

Understanding the Properties of Gallium Implanted LGAD Timing Detectors

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ABSTRACT

ATLAS is proposing a High Granularity Timing Detector (HGTD) to be installed in front of the end-cap calorimeters for the upgrade of High Luminosity LHC project with Low Gain Avalanche Detectors (LGAD) chosen as preferred timing detectors. A beam test campaign has been conducted in order to be able to study the properties of these new detectors under severe conditions in June 2018 with a high-energy pion beam of 120 GeV at the H6A line at the CERN SPS. This study is aimed to understand the properties of gallium implanted LGAD timing detectors which was also included in the latest beam test campaign. A simple time reconstruction method of Constant Fraction Discriminator (CFD) was carried out to calculate the time resolution of this sensor. Preliminary studies show that boron implanted sensor, W9LGA35, has a better time resolution (32.88 ± 0.08 ps) than gallium implanted sensor, W6S1021 (52.93 ± 0.15 ps).

Keywords: Timing detector; LGAD; ATLAS.

1 Introduction

Large Hadron Collider (LHC) at CERN is projected to start a new period called the High Luminosity LHC (HL-LHC) with increased number of collisions and enhanced data sampling to provide more accurate measurements for new physics discoveries. A long shutdown is foreseen to take place on 2024-2026 and all of its detectors will withstand a major upgrade as a consequence to cope with the more severe high-radiation environment. An integrated luminosity of $\mathcal{L} = 4000 \text{ fb}^{-1}$ is expected to be obtained thus creates a new challenge for the detector sensors and the electronics [1].

ATLAS is proposing to install a High Granularity Timing Detector (HGTD) in front of the end cap and forward calorimeters. Low Gain Avalanche Detectors (LGAD) are chosen as the timing detectors with thickness of about 50 μm and surface area of $1.3 \times 1.3 \text{ mm}^2$. This new detector is expected to have a time resolution of about 30 ps to embellish a more precise timing measurement.

This paper is presented as follows: Section 2 covers the underlying concept about the sensors and the read-out boards. The setup which was constructed in the latest beam test is explained in Section 3. The method of time reconstruction is briefly discussed in Section 4. Section 5 discloses the results and discussion. The summary and conclusion of this paper is presented in Section 6.

2 Sensors and Read-Out Boards

2.1 Low Gain Avalanche Detectors (LGAD)

LGAD production was first developed by CNM (Centro Nacional de Microelectrónica), Barcelona, Spain [2]. Development of LGAD is intended for tracking and timing measurement on high energy physics and medical applications fields. LGAD is mainly composed of silicon semiconductor which is able to detect only primary ionization to be converted as a signal charge in contrast to gas detectors because of low energy requirement to produce a signal and low noise electronics [3]. The avalanche effect generated by LGAD can be obtained through an additional region with adequate strength of electric field resulting in multiplication of charge carriers that pass over the region.

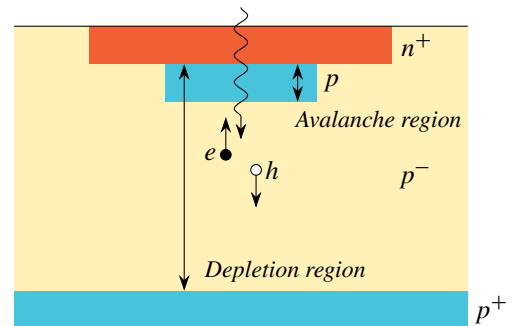


Figure 1: Cross section of an LGAD diode.

LGADs are constructed by inserting a highly-doped p -layer just below the thin n^+ layer as depicted in **Figure 1**. The maximum electric field occurs at the n^+-p junction. Electrons are produced below the amplification region (on the low doped p^- bulk) due to charged particles which penetrate the sensor. The electrons need to traverse toward the collecting electrode on the top part of the device through the amplification region. Sufficient strength of electric field may accelerate electrons or holes to collide with the lattice imperfections resulting in creation of another electron-hole pair. These generated holes then drift towards the p^+ region on the bottom part of the device. The insertion of highly-doped p -layer as an amplification region thus establishes an internal gain because of the avalanche effect.

One property which is essential to a sensor is the time resolution. The total time resolution per hit is defined as a quadratic sum of electronic noise (σ_{elec}), dispersion due to the non-uniform energy deposition which causes fluctuations in the Landau distribution term (σ_L), and clock distribution (σ_{clock}). The governing equation to calculate the time resolution can be written as follow.

$$\sigma_{\text{tot}}^2 = \sigma_{\text{elec}}^2 + \sigma_L^2 + \sigma_{\text{clock}}^2 \quad (1)$$

The electronic noise is mainly composed by two prevalent effects: jitter (σ_{jitter}) and time walk ($\sigma_{\text{time walk}}$).

$$\sigma_{\text{jitter}} = \frac{N}{(dV/dt)} \simeq \frac{t_{\text{rise}}}{(S/N)} \quad (2)$$

$$\sigma_{\text{time walk}} = \left[\frac{V_{\text{th}}}{(S/t_{\text{rise}})} \right]_{\text{rms}} \propto \left[\frac{N}{(dV/dt)} \right]_{\text{rms}} \quad (3)$$

In both Equations 2 and 3, N is the electronic noise, t_{rise} is the rise time of the signal, S is the signal amplitude, and V_{th} is the voltage used as threshold to determine the time of arrival. Both terms depend on the signal slope, dV/dt . The Landau distribution term can be manipulated through thickness, pad size, doping, and radiation hardness optimization. The clock distribution term depends on the size of the time-to-digital converter (TDC) bin.

The sensor studied in this paper is a silicon sensor with the p -type amplification layer implanted with gallium. The sensor was produced by CNM with a run and sensor number of 10924 W6S1021. The sensor has a thickness of $50 \mu\text{m}$ with a $1.3 \times 1.3 \text{ mm}^2$ active area. To measure the time resolution of the sensors, a silicon photo multiplier (SiPM) was used as the timing reference as it has on average slightly better time resolution as the LGAD. The performance of the the W6S1021 gallium implanted sensor was compared to a boron implanted wafer, with a run and sensor number of CNM 9088 W9LGA35. In both cases, the sensors are unirradiated.

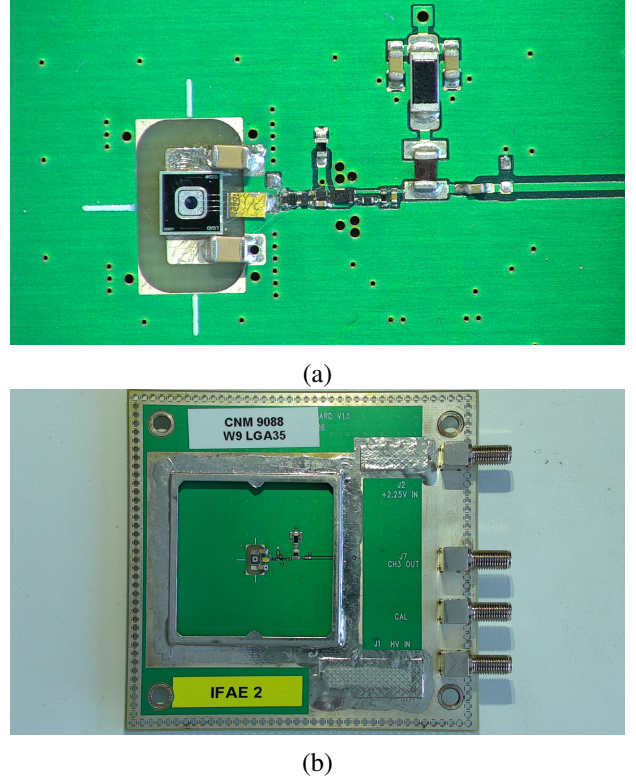


Figure 2: Example of (a) electronics in a read-out board with boron implanted LGAD sensor CNM 9088 W9LGA35 attached to it and (b) the overall read-out board with ports of input and output.

2.2 Read-Out Boards

To carry out a performance test, the sensors were affixed in read-out boards. For single pad sensors, a single channel board was used as visualized through **Figure 2** (a) and (b) as an example. Each read-out board consists of a specially designed amplifier as depicted in **Figure 2** (a) and is labeled as the first-stage amplifier. This electric circuit amplifies the electric signal generated by the sensor to be forwarded to the second-stage amplifier. The second-stage amplifier was externally connected to the read-out board through an output port. This amplifier also acts as a connector between the read-out board and an oscilloscope or other signal processing device.

The sensor was mounted using a double side conductive tape and needed to be positioned with high precision. The sensor was connected to the amplifier circuit through a series of wire bonds to minimize the effect of inductive coupling between them. The amplifier circuit with mounted sensor on it requires to be covered using a metal cover on both sides to create a simple Faraday cage thus blocking the circuit from disruptive external static electromagnetic field. All of the boards needed to be arranged and configured to undergo a beam test to assess the performance of the sensors under harsh environment.

3 Beam Test Setup

A beam test campaign was conducted in June 2018 at the H6A line at CERN SPS using high-energy pion beam of 120 GeV. The setup was constructed as follows: a beam telescope based on MIMOSA planes was installed with a few micrometer scale precision to support position-dependent measurement, such as efficiency or gain as a function of pad position.

Following the telescope, 4 DUTs (devices under test) were arranged linearly with the beam and telescope. In each batch, up to 8 boards can be mounted at the same time providing more efficient data taking process. The pulses of those 8 sensors can be read by 2 oscilloscopes with the same sampling rate and bandwidth. One SiPM was used in each batch as a reference.

A scintillator and FE-I4 planes were also used to provide the triggers when data acquisition was being administered. The acquired number of triggers and events collected by the sensors were always synchronized manually. A National Instruments (NI) crate was used to gather data from the telescope and FE-I4 planes. A schematic of the setup is presented through **Figure 3**.

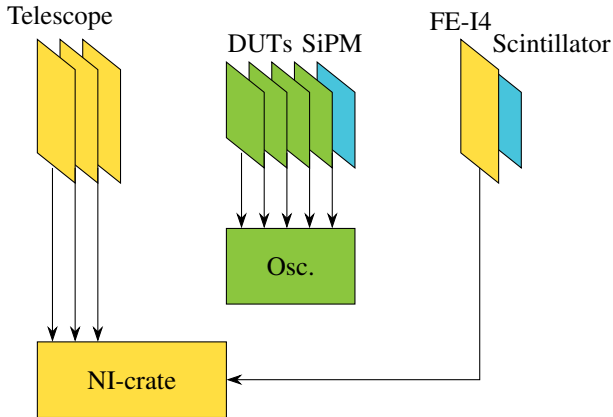


Figure 3: Schematic of beam test setup for data acquisition process.

4 Time Reconstruction Techniques

To calculate the time resolution of the sensors, a Constant Fraction Discriminator (CFD) method was invoked. This method uses a constant fraction (f_{CFD}) of the maximum amplitude as minimum threshold. The presented study used $f_{\text{CFD}} = 0.2$ as a default fraction. A distribution of time differences between the sensor and the SiPM can be fitted with a Gaussian function. The time resolution is then calculated by measuring the width of the fitted Gaussian function. The time construction using CFD method was obtained using PyAna, a code developed by HGTD team. The time resolution was extracted using ROOT.

5 Results and Discussion

This study presents results from W6S1021, W9LGA35, and also the SiPM as a reference from the latest beam test. The test was conducted in -20°C and -32°C to simulate the foreseen rough environment. The bias voltage applied to W6S1021 was varied from 40.0 V to 60.0 V with an increment of 5.0 V. The maximum bias voltage of 60.0 V was chosen based on an I-V study beforehand. The bias voltage applied to W9LGA35 and SiPM was 190.0 V and 27.0 V, respectively.

5.1 Pulse Amplitude and Charge

Example of pulse amplitude and charge distribution of both W6S1021 and W9LGA35 sensors are presented through **Figure 4** with the bias voltage applied to W6S1021 being the maximum for the respective sensor. The pulse amplitude distribution for gallium implanted W6S1021 slightly differs from the boron implanted W9LGA35 due to difference in electric field strength generated by the amplification layer caused by different dopants.

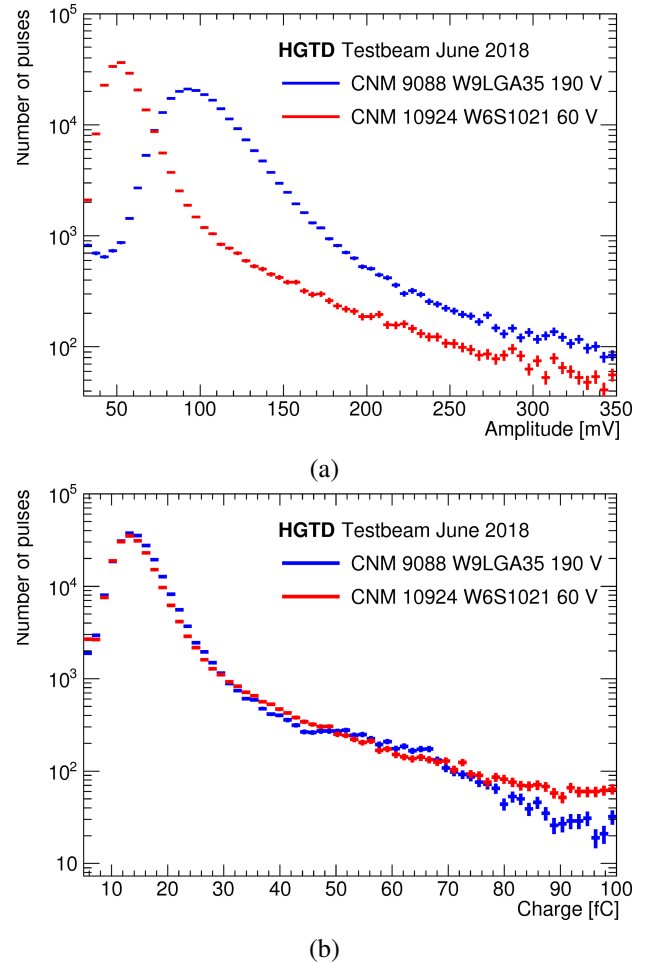


Figure 4: Distribution of the (a) pulse amplitude and (b) charge for both W9LGA35 and W6S1021 sensors.

5.2 Time Resolution

The time resolution for W6S1021 and W9LGA35 have been calculated using the CFD method for various bias voltages in two different temperatures. As mentioned before, the CFD fraction number was not optimized accordingly to this specific case. The chosen value of $f_{CFD} = 0.2$ showed good results from a previous study of this sensor [1]. An example for the CFD time subtraction between the LGADs and the SiPM are depicted in **Figure 5** with the Gaussian fit to the peak of the distribution.

The width of the Gaussian fit was found iteratively to obtain the time resolution result. This method was carried out to calculate the time resolution for each sensor with variation in bias voltage and temperature. Relation between the time resolution and bias voltage is visualized in **Figure 6** for temperatures of -20°C and -32°C .

Using the maximum voltage applied to each sensor, a time resolution of (58.72 ± 0.18) ps at -20°C and (52.93 ± 0.15) ps at -32°C for W6S1021 was achieved. The uncertainty comes from statistical calculation. For W9LGA35, the time resolution is (34.95 ± 0.09) ps at -20°C and (32.88 ± 0.08) ps at -32°C .

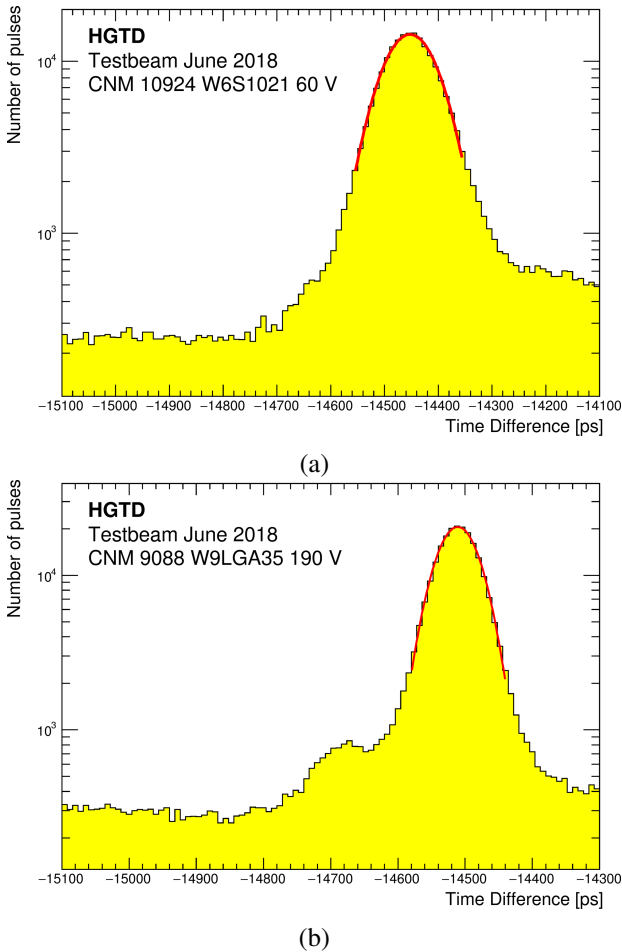


Figure 5: Histograms of subtracted CFD time between (a) W6S1021 and (b) W9LGA35 with the SiPM.

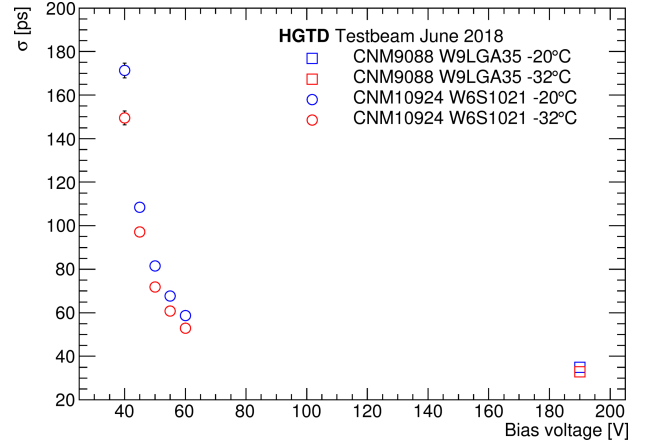


Figure 6: Time resolution of W6S1021 and W9LGA35 at -20°C and -32°C calculated using $f_{CFD} = 0.2$.

The time resolution requirement for the overall HGTD is 30 ps as mentioned before. As the timing detector would be installed in two layers, each layer may provide a time resolution around $30\sqrt{2}$ ps = 42.43 ps. The boron implanted W9LGA35 shows better time resolution than the gallium implanted W6S1021. The difference in material used as dopant for the multiplication layer gives different behavior of electrons and holes when experiencing the charge multiplication. The ionization rate of charged particles penetrating the multiplication layer is strongly dependent on the strength of electric field applied thus related to the choice of material for the multiplication layer.

Variation in bias voltage affects the internal gain of an LGAD. When a sensor is operated near to the avalanche breakdown (the maximum bias voltage that can be applied to a sensor), its gain becomes a rapidly increasing function of the applied bias voltage [4].

Time resolution value for W6S1021 gets better as it approaches the maximum bias voltage near the breakdown voltage. This trend agrees well with the expected result of the sensor's behavior reaching breakdown voltage viewed from the electronic noise contribution. Being in higher voltage indicates better signal-to-noise ratio thus minimizing the jitter effect. High voltage also gives steeper slope of dV/dt to both jitter and time walk effects resulting in better time resolution. The signal-to-noise ratio for both sensors is plotted through **Figure 7**.

Temperature also plays role in affecting gain of a sensor. The mean free path of electrons and holes is a function of temperature. Therefore, variation of temperature influences the avalanche multiplication. Previous studies showed result that as the temperature increased, inversely, internal gain of the sensor is decreased [5, 6]. These studies were performed on an APD (Avalanche Photo Diode), but agree well with our result.

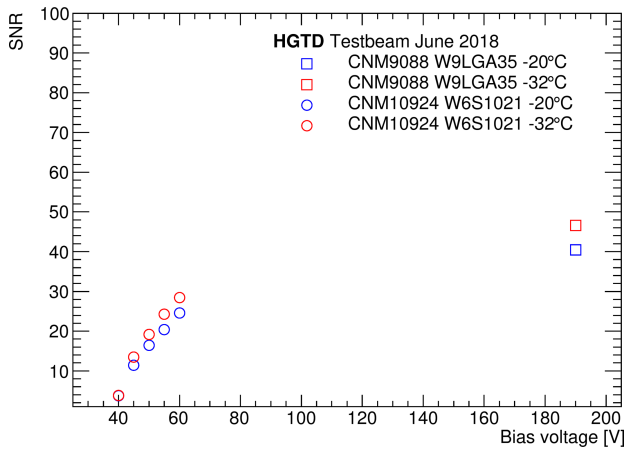


Figure 7: Signal-to-noise ratio of W6S1021 and W9LGA35 at -20°C and -32°C .

When the internal gain of a sensor decreases, the time resolution of the sensor is also decreased with respect to increased temperature. Our result agrees well with the mentioned studies that the trend of both W6S1021 and W9LGA35 in lower temperature (-32°C) gives better time resolution than in higher temperature (-20°C).

6 Concluding Remarks

Several properties of gallium implanted (CNM 10924 W6S1021) and boron implanted (CNM 9088 W9LGA35) LGAD sensors have been investigated. A beam test campaign was conducted in June 2018 to obtain data required for this study using a pion beam with energy of 120 GeV at the CERN SPS facility. A time resolution calculation was carried out using the CFD method with $f_{\text{CFD}} = 0.2$. Preliminary studies show that the boron implanted sensor has a better time resolution than the gallium implanted sensor. Bias voltage variation for W6S1021 shows good agreement with the expected behavior of this sensor when applied to a bias voltage near the breakdown. Variation in temperature result is also in accord with the expected result. Both sensors show better performance in lower temperature. Both sensors have very large signal-to-noise ratio when the maximum voltage is applied.

Considering that the HGTD will be operated in a high radiation environment, a study to comprehend the properties of irradiated sensors is required in the future. An irradiated gallium-doped silicon sensor was unavailable when the June 2018 beam test campaign took place thus the properties of irradiated gallium implanted sensors are still to be studied at future beam test campaigns.

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