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Picosecond timing resolution with 3D trench silicon sensors

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Future vertex detectors operating in colliders at very high instantaneous luminosity will face great challenges in the event reconstruction due to the increase in track density. To guarantee good detector performance the additional information of the hit time stamping will be fundamental. In this paper the potentiality of the 3D trench silicon pixels developed by the INFN TimeSPOT collaboration is discussed. The latest results from a beam test at SPS/H8 are presented, showing a time resolution of the order of 10 ps for both irradiated ($2.5 \cdot 10^{16}$ 1 MeV n_{eq}/cm^2) and non-irradiated pixels featuring a detection efficiency close to 99% with the sensors properly tilted. For such characteristics, the 3D trench silicon pixels have proved to be a promising option for future vertex detectors operating at very high instantaneous luminosity.

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1. Introduction

With the next upgrade of LHC, the High Luminosity LHC, the collider will achieve instantaneous luminosities a factor of five larger than the LHC nominal value and the generation of tracks inside the trackers of the experiments LHCb, ATLAS, CMS, ALICE will become so high that the pattern-recognition and reconstruction systems now available will be slowed down and a great number of ghost tracks will be created, causing an inefficient extraction of signals. Concerning the LHCb Upgrade2, 2000 tracks from 40 pp interactions will cross the vertex detector (VELO) at each bunch crossing. To guarantee good detector performance the additional information of the hit time stamping with an accuracy of at least 50 ps is needed [1]. There are several studies looking for the best technology to achieve this level of timing precision, but a very promising option today is the 3D trench silicon pixel developed by the INFN TimeSPOT collaboration. In this paper the new results from the latest beam test are presented, highlighting the comparison between the irradiated ($2.5 \cdot 10^{16}$ 1 MeV n_{eq}/cm^2) and non-irradiated sensors behaviour.

2. 3D silicon sensors and the TimeSPOT sensor

3D silicon sensors were first proposed by Sherwood Parker and collaborators in 1997. Unlikely planar sensors, with 3D technology the electrodes of both doping types are penetrating partially or entirely through a high-resistivity silicon substrate, perpendicularly to the wafer surface. As a consequence the electric field is parallel to the wafer surface, starting from one electrode type going to the another (Figure 1). With respect to the planar sensors, this design allows to have extremely fast signals and robustness to bulk damages thanks to the short inter-electrode distance. Moreover, the full depletion voltage is lower since it is strictly dependent on the substrate thickness [2].

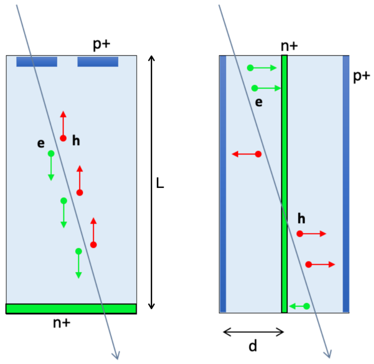

Figure 1: Comparison between 3D and planar silicon sensor design.

Within the TimeSPOT (Time and SPace real-time Operating Tracker) project, 3D silicon sensor with trench-shaped electrodes were designed, fully simulated and characterized [3][4]. The shape of the electrodes was chosen in order to maximize the timing performance: the goal is going towards uniformity in both the weighting field and the charge carriers velocity, aiming at the saturation regime thanks to the high and uniform electric field.

By means of TCAD simulations it is possible to compare the weighting and electric field maps of 3D silicon sensors with different electrode shapes. Figure 2 (left) displays the comparison between

a standard geometry with 5 columns and the trench design: both the weighting and electric fields are more uniform in the trench case. As a result the pulsed current signal is mostly independent from the charged particle hit position, with a short charge collection time across the whole substrate.
The TimeSPOT sensors are 55 μm × 55 μm pixels with an active thickness of 150 μm (Figure 2, right). The n++ doped readout trench is 40 μm long and 135 μm deep and it is placed in between the two p++ doped bias trenches. Under the pixel there is a support wafer of 350 μm thickness.

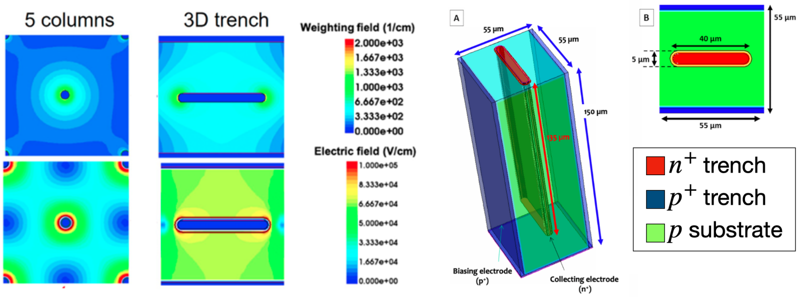

Figure 2: Comparison of weighting and electric fields for two different 3D silicon sensor electrode shape, columnar and trench design. TCAD simulation at -150 V bias voltage (left). The TimeSPOT 3D silicon sensor design (right).

The TimeSPOT sensors were produced at the Fondazione Bruno Kessler (FBK) using a single-sided fabrication process. Two batches have been produced so far, in 2019 and in 2021.

3. The Devices Under Test and the Front-end electronics

The devices under test (DUT) are pixels and triple strips (three strips made of 10 pixels read out together). The characterization was performed both for sensors irradiated with neutrons up to $2.5 \cdot 10^{16}$ 1 MeV n_{eq}/cm^2 and non-irradiated ones.
To read out the fast current signals all the sensors are endowed with a custom front-end electronics based on a trans-impedance amplifier (TIA) scheme with two amplification stages. This front-end electronics features a signal-to-noise ratio S/N of about 20 and an electronic jitter below 7 ps at 2 fC input charge.

4. The SPS/H8 beam test setup

The beam test was performed at CERN SPS/H8. The TimeSPOT sensors were characterized with a 180 GeV/c pion beam with 8 mm of transverse size.
A scheme of the setup is displayed in Figure 3. Two sensors were placed in a Radio-Frequency shielded box: the device upstream was endowed with a support with piezo-electric stages, that allowed to move the board in the transversal plane with respect to the beam. The DUT was mounted on a fixed support that could be rotated. Moreover this second sensor could be operated down to -40°C by means of a polystyrene box filled with dry ice: in this way it was possible to test the irradiated devices as well.
The time-tag of the setup was provided by two MCP-PMTs, placed outside the box; their average time resolution is approximately 5 ps.

The full setup was read out with a 8 GHz analog bandwidth, 20 GSa/s 4 channels oscilloscope (the Rhode&Schwartz RTP084). The two silicon sensors and the two MCPs waveforms are recorded and analyzed in order to determine the time of arrival of the crossing particle.

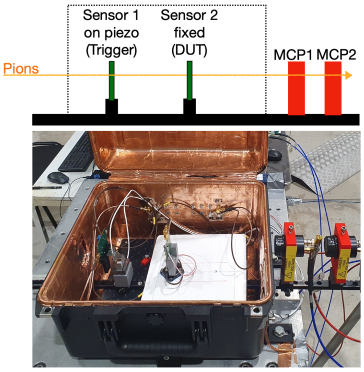

Figure 3: The setup in the SPS/H8 experimental area.

5. Waveform analysis and results

Different algorithms are considered in order to determine in the best way the time of arrival of the particles crossing both 3D silicon devices and the MCP-PMTs. The *Spline* method consists in interpolating the rising edge of the pulse with a Spline to avoid the fluctuations due to the oscilloscope sampling, and taking as the reference time the one corresponding to the 20% of the signal amplitude. The *Leading Edge* method considers as time of arrival the one corresponding to a threshold of 15 mV, with a proper linear interpolation around that point. The *Reference* method, known in literature as the Amplitude Risetime Compensated method [5], consists in subtracting to each waveform a delayed copy of itself, then taking the 50%-amplitude time as the reference one.

5.1 Amplitude distributions

To check the charge collection performance of the sensors the trend of the maximum amplitudes of the pixel waveforms is observed as a function of the bias voltage. In the case of the non-irradiated sensor (Figure 4, right), the Landau-shaped distribution is well distinguishable from the noise peak even for low bias voltages, ensuring a good sensor performance in a wide range of bias voltages.
Regarding the irradiated pixel (Figure 4, left), an higher bias voltage is necessary to recover the expected amplitude distribution of the non-irradiated sensor, which is however recovered for bias voltages higher than 100 V in absolute value.

5.2 Timing performance

The time resolution is extrapolated taking the difference of the time of arrival of the particle in the pixel under test and the average of the time of arrival in the two MCP-PMTs. A typical time distribution for the non-irradiated pixel is displayed in Figure 5 (left). The distribution is not perfectly symmetric and the sum of two gaussians was chosen as the fit function to include the contribution of the tails. The time resolution as a function of the bias voltage for the three different

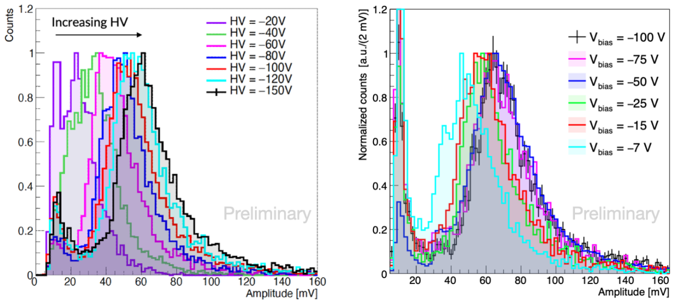

Figure 4: Maximum amplitudes distribution for the irradiated pixel (left) and the non-irradiated pixel (right) for different bias voltages.

analysis methods is displayed in Figure 5 (centre). The best result is 11 ps, obtained at a bias voltage of -100 V with the *Reference* method. Also the *Spline* and *Leading Edge* methods show promising results, all below 30 ps.

Figure 5 (right) displays the comparison between the time resolution obtained with the irradiated and non-irradiated sensor as a function of the bias voltage. Also the irradiated sensor shows an excellent time resolution, reaching the result of approximately 10 ps at a -150 V bias voltage.

Concluding, in both the irradiated and non-irradiated pixels there is no dependence of the time resolution on the bias voltages below -20 V.

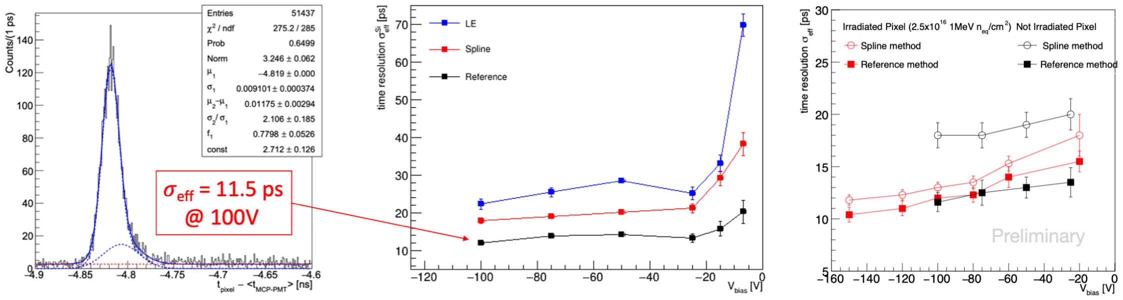

Figure 5: Distribution of the time of arrival of the non-irradiated pixel with respect to the average of the two MCP-PMTs (left). Time resolution of the non-irradiated pixel as a function of the bias voltage (centre). Comparison of the time resolution of the irradiated and non-irradiated pixel as a function of the bias voltage (right).

5.3 Detection Efficiency

The trench-shaped electrode design implies a geometrical efficiency of approximately 80%, given that the trenches are inactive volumes. The dependence of the efficiency on the tilt angle with respect to the normal incidence is thus a fundamental measurement to establish the viability of this technology.

A single pixel is placed centered and upstream with respect to a triple strip: the detection efficiency is estimated counting how many events triggering a signal in the pixel would generate a signal in the triple strip as well. To do so, the distribution of the time of arrival of the triple strip with respect to the two MCP-PMTs is considered. Fitting the distribution with a double gaussian and a constant term (Figure 6, left), the efficiency is evaluated as the number of events populating the peak, N_{trcks}, over the total number of trigger events,N_{tot}: $\epsilon = \frac{N_{trcks}}{N_{tot}}$. Figure 6 (right) displays the detection efficiency as a function of the triple strip tilt angle with respect to the normal incidence. The efficiency at normal incidence is compatible with the expected geometrical calculations and at tilt angles larger than 10° the efficiency is close to 99% for -100 V bias voltage. The irradiated triple strip fully recovers the efficiency performance for a bias voltage of -130 V.

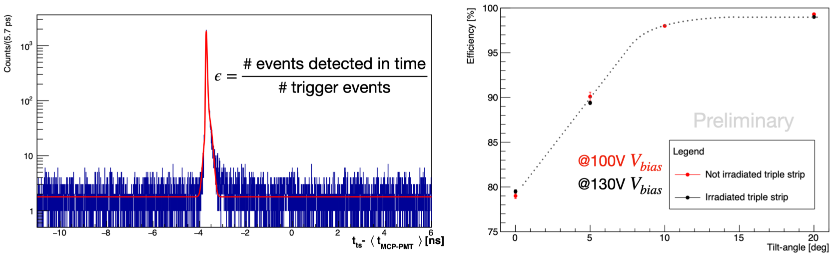

Figure 6: Time of arrival of the triple strip with respect to the two MCP-PMTs for the non-irradiated pixel at normal incidence (left). Detection efficiency as a function of the tilt angle for the irradiated and non-irradiate triple strip (right).

6. Conclusions

In this paper the potentiality of the TimeSPOT 3D sensor was discussed. With a time resolution of the order of 10 ps for both the irradiated and non-irradiated pixels and an efficiency close to 100% for tilt angles higher than 10°, this kind of sensors proved to be an excellent option for the tracking detectors for High Luminosity LHC and beyond.

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