The CIGS semiconductor detector for particle physics

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Semiconductor detector

- Silicon crystal is the mainstream
- Crystal is high quality
Malfunction in the high radiation environment

- Radiation causes the lattice defect by nucleus scattering
- Degrading semiconductor properties
- Increasing leakage current
Recovery type semiconductor: CIGS: Cu(In, Ga)Se$_2$

- Recovery by the compensation of defects by heat annealing.
- Cu-ion and/or Alkali-ions (mixed at production) may fill in defects.
- High radiation tolerant solar cell has been investigated by JAXA.

Solar cell >> High radiation tolerant particle detector!
Radiation level example: LHC-ATLAS experiment

- New particle search (heavier) -> high energy and/or high luminosity

- NIEL (1 MeV n_{eq.}/cm^2)
  - LHC: \(10^{15}\)
  - HL-LHC: \(10^{16}\)
  - FCC/HE-LHC: \(10^{17}\)

- TID (MGy)
  - LHC: 0.7
  - HL-LHC: 7
  - FCC/HE-LHC: 70

Inner most layer will be replaced at half of experimental period

~20 pp collision / bunch crossing

~200 pp collision / bunch crossing
Radiation tolerance for the CIGS solar cell

- 70 MeV proton irradiation at CYRIC, Tohoku University.
- $3 \times 10^{15}$ and $10^{16}$ (1 MeV n$_{eq.}$/cm$^2$)
- 2 and 7 MGy

Annealing by sun light equivalent (1 Sun, 95°C)

Jiro Nishinaga et al 2023 Jpn. J. Appl. Phys. 62 SK1014

Recovery is confirmed.
Detecting alpha-particle by the p-n structure CIGS.

Normally, CIGS is p-type
Thickness: ~2 μm

Band Gap
CIS: 1.0 eV, CGS: 1.7 eV
Si: 1.1 eV

Density
CIGS: 5.7 g/cm³
Si: 2.33 g/cm³

Output is expected as GEANT4 estimation

- Alpha 5.3 MeV, 2 μm CIGS
- 0.45 MeV -> (120 k e/h pairs) -> 19.2 fC
Beam test @ HIMAC  
(Heavy Ion Medical Accelerator in Chiba)

- 2022 1/9 - 1/10, 2022 11/24-11/25
- Heavy ions deposits large energy in the detector -> Detectable with thin layer.
  - $^{132}\text{Xe}^{54+}$ 400 MeV/n @ 2 um-thick CIGS : 6.5 MeV -> $277.3 \text{ fC}$
  - MIP@300 um-thick silicon : 0.11 MeV (22k e/h pairs) -> $3.6 \text{ fC}$  x100!

- Beam condition
  - 400 MeV/n Xe-132 beam
  - $\phi \sim 4 \text{ mm}$ (measured by fluorescent plate)
  - $10^4$ - $10^7$ ppp in 3.3 s cycles.
The CIGS detector successfully detects single particle!
Radiation damage and recovery for the 2 µm thick CIGS 1

- Recovery is confirmed. We can develop as a particle detector with a recovery feature!

Heat annealing 130°C, 5 hours
TID ~ 80 kGy
Radiation damage and recovery for the 2 µm thick CIGS 2

- Recovery by 130 °C annealing is confirmed up to 0.8 MGy
- Repeatable
- Strong temperature dependence between 90 - 130 °C
Leakage current and depletion depth

- Leakage current: Recovered to be the value before irradiation
- “Critical defects” for charge collection and leakage current may be almost recovered by annealing

Depletion depth:
- Partially Recovered
- Acceptor concentration may be increased
Coming investigation

- Temperature and time dependence of recovery
- CIGS solar cell.
- Detector performance after recovery from HL-LHC level damage.
- CIGS detector

Future investigation

- Basic investigation
- Compensation mechanism
- Acceptor behavior after irradiation
- Gamma and neutron irradiation
- To separation of NIEL and TID damage
- Future fabrication
- Thicker CIGS detector: So far investigated up to 5 µm thick
- Strip/Pixel type electrodes
Conclusion

• In recent high energy/intensity particle physics experiment, the radiation damage of silicon detector is being serious.
  • The CIGS semiconductor which has recovery feature shed new light to the super radiation hard detector.
• The CIGS detector has been evaluated with heavy ions at HIMAC
  • It is confirmed to detect single particle and the recovery of radiation damage up to 0.8 MGy.
• Temperature / Time dependences has been investigated.
  • Understanding of acceptor behavior are important.
Backup
The charge collection does not depend on depletion depth.

cf. collection charge is proportion to the depth of depletion depth.
Consideration: Drifting by slope of band gap

- CIGS is mixed of CIS and CGS
- Band gap slope due to the mixing shade along the depth cause drifting
  - Like SiGe semiconductor (Si: 1.1 eV, Ge: 0.6 eV)
- Non or Low voltage operational detector would be developed.
- Wide-gap type CIGS can be possible increasing CGS ratio

Cu(In,Ga)Se$_2$ の構造

Band Gap
- CIS: 1.0 eV
- CGS: 1.7 eV
Applications in high radiation environment

- Car (in engine)
- Space mission
- Monitor in nuclear plant
- Emergency response

Temperature (°C)

Total dose (kGy)

Application region of Si
Toward single charged particle detection

Bethe-Bloch on PDF

\[
\left\langle -\frac{dE}{dx} \right\rangle = \frac{K Z^2 Z}{A \beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right] \cdot \frac{dE}{dx} \propto \rho
\]

<table>
<thead>
<tr>
<th></th>
<th>Band Gap (Mean excitation)</th>
<th>Density</th>
<th>#e-h pairs (Si normalized)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.1 (3.6)</td>
<td>2.33</td>
<td>1</td>
</tr>
<tr>
<td>SiC</td>
<td>3.2 (7.8)</td>
<td>3.21</td>
<td>0.64</td>
</tr>
<tr>
<td>C (Diamond)</td>
<td>5.5 (12)</td>
<td>3.5</td>
<td>0.45</td>
</tr>
<tr>
<td>CIGS</td>
<td>1.2 (BGx2.5 ?)</td>
<td>5.7</td>
<td>(2.93)</td>
</tr>
<tr>
<td>AlN</td>
<td>6.2 (15.3)</td>
<td>3.26</td>
<td>0.33</td>
</tr>
<tr>
<td>Ga$_2$O$_3$</td>
<td>4.8 (BGx2.5 ?)</td>
<td>6.44</td>
<td>(0.83)</td>
</tr>
<tr>
<td>GaN</td>
<td>3.4 (8.9)</td>
<td>6.15</td>
<td>1.07</td>
</tr>
</tbody>
</table>

22,400 e-h / 300 um

50 um thick silicon <-> 17 um thick CIGS >> 10-20 umCIGS

* Charge collection efficiency needs to be considered.
CIGS imaging sensor

https://www.aist.go.jp/Portals/0/resource_images/aist_j/aistinfo/aist_today/vol08_01/vol08_01_p27.pdf

- Joint development of AIST and Rohm developed at 2008
- High sensitivity infrared camera
- 10x10 \text{um}^2 \text{ pixel CCD}
- 352x288 pixels
- Deposition on the read out CMOS
- No bump bonding is necessary

Achievement of pixel detector

*産総研、Rohm株式会社
Use in the heavy ion experiment
RIKEN : TadaAki Isobe

• RIKEN RIBF : Creation of heavier nuclei and neutron rich nuclei
• Identification of created particle is important.

Scintillator :
:) Reduction of output

Gas chamber :
:) The gas can be purged in case of rad. damage. :
( Remnant in case of high intensity beam

Expecting of rad. hard semiconductor detector to replace them.
Application of spot scanning

Proton spot scanning

New semiconductor detector improves position resolution and intensity tolerance.

- Gas chamber has been used
- Less position resolution
- Remnant happens due to slow response in case of high intensity.

-> Reduction of the system QA and also treatment time.