PROCEEDINGS OF SCIENCE

Detailed investigation of Acceptor Removal in LGAD

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A Low Gain Avalanche Diode (LGAD) sensor is developed for high-precision timing measurements. For applications of LGAD detectors in high-energy and high-luminosity hadron collider experiments, the detector must exhibit sufficient radiation tolerance against both Total Ionizing Dose (TID) and Non-Ionizing Energy Loss (NIEL) effects. In previous studies, the oxygen concentration in the sensor has been suggested to play a significant role in radiation-induced degradation, as the formation of B_iO_i complexes was considered a major cause of acceptor removal in the gain layer. In this study, we developed radiation-hard LGAD prototypes with reduced oxygen concentration using process improvements and the Partially Activated Boron method. Radiation tolerance was evaluated through depletion voltage and timing resolution measurements after irradiation with 45 MeV protons. The results show that the radiation tolerance of LGAD does not depend significantly on the oxygen concentration, suggesting that B_iO_i defects are not the dominant cause of acceptor removal in the gain layer.

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1. Introduction

Tracking detectors in future high-energy and high-luminosity hadron colliders must be capable of correctly associating tracks originating from the hard-scattering vertex among a large number of pile-up vertices. Detectors with both high spatial and timing resolutions can effectively suppress pile-up by utilizing the vertex time information, thereby enabling high-quality track reconstruction.

A capacitively-coupled Low Gain Avalanche Diode (AC-LGAD) are semiconductor detectors that provide excellent spatial resolution of $O(10)$ μm and timing resolution of $O(10)$ ps.

However, LGADs currently lack the required radiation tolerance of $O(10^{16})$ $\mathrm{n_{eq}/cm^2}$ for application as tracking detectors in future high-luminosity collider experiments. This limitation arises mainly from the so-called acceptor removal effect, where radiation damage deactivates acceptor dopants in the gain layer and reduces the signal amplification capability.

To mitigate this effect, KEK and the University of Tsukuba, in collaboration with Hamamatsu Photonics K.K. (HPK), have developed prototype LGAD sensors with reduced oxygen concentration through process optimization and the Partially Activated Boron (PAB) method. In the PAB method, oxygen-related defect formation is suppressed by implanting a higher concentration of inactive boron compared to conventional LGADs.

We have conducted proton irradiation experiments on these prototype sensors to evaluate their radiation tolerance based on time resolution and IV characteristic measurements. In this paper, we present an evaluation of the influence of oxygen concentration on the radiation tolerance of LGAD sensors.

2. LGAD sensors

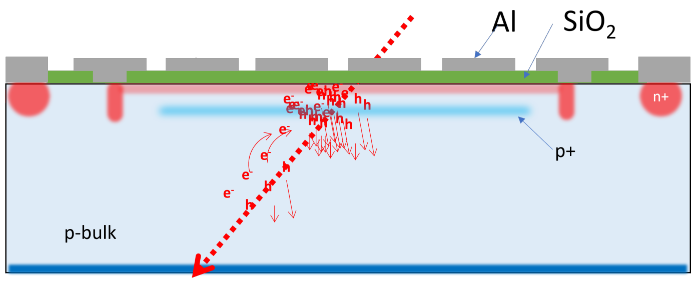


Figure 1: Structure of AC-LGAD detector.

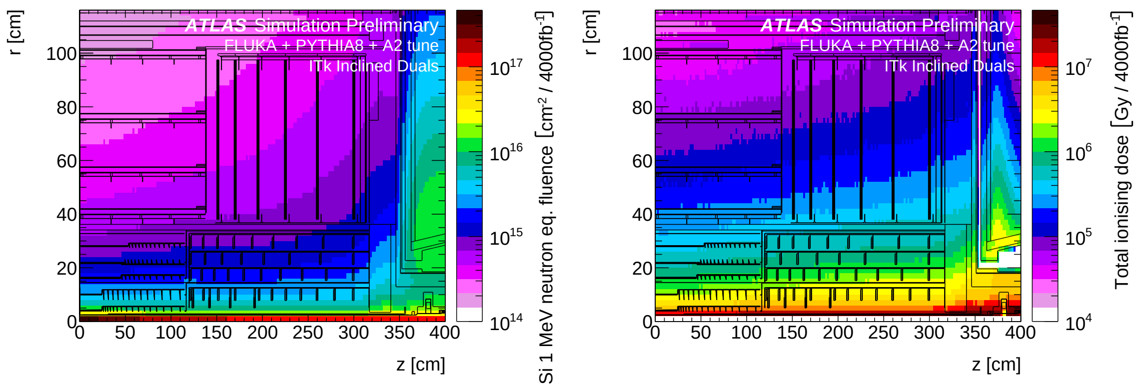
The LGAD has the basic structure of an n^+-in-p type silicon detector, as shown in Fig.1. It includes an additional highly doped p^+ layer beneath the n^+ electrode, with a higher boron concentration compared to that in the p-bulk region. Specifically, the n^+ electrode is doped with phosphorus at a concentration of $O(10^{17})$ $\mathrm{cm^{-3}}$, and the p^+ layer is doped with boron at a concentration of $O(10^{16})$ $\mathrm{cm^{-3}}$.

This additional highly doped p^+ layer creates a high electric field region exceeding 300 kV/cm between the n^+ and p^+ layers. The strong electric field induces avalanche multiplication of the electron–hole pairs generated by incident particles, thereby amplifying the signal by a factor of approximately 10–20.

The time resolution of a detector is generally limited by the jitter term, which is inversely proportional to the S/N. Owing to its internal charge multiplication mechanism, the LGAD sensor can enhance the signal amplitude while maintaining a high S/N ratio, thereby achieving excellent time resolution on the order of $O(10)$ ps.

3. Radiation Tolerance of LGAD

3.1 Acceptor Removal



(a) NIEL **(b)** TID

Figure 2: Simulation of radiation damage in the ATLAS inner tracking detector at an integrated luminosity of $4,000\ \mathrm{fb}^{-1}$ for (a) NIEL and (b) TID,collisions at a center-of-mass energy of 14 TeV and a proton–proton inelastic cross section of 79.3 mb is assumed [1].

Radiation damage in LGAD includes both NIEL and TID effects, similar to those observed in conventional silicon detectors. Among them, NIEL damage deactivates electrically active acceptors, a phenomenon known as acceptor removal.

The microscopic mechanism of acceptor removal is considered to be the inactivation of boron atoms caused by NIEL-induced defects. Substitutional boron (B_s) is converted into interstitial boron (B_i), and the inactivated boron then combines with oxygen in the silicon bulk to form B_iO_i complexes that introduce donor levels [4].

$$\mathrm{Si_i} + \mathrm{B_s} \longrightarrow \mathrm{B_i} \tag{1}$$

$$\mathrm{B_i} + \mathrm{O_i} \longrightarrow \mathrm{B_iO_i} \tag{2}$$

When acceptor removal occurs, the effective acceptor concentration in the p^+ layer decreases, leading to a reduction in the multiplication gain under the same applied voltage. To compensate for the deterioration of time resolution caused by this gain reduction, the detector must be operated at a higher voltage. Therefore, as radiation damage increases, the operation voltage also rises.

If the average electric field in the sensor exceeds 12 V/μm, Single Event Burnout (SEB) may occur [2]. SEB is caused by high local currents generated when electron–hole pairs are accelerated by the strong electric field, leading to thermal breakdown. For a 50 μm-thick LGAD, SEB occurs at voltages above approximately 600 V.

At the HL-LHC, the integrated luminosity is expected to reach $4,000\ \mathrm{fb}^{-1}$, resulting in an extremely harsh radiation environment for the inner tracking detectors. For the ATLAS ITk Pixel detector, the innermost layer (Layer 0) is expected to require radiation tolerance on $O(10^{16})\ \mathrm{n_{eq}/cm^2}$, while Layer 1 requires tolerance on $O(10^{15})\ \mathrm{n_{eq}/cm^2}$ (Fig. 2).

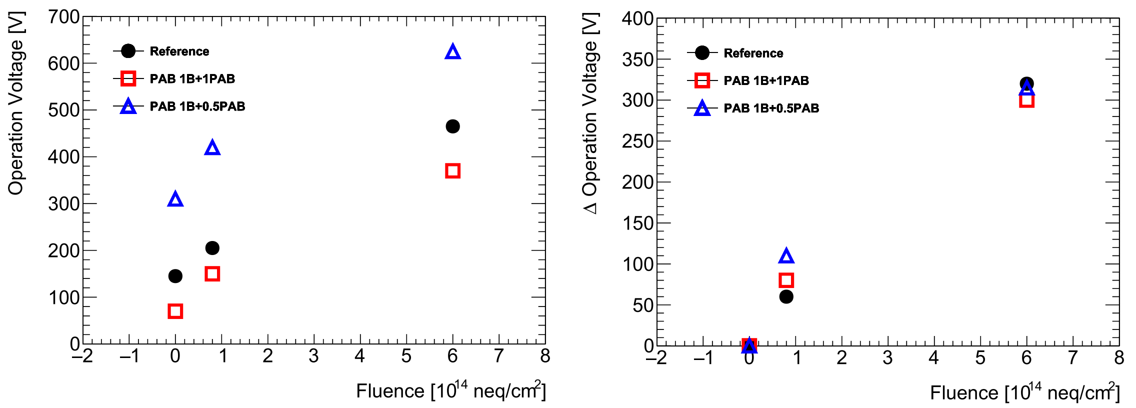
To be used as tracking detectors under such conditions, LGAD sensors must withstand fluences above $O(10^{15})\ \mathrm{n_{eq}/cm^2}$. This requires suppressing acceptor removal in the gain layer and preventing excessive increases in operating voltage.

3.2 Effects of Oxygen Concentration

When the oxygen concentration in the sensor is high, boron atoms that become inactive after irradiation can combine with oxygen to form $\mathrm{B_iO_i}$ complexes. These $\mathrm{B_iO_i}$ complexes create donor levels, which are believed to contribute to acceptor removal. Therefore, we investigated whether the oxygen content in the sensor affects the radiation tolerance of the LGAD and fabricated samples with reduced oxygen concentration.

Two methods were used to lower the oxygen concentration in the sensor: 1) minimizing oxygen contamination during the sensor fabrication process, and 2) removing oxygen by pre-doping the p^+ layer with inactive boron. In the first method, the sensor region is conventionally formed by epitaxial growth on a support substrate. However, because the interface between the epitaxial layer and the support substrate is smooth, oxygen from the substrate diffuses into the epitaxial layer during post-implantation annealing. By minimizing the annealing time, we successfully reduced the oxygen concentration down to the detection limit of SIMS.

The second method is called the Partially Activated Boron (PAB) method. PAB removes oxygen from the sensor in advance by introducing a higher concentration of inactive boron than in standard samples. This approach is expected to suppress the formation of $\mathrm{B_iO_i}$ after irradiation and thereby reduce donor level generation.



(a) Operation Voltage **(b)** Value of increase in operation voltage from non irradiated

Figure 3: Plot of radiation dependence of samples with PAB applied for sensors with high oxygen concentrations. (a) operation voltage and (b) increase in operation voltage is plotted as a function of the fluence. 1B+1PAB is a sample injected with the same amount of inactive boron as active boron, and 1B+0.5PAB is a sample injected with half the amount of active boron [3].

In previous studies [3], the oxygen concentration in the sensor was much higher than the amount of inactive boron pre-doped into the layer, and thus the oxygen could not be fully removed. As a result, no improvement in radiation tolerance was observed, as shown in Figure 3.

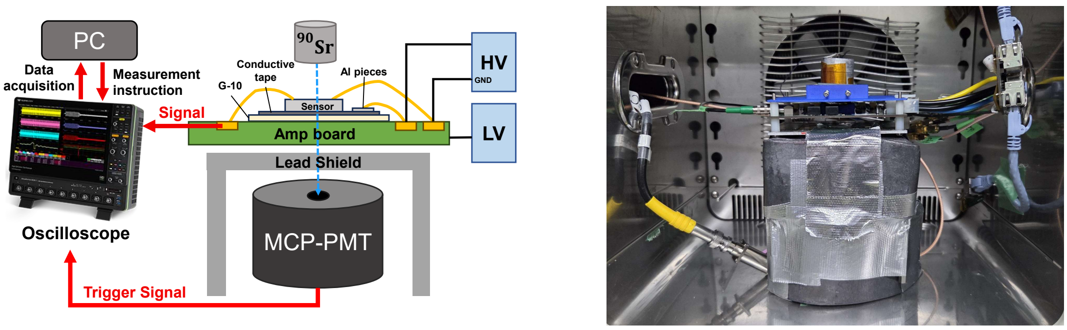
In this study, the PAB method was applied to samples in which the oxygen concentration had already been reduced using method (1). To investigate the effect of oxygen concentration on acceptor removal, we evaluated the radiation tolerance of two samples: one with reduced oxygen concentration achieved by process optimization (Low Thermal Budget, LTB), and another with additional inactive boron pre-doping (LTB+PAB).

4. Results

To investigate radiation tolerance, irradiation experiments were conducted at RARiS (formerly CYRIC), Tohoku University, in January 2025. The samples were irradiated with a 45 MeV proton beam at fluences of 6.9×10^{13}, 6.3×10^{14}, 1.5×10^{15}, and 4.1×10^{15} n_{eq}/cm^2.

4.1 Beta ray measurement

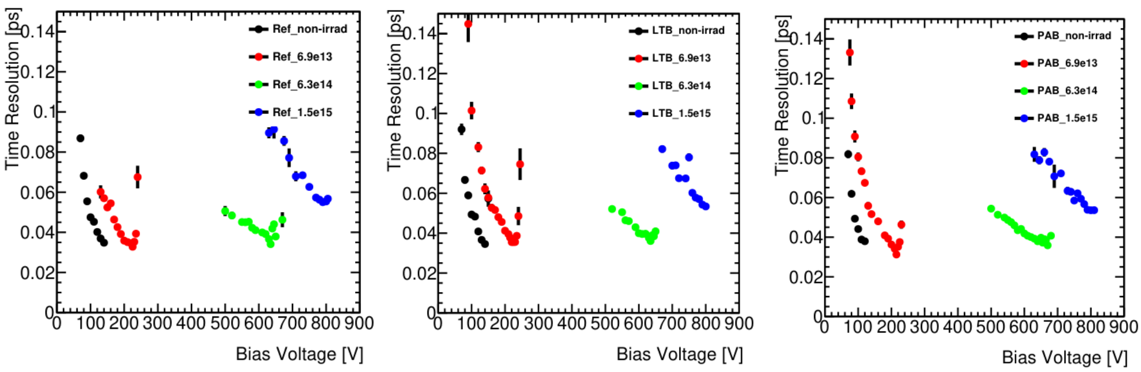
The radiation tolerance was evaluated using ^{90}Sr β rays. After irradiation, the samples were annealed for 80 minutes at 60 °C and then measured at −20 °C. Signal measurements were performed using the setup shown in Fig. 4. An HPK MCP-PMT (R3809U-52) positioned beneath the sensor was used to provide the timing reference and to trigger the WaveRunner 8208HD oscilloscope (2 GHz bandwidth, 10 GS/s sampling rate, 8 input channels, and 12-bit vertical resolution).



(a) (b)

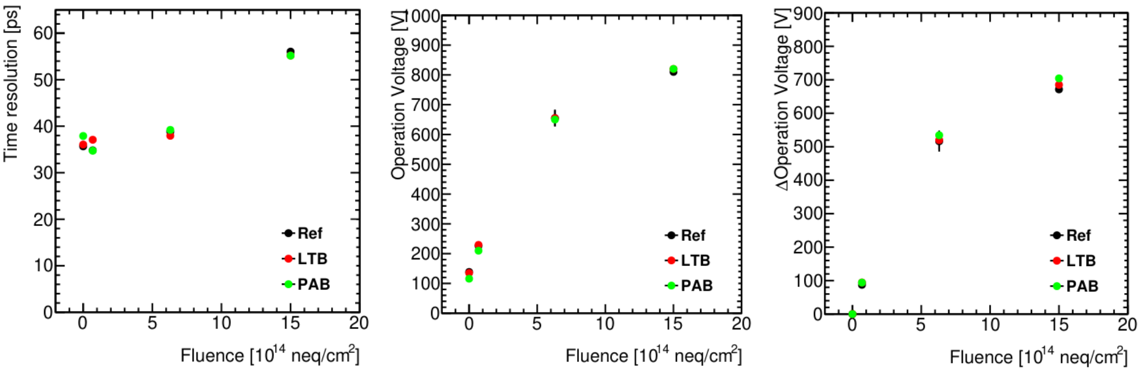
Figure 4: (a) Schematic illustration of the measurement setup using a ^{90}Sr source. (b) Photograph of the actual experimental setup.

β-ray signal measurements were performed at various bias voltages, and a plot of time resolution versus bias voltage was obtained, as shown in Fig. 5. Each plot was fitted with a quadratic function, and the best time resolution and corresponding applied voltage (defined as the operation voltage) were determined from the minimum point of the fit for each sample and irradiation level. The sample irradiated with 4.1×10^{15} n_{eq}/cm^2 was not plotted because the signal was too weak to be distinguished from the noise. The dependence of optimal time resolution, operation voltage, and the increase in operation voltage relative to the non-irradiated condition are shown in Fig. 6.



(a) Reference **(b)** LTB **(c)** PAB

Figure 5: Time resolution is plotted as a function of bias for (a) reference,(b) LTB and (c) PAB samples.



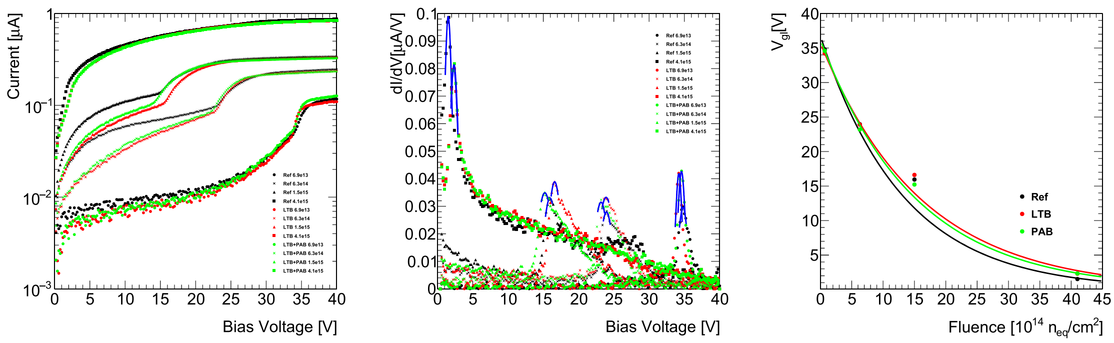
(a) Time Resolution **(b)** Operation Voltage **(c)** Value of increase in operation voltage from non-irradiated

Figure 6: Dependence of (a) time resolution,(b) Operation voltage and (c) value of increase in operation voltage from non-irradiated on irradiation dose.

As seen in Fig. 6, there is no significant difference between the Reference, LTB, and PAB samples. This result suggests that the oxygen concentration does not strongly affect acceptor removal in the p^+ layer of the LGAD, indicating that B_iO_i defects are not the dominant factor.

4.2 Depletion voltage of gain layer

As another method of evaluation, we calculated the total depletion voltage of the gain layer (V_{gl}) from the IV curve and compared its dependence on irradiation dose. When a reverse bias voltage is applied to the LGAD, the gain layer is depleted first, followed by the depletion of the bulk region. Therefore, the voltage at which the slope of the IV curve changes sharply can be interpreted as the full depletion voltage of the gain layer. Figure 7a shows the measured IV characteristics of the irradiated samples, and Figure 7b shows the corresponding differential curve (dI/dV). V_{gl} was determined as the voltage at which dI/dV reached its maximum, and the dose dependence of V_{gl} for each sample is plotted in Figure 7c.



(a) IV Curve **(b)** dI/dV **(c)** Total depletion voltage of gain layer

Figure 7: Dose dependence of depletion voltage of gain layer.

The data in Figure 7c were fitted using Eq. (3):

$$V_{gl}(\phi) = V_{gl}(0)e^{-C\phi} \tag{3}$$

Comparison of the total depletion voltages among the three samples with different oxygen concentrations shows no significant difference. From both the dose dependence of the LGAD operation voltage obtained from the signal measurements and the total depletion voltage of the gain layer derived from IV analysis, it can be concluded that the oxygen concentration in the LGAD does not have a significant effect on acceptor removal.

Previous studies reporting B_iO_i defects as the dominant factor in acceptor removal were based on measurements of p-type silicon detectors with low doping concentrations on the order of $\mathcal{O}(10^{13})$ cm^{-3}. In contrast, the p^+ layer of the LGAD has a much higher doping concentration of $\mathcal{O}(10^{16})$ cm^{-3}. Therefore, in such a highly boron-doped environment, it is possible that other defect species, such as B_iB_s, dominate over B_iO_i defects.

5. Conclusions

The gain layer of the LGAD is highly sensitive to the effective doping concentration in the p^+ layer, and acceptor removal in this region due to radiation damage remains a major issue. To suppress the formation of donor levels associated with B_iO_i, which has been considered a primary cause of acceptor removal, we fabricated samples with reduced oxygen concentrations in the sensor by improving the fabrication process and by introducing pre-doped inactive boron (PAB).

The radiation tolerance of the irradiated samples was evaluated using both the depletion voltage of the gain layer and the operation voltage. The results indicate that the radiation tolerance of the LGAD does not depend significantly on the oxygen concentration.

We therefore conclude that improving acceptor removal in LGAD requires a different approach, rather than focusing solely on the suppression of B_iO_i formation.

Acknowledgments

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