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To cite this article: J. Mulvey *et al* 2022 *JINST* 17 C10001

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Preliminary test results of LGADs from Teledyne e2v for the LHC's High-Luminosity upgrade

J. Mulvey,^{a,*} P. Allport,^a R. Bell,^b D. Bortoletto,^c M. Gazi,^c L. Gonella,^a D. Jordan,^b
I. Kopsalis,^a S. McMahon,^d R. Plackett,^c K. Stefanov,^e E.G. Villani^d and M. Watkins^b

^aThe University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom

^bTeledyne e2v, 106 Waterhouse Lane, Chelmsford, Essex, CM1 2QU, United Kingdom

^cThe University of Oxford, Parks Road, Oxford, OX1 3PU, United Kingdom

^dRutherford Appleton Laboratory, Harwell Campus, Didcot, OX11 0QX, United Kingdom

^eThe Open University, Walton Hall, Kents Hill, Milton Keynes, MK7 6AA, United Kingdom

E-mail: jfm035@student.bham.ac.uk

ABSTRACT. This paper presents initial testing of the first batch of LGAD sensors fabricated by Teledyne e2v in collaboration with the University of Birmingham, University of Oxford, Rutherford Appleton Laboratory and the Open University. Wafers with different energy and dose of the gain layer implant have been characterised with IV, CV and gain measurements. The same set of measurements were made using PiN diodes fabricated on the same wafer as a reference. Results are in-line with expectations and with LGADs produced at more established vendors. Preliminary results suggests Te2v LGADs have a moderate gain in the order of 10 to 50 before irradiation at operational voltages well below breakdown, as required for optimal timing resolution.

KEYWORDS: Timing detectors; Particle tracking detectors; Si microstrip and pad detectors; Radiation-hard detectors

*Corresponding author.

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1 Introduction

The LHC's High-Luminosity upgrade will see a large increase in pile-up with up to 200 events per bunch crossing (25 ns) [1]. These overlapping events make track reconstruction challenging and this limits the ability to correctly associate tracks with their primary vertices. To aid with track reconstruction, ATLAS and CMS plan to use dedicated timing layers installed outside of the trackers to add fine timing information to each track [1, 2]. The technology chosen for these timing layers is Low Gain Avalanche Detectors (LGADs) [3]. An LGAD is an n-well in p-bulk sensor with an additional boron implant which gives the sensor an intrinsic gain and good time resolution on the order of 30 ps [4]. LGADs for the ATLAS and CMS timing layers are a mature technology fabricated at many well established vendors, such as Hamamatsu, CNM and FBK [5–7]. This paper presents results from the first LGAD fabrication batch from Teledyne e2v (Te2v), a silicon foundry based in Chelmsford, U.K. Te2v has been primarily involved in developing and manufacturing CCDs for science applications, particularly in space and astronomy, with the capability for high production volume of silicon sensors.

2 Sensor design

The initial batch of 22 wafers from Te2v came out of fabrication in November, 2020. Eight varieties of different implant energy, E , and dose, D , of the gain layer were produced to study the optimal doping density and depth of the gain layer for this process. Each variant had up to three identical wafers which could be tested at the University of Birmingham, the University of Oxford, the Rutherford Appleton Lab (RAL) and at Te2v. The gain layer is produced by implanting boron atoms in the wafer during fabrication.

In each test field, shown in Figure 1, there are: eight 1 mm devices, two 2×2 1 mm arrays, two 2 mm devices and one 4 mm device. This structure is mirrored down the centre of each field to give a set of LGADs and a set of PiNs (without the gain layer). Besides the 4 mm device, each of the other sized devices have different flavours where properties, such as the distance from pad to guard ring, are varied. For the 1 mm devices, there are four flavours with each coming as a

pair. Each test field on a wafer is identical except for where on the wafer it is located, meaning uniformity of the wafer can be checked by comparing different test fields.

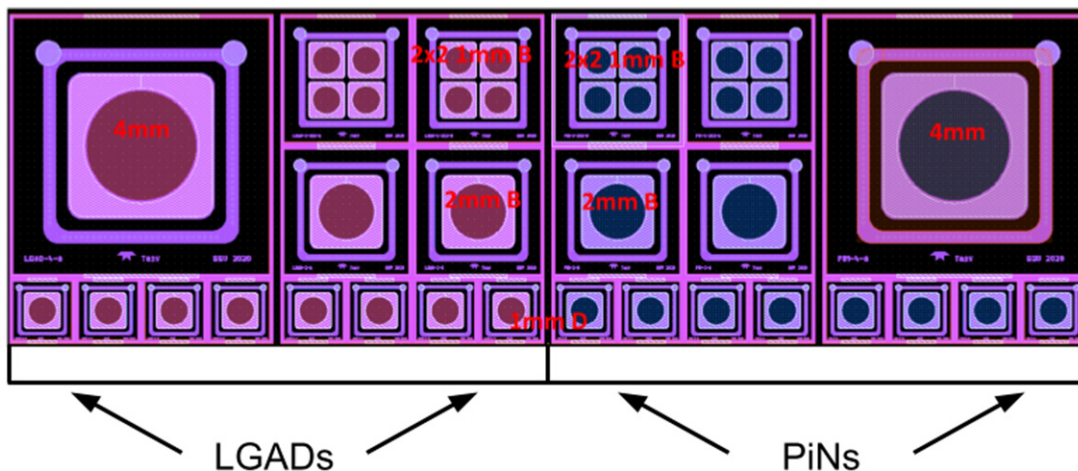


Figure 1. An example test field from the wafers in batch one. Each test field contains LGADs and PiNs of various sizes and flavours. Each test field on a wafer is identical other than where on the wafer it is located.

3 Preliminary characterisation

The first characterisation of a device is the measurement of its leakage current as a function of voltage up to breakdown. Figure 2(a) shows a sample of IV curves for 1 mm devices of a wafer with the lowest gain layer implant energy for this first fabrication batch. For 1 mm devices, there is little difference between LGADs and PiNs. From the IV curve, a breakdown voltage can be determined. Breakdown can be defined as a significant increase in leakage current as a function of bias voltage. The K -factor characterisation method is one way of numerically defining the breakdown. The K -factor, K , is defined as,

$$K = \frac{V}{I} \cdot \frac{dI}{dV}, \quad (3.1)$$

where V is the bias voltage applied across the device and I is the current flowing through it [8]. A value of $K = 4$ is chosen and defined as “soft breakdown”. The breakdown voltage using this method can then be plotted against the normalised wafer implant energy as seen in Figure 2(b). The PiNs contain some variability in their breakdown voltage but there is no clear trend with implant energy, as expected, given there is no gain layer. However, the LGAD’s clearly see a decrease in breakdown voltage as the implant energy increases. It should be noted that the implant dose was not the same for each of these three wafers, although the wafer with the highest implant energy also had the highest implant dose.

The dependence of capacitance on applied voltage gives a measure of the variation of doping concentration with depth. Figure 3(a) shows the CV curves for 1 mm and 4 mm LGADs and PiNs. The difference in capacitance between the two sizes is consistent with the factor of 16 difference in the area. The change in shape between LGADs and PiNs is also expected. As the bias voltage

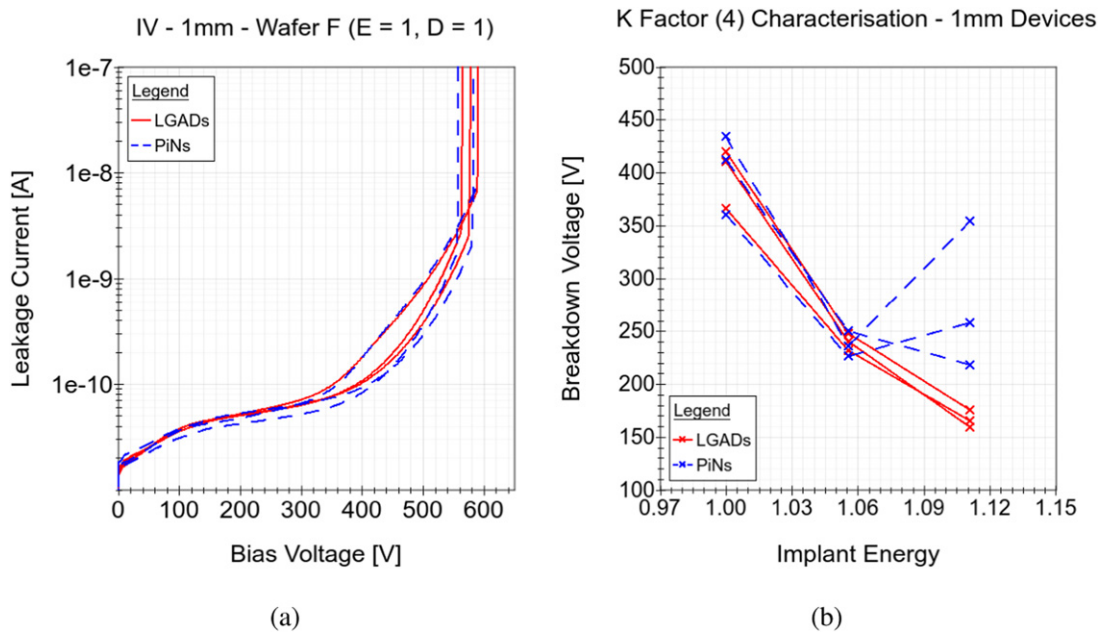


Figure 2. (a) Example IVs for 1 mm devices. Onset of breakdown begins at around 400 V, but full breakdown does not occur until around 575 V. (b) Breakdown voltage as a function of implant energy. Breakdown is defined using the K -factor method. Note that the implant dose is not the same for each wafer.

increases, the thickness of the depletion region of the sensor increases, decreasing the capacitance. For a PiN, this happens very quickly and the bulk is fully depleted within around 10 V. For an LGAD, the gain layer must be depleted first. Since the gain layer is more strongly doped, it takes around 20 V to 30 V to deplete and then a further 10 V for the bulk to deplete, just like the PiN. The voltage at which the gain layer and bulk deplete (the latter known as full depletion) can be identified and plotted against the normalised implant energy. Figure 3(b) clearly shows that the LGAD’s gain layer depletion and full depletion voltages increase for the highest implant energy, suggesting that the gain layer is deeper. As expected, the difference between the gain layer and full depletion voltages remain fairly constant for each implant energy. The PiNs show some variability between each other, but there is no correlation between full depletion voltage and implant energy, as expected.

The intrinsic gain of an LGAD was investigated by injecting charge with a 1064 nm pulsed laser. The resultant signal from the LGAD is then amplified and triggers an oscilloscope. This signal is then integrated over a specified time window and this is repeated over a range of voltages as well as for the PiN. By assuming the PiN has a gain of approximately one, the ratio of integral for LGAD to PiN can be calculated and plotted as a function of voltage as done in Figure 4. So far, these preliminary results show good agreement with each other, irrespective of the laser conditions or electronic readout. There is also good agreement when comparing results taken at the University of Birmingham with those taken at the University of Oxford, also shown in Figure 4. The gain of these LGADs range from 10 to ~50 depending on the bias voltages. This is in line with results from other LGADs produced and tested within the RD50 collaboration [9].

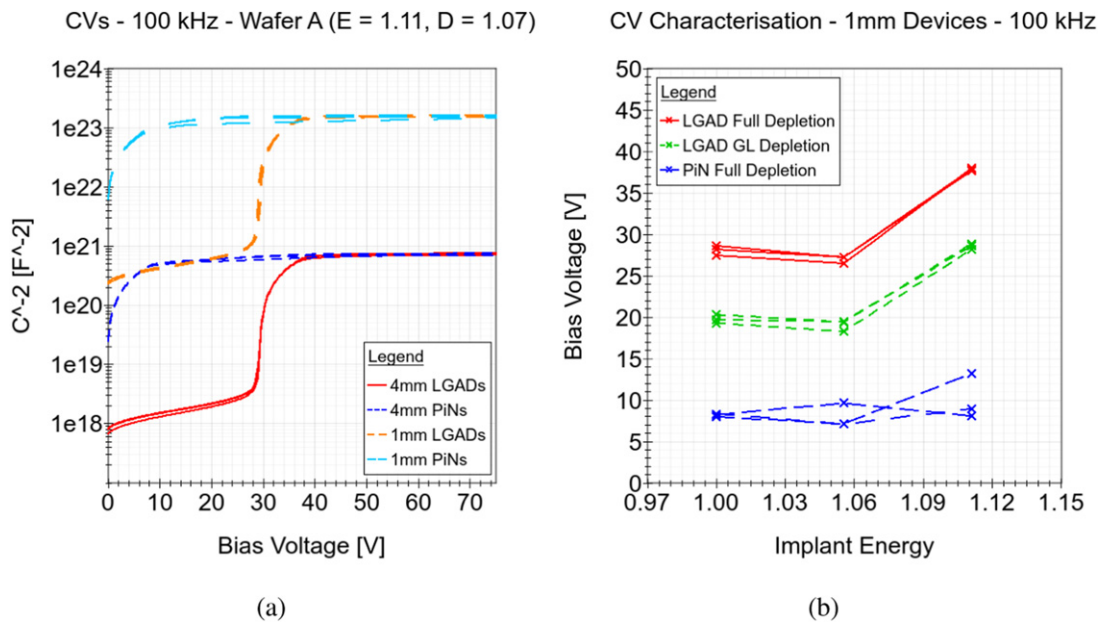


Figure 3. (a) Example CV curves measured at 100 kHz where the inverse square of the capacitance is plotted as a function of bias voltage. (b) As a function of wafer implant energy, the various depletion voltages are calculated and compared.

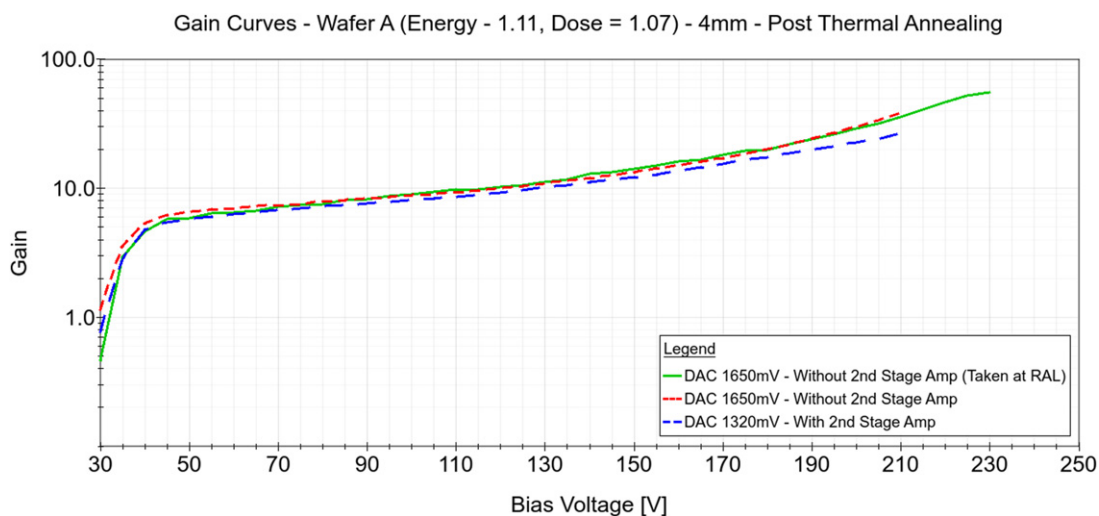


Figure 4. The intrinsic gain of an LGAD as a function of bias voltage. The gain of a PiN is assumed to be one.

4 Conclusions and outlook

Three different wafers with varying implant energy and dose for the gain layer have undergone initial testing and characterisation. The presence of a gain layer has been shown through capacitance

measurements when compared to PiNs. The implant energy/dose was also shown to have an impact on the depletion region of the LGADs as well as their breakdown voltages. However, more work is needed to test more variations of wafers to identify whether the implant energy, dose or both cause this correlation. Preliminary gain measurements have also demonstrated the gain lies in the expected range of 10 to 50. Looking forward, gain measurements need to be refined to ensure laser conditions and readout electronics are consistent and hence comparable. Of course, the next major step is to commission an experimental setup to measure the timing properties of these LGADs, ensuring that they can reach the ~ 30 ps time resolution required.

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