Silicon photomultiplier low temperature characterization for future neutrino detectors

Yujing Sun, Koun Choi, Jelena Maricic, Marielle Dela Cruz, Christina Nelson, Marc Rosen, Radovan Milincic
Department of Physics and Astronomy, University of Hawaii at Manoa
E-mail: ysun7@hawaii.edu, kounchoi@hawaii.edu

Abstract. Silicon photomultipliers (SiPMs) are compact solid state photodetectors having single photoelectron (PE) level sensitivity. Due to their attributes, they are being considered for the photo detection systems of future neutrino detectors. Consequently, comprehensive studies of SiPMs at cryogenic temperatures are required since the data provided by the manufactures do not cover this temperature regime. In this work, SiPMs are tested for proper operation in a cryostat for the expected lifetime of the future experiments. The characterization of SenSL C-series SiPMs and their long-term mechanical durability are discussed. Performance of SiPMs from other vendors are also discussed.

1. Introduction
The aim of the next generation of ultra large-scale neutrino detectors [1, 2] is aiming to resolve fundamental questions such as the neutrino mass hierarchy and CP violation in the leptonic sector. For these large-scale neutrino detectors, the challenge is to design an affordable and effective large-area photon detection (PD) system which can provide a trigger for non-beam events such as proton decay, atmospheric neutrinos and astrophysical neutrinos. It can also help to improve the reconstruction accuracy.

Silicon photomultipliers or silicon photoelectron multipliers (SiPMs) are highly attractive photo sensors for the new PD system. The Deep Underground Neutrino Experiment (DUNE) [1], a 40 kt liquid argon time projection chamber (LArTPC), uses SenSL C-Series 6 mm² devices [3] for the PD system of the reference design. The 128-nm scintillation photons from LAr will be shifted to the photon detection efficiency (PDE) peak of the device by wavelength shifter painted on the surface of the light guides. The shifted photons will propagate through the light guide to the end of the bar where SiPMs are mounted. Details of the PD system for the reference design of the DUNE experiment can be found in [4].

2. Silicon Photo Multipliers (SiPMs)
SiPMs are solid-state devices which are safe from stray light, immune to electromagnetic fields and stable with temperature variations. SiPMs have a pixellated structure which consists of an array of Geiger-mode avalanche photodiodes (G-APD) and quenching resistor pixels on common silicon substrate. Pixel sizes vary from 10 to 100 μm and SiPMs currently have active areas ranging from 1 mm² to 6 mm², containing several hundred to several tens of thousand pixels. SiPMs have low operating voltage (typically <100 V), however, their gains are comparable to...
those of PMTs. The spectral sensitivity usually ranges from UV through NIR, peaking at the visible light. They also have high photon detection (PDE) efficiency (40 to 80%), single photoelectron (SPE) level resolution, low dark-count rate (DCR), fast rise time and relatively low cost compared to conventional PMTs. Using multiple devices, the area can be handily scaled up as required.

3. Experimental Setup
The SiPMs were tested in LN$_2$ instead of LAr, as no significant performance differences are expected for a temperature difference of 10 K. The PCB is designed based on the MicroBF-SMA-6mm circuit schematics provided by SenSL. To amplify the signal, a low noise amplifier ZFL-1000LN+ from Mini-Circuits (recommended by SenSL) was used. To provide a testbed for many SiPMs, soldering should be avoided and so pogo pins were used to connect the SiPMs to the PCB. The experiment was set up in a dark box and the data were taken with an oscilloscope and a DAQ computer.

4. Characteristics of SenSL C-series 60035 6mm$^2$ SiPM
SenSL’s sensors feature industry-leading low DCR and exceptional breakdown voltage uniformity within ±250mV. The recent product C-Series 60035 has significant improvements in DCR and after-pulse rate. The performance of the SenSL C-Series SiPMs was measured in a cryostat and shows clear SPE resolution and a similar gain as in room temperature as shown in Fig. 1. The test were carried out up to an over-voltage (the difference between the bias voltage and the breakdown voltage) of +7.2 V. A DCR of 1200 kHz at room temperature is significantly reduced to $\approx$10 Hz in the cryostat as shown in Fig. 2.

Cross-talk is a phenomenon where photons emitted by the avalanche fall into the neighbour pixel and trigger a second avalanche. After-pulses are generated when electrons produced in an avalanche are trapped and released again after some delay which can last from ns to several $\mu$s. Cross-talk and after-pulse will both reduce the photon counting resolution; the after-pulse will also reduce the prompt to delayed LAr scintillation light ratio. It was found that the cross-talk and after-pulse rates in LN$_2$ agree with the probabilities measured at room temperature by the manufacturer as shown in Fig. 2.

Long-term mechanical durability was measured by periodically exposing the SiPMs to room temperature. After each exposure cycle, the SiPMs were visually inspected under a microscope and checked for gain, DCR, cross-talk and breakdown voltage. A few scratches gradually built up but there was no obvious degradation or change in any characteristic.

Figure 1. SenSL C-Series 60035 SiPM dark pulse integral distribution at over-voltage of +5.2 V (left) and gains as a function of bias voltage (right).
5. **SiPMs from other vendors**

NDL 11-2222B-S and AdvanSiD NUV SiPMs failed cryogenic tests. KETEK PM6660 has a reduced operating range in LN$_2$ and two orders of magnitude higher after-pulse rate than SenSL C-Series 60035. Hamamatsu SIL-STD (standard) and TFC-STD SiPMs have extremely high after-pulse rate similar to KETEK products. Hamamatsu SIL-LCT (low cross-talk) and TFC-LCT SiPMs have reduced after-pulse rates but still approximately ten times more than SenSL products. Tab. 1 summarizes the measured characteristics mentioned above.

| Company    | model   | cryogenic test | gain    | dark rate(size) | after pulse | cross talk |
|------------|---------|----------------|---------|-----------------|-------------|------------|
| SenSL      | C-Series| ok             | $2.4 \times 10^6$ | $3(0.08\text{Hz/mm}^2)$ | 0.2%       | 12%        |
| AdvanSiD   | NUV     | 100% failure   | -       | -               | -           | -          |
| NDL        | 11-2222B-S | 100% failure | -       | -               | -           | -          |
| KETEK      | PM6660  | <2 V over-V    | -       | too high        | -           | -          |
| Hamamatsu  | SIL-LCT, TFC-LCT | ok     | $2.1 \times 10^6$ | $2(0.2\text{Hz/mm}^2)$ | 2.5%       | 10%        |

**Table 1.** The measured properties of SiPMs from several vendors tested at +2.5 V over-voltage.

6. **Conclusion**

The SenSL C-Series 60035 SiPM characterization result at cryogenic temperature are consistent with those for room temperature. The SiPM is also suitable for the DUNE PD system. Hamamatsu LCT series could also be a good candidate if the after-pulse rate can be lowered. Until the specific requirements for the DUNE PD system are fully developed, we will keep seeking alternatives.

**Acknowledgement**

We acknowledge the cooperation of the DUNE collaboration in providing their test results. We also acknowledge the Department of Energy for funding our lab construction and operation.

**References**

[1] DUNE collaboration, Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE): Volume 2: The Physics Program for DUNE at LBNF, arxiv: 1512.06148

[2] Hyper-Kamiokande Proto-Collaboration, Physics potential of a long-baseline neutrino oscillation experiment using a J-PARC neutrino beam and Hyper-Kamiokande, arxiv: 1502.05199
[3] SenSL, http://sensl.com/downloads/ds/DS-MicroCseries.pdf C-Series Low Noise, Fast, Blue-Sensitive Silicon Photomultipliers DATASHEET

[4] DUNE collaboration, Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE): Volume 4: The DUNE Detectors at LBNF, arxiv: 1601.02984