Nuclear Inst. and Methods in Physics Research, A 936 (2019) 608–611

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Development of ultra fast silicon detector for 4D tracking

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ARTICLE INFO

Keywords:
Timing
Silicon detector
UFSD
LGAD
4D particle tracking
Radiation damage

ABSTRACT

The Ultra Fast Silicon Detectors (UFSDs) are a new kind of silicon detectors based on Low Gain Avalanche Diodes technology. The UFSDs are optimised for time measurements with the goal of both excellent space and time resolution, which makes them a very good candidate for 4D tracking. In this paper, we will briefly explain their innovative design and show the status of the latest development. Recent measurements at the H8 beam line (CERN) will be reported, based on the UFSDs from two manufacturers: FBK and HPK. In particular, UFSDs of different thicknesses, with different doping concentrations and with different dopants of the gain layer have been studied. A time resolution of 35 ps has been achieved for a 50 μm thick design and the results have been found to be in very good agreement with the expectations.

Contents

1. Introduction

The Ultra Fast Silicon Detector (UFSD) [1] is a new kind of silicon detector based on Low Gain Avalanche Diodes technology and optimised for time measurements. The UFSDs are n-on-p diodes with the additional inclusion of a highly doped p^+-type layer (gain layer) just below the n-contact, which is responsible for the charge multiplication mechanism (in reverse bias regime). By choosing the properties of such layer we are able to control the avalanche mechanism up to a value of the internal gain (between 5–70) that allows managing the noise. Indeed, as the gain is higher, both the signal and the detector noise grow but the noise grows faster. Anyway, as long as the detector noise stays below the electronic noise level, the signal to noise ratio increases and the time resolution improves.

The UFSD detectors might play an important role for the next generation colliders. For example, at the HL-LHC (High-Luminosity LHC [2]), âĂÍ the pile-up will be about 140, with a probability of merged vertices greater than 10%. This high pile-up density would have a significant impact on the physics reach of the experiments through the degradation of track reconstruction, of the assignment to the true primary vertex and through the rejection of non-interesting events. Therefore, if the spatial information alone is not enough to uniquely associate each track to its vertex, the idea is to use a *precise* time information associated to each track (4D tracking) to perform the correct vertex assignment. The UFSD is a perfect candidate for a 4D detector (see [3,4] for a comprehensive review). High-resolution timing detectors could also be beneficial to other fields both in particle physics (e.g. Particle IDentification) and in medical facilities (e.g. Positron Emission Tomography).

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https://doi.org/10.1016/j.nima.2018.09.110
Received 30 June 2018; Received in revised form 20 August 2018; Accepted 24 September 2018

First applications of UFSD are envisioned in upgrades of experiments (CMS [5][1] and ATLAS [6][2]) at the HL-LHC: with a beamspot time spread of 150–180 ps, the required time resolution would be of the order of ∼30 ps per layer (to reduce the wrong track-to-vertex associations to a level comparable to the current LHC running conditions). Another requirement for these detectors is the capability to withstand the very high radiation levels expected: for the CMS experiment the detectors have to withstand a fluence up to about $2 \cdot 10^{15}$ $\mathrm{n_{eq}/cm^2}$ while for the ATLAS experiment up to $9 \cdot 10^{15}$ $\mathrm{n_{eq}/cm^2}$.

In the UFSD matrix structure, the high electric field generated by the gain layer needs to be terminated correctly to avoid electromagnetic cross-talk between pixels and an early breakdown. In the current design, the gain termination is achieved by an additional implant of n^{++} doping, called Junction TErmination (JTE), that surrounds the gain layer and extends onwards for a thickness of a few microns. This geometry, therefore, creates a dead area between pads, where there is no multiplication, which limits the geometric efficiency (i.e. the fill factor, the ratio between the active and total area). With a pad area of 1 × 3 $\mathrm{mm^2}$, the current fill factor is about 91%. The detection efficiency of the detector in the active area is instead 100%.

It has been proven [7] that UFSD with a thickness of 50 μm combined with a gain G = 20–30 provides excellent performances in terms of timing. In [7] a time resolution between 27 ps and 34 ps (depending on the bias voltage) has been achieved in a beam test with a not irradiated 45 μm thick single pixel UFSD fabricated by CNM[3] with an active area of 1.7 $\mathrm{mm^2}$.

The time resolution has been shown to deteriorate with fluence due to the disappearance of the gain. This effect is caused by the acceptor removal mechanism [8] that decreases the concentration of the active dopant in the gain layer. To improve the radiation resistance of the UFSD, several prototypes have been produced and studied. Several different combinations of the gain layer have been analysed varying the doping concentration, the diffusion temperature (Low Diffusion, LD, High Diffusion, HD) and the dopant type: Boron (B) or Gallium (Ga), both with and without a co-implantation of Carbon. Details and results of radiation hardness tests of these prototype are reported in [9]. The results have shown that a Boron-Carbonated gain layer and an LD (narrower) gain layer implants are the most promising techniques to improve the radiation resistance.

In this paper the results obtained in a beam test setup from the study of the time resolution of not-irradiated single pixel UFSDs are reported. Several UFSD prototypes from two manufacturers have been tested: FBK[4] (same UFSD wafer production of [9]) and HPK.[5]

2. Detectors used

The HPK UFSDs tested are the first Hamamatsu production; they are single pixel detectors with a circular design, with an active area of 0.785 $\mathrm{mm^2}$ (1 mm of diameter) and of two different thicknesses: 80 μm and 50 μm. Four different doping concentrations have been used (A, B, C, D); the doping concentrations considered in this paper were the type C and D, i.e. the two highest since they are more interesting in terms of radiation hardness. The results on time resolution for four HPK detectors (HPK 80C, HPK 80D, HPK 50C, HPK 50D) are reported.

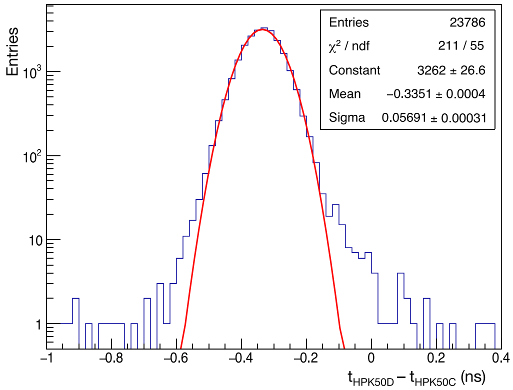

Fig. 1. Time difference distribution between two HPK detectors obtained in the beam test setup; the voltage applied was 430 V and 290 V for the HPK50C and HPK50D respectively. Here the time resolutions obtained were 43 ps for the HPK50C and 36 ps for the HPK50D.

The FBK detectors were also studied; in the first half of 2017, FBK produced 50 μm thick UFSDs with different doping concentrations and dopants of the gain layer. In this paper the results on time resolution of a single pixel detector with an active area of 1 $\mathrm{mm^2}$ is reported. In particular, the detector studied, FBK 50W15, uses a different solution for the dopants of the gain layer, Gallium with a Carbon co-implantation: this is the first working Gallium UFSD production.

3. Experimental setup and electronics

The time resolution of HPK and FBK detectors has been studied at the H8 test beam line at CERN. The beam was mainly composed by pions with a momentum of 180 GeV/c. The trigger for data acquisition was obtained by the coincidence of the self-trigger from the UFSDs.

The front-end and readout electronics are key parameters for time resolution measurements; indeed the coupling between detector and electronics is of fundamental importance. As front-end electronics, a C2 Cividec amplifier [10] has been used; it is a BroadBand Amplifier (BBA)[6] and in particular is a low-noise current amplifier which allows maintaining a wide bandwidth (2 GHz). The C2 Cividec has an amplification factor of 100; this value was necessary because the UFSD signal amplitude is, on average, less than one mV.

The time information has to be stored for the readout; this is typically done by a Time to Digital Converter (TDC). Anyway this would bring by definition a contribution jitter (nowadays between 15–30 ps) which affects the final time resolution. Therefore we used an Oscilloscope Lecroy 640 Zi [11] as readout electronics; the contribution of the oscilloscope to the measured time resolution is indeed totally negligible (of the order of 1 ps). This allows to obtain a final time resolution closer to the intrinsic resolution of the detector.

4. Results

Thanks to the oscilloscope readout, the full waveforms of the signals have been recorded; in this way, it was possible to apply a Constant Fraction Discriminator (CFD) technique (instead of a fixed threshold) to disentangle the time measurement from the amplitude of the signal.

Several time differences between the arrival times of not-irradiated UFSDs have been considered. In Fig. 1 the time difference between

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[1] The CMS high-resolution timing detector uses one layer, covering the acceptance region $1.5 < |\eta| < 3$. The detector comprises two disks, one on each side of CMS, positioned between the tracker and calorimeters. The detector uses ∼3 k UFSD matrix sensors, with 1536 pixels; each pixel has an active area of 1 × 3 $\mathrm{mm^2}$.

[2] The ATLAS high-resolution timing detector uses two layers, covering the acceptance region $2.4 < |\eta| < 4$. The detector comprises of two double-layer disks, one on each side of ATLAS, positioned in front of the Liquid Argon calorimeter. The detector uses ∼14 k UFSD matrix sensors, with either 240 or 480 pixels; each pixel has an active area of 1.3 × 1.3 $\mathrm{mm^2}$.

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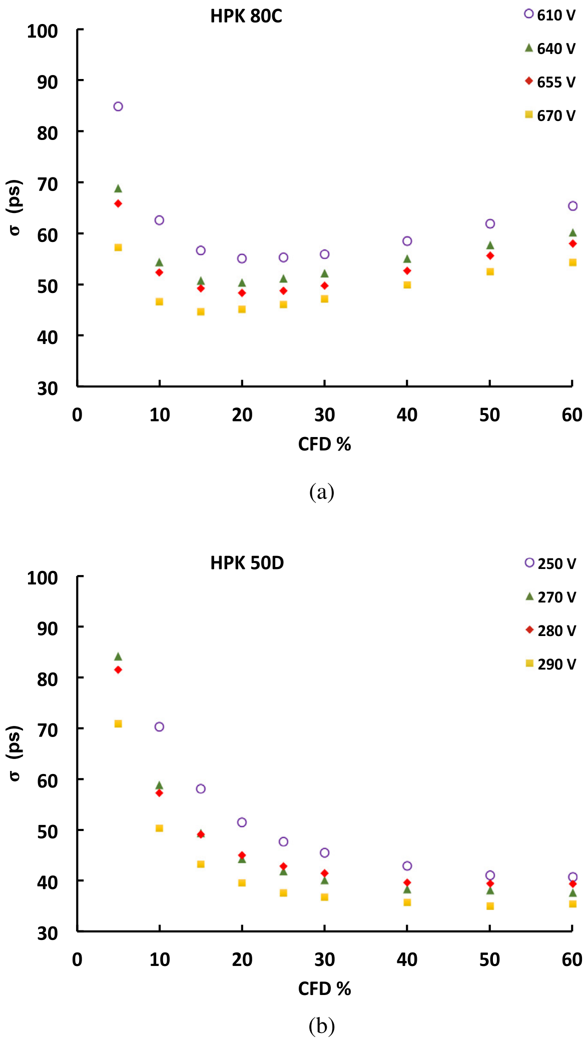
[6] In general, a BBA, when compared to other categories (like the Charge Sensitive Amplifier), takes full advantage from a detector like UFSD, with a very fast slew rate; it has a large bandwidth and by not shaping the signal it has a dV/dt ∼ di/dt.



(a)

(b)

Fig. 2. The time resolution versus the Constant Fraction Discriminator (CFD) threshold for several applied bias voltage for two HPK detectors:(a) HPK80C, (b) HPK50D. The errors have been estimated to be about 6% of the measured value (not reported to obtain a more readable plot).

two HPK detectors is shown. This plot is a typical representative of the difference time distribution between two sensors. It can be noticed that the distribution follows the gaussian function, with some tails deviation. These not-gaussian tails are also the reason for the χ^2/ndf $\sim$3.8. Anyway, selecting a central (gaussian) region with a total of 96% of the events, it becomes χ^2/ndf $\sim$1.2, giving a uniform detectors response. The final time resolution of the HPK and FBK detectors have been studied for several values of the CFD and for different applied bias voltage; it should be pointed out that higher value of voltage corresponds to higher detector gain. In Fig. 2 the time resolution versus the CFD for two HPK detectors of different thickness at several voltages is reported. As expected, for low values of the CFD the time resolution is worse: this is due to the jitter contribution (noise from both the electronics and the detector itself), which is larger for smaller slew rates, as it happens at the beginning and at the maximum of the signal. For higher values of the CFD, from about (15–20)%, the behaviour is different, depending on the thickness of the detector (see Fig. 2): for the 50 μm thick one, the trend is flat. On the contrary, for the 80 μm thick detector, after the initial reduction in time resolution, around CFD=25% a degradation is observed; this is due to the Landau contribution (shape variation due to the non-uniform event by event energy deposition), larger for thicker detectors. In addition, the time resolution improves for higher voltage applied (or rather higher gain) for both thickness.

Table 1
Time resolution results for the beam test set up.

Beam test	Gain	Time resolution (ps)
HPK 80C	45 ± 7	45 ± 3
HPK 80D	42 ± 6	47 ± 3
HPK 50C	26 ± 4	40 ± 3
HPK 50D	31 ± 5	35 ± 2
FBK 50W15	27 ± 4	40 ± 7

These sets of measurements have been found to be in good agreement with the predictions [3] of the simulation program Weightfield2 (WF2) [12]; here both jitter and Landau contributions are considered and the simulation perfectly fits the experimental trend. The Landau contribution is the physical limit on the time resolution and it has been found to be independent on the gain; for a 50 μm detector the Landau non uniform charge deposition limits the time resolution at about 30 ps (higher values for thicker detectors).

For each detector, a CFD value has been extracted as the one that minimises the time resolution; therefore, for each detector and each applied bias voltage, one value of time resolution is considered. Fig. 3 reports the comparison among the HPK and FBK UFSDs time resolution versus the gain. The gain values of the detectors have been measured considering the charge released from a MIP and comparing it with the charge released in an equivalent detector (same thickness) without gain.

All the detectors tested performed well, with a time resolution better than 50 ps for a gain higher than 25. In particular, for the 80 μm thick HPK sensors, a time resolution of 45 ± 3 ps has been achieved for a gain of about 45. For the thinner HPK sensors, as expected, an even better time resolution has been reached: 35 ± 2 ps for HPK50D, for a gain of about 31. The measurements of HPK detectors with the same thickness are comparable.

The results concerning the FBK sensors were obtained with reduced statistics; however, the results are still compatible with all the HPK50 detectors. The time resolution reached for the FBK 50W15 was 40 ± 7 ps at a gain of about 27.

For all the detectors, as expected, the time resolution improves with the gain (i.e. with the bias voltage). A saturation of the time resolution with high gain can be deduced from the trend of the lines (the limit is due to the Landau contribution).

In Table 1 the best time resolutions achieved (which corresponds to the higher gain value) for all the detectors are reported.

5. Conclusion and outlook

UFSDs are potentially a good candidate for the next generation colliders; a time resolution of 35 ps has been achieved for a single pixel 50 μm thick UFSD (using a Boron implant) with an active area of 0.785 mm^2.

Beam test results on time resolution of the first production of HPK and FBK of 50 μm UFSDs (with several solutions for radiation hardness) have been presented; all the tested devices are perfectly working with good performances, see Table 1 for the time resolutions results. It can be noticed that the time resolution does not depend on the different implant design studied but just on the thickness. The results obtained for HPK and FBK have been also compared to simulations, finding a very good agreement. As expected, thinner sensors lead to a better time resolution.

The *R&D* on UFSD is still ongoing. Sensors with a thickness of 35 μm have been produced, and an improved time resolution of about 23 ps has been reached [13] (even if the signal is much smaller).

Regarding the radiation hardness, we plan to further investigate the property of carbonated gain layer coupled to different temperature of diffusion, in order to further improve the performance.

Thin UFSD detector design can be interesting also for applications necessitating low material budget; however at the moment the support silicon wafer is thick, of the order of 300–500 μm (for handling reasons). The plan is to try to reduce and almost eliminate this layer.

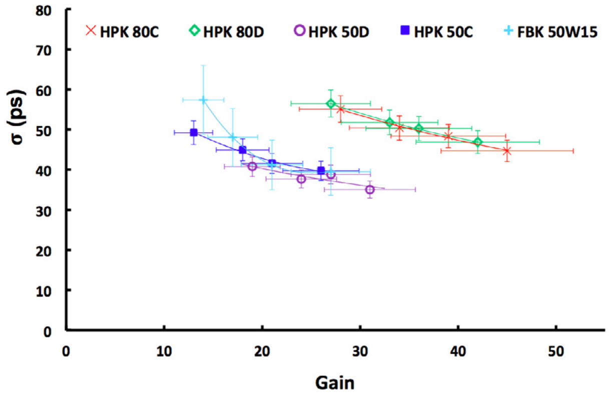


Fig. 3. The time resolution of HPK and FBK detectors versus the gain. The errors for the time resolution of HPK and FBK detectors have been estimated as 6% and 15% of the value respectively, while the error on the gain has been estimated as the 15% of the value.

Another plan is to try to produce monolithic UFSD, i.e. with the sensor and the front-end electronics integrated in the same silicon substrate.

A further important *R&D* addresses the fill factor. Evolution of the current UFSD matrix design (considering a pixel pad area of 1 × 3 mm^2) can improve the fill factor to 96%, reducing at the limit the space between two pixels. Another interesting technique, already used in the design of Silicon PhotoMultipliers, is to terminate the gain layer with shallow trenches with the termination implants within the trench. In this way, the fill factor can go close to 100%. The last option under study, and maybe the one with the highest potential, is represented by the Resistive AC-coupled Silicon Detectors (RSD) project [14] (fill factor of 100%) whose design gets rid of gain segmentation by definition.

Acknowledgments

We thank our collaborators within RD50, ATLAS and CMS who participated in the development of UFSD. Part of this work has been financed by the European Union's Horizon 2020 Research and Innovation, Italy, funding program, under Grant Agreement no. 654168 (AIDA-2020) and Grant Agreement no. 669529 (ERC UFSD669529), and by the Italian Ministero degli Affari Esteri and INFN Gruppo V.

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