Chalcogenide semiconductor detector with high radiation tolerance

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Outline

1. What is $Cu(In,Ga)Se_2$?

2. Growth and Characterization of CIGS

3. Radiation tolerance of CIGS solar cells

Classification of solar cells

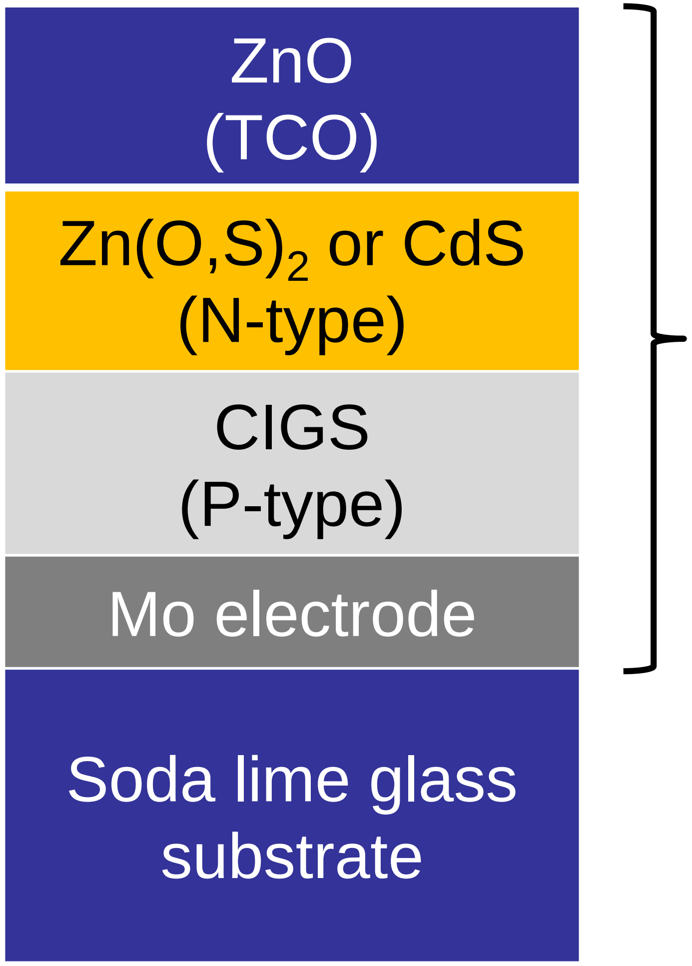
- Solar cells
  - Silicon
    - Crystalline
      - Single crystalline
      - Polycrystalline
    - Thin Films
  - Compounds
    - Single crystalline – GaAs, InP
    - Polycrystalline – CIGS, CdTe
  - Organic
    - Dye-sensitized
    - Organic Thin Films
    - Hybrid – Perovskite

CIGS: $CuIn_{1-x}Ga_xSe_2$

What is CIGS?

Elemental semiconductor	IV	Si, Ge
Binary compound semiconductor	III V	GaAs, GaN, InP
	II VI	ZnSe, CdTe, ZnO
Ternary compound semiconductor	I III VI	$CuInSe_2$, $AgGaS_2$
	I III_a III_b VI	$Cu(In, Ga)Se_2$, $Ag(In, Ga)Se_2$

Schematic structure of CIGS solar cells



Total
thickness is
about 5 μm.

*Solar Frontier: SFK190-S

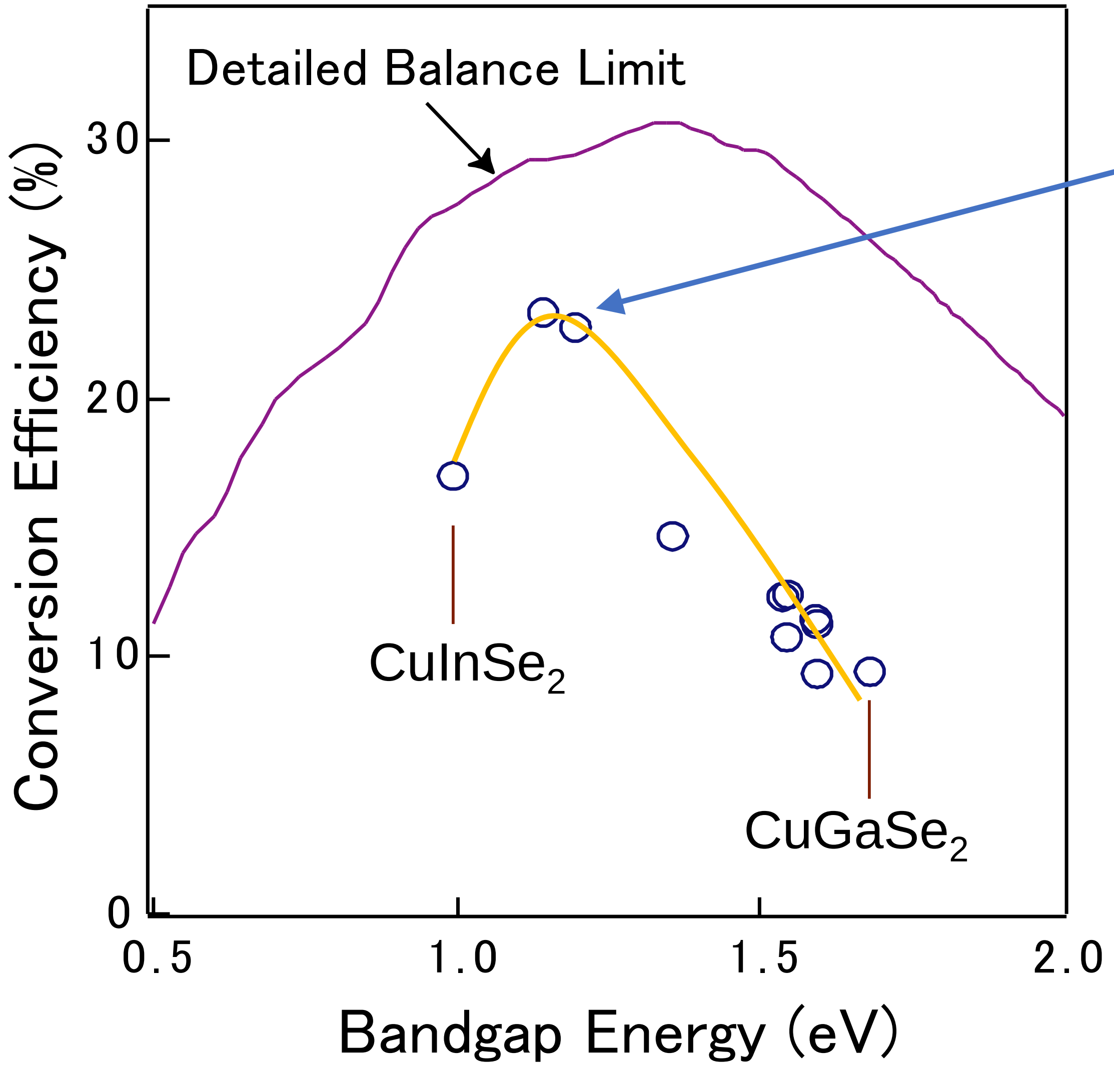
3kW CIGS module
(η=15%, 20m²)

Cu: 45g, In: 49g,
Ga: 20g, Se:112g

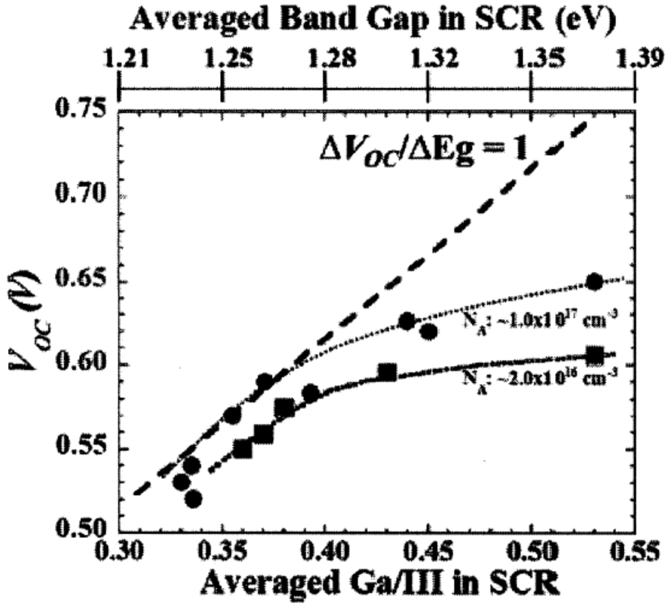
***3kW Crystalline Si module**
Si:15kg

Low-cost and Resource Saving

Conversion efficiency of CIGS solar cells

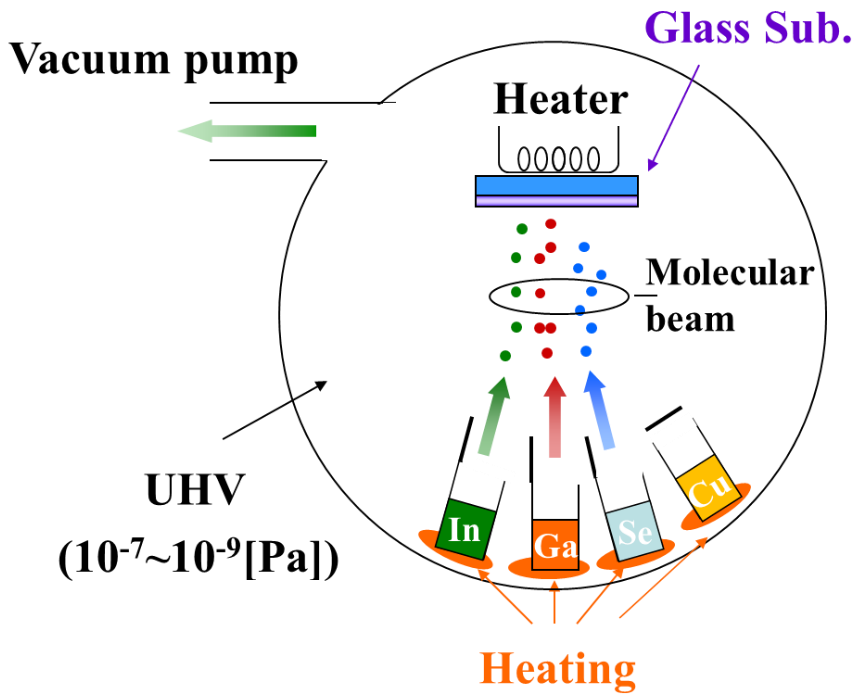


World Record:
η = 23.4%
(Solar Frontier,
CuAgInGaSeS, 1.0 cm^2)

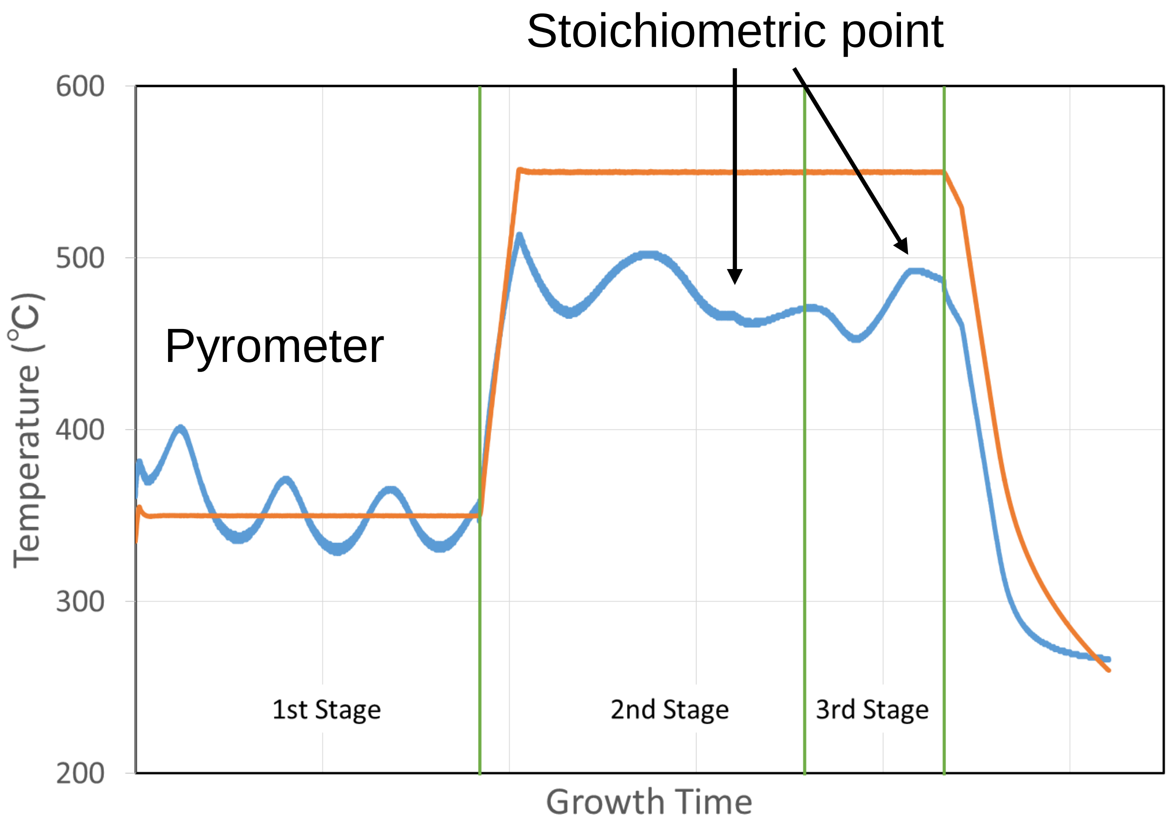


*J. Chantana, et al. JAP 114 (2013) 084501.

The 3-stage evaporation of CIGS



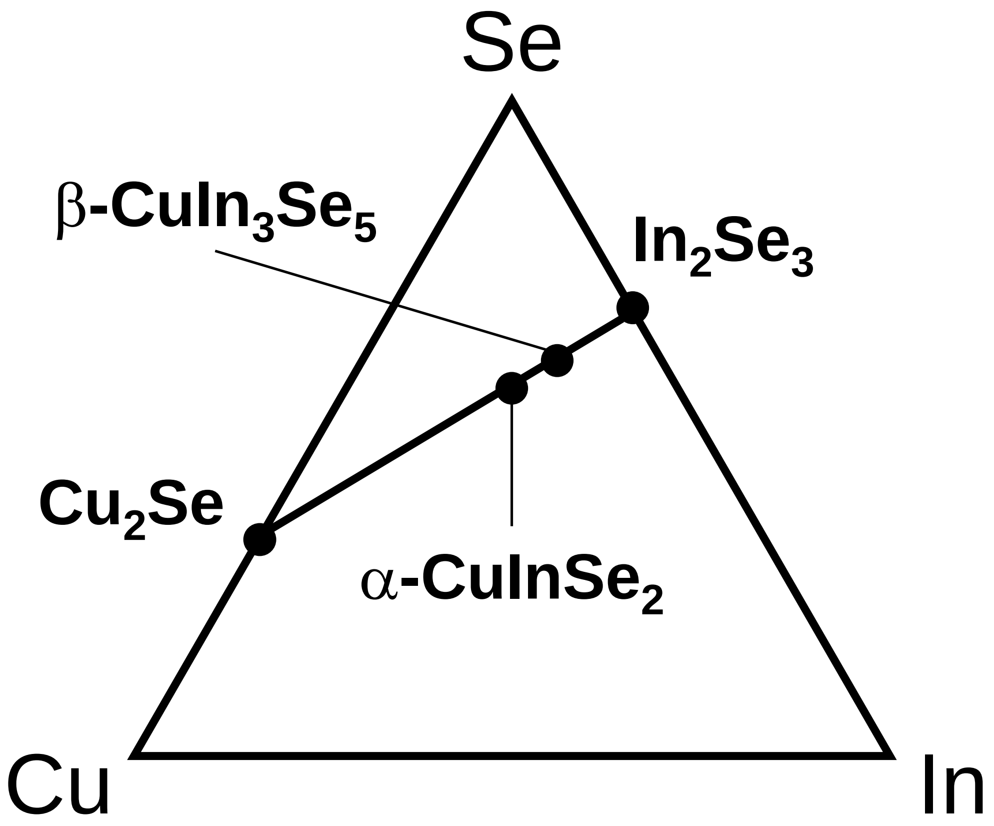
Molecular Beam Deposition



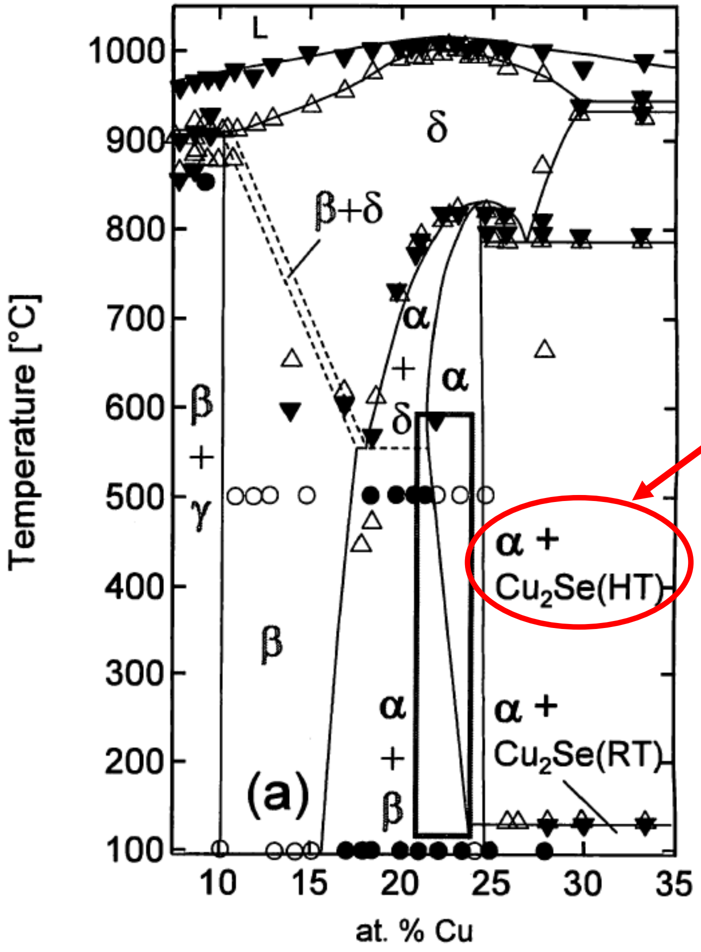
1st stage: In, Ga, Se
2nd stage: Cu, Se
3rd stage: In, Ga, Se

1st stage: $(In,Ga)_2Se_3$
2nd stage: $Cu(In,Ga)Se_2 + Cu_2Se$
3rd stage: $Cu(In,Ga)Se_2 + Cu(In,Ga)_3Se_5$

Cu-In-Se system



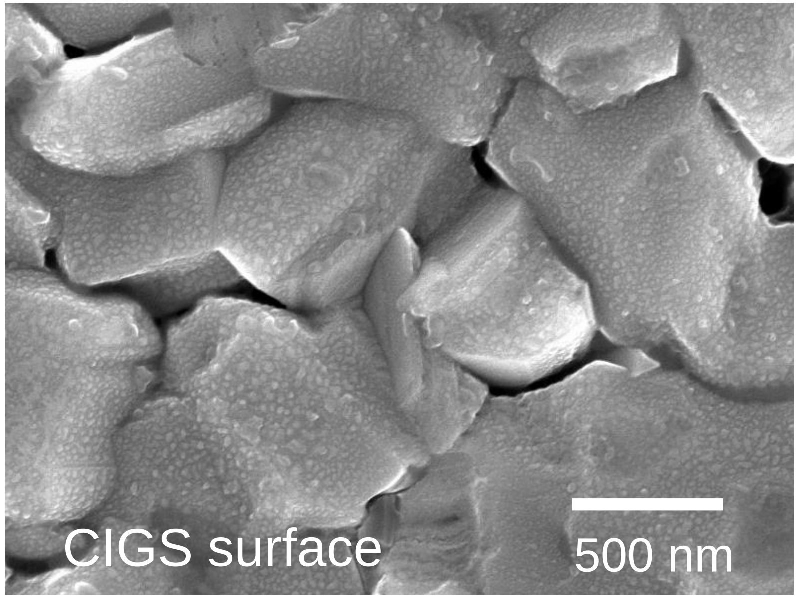
1st stage: In_2Se_3
2nd stage: $CuInSe_2$ + Cu_2Se
3rd stage: $CuInSe_2$ + $CuIn_3Se_5$

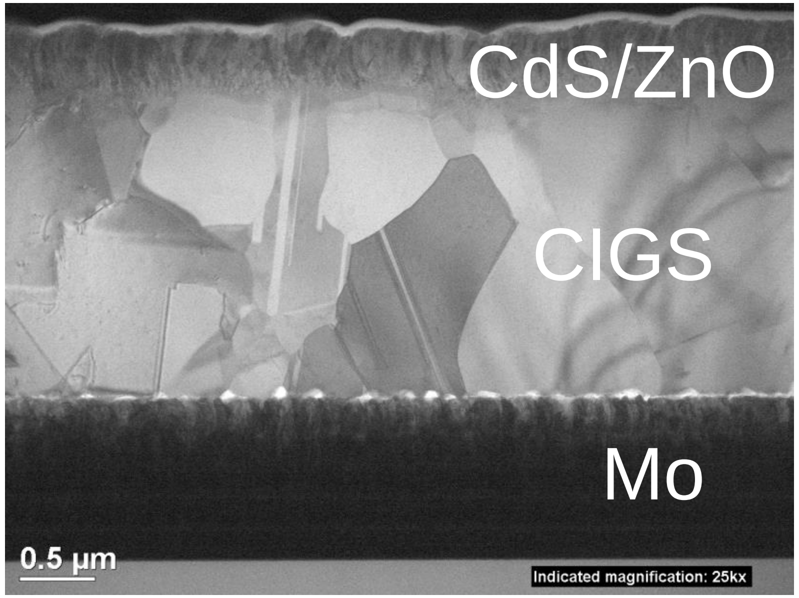


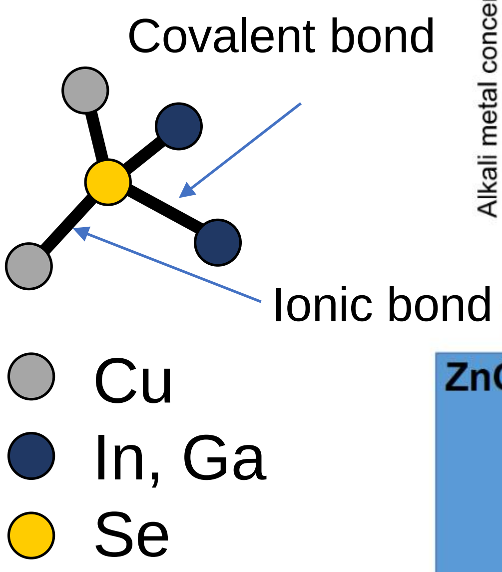
Cu rich
→ CIS + Cu_2Se

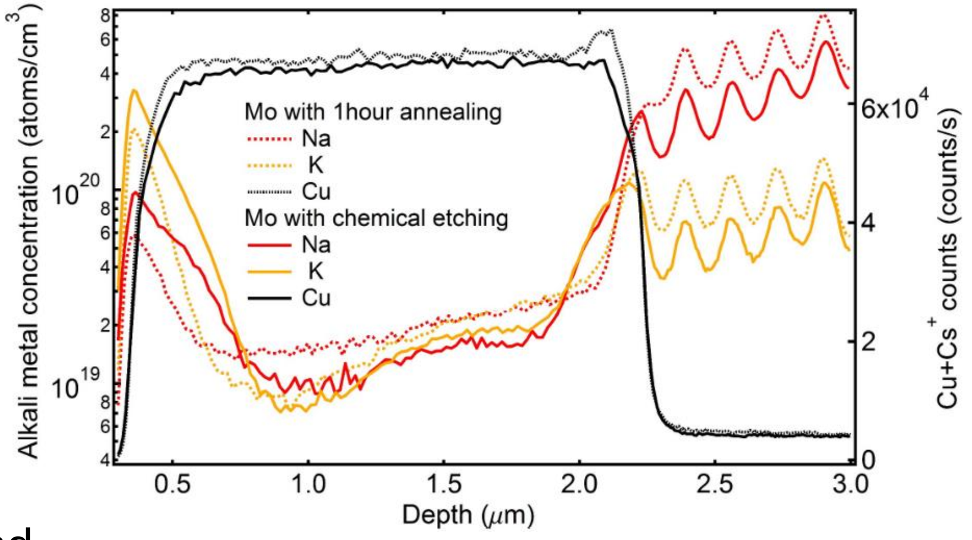
*Gödecke, Haalboom, Ernst, Zeitschrift für metalkunde, 2000. 91: p.622-662

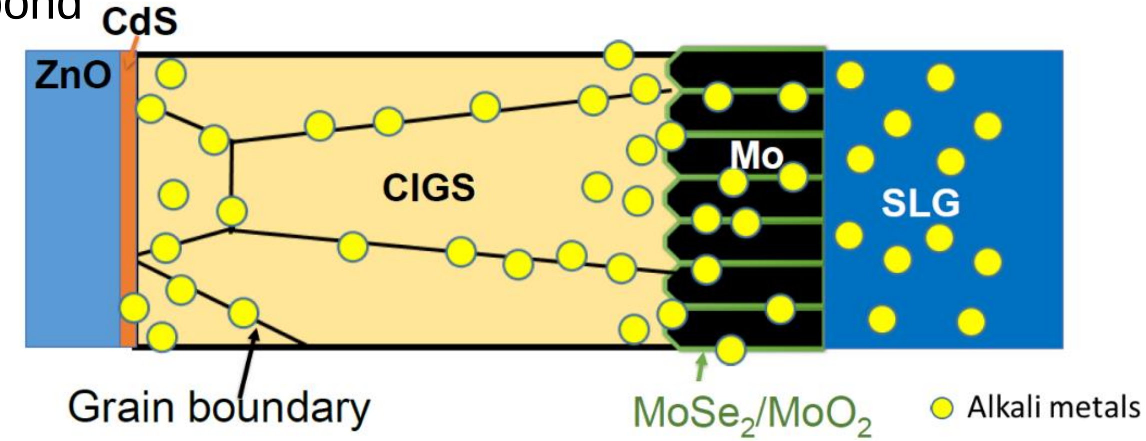
SEM, TEM images and SIMS







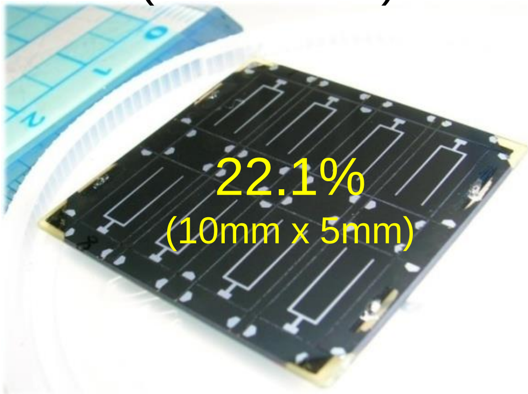




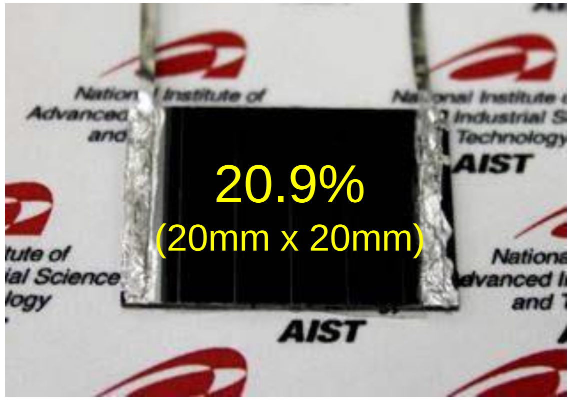
- Cu vacancies are shallow acceptors.
- Na ions suppress incorporation of In atoms into Cu vacancies.

Variety of research on CIGS at AIST

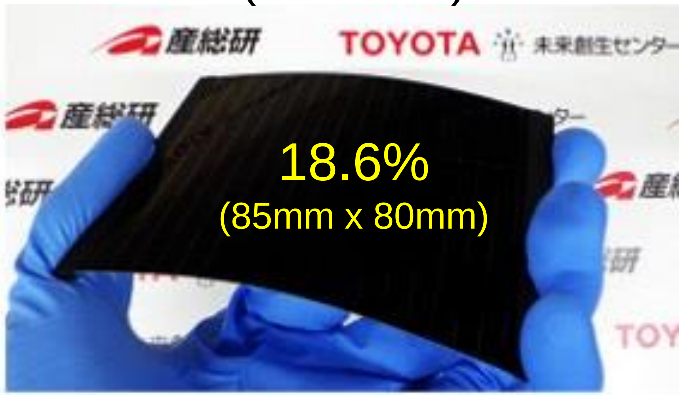
CIGS solar cell
(Glass sub.)



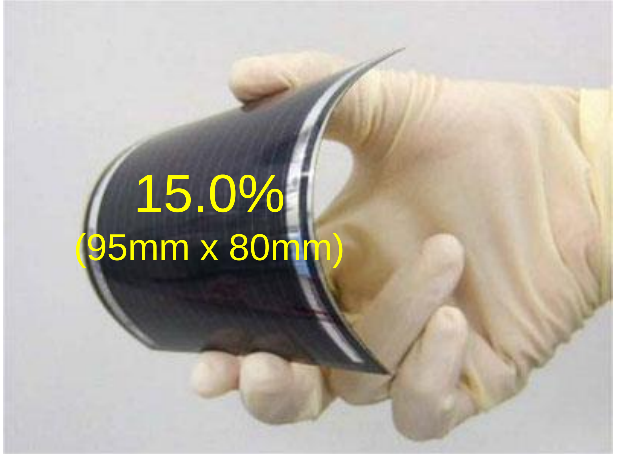
CIGS submodule
(Glass sub.)



Flexible submodule
(Film sub.)

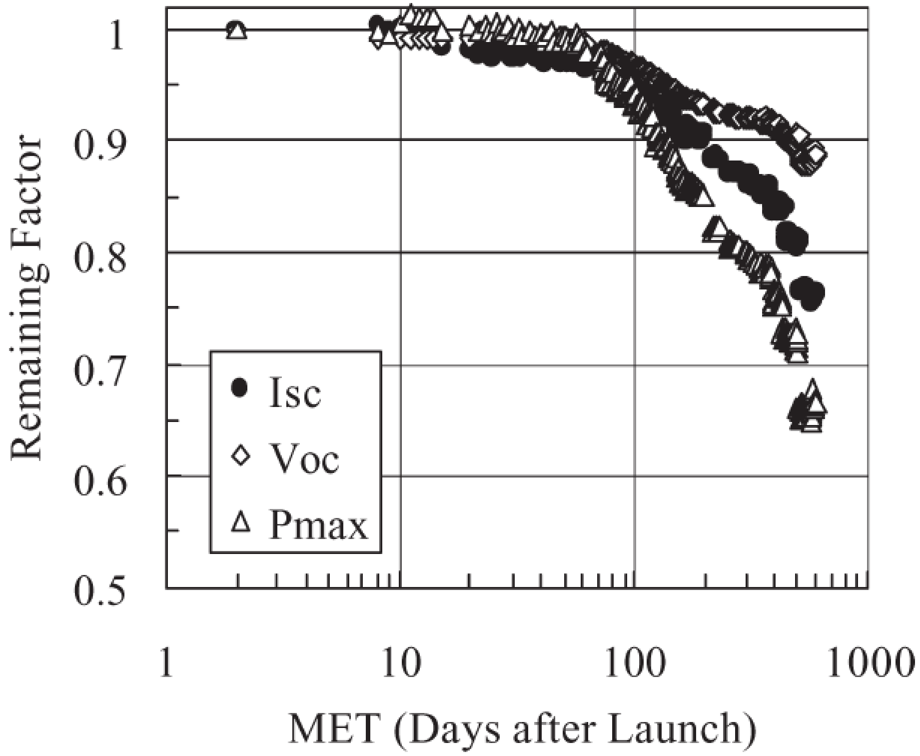


Flexible submodule
(Stainless-steel sub.)

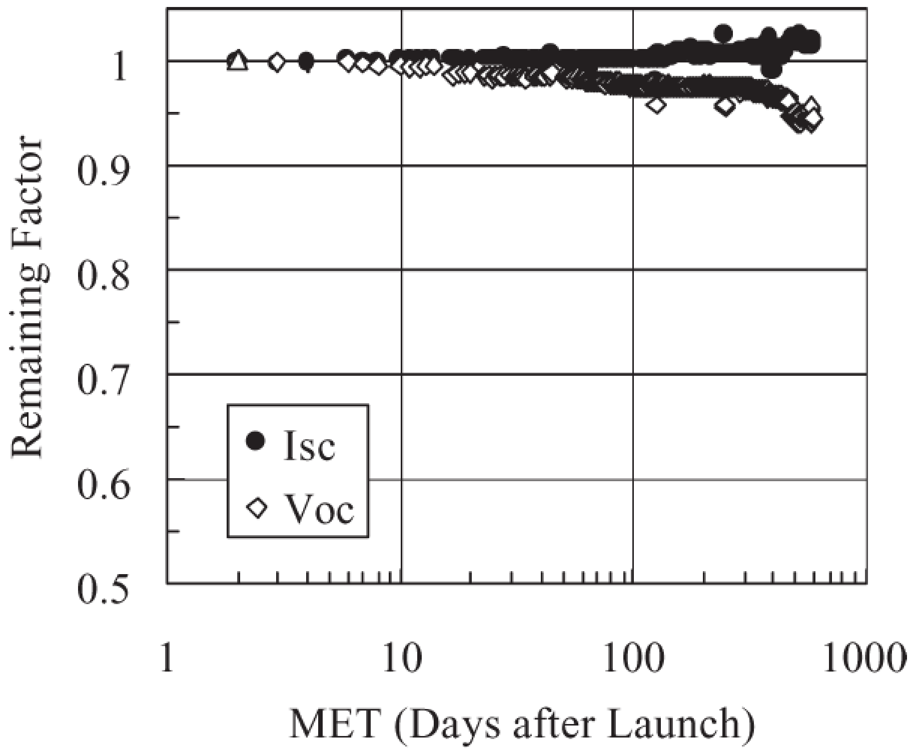


High radiation tolerance of CIGS (JAXA group)

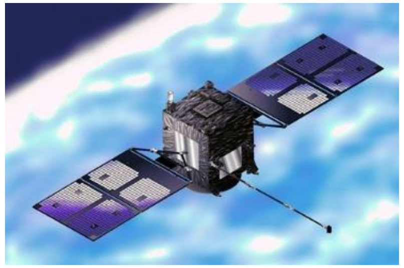
InGaP/GaAs dual-junction cell



CIGS solar cell



The radiation response of solar cells was demonstrated by Mission Demonstration-test Satellite No.1(MDS-1) ”Tsubasa”.



*M. Imaizumi, et al, Prog. Photovolt: Res. Appl. **13**, 529-543 (2005).

Radiation tolerance of solar cells

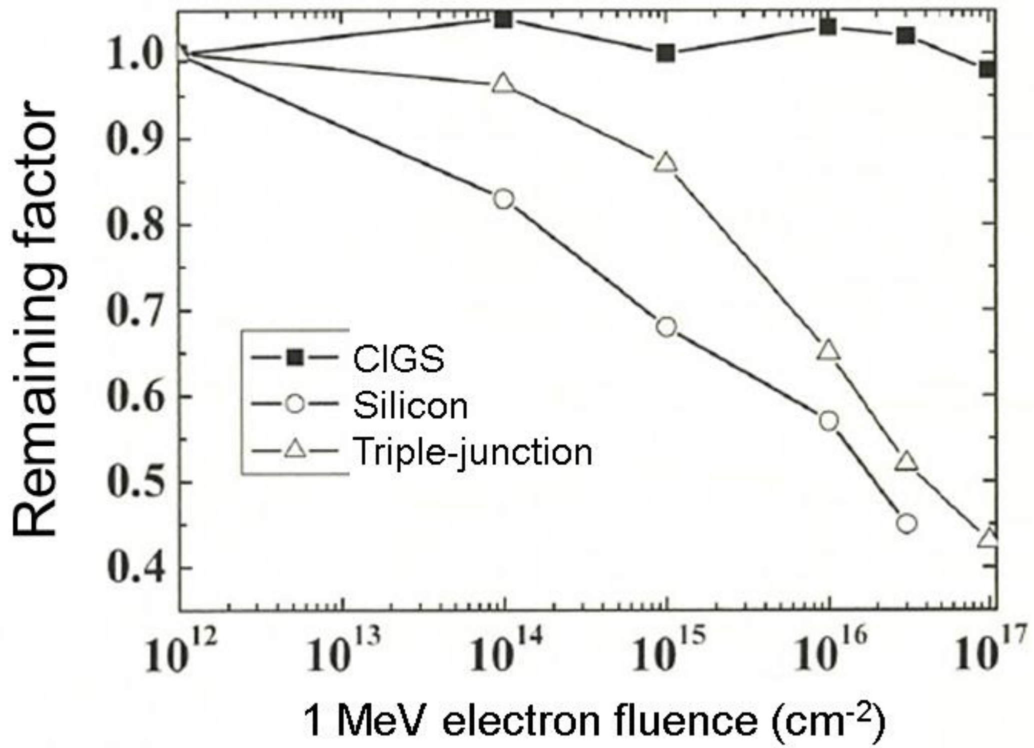


図 1　CIGS太陽電池，宇宙用シリコン太陽電池，宇宙用３接合太陽電池の１MeV電子線による電気性能の劣化特性

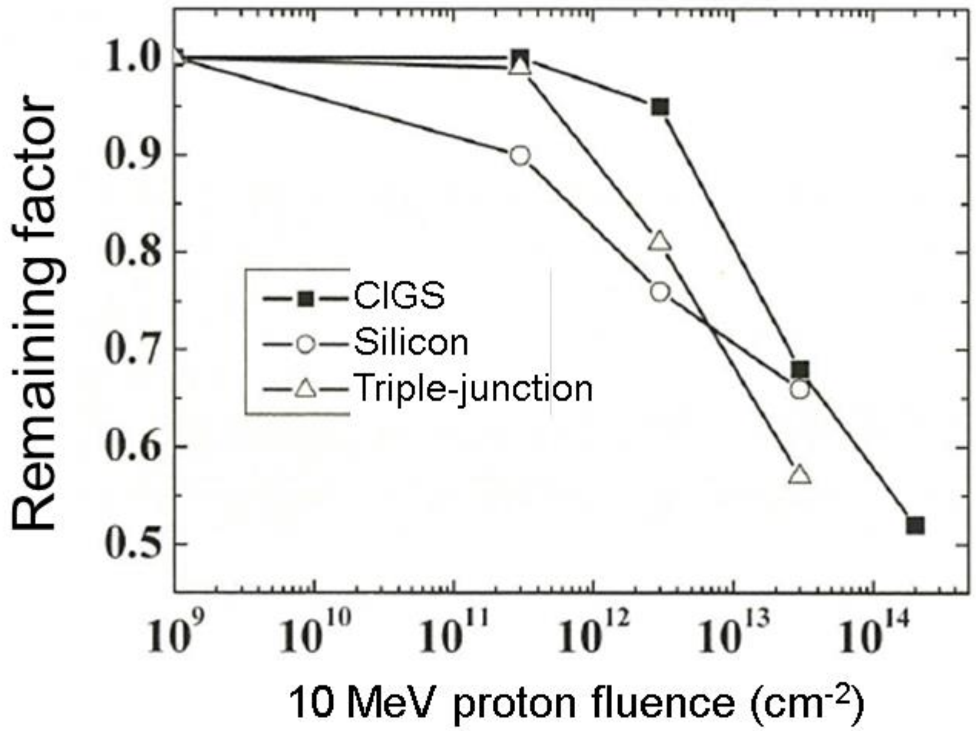


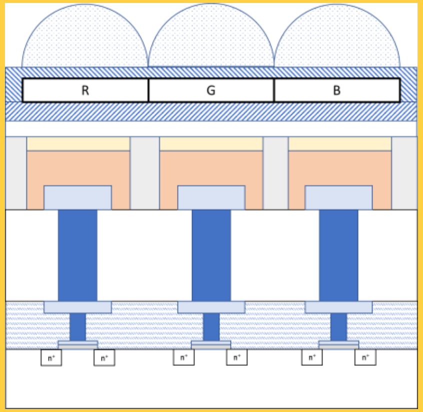
図 2　CIGS太陽電池，宇宙用シリコン太陽電池，宇宙用３接合太陽電池の10 MeV陽子線による電気性能の劣化特性

*川北史朗(JAXA), 化合物薄膜太陽電池の最新技術II, 2014年、シーエムシー出版.

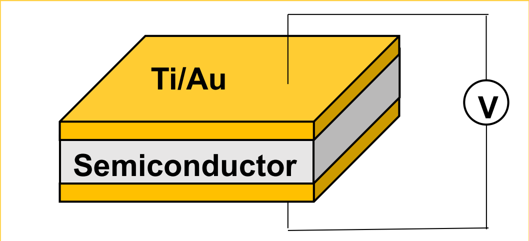
TIA KAKEHASHI projects

AIST

J. Nishinaga



CIGS image sensors



Widegap Semiconductors

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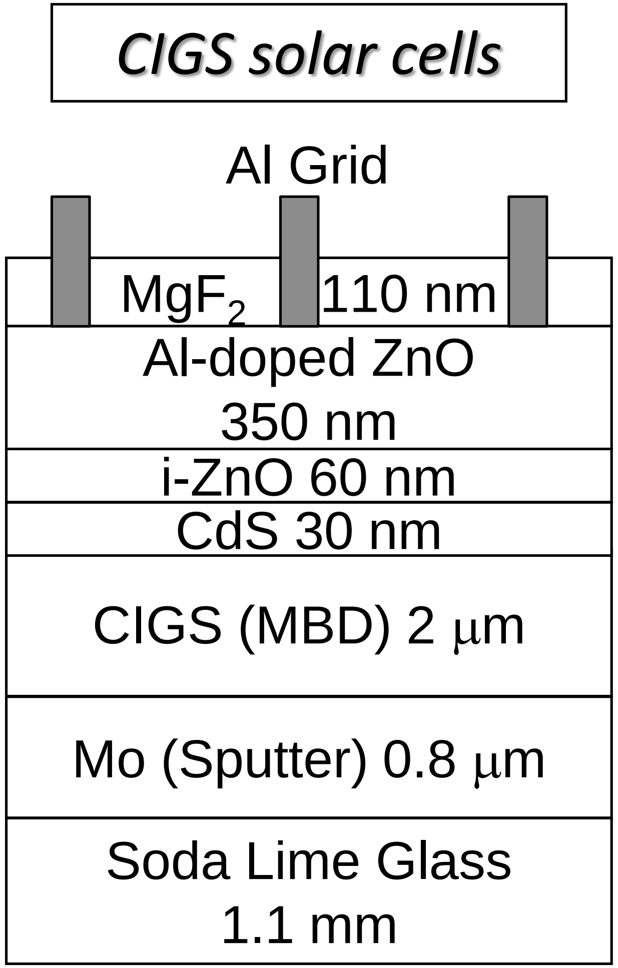
NIMS

M. Imura

TIA EXA
TIA Emerging electroniX research Alliance

かけはし

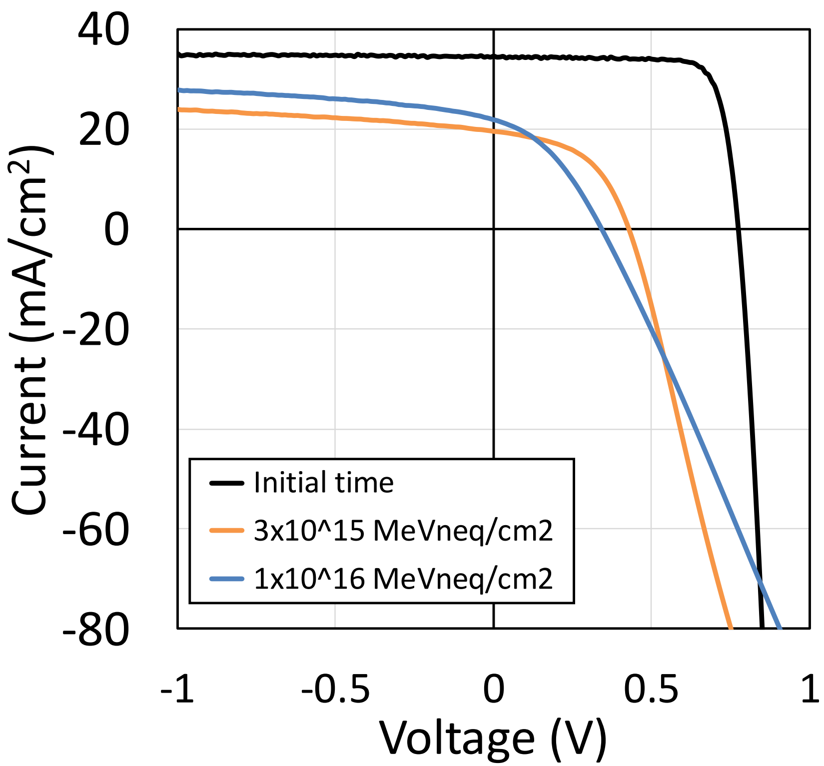
CIGS solar cell, Proton irradiation

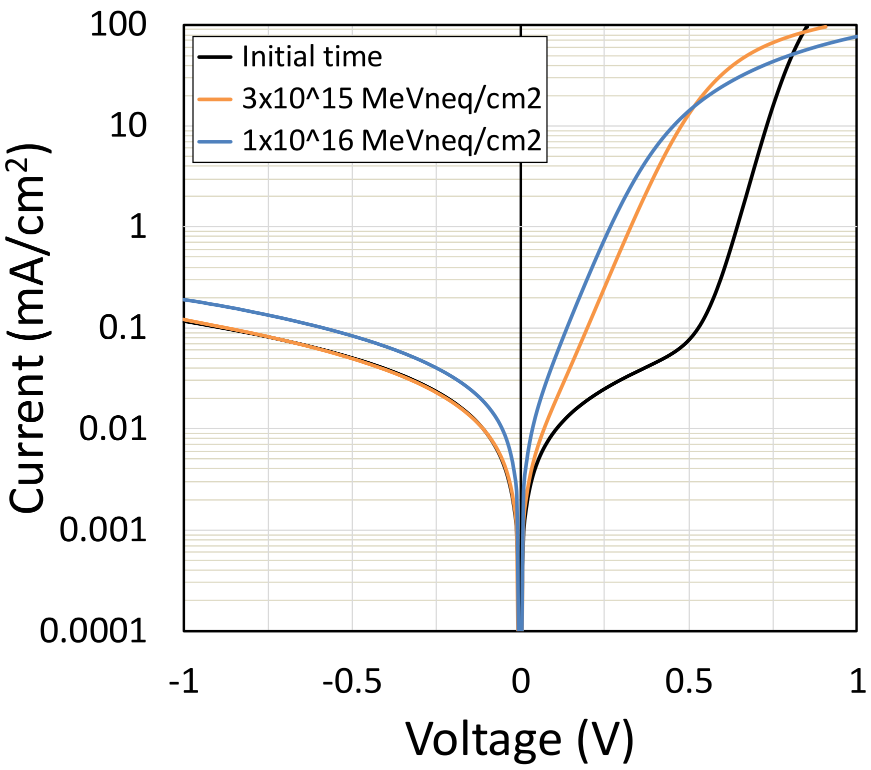


- CYRIC in Tohoku Univ.
- AVF Cyclotron
- 70 MeV proton at -15℃
- Dose (NIEL): 3×10^{15} MeV n_{eq}/cm^2
  1×10^{16} MeV n_{eq}/cm^2

- *I*-*V* curve (Dark and Light)
- *C*-*V* profiles (Dark)
- Heat-light annealing (90℃, 1Sun)

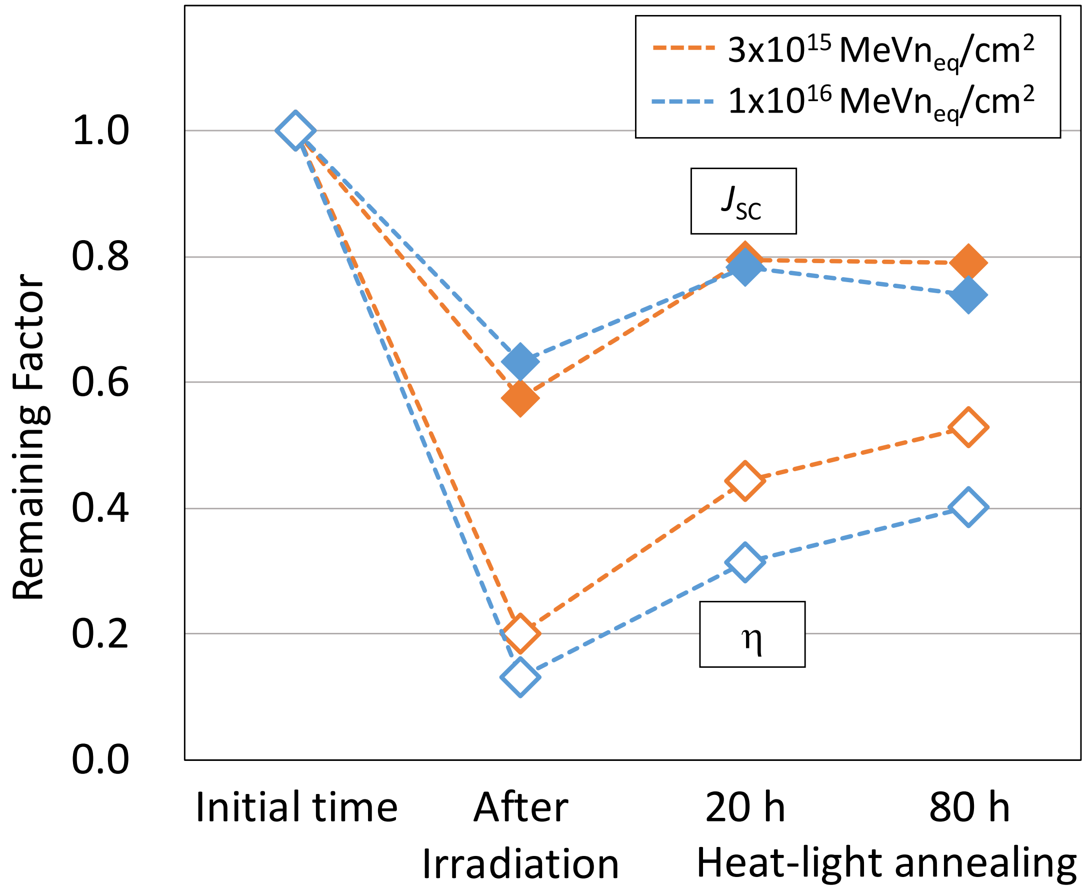
I-V curves after proton irradiation

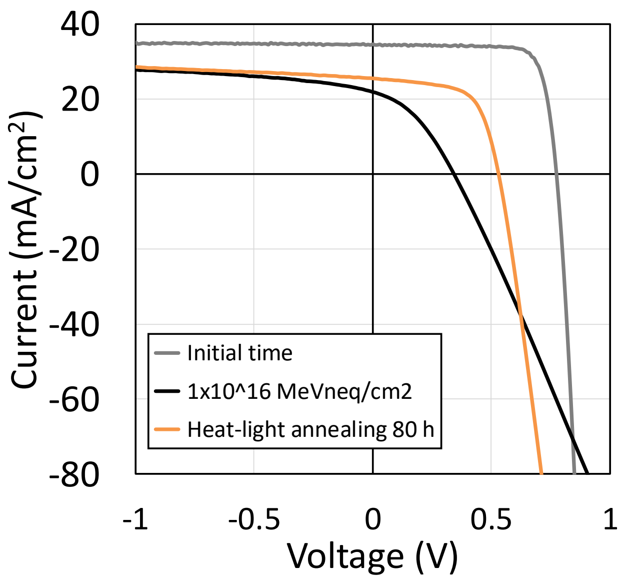


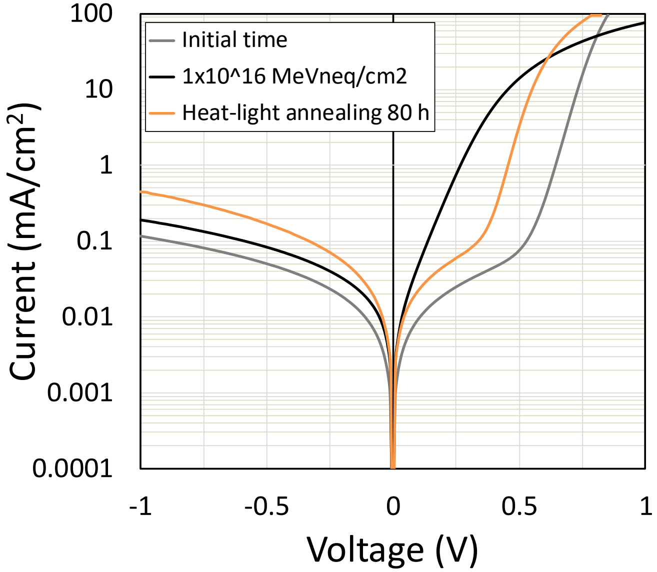


	Eff. (%)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	$R_{sh,\ dark}$ (Ωcm^2)	$R_{ser,\ dark}$ (Ωcm^2)	$N_{cv,0V}$ (cm^{-3})	n_{dark}
Initial time	21.4	0.774	34.7	0.795	3×10^3	0.5	5×10^{16}	1.3
$3\text{x}10^{15}$ MeVn_{eq}/cm^2	4.1	0.429	19.6	0.493	4×10^3	3.1	3×10^{16}	1.9
$1\text{x}10^{16}$ MeVn_{eq}/cm^2	2.8	0.34	22.0	0.373	1×10^3	7.0	1×10^{16}	2.0

Damage recovery by Heat-light annealing

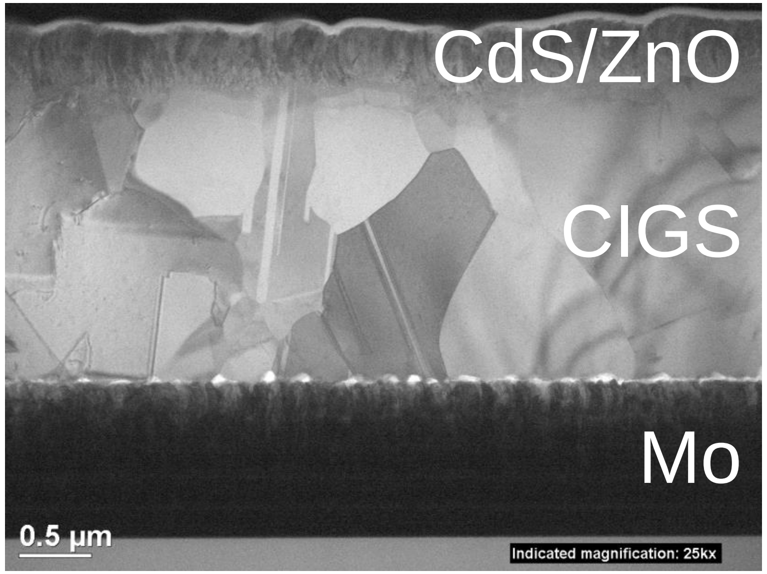


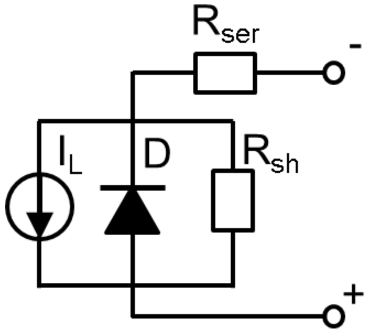


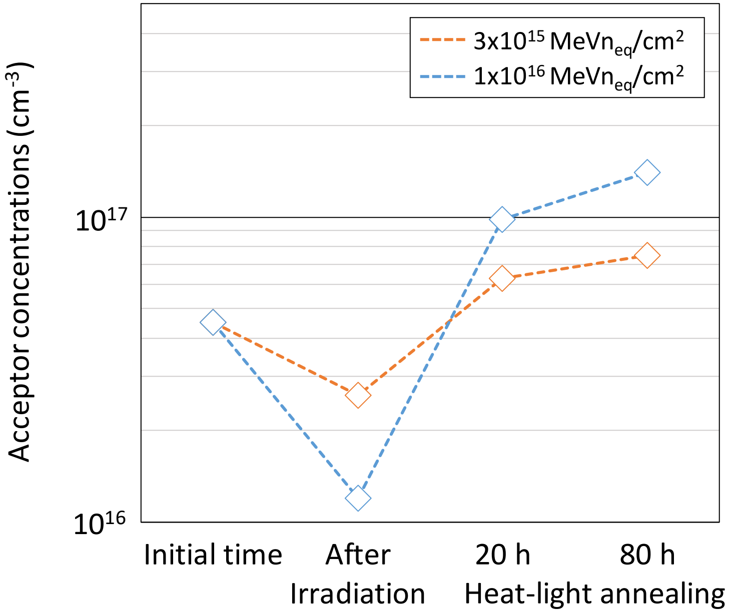


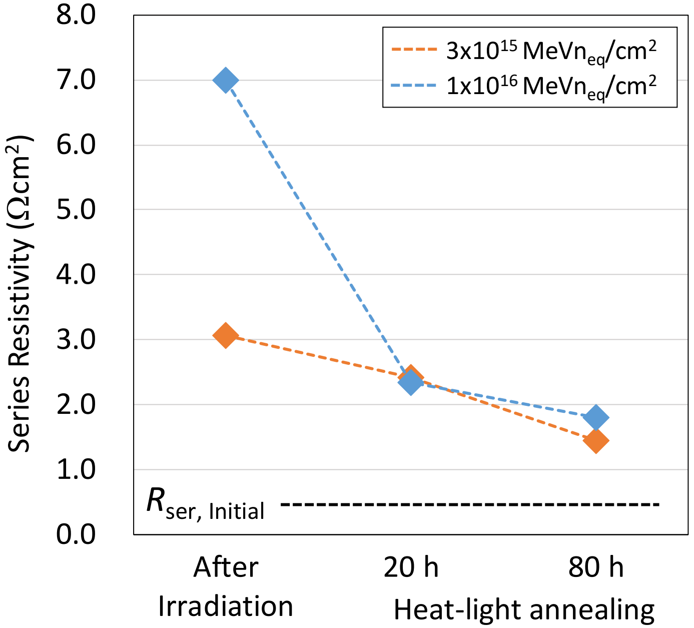
Light current are almost recovered by heat-light annealing for 80 hours.

Diode parameters, Carrier concentrations





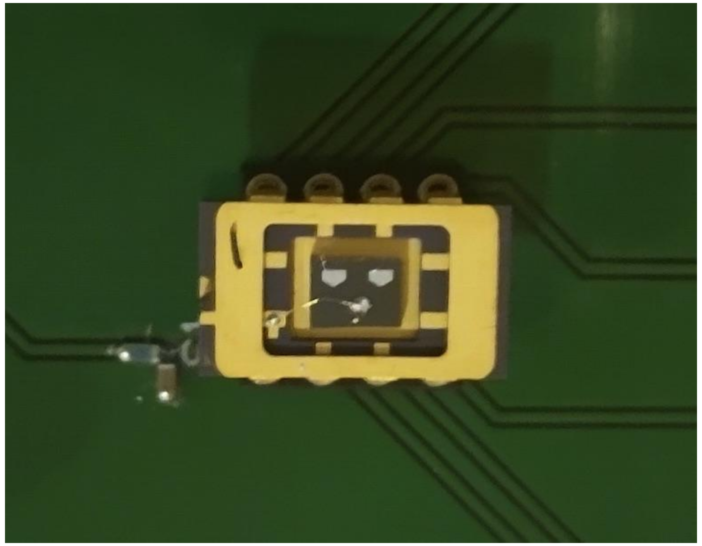


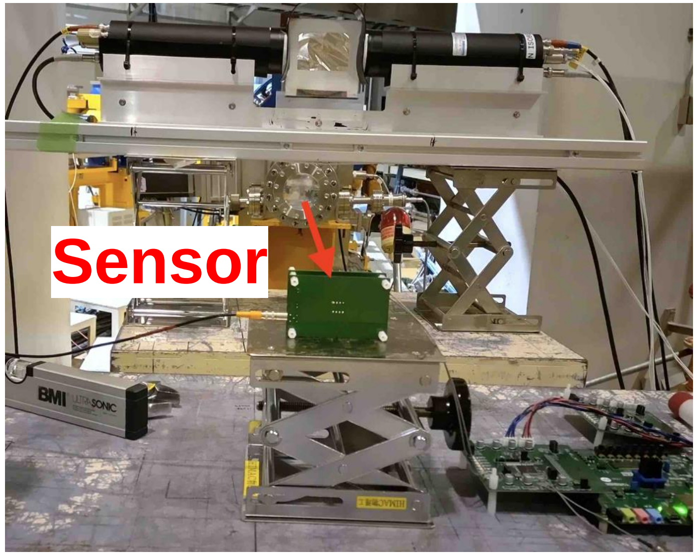


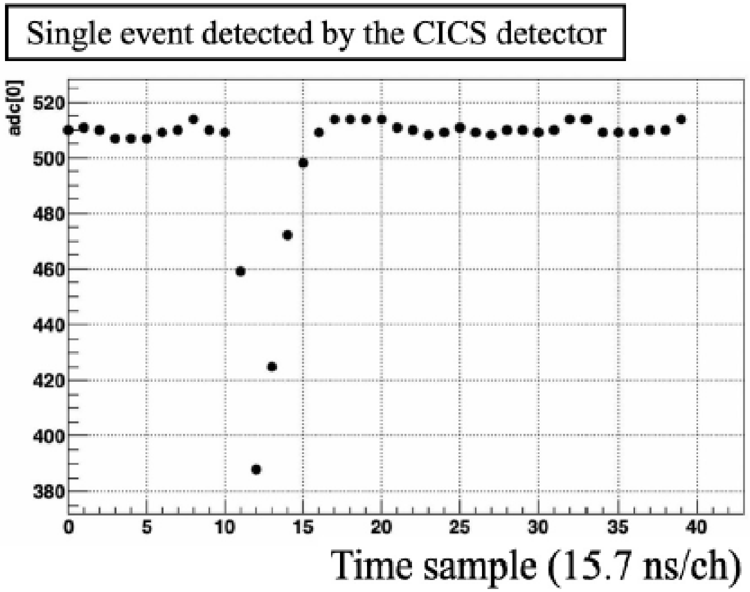
	$R_{ser, dark}$ (Ωcm^2)	$N_{cv,0V}$ (cm^{-3})	$J_{0,dark}$ (mA/cm^2)	n_{dark}
Initial time	0.4	5×10^{16}	1×10^{-8}	1.4
$1x10^{16}$ $MeVn_{eq}/cm^2$	7.0	1×10^{16}	6×10^{-3}	2.0
Heat-light 20 h	2.3	1×10^{17}	3×10^{-5}	1.5
Heat-light 80 h	1.8	1.4×10^{17}	1×10^{-6}	1.3

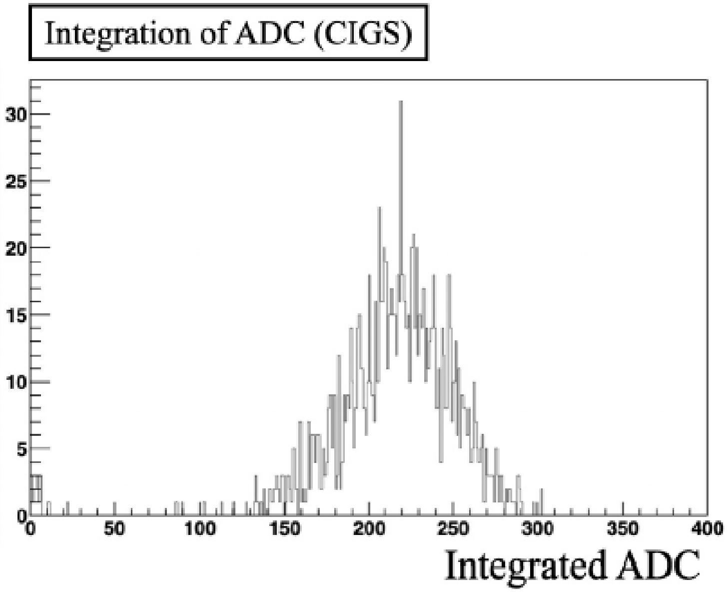
Heavy Ion beam test at HIMAC

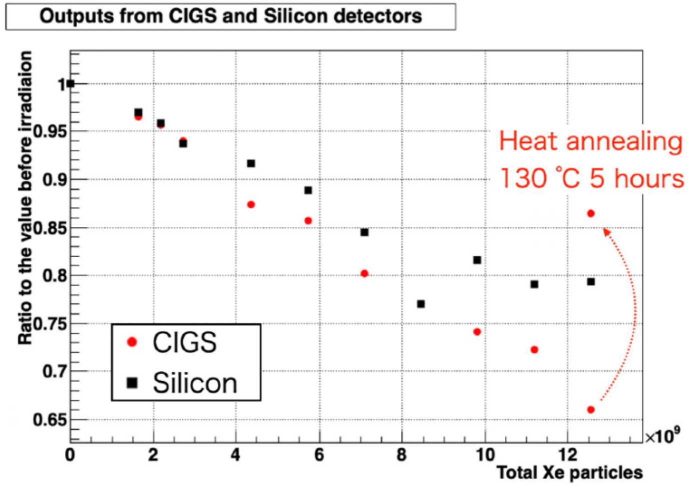
HIMAC: Heavy Ion Medical Accelerator in Chiba, Xenon 400 MeV/n (52,400MeV)







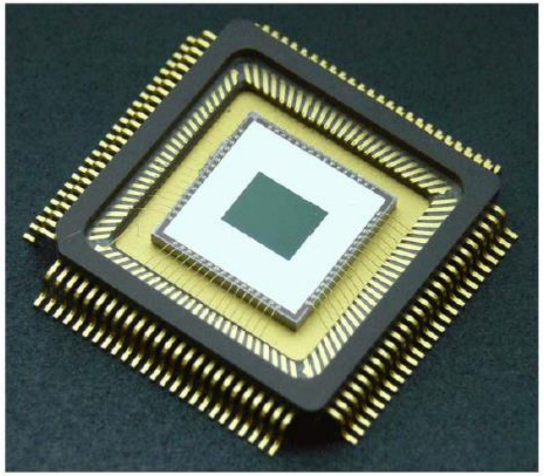


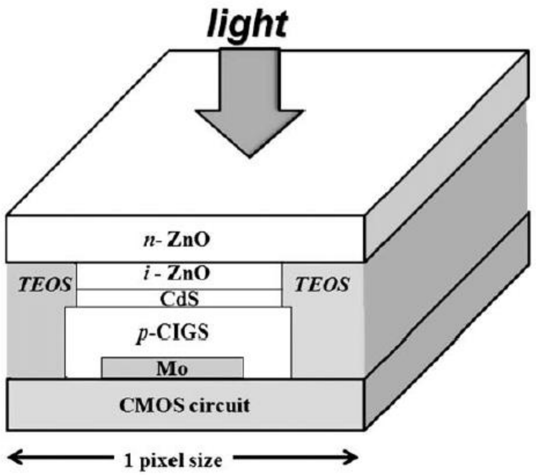


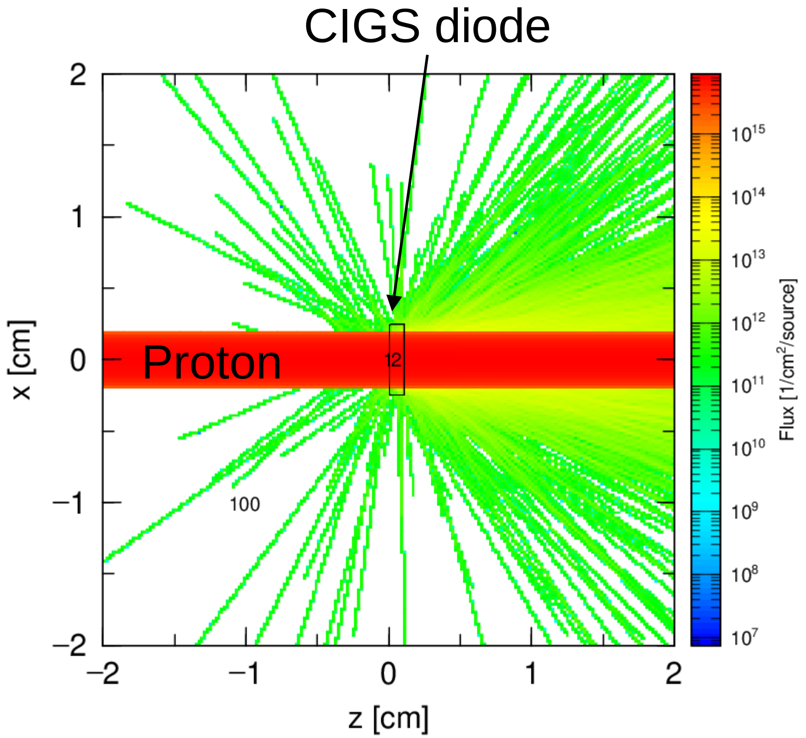
-Xenon 400 MeV/n (52,400 MeV)
@ 2 um-thick CIGS
6.5 MeV → 277 fC
*Assuming excitation energy of 3.0 eV

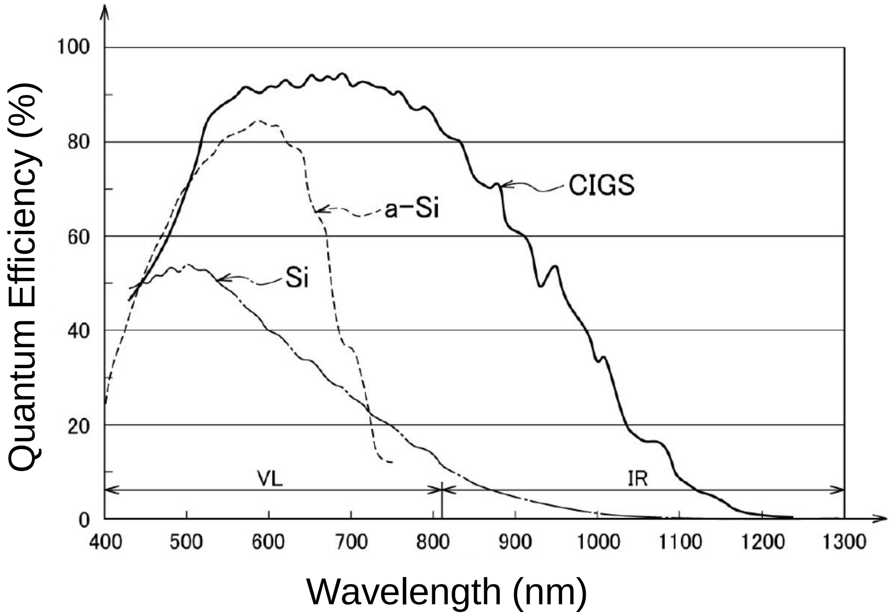
Output is decreased after irradiation, but the output is recovered by annealing.

CIGS image sensors









Proton 70 MeV	CIGS 2um	Si 150 um
NIEL ($MeVn_{eq}/cm^2$)	1×10^{16}	1×10^{16}
TID (Gy, J / kg)	4.4×10^{6}	6.0×10^{6}
Energy loss (J / cm^2)	***5.1***	210

*K. Miyazaki, et al. Thin Solid Films **517**(2009) 2392. 特開2014-127945.

Summary

CIGS solar cells

- CIGS has potential for high efficiency and cost-saving solar cells.
- CIGS solar cells are fabricated on soda lime glass substrates since the grain boundaries don't act as recombination centers.
- Excellent radiation tolerance of CIGS solar cells has been reported.

Radiation tolerance and applications

- CIGS solar cells have high radiation tolerance because the defects induced by radiation absorption are recovered by heat-light annealing.
- CIGS is a promising material for image and particle detectors in high radiation environment.