Characterization of Cryogenic SiPM Down to 6.5 K

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SiPM operation at very low temperatures has the potential to improve detector systems for experiments at cryogenic temperatures. We characterized electrical and optical properties of a commercially available cryogenic SiPM over a temperature range of 6.5 K-286 K, such as breakdown voltage, quenching resistance, gain, pulse waveform, photon detection efficiency and dark count rate. We observed a non-linear temperature dependence of the breakdown voltage and a small change of the pulse waveform at low temperatures. The SiPM gain and maximum allowed overvoltage decrease at low temperatures, however, stable operation down to 6.5 K has been demonstrated. Furthermore, the feasibility of assembling a detector with a plastic scintillator was studied.

KEYWORDS: Silicon photomultipliers (SiPM), Cryogenics, Scintillation detector

1. Introduction

At the Paul Scherrer Institute, several experiments at cryogenic temperatures are under development, such as muCool (development of ultra-cold high-brightness muon beam line) [1], HyperMu (measurement of hyperfine splittings in muonic atoms) and muonium production from super-fluid helium for testing the gravitational interaction of anti-matter [2]. These experiments make use of scintillators at cryogenic temperatures, however, their scintillating light is typically transported to an environment at warmer temperatures before being detected by photo-detectors. Operation of Silicon Photo-Multipliers (SiPM) in the cryogenic environment could reduce the complexity and allow for finer detector segmentation while improving energy and timing resolutions due to the increased light collection.

Few studies [3], [4] and [5] have already partially characterized SiPMs below liquid nitrogen temperatures. In this study, we characterized a commercially available SiPM in the temperature range from 6.5 K to 286 K.

2. Experimental setup

The tested SiPM is the S13370-3050CN model (also known as VUV MPPC) from Hamamatsu Photonics with a (3×3) mm² active area [6]. It was originally designed for detecting scintillation light of liquid xenon and liquid argon. One peculiarity of this model is the absence of the epoxy layer protecting the silicon surface. This improves not only the VUV sensitivity but also the mechanical stability at low temperatures by reducing the mechanical stress due
to thermal contraction. This SiPM also has metallic quenching resistors to maintain the pulse waveform also at low temperatures.

In our setup, the SiPM was thermalized to a cold stage connected to a cryo-cooler by contacting its ceramic package as shown in Fig. 1. Moreover, the two pins and the coaxial cable are thermally contacted to the cold stage. The SiPM was protected from thermal radiation by two thermal shields: one contacted to the cold stage down to 6.5 K, the other at around 100 K. The temperature was controlled by two heaters on the cold stage and maintained with a stability of ±0.1 K during the measurements.

Fig. 1. Left: SiPM mounted on the cold stage. Thermal shields are removed. Right: Schematic view of the cryostat.

3. Measurements and results

3.1 Electrical properties

Current-voltage curves for various temperatures were measured by illuminating the SiPM with a weak LED light (Fig. 2). A baseline and Geiger mode regions of the curve were fitted with a linear and cubic functions in semilogarithmic scale and breakdown voltages were extracted as intersection points of two functions. We observed a non-linear temperature dependence of the breakdown voltage at low temperatures, which can be explained by Baraff’s model [7].

Fig. 2. Left: Measured current-voltage curves for various temperatures with LED on. Right: Measured temperature dependence of the breakdown voltage. The red curve is a fit with a second order of polynomial. The blue dashed line is a linear extrapolation from 286 K with a temperature coefficient from [8].
Furthermore, the resistance of the quenching resistors were measured by applying forward bias voltages. We observed only an increment of 19% from 286 K to 6.5 K. This small temperature dependence does not alter the pulse waveform at low temperatures.

### 3.2 Waveform analysis

Waveforms at the pre-amplifier output have been recorded for various overvoltages and temperatures as shown in Fig. 3. The SiPM was illuminated with a pulsed blue LED light and the recording was synchronized with the LED pulses. One initial problem, visible in Fig. 3, was periodic noise in phase with the LED pulse which can be subtracted in the data or suppressed in the measurement. In another previous measurement with a different setup, we could show that the prompt peak of the waveform remains basically unaffected down to temperature of 40 K. On the contrary, the amplitude of the tail decreases with decreasing the temperature, while its falling time increases.

![Fig. 3. Examples of single photo-electron signals with a constant overvoltage of 0.75 V.](image)

The SiPM gain was obtained by measuring the integrated charge of the single photo-electron waveform (Fig. 4 Left). The linearity with respect to bias voltages holds for all temperatures. The photo-electron peaks of the charge spectra were clearly separated even at 6.5 K. However, at low temperatures we observed a decrease of the maximal overvoltage that can be applied because of the increased after-pulse rates. For instance at 6.5 K, the maximal overvoltage was approximately 1.0 V.

Relative photon detection efficiencies (PDE) were measured by using the same pulsed LED (Fig. 4 Right). The average number of detected photons was evaluated assuming Poisson statistics. The results have relatively large non-estimated systematic uncertainties probably related to the light conditions during the data taking. However, no large decrement of relative PDEs at low temperatures were observed.

![Fig. 4. Left: Gain versus bias voltage. Right: Relative PDE versus bias voltage.](image)
Dark count rates were measured by acquiring waveform data with the LED off and a random trigger. Due to a relatively small signal-to-noise ratio for low overvoltages, we applied a digital filtering algorithm to the raw waveforms in order to improve the signal-to-noise ratio. The dark count rate was evaluated from the probability of finding a signal in a certain time window by assuming Poisson statistics. It was largely decreased with decreasing temperature: 456 kHz at 286 K and 11 kHz at 250 K with the overvoltage of 2.25 V.

4. Applications

We investigated the performance of a plastic scintillator-SiPM assembly at cryogenic temperatures. The scintillator was glued on the SiPM active area as shown in Fig. 5. Because of the absence of the protection layer, the scintillator size was chosen to be smaller than the active area of the SiPM to avoid a conflict with the bond wires. A stable operation of the scintillator-SiPM assembly at 44 K was confirmed by detecting \( \beta \)-rays of \(^{90}\text{Sr}\).

5. Conclusion

We characterized a cryogenic SiPM over a temperature range from 6.5 K to 286 K. The breakdown voltage depends linearly on the temperatures till around 200 K and saturates to a constant value at lower temperatures. Because of the increase of after-pulse probability, the maximal applicable overvoltage decreases at low temperatures. However, the SiPM is still operational down to 6.5 K with a similar performance as at room temperature. Furthermore, a scintillator-SiPM assembly was successfully tested at cryogenic temperatures.

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