High-efficiency CIGS photovoltaics

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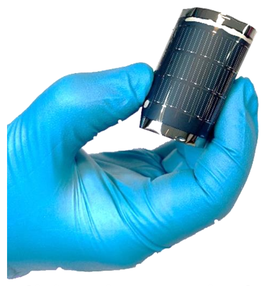
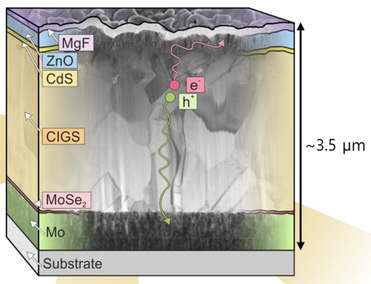
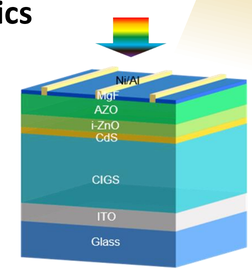
CIGS photovoltaics at a glance

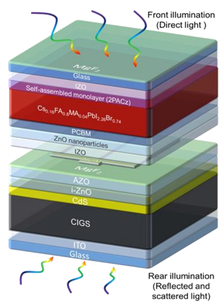


Flexible photovoltaics





Bifacial Solar Cells

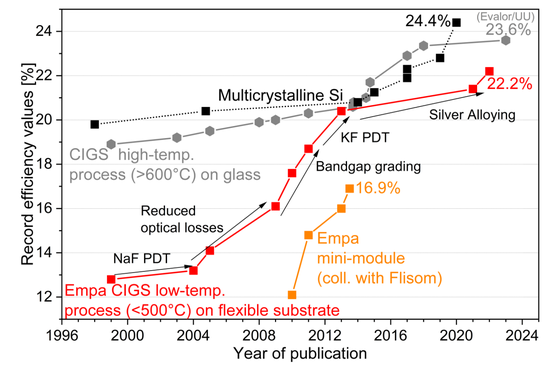


Tandem devices

$Cu(In,Ga)Se_2$ (CIGS) photovoltaics

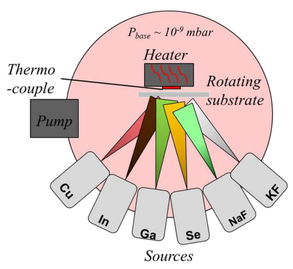
- Thin film multi-crystalline layers
- Stable, efficient
  - State-of-the-art: same V_{OC} deficit as c-Si
- Flexible, lightweight, uniform appearance
- Low carbon footprint

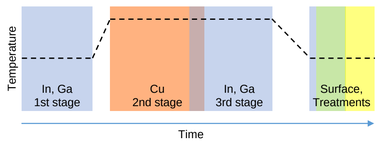
Progresses of Empa in global context



Single-junction devices

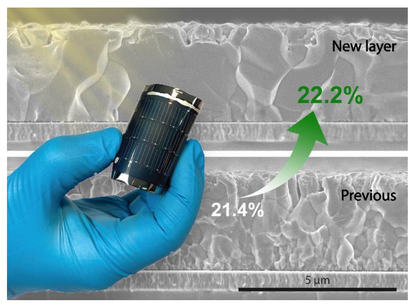
CIGS 3-stage deposition



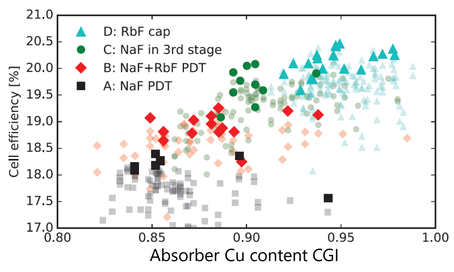


Record flexible CIGS cells
22.2% flexible solar cell (2022)
Previous marks: 20.8% (2019), 21.4% (2021)
(externally certified values)

High performance flexible solar cells



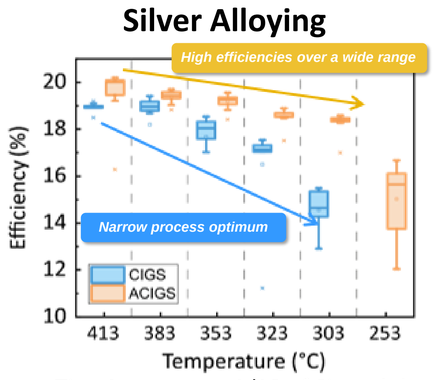
Absorber treatments with alkali



[Carron, Adv. Energy Mat., 2019, 10.1002/aenm.201900408]

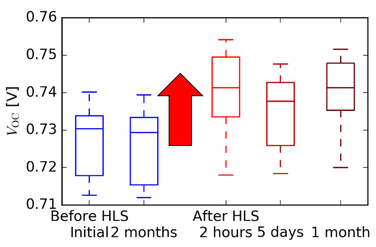
- Light and heavy alkali (e.g. Na, K, Rb)
- Co- and post-deposition
- Improved voltage
- Surface tailoring, higher J_{SC}, reduced shunting

Silver Alloying



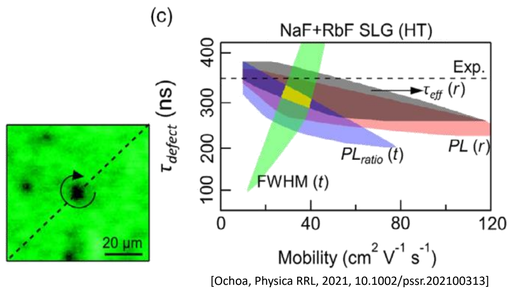
- Tiny Ag amount: 1/10 of Si modules
- Improved morphology, PV performance
- Enhanced tolerance vs low process T

Solar cell treatments



Heat and light soaking
- Manipulation of carrier density
- Stable, long-term improvements

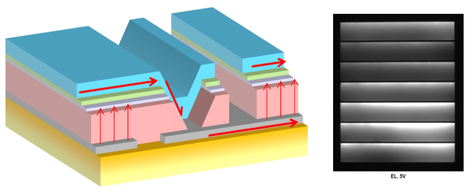
Advanced characterization & modelling

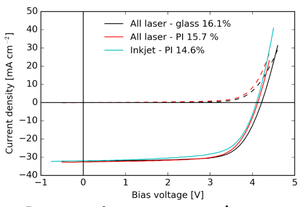


[Ochoa, Physica RRL, 2021, 10.1002/pssr.202100313]

- Quantitative analysis of charge transport near extended defective regions

Minimodules, industrialisation



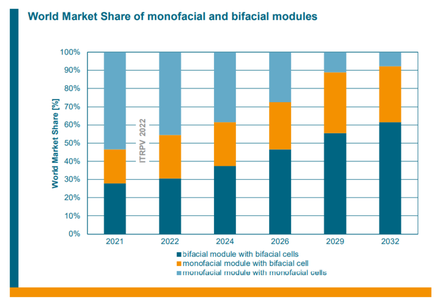


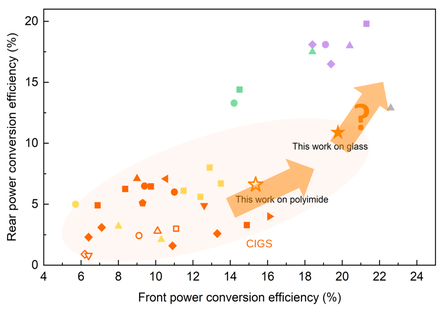
- Minimodules, proof-of-concept
- Validation of transferrability
- Manufacturability: processes simplified and more robust

Patterning approaches
- All-laser
- Mechanical scribing
- Inkjet approaches

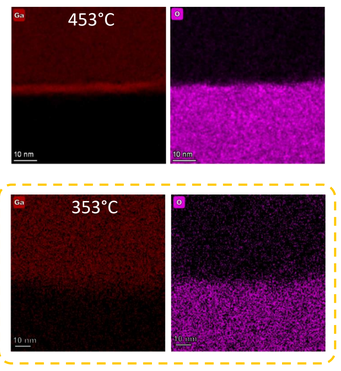
CZTSSe: Earth abundant thin-film alternative [Moser, ACS Appl. Energy Mater., 2023, 10.1021/acsaem.3c02483]

Bifacial solar cells

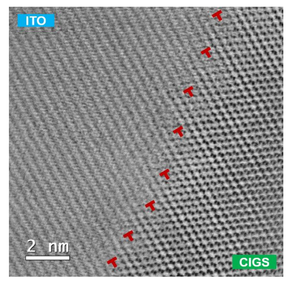




Silver-enabled low-temperature process
- Sharp interface, no GaOx formation (FF)



[Yang, Nat Energy, 2022, 10.1038/s41560-022-01157-9]

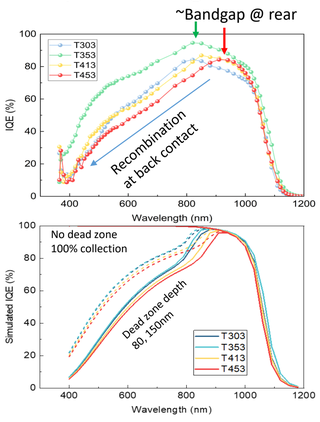


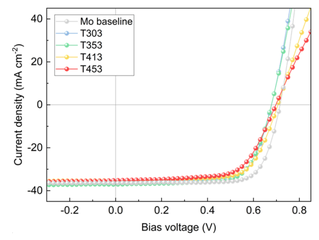
Misfit dislocations at CIGS/ITO interface

Record bifacial CIGS solar cell
23.0 mW/cm² $BiFi_{300}$ (30% albedo)

Illumination	V_{OC} (mV)	J_{SC} (mA cm^{-2})	FF (%)	PCE (%)
Front	707.85	37.13	75.23	19.77
Rear	697.67	20.41	76.46	10.89

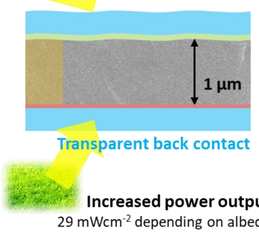
Bandgap engineering
- Steep gradient
- Improved charge collection, EQE and J_{SC}





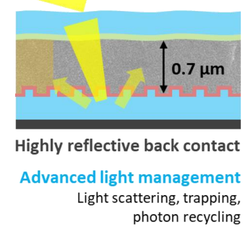
Next frontier for CIGS: Overcome rear interface recombination

(a) Bifacial architecture
Efficiency >25%



Increased power output
29 mWcm^{-2} depending on albedo

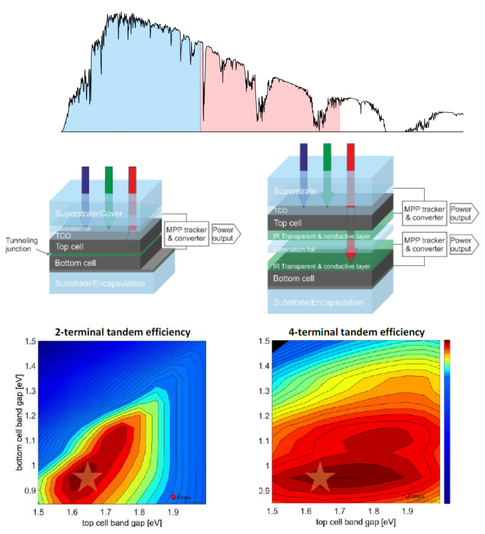
(b) Highly reflective
Efficiency >25%



Advanced light management
Light scattering, trapping, photon recycling

CIGS for tandem solar cells

Tandem configurations



Overcoming Shockley-Queisser limit of single junctions

[Kothandaraman, Small Methods, 2023, 10.1002/smtd.202000395]

Efficiency		Top cell	Bottom cell
30.2 mW/cm²	4T	Empa	Bifacial CIGS
29.0%	4T	National University Singapore 10.1002/solr.202300339	CIS

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NUS National University of Singapore

As bottom cell: low bandgap or bifacial CI(G)S [Krause, Solar RRL, 2023, 10.1002/solr.202201122]
- Ideal low bandgap, high current
- Allow reduced top cell bandgap (better performance and long-term stability)

As top cell: high bandgap CIGS

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Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

PERCISTAND

CUSTOM-ART
Disruptive kesterite-based

HiBITS

SITA Stable Inorganic TAndem solar cells