



# Low Gain Avalanche Detector development for the LHC's High-Luminosity upgrade at Teledyne e2v

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## ABSTRACT

The need for ultra-fast timing is a result of the expected pile-up at the High-Luminosity LHC General-Purpose Detectors. Track timing resolution of the order of tens of picoseconds is required to sufficiently resolve individual vertices. In collaboration with Teledyne e2v, 22 six-inch wafers with Low Gain Avalanche Detectors, featuring a 50  $\mu\text{m}$  thick high-resistivity epitaxial layer and different gain layer implants, have been completed successfully. Using transient current technique, the charge gain of a  $1 \times 1 \text{ mm}^2$  LGAD device from one of the wafers was found to be higher than 10, with jitter reaching 10 ps when biased at 240 V. Tests with other wafers are under way.

## 1. Introduction

After upgrading the Large Hadron Collider (LHC) to the High-Luminosity LHC (HL-LHC), projections estimate that the average number of proton–proton interactions will increase up to 200 per bunch crossing [1]. The overall increase of the number of interactions will result in particles from other interactions (pile-up) being detected alongside particles from the interaction of interest. Consequently, the reconstruction precision will be degraded, and individual interaction may not be resolved [2].

Pile-up suppression can be achieved by including timing information in addition to the spatial measurement. However, the timing resolution must be of the order of tens of picoseconds to disentangle overlapping events [2]. For this purpose, ATLAS plans to include the High-Granularity Timing Detector (HGTD) outside the Inner Tracker, with CMS implementing similar systems. The sensors used in the HGTD are the Low Gain Avalanche Detectors (LGADs) [1], which utilize a highly doped gain layer to achieve timing resolutions of around 30 ps [3,4].

## 2. LGAD production and capacitance measurements

This study presents results from Low Gain Avalanche Detector devices manufactured by a commercial silicon foundry Teledyne e2v (Te2v) based in the United Kingdom. The device design uses a 50  $\mu\text{m}$

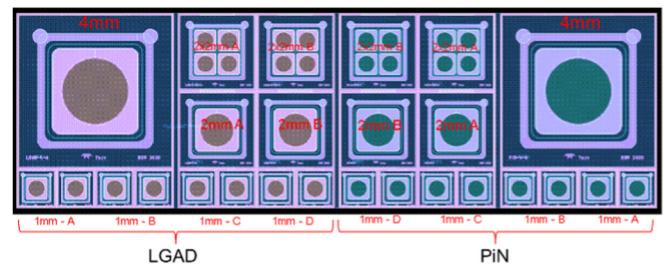


Fig. 1. A section of a wafer with  $4 \times 4 \text{ mm}^2$ ,  $2 \times 2 \text{ mm}^2$ ,  $1 \times 1 \text{ mm}^2$  and array LGAD (left) and PiN devices (right).

epitaxial Si layer with boron used as a dopant to form the gain layer present in the LGADs. The LGADs are compared to PiN diodes of the same layout, which are identical to the LGADs, but lack the gain layer responsible for charge multiplication. LGAD and PiN devices of various sizes are shown in Fig. 1.

As part of the first LGAD production run of Teledyne e2v, 22 six-inch wafers with LGADs were fabricated, with a total of 8 different combinations of manufacturing parameters — gain layer implant dose and gain layer implant energy. The various combinations are listed in

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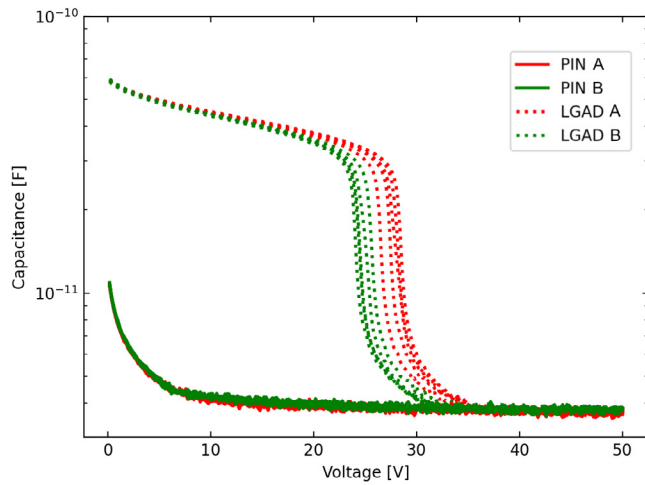


Fig. 2. Capacitance of  $1 \times 1 \text{ mm}^2$  LGADs and PiN diodes from Wafer A and Wafer B as a function of applied bias voltage. Values for 5 individual devices per wafer are shown, with measurements performed at the frequency of 100 kHz.

Table 1

Combinations of manufacturing parameters (gain layer implant dose and energy) featured in the first LGAD production of Teledyne e2v with the corresponding Wafer codes.

| Wafer code | Gain layer implant dose <sup>a</sup> | Gain layer implant energy <sup>a</sup> |
|------------|--------------------------------------|----------------------------------------|
| A          | 1.07                                 | 1.11                                   |
| B          | 1.07                                 | 1.05                                   |
| C          | 1.07                                 | 1.00                                   |
| D          | 0.92                                 | 1.05                                   |
| E          | 1.15                                 | 1.05                                   |
| F          | 1.00                                 | 1.00                                   |
| G          | 1.00                                 | 1.05                                   |
| H          | 1.00                                 | 1.11                                   |

<sup>a</sup>Normalized to a reference value — arbitrary units.

Table 1. Fig. 2 shows the capacitance of  $1 \times 1 \text{ mm}^2$  LGAD and PiN devices from Wafers A and B, as a function of applied bias voltage. Due to a broader gain layer formed by higher implant energy, the LGAD devices from Wafer A exhibit a higher depletion voltage compared to those from Wafer B.

### 3. Charge gain and jitter measurements

The charge gain and jitter measurements were performed by using a Transient Current Technique (TCT) [5], with a 1064 nm laser produced

by QD Laser (QLD106G-6410, manufactured in Kawasaki, Japan) as the source of monochromatic beam of photons. The energy delivered by one laser pulse can be approximated to that of a minimum ionizing particle (MIP). The tested LGAD and PiN devices were of  $1 \times 1 \text{ mm}^2$  size, chosen from Wafer A. It was observed, that after laser dicing of the wafers, the breakdown voltage of the devices decreased. This decrease was at least partially reversed by thermally annealing the devices for 2 h at  $150^\circ\text{C}$ . The devices were bonded to a Santa Cruz Readout board v1.1 which acts as a first stage transimpedance amplifier. A second stage amplifier (FEMTO HAS-X-2-40) was used to further amplify the signal, which was then read out by a Rhode&Schwarz RTP044 oscilloscope (sampling rate 20 GSa/s, bandwidth 4 GHz, digital low-pass filter applied at 1 GHz to suppress noise with no significant effect on the device signal waveforms). The effect of the two amplification stages was simulated using SPICE and their combined gain was determined to be 92.5 dB for  $1 \times 1 \text{ mm}^2$  devices with input capacitance of 2 pF (approx. constant up to 1 GHz).

#### 3.1. Collected charge and charge gain

The area under the LGAD and PiN signal is calculated by numerical integration of the waveform within a 3 ns window that contains the signal — an example waveform is shown in Fig. 3. By measuring the area under the signal and using the estimated gain of the chain of amplifiers, the charge collected by the individual  $1 \times 1 \text{ mm}^2$  devices under test was determined. Assuming that the only difference between the LGAD and the PiN is the absence of the gain layer in the latter, the ratio of their respective collected charge gives the charge gain of the LGAD. All measurements were taken at room temperature. The data is visualized in Fig. 4.

#### 3.2. Jitter measurements

The intrinsic jitter of the devices was investigated using the same setup at room temperature, by measuring the standard deviation (spread) of the time delay between the laser trigger signal and 50% of the LGAD signal amplitude. In general, the standard deviation of the delay is regarded as the timing resolution [2], however as we were using a monochromatic laser and kept the target position the same, the spread of the delay is not affected by Landau and distortion contributions. Since these contributions are not present, the delay spread is dominated by the intrinsic jitter of the device, assuming negligible contributions from the laser pulse, trigger, and the amplifiers. Under such conditions, we use the delay spread as a measurement of the intrinsic jitter (at least its upper bound).

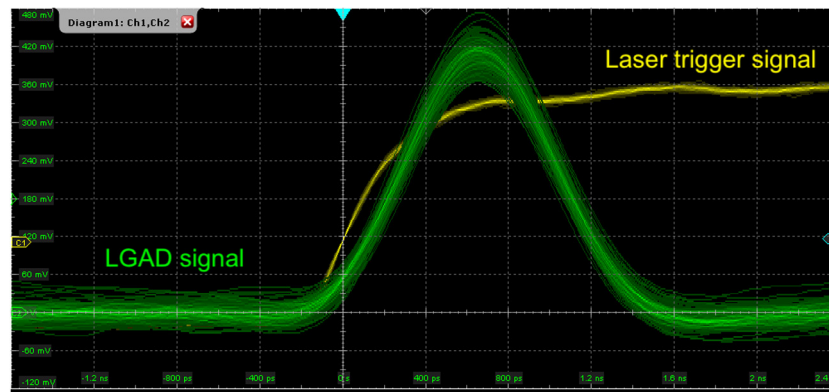


Fig. 3. Rhode&Schwarz RTP044 oscilloscope output showing laser trigger signal (yellow) and an example LGAD signal waveforms after two stages of amplification (green). A bias voltage of 200 V is applied across the LGAD device under investigation. The displayed span of the horizontal and vertical windows are 4 ns and 600 mV, respectively (the vertical span only applies to the LGAD signal and not the Laser trigger signal).

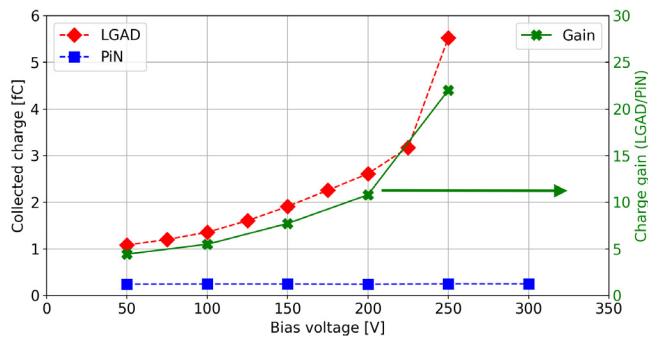


Fig. 4. Charge collected by  $1 \times 1 \text{ mm}^2$  LGAD and PIN diode from Wafer A, as a function of applied bias voltage. The laser is set to deliver a MIP-equivalent signal. The green cross-markers show charge gain of the LGAD device as a function of applied voltage (see right axis).

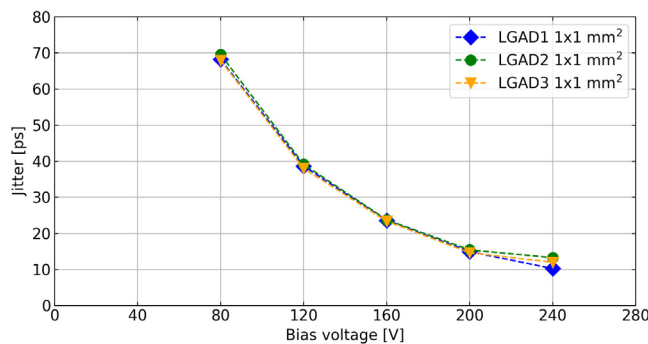


Fig. 5. Jitter of three  $1 \times 1 \text{ mm}^2$  LGAD devices from Wafer A as a function of applied bias voltage measured at room temperature.

The results for three  $1 \times 1 \text{ mm}^2$  LGAD devices from Wafer A are shown in Fig. 5 as a function of applied bias voltage across the LGAD. No stray contributions to the jitter (for example those caused by the amplifier) were subtracted at this stage.

## 4. Conclusion and discussion

The performance of LGAD devices from the first LGAD production run of Teledyne e2v was demonstrated, with  $1 \times 1 \text{ mm}^2$  LGAD devices from Wafer A achieving charge gain greater than 10 at bias voltage above 200 V. The obtained minimum jitter of 10 ps is comparable to measurements performed on unirradiated LGAD devices from CNM Run 13002 [6]. Further investigation into the other timing resolution components is planned. Additionally, we are preparing further jitter and timing measurements using the other available wafers to compare their performance.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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