CHARACTERIZATION OF ELECTRICAL PROPERTIES OF LOW GAIN AVALANCHE DIODES

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Abstract

Low Gain Avalanche Diodes (LGADs) are a type of silicon detector based on the Avalanche Photo Diode (APD), a preceding silicon-based detector technology. First fabricated at the Institute of Microelectronics of Barcelona (IMB-CNM), LGADs have been designed to be especially suitable for use in high energy physics experiments like the LHC. Part of this Summer Student Project involved measuring the dependence of the efficiency and charge collection of an LGAD pixel on temperature and applied reverse bias voltage. The laboratory setup used to test the LGAD was made remotely accessible via a pre-existing LabVIEW based Timing Control Automation Software and the use of TeamViewer. The data collected from these lab tests was analysed using another pre-existing C++ and ROOT based analysis framework. The results from the data were interpreted and visualized using C++ and pyROOT. The LGAD tested showed the expected increase in charge collected and increase of efficiency with respect to increasing applied reverse bias voltage. In addition, the maximum efficiency was reached at notedly lower voltages at lower temperatures. This report describes the measurement and analysis procedure carried out to obtain these results.

INTRODUCTION

How Charge Is Collected in Silicon Detectors

Silicon diodes can be used to detect minimum ionizing particles (MIPs) by applying a reverse biased voltage across them. This voltage creates an electric field that pulls charge carriers (electrons and holes) away from the p-n junction of the diode, leaving a depletion zone that can be increased across the whole diode. When an ionizing particle goes through this depletion zone, it produces free charge carriers that then drift to their respective electrodes, inducing a charge that can be read out from the diode by external electronics. The electrical signal readout is proportional to the amount of energy deposited by the incident MIP.[1]

The Structure of Low Gain Avalanche Diodes (LGADs)

A low gain avalanche diode is designed to leverage the avalanche effect that happens when the diode is subjected to a high electric field[2]. The field can be made high enough to accelerate charge carriers as they drift to their respective electrodes, so that they cause secondary ionization and consequent charge multiplication[9]. This amplifies the signal that is read out. By introducing a second moderately doped p type gain layer under the highly doped n type layer of the diode, an "amplification" region is created just beneath the collecting electrode[3]. The region of high electric field created in this gain layer is what makes secondary impact ionization possible[2]. With an electric field that is approximately 300kV/cm, only electrons are responsible for the charge multiplication produced by impact ionization and the signal is amplified by a factor of about 10[4]. This moderate gain helps to increase the signal to noise ratio (SNR) of the diode, giving LGADs their advantage over APDs. A high SNR means signal events are well distinguished from noise events and the signals read out are better[3].

LAB SETUP AND DATA ACQUISITION (DAQ) SOFTWARE

The Charged Particle Measurement System

The lab setup was a Charged Particle Measurement System, used to test the LGADs. It consisted of a climate chamber, and an aluminum frame where a radioactive source (Sr90 sample) and two sensors i.e the Device Under Testing (DUT) and Trigger, were aligned. The frame was placed inside the chamber. External electronics also connected to this setup included first and second stage amplifiers, Low Voltage and High Voltage Power Supplies, and an oscilloscope. Adjustments to the compliance levels, low voltage settings for these external electronics, high voltage and oscilloscope settings for the entire setup were made via a Timing Control Automation Software.

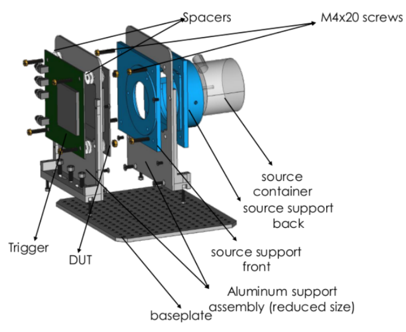

Figure 1: Charged Particle Measurement System

The Timing Control Automation Software

The LabVIEW based data acquisition software used was organized into four user interface tabs. The user has control of all High Voltage, Low Voltage, Temperature, Oscilloscope and Triggering Mode settings, as well as charged particle and

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auto-trigger sequencing and programming settings through its graphical interface. A fifth tab that shows the waveform of each signal read in real time was also available, but only during data taking[5, pg. 14-21].

To detect the charged particles emitted from the radioactive source, a high, reverse biased voltage was applied across the sensors incrementally, until they were fully depleted. The temperature and voltage points at which the LGADs were tested were preset before the data taking process began. With the oscilloscope set to coincidence trigger (i.e record a signal only when both the DUT and the Trigger recorded an event above a given threshold), a total of 5000 events were recorded for each voltage point. The three temperatures tested were -25C,-15C and -5C (temperature and voltage points shown in Figure 2 below are not the actual points that were used during data taking).

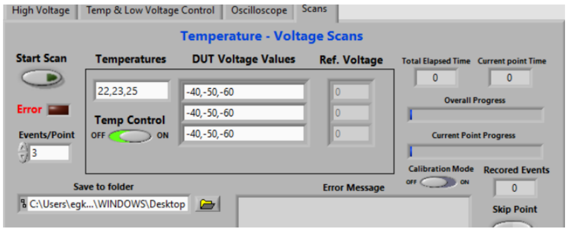

Figure 2: An example of what the fourth tab of the LabVIEW DAQ Software looks like

The signal generated at each event was then converted to a digital signal by the oscilloscope. This data was then written to text files for further analysis.

ANALYSIS

Fits and Probability

The C++ based analysis framework that was used to interpret the data[5, pg. 26-54] performed a range of tasks implemented through several classes. These tasks included converting the text files to Root files, analysing the details of each waveform recorded from each event, then taking all the waveforms recorded from a single channel (i.e from one sensor) and analysing those. Multiple fits[5, pg. 35] were also applied to the analysed data, to extract the values that would be used to study the efficiency and charge collection of the sensors. These results are presented below.

Median Rate and Efficiency

Sr90 (Strontium 90), the charged particle source used during these lab tests, is a radioactive isotope of Strontium that undergoes β^- decay. The rate of decay events can be described by an exponential probability distribution because this rate follows the exponential decay law [eq (1)].

$$A = A_0 e^{-\lambda t} \quad (1)$$

where A is the rate at which radioactive particles are emitted, λ is the probability of decay per nucleus per unit time (the decay constant) and t is the time[6].

It follows then that the number of events recorded while the sensors were being tested can be described by a Poisson probability distribution. By recording these events in a histogram, the median rate recorded was calculated and used to characterize how the sensor's efficiency increases with voltage[Figures 3,4]. The recorded median rate, and therefore the efficiency of the sensor increased with applied voltage. This is because the volume of the detector that is sensitive to the ionizing particles emitted by the decaying source increases as higher voltages are applied to the sensor. At lower applied voltages, some events are not recorded because the incident particles are reabsorbed as they go through the non-depleted regions of the sensor. This is why the recorded median rate is lower at low voltages. Further increases in voltage beyond the maximum depletion point send the sensor into breakdown.

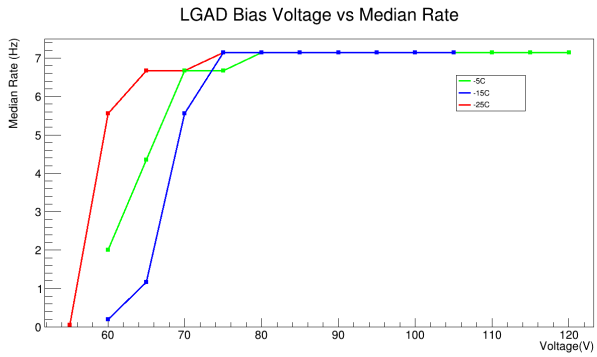

Figure 3: Median Rate against Bias Voltage for the 3 temperature points measured in the lab

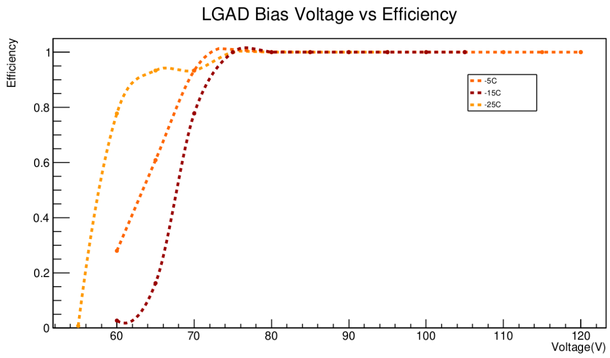

Figure 4: Efficiency against Bias Voltage for the 3 temperature points measured in the lab (left axis is Median Rate (Figure 3) normalised to the maximum value)

In addition to the three temperature points measured in the lab (-5C, -15C and -25C), nine more temperature points that were measured and already partially analysed prior to this Summer Student project were also added to this library of data [Figure 5].

Charge Collected

The data also showed an increase in the charge collected with increasing voltage. This is because charge collected from a single event in the sensor is proportional to the energy

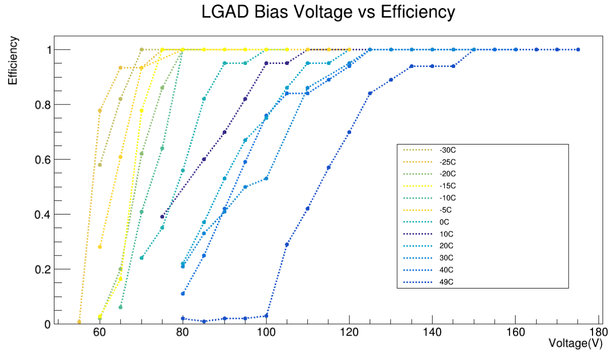

Figure 5: Efficiency against Bias Voltage for all 12 temperature points

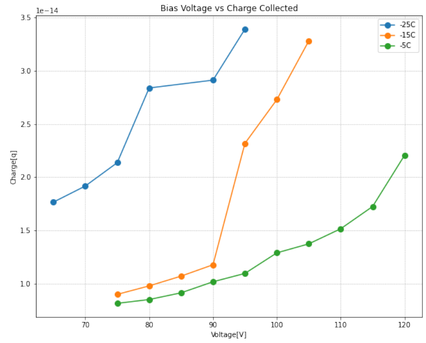

Figure 7: Charge Collected at -25C, -15C and -5C

deposited by the incident ionizing particle and the signal produced. The fluctuations in this deposited energy can be described by a Landau Distribution[1,7]. By fitting the charge collection data from each sensor with a convolution of the Landau and Gauss distributions (the Gauss distribution accounting for noise contributions to the signal and Gaussian parts of the energy distribution[8]), the Most Probable Value (MPV) for the charge collected at each voltage point was determined (see Figure 6).

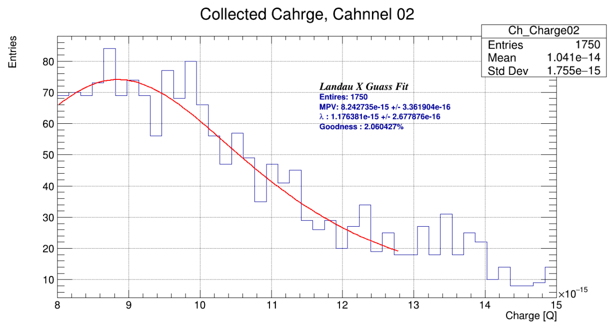

Figure 6: MPV from LandauxGauss fit on data collected at -5C, -70V

The MPVs were then plotted against the bias voltage for three different temperatures to visualize this relationship (see Figure 7).

CONCLUSION

From PiN diodes to APDs, LGADs and even 3D sensors, silicon-based radiation detectors have been, and will continue to be used extensively as particle detectors in high energy physics[10]. LGADs, for example, are expected to be used at CMS and ATLAS as part of the MIP Timing Detector upgrade for CMS and the High Granularity Detector upgrade for ATLAS. This is because the 30ps timing resolution required for both these experiments is possible using LGADs of a given thickness, up to a given amount of radiation fluence[2].

The efficiency and charge collection tests and analyses done during this Summer Student project provided an invaluable, hands-on exposition of the performance of LGADs as MIP detectors, and of some of the data acquisition techniques used when studying these detectors. The data collected can be used to further analyse the timing performance of these LGADs. The timing resolution can be determined by calculating the signal contributions made by the noise of the detector plus the read-out electronics (jitter) and the noise due to the fluctuations of the energy deposited in the sensor (Landau noise). Understanding the performance of these detectors helps the development of better detector technologies in the future.

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