Willkommen
Welcome
Bienvenue

Empa
Materials Science and Technology

Technologies photovoltaiques émergentes pour production d'électricité

Dr. Romain Carron

Empa – Swiss Federal Laboratories for Materials Science and Technology
Überlandstrasse 129, CH-8600 Dübendorf, Switzerland

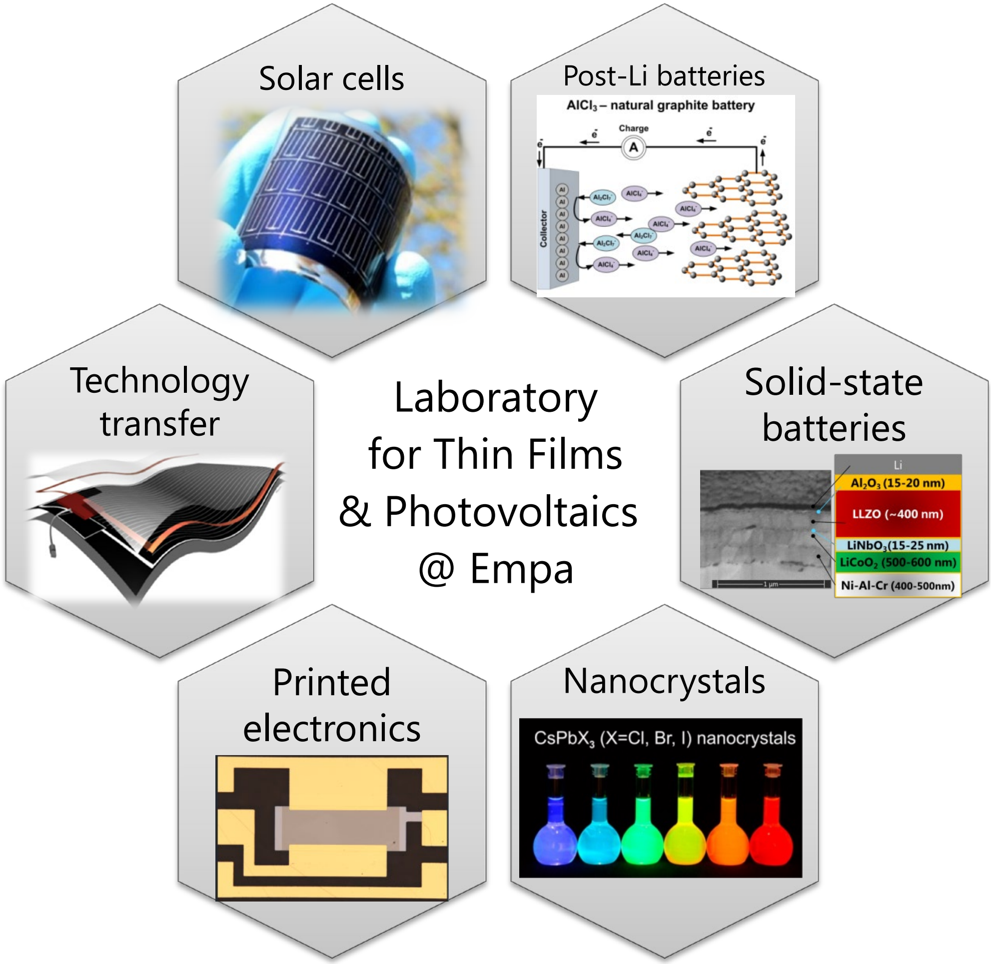
Forum Photovoltaïque
HEIG-VD, site de Cheseaux, 04.11.2021

Empa - Laboratory for Thin Films and Photovoltaics

Next generation thin film solar cells
for affordable, energy-sustainable future

- Perovskite
- Flexible $Cu(In,Ga)Se_2$ (CIGS)
- Combination: tandem applications

Focus @ Empa: flexible substrates



Perovskite: hybrid vapor-solution method

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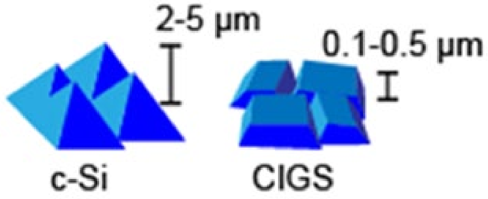
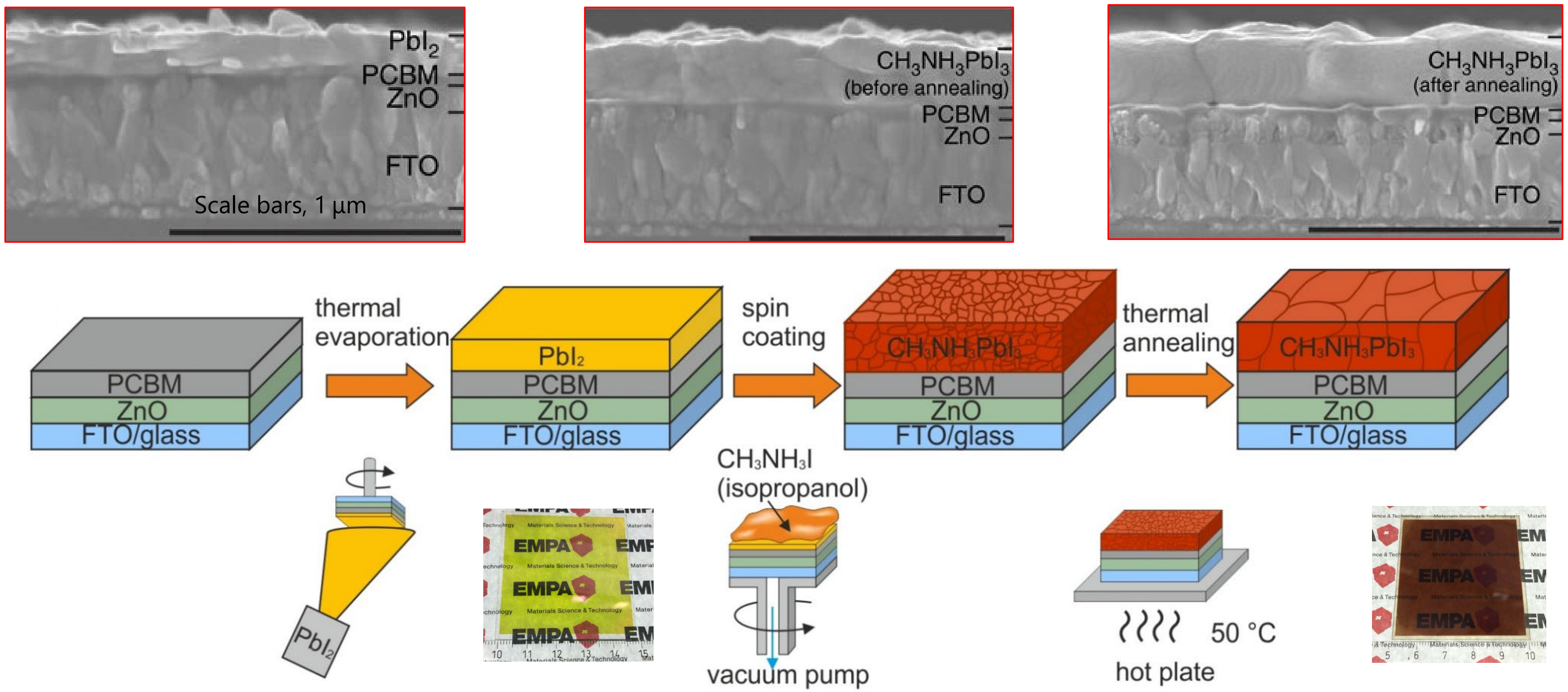
- ❑ Challenge: conformal coating on rough surface
- ➢ Developed a hybrid vapor-solution process





F. Fu et al., *Nature Communication* 6, 8932 (2015)

Perovskite scale-up (hybrid approach)

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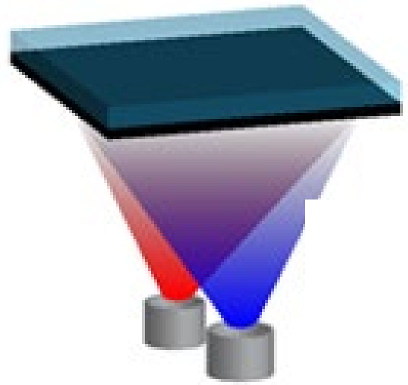
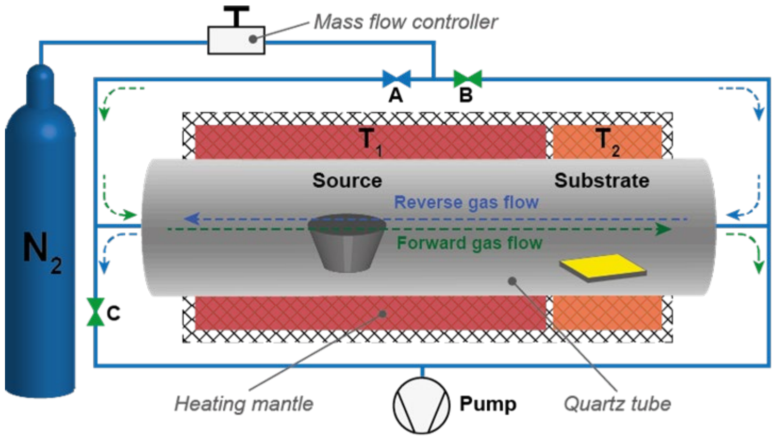
- Avoid spin-coating
  in view of large-area deposition

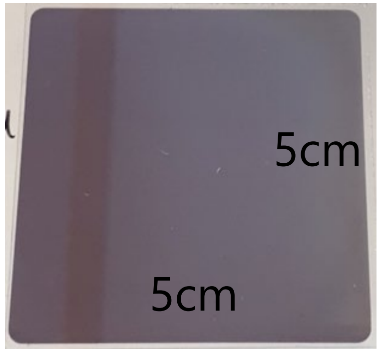


Step 1 (PVD): template

vapor



Step 2 (CVD):
Exposure to FAI vapor

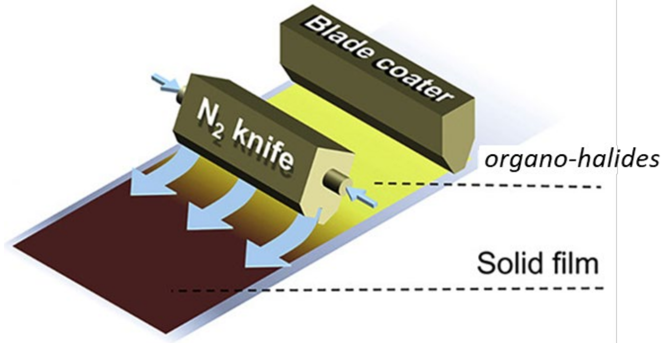


PVD-CVD perovskite

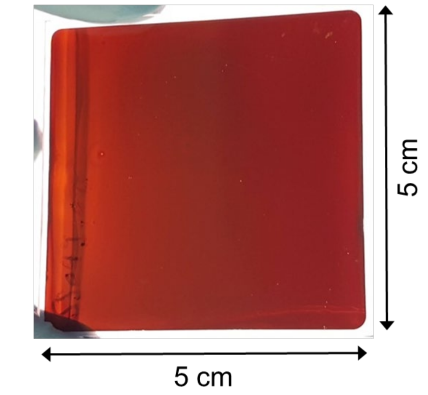
J. Mater. Chem. A, 2020, 8, 21973-21982

J. Mater. Chem. A, 2021, DOI: 10.1039/D1TA07579A

solution

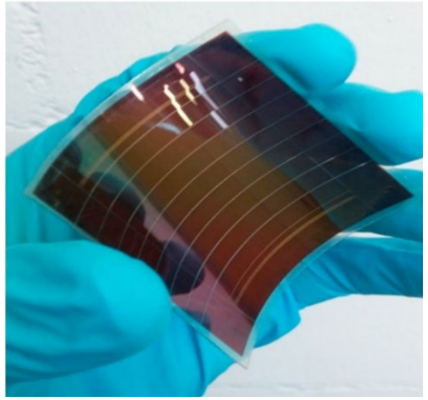


Step 2 (blading/printing):
Organic halide solution
without toxic solvent

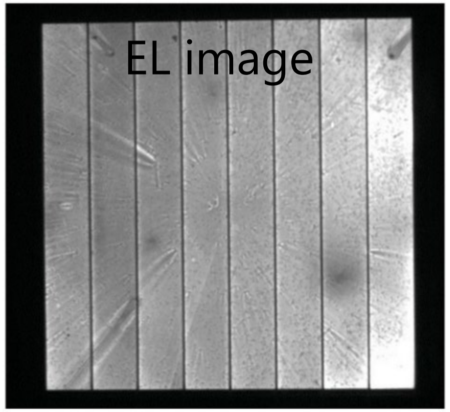


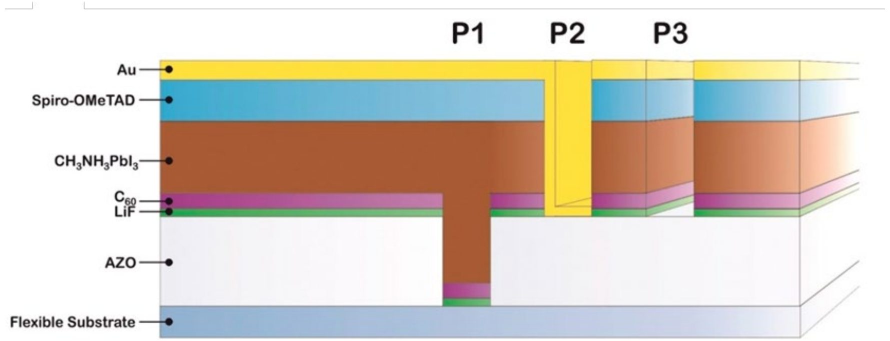
PVD-Blade coated
triple-cation perovskite

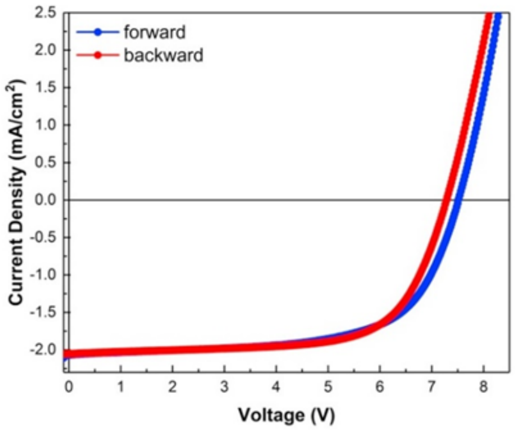
Perovskite: all-laser scribed flexible mini-module

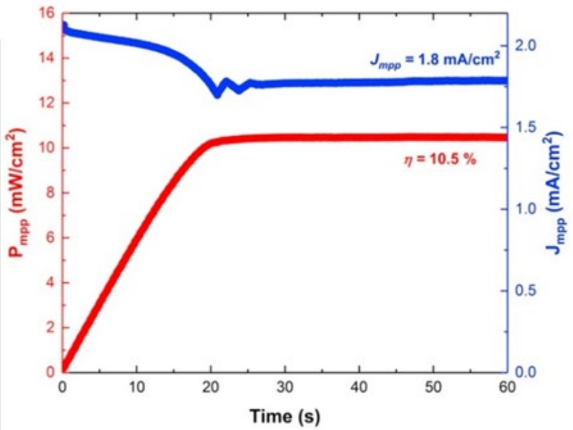


In collaboration with Flisom









First proof-of-concept:
<u>All-laser scribed f</u>lexible perovskite mini-modules
Efficiency: 10.5%
Aperture Area = 10.2 cm^2
GFF = ~94%

S. Pisoni et al., Nano Energy 2018, 49, 300-307

Lead-free perovskite: >10% flexible Sn-based cells

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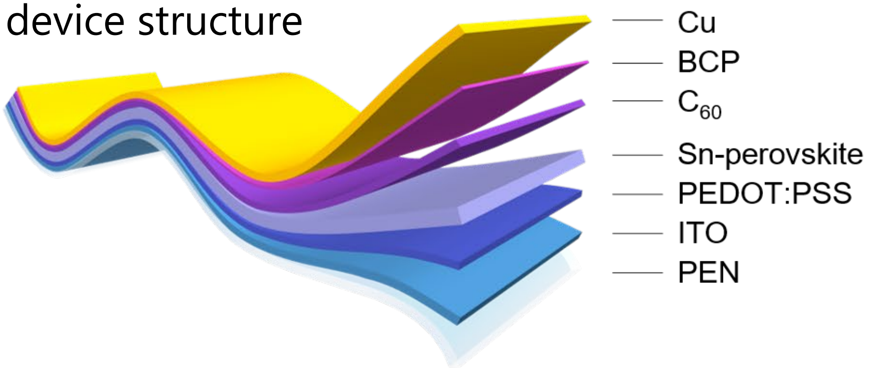
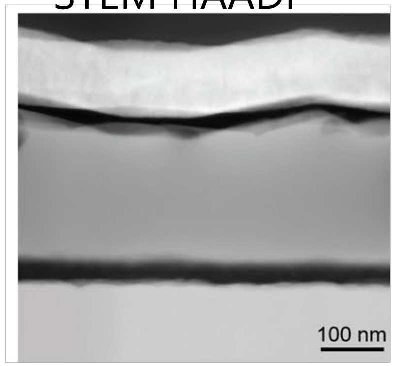
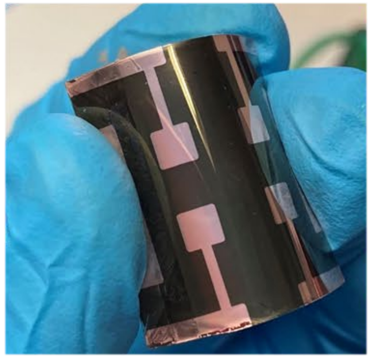
device structure

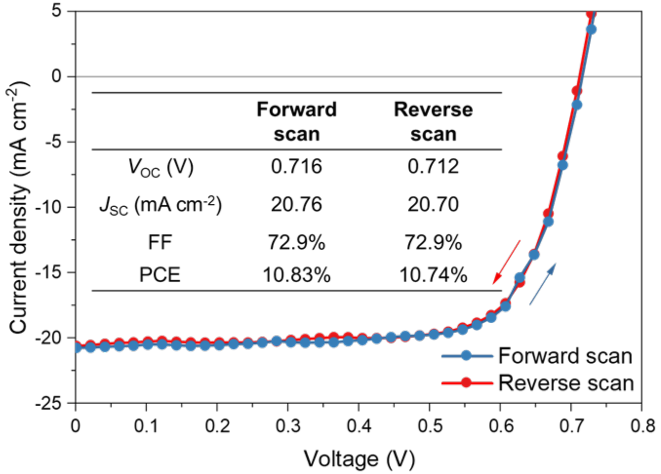


STEM HAADF



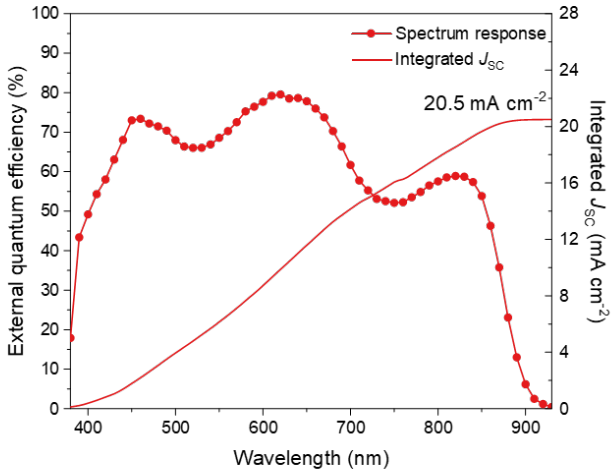


J-V performance

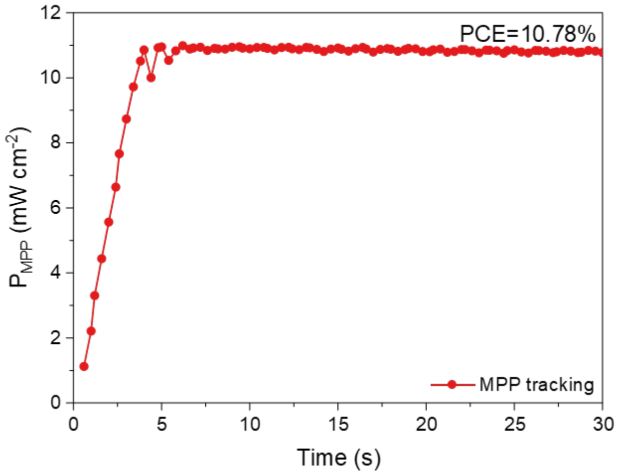


	Forward scan	Reverse scan
V_{OC} (V)	0.716	0.712
J_{SC} (mA cm^{-2})	20.76	20.70
FF	72.9%	72.9%
PCE	10.83%	10.74%

EQE and integrated J_{SC}

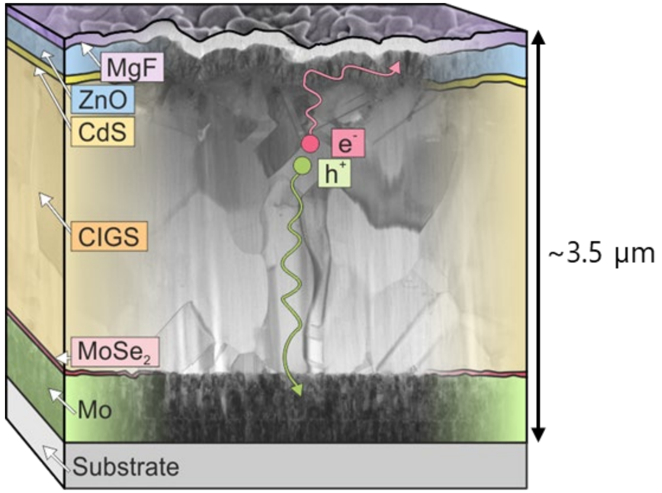


MPP tracking



- A champion PCE >10% on flexible substrate

Single junction $Cu(In,Ga)Se_2$ CIGS solar cells



- **Empa**: low-temperature process **on flexible polymer**
- Co-evaporation for roll-to-roll manufacturing

- Thin film multicrystalline solar cells
- Stable, efficient
  - State-of-the-art: same V_{OC} deficit as c-Si
- Uniform appearance
- Flexible, lightweight
- Low carbon footprint

Spin-off: Flisom AG

CIGS on polymer

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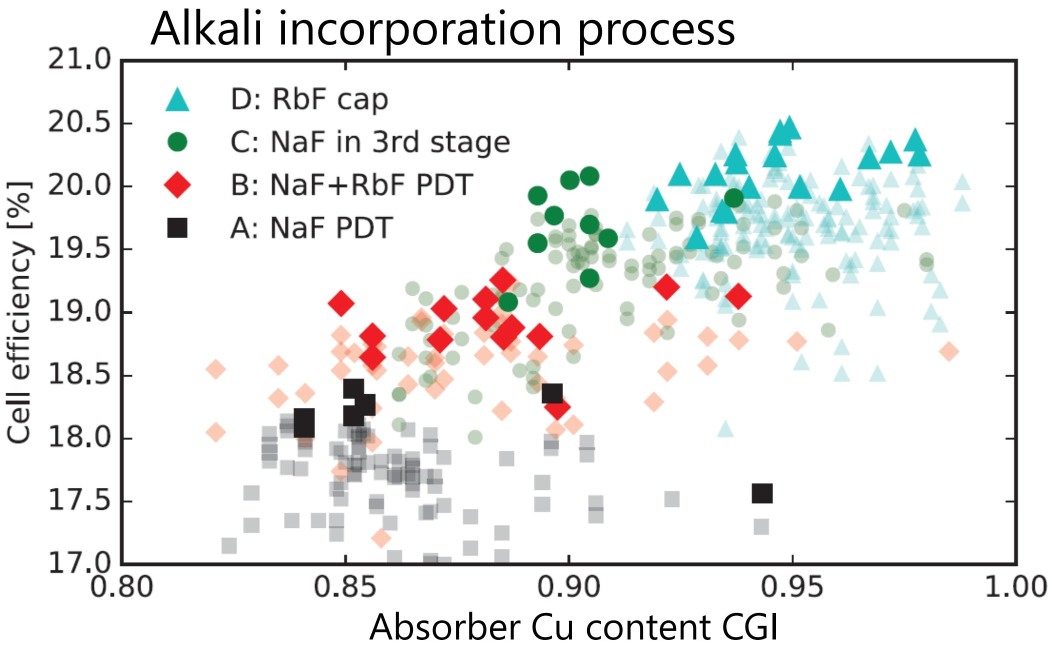
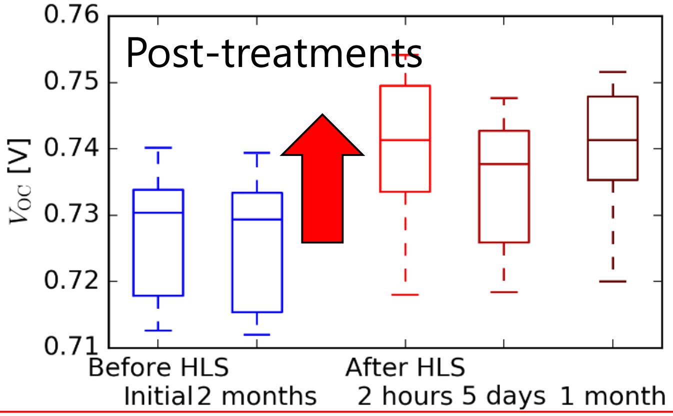
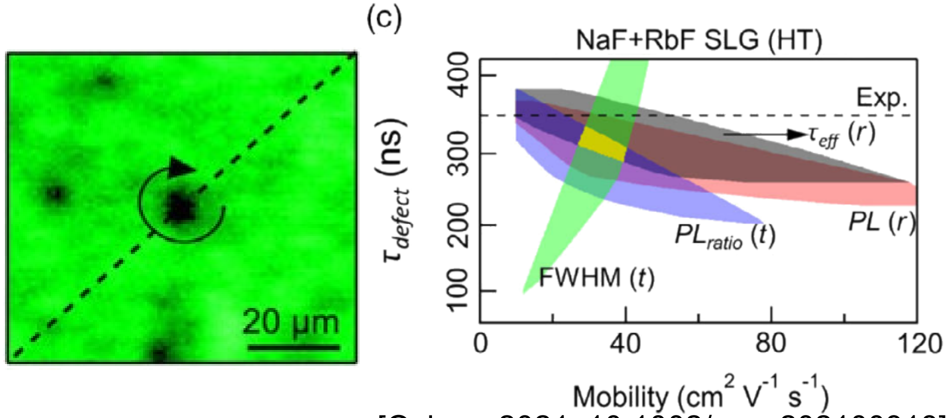
- 21.4% efficiency on flexible polymer substrate
  [EUPVSEC 2021]

- Selected investigation topics
  - Absorber composition (gradient, alloying)
  - Doping with alkali elements
  - Interface tailoring
  - Post-treatments
  - Contact layers
  - Alternative device architectures



[Carron et al, Adv. Energy Mat. 1900408 2019]

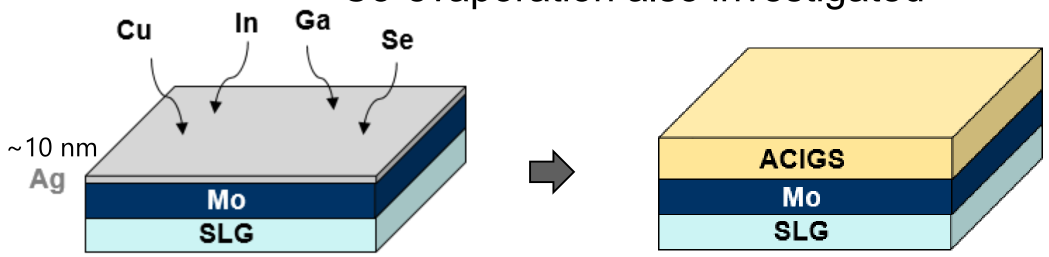




[Ochoa, 2021, 10.1002/pssr.202100313]

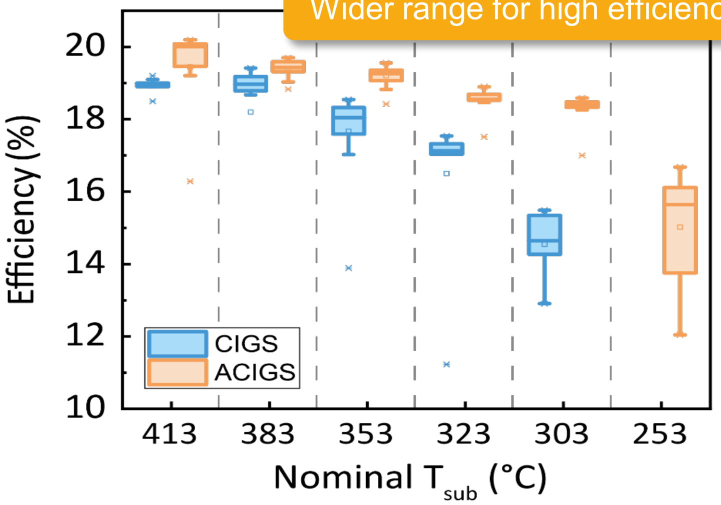
CIGS - Absorber alloying

Ag precursor layer method
Co-evaporation also investigated

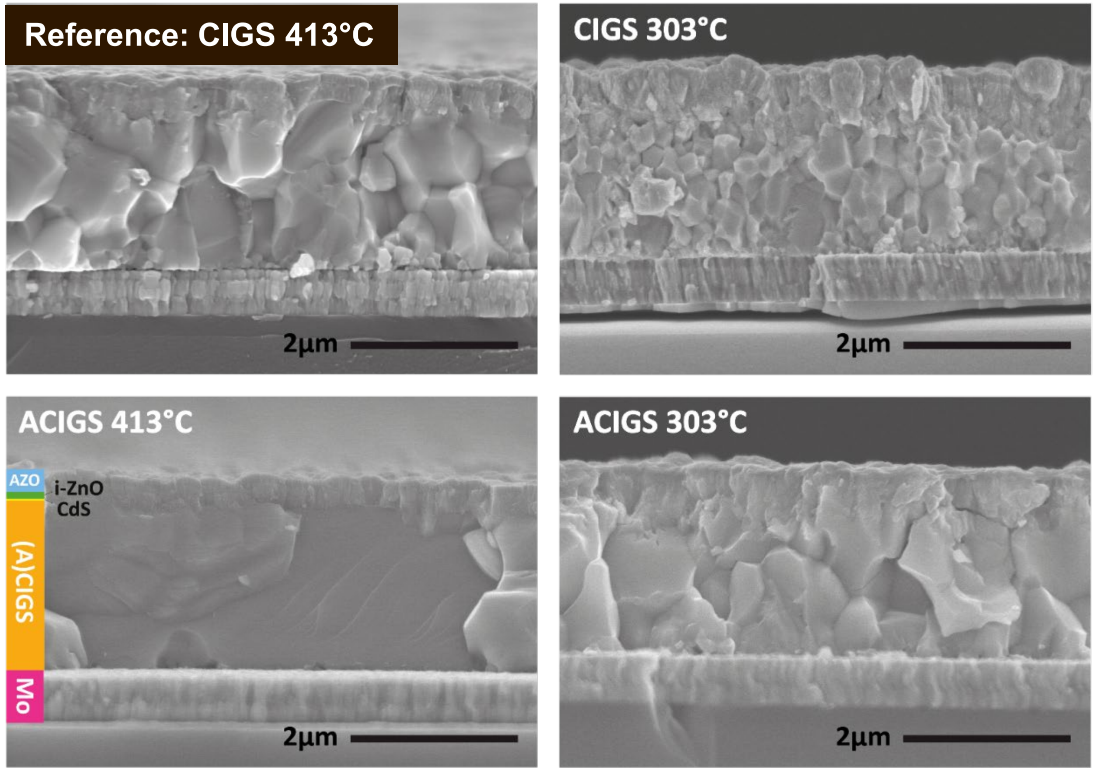


Easy to implement in existing manufacturing lines

Wider range for high efficiency



Wider process temperature window



Improved microstructure

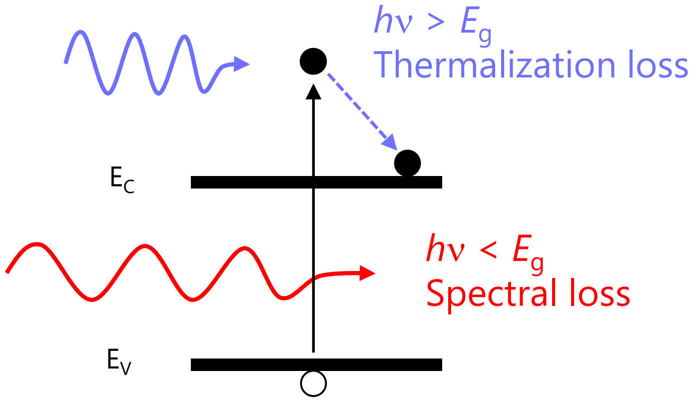
	V_{OC} (mV)	J_{SC} ($mAcm^{-2}$)	FF (%)	Eff. (%)
ACIGS on SLG	737	35.5	77.8	20.3
ACIGS on PI	735	35.7	76.4	20.1

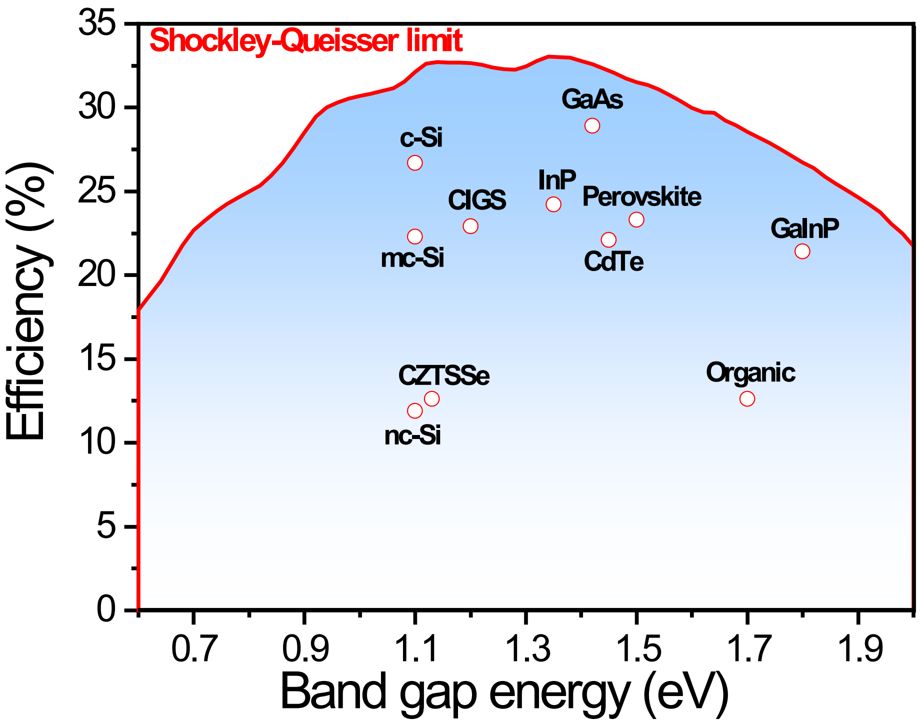
Process independent from substrate (SLG, poyimide)

Tandem solar cells

Beyond Shockley-Queisser limit

- 2 main losses mechanisms
  - Thermalization
  - Incomplete absorption





Nature Reviews Chemistry 1, 0095 (2017)

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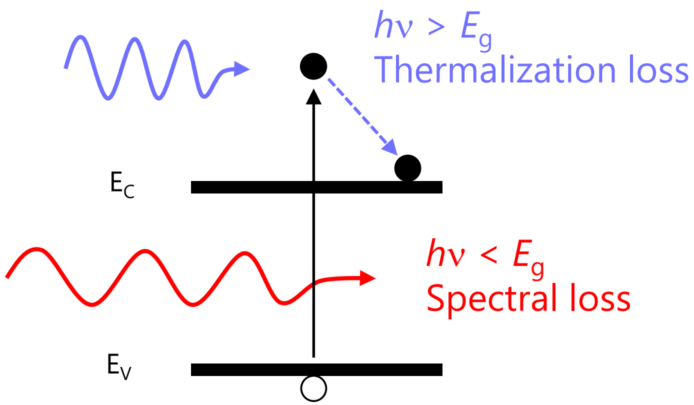
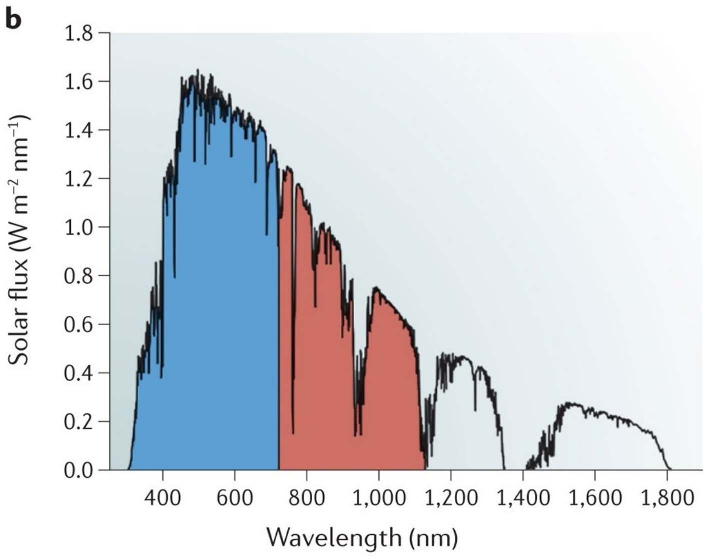
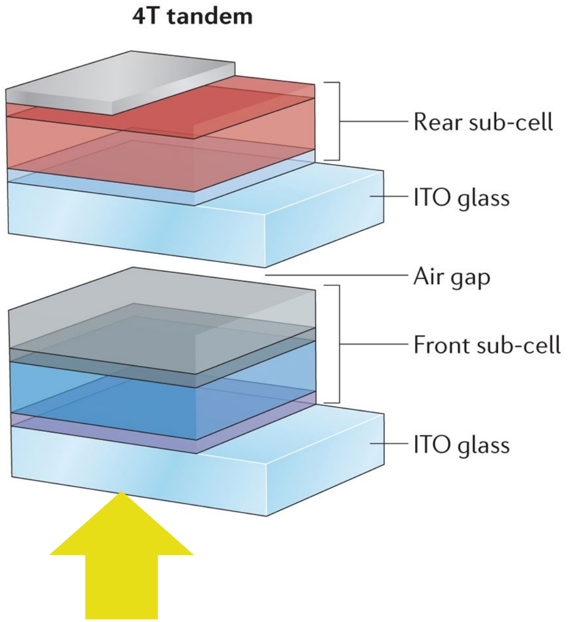


➢ 2-junction "tandem" solar cells





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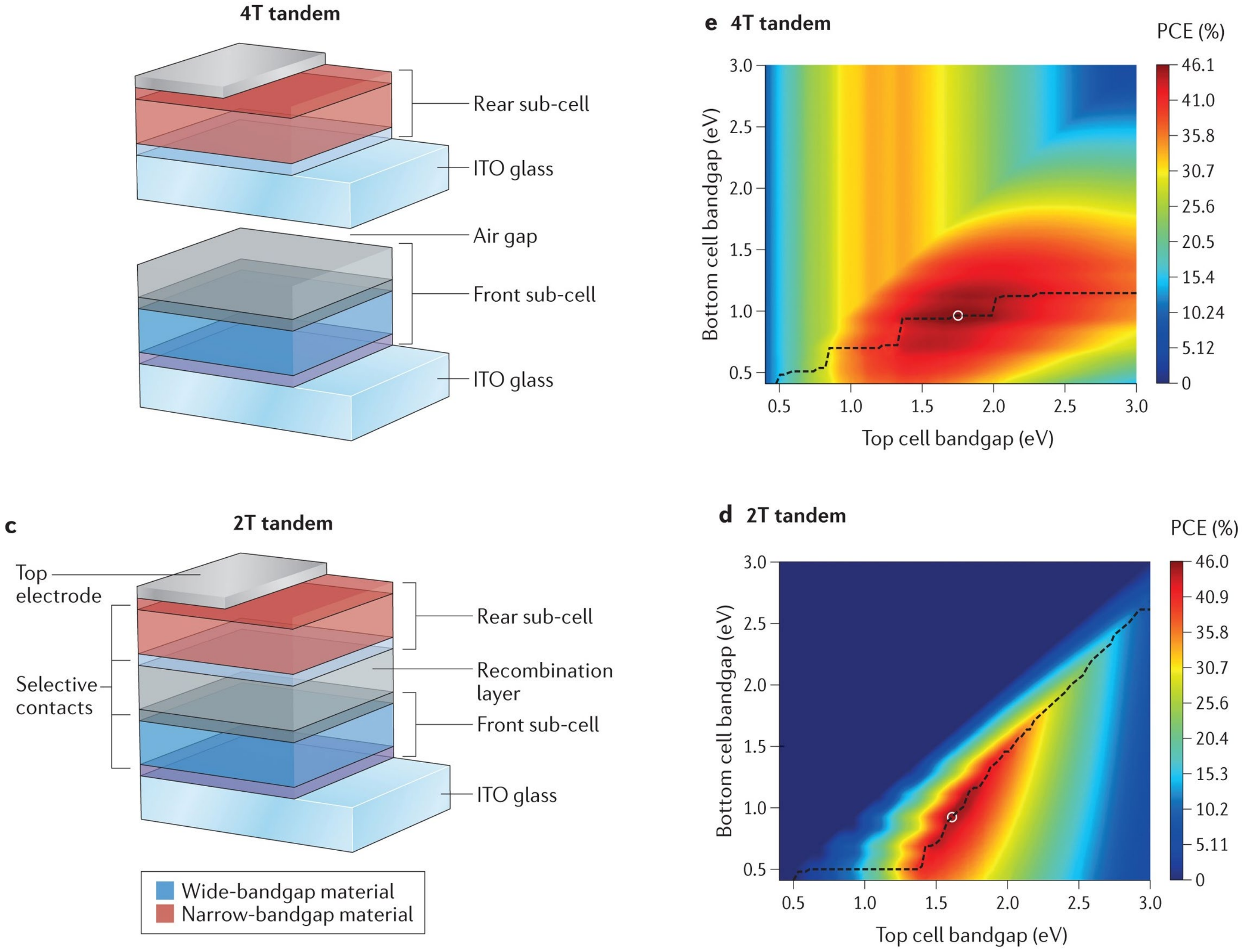
Tandem solar cells



Nature Reviews Chemistry 1, 0095 (2017)

4-terminal tandem cell

- Add-on to existing industrial line
- Top and bottom cells processed independently

Requirements

- Semitransparent top cell
- 3 highly transparent TCOs
- 2 independent circuits

2-terminal tandem cell

- Simpler system integration
- Less parasitic absorption

Requirements

- Current matching
- Low-T top cell or T-stable bottom cell
- 1 highly transparent TCOs

➢ High efficiency limit ~45% for both configurations

Low bandgap $CuInSe_2$ for tandem applications

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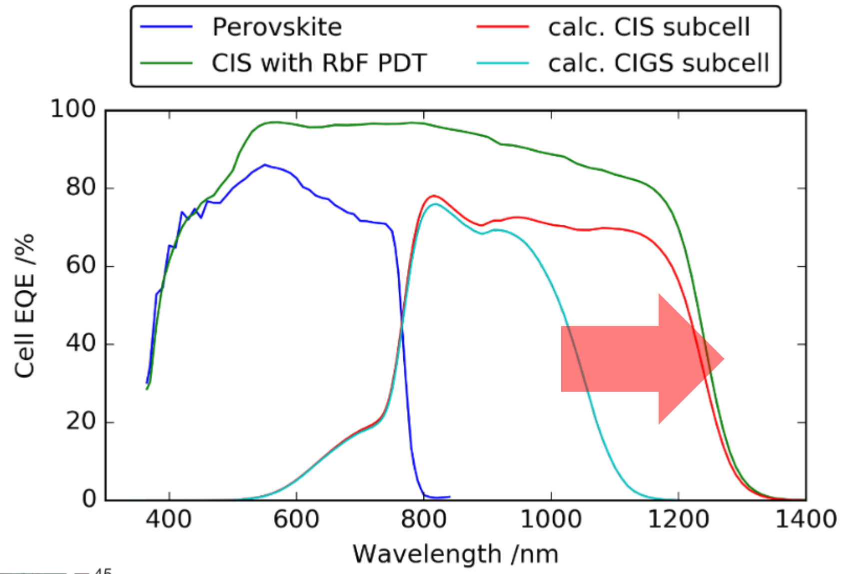
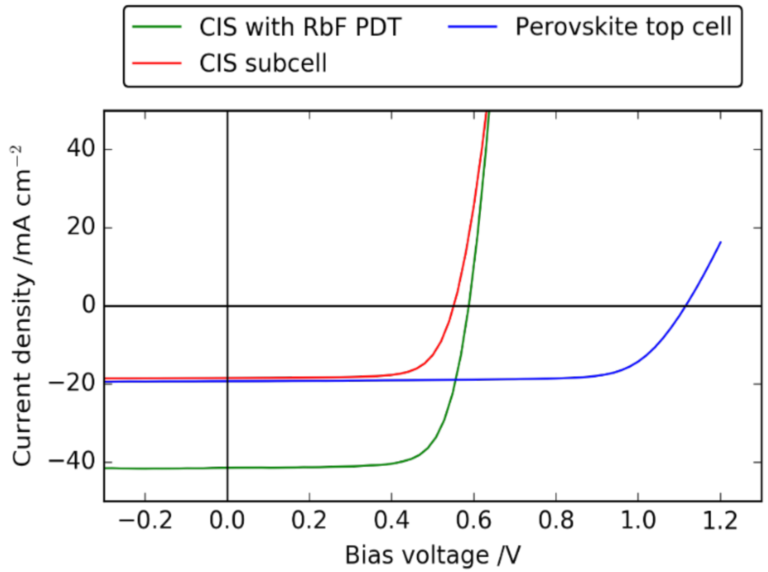
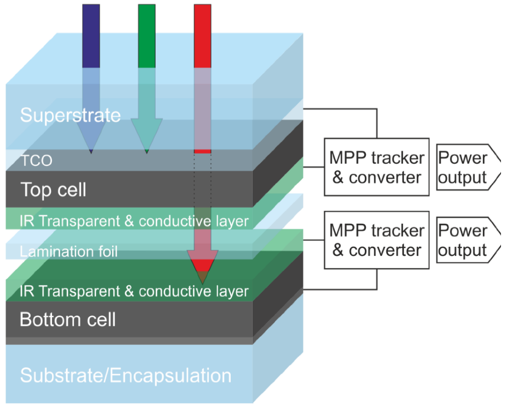
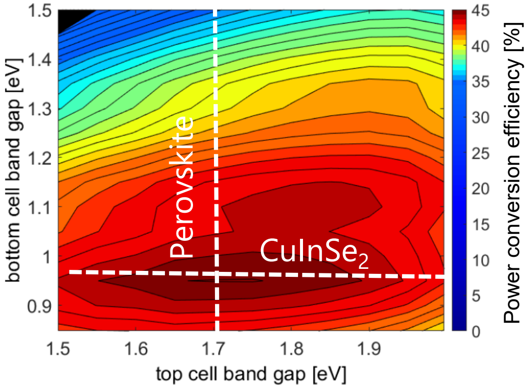
Highly suitable candidates:

- Perovskite: E_g ~ 1.7 eV
- $CuInSe_2$: E_g ~ 1.0 eV
  - Composition change
  - Low bandgap
  - Efficiency: 15% -> 19.2%









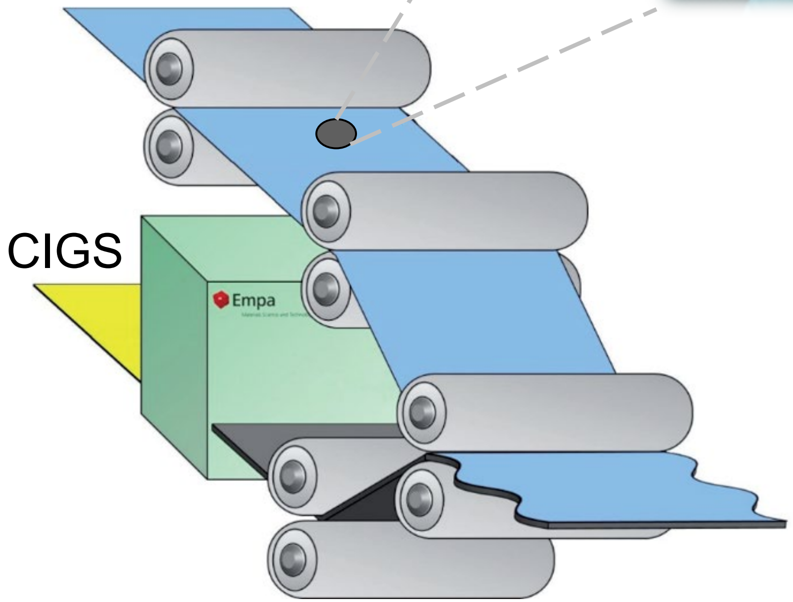
	V_{OC} (mV)	J_{SC} ($mAcm^{-2}$)	FF (%)	Eff. (%)
CIS standalone	609	42.3	74.4	19.2
Perovskite top cell	1'115	19.2	75.2	16.1
CIS bottom cell	581	18.6	74.2	8.0
4-terminal tandem projected				24.1

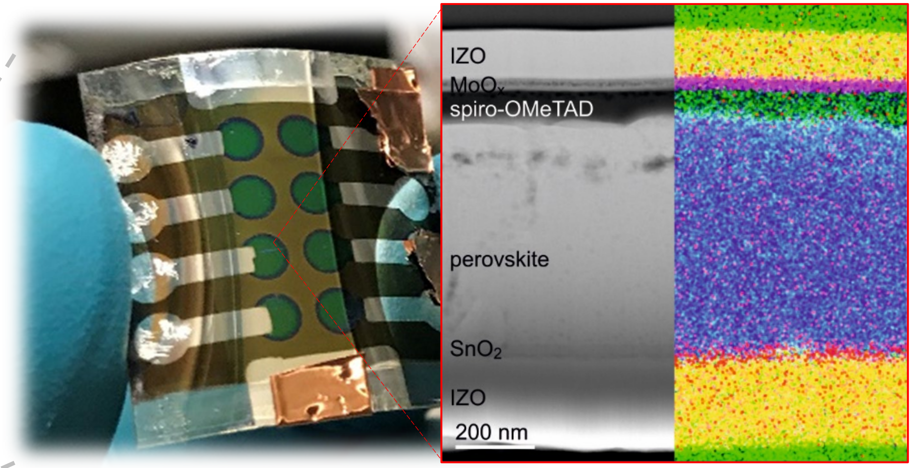
Rigid substrates

T. Feurer *et al.*, Adv. Energy Mater. 2019, 1901428

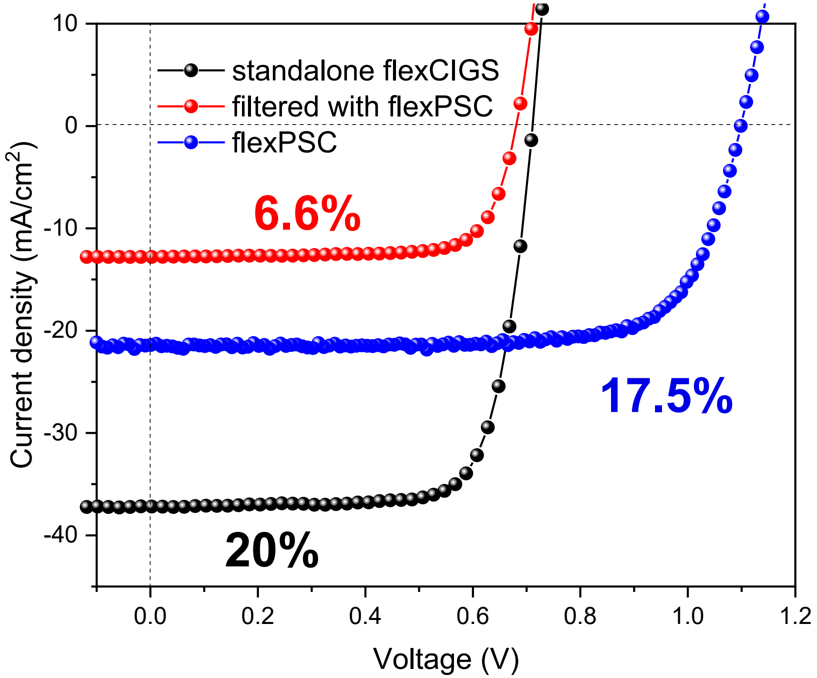
Flexible perovskite-CIGS thin film tandems

R2R process





NIR-transparent PSC grown on flexible CIGS frontsheet



	PCE (%)	MPP (%)	V_{OC} (V)	J_{SC} (mA/cm²)	FF (%)
Flex-PSC	17.7	17.5	1.1	21.4	75.3
Flex-CIGS SA	20	20	0.714	37.2	75.2
Flex-CIGS filtered	6.6	6.6	0.683	12.8	75.6

24.1% flexible perovskite-CIGS 4-terminal tandems

Unpublished results

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Thank you for your attention!

CIS; Bridge POWER

FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

ImproCIGS; ACIGS; CIGSPSC Tandems

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE

ETH Zurich Postdoctoral Fellowship

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

AMYS

Strategic Focus Area
Advanced Manufacturing

Horizon 2020: PERCISTAND

PERCISTAND

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