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Test of Ultra Fast Silicon Detectors for the TOTEM upgrade project

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Abstract: This paper describes the performance of a prototype timing detector, based on 50 μm thick Ultra Fast Silicon Detector, as measured in a beam test using a 180 GeV/c momentum pion beam. The dependence of the time precision on the pixel capacitance and bias voltage is investigated in this paper. A timing precision from 30 ps to 100 ps (RMS), depending on the pixel capacitance, has been measured at a bias voltage of 180 V.

Keywords: Analogue electronic circuits; Performance of High Energy Physics Detectors; Solid state detectors; Timing detectors

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2017 JINST 12 P03024

Contents

1 Timing detector for the TOTEM proton time of flight measurement at the LHC

The TOTEM experiment will install new timing detectors to measure the time of flight (TOF) of protons produced in central diffractive (CD) collisions at the LHC [1].

The CD interactions measured by TOTEM at $\sqrt{s}$ = 13 TeV are characterized by having two high energy protons (with momentum greater than 5 TeV) scattered at less than 100 μrad from the beam axis. In the presence of pile-up[1] events it is necessary to associate each particle to its production vertex so that the event properties are correctly measured. The TOF detectors installed in the TOTEM Roman Pots (RPs)[2] will measure with high precision the arrival time of the CD protons on each side of the interaction point. They will operate in the LHC with a scenario of moderate pile-up (about one interaction per bunch crossing) and a time precision of at least 50 ps per arm is required to efficiently identify the event vertex [2]. Since the difference of the arrival times is directly proportional to the longitudinal position of the interaction vertex ($z_{VTX} = c\Delta t/2$), a precision of 50 ps will allow knowing the longitudinal interaction vertex position to less than 1 cm.

The timing detector will be installed in four vertical RPs located at 210 m from the interaction point 5 (IP5) of the LHC. The detector comprises four identical stations, each consisting of four hybrid boards[3] equipped either with an ultra fast silicon detector (UFSD) [3–6] or with a single crystal chemical vapor deposition (scCVD) diamond sensor [7, 8]. Every board houses 12 independent amplifier each bonded to a single pad (pixel) of the sensor. The typical time precision of one plane equipped with scCVD is in the range of 50 - 100 ps, while it is in the 30 - 100 ps range for one equipped with an UFSD sensor. Combining TOF measurements from 4 detector planes will provide an ultimate time precision better than ~50 ps, which translates in a precision on the longitudinal position of the interaction vertex σ_z <1 cm.

[1]Probability that more than one interaction is produced during the same bunch crossing.

[2]Special movable insertion in the LHC vacuum beam pipe that allow to move a detector edge very close to the circulating beam.

[3]The particle sensor and the amplification electronic are mounted on the same PCB.

2 Ultra Fast Silicon Detector

Ultra Fast Silicon Detectors, a new concept in silicon detector design, associate the best characteristics of standard silicon sensors with the main feature of Avalanche Photo Diodes (APD). UFSD are thin (typically 50μm thick) silicon Low Gain Avalanche Diodes (LGAD) [9, 10], that produce large signals showing hence a large dV/dt, a characteristic necessary to measure the time (t) accurately. Charge multiplication in silicon sensors happens when the charge carriers drift in electric fields of the order of $E \sim 300\,\text{kV/cm}$. Under this condition the drifting electrons acquire sufficient kinetic energy to generate additional electron/hole pairs. A field value of 300 kV/cm in a semiconductor can be obtained by implanting an appropriate charge density around $N_D \sim 10^{16}/cm^3$, that will locally generate the required very high fields. Indeed in the LGAD design (figure 1) an additional doping layer is added at the $n-p$ junction which, when fully depleted, generates the high field necessary to achieve charge multiplication.

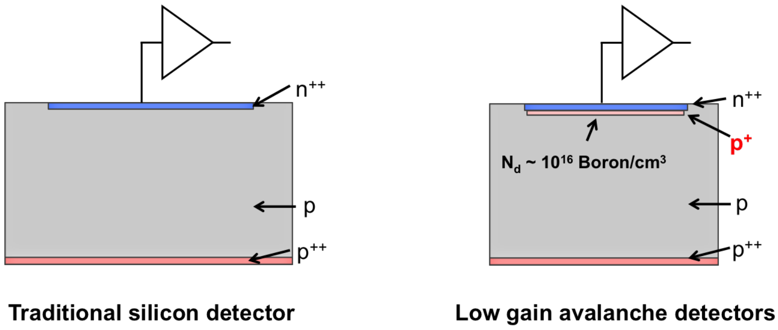

Figure 1. Comparison of the structures of a silicon diode (left) and a Low-Gain Avalanche Diode (right). The additional p^+ layer near the n^{++} electrode creates, when depleted, a large electric field that generates charge multiplications.

First results of time resolution of thin LGADs (UFSD) in a beam test have been published in 2016 [11].

Radiation tolerance studies have shown [12, 13] that LGAD sensors can withstand up to 10^{14} equivalent neutron/cm^2 without loss of performance.

LGAD sensors can be built in many sizes and shapes, ranging from thin strips to large pads. The measurements reported here have been performed on a 2 cm^2 50μm thick UFSD sensor, manufactured by CNM[4] with a structure specifically designed for the TOTEM experiment, mounted on a standard TOTEM hybrid board [7].

3 Description of the UFSD-based timing board

The UFSD sensor used for the prototype timing plane has 16 pixels with the pixel layout shown in figure 2.

Prior to the gluing of the sensor on the hybrid board, each of the 16 pixels had been tested to determine its maximum operating voltage.

[4]http://www.cnm.es: Centro Nacional de Microelectrónica, Campus Universidad Autónoma de Barcelona. 08193 Bellaterra (Barcelona), Spain.

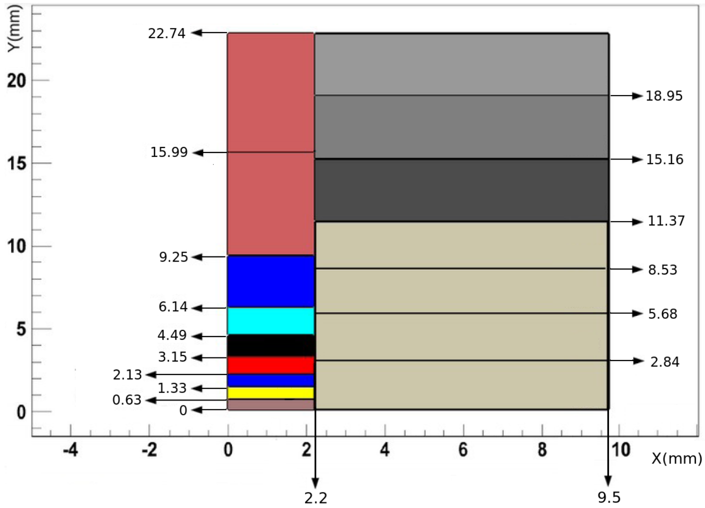

Figure 2. Sensor geometry of the TOTEM UFSD prototype made up of 16 pixels of different dimensions.

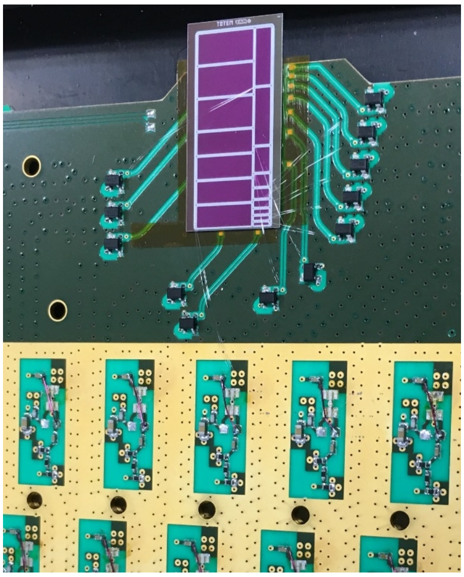

Figure 3. The UFSD sensor mounted on the TOTEM hybrid board.

Only pixels with a breakdown voltage higher than 180 V and a leakage current lower than 0.1 mA, were bonded to the read-out amplifier by means of standard 25 μm aluminum wires (figure 3).

The UFSD output pulse current shape simulated with the simulation program Weightfield2,[5] developed particularly for LGAD devices [14], assuming a bias voltage of 200 V and a sensor gain of 10 is shown in figure 4.

The detector generates a current whose maximum is about 8 μA.

Capacitance of the 50 μm thick UFSD pixels scales linearly with their area as $\sim$2 pF/mm^2: dimensions and relative capacitance for the pixels measured here are summarized in table 1.

[5]Open source code may be found at http://personalpages.to.infn.it/~cartigli/Weightfield2/Main.html.

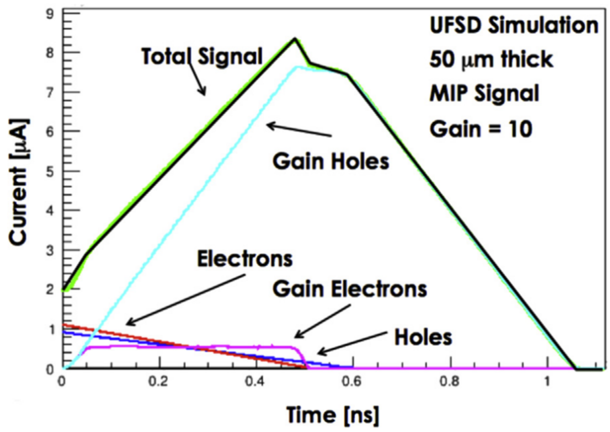

Figure 4. Simulations of the pulse shape from a 50 μm UFSD with a gain of 10 (from [15]). The plot shows the contribution of each component of the generated charge.

Table 1. Characteristics of the 50 μm UFSD pixels used in the tests.

Pixel N	Surface [mm^2]	Capacitance [pF]	Preamplifier feedback [ohm]
1	1.8	3.1	1 k
2	2.2	4.4	1 k
3	3.0	6.0	1 k
4	7.0	14	1 k
5	14	28	300

4 Front end electronics

Given the UFSD intrinsic charge amplification one expects the primary charge presented at the input of the amplifier to be 10-100 times larger than the one expected from a diamond sensor. The TOTEM hybrid, originally designed for scCVD diamonds [7], was modified for the UFSD eliminating the second amplification stage, referred elsewhere as ABA (Avago Broadband Amplifier ABA-53563). The amplification chain for UFSD has only 3 active elements (one BFP840ESD and two BFG425W BJT transistors). Moreover, since the UFSD pixels have a larger capacitance than diamond sensors, in order to maintain a fast rise time the feedback resistor of the preamplification chain has has been reduced to 1kΩ or 300Ω, accordingly to the capacitance of the pixel (see table 1).

5 Test beam measurements

The time precision of the UFSD sensors has been measured at the H8 beam line of the CERN SPS with a 180 GeV/c pion beam, by computing the time difference of the signal produced by particles crossing a Micro Channel Plate (MCP) PLANACON^{TM} 85011-501[6] and one of the UFSD pixels. The particle rate was $\sim 10^3$ /mm^2/s, the HV on the UFSD was set initially at 180 V, which is the maximum voltage before pixels breakdown, and varied down to 140 V. The maximum current

[6]PLANACON^{TM} Photomultiplier tube assembly 85011-501 from BURLE.

allowed in the present measurement was 0.1 mA. A screen shot from the oscilloscope with the signals from the MCP and the UFSD detectors is shown in figure 5.

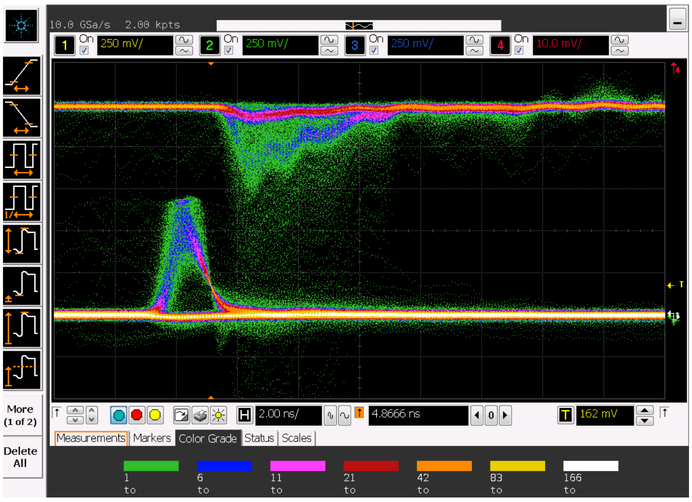

Figure 5. Event display of several MCP (top) and UFSD (bottom) signals. The oscilloscope record was triggered by the UFSD signal.

The UFSD pixels that we tested have an area ranging between 1.8 mm^2 and 14 mm^2. The 2.2 mm^2 UFSD pixel shows an average Signal to Noise Ratio (SNR) of ~60 (figure 6), defined as the ratio between the pulse height and the RMS voltage of the baseline. The risetime, defined as the average time for the signal to go from 10% to 90% of its maximum, is 0.6 ns (figure 7).

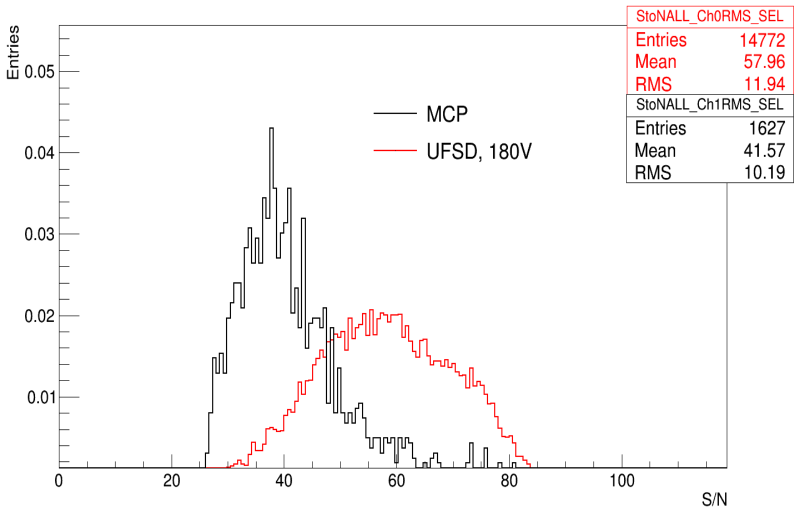

Figure 6. Signal to Noise ratio of the MCP and of the 2 mm^2 UFSD pixel.

The UFSD SNR curve for the events used in this analysis does not show the typical Landau curve tail; this is due to the saturation of ~ 10% of the signals and may include the effect of a non linearity in the modified amplification chain.

Signals are recorded with a 20 GSa/s DSO9254A Agilent oscilloscope. The time difference between the MCP and the 2.2 mm^2 UFSD pixel is shown in figure 8. The difference is computed

2017 JINST 12 P03024

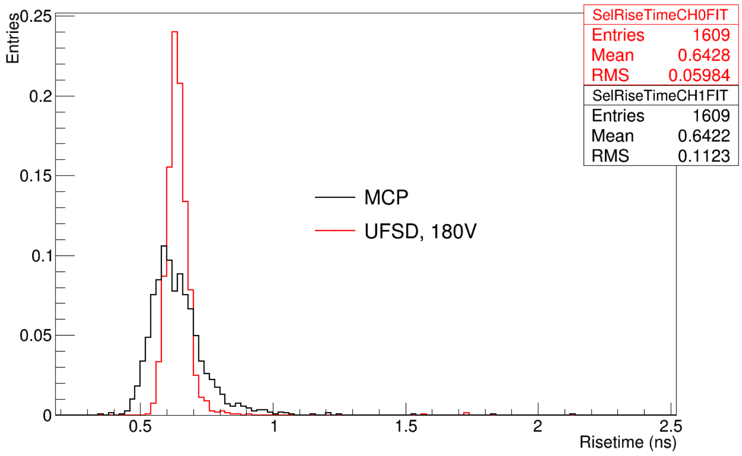

Figure 7. Risetime of the MCP and of the 2 mm^2 UFSD pixel.

off-line by using a constant fraction discrimination with a threshold at 30% of the maximum for both the UFSD and the MCP signal.

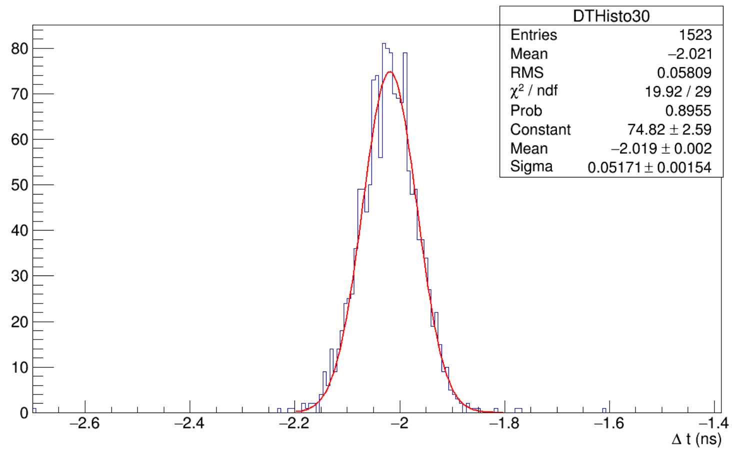

Figure 8. Difference of the arrival time measured by the MCP and by the 2.2 mm^2 UFSD pixel biased at 180 V.

The MCP time precision was obtained from other measurements and is (40 ± 5) ps. The results of the measurements are summarized in table 2.

Figures 9 and 10 show the UFSD time precision[7] as a function of the pixel capacitance and of the applied bias voltage respectively; the second set of measurements was performed on the pixel with an area of 2.2 mm^2. The precision of the measurement is mainly due to the uncertainty with which the MCP time precision is known.

The trend of the measurements suggests that a time precision of less than 30 ps could be reached for the smallest area pixel biased at 200 V.

[7]To estimate the UFSD time precision the standard deviation (σ_{DT}) of the distribution of the arrival time difference between the MCP and the UFSD pixel is calculated in advance. The UFSD time precision, σ_{UFSD}, is then obtained as $\sigma_{UFSD} = \sqrt{\sigma_{DT}^2 - \sigma_{MCP}^2}$, with σ_{MCP} =40 ps.

Table 2. Results of the time precision measurements as a function of the pixel capacitance, pixel surface area and of the applied bias Voltage. The uncertainty on the measured values is of ∼ 5 ps and depends essentially on the uncertainty of the MCP reference measurement.

Surface [mm^2]	Capacitance [pF]	HV [V]	Time precision [ps]
1.8	3.1	180	32
2.2	4.4	180	33
3.0	6.0	180	38
7.0	14	180	57
14	28	180	102
2.2	4.4	140	49
2.2	4.4	160	41
2.2	4.4	180	33

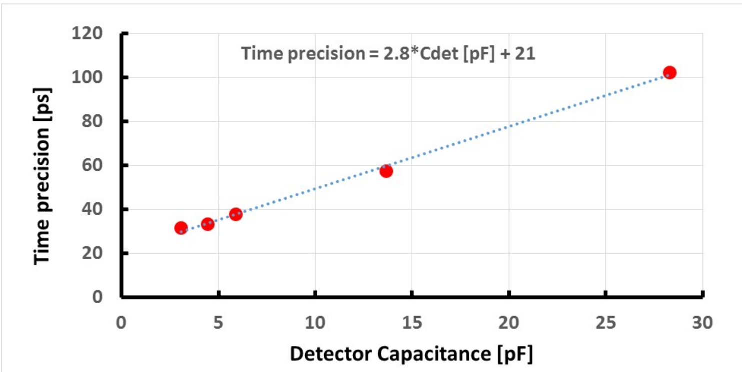

Figure 9. UFSD time precision as a function of the pixel capacitance for a bias of 180 V.

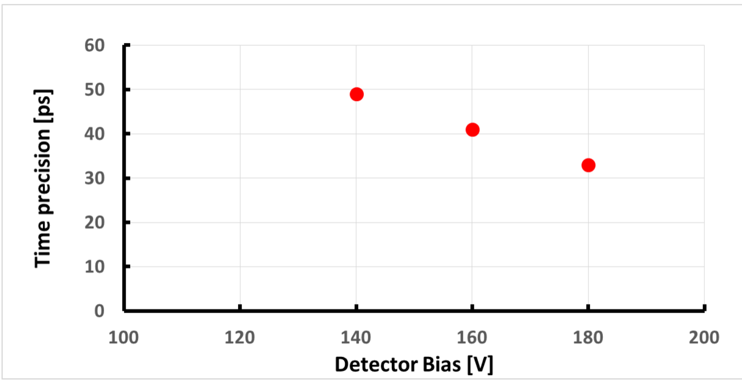

Figure 10. UFSD time precision (2.2 mm^2 pixel) as a function of the applied bias Voltage.

6 Conclusions

In this contribution we described the timing performance of a 50 μm thick UFSD detector on a beam of minimum ionizing particles. A time precision in the range of 30-100 ps has been measured, depending on the pixel capacitance. The UFSD technology will be used by TOTEM experiment in the vertical RPs together with scCVD sensors.

2017 JINST 12 P03024

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