Study of radiation tolerance of $Cu(In,Ga)Se_2$ detector

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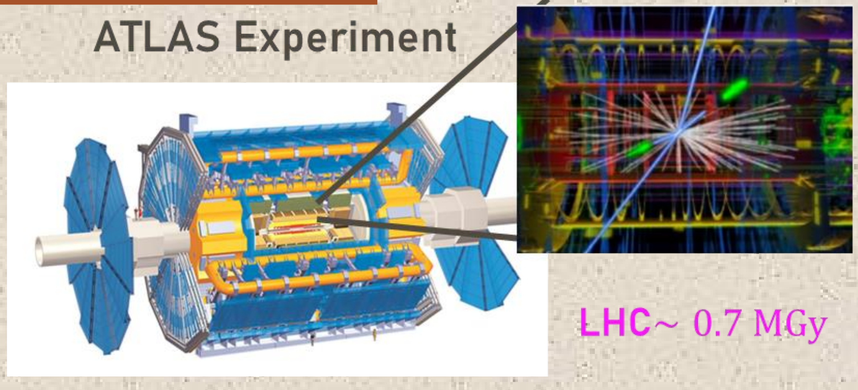
Contents

- Introduction
- Study of radiation tolerance of CIGS
  - Heavy ion ($^{132}Xe^{54+}$) irradiation experiment
  - Proton irradiation experiment

Study of the radiation tolerant semiconductors

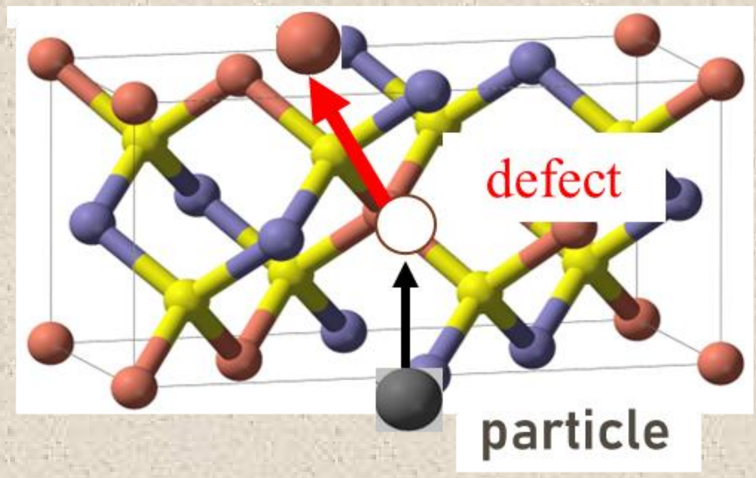


Hadron Collider Experiment

High energy experiment (LHC) plans to construct

the higher energy and luminosity accelerator for the new particle search.

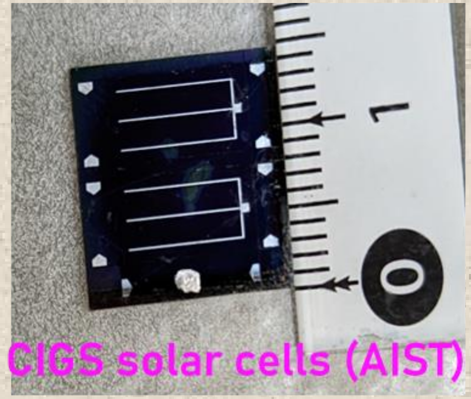
→ Giving serious radiation damage to detectors.



Performance deterioration by radiation damage

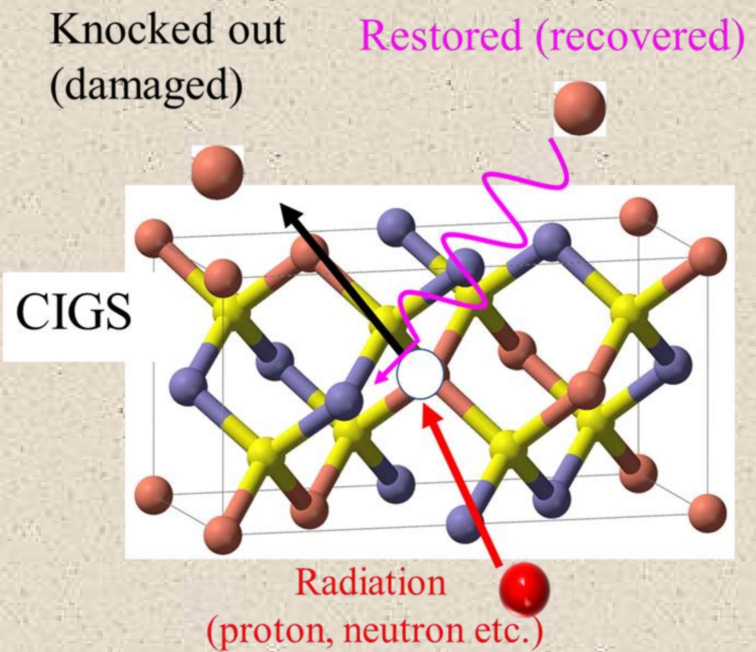
- Increasing leakage current
- Increasing depletion voltage
- Decreasing in collected charge from signal

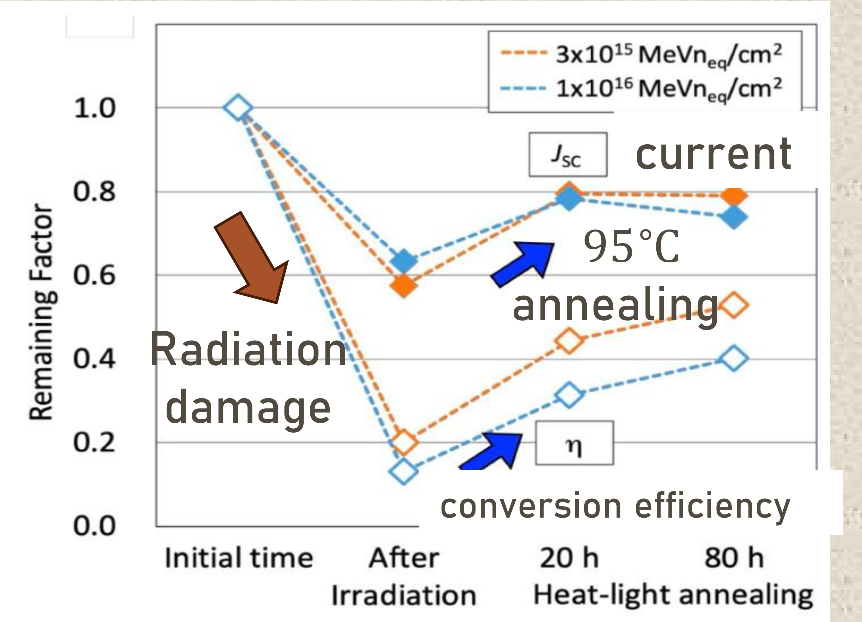
Radiation hardness semiconductor (CIGS)



A CIGS is an alloy semiconductor of $CuInSe_2$ and $CuGaSe_2$

- Developed as a solar cells
- High radiation tolerance (recovered radiation damage by heat annealing)





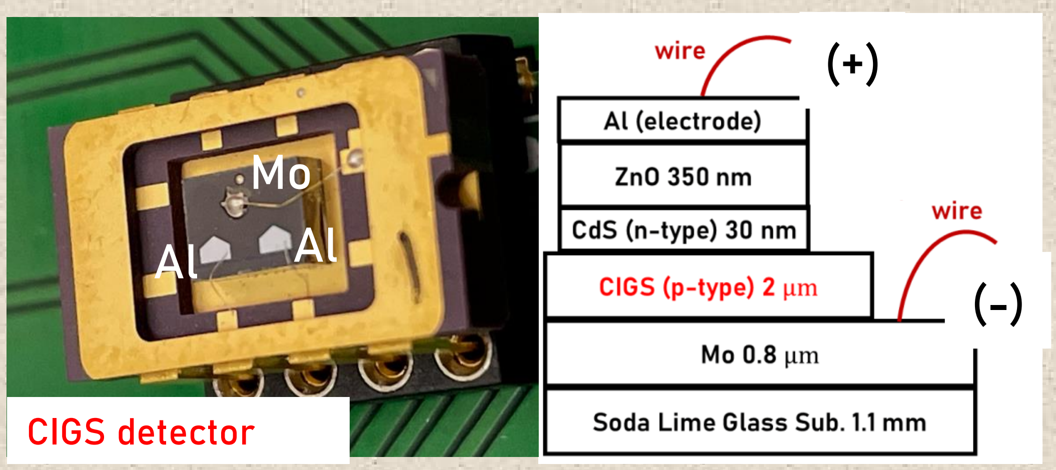
Observed current recovery by thermal annealing (in CIGS solar cells)

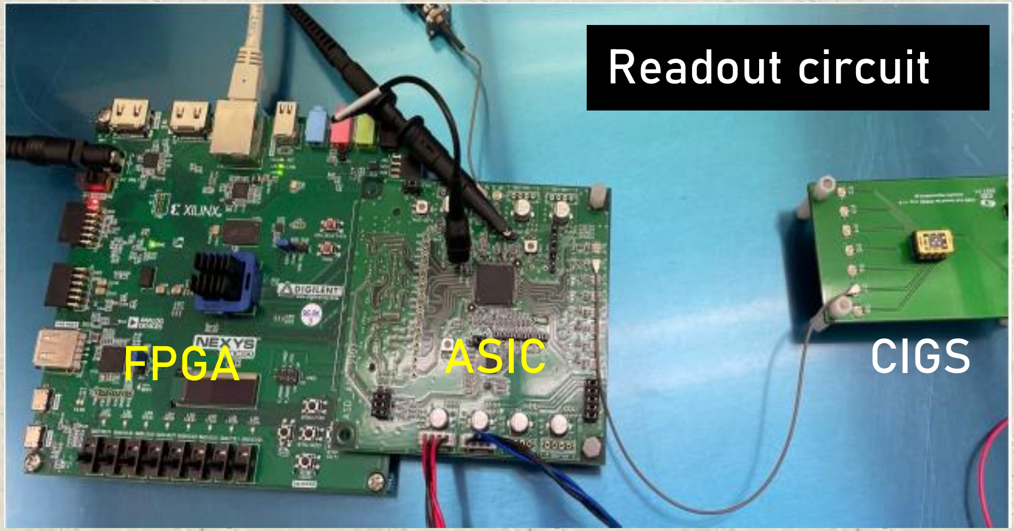
Challenging in development of CIGS detector radiation hardness detector with CIGS

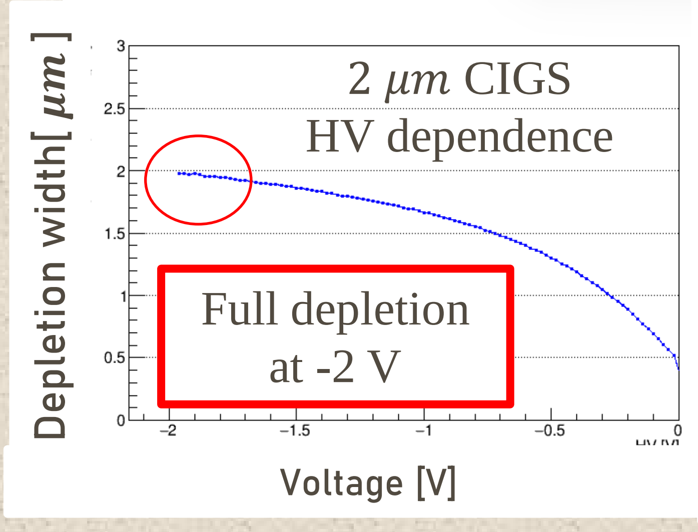
Development of CIGS detector

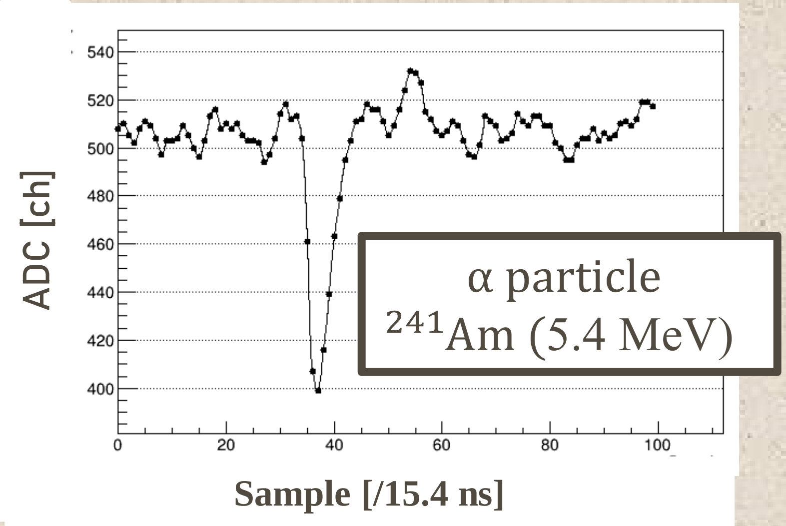
Specifications of CIGS detectors

- p-type (CIGS), n-type (CdS)
- thickness $2\ \mu m, 5\ \mu m$ ($10\ \mu m$ developing)
- Active area : $5\ \mathrm{mm}^2/\mathrm{channel}$
- Operation Voltage : -2 V









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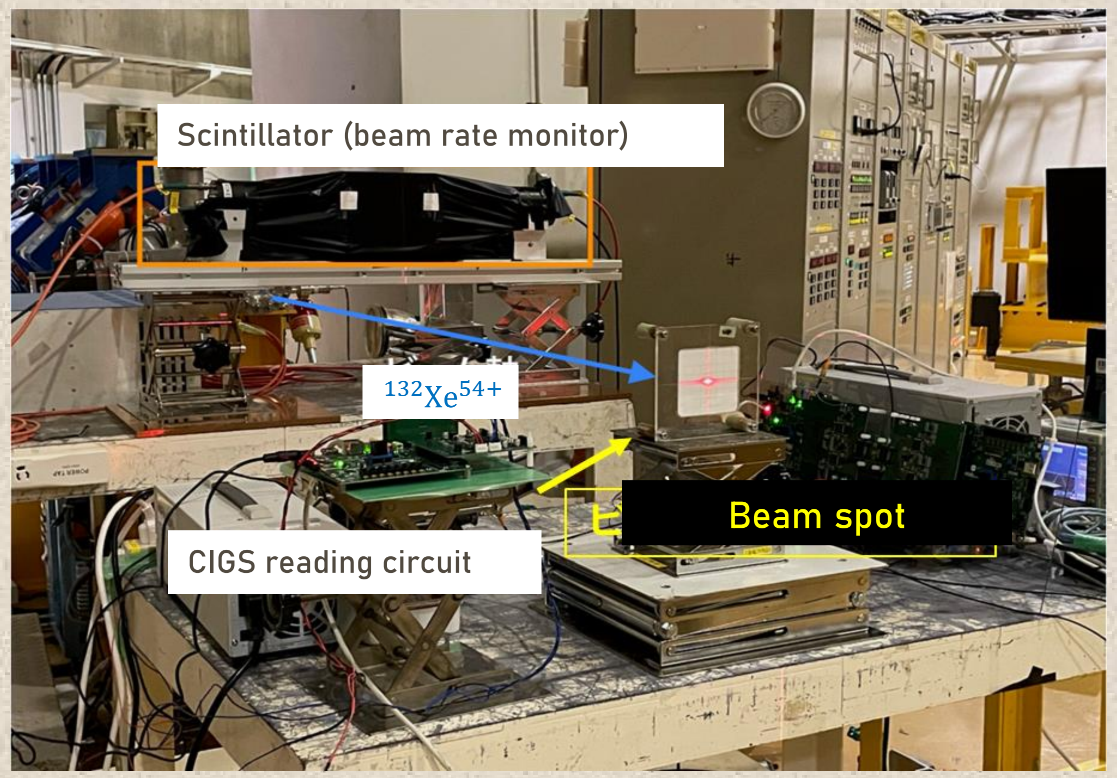
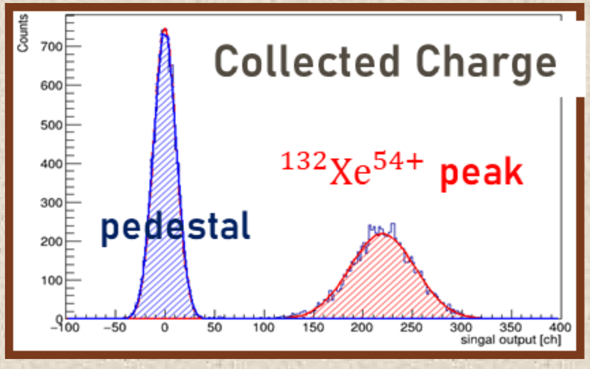
Irradiation experiment at HIMAC

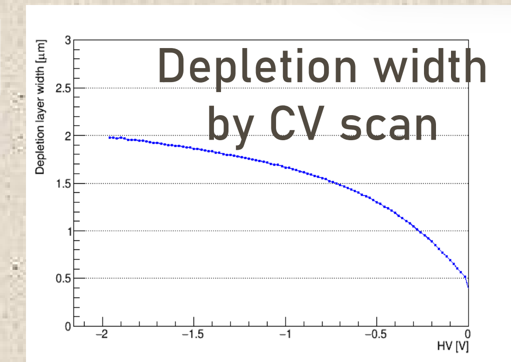


HIMAC Beam Condition

- Beam : $^{132}Xe^{54+}$ ion
- Energy : 400 (MeV/u)
- Beam size (ϕ) : 3-5 mm
- Fluence : 10^7 /3.3 s (ppp)

Measurement parameters



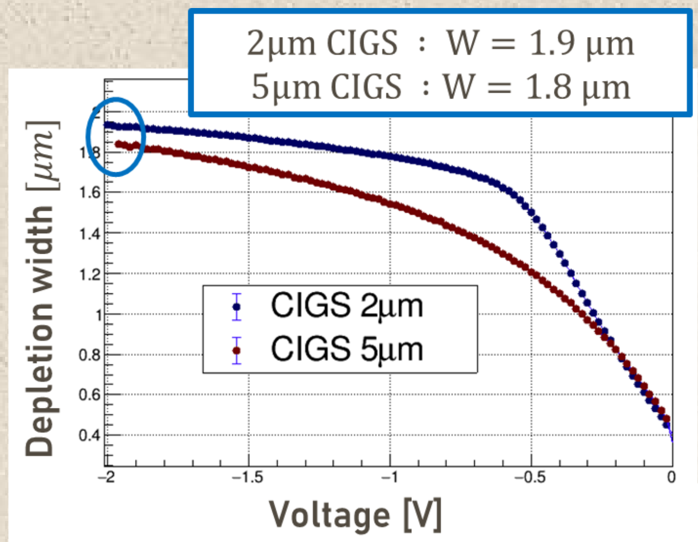


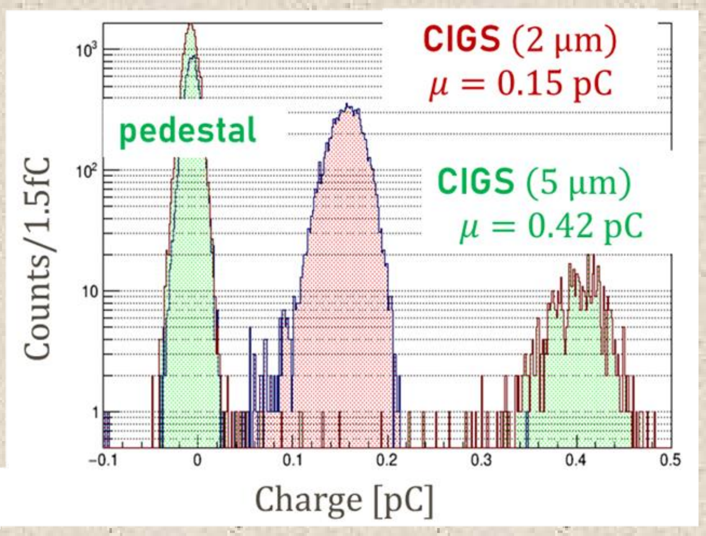
1. CIGS thickness dependence (2 μm and 5 μm thick CIGS detectors)
2. Recovery mechanism of radiation damage (2 μm thick CIGS detector)

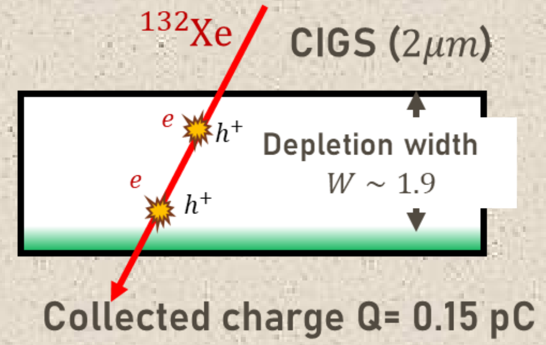
Thickness dependence of CIGS detector peformances

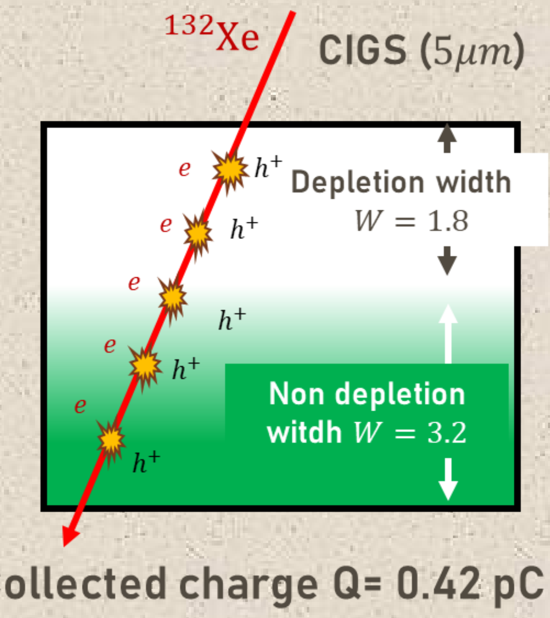
The collected charge is proportional to depletion width ($Q \propto W$).

Both of depletion width (V=-2V) are about 2 μm, but collected charge of 5 μm CIGS detector was **2.5 times larger** than one of 2 μm CIGS detector







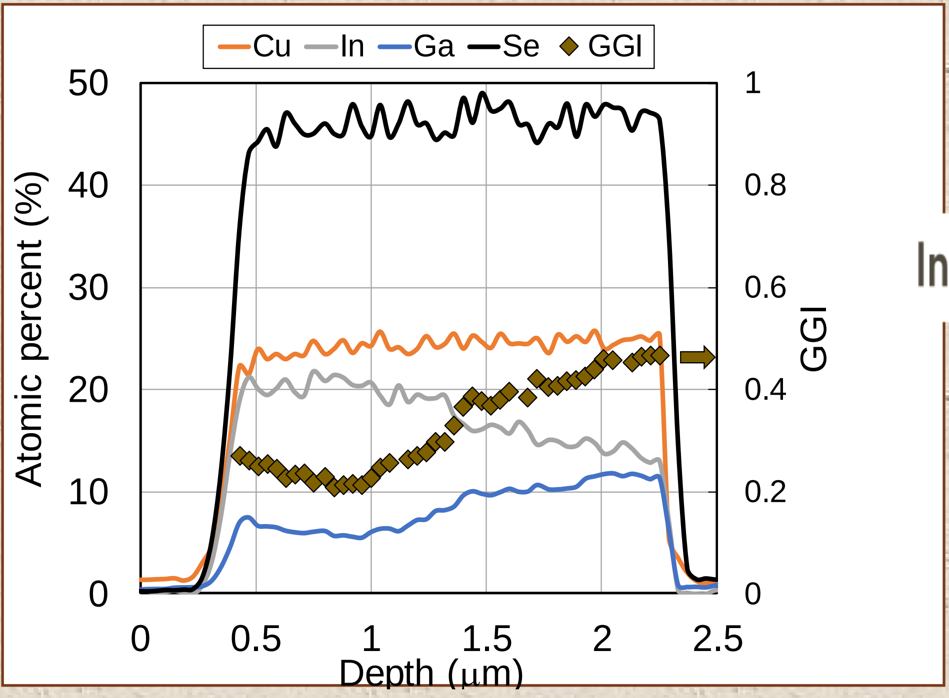


Is it possible to collect charges in non-depletion region ??

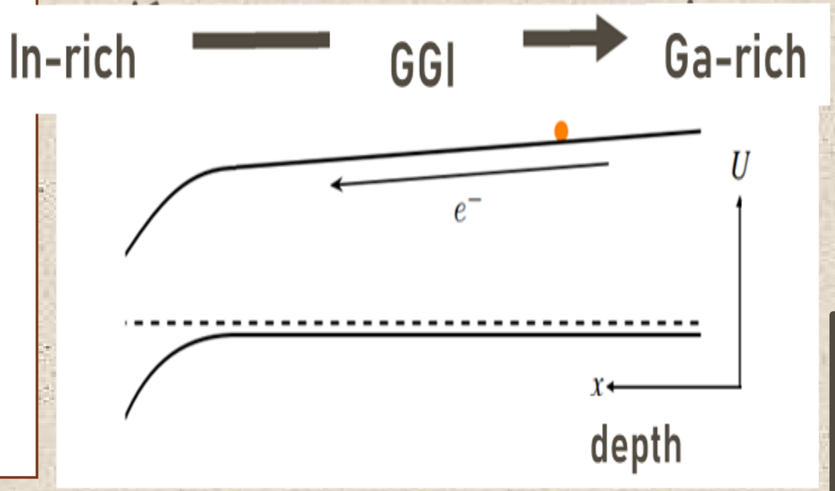
Energy gradient of CIGS layer

CIGS is an alloy semiconductor $CuInSe_2$ and $CuGaSe_2$.
Energy gap of CIGS changes with Ga composition ratio (GGI=[Ga]/[In]+[Ga]).

$$1.01\ \mathrm{eV}\ [\mathrm{GGI}=0] < E_g < 1.64\ \mathrm{eV}\ [\mathrm{GGI}=1]$$



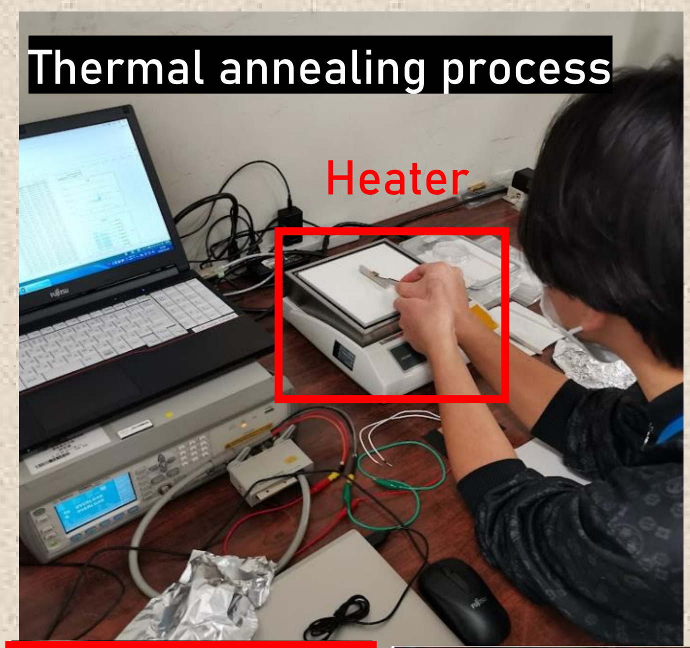
CIGS layer has GGI gradient for depth direction
→ Promoting electron diffusion

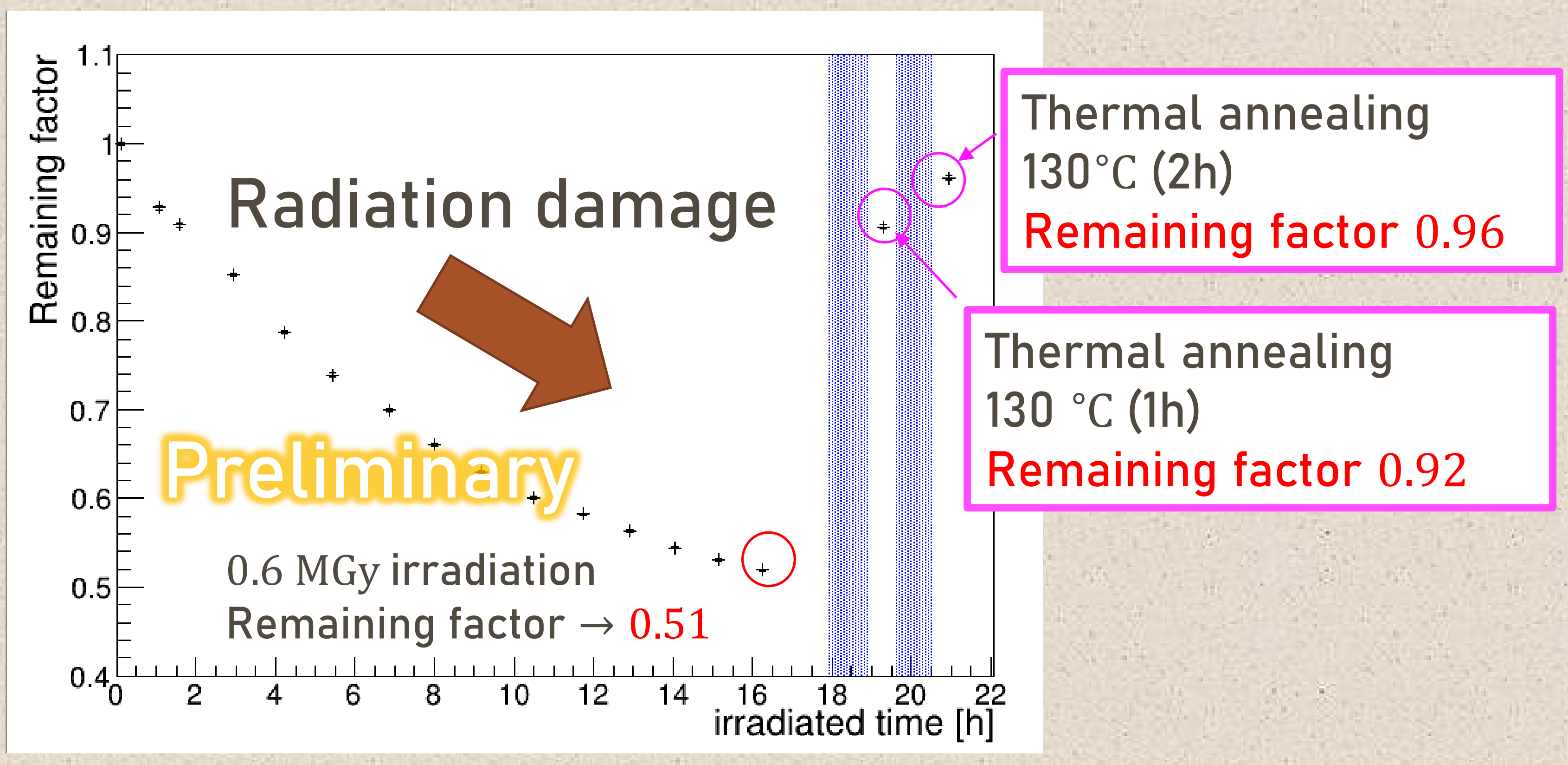


Not need for full depletion

It allows
low voltage operation!

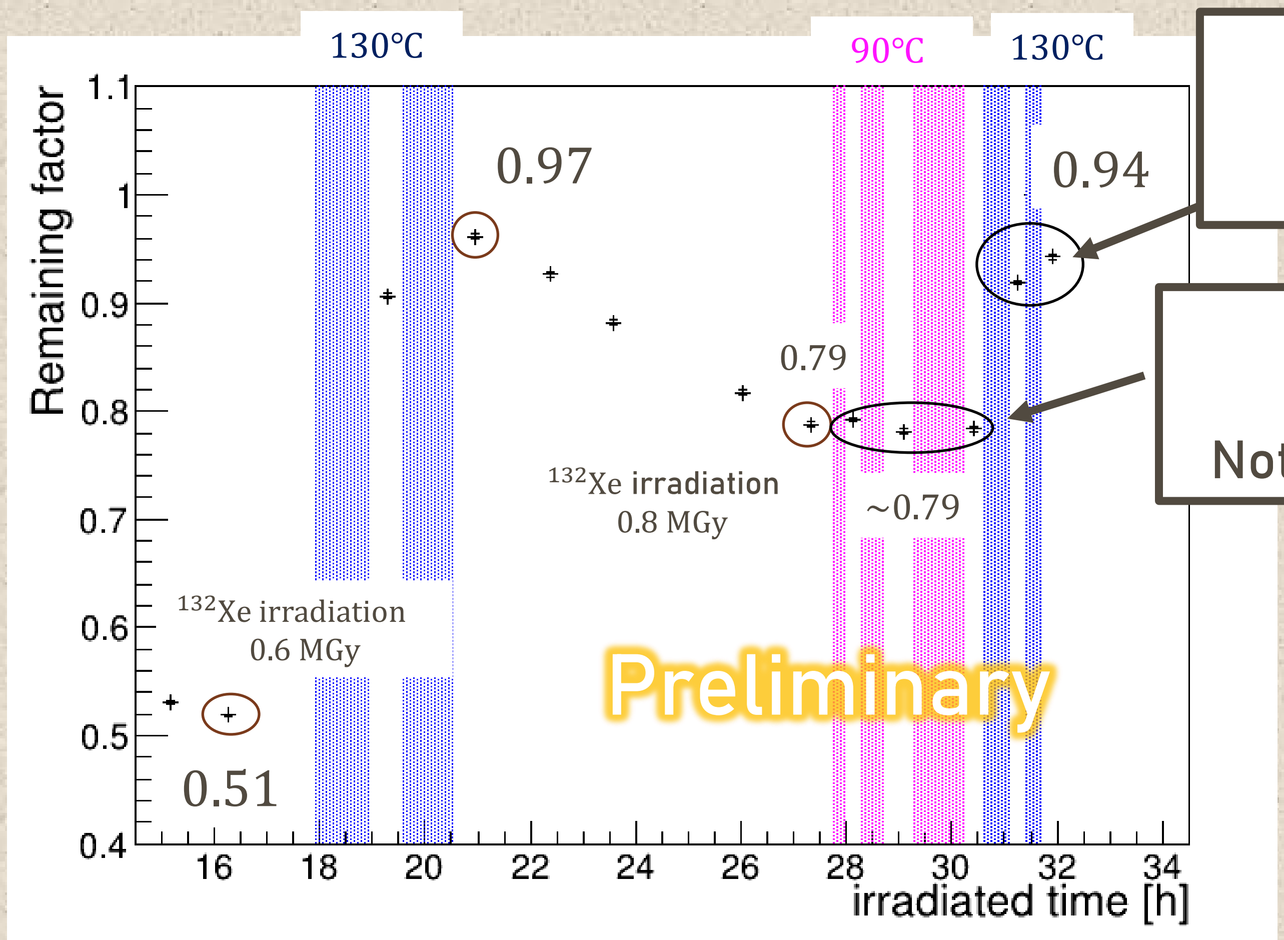
Study of the recovery mechanism by thermal annealing





After 2 hours thermal annealing at 130 ℃
Recovered to the same level as before irradiation

Study of the recovery system by thermal annealing (2)

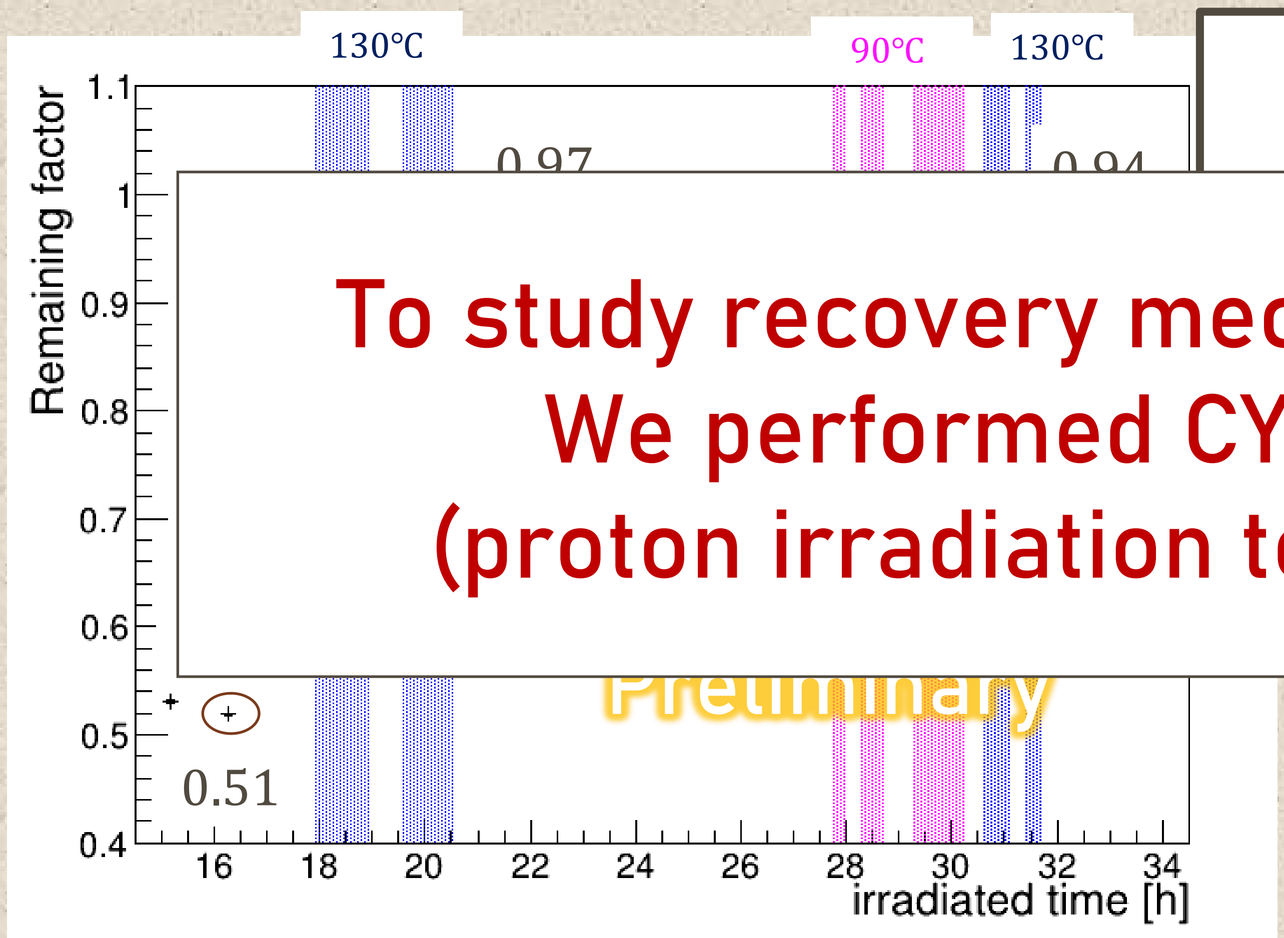


2nd 130℃ thermal annealing
(+30 min, +20 min)
0.79 → 0.94 (+50 min)

90℃ thermal annealing
(+15 min, +30 min, +1h)
Not sufficient recovery (insufficient annealing time)

Thermal annealing mechanism has
- **Strong temperature dependence**
- **Continuity of thermal recovery**

Study of the recovery system by thermal annealing (2)



2nd 130℃ thermal annealing
(+30 min, +20 min)

time)

To study recovery mechanism more detail,
We performed CYRIC experiment
(proton irradiation to CIGS solar cells)

has

- Strong temperature dependence
- Continuity of thermal recovery

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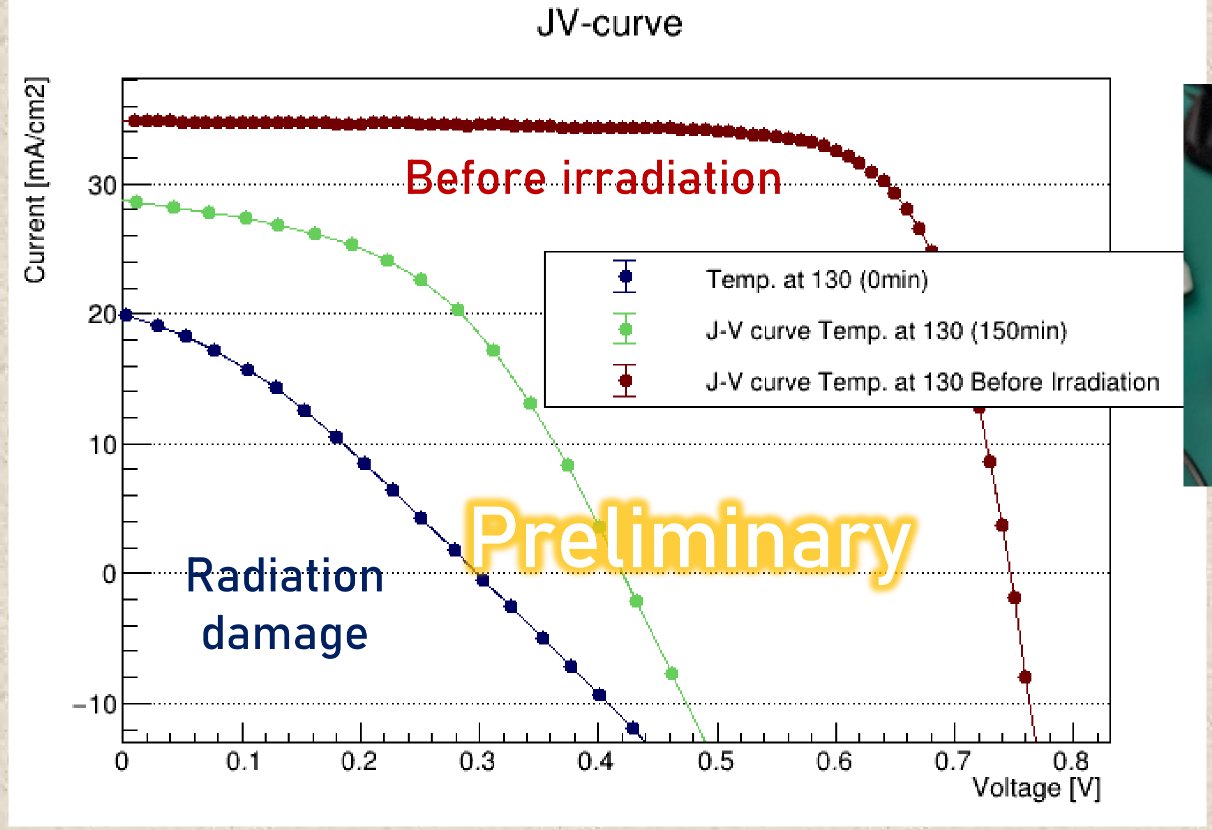
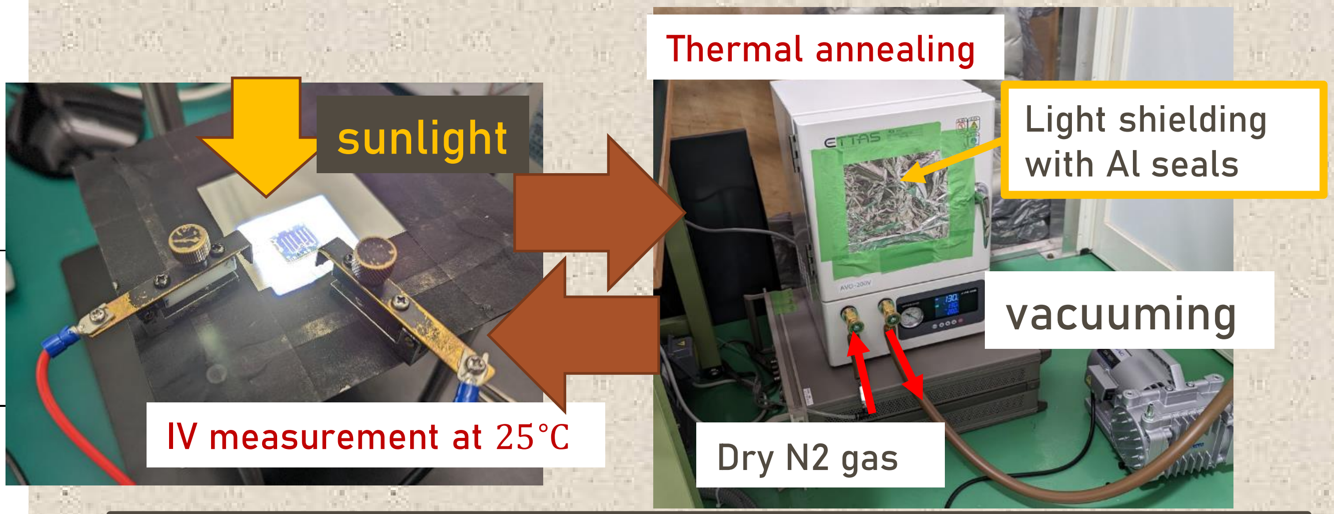
Proton irradiation experiment at CYRIC

CIGS solar cells (AIST)

CYRIC experiment : Irradiated 70 MeV proton to CIGS solar cells ($7 \times 10^{15}\ n_{eq}$)

→ Study the heating time and temperature dependences of recovery mechanism





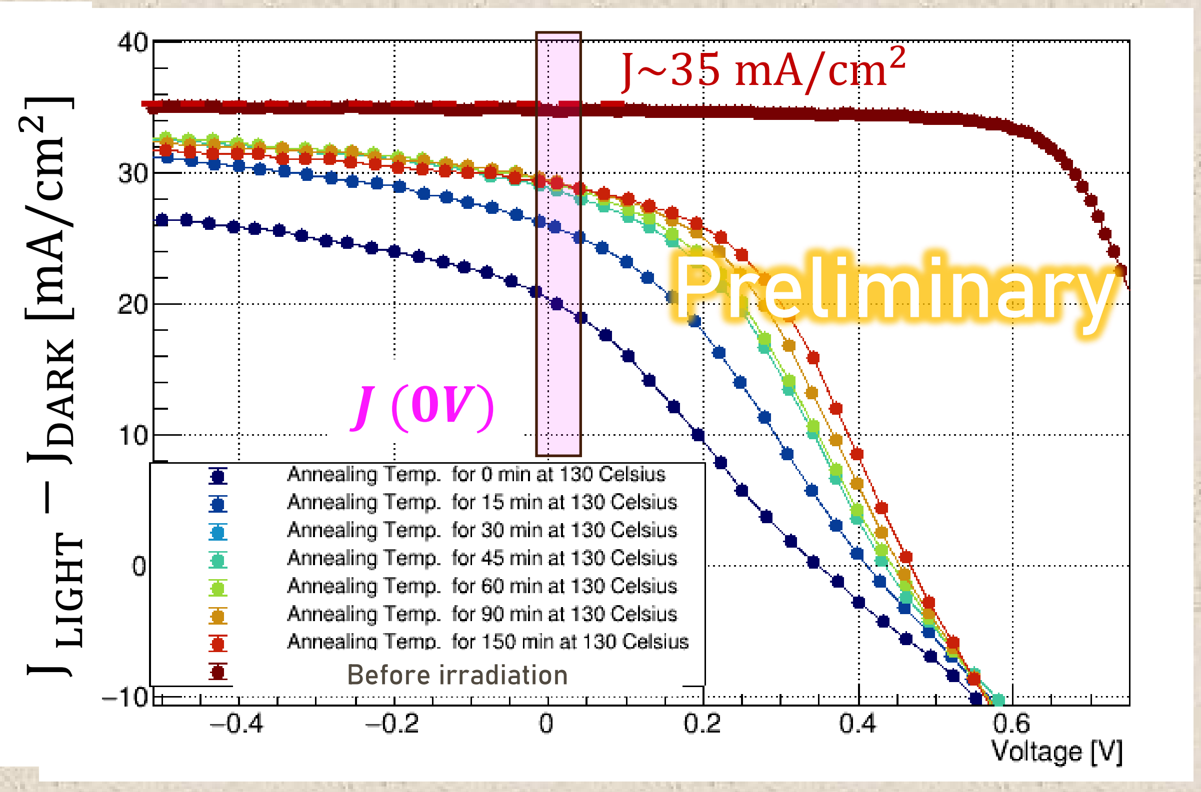
IV curve of CIGS solar cells

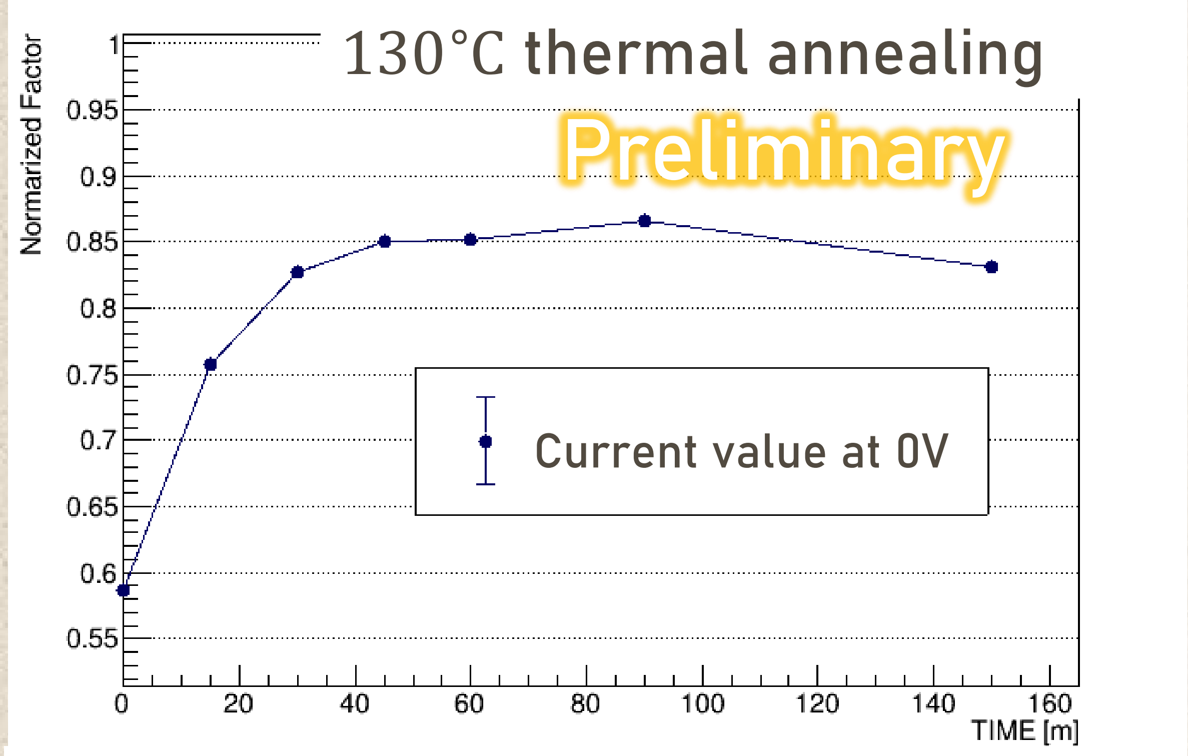
- J $[\mathrm{mA/cm^2}]$ decreased due to proton irradiation
  $J_{sc}(0V)$: 35 → 20 $\mathrm{mA/cm^2}$
- Recovered J by thermal annealing (2.5 h) at 130°C
  $J_{sc}(0V)$: 20 → 28 $\mathrm{mA/cm^2}$

Current recovery dependence of annealing time

The measurement current with incident sunlight is including dark current.

Excluded dark current : $J = J_{LIGHT} - J_{DARK}$

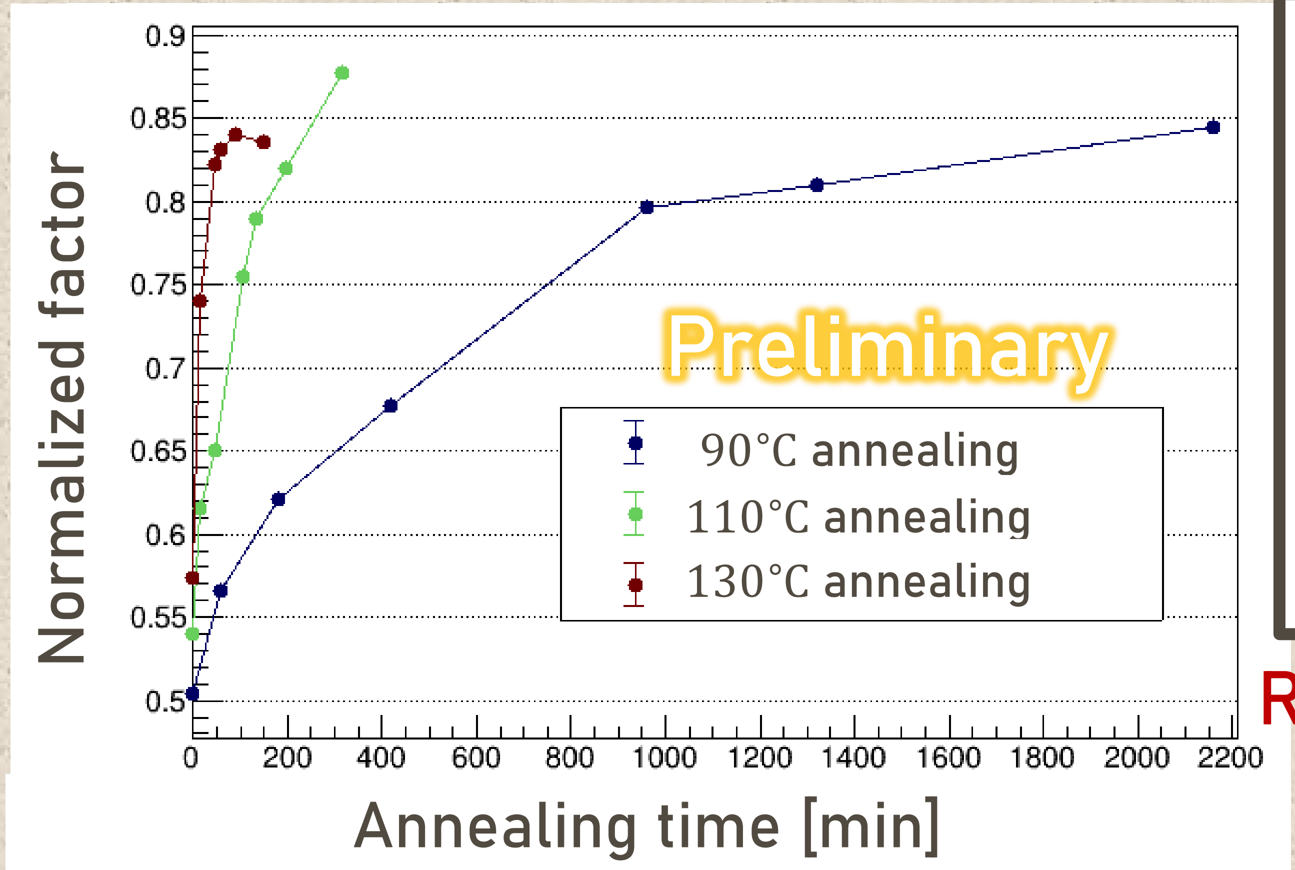




J recovered rapidly to saturation value $(\sim 1h)$

Heating temperature dependence of recovery speed

I annealed CIGS solar cells at three differential temperatures (90°C, 110°C, 130°C).



130°C annealing : $J_{0V} = 0.57 \rightarrow 0.85$ (1h)

90°C annealing : $J_{0V} = 0.50 \rightarrow 0.57$ (1h)

Comparable with recovery speed of collected charge at HIMAC experiment

130°C annealing: $Q = 0.79 \rightarrow 0.94$ (1h)

90°C annealing: $Q = 0.79 \rightarrow 0.79$ (1h)

Recovery speed is greatly depending on heating temperature

Conclusion

- CIGS semiconductor has been developed as a solar cells.
  - Observed recovery of radiation damage by thermal annealing
  - We developed plot type of CIGS detector (2 μm)
- Heavy ion irradiation experiment at HIMAC
  - Observed recovery of collected charge and leakage current by $130°C$ annealing (→ same level of before irradiation)
- Proton irradiation experiment at CYRIC
  - Observed strong annealing temperature dependence of recovery speed

  → Comparable with recovery speed of HIMAC experiment

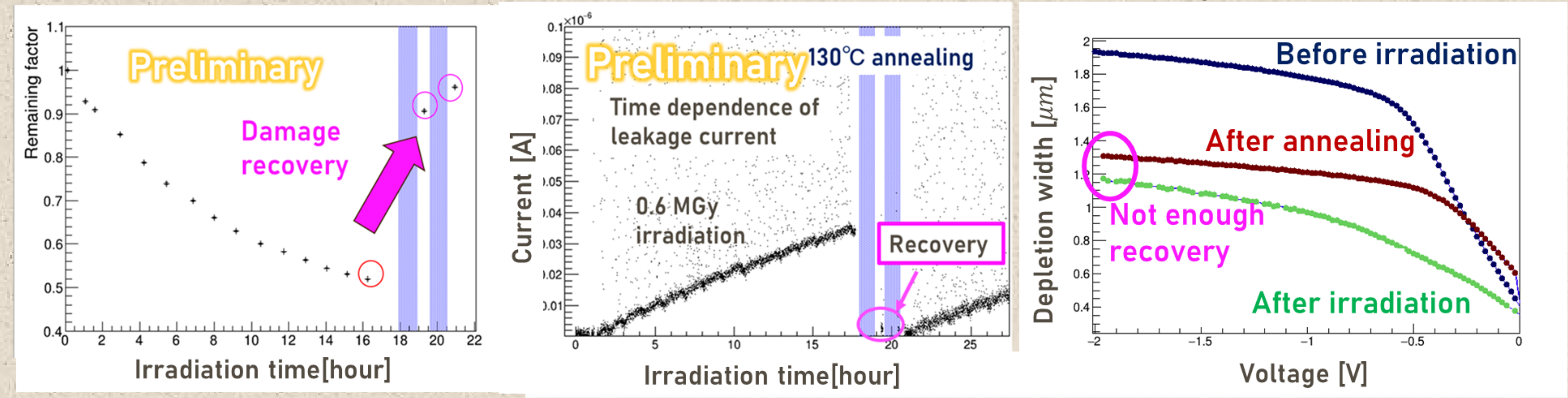
Thank you

Backup

Results of heat treatment at 130°C in each parameter

Annealing results of three detector performances

1. Collected charge from Xe beam
2. Leakage current
3. Depletion width

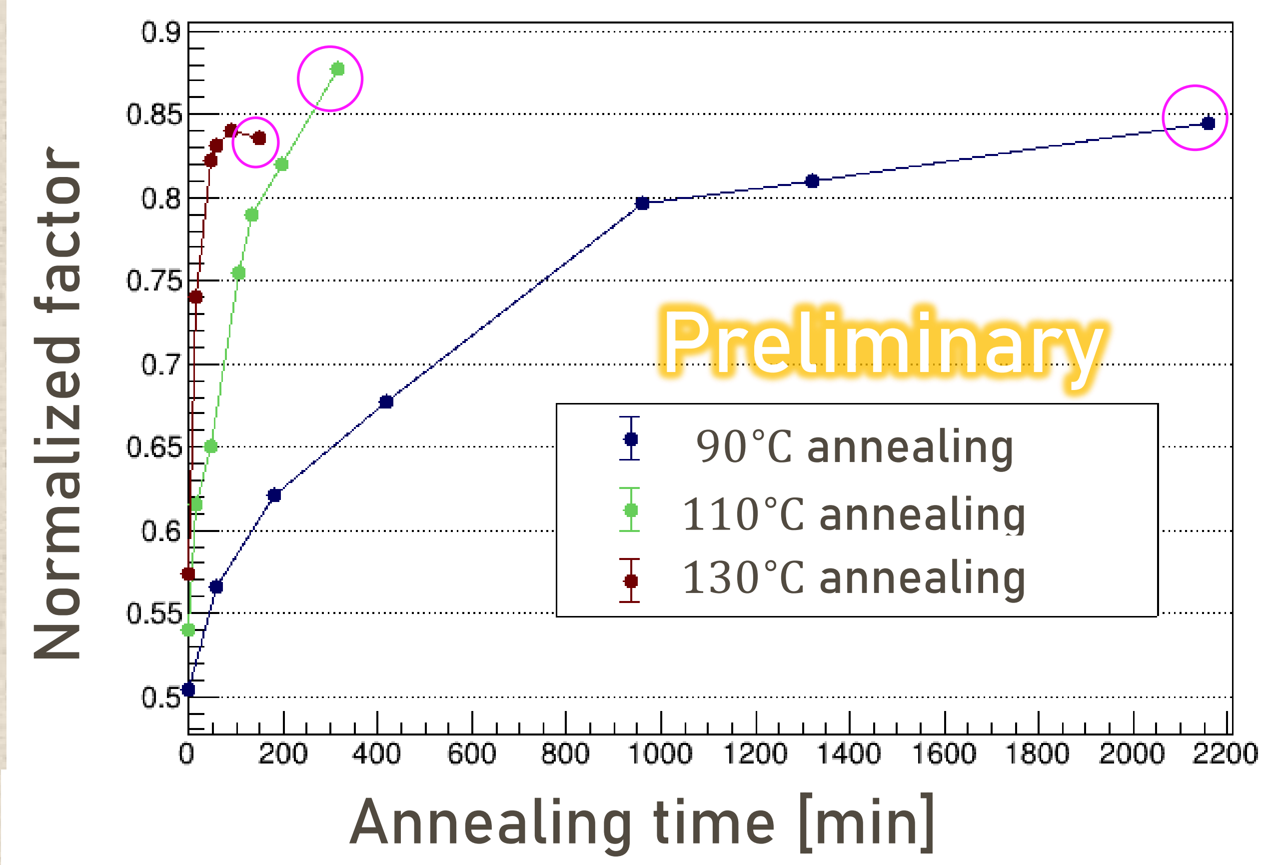


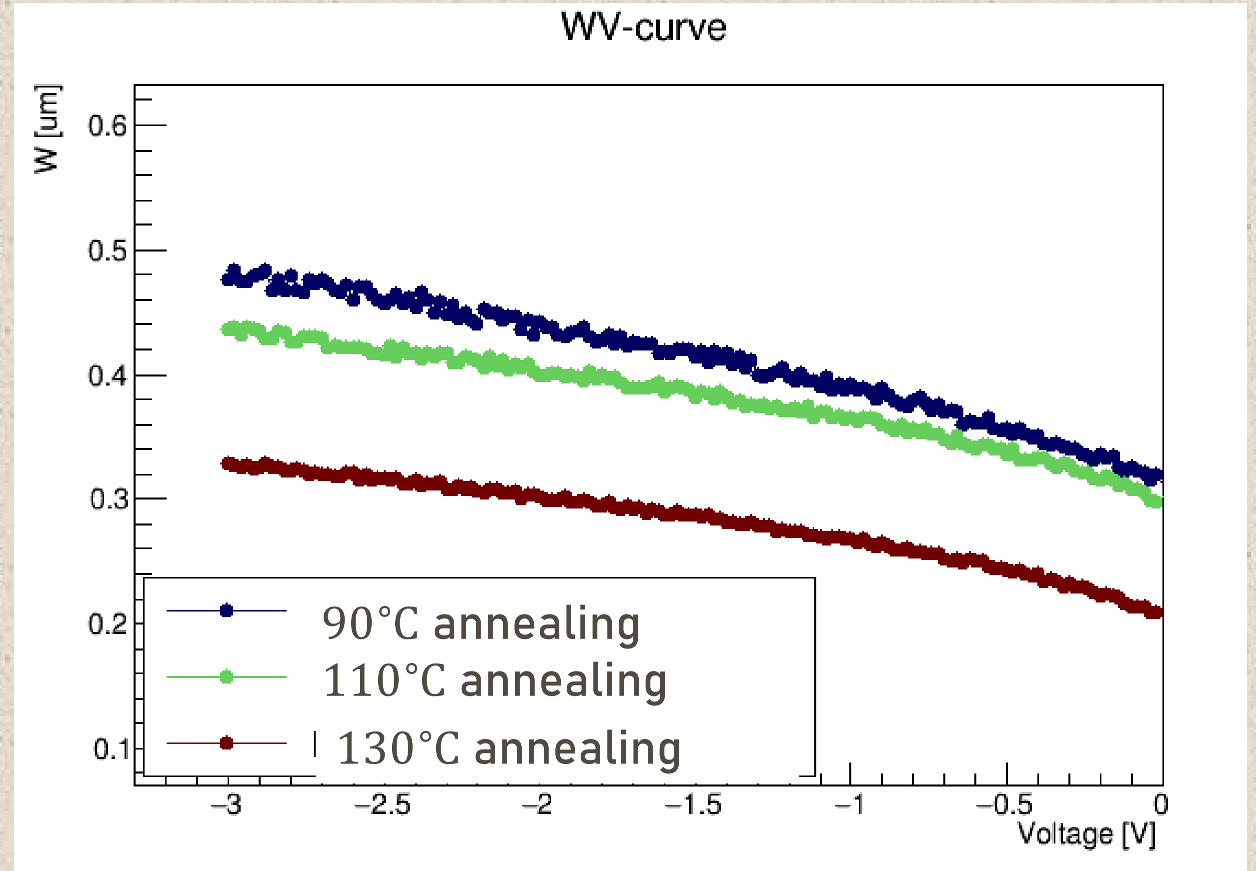
By 130°C thermal annealing for few hours

Recovered collected charge and leakage current → decreasing lattice defects

Not recovered depletion width → Not decreasing Ion (accepter) concentration

Depletion width at each annealing time





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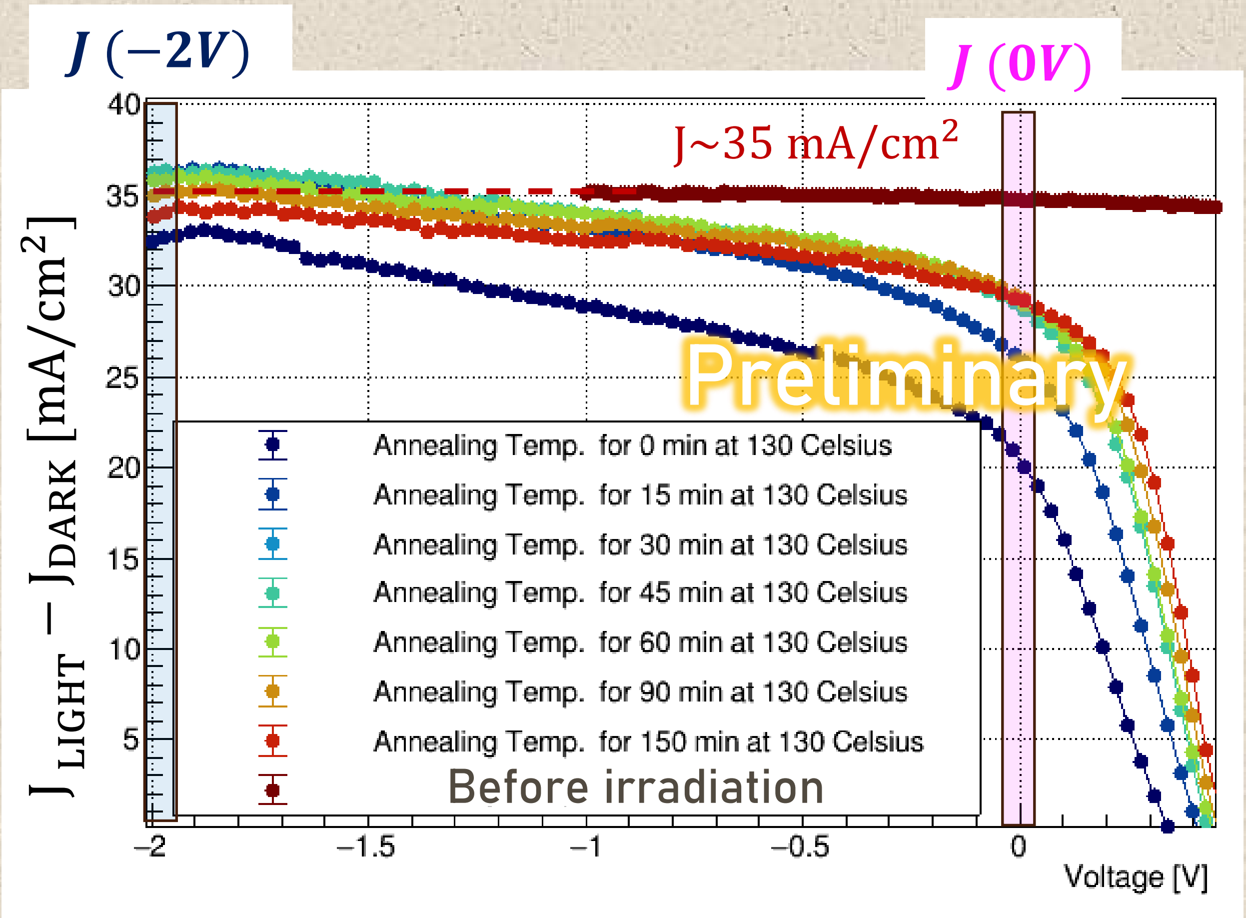

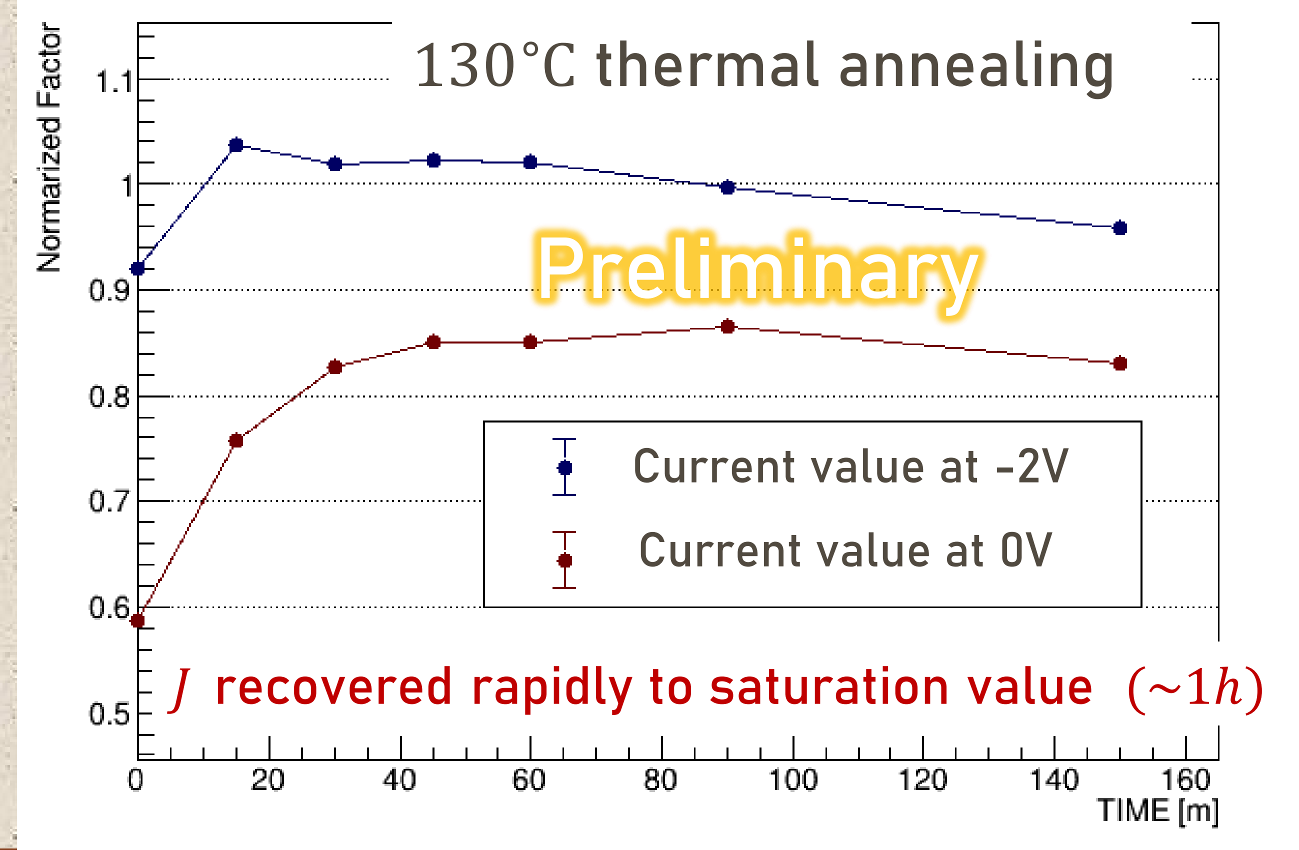

Heating temperature dependence of recovery speed

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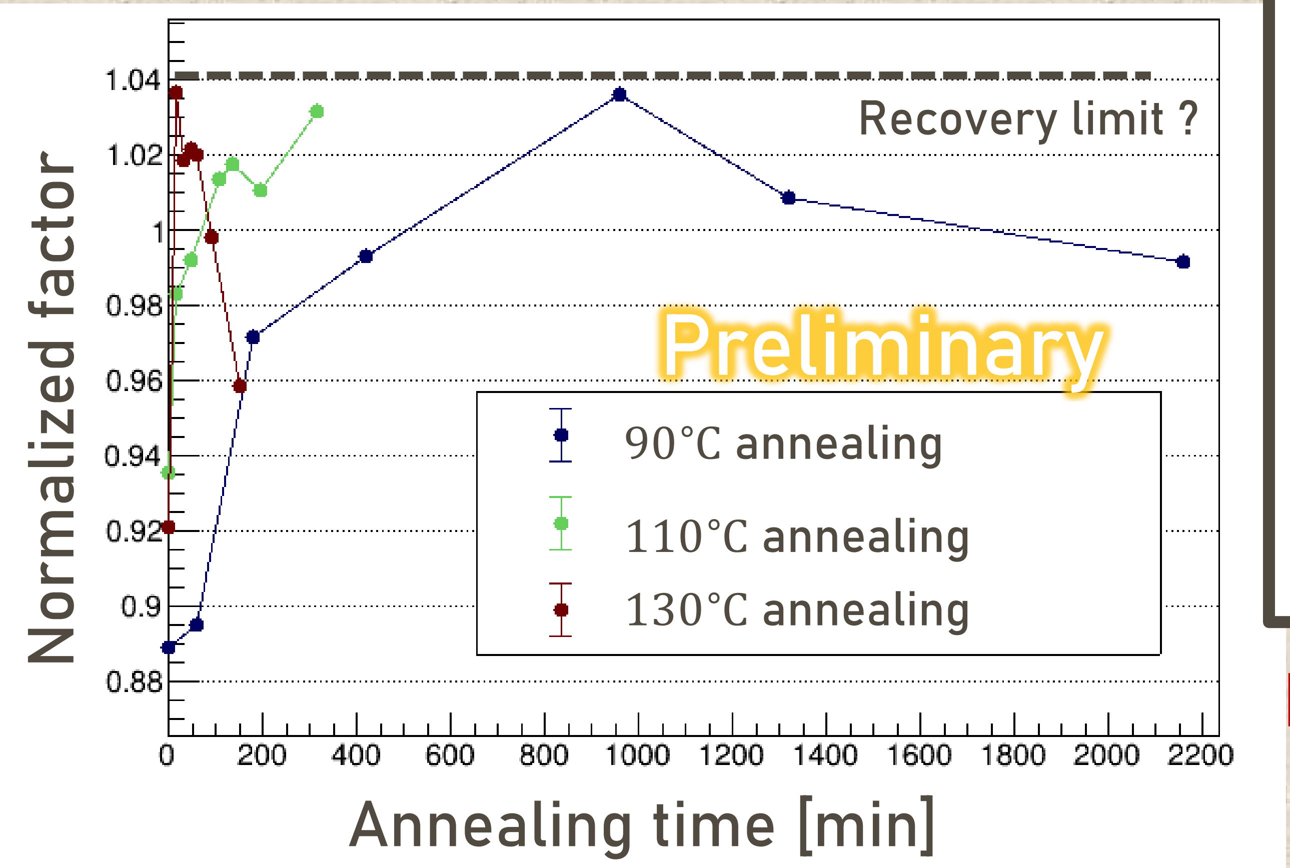


130°C annealing : $J_{2V} = 0.92 \rightarrow 1.04$ (1h)

90°C annealing : $J_{2V} = 0.89 \rightarrow 0.895$ (1h)

Comparable with recovery speed of HIMAC experiment

130°C annealing: $Q = 0.79 \rightarrow 0.94$ (1h)

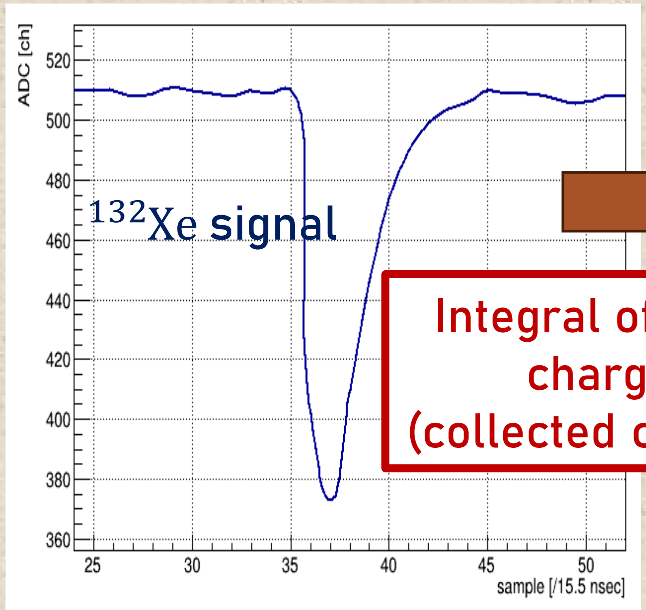
90°C annealing: $Q = 0.79 \rightarrow 0.79$ (1h)

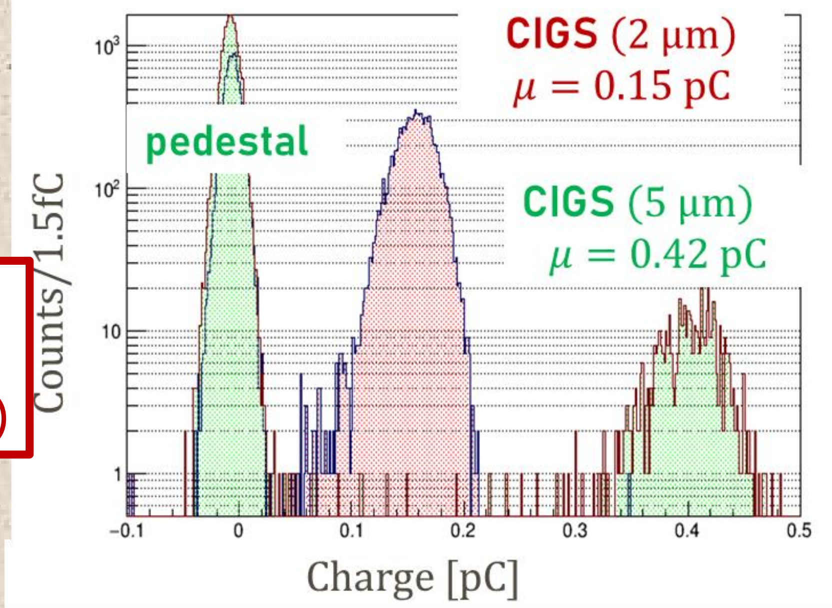
Recovery time is greatly depending on heating temperature

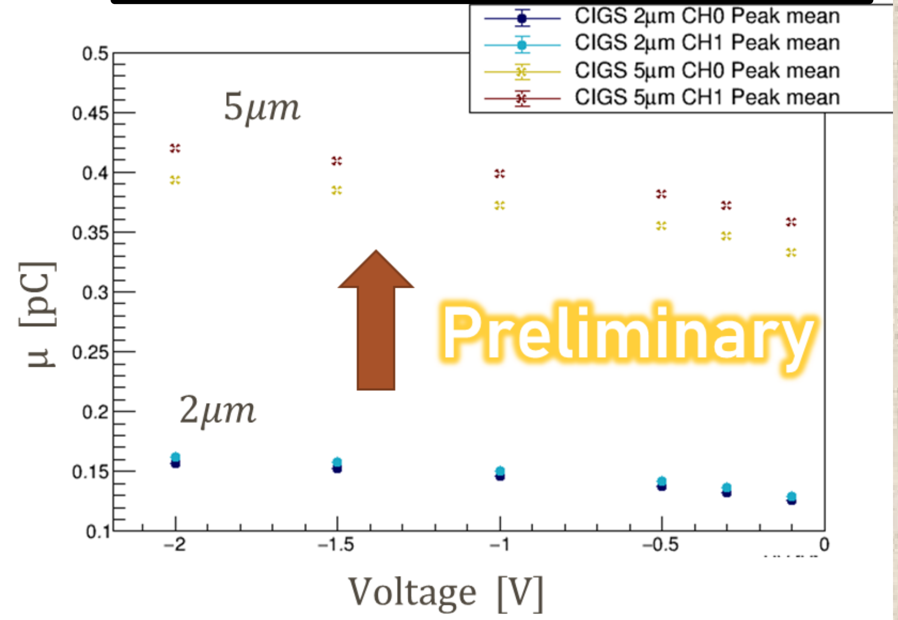
1. Study of Thickness dependence of CIGS (Collected Charge from xenon signal)

Collected charge evaluation: Xe beams (p=400 MeV/u) were irradiated to 2 µm and 5 µm CIGS semiconductor detectors, respectively.

$Q_{5\mu m} \cong 2.5\ Q_{2\mu m}$
(Equivalent to thickness ratio)







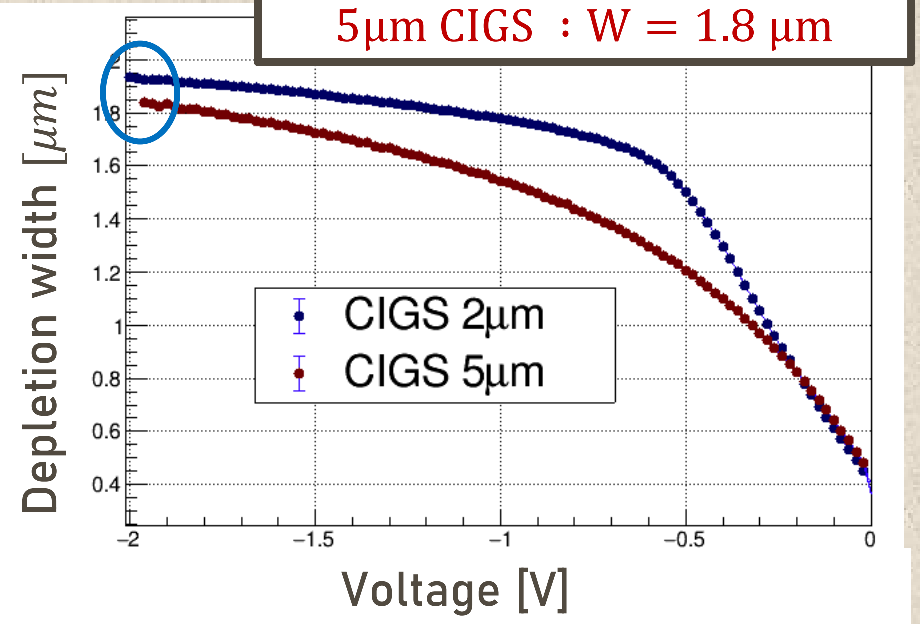
1. Study of Thickness dependence of CIGS (depletion width measuremnt)

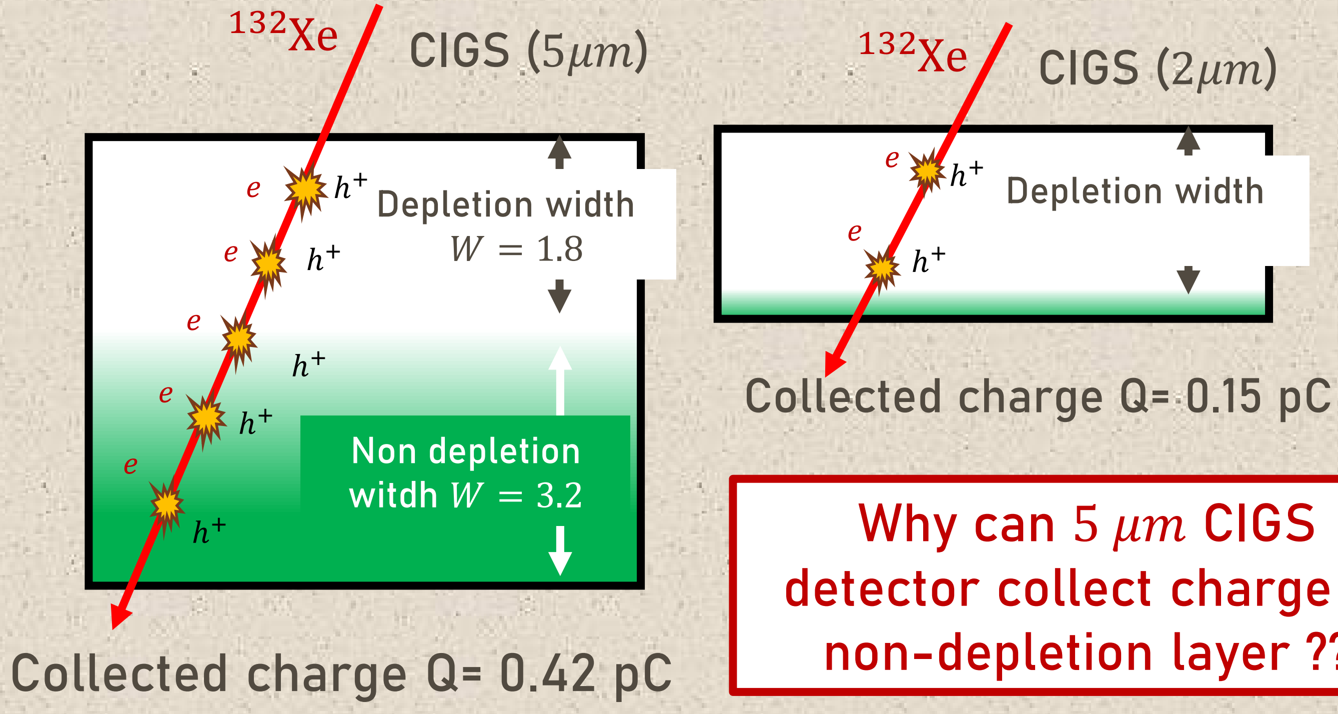
Amount of charge collected is proportional to depletion layer thickness $Q_{det} \propto W$

Depletion width (W) can be obtained by capacitance (C_j) measurement

$$C_j \equiv dQ/dV = dQ/(WdQ/\varepsilon_s) = \varepsilon_s/W \quad [W: \text{depletion width}, \varepsilon_s: \text{permittivity} (= 13.5\varepsilon_0)]$$

2μm CIGS : W = 1.9 μm
5μm CIGS : W = 1.8 μm





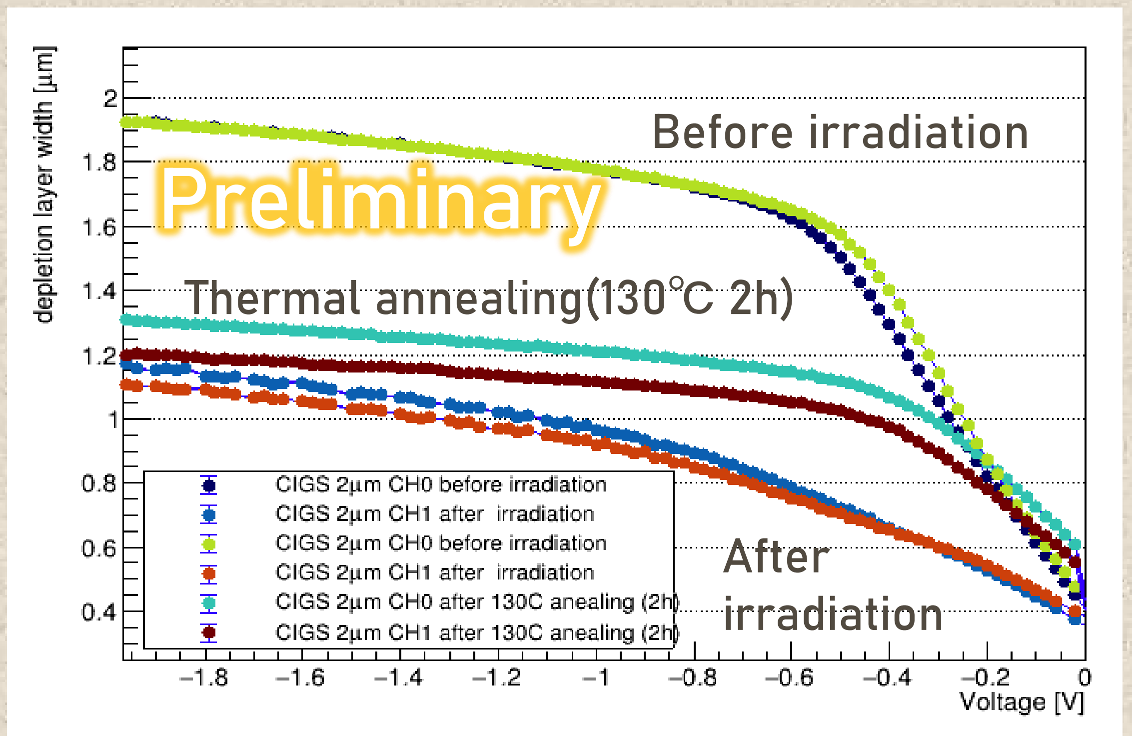
Why can 5 μm CIGS detector collect charge in non-depletion layer ??

Evaluation of depletion layer width after irradiation and thermal annealing

The depletion layer width can be obtained by capacitance measurement

$$C_j \equiv dQ/dV = dQ/(WdQ/\varepsilon_s) = \varepsilon_s/W$$

$$[W\ :\ \text{depletion width},\ \varepsilon_s\text{: permittivity}\ (= 13.5\varepsilon_0)]$$



	CH	Before irradiation	After irradiation (0.8 MGy)	After annealing 130℃, 2h
Depletion width [um] at V=-2V	CH0	1.93 (1)	1.17 (0.61)	1.31 (0.68)
	CH1	1.93 (1)	1.11 (0.57)	1.20(0.62)

After irradiation : comparable with decreasing ratio of collected charge ~ 0.6

After annealing : Not sufficient of recovering