Monolithic Perovskite Tandem Solar Cells: Towards 30% Efficiency

Steve Albrecht [1,4], Eva Unger [2], Christian Kaufmann [3], and Bernd Stannowski [3] + many more

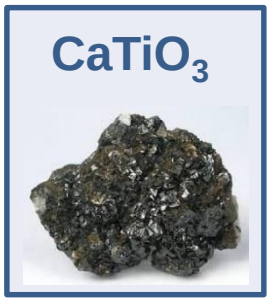
[1] Investigator Group Perovskite Tandem Solar Cells, [2] Investigator Group Hybrid Materials Formation and Scaling, [3] PVcomB, Helmholtz-Center Berlin, Germany

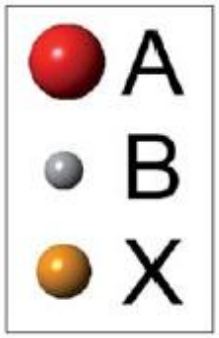
[3] Faculty IV - Electrical Engineering, Technical University Berlin, Germany

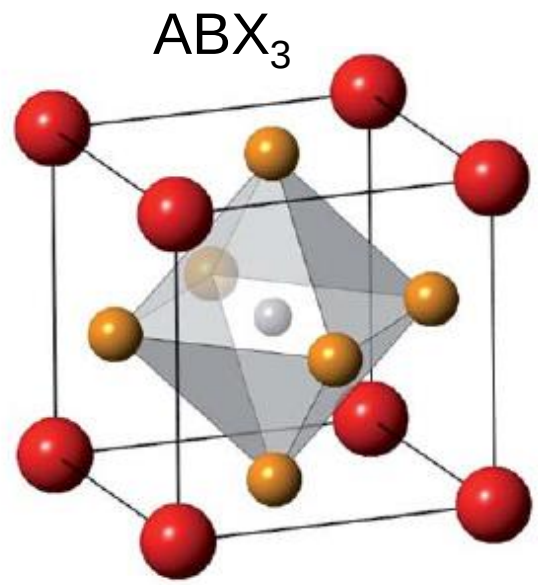
HySPRINT Industry Day – Nov. 2020

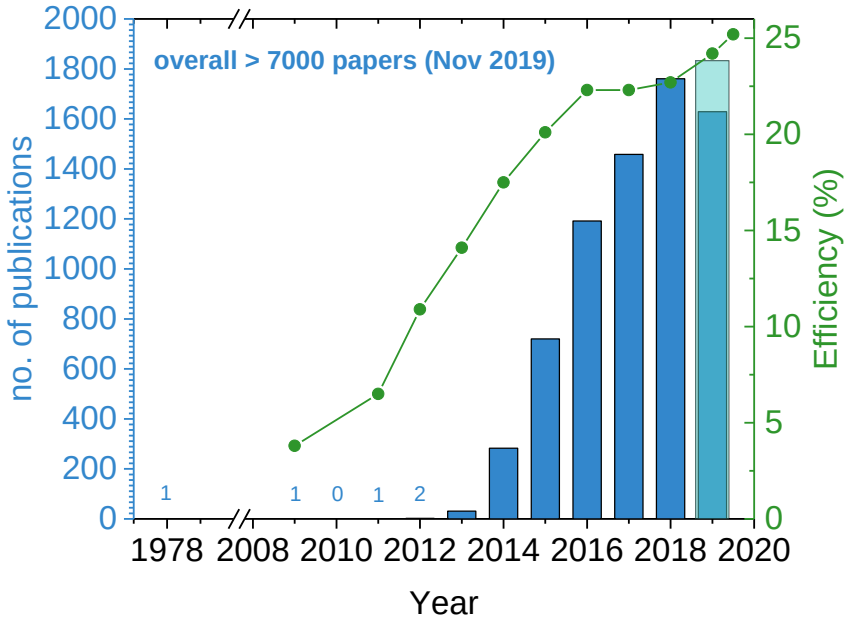
PEROVSKITE PRINTING PHOTONICS

Perovskite: Crystal Structure and History







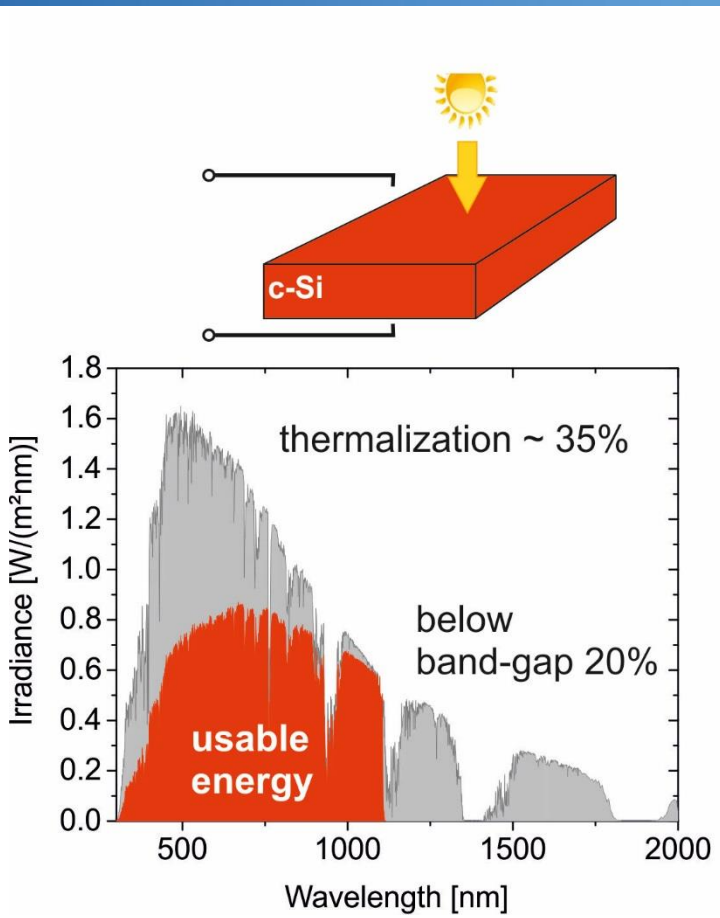


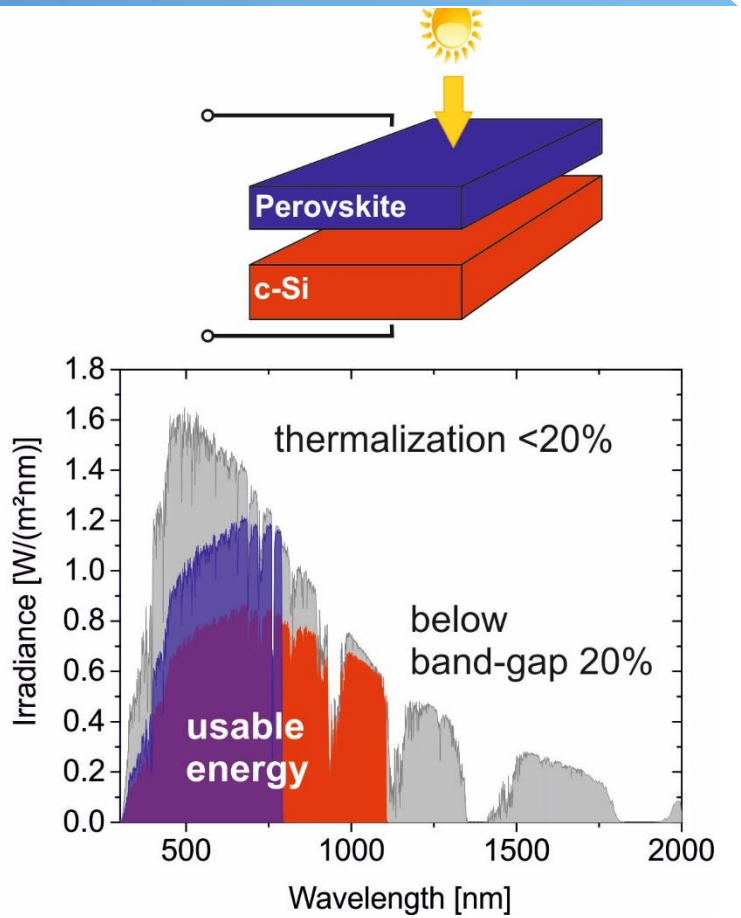
Snaith et al., Energy Environ. Sci., 2014, 7, 982

Source: Web of Science
Search in title „perovskite solar cell“

- First discovered as $CaTiO_3$ in 1840 by Gustav Rose
- 2000 perovskites are currently known
- First organic-inorganic Perovskites by Dieter Weber in 1978
- First application in solar cells late 2008/09 with 3.8%, today over 25% efficiency

Motivation for Tandems

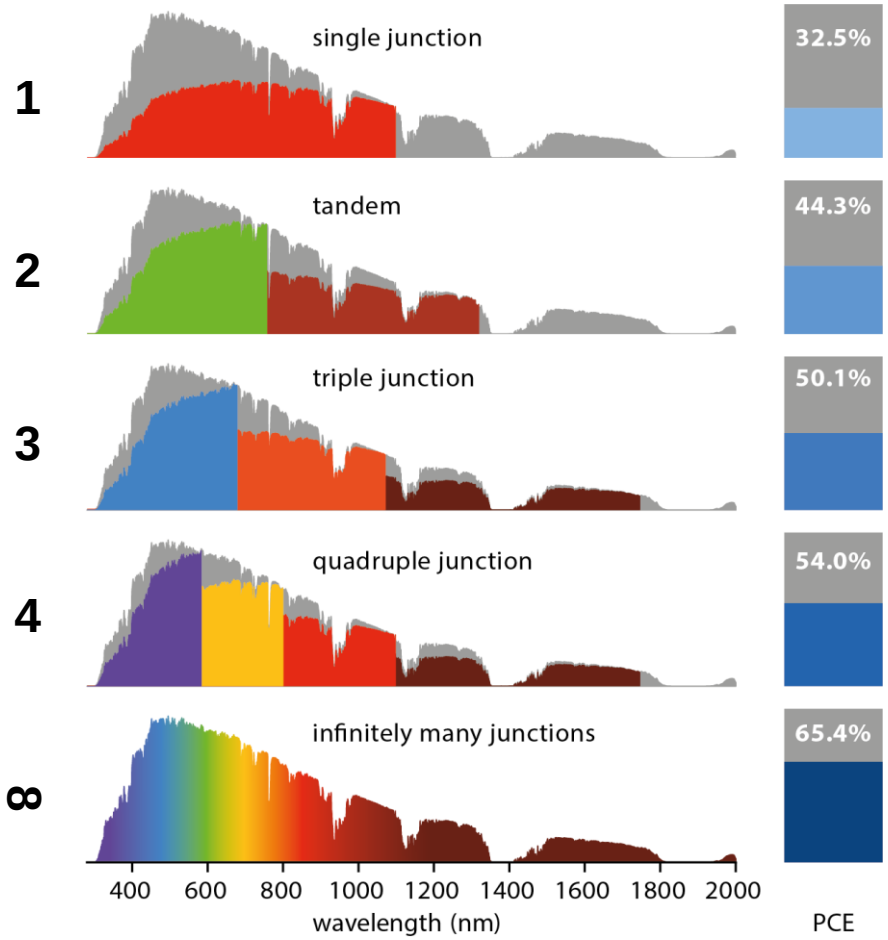




- high loss from thermalization

- high energy photons are absorbed by perovskite
  - converted at a high voltage
  - reduced losses from thermalization
- infrared photons are transmitted into c-Si
  cover a wide spectral range of absorption

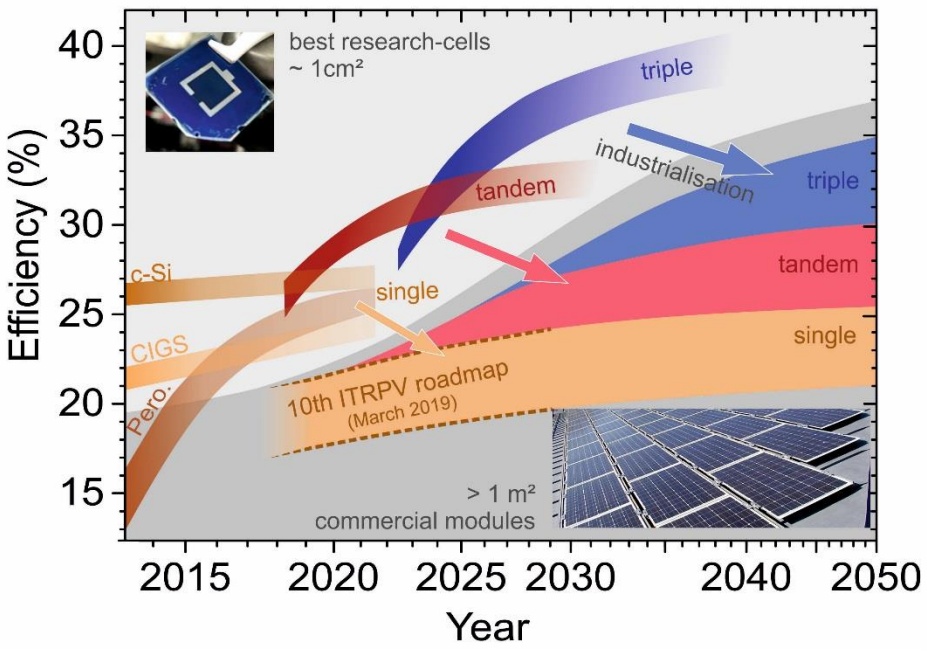
Motivation for Multi-junctions

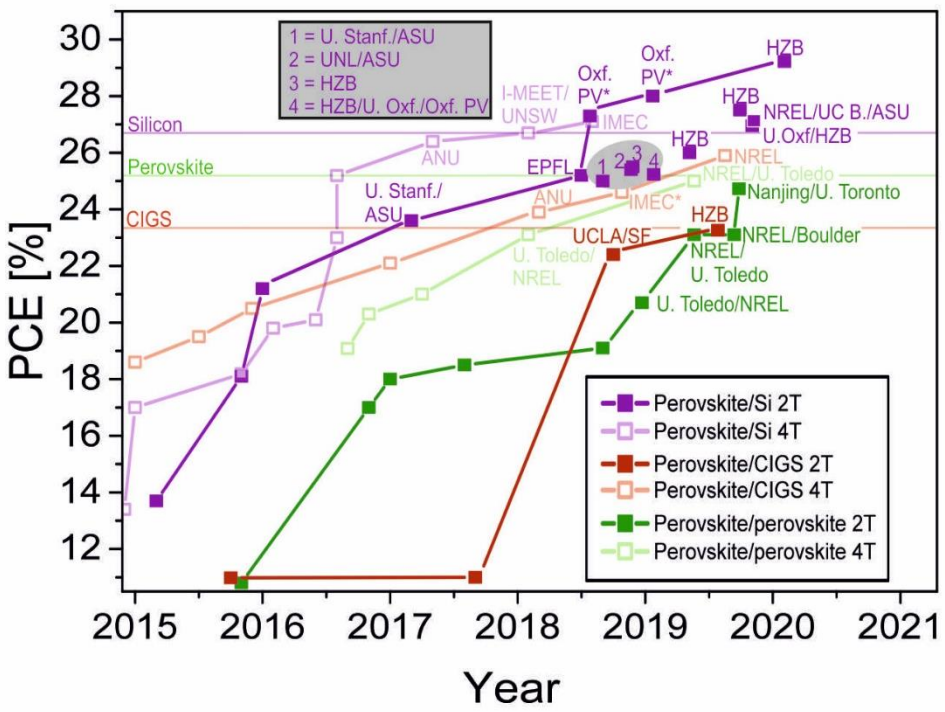


- Efficiency limit increases with no. of sub-cells/junctions
- Triple junction with >50% limit
- Infinite no. of junctions >65%
- Even higher limits for concentrated sun-light

Image courtesy: Klaus Jäger (HZB)

Motivation for Pero Tandems





- Single junctions will be limited in efficiency
- Multi-junctions with perovskite top cells can overcome fundamental limitations

- Main 2T achievements:
- Different teams reach ~27% with Perovskite/Si
  - Higher than best Si single junction!
- After long time w/o results: Recently promising results 24.2% with Perovskite/CIGS tandems
  - Similar to best CIGS single junction!
- Improvements in Sn-based Perovskites enabled 24.2% Perovskite/Perovskite tandems

certified, > 1cm²

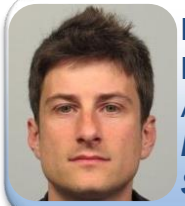
Jost et al., Advanced Energy Materials, 2020,
DOI: 10.1002/aenm.201904102

3 Groups for Perovskite Research @ HZB

HZB Helmholtz Zentrum Berlin

HySPRINT Helmholtz Innovation Lab

BMBF Young Investigator Group
Eva Unger
Hybrid Materials Formation&Scaling



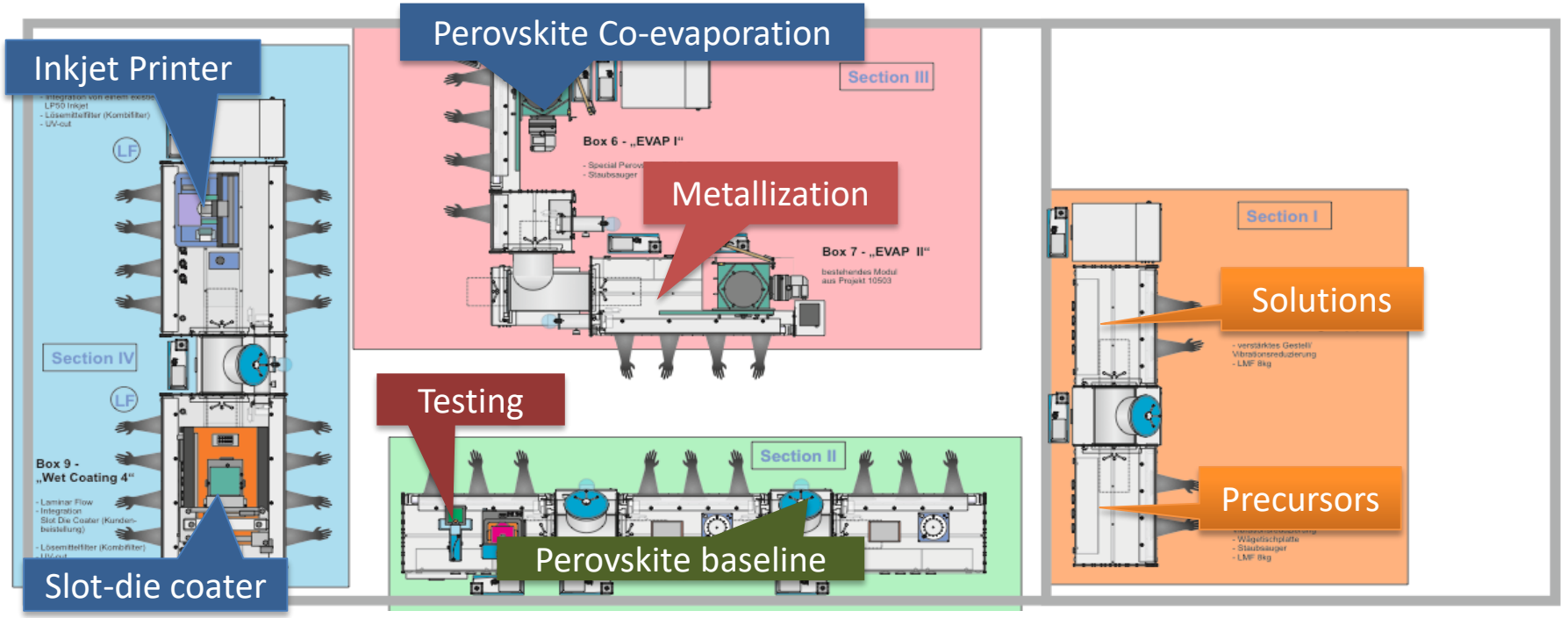
Helmholtz-Young Investigator Group
Antonio Abate
Perovskite PV Stability & Interfaces

BMBF-Young Investigator Group
Steve Albrecht
Perovskite Tandem Photovoltaics

Larger area

stable

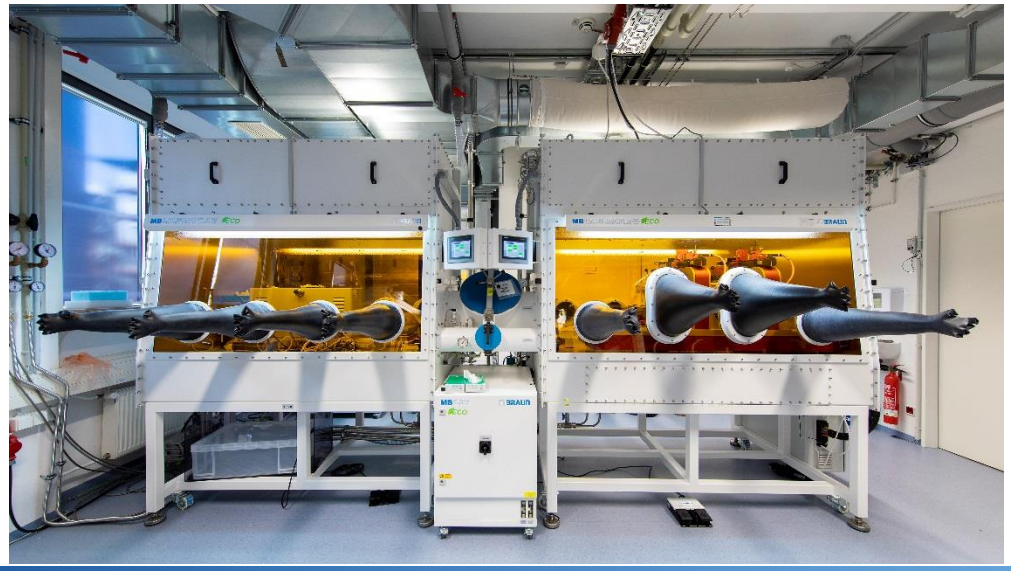
multijunction devices



The HySPRINT Perovskite Lab @ HZB

HZB Helmholtz Zentrum Berlin

HySPRINT Helmholtz Innovation Lab



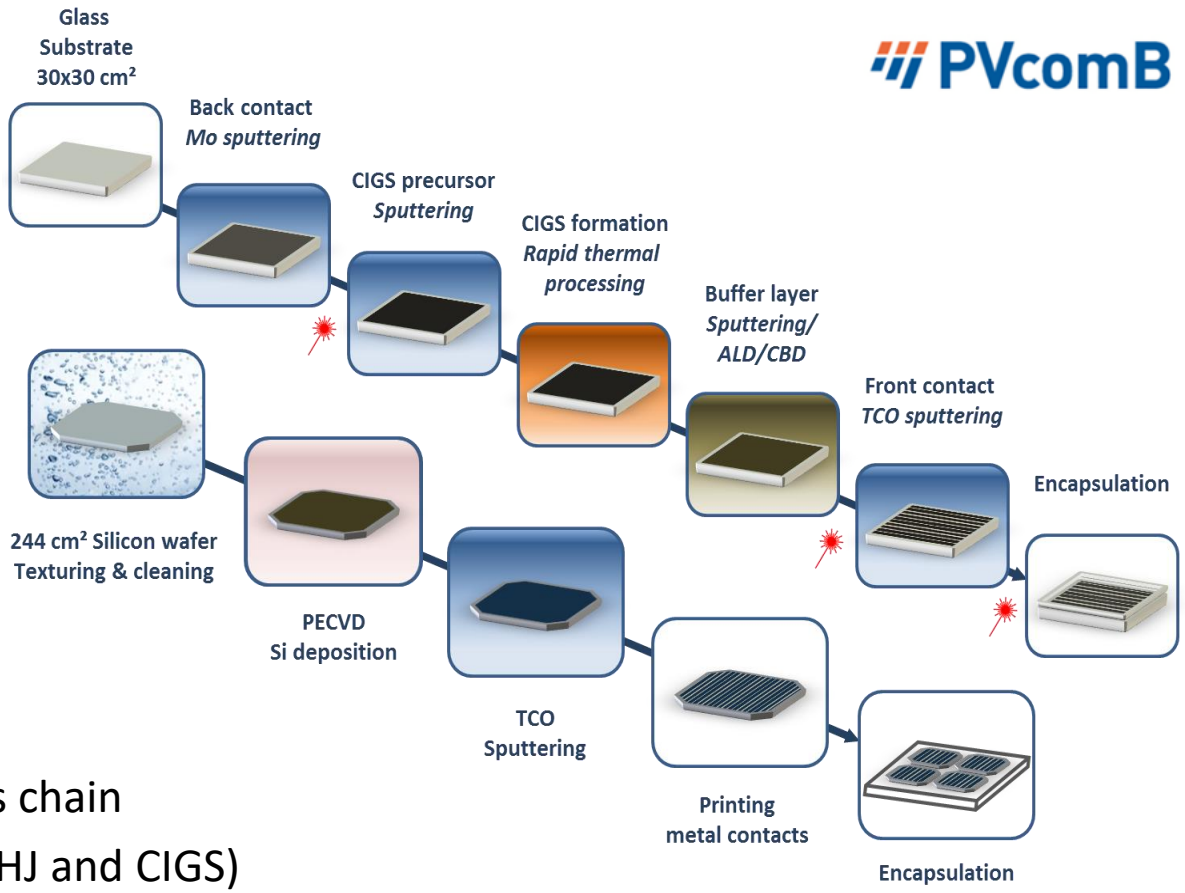
>40 users working on perovskite solar cell related questions

check out virtual lab tour

PVcomB – baselines for solar technologies

HZB Helmholtz Zentrum Berlin

PVcomB



Objectives

- Transfer results from HZB‘s research into industry

Approach

- Run complete baseline process chain
- PVcomB’s core technologies (SHJ and CIGS)
- Support development of industrial partners
- Advance TRL of early-stage technologies:
  - **Multi-junctions**
  - Building integrated PV
  - Solar fuels

visit break-out session #2

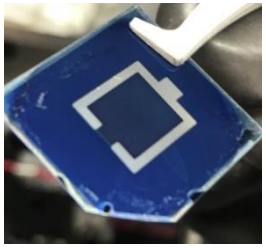
Outline

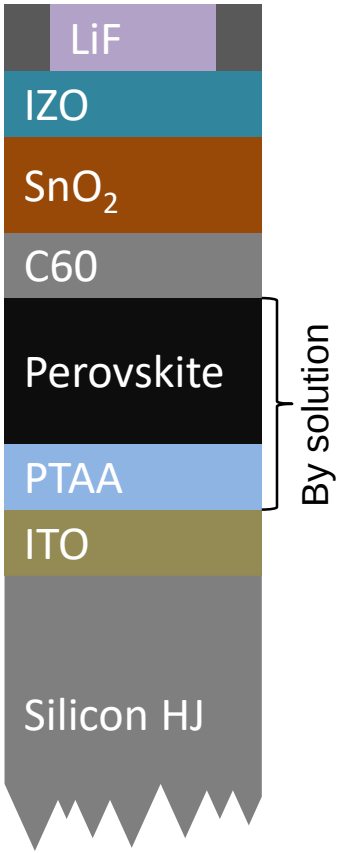
1. **Results on Perovskite/Silicon Heterojunction (SHJ) Tandems**
2. **Results on Perovskite/CIGS Tandems**
3. **Upscaling of Perovskite-based Tandems**

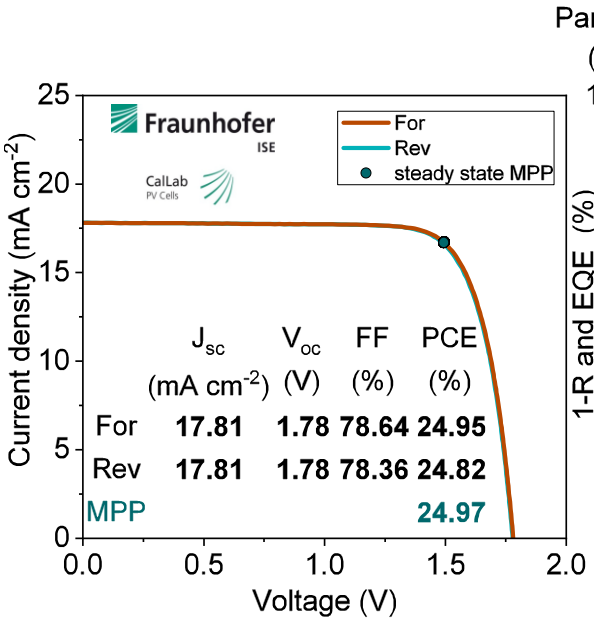
P3 PEROVSKITE PRINTING PHOTONICS

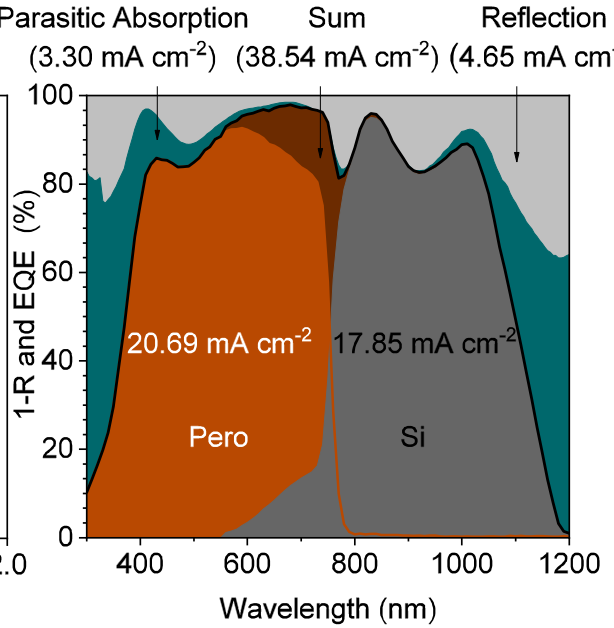
Results on Perovskite/SHJ Tandems

HySPRINT's 1st Perovskite/Silicon Tandem





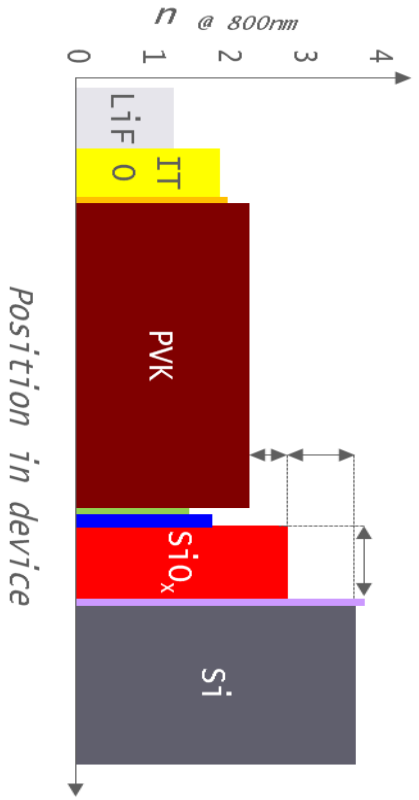




- Certified 24.97% PCE
  - Certified J_{sc} close to J_{sc_EQE} measured in-house
- Highly unmatched currents
- High NIR reflection due to non optimized optics
  - Non optimized nc-SiOx:H thickness and top-contact

Köhnen et al., Sustainable Energy & Fuels, 2019,3,1995

Nano-crystalline silicon oxide interlayer



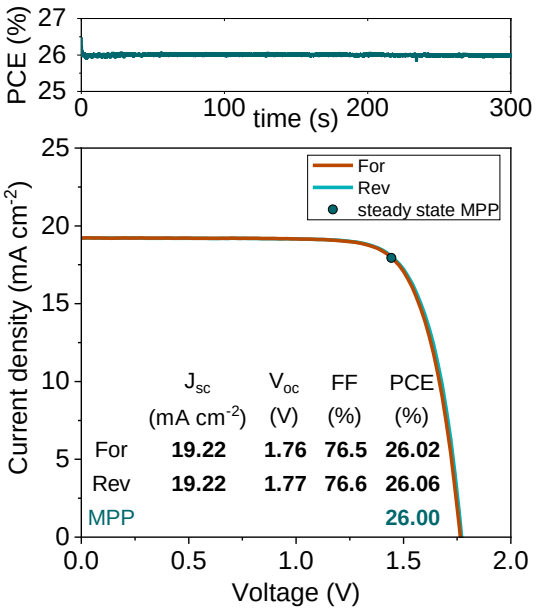
a) $n_1 = \sqrt{n_0 \cdot n_2}$

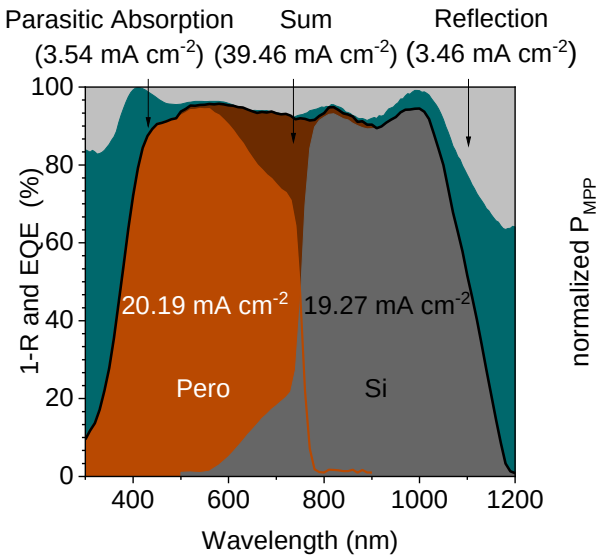
b) $n_1 \cdot d_1 = k \cdot \frac{\lambda_0}{4}$

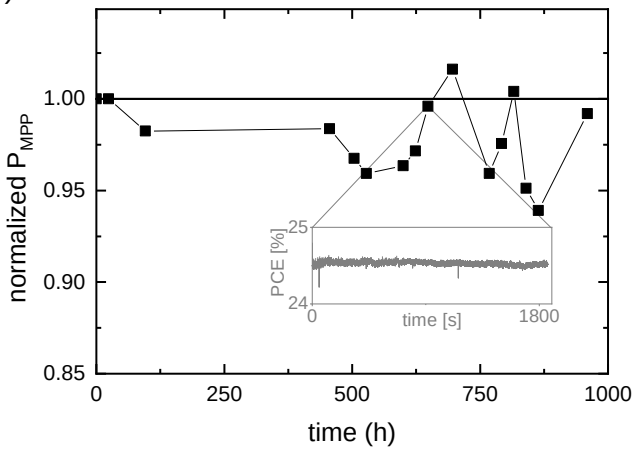
- Higher refractive index enhances light in-coupling to Si
- Optimum for ~ 100 nm thickness and n~2.7
  - Closer to current matching, reduced reflection loss
- 25.2% certified tandem efficiency realized

Mazzarella et al., Adv. Ener. Mater. 2019, 9, 1803241

Further optimized monolithic tandem



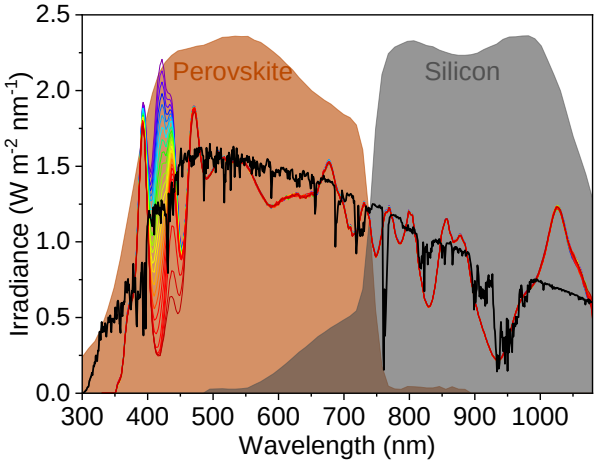


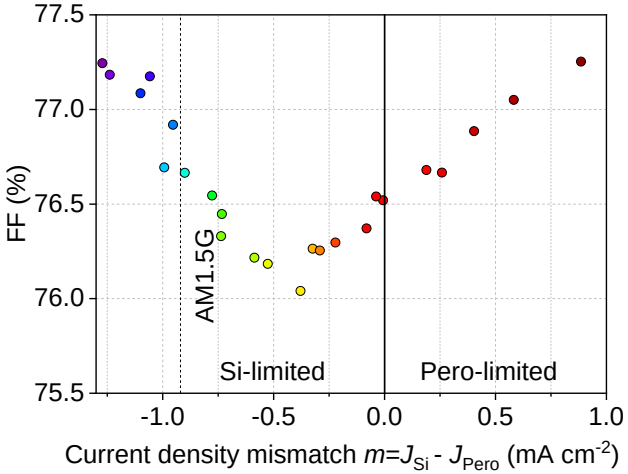


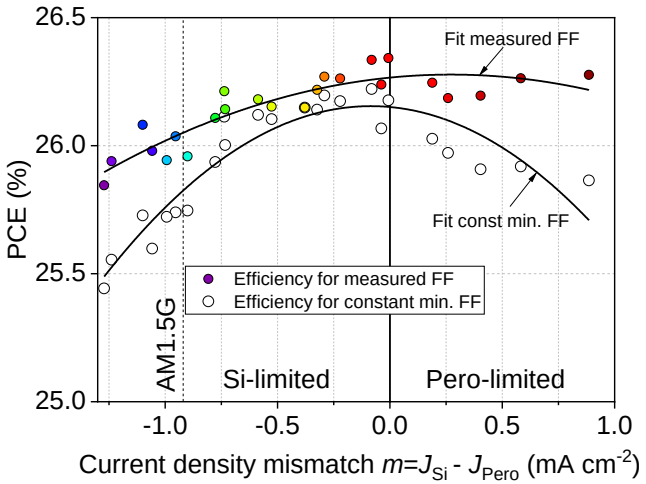
- Optimized thickness and top-contact
- Nearly matched sub cells, reduced reflection
- PCE of 26.0% highest scientifically published value to date
- Over 40 mA/cm² (19.8 matched) at 25.5% achieved as well
- >98% stability after 1000h in air

Köhnen et al., Sustainable Energy & Fuels, 2019,3,1995

FF Analysis under mismatch conditions





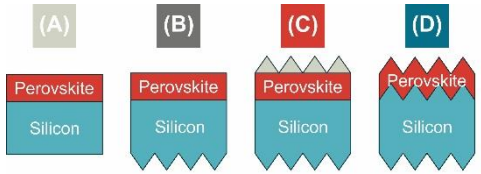


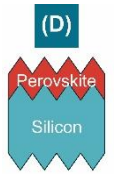
- 1.3% FF gain per mA/cm² mismatch
- Reduces sensitivity on spectral changes – impact on outdoor performance
- From electrical simulations: recombination layer non-linear

visit
break-out session #7

Köhnen et al., Sustainable Energy Fuels, 2019,3,1995

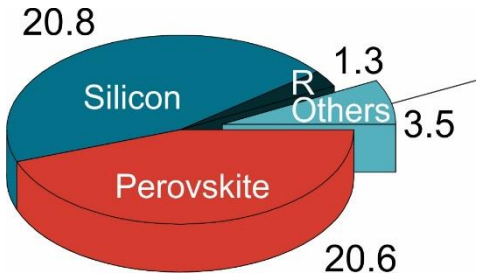
Position and influence of texture: performance





[mA/cm²]

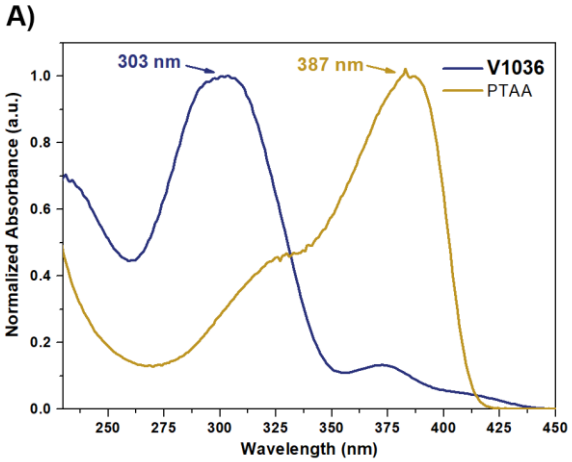
Device design	E_g opt. [eV]	J_{SC_SIM} [mA cm^{-2}]	V_{OC} [V]	$V_{OC,\ pero}$ [V]	FF [%]	PCE [%]
Flat (A)	1.69	19.07	2.00	1.29	80	30.5
Back-side texture (B)	1.65	20.01	1.96	1.25	80	31.4
Back texture + LM foil (C)	1.66	19.97	1.97	1.26	80	31.5
Both-side texture (D)	1.66	20.56	1.97	1.26	80	32.5

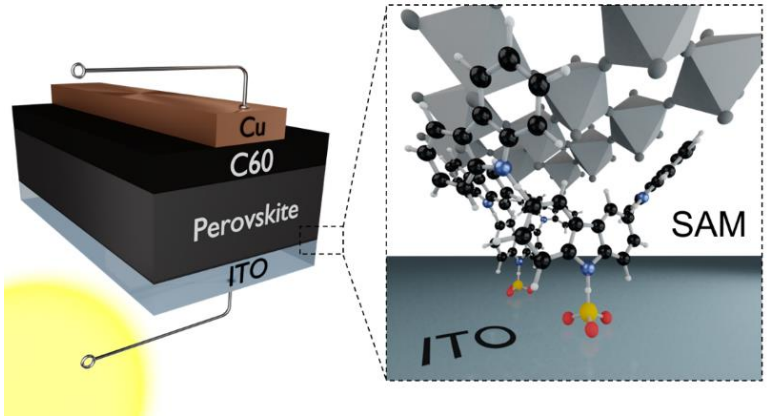


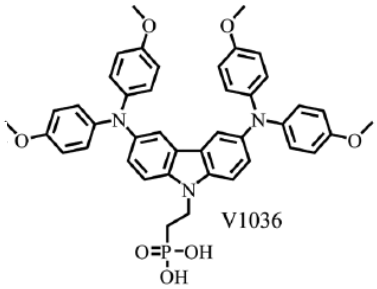
- Optimized band gap 1.66 – 1.69 eV
  - Depends on the device architecture
- Highest efficiency potential for device (D) due to higher photocurrent
  - However: assumption to have same Pero quality on textured surface
  - **Increasing the top-cell Voc highly important**
  - **Increase the FF to 80% and above**

Jost, et al., Energy & Environ. Science, 2018,11,3511

1st Generation hole transporting SAM V1036



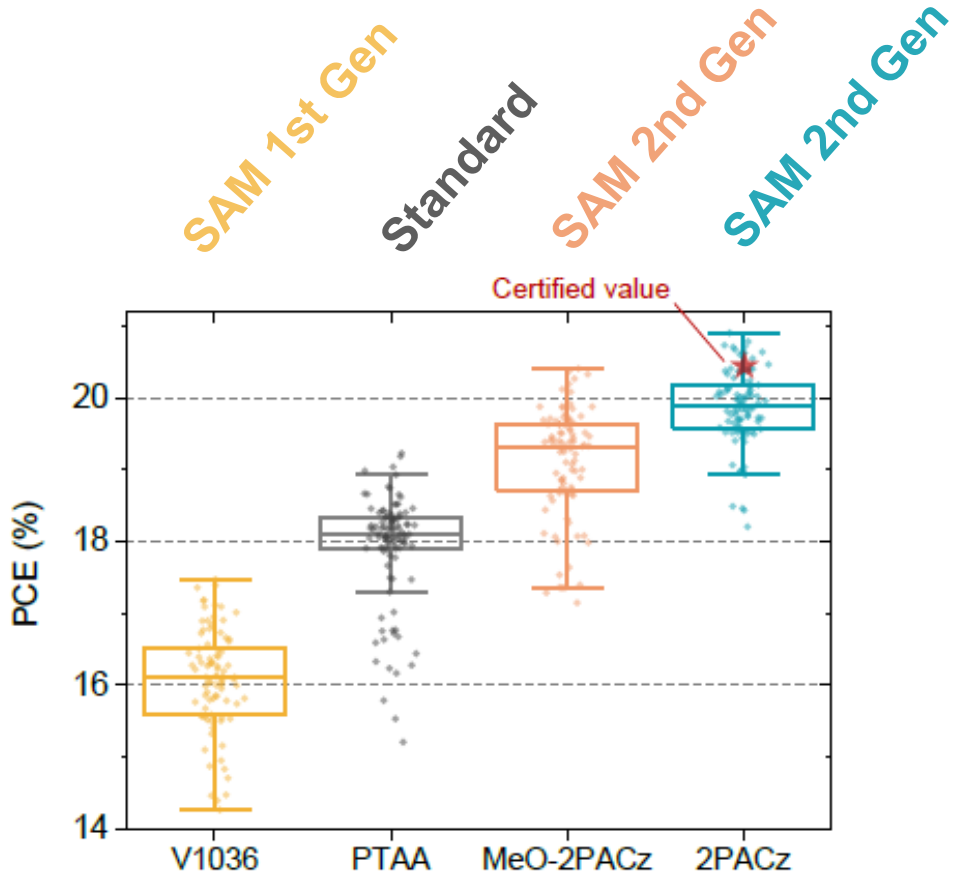


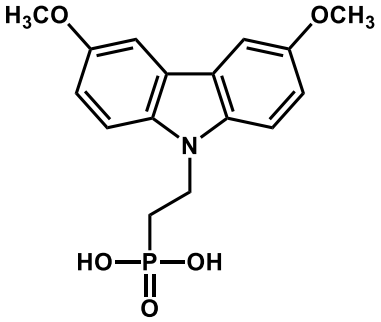


- Covalent bonding to ITO, robust against solution processing
- Reduced absorption loss
- Close to 18% PCE in p-i-n perovskite solar cell

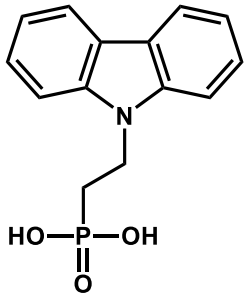
Magomedov, Al-Ashouri et al., Advanced Energy Materials, 2018,8,1801892

2nd Generation SAM Meo-2PACz, 2PACz





MeO-2PACz



2PACz

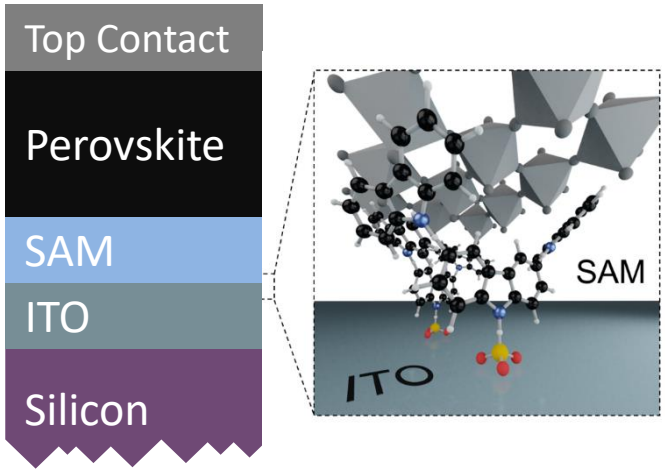
- Terminated by methoxy groups
- Simplest possible Carbazole SAM

Al-Ashouri et al., Energy Environ. Sci., 2019, Advance Article DOI: 10.1039/C9EE02268F

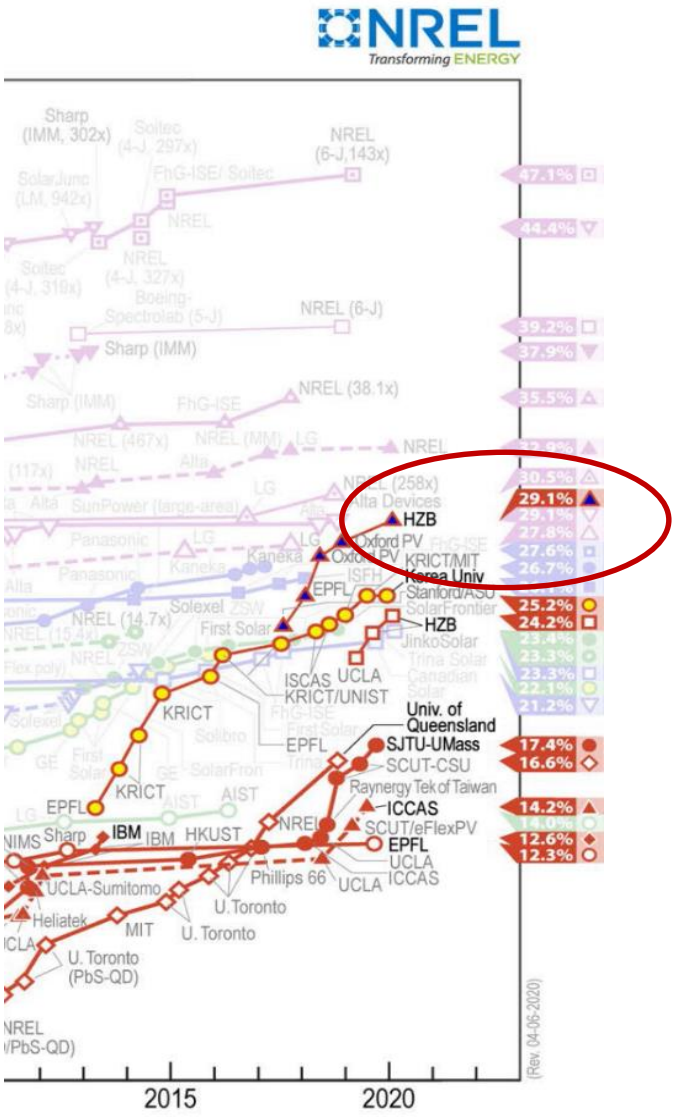
Patents : DE 10 2018 115 379.1, PCT/EP2019/060586, DE 10 2019 116 851.1

MeO-2PACz and 2PACzprovided by

3rd Generation SAM: Perovskite/Si Tandems



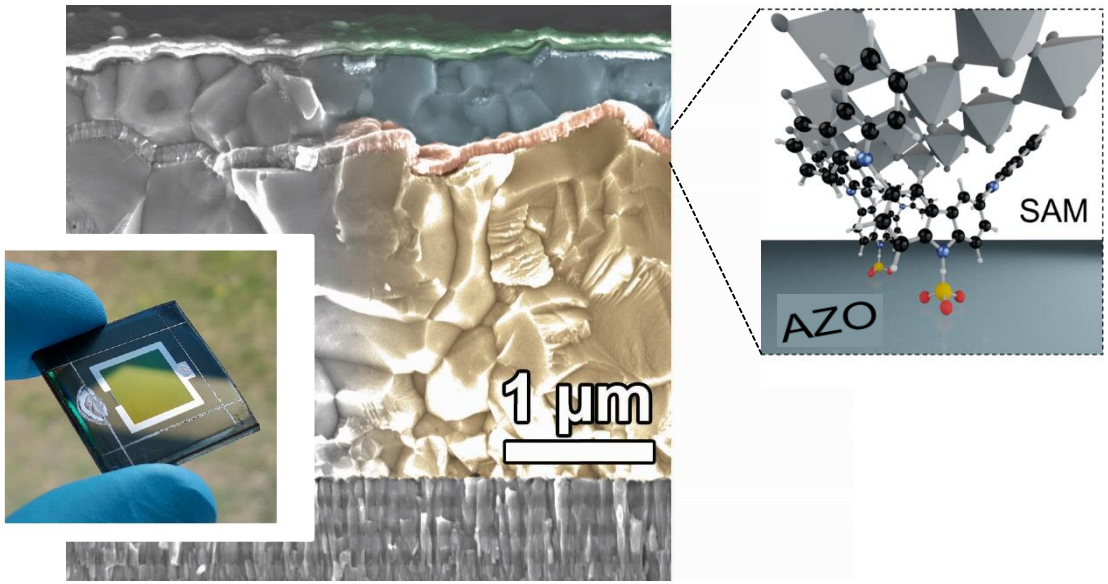
- 3rd generation of SAM molecules
- integrated into Pero/Si tandem
- Fine-tuning and stabilizing of Perovskite band gap to ~1.68 eV
- Enhanced hole extraction for higher FFs
- **Record 29.15% efficiency (>1 cm²)**
- **Promising stability data (300 h)**

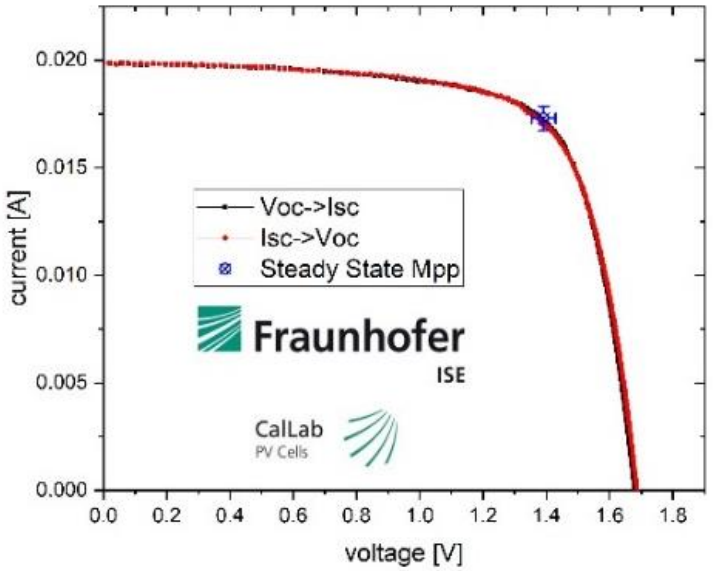


Al-Ashouri, Köhnen et al, Science (2020) accepted

Results on Perovskite/CIGS Tandems

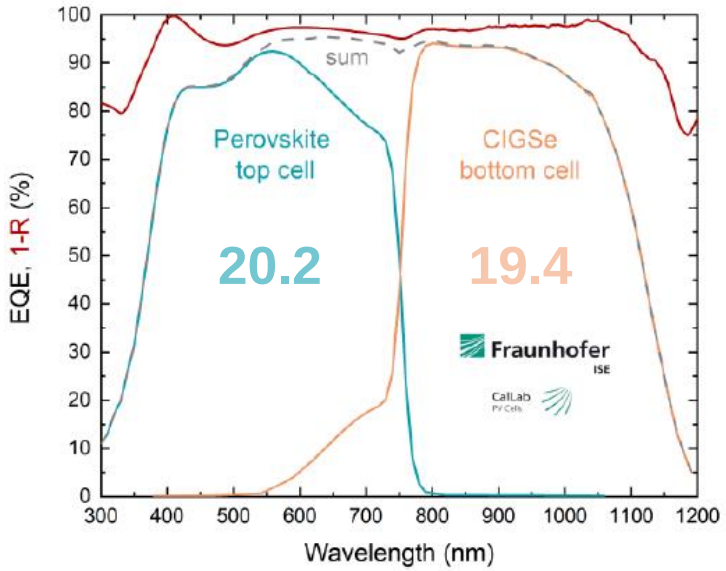
World Record 2T Perovskite/CIGSe Tandem 2019





- 2nd Gen SAM integrated directly on top of rough CIGSe
- Optimized optics and SAM-improved Voc

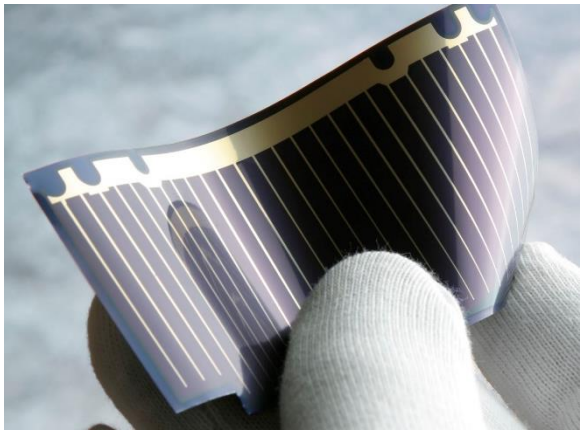
Area (cm²)	MPP (%)	Jsc (mA/cm²)	Voc (V)	FF (%)
1.035	23.26	19.17	1.68	72



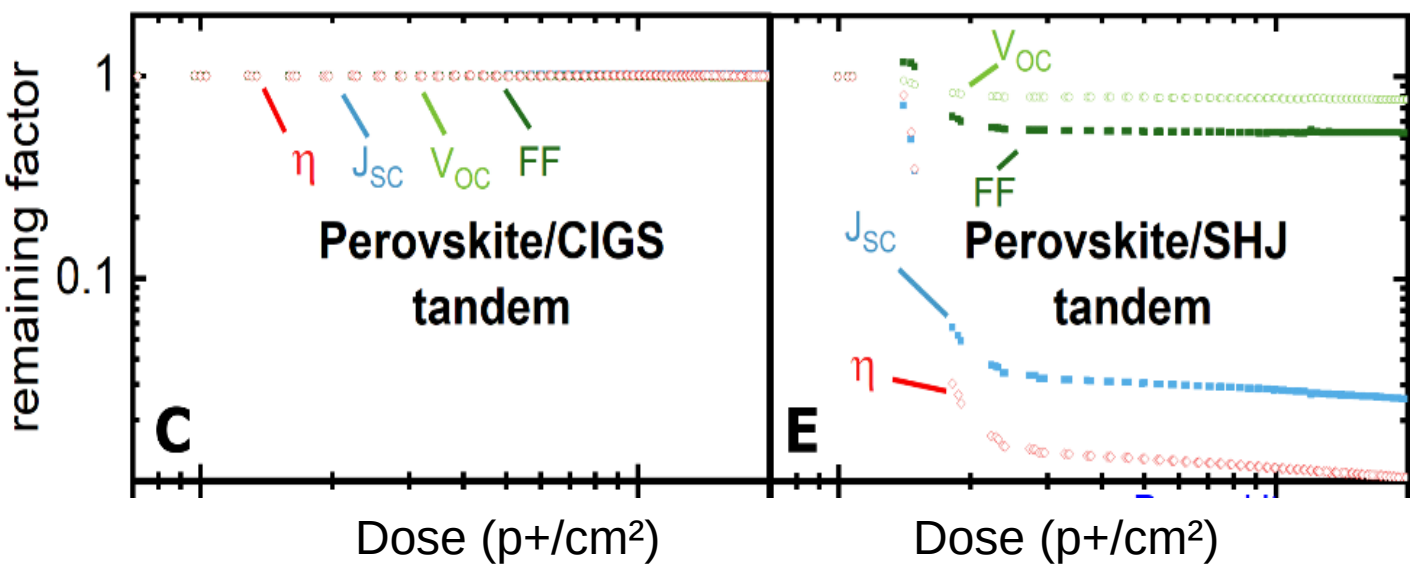
Al-Ashouri et al., Energy Environ. Sci., 2019, Advance Article DOI: 10.1039/C9EE02268F

Perovskite/CIGSe Tandem: flex and space

- Flexible may give access to “new“ PV applications and markets.



UNIVERSITY OF CAMBRIDGE

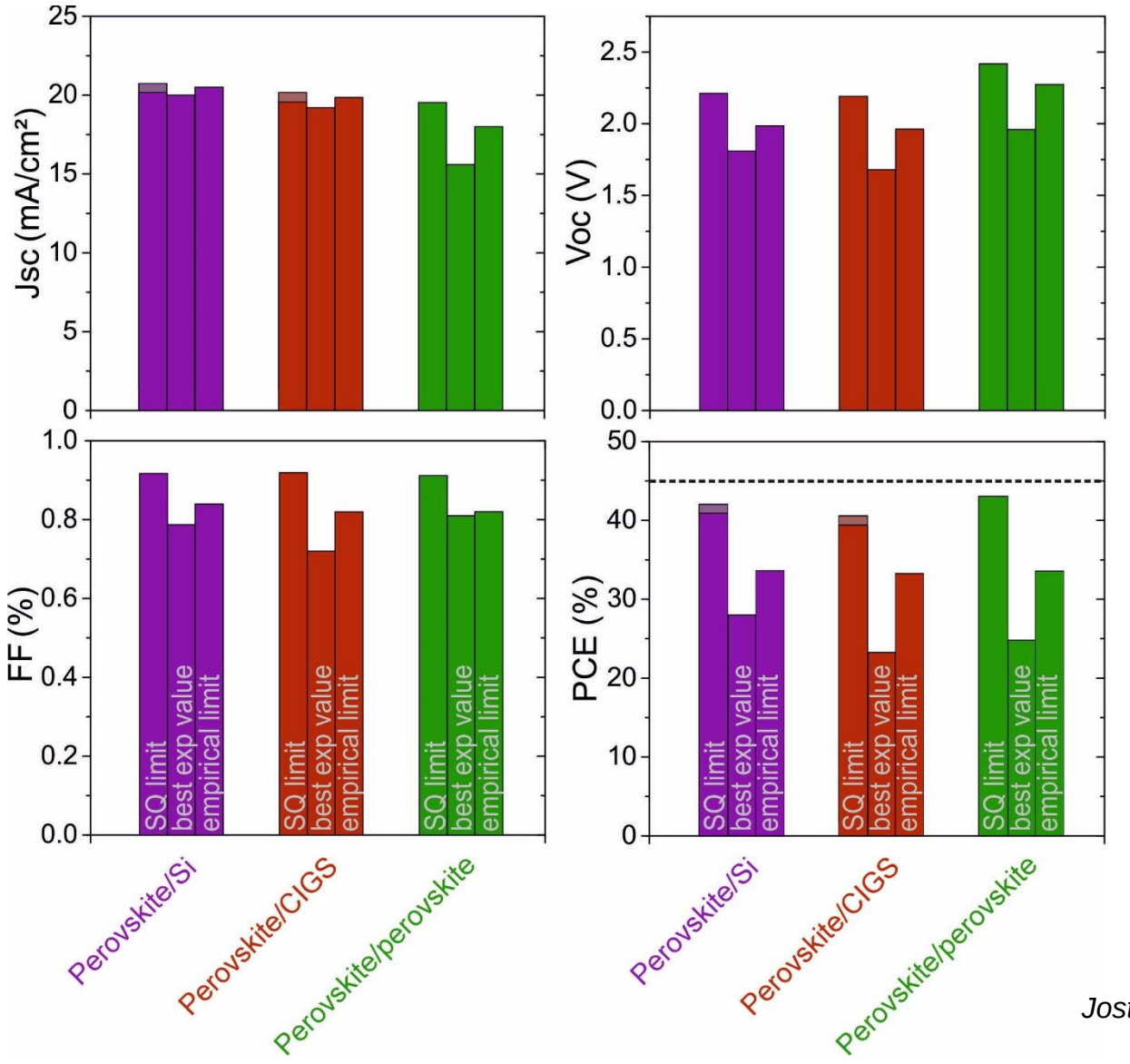


- Pero/CIGS is stable under proton dose of >50 years at the ISS orbit!

Lang, et al., Joule, (2020),5, 1054

Lang et al., Advanced Materials (2016), 28, 8726

Finally >30%



What we learn:

- Perovskite-based tandem solar cells with **Silicon**, **CIGS** or **perovskite** bottom cells have around 34% efficiency potential

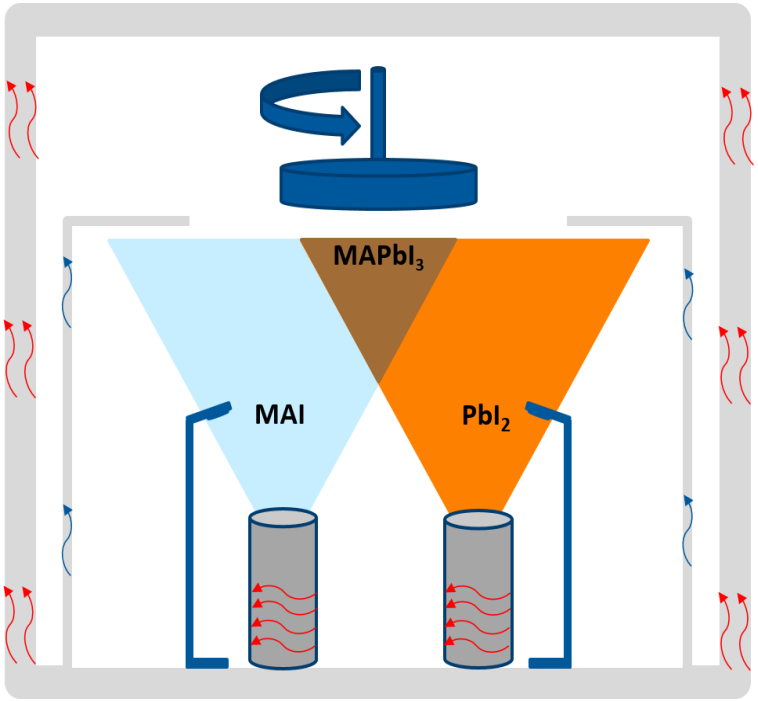
Jost et al., Advanced Energy Materials, 2020,
DOI: 10.1002/aenm.201904102

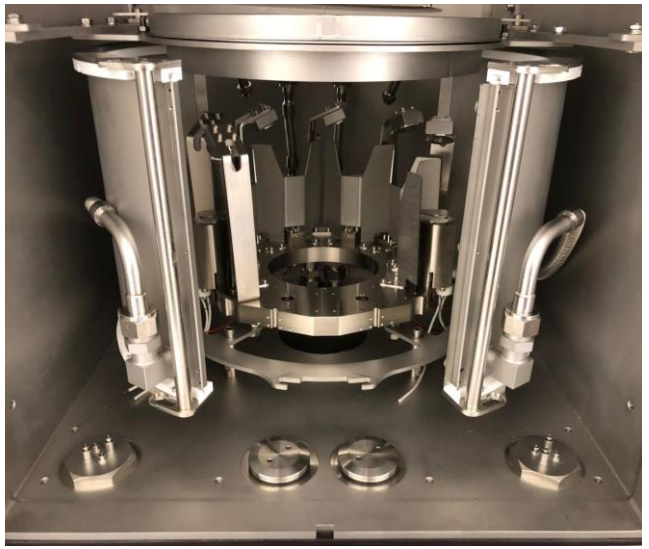
Upscaling of Perovskite Solar Cells

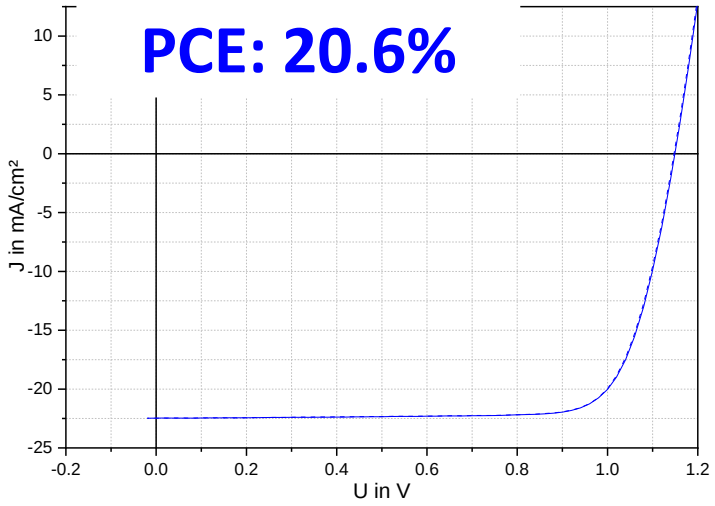
Direct Co-Evaporation of Perovskite

New concept:

- thermal management system:
  - actively cooled and heated surfaces
- trapping of volatile MAI on cooled surfaces:
  - no re-evaporation from chamber walls
  - direct co-evaporation





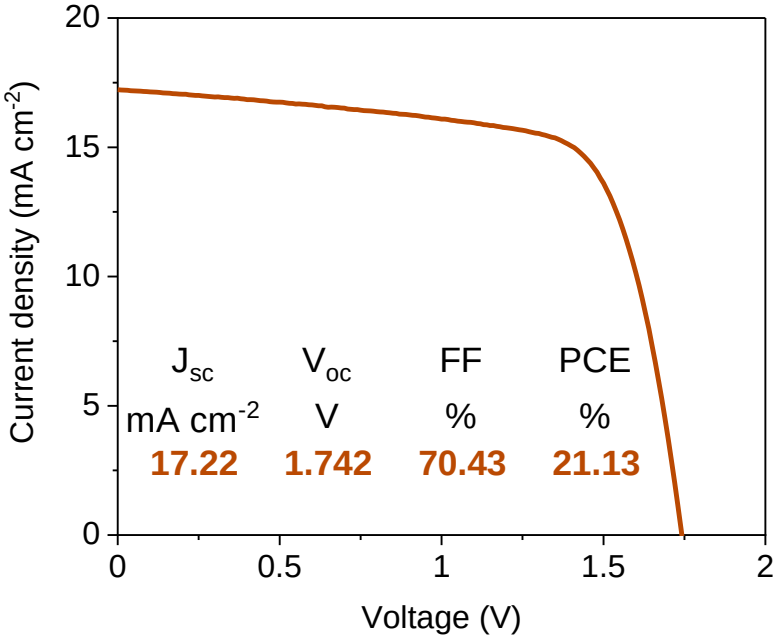


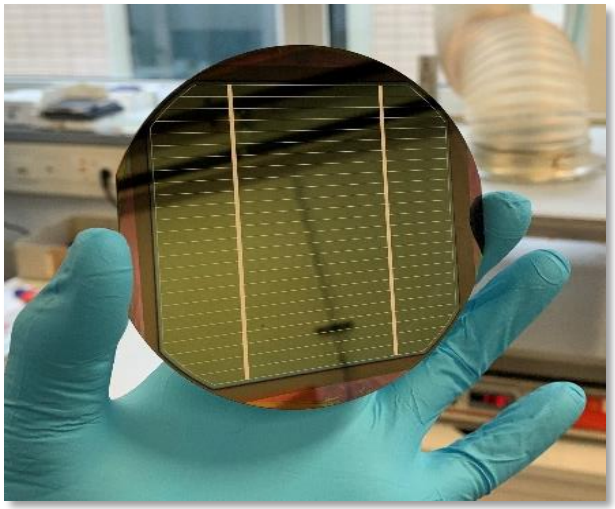
Roß et al., ACS Appl. Mater. Interfaces 2020, 12, 35, 39261–39272

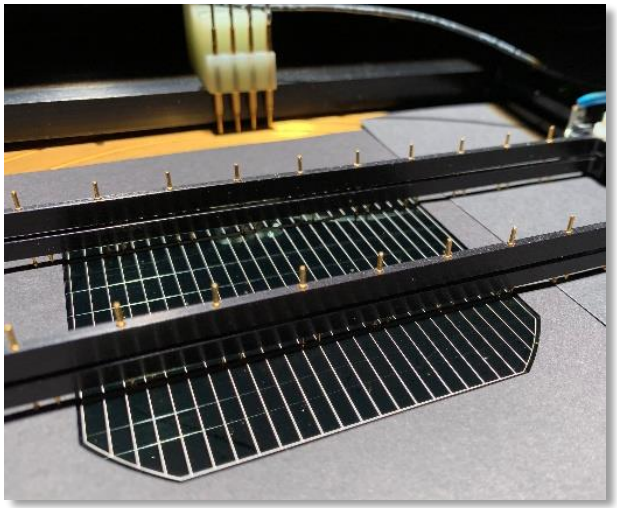
Large area Perovskite/Silicon Tandem

Proof-of-concept large area Perovskite/Si tandem:

- 60 cm² active area
- Perovskite absorber fully evaporated
- Front contact screen-printed at low temp.
- 21% PCE including shadowing losses







Köhnen and Roß, EUPVSEC-2020

New Perovskite Cluster Tool “KOALA”

- Designed for 6” top cells for perovskite-based tandem solar cells
- Focus on vacuum deposition
  - Co-evaporation
  - Sputter deposition
  - ALD
- Baseline integration + industry collaboration
- Planned installation: Q2 2021

VON ARDENNE

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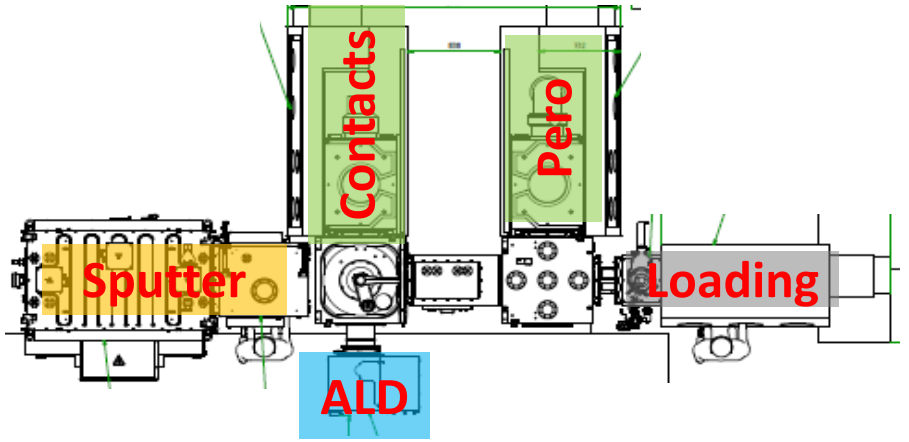
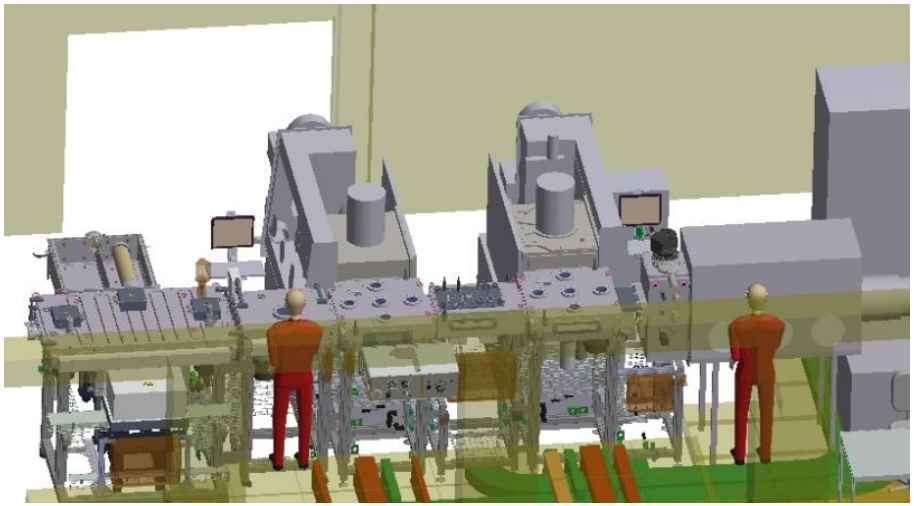
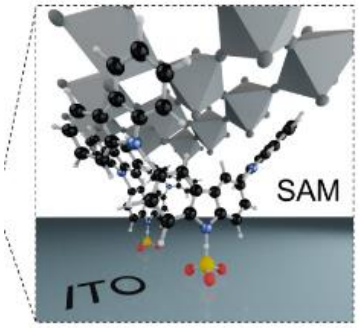
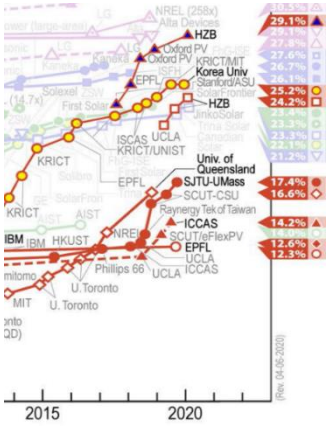


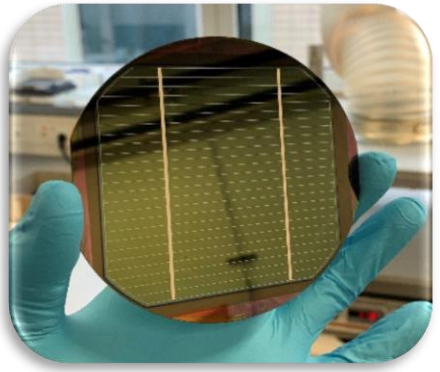


Conclusion

- Perovskite-based tandem solar cells: promising for next generation modules
- New versatile hole transporting SAMs
  - **Record certified 24.16% 2T Pero/CIGS tandem**
  - **Record certified 29.15% 2T Pero/Si tandem**
    - **Promising stability**
- New cluster tool for perovskite-based tandems on full wafer format
- Upscaling of perovskite via printing and thermal evaporation
  - **Promising tandem results with scalable methods**
  - **60 cm² perovskite/silicon tandem with 21%**







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