ATL-HGTD-PROC-2023-007
16 November 2023

Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector: laboratory and test beam campaigns

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Abstract

The High Granularity Timing Detector (HGTD) is designed for the mitigation of pile-up effects in the ATLAS forward region and for bunch per bunch luminosity measurements. HGTD, based on Low Gain Avalanche Detector (LGAD) technology and covering the pseudorapidity region between 2.4 and 4.0, will provide high precision timing information to distinguish between collisions occurring close in space but well-separated in time. Apart from being radiation resistant, LGAD sensors should deliver 30 ps time resolution per track for a minimum-ionising particle (35 ps per hit) at the start of lifetime, increasing to 50 ps per track (70 ps per hit) at the end of HL-LHC operation. Each readout cell has a transverse size of 1.3×1.3 mm^2 leading to a highly granular detector with about 3 millions of readout electronics channels. A dedicated ASIC for the HGTD detector, ALTIROC, is being developed in several phases producing prototype versions of 2×2, 5×5 and 15×15 channels. HGTD modules are hybrids of the LGAD and ALTIROC connected through flip-chip bump bonding process. Several test beam campaigns have been conducted at DESY and CERN SPS between 2021 and 2022. A summary of the results from LGAD-alone and hybrids will be presented.

Keywords:
HL-LHC, HGTD, LGAD, ATLAS, Test Beam

1. Introduction

The High Luminosity Timing Detector (HGTD) is being constructed for the High Luminosity (HL) phase of the Large Hadron Collider (LHC) at CERN [1]. The HGTD will be installed in front of the end-cap and forward calorimeter at $2.4 < \eta < 4.0$ to measure charged-particle trajectories in time as well as space, mitigating the pileup and augmenting the reach of new all-silicon Inner Tracker (ITk) [2] in the forward region. Low Gain Avalanche Detector (LGAD) [3] with good timing resolution, benefited by the internal gain mechanism, was chosen as the sensing technology for the project. The sensors should maintain a time resolution per hit better than 35 ps before irradiation and 70 ps after having received a fluence up to 2.5×10^{15} n_{eq}/cm^2 1 MeV neutron equivalent. The minimum collected charge for a MIP should exceed 4 fC and the detection efficiency should be higher than 95%. During the past years, the LGAD technology has been widely studied by many producers including CNM [4], FBK [5], BNL [6], HPK [7], IHEP-IME [8] and USTC-IME [9].

Each LGAD sensor pixel is read out by a front-end ASIC channel. A front-end ASIC called ALTIROC (ATLAS LGAD Time Read Out Chip), is being developed to meet the requirements on time resolution and radiation hardness. One HGTD module includes two hybrids of the LGAD and ALTIROC connected through flip-chip bump bonding process.

This paper aims to show the performance of LGAD-alone and hybrids measured in the laboratory and test beam in the last two years. Section 2 describes the test results of LGAD-alone in laboratory. Section 3 covers the performance of LGAD-alone at DESY and CERN SPS, and the performance of hybrids at CERN SPS. The conclusion and outlook are presented in Section 4.

2. Laboratory measurements

2.1. Evaluation of radiation hardness

The gain reduction of LGADs after irradiation with reactor neutrons and charged hadrons has been studied, which is attributed to removal of acceptors in the gain layer [10]. Considering the depletion voltage of the gain layer (V_{gl}), which can be extracted from Capacitance-Voltage (C-V) curves, is proportional to the amount of effective doping concentration in the gain layer. The ratio $V_{gl}(\Phi_{eq})/V_{gl}(0)$ depends upon the value of the acceptor removal constant c [11]:

$$\frac{V_{gl}(\Phi_{eq})}{V_{gl}(0)} = \frac{N(\Phi_{eq})}{N(0)} = e^{-c\Phi_{eq}}, \quad (1)$$

where Φ_{eq} is the irradiation fluence, $V_{gl}(0)$ ($V_{gl}(\Phi_{eq})$) is the depletion voltage of the gain layer before irradiation (after a fluence Φ_{eq}), $N(0)$ ($N(\Phi_{eq})$) is the initial (final) effective doping concentration of the gain layer. The smaller the value of c, the higher the gain implant radiation hardness.

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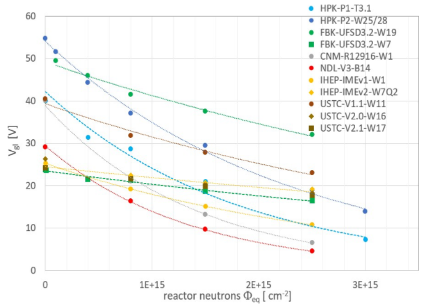
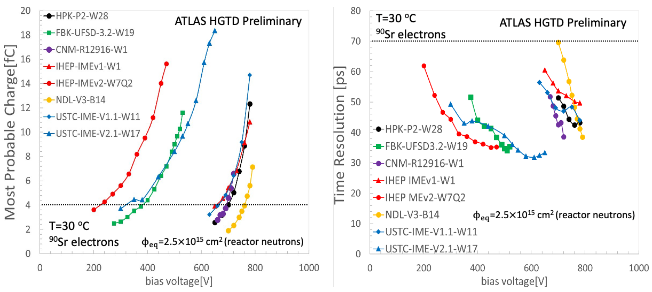


Figure 1: V_{gl} as a function of reactor neutrons fluence.

Sensors from different vendors were irradiated to at least three fluences (8×10^{14}, 1.5×10^{15} and 2.5×10^{15} n_{eq}/cm^2) at the TRIGA reactor in Ljubljana, Slovenia, with reactor neutrons [12]. Figure 1 shows the V_{gl} as a function of reactor neutrons Φ_{eq}. The carbon-enriched sensors produced by FBK, IHEP-IME and USTC-IME have the smallest c, in the range of 1-2×10^{-16} cm^2 indicating the highest radiation hardness. There are two possible advantages of carbon enrichment in the gain layer: (1) carbon competes with boron in forming the ion-defect complexes, so that boron deactivation is suppressed; (2) substitutional carbon atoms tend to pair with boron interstitials and form centers with an energy level of approximately 80% of the boron acceptor level energy [13].

2.2. *β-source measurement*

The LGADs from different vendors, which are exposed to fluences up to 2.5×10^{15} n_{eq}/cm^2, were measured with a ^{90}Sr β-source system [7]. The collected charge as well as timing resolutions are extracted with a fast reference LGAD with tens of ps timing resolution which also acts as a trigger. The results are shown in Figure 2. After irradiation, the collected charge can reach 4 fC and the timing resolution can be better than 70 ps at sufficient bias voltage; and carbon-enriched LGADs allow for lower bias voltages.



(a) (b)

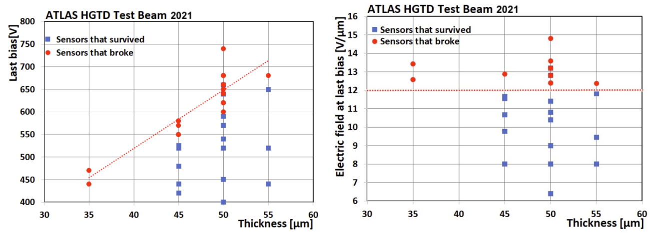
Figure 2: Collected charge (a) and time resolution (b) as a function of bias voltage of sensors from different vendors [14]. The requirements of the HGTD project are indicated by the horizontal dotted lines.

3. Test beam campaigns

One HGTD beam test campaign was conducted at DESY on beam line 24 using a 5 GeV electron beam followed by a campaign at the CERN SPS H6A line using a high-momentum 120 GeV pion beam. The setups used at DESY and CERN-SPS are described in [15] [16]. They are mainly aimed to characterize the performance of LGAD-alone and hybrids.

3.1. *Single event burnout*

It has been shown in the laboratory, using ^{90}Sr-electrons that some sensors can be operated at voltages exceeding 700 V at -30 °C, to collect enough charge and achieve targeted time resolution. However, many of the sensors underwent destructive breakdown at voltages that were $\sim$ 100 V lower than those at which the sensors were successfully operated in laboratory tests. The phenomenon of the destructive breakdown is called single event burnout (SEB) [17]. To determine the safe zone of operation, a large set of sensors from various producers, with different designs, were tested in two different beam test campaigns at DESY and CERN SPS in 2021 [18].



(a) (b)

Figure 3: Comparison of (a) the thickness with the last tested bias and (b) the thickness with the electric field in the sensor. In both plots the red circles mark sensors that broke and the red dashed line indicates 12 V/μm [18].

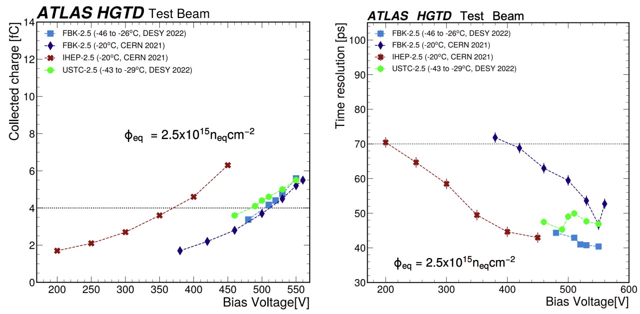
As can be seen in 3, sensors start to break when the average electric field in the sensor reaches 12 V/μm regardless of the LGAD design. To account for uncertainties and the fact that breakdown depends exponentially on the field, a safe zone is defined as the average electric field < 11 V/μm.

3.2. *Performance of sensors*

In previous beam test [15] and laboratory measurements, it was observed that the addition of carbon in the gain layer reduces the operating voltage needed to collect the same charge by a reduction of the acceptor removal rate after irradiation. So to avoid the SEB effect (maximum bias voltage is 550 V for 50 μm thick LGADs), the promising LGAD sensors with carbon-enriched gain layer were tested at DESY and CERN SPS [16]. The reference detector used was a SiPM (with a time resolution of 62.6 ps) at DESY and a CNM LGAD (with a time resolution of 55.0 ps) at CERN SPS.

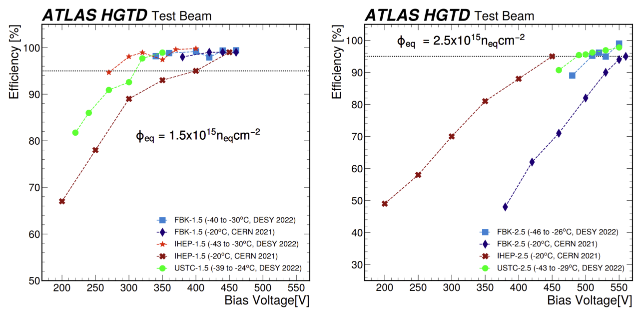
The minimum required collected charge of 4 fC, shown in Figure 4 (a), is reached at a bias voltage around 370 V, 500 V and 470 V for IHEP, FBK and USTC sensors, respectively and Figure 4 (b) shows that their timing resolution can be better than 70 ps at bias voltages below 550 V.

The hit detection efficiency is defined as the fraction of tracks reconstructed by the beam telescope that are expected to traverse the sensitive region of the LGAD sensor actually producing a hit, for which the charge in the sensor is greater than a



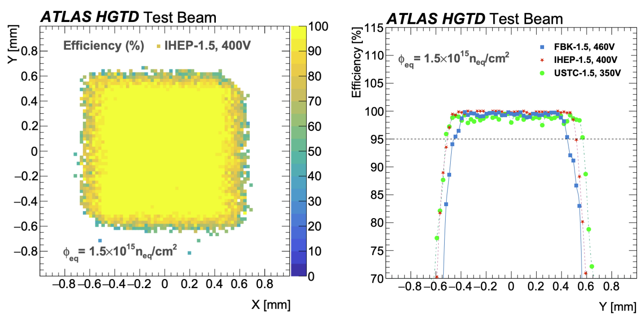
(a) (b)

Figure 4: Collected charge (a) and time resolution (b) as a function of bias voltage of single-pad sensors from different vendors (FBK, IHEP-IME and IHEP-IME) after an irradiation at a fluence of 2.5×10^{15} n_{eq}/cm^2 [16]. The requirements of the HGTD project are indicated by the horizontal black dotted lines.



(a) (b)

Figure 5: Efficiency as a function of bias voltage of single-pad sensors from different vendors (FBK, IHEP and USTC) after an irradiation at a fluence of (a) 1.5×10^{15} n_{eq}/cm^2, (b) 2.5×10^{15} n_{eq}/cm^2 [16]. The dotted line at 95% corresponds to the efficiency needed for operation of the HGTD after irradiation.



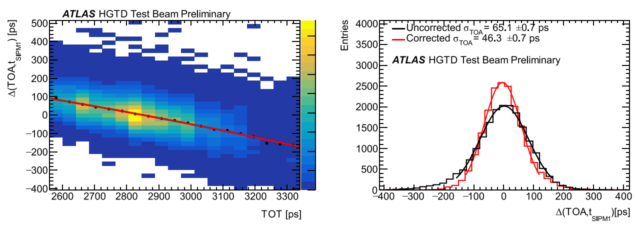
(a) (b)

Figure 6: Efficiency map of the IHEP sensor irradiated at a fluence of 2.5×10^{15} n_{eq}/cm^2, operated at a bias voltage of 400 V. The sensor was tested at DESY with a 5 GeV electron beam. (a) 2D maps of the efficiency as a function of hit position in the sensor plane. (b) Projections on the y-axis of the efficiency [16]. The dotted line at 95% corresponds to the efficiency needed for operation of the HGTD after irradiation.

threshold value of 2 fC [19]. The EUDET telescope [20] was used at DESY, while the MALTA telescope [21] was used at CERN. Figure 5 shows the measured efficiencies as a function of the bias voltage. Figure 6 shows the two-dimensional (2D) map and the 1D projection of the efficiency as a function of the hit position. The efficiency in the center region of the sensors is larger than 99.8% and is uniform.

3.3. *Performance of hybrids*

The ATLAS LGAD Time ReadOut Chip (ALTIROC) ASIC is being developed. Several prototype versions called ALTIROC0 with 2×2, ALTIROC1 with 5×5 and ALTIROC2 with 15×15 channels have been fabricated. The hybrids of the LGAD and ALTIROC connected through flip-chip bump bonding are called bare modules. The bare module with ALTIROC0 has shown satisfying results [19]. The hybrid composed of HPK2 W42 5×5 sensor and ALTIROC1, and the hybrid composed of UFSD4 15×15 (full-size) sensor and ALTIROC2 are tested at CERN SPS and the results are presented here. The time resolution of a hybrid using the ALTIROC1 operated at a bias voltage of −265 V, shown in Figure 7, is 46.3 ± 0.7 ps, after time-walk correction together with Gaussian fits [22]. The efficiency and inter-pad gap is measured from a hybrid [14] with a full-sized sensor operated at a bias voltage of −180 V. Figure 8 shows an efficiency of better than 95% and inter-pad gap distance (defined by the region between adjacent pads where the efficiency is below 50%) is smaller than 70 μm.

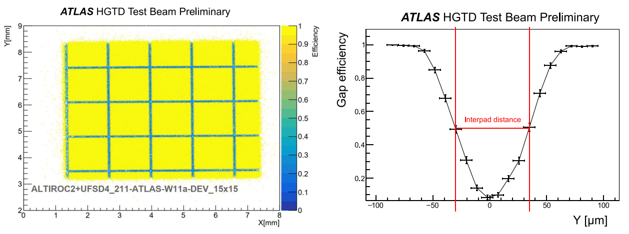


(a) (b)

Figure 7: (a) Distribution of the time difference between the sensor board and quartz+SiPM system as a function of the time-over-threshold (TOT). The dots correspond to the mean value of the time-of-arrival (TOA) distribution and the red line is a fit used to perform the time-walk correction. (b) Distributions of the time difference between the sensor board and quartz+SiPM systems before (black) and after (red) the time-walk correction together with Gaussian fits. The numbers are the fitted Gaussian widths where the time resolution of the quartz+SiPM system has been subtracted quadratically [22]. The measurements were performed with 120 GeV pions beam at CERN SPS H6 beam line.

4. Conclusion and outlook

The LGAD, as a fast timing as well as radiation hard silicon based detector, has reached a mature state in recent years. Carbon-enriched LGADs from three vendors (FBK, IHEP-IME and USTC-IME) have been studied both in terms of radiation hardness and performances in timing resolution and detection efficiencies. When irradiated at fluences of 2.5×10^{15} n_{eq}/cm^2, the LGADs were operated at voltages below 550 V and achieved the objectives of: (1) Collected charge of more



(a) (b)

Figure 8: (a) Efficiency map of hybrid with full-sized sensor. (b) Gap Efficiency versus y of full-sized sensor zoomed around an inter-pad region. Vertical lines mark 50% efficiency obtained with linear interpolation, difference in their positions is taken as the inter-pad distance [14]. The measurements were performed with 75 GeV pions beam at CERN SPS H6 beam line.

than 4 fC while guaranteeing an optimal time resolution better than 70 ps, (2) uniform efficiency above 95% in the sensitive regions of the sensor with a charge threshold of 2 fC. These results confirm the feasibility of a silicon-based LGAD timing detector for the HL-LHC. The IHEP-IME and USTC-IME Pre-production is in progress and the laboratory tests of the sensors produced in the first batches are ongoing. Tests with accelerator beams are expected soon. The timing resolution of the hybrid composed of ALTIROC1 and HPK2 W42 5×5 sensor operated at a bias voltage of −265 V is 46.3 ± 0.7 ps. As for the hybrid composed of ALTIROC2 and UFSD4 15×15 sensor operated at a bias voltage of −180 V, the efficiency can be better than 95% and inter-pad gap distance is smaller than 70 μm. Based on these impressive results, an improved version of the ASIC, ALTIROC3, has been produced and is currently being tested.

Acknowledgements

This work was supported by MINECO, Spanish Government, under grant RTI2018-094906-B-C21, the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 754510, the Spanish Government, under grant FPA2015-69260-C3-2-R and SEV-2012-0234 (Severo Ochoa excellence programme); and by the H2020 project AIDA-2020, GA no. 654168, "the Fundamental Research Funds for the Central Universities" of China (grant WK2030040100), the National Natural Science Foundation of China (No. 11961141014) and the Chinese Academy of Sciences (Grant NO.: GJJSTD20200008). The contributions from JSI, DESY and CERN technical staff and students is acknowledge.

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