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Displacement Damage induced in 150 nm CMOS SPADs by 2 MeV electrons

E. PONTICELLI

Dipartimento di Fisica "Ettore Pancini", Università degli Studi di Napoli Federico II Napoli, Italy

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Summary. — This work investigates the degradation induced to 150 nm CMOS Single-Photon Avalanche Diodes (SPADs) by 2 MeV electrons. Radiation-induced damage effects are investigated through a Dark Count Rate (DCR) analysis. Different architectures of CMOS SPADs are tested. Displacement Damage results in lattice defects that lead to a DCR increase mostly due to thermal contributions in most linear-region operating devices. The study reveals an interesting behavior of DCR as a function of both the absorbed dose and the applied voltage. This suggests a strong tunneling contribution to radiation-induced noise, alongside the thermal one, in a peculiar way for Geiger-mode devices such as SPADs.

1. – Introduction

CMOS technology allows integrating part of the readout electronics in the substrate of SPADs themselves. This guarantees low power dissipation and digital pixel outputs. CMOS SPADs can also offer a very small-time resolution, of the order of 100 ps, and high granularity. SPADs are employed in many scientific sectors involving significant radiation levels, which can easily damage devices. It is well known that damage in detectors results in higher output noise levels. Therefore, it is fundamental to study SPADs' response to radiation damage. Displacement Damage is more likely to be caused by heavy particles such as protons or ions. For this reason, Displacement Damage induced by electrons in semiconductor detectors has not been thoroughly studied in the past.

2. – Noise in SPADs

SPADs operate over junction's breakdown voltage V_{BD}, in the so-called "Geiger region". In this mode, a large avalanche current is generated and the gain can be as high as 10^6–10^7. However, electron-hole pairs randomly generated in the depletion region can trigger avalanches even when no photons are hitting the SPAD. The corresponding output current is called Dark Current I_{dark} and the Dark Count Rate (DCR) is the rate of randomly triggered avalanche pulses.

Table I. – *Fluence and DDD concerning the 2 MeV electrons irradiation.*

Fluence (e/cm^2)	DDD (TeV/g)
$(3.4 \pm 0.3) \cdot 10^{12}$	155 ± 15
$(6.9 \pm 0.7) \cdot 10^{12}$	309 ± 30

DCR is generally due to thermally generated pairs, according to the Shockley-Read-Hall model [1], afterpulsing or tunneling effects, both of band-to-band- and of trap-assisted type [2].

3. – Displacement Damage

Displacement Damage is a particular kind of radiation-induced damage that results in the dislocation of atoms in the crystal lattice of a semiconductor. The incoming particle can be energetic enough to dislocate an atom creating a Frenkel pair that can possibly cause further dislocations, forming cluster defects. Displacement Damage is quantified in terms of Displacement Damage Dose (DDD) (MeV g^{-1}) as

$$DDD = NIEL \cdot \Phi, \tag{1}$$

where the term NIEL stands for “Non-Ionizing Energy Loss” (MeV cm^2 g^{-1}) and Φ is the particle fluence (cm^{-2}). Displacement Damage increases both Dark Current and DCR. This is because it contributes to creating traps in the bandgap, which enhances thermal-generated-pairs probability [1] and tunneling effects [2].

4. – Experimental setup

Two architectures of CMOS SPADs were tested, both named after their junction types. PN structures were characterized by a p+/n-well junction with a high doping concentration and a high electric field at the junction. Their V_{BD} was about 17 V. PWN structures featured a lower junction electric field instead, induced by their p-well/n-well kind of junction and had a V_{BD} value of about 24 V. Every pixel was provided with a metallic shield in order to border the light impact on the active region of the SPAD, so creating an optical window.

Two devices were tested, both presenting PN and PWN SPADs built in different optical window sizes and arranged in different configurations, meaning arrays and matrices. The irradiation test was performed at the ILU-6 Accelerator at the Institute of Nuclear Chemistry and Technology in Warsaw. The two tested devices were irradiated with different doses as shown in table I, that also exhibits the absorbed Displacement Damage Doses. During irradiation, no bias was applied.

5. – Analysis

After irradiation, both PN and PWN structures showed an increase of DCR values of about one order of magnitude. Figure 1 shows this behavior for the two irradiated devices and a third, non-irradiated device. The plots display DCR values as a function of the applied bias voltage V_{bias} for 10 μm optical window SPADs. PN structures show higher values of DCR than PWNs both before and after irradiation.

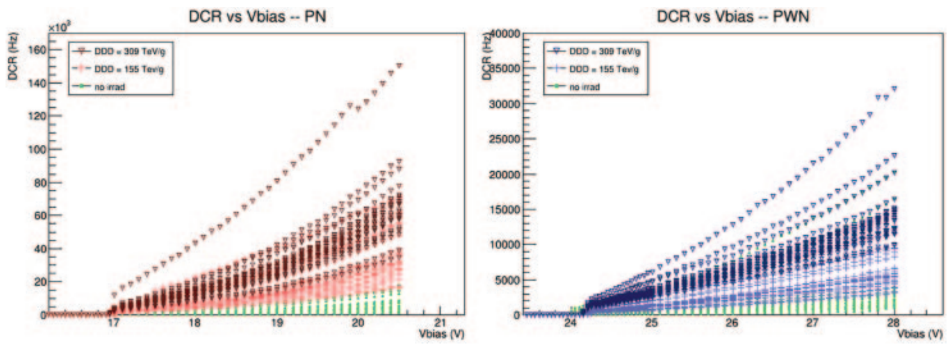

Fig. 1. – Dark Count Rate as a function of bias voltage V_{bias} for PN structures (on the left) and PWN structures (on the right).

Many proposals have been made in literature in order to identify universal parameters for damage measurement. In this respect, in [3] the K_{dark} parameter was proposed as

$$K_{dark} = \frac{\Delta G}{DDD}, \tag{2}$$

where ΔG is the Generation Rate variation of charge carriers in the specific device. In [3], K_{dark} was estimated for many kinds of devices. Hadron-induced damage has been largely studied, while not so much information is available about electron-induced damage. Data also only concerned linear-operating devices. For SPADs in particular, DCR can be expressed in terms of Generation Rate as showed in (3), where ϵ_{trigg} is the trigger efficiency, A is the active area and W is the depletion region width. Once these parameters have been estimated, it is possible to extrapolate the K_{dark} parameter as reported in (4):

$$DCR = \Delta G \cdot \epsilon_{trigg} \cdot A \cdot W, \tag{3}$$

$$K_{dark} = \frac{\Delta DCR/DDD}{\epsilon_{trigg} \cdot A \cdot W}. \tag{4}$$

For this purpose, the behavior of the mean value of DCR as a function of Displacement Damage Dose has been studied for bias values of 2 V, 3 V and 4 V overvoltage (V_{OV}) above V_{BD}. Figure 2 shows an increase of DCR both with DDD and the applied voltage.

TABLE II. – *α and K_{dark} values at V_{OV} = 2 V, 3 V, 4 V extrapolated from DCR vs. DDD fits.*

	PN		PWN	
V_{OV} (V)	α $(\frac{\text{Hz}\cdot\text{g}}{\text{TeV}})$	$K_{dark}(\text{cm}^3\text{s}^1(\text{MeV/g})^{-1})$	α $(\frac{\text{Hz}\cdot\text{g}}{\text{TeV}})$	$K_{dark}(\text{cm}^3\text{s}^1(\text{MeV/g})^{-1})$
2	67 ± 6	$(1.3 \pm 0.1) \cdot 10^6$	15 ± 1	$(2.3 \pm 0.2) \cdot 10^5$
3	120 ± 10	$(2.0 \pm 0.2) \cdot 10^6$	23 ± 2	$(3.0 \pm 0.3) \cdot 10^5$
4	190 ± 20	$(2.9 \pm 0.2) \cdot 10^6$	31 ± 3	$(3.9 \pm 0.3) \cdot 10^5$

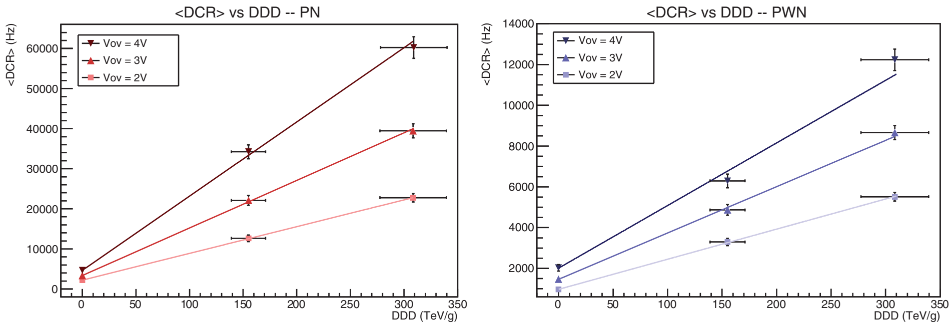

Fig. 2. – Mean Dark Count Rate as a function of Displacement Damage Dose at $V_{OV} = 2\,\mathrm{V}, 3\,\mathrm{V}, 4\,\mathrm{V}$ for PN structures (on the left) and PWN structures (on the right)

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Linear fits were performed. The slopes α are shown in table II and they correspond to the numerator of (4). Table II also shows the obtained K_{dark} values.

It becomes clear that the K_{dark} parameter grows with the applied voltage. Also, PN SPADs exhibit higher K_{dark} values than PWN SPADs by about one order of magnitude.

6. – Conclusions

The discussed results can be explained by the significant contribution to noise from tunneling effects for this kind of devices when damaged. Tunneling probability grows with the electric field intensity [2]. High bias voltages correspond to high K_{dark} values because they lead to high electric fields at the junctions, enhancing tunneling contribution to noise. The correlation between high electric fields and high K_{dark} values also explains the difference in DCR increase between PN and PWN structures. PNs have indeed higher doping concentrations and higher electric fields than PWNs. Geiger-mode devices like SPADs are proven to be significantly sensitive to Displacement Damage. Consequently, they cannot be included in a universal Displacement Damage model. This is because the greatest contribution to noise in SPADs comes from tunneling more than from thermal effects. With the aim of finding a Displacement Damage model for Geiger-mode devices, further studies about hadron-induced Displacement Damage are in progress.

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