Prepared for submission to JINST

15TH Topical Seminar on Innovative Particle and Radiation Detectors (IPRD19)
14-17 October 2019
Siena, Italy

Evolution of the design of ultra fast silicon detector to cope with high irradiation fluences and fine segmentation

M. Ferrero,[a,1] R. Arcidiacono,[a] G. Borghi,[b] M. Boscardin,[b] N. Cartiglia,[c] M. Costa,[d] G.F. Dalla Betta,[e] F. Ficorella,[b] M. Mandurrino,[c] M.M. Obertino,[d] L. Pancheri,[e] G. Paternoster,[b] F. Siviero,[d] V. Sola,[c] A. Staiano,[c] M. Tornago,[d] and M. Centis Vignali[b]

[a] *Università del Piemonte Orientale, Novara, Italy*
[b] *Fondazione Bruno Kessler, Trento, Italy*
[c] *Istituto Nazionale di Fisica Nucleare Torino, Italy*
[d] *Università degli Studi di Torino Torino, Italy*
[e] *Università di Trento Trento, Italy*

E-mail: marco.ferrero@uniupo.it

[1]Corresponding author.

ABSTRACT: The recent development in the design of Ultra Fast Silicon detector (UFSD), aimed at combining radiation resistance up to fluences of 10^{15} n_{eq}/cm^2 and fine read out segmentation, makes these sensors suitable fo high energy physics applications.

UFSD is an evolution of standard silicon sensor, optimized to achieve excellent timing resolution (~ 30 ps), thanks to an internal low gain (~ 20). UFSD sensors are n in p Low Gain Avalanche Diode (LGAD) with an active thickness of ~ 50 μm. The internal gain in LGAD is obtained by implanting an appropriate density of acceptors (of the order of ~ $10^{16}/cm^3$) close to the p-n junction, that, when depleted, locally generate an electric field high enough to activate the avalanche multiplication; this layer of acceptor is called gain layer.

The two challenges in the development of UFSD for high energy physics detectors are the radiation hardness and the fine segmentation of large area sensors. Irradiation fluences of the order of 10^{15} n_{eq}/cm^2 have a dramatic effect on the UFSD: neutrons and charge hadrons reduce the active acceptor density forming the gain layer; this mechanism, called initial acceptor removal, causes the complete disappearance of the internal gain above fluence of 10^{15} n_{eq}/cm^2. For the segmentation of UFSDs, the crucial point is the electrical insulation of pads and the extension of the inactive area between pads.

In this paper we present the latest results on radiation resistant of LGADs with different gain layer designs, irradiated up to $3 \cdot 10^{15}$ n_{eq}/cm^2. Three different segmentation technologies, developed by Fondazione Bruno Kessler (FBK) in Trento, will also be discussed in detail in the second part of the paper.

KEYWORDS: UFSD, LGAD, Silicon, Tracking, Acceptor Removal

Contents

1 Introduction

The development of 4D tracking detectors is one of the new challenges in the design of High Energy Physics (HEP) experiments [1]. Consider, as an example, the High Luminosity upgrade of LHC (HL-LCH): the average number of events per bunch crossing will be 150-200, with a timing rms spread of $\sim 150\ ps$ and a mean distance between vertexes of 500 μm. Considering a spatial resolution of the vertexes along the beam axes of 250-300 μm (current resolution of ATLAS and CMS), there will be a probability of 10%-15% of two events overlapping in space, leading to a degradation in events reconstruction (events loss). The addition of the time information, with resolution of 30-40 ps, will separate in time events superimposed in space, reducing the affective overlapping probability to the current LHC level. The application of 4D tracking in HEP experiments requires devices with high space and time resolution. The Ultra Fast Silicon Sensor (UFSD) is a promising candidate for such application.

UFSD is an innovative silicon sensor, which combines moderate internal gain (between 5-50) with thin active thickness ($\sim 50\ \mu m$) to generate signals with high slew rate (dV/dt) and low noise: these are the two main ingredients to achieve an excellent time resolution. The time resolution of 30-40 ps, the possibility of a fine segmentation and the radiation resistance up to fluence of $\sim 10^{15}\ n_{eq}/cm^2$ make this device a good candidate for 4D tracking [2].

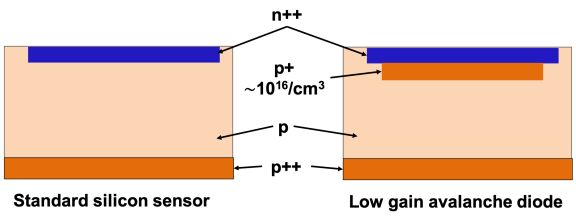

Figure 1. Schematic view of a traditional silicon sensors on the left and of a LGAD on the right. The addition of the p^+ layer, close to the n-electrode, in reverse bias condition generates locally an electric field high enough to activate the avalanche multiplication process.

UFSD is based on Low Gain Avalanche Diode (LGAD) technology [3], a n-in-p diode with the addition of a thin highly doped p^+ ($\sim 10^{16}/cm^3$) layer, called gain layer, close to the n electrode, which is responsible of the avalanche multiplication mechanism in reverse bias operation. In silicon sensors the charge multiplication occurs in presence of an electric field of the order of 300 kV/cm: the charge carriers in this high field acquire enough kinetic energy to generate additional carriers via impact ionization. In standard silicon sensors, figure 1 (left), to have impact ionization is necessary to apply a very high external bias voltage, which inevitably causes the breakdown of the device; in LGADs, on the other hand, figure 1 (right), the p^+ layer locally generates an electric field high enough to activate the charge multiplication process.

2 Radiation resistance

The radiation resistance is the first challenge for the development of a 4D tracker, for HEP applications. It has been shown in previous studies [4], that one of the effects of the radiation damage in LGADs is the gain reduction, due to the initial acceptor removal mechanism in the gain layer. This mechanism in not fully understood, but it seems plausible to be caused by the removal of the acceptors from their lattice sites, due to the formation of ion-acceptors complexes with the interstitial silicon atoms created by the irradiation. The initial acceptor removal can be described by the equation 2.1

$$N_A(\phi) = N_A(0)e^{-c\phi} \tag{2.1}$$

where $N_A(\phi)$ and $N_A(0)$ are respectively the active acceptor density after an irradiation fluence ϕ and the initial acceptor density, while c is the initial acceptor removal rate/coefficient (lower c means more radiation resistance of the gain layer). The acceptor removal coefficient depends upon: initial acceptor density, higher is the initial acceptor density lower is the coefficient [4]; type of radiation (neutrons, charged hadrons, pions).

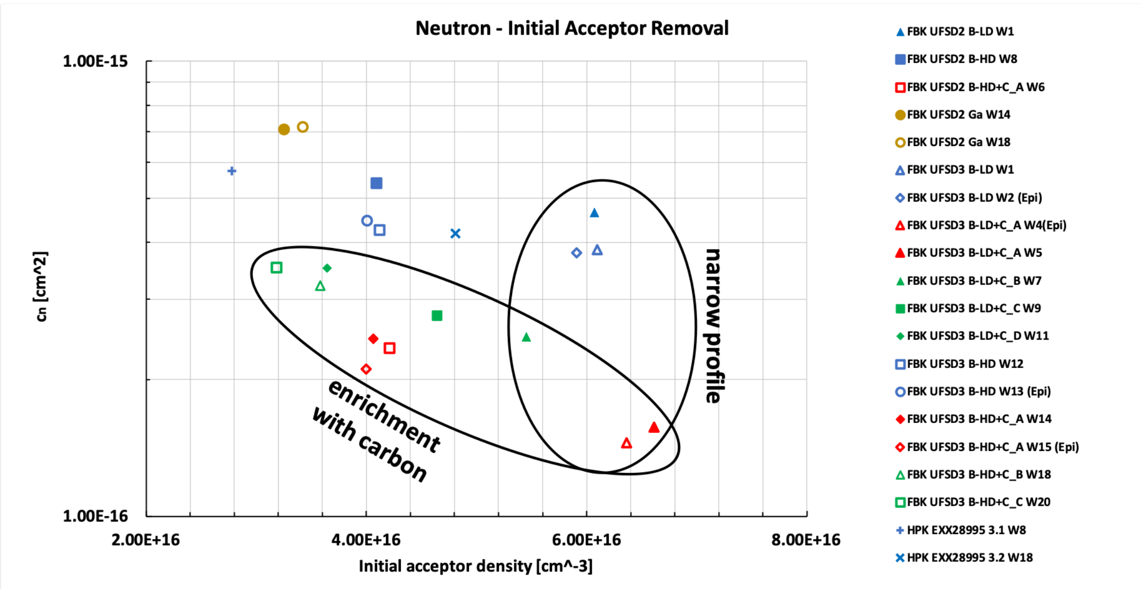

Figure 2. Acceptor removal coefficients as a function of the initial acceptor density, measured on different type of gain layers: narrow, wide, enriched and not with atom of carbon.

LGADs with different gain layers have been fabricated by the two manufactures FBK and Hamamatsu Photonics (HPK) and have been irradiated with neutrons at the JSI research reactor of TRIGA type in Ljubljana [5], with the aim of identifying the most radiation resistant design. The acceptor removal measurements (measurement methodology described in [4]) performed on this variety of devices are summarized in figure 2. The acceptor removal coefficients measured on gain layers with narrow and wide implant profile, enriched or not with atoms of carbon, are plotted as a function of the initial acceptor concentration. From these measurements it can be seen that gain layers enriched with carbon (red and green markers) are more radiation resistant than not enriched ones (blue markers), probably due to the production of ion-carbon complexes instead of ion-acceptor ones. A second interesting result is that gain layers with narrower implant profile and higher initial doping density are less prone to acceptor removal than those with a wider and less doped gain layer implant.

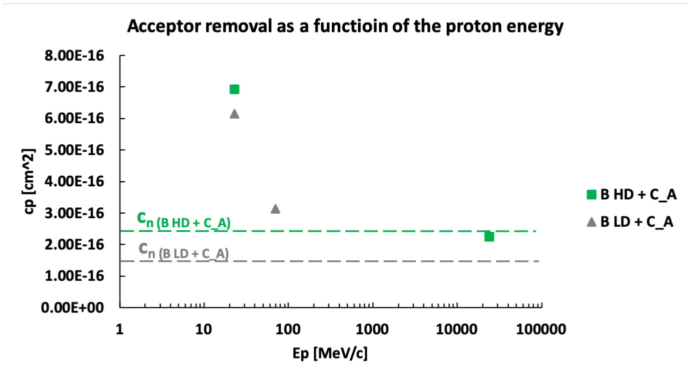

Figure 3. Acceptor removal coefficients as a function of the irradiation proton energy, measured on two different types of gain layer: narrow (green markers) and wide(grey markers) enriched with carbon.

The acceptor removal mechanism has been studied also with irradiation campaigns with protons of different energies. Figure 3 shows the acceptor removal coefficients, in two different types of gain layer (narrow and wide enriched with carbon), as a function of the proton energy. Protons with energy below the GeV produce a greater acceptor removal than neutrons (dashed lines).

3 Segmentation technologies and their characterization

The development of a 4D tracker for HL-LHC experiments requires in the same sensor not only an excellent time resolution but also a good spatial granularity. This implies the development of multi-pad devices, segmented with appropriate structures to electrically isolate adjacent pads, in the case of LGADs. The presence of isolation/termination structures inevitably entails the introduction of a discontinuity between neighbouring multiplication layers, reducing the fill factor (ratio between active area and total area of the device) of the device. Three different LGAD segmentation technologies will be compared below: the standard one, based on Junction Termination Extension (JTE) and *p*-stop placed in the inter-pad region; Trench Isolation (TI), where the electrical isolation of the pads is due to physical trenches; the resistive AC-coupled technology based on AC coupling between segmented metal pads and the sensor cathode.

The characterization of these segmentation technologies was performed at the Laboratories for Innovative Silicon Sensors of the INFN and University of Turin using the Front Transient Current Technique (TCT) equipment. The TCT setup [6] is equipped with a pulsed and focused infrared laser, of wavelength 1064 *nm* and laser spot of minimum diameter $\sim$ 10-15 μm. The IR laser simulates very well the passage of a MIP, in $\sim$ 50 μm thick sensors, since its attenuation length in silicon is of $\sim$ *mm*. All the sensors characterized were wirebonded on test boards and read out by Cividec Broadband amplifiers [7] with gain 40 *dB* and bandwidth 2 *GHz*; the signals were acquired with a LeCroy scope using the TCT software, developed in Labview.

3.1 Standard technology

The standard segmentation technology adopted by FBK in multi-pad UFSDs is based on JTE and *p*-stop implants [8]. The JTE is a deep n^{++} implant implemented around each pads, with the aims

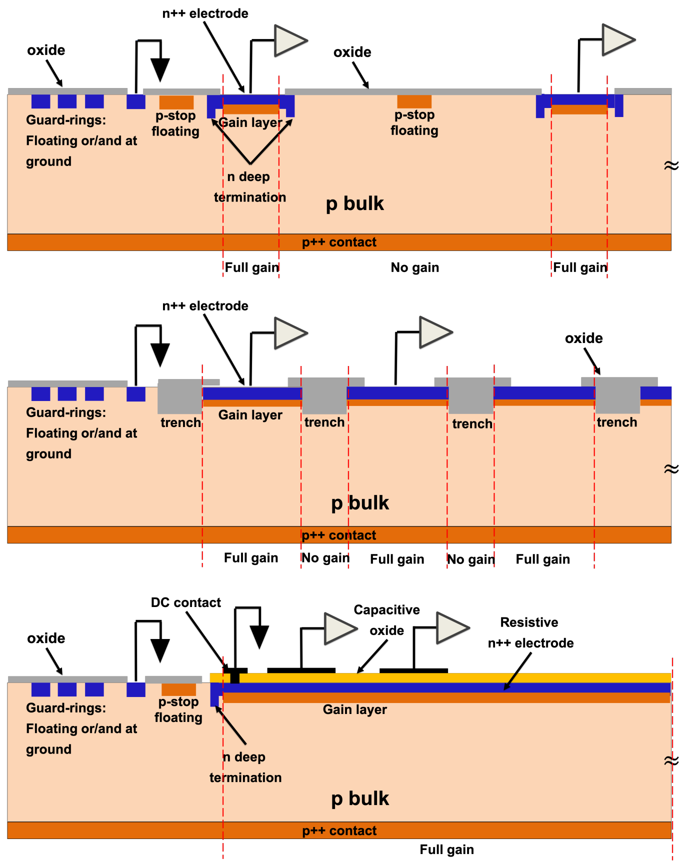

Figure 4. Cross section, not to scale, of a standard LGAD segmentation based on JTE and p-stop (top), Trench Isolated LGAD (middle) and Resistive AC-coupled Silicon Detector (bottom). Vertical dashed red lines indicate a sharp separation between full-gain and no-gain region.

of increasing the breakdown voltage at the pad edge and collecting the electron-hole pairs generated by a particle hitting the inter-pad region; these pairs would generate out-of-time signals due to their long drift path before the cathode. The p-stop is a p^+ implant, with a peak concentration range between 10^{16} and $10^{18}/cm^3$, which isolates electrically two adjacent pads. These termination structures introduce a no-gain region between pads, reducing the geometric efficiency of the device. A sketch of the cross section (not-to-scale) of the standard edge region of a pad is shown in figure 4, where the division between full-gain and no-gain region is highlighted by dashed red vertical lines.

In the third UFSD production at FBK (UFSD3), owing to the lithographic process based on stepper technology, three different termination layouts with as many inter-pad distances have been implemented: Aggressive, Intermediate and Safe, with nominal distance of ~ 10, ~ 20 and ~ 30 μm, respectively. An example of inter-pad measurement, performed with Front-TCT technique, on the Intermediate UFSD3 layout is shown in figure 5, which shows the profile of the collected charge obtained moving the laser spot from a pad to the adjacent one. The charge shape is due to the Gaussian profile of the laser beam. For this reason, each profile of collected charge has been fitted with convolution of a step and a Gaussian function (dashed lines). The inter-pad width has been measured as the distance between the two profiles at the 50% of the full gain in the core of the pad. In table 1 are summarized the results of the UFSD3 inter-pad measurements. It is important to notice that the Intermediate and Aggressive suffer of early breakdown, investigated and solved in later production.

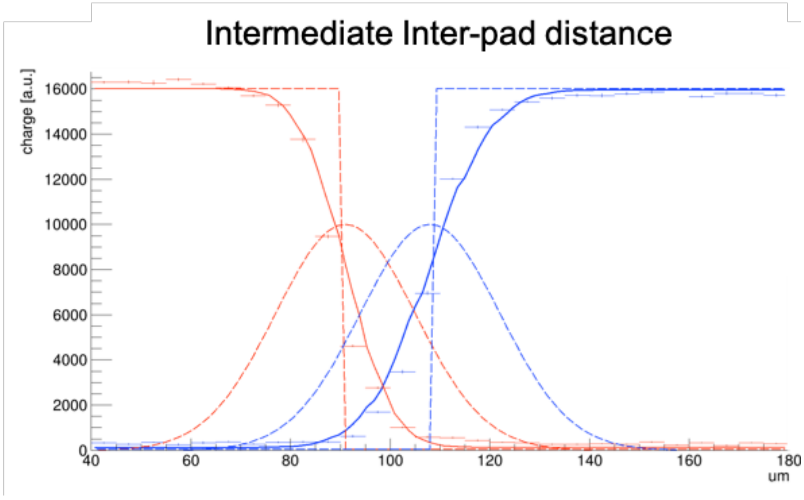

Figure 5. Collected charge profiles on two adjacent pads of the UFSD3 intermediate layout, obtained with a TCT scan. Solid lines are the fit functions given by the convolution of step and gaussians functions (dashed lines).

Table 1. Inter-pad distances measured and comparison with nominal ones.

Layout	Nominal distance [μm]	Measured distance[μm]
Safe	31	30.4
Intermediate	20.5	16.7
Aggressive	11	16.4

3.2 Trench isolated LGADs

An alternative approach to the LGAD standard segmentation structures is the deep trench isolation technology, based on deep and narrow trenches, which physically separate and electrically isolates the multiplication layers of adjacent pads. Trench isolation (TI) is a technology used in CMOS image sensors [9] and silicon photomultipliers [10]; the trenches, less than 1 μm wide, are dug with deep reactive ion etching technique and filled with silicon oxide. A trench replaces the JTE and p-stop implants, reducing the inter-pad region and increasing the fill factor of the device. In figure 4 is shown a cross section of a LGAD with trench isolation.

The first LGAD sensors with trench isolation (TI-LGAD) have been produced by FBK on epitaxial wafers with 55 μm active thickness. To facilitate the electrical characterization, sensors with two pads (250 $\mu m \times 375$ μm) surrounded by guard-rings have been fabricated, figure 6 (left); with an optical slit to perform inter-pad TCT measurements. Two different trench designs have been implemented: the first one with a trench grid between pads (version T1), in figure 6 (right-top); the second one where each pad is surrounded by a trench ring (two trench between adjacent pads, version T2), in figure 6 (right-bottom). The nominal distance between multiplication layers in T1 and T2 designs are 4 μm and 6 μm respectively.

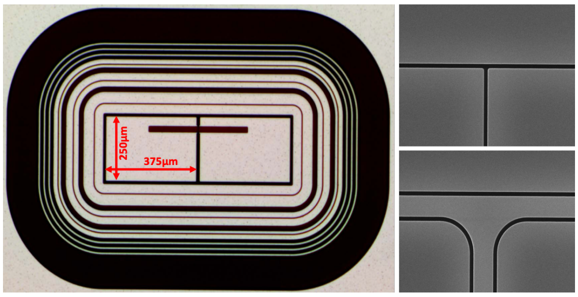

Figure 6. Right: picture of a TI-LGAD. Left: SEM imagine of trench before filling process: one trench grid design (T1) on the top and trench ring design (T2) on the bottom.

TCT measurements have been performed on TI-LGADs to estimate the inter-pad distance: figure 7 shows the profile of collected charge of a TI-LGAD version T2 (red) compared with the profile of an UFSD3 intermediate sensor (green). This profile proves a very good electrical isolation of the two adjacent pads (the collected charge from the read-out pad is zero, when the laser beam hits the nearby one). Moreover, an inter-pad distance of about 7 μm has been measured. In conclusion, the trench isolation technology reduced the inter-pad width by a factor of five compared to the Safe design in UFSD3 and more than a factor of two about Intermediate and Aggressive ones.

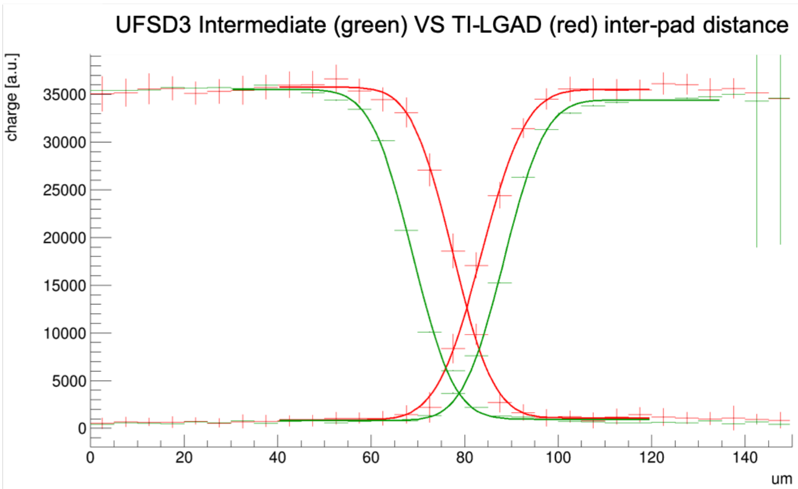

Figure 7. Interpad measurement of a TI-LGAD version T2 (red) compared with a UFSD3 intermediate (green).

3.3 Resistive AC-coupled Silicon Detector (RSD)

RSD sensors are an evolution of standard UFSD with the peculiarity of a unsegmented gain layer, which allows a 100% fill-factor.

In the RSD technology [11], shown in figure 4 (bottom), the read out segmentation is achieved through the implementation of AC metal pads, which are capacitively coupled with the *n*-electrode via a dielectric. A resistive n-electrode allows the signal induction on the AC pads and a controlled discharge of the multiplied charges with a time constant RC of the equivalent circuit. The RC time constant depends on the resistive layer, dielectric thickness and AC pads area, it must be long enough to allow a complete signal induction on AC pads and short enough to minimize the pile-up effects.

The RDS devices have been proposed in 2015 [12] and developed within a collaboration among the Torino division of the National Institute of Nuclear Physics (INFN), the University of Trento and the Fondazione Bruno Kessler (FBK) in Trento. In 2019, FBK produced the first batch of RSD [13], called RSD1, which consist of 15 6" Silicon wafers with high resistivity Float Zone ($\rho > 3\ k\Omega cm$) and Epitaxial ($\rho > 1\ k\Omega cm$) substrate. The aim of RSD1 is to find the best interplay between AC-coupling parameters: dielectric thickness, n-layer resistivity and AC metal pads pitch and size. For this purpose, two dielectric thicknesses, three different splits of dose of n-electrode and various pad sizes and pitch (from 500 μm to 50 μm), have been implemented in RSD1.

Several front-TCT measurements have been performed. The first measurement shown is on a 3×3 pads matrix with 200 μm pitch and 150 $\mu m \times 150\ \mu m$ pad size (wafer 10 [13]), as preliminary characterization of the RSD devices: figure 8 (top-left) shows the 2D map of collected charge for a single AC pad obtained with an integration time of the signal of 5 ns (sensor on top-right). The pad under test shows a collection volume around itself, where the collected charge increases approaching the pad (color scale); this means that the overlap of collection regions between neighbour pads can be used to reconstruct the hit position of the particle by weighting the charges induced in many AC pads. Similar results have been obtained on a 3×3 pads matrix, 50 μm pitch and 35 $\mu m \times 35\ \mu m$ pad size, coming from wafer 8 [13], figure 8 (bottom), with an integration time of 2.7 ns.

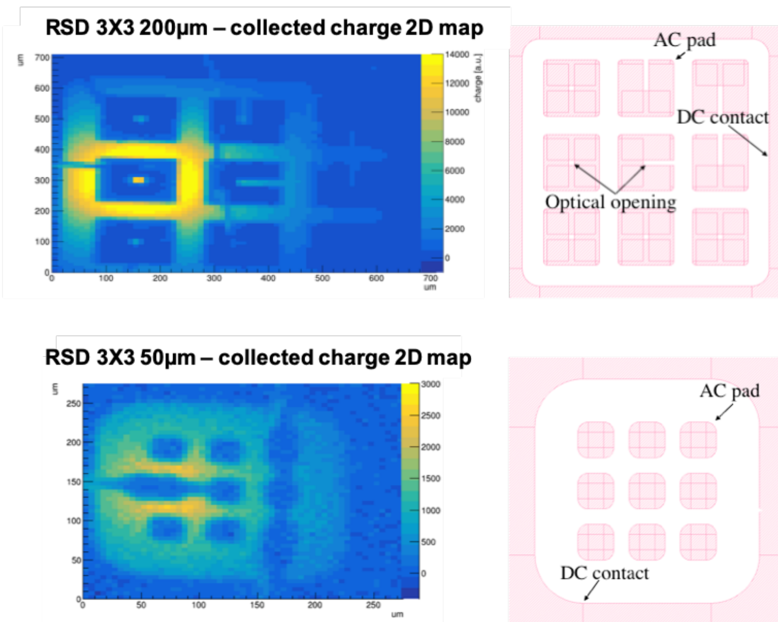

Figure 8. On the left, 2D maps of induced charge with TCT setup in 200 μm pitch RSD from wafer 10 (top) and in a 50 μm pitch RSD from wafer 8 (bottom) [14]. The two maps of charge have been obtained for integration time of 5 ns and 2.7 ns, respectively. On the right, the layout of the two devices under test, the 200 μm pitch one on the top and the 50 μm pitch one on the bottom.

4 Conclusion

The study of different types of gain layers allowed to identify the most radiation resistant LGAD design, improving by a factor two the acceptor removal rate in sensors with narrow and carbon-enriched gain layers compared to wider and not enriched ones.

The requirement of a fine segmentation in UFSDs, for 4D particle tracking applications, led to the development of two innovative segmentation technologies by FBK: TI and RSD, as an alternative to the standard technology based on JTE and *p*-stop implants. Preliminary TCT characterizations on TI-LGADs shows an excellent electrical isolation between adjacent pads and a decrease more than a factor of five of the no-gain region compared to the best working standard LGAD. Preliminary measurements on RSDs demonstrate the feasibility of fine segmented AC-coupled silicon sensor with internal gain and fill-factor of 100%. Results shown in this work set a solid technological starting point for the development of 4D-tracking particle detectors with high space and time resolution.

Acknowledgments

We thank the Fondazione Bruno Kessler of Trento, the INFN - Gruppo V and RD50 collaboration for the development of UFSD sensors. The work was supported by the United States Department of Energy, U.S. Department of Energy grant number DE-SC0010107. Part of this work has been financed by the European Union Horizon 2020 Research and Innovation 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. Thanks to Dipartimento di Eccellenza, University of Torino (ex L. 232/2016, art. 1, cc. 314, 337).

References

[1] N. Cartiglia et al., *Tracking in 4 dimensions*, *Nucl. Instrum. Meth. A* **845** (2017) 47.

[2] H. F.-W. Sadrozinsky, A. Seiden, N. Cartiglia, *4D tracking with ultra-fast silicon detectors*, *Rep. on Prog. in Phys.* **81** (2018) 026101.

[3] G. Pellegrini et al., *Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications*, *Nucl. Instrum. Meth. A* **765** (2014) 12.

[4] M. Ferrero et al., *Radiation resistant LGAD design*, *Nucl. Instrum. Meth. A* **919** (2019) 16.

[5] L. Snoj, G. Zerovnik and A. Trkov, *Computional analysis of irradiation facilities at the JSI TRIGA reactor*, *Appl. Radiat. Isot.* **70** (2012) 483.

[6] http://particulars.si.

[7] https://cividec.at

[8] G. Paternoster, et al., *Developments and first measurements of Ultra-Fast Silicon Detectors produced at FBK*, *JINTS* **12** (2017) C2077.

[9] A. Tournier, et al., *Pixel-to-pixel isolation by deep trench technology: Application to CMOS image sensor*, Proceedings of the 2011 International Image Sensor Workshop (IISW 2011), Hokkaido (Japan), June 8-11, (2011).

[10] C. Piemonte, et al., *Performance of NUV-HD Silicon Photomultiplier Technology*, *IEEE T. Electron Dev.* **63** (2016) 1111.

[11] M. Mandurrino, *Resistive AC-Coupled Silicon Detectors (RSD). A new frontier in high-efficiency 4D particle tracking*, IEEE NSS/MIC Conference, Sydney, Australia, November 2018.

[12] N. Cartiglia, *Topics in LGAD Design*, Presented at the 10^{th} TREDI Workshop, Trento, Italy, February 2015.

[13] M. Mandurrino, *First production of Resistive AC-Coupled Silicon Detectors (RD) at FBK*, Presented at the 34^{th} RD50 Workshop, Lancaster, UK, June 2019.

[14] M. Mandurrino, et al., *Demonstration of 200, 100 and 50 µm pitch resistive AC-Coupled Silicon Detectors (RSD) with 100% fill-factor for 4D particle tracking*, *IEEE Electron Dev. Lett.* **40** (2019) 1780.