Silicon photomultipliers characterization for future neutrino detectors

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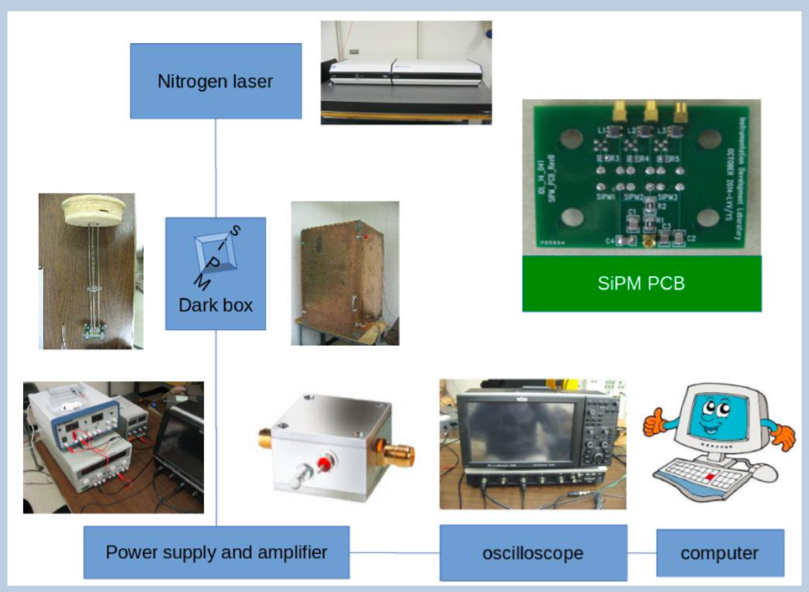
Abstract

For neutrino detectors with large scale, it is new challenge to design an affordable and effective large-area photon detection (PD) system. The PD system also needs to provide trigger on non-beam events such as proton decay, atmospheric neutrinos and astrophysical neutrinos, as well as good event timing resolution.
The silicon photomultilier or silicon photoelectron multipliers (SiPMs) are highly attractive photo sensors for the new PD system. The Deep Underground Neutrino Experiment (DUNE) [1], 40 kT liquid argon time projection chamber (LArTPC), selects SensL C-Series 6 mm^2 devices 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, then will be transported through light-guide to the SiPMs mounted at end of the bar. Details of the PD system design for the Reference Design of the DUNE experiment can be found in [2].
A comprehensive testing of SiPMs in cryostat is necessary since the data sheet provided by the manufactures in the market does not cover this temperature regime. In this work, SiPMs are carefully tested to properly operate in cryostat for the expected lifetime of the future experiments. The characterization of the recently developed SiPMs by SensL in cryostat including gain, dark count rate (DCR), cross-talk, after-pulse rate and long-term mechanical durability are shown. Comparison of SiPMs from other vendors are also discussed.

Experimental Setup

- The SiPMs are tested in LN_2 (only 10K lower than LAr, no significant performance differences are expected) - a darkbox, oscilloscope, DAQ computer, nitrogen laser & optical fiber, MMCX connectors, low noise ZFL-1000LN+ amplifier from Mini-Circuits (recommended by SenSL) are used



The PCB is designed based on the MicroBF-SMA-6mm circuit schematics provided by SenSL. To repeat tests for many SiPMs, pogo pins are used to connect the SiPMs to the PCB through mechanical press. The feasibility of this setup has been proved as we have performed many tests in LN_2.

SiPMs from other vendors

- NDL 11-2222B-S and AdvanSiD NUV SiPMs failed cryogenic tests.
- KETEK PM6660 has a reduced operative 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.

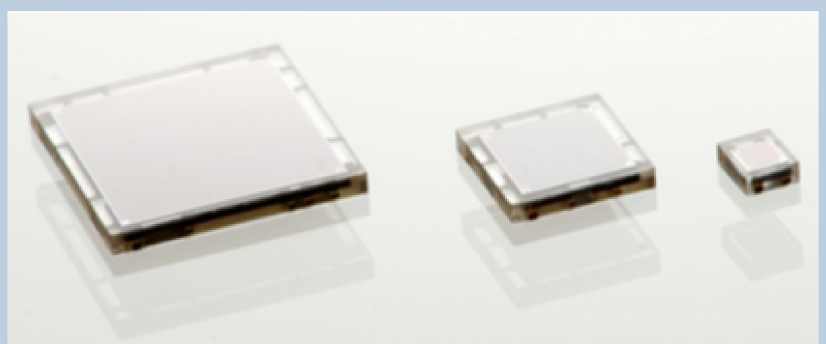
The characteristics of SenSL C-Series and HAMAMATSU SIL-LCT SiPMs at 2.5 V over-voltage are listed in the table below.

Company	model	cryogenic test	gain	dark rate	after pulse	cross talk
SenSL	C-series	ok	2.4E+06	3(0.08Hz/mm^2)	0.2%	12%
AdvanSiD	NUV	50% failure	-	too high	-	-
NDL	11-2222B-S	100% failure	-	-	-	-
KETEK	PM6660	ok	-	-	too high	-
Hamamatsu	SIL-LCT, TFC-LCT	ok	2.1E+06	2 (0.2Hz/mm^2)	2.5%	10%

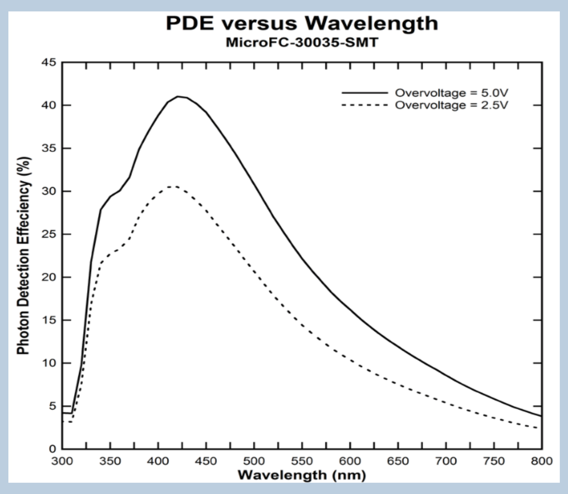
The result of properties of SiPMs from several vendors tested in our lab.

Silicon Photo Multipliers (SiPMs)

SiPM is solid state, compact size photodetector for low level light. It has pixelated structure which consists of an array of Geiger-mode avalanche photodiodes (G-APD) and quenching resistor pixels on common silicon substrate. When it absorbs a photon, avalanche is triggered and it produces a current pulse of tens of nanosecond long containing 10^5 to 10^6 electrons. This gain is comparable to that of a PMT. In practical SiPMs, identical micro pixels are arranged in a rectangular pattern.



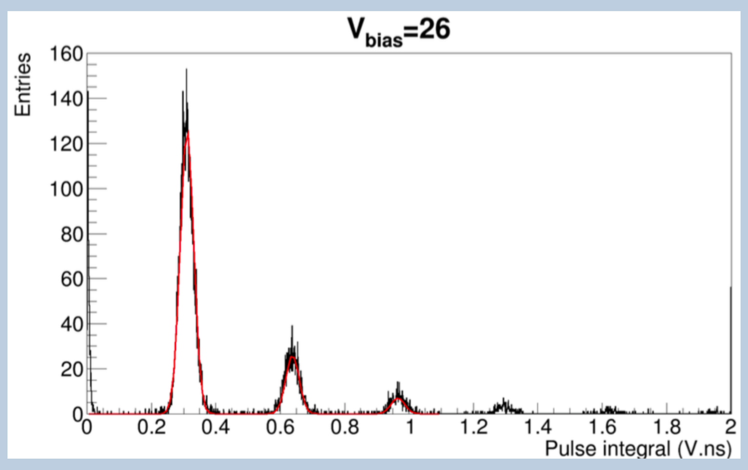
The size of a pixel varies from 10 to 100 μm and SiPMs have active areas ranging from 1 mm^2 to 6 mm^2, containing several hundred to several tens of thousand pixels in it. The spectral sensitivity of SiPMs usually ranges from UV through NIR, peaking in the visible. The photon detection efficiency of SenSL SiPM C-series 60035 is shown below. Picture is taken from [3].

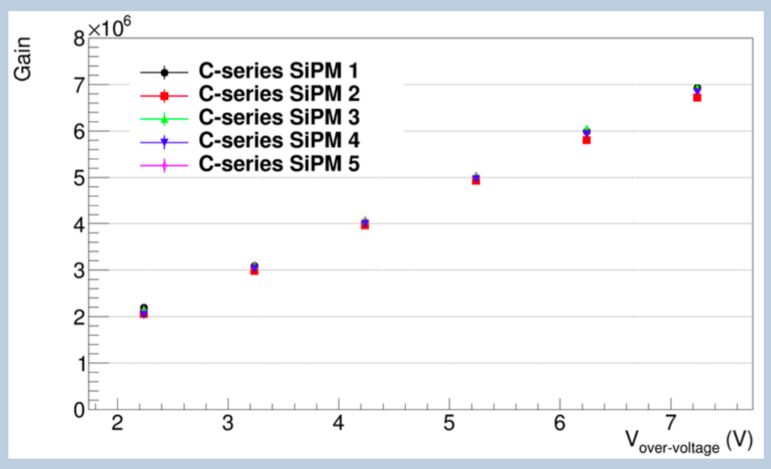


Typical properties of SiPMs that is attractive for new PD system are:
- **solid-state** (cannot be damaged by stray light, immune to electromagnetic fields and stable with temperature variations)
- **low operating voltage** (<100V)
- **single photoelectron (SPE) level resolution**
- **high photon detection (PDE) efficiency** (40 to 80%)
- **low dark-count rate** (DCR)
- **fast rise time** (<1ns)
- **relatively lower cost** than conventional PMTs
- **can be scaled up as required**

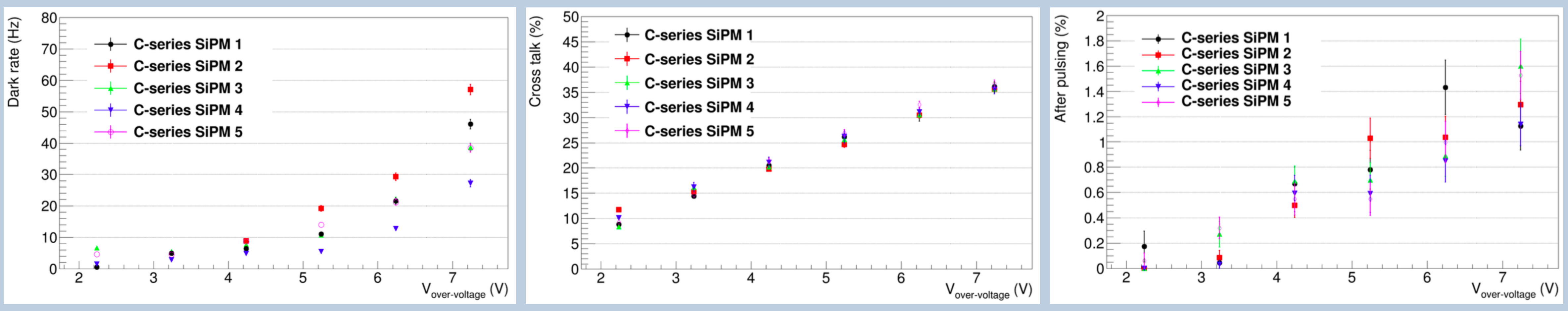
Characteristics of SenSL SiPM C-series 60035 6mm^2

SenSL's sensors feature industry-leading low DCR, exceptional breakdown voltage uniformity of ±250mV. Especially, the recent product C-Series 60035 has significant improvements in DCR and after-pulse rate. The performances of SenSL C-Series under room temperature are well characterized and documented by SenSL [3]. The performance characteristics at about LAr temperature are studied in our lab and it is found to properly operate in cryostat.

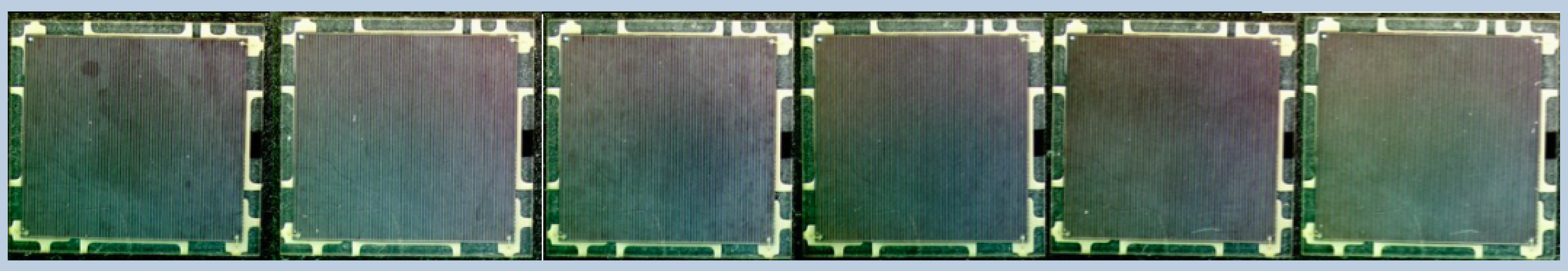




The SenSL C-Series SiPMs are confirmed to operate with clear SPE resolution and the same gain as in room temperature in cryostat, and tested to operate up to over-voltage (the difference between the biasing voltage and the breakdown voltage) of +7.5 V. DCR of ∼1200 kHz in room temperature is significantly reduced to ∼10Hz in cryostat.



Cross-talk is a phenomenon when 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 μs. The cross-talk and after-pulse will both deteriorate the photon counting resolution. And the after-pulse will also degenerate the measurement of the prompt to delayed LAr scintillation light ratio. In our study it is found that the cross-talk and after-pulse rates in LN_2 agree with the probabilities measured in the room temperature [3].



Long-term mechanical durability is confirmed by periodically exposing SiPMs to room temperature. After each exposure cycle, SiPMs were visually inspected under microscope and characteristically checked on gain, DCR, cross-talk and breakdown voltage. A few scratches gradually build up but there is no obvious degradation or change in any characteristic. A similar test being conducted at Louisiana State University using SenSL B and C-Series SiPMs also shows no change in DCR or gain detected to date [4]. Besides mechanical durability tests, an aging test has been done in Indiana University [5] and no significant changes in DCR or gain have been observed under long term cryogenic exposure.

Conclusion & Acknowledgement

The SenSL C-Series 60035 SiPM characterization in cryogenic temperature results are consistent with data sheet for room temperature. It is also suitable for DUNE PD system. Hamamatsu LCT series can also be a good candidate if after-pulse rate is lowered. Until the specific requirements for DUNE PD system are fully developed, we will keep seeking alternatives. We acknowledge the cooperation of the DUNE collaboration in providing their test results. We also wish to acknowledge the support of the Department of Energy for funding our lab construction and operation.

References

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[4] Thomas Kutter, Silicon Photomultiplier Requirements and Testing, LBNE internal document 10881
[5] S.Mufson et al., Recent Progress in Bar Technology/SiPM Aging Studies at Indiana University, LBNE internal document 10817