A novel detector for low-energy photon detection with fast response

Neil Moffat, Richard Bates, Mark Bullough and Nicola Tartoni

***Abstract*—A new avalanche silicon detector concept is introduced with a low gain in the region of 5 to 10, known as a Low Gain Avalanche Detector, LGAD. The lower gain reduces noise in comparison with a standard avalanche photodiode. The LGAD can be segmented to produce hybrid pixel detectors for low energy X-ray detection. Thin LGAD′s produce the same, or larger, signals as standard PIN diode detectors produced by minimum ionising particles (mips), however the collection time is reduced. The thickness reduction factor of an LGAD sensor is equal to the gain of the LGAD. For example; a 30μm thick sensor with a gain of 10 will give the same signal from a mip as a 300μm thick PIN diode. The LGAD has a fast rise time, useful for fast silicon timing detectors with sub-ns rise times from X-ray or mip interactions. Simulation of LGADs, using Sentaurus TCAD, of a pixelated device has been performed to determine the implant structures for the required gain and high voltage characteristics and to understand the in-pixel gain uniformity for a range of pixel sizes. Devices have been fabricated at Micron Semiconductor which produce the desired gain (measured to be approximately 10) and electrical performance with a breakdown voltage $>$ 400V. LGAD sensors compatible with the Timepix readout system with varying pixel sizes have been fabricated. X-ray measurements have been performed on 5mm pads with a minimum detetable energy of 17.5 keV. Along with the detection of low energy photons these devices have been shown to produce a very fast response. Devices with this technology will be used in both the ATLAS and CMS timing detectors using pixels of the order 1mm x 1mm. Pixels have been fabricated in 2x2, 3x3 and 5x5 arrays. The measurements of gain and gain uniformity are presented.**

I. Introduction

Silicon detectors for high energy physics and medical applications are well established based on the PIN diode technology [1]. In addition, more recently silicon photodetectors have been introduced at synchrotron sources as X-ray detectors [2]. Silicon detectors are extremely versatile and can be fabricated as single pads but also as arrays of pixels. This has the advantage of increasing spatial resolution. The Avalanche Photodiode (APD) was developed in order to detect low energy photons. This type of detector exhibits an internal signal gain, proportional to the applied bias voltage. When operated in the linear region, gains in the region of 10-100 can be expected. With high gain comes inherent gain noise, associated with the multiplication process.

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More recently modification in the doping profiles in the APD has enabled the fabrication of a device with a lower gain, in the region of 5-10. These devices are known as Low Gain Avalanche Detectors (LGAD) [3]. The lower gain reduces noise and reduces detector dependence on device temperature and applied bias voltage compared with standard APDs.

The LGAD can be segmented to produce hybrid pixel detectors for low energy X-ray detection. One example is to couple a segmented LGAD to the Timepix chip [4]. This has a minimum detectable signal of $\approx$ 1000 electrons to be above the noise floor, which corresponds to an incident X-ray of $\approx$ 4keV. Therefore an LGAD device coupled to the Timepix chip with a gain of 10 would enable the detection of a 400 eV energy x-ray. The backside implant of such a detector must be kept thin to allow the X-ray to enter the sensors' sensitive volume.

Thin LGAD devices will produce the same, or larger, signals as standard PIN diode detectors produced by minimum ionising particles (mips), however the collection time will be much reduced. The thickness reduction factor of an LGAD sensor is equal to the gain of the LGAD. For example a 30μm thick sensor with a gain of 10 will give the same signal from a mip as a 300μm thick PIN diode.

The LGAD structure also produces a fast rise time which allows fast silicon timing detectors with sub-ns rise times from X-ray or mip interactions.

II. LGAD Concept and Fabrication Challenges

The basic doping profiles of the LGAD structure is shown in figure 1, showing a $n^+/p/p^-/p^+$ structure. The figure shows

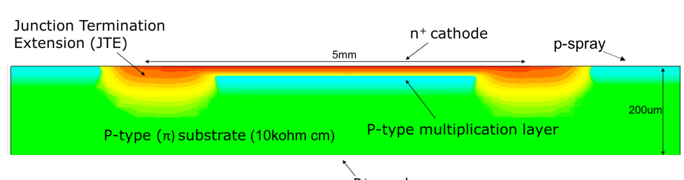

Fig. 1: Schematic cross-section of the LGAD pad design. A p-type layer is diffused below the N^+ electrode to form the $n^+/p/p^-$ junction where the multiplication takes place.

a highly doped n^+ cathode electrode with a moderately doped p-type region below, known as the multiplication implant. The n-type electrode has a peak doping concentration of order 1×10^{19} cm^{-3} and has a shallow profile into the bulk of ≈ 1 μm. , which is typical for a PIN diode. The p-type

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multiplication implant has a peak doping concentration of order 1×10^{16} cm^{-3} and has a significantly deeper profile into the bulk (≈ 4 μm) than the n$^+$ electrode. The bulk material is high resistivity p-type silicon (approximately 10 kOhm-cm) with a p$^+$ anode electrode on the backside.

When a reverse bias is applied the bulk region becomes fully depleted of free charge carriers. The electric field across the device is shown in figure 2. This figure shows the maximum electric field in the device is between the n$^+$ implant and the p-type multiplication implant and proportional to the square root of the p-type doping density. The radiation induced electrons

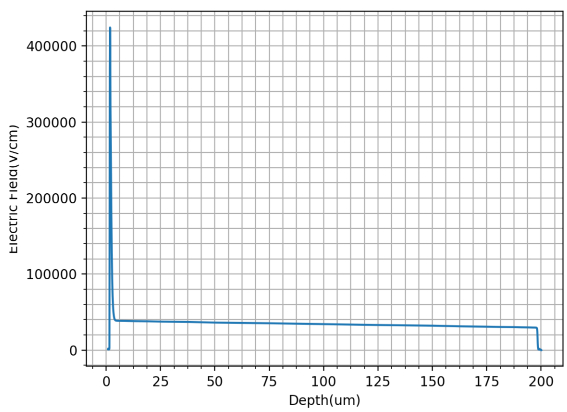

Fig. 2: Typical electric field profile through device showing high electric field at junction between n+/p region. The device is 200 μm thick with a reverse bias of 700 V

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in the detector cross this high field region. For sufficiently high electric fields impact ionisation occurs which results in multiplication of the carriers and a signal gain. The electron-hole pair generation rate, G, due to impact ionisation is given by [4]

$$G = \alpha_n n \nu_n + \alpha_p p \nu_p \tag{1}$$

where (n, p), (ν_n, ν_p) and (α_n, α_p) are the electron and hole density, velocity, and ionisation rate respectively. The ionisation rate strongly depends on the electric field (E) and maybe defined as

$$\alpha = \frac{E}{E_{th}} \exp[-E_i/E] \tag{2}$$

where E is the high-field in the device, E_{th} is the high-field effective ionisation threshold energy (for silicon equal to 3.6 eV for electrons and 5.0 eV for holes) and E_i is the threshold field due to ionisation scattering. Increasing the high-field will increase the electron-hole pair generation rate. It is of great importance to control the fabrication process carefully as small changes in the doping profile can effect the maximum electric field, resulting in a loss of gain or early breakdown.

An important issue for these devices is to be able to run them at a reasonably high breakdown voltage > 400V. Due to the nature of the devices, a high electric field is present at the perimeter of the cathode, in order to reduce this an additional deep n$^+$ doping region (known as the Junction Terminating Extension, JTE) is present. This helps to control the field to inside the pixel, increasing the breakdown voltage as well as decreasing the leakage current but with the draw-back of a reduced fraction of the surface area of the detector with multiplication.

III. Low Energy X-ray Detection

As previously discussed to be able to detect low energy X-ray's one needs to fabricate a device with the gain in the region of 10. Pad diodes with a range of designs have been fabricated at Micron Semiconductor Ltd which produce this required gain value [6]. Measurements of gain from a 5mm pad LGAD detector have been made using the Transient Current Technique (TCT) and are shown in figure 3 with gain $\approx$ 10-20, showing a linear response to voltage. TCT uses a laser to induce current in a detector from the front or backside, this can be modified to induce current from the side (Edge-TCT).

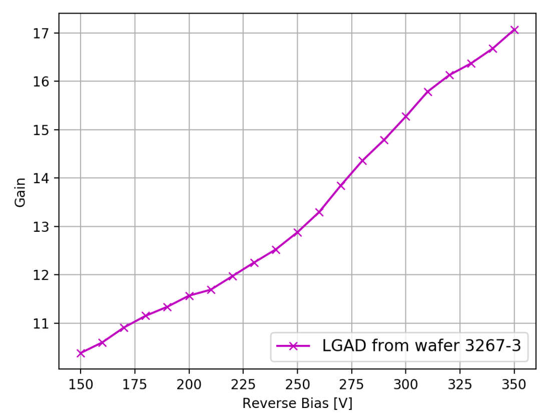

Fig. 3: Gain as function of voltage for a 5mm pad LGAD device from wafer 3267-3

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X-ray measurements were taken to record spectrum and peak position using a variable X-ray source with a range of 10-50 Kev. The peak positon against voltage is shown in figure 4 for a range of X-ray energies. The minimum detectable energy was 17.5 KeV from a Molydenum target. The relatively high energy value is due to the large detector capacitance, using a smaller pixel size the capacitance will be reduced and hence the minimum detectable energy can reduced to $\leqslant$ 1 keV.

Simulation using Sentaurus TCAD of a pixelated device has been performed in order to define adequate pixel sizes for fabrication. During this process it became clear that pixel sizes of the order 55μm pitch (Standard Timepix) would have issues with gain uniformity. The main issue is caused by the JTE which causes a non uniform distribution of the electric field. A low field region is present just below the multiplication region causing electrons to be collected via the outer, no gain, regions of the pixel. This creates a no gain LGAD device, acting as a PIN diode in this case. Solutions to this are to increase the pixel size, decrease JTE width or to remove the JTE. The issue with removing the JTE would be a reduced breakdown voltage.

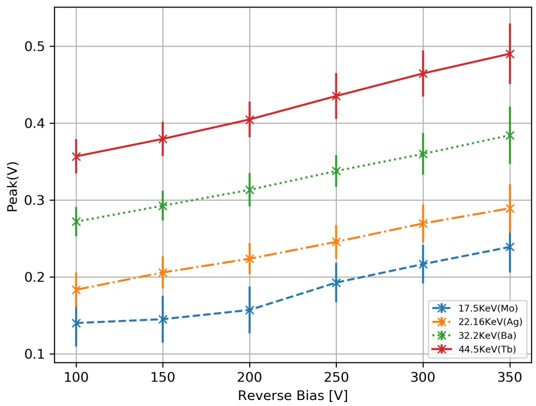

Fig. 4: X-ray energy against voltage in a 5mm LGAD device from wafer 3267-3,

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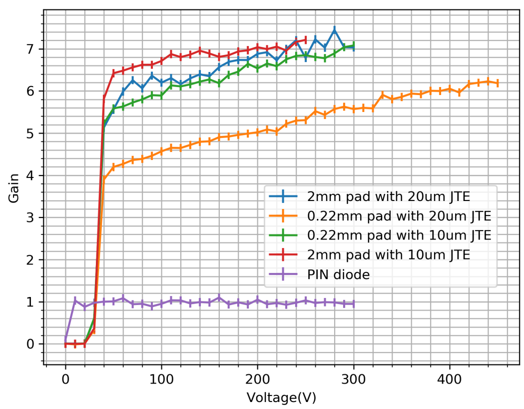
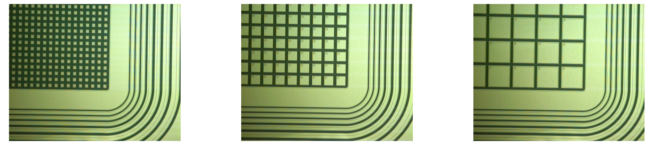


Fig. 5: Gain as a function of voltage for LGAD pad sizes 0.22mm and 2mm from wafer 3331-11.

An example of this issue is shown in figure 5, where the gain is plotted as function of voltage for four devices. Of the four devices, two have an active area of 2mm^2 and two have an active area of 0.22mm^2. Of these one of each has a JTE width of 10μm and 20μm. If we compare the gain collected for each of these devices at 250V, we see that the gain for both 2mm pads is $\approx$ 7. However the gain for the 0.22mm pads differs, where one has a gain of $\approx$ 7 and the other $\approx$ 5. This difference in gain is due to the JTE effect on the small pixel size., where the JTE width is comparable with pad size. This issue is amplified as the pixel size reduces as discussed previously.

Detectors have been fabricated at Micron Semiconductor Ltd which have a range of pixel sizes compatible with the Timepix readout system. These have a pixel pitch of 55μm, 110μm and 220μm, all including the JTE structure shown in figures 6a, 6b and 6c respectively . However the 55μm pitch arrays have a variety of designs, which include removing the JTE structure and modifying the multiplication layer implant.

Along with the possibility of detecting low energy photons, these devices have been shown to produce a very fast response [7] and this technology will be used in both the ATLAS and CMS timing detectors using large pixels of the order 1mm x 1mm. Arrays of such pixels have been fabricated arranged in 2x2, 3x3 and 5x5 matrices.



(a) 55μm Array (b) 110μm Array (c) 220μm Array

Fig. 6: Medipix arrays of various pixel pitch.

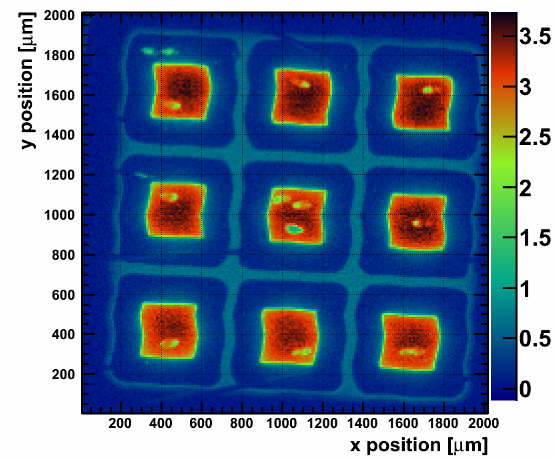


Fig. 7: Raster scan of a 3x3 LGAD array from wafer 3331-11, showing gain as a function of laser position.

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First measurements of LGAD arrays using TCT were performed to characterize a 3x3 LGAD array of 0.5mm pixels. A rastor scan was performed on the entire array looking at gain uniformity shown in figure 7. The full array was wire bonded to the same readout channel, thus charge collected at a given laser position is the sum of the charge from all the pixels. Therefore no information can be given for charge sharing. Gain regions, in red, are surrounded by an aluminium electrode where no charge is collected due to the lgiht being reflected. Charge collected between pixels shows no gain as the electrons are collected through the JTE of the surrounding pixels. A reasonable gain uniformity is shown from pixel to pixel however further work is needed to fully characterize this.

IV. Conclusion

In conclusion this work describes the novel use of the LGAD device in producing a low-energy photon detector. The requirement of the gain layer along with its timing capabilities are described and results given. The results show that small pixel arrays with gain can be produced for use with hybrid pixel readout systems. X-ray measurements show promising results for use in synchrotron applications.

Acknowledgment

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