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Performance of 3D trench silicon pixel sensors irradiated up to $1 \cdot 10^{17}$ 1 MeV n_{eq} cm^{-2}

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ABSTRACT

Tracking particles at extreme fluences requires the accurate measurement of the charged particle timing at the pixel level in order to cope with the increased occupancy of HL-LHC experiments. Maintaining this precision throughout the operational life of the detector is crucial. This work demonstrates that the 55×55 μm^2 wide 150 μm thick 3D trench-type pixels, developed by the TimeSPOT Collaboration, maintain the performance of non-irradiated sensors even after exposure to fluences as high as $1 \cdot 10^{17}$ 1 MeV n_{eq} cm^{-2}. The preliminary results of a beam test characterization using minimum ionizing particles at the SPS North area beam facility reveal that the charge collection and the time resolution of the irradiated sensors are comparable to those of non-irradiated ones, by increasing the operational bias voltage. A minor reduction in detection efficiency, approximately 4%, is observed post-irradiation. Currently, 3D trench-type pixels are among the fastest pixel detectors available for tracking charged particles and hold significant promise for future tracking system upgrades. This preliminary evaluation suggests their suitability for use in even harsher radiation environments than High Luminosity Large Hadron Collider (HL-LHC) such as future experiments at the Future Circular Hadron Collider (FCC-hh).

1. Introduction

The increase of instantaneous luminosity in high energy physics experiments will raise the occupancy of tracking detectors, impacting the tracking and the vertex reconstruction efficiencies, and thus the overall event reconstruction. Furthermore, future detectors will need to be more radiation hard to ensure optimal performance throughout acquisition runs. Studies by LHCb collaboration [1] show that measuring the time of the tracks with 10 ps accuracy can mitigate occupancy issues and restore vertex reconstruction efficiency. The TimeSPOT R&D project has developed innovative silicon pixel sensor optimized to improve the time resolution of 3D sensors, the 3D trench pixel. This sensor has shown excellent time resolution and detection efficiency for detecting Minimum Ionizing Particles (MIP) [2,3]. The radiation hardness of these sensors was already proven up to $2.5 \cdot 10^{16}$ 1 MeV n_{eq} cm^{-2} [4]. This work presents preliminary results from a beam test characterizing 3D trench sensors irradiated up to $1 \cdot 10^{17}$ 1 MeV n_{eq} cm^{-2}, in terms of charge collection, time resolution and detection efficiency.

2. Irradiated 3D trench sensors

3D trench sensors are silicon pixels optimized to achieve best timing performance for minimum ionizing particles detection. Each pixel has a size of 55 μm × 55 μm and is characterized by an electrode configuration that presents two external ohmic-wall electrodes, which extend over the entire pixel matrix and provide the proper bias voltage to each pixel, and a collecting trench electrode 40 μm long and 5 μm thick connected to the input of the front-end electronics [5]. The depth

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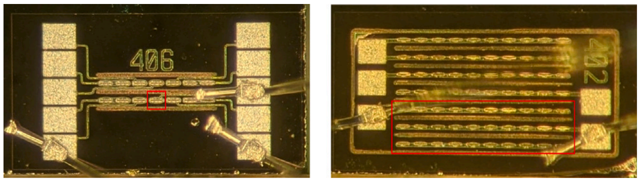

Fig. 1. 3D trench test structures. (Left) Single pixel sensor. (Right) triple pixel-strip structure. The red boxes represents the nominal area of the test structures, which is 55 μm × 55 μm for the single pixel and 550 μm × 165 μm for the triple pixel-strip.

of the sensitive volume is 150 μm while the collecting electrode is 135 μm deep. The devices under test are 3D trench sensor from the second TimeSPOT batch produced by FBK (Trento, Italy). These test structures have pixels arranged in different readout configurations, see Fig. 1. The single pixel structures allow to readout a single 3D trench pixel, while the triple pixel-strip structures group thirty pixels in three rows, sharing readout electrodes, allowing to readout a larger area through a single channel. The test structures have been irradiated with neutrons at the TRIGA Mark II Reactor at the Jožef Stefan Institute in Ljubljana, Slovenia [6], at a fluence up to $1 \cdot 10^{17}$ 1 MeV n_{eq} cm^{-2}. The structures were then wire bonded to the TimeSPOT front-end electronic boards [7] and stored back in a temperature controlled environment at −20 °C to avoid annealing.

3. Beam test setup

The irradiated 3D trench sensors were tested at the SPS H8 beam-line with a 180 GeV/c π^+ beam. The setup, shown in Fig. 2, includes up to four detectors aligned along the beam line which can be arranged in two distinct configurations: one for amplitude and timing measurements and the other for efficiency characterization. In both the configurations the irradiated sensor is cooled between −40 °C and −20 °C using dry ice and is housed within a polystyrene box. For amplitude and timing measurements, one non-irradiated 3D trench pixel sensor was placed upstream of the device under test (DUT), and two micro-channel-plate photomultiplier tubes (MCP-PMTs) were used as timing references having a 3–4 ps accuracy in the particles time of arrival. The non-irradiated sensor serve to trigger the acquisition and was positioned outside the insulated box and mounted on a movable holder controlled by piezoelectric linear stages, allowing precise alignment with the DUT. For the efficiency characterization a second non irradiated pixel have been placed downstream the DUT, which in this case was an irradiated triple strip sensor, to be used together with the other non irradiated pixel as a trigger for the efficiency evaluation.

The signals from the 3D sensors and the MCP-PMTs were recorded by a 8 GHz analog bandwidth 20 GSa/s 4 channels digital oscilloscope. For the amplitude and timing measurements, the typical trigger required the coincidence, in a 20 ns time window, of two signals: one of the MCP-PMTs and one of the non-irradiated 3D trench sensors. This trigger avoid bias on the characterization of the DUT since it is not involved in the trigger condition. For the efficiency measurements, a coincidence between the signals from the two non-irradiated pixels, positioned upstream and downstream of the DUT, was required. This ensures that only events where hadrons passed through the DUT were recorded.

4. Analysis and results

The analysis method consists of evaluating the DUT signal amplitude, measured as the peak of the waveform subtracted by the baseline, calculated event by event, and the TOA of each waveform, which is evaluated with the Spline method. This method consist of a CFD (Constant Fraction Discriminator) algorithm applied to the waveform after being interpolated by means of splines, in order to reduce the oscilloscope sampling frequency jitter, which gets the time at the 20% of the signal amplitude. The efficiency is measured by counting the number of events detected by the triple-strip sensor with respect to the number of particles detected by both the non-irradiated pixels.

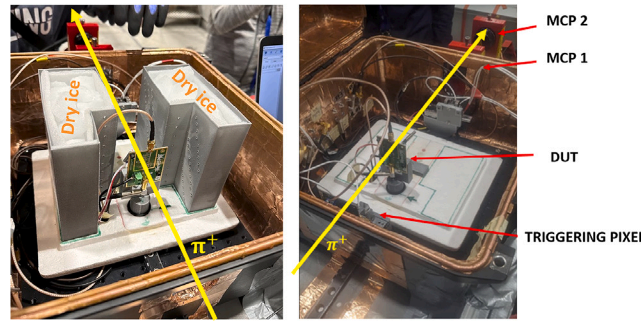

Fig. 2. Pictures of the beam test setup.

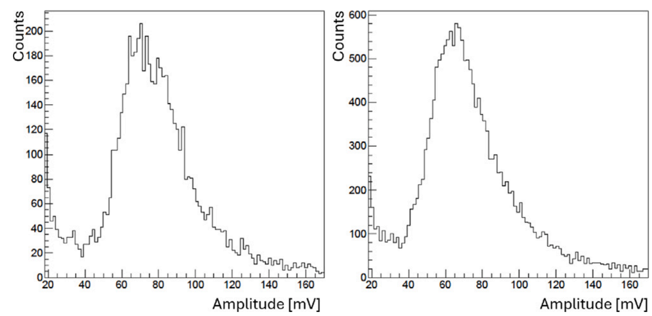

Fig. 3. Amplitude distributions of 3D trench single pixels. (Left) Non-irradiated pixel at 100 V. (Right) Pixel irradiated at $1 \cdot 10^{17}$ 1 MeV n_{eq} cm^{-2} at 250 V.

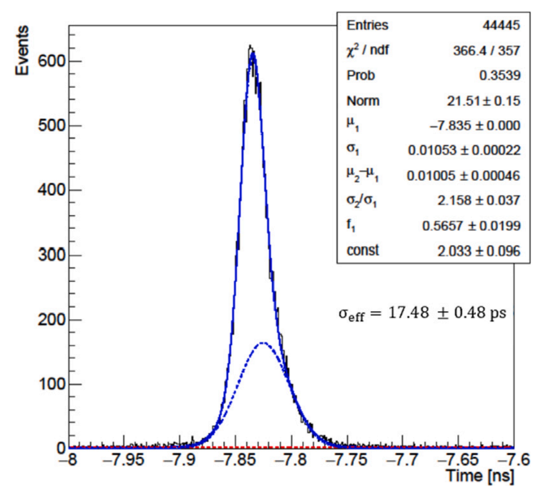

Fig. 4. Time distribution of a 3D trench pixel irradiated at $1 \cdot 10^{17}$ 1 MeV n_{eq} cm^{-2} at 250 V. A fit of two gaussian functions, describing the signal, with a constant function for the background, is imposed to the distribution to determine the time resolution.

Fig. 3 shows amplitude distributions for the non-irradiated 3D trench sensor operated at 100 V (left) and the irradiated sensor at a $1 \cdot 10^{17}$ 1 MeV n_{eq} cm^{-2}, operated at 250 V (right). Results indicate that the charge collection performance of the irradiated sensor is restored at the bias voltage of 250 V.

The ToA distribution of the $1 \cdot 10^{17}$ 1 MeV n_{eq} cm^{-2} pixel operated at a bias voltage of 250 V (Fig. 4) shows an excellent time resolution of 17.48 ± 0.48 ps, comparable to the previously published 17.8 ± 1.0 ps for the non-irradiated sensor [2].

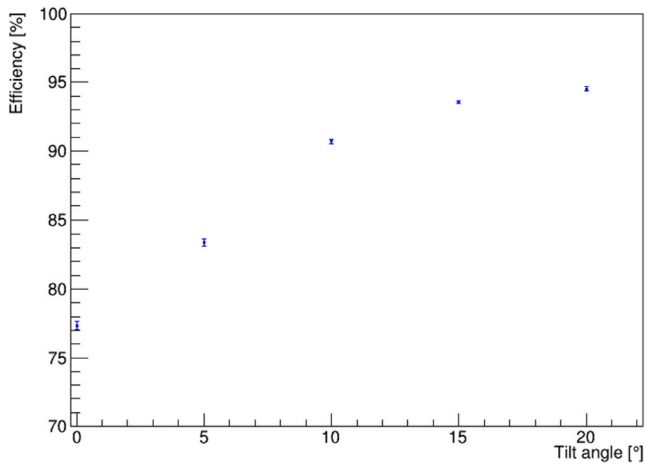

Fig. 5. Detection efficiency of $1 \cdot 10^{17}$ 1 MeV n_{eq} cm^{-2} triple pixel-strip structure at 250 V.

The detection efficiency of the irradiated 3D trench sensors was also evaluated. Using two triggering pixels as a reference, the efficiency of the wider triple-pixel-strip sensor was assessed. Results, measured as a function of tilt angle (Fig. 5), showed the irradiated sensor achieving 95% efficiency at 20 degrees, compared to 99% for the non-irradiated structure [2].

5. Conclusion

The preliminary results from beam test characterizations indicate that 3D trench-type sensors exhibit exceptional radiation hardness, enduring fluences up to $1 \cdot 10^{17}$ 1 MeV n_{eq} cm^{-2}. When operated at a bias voltage of 250 V, these irradiated pixels feature charge collection performance similar to that one of a non irradiated sensor, a time resolution of 17.48 ± 0.48 ps, and a decrease of about 4% in detection efficiency has been observed after irradiation. Data analysis aiming to further explore performance trends as a function of bias voltage are ongoing. The preliminary results reported in this work demonstrate that 3D trench sensors not only meet but potentially surpass the requirements for tracking detectors in the HL-LHC environment, showing promising compatibility for applications in the more challenging radiation conditions expected at the Future Circular Hadron Collider.

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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References

[1] LHCb Collaboration, Framework TDR for the LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era, Technical Report, CERN, Geneva, 2021, URL: https://cds.cern.ch/record/2776420.

[2] F.B., et al., Charged-particle timing with 10 ps accuracy using timespot 3D trench-type silicon pixels, Front. Phys. 11 (2023) 1117575, http://dx.doi.org/10.3389/fphy.2023.1117575.

[3] A. Lampis, Innovative silicon pixel sensors for a 4D VErtex LOcator detector for the LHCb high luminosity upgrade, University of Cagliari, 2023, URL: https://cds.cern.ch/record/2878228. Ph.D. thesis University of Cagliari.

[4] F.B., et al., Characterisation of highly irradiated 3D trench silicon pixel sensors for 4D tracking with 10 ps timing accuracy, Front. Phys. 12 (2024) http://dx.doi.org/10.3389/fphy.2024.1393019, URL: https://www.frontiersin.org/journals/physics/articles/10.3389/fphy.2024.1393019.

[5] G. Forcolin, M. Boscardin, F. Ficorella, A. Lai, A. Loi, R. Mendicino, S. Ronchin, G.-F. Dalla Betta, 3D trenched-electrode pixel sensors: Design, technology and initial results, Nucl. Instrum. Methods Phys. Res. A 981 (2020) 164437, http://dx.doi.org/10.1016/j.nima.2020.164437, URL: https://www.sciencedirect.com/science/article/pii/S0168900220308342.

[6] L. Snoj, et al., Computational analysis of irradiation facilities at the JSI TRIGA reactor, Appl. Radiat. Isot. 70 483 (2012).

[7] G.M.C., et al., Front-end electronics for timing with pico-second precision using 3D trench silicon sensors, J. Instrum. 18 (01) (2023) P01039, http://dx.doi.org/10.1088/1748-0221/18/01/P01039.