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Ultra-fast silicon detectors for 4D particle tracking development

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Summary. — In this contribution I will review the state-of-the-art and developments of the Ultra-Fast Silicon Detectors (UFSD) project, designed to provide accurate particle tracking in both space and time. Working principles, technology, measurements and TCAD (Technology Computer-Aided Design) simulations of Low-Gain Avalanche Detectors (LGAD) are described, highlighting the advantages of having large output signal without high-gain regimes as in standard APD structures, where also noise is typically enhanced.

1. – The Ultra-Fast Silicon Detector project

A fundamental tool for measuring trajectories of charged particles is the silicon sensor. The recent development of a new type of technology promises to significantly improve our capabilities in detecting particles by means of simultaneously maintaining a high granularity typical of spatial tracking while adding very good time measurements. As the density of events is such that they occur in different locations, traditional 3D tracking information is sufficient to correctly reconstruct each vertex. However, in the high-luminosity Large Hadron Collider (HL-LHC) at CERN, the density of events is so large that they will be spatially overlapped. This effect, in principle, may degrade the reconstruction process leading to event loss. A timing precision of 30 ps should allow to almost completely avoid any overlap, making timing information roughly equivalent to additional luminosity.

To combine time and position determination Ultra-Fast Silicon Detectors [1-3] (UFSD) technology has been developed. UFSD are based on Low-Gain Avalanche Detectors (LGAD) diodes, with a gain of 10–20 produced by a p^+-type doping layer (B or Ga) added just below the n-contact. This layer is at the basis of the charge multiplication, a mechanism which is responsible for high amplitude and short rise time in the output signal. In LGAD the doping profile of gain-layer 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

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device capacitance and, in turn, the signal amplitude: thick sensors have large signals but low slew rates: experimental results and simulations indicate that a thickness of $\sim$50 μm combined with a gain $G \simeq 20$ provide optimum performance.

The typical fluctuations in measuring the time of a signal are due to jitter, nonuniform charge deposition (Landau noise), time-walk and finally also to digitalization and other distortion terms caused by variations of the signal shape. A good time resolution is obtained when: 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; Landau noise is kept low so that it contributes to the single measurement with a constant term $\sim$30 ps.

2. – Sensor production, simulation and testing

Our first UFSD production of 300 μm LGAD by Fondazione Bruno Kessler, Trento, was dated March 2016, while now we are in the process of completing the UFSD-2 production, with 50 μm-thick active region LGAD including boron, boron-carbon, gallium and gallium-carbon doping configurations. The use of carbon seems to be crucial in order to avoid some particular effects of radiation in silicon. Indeed, it is well known from the literature that radiation is able to produce acceptor traps. But along with this effect, also the inactivation of doping species could be observed as the fluence increases. In particular, the kick-out of boron from substitutional to interstitial sites is know to cause the so-called effect of acceptor removal. So, the idea is to implant carbon with very-low diffusion process in order to occupy the interstitials sites that can eventually host the inactivated boron/gallium.

To predict the behavior of the UFSD read-out and LGAD sensors we used an in-house code, Weightfield2 [4] (WF2), able to simulate not only the internal multiplication but even the time-tagging circuitry. 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. Eperimentally, we tested several 300 and 50 μm thick $1.2\times1.2\,\text{mm}^2$ UFSD sensors produced by Centro Nacional de Microelectrónica, Barcelona, with π-mesons with momentum of 180 GeV/c at CERN SPS-H8 facility. The timing resolution we obtained for a single UFSD is measured to be 34 ps at 200 V and 27 ps at 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.

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