
Deep-Junction LGAD to achieve high granularity and radiation hardness

---

Dr. Simone Michele Mazza
Assistant Project Scientist, Santa Cruz Institute for Particle Physics

1 Abstract

This activity aims at developing a new type of LGAD sensor for timing applications, featuring fine pixel segmentation and the possibility to achieve very high radiation resistance. In conventional LGAD sensors, the pixel dimension is limited to 0.5-1 mm due to the presence of an inter-pixel not-sensitive region. Such a region is, typically, 60-70μm wide and acts as the main limiting factor in decreasing the pixel size of LGADs. The project goal is to produce segmented thin LGADs (Deep-Junction LGAD), based on 50 μm thick Silicon wafers, with small pixels down to 100 μm and a 100% fill factor. These devices would provide high spatial resolution preserving at the same time the excellent timing resolutions of 30 ps, already reached with thin LGAD sensors produced at FBK. Furthermore, by adjusting the design by controlling the p/n degradation with radiation damage, this type of LGAD has a high potential to significantly increase the radiation-hardness reach of LGADs.

2 Motivation and goals

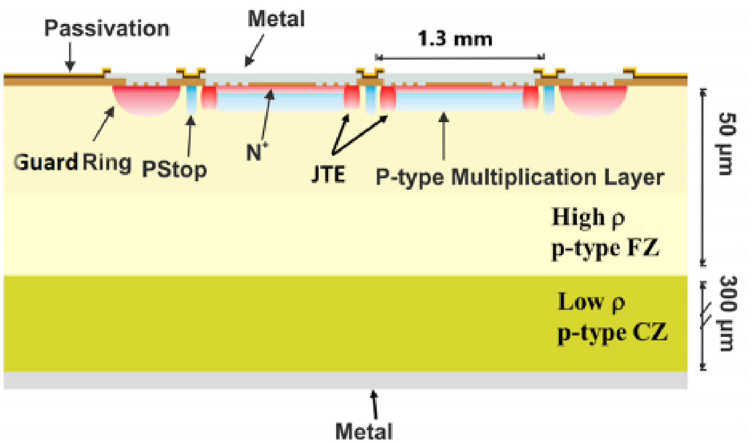

Figure 1: Schematic design of the LGAD Junction Termination Extension (JTE) [1] used in conventional LGADs.

Low Gain Avalanche Detectors (LGADs) are thin silicon sensors with modest internal gain and exceptional time resolution [2–4]. The internal gain is due to electric fields created by a highly doped p+ region (called the multiplication or gain layer) just below the n-type implants of the electrodes. Currently, LGAD technology has some limitations:

- Granularity: the high electric field under the metal electrodes requires the presence of a protection structure to avoid breakdown, the Junction Termination Extension (JTE) (Fig. 1), which separates the pads. This limits the granularity of LGADs to the mm scale. There are several new types of LGADs under development that hope to overcome this limitation, including AC-LGADs, TI-LGADs, and iLGADs.
- Radiation hardness: even though a lot of progress was made in the previous half a decade, LGADs are still limited in radiation hardness to a few 1E15 Neq. The highest radiation

resistance is currently achieved with a combination of a deep gain layer and carbon implantation.

In this project, we propose to pursue the production of a new type of LGAD that can solve the granularity problem and has the potential to increase the radiation hardness reach of LGADs: the Deep-Junction LGADs (DJ-LGAD in short) [5]. DJ-LGAD was patented by the SCIPP gout at UC Santa Cruz in 2021 (B. Schumm, S. Mazza, Y. Zhao, C. Gee [6]). The Deep Junction approach permits granularity on the same scale as that of conventional silicon diode sensors, while maintaining a direct coupling of the signal charge to the readout electrodes.

2.1 *Granularity*

This new design features a multiplication zone that is de-coupled from the readout plane by burying a high-field diode junction several microns below the surface of the device, separated from the surface readout plane by a region of lower field that is still high enough to maintain drift-velocity saturation (Fig. 2).

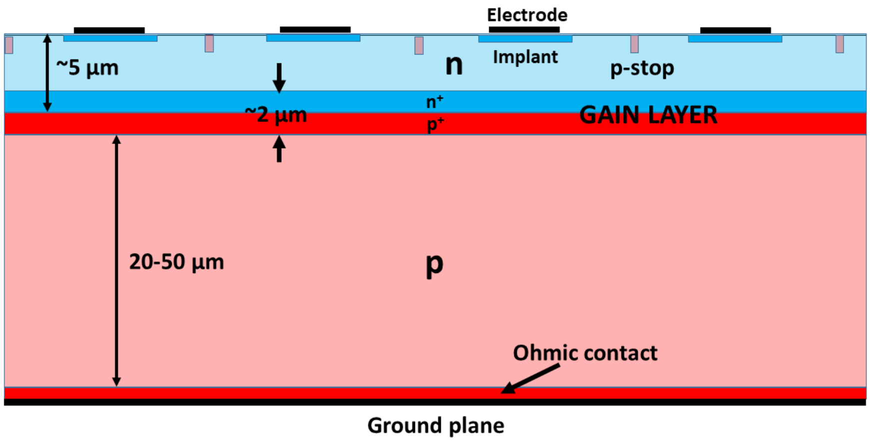

Figure 2: Schematic depiction of the DJ-LGAD concept.

In this way the high field area is kept sufficiently far from the segmented area of the silicon so that inter-channel breakdown is avoided, allowing for the standard pixelization of the readout plane, and the achievement of granularity as fine as tens of microns. This allows having a fine granularity without the charge-sharing mechanism of AC-LGADs, without the double-sided processing of iLGADs, and potentially with a lower IP-gap of TI-LGADs. The first prototype of DJ-LGAD was fabricated last year and it shows promising performance in terms of pad insulation, although the gain layer needs to be refined to reach higher gain [7]. This first production was made using the wafer 2 wafer bonding technique, which proved to be a lengthy and difficult approach. The proposed production will be at FBK and will use the epitaxial growth approach (Fig. 3), which goes as follows:

- Processing of standard thin p-wafer with standard LGAD implantation
- Epitaxial Growth of n-type layer
- Processing of top layer implant with standard silicon pixelization

Such devices will allow fine pixelization while maintaining the great gain and timing properties of LGADs.

FBK has an excellent history of LGAD production and new prototype innovation; Furthermore, it has access to epitaxial growth technology. On top of this, one issue of DJ-LGAD termination is the termination of the deep gain layer. This has been studied in the first prototype production with asymmetric p+ and n+ layers [7]; however, a better approach is to dig deep trenches to terminate the gain layer at the edges. FBK has access to this technology as well.

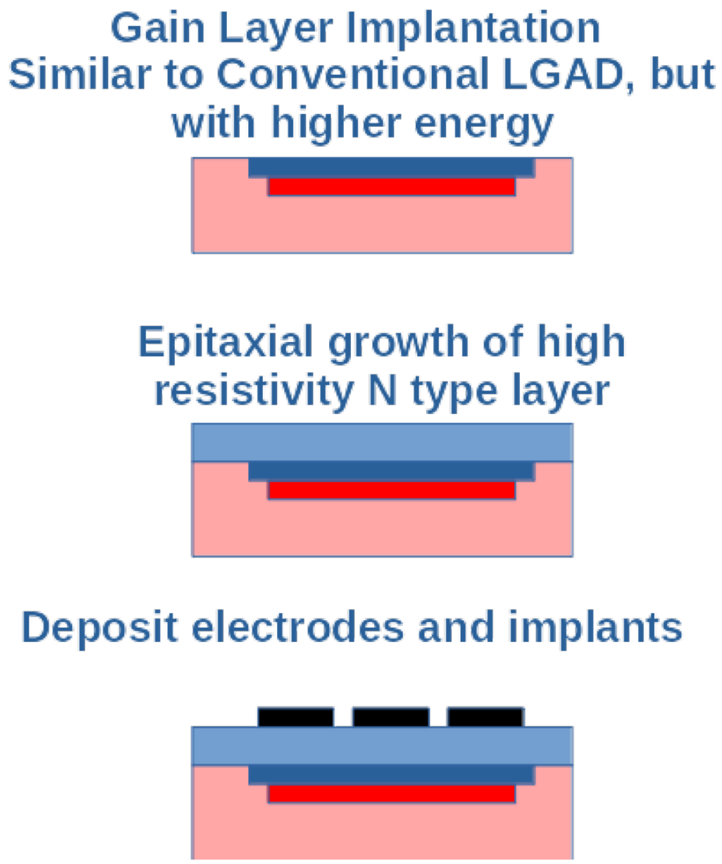

Figure 3: DJ-LGAD production with epitaxial growth.

2.2 Radiation hardness

The DJ-LGAD technology might also improve the radiation hardness reach of the LGAD technology. It was known for a long time that deep gain layers improve the radiation hardness of LGADs (e.g. [8]). However, a deep gain layer usually has to be carefully crafted and the performance before irradiation is not great in terms of time resolution if the initial dose is too high [9]. Therefore, the initial dose cannot be too high and the gain layer cannot be too deep, limiting the radiation hardness reach of the approach.

What is proposed is a device with a deep junction that initially performs as a standard 'shallow' gain layer, but with radiation damage, the gain layer progressively becomes very 'deep' if the n++ layer degrades slightly slower than the p++ layer. In Fig. 4 the doping concentration inside the device is shown for a new device and different levels of radiation damage, in Fig. 5 the resulting electric field can be seen. The process goes as follows:

- Initial implantation has a 'shallow' (p++ and n++ close together, both highly doped) that is 'deep' in the sensor. The device operates as a standard LGAD sensor with a shallow gain layer (good timing performance).

- With radiation damage the p++ and n++ degrade, from literature n++ should degrade faster than p++ [10]; however, the effect of acceptor removal in p and n layers is not studied in-depth and needs to be evaluated. Nevertheless, the ratio of removal of p++ and n++ can be adjusted with carbon and oxygen implantation respectively. The co-implantation of carbon and oxygen should not change the electric proprieties and at the same time, it can slow down the process of degradation.
- As n++ degrades faster than p++ the electric field between the deep gain layer and the surface gradually rises.
- Eventually, the gain layer becomes a very 'deep' gain layer allowing it to still have substantial gain even after high radiation damage.

FBK was one of the leading manufacturers in the production of radiation hard LGAD technology, making it suitable for the project. Furthermore, FBK has long-standing expertise in carbon co-implantation and can also do oxygen co-implantation.

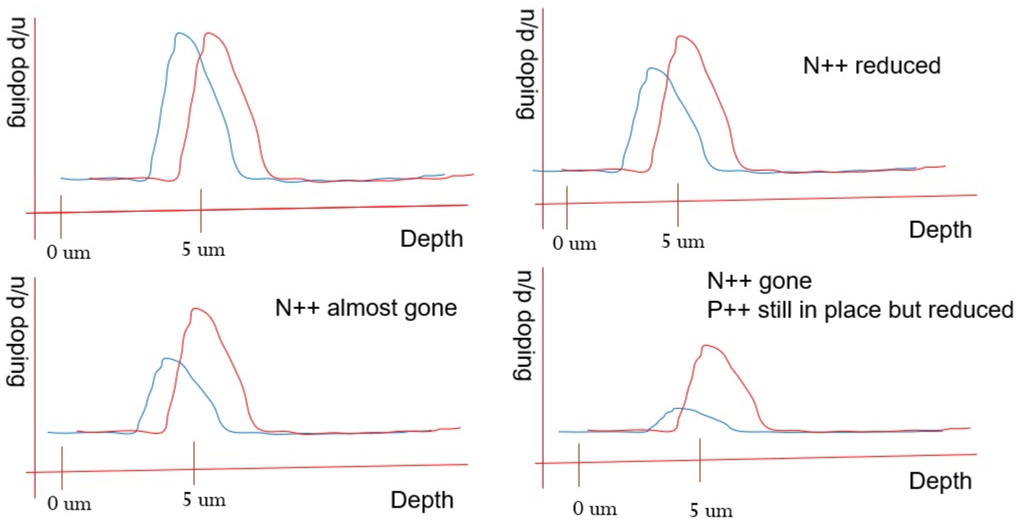

Figure 4: Evolution of deep gain layer doping concentration with radiation hardness.

Another prototype in development is the compensated gain layer by the Torino group [11], the concept is similar, but in the cited case it is co-implantation of n and p in the gain layer. The DJ approach, instead, removes the complication of n and p co-implantation mechanics. The study of acceptor removal and carbon/oxygen effect on p and n layers can be shared between the two projects. Furthermore, the two approaches could be combined in the future: a DJ gain layer with compensated n and p layers so that the acceptor removal effect is slowed down and the gain layer slowly becomes a deep gain layer.

3 Activity description

The projects activities focus on the realization and characterization of the DJ-LGAD sensors. The realization of the sensors will see two preparatory steps. On the technological side, two test batches of wafers will undergo "short loops" consisting of a reduced number of key fabrication steps. The aim of the first short loop is to determine the quality of the epitaxial growth of silicon on the implanted wafers, and its effect on the implant themselves. Secondary Ion Emission Spectroscopy (SIMS) measurements will be used to determine the doping distribution of the gain implants after the epitaxial growth. The second short loop is dedicated to the trench isolation of this batch. Due to the nature of the project the lithography that will be employed might result

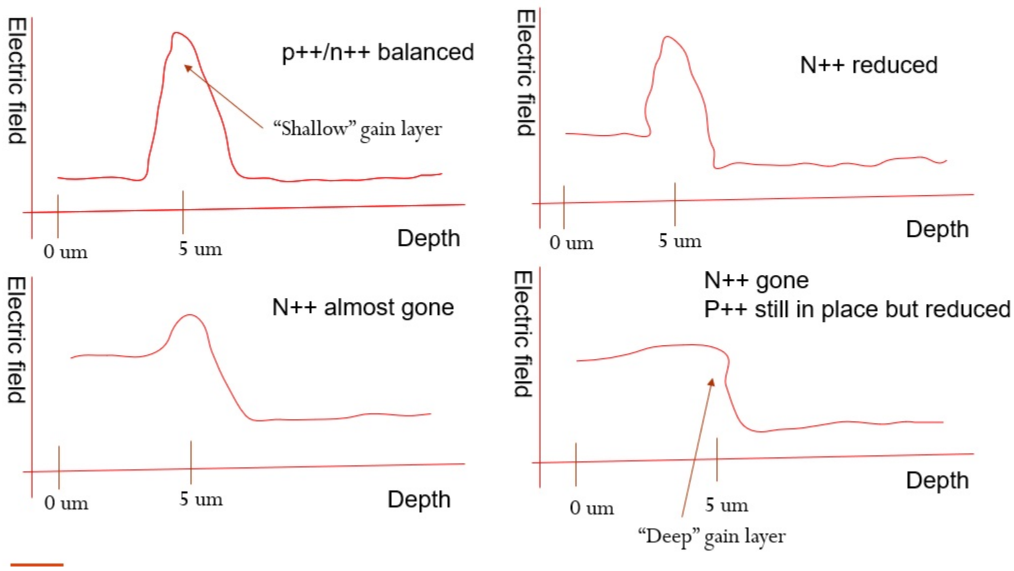

Figure 5: Evolution of deep gain layer electric field with radiation hardness.

in relatively broad trenches. The effect of the trenches on subsequent lithography operations and the mitigation of these effect will be studied in this short loop. The device structure will be optimized employing Technology Computer Aided Design (TCAD) simulations. A first round of simulation will employ rough and ideal doping profiles to find the most promising designs of the devices, the multiplication structure, and its termination. Two strategies are foreseen for the multiplication structure termination: an NGAIN implant broader than the PGAIN implant, and a termination based on trench isolation. Once the most promising geometries are found, the SIMS profiles obtained from the short loop wafers will be used to produce more realistic simulations of the devices and further refine their design. The simulations and short loops will provide the data to guide the design of the sensors and the choice of the sensors fabrication parameters. The sensor design will contain pad and pixel sensors, focusing on the study of different geometries of the multiplication structure termination. Several wafers will be processed to fabricate the sensors. The fabrication parameters will be varied among wafers to study their effect on the sensors.

The characterization of the sensors will see several stages. Measurements performed on the wafers (IV, CV), ...

4 Project cost

To be defined with other groups, FBK and RD50 management, likely around 100k$

References

[1] G. Pellegrini et al. *Status of LGAD production at CNM*. Contribution to the 30th RD50 Workshop, Krakow, Poland, https://indico.cern.ch/event/637212/contributions/2608652/attachments/1470919/2276240/pellegrini_rd50.pdf. 2017. URL: https://indico.cern.ch/event/637212/contributions/2608652/attachments/1470919/2276240/pellegrini_rd50.pdf.

[2] G. Pellegrini et al. “Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications”. In: *Nucl. Instrum. Meth.* A765 (2014), pp. 12 –16. DOI: 10.1016/j.nima.2014.06.008.

[3] M. Carulla et al. *First 50μm thick LGAD fabrication at CNM*. 28th RD50 Workshop, Torino, Italy, June 7th 2016. 2016. URL: https://agenda.infn.it/getFile.py/access?contribId=20&sessionId=8&resId=0&materialId=slides&confId=11109.

[4] H. F. W. Sadrozinski et al. “Ultra-fast silicon detectors (UFSD)”. In: *Nucl. Instrum. Meth.* A831 (2016), pp. 18–23. DOI: 10.1016/j.nima.2016.03.093.

[5] S. Ayyoub et al. "A new approach to achieving high granularity for silicon diode detectors with impact ionization gain". In: (Jan. 2021). arXiv: 2101.00511 [physics.ins-det].

[6] *DJ-LGAD patent, https://patents.google.com/patent/WO2021087237A1/en.*

[7] *S. Mazza, Deep Junction LGAD: a new approach to high granularity LGAD, https://indico.cern.ch/event/1132520/contributions/5140036/.*

[8] S. M. Mazza et al. "Tuning of gain layer doping concentration and Carbon implantation effect on deep gain layer". In: *J. Phys. Conf. Ser.* 2374.1 (2022), p. 012173. DOI: 10.1088/1742-6596/2374/1/012173. arXiv: 2201.08933 [physics.ins-det].

[9] *Technical Design Report: A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade*. Tech. rep. Geneva: CERN, 2020. URL: https://cds.cern.ch/record/2719855.

[10] R. Wunstorf et al. "Investigations of donor and acceptor removal and long term annealing in silicon with different boron/phosphorus ratios". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 377.2 (1996). Proceedings of the Seventh European Symposium on Semiconductor, pp. 228–233. ISSN: 0168-9002. DOI: https://doi.org/10.1016/0168-9002(96)00217-3. URL: https://www.sciencedirect.com/science/article/pii/0168900296002173.

[11] *V. Sola, Present and future development of thin silicon sensors for extreme fluences, https://indico.cern.ch/event/1044975/contributions/4663663/.*