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Direct MIP detection with sub-10 ps timing resolution Geiger-Mode APDs

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ABSTRACT

In this work we present and discuss the use of state-of-the-art Geiger-mode APDs, also known as single-photon avalanche diodes (SPADs), for the detection of minimum ionizing particles (MIPs) with best-in-class timing resolution. The SPADs were implemented in standard CMOS technology and integrated with on-chip quenching and recharge circuitry. Two devices in coincidence allowed to measure the time-of-flight of 180 GeV/c momentum pions with a coincidence time resolution of 22 ps FWHM (9.4 ps Gaussian sigma). This result paves the path for new generation of cheap plug-and-play trackers with extremely high spatial and timing resolution, meant to be used in beam test facilities.

1. Introduction

The detector system used in this work relies on the SPAD-based sensor presented in [1]. This device's cross-section is based on a substrate-isolated type, where a *p-well* (PW) layer forms the anode of the SPAD and a *buried n-well* (BNW) layer creates the cathode contact. The latter is connected to the high voltage through a *deep-n-well* (DNW). The SPAD Fig. 1*(a)* presents a *p-i-n* structure [1]. The chip Fig. 1*(b)* integrates four independent SPAD pixels with a diameter of 25 μm. A dedicated on-chip front-end circuitry is implemented in close proximity to each SPAD. The circuit is designed to enable a tunable dead time, as short as 3 ns, supporting very high count rates while still maintaining very low afterpulsing [1].

In this work, presented in details in [2], we implemented a complete and optimized system-on-board to further improve performance. The resulting system comprises a motherboard, where all needed voltage levels are derived from a single 5 V power supply. A full system control is achieved with a serial bus interface that allows the tuning of the device operating point from an host computer.

The output of the chip is connected to fast SiGe comparators (Analog Device ADCMP572) that drive 50 Ω lines. This solution reduces the capacitive load at the chip's output (high impedance node) and helps propagate the signal through a high-frequency cable to the timestamping electronics. In addition, the use of these comparators makes it possible to achieve high signal slew rate (≥1.6 V/ns). In this configuration, the timestamp of each signal is measured directly on the analog waveform at a fixed threshold. Before the measurement on particle beam, the device has been characterized with a femtosecond laser. The results showed a timing resolution of 7.5 ps FWHM for 28 V bias voltage.

2. Beam test results

The setup used for the ToF measurement of MIPs is shown in Fig. 2. It consists of two systems-on-board, both mounted on motorized linear stages with sub-micrometer positioning resolution to allow a proper detector alignment and to guarantee the acquisition of coincidence measurements. We installed the setup on the H8 beamline in the CERN North Area. This beamline delivers 180 GeV/c momentum pions produced on a graphite target by the interaction of protons accelerated by the Super Proton Synchrotron (SPS). The two detectors were positioned at the center of the beam, where the intensity is the highest. Coincidence events were acquired for two bias voltages, 24 V and 27 V, corresponding to approximately 2.5 V and 5.5 V V_{ex}, respectively. The MIP measurement results are summarized in Table 1. Dark count rate has been measured for this SPAD at room temperature for both voltages. The result was 100 cps and 70 cps for 27 V and 24 V respectively. After the exposure to the beam, no significant change in this values has been observed. The dark count rate has been measured after the beam-time showing a negligible increasing.

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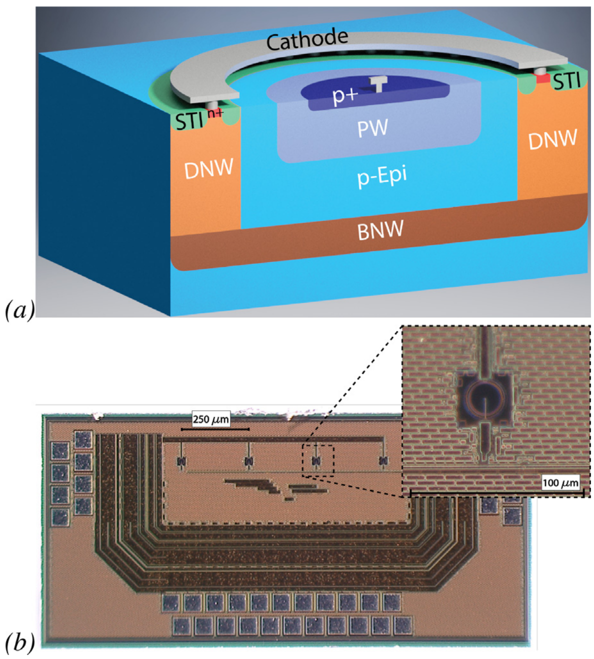

Fig. 1. *(a)*: SPAD cross section. *(b)*: Micrograph of the implemented chip embedding 25 μm diameter SPADs with integrated pixel circuit [1].

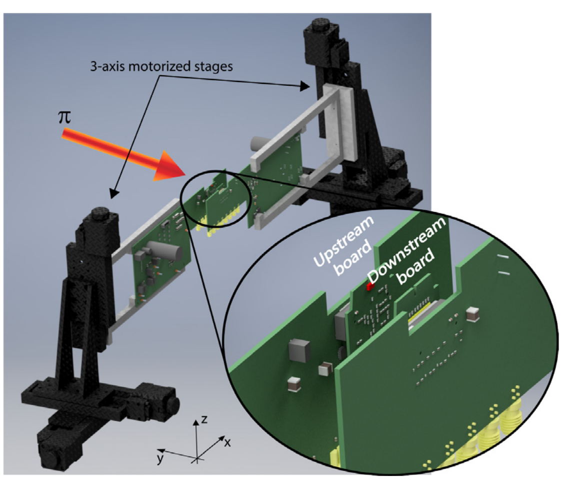

Fig. 2. Experimental MIP coincidence measurement setup.

3. Discussion and future developments

The high potential in terms of good timing resolution with SPAD has been deeply studied by [3]. In this work we showed how Geiger-mode devices (i.e., SPADs) can detect MIPs with a sub-10 ps timing precision. This result paves the way to the implementation of future high timing resolution particle trackers based on this kind of detector. A comparison with the state of the art is reported in Table 2. During next test beam the same setup will be used to measure the detection efficiency and the timing resolution for higher over voltage values. In a second step a multi channel prototype chip will be developed and tested.

Table 1
Summary of the MIP detection measurement results. The Gaussian sigma has been obtained by dividing the FWHM by $2\sqrt{2ln(2)}$. Assuming that the response is the same for both SPADs, the σ_{single} values have been obtained by dividing the σ values by $\sqrt{2}$. The errors have been evaluated using statistical error propagation.

Bias (V)	FWHM (ps)	FWTM (ps)	σ (ps)	σ_{single} (ps)
24	27 ± 1	104 ± 4	11.5 ± 0.4	8.1 ± 0.3
27	22 ± 2	62 ± 3	9.4 ± 0.7	6.6 ± 0.5

Table 2
Comparison of the performance of the device presented with the state-of-the-art.

Device	σ_{single} (ps)	Time walk	Pre-amplifier	Detection efficiency
AQUA SPAD	6.4	No	No	99% [3]
TIMESPOT [4]	11.5	Yes	Yes	99%
UFSD [5]	27	Yes	Yes	99%

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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