ARTICLE IN PRESS

Nuclear Inst. and Methods in Physics Research, A ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Characterization of silicon photomultipliers for new high-energy space telescopes

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ARTICLE INFO

Keywords:
SiPM
Space telescope
Qualification
Characterization
Performance

ABSTRACT

Photon detection is a major issue of high-energy astronomy instrumentation. One classical setup that has proven successful in space missions is the combination of photomultiplier tubes (PMTs) with scintillators, converting incoming high-energy photons into visible light, which is converted in an electrical impulse. Although being extremely sensitive and rapid, PMTs have the drawback of being bulky, fragile, and requiring a high-voltage power supply of thousands volts. The silicon photomultipliers (SiPM) appear to be a promising alternative to PMTs in many applications such as small satellites. We have started a R&D program to assess the possibility of using SiPMs for space-based applications in the high-energy astronomy domain. We present here the results of our characterization of SiPMs coming from several manufacturers. Each detector has been tested at low temperature and pressure to study its performance in a representative space environment. For this, we developed a dedicated vacuum chamber with a specific mechanical and thermal controlled system. Once dark current, dark count rate and PDE were measured, we made irradiation tests on two selected detectors to understand the susceptibility of SiPM to radiation damage. Finally, we aim to perform thermal cycling and mechanical tests on detectors and study their coupling to scintillators, in parallel with their space qualification.

1. Introduction

Silicon Photo-Multipliers (SiPMs) appear to be the next generation of detectors to replace traditional Photo Multiplier Tubes (PMTs) in many high-energy astrophysics applications [1]; they can be used either for direct light detection or to readout a scintillator detector that converts incoming high-energy photons into visible light. The technical characteristics of SiPMs are powerful arguments for using them on future space telescopes: their use avoids operating high voltage supplies, ensuring robustness and reliability. Moreover, as they are insensitive to magnetic fields, we can use them in high field environments instead of PMTs. Their high Photon Detection Efficiency (PDE) would enlarge the overlap in cosmic-ray energies detected with ground-based facilities. At last, their low power consumption decreases the thermal dissipation. Consequently, one option would be to associate inorganic scintillators ($LaBr^3$, $CeBr^3$, ...) to SiPM detectors [2,3], in order to form a calorimeter for a space instrument to determine the energy of the incident photons [4]. The short decay time allows measurement of fast coincidences, which opens the way of measuring the time-of-flight of the photons, a crucial parameter for reducing instrumental background noise in space environment.

In 2015, we started a R&D study with a measurement campaign on three commercial devices; we selected SiPM references from Hamamatsu, SensL and Ketek (respectively S12572-050C, SB30035-SMT and PM3350-B63T75S-P4) to characterize their performance at room temperature under atmospheric pressure, and especially at low temperatures and pressures [5]. Then we studied their susceptibility to radiation, with a particular emphasis on the effects of protons, aboard a satellite, as well as to hostile phenomena such as Van Allen radiation belts. An irradiation test was carried out at room temperature on non-polarized detectors on the UCL cyclotron bench in Louvain (Belgium). Due to their good performance, the Ketek and SensL detectors have been chosen to be irradiated under a fluence of 2.10^{11} protons/cm^2 by protons of 50 MeV [6].

This level would allow a variety of orbits, from LEO to GEO. Afterward, we focused our studies on the effect of annealing after a proton irradiation to evaluate a potential recovery. Lately, we are in

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https://doi.org/10.1016/j.nima.2017.11.005
Received 28 September 2017; Accepted 3 November 2017
Available online xxxx
0168-9002/

Please cite this article in press as: K. Lacombe, et al., Characterization of silicon photomultipliers for new high-energy space telescopes, Nuclear Inst. and Methods in Physics Research, A (2017), https://doi.org/10.1016/j.nima.2017.11.005.

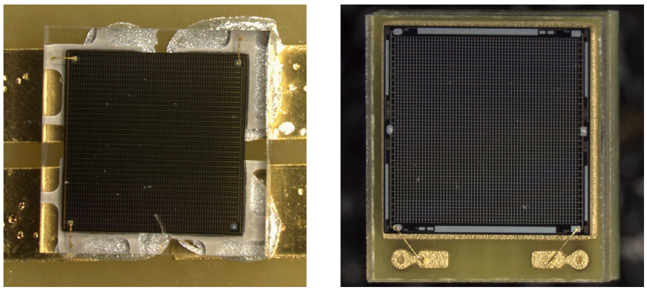

Fig. 1. Pictures of SiPM detectors SensL & Ketek observed under binocular (Left picture : 4774 cells of 35 μm pitch/Right picture : 3600 cells of 50 μm pitch).

progress to study two new references of SensL and Ketek (Figs. 1 and 2), to rise the statistics and develop a first matrix prototype of several chips on the same substrate [7].

2. Setup and configuration

We developed a dedicated thermal vacuum test bench in order to characterize the SiPMs in an environment relevant for space applications. We designed a 30 dm^3 vacuum chamber equipped with Peltier coolers to operate at low temperature (−22 °C ± 0.5 °C) and low pressure (∼10^{-4} mbar). A single mechanical support holds a specific low-noise electronics board containing both four detectors (2 SensL & 2 Ketek references) and three thermal probes mounted as SiPM, to ensure thermal stability and avoid EMC issues (Fig. 3). Firstly, we used a halogen source, covering a 350 to 800 nm wavelength range, going through a monochromator, for PDE measurements. Secondly, to observe the pulse area distribution and then obtain the gain value, a LED driver generates a light pulse at 400 nm, illuminating each SiPM via external and internal optical fibers.

3. Results

3.1. Dark current as a function of temperature

In this section, we present some results on dark current (DC), a source of noise intrinsic to the SiPM as a function of temperature. Dark Count Rate measurements supplement it, for both Ketek & SensL detectors. Next, we report Photo Detection Efficiency (PDE) and the pulse area distribution to observe the single photon. Thus, one way to suppress dark current is by cooling the detector to lower temperatures. We are studying this thermal dependence to find a temperature range ensuring the best performance of SiPMs. We measured dark current as a function of overvoltage [8] and evaluated the break down voltage at +23 °C and −22 °C at ∼10^{-4} mbar for the Ketek and SensL SiPMs (Fig. 4).

For the Ketek detector, we found a breakdown voltage temperature coefficient of dV^{BD}/dT = 21.6 mV/°C which is very close to the value provided in the manufacturer datasheet. For the SensL detector our measurements let us calculate an identical temperature coefficient of 21.6 mV/°C as expected. Moreover, at 20% overvoltage, the dark current density is about 2.5×10^{-7} A/cm^2 at −22 °C instead of 7×10^{-6} A/cm^2 at room temperature. In a nutshell, the breakdown voltage slightly decreases with the temperature. In fact, the breakdown voltage of a junction increases with a higher temperature, in relation to a decrease of the values of the ionization coefficients.

3.2. Dark count rate

As the dark current, the dark count rate (DCR) is particularly dependent on temperature; we show here that, in the case of SensL SiPM, it has been reduced by a factor of 3 at the overvoltage of 20%, by making it almost independent of this parameter. The same tendency is observed for the Ketek, which gets a decreasing of 5 by lessening of almost 40 °C at OV = 25% (Fig. 5).

3.3. PDE and single photon at low temperature

Then, to study the PDE, we first measured the pixel capacitance C for each detector. Then, we calibrated the optical chain to know the input photon flux, thanks to a photodiode power sensor in the wavelength range of the R&D from 350 nm to 800 nm [9,10]. Afterward, we measured the SiPM output voltage as a function of the wavelength. Our measurements were made for a bias voltage of 32 V for Ketek and 29 V for SensL SiPM for the temperatures of +23 °C and −22 °C. These results are consistent with the PDE values of Ketek and SensL manufacturers at room temperature. At the low temperature of −20 °C, we observe that the PDE is better than at higher temperature for both SiPM detectors, due to the lower DC, by gaining until 25% at 420 nm peak (Fig. 6).

An example of pulse area spectrum is shown in Fig. 7; we can notice that the different peaks are clearly distinguishable thanks to the low dark count rate, which reduced the peak to valley ratio (a diminution of 40 °C seems to be appropriate to obtain such a good quality of peaks discrimination) [11].

The gain of a SiPM corresponds to the mean number of charge carriers that a single charge generates during the avalanche process in the depletion region of the detector. We calculated it by taking the difference between two consecutive peaks of the pulse area distribution (red histogram in Fig. 7).

3.4. Effect of high proton irradiation on SiPM

The dark current is a source of noise intrinsic to the SiPM detector, generated even though the cells are not exposed to light. This dark current is due to the thermal excitation of electrons into the conduction band, and hence has a strong temperature dependence. Cooling the detectors to low temperatures reduces this noise. We measured the dark current and evaluated the breakdown voltage of two detectors before and after irradiation at three temperatures under different pressure settings. As the Ketek detector is plugged on board, the SensL SiPM is directly stuck on it, going through a pico-ammeter connected to the output of the SiPMs without any front-end electronics to measure the dark current. Only the power supply has been applied to polarize the SiPM placed in the dark chamber without any light source.

Our measurements show that the DC considerably increased for both SiPMs after irradiation, whereas the breakdown voltage remains quite the same. The temperature dependency is also stable; indeed, the dark current slightly decreases with the temperature with the same

SiPM Characteristics	Reference	Number of pixels / Pixel size	Active area	Typical VBD	PDE peak	Gain	Operating temperature	Spectral range / Peak sensitivity	Fill Factor
SENSL	MicroFC-30035-SMT-TA	4774 35 x 35 μm²	3 x 3 mm²	24.5V	41 %	3.10^6	-40°C / 85°C	300 - 950 nm 420 nm	64 %
KETEK	PM3350TP-SB0	3600 50 x 50 μm²	3 x 3 mm²	27 V	> 30 %	2.10^6	-30°C / 40°C	300 - 800 nm 420 nm	63 %

Fig. 2. Table of features of the last SiPM detectors (ongoing study), provided in the manufacturers datasheets.

Please cite this article in press as: K. Lacombe, et al., Characterization of silicon photomultipliers for new high-energy space telescopes, Nuclear Inst. and Methods in Physics Research, A (2017), https://doi.org/10.1016/j.nima.2017.11.005.