Final LGAD Sensors Characterization

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A summary of the characterization of Low Gain Avalanche Detector from the AIDA-2020 Common run manufactured at IMB-CNMI is reported here. Specifically, results are shown concerning the radiation tolerance of LGAD to protons up to a fluence of $10^{15} \text{n}_{\text{eq}}/\text{cm}^2$. Dedicated testing setups using a beta source and a picosecond laser for signal generation were employed. The reduction of the gain and the timing performance degradation against the fluence was studied. The optimum operating voltage was also assessed taking as criterion the appearance of spurious signal (pop-corn noise) beyond a critical bias voltage.
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EXECUTIVE SUMMARY

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1. DEVICE DESCRIPTION AND ELECTRICAL CHARACTERIZATION

The common WP7 run of LGAD sensors at CNM has been completed in February 2019, see figure 1. The devices included samples of the CMS basic matrix\(^1\) with a large-size detector (4x24 matrix, 1x3 mm\(^2\) pads) and active thickness of 45 and 35 µm. Small pad matrices have also been included with the baseline geometry (1.3x1.3 mm\(^2\) pads) foreseen for the ATLAS HGTD. Different widths of the JTE (Junction Terminating Extension), structures have been implemented, with the goal of improving the fill factor of LGAD sensors, by reducing the non-multiplying area between pads. The basic matrix has 63 µm as default distance between adjacent multiplication regions (the JTE is 15 µm wide, plus 14 µm from the JTE to the p-stop and the p-stop is 5 µm wide). In addition, also matrices with reduced inter pad distance (53 and 43 µm) have been implemented. These samples feature narrower JTE width (to 10 µm and 5 µm, respectively).

Diodes of this production with different active thickness and gain were characterized. The IV characteristics was measured with a probe-station and the results are shown in Figure 2.

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\(^1\) During the preparation of the Technical Design Report of the CMS MIP Timing Detector the basic matrix of the sensor was redesigned to optimize the readout ASIC design. Therefore, the matrix design for this AIDA-2020 run does not match the current CMS design. Nevertheless, the AIDA production includes pads with an area identical to the current baseline design of ATLAS and CMS: hence, the studies here reported are still well aligned with the interest of both CMS and ATLAS timing layer collaborations.
The observed reverse current were several orders of magnitude above the values obtained in previous LGAD manufacturing run at CNM. The reason for the large reverse current was found in the too narrow (or even inexistent) overlap between the JTE and the main implant n++. This was an indirect consequence of the redesigning of the pad periphery to reduce the no-gain area between pads. Fortunately, the large DC current did not prevent to carry out the gain and timing studies since in this case the readout of the signal is AC coupled suppressing the large DC component.

2. TIMING ASSESSMENT USING A BETA SOURCE.

The timing resolution has been measured on diodes of the common WP7 production, of 35 and 50 μm thickness, with the following laboratory set-up. The diodes are wire bonded to two read-out boards (UCSC design) with a first stage timing amplifier. The signal is then amplified again with a 36 dB low noise high dynamic range three stage amplifier, and finally read by a fast oscilloscope (40 MS/s 4 GHz bandwidth).

The time resolution is extracted using pair of identical non-irradiated sensors and assuming they have the same characteristic and time resolution. The Time of Arrival (TOA) is extracted using the Constant Fraction method (CFD). This method takes into account that signals with different amplitudes cross a fixed threshold at different times and correct for it.

The TOA difference distribution is plotted for a number of events after some basic quality cut on the amplitude, the RMS and the rise-time. The final resolution will take into account numerous contributions, the most prominent are the Landau effect, and the contributions from the time walk and the jitter.

A time resolution of 25 ps has been achieved for the medium gain 35 μm thick sensors for a CFD cut of 35% (see Figure 3). On the other hand, the low gain sensors performances are worse because of the lower signal to noise ratio.
Comparing the two pair of sensors with the same doping but different thickness we conclude that the thinner sensor reaches the working point at lower bias voltage.

![Time difference distribution](image1)

![time resolution vs CFD](image2)

![time resolution vs CFD](image3)

![time resolution vs CFD](image4)

**Figure 3:** Results on the timing performance of the LGAD diodes with 35 and 50 μm thickness. On the top left picture, the time difference distribution for a CFD cut = 0.36. The distribution is fit and the time resolution of the single sensor extracted assuming that the timing performance of two sensors are identical. In the other 3 boxes: time resolution as function of the constant fraction cut for different bias voltage for the 50 μm (top right) and 35 μm (bottom left) thick diodes. On the bottom right corner, the time resolution is displayed for a diode with 35 μm

3. **ASSESSMENT OF THE GAIN AND TIMING RADIATION TOLERANCE USING A LASER SETUP.**

The study on the radiation tolerance of the LGAD AIDA-2020 common run LGADs was carried out on single pad diodes with an active area of 1.3x1.3 mm² with two active thicknesses: 35 μm and 50 μm. The active area is similar to the area of the CMS and ATLAS baseline design of the pad elements proposed for their MIP timing detectors, see figure 4.

![Figure 4](image5)

**Figure 4:** Layout of the irradiated single pad sensor and cross-section for pad with an active area of 1mm² area.
The diodes were irradiated with protons at the IRRAD CERN facility, five fluence steps were delivered: 6, 10, 30, 100 and 300 (in units of $10^{13} \text{n}_{eq}/\text{cm}^2$). For each thickness and fluence, two diodes were irradiated.

The radiation-induced signal reduction was determined using a laser setup at the Solid State Detector Laboratory at CERN. The experimental stand consists of a picosecond infrared laser that illuminate the diode under study through a square aperture without metallization (optical window). The light-induced pulse is amplified with a CIVIDEC amplifier with a gain of 40 dB and a bandwidth of 2 GHz. After the amplification, the pulse is digitised with a DSO with an analog bandwidth of 2.5 GHz and a sampling rate of 20 Gs per second. The measurements were done at -20 Celsius degrees.

The measured signal amplitudes were normalized to the reference signal provided by a non-irradiated PIN diode with identical to the studied LGADs, except for missing implantation of p+ multiplication layer. The dependence of the signal with the bias voltage and the fluence step is shown in figure 5.

Using the same laser setup the time resolution is measured, more precisely the jitter contribution. First, using different optical components, the laser pulse is split in two pulses, of equal amplitude, then one of the resulting pulses is delayed by a fixed time and, finally, both pulses are recombined. The result is a double peak pulse, see figure 6, with a fixed time interval among them. The interval between the two pulses provides a very precise and stable time standard to

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Figure 5: LGAD signal dependence with the bias voltage for different fluences.

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estimate the jitter contribution to the resolution. Notice that the time difference between the two peaks is not affected by time-walk or Landau fluctuations.

As expected, the signal is reduced with the increasing fluence. Besides, as expected too, the thin diode always achieve a given signal amplitude at a lower bias voltage than the thicker diode. Therefore, for a non-irradiated diode, a given timing resolution can be achieve at a lower bias voltage, see figure 7.

Figure 6 Measured single shot of the double peak pulse used as time standard to determine the timing resolution.

Figure 7: Jitter vs bias voltage for non-irradiated thin (left) and thick diodes(right). The timing resolution achieved is the same for the same SNR figure; though, for the case of the thinner devices less bias voltage is need to achieve a given SNR. The laser amplitude was close to one MIP.

Figure 8: Jitter vs bias voltage for irradiated \(10^{14} \text{ n}_{\text{eq/cm}^2}\) thin (left) and thick diodes(right) The laser amplitude was close to one MIP.
However, for irradiated diodes, a higher signal does not guaranty a better timing resolution. In figure 8, we observe how the Signal-to-Noise ratio (SNR) for the 35 µm thick diode significantly is smaller than the SNR achieved by the 50 µm thick diode at the same fluence point ($10^{14}$ n$_{eq}$/cm$^2$). That is, even though after irradiation the thinner diode has a larger signal than the thicker at a given voltage, the radiation-induced noise is affecting more severely the thin irradiated diode than the thicker and the SNR is degraded. A worst SNR means a worst jitter contribution to the timing resolution.

The timing performance degradation observed in figure 9 is a consequence of the appearance of spurious signal-like pulses (popcorn noise) that prevent the correct determination of the time interval between to pulses. The popcorn noise appears to increase very sharply once the critical voltage is reached (see figure 9) and therefore appears as the main limitation of the thinner diodes in terms of the radiation tolerance comparison between the two samples.

![Figure 9: Waferform for the thin diode irradiated up to a fluence of $10^{14}$ n$_{eq}$/cm$^2$. The sudden increase of the noise observed when the bias voltage is increased just by a 3% explains the sudden timing performance degradation observed in figure 7(left).](image-url)