Fast and Furious: 3D Silicon Sensors Charge Carrier Drift

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Introduction

LHC luminosity upgrades require the development of fast-timing, radiation-hard detectors. 3D silicon sensors are being developed that are able to withstand the projected new radiation levels of HL-LHC and keep within the estimated timing response of 50 ps.

Objective

Perform position-resolved timing characterisation tests on single pixels of **hexagonal and trench 3D silicon** detectors using an infra-red laser to deposit energy equivalent to 1 MIP with a spatial resolution of 1 µm, and a custom designed fast readout electronics chip.

3D Sensors vs. Planar Sensors

The main advantage of 3D sensors over their planar counterparts is that the inter-electrode distance is decoupled from and can be made much shorter than the substrate thickness (see Figure 1).
This allows for increased charge collection efficiency, lower depletion voltages, reduced charge sharing and the ability to incorporate an active edge in the sensor design.

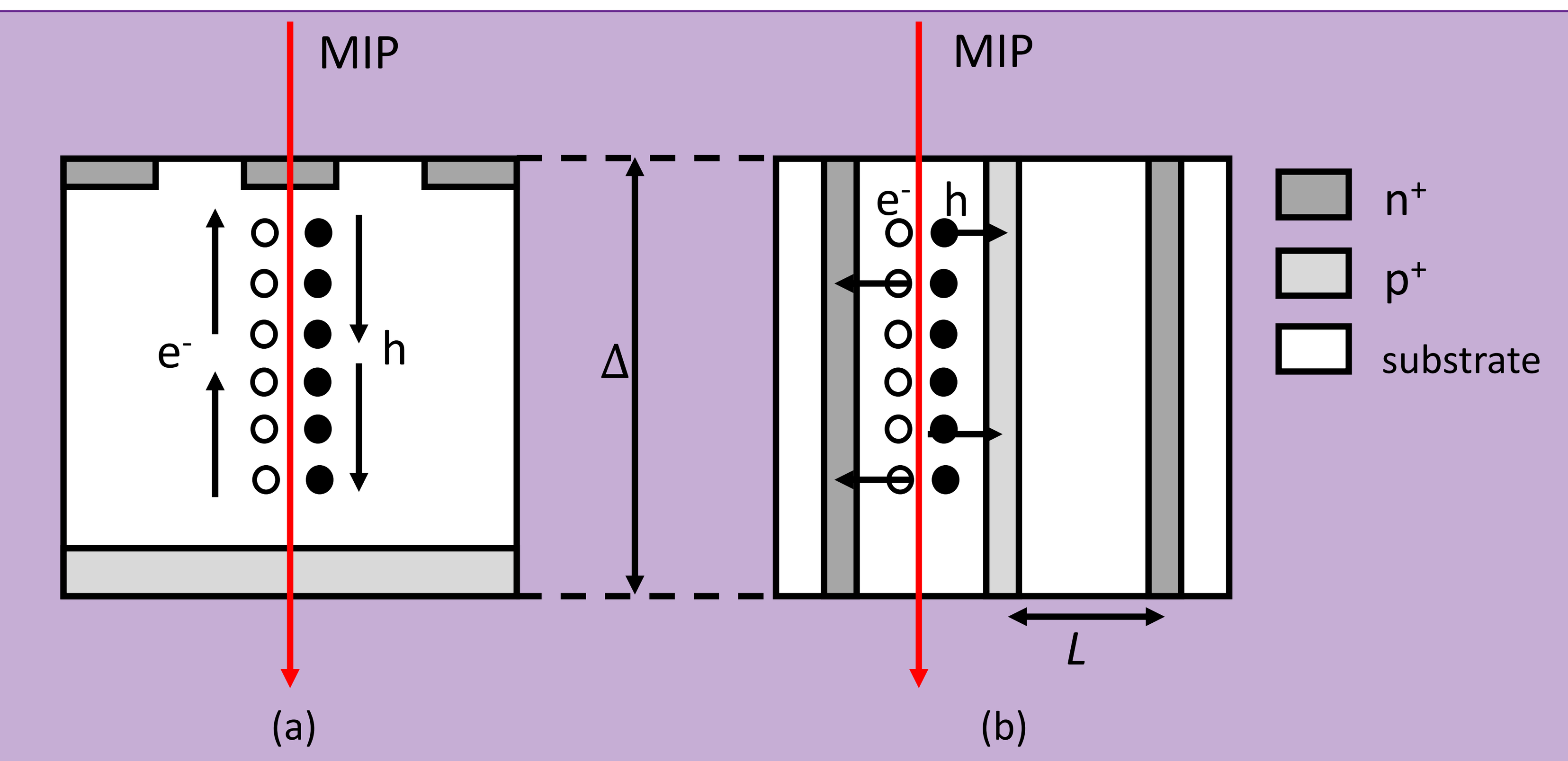

Figure 1: Illustration of the differences in distance travelled by liberated charge carriers in (a) planar sensors, compared with (b) 3D sensors.

Hexagonal Geometry

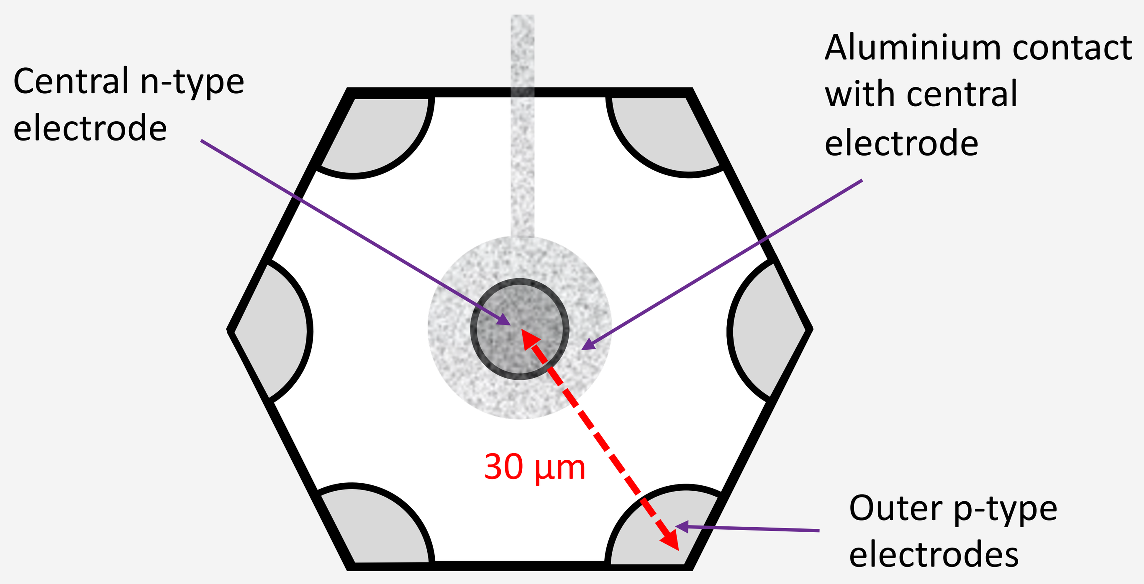

Figure 2: Simple illustration of a single pixel of a 3D hexagonal sensor.

The outer columnar p-type electrodes are the biasing electrodes (-50 V).
The central n-type electrode is the read-out electrode and is read out via an aluminium contact which is invisible to the IR laser. The inter-electrode distance is 30 µm.

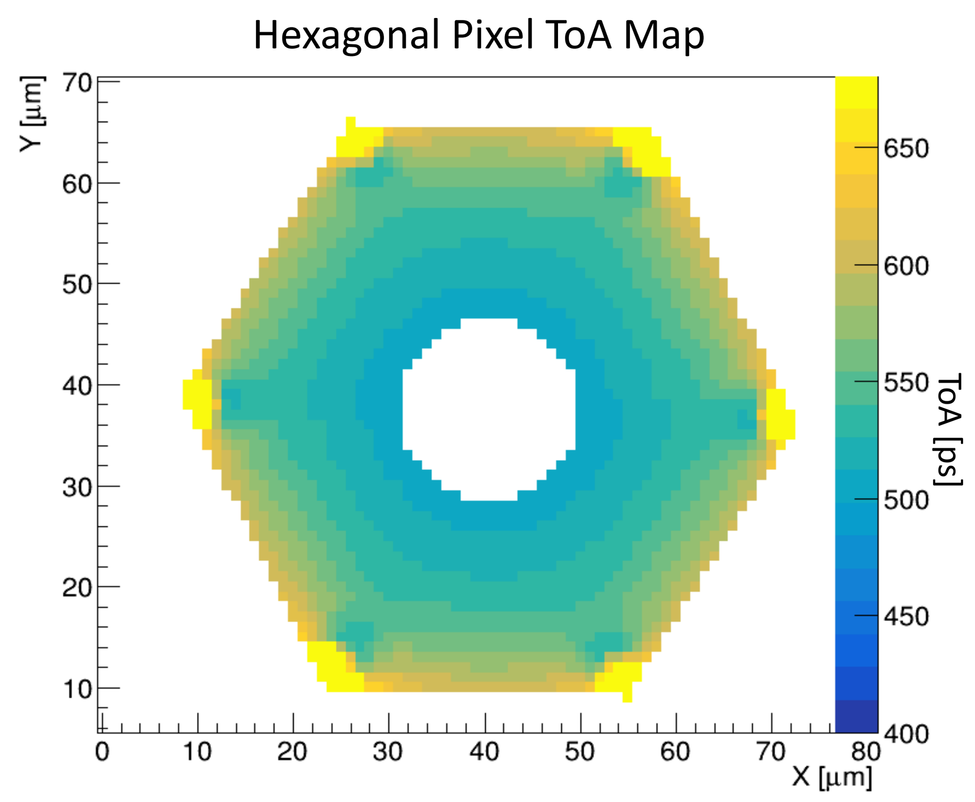

Figure 3: Time of arrival map of a single 3D hexagonal sensor pixel.

Both low and high electric field regions exist in the sensitive volume of the hexagonal geometry and are identified by the blue and yellow colours, respectively. Signal time of arrival changes significantly over the sensitive region of the sensor as it is dependent on electric field strength.

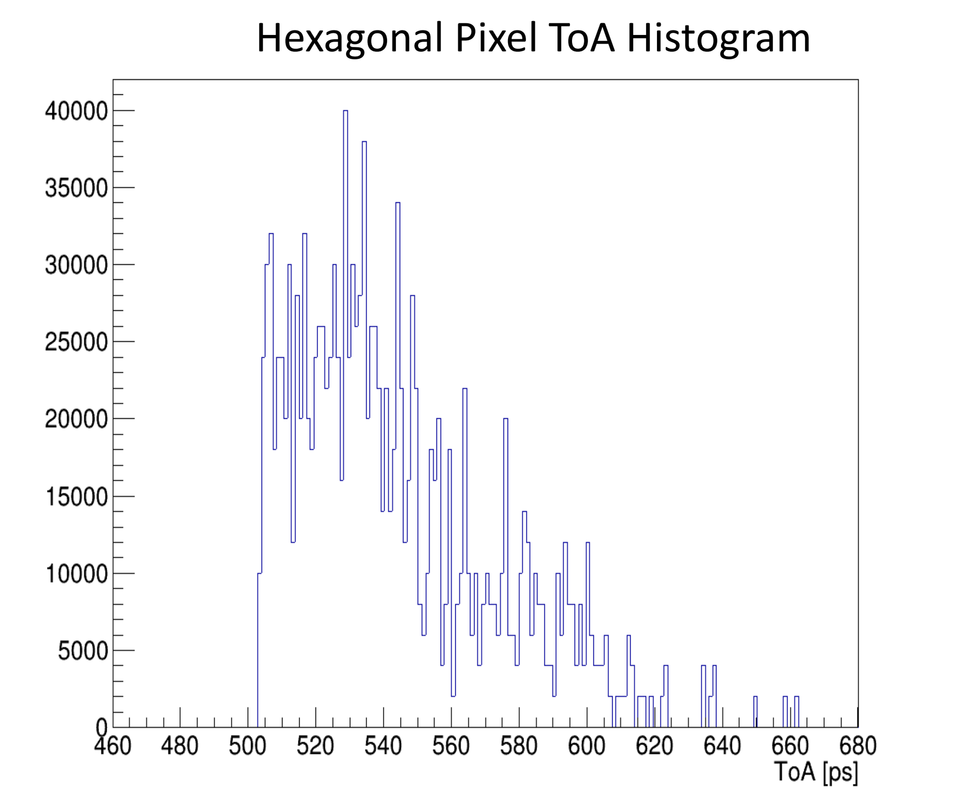

Figure 4: Time of arrival histogram of a single 3D hexagonal sensor pixel

Mean ToA = 543.6 ps
ToA Std Dev = 29.79 ps

The standard deviation (Std Dev) of the time of arrival (ToA) of the signal is broader due to the non-uniformity of the electric field.

Trench Geometry

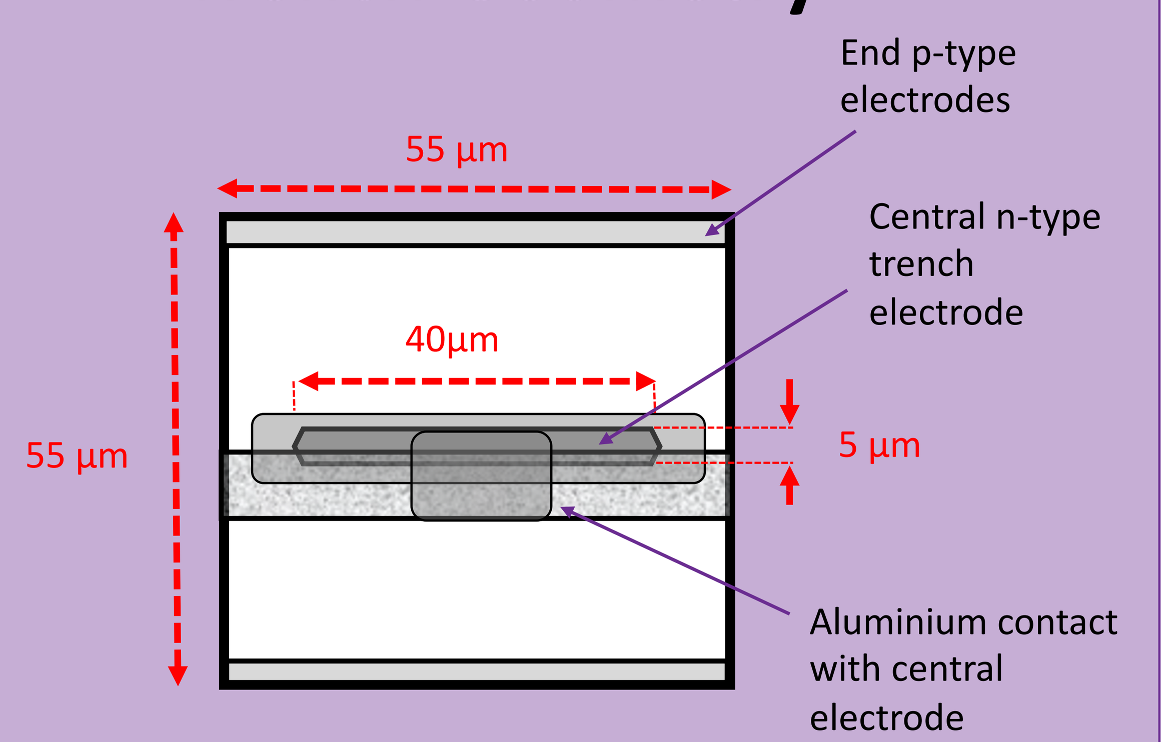

Figure 5: Simple illustration of a single pixel of a 3D trench sensor.

The end p-type trench electrodes are the biasing electrodes (-50 V).
The central n-type trench electrode is the read-out electrode and like the hexagonal pixel, is connected via an aluminium contact. This region again is invisible to the IR laser. The inter-electrode spacing is 27.5 µm.

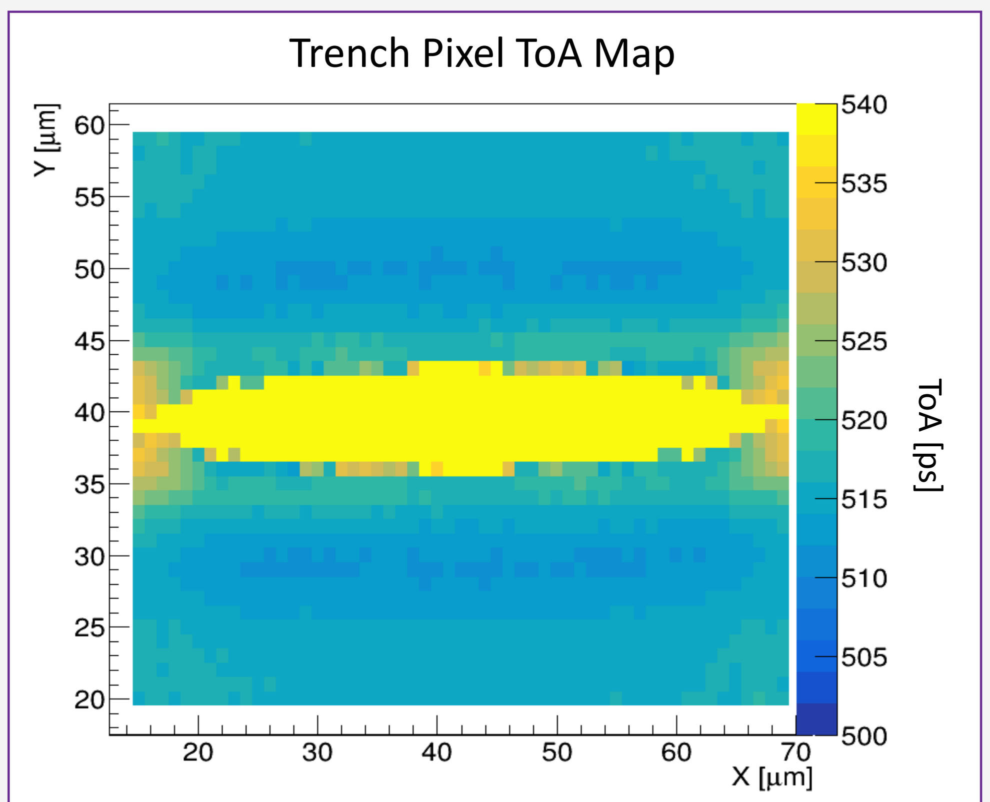

Figure 6: Time of arrival map of a single 3D trench sensor pixel.

The electric field over the sensitive regions remains very uniform for the trench geometry, as can be seen by the blue/yellow regions of the colour map.
As a result, the signal time of arrival changes minimally over the sensor, with the slowest regions midway between trenches.

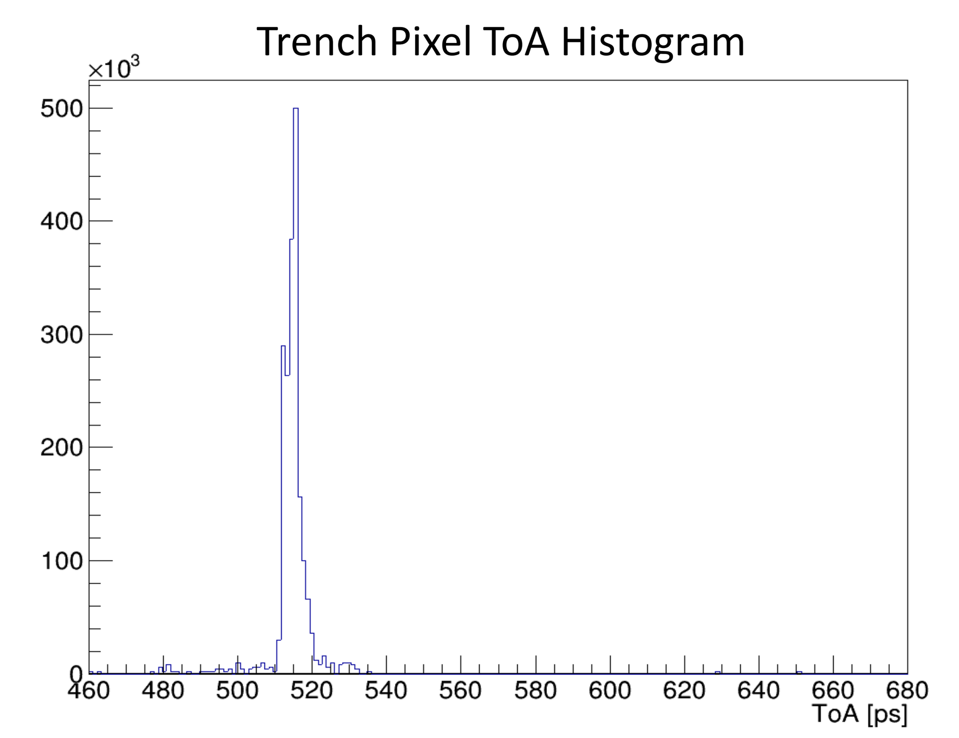

Figure 7: Time of arrival histogram of a single 3D trench sensor pixel

Mean ToA = 514.6 ps
ToA Std Dev = 8.172 ps

The standard deviation of the time of arrival of the signal is narrower due to the high uniformity of the electric field.

Conclusions

The hexagonal 3D sensor geometry exhibits good timing performance, with a timing resolution of **29.8 ps**, however a pronounced tail is seen in the distribution due to the slow periphery of the pixel and may suggest the presence of inefficiencies in charge collection when collected with fast electronics. On the other hand, the trench geometry has excellent timing performance and a sharp ToA distribution with a timing resolution of **8.17 ps**, owing to its extremely uniform geometry.
Timing measurements must be correlated to an efficiency measurement to avoid bias towards the faster parts of the sensitive volume. This is particularly important for the hexagonal geometry as it has slow and weak signals on the boundary. Using fast electronics such as those needed for fast timing means signals from the boundaries are compatible with zero.

References

[1] C. Da Via, G. Dalla Betta, S. Parker, *Radiation Sensors with 3D Electrodes*, CRC Press, 2019.
[2] L. Anderlini et al., *Intrinsic time resolution of 3D-trench silicon pixels for charged particle detection*, JINST 15 P09029, 2020.

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