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Low Gain Avalanche Detectors for 4-dimensional tracking applications in severe radiation environments

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For the High Luminosity upgrade of the CERN Large Hadron Collider (HL-LHC), the collider will reach a peak instantaneous luminosity of $5 \times 10^{34}\, cm^{-2} s^{-1}$, with a total integrated luminosity of $\sim 3000\, fb^{-1}$ after around 12 years of expected lifetime. The pile-up during the $p^+ p^+$ collisions is expected to reach values of $\sim$ 200 and the experiments are expected to be exposed to radiation levels up to $1.6 \times 10^{16}\, n_{eq} cm^{-2}$ at the innermost layers of the detectors. Moreover, in future proposal colliders, like for example FCC-hh, the pile-up is expected to be a factor of five higher while the radiation levels will increase by a factor of ten with respect to the HL-LHC.
Under this scenario, in the framework of ATLAS, CMS, RD50 and other sensor R&D projects, radiation tolerant silicon sensors for timing and tracking applications are being developed. Giving the expected radiation levels and the demanding spatial resolution plus timing capabilities required, one important line of research is focused on silicon sensors with intrinsic charge gain: Low Gain Avalanche Detectors (LGADs).
This paper aims to give an overview of the current status of this technology. The most interesting approaches for future 4-dimensional tracking applications based on the LGAD technology will be presented here. In addition, the latest results on the performance after irradiation of standard LGADs will be reviewed too.

KEYWORDS: LGAD, timing resolution, spatial resolution, fill factor, radiation hardness

1. Introduction

Particle detectors in High Energy Physics are always pushed to their technological limit, and this will be the case for the High Luminosity upgrade of the CERN Large Hadron Collider (HL-LHC). In the HL-LHC environment, the different experiments will need to cope with pile-ups a factor of four higher than in the current LHC experiments [1]. Also, the radiation levels will increase significantly, expecting radiation levels up to $1.6 \times 10^{16}\, n_{eq} cm^{-2}$ at the innermost layers of the detectors at the end of the operation [2]. To cope with the increase in pile-up, the two large general-purpose experiments, ATLAS and CMS, will include special sub-detectors in order to perform timing measurements of minimum ionizing particles (MIP) [3, 4]. These sub-detectors will require timing capabilities of the order of $\sim 30\, ps$. Under this scenario, having detectors able to measure the time of arrival of particles will be necessary. But also guaranteeing that their performance will not be degraded operating under these severe radiation environments. For that, radiation tolerance silicon sensors are being developed in the framework of the RD50 Collaboration.

Expectations for future experiments will push the technological limit of the detectors even further. As an example, for the FCC-hh collider, the pile-up will increase by a factor of five with respect to the HL-LHC operation and the spatial resolution needed for the tracking detectors will be around $\sim 10\, \mu$m, combined with a time resolution of $\sim 10\, ps$ per MIP. For this, high precision 4-dimensional tracking detectors will be needed. Also, the radiation tolerance will be in the order of $10^{17}\, n_{eq} cm^{-2}$ [5]

which will be a major challenge in the design of these future detectors. LGAD technology will be pushed to the limit in order to achieve the best possible time resolution, limiting to the maximum the performance degradation by radiation damage and also benefiting from this to develop future 4D tracking detectors.

1.1 Time resolution and 4D tracking

Independently of the radiation damage, one of the most important challenges to cope with in future tracking experiments is the high occupancy. In the HL-LHC the number of interactions per bunch crossing will be around 200. Taking into account that the expected time spread of the beam spot will be around 200 ps, it will be possible to have the same quality in the event reconstruction resolving tracks with a resolution of 30-40 ps [3]. In future experiments, like LCC-hh, besides improving the timing capabilities of the detectors, they will need to have a higher spatial resolution to cope with even higher pile-ups and it is where 4D tracking will be pushed to the technological limit. Here, we are going to review the current status of 4D tracking technology for HEP. All of the approaches that are going to be reviewed here, take as a base sensing technology the Low Gain Avalanche Detectors (LGADs).

1.2 Low Gain Avalanche Detectors

The basic LGADs technology was pioneered within the RD50 collaboration [6] and consists of an n-on-p silicon detector with an internal gain. To obtain this gain an extra, highly doped, p-layer is added just below the p-n junction of a PIN diode. This highly doped region will create a very high electric field region. This electric field will induce an avalanche multiplication of the electrons and thus will create additional electron-hole pairs. The structure is designed to exhibit a moderate gain with a smooth increase of the gain in a wide range of reverse voltage values. A sketch of the schematic cross-section of a standard pad-like LGAD is shown on the left side of figure 1. This technology has been qualified to be used in the MIP Timing Detector in the CMS experiment and in the High-Granularity Timing Detector in the ATLAS experiment for HL-LHC operations [3, 4].

Moreover, microstrip and pixel detector layouts with fine segmentation pitches can be easily obtained with the LGAD approach with a high SNR value, when LGAD is compared with PIN detector. Therefore, precise measurements of position and time of arrival of the incident particles can be achieved with LGAD designs. A sketch of the cross-section of a strip-like LGAD is shown on the right side of figure 1.

2. LGAD performance optimization

There are different techniques in order to improve the performance of the LGADs in terms of radiation hardness, timing resolution, or spatial resolution for example. In this section, we are going to review the most commonly used ones. In the first place, it is known that the performance is very sensitive to small changes in the gain layer implantation process. One of the most common dopants used to co-implantate together with boron is carbon. Recent studies show that carbon co-implantation mitigates the gain-loss after irradiation while replacing boron with gallium does not improve the radiation hardness as shown on the left side of figure 2 [8]. Also, the position and doping profile of the gain layer plays an important role. The shape of the gain layer profile, its concentration, and its thickness, can be wisely tuned to improve the LGADs performance. Narrower boron doping profiles with high concentration peak, achieved with a low thermal diffusion process, seem to be less prone to be inactivated after irradiation, as is shown on the left side of figure 2.

Also, it is well known that the bulk thickness plays a major role in terms of radiation hardness. Having thinner detectors not only increases the radiation hardness, but also improves their timing performance: faster collection times, with higher slew rates, which in the end implies lower timing

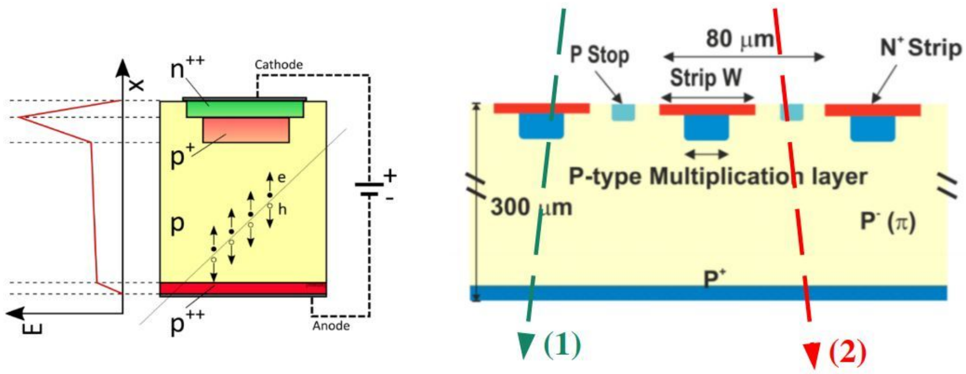

Fig. 1. On the left: a sketch of the cross-section of a pad-like LGAD with a charged particle passing through. A qualitative profile of the electric field amplitude is shown too, where the peak is located in the same region of the gain layer in which the avalanche happens. On the right: a sketch of the cross-section of a strip-like LGAD with two particles passing through: (1) through the gain layer and (2) through the interstrip region [7].

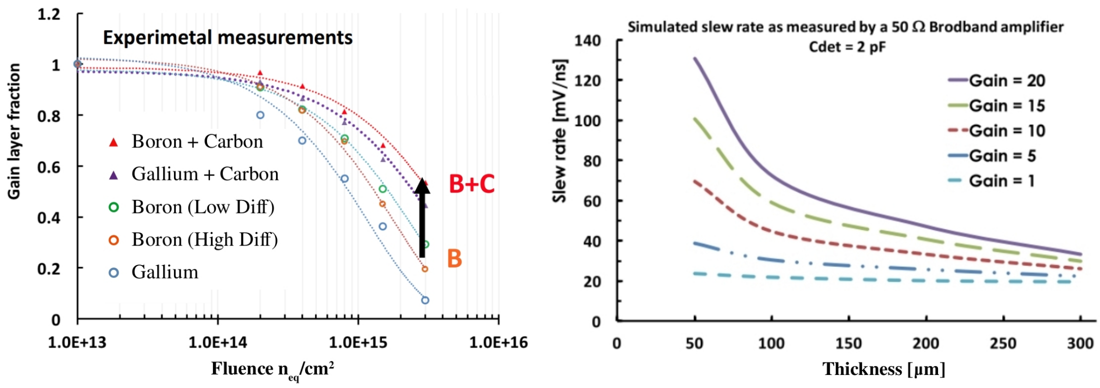

Fig. 2. On the left: gain layer degradation as a function of the fluence for different engineering techniques of the gain layer [8] . On the right: simulated slew rate as a function of the sensor thickness for different gain values [9].

jitters. A simulation of the influence of the LGADs thickness on the slew rate as a function of the gain, is shown on the right side of figure 2.

In segmented LGADs devices, there is an additional parameter, the so-called fill factor, that needs to be optimized. The fill factor problem arises when in segmented LGAD devices some particles deposit the energy in the interpad region and the induced charge generated in the bulk is not amplified as the gain layer is segmented. This can be easily understood looking at figure 1, where the signal generated by particle (1) will be amplified, while the signal generated by particle (2) will not be amplified. Ideally having a 100 % fill factor and therefore improving the spatial resolution will be the goal in this cases. The approaches that are currently addressing this issue within the RD50 collaboration are: Trench Isolation LGADs [10], Deep Junction-LGADs [11], Inverse-LGADs [7] and AC-LGADs [12]. A sketch of the cross-section of all of them can be seen in figure 3 (a), (b), (c) and (d) respectively. All these approaches are going to be reviewed in more detail in the next section.

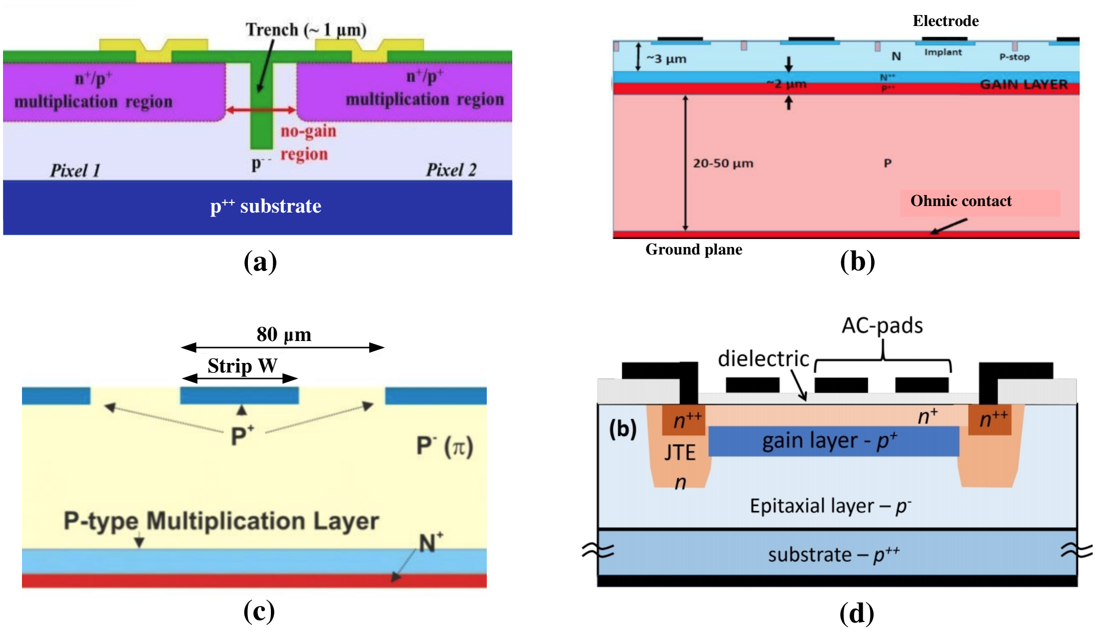

Fig. 3. Sketch of the cross-section of: **(a)** Trench Isolation LGAD (TI-LGAD) [10], **(b)** Deep Junction LGAD (DJ-LGAD) [11] , **(c)** inverse LGAD (iLGAD) [7] and **(d)** AC-Coupled LGAD (AC-LGAD) [13].

3. 4-Dimensional tracking approaches

3.1 Trench Isolation LGADs (TI-LGADs)

This is a novel design of fine segmented LGADs based on the trench-isolation technique. This type of design reduces the width of the no-gain inter-pad region down to less than $10\,\mu m$ from the $20-80\,\mu m$ of the current LGAD technology, enabling the production of sensors with small pixel pitch and high fill-factor [10]. A not-to-scale sketch of the cross-sectional view of an LGAD based on the proposed novel trench-isolated design can be seen in figure 3 (a). Prototypes of TI-LGADs have been produced at FBK laboratories based on a custom CMOS-like fabrication technology. The sensors have been fabricated on p^-/p^{++} wafers with a $55\,\mu$m thick epitaxial layer, using the same multiplication junction technology (ion implantation dose and energy of the doped regions, thermal annealing) used in standard LGAD productions at FBK [14]. Preliminary measurements showed proper isolation between pixels, high breakdown voltage and gain values in the range 5 – 25. Numerical simulations also showed that TI-LGADs can reduce the width of the gain-loss region down to $\sim 6\,\mu m$. It will be feasible to produce LGADs with pixel pitch down to $50\,\mu m$ and with a fill factor higher than 75%. The first results of the current measurements and the gain as a function of the reverse bias are shown in figure 4.

3.2 Deep-Junction LGADs (DJ-LGADs)

The Deep-Junction LGADs (DJ-LGADs) represent a new approach to higher granularity fast timing detectors [11]. A sketch of the cross-section can be seen in figure 3 (b). In this new approach, the high electric field region is localized within the sensor bulk. This is achieved by burying the sensor junction $\sim 5\,\mu m$ below the surface. Then, a low doped n-type substrate lowers the electric field near the surface. Thus, a junction terminal extension (JTE) structure, always present in the standard LGADs designs, is not needed anymore and common pixel segmentation techniques can be used to increase the granularity. The n-type substrate is DC coupling to the electrode.

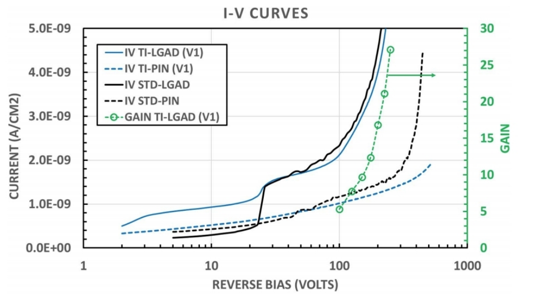

Fig. 4. I-V curves of TI-LGAD (V1) (blue solid line) and respective PIN (blue dotted line); Standard LGAD (black solid line) and PIN (black dotted line). The gain of the TI-LGAD is also reported in green [10].

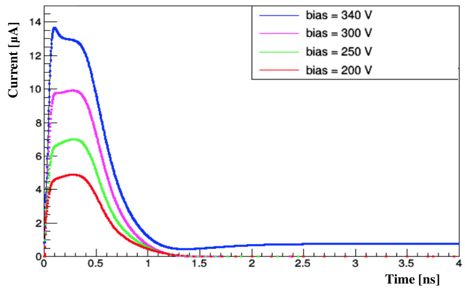

Fig. 5. Simulated pulse shape temporal profiles in one pad of a DJ-LGAD sensor at different reverse bias voltages. They present a fast rise time ($\sim 100\,ps$) and the charge collection time is $\sim 1\,ns$ [11].

This technology is still under development and the production of the first prototype is expected by the end of 2020. The simulations performed with this geometry show promising results. A simulation of the current pulses as a function of the time at different reverse bias voltages is shown in figure 5.

3.3 Inverse-LGAD (iLGADs)

The Inverse-LGADs (iLGADs) is a new concept introduced to mainly cope with the fill-factor problem [6]. Contrary to the conventional LGAD design, the iLGAD has a non-segmented multiplication layer, and it should ideally present a constant gain value all over the sensitive region of the device without gain drops between the signal collecting electrodes. The first strip-like iLGAD prototypes were fabricated at IMB-CNM (CSIC). The iLGAD structure is based on the conventional LGAD process technology but with the difference that the segmentation is now located at the p^+ side, according to the schematic cross-section of the core iLGAD depicted in figure 3 (c). Therefore, the multiplication is no longer coupled to the segmented electrodes and the gain is the same through the strip providing a position-sensitive detector with uniform amplification wherever a particle hits the detector. Test beam measurements carried out with the first prototypes demonstrated the homogeneity in the amplification over all the sensitive region of the device without gain drops between the signal collecting electrodes (100% fill-factor) [7]. Timing measurements were done in the lab with IR-laser obtaining promising results despite the fact that these first prototypes were $300\,\mu m$ thick and therefore not optimized for timing performance. Simulations show that these results can be improved further if thinner sensors are used. As shown in figure 6, they benefit from a much smaller rise time of the signal maintaining a good SNR. This feature will improve the time resolution with respect to the thicker devices.

3.4 AC-LGAD

A sketch of the cross-section of an AC-coupled LGAD (AC-LGAD) can be seen in figure 3 (d). They are p-type sensors based on the LGAD technology with two additional key features: the AC-coupling of the read-out, occurring through a dielectric layer, and a continuous resistive n^+ implant. AC-LGAD devices are provided with one continuous gain layer and the read-out segmentation is obtained simply by the position of the AC pads/strips; therefore, this design allows to reach 100% fill-factor. Two different designs based on the same AC-coupled concept but different read-out pad layouts will be discussed.

Some AC-coupled prototypes were fabricated at BNL [13]. One of these devices, a strip-like AC-

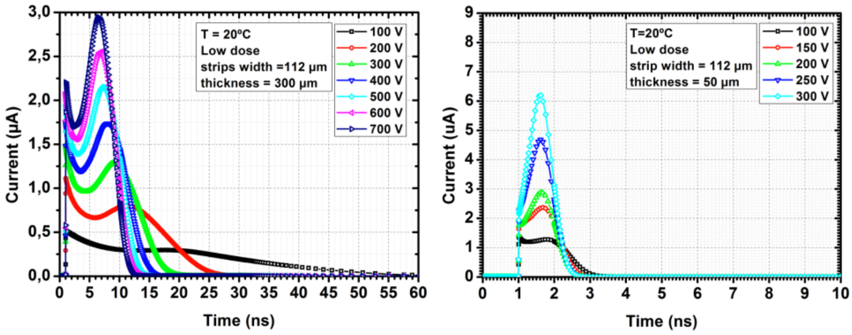

Fig. 6. Transient TCAD simulation from the prototype iLGAD sensors of 300 μm thick produced at IMB-CNM (left) compared to the responds of a similar 50 μm thick strip-like iLGAD sensor (right). Note the different time ranges of the horizontal axis [7].

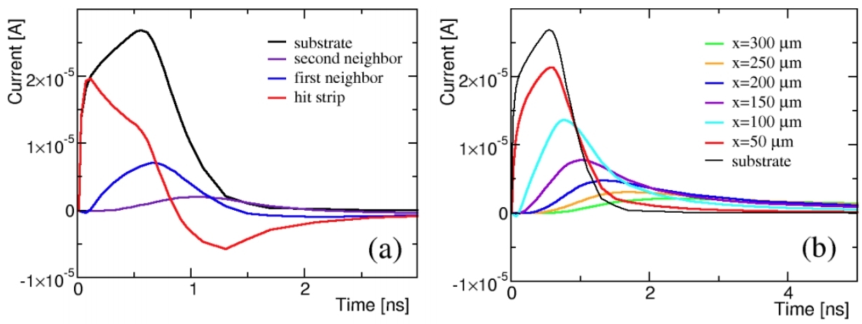

Fig. 7. TCAD simulations of an AC-LGAD sensor: (a) bipolar current pulses on different strips generated by a MIP traversing the sensor; (b) unipolar current pulses from the DC-pad contact as a function of the incident particle's perpendicular distance, x, from the contact [15].

LGAD was measured in a test beam with 120 GeV/c protons [15]. The AC-LGAD sensor consisted of an array of 17 AC-coupled metal strips with a pitch of 100 μm and a width of 80 μm, surrounded by a DC pad and a guard ring structure. TCAD simulations of current pulses for a sensor with the same geometry are shown in figure 7. A signal-to-noise of 27 was measured, wherein this particular sensor most clusters were limited to three strips. A hit efficiency close to 100% was measured for individual strips as well as for a combination of adjacent strips. It was therefore proven that these type of sensors allows for 100% fill factor, as compared with standard LGAD technologies that show significant dead areas at the edges of the pixels. Time resolution on the order of 45–47 ps was measured, which is equivalent to LGADs operated with similar effective gain and read out by the same chain of electronics.

Other AC-coupled LGAD prototypes were produced at FBK, these are called: Resistive AC-coupled Silicon Detectors (RSD) [16]. In the RSD devices signals are spread among neighbouring pads, allowing for a very precise determination of the particle impact point position. The impact point position is determined by a complex analytical expression and it can be improved by modifying the geometry of the AC pads. A few prototypes were tested using an IR-laser system and in a beam test [17]. Data were combined to evaluate the performance of these devices. Studies with laser showed a spatial resolution of around 5 μm for a pixel size up to 200 μm. The dependence of the spatial resolution upon the total signal amplitude, as a function of the pitch-metal value, is shown in figure

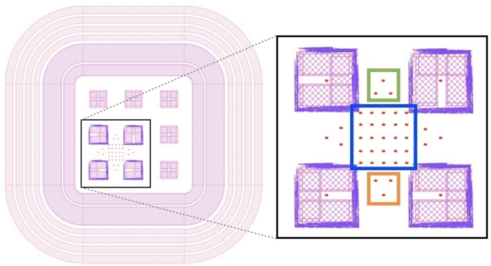

Fig. 8. Sketch of one of the sensors measured in the IR-laser set-up. The red dots represent the locations of the laser shots [17].

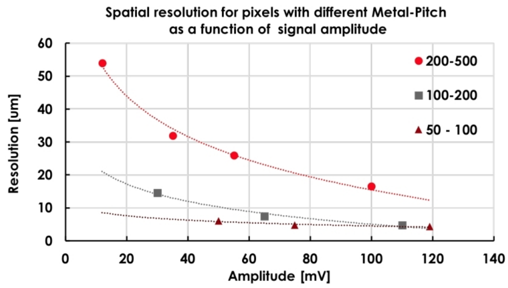

Fig. 9. Spatial resolution as a function of the total signal amplitude for three pad-pitch geometries: 50-100, 100-200 and 200-500 [17].

8. For each matrix, the laser is shot in multiple points in the area among the pads, as shown in figure 9. As expected, the resolution improves with the amplitude, most significantly in larger geometries. For small geometries, the resolution remains almost constant in a large range of amplitudes, showing that the performances are excellent even for low RSD gain. Also, the temporal resolution obtained on the test beam with protons of 120 GeV/c momenta was $\sim 40\, ps$.

4. Radiation hardness overview of LGADs

Several studies have been done to evaluate the LGADs performance after irradiation. In this section, we are going to review the most recent ones carried out within the RD50 collaboration. Samples are produced in different foundries that participate in these studies: CNM (Spain), FBK (Italy), HPK (Japan), IHEP-NDL (China), Micron (UK) and BNL(USA). CIS (Germany) is in preparation for joining the RD50 collaboration.

One first study was performed with LGADs developed by IHEP-NDL [18]. They were produced on an epitaxial layer of $33\, \mu m$ of thickness with two resistivities: 100 and $300\, \Omega\, cm$ and different doping profiles. These samples were irradiated with X-rays up to a dose of $100\, kGy$ and still showed a good performance in terms of time resolution. Also, some samples were neutron irradiated to a fluence of $2.5 \times 10^{15}\, n_{eq} cm^{-2}$ and for the samples with higher resistivity the timing performance measured with a Sr-90 source showed $30\, ps$, as is reported in figure 10.

Thin LGAD samples produced at HPK were irradiated with neutrons at different fluences and an annealing study after irradiation was performed [19]. The gain layer effective dopant concentration was found to decrease exponentially with time after the irradiation, the relative change of the depletion voltage of the gain layer (V_{gl}) with annealing for different samples is shown in figure 11. Nevertheless, the effective doping concentration in the gain layer won't anneal until the yearly technical stops at HL-LHC. The changes in the bulk doping concentration can be well described by the Hamburg model. The annealing of generation current exhibits the same behavior as in standard detectors and follows the NIEL prediction. The standard annealing point of $80\, min\, at\, 60^{0}C$ where most of the studies were done so far, therefore, represents a conservative estimate in terms of required operation voltage. LGAD samples from the same producer were irradiated with neutrons too, but this time with the goal to study the influence of the neutron flux on their performance [20]. At HL-LHC particle fluxes will be around $10^7 - 10^8\, cm^{-2} s^{-1}$ and these samples were irradiated with neutrons at 1.6×10^{10}, 1.6×10^{12}, and $7 \times 10^{12}\, cm^{-2} s^{-1}$. The total fluence achieved in all the cases was $4 \times 10^{14}\, n_{eq} cm^{-2}$ and no significant effects were observed in the depletion voltage of the gain layer or full depletion voltage. Also, no effects were observed in the timing performance or the gain.

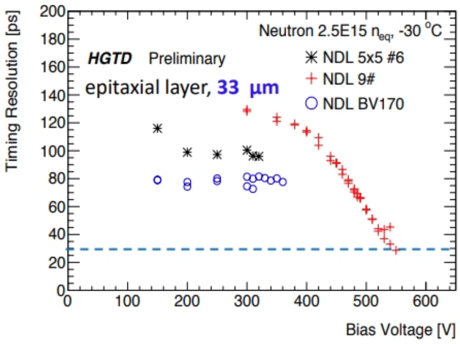

Fig. 10. Time resolution measured with beta particles after irradiation with neutrons. The fluence was $2.5 \times 10^{15}\, n_{eq} cm^{-2}$ and the LGADs were developed at IHEP-NDL (China) [18].

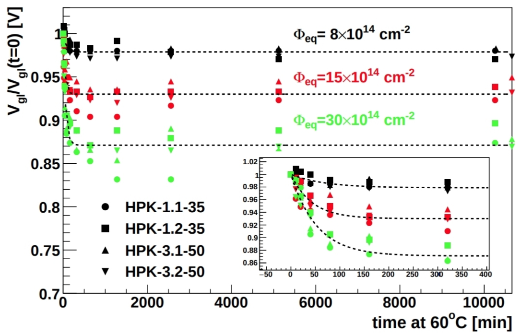

Fig. 11. Relative change of Vgl with annealing for different samples and fluences. The marker shape denotes the sensor type and the color the fluence. The inset shows a shorter time scale [19].

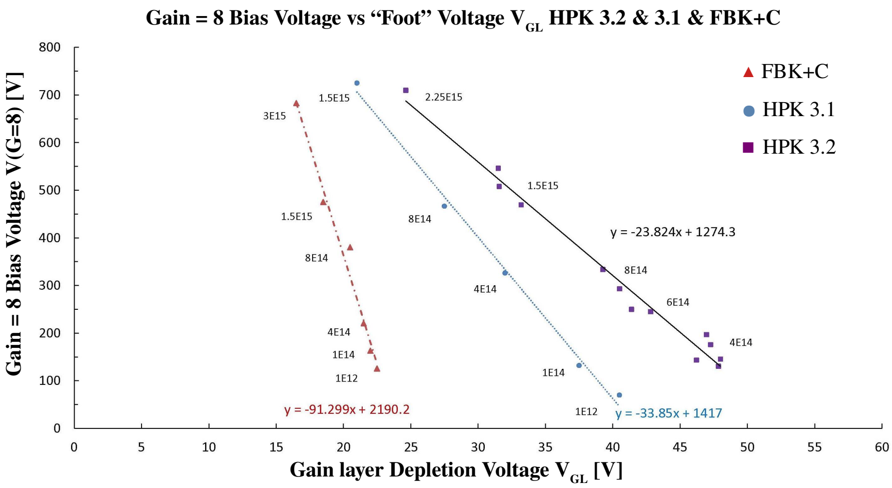

Fig. 12. Correlation between the bias for gain G=8, V(G=8), and the depletion voltage of the gain layer (V_{GL}) for three tested sensors [22].

The performance of the LGADs after irradiation with neutrons and protons is compromised by the removal of acceptors in the thin layer below the junction responsible for the gain [21]. This effect was tested both with capacitance–voltage measurements of the doping concentration and with measurements of charge collection using charged particles [22]. A perfect linear correlation between the bias voltage to deplete the gain layer determined with C-V and the bias voltage to collect a defined charge, measured with charge collection, was found. An example can be seen in figure 12.

The influence of different implantation elements on the gain layer was studied with LGAD samples produced at CNM [23]. The samples were fabricated on $250\,\mu m$ SoI wafers with an active thickness of $50\,\mu m$, and the gain layer was implanted with: boron, boron+carbon, and gallium. For this study, the samples were irradiated with protons and neutrons to 5 different fluences: from $1 \times 10^{14}\, n_{eq} cm^{-2}$ up to $6 \times 10^{15}\, n_{eq} cm^{-2}$. The charge collected measured with Sr-90 source before and after irradiation is reported in figure 13. It is possible to observe a better behavior of the samples doped with B+C, while the ones doped with Ga show worse performance.

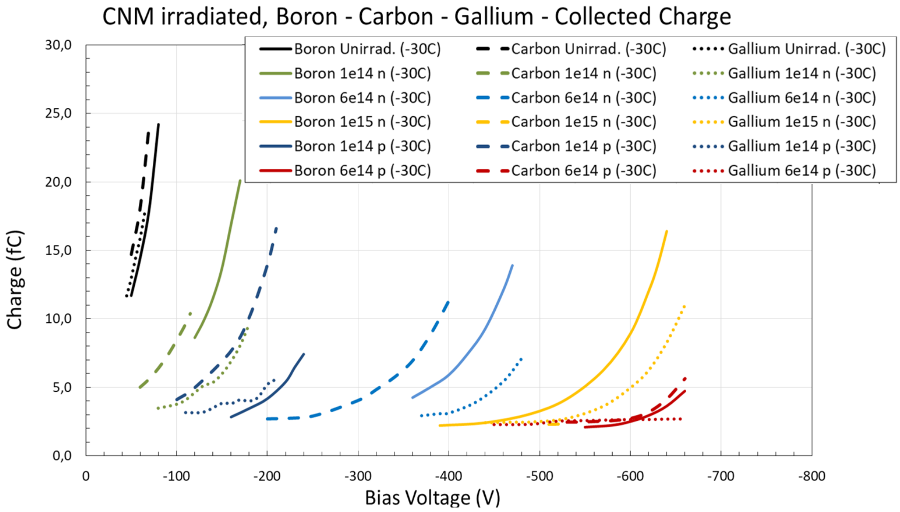

Fig. 13. Charge collection measured with Sr-90 source after irradiation in several CNM LGADs samples. Gain layer implantation: Carbon, Gallium and Boron+Carbon [23].

5. Summary and conclusions

New 4D tracking approaches based on the Low Gain Avalanche Detector technology developed within the RD50 collaboration were presented. They will be the new generation of silicon detectors optimized for high-precision 4D tracking and will be conceived for experiments at future colliders. Results are very promising: the increase of the fill factor with respect to the standard LGAD technology and good performance in terms of timing and spatial resolution. Current studies are very focused on the ATLAS and CMS MIP timing detectors for the HL-LHC operations where LGADs are going to be used. Here the goal is to improve the LGAD performance in order to cope with the demanding requirements of the experiments, where the biggest challenges are: radiation hardness and time resolutions, namely up to $2.5 \times 10^{15}\ n_{eq}cm^{-2}$ and less than 70 ps per hit in a MIP respectively in the case of ATLAS (very similar requirements from CMS). In this context, several studies were done to evaluate the timing performance and charge collection after irradiation. Annealing effects after neutron irradiation in the gain layer were evaluated and the results did not show a significant degradation in their performance, but it is an important parameter to keep under control. The acceptor removal effect and the influence of different dopants in the gain layer were studied too. First results show that carbon co-implantation in the gain layer seems to mitigate the radiation effects in the gain layer. It is possible to conclude that the results presented here go in the right direction and the LGAD technology is evolving to address future needs for the upcoming HEP experiments.

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