Research Center for Photovoltaics

Cu(In,Ga)Se_2 mini-modules with high-mobility In_2O_3:W,H transparent conducting oxide layers

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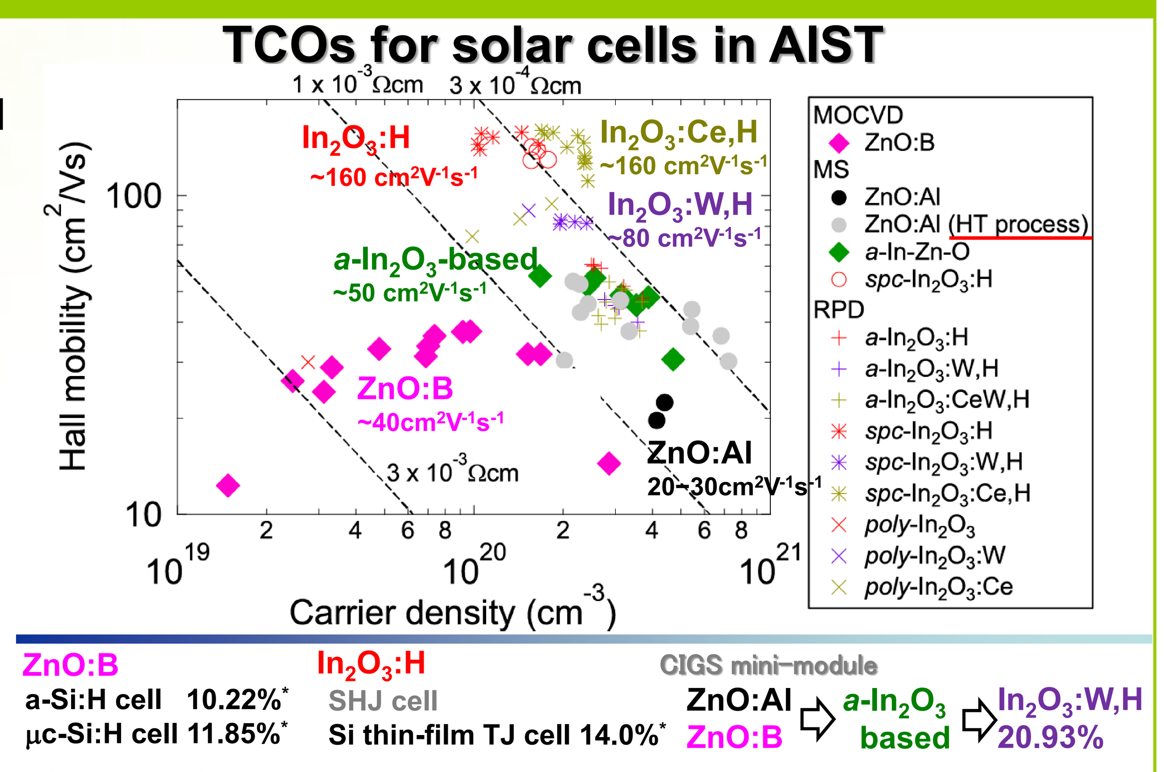
Introduction

High transparency with low R_{sheet} (< 10 Ω/sq) and low T_g (< 200°C) is required for transparent front electrodes in integrated Cu(In,Ga)Se_2 (CIGS) based modules. ZnO-based transparent conductive oxide (TCO) are usually used as the front electrodes. Alternatively, an In_2O_3-based TCO that is normally used in silicon heterojunction solar cells could replace the ZnO-based TCOs because higher conductance and lower free carrier absorption with improved environmental stability can easily be achieved at low deposition temperatures. In this study, we applied In_2O_3:W,H layers to CIGS mini-modules and show the advantage of high-mobility In_2O_3-based TCOs by demonstrating a very high module efficiency (d.a.) of 20.93%. Remaining issues to be solved to achieve higher conversion efficiency will also be discussed.



* Solar cell efficiency table (ver. 52), PIP 26 (2018) 427.

Summary

- High J_{sc} × FF is demonstrated in CIGS mini-modules by high-μ In_2O_3:W,H TCO layer.
  - J_{sc}: 1.5 – 2.0 mA up (vs ZnO/ZnO:Al reference)
  - FF: 0.775
- V_{oc} is independent of the TCO layers, being determined by free-hole density in the CIGS layer.
  - V_{oc}: 0.770 V per subcell
- ZnO/In_2O_3:W,H window layers achieve a high η of 20.93% (d.a.) in a mini-module structure.

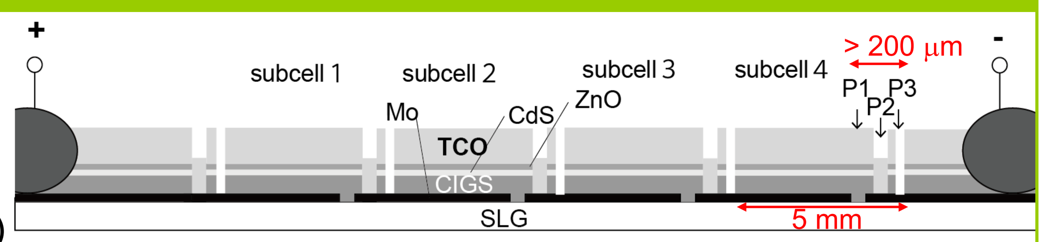
Points to be improved

High resistance TOS layer for the In_2O_3-based TCOs,
Gridded module structure,
Metastable free-hole density, Heat resistive junction

Purpose and Experimental

Purpose

Impact of high-μ In_2O_3-based TCO
Possibility of amorphous TOS as a high resistance layer
(← Large ΔE_c at $Mg_xZn_{1-x}O/In_2O_3$ may affect transport in future…)

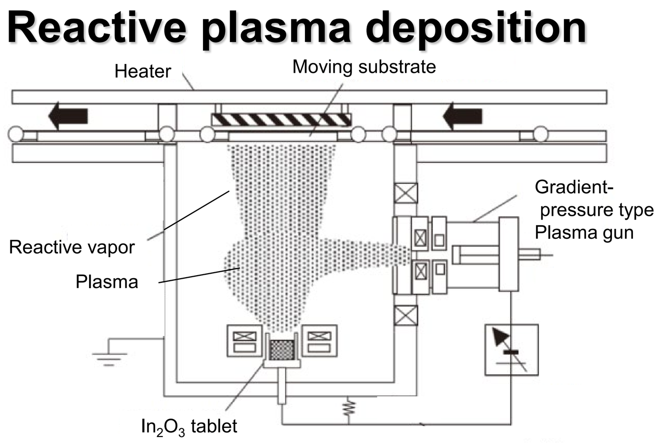


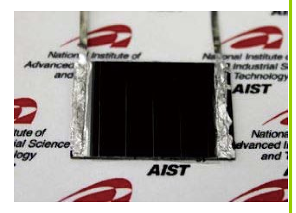
Device structure

ZnO:Al/ZnO/CdS/CIGS/Mo/SLG (reference)
In_2O_3:W,H/ZnO/CdS/CIGS/Mo/SLG
In_2O_3:W,H/a-In-Ga-Zn-O/CdS/CIGS/Mo/SLG

CIGS (2 μm): co-evapo. GGI ratio : ~ 0.4
KF- and NaF- PDT
CdS (30 nm): CBD
i-ZnO, a-In-Ga-Zn-O (50 nm): MS
AZO (720 nm), IWOH (560 nm): MS, RPD
MgF_2 (110 nm): evapo.
Size :subcell (5 mm × 20 mm) × 4

Reactive plasma deposition





Growth rate: ~100 nm min^{-1}

Low particle energies: RPD (< 40 eV) *

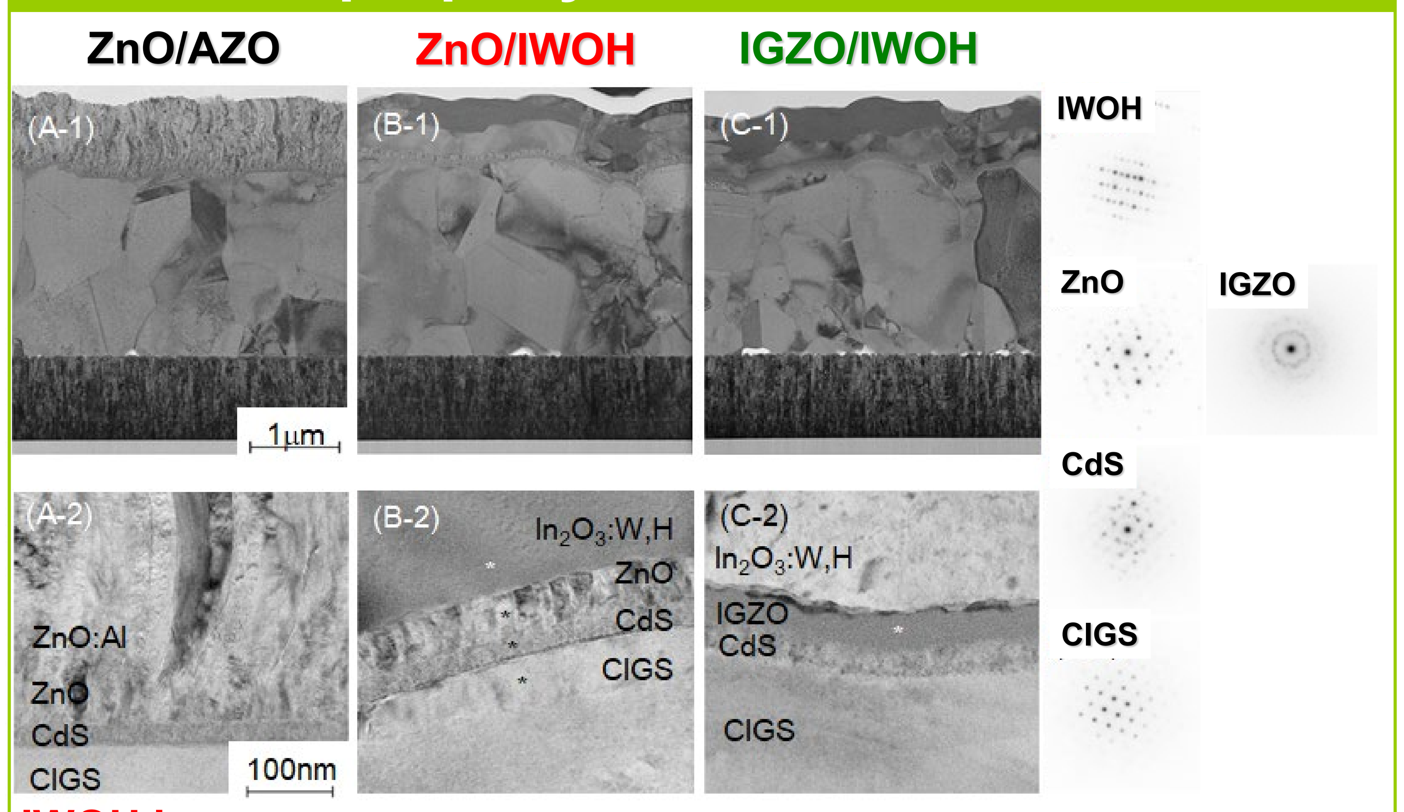
* H. Kitami et al., JJAP 54 (2015) 01AB05.

Process after device fabrication

Dark Heating (150°C, 30 min)
→Relaxed state
Heat Light Soaking (90°C, ~0.5sun, 100 h)
→Metastable state

material	Thickness (nm)	R_{sheet} (Ω sq^{-1})	ρ (Ω cm)	N (cm^{-3})	μ (cm^2 V^{-1} s^{-1})
ZnO:Al	720	8.0	5.8 × 10^{-4}	4.5 × 10^{20}	24
In_2O_3:W,H	560	5.8	3.3 × 10^{-4}	2.6 × 10^{20}	74

Structural property

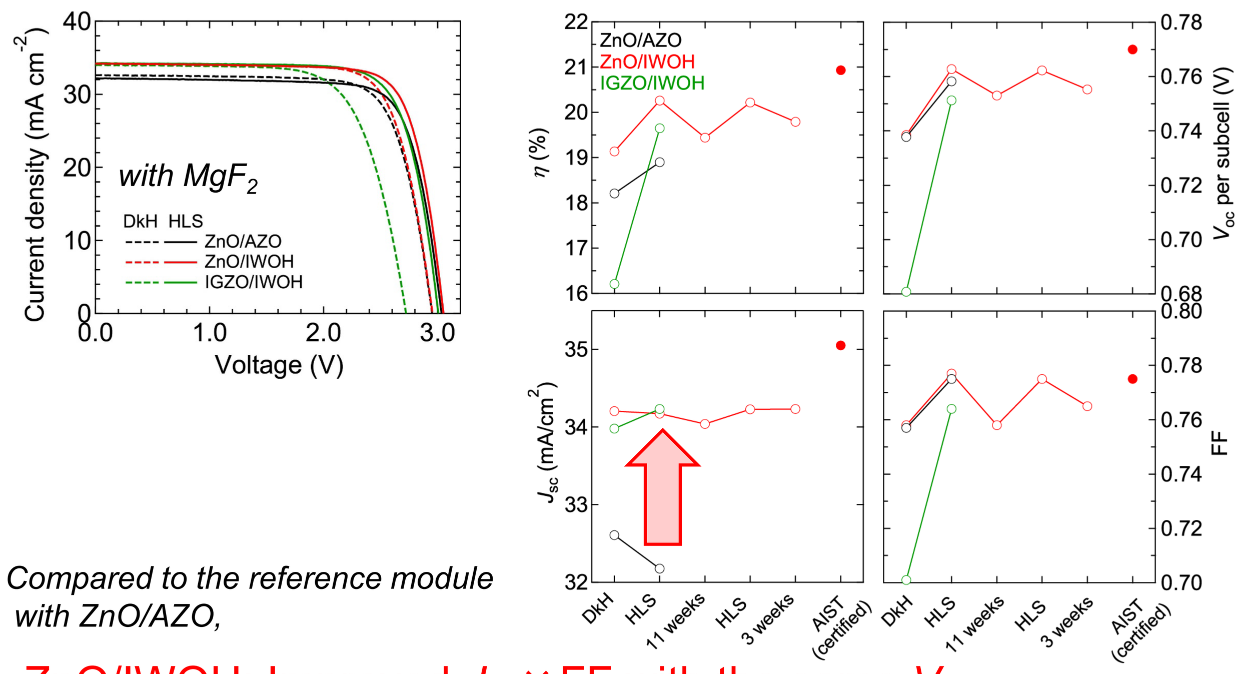


IWOH layer:

RPD without substrate heating and post-annealing at 150°C.
Solid-phase crystallization (amorphous → polycrystalline)
Micrometer-size lateral grains evenly covered the underlying layer.

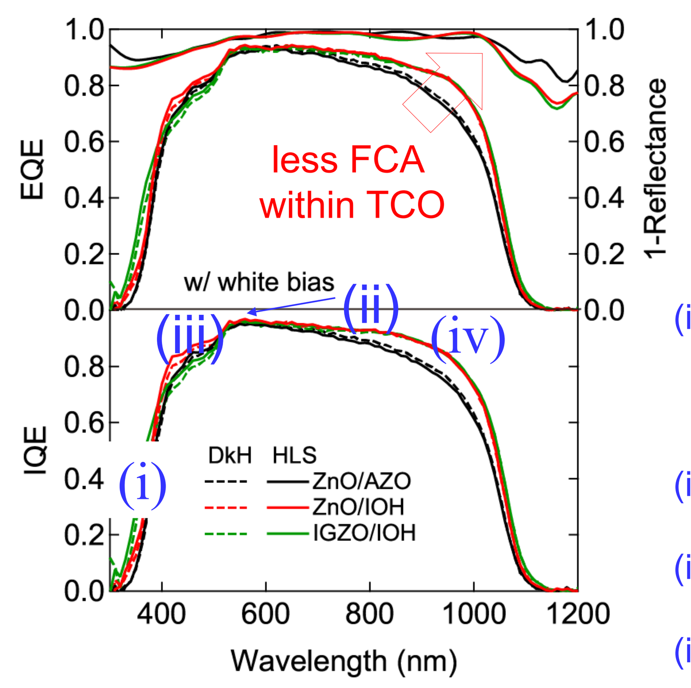
J–*V*, EQE characteristics (effects of window layers, metastable characteristics)

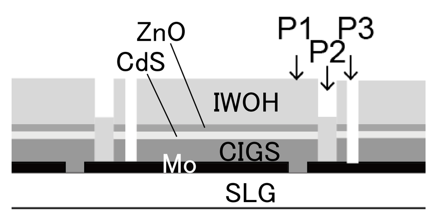
Characteristics in relaxed and metastable states



Compared to the reference module with ZnO/AZO,

ZnO/IWOH: Improved J_{sc} × FF with the same V_{oc}
IGZO/IWOH: Poor V_{oc} in the relaxed state (←recombination through midgap states in a-IGZO?)

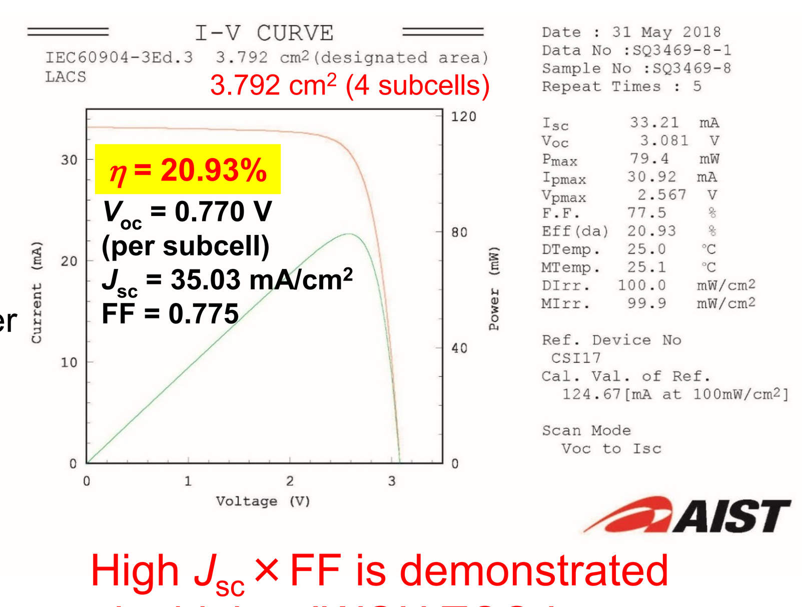




Points to be improved

(i) Abs. loss within ZnO layer
→Widegap TOS (conventional module)
→Gridded module without the ZnO layer (with smooth CIGS)
(ii) Dead area caused by scribing: > 4% (> 200 μm)
(iii) Abs. loss within 30-nm-thick CdS
→New widegap buffer layer
(iv) CIGS sensitivity at longer wavelengths
→Optimization of Ga/(Ga+In) profile

Certified *I*–*V* curve for the mini-module with ZnO/IWOH

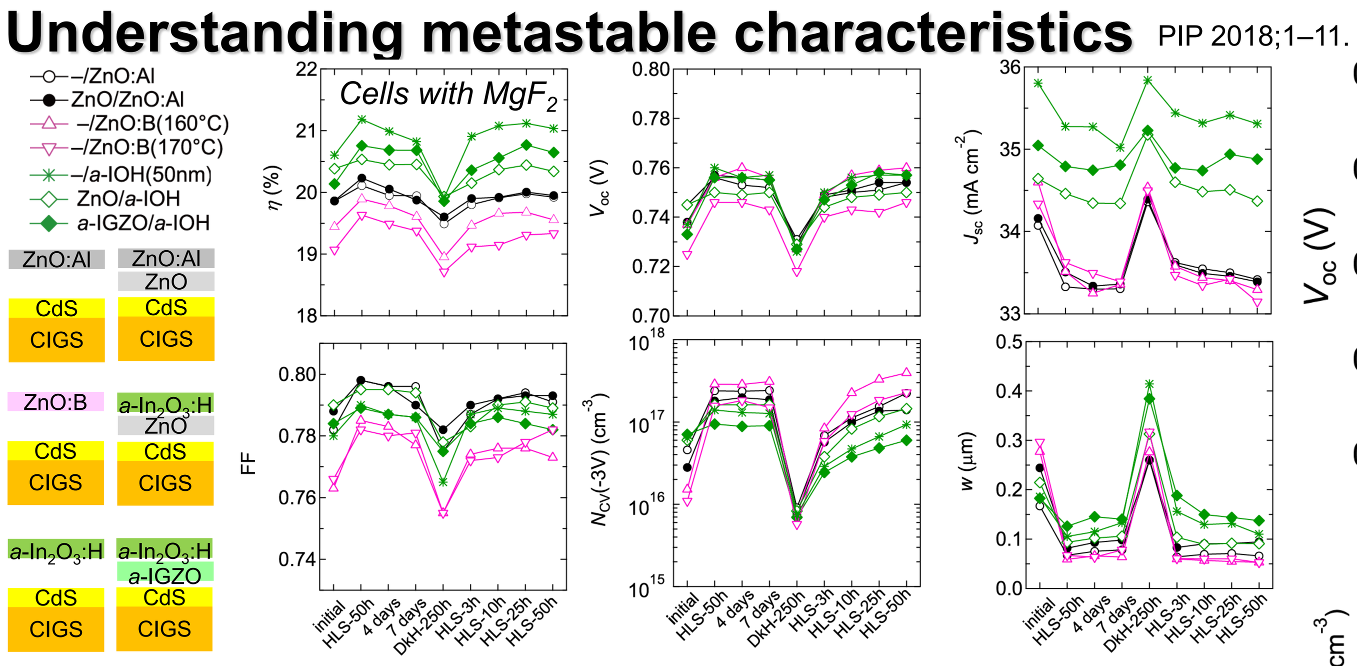


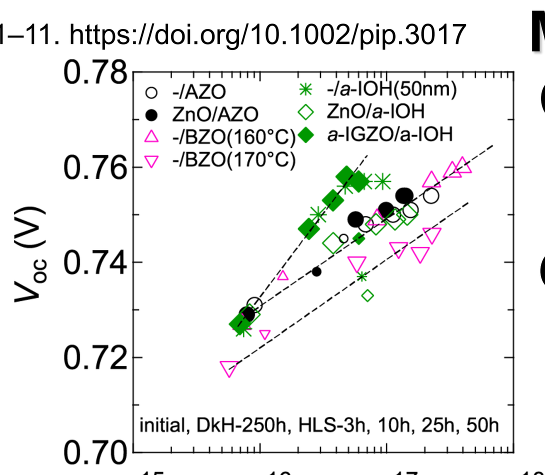
High J_{sc} × FF is demonstrated by high-μ IWOH TCO layer

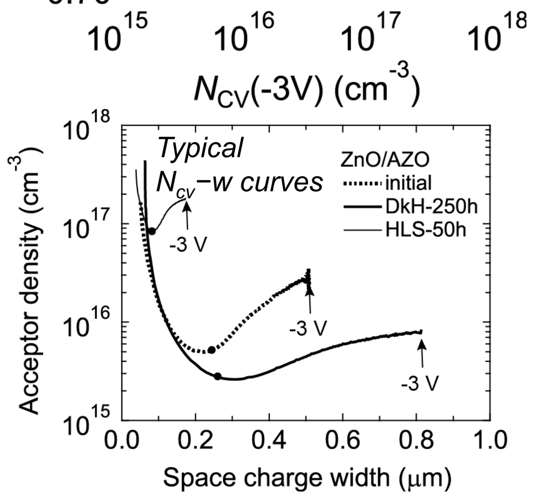
For further improvement…

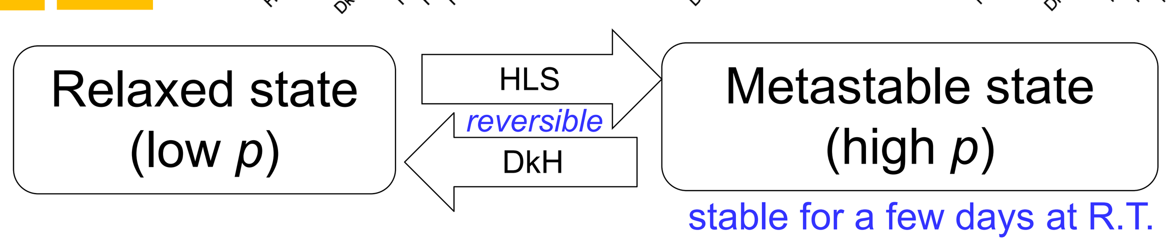
Understanding metastable characteristics

PIP 2018;1–11. https://doi.org/10.1002/pip.3017









Model 1: An amphoteric character of a defect complex (V_{Se}–V_{Cu})*
Model 2: Reversible long-range migration of ions, i.e., Cu and alkali metals (balance between drift and diffusion)

*S. Lany and A. Zunger, JAP 100 (2006) 113725.

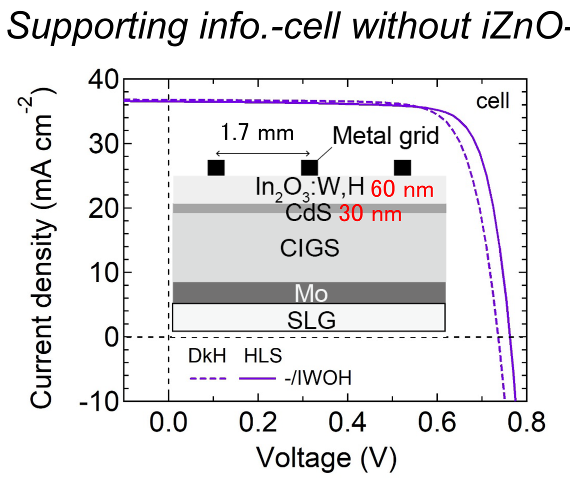
Module structure

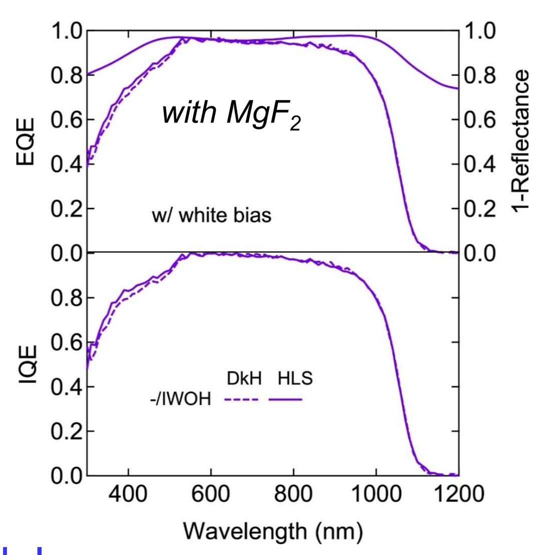
Conventional: In_2O_3(thick)/TOS(widegap)/CdS/CIGS/Mo/SLG

Task: A barrier caused by ΔE_c formed at TOS/TCO may affect the transport.
i.e., $Mg_xZn_{1-x}O$ or a-$In_xGa_{1-x}O/In_2O_3$-based TCO

Gridded: Grid metal/In_2O_3(thin)/CdS/CIGS/Mo/SLG

Supporting info.-cell without iZnO-





High spectral sensitivity
Enough high R_{sh}
(←smooth CIGS layer)
Enough low R_{ser}
(←smooth CIGS)
(←high-μ TCO even in the thin layers)
Low R_c at IWOH/Ag paste reported in SHJ cells*

*E. Kobayashi (Chosyu)
27th EU-PVSEC, 1619 (2012)
28th EU-PVSEC, 691 (2013)

Task: Roughness in modules
Heat (~180°C) resistive junction to apply higher-μ TCO (~160 $cm^2V^{-1}s^{-1}$)
(→ Lower R_{ser} with wider grid distances)