Prepared for submission to JINST

24th international Workshop on Radiation Imaging Detectors, iWoRiD 2023
25 - 29, June, 2023
Oslo Science Park

The CIGS semiconductor detector for particle physics

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Abstract: Silicon is commonly used as a sensor material in a wide variety of imaging application. In recent high-energy and intensity beam experiments, high radiation tolerance is required, and new semiconductor detector consisting of radiation-hard materials have been investigated. The Cu(In,Ga)Se2 (CIGS) semiconductor is expected to possess high radiation tolerance, with the ability to recover from radiation damage through the compensation of defects by ions. The CIGS has originally developed for a solar cell and its radiation tolerance was investigated for the usage in space. The CIGS, featuring a recovery capability, would shed new light to particle detecror in high radiation environments. CIGS detectors (2 and 5 μm thick) were tested by Xe ion (400 MeV/u, ^{132}Xe^{54+}) at HIMAC, successfully detecting single Xe ion with a fast response. The output charge is understandable through estimation with the GEANT4 simulation. With 0.6 MGy irradiation by Xe ions, the CIGS output degraded to 50%, but it was recovered to 97% after the heat treatment under 130 °C for 2 hours. This marks a significant step in confirming that CIGS semiconductors can serve as particle detectors with recovery features for radiation damage.

Keywords: Radiation-hard detectors, Radiation damage to detector materials (solid state), Materials for solid-state detectors

ArXiv ePrint: 1234.56789

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Contents

1 Introduction

Silicon is commonly used as a sensor material in wide variety of imaging application. In recent high energy and intensity beam experiments, high radiation tolerance is required. The semiconductor detectors, particularly those used in hadron colliders, receive the highest radiation in particle physics experiments. These detectors, placed around the collision point to track particles, endure damage from these collisions. The Large Hadron Collider (LHC), the world's highest energy and intensity proton collider, is planing a higher luminosity upgrade, with the radiation levels assuming 10^{16} MeV n_{eq}/cm^2 and 7 MGy for Non Ionization Energy Loss (NIEL) and Total Ionization Dose (TID), respectively. To withstand such high dose levels, detectors have been developed with novel electrode structures, such as 3-D sensors, for example [1]. In anticipation of future hadron collider experiments, the development of higher radiation-tolerant detectors with new innovations is necessary.

A new semiconductor detector based on radiation hard material has been developed. Wide-gap semiconductors, such as Diamond [2] and Gallium Nitride [3], has been investigated globally due to their high binding energy among nucleons and low leakage current. The $Cu(In,Ga)Se_2$ (CIGS) semiconductor is also expected to have high radiation tolerance coupled with a unique feature, recovery through the compensation of defects by ions. Originally developed for solar cells, CIGS's radiation tolerance was initially investigated for space applications [4]. As a preliminary experiment, CIGS solar cells were irradiated with 10^{16} MeV n_{eq}/cm^2 and 7 MGy by 70 MeV proton beam at the Cyclotron and Radioisotope Center (CYRIC), Tohoku University. The CIGS solar cells deteriorated after proton irradiation, with decreased conversion efficiency and short-circuit current density. However, both parameters were gradually recovered through heat-light annealing [5].

This paper describes the demonstration of the world's first CIGS detector, taking advantage of its recovery feature for radiation hardness."

2 The CIGS detector

The CIGS detector and its layer configuration are shown in Figure 1. The geometries of CIGS detectors are approximately 5×4 mm^2, and the thicknesses of active layer (CIGS layer) are 2 or 5 μm. CIGS is a p-type semiconductor and the CdS/ZnO is connected as n-type for the p-n junction. In this detector, two n-type electrodes are prepared for signal read out. More details are described in [5]. The depletion voltage is supplied from CIGS side with -2.0 V and the typical leakage current is about 1 nA.

Since these new detectors have thin active layer, so far only 2 or 5 μm, the detection of single charged particle is challenging due to very small charge outputs. A heavy ion beam is a better choice to test such condition since charge outputs are expected to be large. Of cause, the new detector would be a good candidate as a heavy ion tracker, which also requires radiation tolerance. The expected charge inducing by the penetration of a 400 MeV/u $^{132}Xe^{54+}$ beam on the 2 μm thick detector is estimated by the GEANT4 simulation yielding a value of about 280 fC.

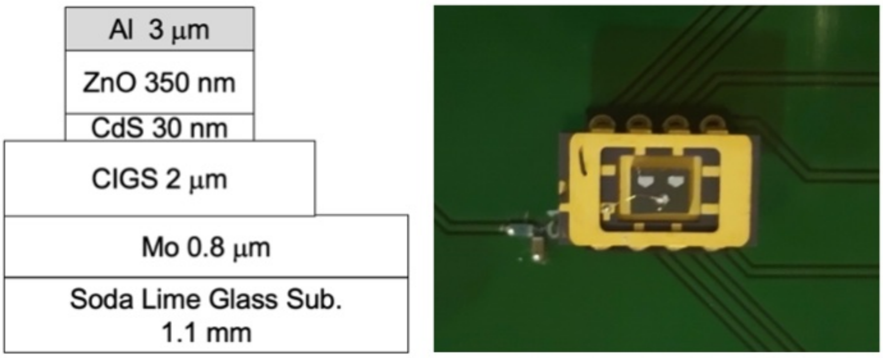

Figure 1. A CIGS detector configuration for 2 μm active thickness. Signals are read out from n-type CdS electrodes under home-base shaped Al pads for wirebonds.

3 Experimental Setup at HIMAC

For demonstration of the CIGS detector, a heavy ion beam, Xe ion (400 MeV/u, $^{132}Xe^{54+}$) at the Heavy Ion Medical Accelerator in Chiba (HIMAC) was selected. We used the PH2 beam line, and the experimental setup is shown in Figure 2. Only detectors were positioned on the beam axis, with the readout circuits, including signal amplification, placed next to the detector. The beam size was adjusted to approximately ϕ 3-5 mm using a fluorescent plate at the beginning. To induce irradiation damage, the beam power was set to 10^7 particles per pulse (ppp) within 3.3-second pulse cycles. The number of Xe beam was monitored by scintillator counter placed off-beam position.

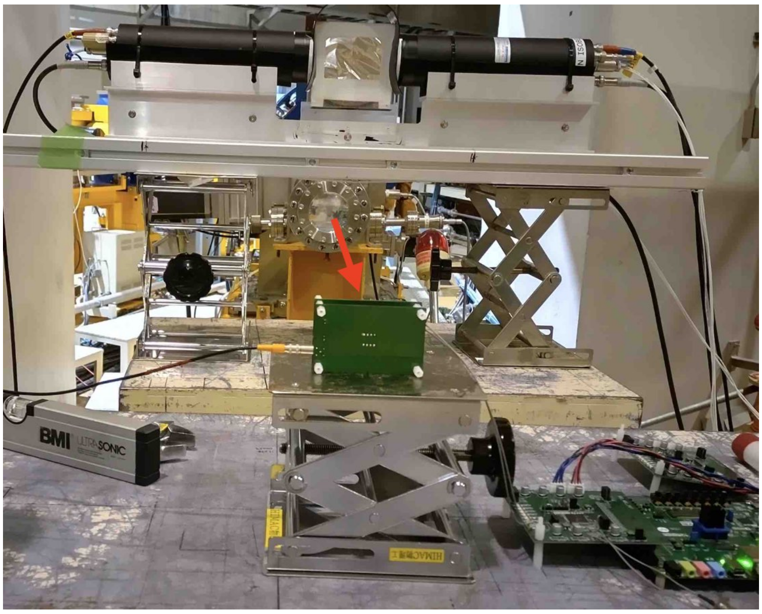

Figure 2. A setup photo at the PH2 beam line. Only detectors were placed on the beam.

4 Results

4.1 Signal output

The outputs from the CICS detector are shown in Figure 3. The data were recorded using the waveform digitizing function in the readout ASIC, and the signal response looks sharp. The charge generated by Xe ion penetration can be estimated by integrating the wave form signal (Integrated ADC). The charge is approximately 180 fC and this value is 64% of the estimation by the GEANT4 simulation. Possible considerations are low charge collection efficiency and/or the excitation density effect, but further investigations are needed for a conclusive understanding. We also irradiated the 5 μm thick CIGS detector and the output is about 2.5 times larger than that of 2 μm thick, as we expected.

In Figure 4, the history of Integrated ADC value normalized to the value of un-irradiated are plotted. The conditions were changed in five periods as followings,

(1) 0-16 h : Irradiation of Xe ion, 0.6 MGy in total : The output decreased to be 0.5,

(2) 18-20 h : Heat annealing with 130 °C : The output recovered to be 0.97,

(3) 20-27 h : Irradiation of Xe ion, 0.2 MGy in total : The output decreased to be 0.8,

(4) 28-31 h : Heat annealing with 90 °C : The output was not changed,

(5) 31-33 h : Heat annealing with 130 °C : The output recovered to be 0.94.

It is confirmed the CIGS detector deteriorates in terms of signal output, likely due to the reduction of charge collection efficiency by defects generated by irradiation. With heat annealing at 130 °C, the signal output almost returned to the initial value. The recovery shows no limits up to 0.8 MGy and is repeatable. Since there was no significant recovery with 90 °C within this time period, the recovery appears to have strong temperature dependence between 90 and 130 °C.

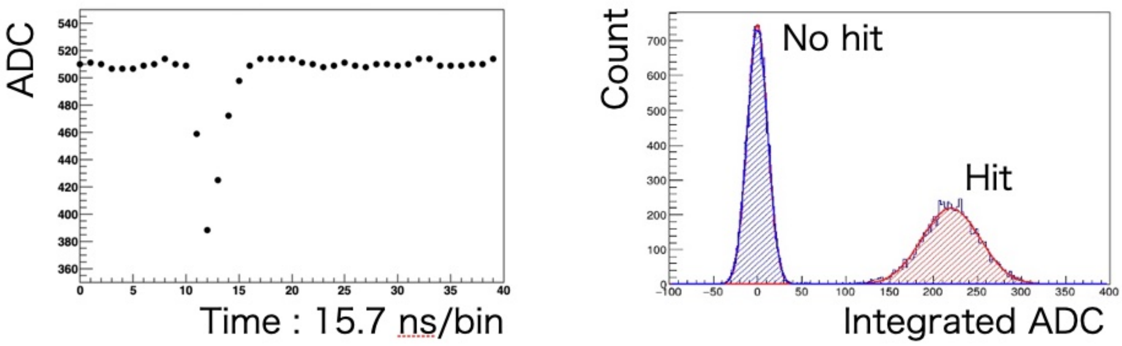

Figure 3. Left) Signal from single Xe ion event. The event is recorded by the wave form digitizing. Right) Integrated ADC values of recorded events. It is clearly separation of hit and no-hit.

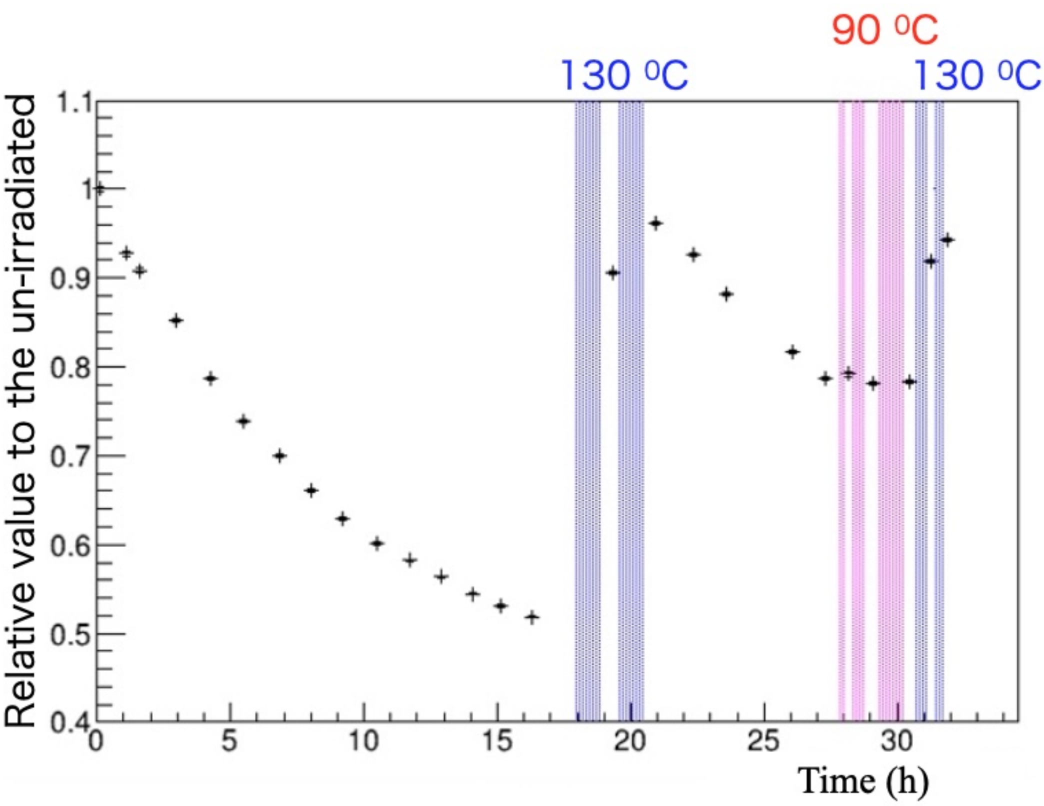

Figure 4. The output history of the CIGS detector.

4.2 Leakage current

The leakage current during 27-hour period, corresponding to periods of (1) to (3) in section 4.1, is shown in Figure 5. The leakage current increased proportionally to the amount of Xe irradiation from 1 nA to 35 nA. After the heat annealing, the current returned to 3 nA, nearly reaching the initial value. With additional Xe irradiation, the leakage current increased with same tendency in period of (1).

Based on the results of signal output and leakage current, it can be inferred that recombination centers generated by radiation damage are passivated by heat annealing.

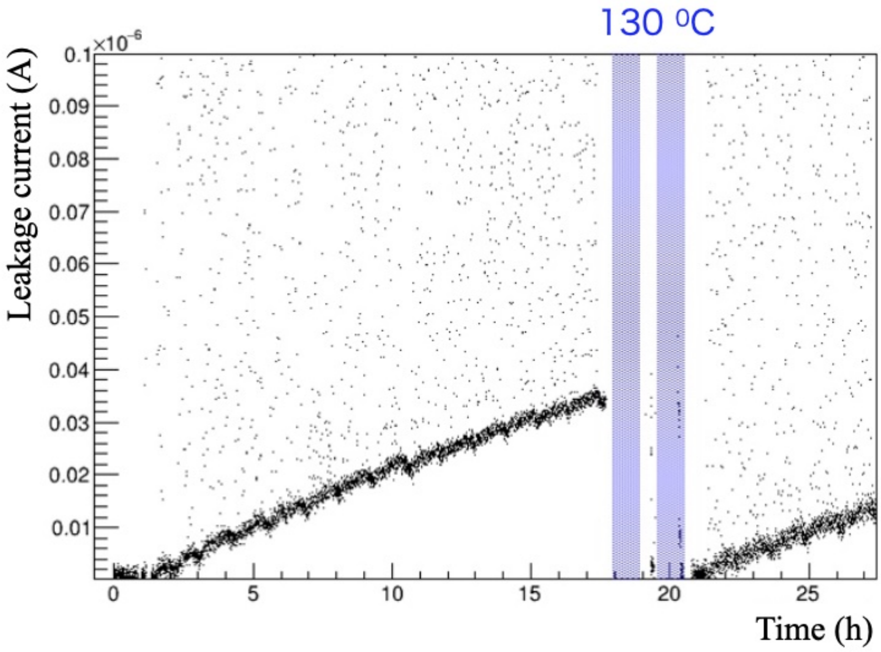

Figure 5. The leakage current history of the CIGS detector.

5 Conclusion

For the particle detector in a high radiation environment, we have developed new semiconductor detectors using CIGS. The 2 μm thick detector was irradiated by Xe ions and it successfully detected a single Xe ion particle with a fast response. For the accumulation of radiation damage, Xe beam was irradiated up to 0.8 MGy. It has been confirmed that the decreased signal outputs can be recovered by heat annealing at 130 °C, and the recovery is repeatable. This marks a major milestone in realizing the CIGS particle detector with a recovery mechanism. Since there was no significant recovery at 90 °C within this time period, the recovery appears to have a strong temperature dependence between 90 and 130 °C.

Acknowledgments

This work was partly supported by the Tsukuba Innovation Arena (TIA) “Kakehashi” and JSPS KAKENHI Grant No. 21K18635 and 23H01191 from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. This work was supported by World Premier International Research Center Initiative (WPI), MEXT, Japan. Part of the experiments was performed under the

Research Project with Heavy Ions at NIRS-HIMAC, program No. 21H455. The authors also wish to thank the accelerator staff at HIMAC for supplying the excellent beams used in this work.

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