Effect of Carbon co-implantation on radiation hardness of LGAD

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Introduction

The Low Gain Avalanche Detectors (LGAD) are silicon sensors specifically tailored for the High Granularity Timing Detector (HGTD) program in the ATLAS detector to answer the unprecedentedly complex pile-up in the High-Luminosity Large Hadron Collider (HL-LHC)[1]. The time resolution of IHEP-IMEv2 LGADs reaches 35 ps before irradiation. A major challenge to these sensors is to maintain time resolution at low bias after withstanding 1 MeV neutron equivalent fluence up to $2.5 \times 10^{15} cm^{-2}$during their operating life in HGTD, given that high energy particles passing through the sensor deactivate gain layer acceptors (acceptor removal), leading to a deterioration of time performance.

IHEP-IMEv2 LGADs are designed aiming at improving device radiation hardness as well as discovering the dependence of acceptor removal to carbon distribution in the critical region of devices. 12 designs vary in carbon implantation dose and carbon thermal load are included in this version. These devices have different carbon density profiles according to SIMS tests, and show different capabilities in radiation hardness.

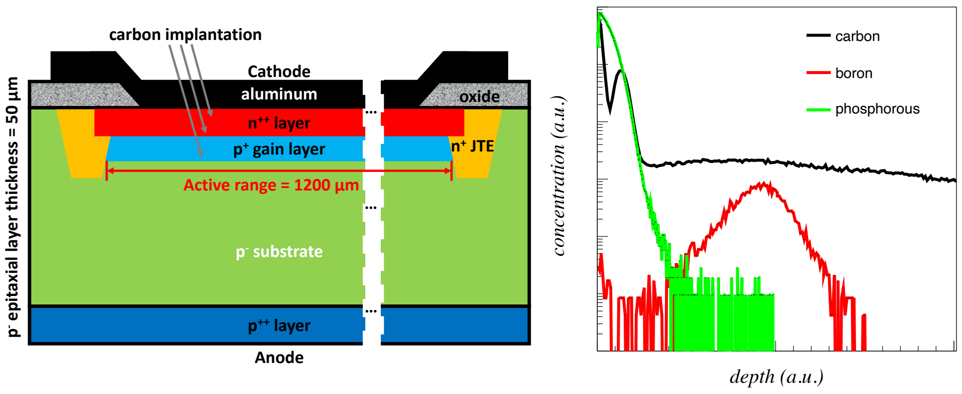


Figure 1:(left) Sketch of the LGAD structure (not to scale) , (Right) Dopants density profile from SIMS .

OLD Acceptor removal parameterization

Active acceptor density in the gain layer region (GL) Ngl after irradiation decreases exponentially and the gain layer depletion voltage Vgl is considered to be proportional with gain layer effective doping density [2]:

$$\frac{V_{gl}(\Phi)}{V_{gl}(0)} = \frac{N_A(\Phi)}{N_A(0)} = e^{-c\Phi}$$

The acceptor removal coefficient c is a quantification of device radiation hardness, c value is a functional of carbon and boron density profiles. Till now the value of c can only be derived from device electrical property before and after irradiation. In this work, a new method to calculate the c value and estimate device radiation hardness at the stage of design is proposed.

NEW Acceptor removal parameterization

Carbon atoms are known to trap silicon self-interstitials in semiconductor industry. Radiation, however, will induce Frenkel pairs (vacancy interstitial pair) in crystalline. The extra Si_i carries kinetic energy from the traversing particle, deactivate boron by kick-out mechanism. Carbon in LGADs thus can help alleviating the deactivation by capturing Si_i.

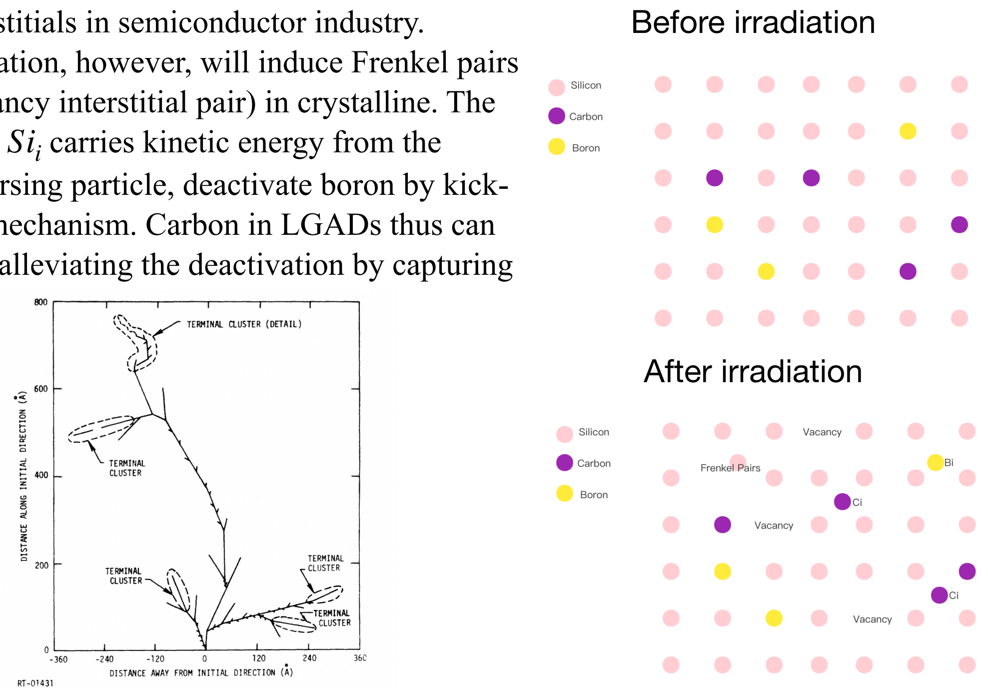


Figure 2:(left) Picture of a typical recoil-atom track with primary energy E of 40 keV, (Right) Schematic diagram of radiation induced defects.

While carbon is able to protect boron atoms from removal, the reacting probability of boron (carbon) and Si_i is unknown, and the abilities of generating displacement damages are different among different incident particles. These parameter values are determined from existent LGAD data and different shapes of density profiles determined from SIMS. A simulation is firstly generated including the reaction listed below:

$$\begin{aligned} Si_s &\rightarrow V + I \\ V + I &\rightarrow Si \\ I + B_s &\rightarrow B_i \\ I + C_s &\rightarrow C_i \end{aligned}$$

By comparing the results of simulation and measurements, parameter values are determined, c values are compared in right.

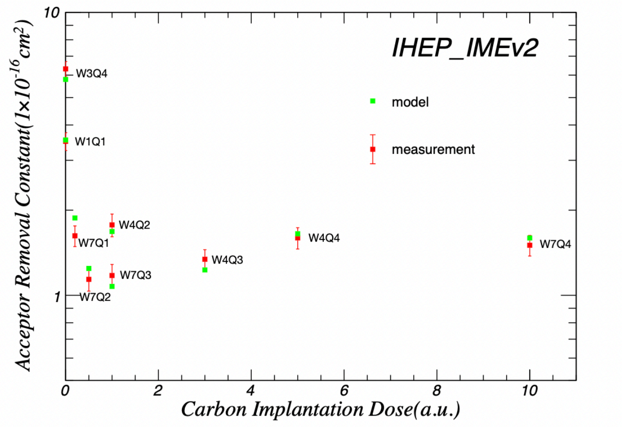


Figure 3:Comparison of c values from simulation and measurements.

From simulation, neutron generates interstitials $\approx 50/cm$, and the probability of carbon to react with Si_i is 0.65 (normalized to boron), while for vacancy is 10, which is consistent with previous simulation results in order of magnitude.

Comparison with other model

The torino parameterization is fit of c values of different initial boron densities and is compared with the parameterization proposed in this work. This parameterization predicts well at large initial born densities but shows poor consistency at low doping. This is resulted from the naive simulation and only 4 reactions are considered. Varies reactions among different types of defects should not be neglected under this circumstance.

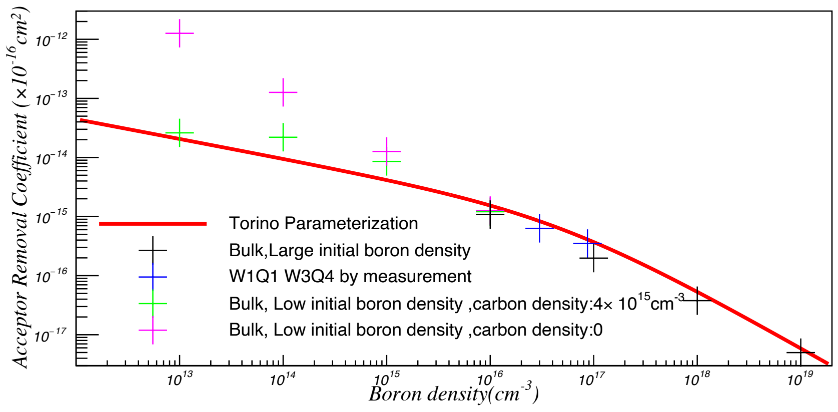
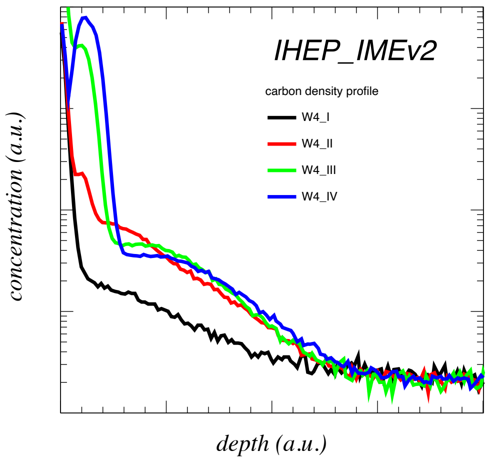


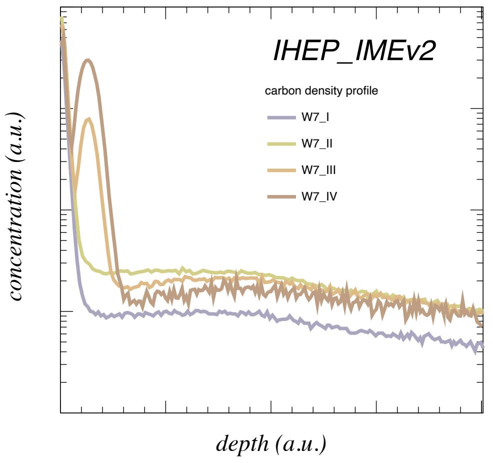
Figure 3:Comparison of c values of this model and Torino parameterization [2].

Carbon induced issues

(1)While it's proved that carbon is able to preserve active boron, carbon implantation is not always good for boron. Carbon has low solid solubility in silicon, large implantation dose will induce clusters to deactivate boron before irradiation and decrease gain. For a shallow carbon penetration depth, immobile peaks after annealing always exist as shown below. Thus separating the carbon peak and boron is necessary.

(2)It is also found that carbon density at boron enriched region does not increase monotonically with implantation dose (in the next 2 plots, carbon dose increase with wafer quadrant, but carbon that diffuses into deeper region does not always increase), indicating a maximum at a certain dose.





Summary

This work aims at modeling the acceptor removal coefficients based on SIMS spectra of IHEP-IMEv2 sensors. The simulation is in consistency with other parameterizations. Thus can help with the design of next version LGAD.

Reference

[1] Technical Design Report: A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade.

[2] M. Ferrero et al. "Radiation resistant LGAD design". In:Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 919 (2019), pp. 16–26.