Design of LGAD Sensor with Low Energy Carbon Implantation and Irradiation Test

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Abstract

The low gain avalanche detectors (LGADs) are thin sensors with fast charge collection which in combination with internal gain deliver an outstanding time resolution of about 30 ps. High collision rates and consequent large particle rates crossing the detectors at the upgraded Large Hadron Collider (LHC) in 2028 will lead to radiation damage and deteriorated performance of the LGADs. The main consequence of radiation damage is loss of gain layer doping (acceptor removal) which requires an increase of bias voltage to

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compensate for the loss of charge collection efficiency and consequently time resolution. The Institute of High Energy Physics (IHEP), Chinese Academy of Sciences (CAS) has developed a process based on the Institute of Microelectronics (IME), CAS capability to enrich the gain layer with carbon to reduce the acceptor removal effect by radiation. After 1 MeV neutron equivalent fluence of $2.5 \times 10^{15}$ $n_{eq}/cm^2$, which is the maximum fluence to which sensors will be exposed at ATLAS High Granularity Timing Detector (HGTD), the IHEP-IME second version (IHEP-IMEv2) 50 $\mu$m LGAD sensors already deliver adequate charge collection >4 fC and time resolution <50 ps at voltages <400 V. The operation voltages of these 50 $\mu$m devices are well below those at which single event burnout may occur.

**Keywords:** Low Gain Avalanche Detectors (LGAD), Carbon implantation, Silicon detector, Radiation hardness, Acceptor removal

1. **Introduction**

In order to exploit full physics potential of the Large Hadron Collider (LHC), the LHC will be upgraded to achieve larger luminosity (High Luminosity-LHC) in 2028. The instantaneous luminosity will reach levels exceeding the present ones by at least a factor of five.\[1\] The low gain avalanche detector (LGAD) sensors are thin ($\approx 50$ $\mu$m) silicon sensors (structure n$^{++}$/p$^+$/p$^-$/p$^{++}$) with outstanding time resolutions ($\approx 30$ ps) and moderate gains ($<100$). With robust performance in the irradiation environment, the LGAD sensors will be feasible to work on HL-LHC. The Centro Nacional de Microelectrónica (CNM) Barcelona started the first developments and measurements of LGAD sensors, which has been followed by many others \[3\] \[4\] \[5\] \[6\] \[7\].
The key property of the LGAD sensor is a gain layer (at n<sup>++/p</sup> + junction) carefully tuned to give sufficient gain at moderate voltages at which the active thickness of the LGAD can be depleted and achieve high drift velocities. Radiation affects mainly the active doping concentration of boron atoms in the gain layer through the so-called acceptor removal mechanism [8] which in turn deteriorates the time resolutions of the LGAD. The rate at which this process occurs depends on several factors, mainly the initial concentration of boron atoms and added impurities to the gain layer. The active acceptors are deactivated exponentially with fluence (Equation (1)), where “c” is called the acceptor removal constant. The \( N_{\text{boron}} \) is the amount of the active boron atoms in the gain layer. The \( \phi_{eq} \) is the equivalent fluence of 1 MeV neutrons.

\[
N_{\text{boron}}(\phi_{eq}) = N_{\text{boron}}(0)e^{-c\phi_{eq}}
\]  

(1)

The usage of carbon implantation to slow down the acceptor removal effect in LGAD sensors was first proposed in [9] and realized by the Fondazione Bruno Kessler (FBK) [7]. The implanted carbon competes with acceptors to form ion-carbon complexes versus ion-acceptor complexes. In the past years, several studies indicated carbon could be the main component to reduce the removal constant “c” [10]. This strategy was also followed by the IHEP-IMEv2 sensor design.

The LGAD sensors with carbon implantation have disadvantages such as the boron deactivation by carbon and leakage current increase [11]. The IHEP-IMEv2 LGAD sensor with low energy carbon implantation has a stable gain layer in which the active boron concentration does not decrease with increasing carbon dose. Meanwhile, the IHEP-IMEv2 carbon enriched LGAD
sensor has the smallest acceptor removal constant among the IHEP-IMEv1 [12], FBK UFSD3 [10] and HPK3.2 [13] LGAD sensors as shown in Table 1. This is reflected in the smallest excess voltage required to compensate for the gain loss due to radiation.

The total radiation goals of the ATLAS High Granularity Timing Detector (HGTD) [14] and the CMS minimum ionizing particles (MIP) Timing Detector (MTD) Endcap Timing Layer (ETL) [15] are $2.5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ and $1.5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ (1-MeV-neutron equivalent fluence) respectively, <2 MGy total ionizing dose (TID) for both. This paper shows the efforts of the Institute of High Energy Physics (IHEP) on solving irradiation issues by implanting carbon into LGAD with low energy (shallow carbon). A careful investigation of processing parameters led to LGAD sensors that fulfill the radiation hardness requirements for application at HL-LHC. The sensors

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Table 1: Acceptor removal constants of different LGAD sensors.

| Producer | Type                  | Acceptor removal constant / $10^{16} \text{ cm}^2$ |
|----------|-----------------------|---------------------------------------------------|
| IHEP     | IHEP-IMEv2 W7-II      | 1.27                                              |
| IHEP     | IHEP-IMEv1 W1-IV      | 3.12                                              |
| FBK      | UFSD3_B LD+C_A Epi(W4)| 1.45                                              |
| FBK      | UFSD3_B LD+C_B(W7)    | 2.48                                              |
| FBK      | UFSD2_B LD (W1)       | 4.66                                              |
| HPK      | HPK3.2                | 3.15                                              |
| HPK      | HPK3.1                | 5.20                                              |
characteristics before and after irradiation are presented.

2. LGAD Design Fabrication

IHEP has developed two versions of LGAD sensors based on the Institute of Microelectronics (IME) process capability and irradiated those sensors at Jozef Stefan Institute (JSI) research reactor with neutrons to evaluate the sensor performance after irradiation. The first version of LGAD sensors that IHEP developed with IME (IHEP-IMEv1) was focusing on the n\textsuperscript{++} layer and the p\textsuperscript{+} gain layer fabrication process optimization \[16, 17\]. A preliminary exploration of the shallow carbon in LGAD was also included in the IHEP-IMEv1 \[12, 18\]. The LGAD sensors with carbon implantation have shown better performance than non-carbon LGAD sensors with the same n\textsuperscript{++} layer and the p\textsuperscript{+} gain layer after irradiation to $2.5 \times 10^{15}$ n\textsubscript{eq}/cm\textsuperscript{2}. The second version of LGAD sensors that IHEP developed with IME (IHEP-IMEv2) was focusing on the carbon implantation and annealing process optimization to improve the radiation hardness. Both IHEP-IMEv1 and IHEP-IMEv2 LGAD sensors were fabricated with an n\textsuperscript{++}/p\textsuperscript{+}/p\textsuperscript{−}/p\textsuperscript{++} structure on silicon wafers with a 50-µm thick high resistivity epitaxial layer as shown in Figure 1. This device is reversed biased, with the high voltage applied on the p\textsuperscript{++} layer anode. Electrons drift to the p\textsuperscript{+} gain layer, where a high-field multiplies them, and then drift to the n\textsuperscript{++} cathode at ground potential. A photo of a single pad device is shown in Figure 2.

In both IHEP-IMEv1 and IHEP-IMEv2 sensor production, the wafers were split into four quadrants. The devices for each reticle include single pads 2×2, 5×5, 15×15 (full size) LGAD and PIN sensors, as shown in Figure
Figure 1: Sketch of the LGAD structure with the active area shown. Height and width are not to scale. The sensor total area is 1200 \( \mu \text{m} \times 1200 \mu \text{m} \). The thickness of the p\(^{-}\) epitaxial layer (p\(^{-}\) substrate) is 50 \( \mu \text{m} \). The carbon atoms were implanted at n\(^{++}\) layer and diffused to p\(^{+}\) gain layer.

Figure 2: Picture of an IHEP-IMEv2 single pad LGAD sensor under a microscope. The active range of 1200 \( \mu \text{m} \) has been labeled with the red line. The metal contact pads were shown in blue.
3. The PIN sensors are identical to LGADs but without p\textsuperscript{+} gain layer.

![Figure 3: The IHEP-IMEv2 4 × 4 cm\textsuperscript{2} size layout mask. The 15 × 15, 5 × 5, 2 × 2, and single pads were allocated and aligned in this mask.](image)

Apart from the carbon process, the IHEP-IMEv2 carbon-enriched LGAD sensors inherited the boron and phosphorus process from the IHEP-IMEv1 W7-IV recipe \cite{16, 17}. The IHEP-IMEv2 has an independent carbon process that implants and diffuses carbon into the active area before the p\textsuperscript{+} layer and n\textsuperscript{++} layer process. This minimizes the carbon influence on changing the boron and phosphorus doping profile. The radiation hardness of the LGAD sensors was optimized using the different carbon processes shown in Table \ref{table2}. The relative carbon doses are expressed with an arbitrary unit (a.u.). Three wafers have carbon implantation. Wafer 4 has four different carbon doses in four quadrants that went through a fast thermal process, while wafer 7 and wafer 8 have eight different carbon doses in eight quadrants that went through a long-time thermal process.
Table 2: Key Parameters on IHEP-IMEv2 LGAD Sensors. The relative carbon doses are expressed with an arbitrary unit (a.u.).

| Wafer | Quadrant | Carbon Dose | Carbon Thermal Process |
|-------|----------|-------------|------------------------|
| 4     | I        | 0.2 a.u.    | fast                   |
| 4     | II       | 1 a.u.      | fast                   |
| 4     | III      | 5 a.u.      | fast                   |
| 4     | IV       | 10 a.u.     | fast                   |
| 7     | I        | 0.2 a.u.    | long-time              |
| 7     | II       | 0.5 a.u.    | long-time              |
| 7     | III      | 1 a.u.      | long-time              |
| 7     | IV       | 3 a.u.      | long-time              |
| 8     | I        | 6 a.u.      | long-time              |
| 8     | II       | 8 a.u.      | long-time              |
| 8     | III      | 10 a.u.     | long-time              |
| 8     | IV       | 20 a.u.     | long-time              |
3. Non-irradiated Sensor Characterization

3.1. Doping Profile by SIMS

IHEP has calibrated the process simulation parameters \[17, 18\] according to the Secondary Ion Mass Spectrometry (SIMS) test results based on the stability of the IME process. The boron and phosphorus doping profiles in the IHEP-IMEv2 sensors, as measured by SIMS, are both highly consistent with those of the IHEP-IMEv1 non-carbon sensors. (Figure 4).

Figure 4: IHEP-IMEv1 and IHEP-IMEv2 doping profiles extracted by SIMS measurements. The IHEP-IMEv2 process, inherited from IHEP-IMEv1, has shown good reproducibility. The minimum detection concentration of boron and phosphorus is $10^{14}$ cm$^{-3}$ and $10^{15}$ cm$^{-3}$.

3.2. I-V and Leakage Current

Current-Voltage (I-V) tests were performed to find the breakdown voltage and leakage current levels. The different carbon doses (0.2 - 20 a.u.) and
different thermal processes (fast and long-time) affect the I-V profile. Non-irradiated carbonated sensor I-V curves from IHEP-IMEv2 sensors are shown in Figure 5. The leakage current measured, at room temperature with bias voltage of -80 V ($\gg V_{fd}$ of the device), versus carbon dose, is shown in Figure 6. The leakage current significantly grows from $10^{-9}$ A to $10^{-6}$ A with increasing carbon dose. Clearly pointing to the formation of carbon-related defects giving rise to higher energy levels in the band-gap and consequently an increase in generation current.

3.3. Capacitance-Voltage and Gain Layer Depletion Voltage

Capacitance-Voltage (C-V) tests were performed to find the gain layer depletion voltage ($V_{gd}$) and full depletion voltage ($V_{fd}$). The different carbon doses (0.2 - 20 a.u.) and different thermal processes (fast and long-time)
Figure 6: The leakage current ($I_{\text{leak}}$) of the LGAD sensors with different carbon dose (0.2 - 20 a.u.) and different thermal processes (fast and long-time) at 80 V. The long-time annealing process increased the leakage current level more than the fast annealing process at carbon doses larger than 1 a.u. The $I_{\text{leak}}$ of the non-carbon sensor at 80 V is 0.68 nA.

affect the C-V. Non-irradiated carbonated sensor C-V curves are shown in Figure 7. The $V_{\text{gl}}$ voltages for all investigated samples are shown in Figure 8. Unlike observation made for the carbonated FBK sensors [11], the $V_{\text{gl}}$ was found to increase with carbon concentration.

The exact phenomena responsible for this behavior needs further investigation. One relevant observation is that IHEP-IMEv2 sensors have shallow carbon implantation, while FBK sensors have a deeper implantation. Hence, a possible explanation is that, due to carbon deactivation of effective dopant, IHEP-IMEv2 sensors have decreased active donors in n++ layer, while in FBK sensors it happens in the p+ gain layer. In the case of the IHEP-IMEv2, the reduction of active donors in the n++ layer shifts the starting point of the space charge area to a shallower region, increases the total depletion depth,
Figure 7: Left: C-V measurements of the LGAD sensors with different carbon dose (0.2 - 20 a.u.) and different thermal processes (fast and long-time) in the bias voltage range from 0 V to -30 V. Right: Amplified view of the C-V measurement around $V_{gl}$. The $V_{gl}$ increases as carbon implantation increases.

and hence increases the $V_{gl}$.

4. Sensor Performance after Irradiation

4.1. Neutron Irradiation and Beta Test Setup

Both IHEP-IMEv2 and IHEP-IMEv1 LGAD sensors [12] were irradiated with neutrons at JSI nuclear research reactor in Ljubljana [19, 20]. Three different irradiation fluences were used: $0.8 \times 10^{15}$, $1.5 \times 10^{15}$, and $2.5 \times 10^{15}$ $n_{eq}/cm^2$. The irradiated LGAD sensors were annealed at 60 °C for 80 min before testing their performance with electrons from a Sr-90 source (beta source test). The beta source tests of IHEP-IMEv2 LGAD sensors are performed in a climate chamber at -30 °C with a Sr-90 radiation source. The LGAD sensors were wire bonded to readout boards, designed by the University of California Santa Cruz (UCSC), using wide bandwidth transimpedance SiGe amplifiers. [21]. Figure 8 shows the beta telescope experimental setup.
Figure 8: The $V_{gl}$ of the LGAD sensors, for both fast and long-time thermal processes, increases as the carbon dose increases from 0.2 to 20 a.u. The range of $V_{gl}$ values spans about $\Delta V_{gl} \approx 1.5$ V.

The lower sensor is used as the trigger for electrons signal in the beta telescope test. The signal pulses from both sensors are recorded by a digital oscilloscope with 2 GHz bandwidth and 40 GS/s sampling rate for offline analysis [12].

4.2. Acceptor Removal Constant

The acceptor removal constants (Equation (2)) which are reflected in the gain-loss are extracted from C-V measurements and calculated by $V_{gl}$ voltages after different radiation fluences. Figure 10 (left) shows the C-V changes after different irradiation fluences. The $V_{gl}$ decrease after ever higher fluence irradiation is a consequence of the loss of effective boron doping in the gain layer. Figure 10 (right) shows that the IHEP-IMEv2 LGAD sensors with 0.5 a.u.carbon implantation and long-time carbon annealing recipe (W7-II) are the most radiation robust. These sensors have an acceptor removal constant
of $1.27 \times 10^{16} \text{ cm}^2$, around 3-5 times lower than the ones typically measured for boron only devices \cite{5, 20, 12, 10, 13}.

\begin{equation}
    V_{gl}(\phi_{eq}) = V_{gl}(0)e^{-c\cdot\phi_{eq}}
\end{equation}

The acceptor removal and loss of gain is the most serious consequence of the radiation damage at HL-LHC. It can be compensated to some extent by increasing the bias voltage, but recent studies \cite{22, 23} showed that the maximum bias voltage that sensors can withstand reliably in the beam is limited to about 550 V for 50 μm thick devices, due to Single Event Burnout (SEB). The charge collection efficiency of the W7-II samples and their timing performance are shown in Figure \ref{fig:11}. It is clear that the required bias for successful operation ($>4$ fC, $<50$ ps) increases with the irradiation fluence. However, for W7-II sensors after $2.5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$, the required performance can be reached at a bias voltage $<400$ V, lower than any other LGAD device studied thus far. Apart from the obvious benefit of avoiding operation close
4.3. Carbon Thermal Process

In IHEP-IMEv2 production, the W4-I and W7-I (0.2 a.u.), W4-II, and W7-III (1 a.u.) wafer quadrants are good control groups to investigate the thermal process influence on the diffusion and activation of carbon. Figure 12 and Figure 13 show the I-V, collected charge, and time resolution of those two control groups. After $2.5 \times 10^{15} \text{ cm}^{-2}$ irradiation fluence, the long-time carbon annealing process (wafer 7) yields sensors with the same charge collection and time resolution as the fast annealing process (wafer 4) but at a lower bias voltage. This is the result of a larger thermal load delivered to the carbon, diffusing more of it into the gain layer. The same conclusion can

Figure 10: Left: C-V measurements of the IHEP-IMEv2 LGAD sensor with 0.5 a.u. carbon dose and long-time carbon annealing recipe (W7-II) before and after $0.8 \times 10^{15}$, $1.5 \times 10^{15}$, $2.5 \times 10^{15} \text{ cm}^{-2}$ radiation fluences. The $V_{gl}$ decreases with radiation fluence increasing. Right: acceptor removal constants of IHEP-IMEv2 LGAD sensors with different carbon doses and two different thermal processes.

to SEB voltage, reduced operation bias leads to smaller power dissipation.
Figure 11: Collected charges (left) and time resolutions (right) of IHEP-IMEv2 W7-II LGAD sensors before radiation and after $0.8 \times 10^{15}$, $1.5 \times 10^{15}$, and $2.5 \times 10^{15}$ n$_{eq}$/cm$^2$ irradiation fluence. The bias voltage needed for maintaining the same charge and time resolution becomes higher. The bias voltage for 4 fC charge collection increases from $<80$ V, before irradiation, to 350 V, after $2.5 \times 10^{15}$ n$_{eq}$/cm$^2$ irradiation.

also be verified by Figure 10 (right) which shows the wafer 7 has a smaller acceptor removal constant with the same carbon dose as of wafer 4.

4.4. Carbon Implantation Dose

It is obvious that long-time carbon annealing, used in wafer 7, is a better process for 50 keV carbon implantation. Figure 14 shows the collected charge and time resolution of sensors with different carbon doses (0.2, 0.5, 1, and 3 a.u.), after irradiation fluence of $2.5 \times 10^{15}$ n$_{eq}$/cm$^2$. Sensors with 0.5 a.u. carbon dose (W7-II) have the best performance after irradiation. They achieve the same charge collection and time resolution as the other carbon dose sensors but at lower bias voltages. These sensors also have excellent performance before irradiation as shown in Figure 11.
Figure 12: I-V measurements of IHEP-IMEv2 W4-I (0.2 a.u. fast annealing), W7-I (0.2 a.u. long-time annealing), W4-II (1 a.u. fast annealing) W7-III (1 a.u. long-time annealing) LGAD sensor after $2.5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ irradiation fluence. Leakage current increased from $10^{-9}$ A to $10^{-7}$ A.
Figure 13: Most probable collected charge (left) and time resolution (right) of IHEP-IMEv2 sensors before irradiation and after $2.5 \times 10^{15}$ n$_{eq}$/cm$^2$ irradiation fluence, for different thermal processes. Sensors with the same carbon dose (0.2 a.u.in black, 1 a.u.in blue) have similar behavior before irradiation, regardless of the thermal process. The long-time carbon annealing LGAD sensors (W7-I, W7-III) show better charge and time resolution after $2.5 \times 10^{15}$ n$_{eq}$/cm$^2$ irradiation fluence.
5. Summary

The IHEP-IMEv2 carbon enriched LGAD sensors show excellent robustness to radiation. In particular, measurements of leakage current level, $V_{gl}$, acceptor removal constant, collected charge, and time resolution before and after irradiation demonstrate that LGAD sensors (W7-II) produced with 0.5 a.u. carbon dose and long-time carbon annealing have excellent performance and superior irradiation resilience. These sensors have the smallest acceptor removal constant ($1.27 \times 10^{-16}$ cm$^2$)\footnote{The lowest bias voltage (400 V) for 50 ps time resolution, and the lowest bias voltage (350 V) for 4 fC charge collection after irradiation fluence of $2.5 \times 10^{15}$ n$_{eq}$/cm$^2$ when compared to past HPK, FBK, CNM, NDL, and USTC LGAD sensors\cite{24}. These sensors already satisfy the requirements for operation in the radiation harsh environments.} the lowest bias voltage (400 V) for 50 ps time resolution, and the lowest bias voltage (350 V) for 4 fC charge collection after irradiation fluence of $2.5 \times 10^{15}$ n$_{eq}$/cm$^2$ when compared to past HPK, FBK, CNM, NDL, and USTC LGAD sensors\cite{24}. These sensors already satisfy the requirements for operation in the radiation harsh environments.
environment of the HL-LHC.

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