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Radiation Damage on SiPM for High Energy Physics Experiments in space missions

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Abstract. Silicon photomultipliers (SiPMs) are a popular choice for various applications, especially in astroparticle physics. These devices are coupled with organic or inorganic scintillators, allowing them to detect scintillation light and Cherenkov light. They are particularly promising for space missions because of their compact size, low operating bias, and non sensitivity to magnetic fields. We studied the effects of proton irradiation at fluences up to 1×10^{11}p/cm^2 on FBK's NUV-HD-lowCT SiPMs with $40\,\mu$m and $15\,\mu$m cell pitches. Proton-induced bulk damage increased the dark count rate (DCR) and dark current, with no significant changes in the breakdown voltage. These results align with previous studies on radiation effects in SiPMs and provide insights to mitigate performance degradation in space applications.

1 Introduction

Silicon photomultipliers (SiPMs) are advanced photodetectors consisting of an array of single photon avalanche diodes (SPADs) connected in parallel. They are widely used in space and ground-based high-energy physics experiments because of their high gain (10^5 – 10^6), low bias voltage requirements ($25 - 70$ V) and resistance to magnetic fields. When used in space missions, SiPMs are exposed to high levels of ionizing and non-ionizing radiation [1, 2], which can cause their performance to deteriorate over time. Radiation damage in can be classified into two types [4]: the first is "surface" damage, usually caused by ionizing energy loss (IEL), which results in charge accumulation at the Si-SiO$_2$ interface. This type of damage is typically caused by X-rays and electrons with energy levels below 300 keV, and it can alter the leakage current and breakdown voltage. The second, which is going to be the main focus of this study, is "bulk" damage caused by non-ionizing energy loss (NIEL), which typically results from gamma rays, electrons, protons, and neutrons with energies exceeding 300 keV [3]. This process creates lattice defects, leading to an increased DCR and after-pulsing effects.

In this work we studied the impact of proton irradiation on different SiPMs produced by Fondazione Bruno Kessler (FBK). For over 10 years, researchers at INFN Bari have been conducting research and development on SiPMs for various astrophysical applications, including the ground-based Cherenkov Telescope Array Observatory (CTAO) [6] and several

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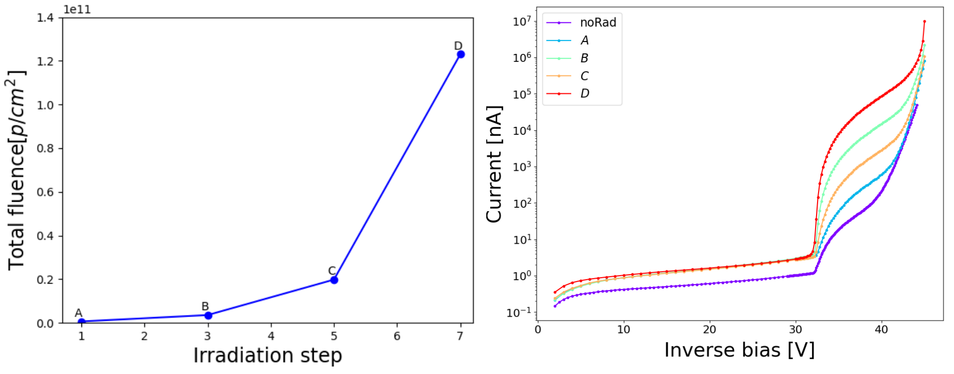

Figure 1. Left panel: Proton fluence levels applied during irradiation testing of SiPMs. Right panel: Reverse IV curves (in dark conditions) measured at room temperature for different fluences on the 15 μm SiPM.

space missions, e.g. HERD [5] and NUSES [7]. Here, we tested NUV-HD-lowCT SiPMs: High Density (HD) SiPMs, sensitive in the blue/near-ultraviolet (NUV) band, with poly-in-trench technology and with a reduction of the optical cross-talk (CT). We exposed four devices with different cell pitch sizes (15 µm and 40 µm) to four fluence levels, reported in Table 1. The left panel of Figure 1 shows the applied proton fluence levels as a function of the irradiation step, ranging from 6.3×10^8 to 1.2×10^{11} p/cm^2.

2 Proton Irradiation and Functional Tests

We performed proton irradiation tests at the Proton Therapy Center - Trento in April 2023. Then the irradiated SIPM have been tested in FBK, Trento. The functional measurements setup, as described in [9], was housed in a light-tight thermostatic chamber with precise temperature control (−50°C to 80°C). Waveform acquisition was performed using an Agilent DSO9104A oscilloscope (10 GS/s, 500 MHz bandwidth). The Differential Leading Edge Discrimination (DLED) method was employed to analyze waveforms [8], separating noise components such as after-pulsing, cross-talk, dark court rate, and gain.

Figure 1 (right panel) displays the results for 15 μm device of the reverse current-voltage (IV) curves measured before (purple line) and after (colored lines) proton irradiation, at room temperature. As the radiation dose increases, the dark current rises significantly above breakdown voltage (V_{bd} = 31.4 ± 0.1 V), while the leakage current (below breakdown voltage) remains unaffected. This suggests that bulk damage, primarily from NIEL, is the dominant degradation mechanism, and that the primary damage manifests as an increase in DCR, a critical performance parameter for SiPMs operating in high-radiation environments.

We then investigated the DCR for all SiPMs, as shown in the left panel of Figure 2. We note that it rises substantially with fluence, reaching approximately 5×10^7 cps/mm^2 at the highest fluence for both cell sizes (red curves), representing an increase of about 2 to 3 orders of magnitude compared to the non-irradiated values (blue curves). All tested SiPMs follow a similar trend of dark current increase with irradiation fluence. We computed the increase factors in DCR with respect to the non-irradiated devices for all fluence levels and for both cell sizes at ~36 HV of reverse bias (corresponding to ~6 OV) and reported them in Table 1.

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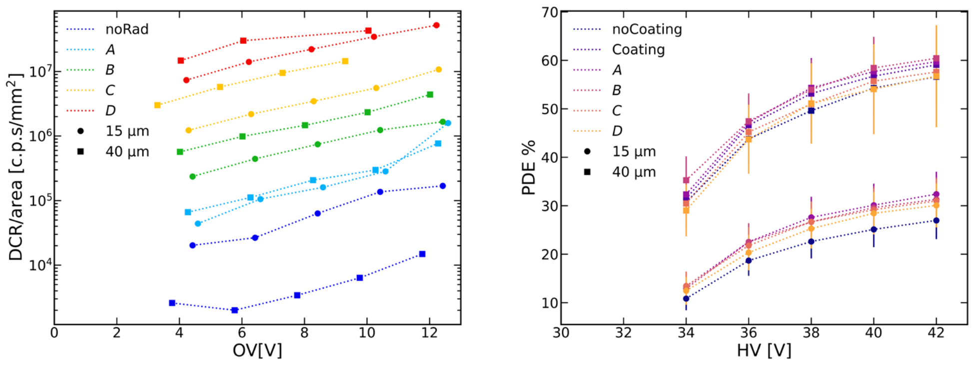

Figure 2. Left panel: Dark Count Rate normalized by the SiPM photon sensitive area (15 μm - dots, 40 μm - squares) at different proton fluence levels, measured at T= −40°C. Right panel: PDE for λ=420 nm of SiPMs with 15 μm (dots) and 40 μm (squares) cell sizes, at different proton fluence levels, with and without coating, measured at room temperature.

Additionally, we present photon detection efficiency (PDE) measurements taken under moderate illumination with a constant excess bias for a wavelength close to the one produced by plastic scintillators (λ = 420 nm). In this measurement we used a pulsed-LED based setup as the one descried in [10]. The results shown in the right panel of Figure 2 indicate that the PDE decreases in relation to the non-irradiated devices (dark blue curves) with increasing fluence. In general, the tested NUV-HD-low-CT SiPMs exhibit high PDE values even at the maximum fluence, showing resilience to the effects of proton irradiation. This consistency is promising for space applications, where reliable light detection is essential.

Fluence (p/cm^2)	Cell Size (μm)	DCR Increase Factor
(A) 6.4×10^8	15	10
	40	13
(B) 2.0×10^{10}	15	35
	40	40
(C) 3.6×10^9	15	100
	40	120
(D) 1.2×10^{11}	15	350
	40	400

Table 1. Fluence levels and corresponding DCR increase factors measured at T=−40°C for OV ~ 6 V.

3 Conclusions

We conclude that the performance degradation in terms of dark current and DCR saturation highlights the challenges in maintaining high PDE and low noise in proton-irradiated NUV-HD-low-CT SiPMs at fluences exceeding 1×10^{10} p/cm^2, particularly in applications where high noise levels could impact sensitivity.

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