Design and characterization of single-photon avalanche diodes in deep-cryogenic applications

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***Abstract*—This paper explores the performance of CMOS single-photon avalanche diodes (SPADs) utilizing Global-Foundries 55 nm BCDLite technology at cryogenic temperatures (CT). SPADs with active diameters ranging from 2 to 60 μm were tested to evaluate performance. We measured I-V characteristics, dark count rate (DCR), photon detection probability (PDP), and breakdown voltage at various temperatures from CT to room temperature (RT). Measurements were conducted using a cryogenic probe station capable of reaching 4K. The study investigated the effects of CT on breakdown voltage and PDP and the impact of tunneling and trap-assisted thermal generation noise on DCR. These findings provide new insights into SPAD performance at CT, supporting advancements in quantum sensing, high-energy physics, and low-temperature photon detection.**

***Index Terms*—Cryogenic temperature, dark count rate (DCR), photon detection probability (PDP), shallow trench isolation (STI), single-photon avalanche diode (SPAD).**

I. Introduction

Single-photon avalanche diodes (SPADs) are widely used in photon counting applications for, but not limited to, SPAD cameras and silicon photomultipliers (SiPMs). SPADs may be fabricated in CMOS-compatible technologies and thus miniaturized and mass-produced for scientific and consumer applications. Due to their reproducibility and reliability thanks to CMOS processes, SPADs have been demonstrated for large-scale applications, such as proximity sensors, requiring to be highly optimized for room-temperature RT [1]. However, cryogenic testing of SiPMs and SPADs, which is essential for quantum sensing, high-energy physics, and quantum computing, remains in its early stages [2], [3].

One of the applications of SPADs requiring CT operation is scintillation photon detection from particle interactions in rare event search detectors based on condensed noble gases, e.g. neutrino and dark matter search experiments. The noble gas in these experiments is cooled to cryogenic temperatures (CT) and liquefied, enabling ionizing particles to interact with argon atoms and produce photons. SPADs are well-suited for detecting these photons, providing crucial information about the particle interactions and their properties. This information is critical for studying neutrino properties, matter-antimatter asymmetry, and supernova mechanisms [3].

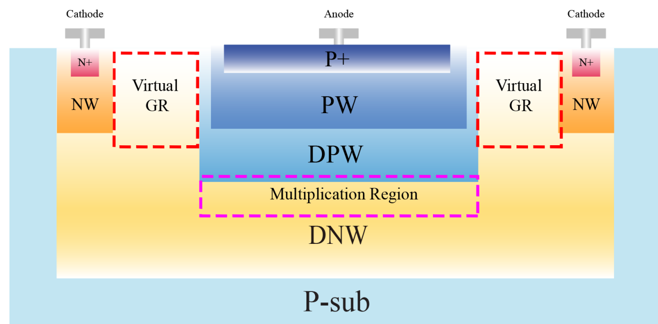

Figure 1. Cross-sections of the CMOS-SPAD.

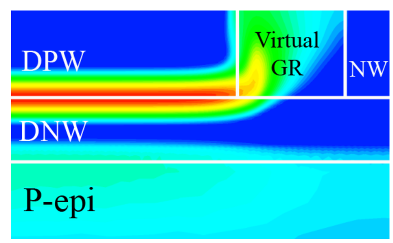

Figure 2. Electric profile of the CMOS-SPAD above its breakdown voltage at 300 K.

This study investigates SPAD performance at CT, focusing on I-V characteristics, dark count rate (DCR), photon detection probability (PDP), and breakdown voltage across various active areas with diameters ranging from 2 to 60 μm. The results provide valuable insights into optimizing SPADs for low-temperature applications.

II. Device structure and simulation

Figure 1 illustrates the structure of the proposed SPADs fabricated using 55nm BCDLite technology [4], [5]. The device features deep junctions, including a deep P-well (DPW) and deep N-well (DNW), with a virtual guard ring (GR) to prevent premature breakdown. Its rectangular shape with rounded edges enhances the fill factor. To evaluate the effectiveness of GR, TCAD Sentaurus simulations were performed to analyze the electric field profile of the SPAD at 300 K, as shown in

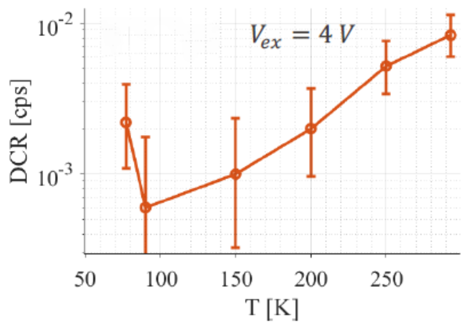

Figure 3. DCR of a SPAD implemented in 55 nm BCDLite technology [2].

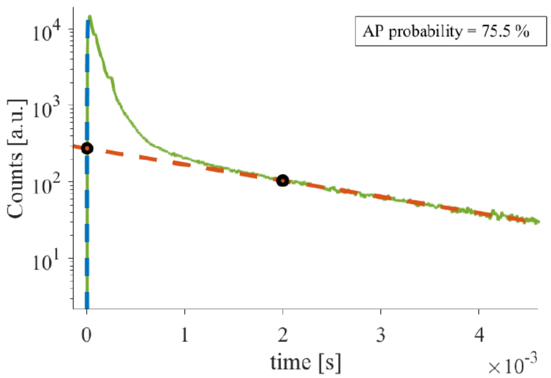

Figure 4. Afterpulsing probability of a SPAD implemented in 55 nm BCDLite technology [2].

Figure 2 with a detail of the junction where the multiplication takes place. The results confirm that the virtual GR effectively mitigates premature edge breakdown. Additionally, SPADs with different diameters were designed to evaluate the impact of device size to various performance parameters.

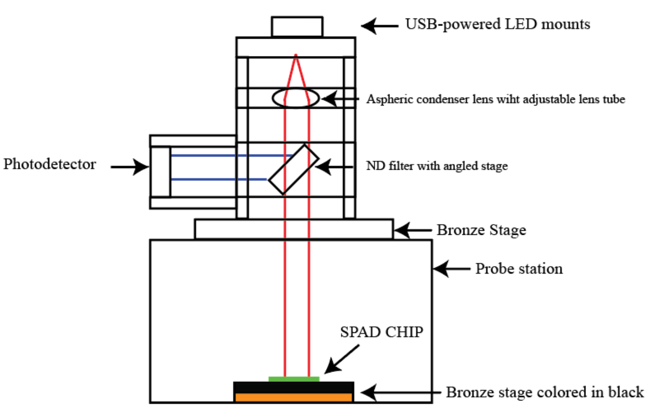

Figure 5. Schematics of PDP setup.

III. Experimental Setup

The measurement setup for SPAD characterization is described hereafter; it was designed for precise and reliable data collection. The I-V characteristics of SPADs, both with and without illumination, were measured using a cryogenic probe station capable of reducing the temperature to 4K. I-V characteristics were analyzed at various temperatures, and changes in breakdown voltage were assessed using a parameter analyzer.

DCR measurements were performed using an external 200 kΩ passive quenching resistor and an oscilloscope across different temperatures. Tunneling noise and trap-assisted thermal generation noise under cryogenic conditions were analyzed at excess bias voltages up to 3 V.

As shown in Figure 3, Morelle et al. observed a sharp rise in DCR below 100K [2]. This increase is closely related to enhanced afterpulsing, caused by prolonged carrier trapping times lasting several milliseconds, as can be seen in Figure 4. In our study, we further investigate DCR characteristics and afterpulsing probability at cryogenic temperatures.

The PDP characteristics were calculated for wavelengths between 400 and 900 nm at excess bias voltages of 1 to 3 V. In the measurement setup shown in Fig. 5, the LED light was collimated using an aspheric condenser lens and attenuated by a reflective ND filter to prevent SPAD saturation. A commercial photodetector measured the reflected light from the ND filter to ensure uniform LED intensity. To minimize internal reflections that could lead to PDP overestimation, the custom stage inside the probe station was coated with black light-absorbing paint.

IV. Conclusion & Future Work

This work explores SPAD design optimized for identifying neutrino interactions and for other applications. The insights gained from this research could lead to breakthroughs in our knowledge of particle physics, potentially revealing new physics beyond the Standard Model. In future work, we plan to demonstrate a digital SiPM (dSiPM) with a 32 x 26 SPAD array capable of accumulating photon counts. Additionally, we will show a 32 x 16 SPAD array with a time-to-digital converter (TDC) with 37-ps least significant bit (LSB). These devices would not only be beneficial for studying neutrinos but also for other applications such as light detection and ranging (LiDAR) and biomedical imaging.

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