)	Avalanche Noise (mV)	Electronic Noise (mV)	Optical Crosstalk (%)
Onsemi	22	123.01	6.1	0.293	0.37	19.8
Advansid	22	91.33	2.4	0.188	0.303	50.5
Advansid (with preamp)	22	92.7	1.73	0.0661	0.111	53.19
Broadcom	22	78.03	3.92	0.3	0.342	8.89
Broadcom (with preamp)	22	79.97	2.63	0.107	0.214	18.4

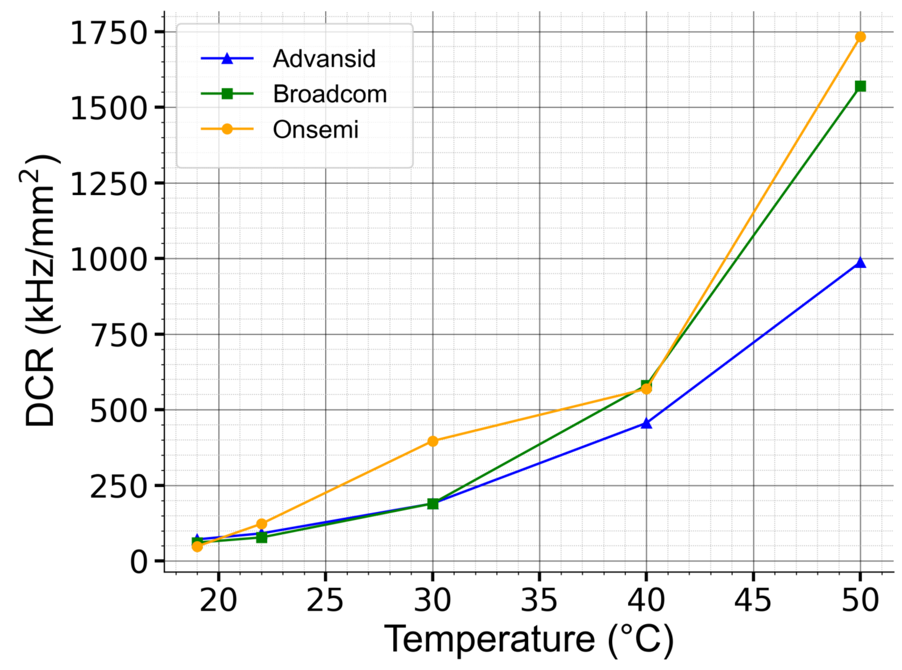

Figure 12: DCR as a function of temperature for Advansid, Broadcom, and Onsemi SiPMs. The Onsemi has the highest DCR.

Discussion and Conclusions

- **Dark Count Rate (DCR):** Onsemi exhibited the highest DCR, 58% higher than Broadcom and 35% higher than Advansid at 22°C. This indicates Onsemi may not be optimal for low-noise applications.
- **Avalanche and electronic noise**: Onsemi has the highest electronic (0.37 mV) and avalanche noise (0.293 mV) among the three technologies, while Advansid shows the lowest (0.0661 mV avalanche noise and 0.111 mV electronic noise with preamplifier).
- **Optical Crosstalk (OCT):** Advansid had over 5 times the OCT probability of Broadcom and 2.5 times that of Onsemi.
- **Gain Comparison:** Onsemi's gain was 55% higher than Broadcom and more than double that of Advansid, though this must be weighed against its higher DCR.
- **Temperature Sensitivity**: Advansid showed a 33% greater sensitivity to temperature changes in breakdown voltage than Broadcom and Onsemi, highlighting potential variability in performance with temperature changes.
- **Conclusions:** In summary, Broadcom offers a balance between low DCR, moderate gain, and low noise, while Onsemi provides higher gain but at the cost of increased noise and DCR. Advansid offers the lowest electronic and avalanche noise but has significantly higher OCT probability.

Acknowledgements

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