New particle detector with the CIGS semiconductor

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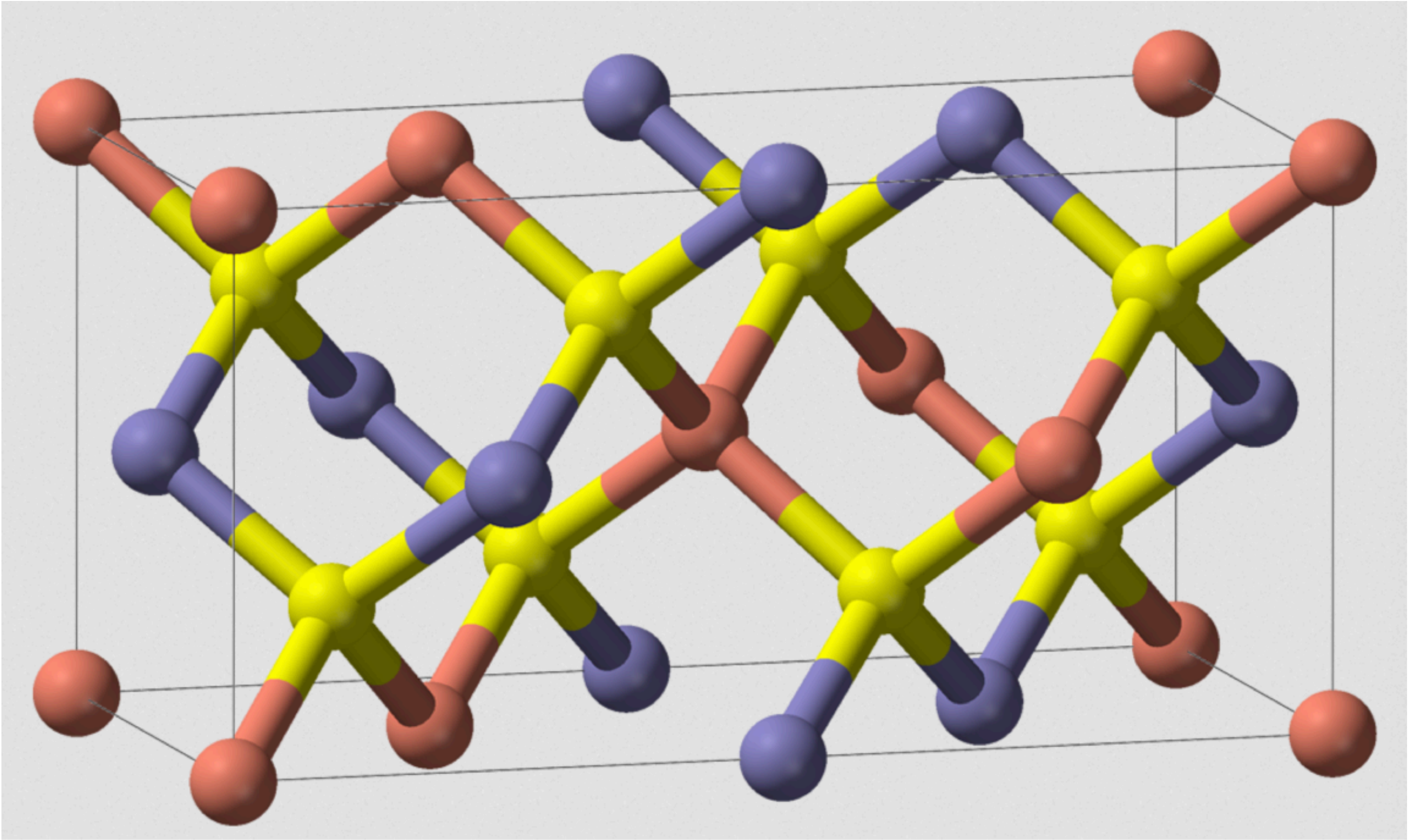
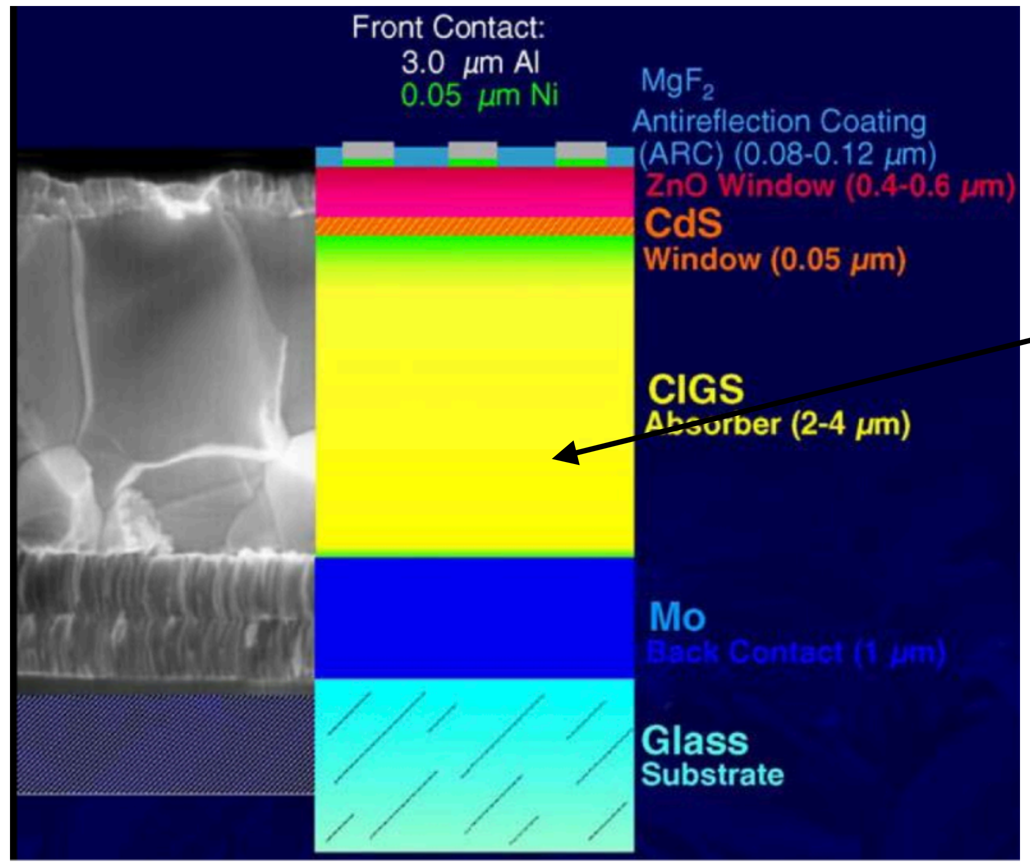
What is the CIGS ? Cu(In, Ga)Se_2. As a solar cell

https://en.wikipedia.org/wiki/Copper_indium_gallium_selenide_solar_cell



CIGS unit cell.
Red = Cu, Yellow = Se, Blue = In/Ga

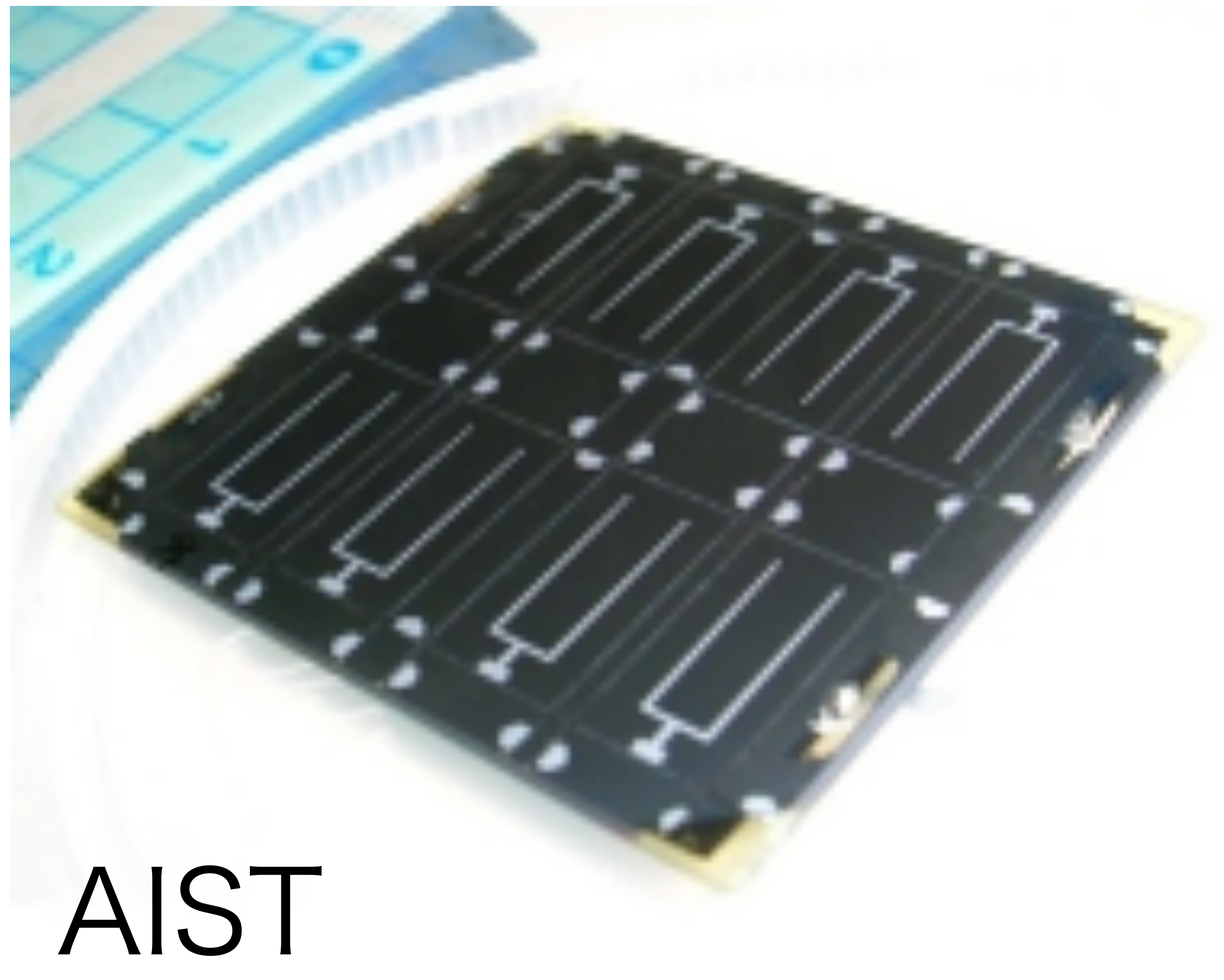


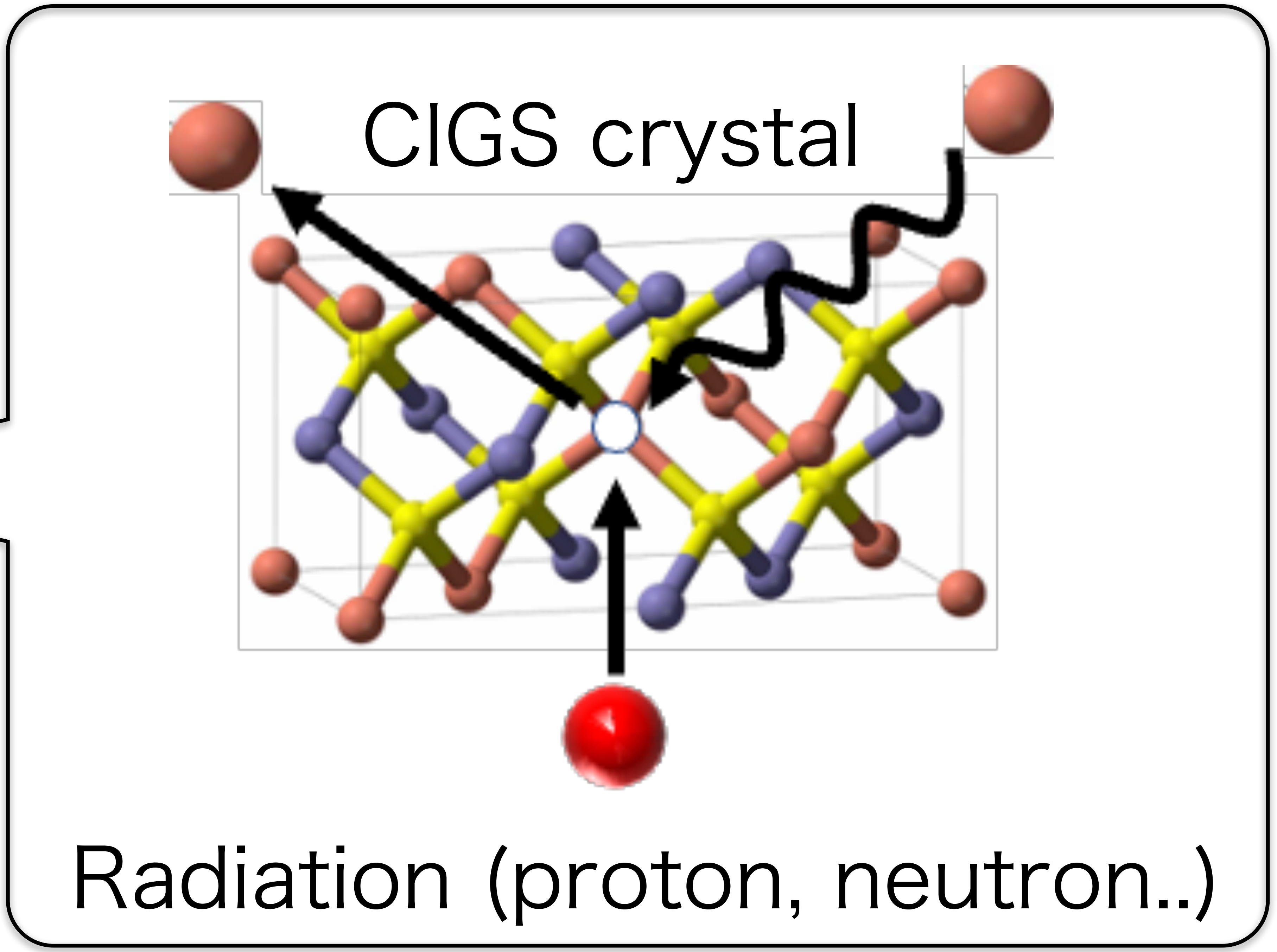
CIGS
2-4 um

- High efficiency : Direct excitation, 2-4 μm thick can be achieved 20% (same as silicon solar cell).
  - Thin material -> Light and Flexible.
- Low cost
- Large are can be possible.
- Degradation resistance : Recovery of radiation damage with heat annealing.

Recovery of the CIGS solar cell

CIGS solar cell





- Recovery by the compensation of defects by heat annealing with lower temperature.
  - 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 !

Recovery of the CIGS solar cell

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

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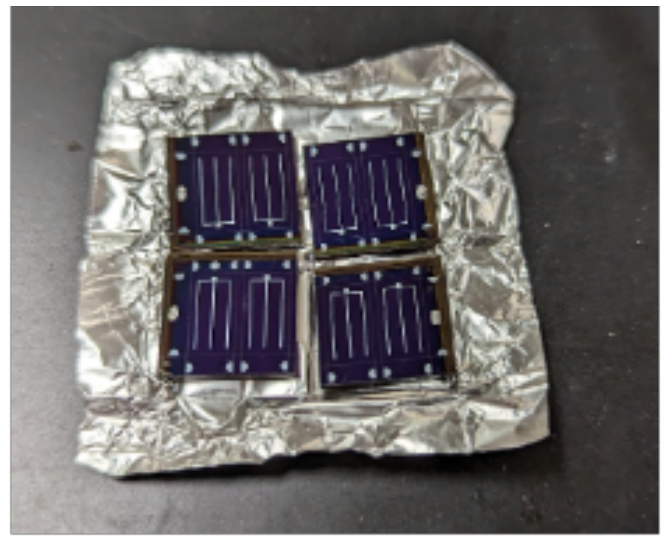
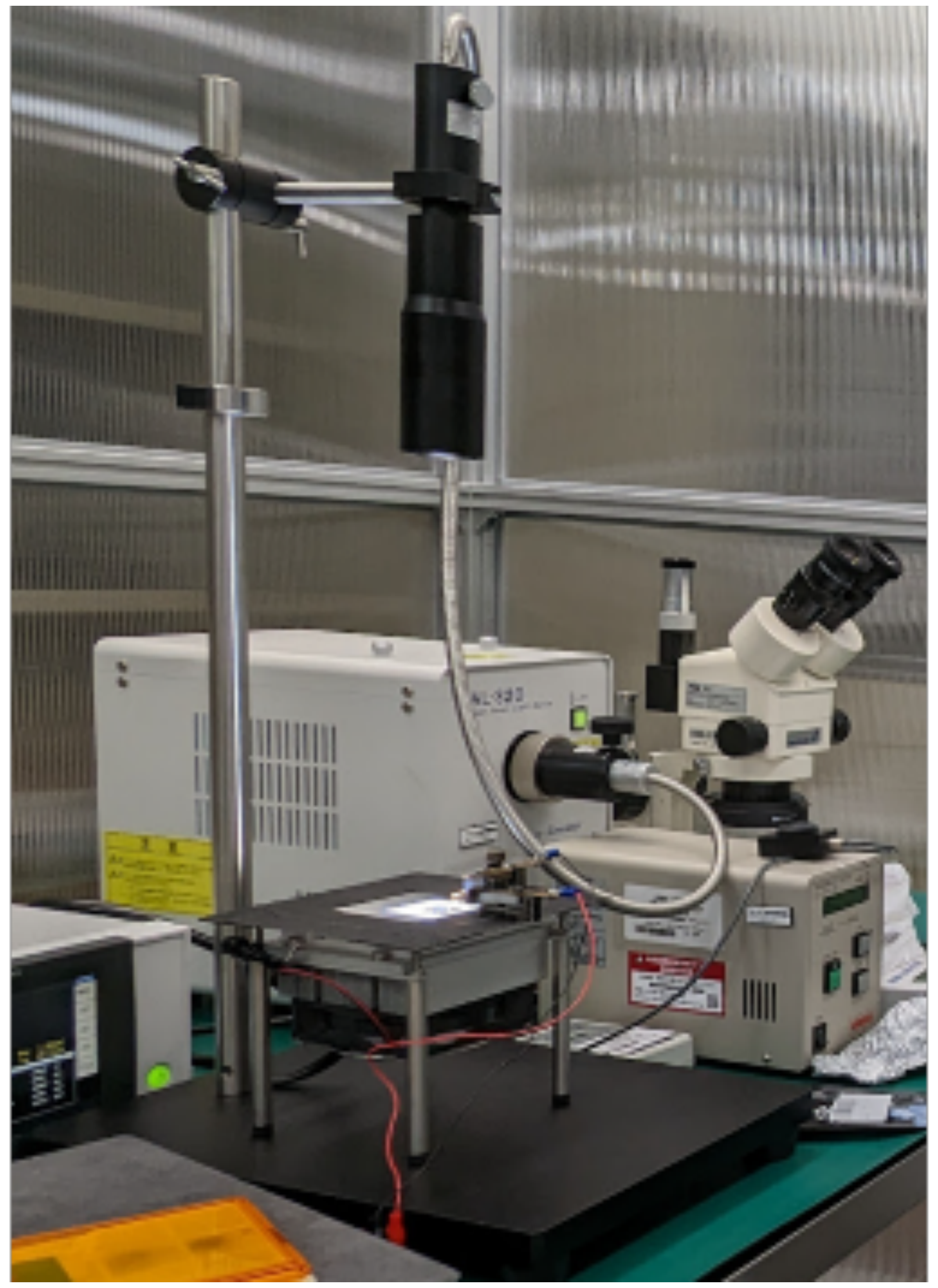
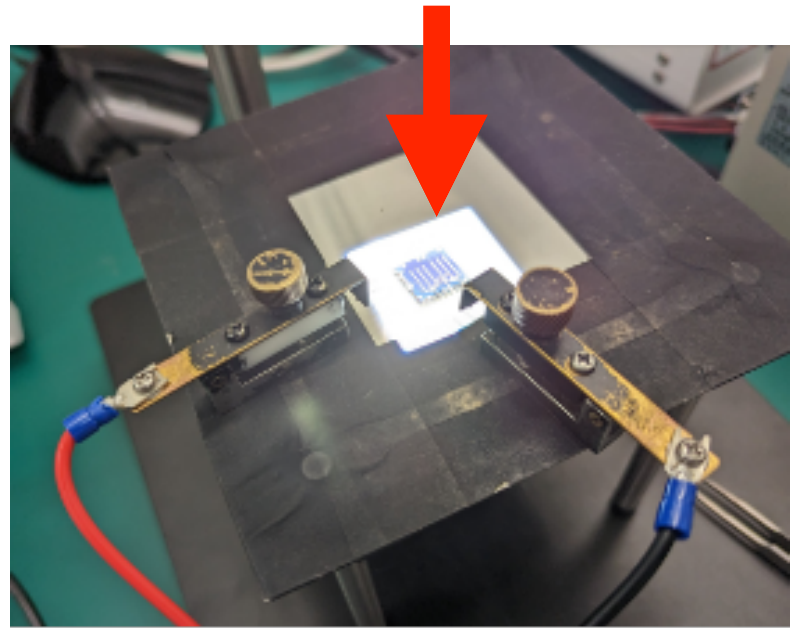
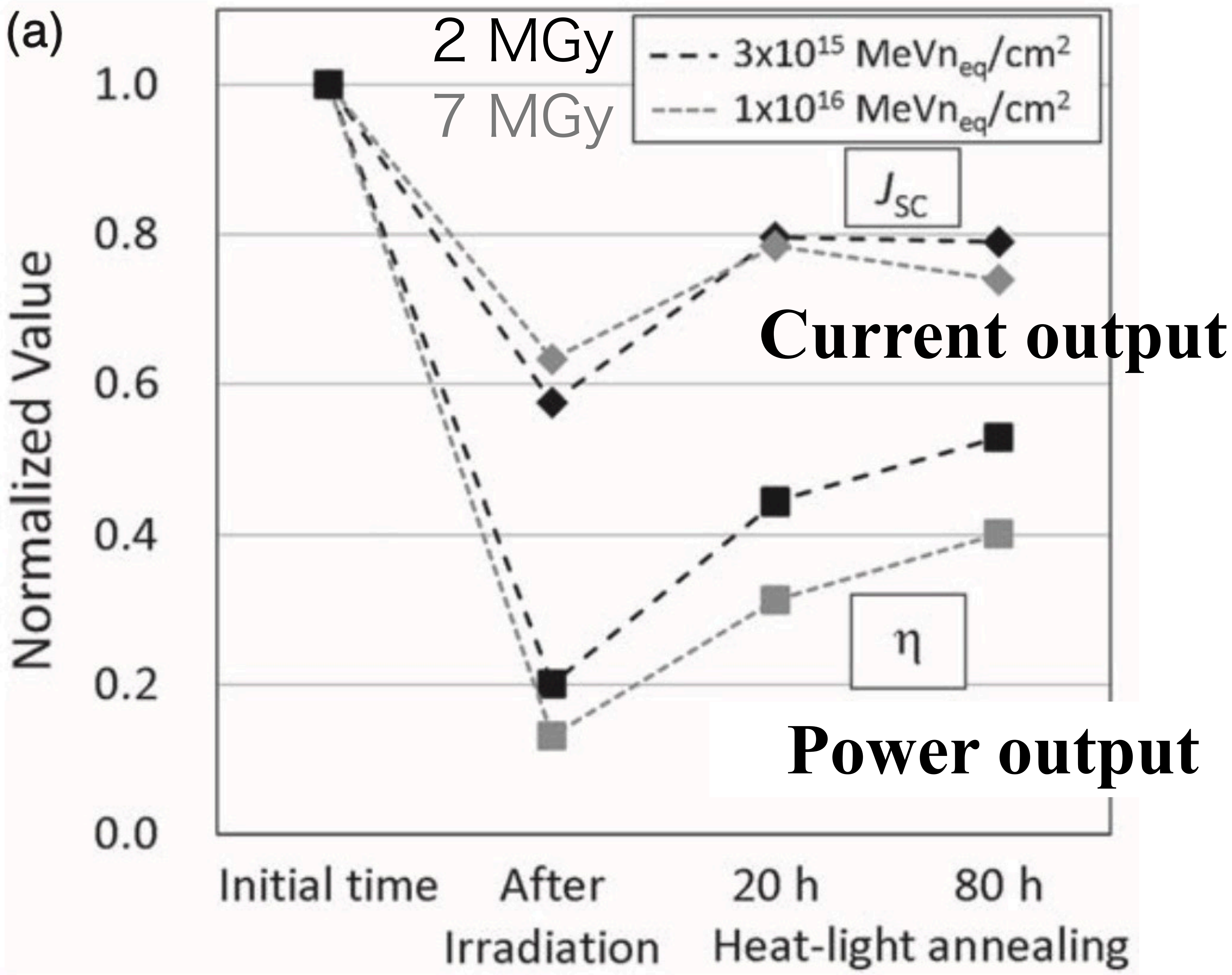




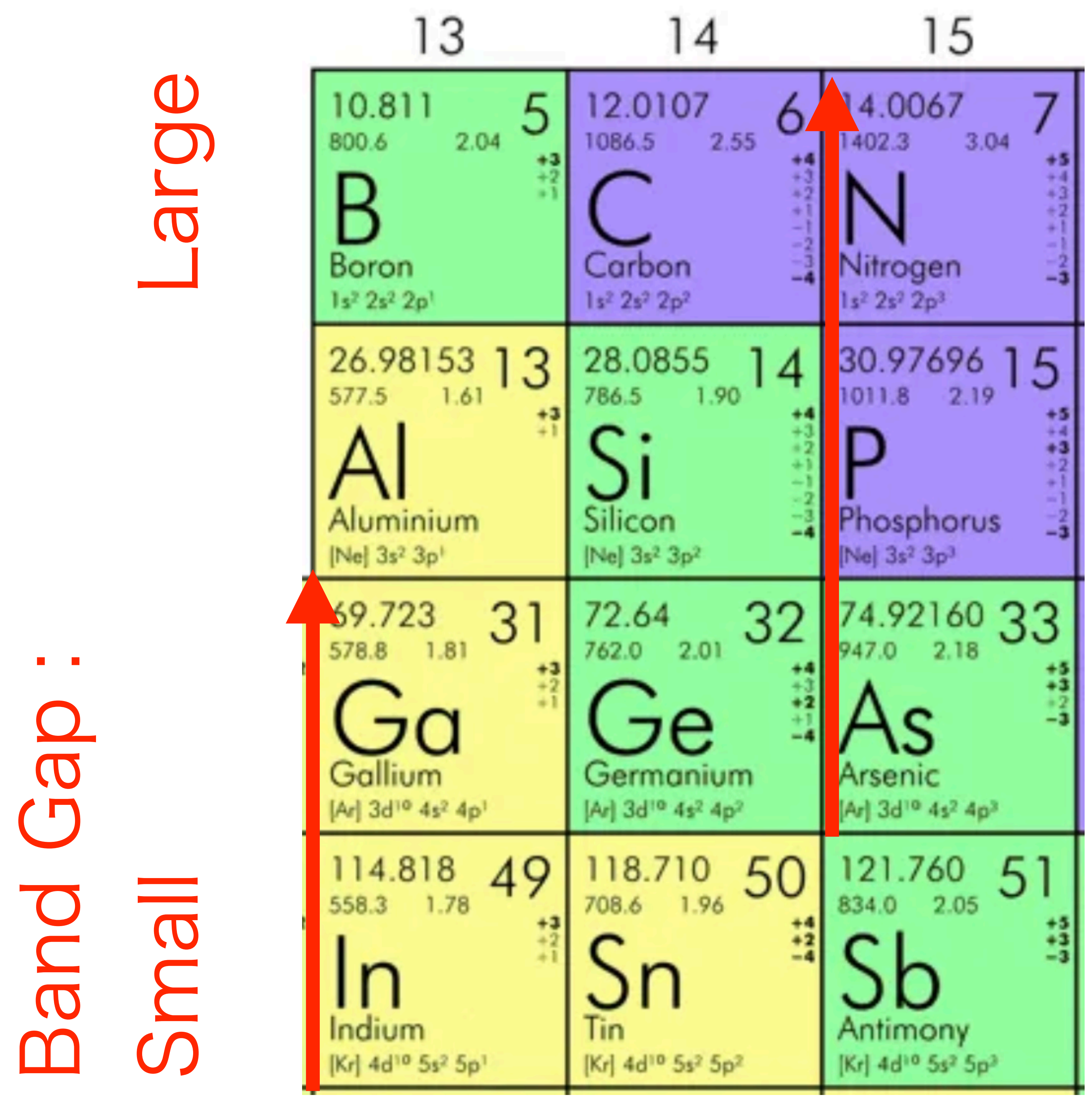
Annealing by sun light equivalent (1 Sun, 95°C)





Recovery is confirmed.

Characteristics of CIGS

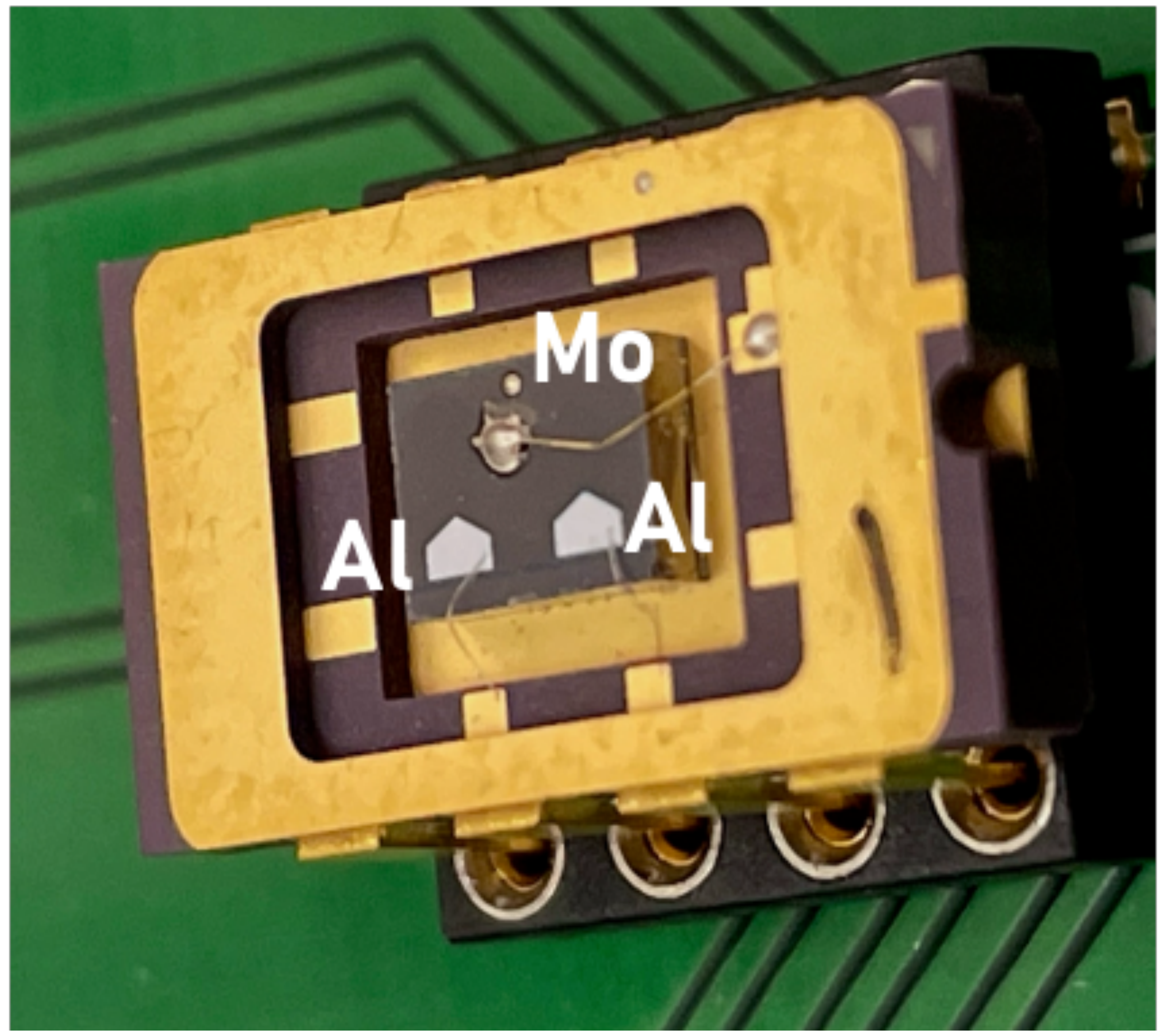


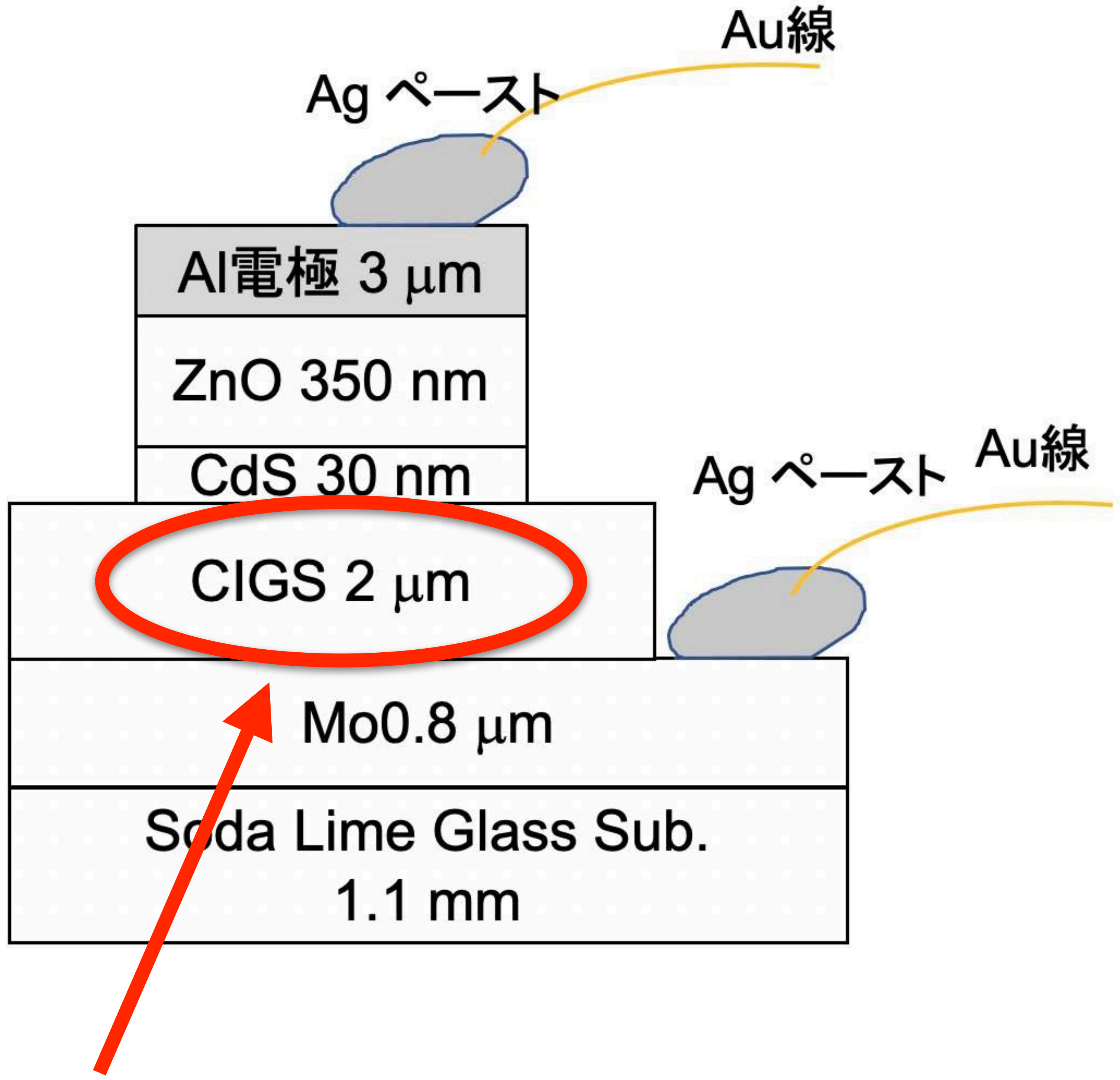
	Band Gap (Mean excitation)	Density (g/cm^3)	Rel. #e-h pairs (Si normarized)
Si	1.1 (3.6)	2.33	1 (~75 pairs/μm)
SiC	3.2 (7.8)	3.21	0.64
C (Diamond)	5.5 (12)	3.5	0.45
CIGS	1.2 (BGx2.5 ?)	5.7	(2.93)
AlN	6.2 (15.3)	3.26	0.33
Ga_2O_3	4.8 (BGx2.5 ?)	6.44	(0.83)
GaN	3.4 (8.9)	6.15	1.07

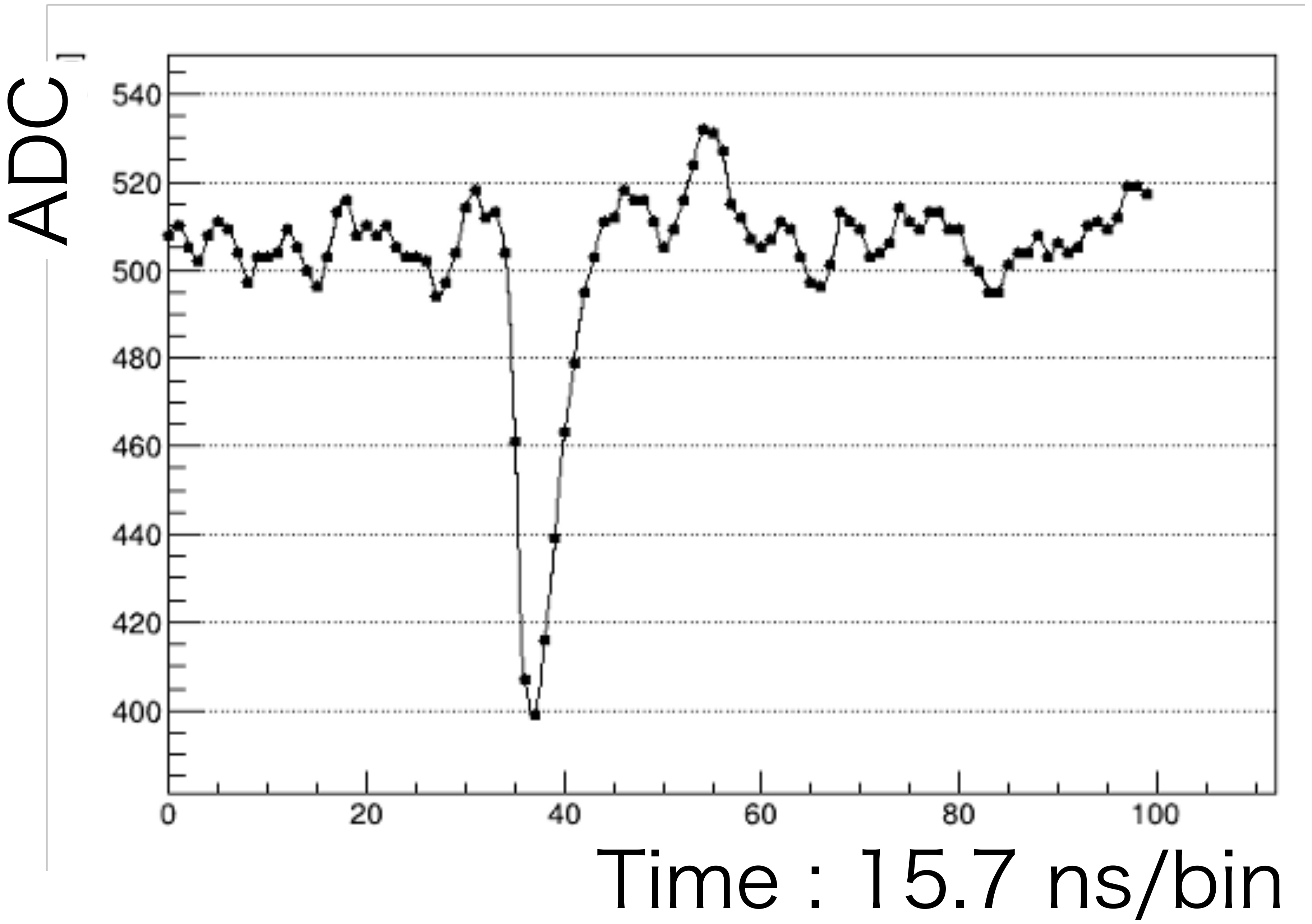
CIGS = Mix of CIS and CGS
BG of CIS : 1.0 eV
BG of CGS : 1.7 eV
BG of our sample is ~1.2 eV

-> Wide-gap semiconductor with enhancing Ga-rich CIGS.

Detecting alpha-particle by the p-n structure CIGS.







Normally, CIGS is p-type

Thickness : ~2 um

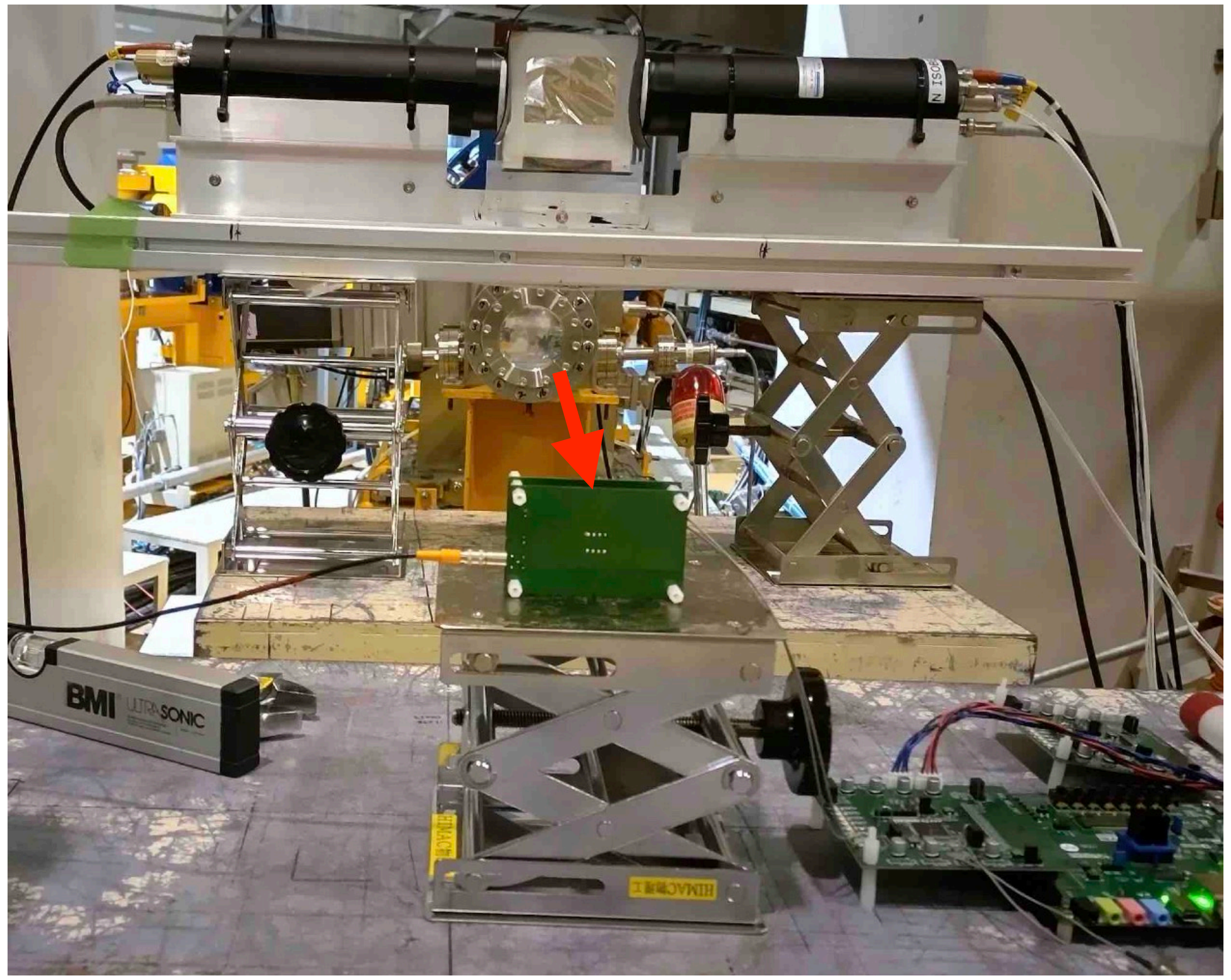
Output is expected as GEANT4 estimation

- Alpha 5.3 MeV, 2 um CIGS
  - 0.45 MeV -> (120 k e/h pairs) -> 19.2 fC

Beam test @ HIMAC (Heavy Ion Medical Accelerator in Chiba)

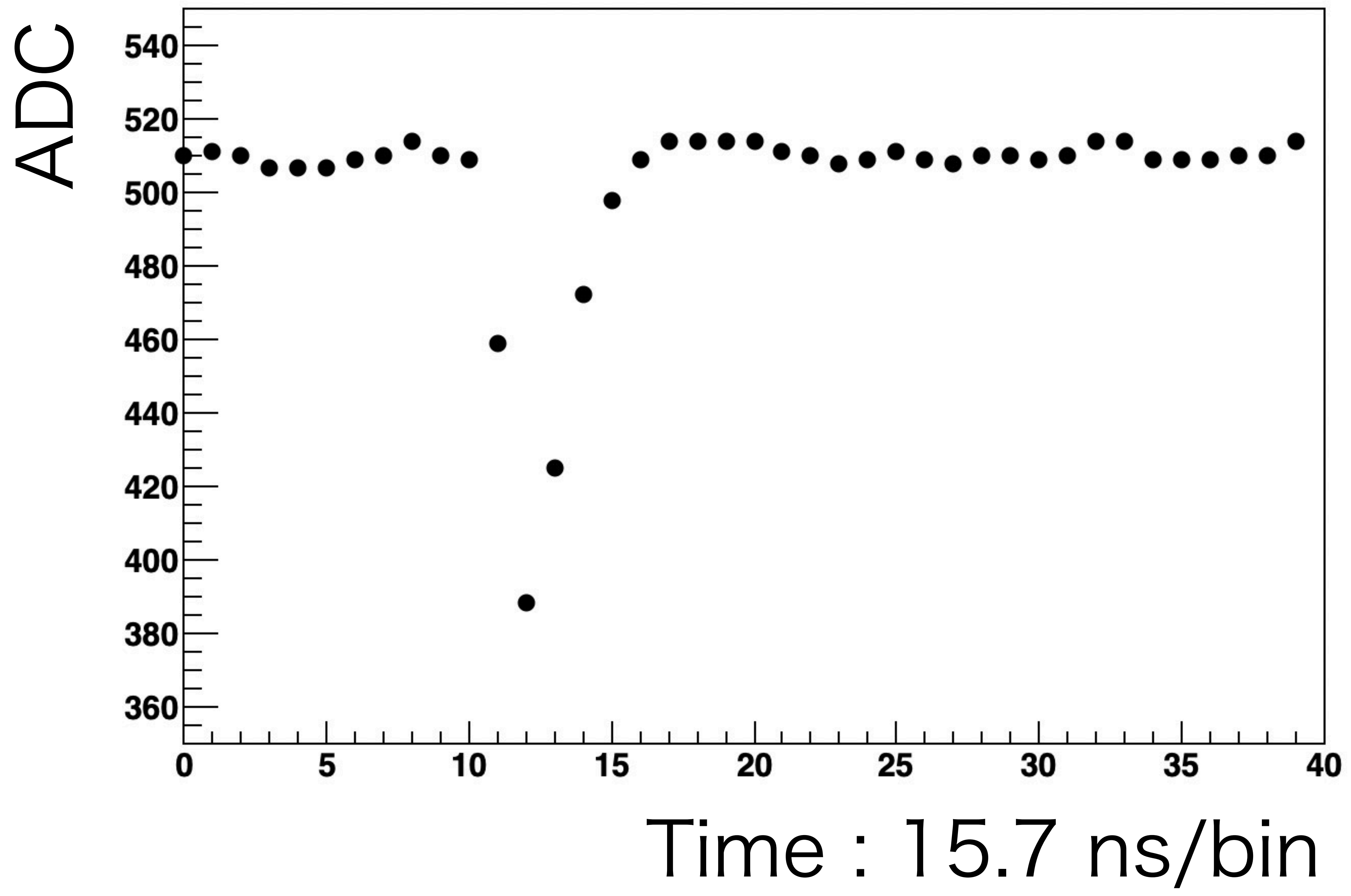
- 2022 1/9 - 1/10, 2022 11/24-11/25
- Heavy ions deposits large energy in the detector -> Detectable with thin layer.
  - $^{132}Xe^{54+}$ 400 MeV/n @ 2 um-thick CIGS : 6.5 MeV -> 277.3 fC
  - MIP@300 um-thick silicon : 0.11 MeV (22k e/h pairs) -> 3.6 fC

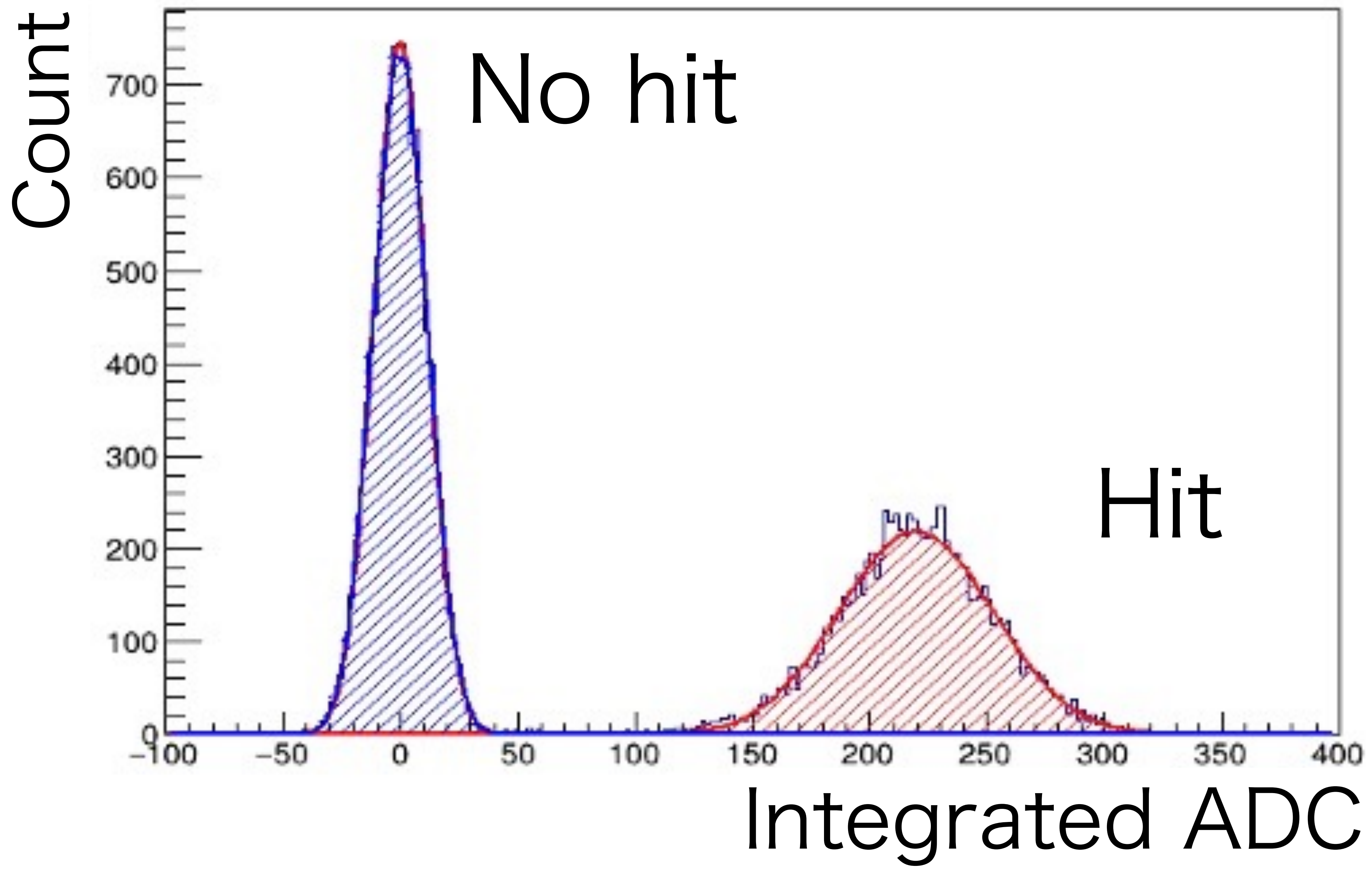
x100!



- Beam condition
  - 400 MeV/n Xe-132 beam
  - φ ~ 4 mm (measured by fluorescent plate)
  - 10^4 - 10^7 ppp in 3.3 s cycles.

CIGS output by Xe ion



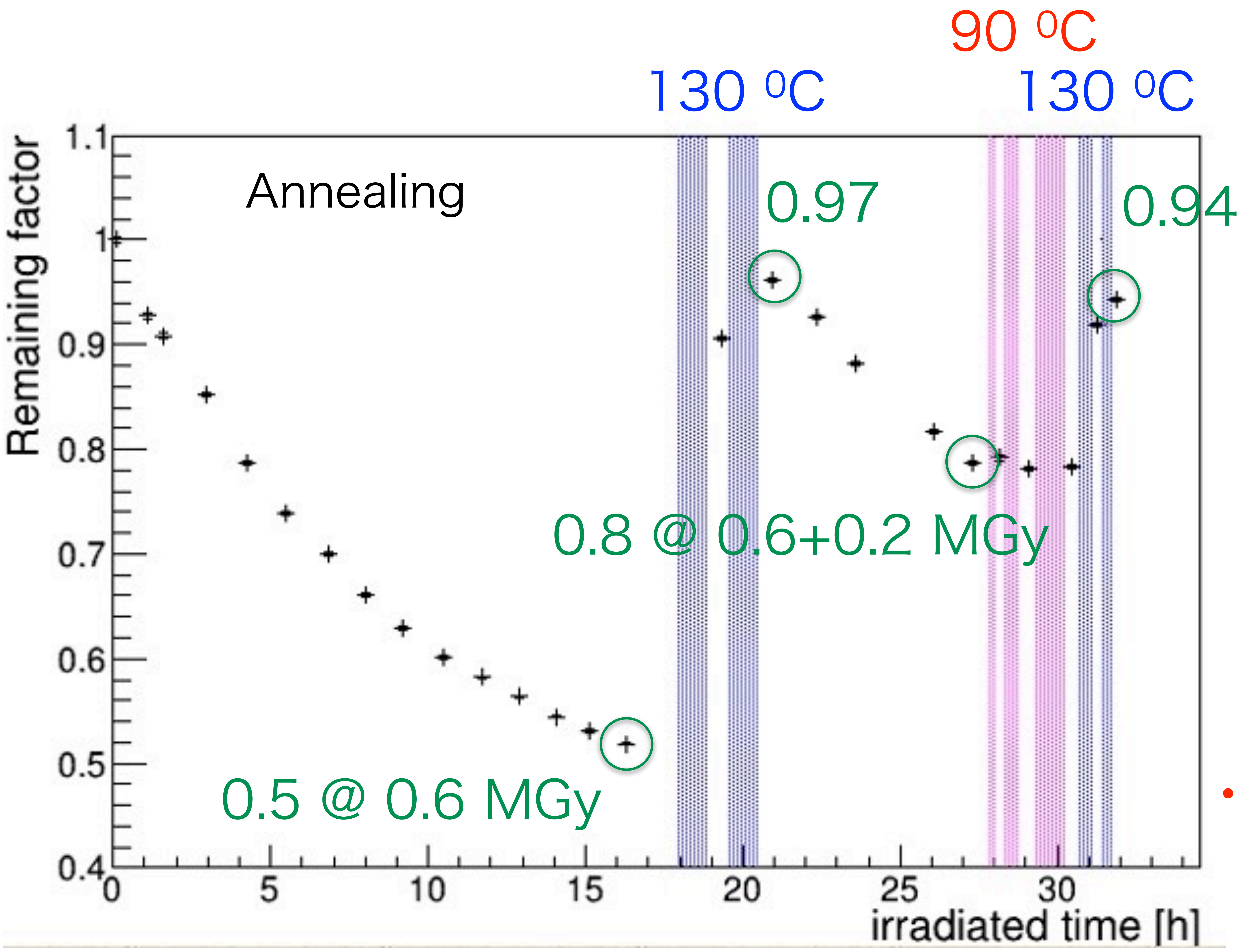


The CIGS detector successfully detects single particle !

Charge is ~180 fC, 64% of Geant4 estimation.

- Density effect ?
- Low charge correction efficiency ?

Radiation damage and recovery of the CIGS detector with Xe ions

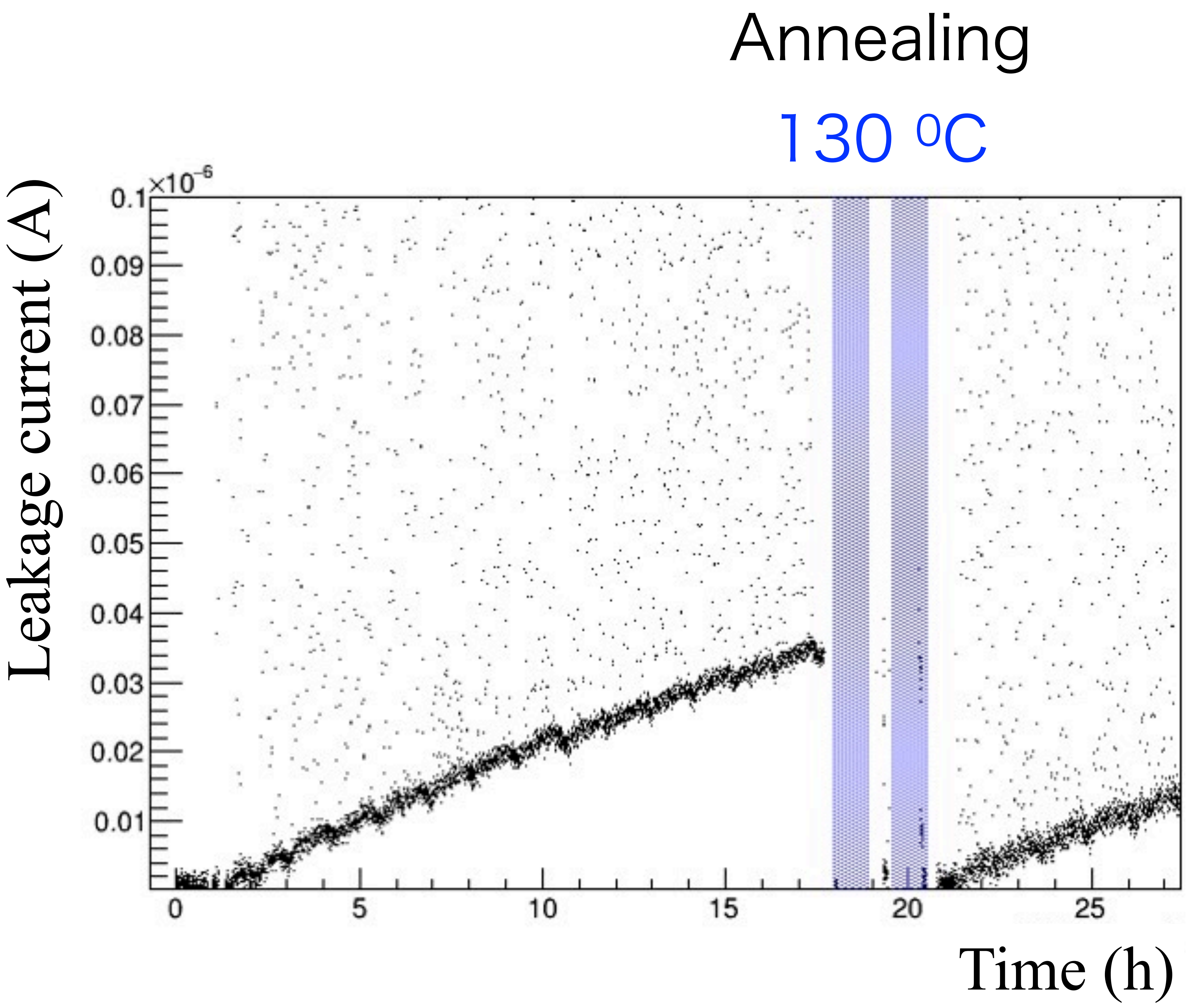


- Recovery by 130 ⁰C annealing is confirmed up to 0.8 MGy
  - Repeatable
  - Strong temperature dependence between 90 - 130 ⁰C

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

https://doi.org/10.1088/1748-0221/19/05/C05042

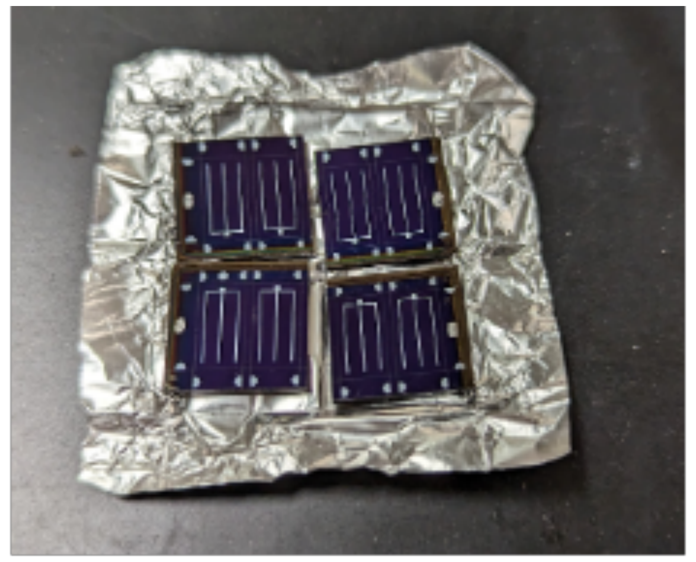
Leakage current



- Leakage current : Recovered to be the value before irradiation
  - "Critical defects" for charge collection and leakage current might be almost recovered by heat annealing

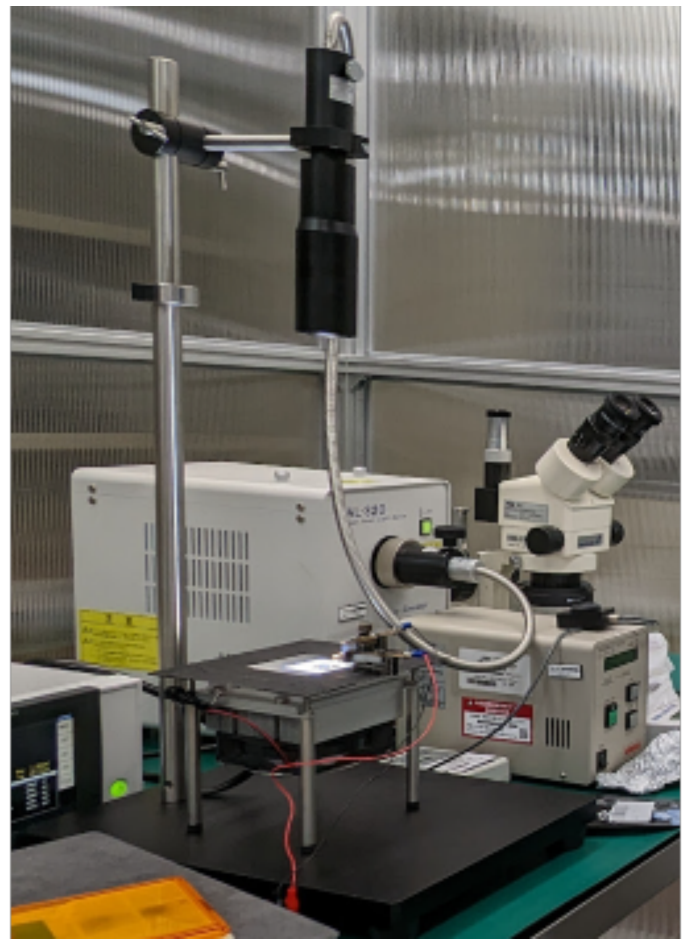
Temperature, Time dependences

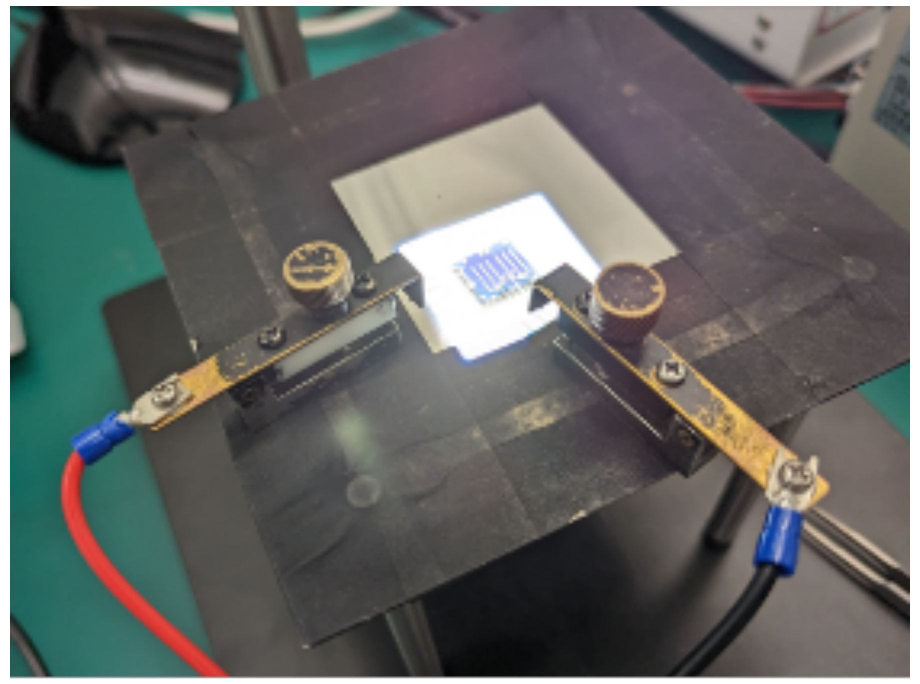
K. Itabashi
Presentation at PSD13, Oxford.

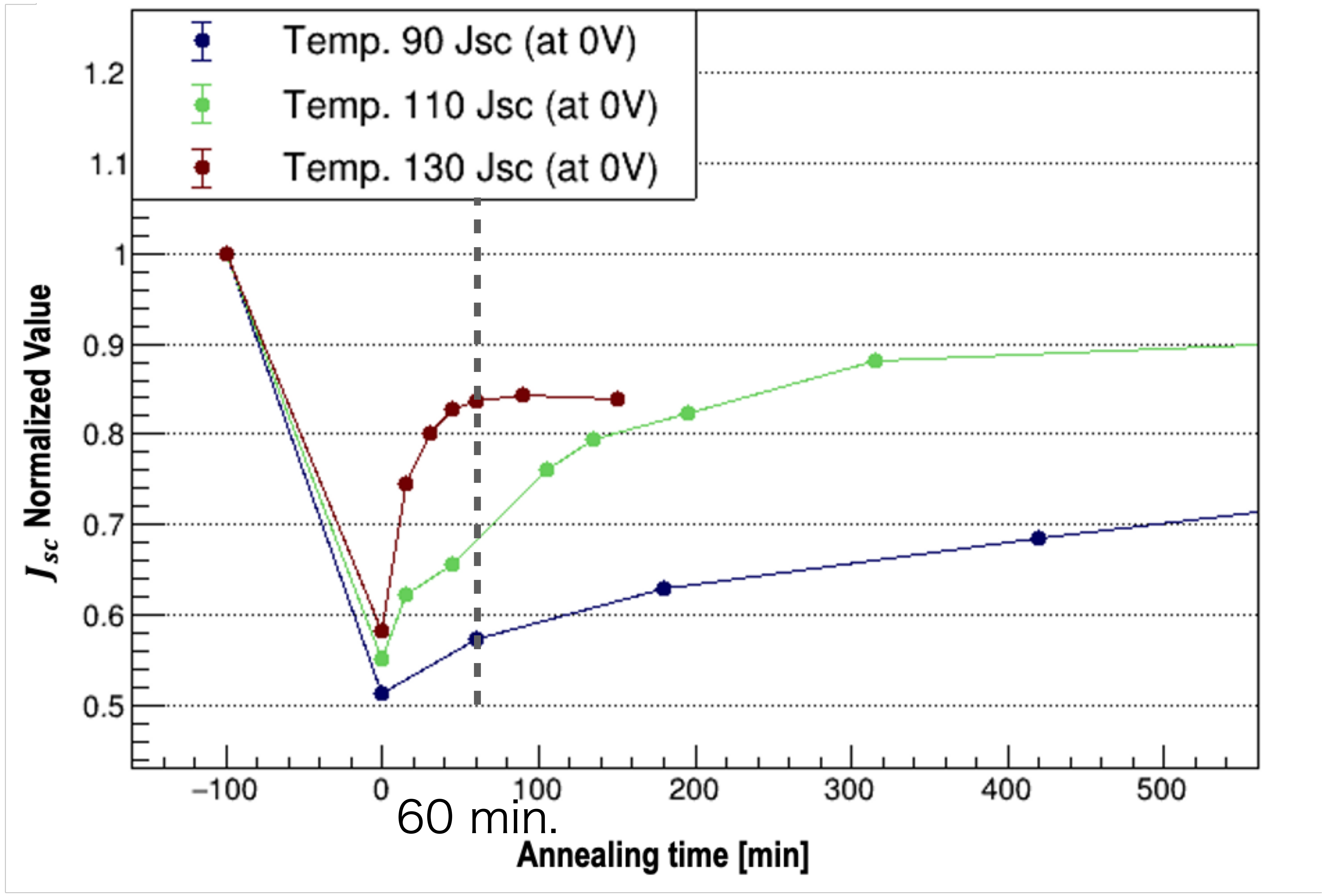


CIGS solar cell

CYRIC irradiation.
10^{16} (1 MeV n_{eq}/cm^2),
7 MGy

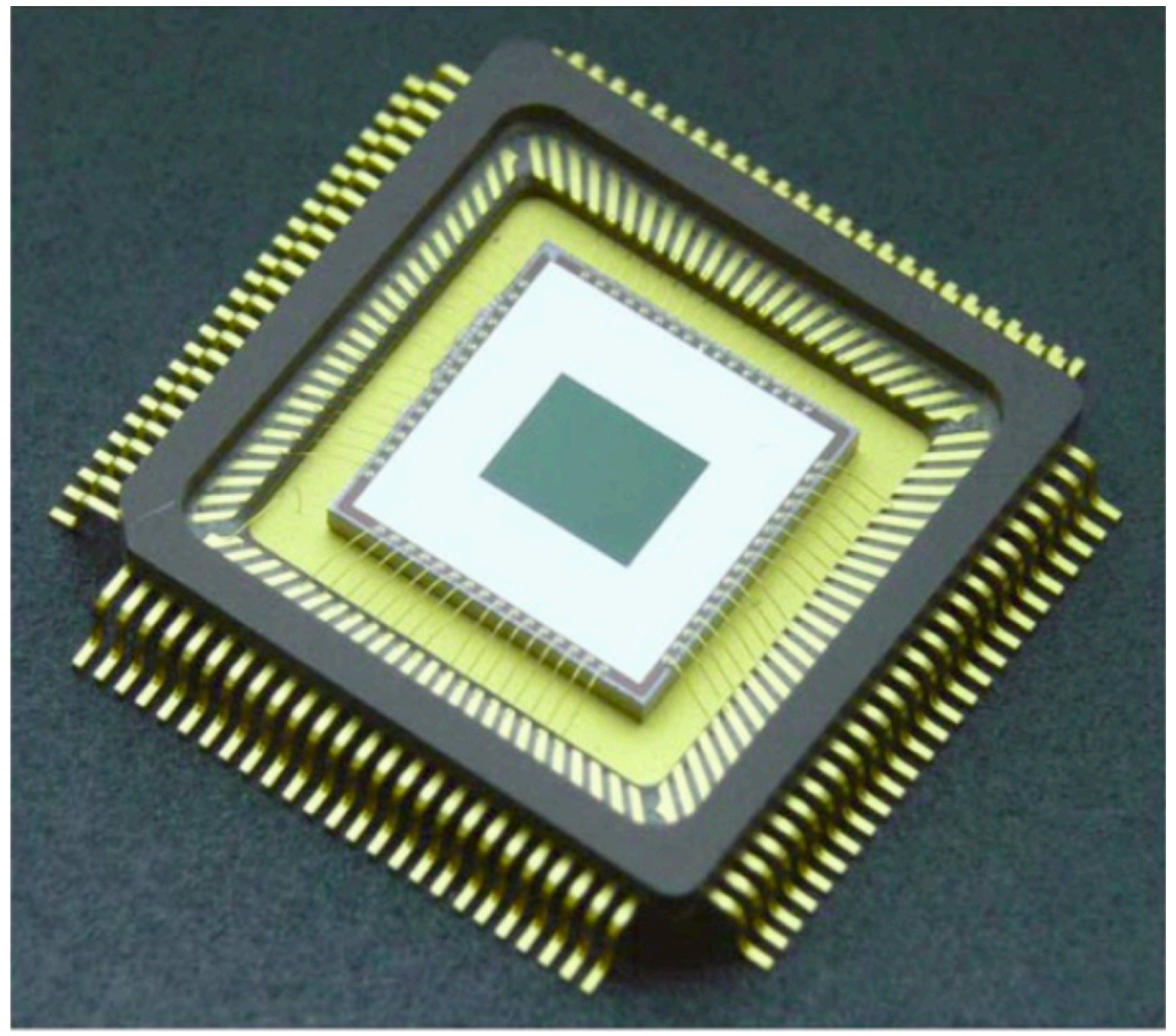






- Large temperature dependence btw 90 - 130 °C is observed.

To be the pixel detector



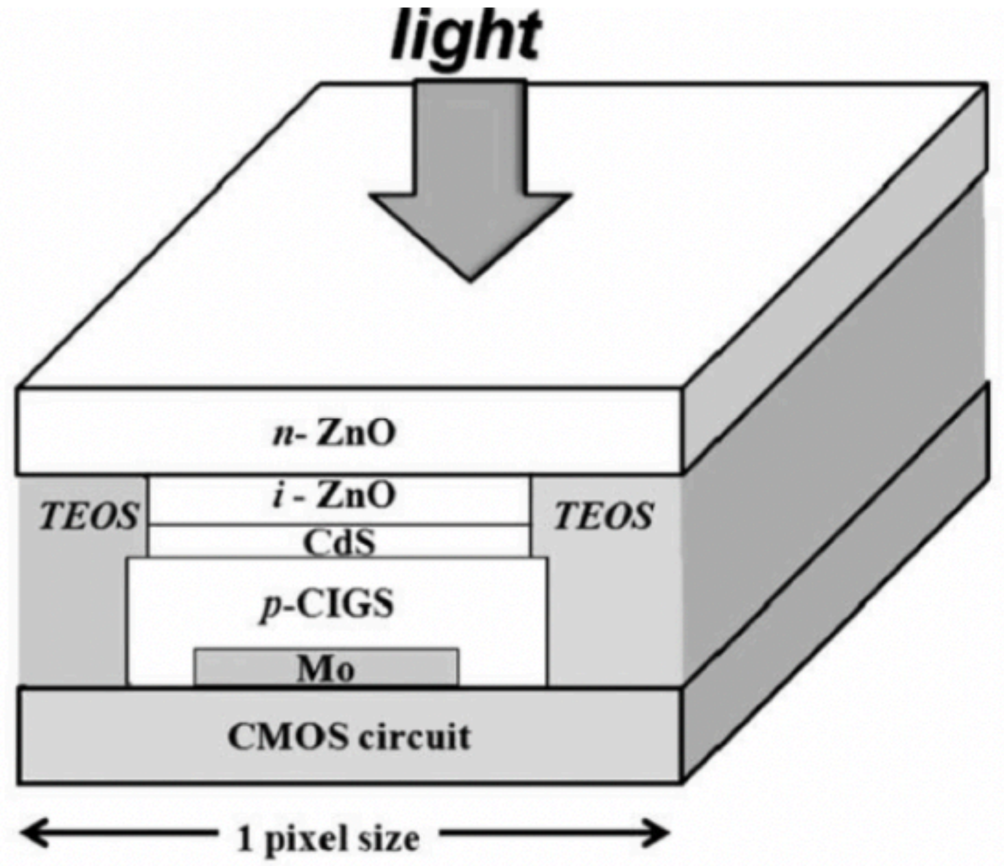


Fig. 2. A schematic structure of one pixel of the CIGS-based image sensor.

*産総研、Rohm株式会社

- It needs to be thicker.
  - Output ratio / thickness , Si : CIGS ~ 1 : 3.
  - 10 - 20 μm is enough for single charged particle ?
- Following CIGS image sensor development.
  - Joint development of AIST and Rohm developed at 2008.
    - For high sensitivity infrared camera
      - $10 \times 10\ um^2$ pixel CCD
      - 352x288 pixels
  - Deposition on the read out CMOS
    - No bump bonding is necessary
- Unfortunately, this development was terminated.

Future investigation

- Basic investigation
  - Understanding compensation mechanism
    - Who is main player of damage and recovery ? -> DLTS measurement.
  - Can boost annealing effect ?
  - Ga-rich wide gap ?
- 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
    - Direct lamination on ASIC

Conclusion

- 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.