Evaluating the Radiation Effects on the Characteristics of the Silicon Avalanche Photodiode with Protons

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Abstract. Silicon avalanche photodiode (Si APD) plays important roles in high sensitive optical detecting applications, such as remote sensing, radiation detection and optical communication etc. However, in the space, the Si APD would unavoidably suffer radiation damage, which would degrade the Si APD performance, like dark current, responsivity and gain etc. Here, we report the results of Si APD radiation tests with protons to evaluate their radiation hardness properties and suitability for space missions. With this motivation, samples have been radiated using 50 MeV protons with maximum does 1E12 p(proton)/cm². The test results show that the Si APD dark current increment is negligible when the radiation dose is below 1E11 p/cm², ~10 nA, satisfying most nanowatt level detecting applications. As the radiation dose further increases to 1E12 p/cm², the Si APD breakdown voltage has a measurable decrement, which subsequently increases the dark current and gain. And through over two years’ in-orbit test, the Si APD dark current keeps below 1 nA, while the responsively is ~4.9 A/W.

1. Introduction
Si APDs are widely used in various applications, including laser ranging[1], optical communication[2, 3] and radiation detection[4] etc. The low cost and compact Si APD is also variously used in space applications because of their high quantum efficiency, low noise. However, in the outer space, the Si APD is unavoidably exposed in the radiation environment, which would degrade their electrical/optical (E/O) performance and restrict their applications, though adding shield could partly reduce radiation dose. When the Si APD is biased below its breakdown voltage, it would operate in linear mode. Similar to p-, intrinsic and n-silicon (PIN) diode, Si APD current is proportional to incident optical power; But due to the internal gain, which does not participate in the system noise, Si APD owns higher signal-to-noise ratio (SNR) than PIN diode.

For the Earth orbit space, radiation source comprises mainly solar energetic-particle events, galactic cosmic radiation, and trapped radiation belts[5, 6]. In the low Earth orbit (LEO), the major radiation source is trapped radiation belts consisting of trapped electrons and protons in the South Atlantic Anomaly and solar protons at the poles of Earth’s magnetosphere [6-8]. Trapped electrons can be shielded effectively to negligible levels with ~3-mm-thick aluminum (satellite case) [9]. However, the radiation due to protons has two major effects on the silicon lattice in Si APDs, namely; ionizing dose damage and accumulated displacement damage [10]. For Si APDs, the accumulated displacement damage is the major factor that increases the bulk leakage current appreciably. Theoretically, radiation effects on
Si APD can be predicted reasonably by the calculations of amount displacement damage energy imparted to the primary knock-on-atoms, but it is not possible to simulate fully the space radiation environments of practical interest. The development of the nonionizing energy loss (NIEL) rate in various semiconductors versus incident particle energy allows us to use mono-energetic particle testing to predict the Si APD on-orbit performance degradation[11]. For instance, for a 500 km circular Sun-synchronous orbit, based on the Space Environment Information System (SPENVIS) [12] and AP8-min and AE8-min models, the total displacement damage dose(behind the 3-mm-thick aluminum) equivalent 50-MeV protons is ~0.80 × 10^9 p/(proton/cm^2) per year.

We have performed displacement damage tests on SLiK Si APD with 180 μm diamenter, provided by Excilitas, using 50 MeV proton source which effectively penetrates the APD package front glass window. In this paper, we mainly focus on the Excilitas’s SLiK Si APD radiation-induced linear-mode performance degradation, such as dark current, responsivity, gain and dark count rate etc.

This paper is organized as follows. In Section 2, we introduce the test samples, test setup and test procedure. In Section 3, we give test result. In Section 4, we present the discussion and conclusion.

2. Experiment Setup

The 50MeV proton radiation source used was provided by the Cyclotron of Louvain la Neuve (CYCLONE) at the Université Catholique de Louvain (UCL) in Belgium, and the flux was set to 1E5-1E9 protons/cm^2.s. Only the APDs were exposed to proton beam, the characterization test circuits and devices were protected from radiation using shield. Figure 1(a) shows the APDs radiation setup and the UCL Proton Beam Line facilities. During irradiating, only the APDs were exposed to the proton beam, E/O characterization test circuits and test devices were shielded. The APD E/O characteristics test set-up mainly comprises of 810 nm light source, high voltage supply, high precision I-V multimeter and TEC driver, as shown in Figure 1(b).

![Figure 1. (a) APDs radiation setup. (b)APD E/O characteristics test set-up configuration](image)

For the SLiK Si APD, namely, SLikAPD#1 and SLikAPD#2, it is integrated with a two-stage thermal electrical cooler (TEC) and a thermistor (TR), which are used to control the APD operating temperature. In additional, in order to protect the APD from water vapor and extreme temperature and keep the operating temperature stable, the APD package is hermetically sealed with glass window (The window in front of the APD was 1.0 mm thick and was made of Borosilicate glass which had a density of 2.6 g/cm^3). The proton source parameters and radiation test step as shown in Table 1. The radiation process is divided into four steps, the proton flux is 1E7 p/(s.cm^2) for step 1 and 1E8 p/(s.cm^2) for step 2-4, and the cumulative fluence of each step is an order of magnitude higher than previous one, and the final cumulative fluence is 1E12 p/cm^2.
Table 1. Proton source parameters and radiation steps

| Multiple radiation steps | Beam Energy (MeV) | Cumulative Fluence (p/cm²) | Flux (p/s.cm²) | Exposure Time (minute) | Temperature (°C) |
|--------------------------|-------------------|-----------------------------|----------------|------------------------|-----------------|
| 1                        | 50                | 1E9                         | 1E7            | 1.6                    | 25              |
| 2                        | 50                | 1E10                        | 1E8            | 1.5                    | 25              |
| 3                        | 50                | 1E11                        | 1E8            | 15                     | 25              |
| 4                        | 50                | 1E12                        | 1E8            | 150                    | 25              |

During the radiation, we have measured the SLiK Si APD linear-mode E/O characteristics at each step. For the SLiK Si APD dark current, responsively and breakdown voltage tests, APDs operating temperature were controlled at 0 °C and directly connected to a high voltage (HV) supply and a high precision I-V multimeter. A light source with 810 nm wavelength and an integrating sphere were used to test the APDs responsively, the light power into APD was controlled to 300 nW by a close loop.

3. Test Results
At different accumulated fluence, 0 p/cm², 1E9 p/cm², 1E10 p/cm², 1E11 p/cm² and 1E12 p/cm², the proton flux was blocked, then the Si APD dark current, breakdown voltage and responsively were measured at 0°C. Figure 2(a) shows the SLiK APD dark current at different radiation dose, which increases with the radiation dose, but the increment is insignificant. For the breakdown voltage at different accumulated fluence, as shown in Figure 2(b), when the accumulated fluence was below 1E11 p/cm², the breakdown voltage had no measurable change due to the radiation. At the final accumulated fluence 1E12 p/cm², there was approximately 3 V increment for the SLiK APD#2 breakdown voltage. Therefore, the radiation effects for the SLiK APDs breakdown voltage were not negligible when the accumulated fluence reached 1E12 p/cm².

![Figure 2](image)

Figure 2. (a) SLiK APD dark current at different radiation dose; (b) SLiK APD breakdown voltage at different radiation dose

The SLiK APD responsivity, as showed in Figure 3, was lowered approximately 3 times at the maximum accumulated flounce 1E12 p/cm².
4. Discussion and Conclusion

According to the test results, when the radiation dose is very high, the Si APD breakdown voltage would decrease, which would significantly increase the dark current, under the same bias voltage and operating temperature. The Si APD inner gain can be expressed as,

\[
M = \frac{1}{1 - \left( \frac{V_r}{V_{\text{BR}}} \right)^n}
\]

where \( V_r \) is the Si APD bias voltage (less than \( V_{\text{BR}} \)), \( V_{\text{BR}} \) is breakdown voltage and \( n (>1) \) is a characteristic parameter decided by the APD structure and material. And the Si APD dark current can be expressed as[13],

\[
I_d = I_s + M \cdot I_b
\]

\( I_s \) is the Si APD surface leakage current, \( I_b \) is its bulk dark current. So as the radiation dose increase, adjusting the Si APD bias voltage will be a very effective measure to mitigate the radiation-induced dark current increment. In addition, decreasing the Si APD volume is another measure to mitigate the radiation-induced dark current increment, the change in dark current per unit depletion region volume can be expressed as[14],

\[
\frac{\Delta I_d}{V} = \frac{q n_i \Phi}{2 K_{gn}}
\]

where \( V \) is the depletion region volume, \( n_i \) is the Si APD intrinsic carrier density, \( \Phi \) is the radiation dose, and \( K_{gn} \) is the damage coefficient for the material type in the depletion region.

We have radiated the Si APD with 50 MeV proton. According to the test results, there was no significant radiation-induced degradation in the responsivity, dark current and breakdown voltage performance when the radiation dose is below 1E11 p/cm\(^2\), this radiation dose could satisfy most LEO mission. For instance, for a 500 km circular Sun-synchronous orbit, the 100 years equivalent 50-MeV protons radiation dose is \( \sim1E11 \) protons/cm\(^2\). Eight SLiK Si APDs have been launched onboard Micius satellite, on 16 August 2016, which features a 500 km circular Sun-synchronous orbit. In the past over two years, their dark current keeps below 1 nA, with \( \sim4.9 \) A/W responsively and 0 °C operating temperature.
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6. References
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