Highly Efficient Monolithic Tandem Solar Cells with Metal-Halide Perovskites

Prof. Dr. Steve Albrecht + many more

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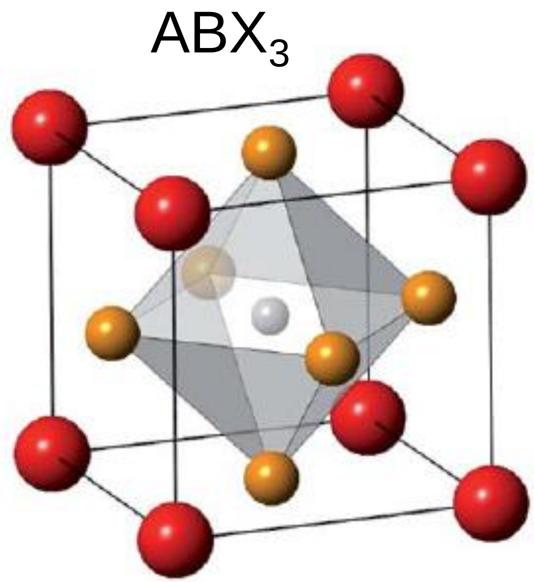
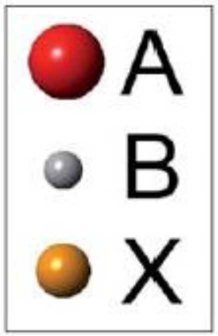
Virtual DPG Meeting "SKM21"

Sept. 27, 2021

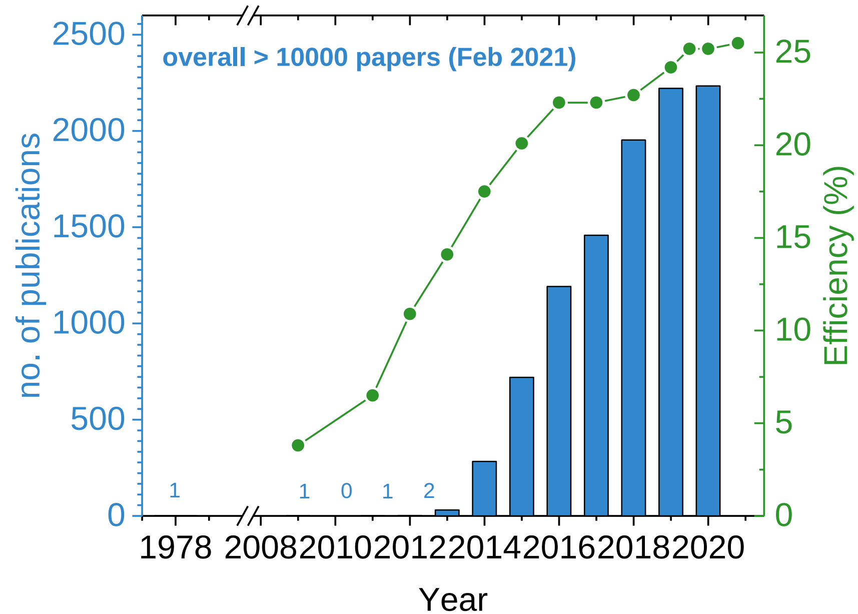
Perovskite: Crystal Structure and History

$CaTiO_3$





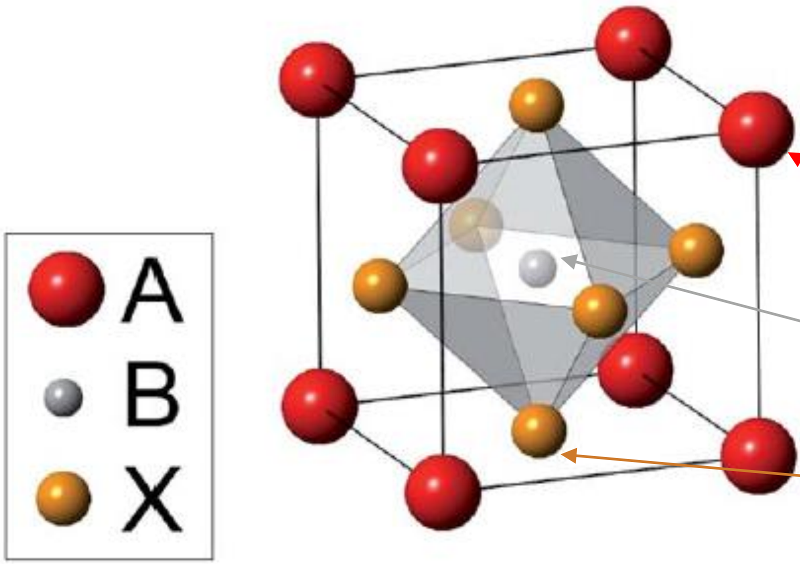
Snaith et al., Energy Environ. Sci., 2014, 7, 982



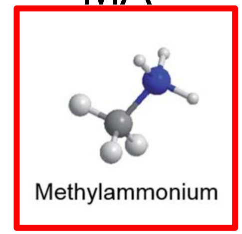
Source: Web of Science
Search in title „perovskite solar cell“

- First name “perovskite” appeared in 1840 by Gustav Rose for mineral $CaTiO_3$
- 2000 perovskites are currently known
- First “organic-inorganic” or “metal-halide” Perovskites by Dieter Weber in 1978
- First application in solar cells late 2008/09 with 3.8%, today over 25% efficiency

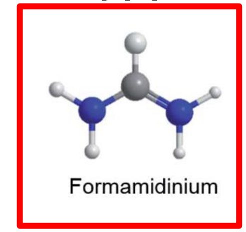
Metal Halide Perovskites



MA



FA



A = $CH_3NH_3^+$ or $HC(NH)_2)_2^+$ or Cs^+

B = Pb^{2+} (also Sb^{2+})

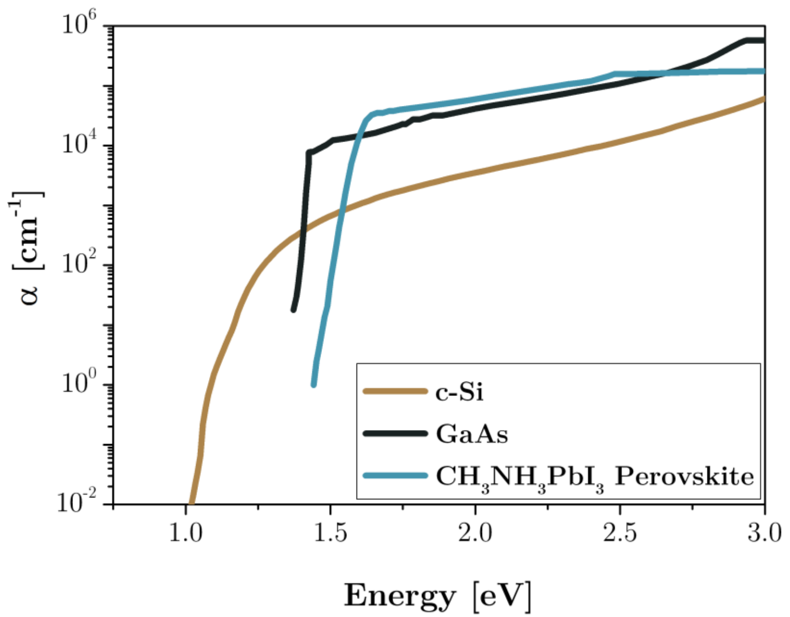
X = I^- or Br^-)

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

Methylammonium lead iodide	**$MAPbI_3$**
„Triple cation“	**$FA_{0.75}MA_{0.2}Cs_{0.05}Pb[I_{0.8}Br_{0.2}]_3$**

Saliba et al., Energy Environ. Sci., 2016, 9, 1989

Metal Halide Perovskites: Optical Properties



Absorber	E_g (eV)	α (cm^{-1})	Urbach energy (meV)
c-Si	1.1	10^2	11
GaAs	1.4	10^4	7
CIGS	1.1	10^3-10^4	25
CdTe	1.5	10^3	10
$MAPbI_3$	**1.55**	**10^3-10^5**	**15**

Organic-inorganic metal halide Perovskites

- Direct, bandgap ~1.55 eV for $MAPbI_3$
- tunable bandgap via composition
- Very few sub bandgap features
- High absorption → thin layers <1 µm required

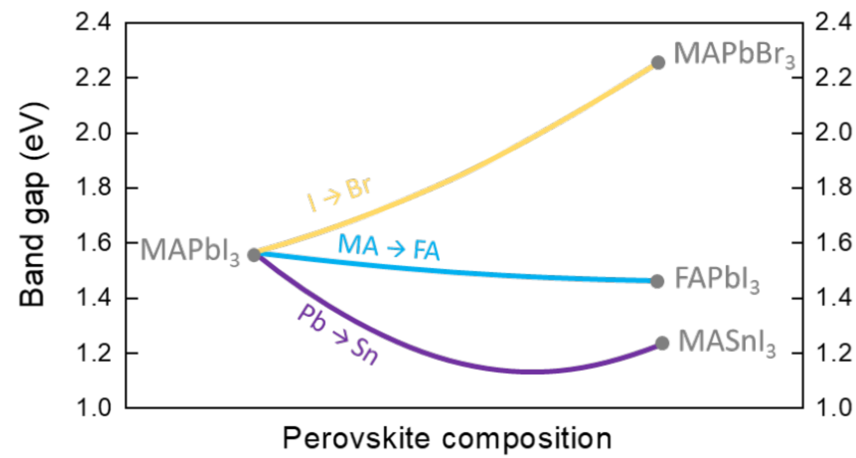
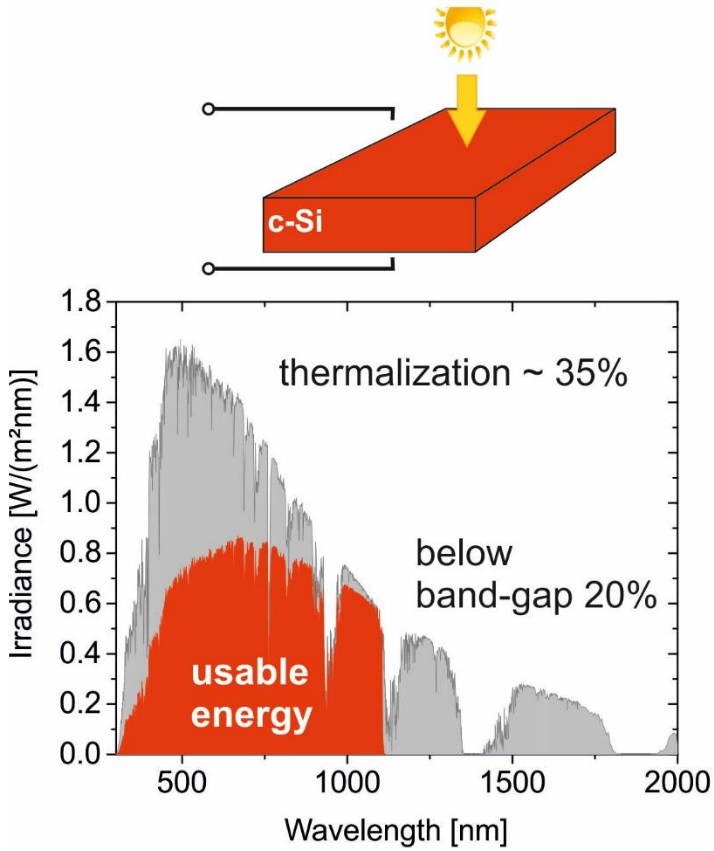
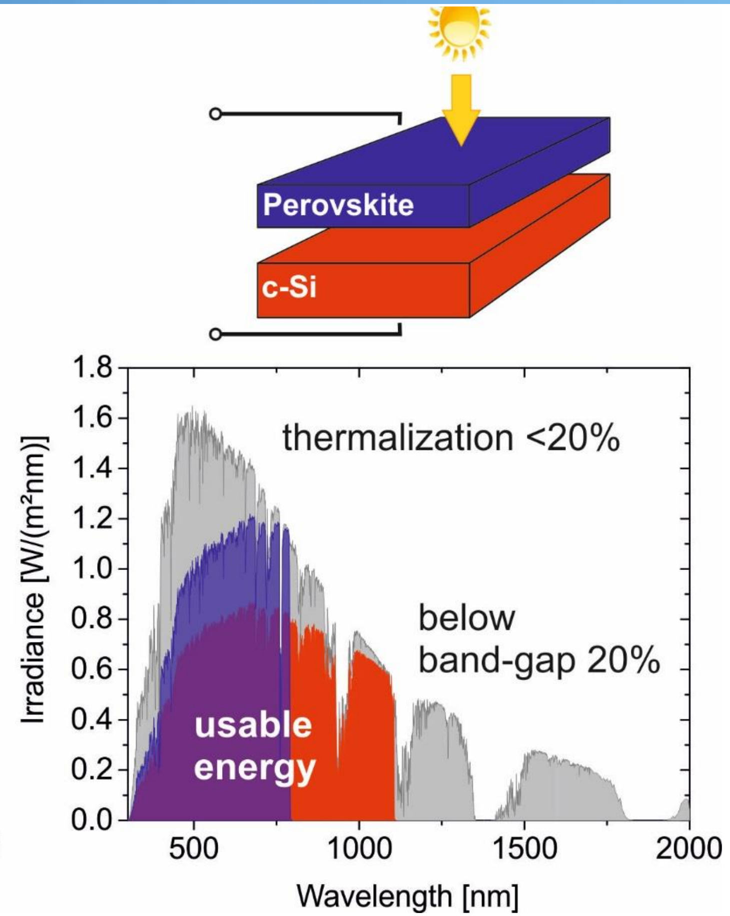


Image courtesy: Selina Olthof (Uni. Cologne)

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 Pero Tandems

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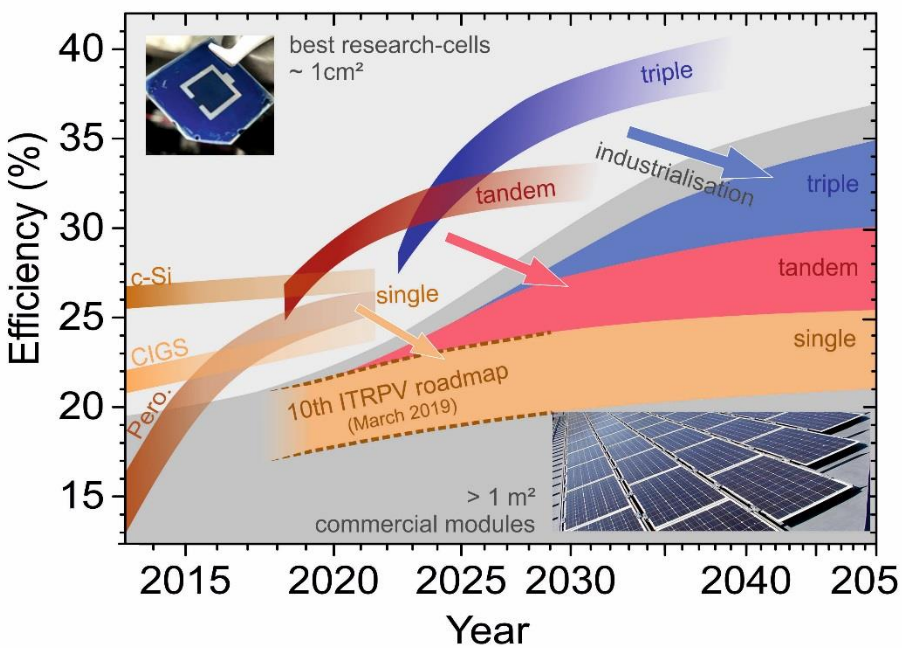
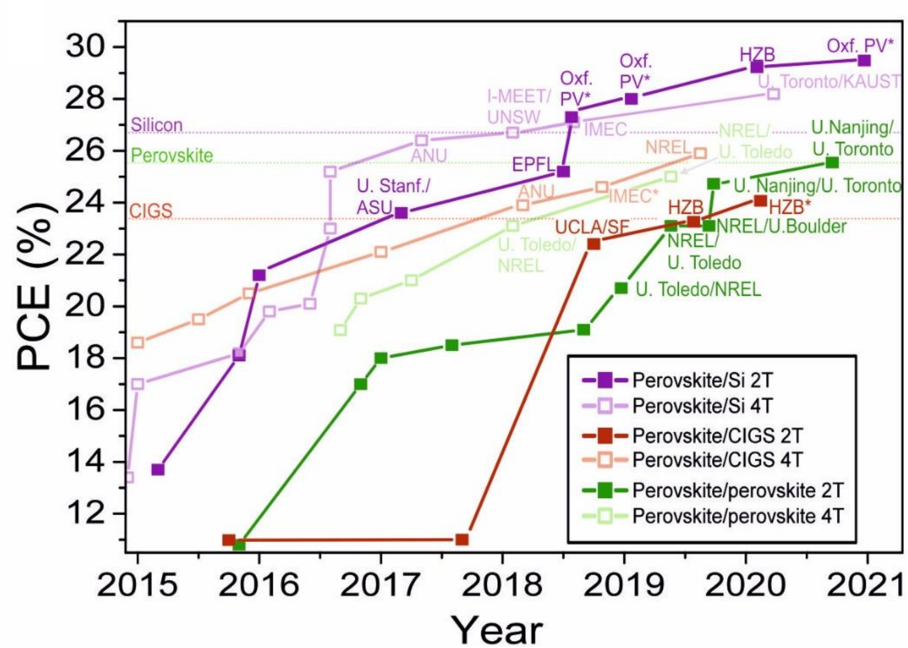




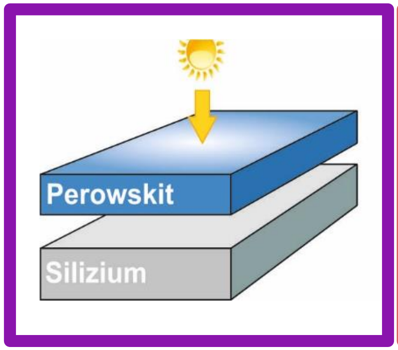
- Single junctions will be limited in efficiency
- Multi-junctions with perovskite top cells can overcome fundamental limitations

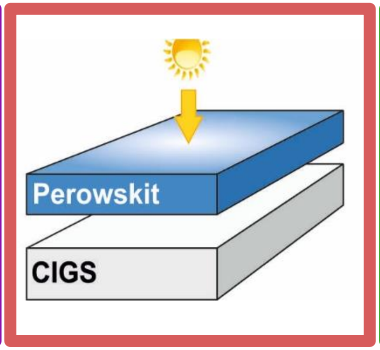
Jost et al., Advanced Energy Materials, 2020,
DOI: 10.1002/aenm.201904102

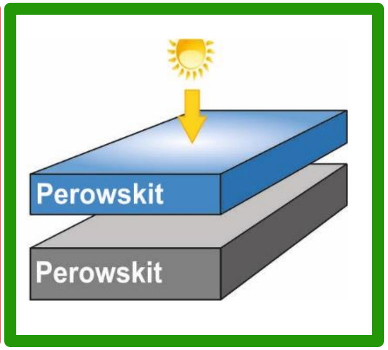
- Main 2T achievements:
- 29.5% record in Dec. 2020
  - Higher than best Si single junction!
- After long time w/o results: Recently promising results 24.2% with Perovskite/CIGS tandems
  - Similar to best CIGS single junction!
- Improvements in Sn-based Perovskites enabled 24.2% Perovskite/Perovskite tandems

certified, > 1cm²

Outline







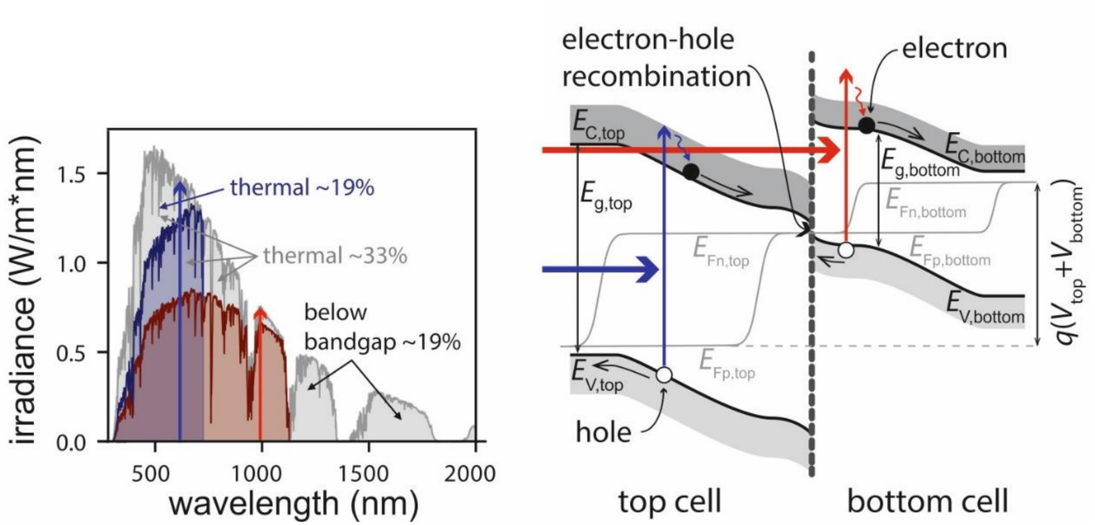
1. Results on Perovskite/Silicon Heterojunction (SHJ) Tandems
2. Results on Perovskite/CIGS Tandems
3. Towards all-Perovskite Tandems
4. Upscaling of Perovskite-based Tandems

Results on Perovskite/SHJ Tandems

How does a 2T-Tandem Solar Cell work?

In series connected tandem:

- 2 absorption events
- 2 electron-hole pairs
- Recombination layer needed



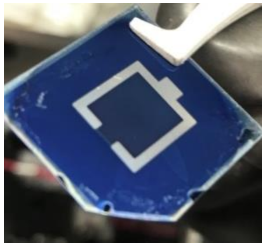
www.istockphoto.com

In series connected tandem:

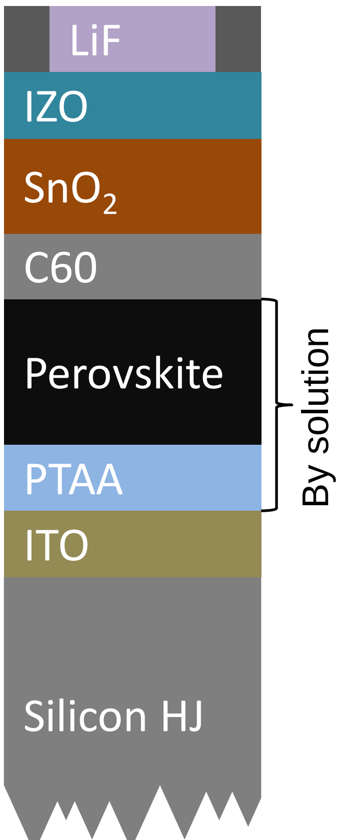
- Voltages add up
- Current limited by limiting sub-cell
- Current matching needed

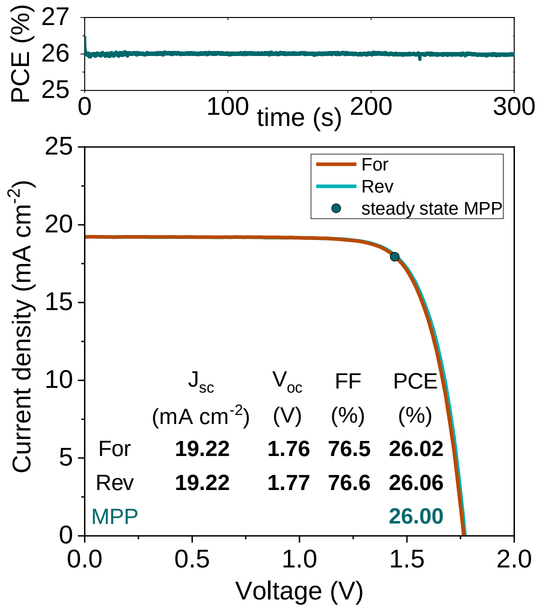
Further optimized monolithic tandem

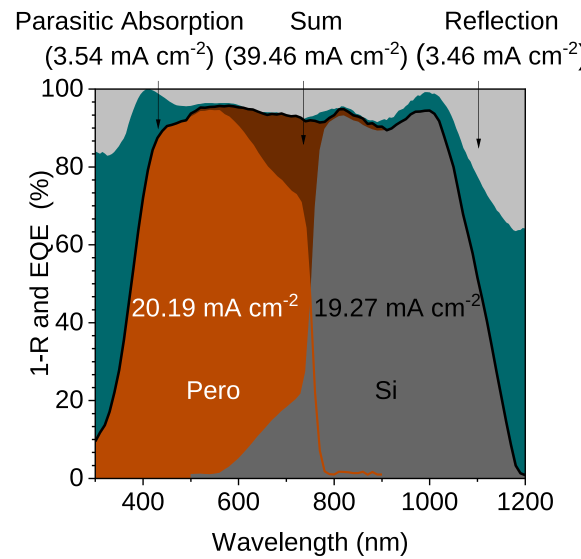
~1 cm²



Overall, ~ 15 layers !



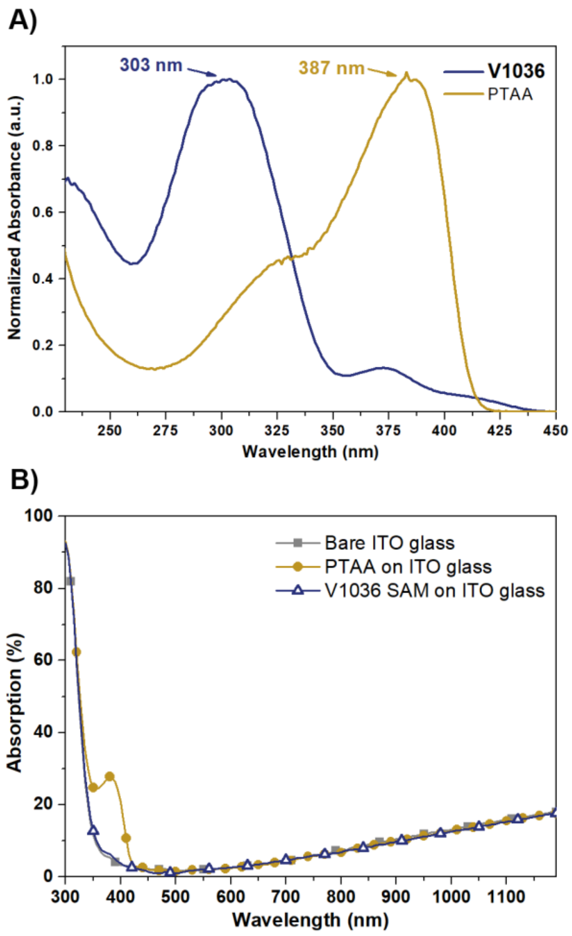


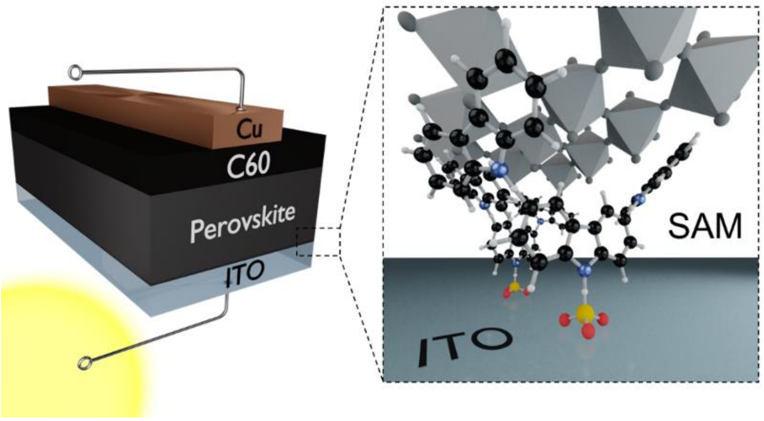


- Perovskite band gap ~ 1.63 eV, Voc ~1.1V
- HTM for perovskite Top-cell was polymer PTAA
  - **Limited Voc due to interface recombination and non-optimized band gap**
  - **Limited FF as well!**

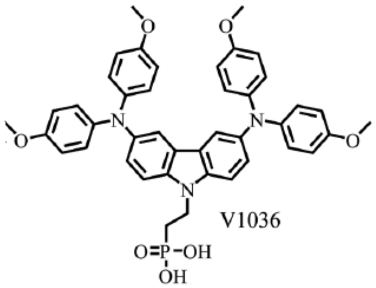
Köhnen et al., Sustainable Energy & Fuels, 2019,3,1995

1st Generation hole transporting SAM V1036





kaunas university of technology

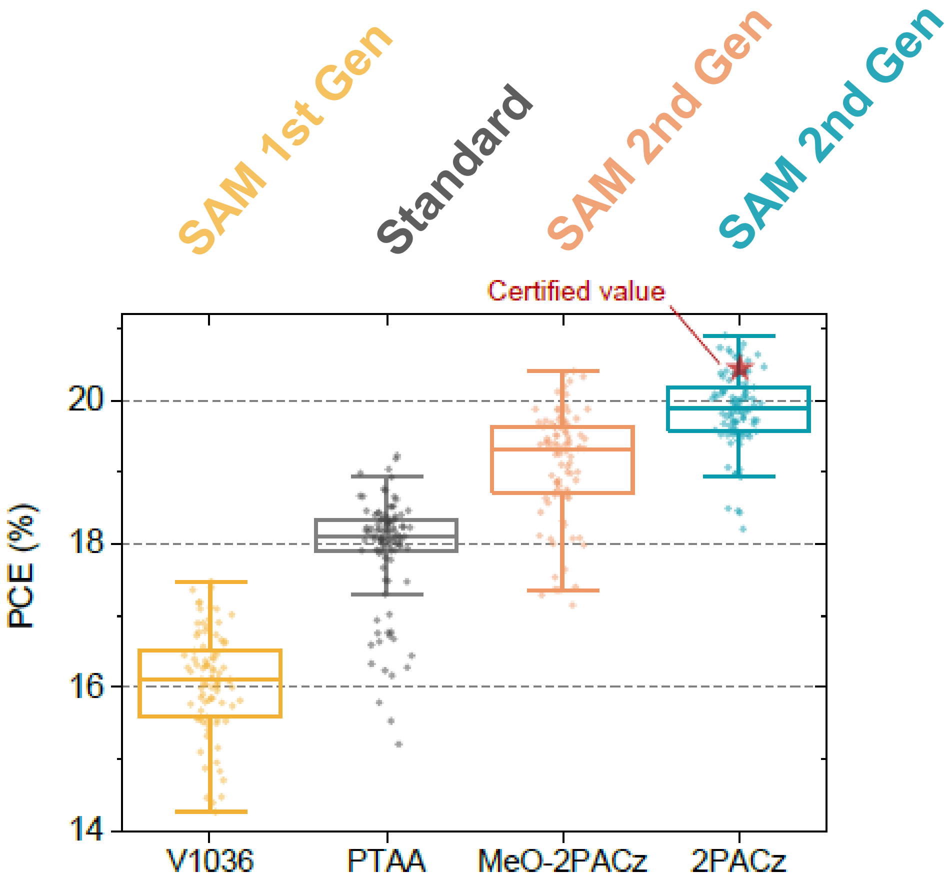


„SAM 1“

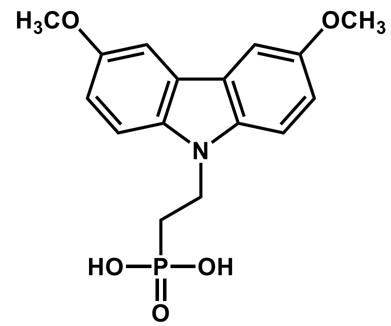
- Covalent bonding to ITO, robust against solution processing
- Reduced absorption loss
- Close to 18% PCE in p-i-n perovskite solar cell

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

2nd Generation SAM Meo-2PACz, 2PACz



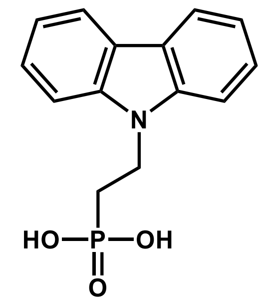
„SAM 2“



MeO-2PACz

- Terminated by methoxy groups

„SAM 3“



2PACz

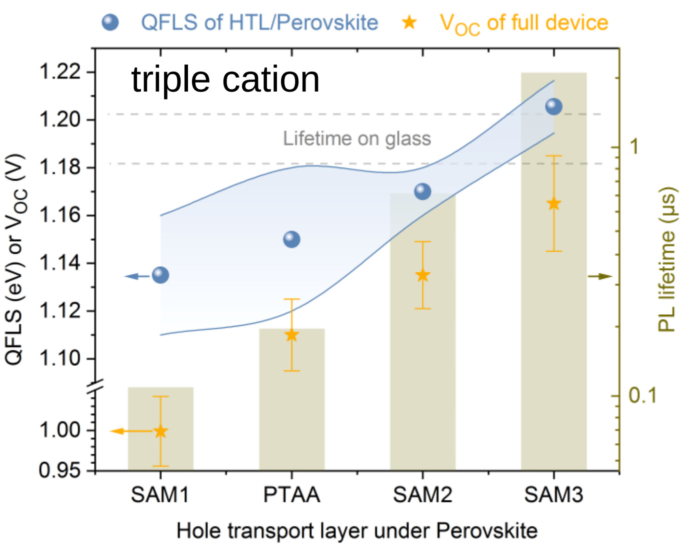
- Simplest possible Carbazole SAM

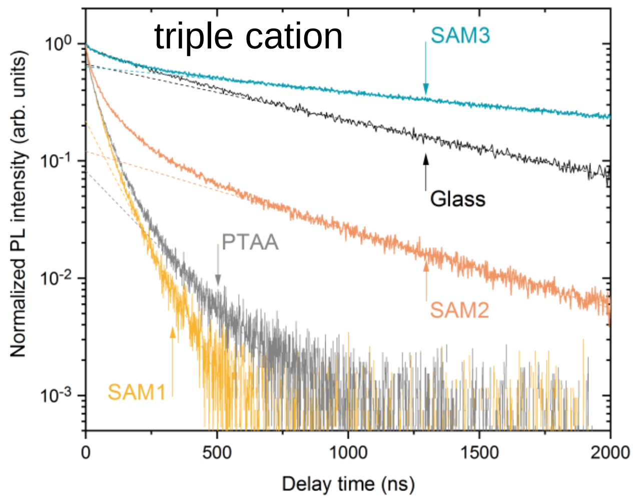
MeO-2PACz and 2PACzprovided by

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

2nd Generation SAM Meo-2PACz, 2PACz



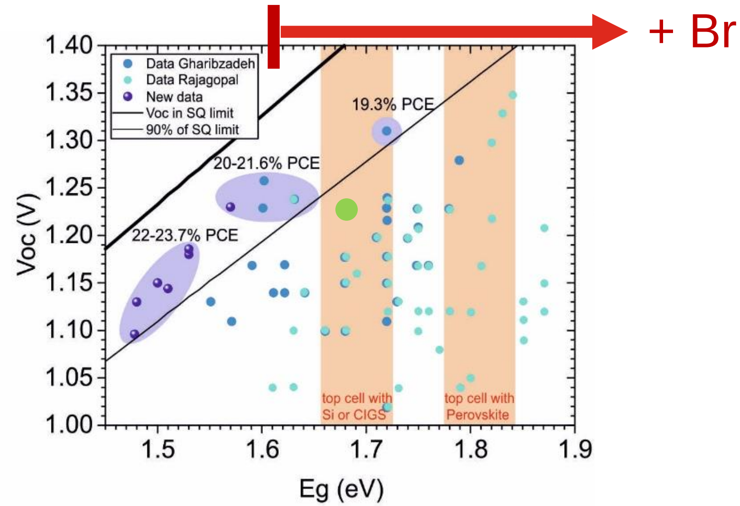


New SAMs 2 and 3 with superior properties:

- Higher PL lifetimes and QFLS and Voc
  - SAM 3: higher than quartz glass (passivation)
- Perfect energetic alignment

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

3^{rd} Generation of SAM: Stable 1.68 eV Perovskite



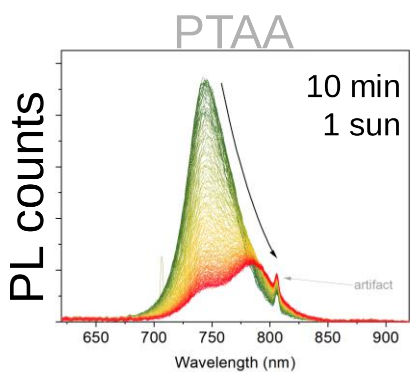
Jost et al., Adv. En. Mater., 2020,DOI: 10.1002/aenm.201904102

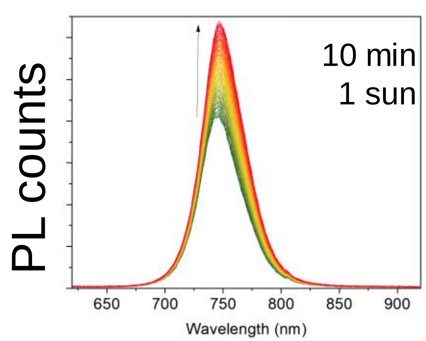
Problem:

- Highest single cell efficiency with 1.5 eV
- For 1.7 eV compositions
  - Limited photo-stability
  - Phase segregation
  - Non-optimized contacts

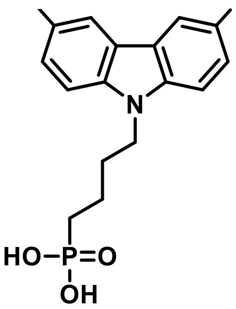
New SAM = Me-4PACz:

- Efficient passivation
  - High QFLS → High V_{oc}
- High photo-stability
  - Reduced phase segregation



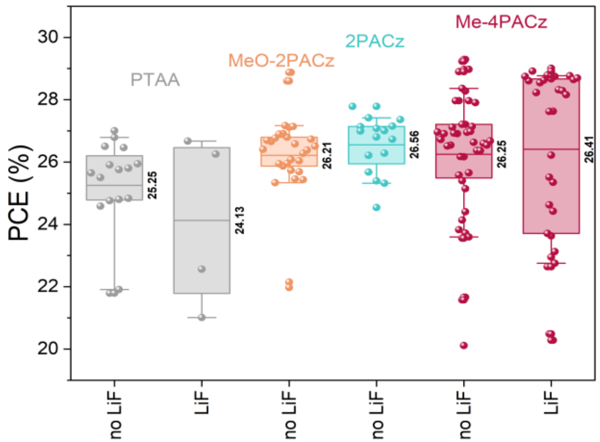


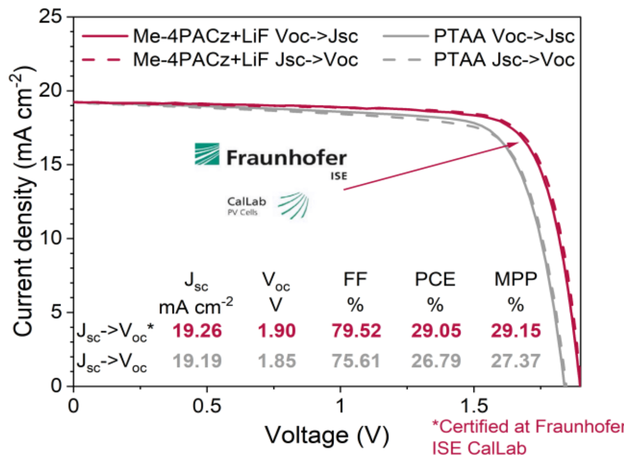
„SAM 4“

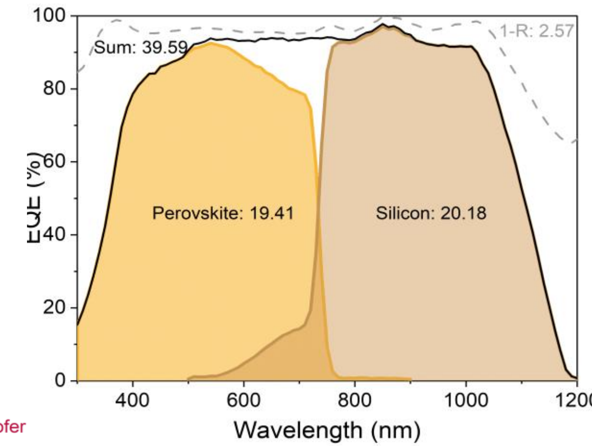


Al-Ashouri, Köhnen et al, Science (2020),DOI: 10.1126/science.abd4016

3rd Generation of SAM: Record Tandem

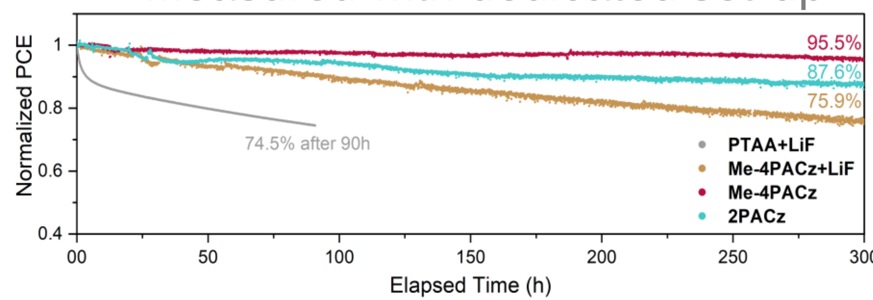






- Fine-tuning and stabilizing of Perovskite band gap to ~1.68 eV
- Enhanced hole extraction for higher FFs
- Slightly Perovskite limited in photocurrent
- **Record 29.15% efficiency (>1 cm²)**
- **Promising stability data (300 h)**

Measured with dedicated set-up



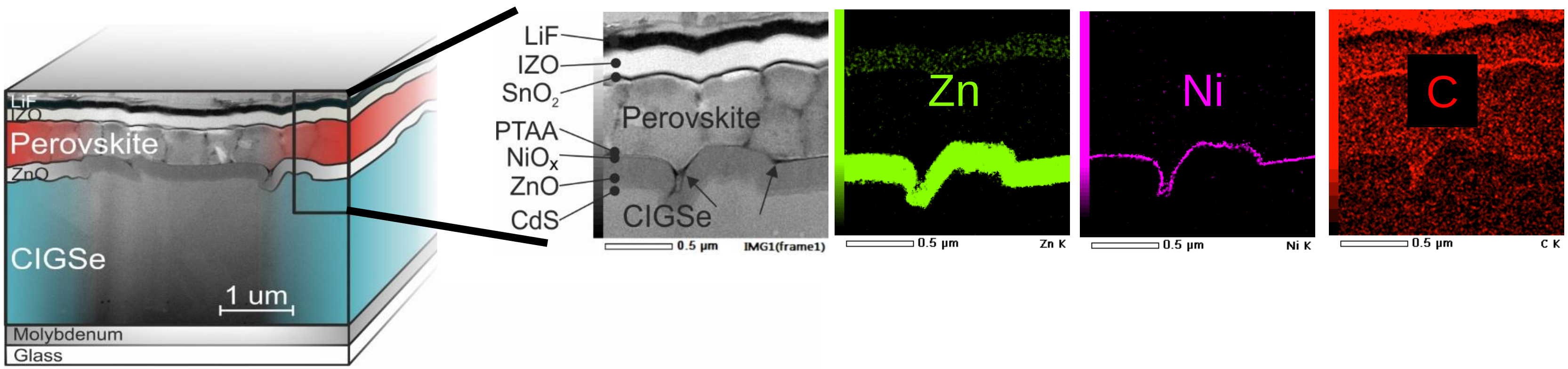
Al-Ashouri, Köhnen et al, Science (2020),DOI: 10.1126/science.abd4016

Results on Perovskite/CIGS Tandems

Recent 2T Perovskite/CIGSe Tandem

- So far <5 publications on monolithic pero/CIGSe tandems
  - › Rough CIGS surface induces problems with spin-coating of top cell
  - › Recently, polished TCO surface was implemented by UCLA and Solar Frontier [1]

- Here, we use conformal ALD layers of NiOx as hole contact [2]



- ALD NiOx prevents shorts on rough surface
- Partial coverage with PTAA enables improved Voc and FF
- 21.6% stabilized efficiency (0.8 cm² active area)

[1] Han et al., Science 2018, 361, 904

[2] Jost et al., ACS Energy Lett. 2019, 4, 2, 583

Record 2T Perovskite/CIGSe Tandem 2019

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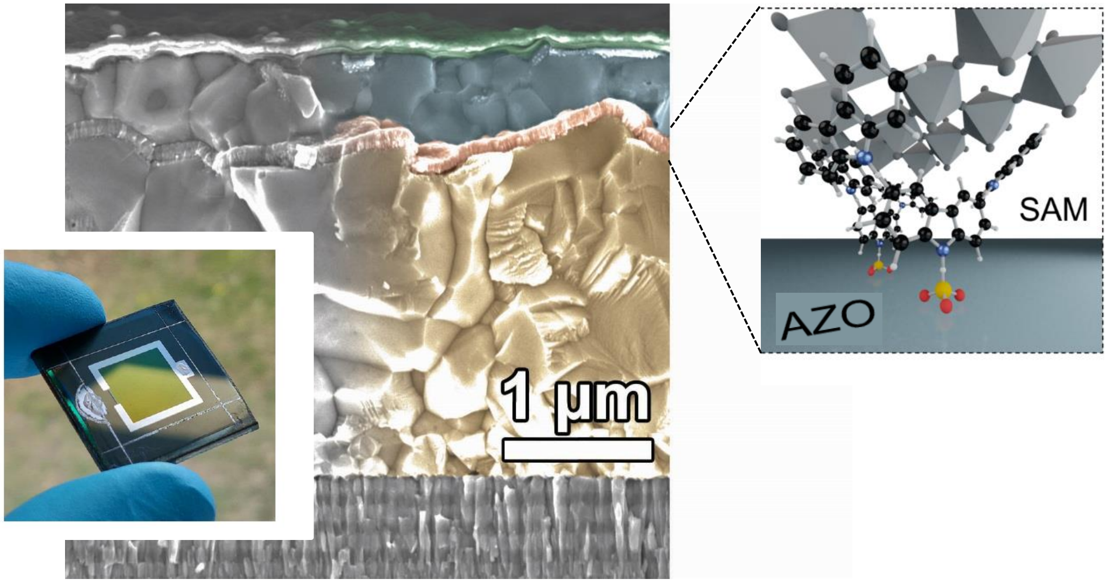
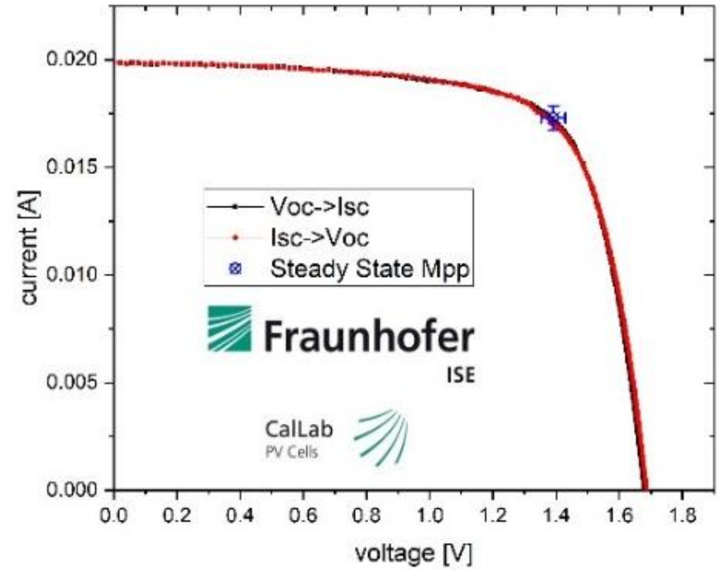
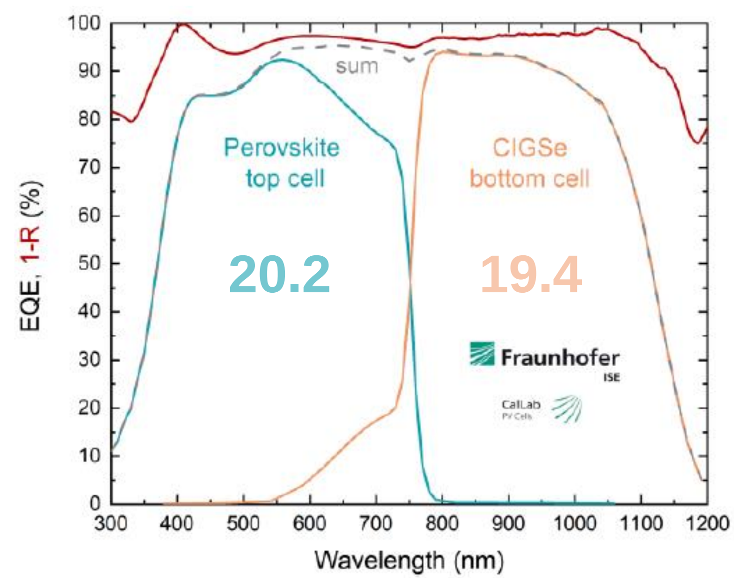


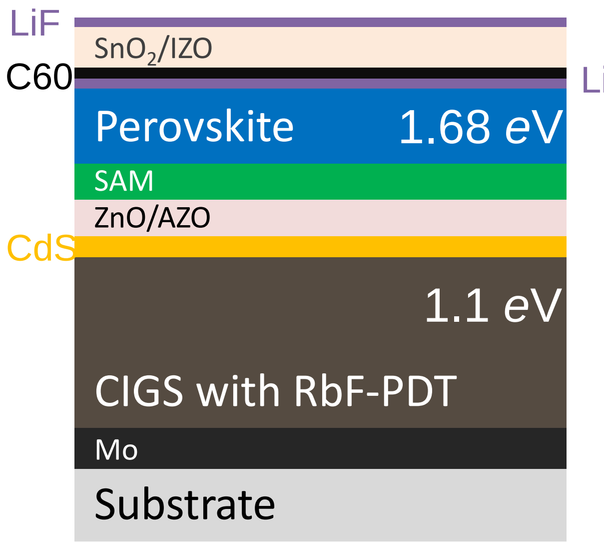


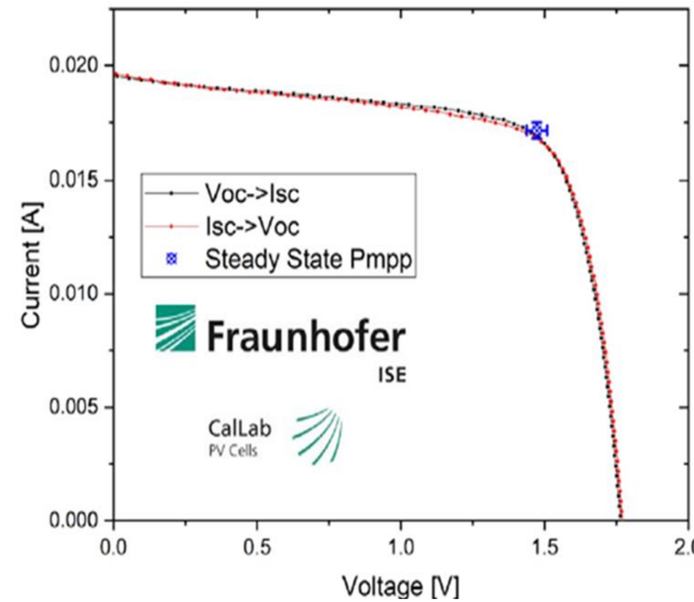


- 2nd Gen SAM integrated directly on top of rough CIGSe
- Optimized optics and SAM-improved Voc

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

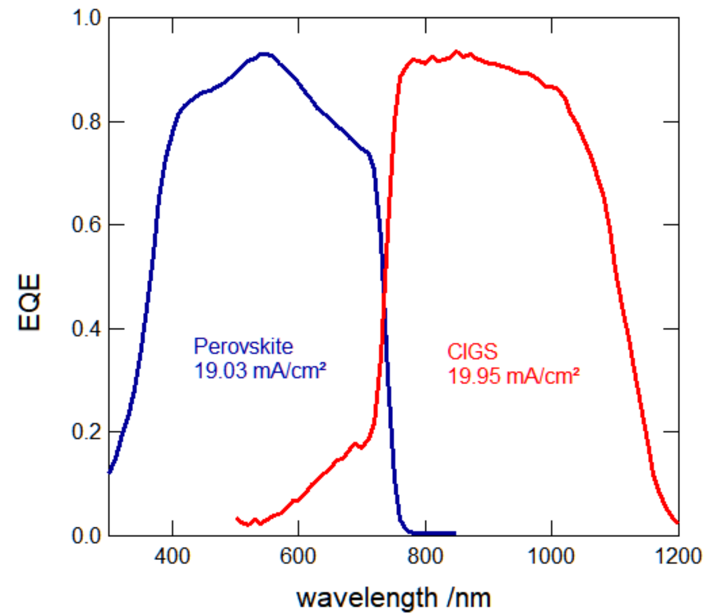




- 3rd Gen SAM integrated directly on top of rough CIGSe
- Optimized perovskite band gap - higher Voc

Area (cm^2)	MPP (%)	Jsc (mA/cm^2)	Voc (V)	FF (%)
1.045	24.16	18.8	1.77	72

Jost et al, manuscript in prep.



Perovskite/CIGSe Tandem: ready for space?

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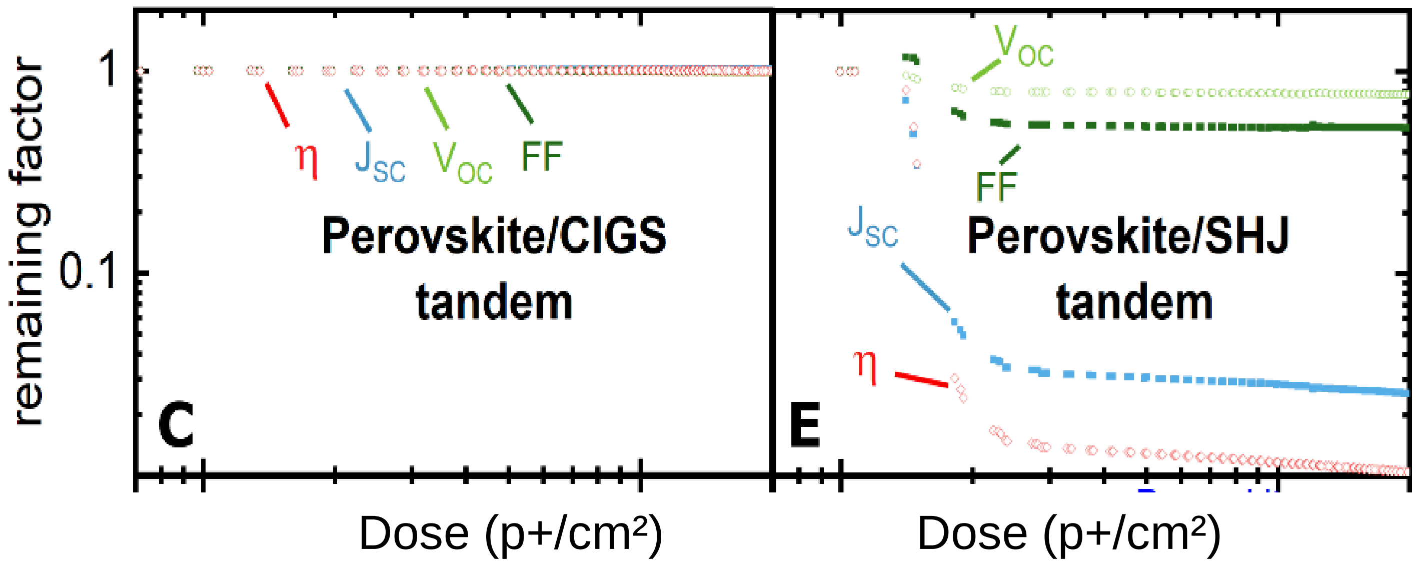
UNIVERSITY OF CAMBRIDGE



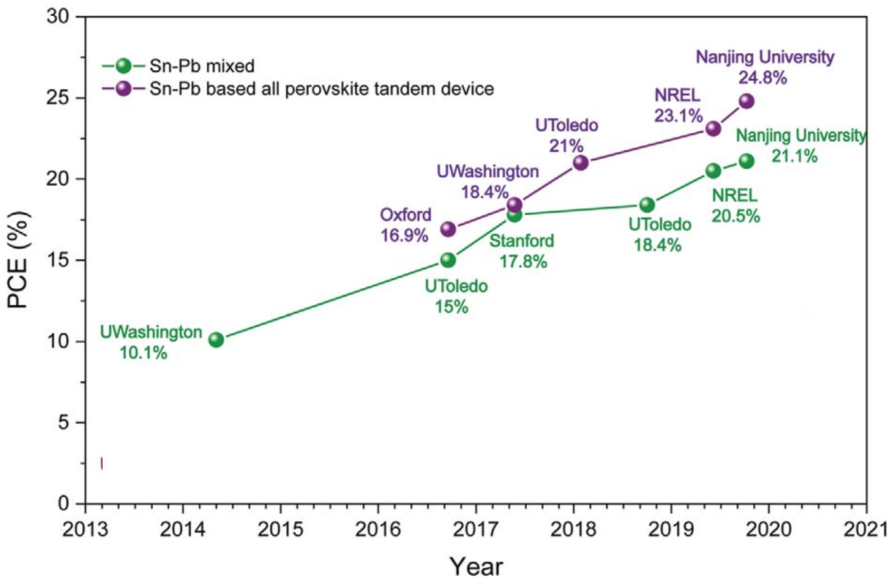
- Pero/CIGS is stable under proton dose of >50 years at the ISS orbit!

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

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

Towards all-Perovskite Tandems

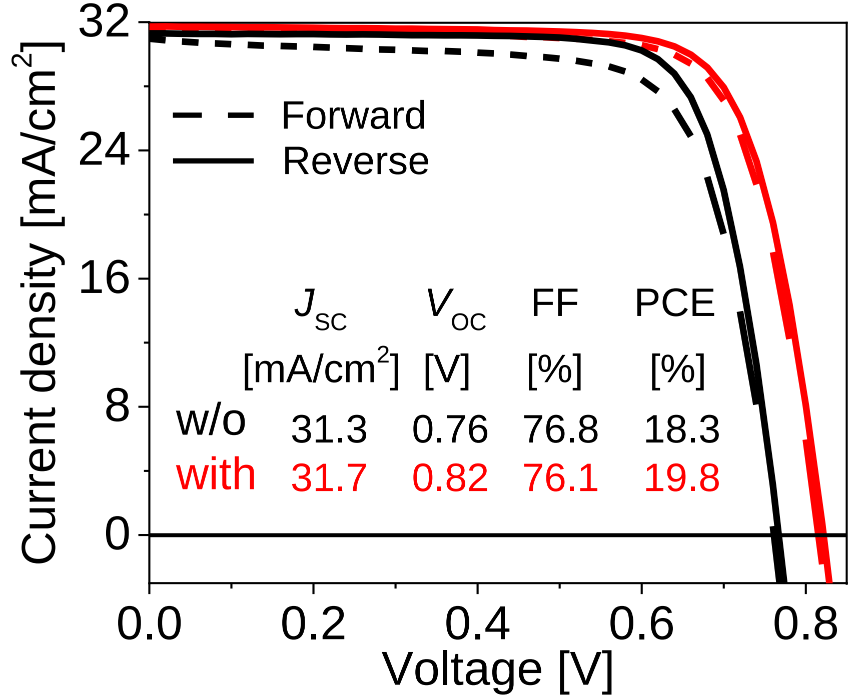
Sn-Pb Low Band Gap Perovskite Solar Cells



*S, Gu, et al. Adv. Mater. **2020**, 1907392.*

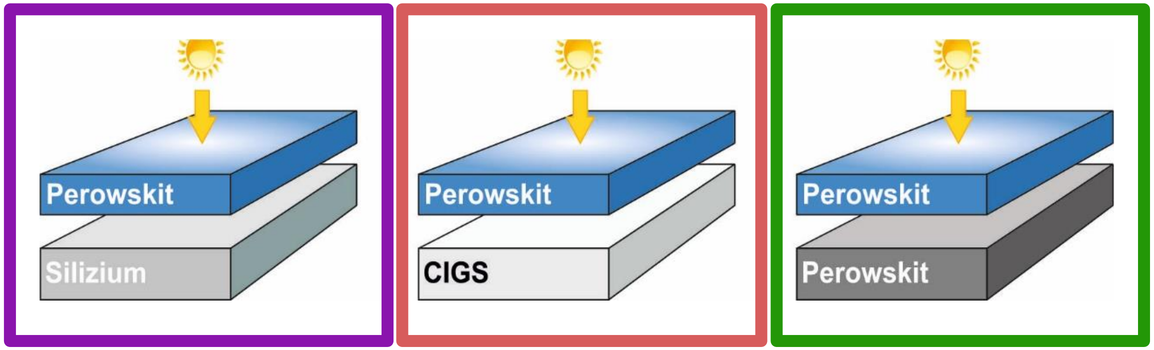
- Progress of all-perovskite monolithic tandem solar cells
- Depends on low band gap Sn-Pb bottom cell

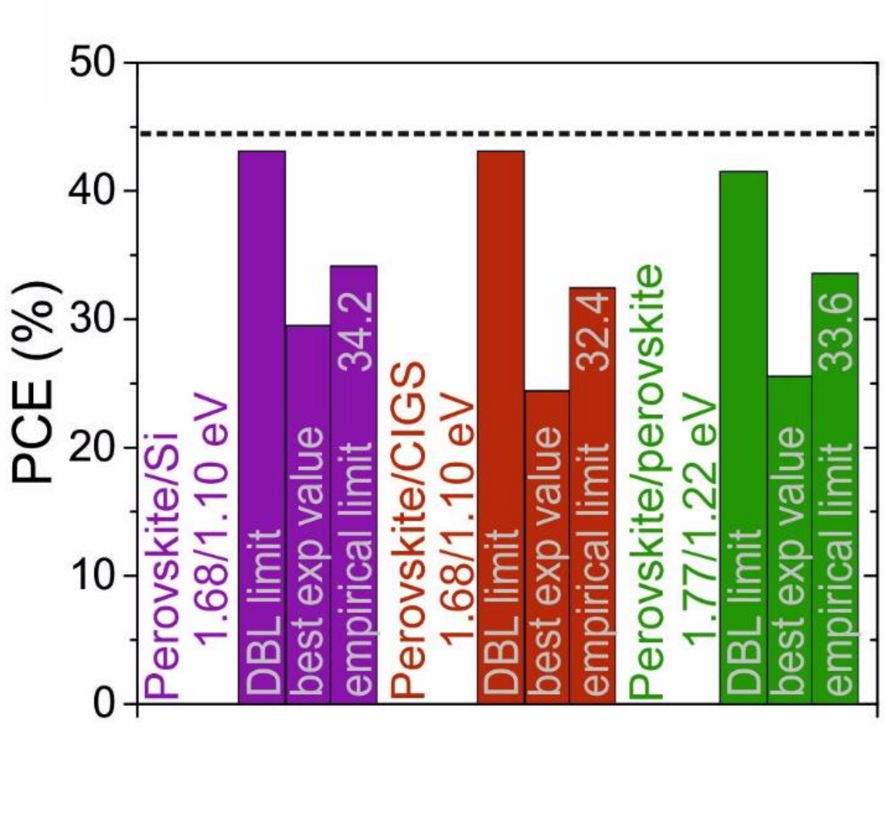
- New additive for Sn-Pb perovskites
- improved lifetime, PL yield and Voc
- Up to 20% with a band-gap of 1.25 eV



Fengjiu Yang, in preparation

Finally >30%





What we learn:

- Perovskite-based tandem solar cells with **Silicon**, **CIGS** or **perovskite** bottom cells have 32-24% efficiency potential

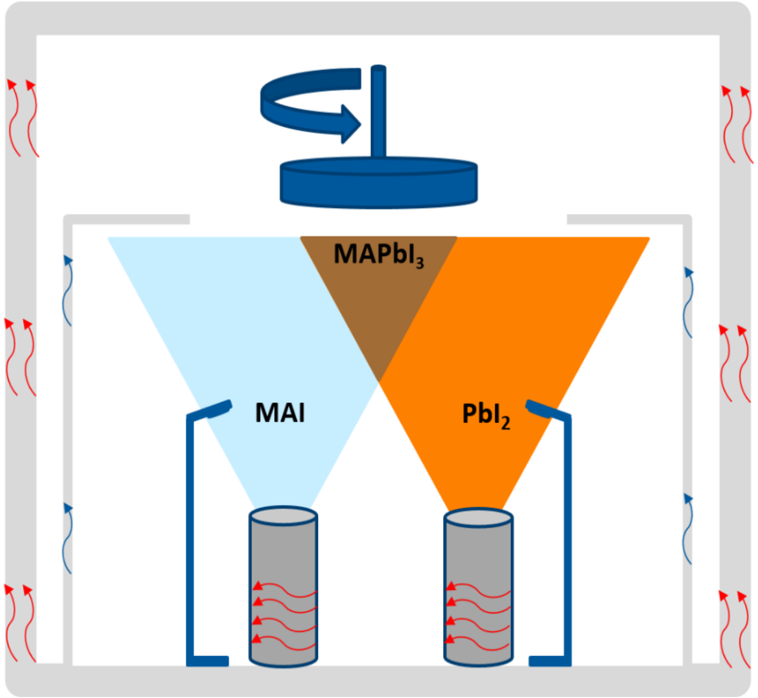
Yang and Albrecht et al., APL Materials submitted

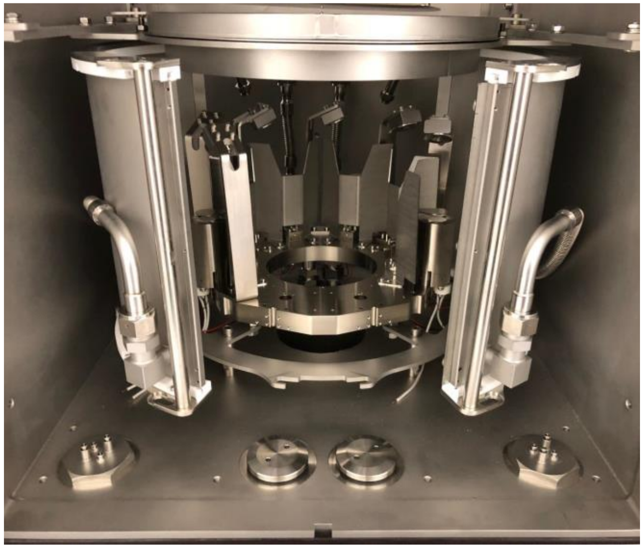
Upscaling of Perovskite Solar Cells

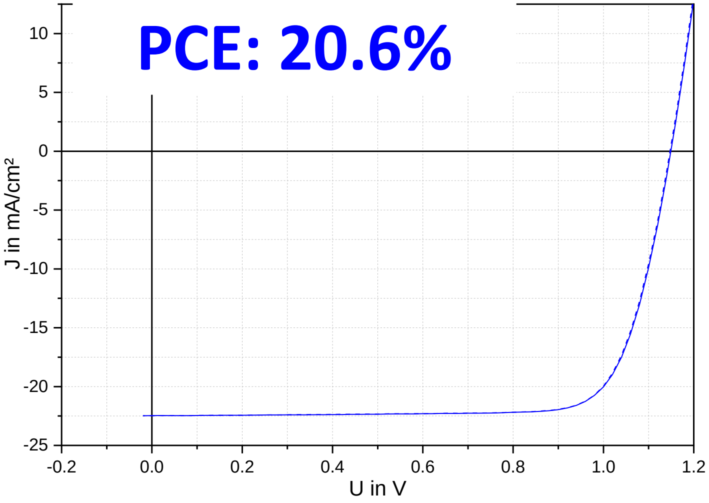
Direct Co-Evaporation of Perovskite

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

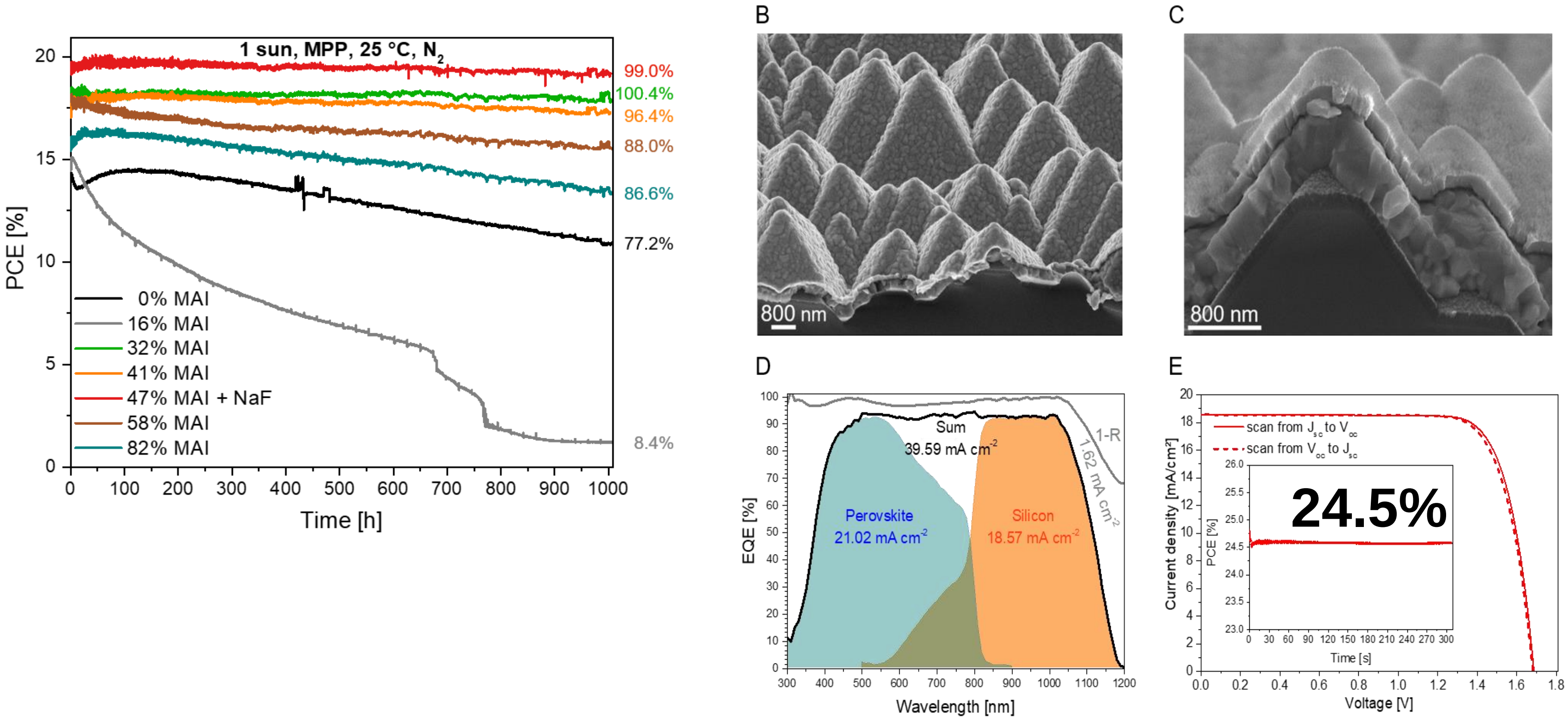






Roß et al., ACS Appl. Mater. Interfaces 2020, 12, 35, 39261–39272

Fully textured co-evaporated pero/Si tandems



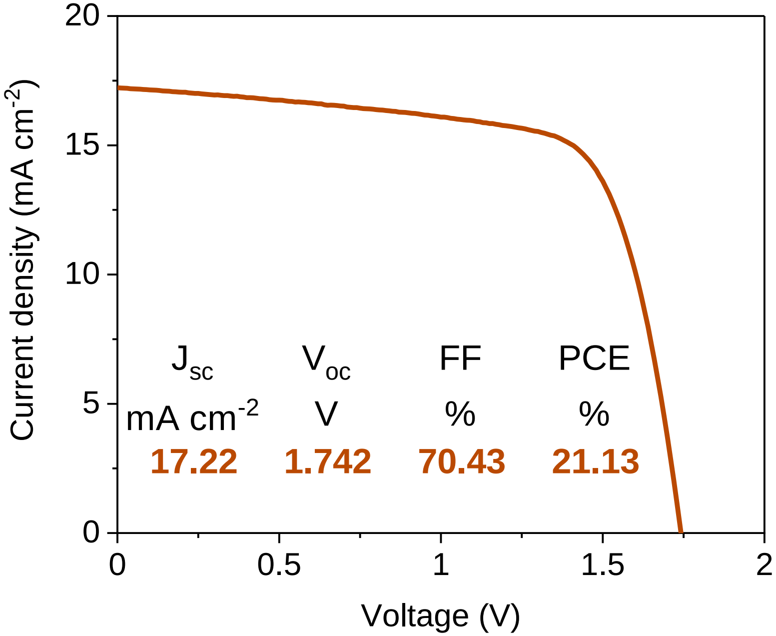
- High stability $MAFAPbI_3$ perovskite composition
- High robustness against top contact processing
- First demonstration of fully textured perovskite/silicon tandems from co-evaporation

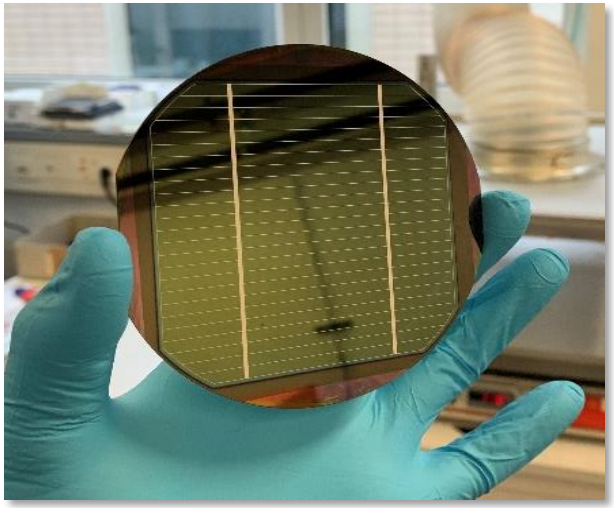
Roß et al., 2021, submitted

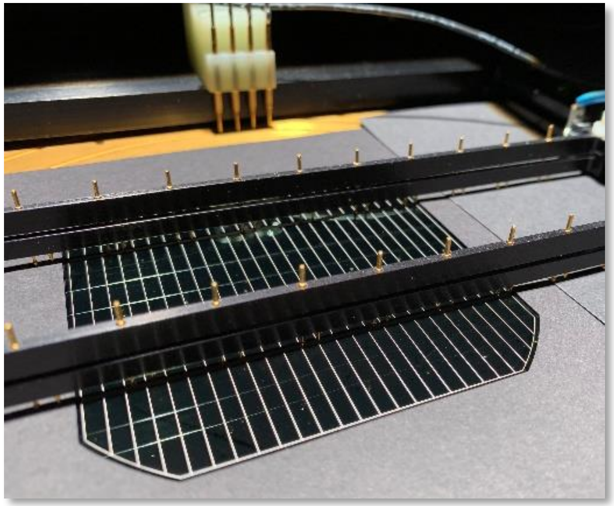
Large area Perovskite/Silicon Tandem

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"

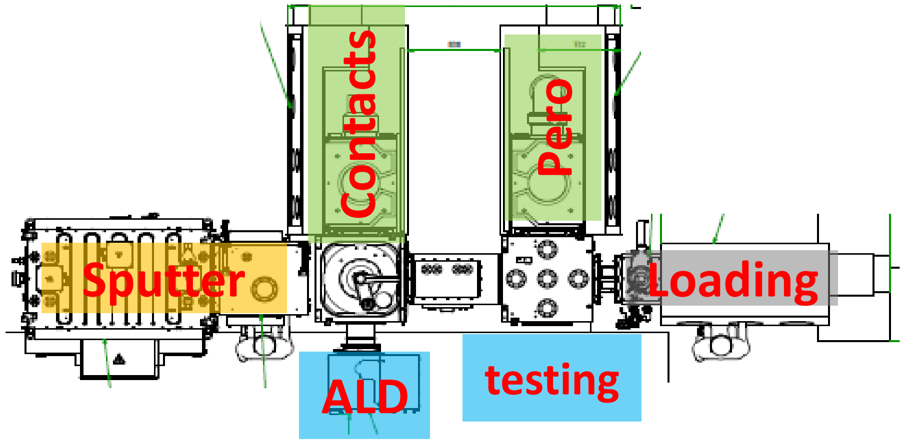
HZB Helmholtz Zentrum Berlin

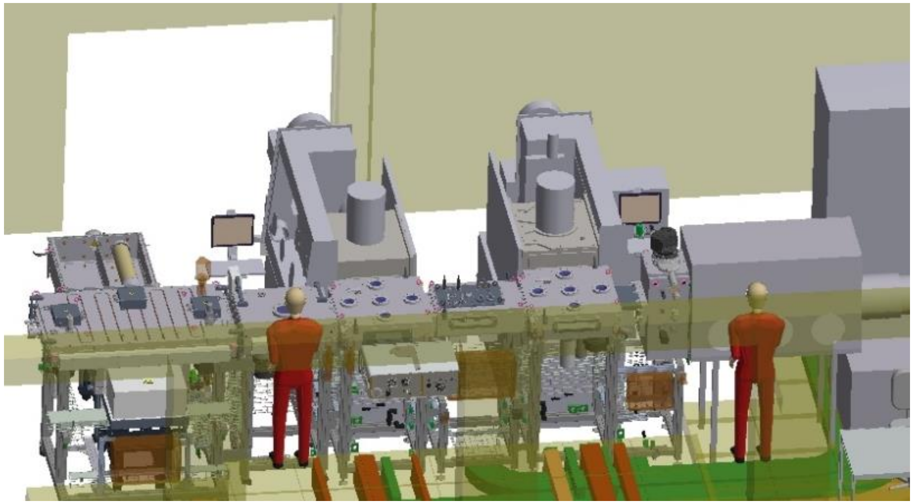
VON ARDENNE

Federal Ministry for Economic Affairs and Energy

CREAPHYS MBRAUN GROUP

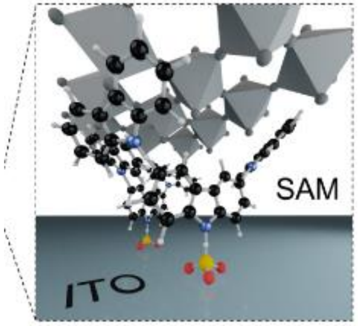
- Designed for 6" perovskite-based tandem solar cells
- Focus on vacuum deposition
  - Co-evaporation
  - Sputter deposition
  - ALD
- Baseline integration + industry collaboration
- Planned operation: 2021

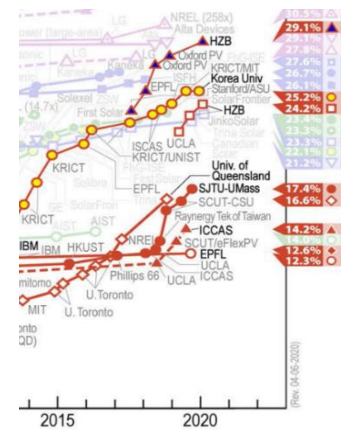


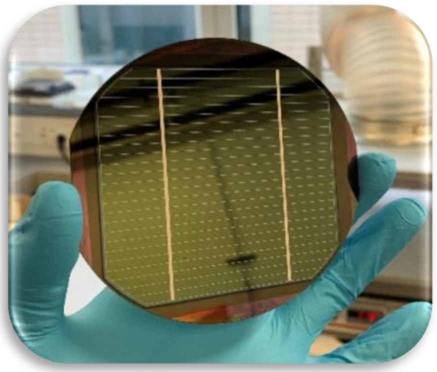


Conclusion and Summary

- Perovskite-based tandem solar cells: promising for next generation modules
- New versatile hole transporting SAMs
  - High passivation, selectivity and fast extraction
  - Stabilizing the 1.68 eV band gap
  - Record certified 24.16% 2T Pero/CIGS tandem
  - Record certified 29.15% 2T Pero/Si tandem
- Upscaling of perovskite via printing and thermal evaporation
  - Promising tandem results with scalable methods
  - First proof-of-concept on textured Si
  - 60 cm² perovskite/silicon tandem with 21%
  - New cluster tool for 6” perovskite-based tandems







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DFG Deutsche Forschungsgemeinschaft

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Thank you for your attention!

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