Novel Strategies for Fine-Segmented Low Gain Avalanche Diodes

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Abstract

Low Gain Avalanche Diodes (LGADs) are now considered a viable solution for 4D-tracking thanks to their excellent time resolution and good resistance to high radiation fluence. However, the currently available LGAD technology is well suited only for applications that require coarse space precision, pixels with pitch in the range 500 µm - 1 mm, due to the presence of a no-gain region between adjacent pixels of about 50 μm, in which the gain is completely suppressed. In this paper, we will discuss the segmentation issues in the standard LGAD technology and we will present two new segmentation strategies aimed at producing LGADs with high spatial resolution and high fill factor. The first presented design is the so-called Trench-Isolated LGAD (TI-LGAD). Here, the pixel isolation is provided by trenches, physically etched in the silicon and then filled with silicon oxide. The second design is the Resistive AC-coupled Silicon Detector (RSD), an evolution of LGADs, where the segmentation is obtained by means of AC-coupled electrodes.

Prototypes of both designs have been produced at FBK and characterized at the Laboratories for Innovative Silicon Sensors (INFN and University of Turin) by means of a laser setup to estimate the space resolution and the fill factor. The functional characterization shows that both technologies yield fully working small pixel LGADs (down to 50 µm), providing the first examples of sensors able to concurrently measure space and time with excellent precision.

Keywords: Silicon sensors, fast detectors, LGAD, TI-LGAD, RSD, AC-LGAD, 4D-tracking
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1. Introduction

Low Gain Avalanche Diodes (LGADs) are silicon sensors based on p-n junction and provided with an internal signal amplification mechanism (gain) [1]. The internal structure is similar to that of silicon Avalanche Photodiodes (APDs), but the gain is much lower ($\mathcal{O}(10)$ with respect to $\mathcal{O}(1000)$ of APD). The combination of low gain and thin active silicon substrates already made LGADs a viable choice for those applications that requires good time resolution and high resistance to radiation, as in the case of detectors for High Energy Physics (HEP) experiments [2, 3].

Another important feature of LGADs is the possibility to arrange the single diodes in large-area segmented sensors (pixel arrays or strips), which are able to provide information on both time and position of interaction of the detected particles.

The latter aspect is a key enabling feature for the so-called "4-dimensional (4D) tracking", which requires a concurrently $\mathcal{O}(10)$ ps time resolution and a $\mathcal{O}(10)$ µm space resolution in Minimum Ionizing Particles (MIP) detection [4]. A first example of a LGAD designed for 4D tracking are the Ultra Fast Silicon Detectors (UFSDs), which have been developed for the High Luminosity (HL) upgrade of LHC. These sensors reach the required specifications in terms of radiation hardness, space and time resolution [5, 6, 7]. However, additional development has to be done to meet the requests of the next generation of HEP experiments and those of other applications, such as x-ray imaging or ion tracking in devices for medical applications (hadrontherapy) [8, 9].

The current R&D activities on LGADs are focused on three different goals, interconnected with each other: (i) improvement of the time resolution; (ii) increase of the radiation hardness (fluences above 10^{15} neq/cm^2); (iii) improvement of the spatial resolution. This paper is focused on the latter task, which has been also the least investigated by the scientific community in the past few years.

In the following section, we discuss the current state-of-the-art technology for segmenting LGADs, pointing out its limiting factors. In section 3 we introduce two new segmentation strategies to develop fine-pitch LGADs. The first proposed scheme is the so-called Trench-Isolated LGAD (TI-LGAD), while the second is the Resistive AC-coupled Silicon Detector (RSD). In both cases, experimental characterization will be shown and discussed.

2. Segmentation of Standard LGAD

A schematic drawing of the internal structure of a n-in-p diode array (PIN) and of an LGAD is shown in Fig. 1. PIN diodes are usually based on a deep and segmented n^+ junction on a high-resistivity p-type substrate. In these sensors, the electrical isolation among pixels is usually provided by a p-doped region (p-stop) that surrounds each pixel.

Segmented silicon detectors with internal multiplication need to face additional hurdles with respect to conventional silicon sensors. Indeed, in LGADs, the basic multiplying structure is usually based on a shallow n^+ junction and on a deep p-type multiplication layer below the junction. This doping region, also named "gain layer", locally increases the electric field to values higher than the impact-ionization threshold (about $2 \times 10^5\,\mathrm{V\,cm^{-1}}$), enabling the mechanism responsible of charge multiplication. When segmented, beside the standard p-stop isolation region, these multiplying junctions require a complex design of the border region, in order to avoid undesired regions with high

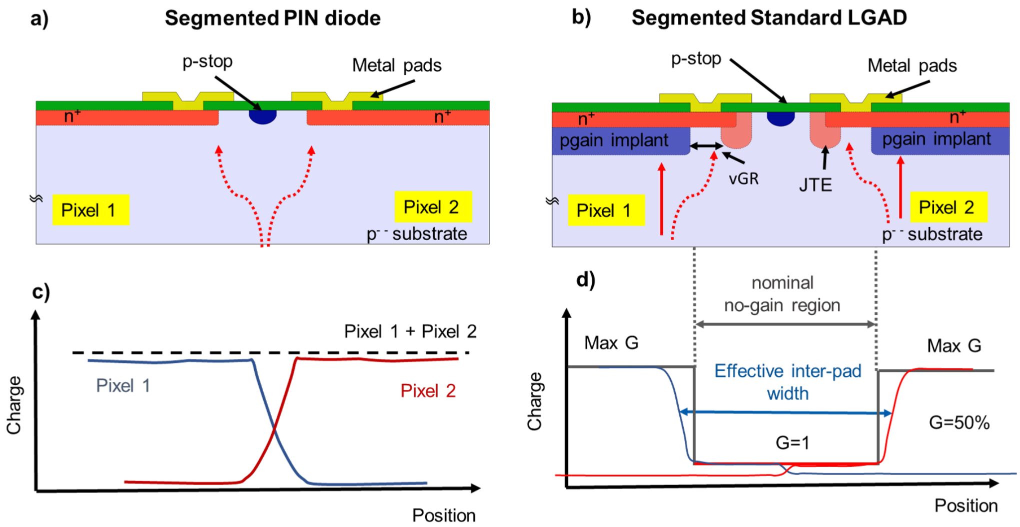

Figure 1: Schematic drawings of a segmented PIN diode (a) and of a segmented LGAD (b). A sketch of the generated signals from PIN and LGAD are reported in c) and d), respectively.

electric field [10]. Therefore, an additional n-type region, named Junction Termination Extension (JTE), is typically included at the n^+ periphery, with the role to control the junction curvature and reduce the electric field at the border. The gain layer is also interrupted below the JTE and at the p-stop regions, also in this case to reduce the electric field and prevent premature breakdown at the pixel edge (or edge-breakdown). To further control the edge electric field, the gain layer is also kept at a certain distance from the edge of the JTE, in order to create the so-called virtual guard ring (vGR).

As a consequence, a relatively wide gap is created between the gain layers of two adjacent pixels: this gap is called "no-gain" region, since the ionization produced by particles impinging in that area is not multiplied. This is represented in Fig. 1 c) and d), where the signal produced by a particle as a function of the impinging position is represented for a PIN and an LGAD detector, respectively. In the case of a PIN diode, the charges generated by a particle interacting at the pixel periphery are typically shared among neighboring pixels and the sum of the signals from all the involved pixels is a constant. In the LGAD case, instead, the signal is multiplied only in the pixel core region and not at the pixel periphery, since, in this region, the generated charges are collected by the JTE and do not cross the gain layer. As a consequence, the total signal is not constant but varies form a maximum value, corresponding to the nominal gain (G), to the minimum G= 1. We can define the fill factor (FF) of the LGAD pixel as

$$FF = \frac{\text{pixel area with signal multiplication}}{\text{total pixel area}}. \tag{1}$$

The nominal width of the no-gain region depends on both technological and physical limitations since (i) the technological constraints of the fabrication process put a limit on the minimum achievable feature size and on the alignment precision which is achievable among different structures; (ii) a too small gap between n-doped regions and p-stop generates high electric fields that would lead to premature edge-breakdown and "pop-corn" noise [11].

In the past few years, several efforts have been made to reduce the width of the no-gain region, by optimizing both the fabrication technology and the sensor layout. Table 1 reports the evolution of the nominal no-gain width in the different batches produced at FBK in the last few years. In the first batch, the no-gain width was 210 µm and it has been reduced in the following productions down to 20.5 µm, a value that could be considered the state-of-the-art of the standard FBK-LGAD technology.

Table 1: Evolution of the no-gain width in FBK productions

Batch	**Year**	**No-gain width**
UFSD 1	2016	210 µm
UFSD 2	2017	66 µm
UFSD 3 - Safe	2018	31 µm
UFSD 3 - Intermediate	2018	20.5 µm

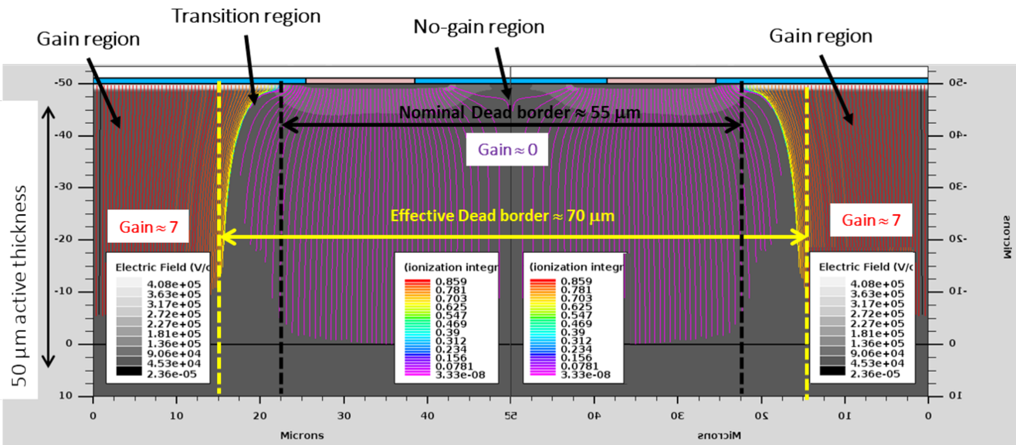

Figure 2: TCAD Simulation of LGAD sensor. The electric field intensity at the border region between two pixel is represented by the gray-scale map. Solid lines show the carriers path through the junction, while the lines color represents the ionization integral value.

An additional factor that could affect the FF of STD-LGADs is the uneven electric field at the pixel border, which could lead to spatial non-uniformity in the charge carriers collection and multiplication.

In order to understand this effect, TCAD simulations (Silvaco simulation tools [12]) have been exploited to investigate the collection mechanisms at the border region of the pixel. Fig. 2 represents the electric field (gray scale map) of a segmented LGAD (same structure represented in Fig. 1), while the solid lines represent the carrier drift path lines, and the lines color is the ionization integral along that carrier path. The bias voltage is about 200 V, and the gain at the pixel core is about 7. The ionization integral reaches a plateau (red lines, corresponding to the maximum gain) in the pixel core region, while it is almost zero in the no-gain region (purple lines). Moreover, it is possible to identify a third region, indicated as "transition region", where the carriers, even though generated in the nominal gain region, are collected by the JTE and are only partially multiplied. The transition region reduces the effective FF of the pixel and plays a very important role in the case of small pixels, or when the pixel area is comparable to substrate thickness (typically 50 µm in thin LGAD). It is possible to define the "effective inter-pixel width" as the distance between the two locations in adjacent pixels where the generated signals are equal to 50% of the maximum signal value, as represented in Fig. 1d. The width of the transition region could depend on multiple factors: (i) bias voltage, (ii) generation depth of the charge carriers, (iii) doping lateral diffusion, and (iv) doping concentration of the gain layer. An accurate simulation campaign of these effects is currently under way.

An experimental measurement of the signal variation at the pixel border of STD-LGAD is reported in Fig. 3. The measurement was performed at the Laboratories for Innovative Silicon Sensors of the INFN and University of Turin, using the Transient Current Technique (TCT) setup described in [Ferrero 2020]. In this setup, a focused 1064 nm laser (spot size of $\sim$ 10 µm) is used to simulate the passage of a MIP in different position of the sensors pixels, directly measuring the sensor response in the inter-pad region.

The sensor in Fig. 3 is a STD-LGAD from FBK-UFSD3 batch production with a nominal no-gain region of 31 µm. It is worth noting that the measured inter-pad width is 38 µm, slightly wider than the nominal one, as suggested by TCAD simulations.

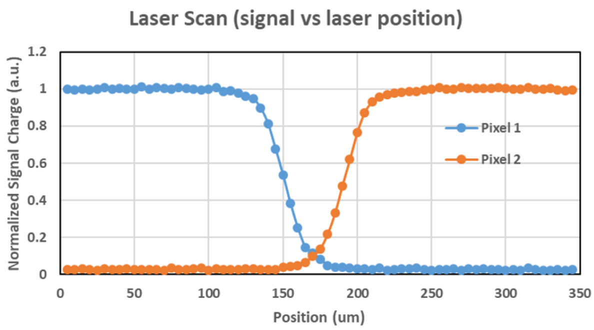

Figure 3: Signal charge vs position of the laser, scanning the inter-pad region (represented in the inset) of a STD-LGAD with a nominal no-gain region of 31 µm.

3. Novel Segmentation Schemes

In order to reduce the width of the no-gain region, novel detectors schemes have been recently proposed. Fig. 4 represents four different segmentation schemes:

a) Standard LGAD;
b) Double-sided LGAD (or inverted LGAD, i-LGAD);
c) Trench-Isolated LGAD (TI-LGAD);

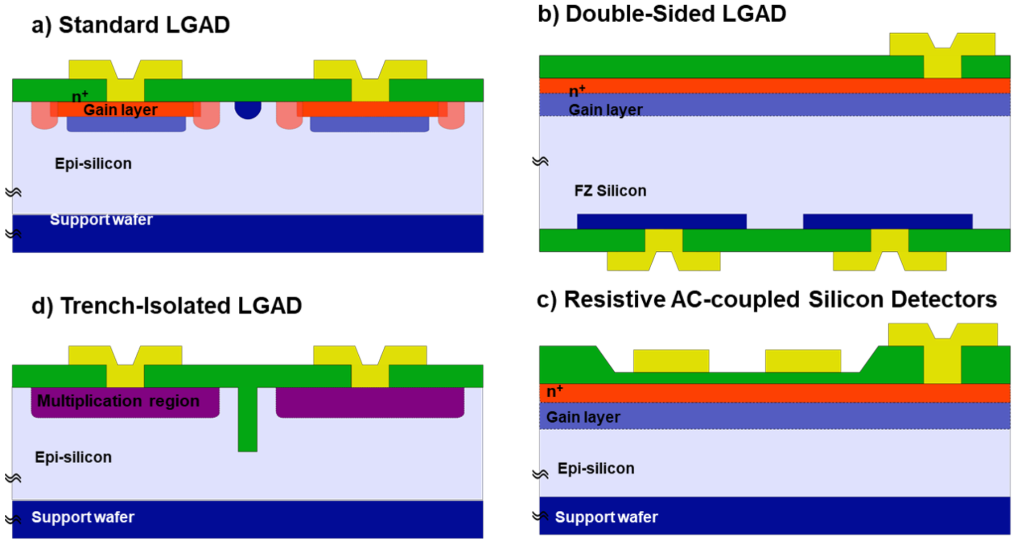

Figure 4: Schematic drawings of different segmentation technologies for LGAD: a) Standard segmentation; b) Double-Sided LGAD; c) Trench-Isolated LGAD; d) Resistive AC-coupled Silicon Detectors;

d) Resistive AC-Coupled Silicon Detectors (RSD, or AC-LGAD).

The Standard LGAD Segmentation has been described in the previous section. In Double-sided LGADs (or inverted-LGAD), the junction and the gain layer are not-segmented and the read-out segmentation is transferred on the back side of the sensor, where p^+ contacts are defined [13, 2]. These sensors are typically produced on thick (about 300 µm) silicon wafers with a double-sided fabrication process. Using this integration scheme, it is possible to produce pixels with 100% FF and a uniform response along the sensitive region [14].

The third technology is the so-called Trench-Isolated LGAD (TI-LGAD). In this new design, the electrical isolation among pixels is obtained by means of trenches, physically etched in the silicon and filled with silicon oxide. Such an isolation scheme makes possible to reduce the no-gain width down to a few microns without affecting the detector performance.

The fourth scheme represents the Resistive AC-coupled Silicon Detectors, in which the multiplying junction is created using a resistive n^+-layer. In these sensors, the n^+-layer and gain layer are not segmented and the read-out segmentation is provided by metal pads that are AC-coupled to the resistive n^+-layer via a thin dielectric layer.

Both RSD and TI-LGADs technologies will be presented in the following parts of this section.

3.1. Trench-Isolated LGAD

An alternative technological solution for the isolation of adjacent components in an integrated circuit device is the so-called Deep Trench Isolation (DTI) technique. This technology consists in the etching of a pattern of trenches in the silicon substrate. The trenches are subsequently filled with dielectric materials, such as silicon dioxide.

In the past years, DTI has been extensively used for pixel isolation in CMOS image sensors [15], as well as in other avalanche detectors, such as Silicon Photomultipliers (SiPM) [16]. In particular, in SiPMs, DTI are also used as an optical barrier to reduce the internal optical cross-talk among adjacent pixels [17].

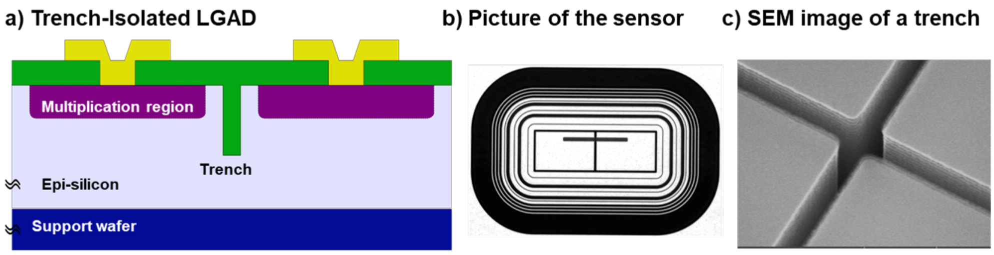

Figure 5: Schematic drawing of TI-LGAD (a); Picture of a 1×2 pads array produced at FBK (b); SEM image of a trench before filling (c).

Trench-Isolated LGADs exploit DTI technology to provide electrical isolation among the pixels of a segmented LGAD. A schematic cross sectional view of TI-LGAD is reported in Fig. 5a. While the multiplying junction scheme (n^+-p^+-p^--p^+) remains the same as STD-LGADs, all the junction termination and isolation structures (JTE and p-stop) are here completely replaced with a single trench, that is less than 1 µm wide. This design offers a clear advantage in terms of reduction of the no-gain region between the pixels and overcomes the technological limitations of the standard technology described in the previous section.

The trench is etched in the silicon substrate during the fabrication process by means of the Deep Reactive Ion Etching (DRIE) technique, which is able to produce submicron trenches with high aspect ratio (up to 20 : 1). A Secondary Electron Microscope (SEM) image of a trench after the etching process is shown in Fig. 5c. After the etching, the trenches are filled with silicon dioxide to passivate the trench surface and to recover the wafer planarity. The first production of TI-LGAD has been carried out at FBK in 2019: a detailed description of these first prototypes and of their characterization can be found in [18].

Preliminary TCAD simulations of these devices show that DTI is effective in reducing the inter-pad width down to 5 µm, a factor of five narrower than in state-of-the-art standard LGADs, without affecting the detector performance [18].

The first produced samples have been characterized by means of a TCT setup and a IR laser source (as described in the previous section). Fig. 6 reports in blue the signals from two adjacent pads of the sensor in Fig. 5b (a 1×2 pads array, with pad size equal to 275 µm $\times$ 375 µm). The laser has been swept along an optical window (an aperture in the metal that crosses the two pixels) shown in Fig. 5b. The same measurement, carried out on a STD-LGAD with a 31 µm wide no-gain region, is plotted for reference. Both the sensor are biased at $200 - 250$ V in order to set the same gain for both the devices (G= 15).

The measured effective inter-pad width of the TI-LGAD sample is 9 µm, much narrower with respect to that of the STD-LGAD (38 µm). In addition, since the two channels are acquired simultaneously, it is possible to demonstrates that good electrical isolation

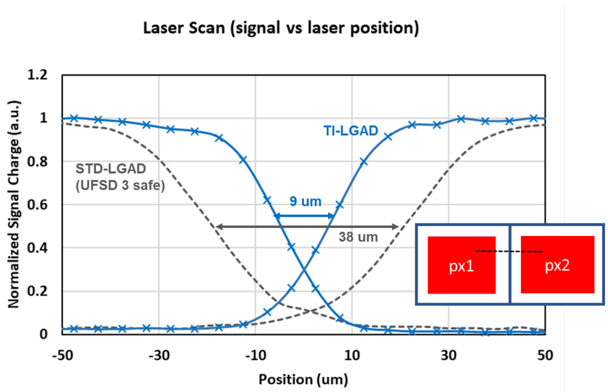

Figure 6: Laser scan through the inter-pad region (represented in the inset) of a TI-LGAD (blue line) and of a STD-LGAD (dark gray line).

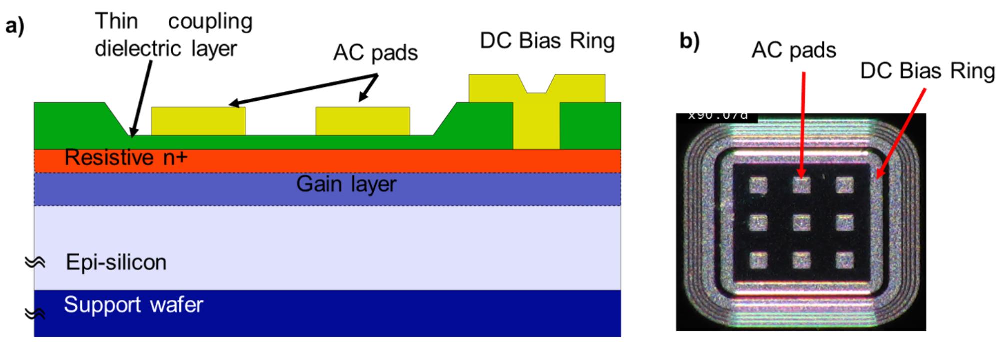

Figure 7: Schematic drawing of Resistive Silicon Detectors (a); Picture of a 3×3 pads array produced at FBK (b).

between the pads is provided by the DTI technology.

With this improved technology it would be possible to produce segmented sensors with 100 µm or 50 µm pitches with a remarkable FF of 83% and 67%, respectively.

3.2. Resistive AC-Coupled Silicon Detectors

A schematic cross section of an RSD sensor is reported in Fig. 7a, together with a picture of a 3×3 pad array produced at FBK (in Fig. 7b). This sensor is designed following the principle of AC-coupled LGADs [19, 20], and optimized for 4D tracking applications. The first production of these sensors has been carried out in the framework of the RSD project, and presented in [21, 22].

In RSD, the n^+ electrode and the gain layer extend along the entire sensor area, without any pattering, thus providing a uniform gain through the sensor. The sensor segmentation is achieved via AC-coupled metal pads that lie on a thin dielectric film, while at the sensor periphery, the n^+ electrode is connected to the ground via an ohmic contact. The size of the AC metal pads determines the readout segmentation, while the thickness of the dielectric layer determine the capacitive coupling between the pads and the n^+ layer. The sensors have been fabricated on silicon wafers with a 50 µm thick epitaxial layer by means of a single-sided fabrication process, based on that used for the production of STD-LGAD, and described in [7]. The major differences with respect to the standard fabrication process regards the tuning of the n^+ sheet resistance and the local thinning of the top dielectric layer, aimed at finely selecting the capacitive coupling between pads and the n^+ electrode.

The signal formation process in RSD is substantially different from that of a standard LGAD, as explained in [23]: in RSD, the signal at the readout pads is mainly induced after that the charge carriers are collected at the n^+ layer and the signal is propagating on the n^{++} layer, discharging to the ground. This mechanism is equivalent of the propagation of a signal in a lossy transmission line. The main advantage of this readout scheme is that the signal is shared among multiple pads, hundreds of microns far from the hit point. The signal sharing through the resistive layer enhances the spatial resolution of the sensor beyond the one achievable with segmented DC sensors (typically quoted as pixel size/$\sqrt{12}$), even at normal particle incidence.

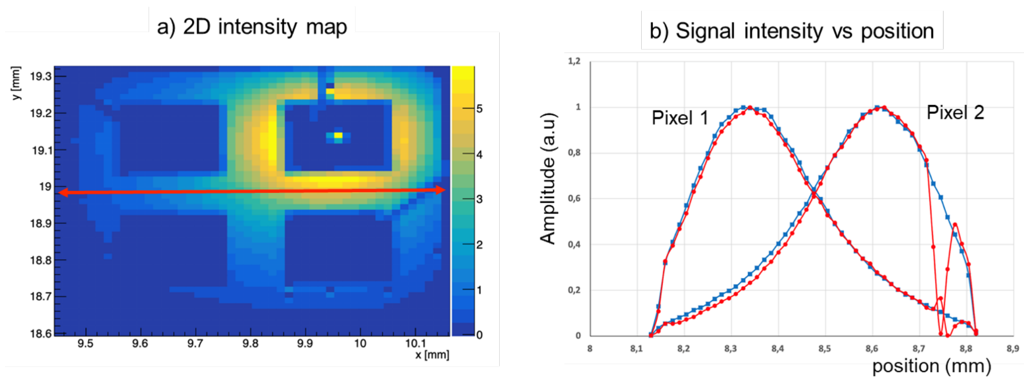

Figure 8: 2D maps of the intensity of the induced charge obtained with a TCT setup (a). The sensor is a 2×2 pads array with 300 µm pitch. In b) the signal from two adjacent pixels acquired with a laser scan along the red line is reported.

Fig 8a reports a laser scan of the detector surface carried out with the same TCT setup mentioned in Section 2. Each point of the image represents the intensity of the signal generated on a single pad of a 2×2 pixels sensor with 300 µm pitch. It is worth noting that the signal intensity decreases radially with the distance from the pad. This can be observed even better in Fig 8b, where the signal sharing between two neighboring pixels is measured by means of a laser, scanning the sensor along the red line in Fig. 8a. It is important to stress that the sum of the signals from the two pixels is almost a constant along the inter-pad region, an evidence that RSD acts as a 100% FF sensor.

To fully exploit the spatial resolution capabilities of this sensor, the position of an hitting particles has to be calculated using a reconstruction algorithm that exploits the signals in multiple pixels. A simple estimation of the hits' coordinates can be done by using the amplitude-weighted centroid of the coordinates of four neighboring pads. Preliminary results about the RSD spatial resolution are presented in [24], where a resolution of 20 µm and 6 µm has been reported for sensors with 200 µm and 100 µm pitch, respectively. The extremely good spatial resolution, obtained with a relatively coarse segmentation, leads to important advantages in terms of number of required readout channels.

4. Conclusions

Latest developments of Low Gain avalanche detectors led this technology to a remarkable level of technological maturity, especially in particle tracking and timing applications. However, the spatial resolution of these sensors is still limited by their coarse segmentation, due to the presence of a no-gain region between adjacent pixels of about 50 μm. It has been demonstrated, also by means of TCAD simulations, as the standard segmentation approach of LGAD suffers from both intrinsic and technological limitations.

Several new segmentation strategies are currently being investigated to overcome these limitations. In particular, two new technologies have been discussed: TI-LGAD and RSD. The first one is able to reduce the inter-pad width to 9 µm, and in perspective down to 5 µm, enabling the possibility to design segmented sensors with fine pitch down to 50 µm. In the RSD technology instead, the improvement in the spatial resolution is reached by exploiting a completely different approach in the signal formation and readout, which is based on AC-coupled electrodes. This readout mechanism enables charge sharing among the pixels, thus reaching a spatial resolution of 6 µm with a 100 µm pitch sensor.

Even if both these new technologies could be considered still at a first stage of development, they already shown very promising results that will be probably further enhanced in the next months thanks to improvements in the fabrication technology and in the sensor design.

Acknowledgments

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