PROCEEDINGS OF SCIENCE

Development of a low-noise SiPM for the DARWIN experiment

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The DARWIN is a future direct dark matter search experiment with 50 tons of liquid xenon (LXe) aiming to discover Weakly Interacting Massive Particles (WIMPs) by detecting scintillation photons generated by the interaction between WIMPs and xenon nuclei. SiPMs (Silicon PhotoMultipliers) have low radioactivity and good photo-detection efficiency for vacuum ultraviolet light. Therefore, SiPMs offer a potential alternative to photomultiplier tubes (PMTs) presently utilized in dark matter experiments with LXe. Nevertheless, SiPMs currently suffer from a dark count rate (DCR) at LXe temperatures that is approximately O(10) times higher than that of PMTs. In this study, we developed a new VUV-sensitive SiPM with lowered electric field for avalanche amplification, and demonstrated that the new SiPMs have 6.5–8.6 times lower DCR at LXe temperatures than that of the conventional SiPMs, achieving a DCR of 0.035–0.069 Hz/mm^2 depending on over-voltages.

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1. Introduction

Dual-phase time projection chambers (TPCs) with gas/liquid xenon (GXe/LXe), such as the XENONnT experiment, have placed strong constraints on the interaction cross-section in the search for Weakly Interacting Massive Particles (WIMPs) with masses ranging from a few GeV/c^2 to a few TeV/c^2 [1]. The LXe TPCs enable to detect prompt scintillation (S1) and delayed electro-luminescence (S2) of ionized electrons produced by the interaction between WIMPs and xenon nuclei, allowing for a discrimination between electronic and nuclear recoils [2]. The upcoming DARWIN (DARk matter WImp search with liquid xenoN) experiment [3], planned for the late 2020s, aims to explore the sensitivity down to the neutrino fog [4], where atmospheric and solar neutrinos become major backgrounds (BGs). To achieve this, it is essential to further minimize radioactive BGs, particularly neutron BGs originating from radioactive impurities (^{238}U / ^{232}Th) present in detector materials [5]. In the current LXe experiments, photomultiplier tubes (PMTs), sensitivive to LXe scintillation light with a wavelength of ~175 nm [6], are used to detect both S1 and S2 signals. However, PMTs have relatively high levels of radioactivity [7], and thus further optimization of their detector materials is required to be used in the DARWIN experiment. Silicon Photomultipliers (SiPM) offers a promising alternative as a low-radioactive photo-detector since it is made of low-radioactive silicon wafers. While SiPMs can reduce radioactive impurities, they suffer from a higher dark count rate (DCR) originating from thermal excitation and tunneling effect. Conventional SiPMs have a DCR per unit area 10-80 times higher than that of PMTs [8], resulting in false S1 signals due to accidental coincidences of DCs. Therefore, in order for SiPMs to be used in future dark matter searches, it is necessary to reduce the DCR to at least the level that realized for PMTs (~0.01 Hz/mm^2) [8]. In this study, we collaborated with Hamamatsu Photonics K. K. to develop SiPMs with reduced DC and investigated their performances.

2. New SiPM with Lowered Electric Field

DC in SiPMs can be attributed to two primary sources: thermal excitation and band-to-band tunneling. At higher temperatures, thermal excitation becomes the primary contribution to DC. However, at a LXe temperature (~165 K), the tunneling effect becomes the dominant contribution for DC in SiPMs. This effect, arising from band-to-band tunneling, exhibits less temperature dependence. The tunneling effect in SiPMs is strongly influenced by the electric field strength for avalanche amplification. Reducing the electric field strength can effectively suppress the tunneling effect and, consequently, reduce DC in SiPMs. In our previous work [9], we developed a dedicated SiPM with lowered electric field with the help of Hamamatsu Photonics K. K., and demonstrated that the optimized SiPMs have 6–60 times lower DCR at LXe temperatures than that of the conventional SiPMs. However, the SiPMs used in our previous study were not sensitive to LXe scintillation light. In this study, we developed a new VUV-sensitive SiPM (MPPC-VUV-LDC-050UM-SPL, referred as SPL) with lowered electric field. This SiPM is similar to the commercial SiPM (S13370-3050CN [10], referred as STD), but its electric field structure is optimized to reduce the DCR as discussed above. The DCR of the STD, measured to be 0.1-0.8 Hz/mm^2 depending on over voltage [11], can potentially be reduced to 0.01 Hz/mm^2 in the SPL, assuming a similar reduction as demonstrated in our previous work. As shown in Table 1, both SiPMs have similar properties in the active area, number of pixels, pixel pitches, and fill factor. However, operation voltage and single photoelectron (p.e.) gain are different due to the optimized electric field structure. In this study, we operated two SPLs labeled as SPL-1(-2) and two STDs labeled as STD-1(-2).

Table 1: Comparison of detector parameters between MPPC-VUV-LDC-050UM and S13370-3050CN.

SiPM	MPPC-VUV-LDC-050UM (SPL)	S13370-3050CN (STD)
Operation voltage	~ 90 V	~ 50 V
Gain (over voltage = 5 V)	1.0×10^6	1.7×10^6
Active area	3 mm × 3 mm	
Number of pixel	14400	
Pixel pitches	15 μm	
Fill factor	60 %	

3. Experimental Setup

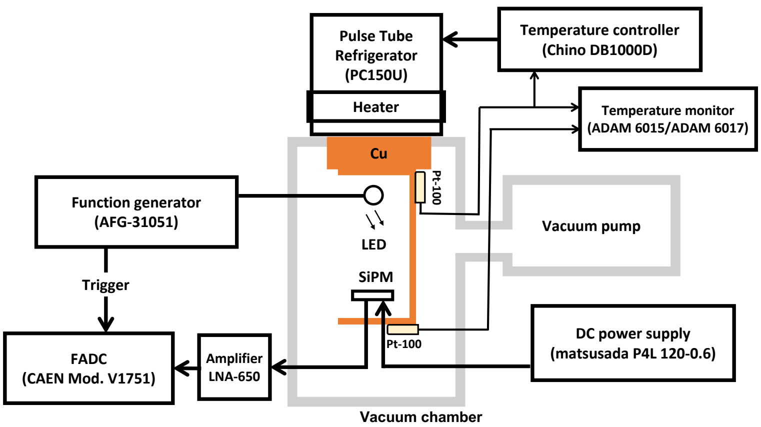

Figure 1: Experimental setup.

The experimental setup used for this study is shown in Figure 1. The SPL and STD were installed inside a vacuum chamber. Each SiPM was biased with the DC power supply (matsusada P4L 120-0.6), and the signals were amplified with a low noise amplifier (RF Bay LNA-650) with a 50 db gain. The amplified signals were then read out using a FADC (CAEN Mod. V1751) with a sampling rate of 1 GHz. The temperature was measured by three Pt-100 sensors and was controlled with a pulse-tube refrigerator (ULVAC CRYOGENICS PC150U) and a heater connected to a temperature controller (Chino DB1000D). The experimental setup was operated at various temperatures, including a temperature range of 153 K to 210 K, as well as at room temperature (296 K). Throughout the measurements, the temperatures were maintained with stability within ± 0.1 K.

4. Measurements and Results

4.1 Gain and Breakdown Voltage

To investigate the single p.e. gain and breakdown voltage (V_{br}) of SiPMs, we measured their responses to the light from a blue LED. The LED was turned on using square pulses with a freqency of 500 Hz and a width of 50 ns from a function generator (Tektronix AFG-31051), which also triggered the data acquisition via the FADC. We obtained 100,000 triggered events for each temperature and bias voltage. Figure 2 shows the pulse area spectrum of STD-1 and SPL-1 at a temperature of 162 K and a bias voltage of 48.4 V and 88.5 V, respectively. The single p.e. gain (G) can be calculated as

$$G = \frac{C_{\mathrm{cell}}(V_{\mathrm{bias}} - V_{\mathrm{br}})}{q}, \tag{1}$$

where C_{cell} is a cell capacitance and q is an electric charge.

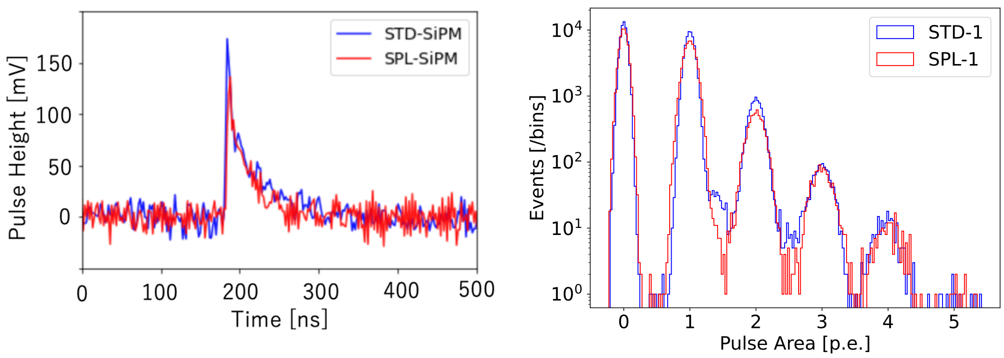

Figure 2: (left) Typical waveforms of single p.e. for SPL (red) and STD (blue) at a temperature of 162 K and a bias voltage of 48.4 V and 88.5 V, respectively. (right) Pulse area spectrum at a temperature of 162 K and a bias voltage of 48.4 V and 88.5 V for STD-1 and SPL-1, respectively.

Figure 3 shows a single p.e. gain of SPL-1 and STD-1 as a function of bias voltage. The slope of the linear fit in figure 3 corresponds to C_{cell}/q, where the cell capacitance of SPL-1 and STD-1 are estimated to be 26.9 fF and 45.7 fF at 162 K, respectively. At this temperature, single p.e. gain of SPL-1 (STD-1) at a bias voltage of 5 V is estimated to be 0.98×10^6 (1.70×10^6). The breakdown voltage (V_{br}), where the single p.e. gain becomes zero, is shown in figure 4 as a function of temperature. From Figure 4, it can be observed that V_{br} of SPL-1 and STD-1 decrease with a slope of 67.8 mV/K and 54.5 mV/K, respectively. Additionally, at the LXe temperature, V_{br} of SPL-1 and STD-1 is estimated to be 83.5 V and 43.4 V, respectively. Notably, no significant sample dependence is observed in the aforementioned characteristics.

4.2 Dark Count Rate (DCR)

In this study, DCR is defined as the number of pulses per second exceeding a threshold of 0.5 p.e.. In order to compare with that of PMTs, it is normalized by the area of each SiPMs. Given its strong temperature dependence, the measurement for DCR was performed with two different

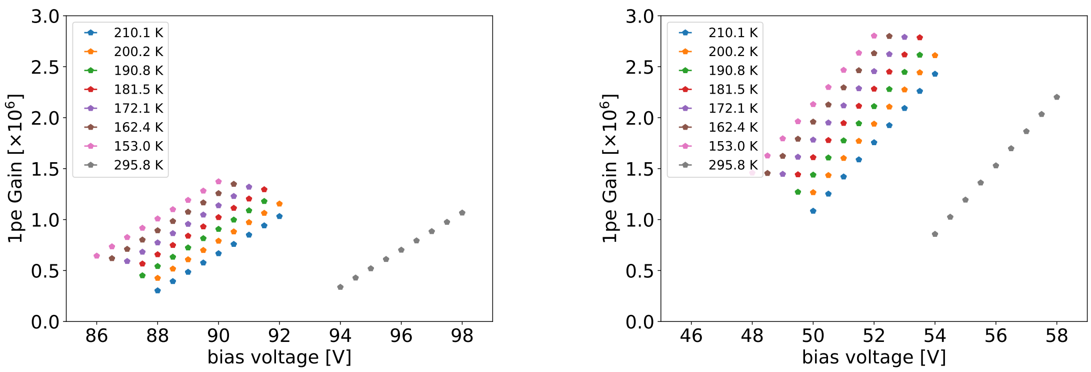

Figure 3: Single p.e. gain of SPL-1 (left) and STD-1 (right) as a function of bias voltage for temperatures ranging from 153 K to 296 K.

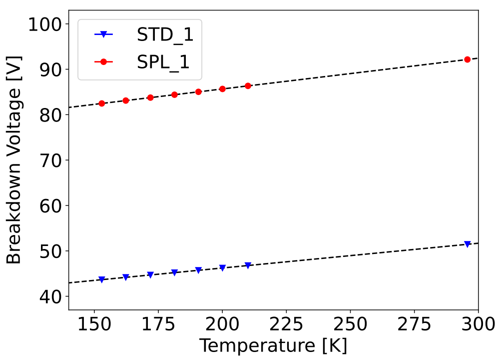

Figure 4: Breakdown voltage of SPL-1 and STD-1 as a function of temperature.

triggers. The random trigger was employed for measurements at temperatures of 200 K, 210 K, and room temperature (296 K) due to high DCR values. Conversely, at temperatures below 200 K, a self-trigger mechanism was utilized with a threshold of 30 mV. This threshold corresponds to 30 % of single p.e. pulse height for SPL at the over-voltage of 3 V

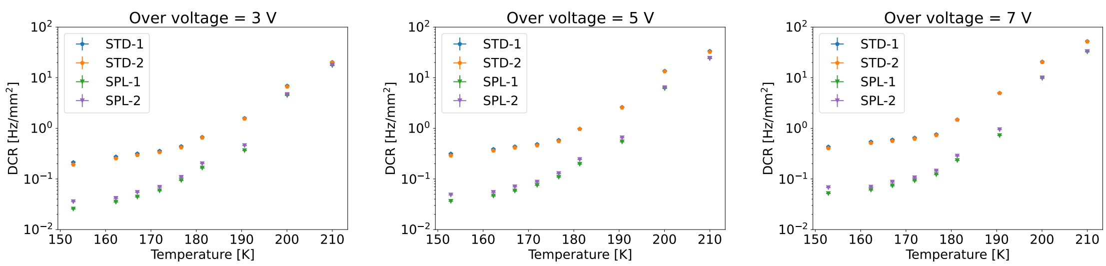

Figure 5: Dark count rate of SPL-1(-2) and STD-1(-2) as a function of temperature. From left to right, over voltage is 3 V, 5 V and 7 V.

Figure 5 shows DCR as a function of temperature at over-voltages of 3, 5 and 7 V. As shown in the figure, temperature dependence of DCR become less significant at a temperature below 180 K.

This behavior is consistent with what we observed in our previous work [9]. The DCR of SPL-1(-2) at LXe Temperature (162 K) is measured to be 0.035–0.061 (0.041–0.069) Hz/mm^2 depending on over-voltages. These are less by a factor of 7.6–8.6 (6.5–7.6) compared with that of STD, suggesting that the optimizing the electric field strength can decrease the DCR.

5. Conclusion

SiPMs offer a promising solution as low-radioactive photo-detectors in direct dark matter search experiments using LXe. However, conventional SiPMs exhibit a DCR per unit area 10-80 times higher than that of PMTs used in LXe experiments. Therefore, it is crucial to minimize the DCR to at least the level achieved by PMTs. The dominant source of DCs in SiPMs at LXe temperature is originating from the band-to-band tunneling effect, which strongly depends on the electric field strength for avalanche amplification. By reducing the electric field strength, the tunneling effect can be effectively suppressed, leading to a decrease in DC in SiPMs. In collaboration with Hamamatsu Photonics K. K., we have developed a novel VUV-sensitive SiPM (MPPC-VUV-LDC-050UM-SPL) with a reduced electric field. We have demonstrated that these newly developed SiPMs exhibit 6.5–8.6 times lower DCR at LXe temperatures compared to conventional SiPMs, achieving a DCR of 0.035–0.069 Hz/mm^2 depending on over-voltages.

Acknowledgments

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