Ultra Fast Silicon Timing Detectors

Status and future developments

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Abstract

The Ultra Fast Silicon Detectors (UFSD) are a novel concept of silicon detectors based on the LGAD technology, which are able to obtain time resolution of the order of few tens of picoseconds. First prototypes with different geometries (pads/pixels/strips), thickness (300 and $50\mu m$) and gain (between 5 and 20) have been recently designed and manufactured by CNM (Barcelona) and FBK (Trento). Several measurements on these devices have been performed in laboratory and in test beam. First results on sensor characteristics (leakage current, breakdown voltage, gain) and time resolution will be discussed and compared to simulation. The expected time resolution, the low material budget and the possibility of segmentation make USFD very interesting candidates for the measurement of the proton time-of-flight in the Precision Proton Spectrometer (CT-PPS).

Introduction and motivation

In order to measure the time of a signal, a TDC records the instant when a signal, which is coming from a detector and has already been pre-amplified, crosses the comparator threshold. The fluctuations of such a measurement are due to a *Jitter term*, depending on the steepness of the signal and the noise level, a *Landau term*, inlcuding the time walk and errors caused by variations of the signal's shape and a *TDC term* caused by the binning approximation.

$$\sigma_t^2 = \left(\frac{N}{dV/dt}\right)^2 + \sigma_{Landau}^2 + \sigma_{TDC}^2 \qquad (1)$$

Whereas the $\sigma_{TDC} = \frac{\Delta t_{TDCbin}}{\sqrt{12}}$ is unavoidable and the time walk can be corrected by specific electronics, it is crucial to keep the $\frac{N}{dV/dt}$ ratio as low as possible.

The perfect sensor for timing should be characterized by:

- a linear response (no breakdown);
- high signal to noise ratio (moderate gain);
- steep signal (small charge collecting time).

Ultra Fast Silicon Detectors

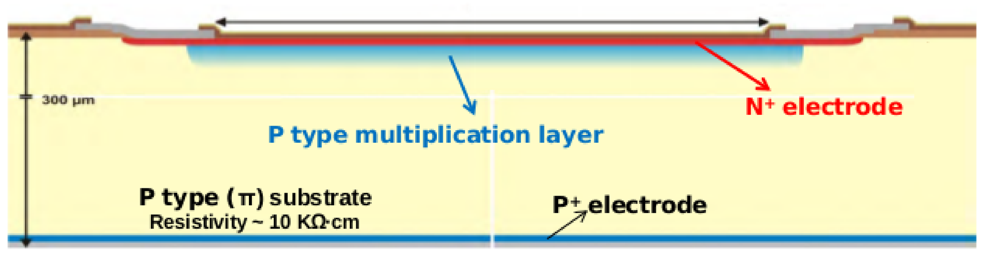
Since the impact ionization rates depend *exponentially* on the electric field (ref. [1]), a locally high electric field is essential to obtain charge multiplication.

The external applied bias should be high enough to saturate the charge velocities but low enough to avoid sensor breakdown:

$$70\,\frac{kV}{cm} \lesssim E_{bias} \lesssim 350\,\frac{kV}{cm}$$

Low-Gain Avalanche Detectors as UFSD

The thickness, segmentation and gain of a LGAD can be optimized to make it an excellent candidate for time measurements.



Low gain : milder electric field, lower noise, no dark current, possible electrode segmentation

Thin sensors : higher signal steepness (dV/dt), higher radiation resistance, lower Landau noise.

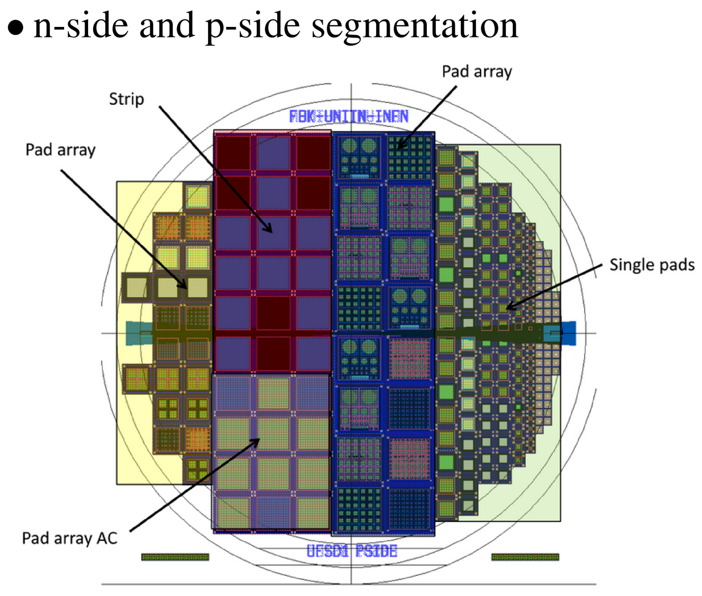
Goal for a 50 μm thick UFSD: $\sigma_t \simeq 30\,ps$.

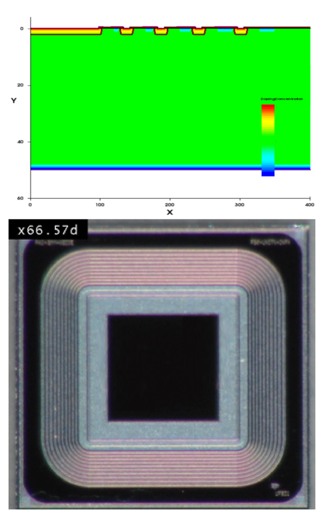
FBK production

FBK (Trento, Italy): in the framework of ERC-UFSD/INFN and MEMS/INFN in collaboration with Torino and Trento.

$300\mu m$ thick LGAD production (released in March):

- 13 wafers, silicon on silicon
- 5 splits of gain in 2% steps
- multiple structures
- n-side and p-side segmentation

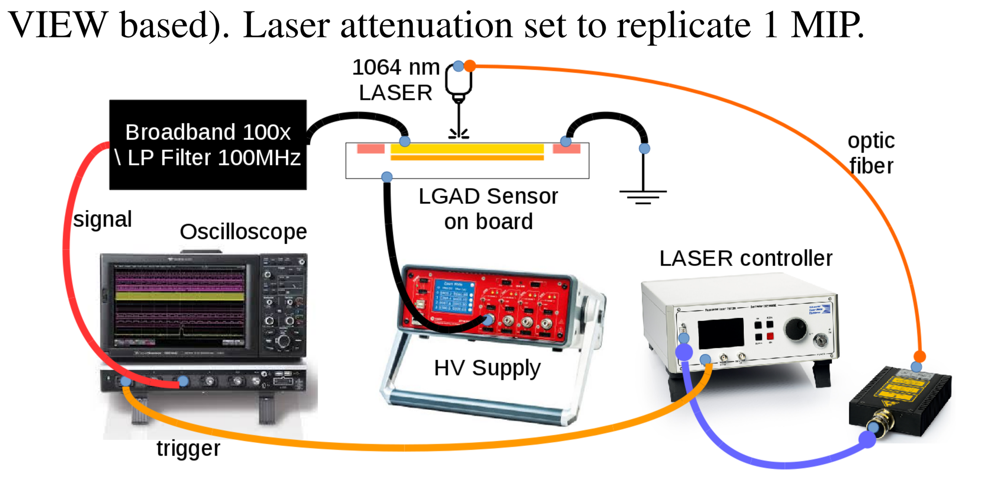




$50\mu m$ and $75\mu m$ expected winter 2016/2017.

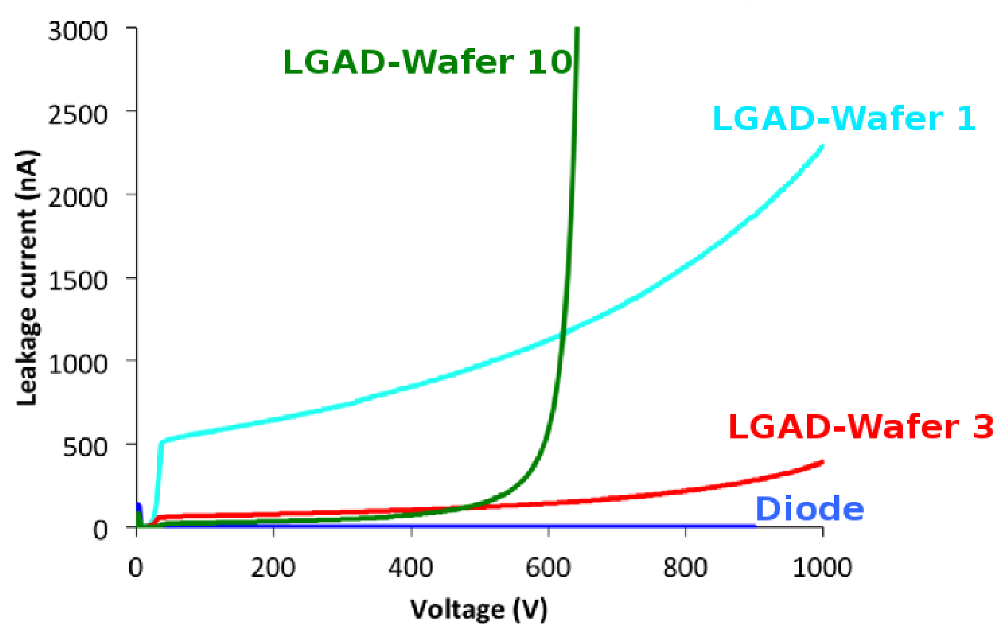
Sensor characteristics

Setup: Climatic chamber with automatic data acquisition (LabVIEW based). Laser attenuation set to replicate 1 MIP.



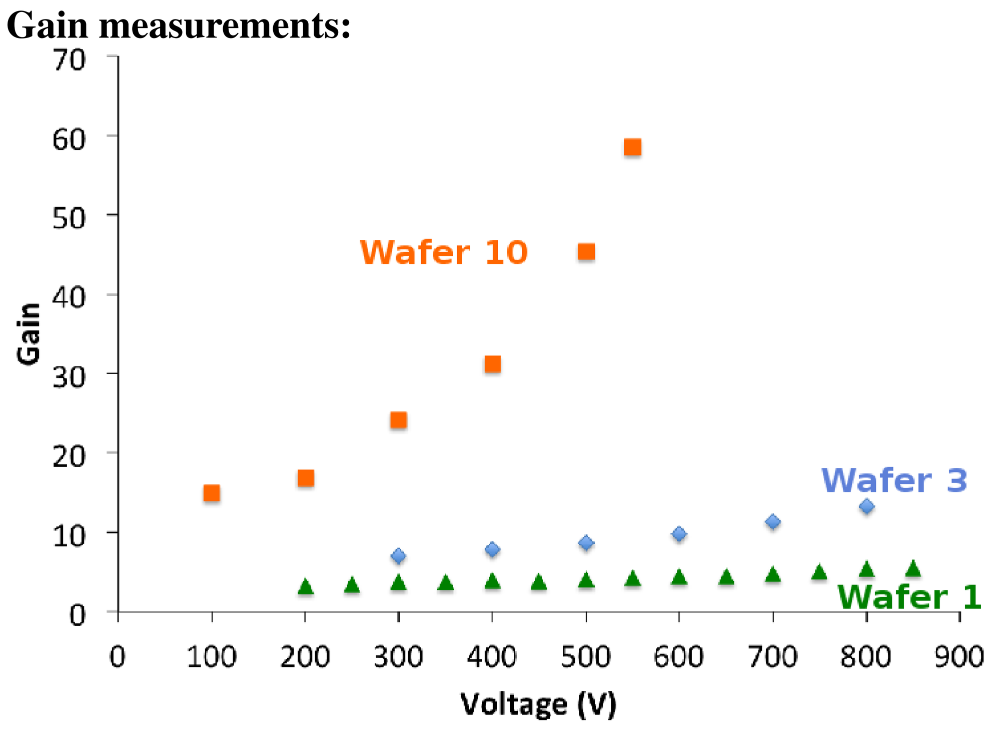
Sensors: FBK production, $300\,\mu m$, single pads $1\,mm^2$, $4\,mm^2$. Wafer 1/3/10, respectively split 1/2/4 of gain.

IV measurements for sensors with different gain:



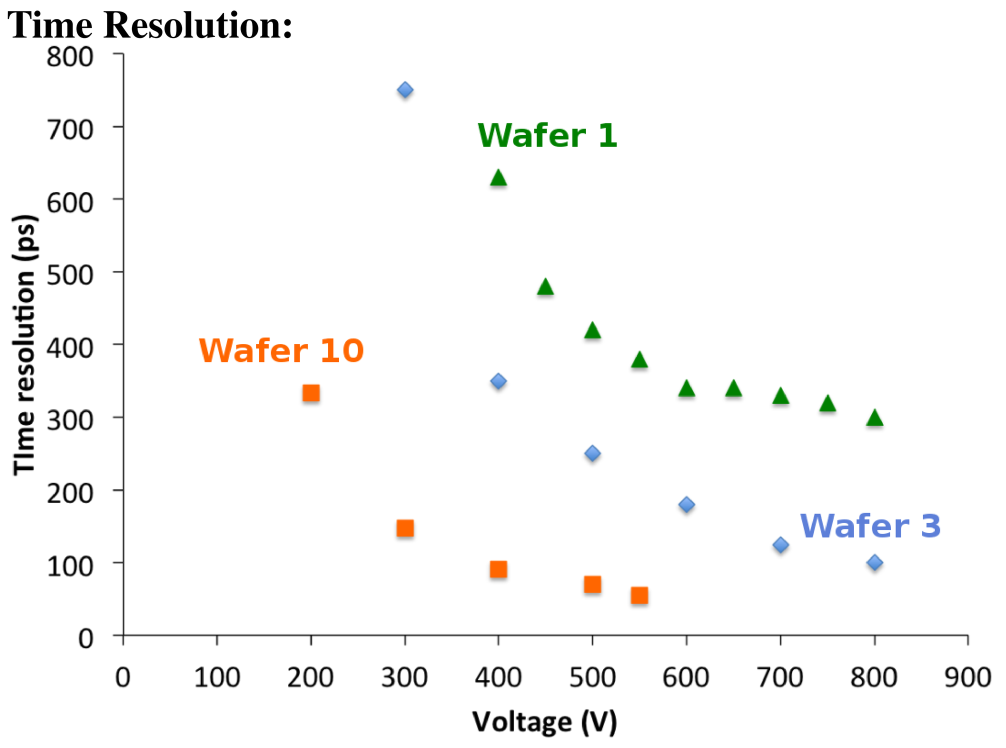
Breakdown voltage decreases with gain, in agreement with simulation. V_{BD}: $> 1000V$ (W1), $\simeq 900V$ (W3), $\simeq 500V$ (W10).

Gain measurements:



Gain is evaluated as the ratio of the LGAD signal area over the DIODE signal area. Good agreement with simulation.

Time Resolution:



σ_t evaluated with constant fraction at 50% of the amplitude.

Wafer 1: $\sigma_t(@800V) \simeq 300ps$

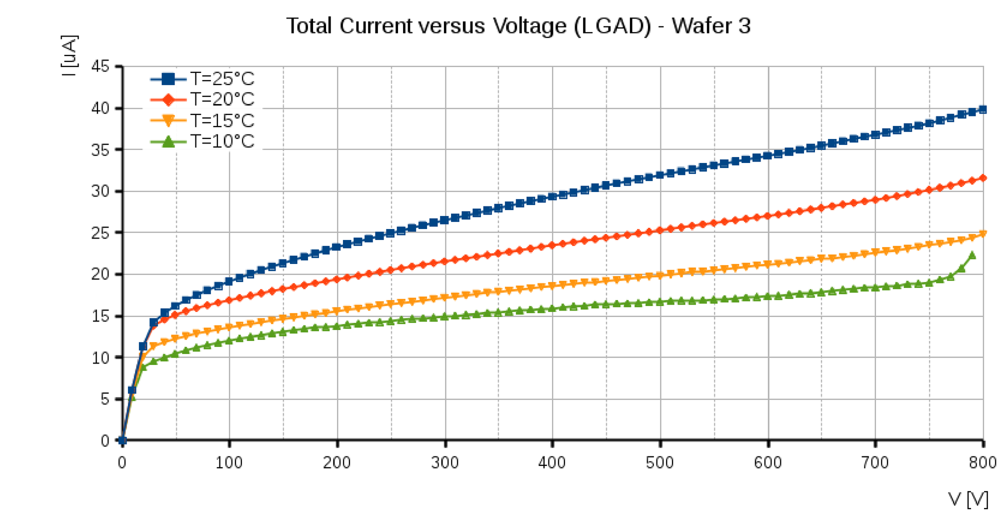
Wafer 3: $\sigma_t(@800V) \simeq 90ps$

Wafer 10: $\sigma_t(@550V) \simeq 55ps$

Characteristics vs temperature

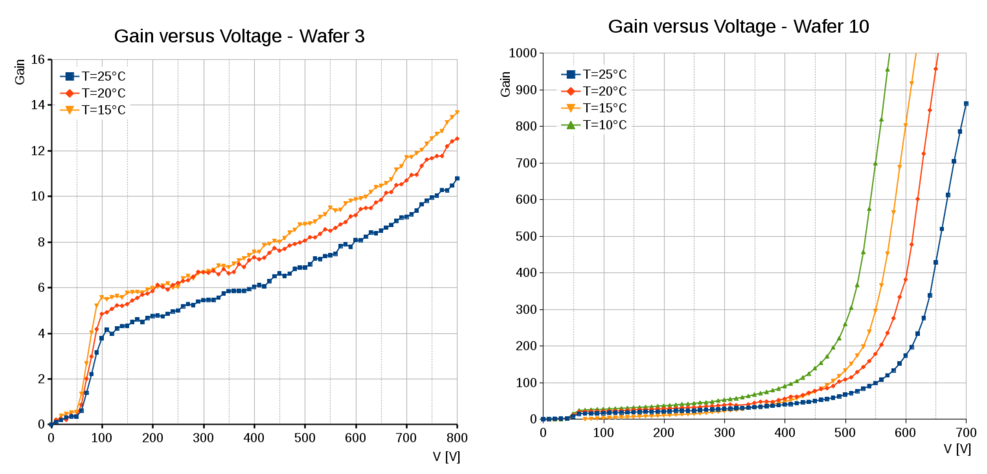
The impact ionization rates vary greatly with temperature (ref. [2]), also through the saturation velocity (ref. [3]).

An increase in the gain is expected for lower temperatures, in addition to a decrease of the internal current in the sensor.

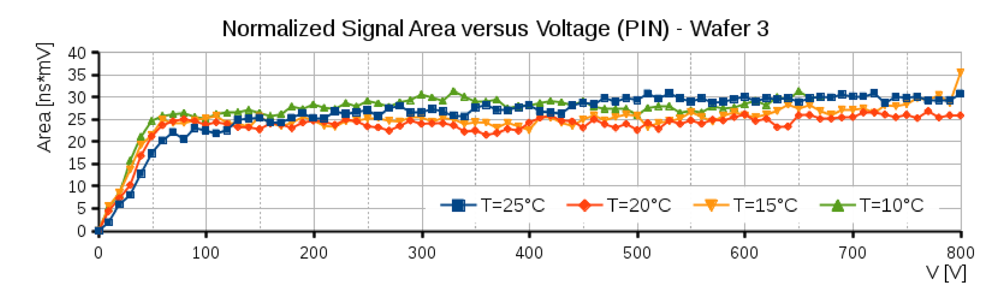


A first sign of breakdown can be seen at $T = 10°C$.

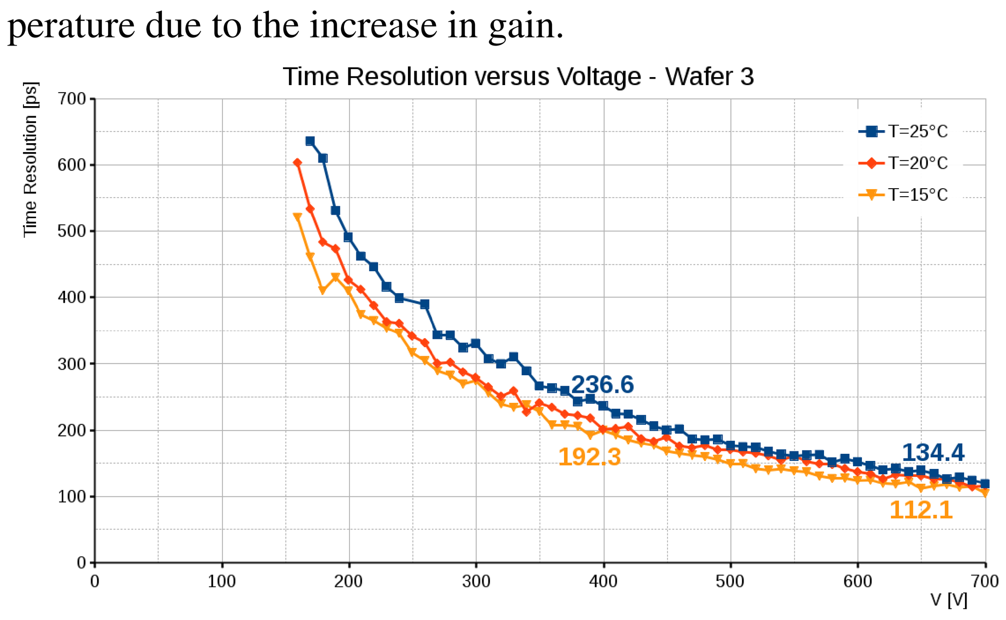
The increase of gain is far more relevant for the sensors which have a high starting gain but it is clearly visible on low gain sensors as well. The increase in gain causes the breakdown to happen for lower external bias values.



The signal area for the diode does not show any dependence on the temperature.



The time resolution σ_t is visibly affected by changes in temperature due to the increase in gain.



The study of the temperature dependence on the sensor performance is crucial for calibration in order to operate at very low temperatures, as requested by some of the major experiments.

References

[1] W Maes, K De Meyer, and R Van Overstraeten. Impact ionization in silicon: a review and update. *Solid-State Electronics*, 33(6):705–718, 1990.

[2] CR Crowell and SM Sze. Temperature dependence of avalanche multiplication in semiconductors. *Applied Physics Letters*, 9(6):242–244, 1966.

[3] C Scharf and R Klanner. Measurement of the drift velocities of electrons and holes in high-ohmic $< 100 >$ silicon. *arXiv:1503.08656v2 [physics.ins-det]*, 2015.

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