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Characterisation and Initial Measurements of Pixellated LGAD Sensors for Soft X-Ray Spectroscopy

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Introduction:

Low-Gain Avalanche Detectors (LGADs) have seen prominent usage and development over the last 10 years in High Energy Physics. This is attributed to the High-Luminosity upgrade proposed for the Large Hadron Collider (HL-LHC). These silicon-based devices benefit from a strong electric field characterised by their intrinsic gain layer to produce fast rise times and a **signal gain of *x5-x20***, through an avalanche charge amplification process [2][1][8]. Recently there has been significant interest in using LGAD devices for X-ray detection in the **low energy range (*250 eV −2 keV*)**. Signals relating to photons in this energy range are normally indetectable above the noise produced by a system's readout electronics [4]. The controlled signal amplification provided by the LGAD aims to separate these low energy photons signals from the noise floor.

A particular area of ongoing research relates to the development of pixellated LGAD sensors for soft X-ray spectroscopic imaging. However, the challenge here is creating a gap in the gain layer to isolate individual pixels. An abrupt change in doping between the gain region and bulk silicon produces a strong electric field across this interface, leading to premature electrical breakdown within the detector.

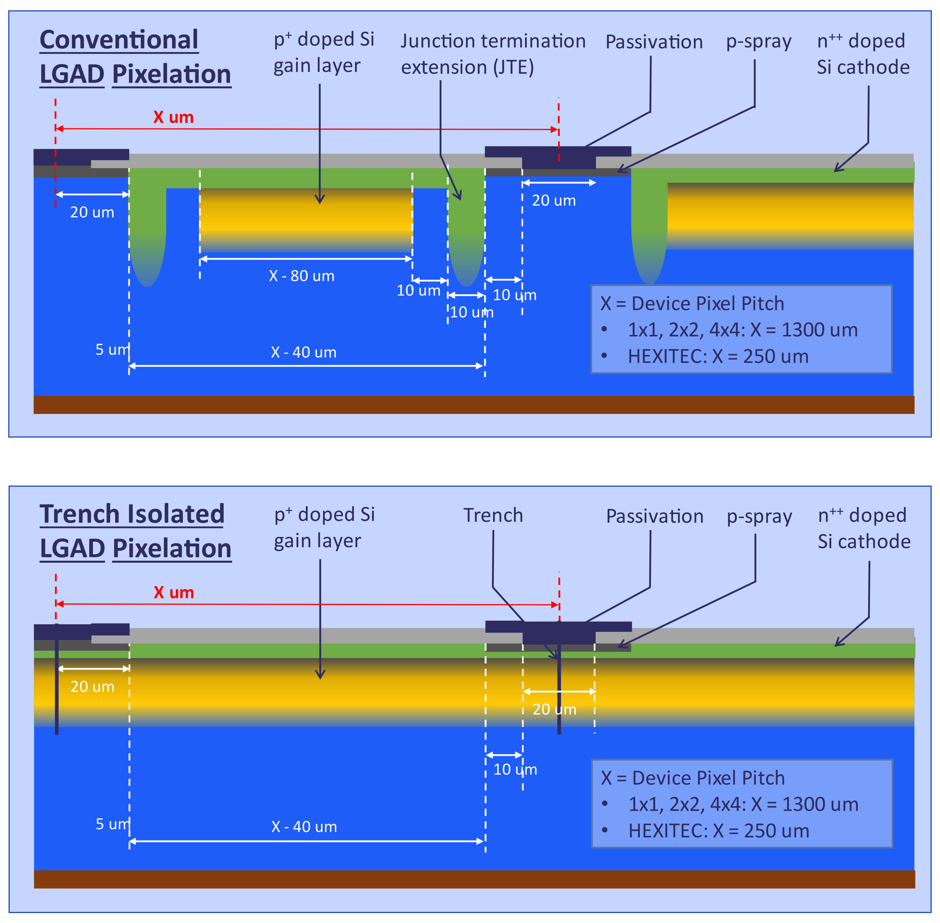

Figure 1: Pixelation schematics for Conventional LGADs (**top**) and Trench Isolated LGADs (**bottom**). The dimensions given relate to the devices obtained from Micron Semiconductor Ltd[4].

Two common methods of LGAD gain layer pixelation commonly employed are:

1. Use of a **Junction Termination Extension (JTE) – [Conventional]**
   Structures of moderate n doping extending from the pixel cathode into the bulk, dispersing the high electric field
2. **Trench Isolation** between pixels – **[Trench]**
   5 um deep and 1 um wide trench etched around each pixel to isolate the gain and cathode regions

LGAD devices were designed in-house, implementing both these methods of pixelation, and manufactured by Micron Semiconductor Ltd. We obtained small pixel arrays sensors (1x1, 2x2 and 4x4 pixels) of *1300 µm* pitch, manufactured on *500 µm* thick float zone silicon with a gain layer doping of *1.2x10¹³ cm⁻³*. Complementary silicon devices of identical geometry were manufactured to act as a control. These multi-pixel devices were bonded to gold-plated ceramics, where wirebonds to the guard ring and individual pixels could be jointly or independently connected to outputs for data collection.

In addition to these multi-pixel devices, LGAD sensors of the same gain layer doping and pixelation methods were designed and manufactured as an 80x80 array of pixels with a pitch of *250 µm* to be interconnected with a HEXITEC ASIC [6] for readout.

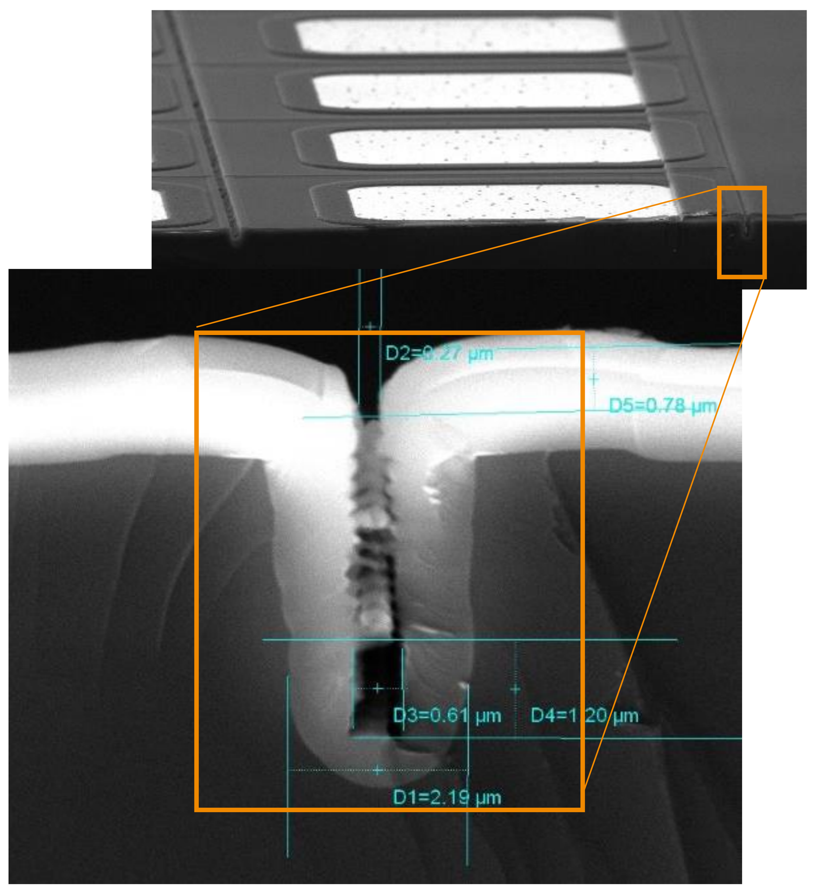

Figure 2: Cross-section obtained of Trench Isolated LGAD device showing trench dimensions. Images provided by Scottish Microelectronics Centre[3].

I-V Sweep Data:

For each device type (conventional, trench & standard p-type silicon) and geometry (1x1, 2x2, 4x4 & HEXITEC) a Current-Voltage Sweep was conducted to characterise the performance of the LGADs, to measure the leakage current output from the sensor during operation and identify the depletion voltage of the sensor's gain layer.

The silicon sensors behave as expected, with the leakage current, (Current Density) slowly increasing. The LGAD devices display their typical characteristic I-V trace [1][5], with the current density plateau from ***-50 V* to *-200 V* bias** indicating the **depletion of the intrinsic gain layer**, giving the sensor's operating voltage region. However, the recorded leakage current for these devices was measured to be very high *(~100 mA)*.

Departures from this trend seem to be present for the HEXITEC devices. These have the most consistent leakage current density across the 3 detector types, however, the characteristic knee in is not present for the LGAD devices but is instead shown for the silicon sensor.

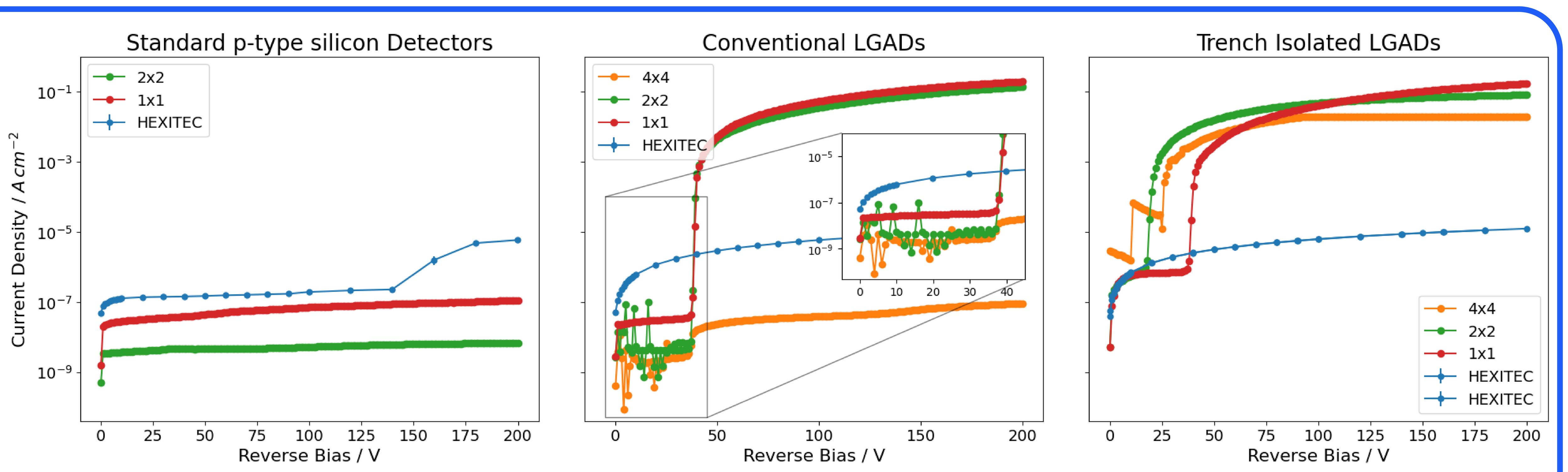

Figure 3a: I-V Characteristic for (**left**) standard p-type silicon detectors (**middle**) conventional LGAD devices and (**right**) trench isolated LGAD devices.. Data is displayed for 4x4, 2x2, 1x1 and HEXITEC devices. Leakage current has been scaled with detector area to be plotted as current density for better comparison across devices.

Alpha Source Spectroscopy:

Standard p-type silicon sensors and LGAD 4x4 devices were irradiated on the pixelated anode by an Am-241 alpha source, unlike the HEXITEC LGAD hybrids (cathode illumination). The alpha particle deposits energy in the pixel surface, causing holes to move through the gain layer and silicon bulk towards the cathode due to the applied bias. This transient charge induces a signal in the pixelated anode which is measured on each device. The distributions of detected alpha particle signal pulse heights and rise times are presented in **Figure 5a and 5b** for both the 4x4 LGAD device and a 2x2 silicon device.

For increasing negative bias across the LGAD sensor, the signal pulse height spectra shifts to higher values as the gain layer becomes more depleted, and the spreading of the spectra indicates an increasing variation in pulse heights (**Figure 5a**). The mean of the peak height distribution at *-80 V* bias is ***~3.2*** times the pulse height measured by the standard p-type silicon sensor. Given that holes were the primary charge carriers, and the impact ionisation coefficient for holes is a factor of 3 smaller than that for electrons, a lower gain is to be expected. The pulse height spectra broadening (particularly for reverse bias voltages ≥ *45 V*) and the variability in calculated rise times (**Figure 6a**) in these LGAD devices suggests that the gain layer within the detector is **not uniformly fully depleted**. This requires further investigation.

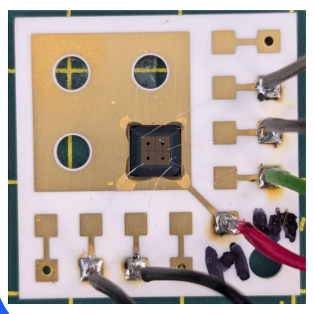

Figure 4a (left): 2x2 LGAD device on gold plated ceramic. Negative bias supplied through back plate.

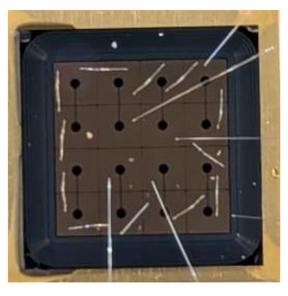

Figure 4b (right): 4x4 LGAD device. The outer ring of pixels are wire bonded together to act as an additional guard ring.

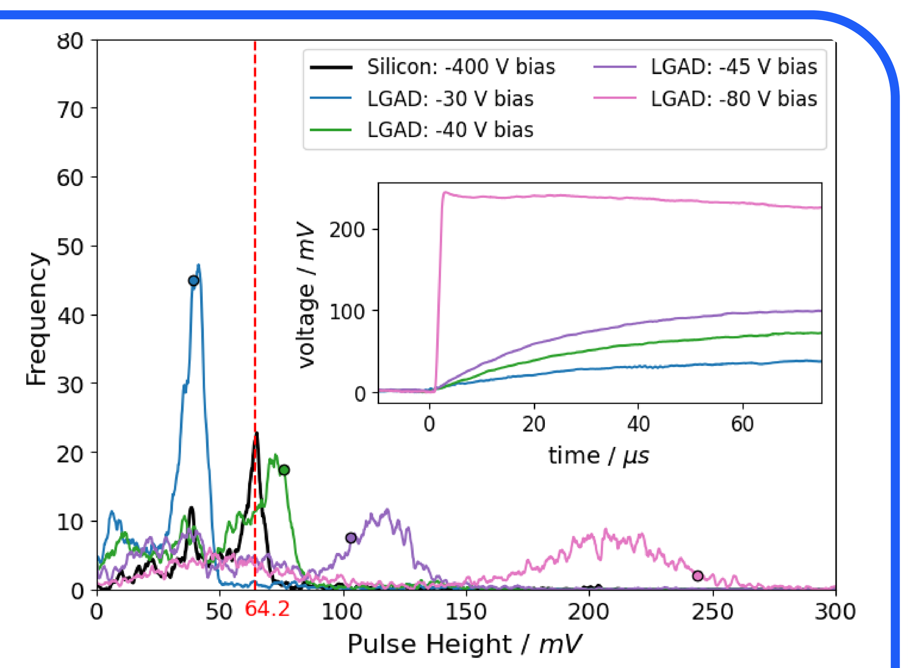

Figure 5a: Pulse height spectra for an Am-241 alpha particle source, measured under vacuum with 4x4 LGAD and 2x2 silicon devices over a range of reverse bias voltages to probe stages of sensor depletion. (Inset) indicates the measured preamplifier pulse shape at each coloured pulse height marker.

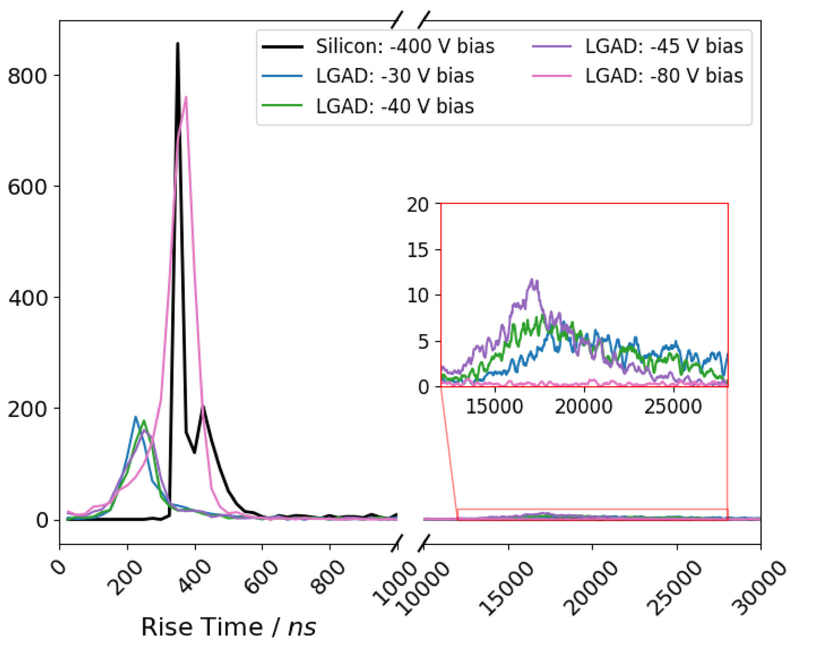

Figure 5b: *10%* to *90%* rise time spectra for an Am-241 alpha particle source, measured under vacuum with 4x4 LGAD and 2x2 silicon devices. (Inset) shows longer rise time signals obtained by the LGAD sensor.

Sealed Source Testing with HEXITEC:

HEXITEC (High Energy X-ray Imaging Technology) is a spectroscopic X-ray imaging camera system developed by the STFC Rutherford Appleton Laboratory [6]. We decided to utilise this system to readout the full array of pixels from the LGAD sensor simultaneously, providing some spatial information to the gain response. The HEXITEC LGAD hybrid devices were exposed to an Fe-55 sealed source with primary photopeak at an energy of ***5.9 keV***, for a 5-minute continuous data collection. The device was operated at *-300 V* bias for gain layer depletion. A Silicon HEXITEC hybrid of identical geometry was used as a non-gain control.

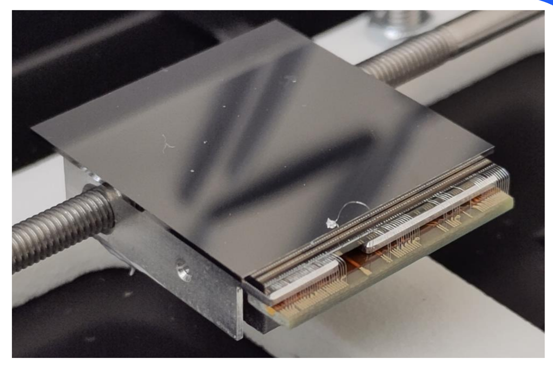

Figure 6: Image of LGAD HEXITEC hybrid detector used for taking sealed source measurements.

The array averaged spectra for both devices is shown in **Figure 7a**. The single Fe-55 photo peak present at *~250 ADU* in the silicon sensor data has been spread out over a range of higher energy ADU bins in the LGAD data; individual pixel spectra display this in more detail (**Figure 7b**). This is as expected for a depleted gain layer. The regions of apparent gain are localised to hotspots as indicated by the colour plots of Region B shown in **Figure 7a**. This supports previous speculation that there is non-uniform gain layer depletion across the detector area.

The spectral peak obtained from pixel (28,6) has its maximum at *~1000 ADU* which would correspond to a ***x4* gain** compared to that measured by the identical silicon HEXITEC sensor (*~250 ADU*). This level of gain is consistent with typical LGAD gain measurements from literature; however, this is only true for 1 pixel in the 80x80 array. Again, lending credence to the idea of spatial non-uniformity in the gain layer depletion or suggest that these hotspots relate to localised defects.

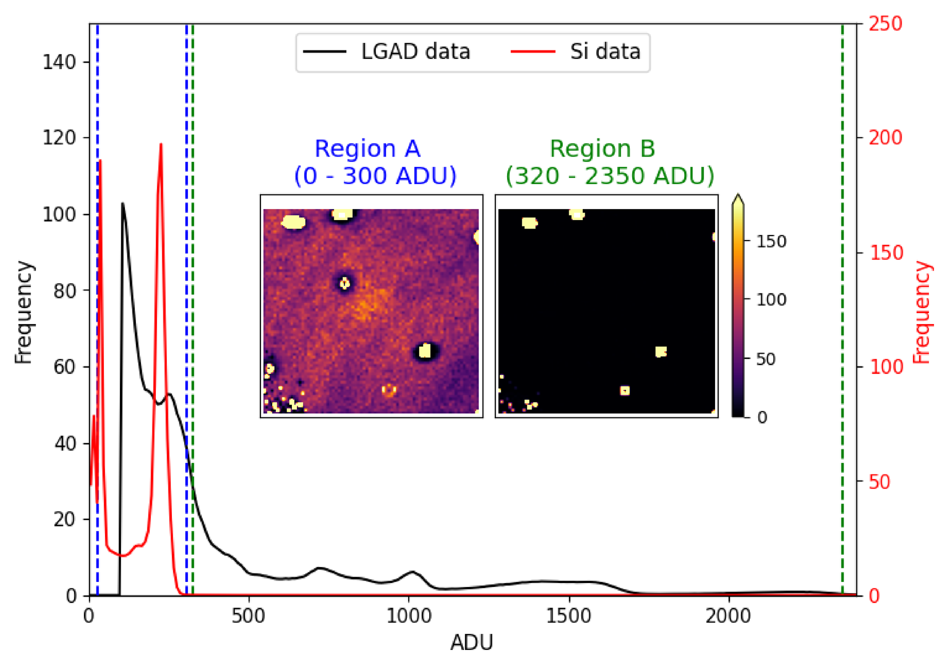

Figure 7a: Array averaged spectral data for the LGAD and silicon HEXITEC hybrid detectors. The pixels in the LGAD sensor's array which have a substantial count in the energy region indicated by region A (left inset – blue) and region B (right inset - green) are displayed.

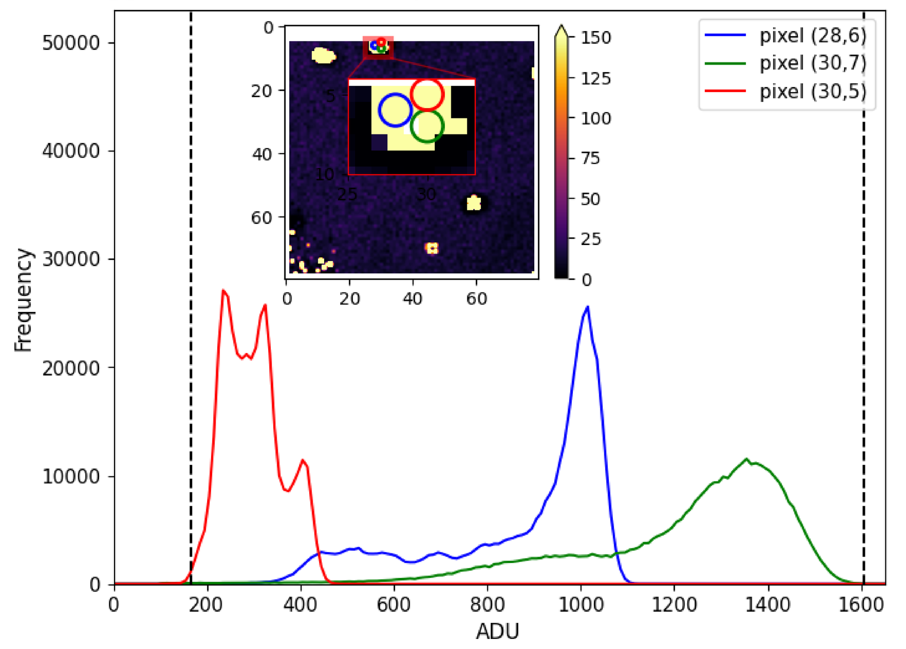

Figure 7b: Spectral data for specific pixels within the LGAD array which have a high number of counts. (Inset) indicates these contributing pixels' locations within a hotspot. These regions seem to indicate localised gain depletion or potential premature breakdown.

Summary & Future Work:

- Low-Gain Avalanche Detector devices irradiated with sealed sources have shown approximately *x3* gain when primary charge carriers are holes and *x4* gain for electrons compared to standard p-type silicon sensors of identical geometry.
- LGAD leakage current is shown in the region of *100 mA* for bias voltages in the range of *-50 V* to *-200 V.*
- Alpha particle and X-ray sealed source measurements indicate non-uniformity in gain layer depletion across the array.
- Further testing to understand this gain layer depletion uniformity and to investigate the effect that a continuous gain layer (trench isolated LGADs) may have.
- Additionally, an I-V measurement and illumination with a *1064 nm* laser will be conducted in an environmental chamber such that the device can be cooled to compensate for the high leakage current.

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