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Impact of proton irradiation on SiPM dark current for high-energy space instruments

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Abstract: As photon detection is a major issue in any high-energy astronomy instrumentation, many space missions combined photomultiplier tubes (PMTs) with scintillators, for converting incoming high-energy photons into visible light, which in turn is converted in an electrical pulse. The silicon photomultipliers (SiPM), instead of photomultiplier tubes (PMTs) which are bulky, fragile, and requiring a high-voltage power supply of up to several thousand volts, seem to be an encouraging alternative in the space field. We started a R&D program to assess the possibility of using SiPMs for space-based applications in the domain of high-energy astronomy. We already presented some results of the detector characterization to study the SiPM performance in a representative space environment, namely at low temperature and low pressure. For this purpose, we developed a dedicated vacuum chamber with a specific mechanical and thermal controlled system. After measuring dark current, dark count rate and PDE (Photon Detection Efficiency), we performed a first campaign of irradiation tests at UCL (Belgium) in order to understand the susceptibility of SiPM to radiation damage on two selected detectors (Ketek and SensL references) with a high level of fluence. Finally we led a new proton irradiation campaign based on several lower levels of fluence and two energies for further study. We then present the results of dark current measurements of irradiated SensL detectors.

KEYWORDS: SiPM, Detectors, Space instruments, Dark current, Proton irradiation

1. Introduction

As photon detection is a major issue in any high-energy astronomy instrumentation, many ground telescopes and space missions combined photomultiplier tubes (PMTs) with scintillators, for converting incoming high-energy photons into visible light, which in turn is converted in an electrical pulse [1][2]. The silicon photomultipliers (SiPM), instead of bulky and fragile PMTs that require a high-voltage of several thousand volts, seem to be an encouraging alternative to PMTs in the space field. They could be used for ensuring better robustness and reliability, and their higher Photon Detection Efficiency (PDE) will enlarge the overlap in detected cosmic-ray energies with ground-based facilities. Furthermore, the insensitivity to magnetic fields allows SiPM to be used in high fields environments and their low power consumption decreases the thermal dissipation. All these technical specifications are powerful arguments for future space telescopes.

We started a characterization campaign in the context of a CNES funded R&D program by first studying performance of Hamamatsu, SensL and Ketek detectors. We compared measurements of dark current, dark count rate, PDE and cross-talk, performed at room temperature and under atmospheric pressure, as well as at low temperatures and low-pressure conditions.

For this purpose, we designed a customized thermal vacuum test bench that allowed us to reproduce the ambient conditions relevant for space-based instruments. We developed low noise electronics to perform an in-depth study of the different detectors and finally selected one of them to evaluate its performance after proton irradiation phases.

The behavior of electronic components and semiconductors exposed to radiation is an essential part of their survival and operational functioning in space. Indeed, during a typical mission, about 50 % of on board incidents are due to radiation. In that purpose, we study the susceptibility to radiation of SiPM technology for using them in space applications, with particular emphasis on the effects of protons. These particles can produce additional defects inside the band gap making it easier for electrons to reach the conduction band and generate increased thermal noise [3][4].

2. Method and Configuration

2.1 The test bench

Figure 1(a) shows the picture of the main element of the test bench, which is a 30 dm^3 vacuum chamber connected to a pumping system that allows reaching residual pressures of about 10^{-5} mbar. This is equipped with Peltier coolers to operate SiPM detectors and the common PCB board (several detectors are mounted on a same support) at a precise regulated temperature of -22°C (monitored by three Pt100 probes onto each test board).

For measuring the intrinsic current of SiPM, we developed both a mechanical copper structure and a low noisy board common for the detectors and temperature probes. In the case of SensL (reference: MicroFC-30035-SMT comprising 4774 cells of 35 x 35 μm^2 side i.e. 3x3 mm^2 size), it is directly stuck on the board as seen in Fig. 1(b).

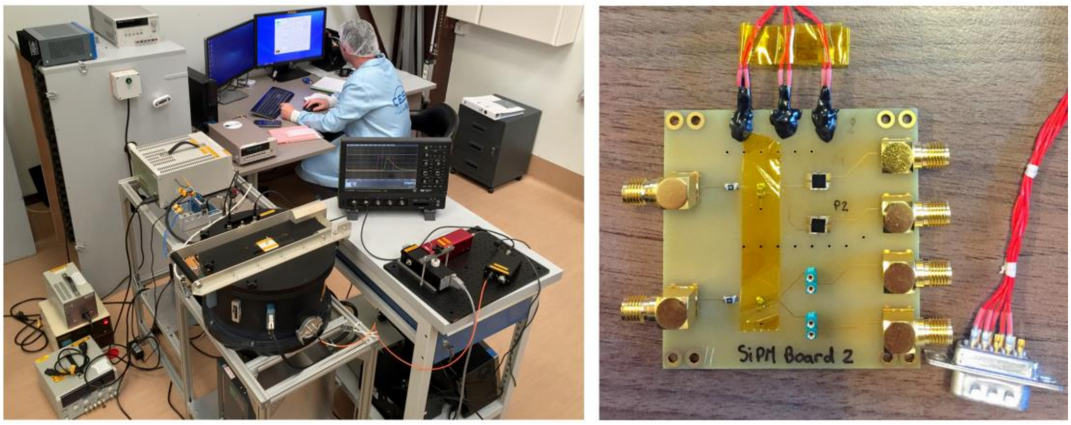

Fig. 1. (a) Left: Picture of the SiPM test bench showing the vacuum chamber (black one) with its surrounding equipment such as oscilloscope, power supply and microammeter. (b) Right: Example of an irradiated SiPM board with two SensL detectors glued on it.

2.2 The irradiation configuration

Before the irradiation, we measured the minimum dark current corresponding to noise intrinsic to each SiPM detector, generated even though the cells are not exposed to light. As it shows a strong temperature dependence, detectors are used to be cooled to low temperatures for reducing the dark current during the nominal characterization [5][6].

We then chose to test several SiPMs on the UCL cyclotron bench in Louvain in Belgium (principle shown in Fig. 2). During the first campaign, the SensL detector was tested at room temperature and irradiated under a flat fluence of 2.10^{11} protons/cm^2 by protons of 50 MeV. A second campaign has been led at 10 MeV and 50 MeV energies, with different values of fluence, from 10^{10} to 7 10^{10} proton/cm^2 (as seen in Table I).

The values of fluence have been chosen for conforming to typical dose of a low Earth orbit space mission (around 1 krad).

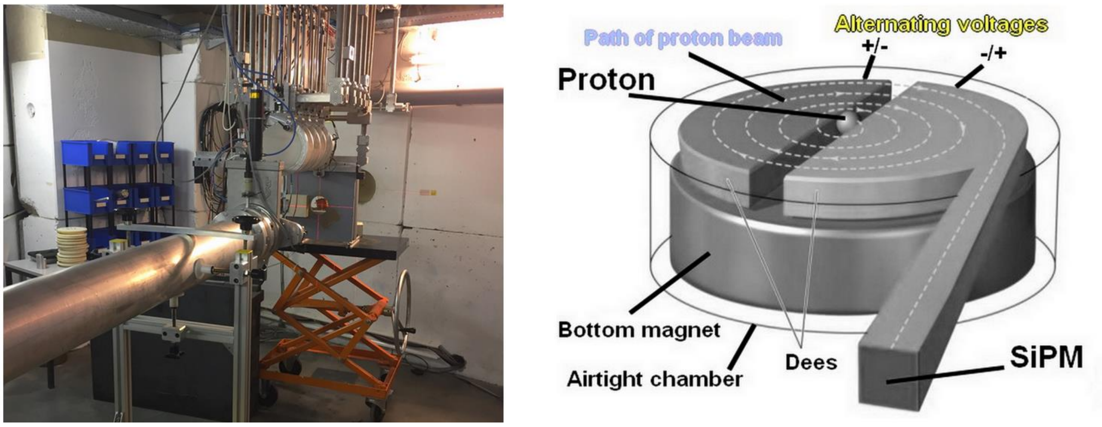

Fig. 2. (a) Left: Picture of the proton beam in UCL. (b) Right: Principle of Cyclotron - UCL Credit.

Table I details the configuration of the irradiation steps (two detectors per board).

Table I. Parameters of the irradiation campaign.

Test board number	ϕ (p/cm^2)	*Energy* (MeV)	*rd* (krad)
1	10^{10}	10	0.55
	5 10^{10}	10	2.75
	7 10^{10}	10	3.86
2	1 10^{10}	49.7	1.59
	5 10^{10}	49.7	3.19

3. Results

We report here some results of dark current measurements made before and after proton irradiation, at several temperatures under different pressure settings. Figure 3 shows the dark current as a function of the bias voltage for three fluence values (measurements at +23°C).

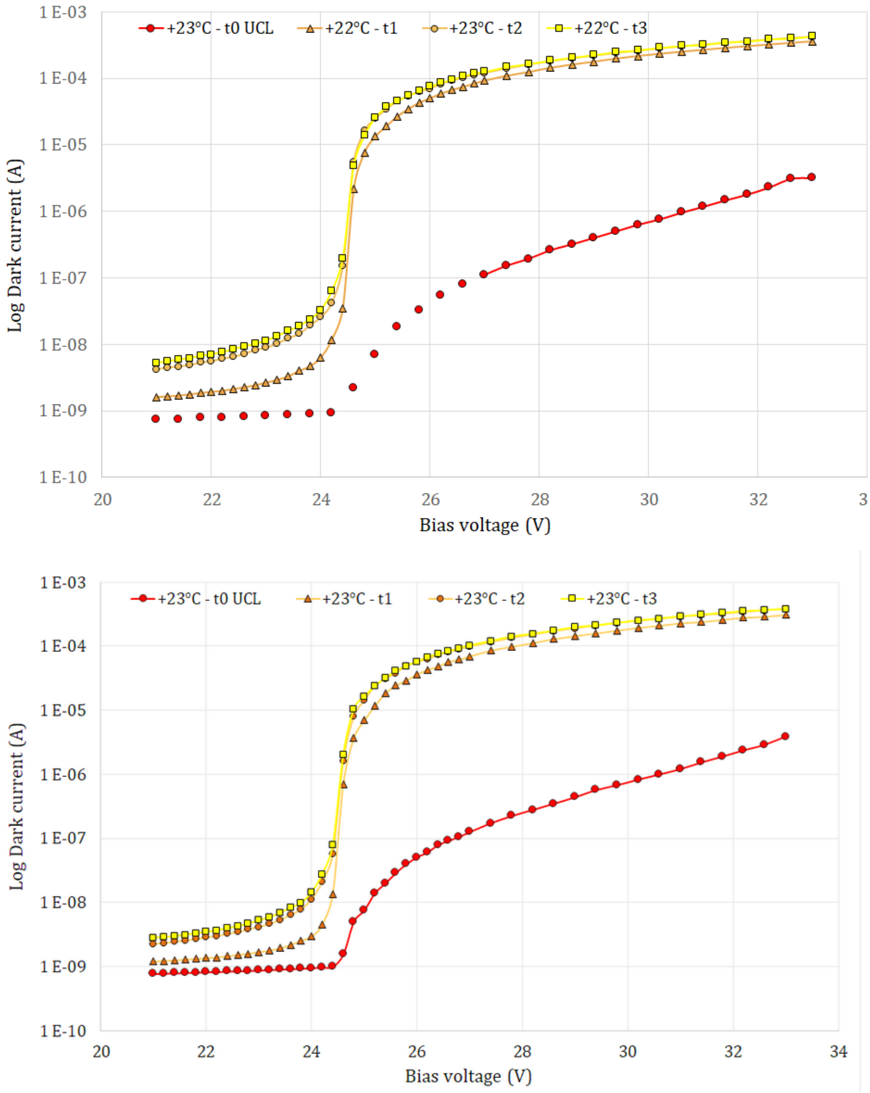

Fig. 3. Dark Current as a function of Bias voltage of two SensL SiPMs before and after irradiation in UCL's Cyclotron at temperature of +25°C – During the irradiation test, the detectors are unbiased.
Top figure: Proton energy of 10 MeV. / Bottom figure: Proton energy of 50 MeV – t1: 1.10^{10} p/cm² / t2: 5.10^{10} p/cm² / t3: 7.10^{10} p/cm².

Our measurements suggest that the dark current considerably increases after irradiation of 4 SiPM detectors, whereas the breakdown voltage remains the same. The temperature dependency is also stable; indeed, the dark current decreases slightly with the temperature with the same coefficient for both curve before and after irradiation.

We can notice that, in the working range (i.e. above breakdown voltage), the dark current at room temperature increases by a factor of around 400. Despite an annealing phase performed on the irradiated boards, there was no significant decrease of dark current and this did not allow detectors to recover a nominal working.

4. Conclusion

In conclusion, we presented examples of dark current measurements made at +23°C to study the impact of proton radiation on SiPM technology. However, despite a fluence decrease compared to the previous campaign, we still found that the dark current increases substantially for all tested detectors. It seems that a threshold has been reached, from which a very high current offset is added to the nominal values versus the temperature.

We observed an overall change in scale, but the shapes of I-V curves stayed the same and indicated that the breakdown value of the SiPM was not impacted by the proton radiation.

Later on, we plan a third campaign, firstly to confirm or not this issue, and secondly to study the flux variation instead of fluence and to evaluate the precise threshold of it when the damage occurs. We will test more SensL detectors of two cell sizes (35 µm and 20 µm) and two new detectors from FBK manufacturer of three different cell sizes (25 µm, 20 µm and 15 µm).

Furthermore, we will investigate whether a long annealing at high temperature would allow recovering the detector properties measured before irradiation. Finally, we will study SiPM with smaller cells and smaller fluence.

Acknowledgment

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