Radiation effects on Single-Photon Avalanche Diodes manufactured in deep submicron CMOS technology

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Abstract. CMOS Single-Photon Avalanche Diodes (SPADs) have been introduced recently in many scientific applications. This paper reports on the performance, in terms of Dark Count Rate (DCR), of a photo-sensor based on CMOS SPADs. The device has been subjected to an accurate investigation, in order to evaluate its behaviour in a radiation environment. Several irradiation tests were conducted, and a complete survey of their effects on the DCR behaviour has been performed. An overall increase in the DCR level has been measured, meaning that new defects have been introduced in the space charge region of the SPADs. Furthermore, for a fraction of the SPADs, DCR measurements show a Random Telegraph Signal (RTS) temporal pattern.

1. Introduction

Complementary metal-oxide-semiconductors (CMOS) Single-Photon Avalanche Diode (SPAD) have been introduced recently in many applications, ranging from industrial to the scientific ones. \cite{1}. CMOS SPADs offer the high performance needed in application requiring the detection of weak light signal at the photon-counting level \cite{2}.

Although SPADs have been widely produced in custom process with excellent results, the CMOS technology offers the possibility to improve the detector response. Indeed, it allows the implementation of SPADs, front-end and signal processing electronics on the same substrate, improving the spatial and the temporal performances of the devices, and allowing signal processing inside the detector itself. Furthermore, CMOS technology allows the low-cost mass production needed to obtain large area sensors suitable for several research applications.

Currently, many experiments in high energy physics, medical physics and space applications took the challenge of developing dense circuits integrated into the detector itself, taking advantage of the maturity of CMOS technology. Beyond the engineering challenge of implementing complex circuits inside the detector, the real challenge is to create competitive devices with high performances and low noise \cite{3}. Compared to custom devices, CMOS SPADs suffer from the high level of dark signals, expressed in term of Dark Count Rate (DCR). This depends on higher concentration of defects and

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contaminants in the adopted substrate and a less accuracy in the CMOS fabrication process compared to the custom one. Defects concentration can be altered also after the fabrication steps due to environment factor. This is the case of devices operating in a radiation environment. In this paper we report the results of the dark signal characterization on a SPAD sensor, developed in a deep submicron CMOS process. Several irradiation tests were conducted in order to test the radiation hardness of the devices. The dark count rate as well as the breakdown voltages (\(V_{br}\)) of the detector have been measured before and after proton irradiation. An overall increase in the DCR level has been measured, suggesting that new defects have been introduced in the space charge region of the SPADs. Furthermore, for a fraction of the SPADs, DCR measurements show a Random Telegraph Signal (RTS) temporal pattern.

2. Materials and methods

2.1. CMOS sensor developed by FBK

The Device Under Test (DUT) is a fully CMOS sensor designed by Fondazione Bruno Kessler (FBK) and implemented in a 150-nm CMOS technology. It is part of a test chips production, purposely made for the study of CMOS SPAD performances [4]. It implements several hundred of SPADs of different dimension according to Table 1

| Optical Window (µm) | 5   | 10  | 15  | 20  |
|---------------------|-----|-----|-----|-----|
| Optical Area (µm²)  | 22  | 97  | 222 | 397 |
| Pitch Size (µm)     | 10.6| 15.6| 20.6| 25.6|

The chip contains SPADs organized in matrix groups of 5x5 elements and in linear arrays of 20 elements. Each SPADs is integrated together with its own front-end electronic. The basic design of the pixel architecture is reported on figure 1. SPADs are connected to a quenching transistor, an enable transistor and a Schmitt comparator, that digitalizes the pulse from the photodiode. Each pixel shares the same output and can be individually addressed through a decoder system.

![Figure 1. Pixel read-out circuit implemented inside the CMOS SPADs sensor.](image)

2.2. Experimental setup
The purpose of this work was the study of the dark signal performances of the detector. To this purpose a fully automatized setup has been developed. Measurements have been performed in a dark environment at a controlled temperature by means of a climatic chamber. The DCR measurement was conducted by means of an external counter connected to the chip output (figure 2). A dedicated software drives the setup instruments [5], so that automatic measurement of DCR have been performed as a function of the bias voltage $V_{bias}$.

![Figure 2. Schematic diagram of the experimental setup realized for the DCR measurements.](image)

2.3. The proton facility
The proton beam tests have been performed at the Laboratori Nazionali del Sud (LNS) in Catania, by means of the tandem accelerator.
The irradiation tests have been performed with a proton beam of 24 MeV extracted in air. The actual energy of the beam on the DUT has been simulated through the FLUKA Montecarlo software, and found to be 20.5 MeV [5].
The beam dosimetry has been performed by means of a calibrated ionization chamber placed along the beam line. The beam profile, measured by means of a radio-chromic film placed in front of the device, showed a non-uniformity on the chip surface well below 10%. An integrated fluence of $5.63 \times 10^{10}$ protons/cm$^2$ has been delivered, corresponding to a Displacement Damage Dose (DDD) of 376 TeV/g. According to [6], such radiation level is greater than that expected for typical space mission applications, but any case below the typical levels in high energy physics collider.

3. Results and discussion
3.1. Dark signal characterization
The device has been subjected to an accurate investigation of the dark count rate behaviour. Figure 3 shows the $DCR - V_{bias}$ plot for a subsample of 20 SPADs before irradiation test. At an overvoltage of 3.3 V, the mean DCR is of the order of the kHz. Breakdown voltage was extracted by subtracting the comparator reference voltage $V_{ref}$ from the transition voltage in the $DCR-V_{bias}$ plots. Figure 4 shows that the mean breakdown voltage value is about 23.5 V.
After irradiation, the DCR measurement have been performed in order to evaluate the irradiation effects on the CMOS SPADs sensor. We characterize DCR on several hundred of SPADs belonging to 2 different chips. While breakdown measures do not show significant changes after irradiation, the situation is more serious for the pedestal of DCR.
Figure 5 shows DCR measurements performed before irradiation, after each run and, finally, a month after the last irradiation. As shown the damage induced by radiation is not spatially uniform: some pixels show a DCR increase of more than two order of magnitude.

**Figure 3.** $DCR$ vs $V_{bias}$ on a sample of 20 CMOS SPADs.

**Figure 4.** Breakdown voltage distribution measured on a sample of 20 SPADs.

Measurements performed a month after the irradiation test, show that a partial recover of the DCR has occurred, being the chip at room temperature.

**Figure 5.** DCR variation after irradiation on a sample of 10 SPADs.

3.2. Random Telegraph Signal noise

After irradiation, many long-time DCR acquisitions on single SPADs showed in many pixels, discrete temporal fluctuations of the DCR between different levels. The percentage of pixels affected by this behaviour after irradiation, depending on the SPADs layout, has found to be even more than 50%. Before irradiation, only a small percentage of SPADs is interested by this behaviour, while for almost all SPADs a stable level of DCR is observed. To clearly present the phenomenon, a DCR measurement frame of few hours on a single SPAD and the corresponding DCR histogram are presented in figure 6 and figure 7. The DCR is observed to randomly switch between different DCR levels and four normal distributions of DCR can be observed.
3.3. Discussion

In silicon devices, DCR is closely linked to the presence of defects and impurities in depletion region according to many mechanisms [7][8][9].

Due to a mechanism known as displacement damage, the concentration of such defects can increase during the detector lifetime if operated in a radiation environment. Displacement damage can affect the detectors performances in many ways, depending on induced defect concentration, energy level and the respective electron and hole capture cross-section [10].

The observed results, can be related to the introduction of new defects with energy levels near the middle of the gap of the devices. According to [9], induced defects, acting as recombination/generation centres facilitate the transition of electrons and holes between bands and thus are responsible for an increase of the reverse current.

Irradiated SPADs showed large fluctuations in the DCR values, well beyond the non-uniformity of the proton beam. This behaviour can be addressed to the relatively low proton fluences and the small SPADs sensitive volume, that results in a large defects formation variability, dominated by statistic effects.

Beside the DCR pedestal increase, long time measurements, showed after irradiation a significant fraction of pixels affected by RTS pattern. Given that the increase in the DCR itself in a photon sensor is dangerous for its functionality, the RTS phenomenon can have a large impact on the noise performance of the sensor.

Post-irradiation measurements showed a large fraction of pixels affected by RTS behaviour. Several mechanisms have been proposed in literature in order to explain RTS in silicon image sensors [11][12][13]. The observed random switching of the DCR between two or more well-defined rates, suggests the presence of a metastable-stable defects located in the space charge region of the device.

4. Conclusion

The purpose of this paper was the understanding of the effects induced by radiation on a CMOS SPAD sensor. At this purpose, an irradiation campaign test has been performed with protons of 20.5 MeV, reaching a DDD of 376 TeV/g.

DCR measurements have been performed before and after the irradiation campaign. The samples demonstrated a significant increase in the DCR pedestal for most of the irradiated pixels, meaning that SPADs are quite sensitive to radiation damage.

Furthermore, several peaks were observed in the DCR distributions of single irradiated SPADs, suggesting the presence of radiation-induced metastable bulk defects.
References

[1] Palubiak D P and Deen M J 2014 CMOS SPADs: Design Issues and Research Challenges for Detectors, Circuits, and Arrays *IEEE J Sel Topics Quantum Electron* **20**

[2] Cova S, Ghioni M, Lacaita A, et al. 1996 Avalanche photodiodes and quenching circuits for single-photon detection *Appl. Opt.* **35** 1956

[3] Rochas A, Pauchard A R, Besse P, Pantic D, Prijic Z and Popovic R S 2002 Low-noise silicon avalanche photodiodes fabricated in conventional CMOS technologies *IEEE Trans. on Electron Devices* **49** 387-394

[4] Pancheri L and Stoppa D 2011 Low-noise Single-Photon Avalanche Diode in 0.15 μm CMOS Technology *Proc. of the European Solid-State Device Research Conf.* 179-182

[5] Campajola M 2017 Noise characterization of Single-Photon Avalanche Diodes M.A. Thesis (Napoli: University of Naples)

[6] Samwell S W, Hady A A, Mikhail J S, Ibrahim M and Hanna Y S 2008 Studying the Total Ionizing Dose and Displacement Damage Dose effects for various orbital trajectories *Proceedings of IAU MEARIM*

[7] Shockley W and Read R T 1952 Statistics of the recombination of holes and electrons *Phys. Rev.* **87** 835–842

[8] Vincent G, Chantre A and Bois D 1979 Electric Field Effect on the Thermal Emission of Traps in Semiconductor Junctions *J. Appl. Phys.* **50** 5484-5487

[9] Xu Y, Xiang P, Xie X and Huang Y 2016 A new modelling and simulation method for important statistical performance prediction of single photon avalanche diode detectors *Semiconductor Science and Technology* **31**

[10] Srour J R and Palko J W 2013 Displacement Damage Effects in Irradiated Semiconductor Devices *IEEE Trans. Nucl. Sci.* **60** 1740–66

[11] Hopkinson G R, Goiffon V and Mohammadzadeh A 2008 Random telegraph signals in proton irradiated CCDs and APS *IEEE Trans. Nucl. Sci.* **55** 2197–2204

[12] Bogaerts J, Dierickx B and Mertens R 2002 Random telegraph signals in a radiation-hardened CMOS active pixel sensor *IEEE Trans. Nucl. Sci.* **49** 249–257

[13] Goiffon V, Magnan P et al. 2011 Evidence of a novel source of random telegraph signal in CMOS image sensors *IEEE Electron Device Lett.* **32** 773–775