Study of time resolution of low-gain avalanche detectors

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Abstract

Low Gain Avalanche Detector (LGAD) is a semiconductor device that amplifies signals inside the sensor using avalanche mechanism. As the multiplication occurs in a thin p-n junction, it can achieve a superior time resolution, e.g., 30 ps as obtained in our previous beam-test study. In combined with excellent 3-D spatial information achievable with semiconductor devices, we are targeting to realize a 4-D detector. Although high-energy beams are very useful in evaluating the time resolution of the LGAD, desk-top measurement systems are very helpful for quick evaluation of LGAD samples under development. We are, therefore, developing a time measurement system using β-rays from a ^{90}Sr source. We obtained a time resolution slightly degraded but similar to the beam-test results. In realizing a 4-D detector, readout needs to be finely segmented with keeping the gain uniform in wider area. As a device with such segmentation, we studied AC-LGAD in which a gain layer is implanted over the entire area of the sensor and the signal is read out by segmented AC pads interleaved with an insulating layer. Several AC-LGAD structures were created in a TCAD simulation, and optimal sensor design parameters were extracted.

Keywords: 4D detector, segmented LGAD, AC-LGAD

1. Introduction

The Low Gain Avalanche Detector (LGAD) is a semiconductor detector implemented with avalanche mechanism for signal amplification. Figure 1 illustrates a typical LGAD structure. In an conventional n-in-p type silicon semiconductor detector, LGAD has a p^+ well implanted under the n^{++} readout implant with the p-type impurity concentration higher than that in the bulk. The junction at the p^+-n^{++} interface acts as the gain layer creating a high electric field sufficient to initiate avalanche multiplication.

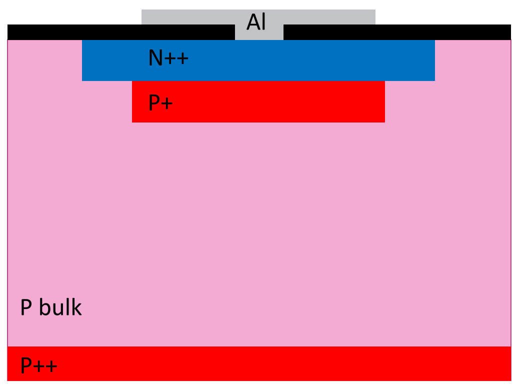

Figure 1: Typical LGAD structure.

Main contributors degrading the time resolution are the time walk and time jitter [1], [2]. The time walk is a fluctuation of the timing exceeding the threshold and is caused by the variation in signal magnitude. The time walk decreases for faster signals with larger signal slope dV/dt. The time jitter is caused by the signal noise and is smaller for the device with better S/N ratio. The LGAD amplifies the signal in the vicinity of the readout electrode and hence makes the signal rise faster. The S/N ratio is maximized for low amplification gain of around ten where the signal is amplified sufficiently while the noise amplification is only partial. As the LGAD meets these conditions, good time resolution is achievable.

The 4-D detector measures the traversing charge particle four-dimensionally providing time information in addition to the 3-D position information. The big challenge for the particle tracker in future accelerator experiments is to deal with the increased pile-up events associated with increasing the accelerator luminosity. The time information of e.g., 30 ps as reported in [5], corresponding to 10 mm in space, is possible to narrow down the candidate hits to be considered for tracking, which would be very effective in reconstructing tracks in high pile-up environment as envisaged in future hadron collider experiments. The additional time information helps reduce the candidate hits, which would reduce the computational load greatly and would change the strategy of tracking.

2. Desk-top time resolution measurement system

The time resolution of LGADs has been measured in beam experiments using large accelerators. We are aiming to develop a desk-top measurement system that allows us evaluating the time resolution much more easily. The system uses a ^{90}Sr β source with the signals read out with flash ADCs, as illustrated in Fig. 2. Two sensors were placed on top of the other, and the bottom sensor was used as triggering β rays. The sensors were 2×2 array of 1.3 mm square pads being evaluated for the CMS experiment [4]. The amplifier board based on wide-band (DC to 3 GHz) InGaP HBT MMIC amplifier chips [4] was home-made. The waveforms are digitized with flash ADCs (CAEN DT5742) at 5 GHz sampling with 12-bit ADCs covering

$V_{pp} = \pm1$ V range. Events are read out when the bottom sensor showed large signal exceeding a preset voltage. The sensors mounted on the amplifier board were placed in a thermostat chamber to control the temperature at -20 ℃.

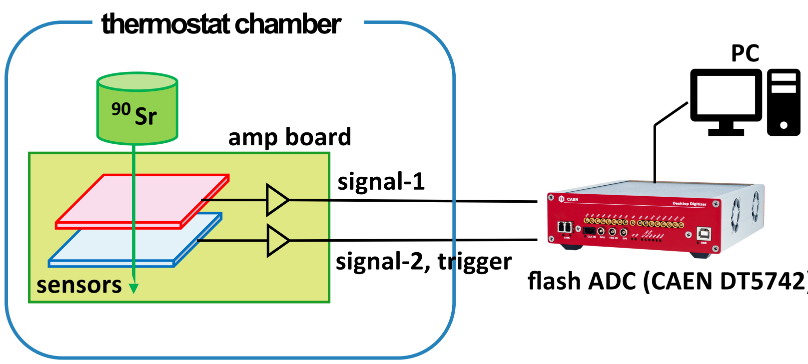

Figure 2: Setup for timing measurements.

Figure 3 shows the distribution of the event-by-event maximum ADCs in the two waveforms (ADC_up and ADC_dwn). As the bottom LGAD signal was used for the event trigger, the pedestal is only seen for the top LGAD. The large population around (ADC_up, ADC_dwn) = (300, 300) corresponds to the case both senors detect penetrating β rays. In the following, we require the difference of the times at the maximum to be within 5 ns as the two sensors are only a few millimeters apart.

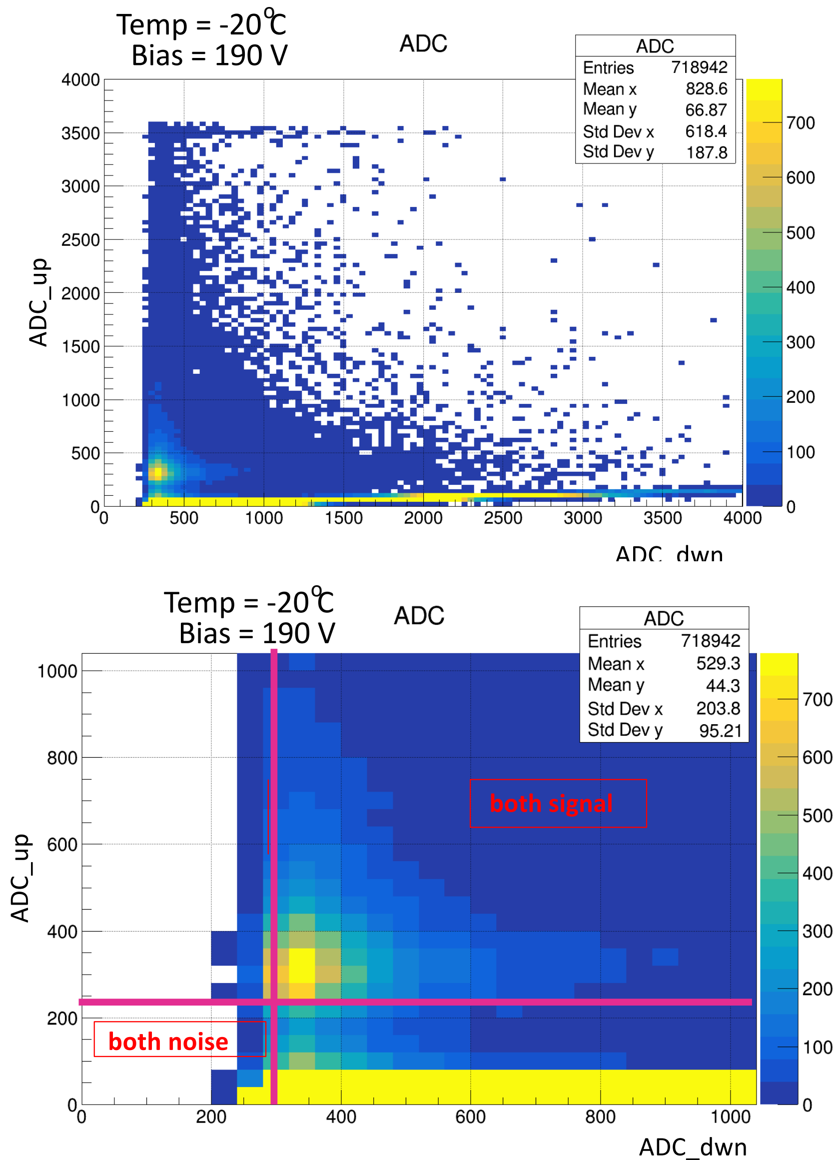

Figure 3: Correlation of maximal ADC values per event (top) in whole range, and (bottom) its expansion showing ADC < 1000.

After removing the noise events, fitting was performed using a quintic function as an example shown in Fig. 4. Using the fitted function, the time

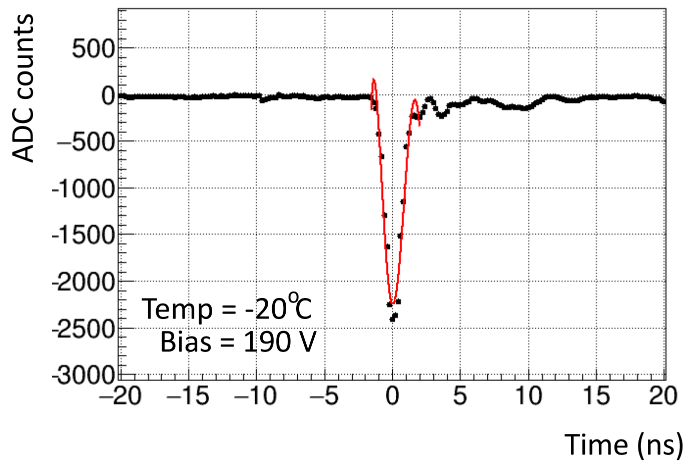

Figure 4: Waveform example of one LGAD signal, fitted with a quintic function.

at exceeding the threshold $V_{\text{threshold}} = V_{\max} \times f$ was derived with varying the fraction f in the range $0 < f < 1$. The time was calculated for each of the two sensors using the same f value. The distribution of time difference as obtained in Fig. 5 was fitted with a Gaussian function. The obtained Gaussian σ can be written as

$$\sigma = \sqrt{\sigma(T_1)^2 + \sigma(T_2)^2}, \tag{1}$$

where the intrinsic time resolution of the two sensors is $\sigma(T_1)$ and $\sigma(T_2)$. As the tested LGADs are identical in design and were operated at the same bias voltage, we can assume that the two sensors have the same intrinsic time resolution. Therefore, the intrinsic time resolution of one LGAD can be calculated as

$$\sigma(T) = \sigma/\sqrt{2}. \tag{2}$$

Figure 6 shows the dependence of the time resolution on the fraction

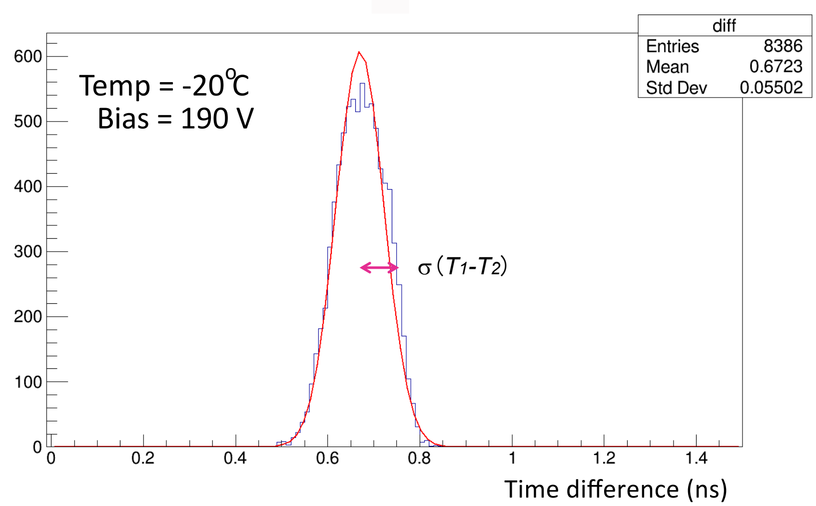

Figure 5: Distribution of time differences, fitted with a Gaussian function.

factor f.

Figure 7 shows the time resolution with respect to the reverse bias voltage. Up to a bias voltage of -200V, the time resolution improves with the voltage, which is considered to be due to an increase in the amplification factor. On the other hand, at higher voltages, the time resolution deteriorates, which is considered to be due to the gain being too large and to the S/N ratio degradation.

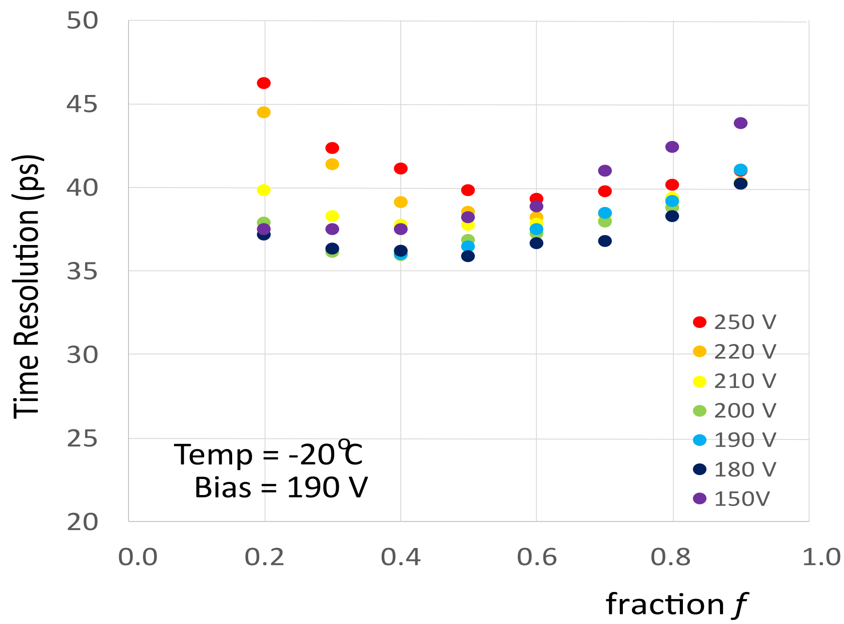

Figure 6: Time resolution as a function of threshold factor. The data points for several bias voltages are plotted.

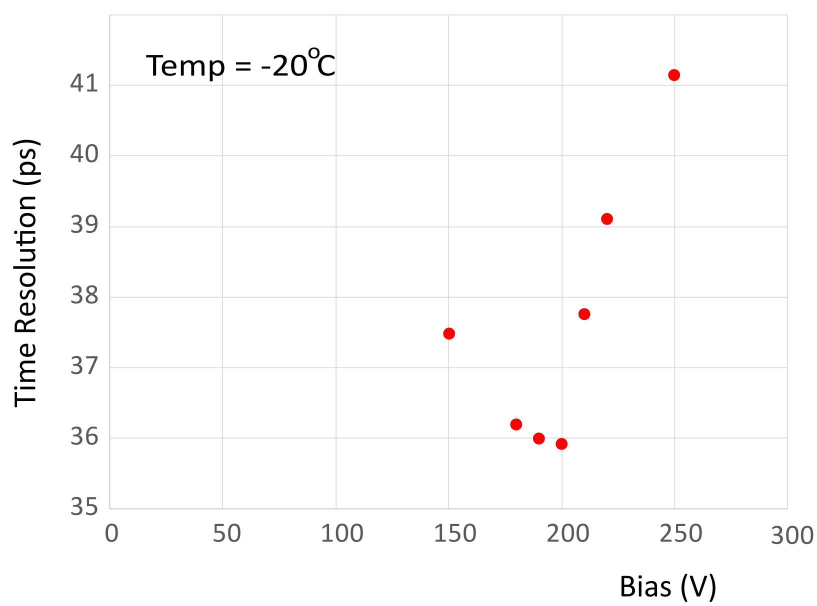

Figure 7: Time resolution as a function of bias voltage for f=0.5.

3. AC-LGAD TCAD simulation

The gain non-uniformity in a conventional strip-type LGAD structure [3] is caused by the limited coverage of the n^{++} and p^{+} gain layer. In AC-LGAD the gain layer is made uniform covering the entire sensitive area while readout segmentation is achieved by AC coupled electrodes. The primary challenge in designing an AC-LGAD is the optimization of the n^{++} layer resistivity. In order to prevent charges escaping to the ground, the n^{++} implant impedance needs to be large enough, which may in turn result in insufficient achievable gain. Also, if the resistance is too high, the collected charge will not escape causing the sensor to charge up. The n^{++} concentration determines the degree of signal spread to the nearby readout electrodes, which is also to be optimized at the same time. Another challenge concerns about the gain. For n^{++} implanted with a lower concentration than standard, it is necessary to increase the p^{+} concentration in stead so as to achieve the similar gain. On the other hand, for excessively high p^{+} concentration, the sensor will break down before achieving sufficient gain.

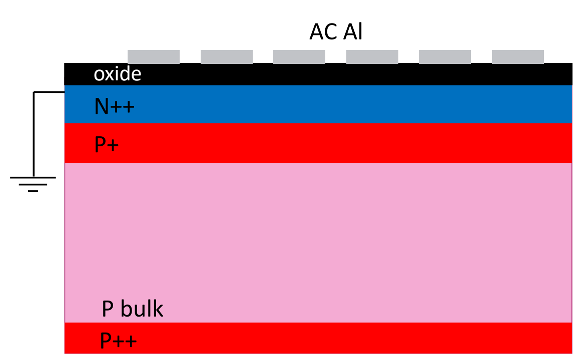

Figure 8: AC-LGAD structure.

An AC-LGAD structure shown in Fig. 9 was created using a TCAD [6], [3] simulation where p^+ and n^{++} gain layers were implanted covering the entire area of a 50 μm thick p-type bulk. The AC coupled Al electrodes were created on top of an oxide film. In this simulation, only five AC-Al electrodes were placed for simplicity. The simulation is two dimensional, and AC-Al pitch and width are 80 μm and 40 μm, respectively. For the reverse bias voltage, a negative voltage is applied to the p^{++} layer created on the back of the sensor, and the n^{++} electrode layer is grounded. The oxide film was trimmed out near the ends where DC-Al electrodes are contacted for grounding the n^{++} electrode.

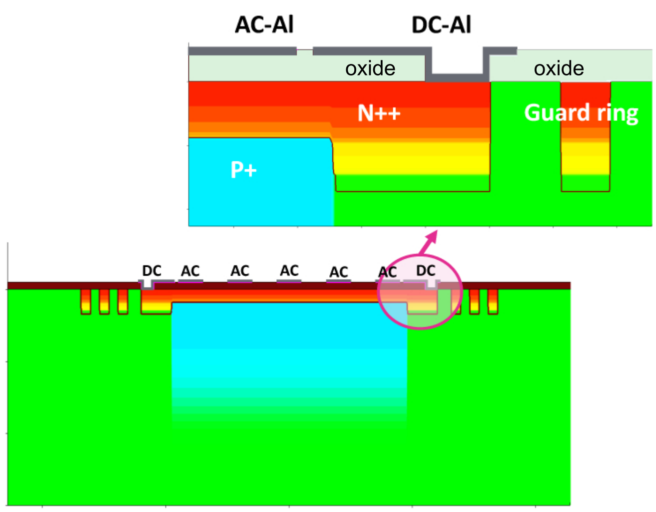

Figure 9: An AC-LGAD structure implemented in TCAD. Structure around the n^{++} electrode end is shown in the enlarged view.

Figures 10 and 11 show simulation results of the signal shape induced on each electrode up to the next-to-next electrode when MIP (minimum ionizing particles) is incident on the center on an electrode. Fig. 10 includes the sets of signal shapes for the three n^{++} concentrations, showing that a 50% change of n^{++} concentration affects significantly on the signal spread. An effect is seen that the charges initially move toward the AC-Al electrode giving positive signal then move away to the neighbors swinging the signal negatively. On the other hand, for the increased n^{++} concentration, the n^{++} resistivity is too low so that certain fraction of the charges flows to the neighboring electrodes, giving significant signal to the next electrodes. Contrarily, the signal will not be seen on the neighbors if the resistivity is too high as for the decreased n^{++} concentration. The signal sharing seems acceptable for this case, but since the charge movement towards the neighbors and finally to the DC-Al electrode is limited, the charges may stay below the AC-Al electrode.

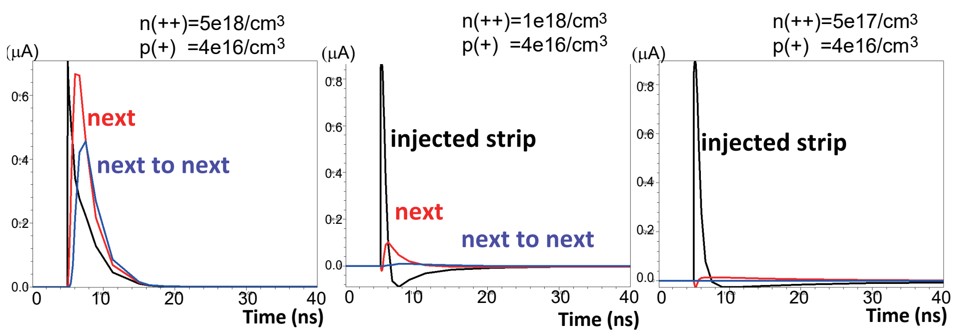

Figure 10: Signal shapes induced on the injected, next and next-to-next strips for three n^{++} concentrations.

Figure 11 shows the induced signal shape for two n^{++} thicknesses. Because the resistance is reduced for thicker n^{++}, the negative signal swing is more enhanced.

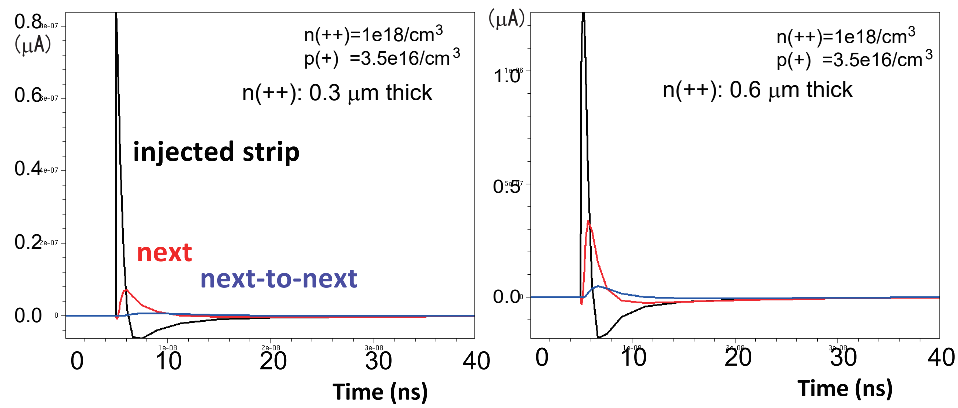

Figure 11: Signal shapes induced on the injected, next and next-to-next strips for two n^{++} thicknesses.

Figure 12 shows the simulation results of the gain at 300 V bias as a function of p^+ concentration plotted for various n^{++} concentrations. Here the gain is of the strip to which MIP was injected at its center, and the corresponding charge is the induced current integrated while the current is positive. The gain tends to increase with increasing p^+ and n^{++} concentrations up to some points. For achieving a gain of 10, $p^+ = 5 \times 10^{16}$ cm^{-3} and $n^{++} = 1 \times 10^{18}$ cm^{-3} are the parameters.

Figure 13 shows the gain uniformity across the strips calculated for the concentration conditions given above and at 300 V bias. About 70% of the charge is collected to the incident electrode when the particle is incident at its center. The charge sum is fairly flat across the strips, indicating uniform gain is obtainable.

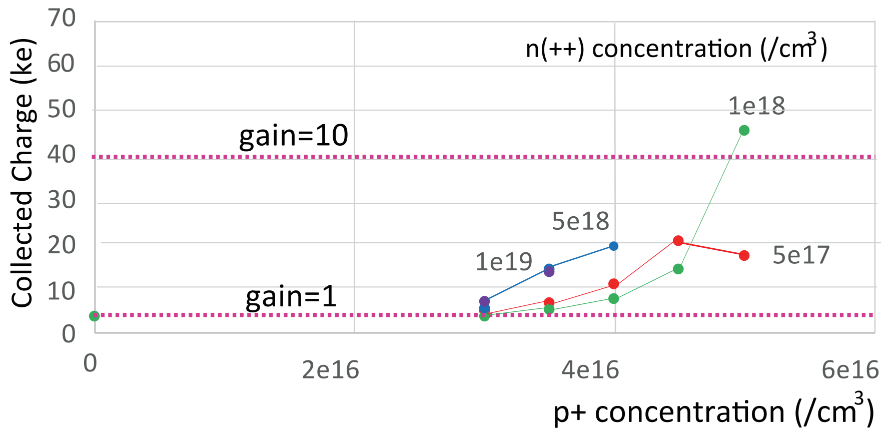

Figure 12: Gain at 300 V bias is plotted as a function of p^+ concentration. The values attached to the curves are n^{++} concentrations.

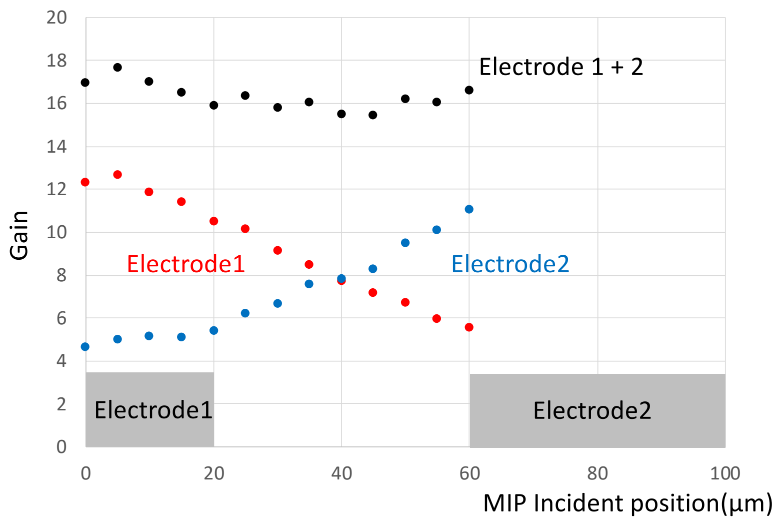

Figure 13: Gain uniformity across the strips.

4. Conclusion

We are developing LGAD sensors to realize a 4-D particle detector for future accelerator experiments. Such a device should also be interesting in new applications in medical equipment such as TOF-PET and in bio-sciences. We reported a desk-top time resolution measurement system using a β-ray source, confirming that the system is useful for quick time resolution evaluation. We also performed a TCAD simulation for designing a segmented AC-LGAD, and conclude that uniform and sufficient gain are obtainable. Prototype AC-LGAD sensors are to be fabricated based on the present study.

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6. References

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