Characterization of new photo-detectors for the future dark matter experiments with liquid xenon

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Abstract. In the last three decades, numerous terrestrial experiments were built to search for a faint interaction between Weakly Interacting Massive Particles (WIMP) and ordinary matter. Among them, experiments using dual-phase xenon time projection chambers (TPCs) are leading the search especially for high mass WIMPs. In these experiments, photomultipliers (PMTs) are used to detect the prompt primary scintillation and secondary electro-luminescence of ionized electrons generated following an interaction between WIMP and a Xe nucleus. However, PMTs have several important shortcomings: their residual radioactivity levels, cost, bulkiness, and stability at cryogenic temperatures. Therefore, several alternative technologies are under consideration toward future dark matter experiments using ∼50 tons of liquid xenon (LXe). One such technology is silicon photomultipliers (SiPM). SiPM have very low radioactivity, compact geometry, low operation voltages and reasonable photo-detection efficiency for vacuum ultra violet (VUV) light. However, current SiPM still have ∼two order of magnitude higher dark count rate compared to PMTs. In order to solve this problem, we are currently developing a new SiPM with the help of Hamamatsu. In this paper, we report the current status of the performance measurements of the new SiPM developed with Hamamatsu to improve the dark count rate (DCR).

1. Introduction

Experiments using dual-phase (liquid/gas) xenon time projection chambers (TPCs) are leading the search for Weakly Interacting Massive Particles (WIMPs) with masses from a few GeV/c^2 to TeV/c^2 [1]. For future experiments with larger detector mass [2], it is important to further decrease backgrounds for reaching the sensitivity limit imposed by atmospheric / supernova relic neutrinos (so called neutrino floor). Although significant effort has been made to lower radioactivity [3], photo-multiplier tubes (PMTs) are still one of the biggest origins of radioactivity in the detectors that use them. Recently, silicon-photomultipliers (SiPM), sensitive to vacuum ultraviolet (VUV) light, were developed by several manufacturers (Hamamatsu, FBK). It is reported that these SiPMs (Hamamatsu S13370-3050CN) exhibit very low intrinsic radioactivity [4]. Therefore SiPMs are expected to replace PMTs for direct dark matter experiments. However, as shown in Table.1, current SiPM have ∼ two orders of magnitude higher dark count rate (DCR) compared with PMTs (Hamamatsu R11410) used in current LXe

Photo-Sensor	SiPM 13370-3050CN	PMT R11410-21
V_{op}	~ 50 V	~ 1500 V
Gain	$\sim 2 \times 10^6$ V	$\sim 5 \times 10^6$ V
Photo-detection efficiency @178nm	~ 24 %	~ 27 %
DCR @LXe temperature ~ 169 K	$\sim 1\ Hz/mm^2$	$\sim 0.01 Hz/mm^2$

Table. 1. Comparison of features between current SiPM and PMT.[4]

SiPM	S12572-015C-SPL SPL SiPM	S12572-015C-STD STD SiPM
Operation Voltage	~ 100 V	~ 65 V
Gain	$\sim 1.4 \times 10^5$ V	$\sim 2.3 \times 10^5$ V
The active area	$3\ mm \times 3\ mm$	
The number of pixel	40000	
Fill factor	53 %	

Table. 2. Comparison of some physical properties between SPL and STD.

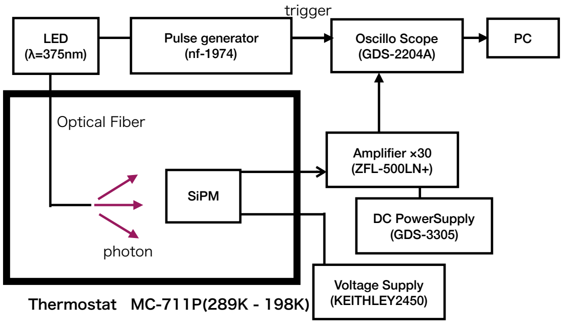

Figure. 1. Block diagram of the setup of this experiments.

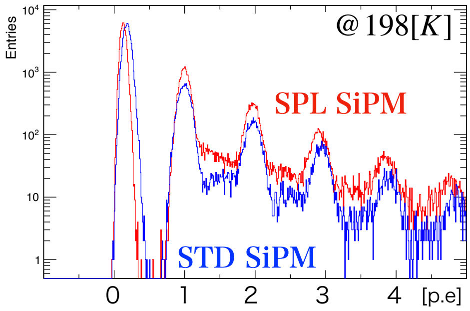

Figure. 2. Pulse distribution of SPL (red line) and STD (blue line) at 198 K.

experiments such as XENON1T/nT [1]. Therefore, it is necessary to reduce the DCR of SiPM at LXe temperature (~169 K) down to ~0.01 Hz/mm^2 for SiPMs to become useful for future dark matter experiments.

2. Comparison of some physical properties between conventional SiPM and new SiPM

We have developed a new SiPM (S12572-015C-SPL, SPL) as a prototype detector with lower DCR in cooperation with Hamamatsu. This SiPM is similar to commercially available SiPM (S12572-015C-STD, STD), but its internal electric field structure was modified to reduce the DCR. Table.2 shows the comparison of some physical properties for SPL and STD. The SPL has a higher operation voltage, but lower gain than the STD.

3. Measurement

3.1. Set-up and measurement procedures

Figure.1 shows a block diagram of the setup for this experiment. The SiPM is installed in a thermostat chamber (MC-711P) the temperature of which can be changed from 198 K to 298 K. Square pulses from a function generator (nf-1974) is used to turn on a LED and trigger the data acquisition via an oscilloscope (GDS-2204A). Voltage from a source meter (KEITHLEY 2450) is applied to the SiPM. Signals from the SiPM are amplified with a low noise amplifier (ZFL-500LN+) and read out using the oscilloscope.

3.2. Pulse height distribution and breakdown voltage

To investigate pulse height and breakdown voltage properties of both SiPMs, we measured pulse height distributions with blue light ($\lambda \sim 375$ nm) from an LED. Figure.2 shows pulse height distributions for both the SPL and STD at 198 K. The first and second peaks corresponds to noise and single photo-electron (SPE), respectively. Figure.3 shows the relation between pulse height and bias voltage (V_{bias}) for the SPL. There is a linear correlation between pulse height and bias voltage. Breakdown voltage (V_{br}) where the pulse height collapses to zero is shown in Fig4, as a function of temperature. The V_{br} of SPL and STD are found to decrease with a slope of 8.95×10^{-2} V/Kelvin (SPL) and 6.28×10^{-2} V/Kelvin (STD), respectively.

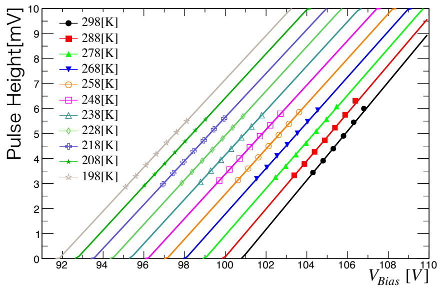

Figure. 3. Pulse height of SPL as a function of bias voltage at several temperatures from 198 K to 298 K.

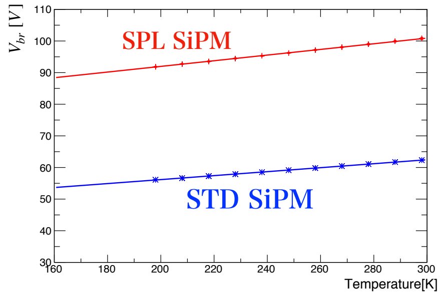

Figure. 4. Breakdown voltage as a function of temperature of SPL (red line) and STD (blue line) with fitted line.

3.3. Dark count rate

The DCR in this study is defined as the number of pulses per second whose height is larger than 0.5 photo-electron (p.e). Dark pulses of SiPMs are mainly originating from thermally exited electrons, resulting in a significant temperature dependence. The DCR as a function of temperature is shown in Fig.5. The Measured data is fitted with a function of the form $AT^{3/2}exp(-B/T)$, where A and B are free parameters. By extrapolating the fitted function down to 169 K, the DCR for STD and SPL can be estimated as 0.041 $\pm$ 0.002 Hz/mm^2 and 0.11 $\pm$ 0.03 Hz/mm^2, respectively. The Measured DCR for SPL is close to the required DCR value for future generation experiments using LXe [2], indicating that changing inner field structure helps to reduce the DCR.

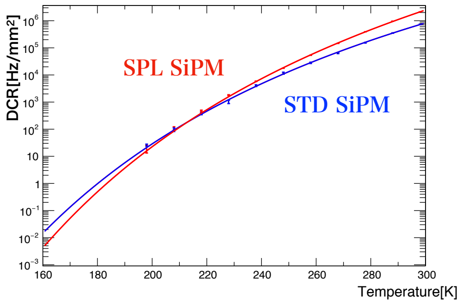

Figure. 5. DCR of SPL (red line) and STD (blue line) as a function of temperature.

4. Summary and outlook

SiPM have very low radioactivity, and are expected to become the new photo-sensors in future dark matter experiments using LXe. However, they still have a very high DCR. We developed a special SiPM with lower DCR (SPL) and operated it in a temperature range from 198K to 298K, demonstrating that the DCR of the SPL can be reduced to 0.041 $\pm$ 0.002 Hz/mm^2, close to a DCR achieved with PMTs used in LXe experiments. We are planning to directly measure their performance at LXe temperature. Currently, these SiPMs are not sensitive to LXe scintillation light (λ $\sim$ 175 nm). However, R&Ds to VUV-sensitive SiPMs with low DCR are ongoing at Hamamatsu.

Acknowledgements

We thank Hamamatsu for the fruitful collaboration and production of the SiPMs used in these studies. This work was supported by DAIKO FOUNDATION and the Japanese Ministry of Education, Culture, Sports, Science and Technology, Grant-in-Aid for Scientific Research, JSPS KAKENHI Grant Number 19H05805.

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