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MILESTONE REPORT

PRELIMINARY CHARACTERISATION OF 3D AND LGAD PROTOTYPES. TEST SET-UP READY IN THE LABORATORIES

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Abstract:

While designing of 3D and LGAD AIDAinnova sensors within WP6 has been completed and production is on-going, results from prototype sensors of similar design from previous productions are summarized in this report. These results demonstrate the readiness of the institutes to assess the performance of the incoming devices from WP6 productions.

AIDAinnova Consortium, 2023.
For more information on AIDAinnova, its partners and contributors please see http://aidainnova.web.cern.ch/

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Executive summary

Novel 3D sensors and LGADs of various types were characterized by the partners in the project. While dedicated AIDAinnova sensor productions are in production, sensors of similar design from previous productions were tested in order to develop experience and tools in time for the evaluation of the WP6 sensors.

The results show a good progress in the direction of achieving LGAD design with efficient inter-pad region thus allowing operation of small pitch LGAD pixel detectors. Several designs were produced and tested, most intensively RSD-DC-LGADs, RSD-AC-LGADs, TI-LGADs and I-LGADs. Radiation hardness of LGAD detectors has also been significantly improved with introduction of carbon in gain layer. The results of the prototype characterization have been used to optimize the process and the design parameters implemented for the WP6 common production.

Timing performance of both Trench-3D and Column-3D sensors was studied with prototypes produced by TimeSpot and RD50 collaborations. Both designs have demonstrated excellent radiations hardness at equivalent neutron fluences up to $10^{16}\,cm^{-2}$ *showing no degradation of timing performance.*

The readiness of testing setups in the laboratories have been demonstrated. At the same time preparations for AIDAinnova WP6 test beam activities have started.

1. INTRODUCTION

Small pitch position sensitive hybrid detectors with good timing capabilities and radiation hardness are at the focus of many detector R&D activities. The future experiments in particle physics will require very good position resolution (few μm) combined with timing capabilities (few tens of ps). The two technologies investigated in WP6, LGAD and 3D sensors, have demonstrated at prototype level to be very promising candidates to fulfil time and spatial resolution requirements at medium and extreme fluence levels. The AIDAinnova productions will investigate different technological options to improve the 4D resolutions and the radiation hardness.

Low gain avalanche detectors exploit gain layer of highly doped p-type silicon sandwiched between the active highly resistive p-bulk and n^{++} implant (structure $n^{++} - p^{+} - p - p^{++}$) to establish high enough electrical fields for impact ionization, hence gain. The gain is required to allow use of thin active thickness LGADs which have short drift times, small impact of Landau fluctuations and retain good signal to noise ratio.

There are two main problems to overcome for the implementation of LGADs in pixelated detectors for medium to high fluence environments. Standard LGADs have a region between the pixels where there is no gain, hence the active area is reduced. Several different proposals have been tried to overcome this problem and they were tested by the WP6 groups. The second issue is related to the de-activation of the gain layer with fluence.

Another technology investigated within WP6 are 3D detectors suitable for timing applications. There are two main directions in 3D sensor designs: a conventional Column-3D sensor, essentially similar as ATLAS/CMS pixel detectors at HL-LHC, with optimized column layout for timing and a so-called Trench-3D detector developed within the TimeSpot project [19, 20]. Both detector types prototypes were evaluated by the WP6 institutes.

2. TESTING INFRASTRUCTURE

All the groups involved in the characterization task of WP6 have setups for testing static characteristics of sensors (Capacitance and Current voltage) in probe station. All of them have also access to Scanning Transient Current Technique systems and system for measurement of timing properties of fine pitch sensors. Different single/few channels discrete electronics was developed to read short induced currents in the sensors: UCSC boards (1-4 channels), INFN-CA TimeSpot amplifier and UZH readout boards. They were all used to test the sensors. Several groups also set up advanced Two Photon Absorption TCT systems and at NIKHEF and CERN there is possibility to use X-rays for testing the sensors.

Groups within WP6 have started preparations for dedicated test beam activities with all the required parts needed at hand. The test beams including the devices produced within AIDAinnova runs are planned in near future.

3. TESTING OF LOW GAIN AVALANCHE DETECTORS

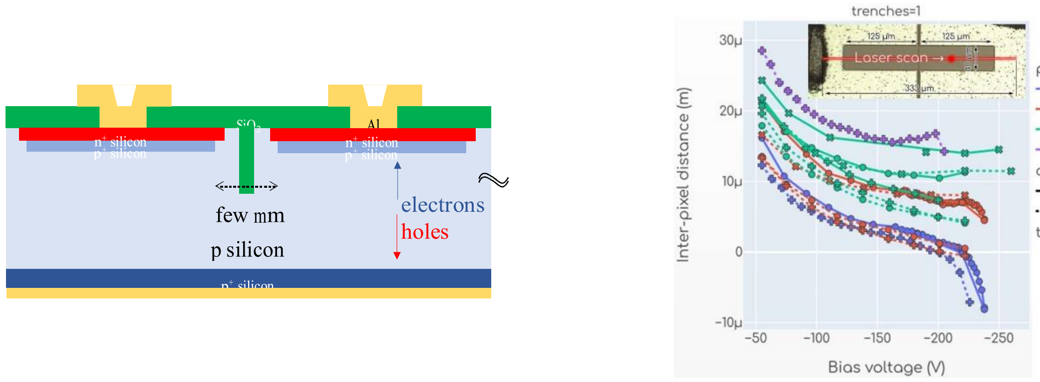
The strategy for sensor testing was driven by two clear objectives: understanding the operation of gain sensors and testing of different sensor designs to increase the fill factor of the conventional LGADs.

The former objective concentrated to improvement of radiation hardness and understanding of operation of sensors for different particle types [1, 2]. Several solutions for improvement of radiation hardness beyond few $\Phi_{eq} > 10^{15}$ cm^{-2} were proposed, such as: carbon enrichment [3], use of compensated material [4], high temperature annealing [5]. Gain was found to depend on free carrier/ionization density, hence different gains were observed for different particle types and energies and similarly also for angled tracks [6, 7]. Screening of the electric field in the gain layer by the multiplied carriers leading to polarization has been identified as the reason for smaller gain at large ionization density [8].

In conventional LGADs, the fill factor is limited, and pixel areas of around 1 mm² are typically used. However, in recent years, proposed designs that offer solutions to this limitation have been investigated, and this report presents the latest results from these characterizations.

3.1 TRENCH-ISOLATED LGADS

Trench-Isolated LGADs (TI-LGADs) were produced in the framework of RD50 collaboration [9]. The isolation is achieved with one or two SiO_2 trenches between the pixels (see Fig. 1a). The electric field lines in the inter-pad region, which is of only few microns, end mainly in the gain layer. An effective inter-pad gap of only few microns was achieved (see Fig. 1b) [10, 11] thus allowing small pitch devices. Devices were also tested in the 120 GeV pion beam and expected performance, defined by gain layer, in terms of collected charge and timing resolution were measured as shown in Fig. 2 [11]. The design variations that have resulted in the better effective inter-pad distance have been implemented in the common WP6 TI-LGAD production currently on-going at FBK. The performance of irradiated devices was investigated and shown that without carbon enrichment of gain layer TI-LGADs are limited to applications with $\Phi_{eq} < 10^{15}$ cm^{-2} [11], similarly to other LGAD designs.



(a) (b)

Figure 1: (a) A schematic view of the TI-LGAD device. (b) Measurements of the inter-pad distance for the different designs of the TI-LGADs with a single trench isolation using TCT: different pixel insolation V1,V2,V3,V4, trench depths D1,D2,D3 and contact types are shown, details in [11].

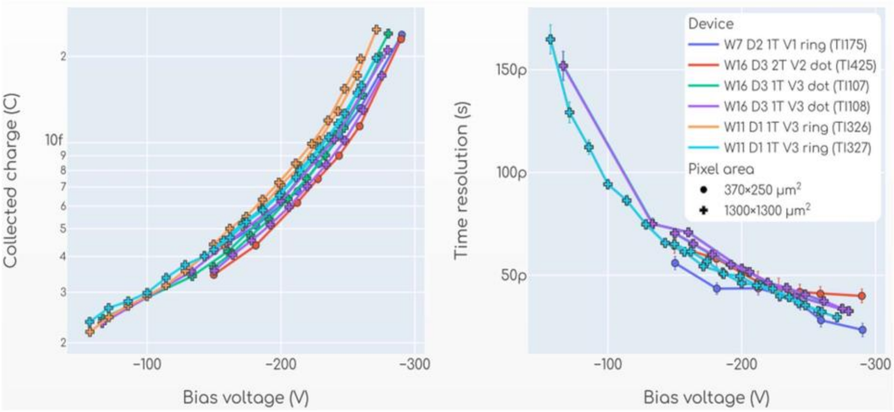
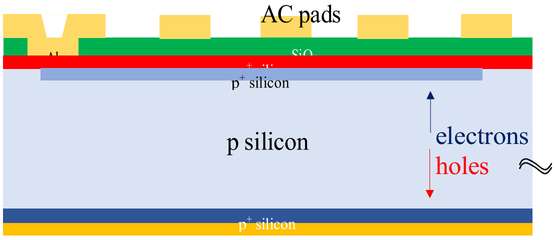


Figure 2: Dependence change collection and time resolution for the TI-LGAD devices on voltage in test beam. Note that the performance is similar to standard LGAD devices with same gain layer doping [11].

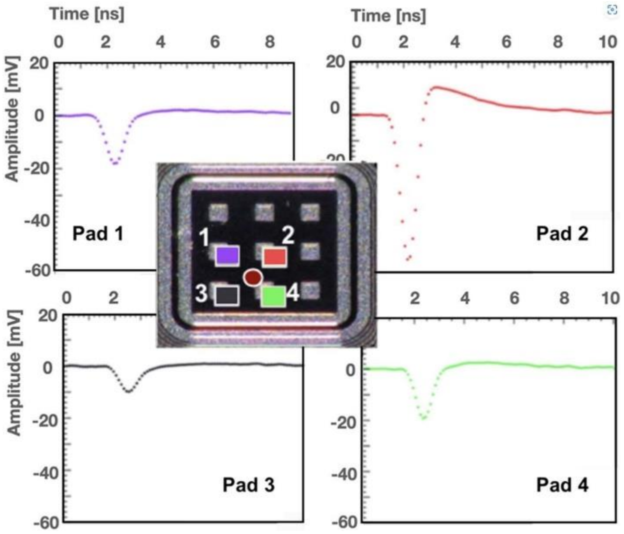
3.2 AC(RSD) - LGADS

In the development of the AC-LGADs (shown in Fig. 3a) a n^+ layer acts like a resistive layer slowly discharging the electrons produced in the multiplication, while a bipolar pulse is induced in the electrodes (see Fig. 3b). These devices were produced by FBK (RD50 and INFN project [12, 13]) and CNM (RD50 [14]) and were intensively tested in terms of signal formation.

AC-LGADs are limited in HEP applications as at high rates the bipolar pulses in sensing electrodes will overlap shift of the signal base line and there could be also substantial signal induction in neighboring electrodes. Moreover, radiation may affect also the resistivity of n^+ layer and by that the signal formation.



(a)

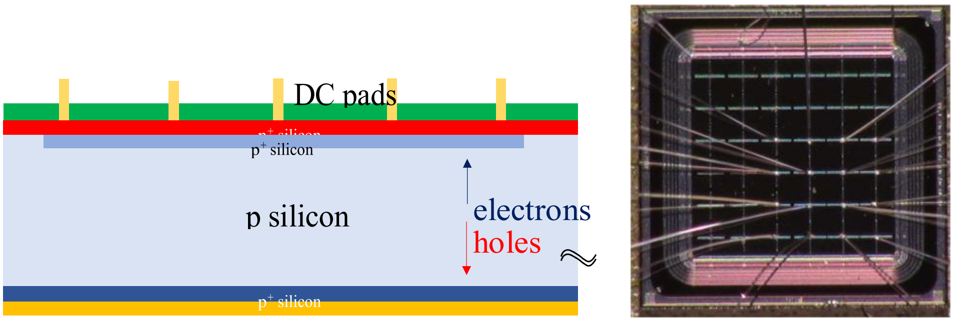


(b)

Figure 3: (a) A schematic view of the AS-LGAD device. (b) Signals observed in the four neighbouring electrodes after creation of e-h pairs by short laser pulse.

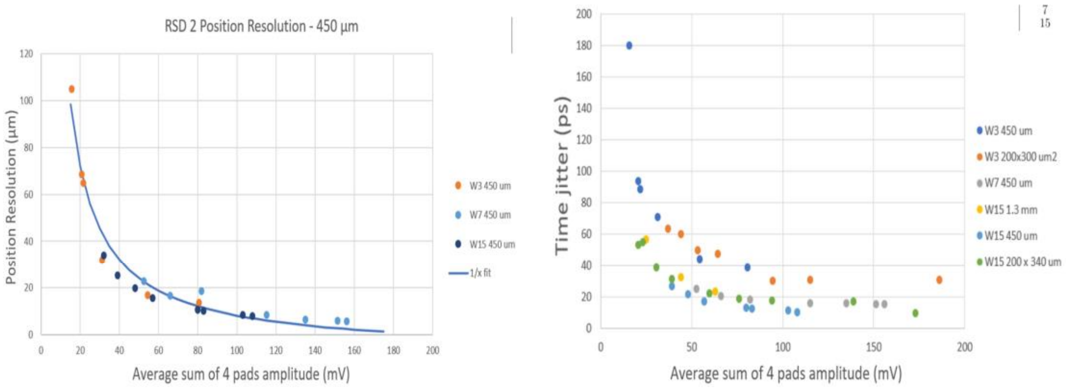
3.3 DC(RSD) - LGADS

In DC-LGADs (RSD) [15] the metal electrodes are in DC contact with the n$^+$ layer, as shown in Fig. 4a. The narrow cross-shaped neighbouring electrodes (see in Fig. 4b a device from a FBK production) resistively share charge in a similar way as for AC-LGADs, but the pulses are shared by the neighbours only and signals are unipolar. Measurements have shown a superb position and time resolution as shown in Fig. 5 [16, 17]. The use of large readout pitch is beneficial for achieving excellent time and position resolution with reduced density of readout nodes. Similarly, to AC-LGADs these devices have limited rate capability. The same considerations concerning the radiation damage as for AC-LGADs remain.



(a) (b)

Figure 4: (a) A schematic view of the DC-RSD device. (b) Photo of the RSD test device with a square cell of 450 µm.



(a) (b)

Figure 5: Dependence of (a) reconstructed position resolution and (b) time resolution on signal for different investigated wafers for 450 × 450 µm cell size. Focused IR light (TCT) was used to generated e-h pairs.

3.4 INVERSE LGAD

The Trenched Inverse-LGADs (T-ILGAD) [18], whose design is shown in Fig. 6, are currently being manufactured in thin substrates at CNM and new prototypes based on this design are not yet available for testing. However, large area (1 cm²) thick sensors with very fine-pitch (25 µm) pixelation, based on the first ILGAD generation architecture [19] and manufactured by FBK, have been successfully tested for low energy x-ray spectrometric applications [20]. This represents the first implementation of a 100% fill factor LGAD technology with a large area sensor and very small pitch.

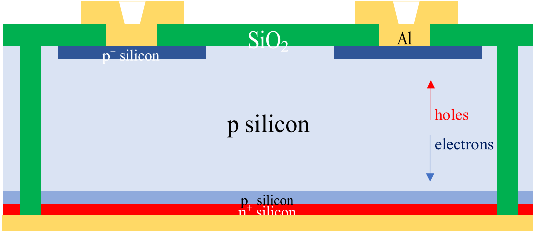
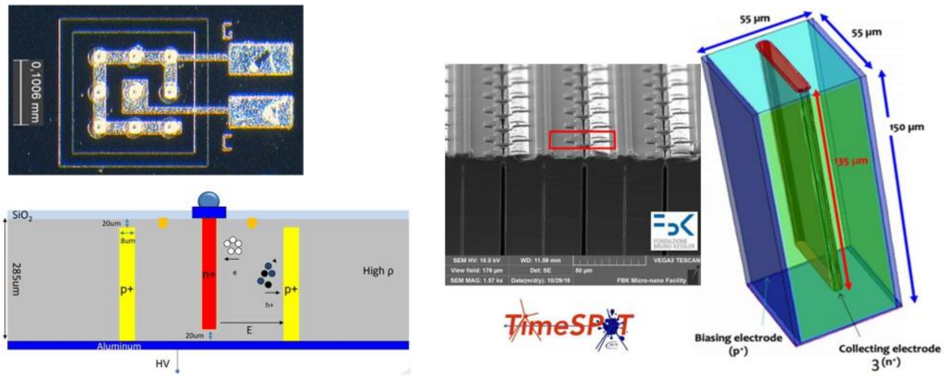


Figure 6: Schematic view of the iLGAD device that will be produced in the AIDAinnova. The active thickness is 50 µm.

4. TESTING OF 3D DETECTORS

The sensors produced within the RD50 (Column-3D by CNM) [21] and TimeSpot projects (Trench-3D by FBK) [22] were investigated for timing performance and are shown in Fig. 7.



(a) (b)

Figure 7: 3D detectors for 4D tracking applications: (a) Column-3D and (b) Trench-3D.

4.1 TRENCH-3D DETECTORS

Trench-3D devices have reached the theoretical limit of weighting field contribution to the time walk for a given cell size [23]. The cell can be seen as two back-to-back thin pad detectors, see Fig 7b. Short drift distance (half of the cell dimension) and large thickness with respect to the cell size, minimize contribution from Landau fluctuations as well, except for the inter-cell region. A superb time resolution of ∼ 10 ps was reached in the test beam using a few cell readout with discrete electronics also after high fluence of 2.5×10^{16} cm^{-2} (see Fig. 8) [24].

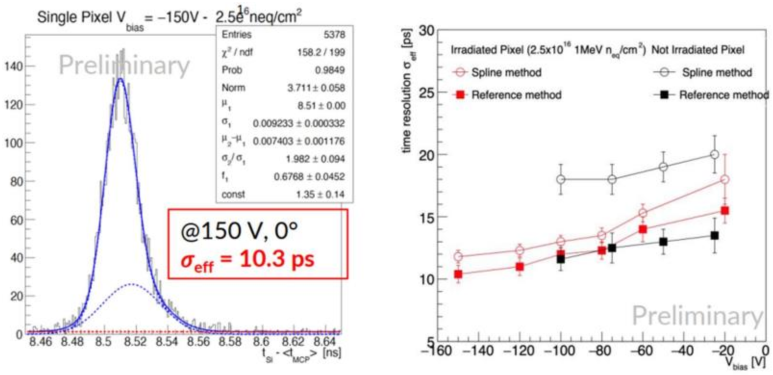


Figure 8: The distribution of the difference in time of arrival (ToA) difference between Trench-3D detector and MCP time reference after fluence of 2.5×10^{16} cm^{-2} and dependence of achievable time resolution on bias voltage.

4.2 COLUMN-3D DETECTORS

A conventional Column-3D sensors ($50{\times}50\ \mu\mathrm{m}^2$) have also demonstrated good time resolution up to equivalent fluence of $10^{16}\,\mathrm{cm}^{-2}$ (see Fig. 7a) [25]. The contributions to the time resolution measured with discrete electronics show weighting field/distortion component as dominant contribution, which is at the comparable cell size worse than for the Trench-3D. The measured values agree with simulated [26], where the simulation predicts the time resolution of around 13 ps for $25 \times 25\mu\mathrm{m}^2$ cell size.

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ANNEX: GLOSSARY

Acronym	**Definition**
LGAD	Low Gain Avalanche Detector