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Cryogenic Characterization of FBK RGB-HD SiPMs

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Abstract: We report on the cryogenic characterization of Red Green Blue - High Density (RGB-HD) SiPMs developed at Fondazione Bruno Kessler (FBK) as part of the DarkSide program of dark matter searches with liquid argon time projection chambers. A dedicated setup was used to measure the primary dark noise, the correlated noise, and the gain of the SiPMs at varying temperatures. A custom-made data acquisition system and analysis software were used to precisely characterize these parameters. We demonstrate that FBK RGB-HD SiPMs with low quenching resistance (RGB-HD-LR$_q$) can be operated from 40 K to 300 K with gains in the range 10^5 to 10^6 and noise rates on the order of a few Hz/mm^2.

Keywords: SiPMs

Contents

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1 Introduction

Silicon photomultipliers (SiPMs) are of special interest for the development of argon- and xenon-based cryogenic detectors for dark matter, whose performance strongly depend on efficient detection of single scintillation photons. Operating SiPMs at cryogenic temperature (87 K for argon and 165 K for xenon) introduces both challenges and advantages over room temperature operation.

Building on its strong history of SiPM development [4, 7, 8], FBK [1] has developed a new generation of devices called the Red Green Blue - High Density (RGB-HD) SiPM [5]. We evaluated the RGB-HD SiPMs for possible use as photosensors in the DarkSide program of dark matter searches with liquid argon time projection chambers [2, 3].

This paper details the performance of RGB-HD SiPMs in the temperature range from 40 K to 300 K. Section 2 introduces the two variants of RGB-HD SiPMs that we tested; section 3 gives a brief overview of the cryogenic setup, the readout chain, and the analysis software (for a more detailed description, we refer the reader to Ref. [1]); finally, in section 4, we detail the results obtained with these devices.

2 RGB-HD SiPMs

An introduction to the performance of RGB-HD SiPMs can be found in [5]. Here we focus on the cryogenic performance of RGB-HD SiPMs. We studied two variants of RGB-HD SiPMs, the RGB-HD High quenching Resistor (RGB-HD-HR$_q$) and the RGB-HD Low quenching Resistor (RGB-HD-LR$_q$). The RGB-HD-HR$_q$ SiPMs reported here were fabricated with a SPAD size of $25 \times 25\,\mu\mathrm{m}^2$and the RGB-HD-LR$_q$ SiPMs had a SPAD size of $20 \times 20\,\mu\mathrm{m}^2$. The capacitance per unit area is $50\,\mathrm{pF/mm}^2$ in both cases. The size of all of the SiPM arrays tested was $5 \times 5\,\mathrm{mm}^2$.

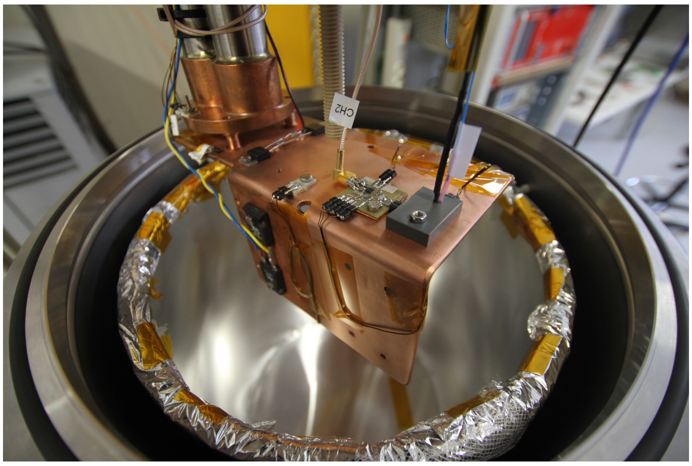

Figure 1. Detail of the cold finger, positioned just above the top opening of the stainless steel cylindrical cryostat. Also visible is the PTFE tube covered with superinsulator. On the right hand side of the cold finger, a black box contains the SiPM under test. Two unjacketed optical fibers, connected to an LED and to a laser source placed outside the vacuum chamber, penetrate the top side of the black box, delivering calibrated light signals to the SiPM under test. In the center of the cold finger is a cryogenic pre-amplifier, and on the left are the cold head of the cryocooler and the set of high power film resistors used to control the temperature.

3 Setup and analysis

The cryogenic setup is contained in a stainless steel cryostat sealed with two DN 320 ISO-K flanges and pumped to a vacuum level of about 10^{-2} mbar with a Pfeiffer ACP15 multi-stage roots evacuation pump. A Cryomech PT90 pulse tube cryocooler, with 90 W of cooling capacity at 77 K, is mounted to the top flange of the cryostat. The cold head of the cryocooler is equipped with a cold finger that holds the SiPM assembly under test, as shown in Figure 1. The system is optimized for fast thermal cycling: the cold finger can be cooled down to 40 K in about 40 min. The cold finger is also equipped with a platinum RTD connected to a Lakeshore 335 temperature controller that supplies a set of high power metal film resistors mounted on the cold finger with the thermal load required for temperature regulation.

The readout chain is composed of a Keithley 2450 SourceMeter that serves as bias source for the SiPM; a cryogenic pre-amplifier, based on a high speed, low-noise operational amplifier configured as a trans-impedance amplifier (TIA) with a feedback resistor of 500 Ω, resulting in a gain of 0.5 mV/μA; a single stage, non-inverting warm amplifier, configured for a gain of 28.8 V/V; and a CAEN V1751 1 GS/s 10 bit digitizer configured for interleaved acquisition and operating in auto-trigger mode.

A custom data analysis software developed at FBK reads the data saved by the digitizer, performs a detailed analysis of the devices' response, and saves all the relevant SiPMs parameters: primary Dark Count Rate (DCR), Direct Cross-Talk (DiCT), Delayed Cross-Talk (DeCT), and AfterPulsing (AP). The program also stores information about the single cell signal features: amplitude, recharge time, and total charge delivered in a fixed time gate.

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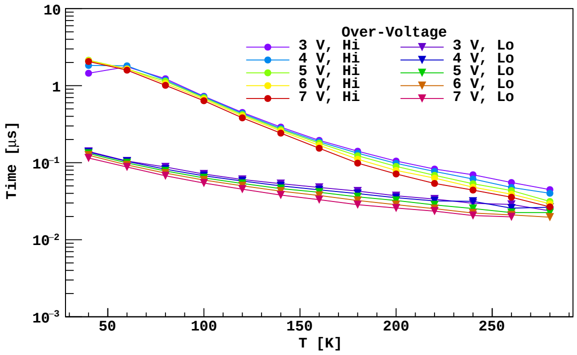

Figure 2. SPAD recharge time constant as a function of over-voltage and temperature for the RGB-HD-HR$_q$ (circular markers) and RGB-HD-LR$_q$ (triangular markers) SiPMs.

4 Results

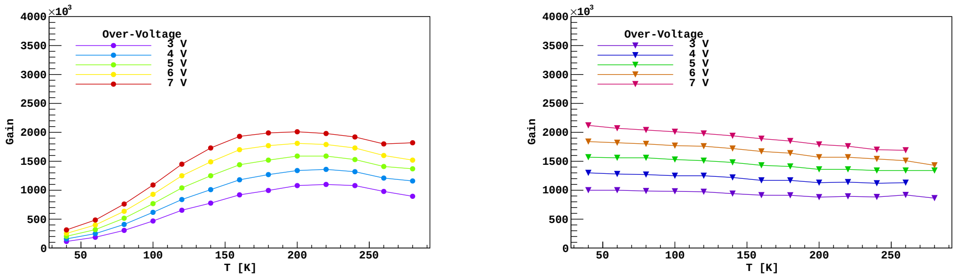

Figure 3. Gain as a function of over-voltage and temperature for the RGB-HD-HR$_q$ (left) and RGB-HD-LR$_q$ (right) SiPMs measured within a 500 ns integration gate.

As we discuss in Ref. [1], all FBK SiPMs are passively quenched using a polysilicon resistor. This resistance increases as temperature decreases, which leads to an increase in the single cell recharge time and hence the slow component of the SiPM pulse, τ_s. Operation at cryogenic temperature therefore increases the length of the SiPM signal to several microseconds, leading to incomplete integration of the released charge within the 500 ns gate. RGB-HD-LR$_q$ SiPMs were developed with a low resistance that depends weakly on temperature to overcome this problem. This reduces the temperature variation of the SPAD recharge time so that even at the 87 K argon boiling point, the SiPM signal is fully contained within the 500 ns gate. Figure 2 shows the SPAD recharge time for both the RGB-HD-HR$_q$ and RGB-HD-LR$_q$ SiPMs. At low temperatures, the RGB-HD-LR$_q$ SiPMs have a recharge time one order of magnitude faster.

The effect of the pulse length variation on the charge collected within the 500 ns gate is shown in Figure 3. The performance of the RGB-HD-LR$_q$ SiPM shows almost no variation, in contrast with the RGB-HD-HR$_q$ device.

The fast peak of the pulse is almost unaffected by temperature. Its amplitude increases linearly with over-voltage and only very slowly with temperature for both devices, as shown in Figure 4.

The DCR as a function of temperature and over-voltage is shown in Fig. 5. When operated at low temperature, both variants show a DCR reduced by over five orders of magnitude relative to room temperature. The DCR for the two variants is of the same order of magnitude over the studied

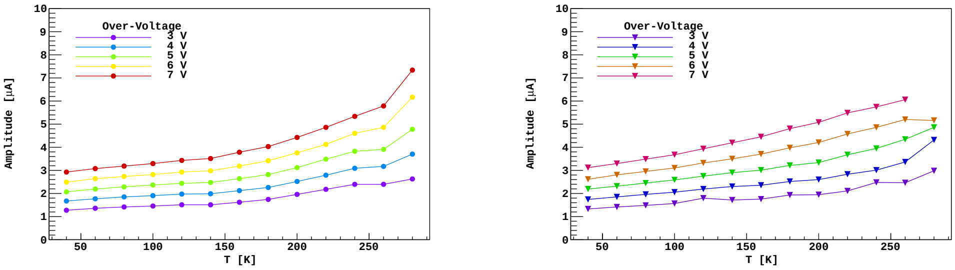

Figure 4. Amplitude of the average SPAD response as a function of over-voltage and temperature for the RGB-HD-HR$_q$ (left) and RGB-HD-LR$_q$ (right) SiPMs.

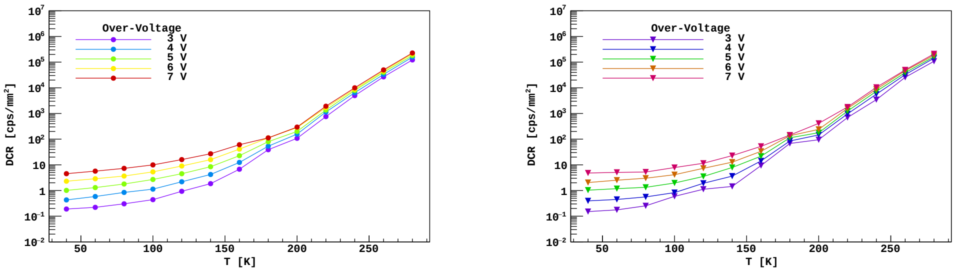

Figure 5. DCR as a function of over-voltage and temperature for the RGB-HD-HR$_q$ (left) and RGB-HD-LR$_q$ (right) SiPMs.

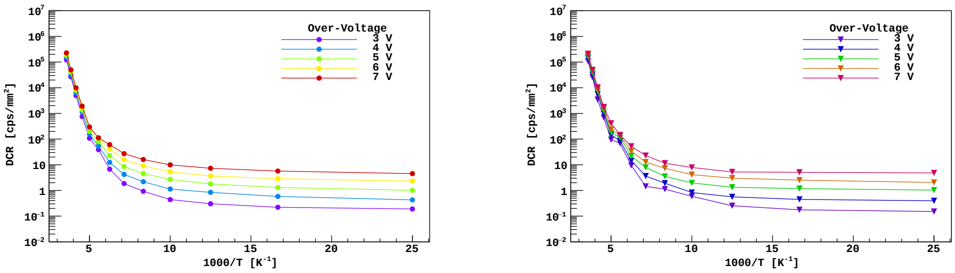

Figure 6. DCR as a function of over-voltage and the inverse of temperature for the RGB-HD-HR$_q$ (left) and RGB-HD-LR$_q$ (right) SiPMs. This representation allows the two mechanisms responsible for DCR to be distinguished: thermal generation (steep region) and field enhanced effects (plateau region).

temperature range. The Arrhenius plot, shown in Figure 6, allows one to distinguish between the different mechanisms that give rise to the primary dark count rate. At high temperature (steep region), the dominant mechanism is thermal generation, which has an exponential dependence on temperature, while field-enhanced effects [6] dominate at low temperature, where the DCR reaches a plateau.

The two variants of RGB-HD technology have similar correlated noise levels. RGB-HD-HR$_q$ SiPMs have a lower afterpulsing (AP) probability, as shown in Figure 7, and the AP for both variants increases with temperatures below 100 K. Direct cross talk, shown in Figure 8, has a weak dependence on the temperature and increases linearly with over-voltage. Overall, the direct cross talk probability is lower for RGB-HD-LR$_q$ devices. Delayed cross talk, as shown in Fig.9, is always lower than 5 % for both variants.

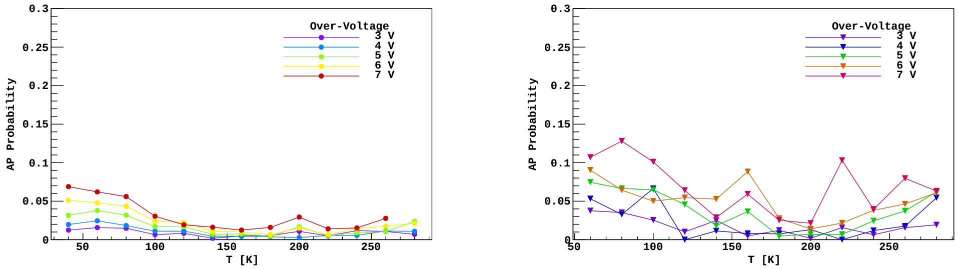

Figure 7. AP as a function of over-voltage and the inverse of temperature for the RGB-HD-HR$_q$ (left) and RGB-HD-LR$_q$ (right) SiPMs.

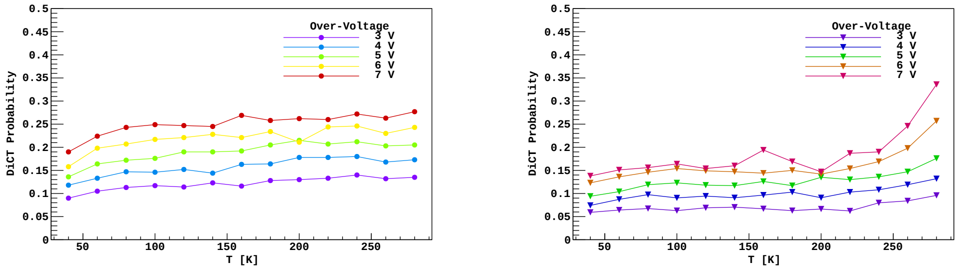

Figure 8. DiCT as a function of over-voltage and temperature for the RGB-HD-HR$_q$ (left) and RGB-HD-LR$_q$ (right) SiPMs.

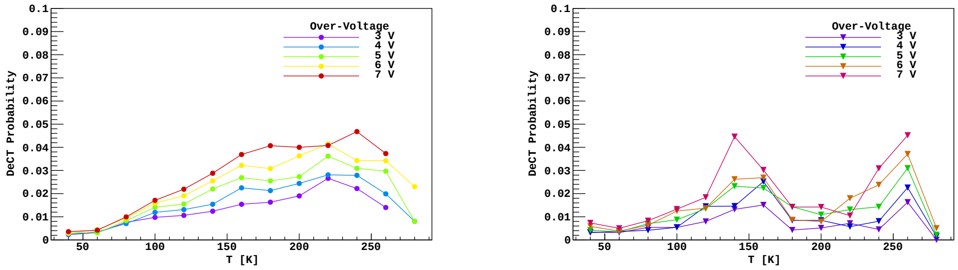

Figure 9. DeCT as a function of over-voltage and temperature for the RGB-HD-HR$_q$ (left) and RGB-HD-LR$_q$ (right) SiPMs.

5 Conclusions

We compared the performance of two variants of RGB-HD SiPMs produced by FBK in the range from 40 K to 300 K. The RGB-HD-LR$_q$ SiPMs were shown to have a fast signal at low temperature that is fully contained within a 500 ns integration gate, gains in the range 10^5 to 10^6, and noise rates below 1 Hz/mm^2 in the temperature range from 40 K to 300 K. These features make the RGB-HD-LR$_q$ SiPMs attractive for use in the DarkSide family of experiments.

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