Ultra-Fast Silicon Detectors

A roadmap for the development of particle tracking in space and time

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Abstract

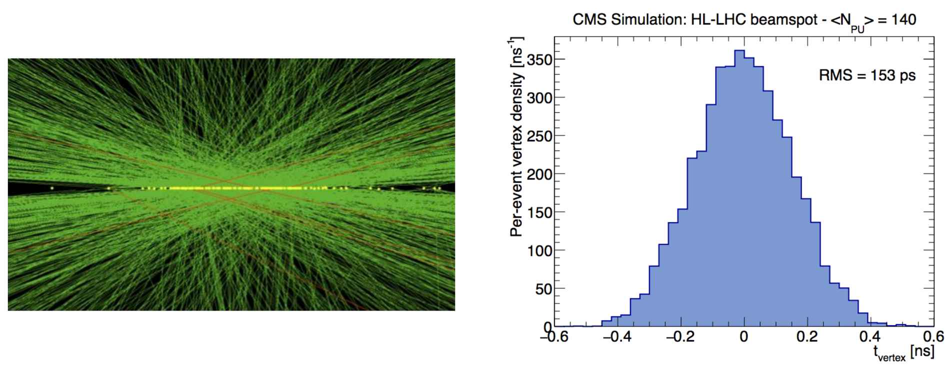
In this contribution I will review the most recent progresses towards the development of a silicon detector able to provide accurate measurements in both space and time, the so-called 4-dimension tracking. In particular, the Ultra-Fast Silicon Detectors (UFSD) project is described by discussing working principles of devices, technological state-of-the-art, measurements and TCAD (Technology Computer-Aided Design) simulations. To have a satisfactory timing resolution UFSD are based on the Low-Gain Avalanche Detectors (LGADs) principle, where carriers multiplication is obtained and kept under control through the implantation of a highly-doped p-type layer. This fact ensures larger output signals, very important for accurate time measurements, while providing the advantage of not having high-gain regimes as in standard APD structures, where also noise is typically enhanced. In the presentation I will also review the most recent beam test results, and the quest for a radiation resistant design.

Introduction and motivation

The measurement of trajectories of **charged particles** is ubiquitous in applications of physics to a wide variety of areas, from cosmic rays in space science, to ionized molecules in mass spectrometers and charged particles in medical treatment.
These applications typically require measurements of particle locations to some opportune **accuracy** and at a certain **hit rate**.
A fundamental tool for making such measurements is the **silicon sensor**, however a limitation has been the **signal formation** process, which has traditionally limited the ability to measure the particle arrival time.
The recent development of a new type of silicon technology promises to significantly enhance our measurement capabilities by means of simultaneously maintain an **high granularity** typical of spatial tracking and also the **high rate** in data collection to make very good **time measurements**.

Timing at High-Luminosity LHC

As the **density of events** is such that they occur in different locations traditional 3-dimensional (3D) tracking information is sufficient to correctly reconstruct each vertex.
In HL-LHC, where the number of events per bunch crossing will be of the order of 150-200, the density of **events** are so large that they will be **spatially overlapped** (10-15% of vertexes composed by two events). This effect, in principle, may **degrade the reconstruction** process and lead to **event loss**.

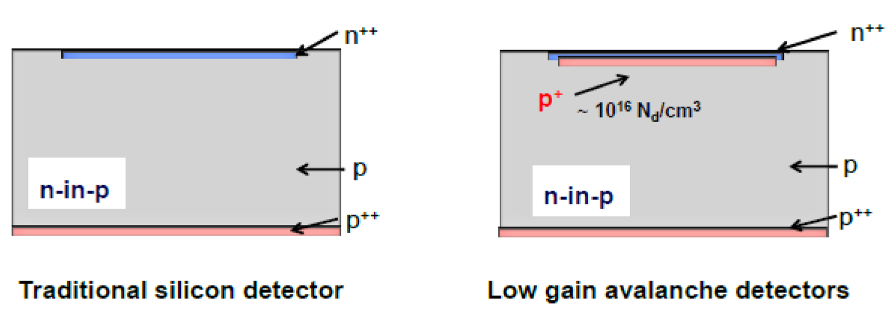


Left: z-vertex distribution for a single bunch crossing at HL-LHC with an rms of ~150 ps. Right: distribution of interaction time at HL-LHC considering an average pile-up of 140 vertexes.

The **timing information** can drastically improve this scenario: For example, a precision of **30 ps** should allow to almost completely avoid any overlapping event, making timing information roughly equivalent to **improved luminosity**.

The Ultra-Fast Silicon Detector project

As argued, we want to combine time and position determination by using silicon technology in one single device. To this purpose **Ultra-Fast Silicon Detectors** (UFSD) have been developed.
In order to obtain **large signals** and **short rise time** we have to deal with **thin devices** able to generate a large number of charge carriers. So, we need for **charge multiplication**.

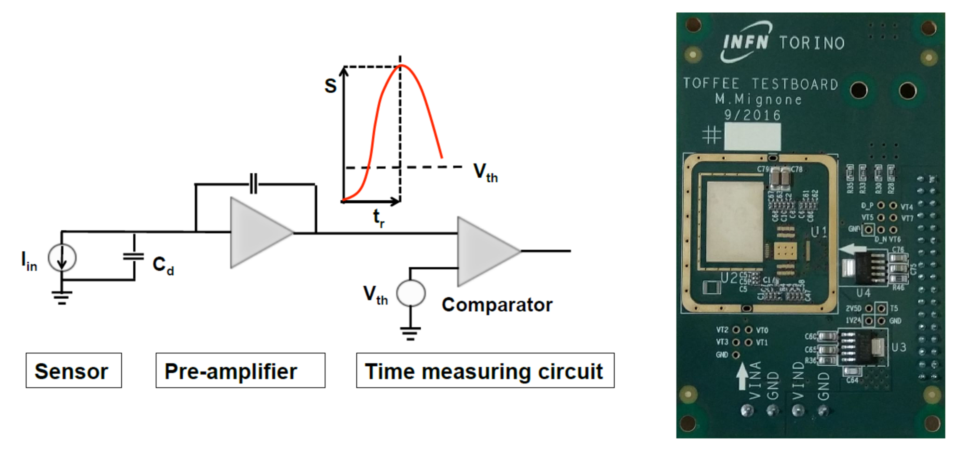


Left: no-gain n-in-p Si detector. Right: LGAD design, with the introduction of a thin p^+-type layer below the junction.

UFSD are based on **Low-Gain Avalanche Detectors** (**LGAD**) with a gain of 10-20 produced by an additional $\boldsymbol{p^+}$**-type doping** layer (B or Ga) just underneath the n^{++} contact well. Since, typically, a minimum ionizing particle (MIP) creates approximately **73 electron/hole pairs** per µm we don't need high gain operating regimes which, in turn, would cause high excess noise factors.
In LGAD the implant of gain-layer doping must be accurately engineered in order to obtain a gain which is enough to generate a measurable signal but not too high so that SNR is maintained under control. On the other hand, the sensor thickness affects the **device capacitance** and, in turn, the **signal amplitude**: thick sensors have large signals but low **slew-rates**. So a trade off must be found.
Experimental results and simulations indicate that a thickness of ~50 µm combined with a gain $G \simeq 20$ provides optimum performances.

The read-out of LGADs for timing

In order to measure the time of a signal, the sensor output is read by a **preamplifier** that shapes the signal. Then, through a **time-to-digital converter** (**TDC**), a comparator measures the time of arrival by recording the instant when the signal crosses the threshold V_{th}.



Left: main components of a time-tagging detector. Right: our realization of a test-board for UFSD.

The fluctuations of such a measurement are due to **jitter** (mostly coming from electronic noise and from amplifier slew rate), to **Landau** and **time walk** terms (respectively realated to amplitude fluctuations and irregularities of the primary signal) and finally also to the **TDC** component and other distortion terms caused by variations of the signal shape:

$$\sigma_t^2 = \sigma_{\text{jitter}}^2 + \sigma_{\text{Landau}}^2 + \sigma_{\text{TimeWalk}}^2 + \sigma_{\text{TDC}}^2 + \cdots ,$$

where

$$\sigma_{\text{jitter}} = \frac{N}{\mathrm{d}V/\mathrm{d}t} = \frac{t_{\mathrm{r}}}{\mathrm{SNR}}$$

(being N the noise and t_{r} the rise-time), the term $\sigma_{\text{TDC}} \sim \Delta t_{\text{bin}}/\sqrt{12}$ turns out to be unavoidable and where the time walk can be corrected by specific electronics.
Finally, a good **time resolution** is obtained if:

- jitter and time walk are minimized by detectors with very fast slew rates, low intrinsic noise and read out with low noise amplifiers
- signal distortions are minimized by operating the sensor in a regime where the carrier's **drift velocity is saturated** and the sensor geometry is such that the **weighting field is uniform**
- time uncertainty caused by non-uniform charge deposition (Landau noise) is kept under control and it contributes to the single measurement with a constant term of ~30 ps

Sensor production and radiation issues

The first production of 300 µm LGAD by **Fondazione Bruno Kessler**, **FBK** (March, 2016):

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

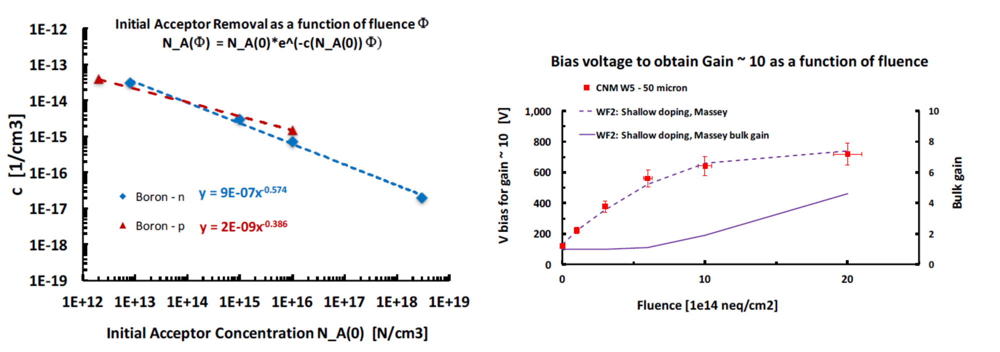
Now we are in the process of completing **UFSD-2** production (again by **FBK**), with

- 50 µm-thick active region
- 18 wafers, 10 with B-doping and 8 Ga-doped
- 4 and 3 splits of gain, respectively

It is well known from literature that radiation in silicon is able to produce lattice defects acting, according to their **ionization energies**, as **traps** or **dopant** elements. This is a crucial issue since the environment in which we would operate UFSD (i.e. HL-LHC) is such that the sensors will be exposed to an equivalent fluence of $5{\cdot}10^{15}$ neutrons per cm^2.
Along with this effect, also the **inactivation** of implanted impurities could be observed as the fluence ϕ increases. In particular, the kick-out of boron from substitutional to interstitial sites (due to neutrons and charged particles) is know to cause the so-called effect of **acceptor removal**.
The final acceptor concentration, which accounts for effective generation of traps $g_{\text{eff}}\,\phi$ and doping removal, is a function of the initial (nominal) acceptor density $N_{\mathrm{A}}(0)$ and has the following empirical form:

$$N_{\mathrm{A}}(\phi) = g_{\text{eff}}\,\phi + N_{\mathrm{A}}(0)\,\mathrm{e}^{-c(N_{\mathrm{A}}(0))\phi}$$

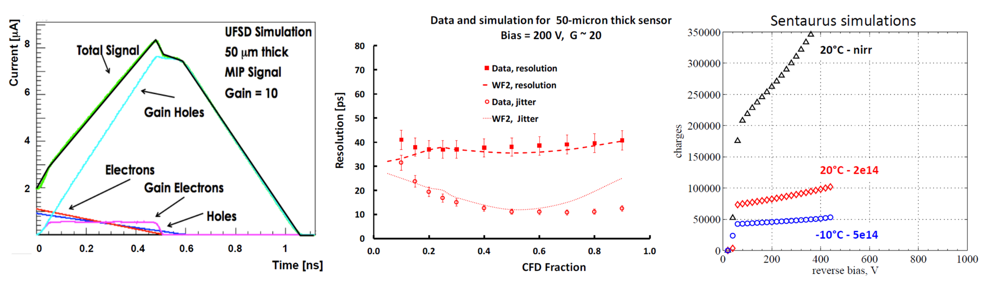
where c is a fitting parameter which depends on $N_{\mathrm{A}}(0)$ itself and where, typically, $g_{\text{eff}} \simeq 0.02$ cm^{-1}.



Left: boron removal coefficient as a function of the initial concentration under proton and neutron irradiation. Right: bias voltage needed to have $G = 10$ as a function of irradiation in 50 µm-thick CNM sensors implanted with a shallow gain layer.

Circuit and device simulations

In order to predict the behavior of the UFSD-readout system and of LGAD sensors solely (with or without the presence of particle irradiation) we developed an in-house code, **Weightfield2** (**WF2**), able to simulate not only the **internal multiplication** but even the **time-tagging circuitry**.

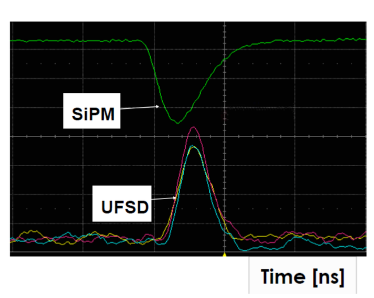


Simulations of a 50 µm-thick UFSD sensor. Left (WF2): current signal. Middle (WF2): Time resolution (total and jitter contribution as a function of CFD value). Right (TCAD Sentaurus): collected charge as a function of inverse bias, fluence and temperature.

Moreover, also a device-level TCAD commercial tool (Synopsys **Sentaurus**), based on the finite-boxes **drift-diffusion** (DD) model, is used to numerically test our structures.

Beam test results

We tested several 50 µm-thick 1.2×1.2 mm^2 UFSD sensors produced by CNM with π-mesons with momentum of 180 GeV/c at CERN SPS-H8 facility. The measurement setup included broadband amplifiers and a trigger board comprising of a SiPM coupled to a quartz bar.



UFSD Timing resolution		
	Vbias = 200 V	Vbias = 230 V
N = 1	34 ps	27 ps
N = 2	24 ps	20 ps
N = 3	20 ps	16 ps

Left: signals of a beam test event showing the coincidence of three 50 µm-thick UFSD sensors and the SiPM trigger counter. Right: timing resolution for single (N = 1), doublet (N = 2) and triplets (N = 3) of UFSD for different operating bias.

As shown in the previous table, the timing resolution of a single UFSD is measured to be 34 ps for 200 V and 27 ps for 240 V. Moreover, a system of **three UFSD** has a measured **timing resolution** of 20 ps for a bias of 200 V, and **16 ps** at 240 V.

Aknowledgments

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