PROCEEDINGS OF SCIENCE

Development of HPK Capacitive Coupled LGAD (AC-LGAD) detectors

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Detectors with $O(10)$ µm spatial resolution and $O(10)$ ps timing resolution allow to construct powerful particle trackers for future hadron or lepton collider experiments. LGAD (Low Gain Avalanche Diode) is a semiconductor detector technology to improve timing resolution. Capacitive Coupled LGAD (AC-LGAD) detectors have been developed with HPK in order to meet both spatial and timing resolution requirements. Prototype samples with finely segmented electrodes have been produced and tested with various sensor fabrication parameters: doping concentrations, active thickness and electrode coupling capacitance. Timing resolution and signal height were evaluated with beta-rays. As a result, 100 µm pitch pixel detectors have been successfully developed achieving a good signal to noise ratio and 30 ps timing resolution with beta-rays. The detectors have to meet radiation hardness requirements as well, in particular to be used as inner trackers for hadron colliders. One of the major mechanisms of radiation damage of LGAD detectors is acceptor removal: shallow dopants in the gain layer of LGAD detectors are reduced by radiation. Two novel ideas are tested for effectiveness on delaying the acceptor removal.

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1. Introduction

Detectors with $O(10)$ µm spatial resolution and $O(10)$ ps timing resolution will be needed in future hadron or lepton collider experiments in order to deal with increasing pile-up as well. The Low-Gain-Avalanche-Diode (LGAD) is a semiconductor detector technology developed to improve timing resolution. Capacitive Coupled LGAD (AC-LGAD) detectors have been successfully developed [2], achieving a timing resolution of 20 ps for minimum ionizing particles (MIPs). Concerning spatial resolution, 100 µm pitch pixel detectors have been successfully developed with a good signal to noise ratio and small cross talk [1].

The detectors have to meet radiation hardness requirements in order to withstand the large particle fluences expected in future experiments. One of the major problems of radiation hardness of LGAD detectors is acceptor removal, whereby shallow dopants in p^+ gain layer is reduced by radiation damage. This requires higher voltages to be applied to the detector than before irradiation to compensate the weaker electric field in gain layer, which puts the detector at risk of single-event-burnout [4]. Prototype detectors developed with two novel ideas to reduce acceptor removal effect have been produced and tested.

In this contribution, two main topics are discussed. First, the timing resolution performance of AC-LGAD detectors. Second, the performance of LGAD detectors employing two ideas to mitigate the acceptor removal effects after proton irradiation.

2. AC-LGAD prototype

The LGAD sensor is an n^+-in-p semiconductor detector with a gain layer made by implantation of additional p^+ below the n^+ implantation. That gain layer generates a local high electric field which develops avalanche multiplication, resulting in generation of a large amount of electron and hole pairs. The rapid movement of these electron and hole pairs in the local high electric field creates a large signal instantaneously, leading to a superior timing resolution.

In conventional LGAD detector, shown in Fig. 1, individual gain layer for each electrode is structured with finely segmented readout. This detector has areas without gain layers between the electrodes, which lead to a low fill factor. A capacitively-coupled LGAD (AC-LGAD), shown in Fig. 2, has been developed to solve this low fill factor problem. AC-LGAD has a single uniform gain layer under segmented electrodes which couple with the gain layer via oxide. AC-LGAD has been successfully developed with pixel pitch 100 µm with 100% fill factor and small cross talk [1].

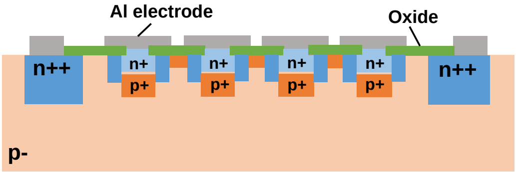


Figure 1: DC-LGAD

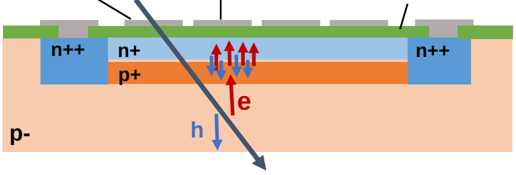


Figure 2: AC-LGAD

3. Measurement setup

The sensor performance is evaluated by using ^{90}Sr β rays. The sensor electrodes are connected to a 16-ch amplifier board [2] by wire bonding. The reverse bias voltage is applied to the backside of the sensor via conductive tape. Signal outputs from the amplifier are recorded by a LeCroy waverunner 8000HD oscilloscope. The amplifier board with LGAD sensor is set horizontally in a thermostatic chamber and a ^{90}Sr source placed above the sensor. The Photek MCP-PMT 240 placed under the sensor provides the timing reference and trigger for oscilloscope.

4. Timing resolution performance

The timing resolution of LGAD sensors consists of three factors: difference of arrival time due to the signal size (time walk), electronics noise (jitter) and the effect of non-uniform charge deposition through the depth by MIP particle (charge collection noise). The jitter is reduced by larger signal and smaller noise. Thinner active thickness sensors performed smaller charge collection noise because of smaller Landau fluctuation of energy deposition. Since time walk effect could be mitigated by using constant fraction discriminator, the effect was neglected in this paper.

Timing resolution is evaluated as the sigma of a gaussian function fitted to the differences between the signal arrival times and timing reference after having corrected for the time walk. The charge collection noise effect can be assessed from β ray measurements by subtracting the jitter contribution from overall timing resolution. Table 1 shows measurement results of timing resolution for each active thickness sample and estimated charge collection noise by calculating jitter from rise time of pulse, signal size and electrical noise. A timing resolution of ∼ 30 ps was obtained. The sensor type used is 2x2 pixelated with pixel size of (500 µm)^2. Thinner sensor showed overall better timing resolution due to the suppression of charge collection noise effect while the jitter contribution is largest due to smaller signal amplitude.

Sensor active thickness	50 µm	30 µm	20 µm
timing resolution [ps]	38.8	31.5	31.2
jitter [ps]	9.8	11.8	15.9
charge collection noise [ps]	37.5	29.2	26.8

Table 1: Timing resolution summary

5. Radiation tolerance of LGAD

Shallow dopants in gain layer of LGAD are transformed into defect complexes which no longer have characteristics of shallow dopants due to non-ionising energy loss (NIEL). This transformation of acceptors called acceptor removal results in increasing operation voltage [3]. Suppression of the acceptor removal effect is needed to have radiation tolerance of the gain layer for the future high energy experiments. Prototypes of LGAD adopting two novel ideas, described in Section 5.1 and Section 5.2, for suppressing acceptor removal effect were produced, irradiated and evaluated. The irradiation campaign was done at CYRIC at Tohoku University with a 70 MeV proton beam at -15°C. Sensors were irradiated to 8×10^{13}, 6×10^{14}, 3×10^{15} $\mathrm{n_{eq}/cm^2}$ with uniform scanning, and tested with the β ray measurement setup described in Sec 3.

5.1 Compensation method

In the compensation method, both acceptors and donors are implanted in the p^+ gain layer and characterize the p^+ layer by the effective p^+ concentration which is the difference of p^+ and n^+ concentrations. Both of the n^+ and p^+ are reduced by radiation damage due to acceptor and donor removal. If n^+ removal is faster than p^+ removal, effective p^+ concentration may reduce slower than in a conventional p^+ layer. Prototypes were produced with 5 sets of parameters as shown in Table. 2. In the table, parameter a represents the doping concentration of Reference, for instance, "10a" means 10 times higher doping concentration of p^+ than in Reference.

	10B+9.2P	5B+4.05P	2.5B+1.5P	1.5P+0.55P	Reference
p^+ Boron	$10a$	$5a$	$2.5a$	$1.5a$	a
n^+ Phosphorous	$9.2a$	$4.05a$	$1.5a$	$0.55a$	0
effective p^+	$0.8a$	$0.95a$	a	$0.95a$	a

Table 2: Parameters of compensation prototypes

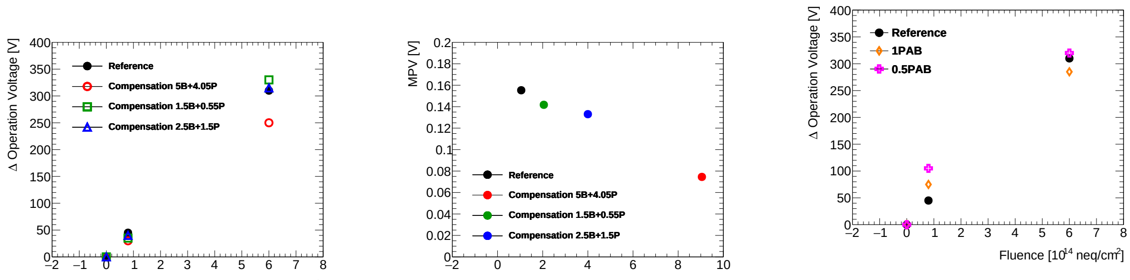
Sensors were irradiated to the same fluence described in Sec. 5. The performance of prototypes was evaluated by IV measurement and β-ray signal measurement before and after irradiation. The fluence dependence of operation voltage is shown in Fig. 3a. An improvement in suppressing the increment has been observed for compensation 5B+4.05P prototype. However, a pulse height degradation for higher dope concentration was found as shown in Fig. 3b. It is suspected that avalanche multiplication is hindered by the dense dopants. Therefore, increase of doping concentration does not simply improve the radiation tolerance.

5.2 Partially-Activated-Boron

Boron in p^+ gain layer is fully activated by a proper annealing process in conventional LGAD sensors; it is de-activated by NIEL damage and combines with residual oxygen that acts as new donor level [5]. The presence of intrinsic inactive boron atoms before radiation damage cleans up oxygen contamination and this prevents from creating additional donors.

The prototypes were produced under two conditions depending on the amount of inactivated boron: 1PAB for the same amount of activated boron and 0.5PAB for half the amount of activated

PoS(VERTEX2023)032



(a) Fluence dependence of increment of operation voltage for compensation prototypes

(b) Doping concentration dependence of MPV for Partially-Activated-Boron prototypes

(c) Fluence dependence of increment of operation voltage for Partially-Activated-Boron prototypes

Figure 3: Results of compensation prototypes and Partially-Activated-Boron prototypes

boron. Sensors were irradiated to the same fluence described in Sec. 5. Performance of prototypes was evaluated by IV measurement and β-ray signal measurement with the setup described in Sec. 3 before and after irradiation. Fluence dependence of the operation voltage is shown in Fig. 3c. Improvement in suppressing the increment of operation voltage was not evident in any of the two configurations.

6. Conclusion

AC-LGAD sensors have been successfully developed. Sensors with different thickness down to 20 µm have been tested to reduce charge collection noise. 20 µm prototype achieved 31.2 ps timing resolution for MIPs. To enhance radiation hardness of LGADs, two novel ideas have been tested. Compensation is effective with higher doping concentrations but the pulse height before irradiation is observed to decrease with the concentration. No significant improvement has been observed for the Partially-Activated-Boron technique.

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