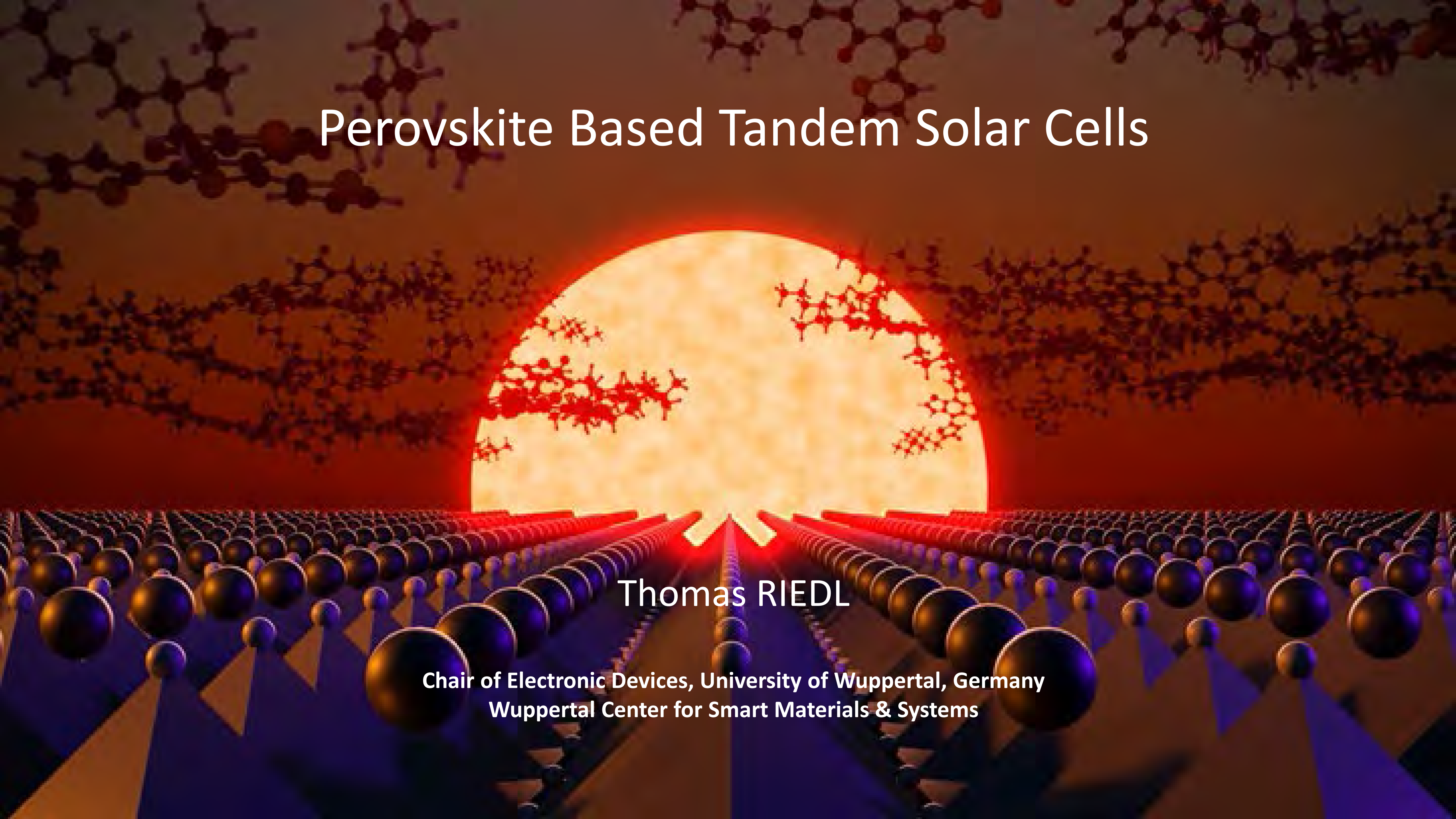
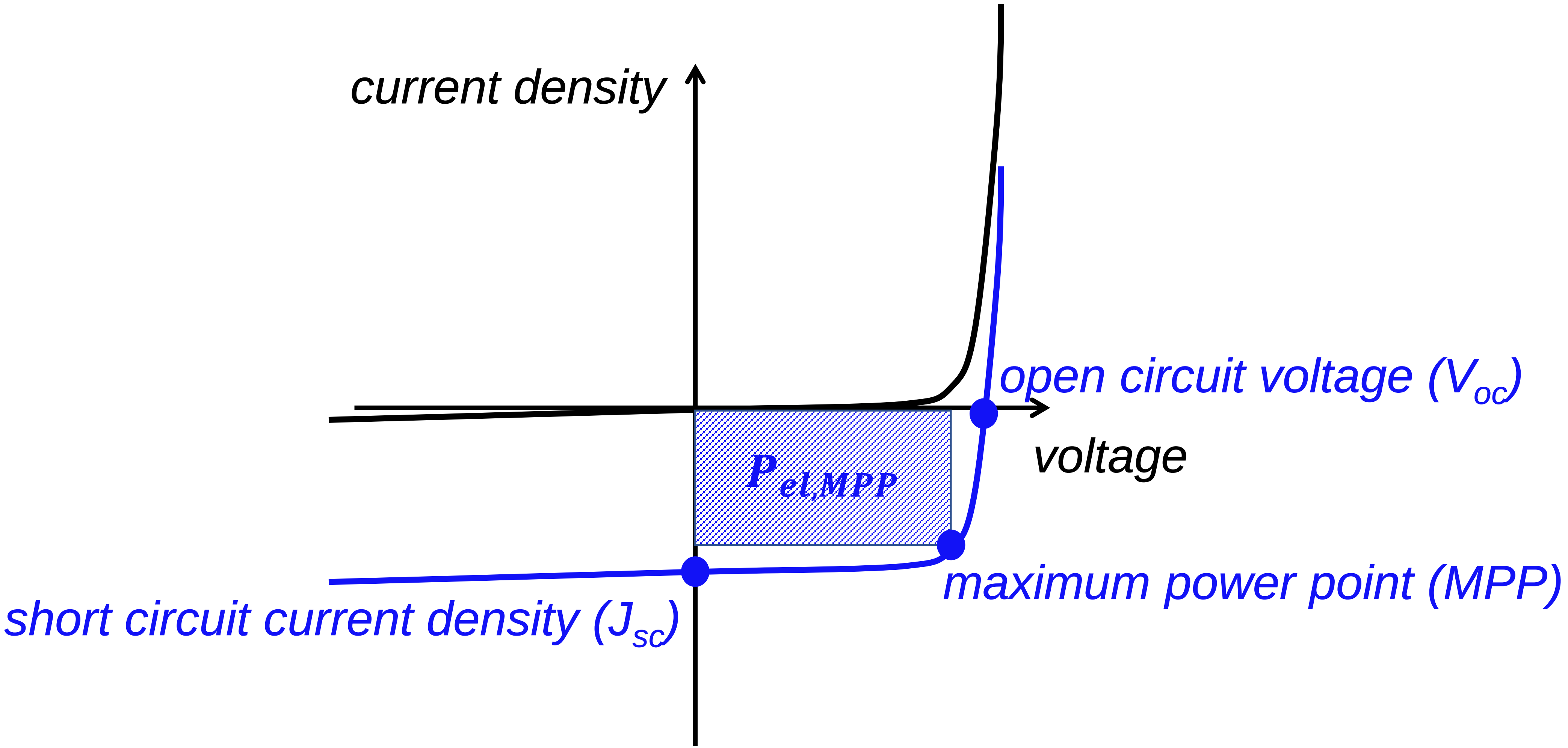


Perovskite Based Tandem Solar Cells

Thomas RIEDL

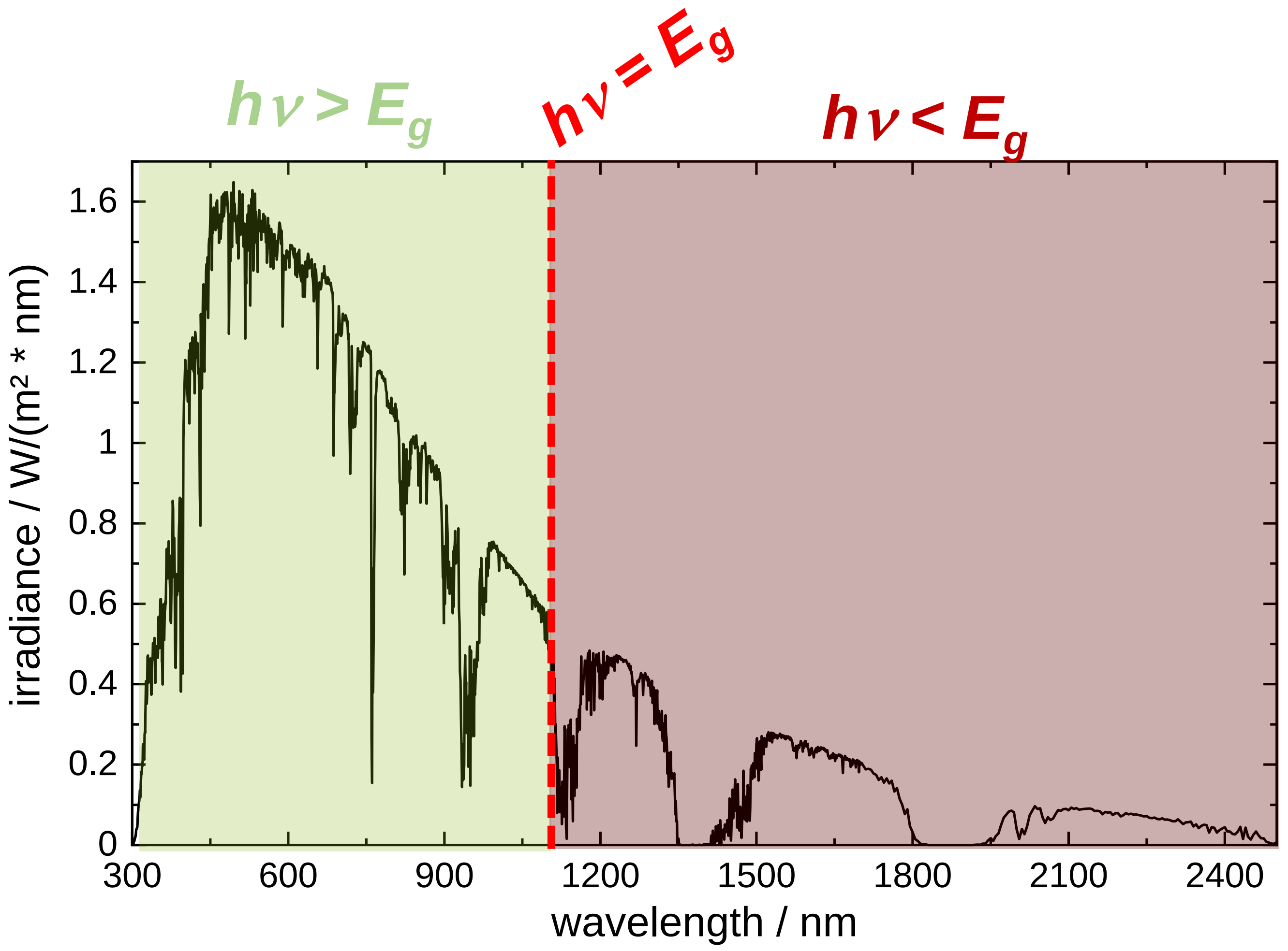
Chair of Electronic Devices, University of Wuppertal, Germany
Wuppertal Center for Smart Materials & Systems

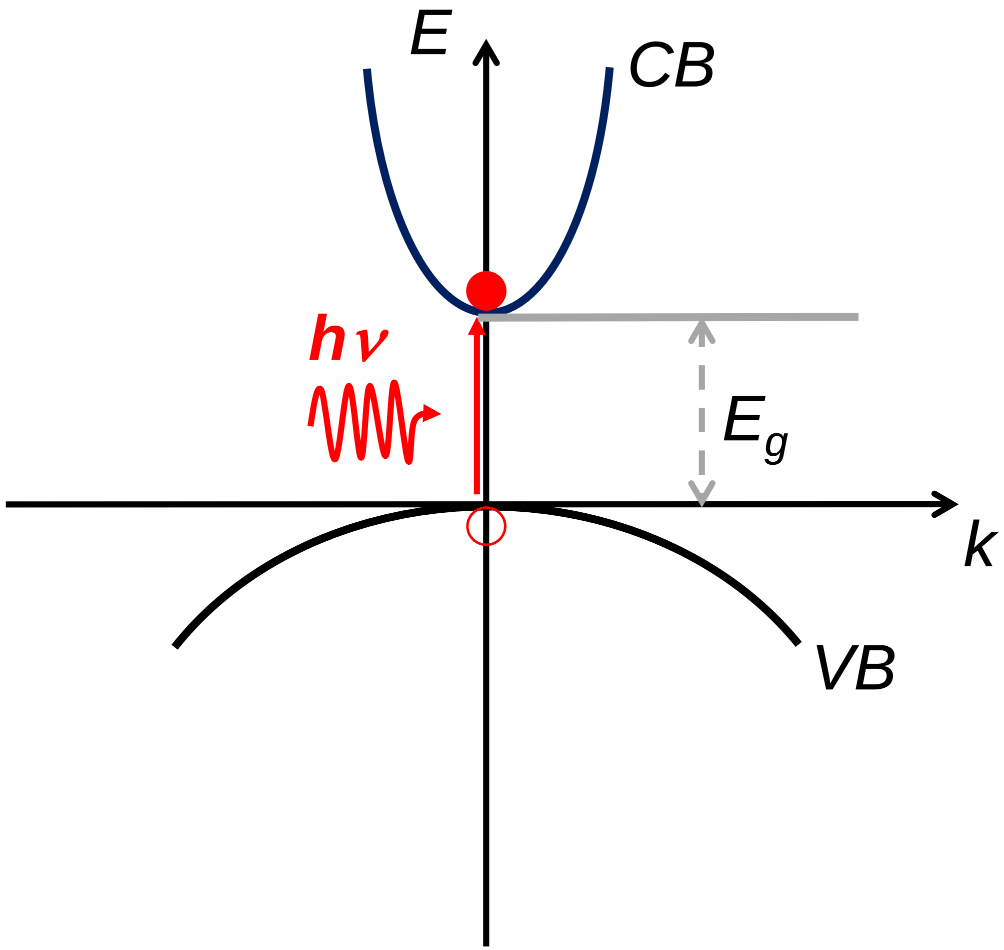
Motivation – why tandem cells ?



Power conversion efficiency $\eta = \frac{P_{el,MPP}}{P_{optical}}$

Motivation – why tandem cells ?





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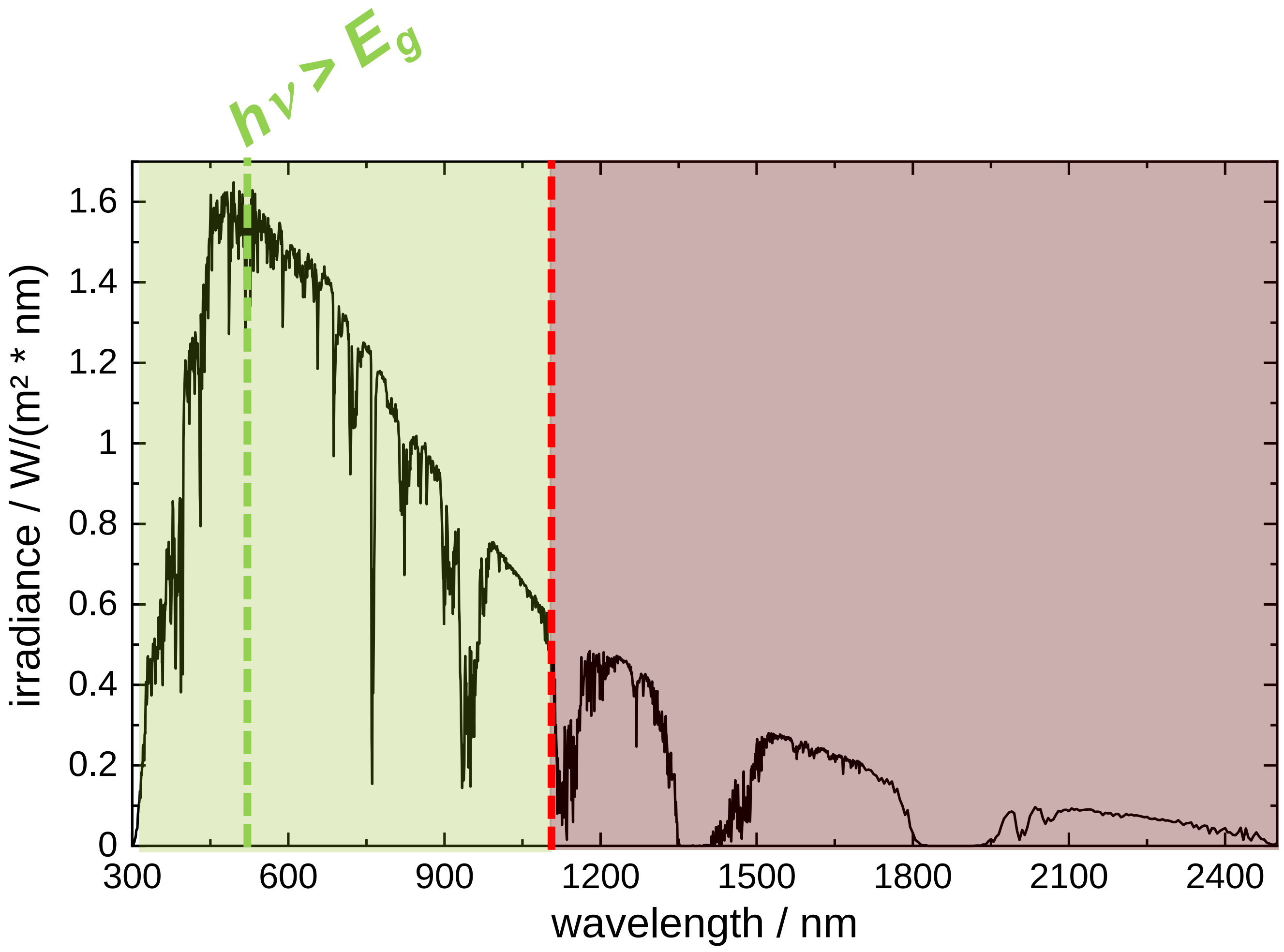
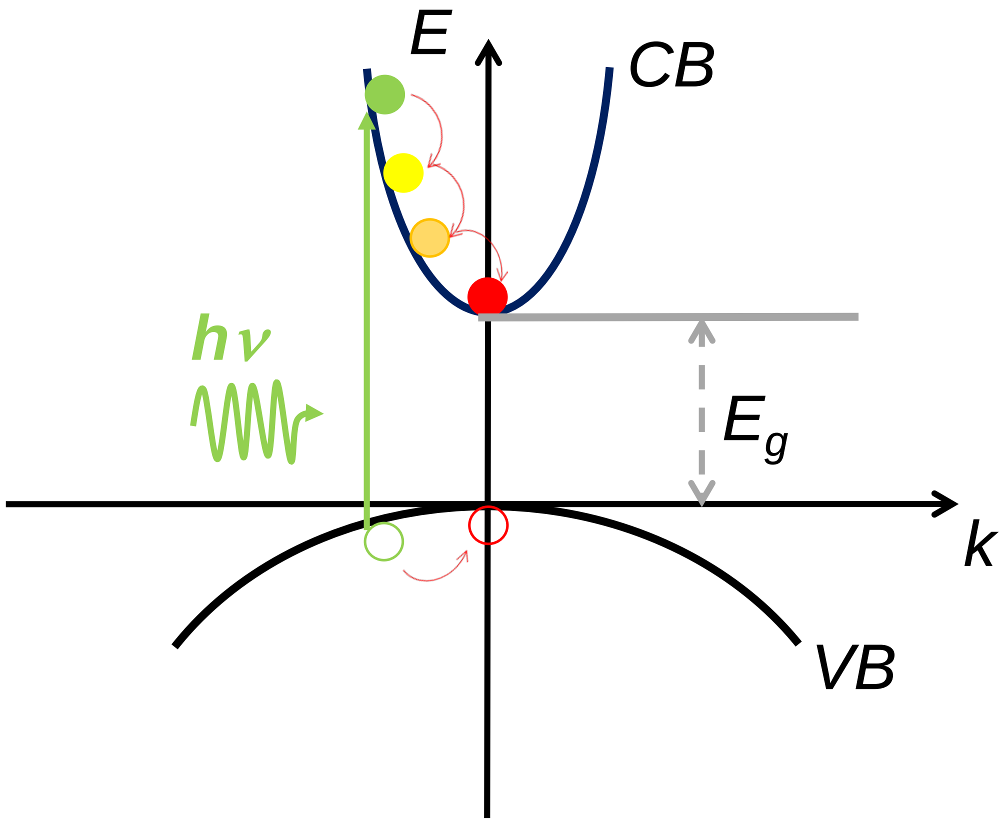
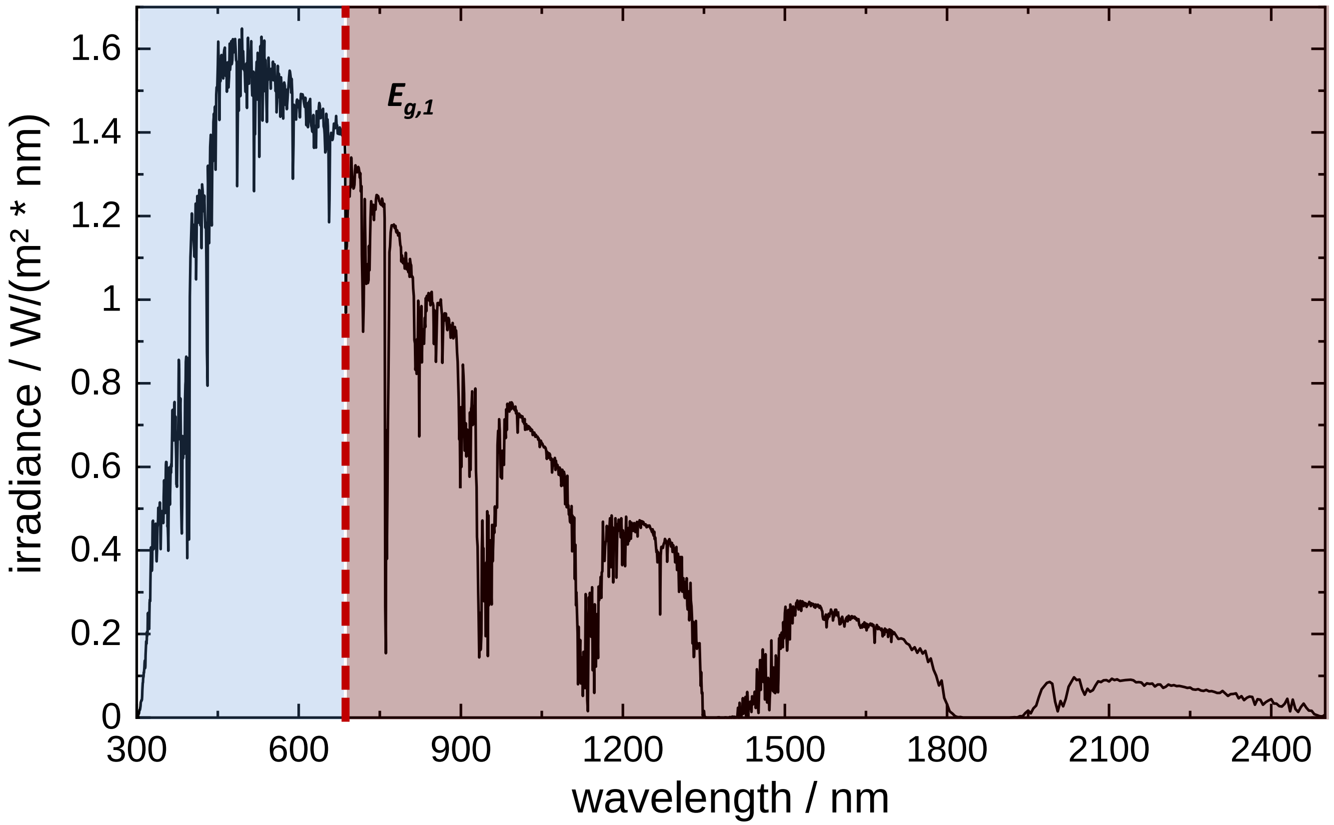
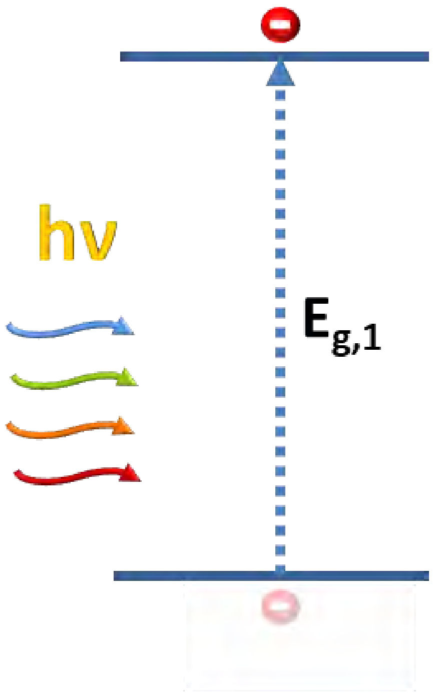




$h\nu - E_g$ is lost for electrical energy conversion

Motivation – why tandem cells ?





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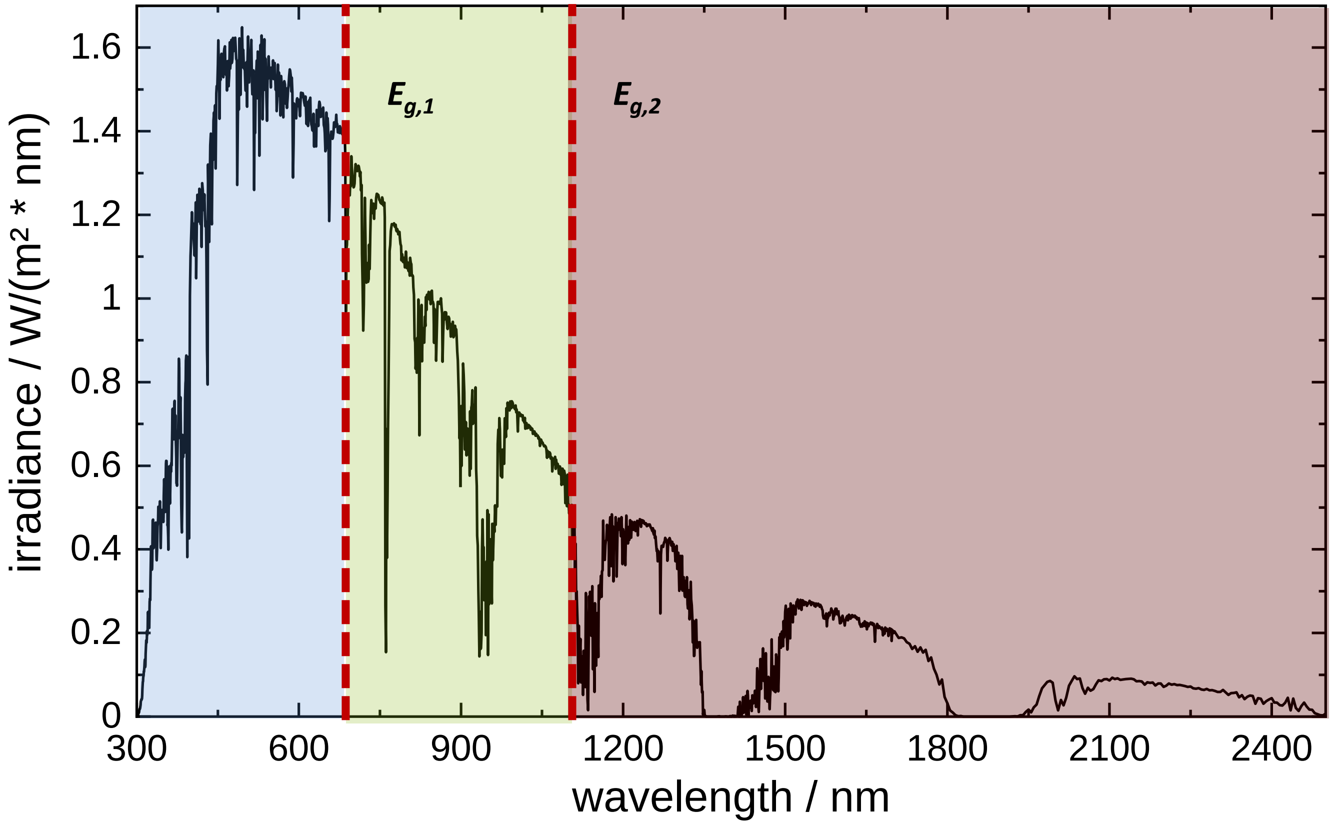
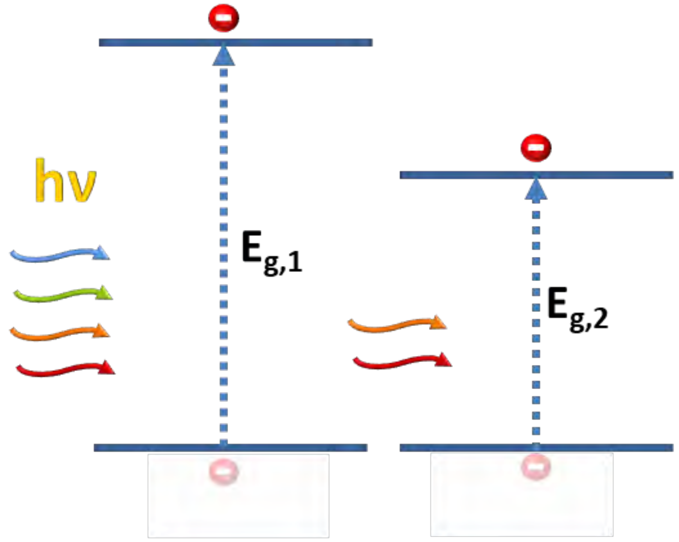
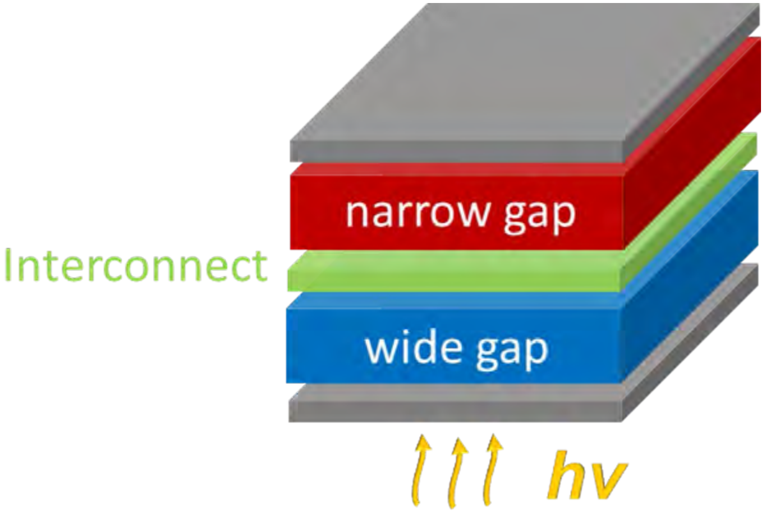
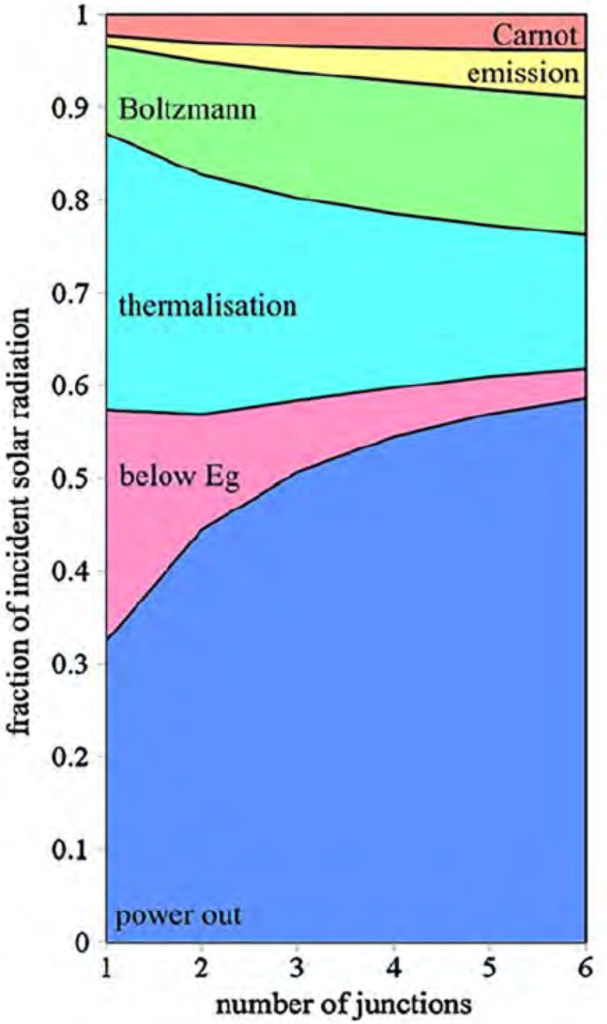






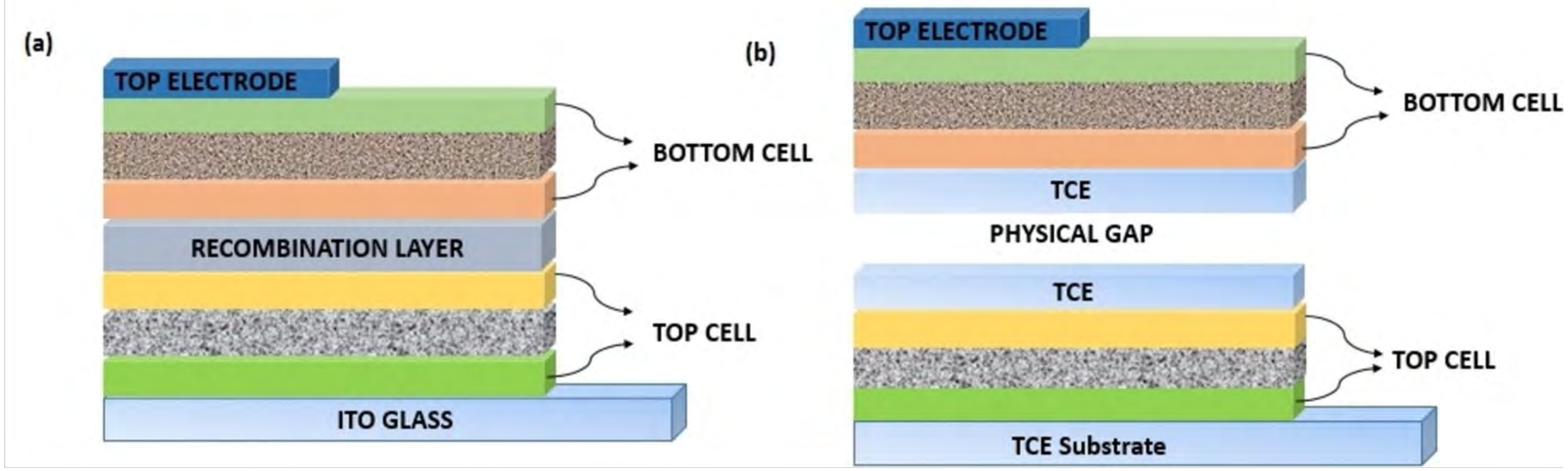
Tandem Cells



Prog. Photovolt.19, 286 (2011)

$$eV_{oc} = E_g\left(1 - \frac{T_A}{T_S}\right) - kT_A \ln\left(\frac{\Omega_{emit}}{\Omega_{abs}}\right)$$

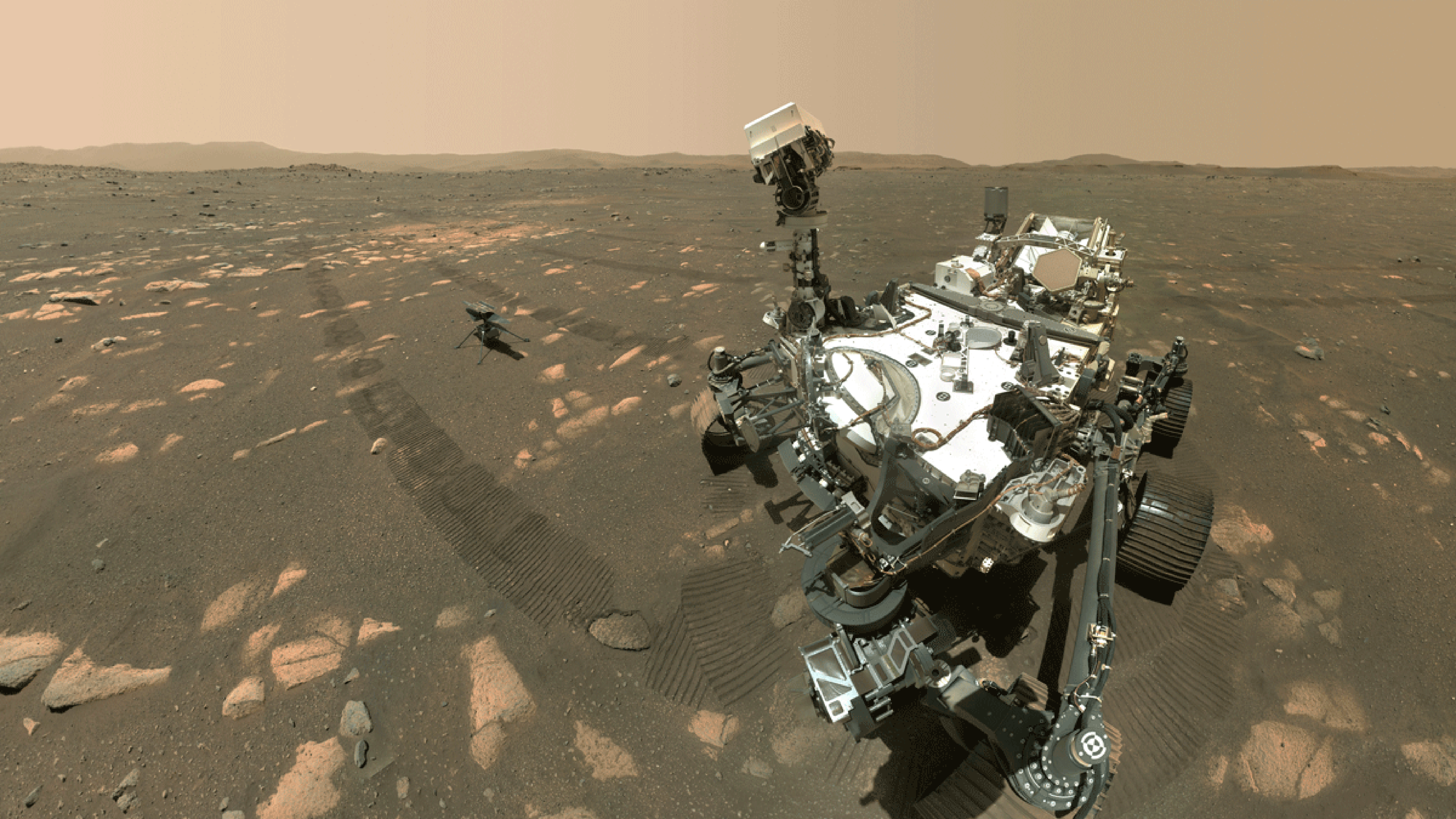
Carnot Boltzmann

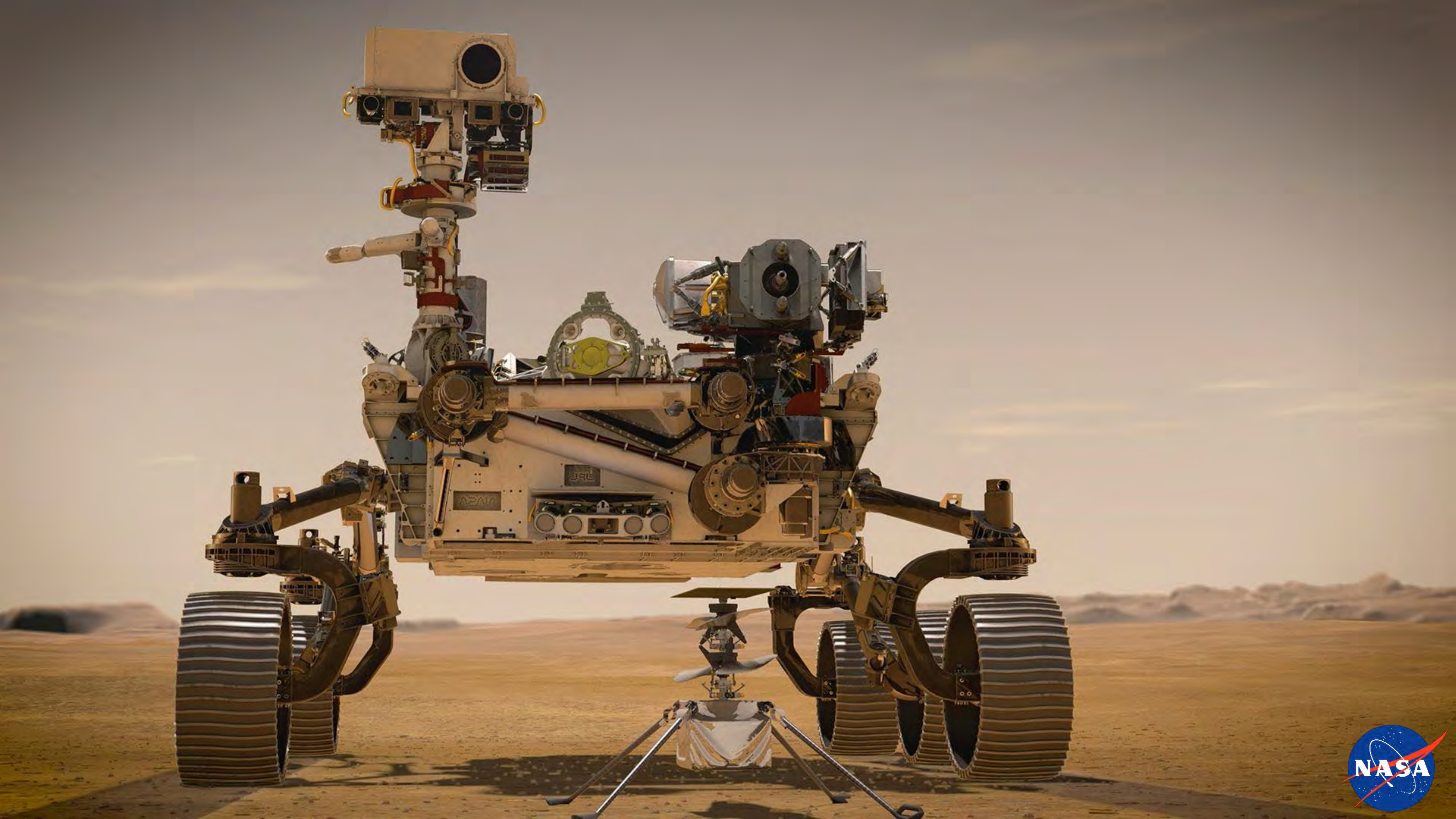


2-terminal
‚monolithic'
current matching required

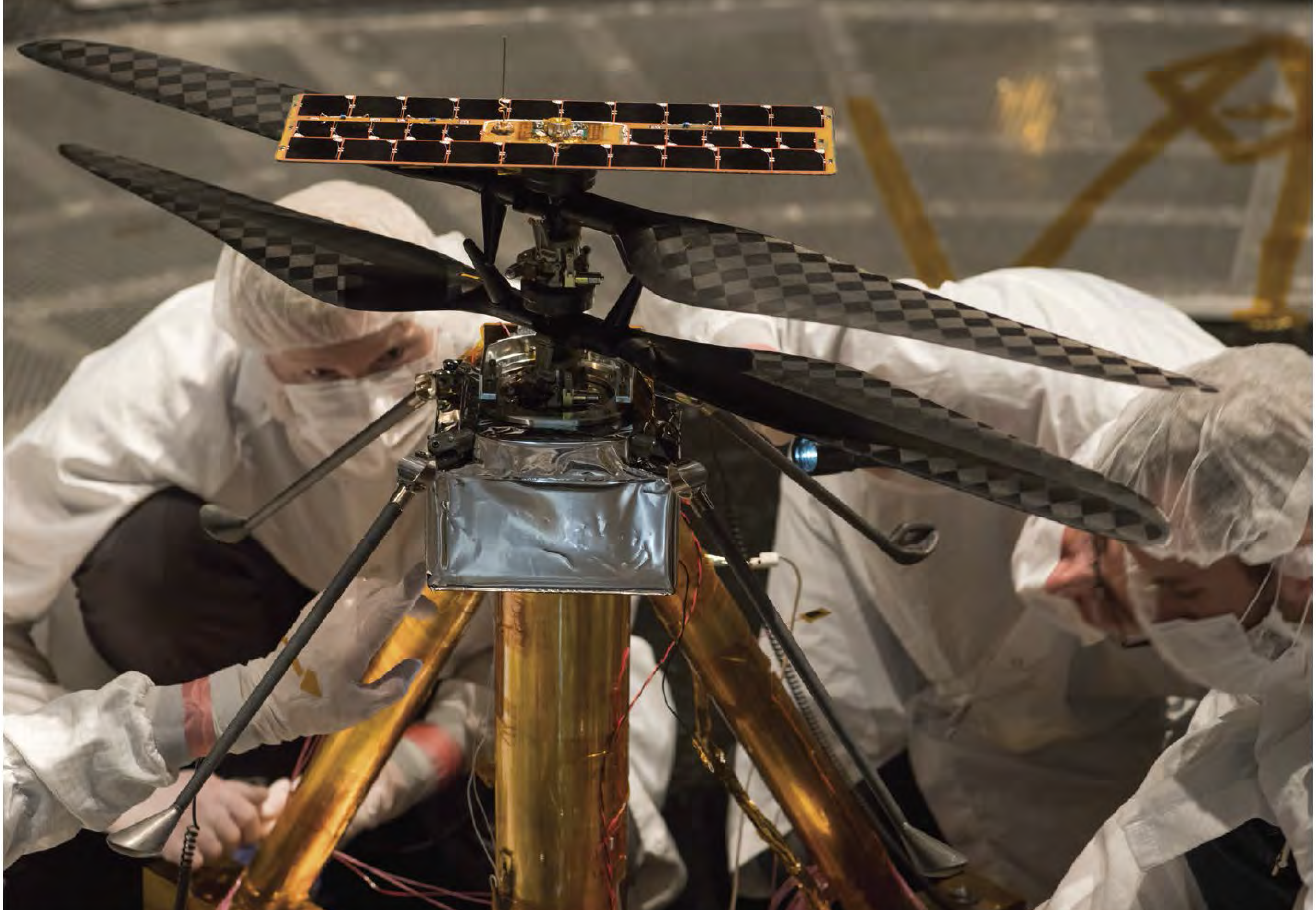
4-terminal
no current matching required
more complicated circuitry

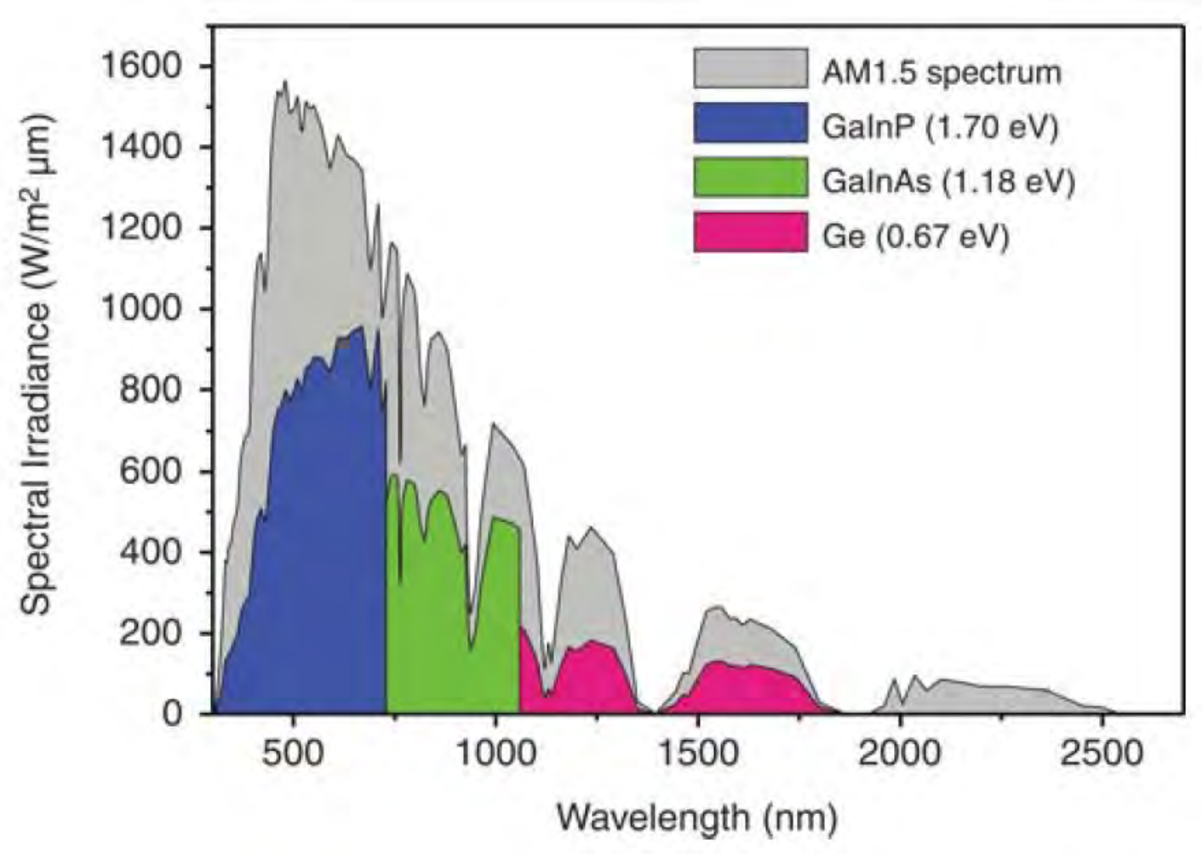
ChemistrySelect 2022, 7, e20220066

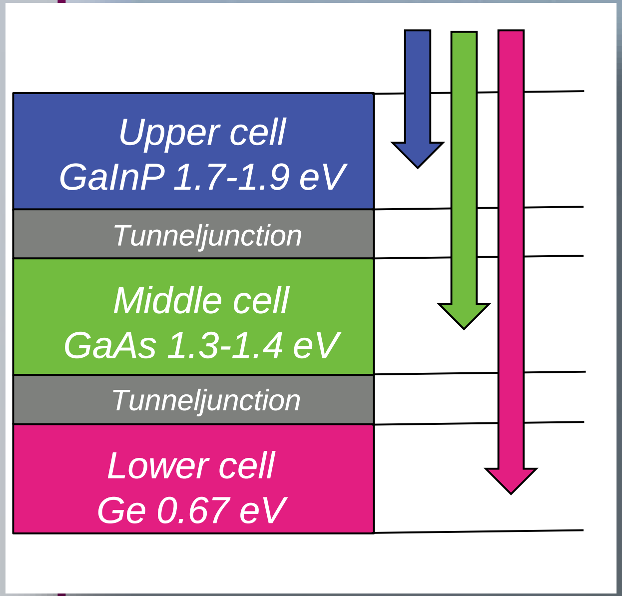


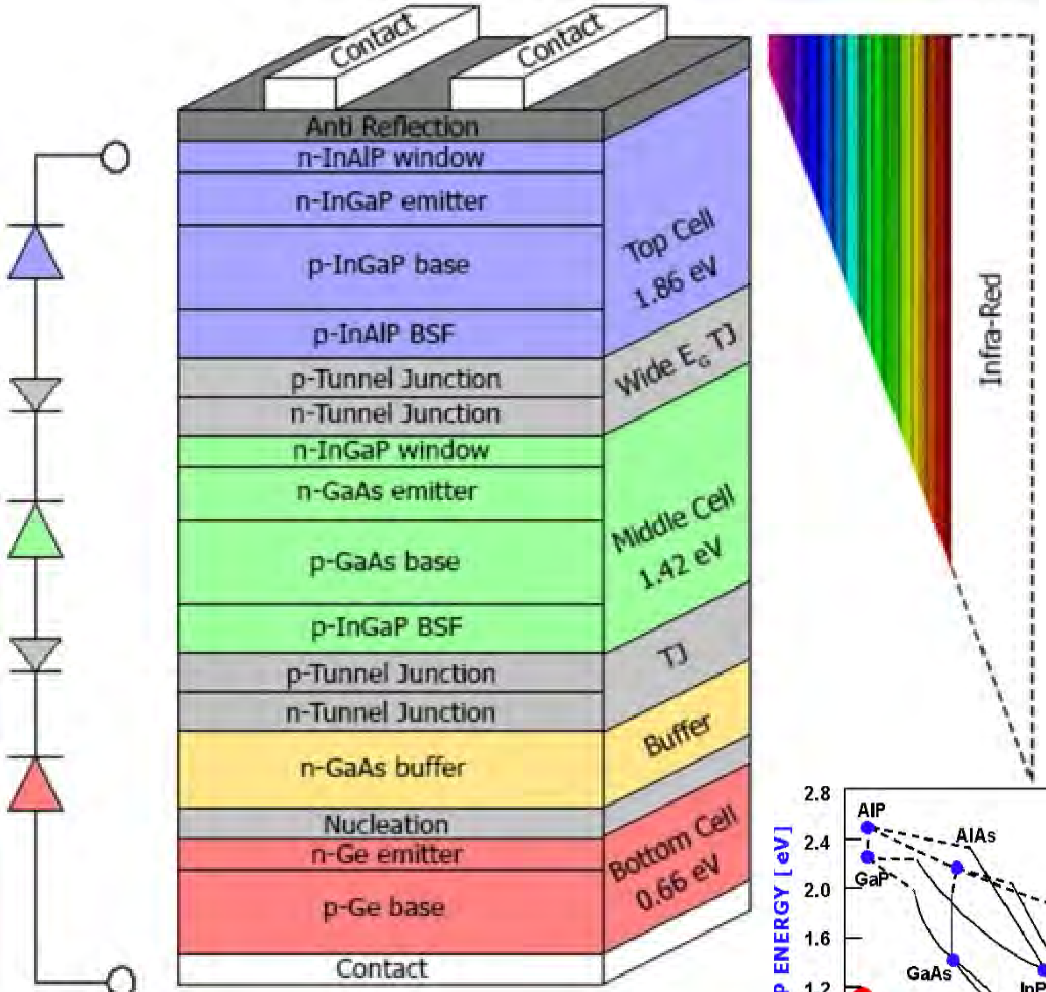

NASA

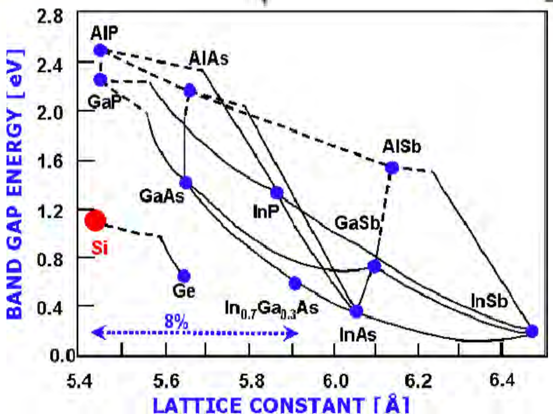
This illustration shows the Mars Helicopter on the surface of Mars.




1600
1400
1200
1000
800
600
400
200
0
Spectral Irradiance (W/m² μm)
500
1000
1500
2000
2500
Wavelength (nm)
AM1.5 spectrum
GaInP (1.70 eV)
GaInAs (1.18 eV)
Ge (0.67 eV)


Upper cell
GaInP 1.7-1.9 eV
Tunneljunction
Middle cell
GaAs 1.3-1.4 eV
Tunneljunction
Lower cell
Ge 0.67 eV

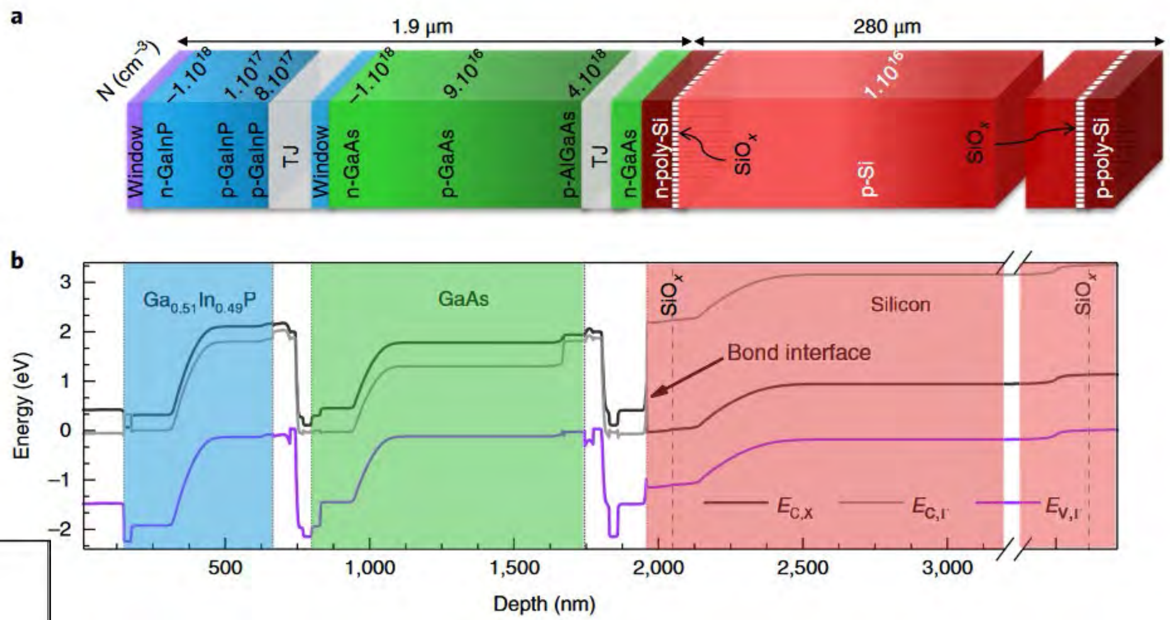




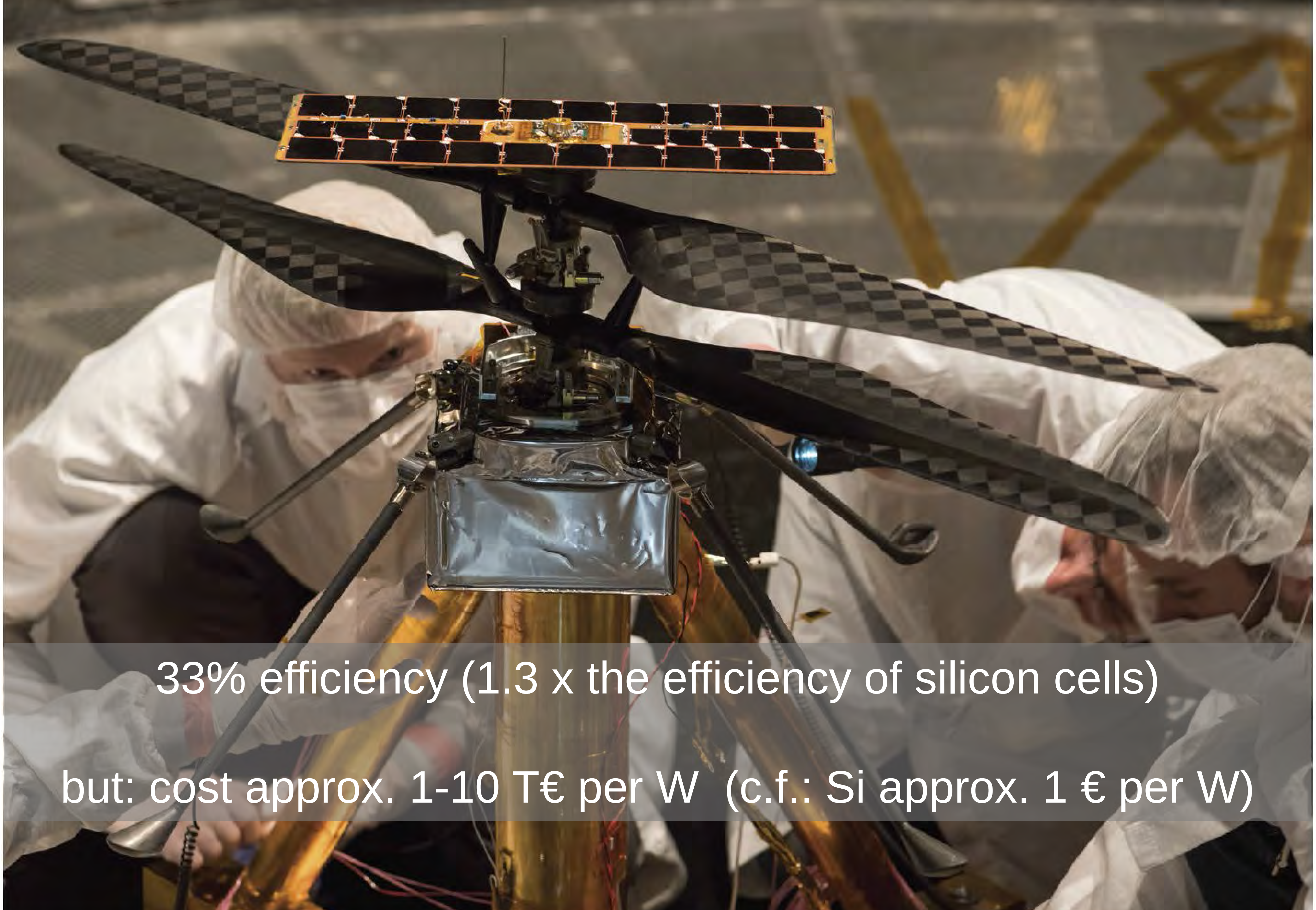
ARTICLES
https://doi.org/10.1038/s41560-018-0125-0
nature energy
Corrected: Author Correction; Author Correction

III–V-on-silicon solar cells reaching 33% photoconversion efficiency in two-terminal configuration

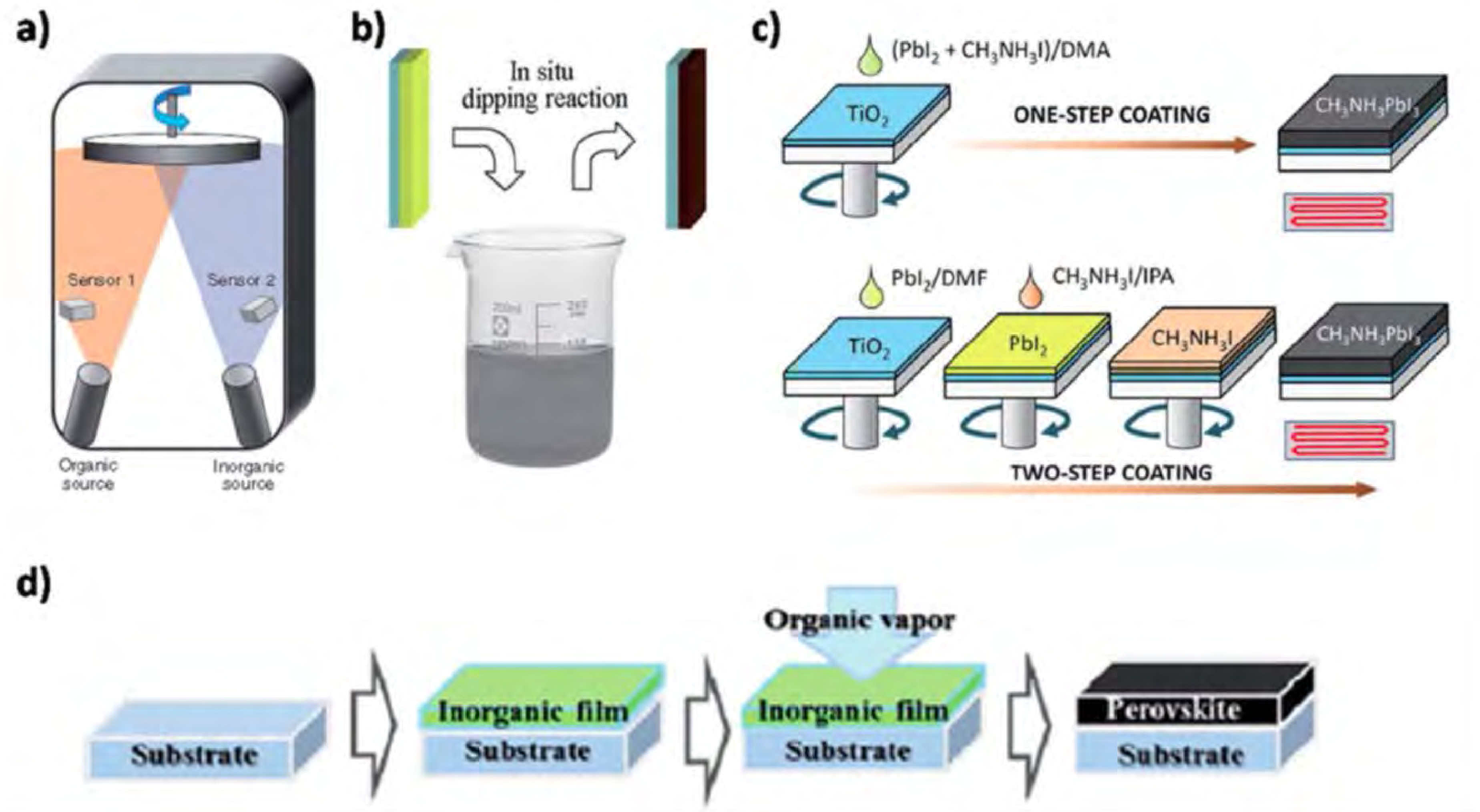
Romain Cariou[1,4*], Jan Benick[1], Frank Feldmann[1,2], Oliver Höhn[1], Hubert Hauser[1], Paul Beutel[1], Nasser Razek[3], Markus Wimplinger[3], Benedikt Bläsi[1], David Lackner[1], Martin Hermle[1], Gerald Siefer[1], Stefan W. Glunz[1,2], Andreas W. Bett[1] and Frank Dimroth[1]



DOI: 10.5130/pamr.v3i0.1413


33% efficiency (1.3 x the efficiency of silicon cells)
but: cost approx. 1-10 T€ per W (c.f.: Si approx. 1 € per W)

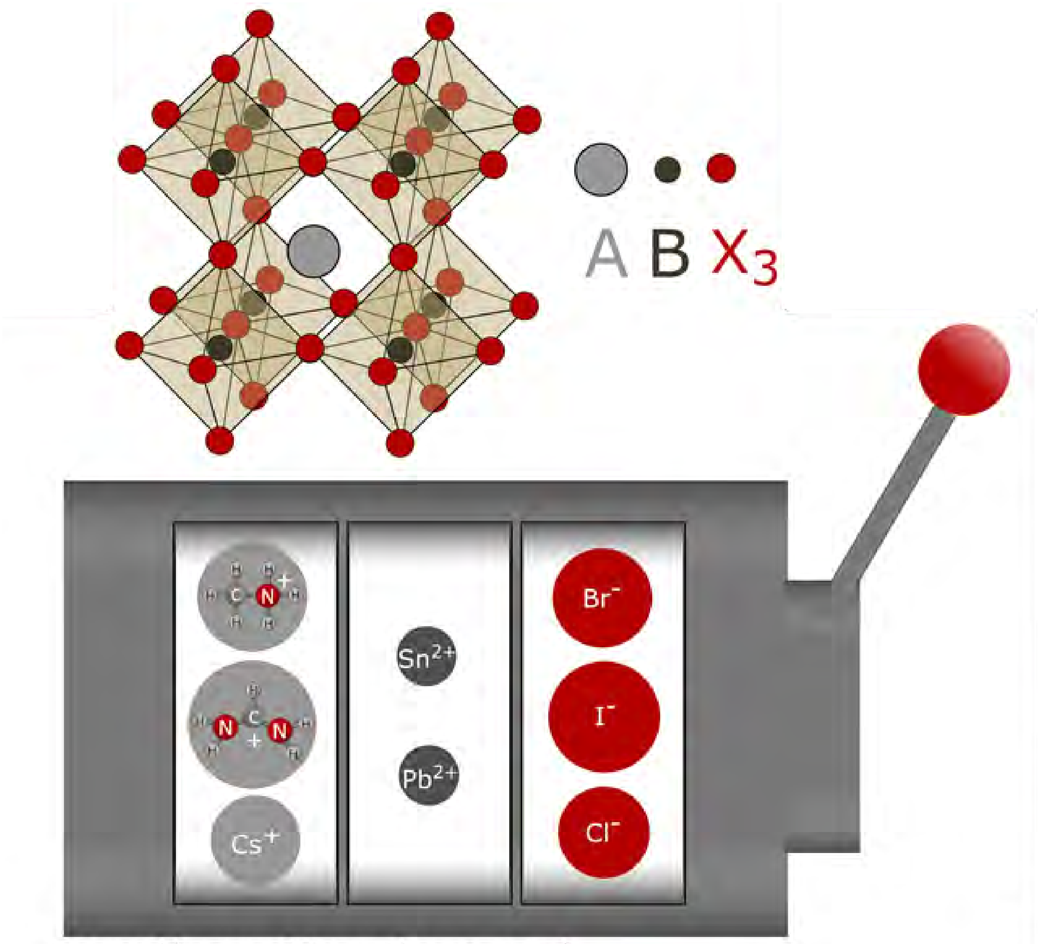
Perovskites – the low-cost alternative?



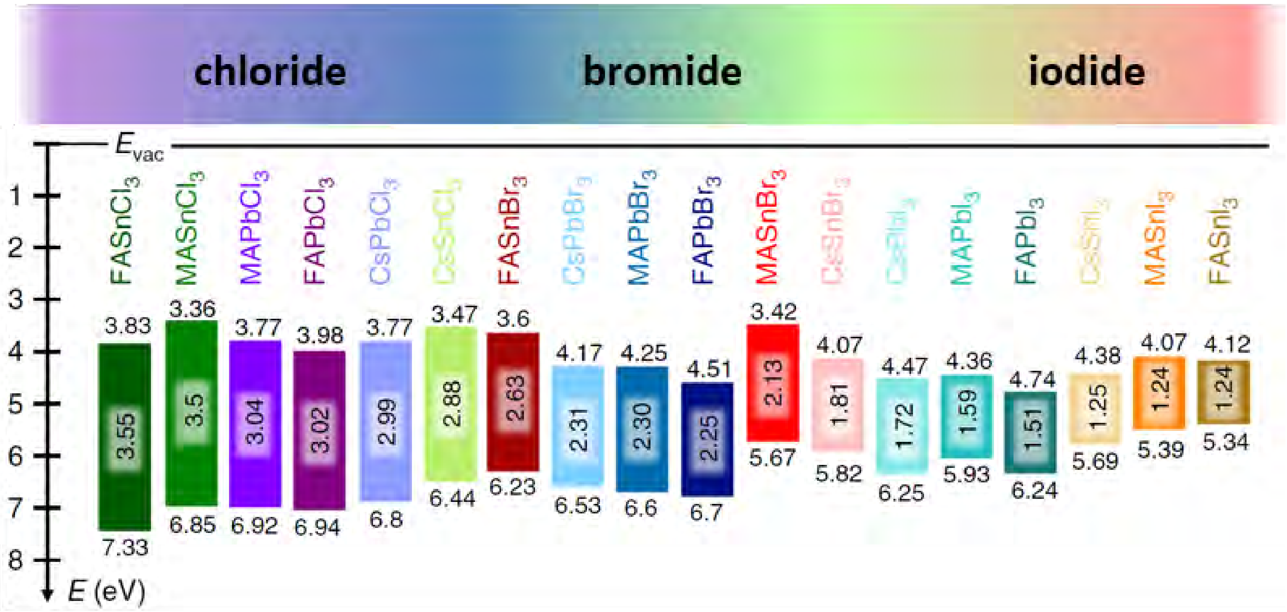
J. Mater. Chem. A, 2015, 3, 9032–9050

solution processing, low temperature, low cost

Perovskite Band Gap Tunability



https://perowskit.wordpress.com/



Tao, et al. Nature commun. 10, 2560 (2019)

Perovskite based tandem cells

CIGS – Perovskite

Pro: CIGS established cell technology, stable

Con: **Cd content, abundance of elements, high-T process**

Silicon – Perovskite

Pro: high efficiency, Si cell highly developed

Con: **high-T process**, not flexible

Perovskite – Perovskite

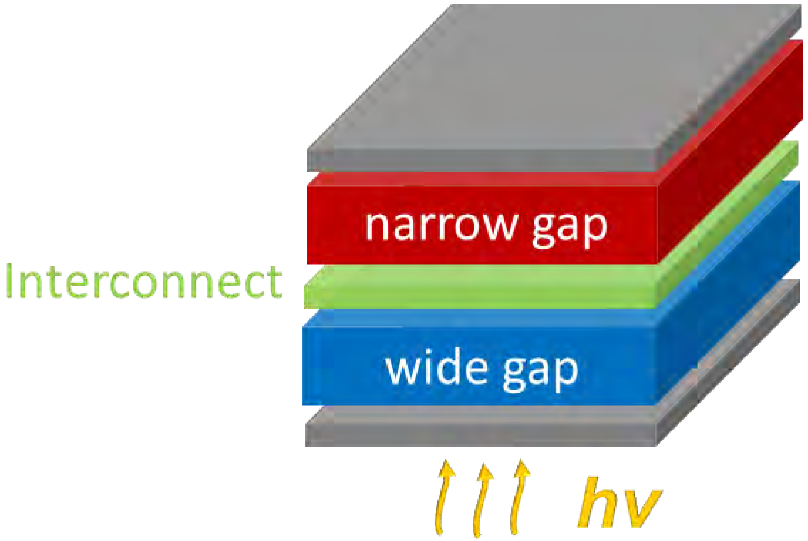
Pro: low temperature, large area, high throughput

Con: **narrow-gap cell potentially unstable (Sn-based)**

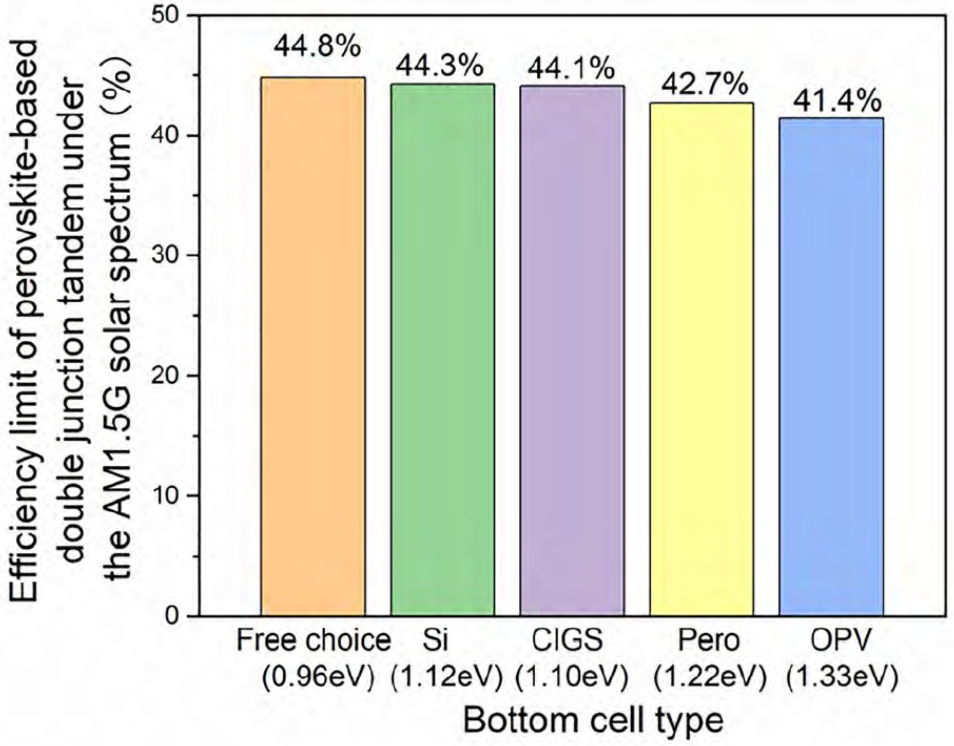
Organic – Perovskite

Pro: low temperature, large area, high throughput, **reduced Pb/Sn**

Con: **still low efficiency?**

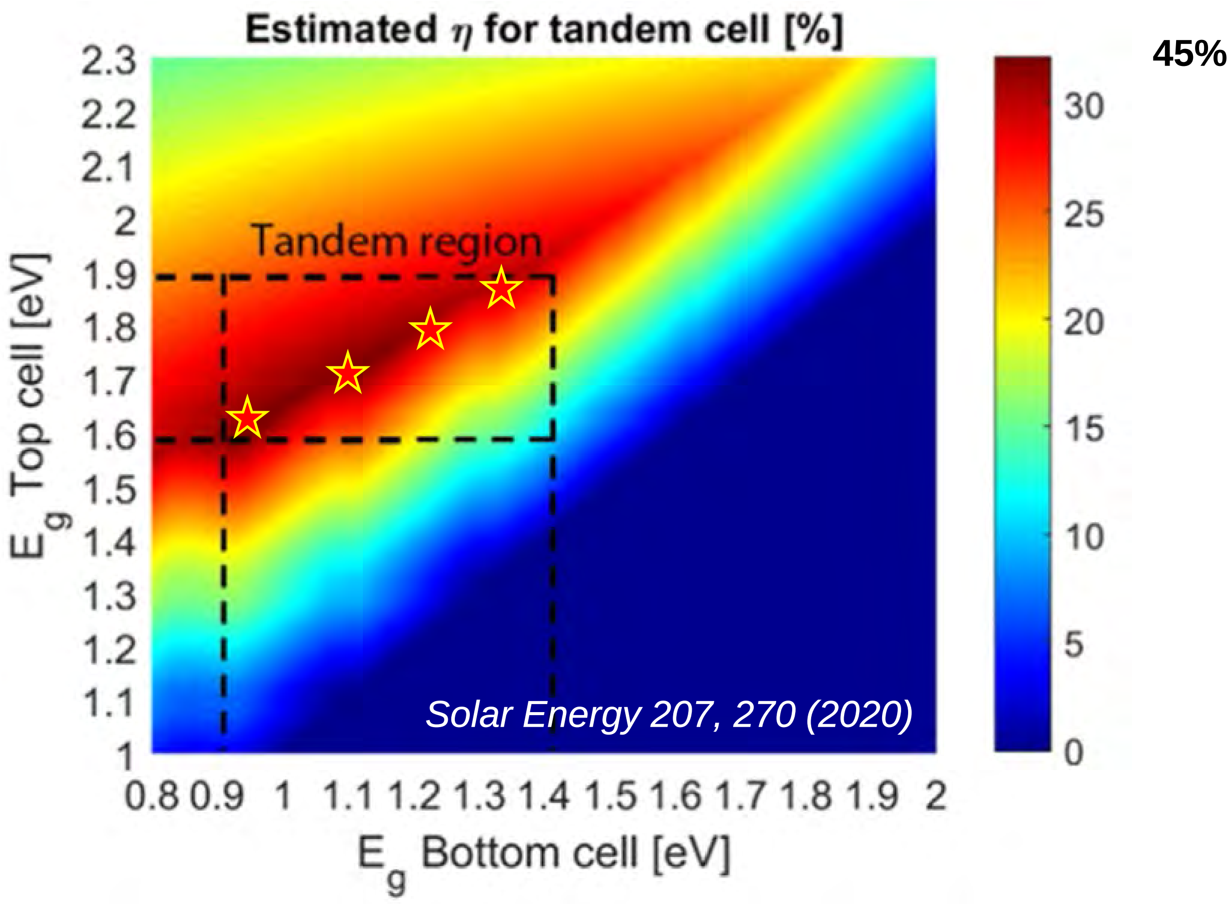


Efficiency estimates



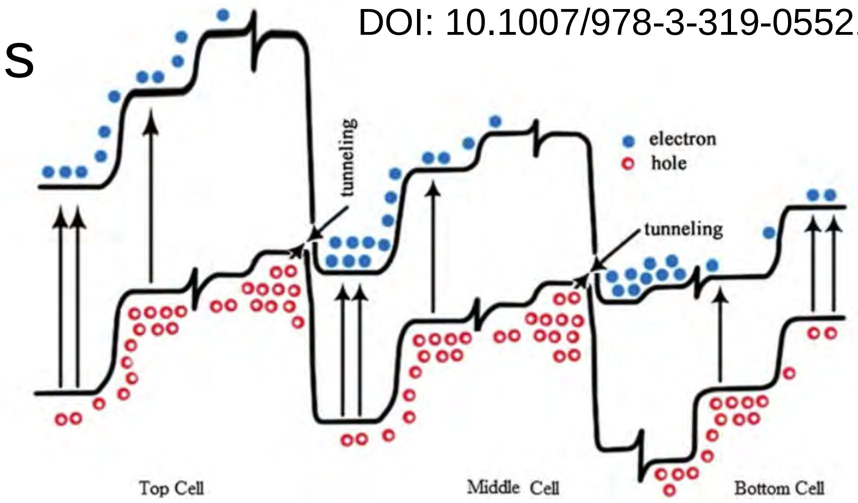
Bottom Cell Type	Low bandgap(eV)		High bandgap (eV)	Open Circuit Voltage V_{OC} (V)	Short Circuit Current J_{SC} (mA/cm²)	PCE (%)
Free choice	0.96	★	1.63	2.032	24.6	44.8
Si	1.12	★	1.73	2.273	21.6	44.3
CIGS	1.10		1.72	2.246	21.8	44.1
Perovskite	1.22	★	1.81	2.441	19.3	42.7
OPV	1.33	★	1.88	2.609	17.4	41.4

Appl. Phys. Rev. **8**, 041307 (2021)

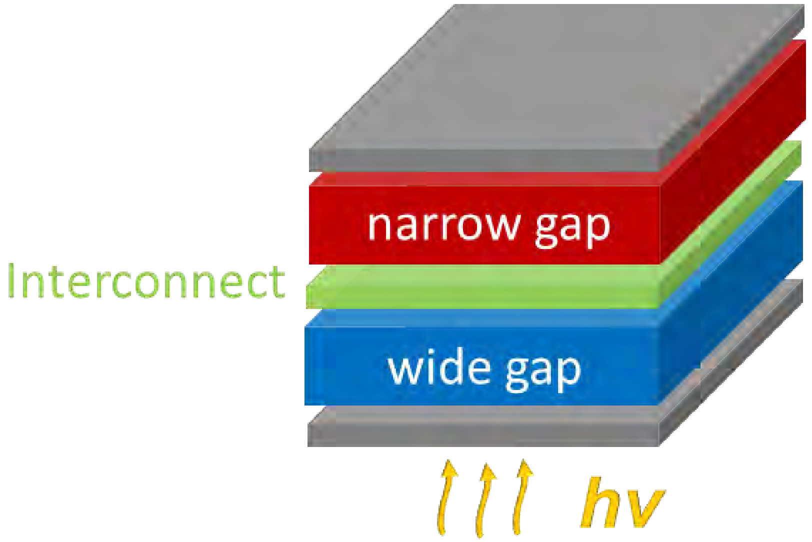


Interconnect

III/V's



DOI: 10.1007/978-3-319-05521-3_16



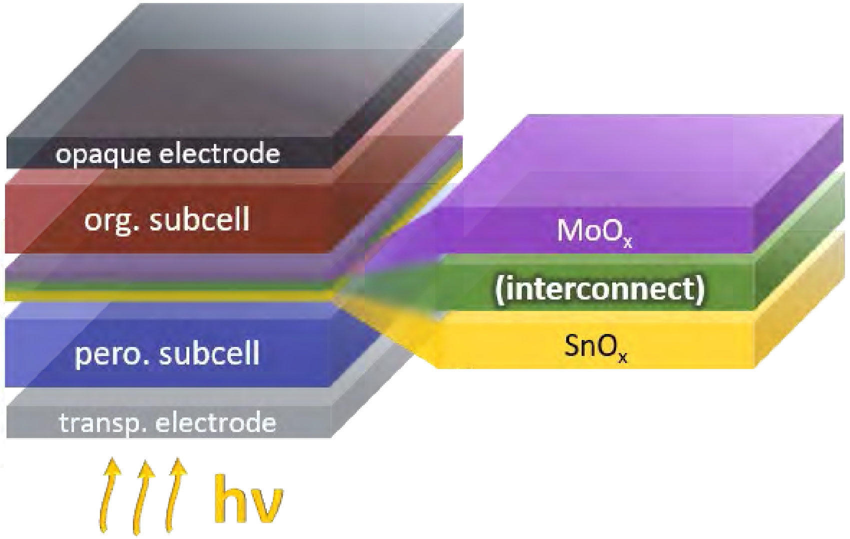
Requirements:

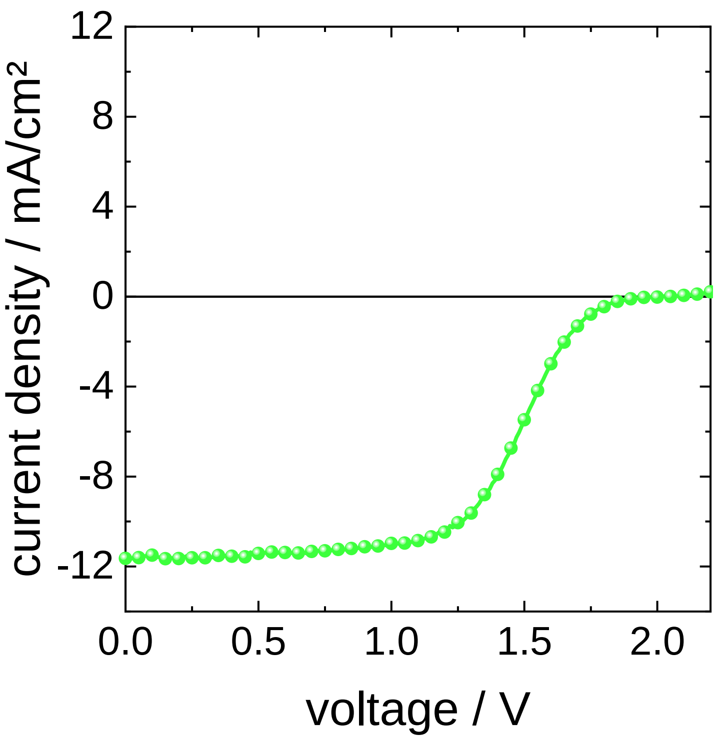
- *loss-free recombination of electrons from one sub-cell with holes form the other sub-cell → addition of Voltage; high Fill Factor*
- *optically transparent*
- *protects the bottom cell against deposition of the subsequent cell*

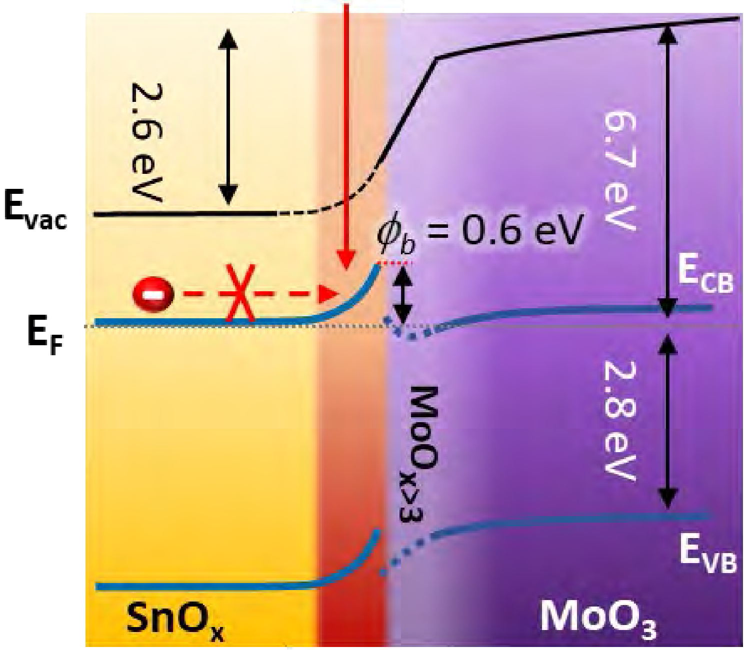
SnO_x / MoO_x Junction

coll. with
Dr. Selina Olthof

Tandem with only SnO_x / MoO_x junction







→ *strong s-shape, low FF*

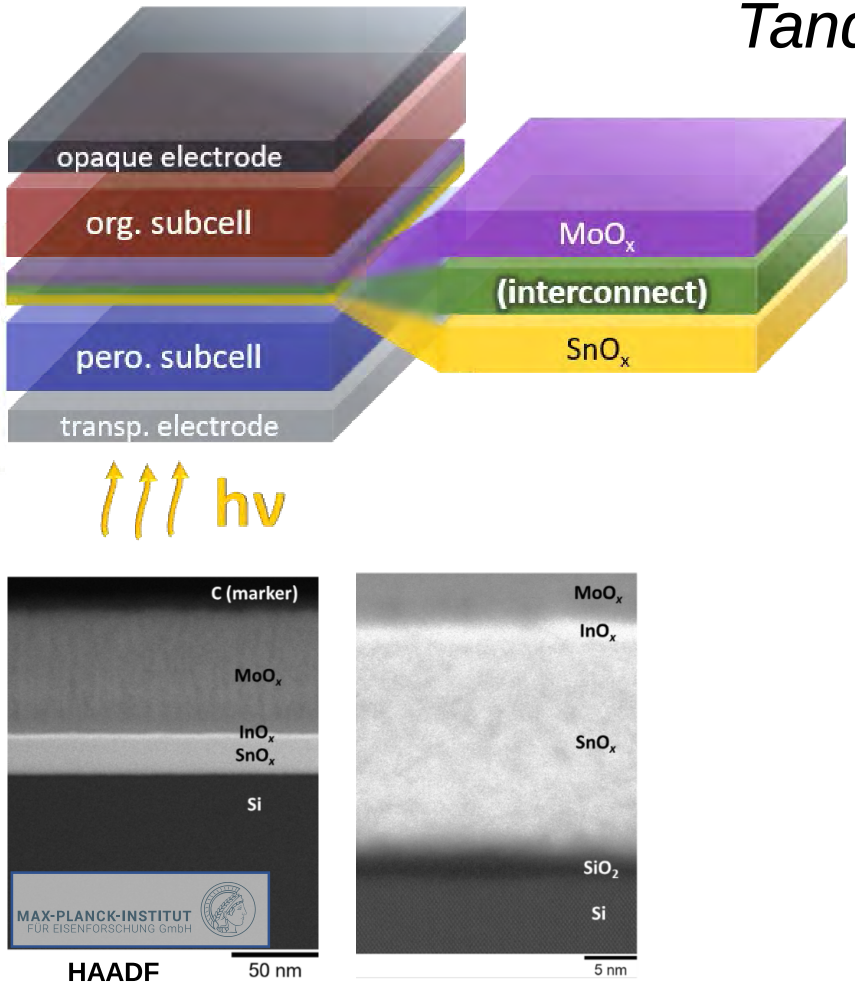
→ *energetic barrier between SnO_x and MoO_x* adds a diode-like non-linearity

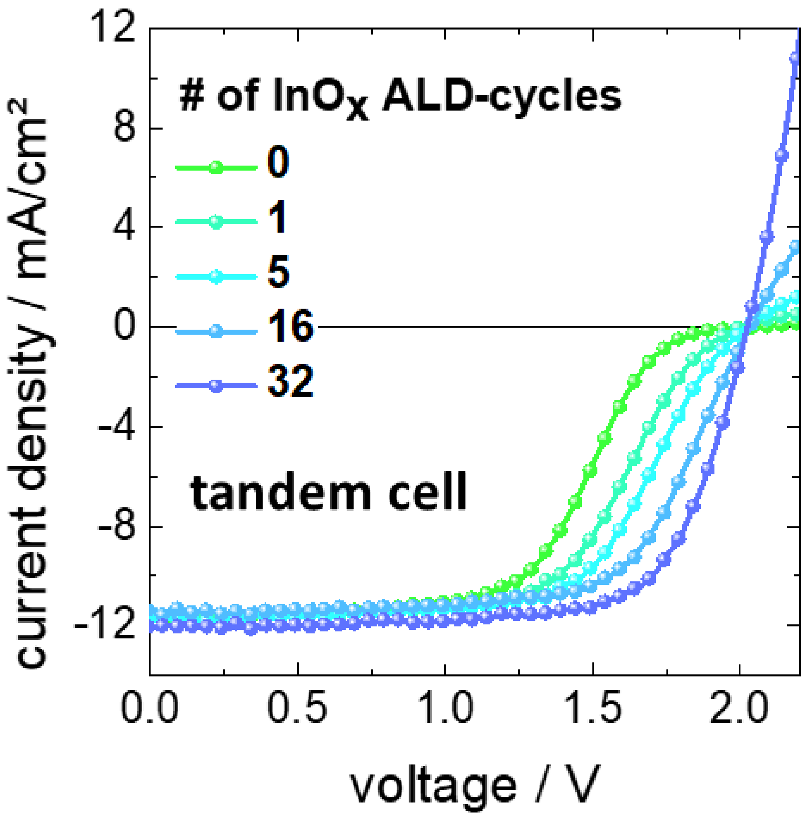
Brinkmann et al. Nature 604, 280 (2022)

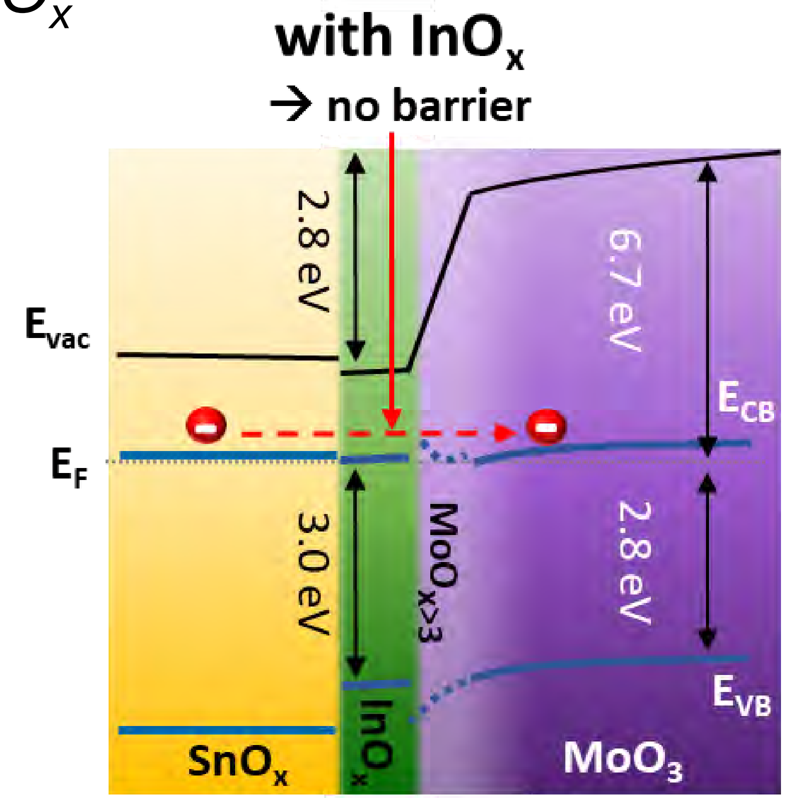
ALD-InO_x as interconnect

coll. with
Dr. Selina Olthof

Tandem with SnO_x/ALD-InO_x/MoO_x







→ *with 32 ALD cycles of InO_x (1.5 nm) well behaved J/V characteristcs (no S-shape)*

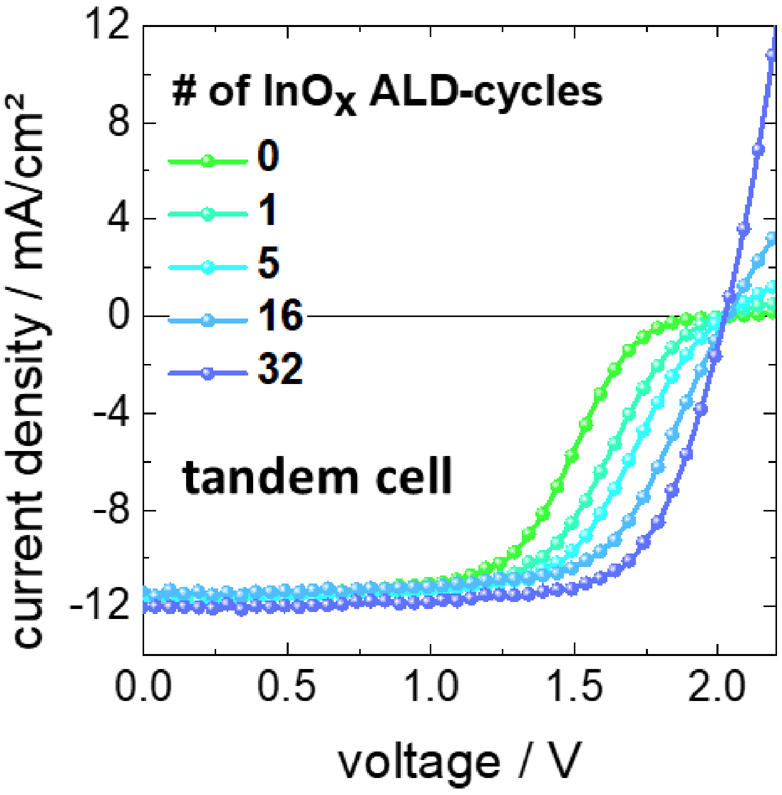
Brinkmann et al. Nature 604, 280 (2022)

BERGISCHE UNIVERSITÄT WUPPERTAL

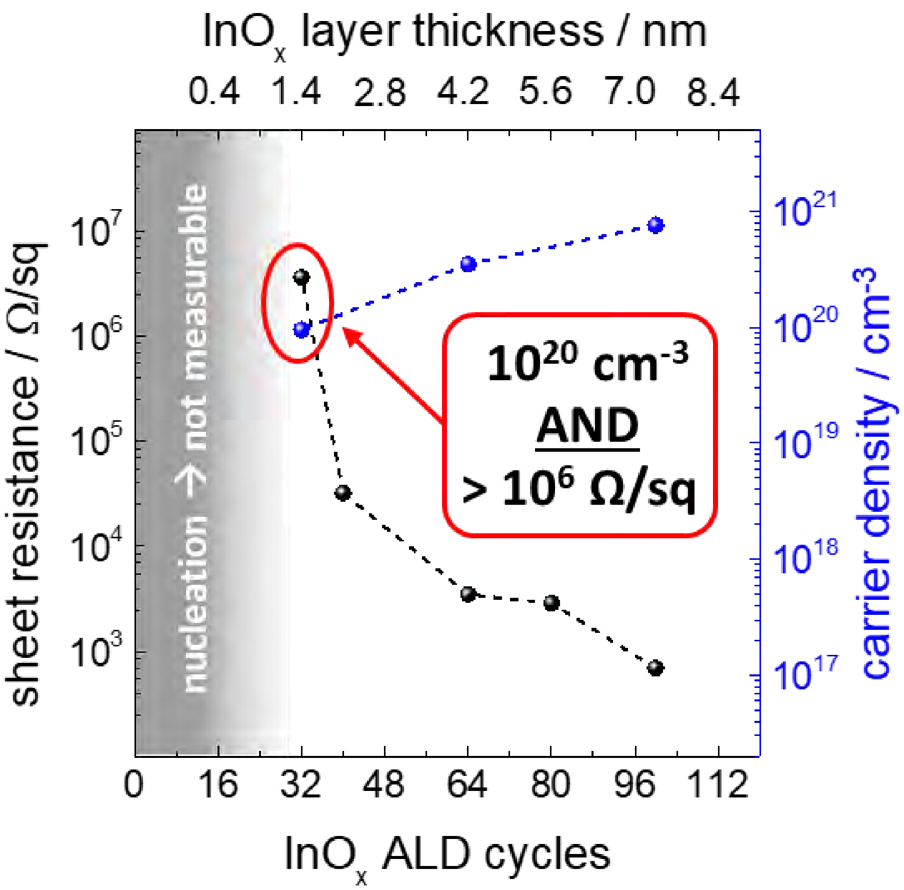
ALD-InO_x as interconnect

coll. with Dr. Selina Olthof

Universität zu Köln

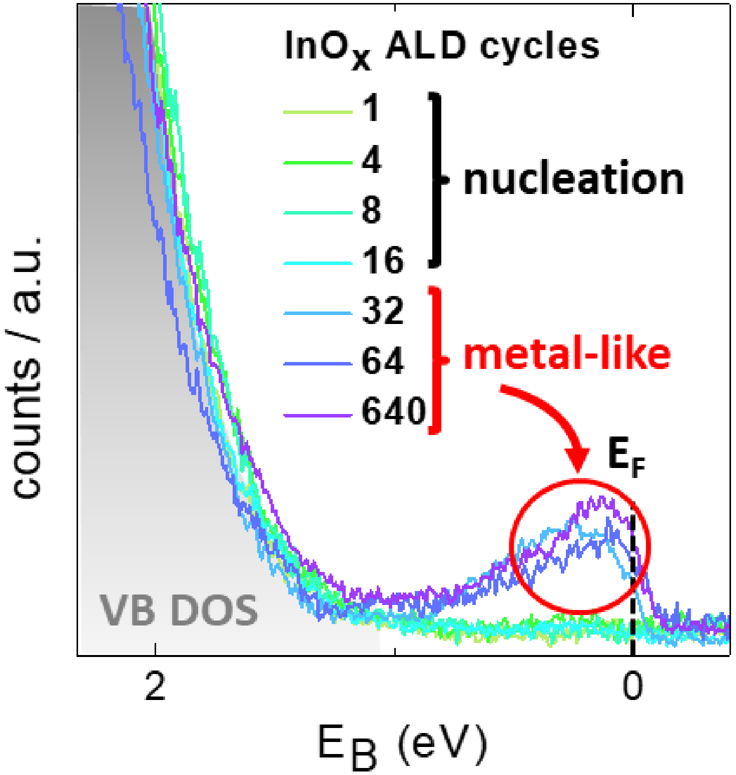


electrical properties



carrier density > 10^{20} cm^{-3}

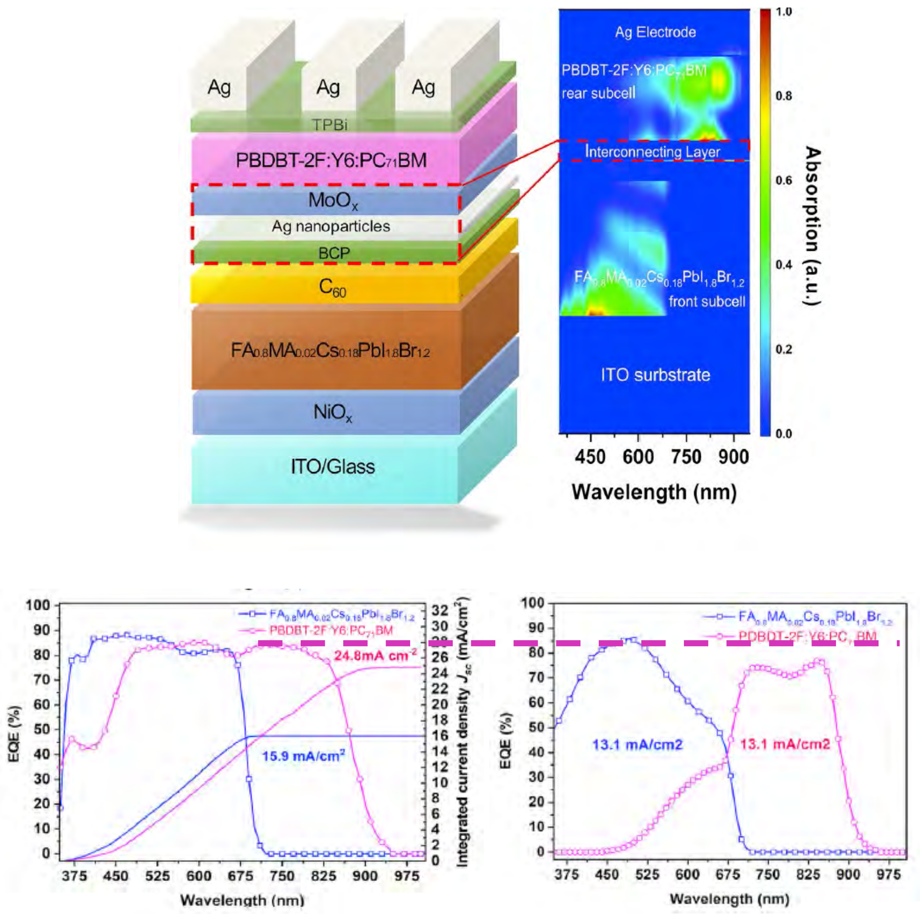
UV photoelectron spectroscopy



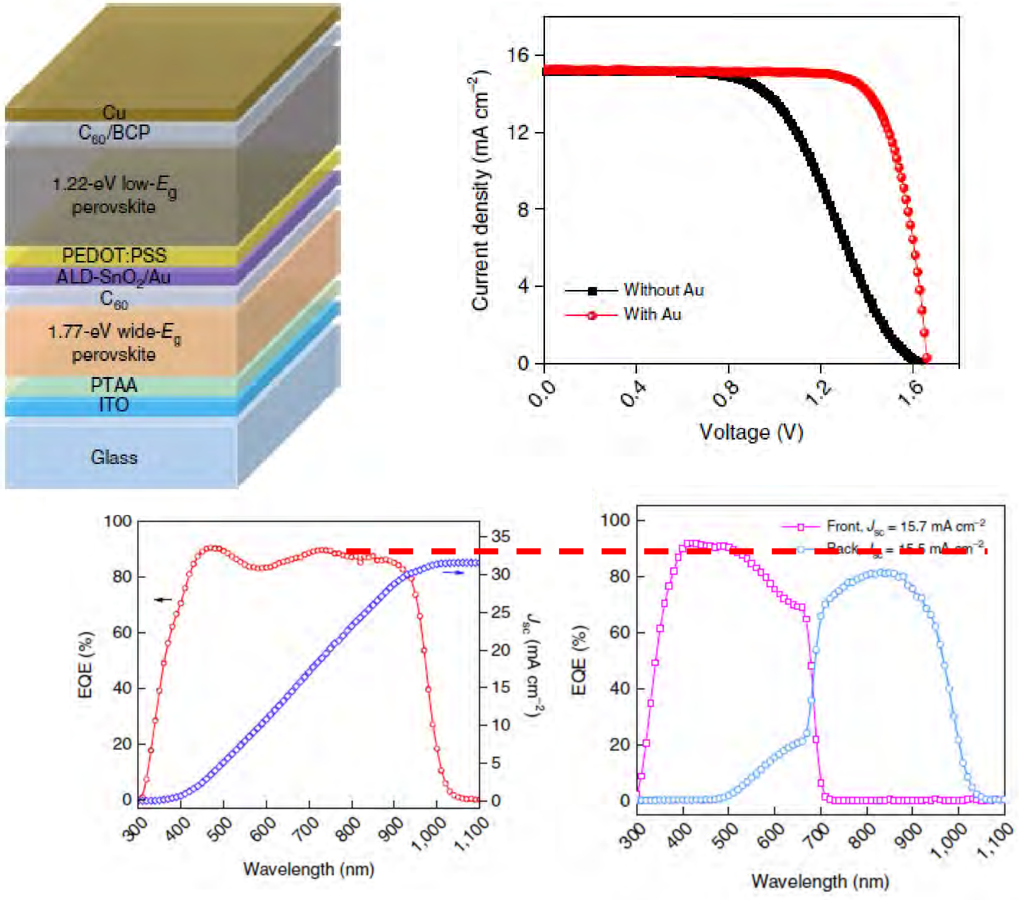
metal-like behaviour

Brinkmann et al. Nature 604, 280 (2022)

Metals as interconnect



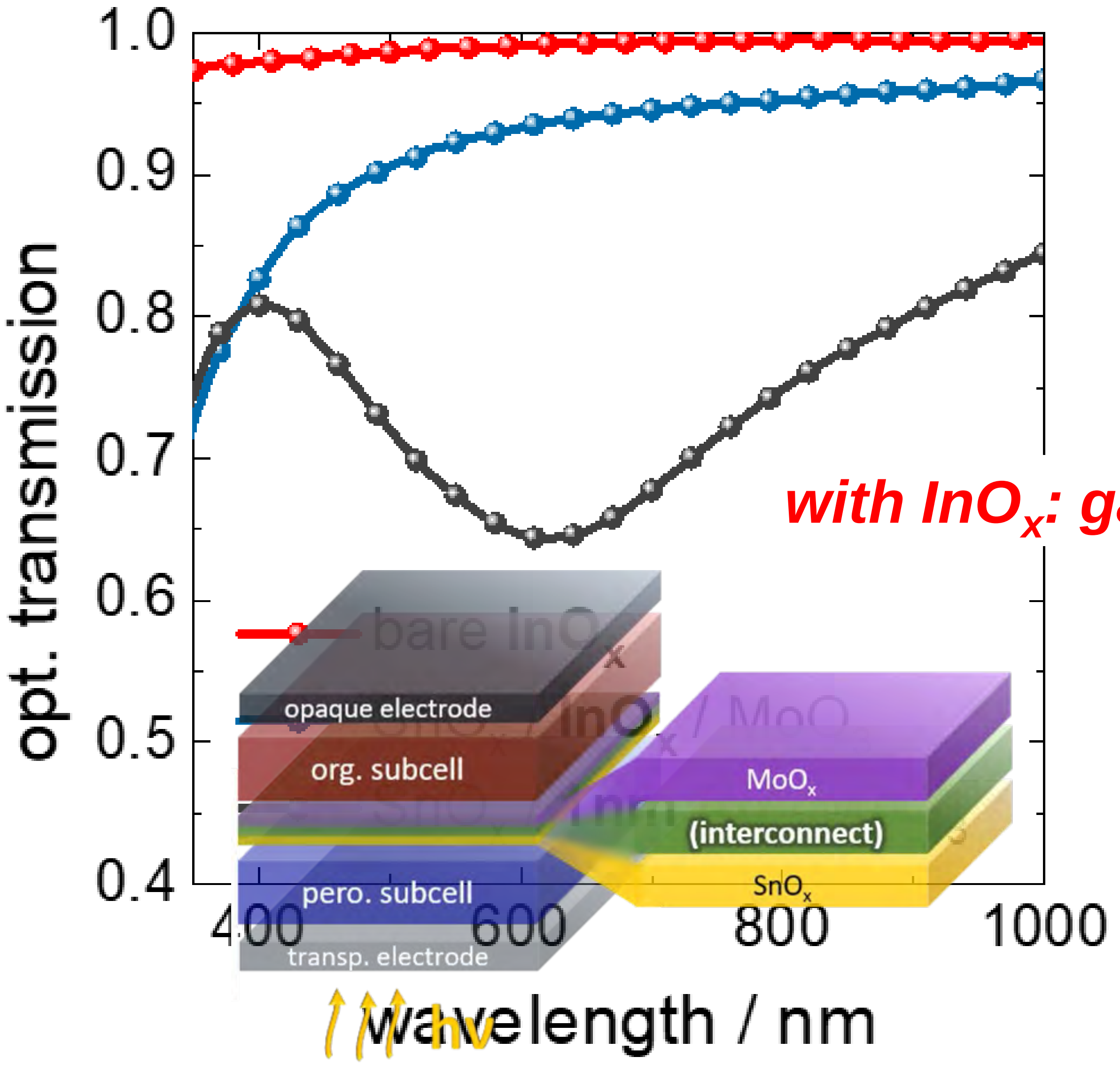
Joule 4, 1594 (2020)

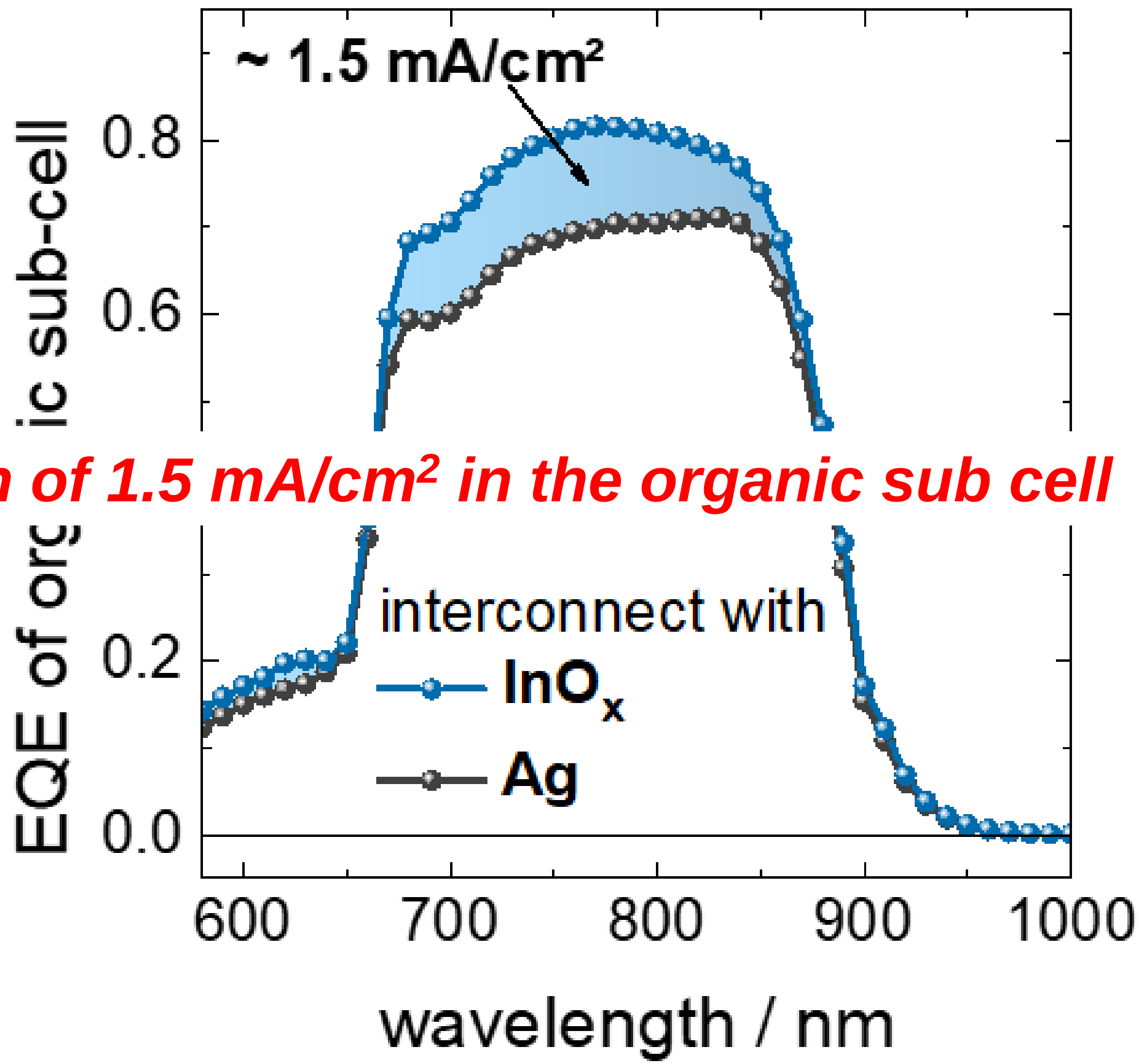


Nature Energy **4**, 864–873 (2019)

BERGISCHE UNIVERSITÄT WUPPERTAL

ALD-InO_x vs. thin metal

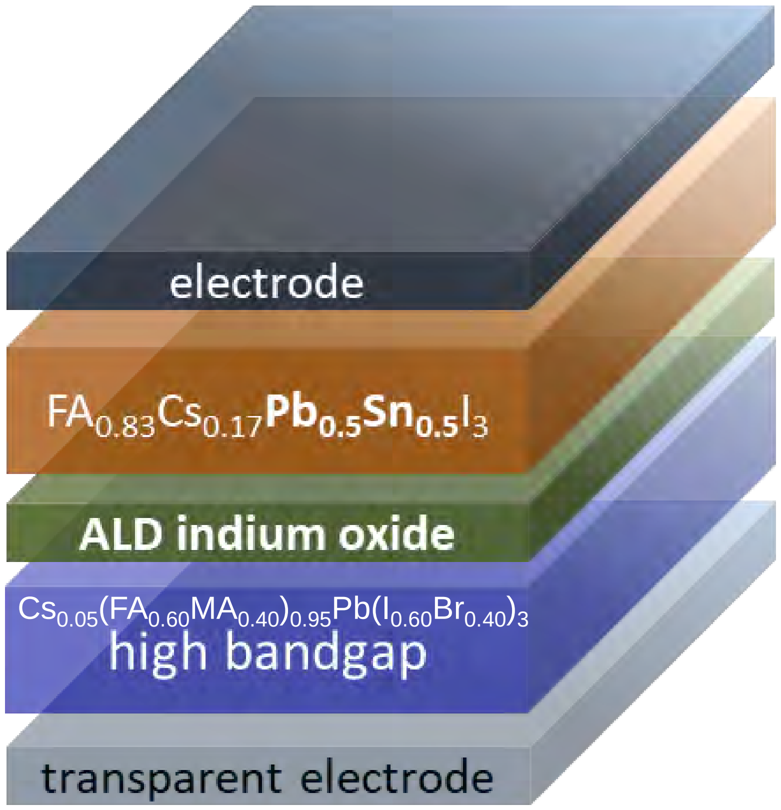


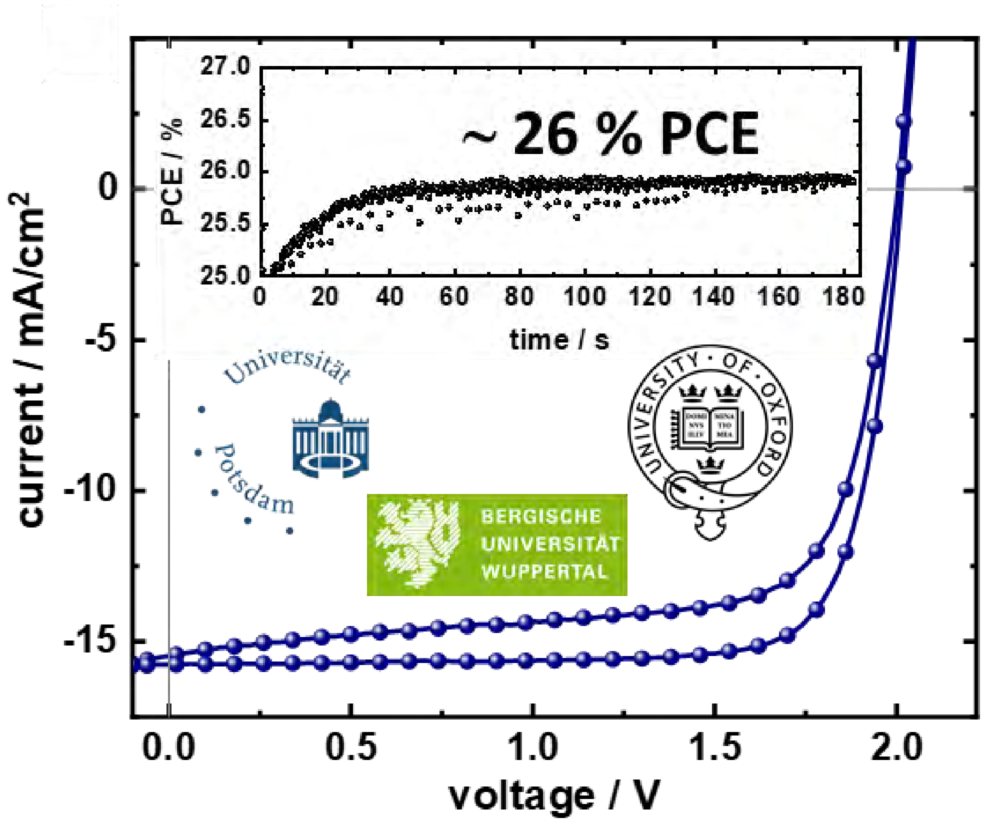


with InO_x: gain of 1.5 mA/cm² in the organic sub cell

Interconnect for all-perovskite tandems

perovskite-**perovskite** tandem

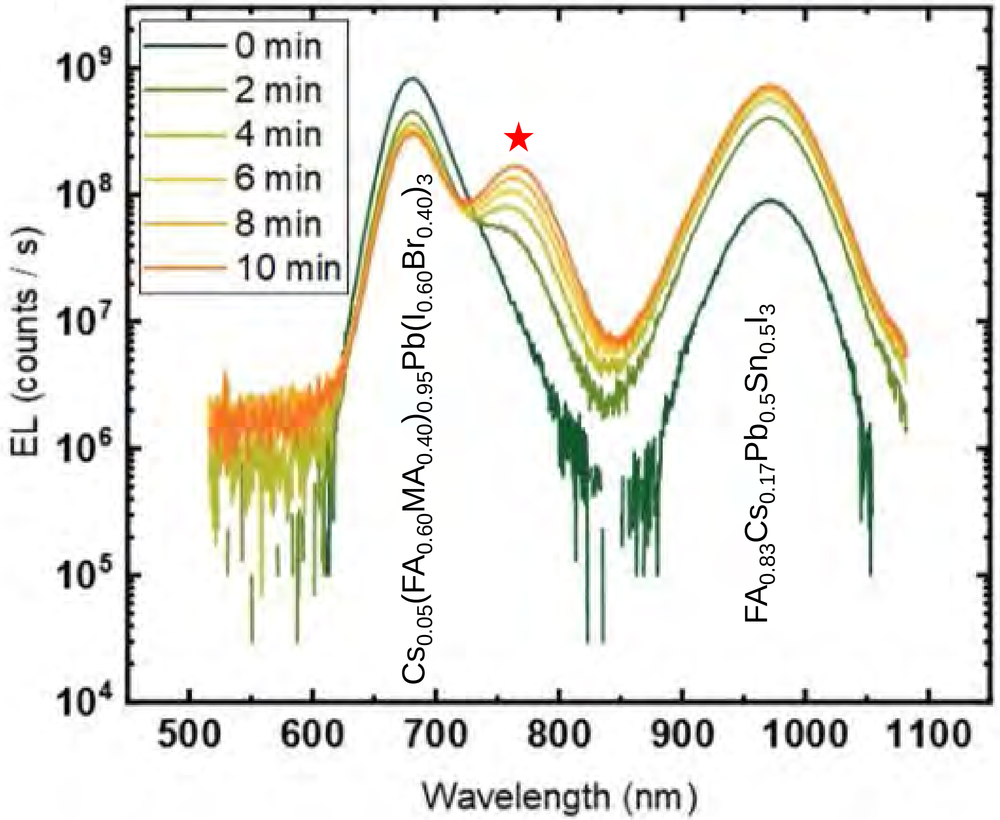




All-perovskite tandem with low gap perovskite → PCE of ~ 26%

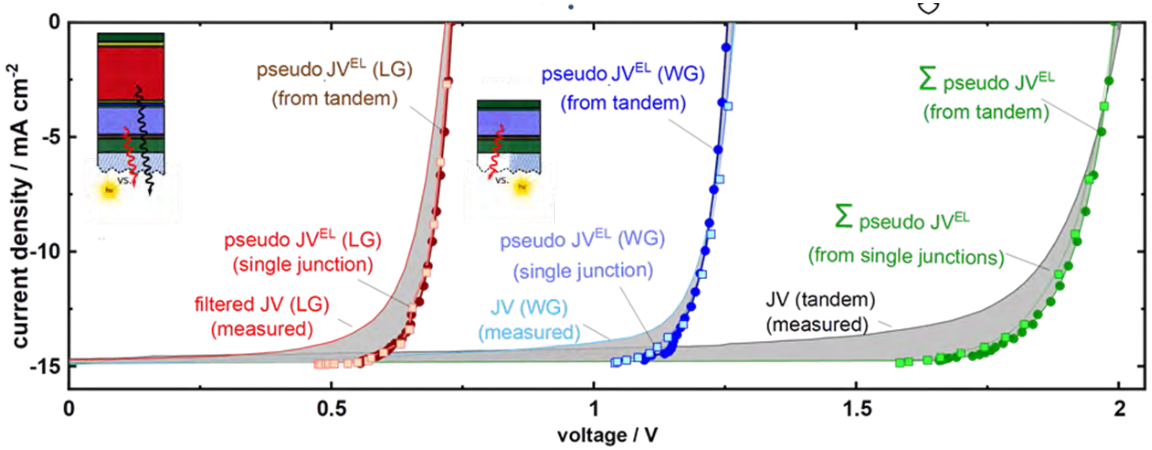
Adv. Energy Mater. 2023, 13, 2202674

Sub-cell characterisation



★ Halide segregation

$$QFLS_{EL} = k_B T \cdot \ln\left(ELQY \cdot \frac{J_{inj}}{J_{0,rad}}\right)$$



Sub-cell analysis (electroluminescence): **pseudo-JV**s from integrated **sub-cells match single juctions** + add up perfectly to **the tandem**

→ InO$_x$ interconnect almost lossless

Adv. Energy Mater. 2023, 13, 2202674

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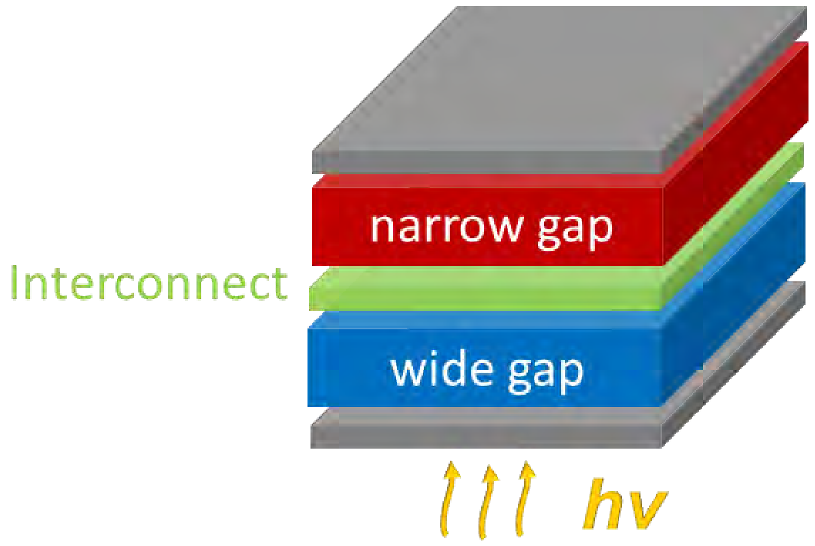
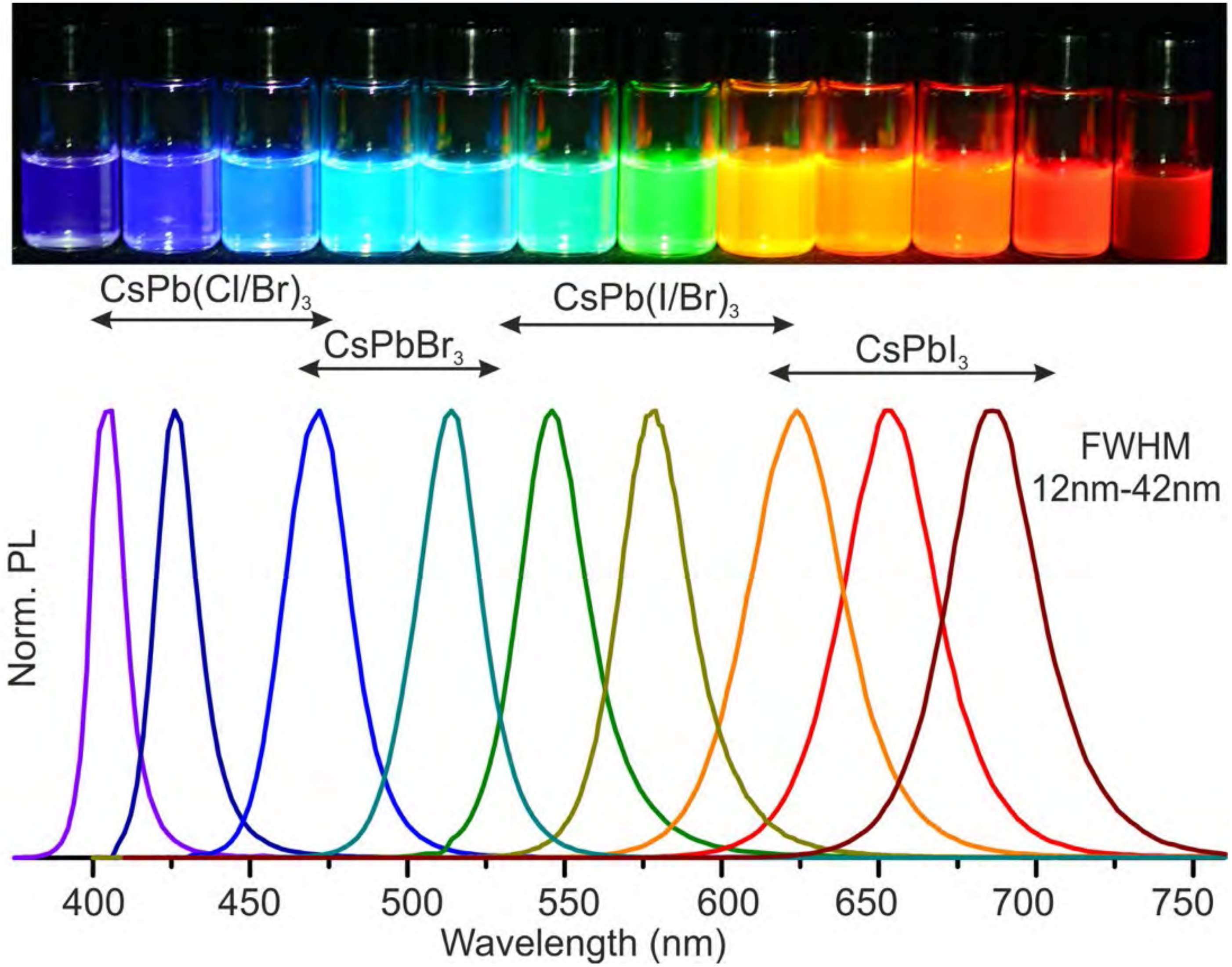
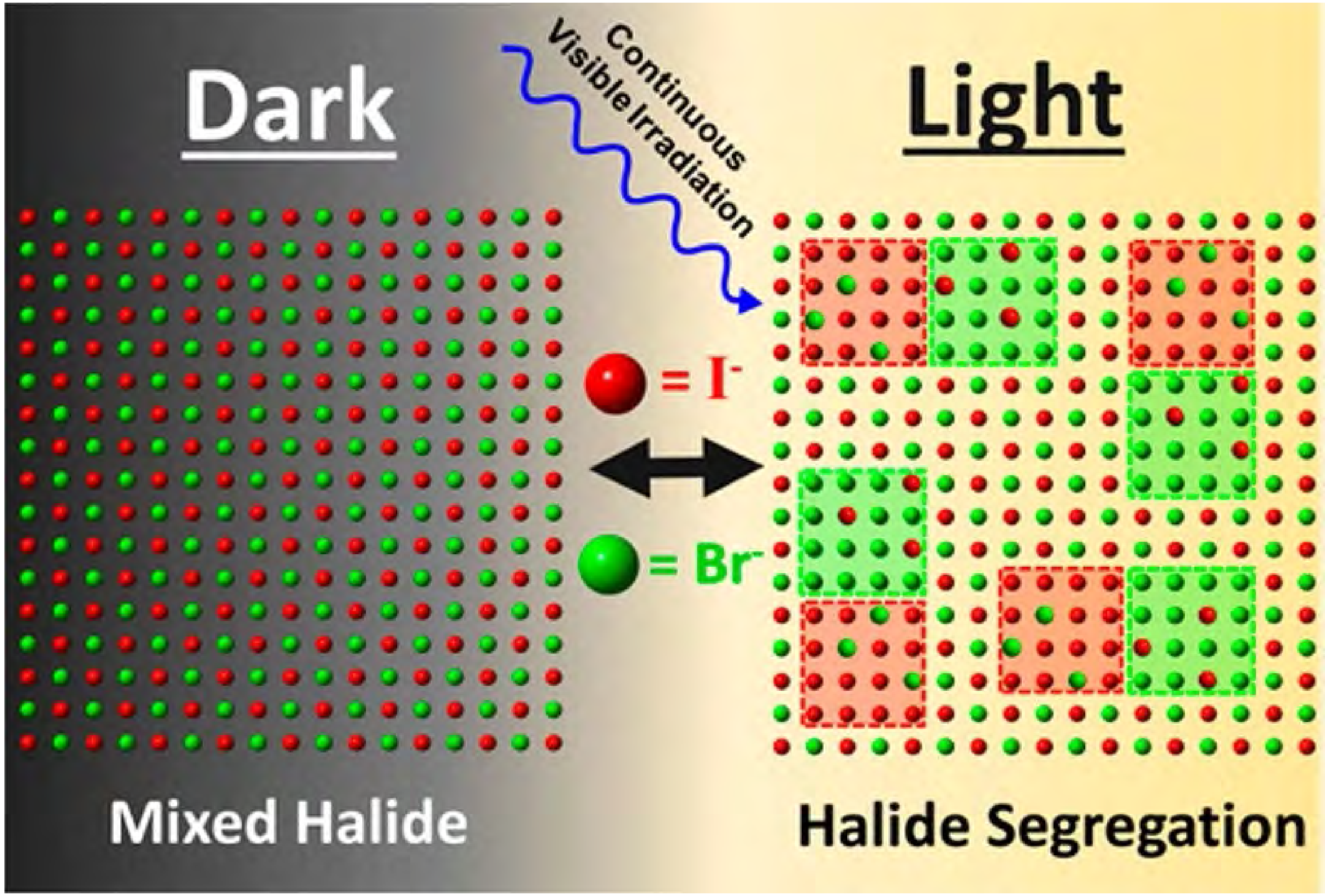


Wide-gap Perovskites – Mixed Halides

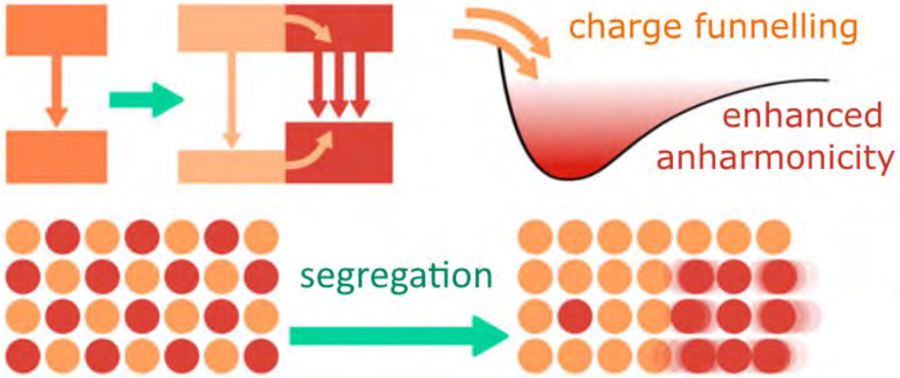


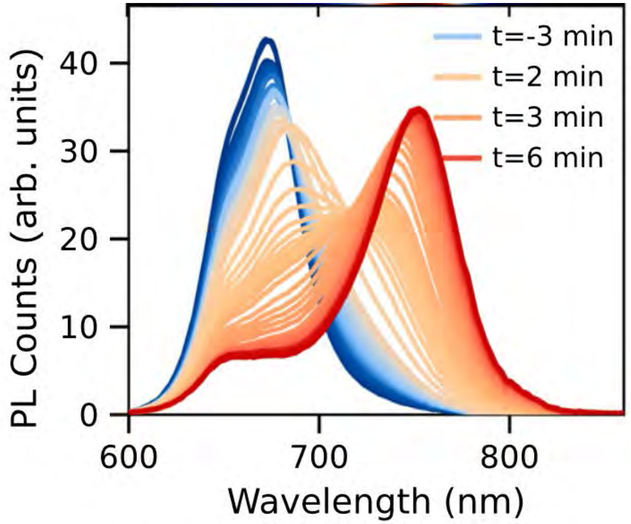
Nano Letters, 15, 5635 (2015)

Mixed-Halide Perovskites



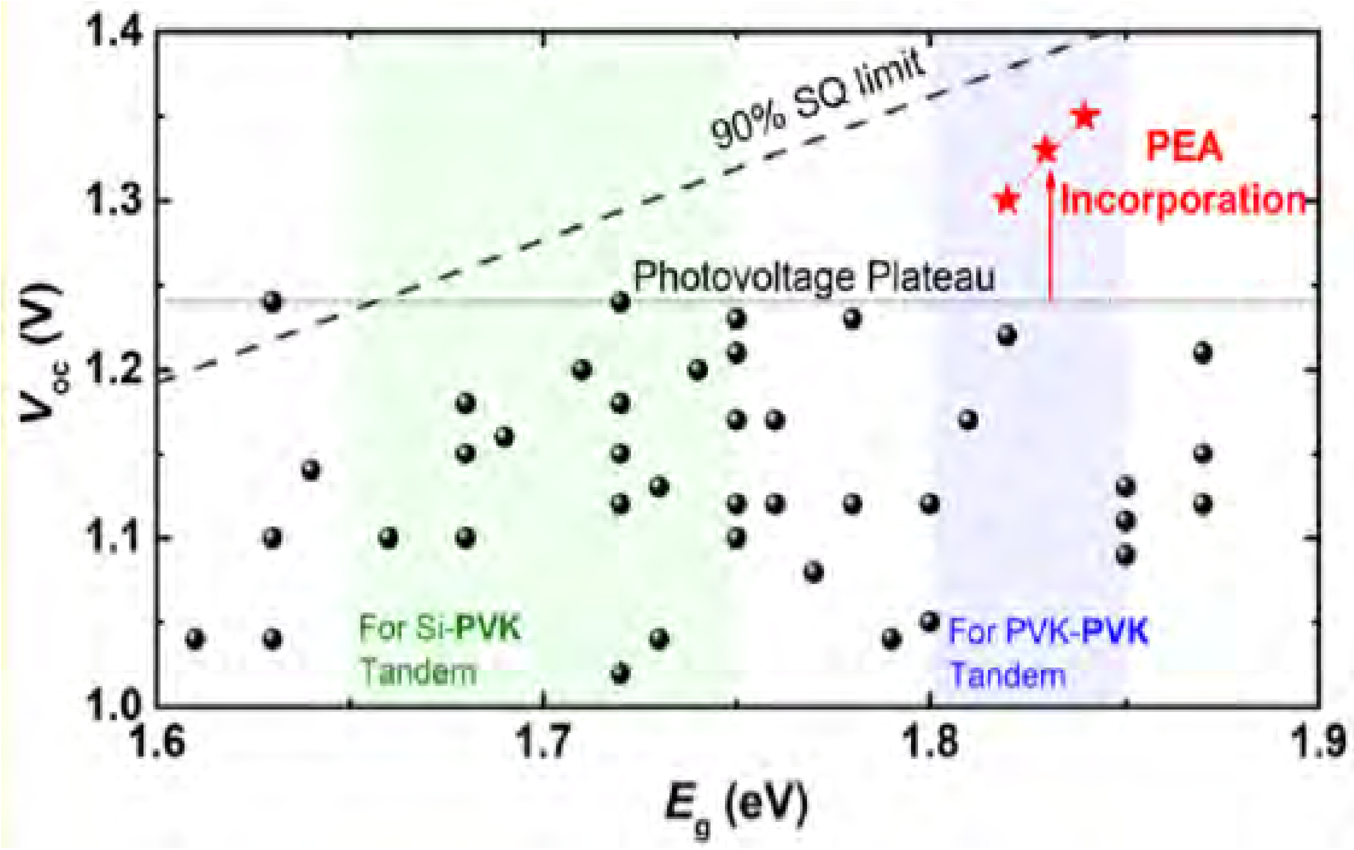
ACS Energy Lett. **3**, *204 (2018)*

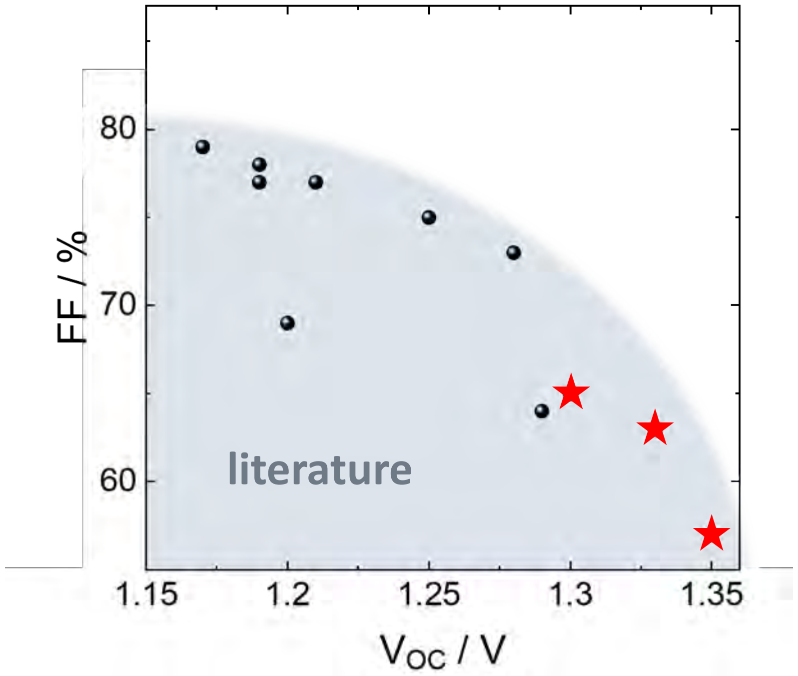




Nat. Comms. **12**, *6955 (2021)*

V_{OC} loss in wide-gap perovskite cells



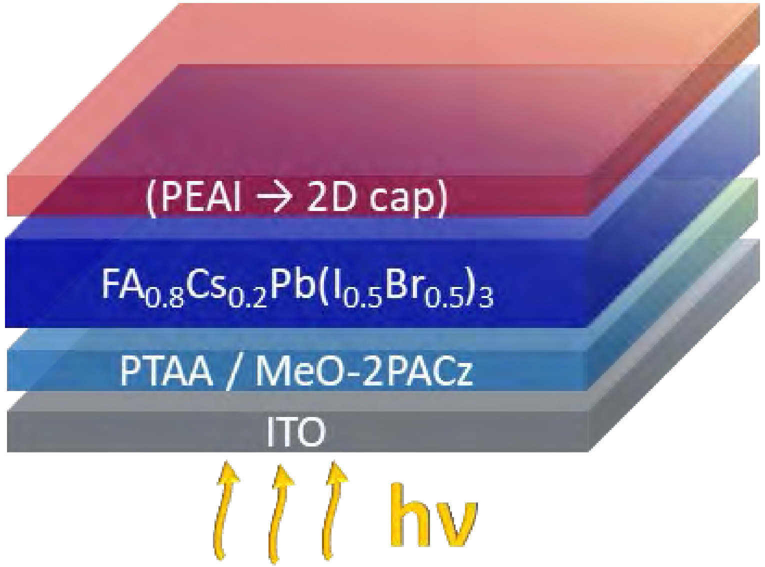


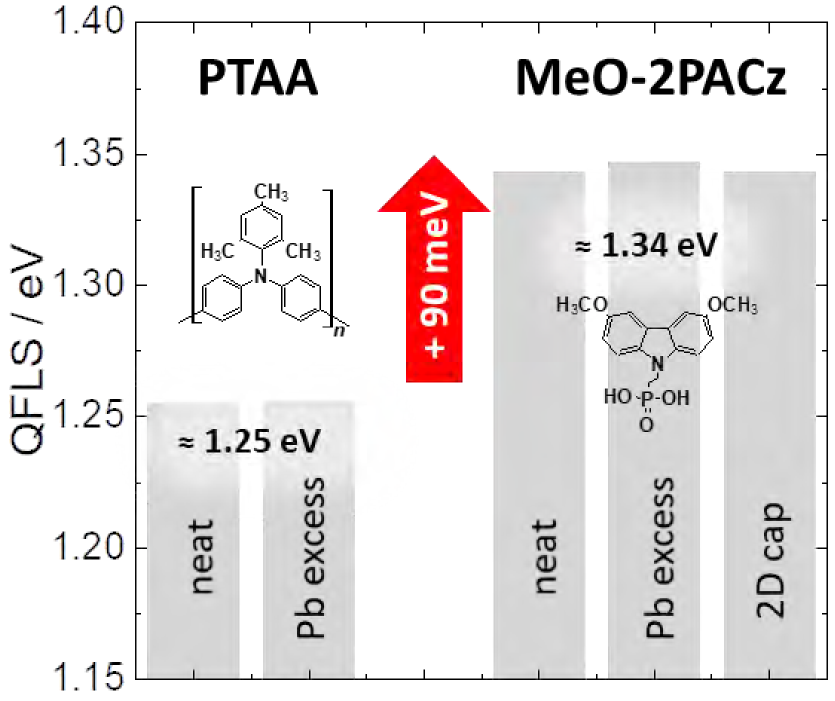
Rajagopal et al., Nano Lett. 2018, 18, 3985−3993

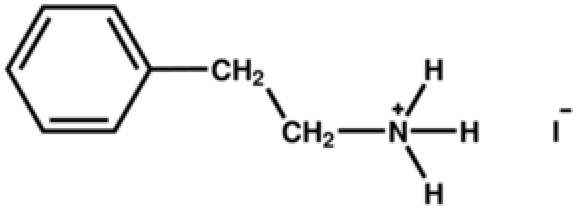
Effect of HTL on quasi fermi level splitting

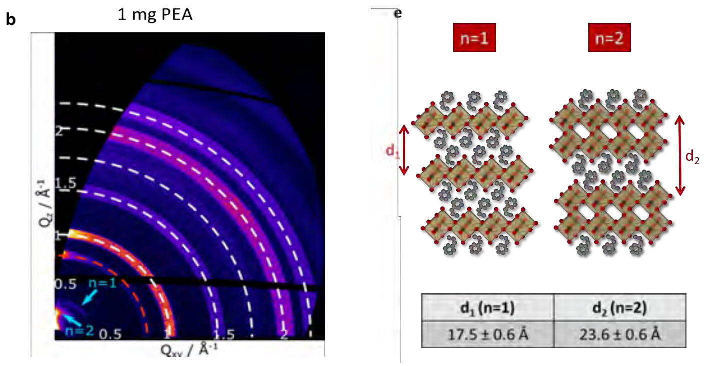
coll. with
Dr. Martin Stolterfoht

$FA_{0.8}Cs_{0.2}Pb(I_{0.5}Br_{0.5})_3$ E_g = 1.85 eV







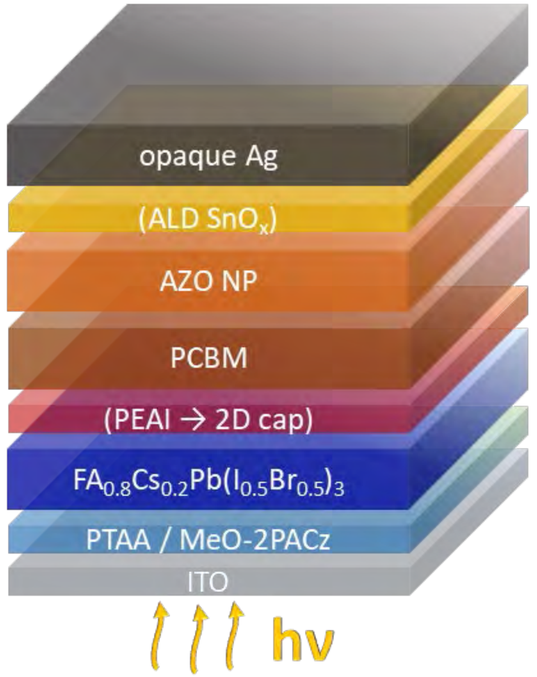


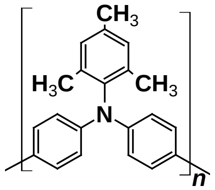
GIWAXS by L. Merten, U Tuebingen

Brinkmann et al. Nature 604, 280 (2022)

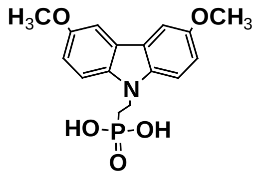
Wide-gap perovskite cell

coll. with
Dr. Martin Stolterfoht



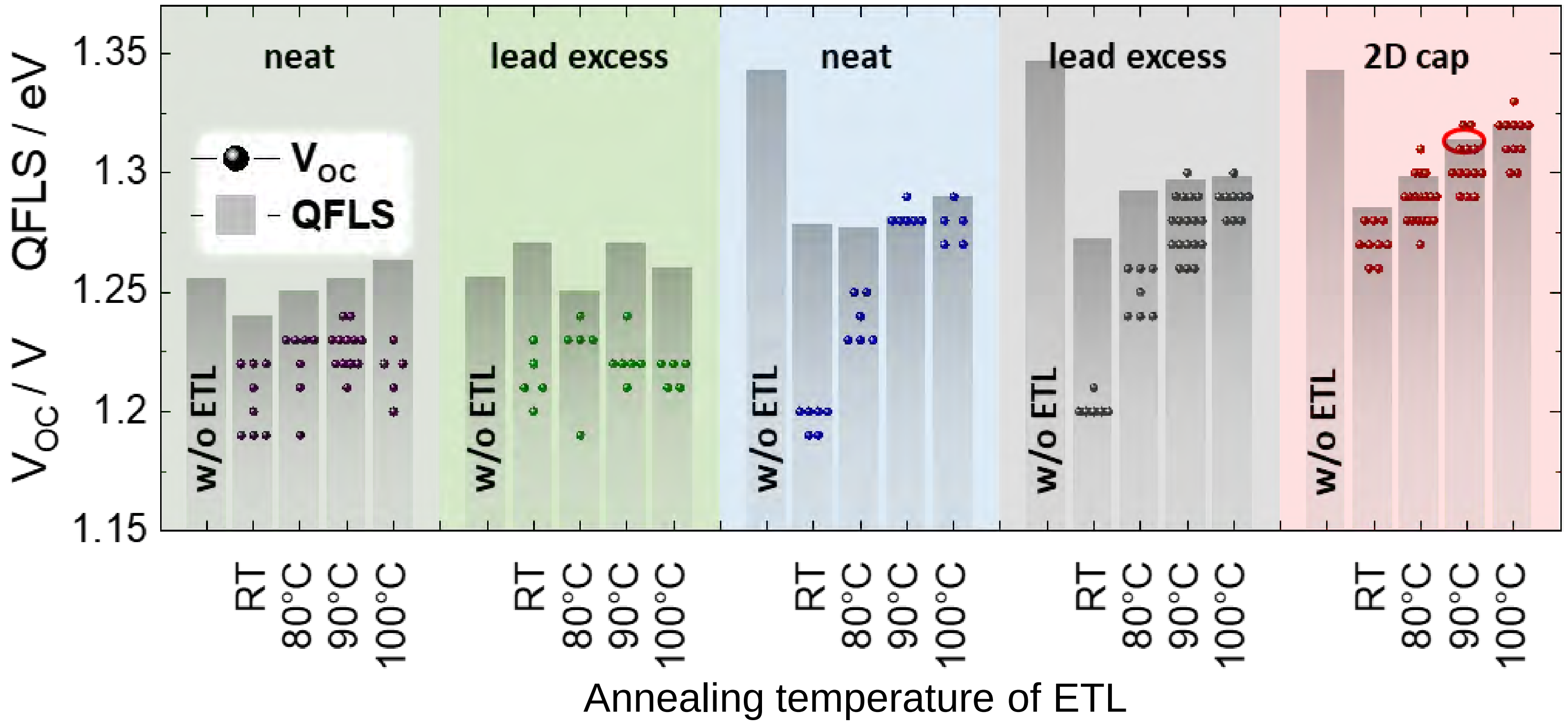


PTAA



MeO-2PACz

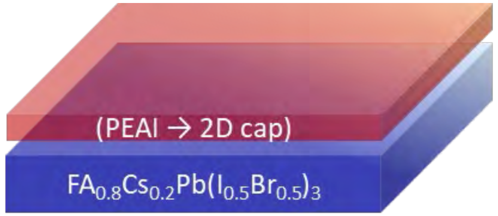
self-assembled monolayer

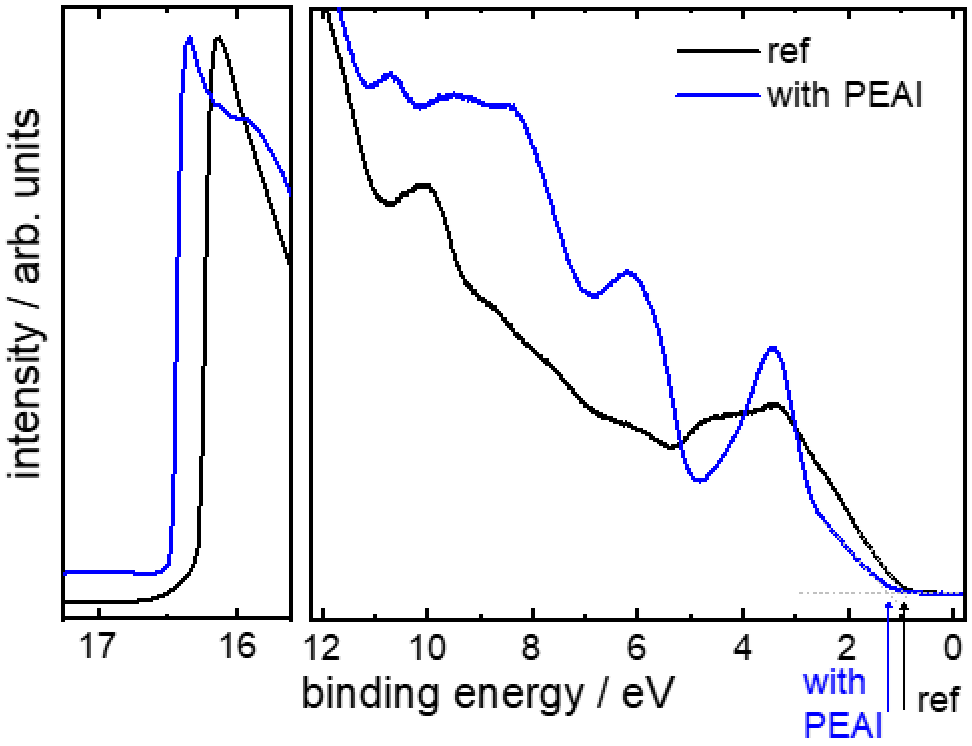


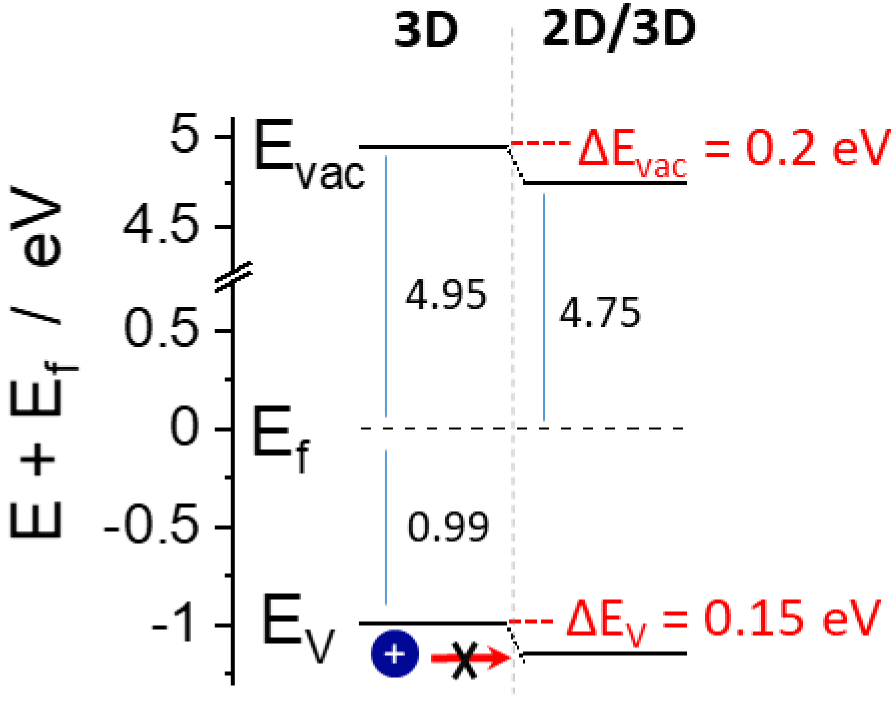
Losses at interfaces more critical than in the bulk!

3D/2D interface – electronic structure

coll. with
Dr. Selina Olthof

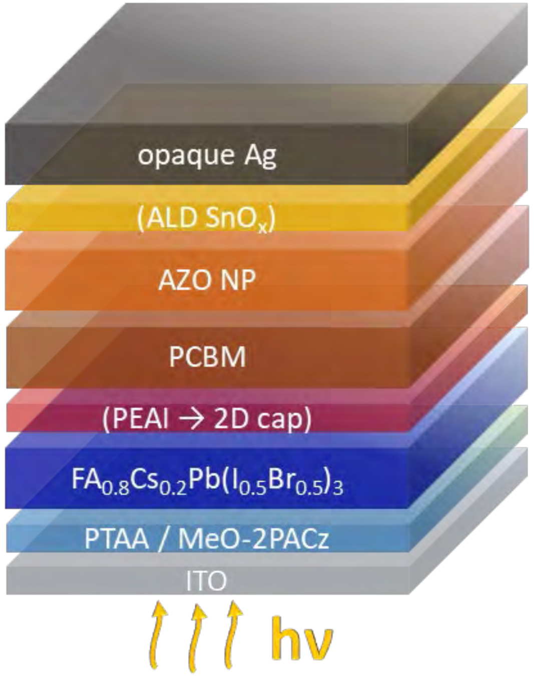


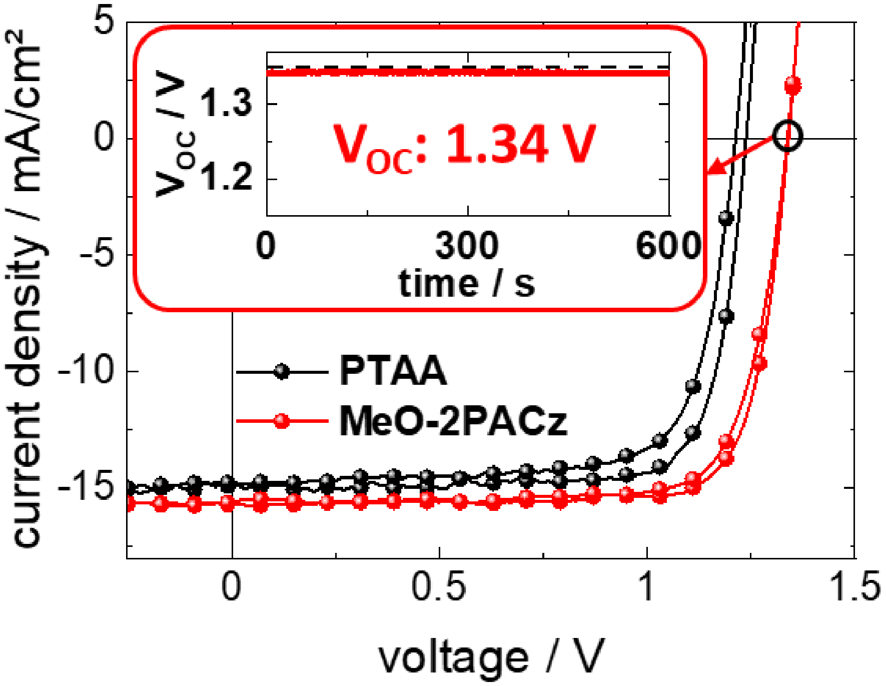


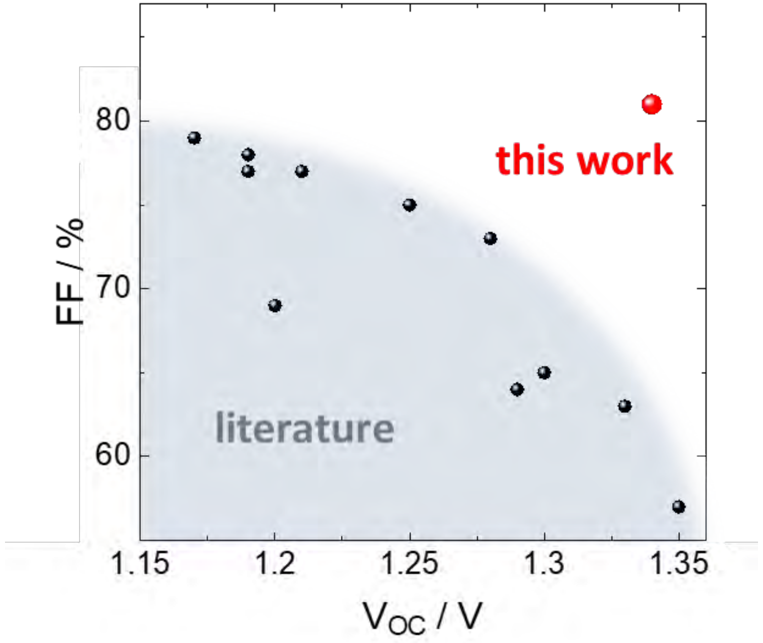


Brinkmann et al. Nature 604, 280 (2022)

Wide-gap perovskite cell





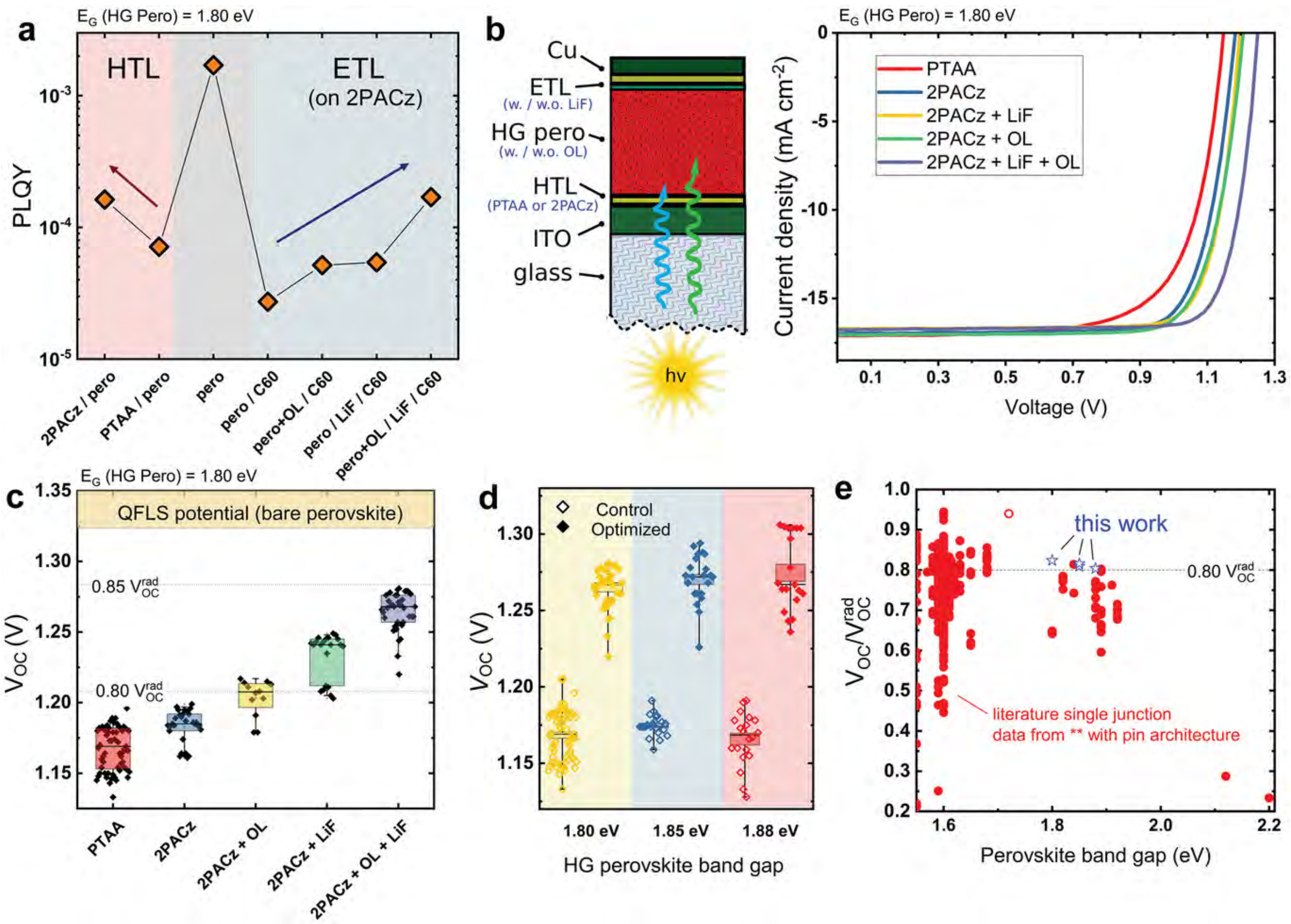


→ **high V_{oc} <u>and</u> high *FF***

→ **record for wide-gap PSCs with Br/I > 2/3 (E_g = 1.8 - 1.9 eV)**

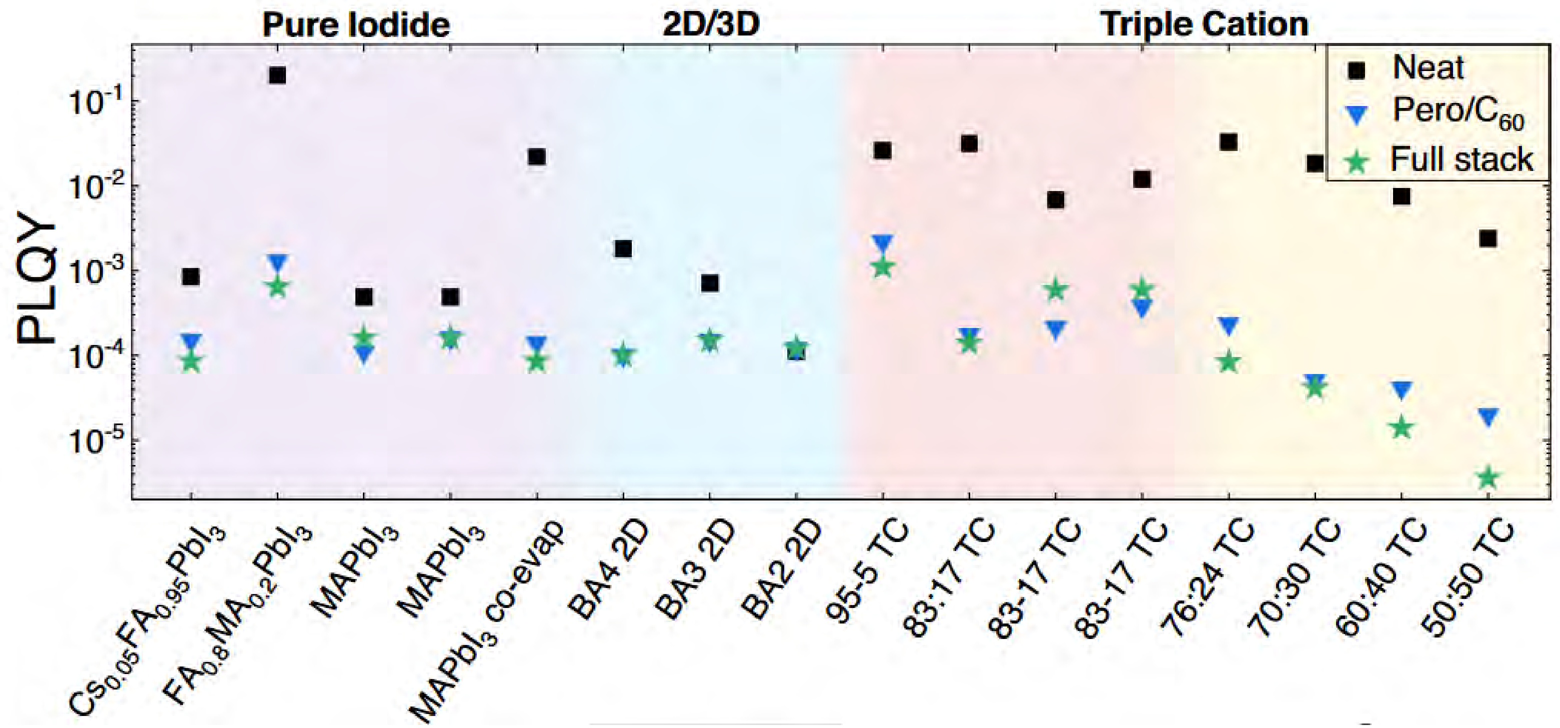
Brinkmann et al. Nature 604, 280 (2022)

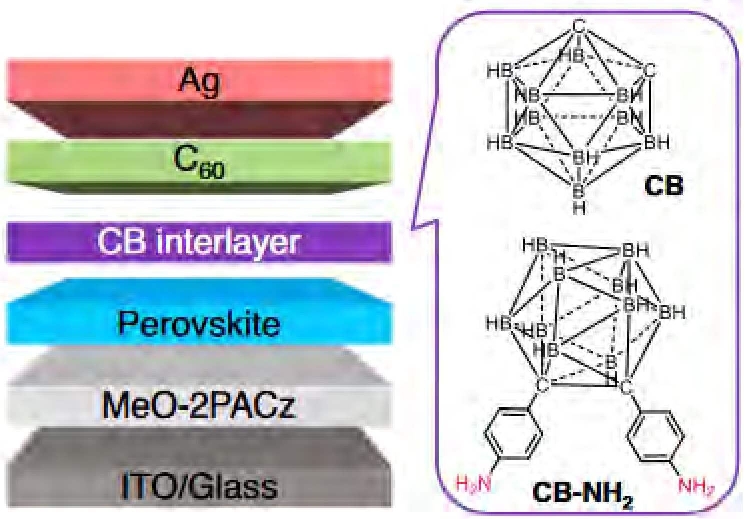
Wide-gap Perovskite

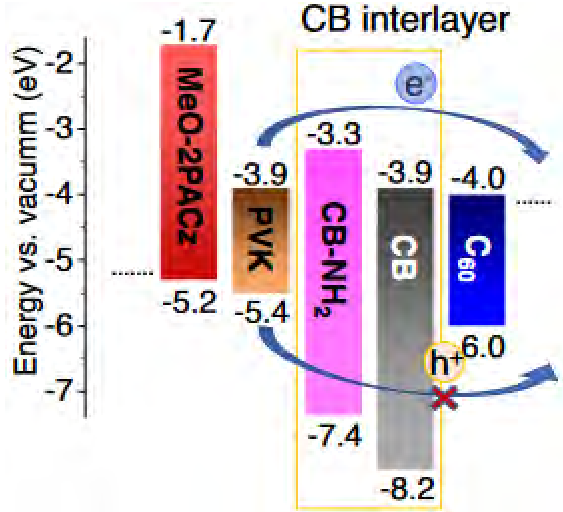


Adv. Energy Mater. 2023, 13, 2202674

Wide-gap Perovskite



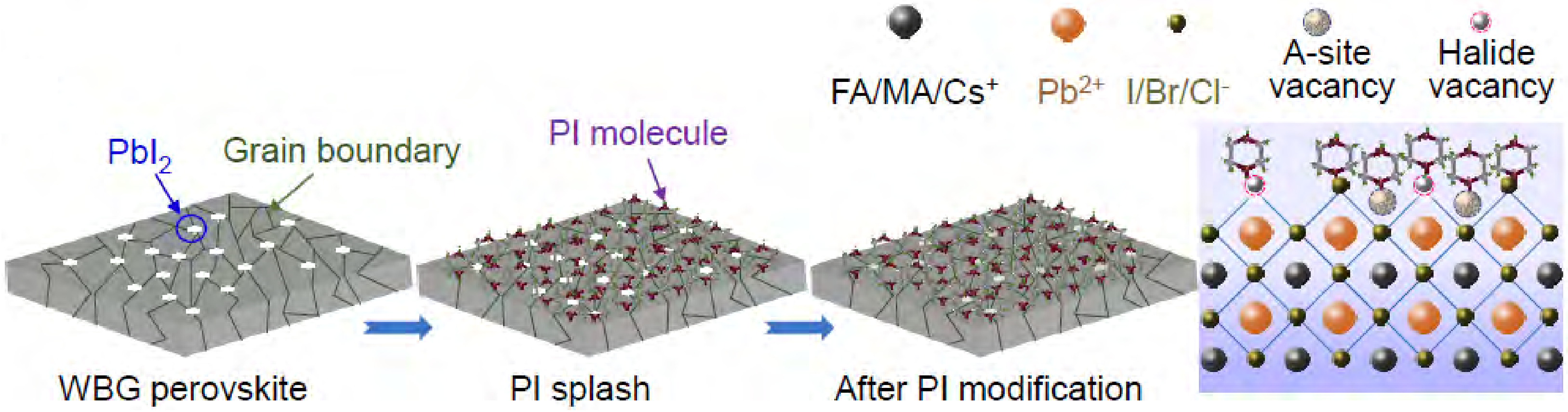


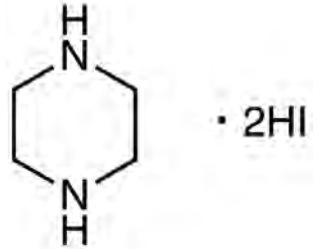


Nat. Comms. 13, 7454 (2022)

Wide-gap Perovskite

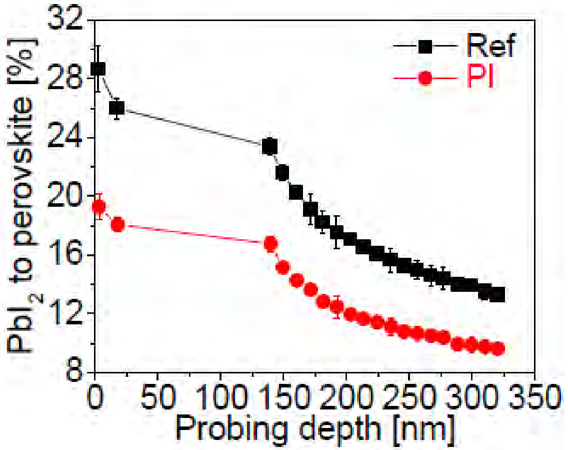
$FA_{0.78}Cs_{0.22}Pb(Br_{0.3}I_{0.7})_3$+10%$MAPbCl_3$

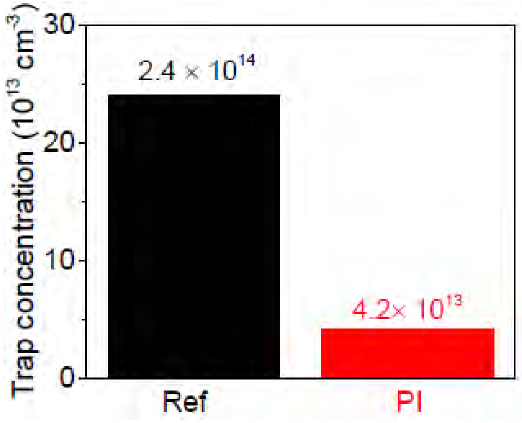




piperazinium iodide

J. Am. Chem. Soc. 2020, 142, 47, 20134–20142

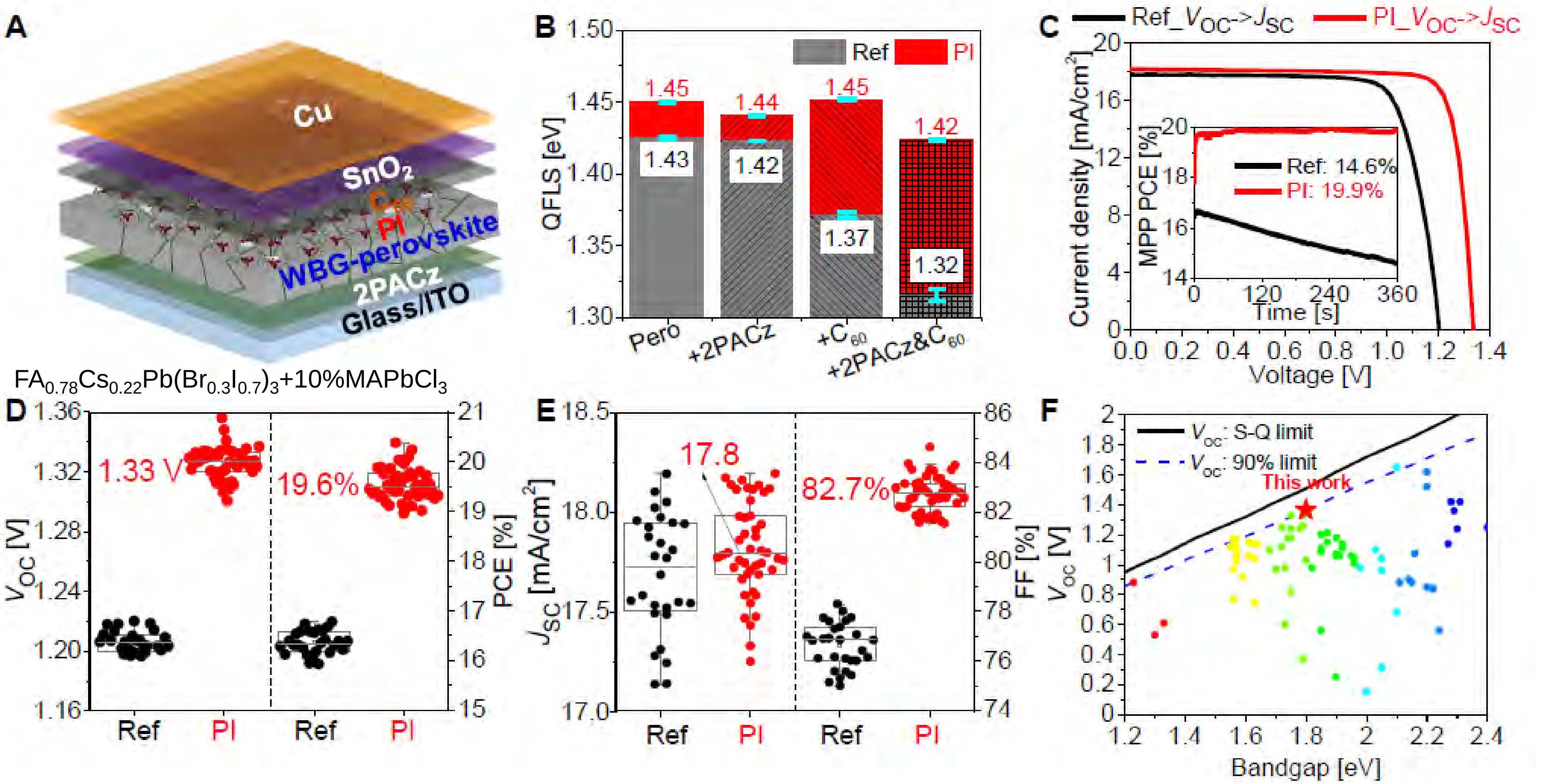




Piperazinium iodide reduces recombination loss in 1.80 eV triple-halide perovskites

Nature Energy (under review)

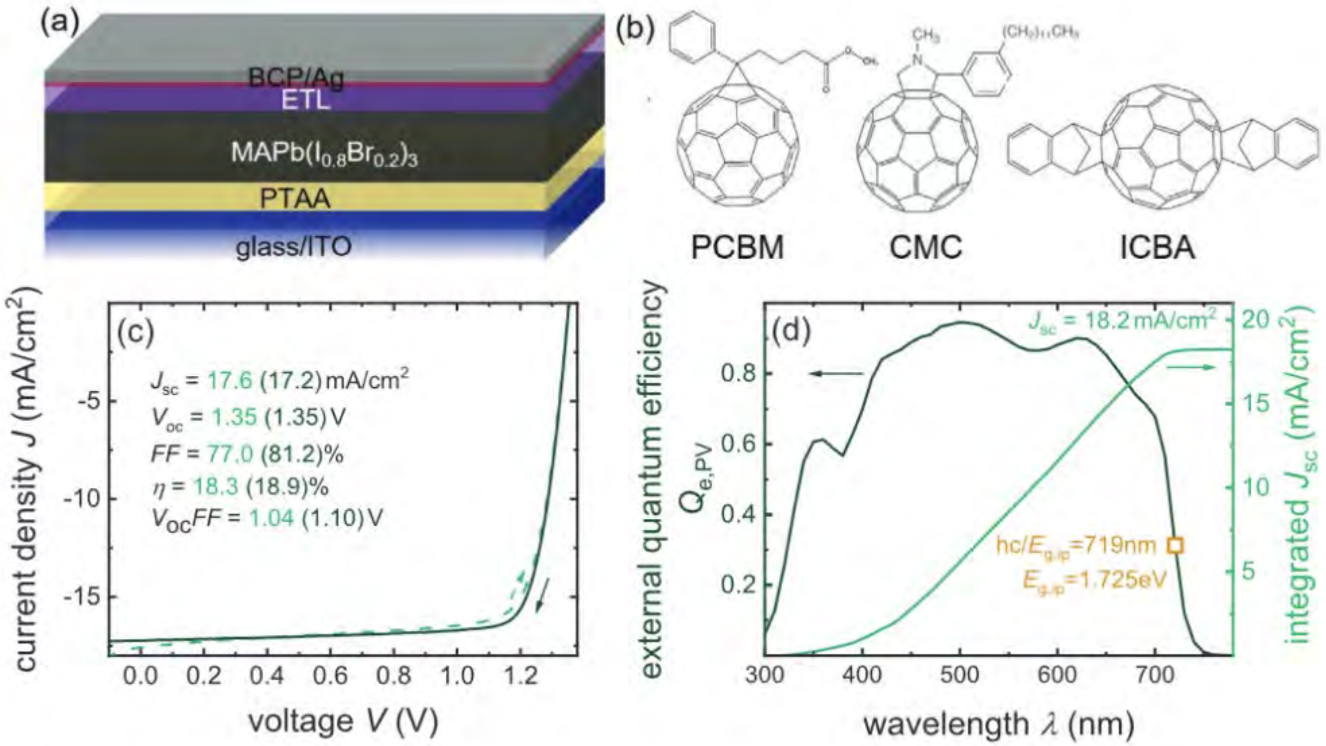
Wide-gap Perovskite

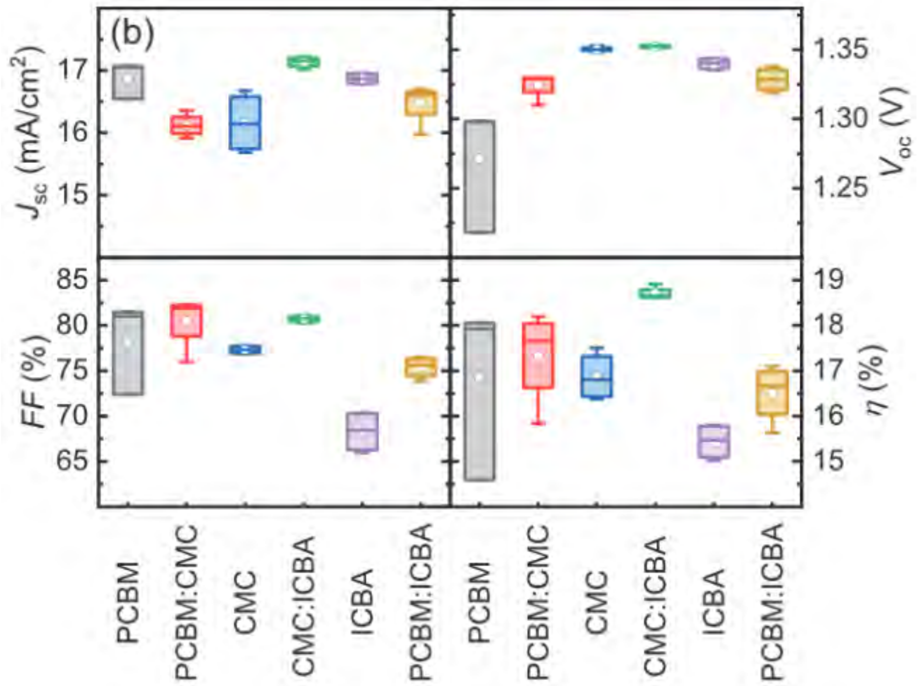


Record high V_{oc} of 1.36 V for a 1.80 eV wide gap perovskite solar cell (ΔV_{oc} = 0.44 V)

Nature Energy (under review)

Wide-gap Perovskite





V_{oc} of 1.35 V of a 1.725 eV wide gap perovskite solar cell (ΔV_{oc} = 0.375 V)

Adv. Energy Mater. 2021, 11, 2003386

Perovskite based tandem cells

CIGS – Perovskite

Pro: CIGS established cell technology, stable

Con: **Cd content, abundance of elements, high-T process**

Silicon – Perovskite

Pro: high efficiency, Si cell highly developed

Con: **high-T process**, not flexible

Perovskite – Perovskite

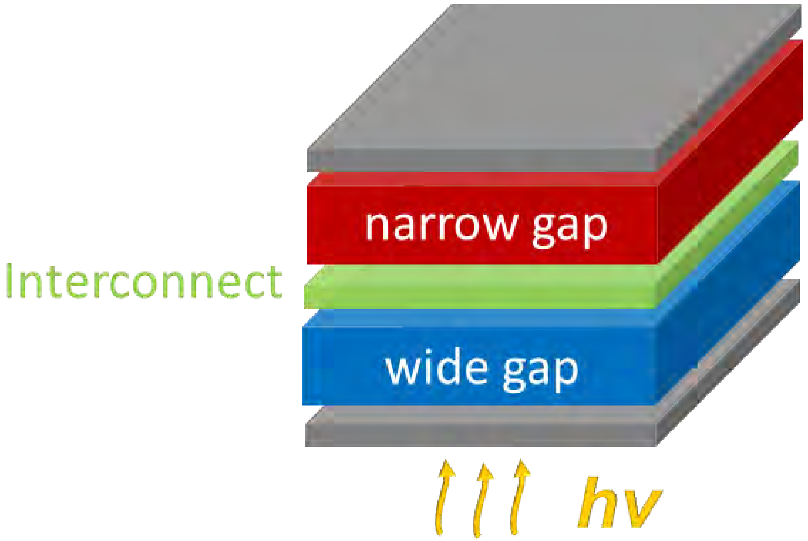
Pro: low temperature, large area, high throughput

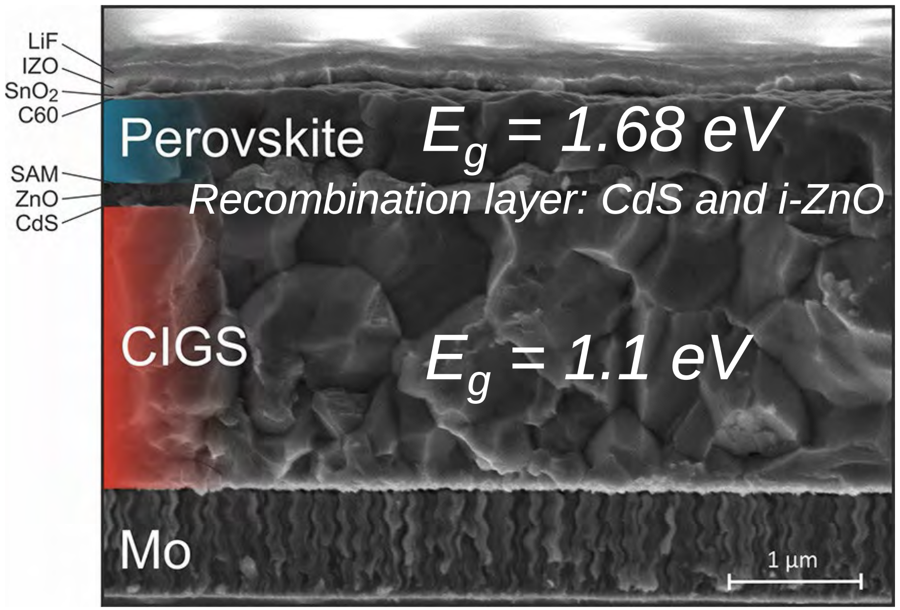
Con: **narrow-gap cell potentially unstable (Sn-based)**

Organic – Perovskite

Pro: low temperature, large area, high throughput, **reduced Pb/Sn**

Con: **still low efficiency?**





ACS Energy LETTERS
http://pubs.acs.org/journal/aelccp

Perovskite/CIGS Tandem Solar Cells: From Certified 24.2% toward 30% and Beyond

Marko Jošt,* Eike Köhnen, Amran Al-Ashouri, Tobias Bertram, Špela Tomšič, Artiom Magomedov, Ernestas Kasparavicius, Tim Kodalle, Benjamin Lipovšek, Vytautas Getautis, Rutger Schlatmann, Christian A. Kaufmann, Steve Albrecht,* and Marko Topič

Cite This: ACS Energy Lett. 2022, 7, 1298–1307 Read Online

+ The main improvement: increased open-circuit voltage of PSC (1.68 eV) (SAM Me-4PACz HTL, PEAI additive, and LiF interlayer)

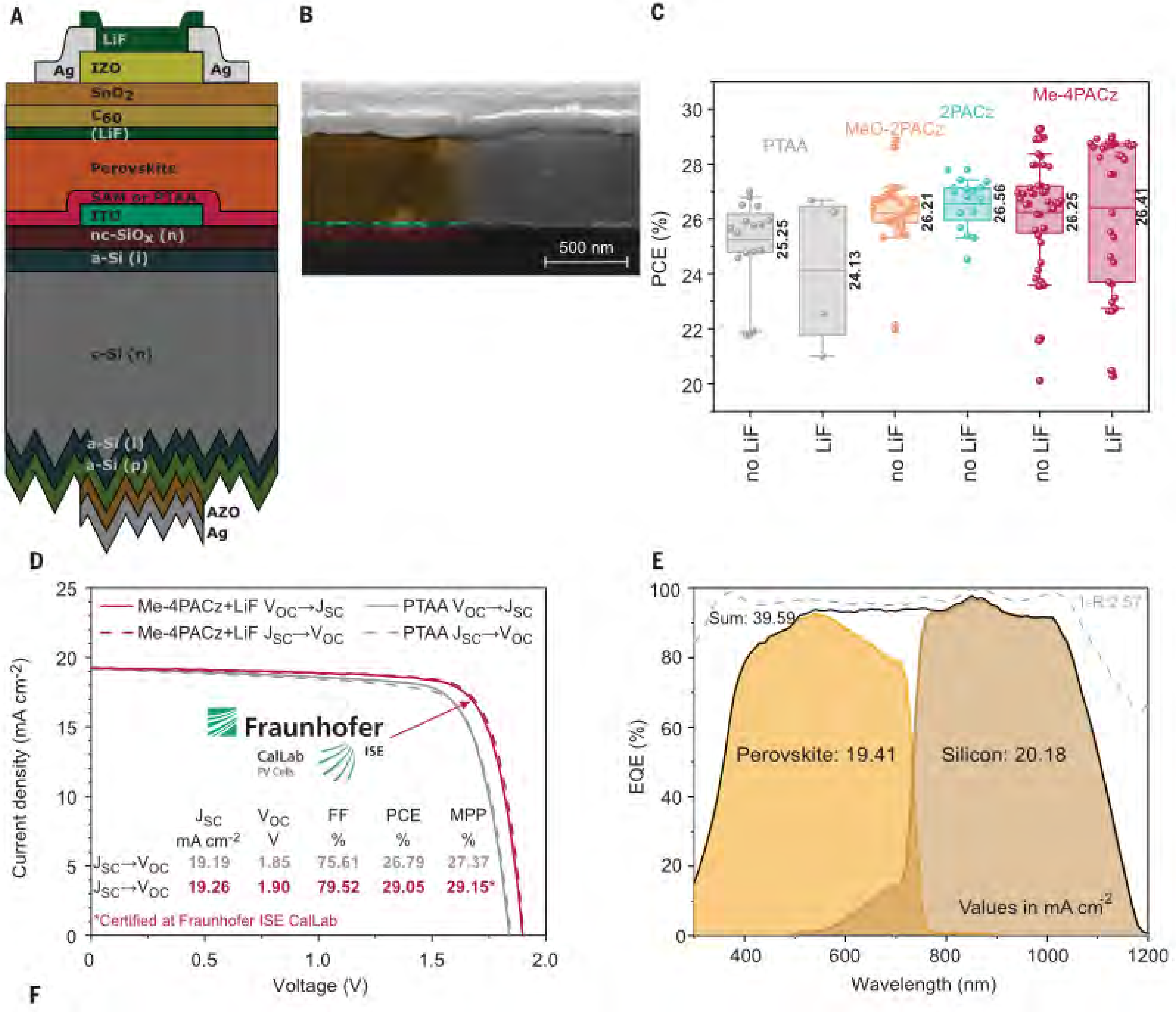
- poor fill factor (FF = 71.2%; shunts) and short-circuit current density only 18.8 mA/cm^2

simulation	nonencapsulated				encaps
	E_g = 1.65 eV	E_g = 1.68 eV	E_g = 1.70 eV	E_g = 1.72 eV	E_g = 1.69 eV
Pero J_{SC_SIM} ($mA\ cm^{-2}$)	19.92	19.93	19.92	19.33	18.8
CIGS J_{SC_SIM} ($mA\ cm^{-2}$)	19.92	19.92	19.93	19.92	18.8
J_{SC_SIM} ($mA\ cm^{-2}$)	19.9	19.9	19.9	19.3	18.8
FF (%)	80	80	80	80	80
V_{OC} (V)	1.96	1.99	2.01	2.03	2.00
PCE (%)	31.2	31.6	32.0	31.3	30.0

SOLAR CELLS

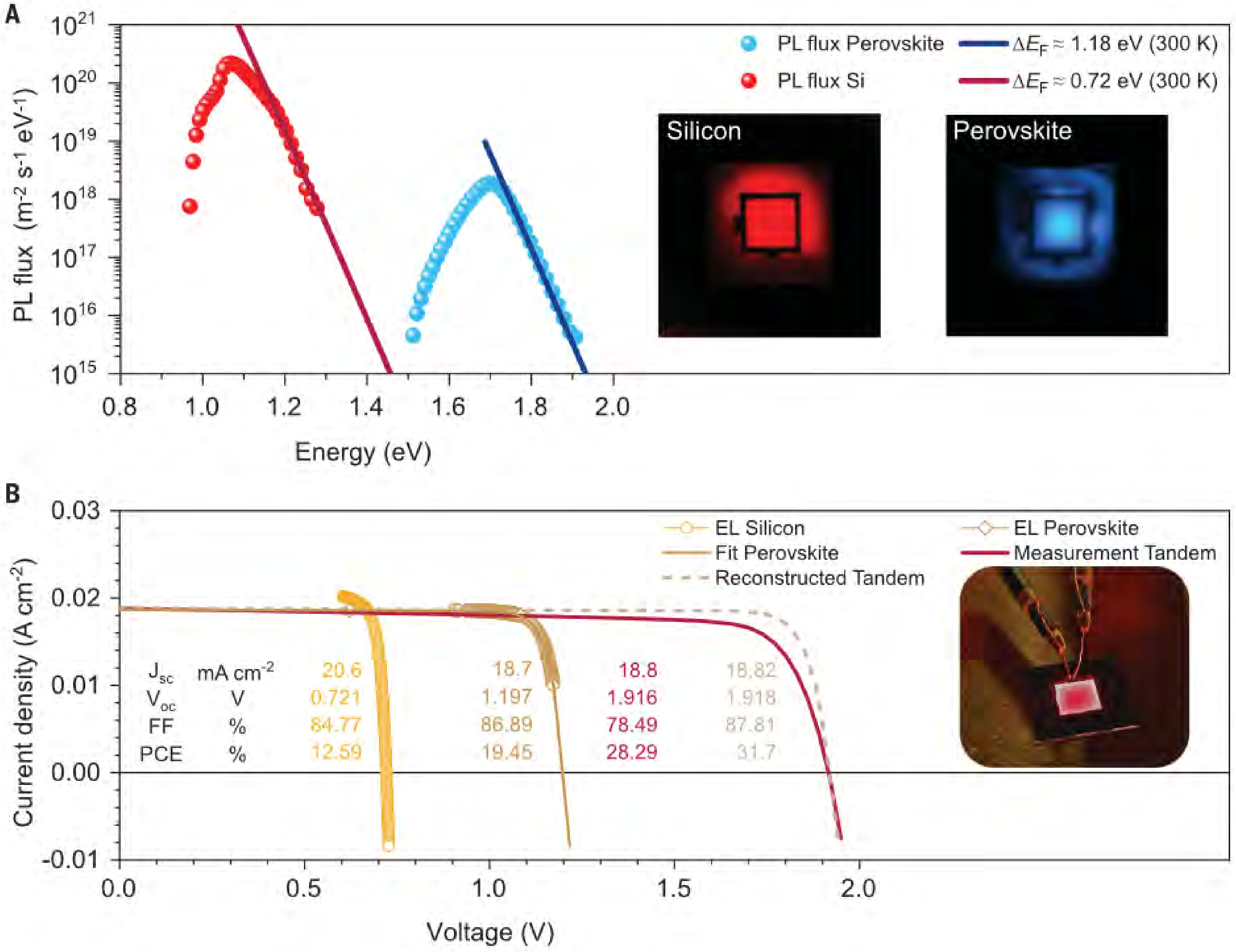
Monolithic perovskite/silicon tandem solar cell with >29% efficiency by enhanced hole extraction

Amran Al-Ashouri[1]*, Eike Köhnen[1]*, Bor Li[1], Artiom Magomedov[2], Hannes Hempel[3], Pietro Caprioglio[1,4], José A. Márquez[3], Anna Belen Morales Vilches[5], Ernestas Kasparavicius[2], Joel A. Smith[6,7], Nga Phung[6], Dorothee Menzel[1], Max Grischek[1,4], Lukas Kegelmann[1], Dieter Skroblin[8], Christian Gollwitzer[8], Tadas Malinauskas[2], Marko Jošt[1,9], Gašper Matič[9], Bernd Rech[10,11], Rutger Schlatmann[5,12], Marko Topič[9], Lars Korte[1], Antonio Abate[6], Bernd Stannowski[5,13], Dieter Neher[4], Martin Stolterfoht[4], Thomas Unold[3], Vytautas Getautis[2], Steve Albrecht[1,11]†



Perovskite used (E_g 1.68 eV): $Cs_{0.05}(FA_{0.77}MA_{0.23})_{0.95}Pb(I_{0.77}Br_{0.23})_3$

Science 370, 1300–1309 (2020)



Efficiency > 31% predicted from sub-cell analysis

Science 370, 1300–1309 (2020)

Perovskite/Silicon

33.2%! KAUST Team Sets World Record for Tandem Solar Cell Efficiency

APRIL 14, 2023 BY ALEINA IN TECHNOLOGY

PVTIME – Researchers at the King Abdullah University of Science and Technology (KAUST) Photovoltaics Laboratory (KPV-Lab) of the KAUST Solar Center, a leading institute of research excellence in the Kingdom of Saudi Arabia, claimed on 13 April that it has produced a perovskite-silicon tandem solar cell with a power conversion efficiency of 33.2%, which was confirmed by the European Solar Test Installation (ESTI) as the top of the National Renewable Energy Laboratory's (NREL) Best Research-cell Efficiency List.

Meyer Burger to commercialize 29.6%-efficient perovskite tandem solar cells

Meyer Burger is working with several research institutes in Switzerland and Germany to integrate perovskite tandem technology into its manufacturing processes.

DECEMBER 14, 2022 SANDRA ENKHARDT

HIGHLIGHTS | MODULES & UPSTREAM MANUFACTURING | TECHNOLOGY AND R&D | GERMANY | SWITZERLAND

Multijunction Cells (2-terminal, monolithic)

- **LM** = lattice matched
- **MM** = metamorphic
- **IMM** = inverted, metamorphic
- ▽ Three-junction (concentrator)
- ▼ Three-junction (non-concentrator)
- △ Two-junction (concentrator)
- ▲ Two-junction (non-concentrator)
- ⊡ Four-junction or more (concentrator)
- □ Four-junction or more (non-concentrator)

Single-Junction GaAs

- △ Single crystal
- △ Concentrator
- ▽ Thin-film crystal

Crystalline Si Cells

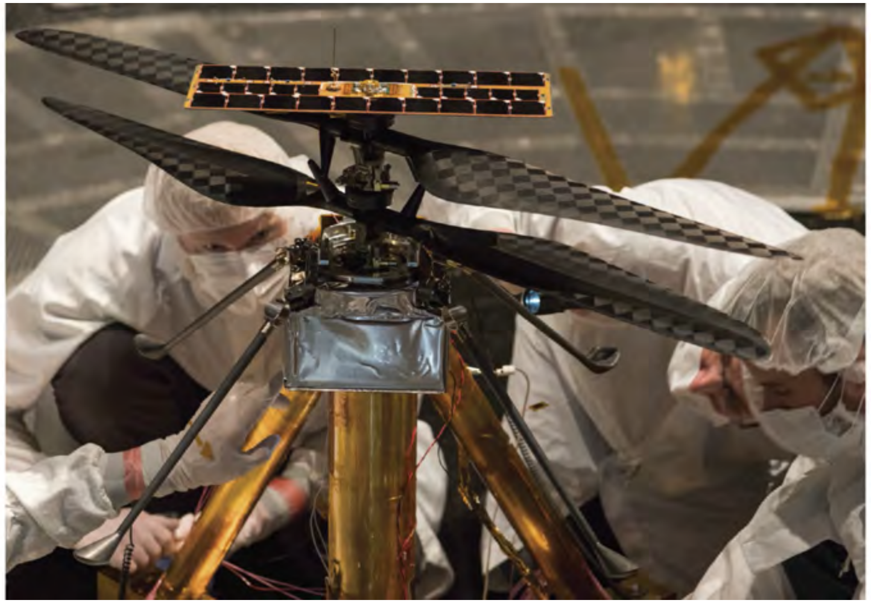
- ⊡ Single crystal (concentrator)
- ■ Single crystal (non-concentrator)
- □ Multicrystalline
- ● Silicon heterostructures (HIT)
- ▽ Thin-film crystal

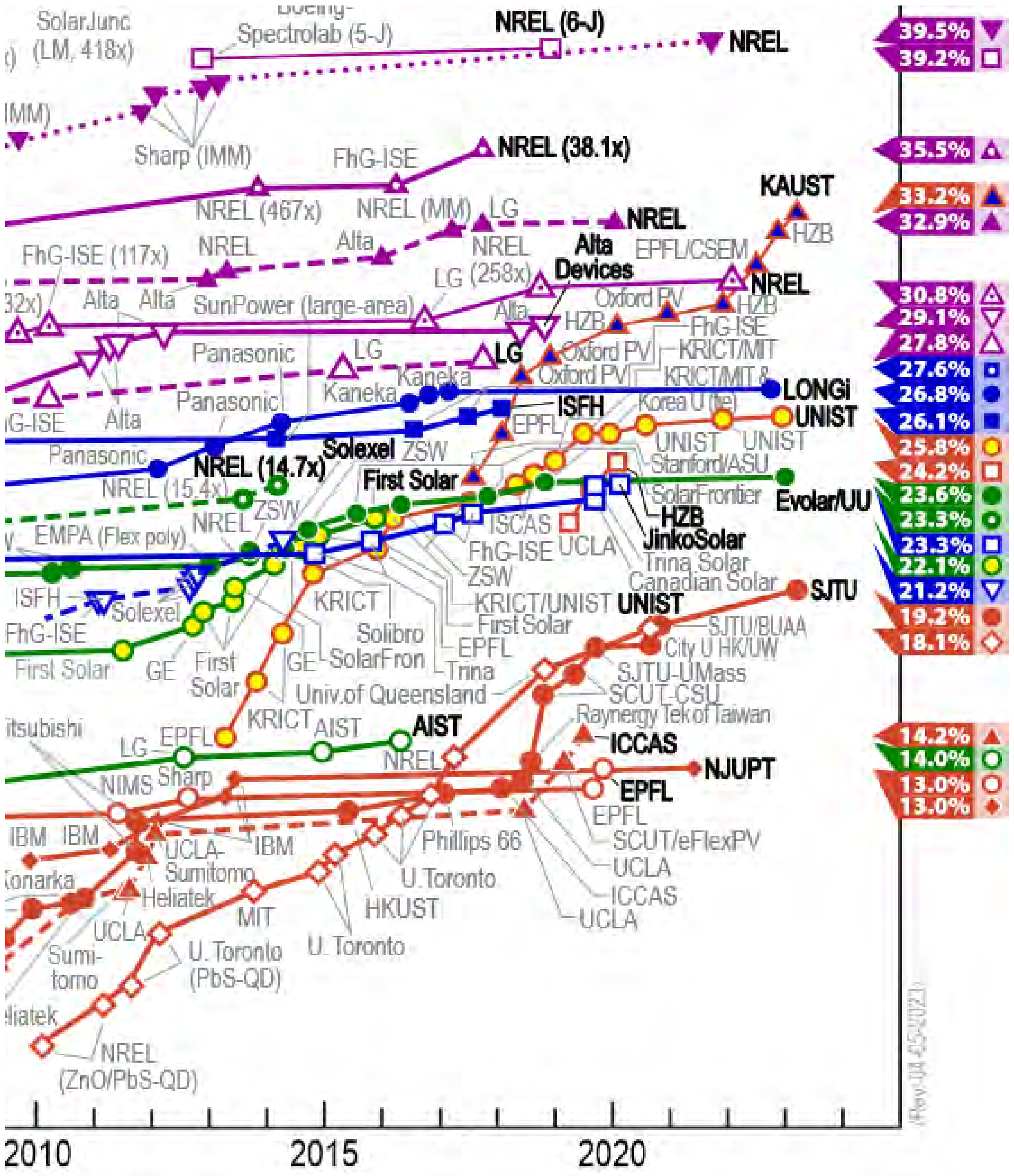
Thin-Film Technologies

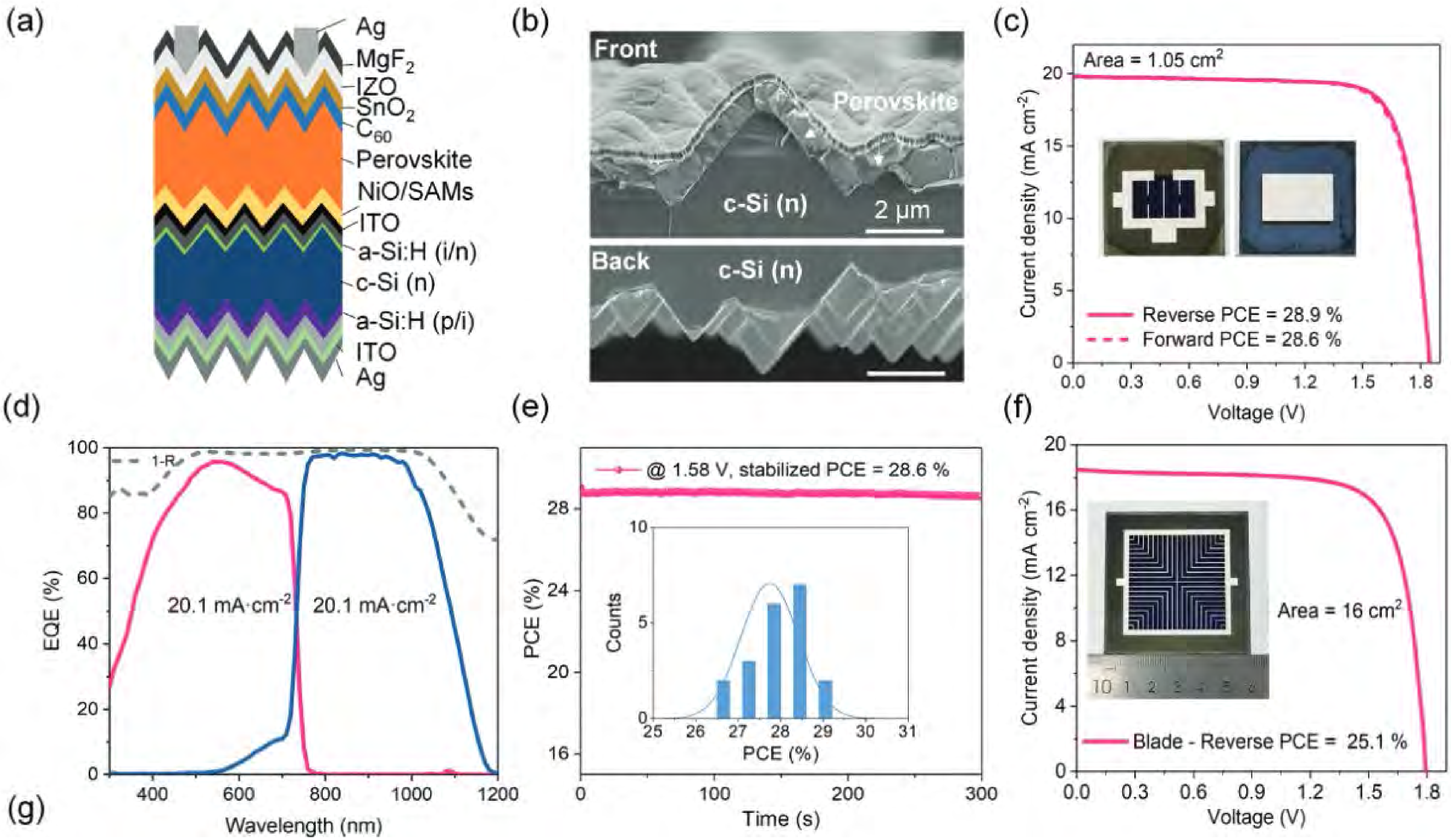
- ⊙ CIGS (concentrator)
- ● CIGS
- ○ CdTe
- ○ Amorphous Si:H (stabilized)

Emerging PV

- ○ Dye-sensitized cells
- ○ Perovskite cells
- ▲ Perovskite/Si tandem (monolithic)
- ● Organic cells
- ▲ Organic tandem cells
- ◆ Inorganic cells (CZTSSe)
- ◇ Quantum dot cells (various types)
- □ Perovskite/CIGS tandem (monolithic)



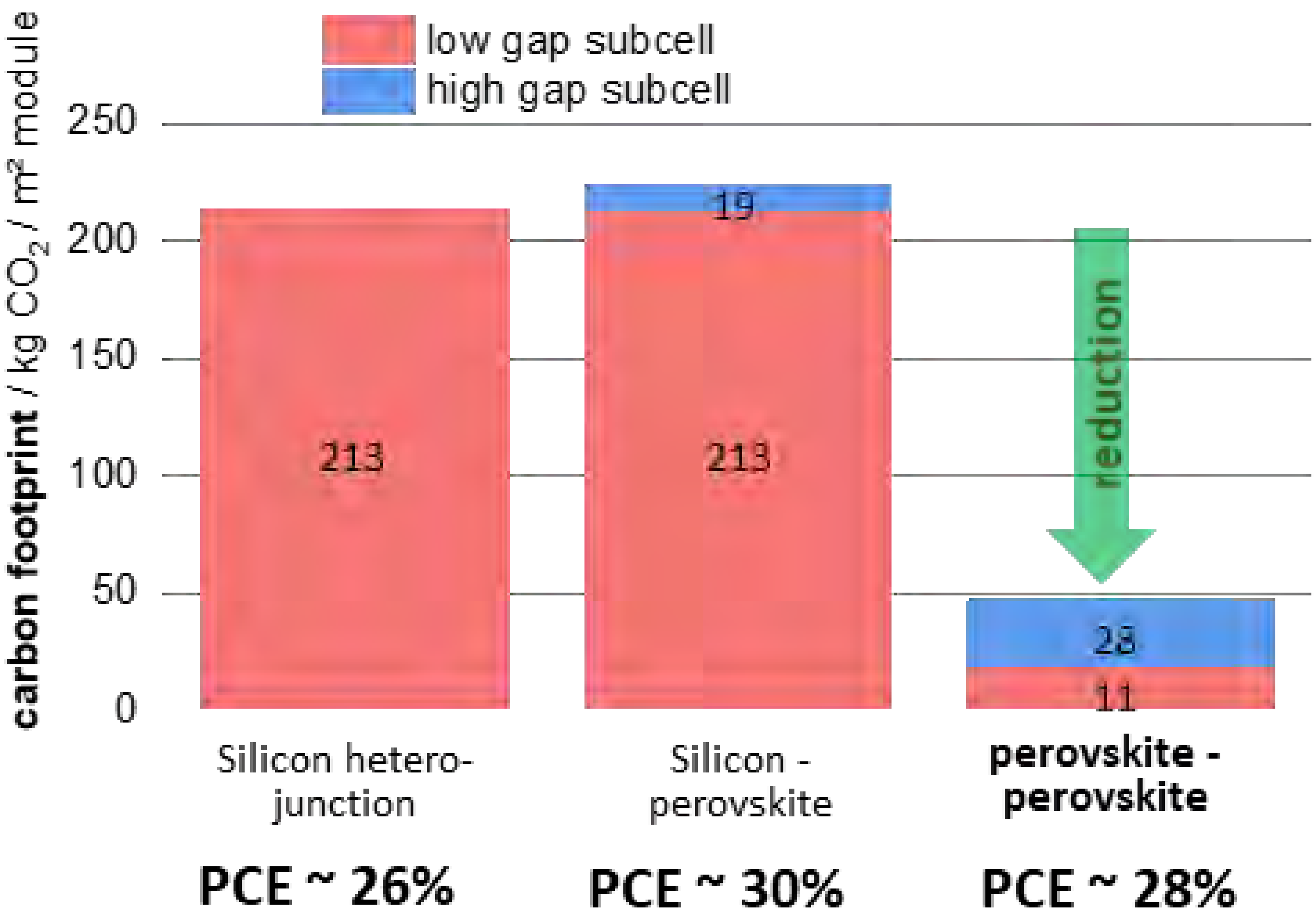




Adv. Mater. 2023, 35, 2207883

BERGISCHE UNIVERSITÄT WUPPERTAL

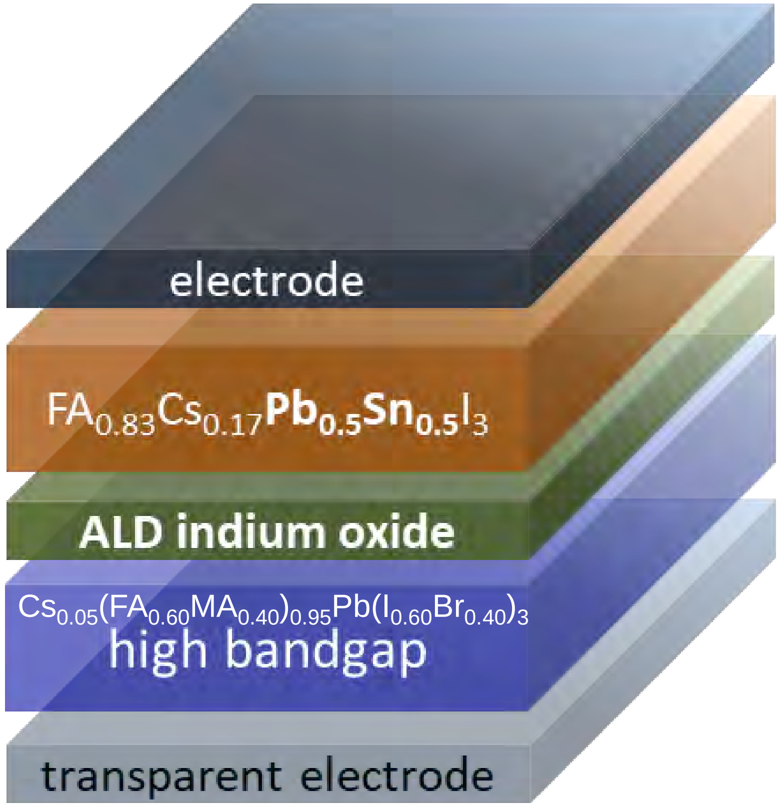
Carbon footprint

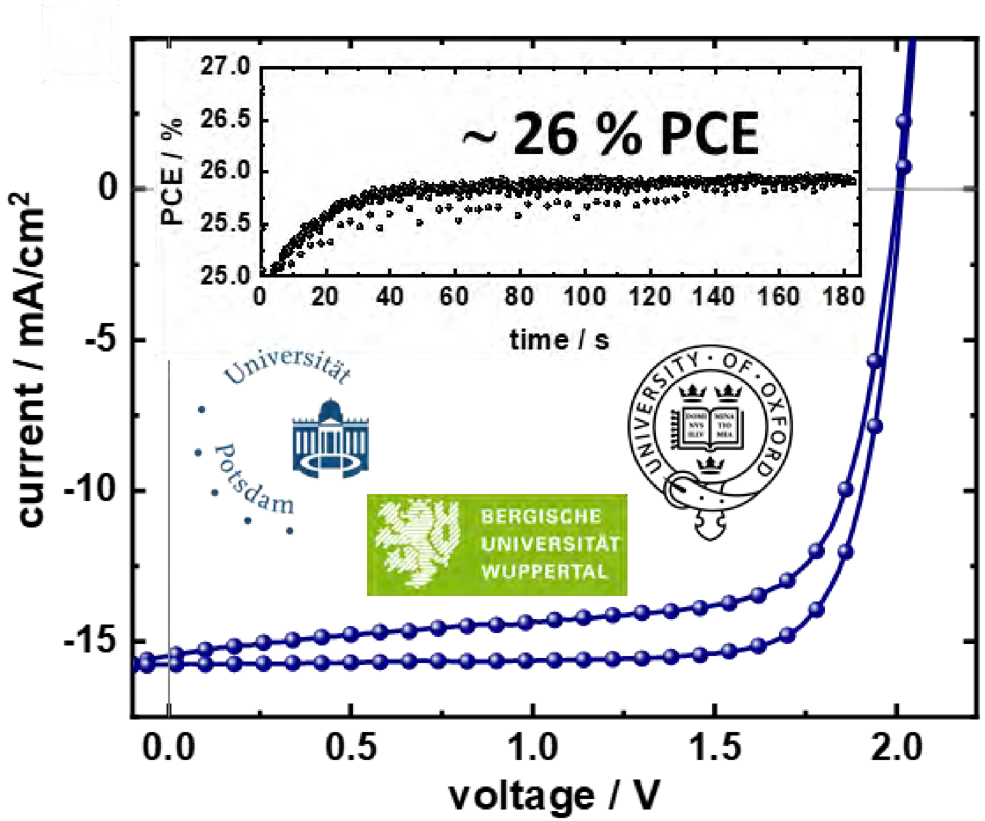


Tian et al. Science Adv. 6, 31, eabb0055 (2020)

Perovskite/Perovskite

perovskite-**perovskite** tandem

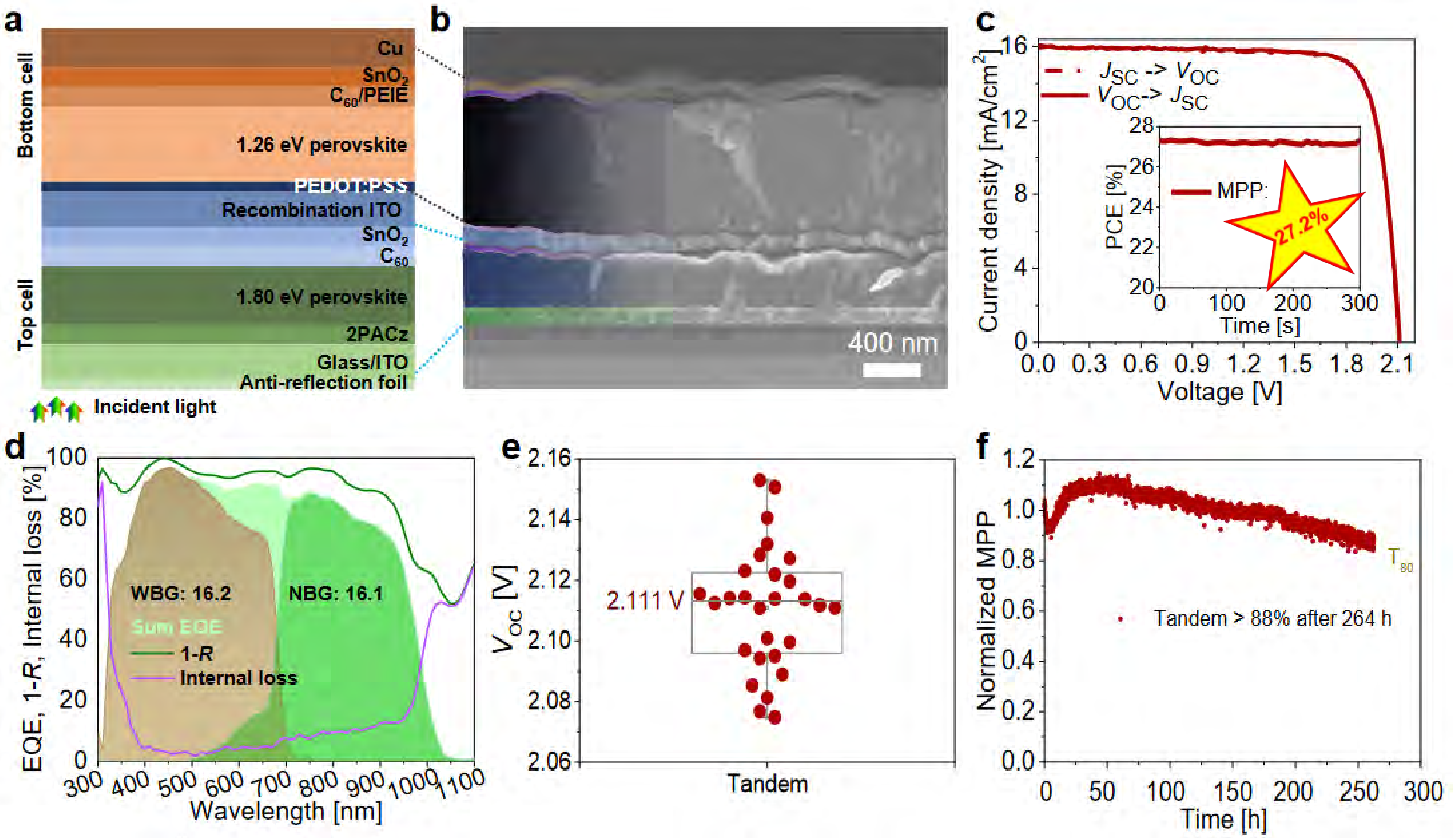




All-perovskite tandem with low gap perovskite → PCE of ~ 26%

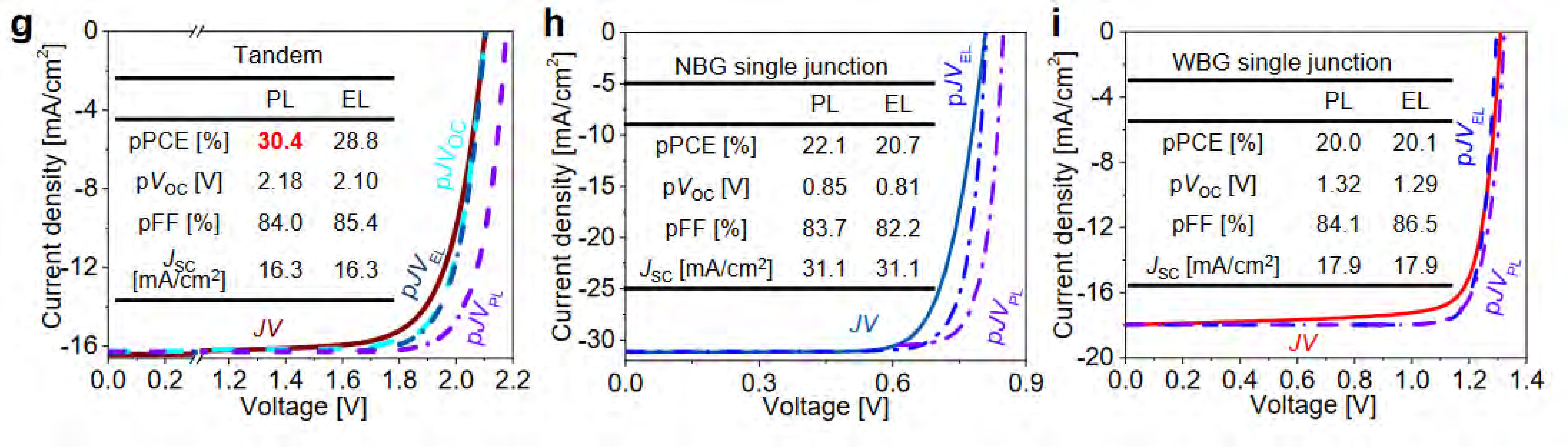
Adv. Energy Mater. 2023, 13, 2202674

Perovskite/Perovskite



Nature Energy (under review)

Perovskite/Perovskite

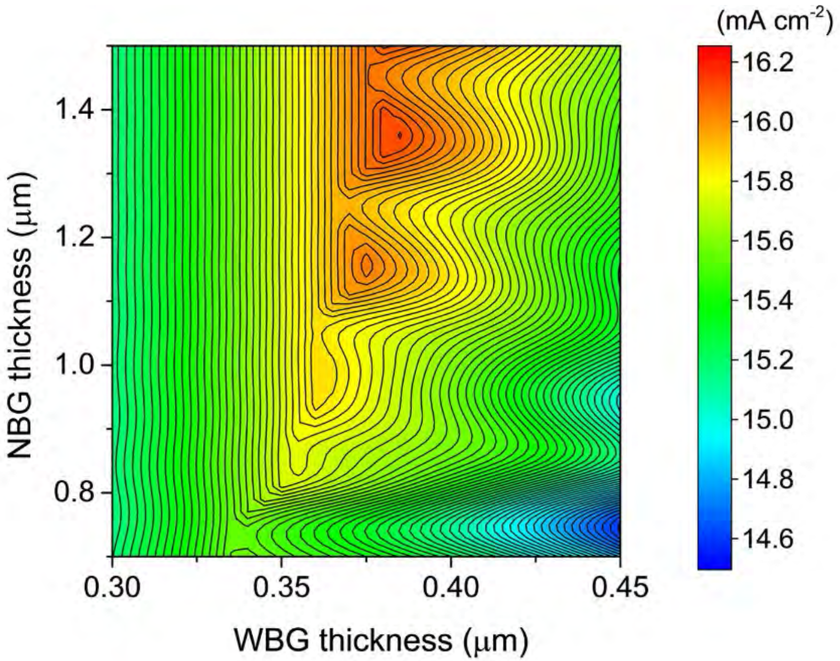


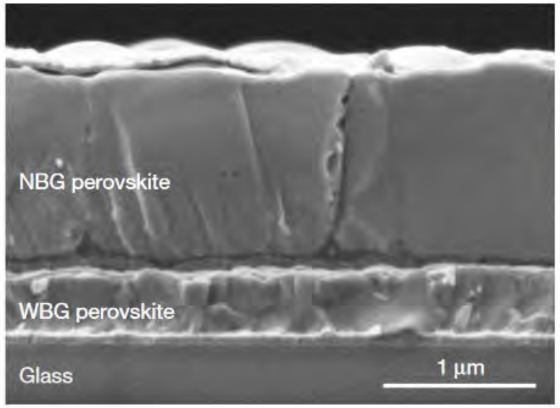
Sub-cell analysis projects efficiency > 30%

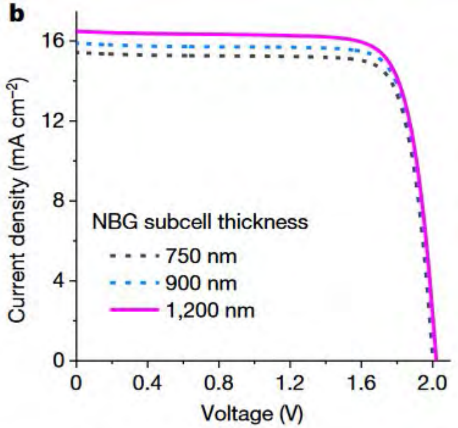
Nature Energy (under review)

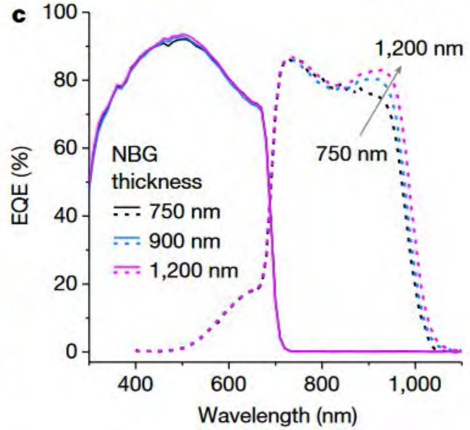
Narrow Bandgap Perovskite

Sargent, Tan et al. Nature 603, 73–78 (2022)





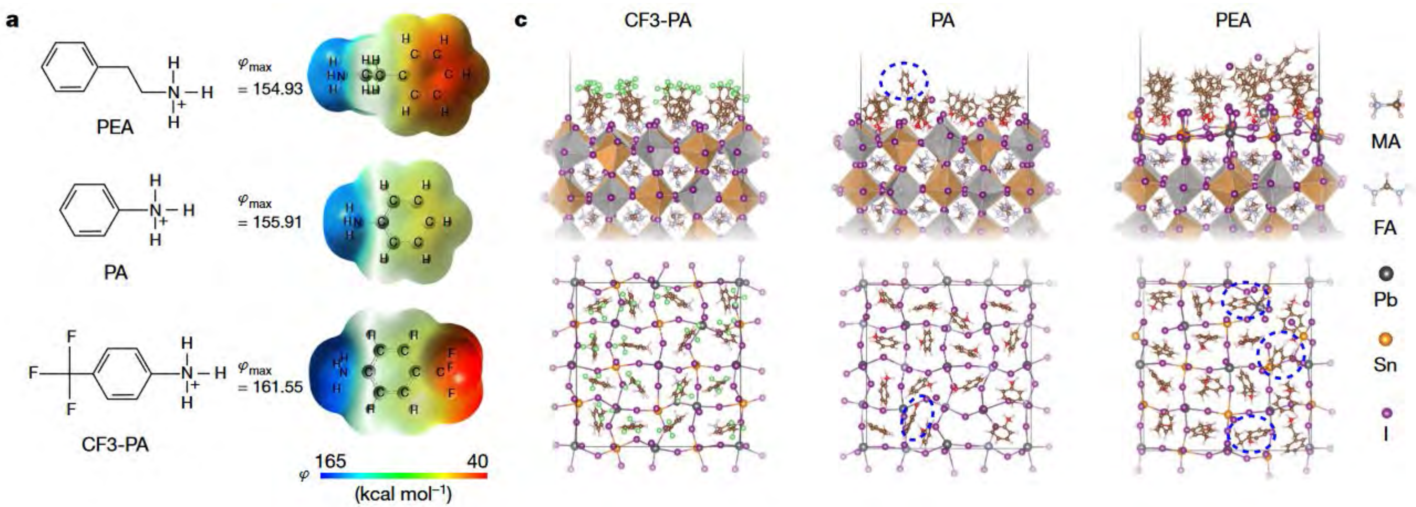


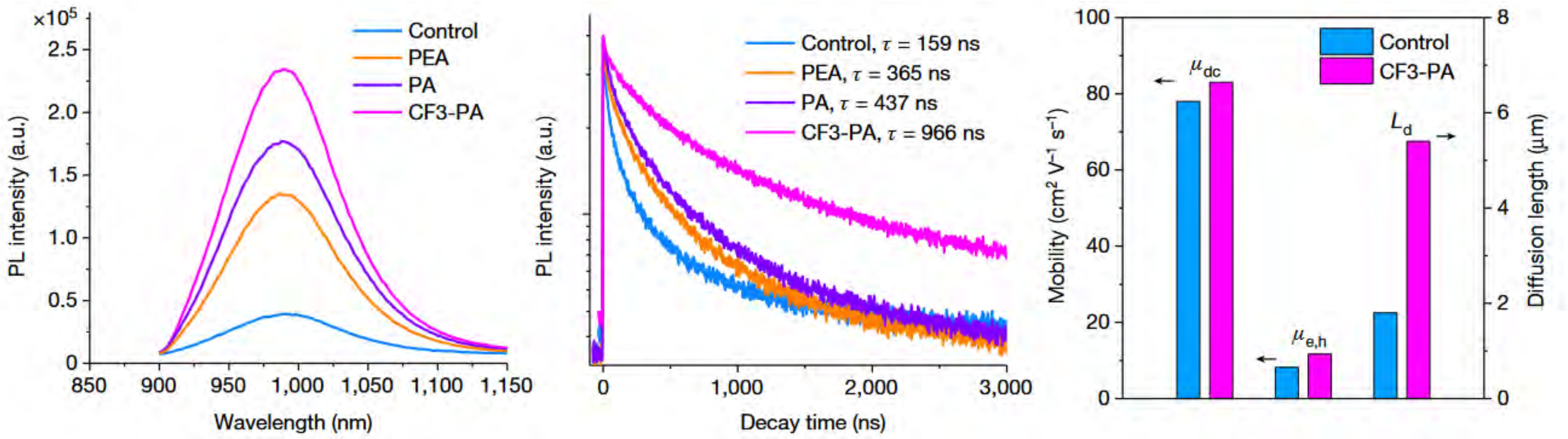


Narrow gap cell needs to be very thick ~ µm
Problem: limited carrier diffusion length

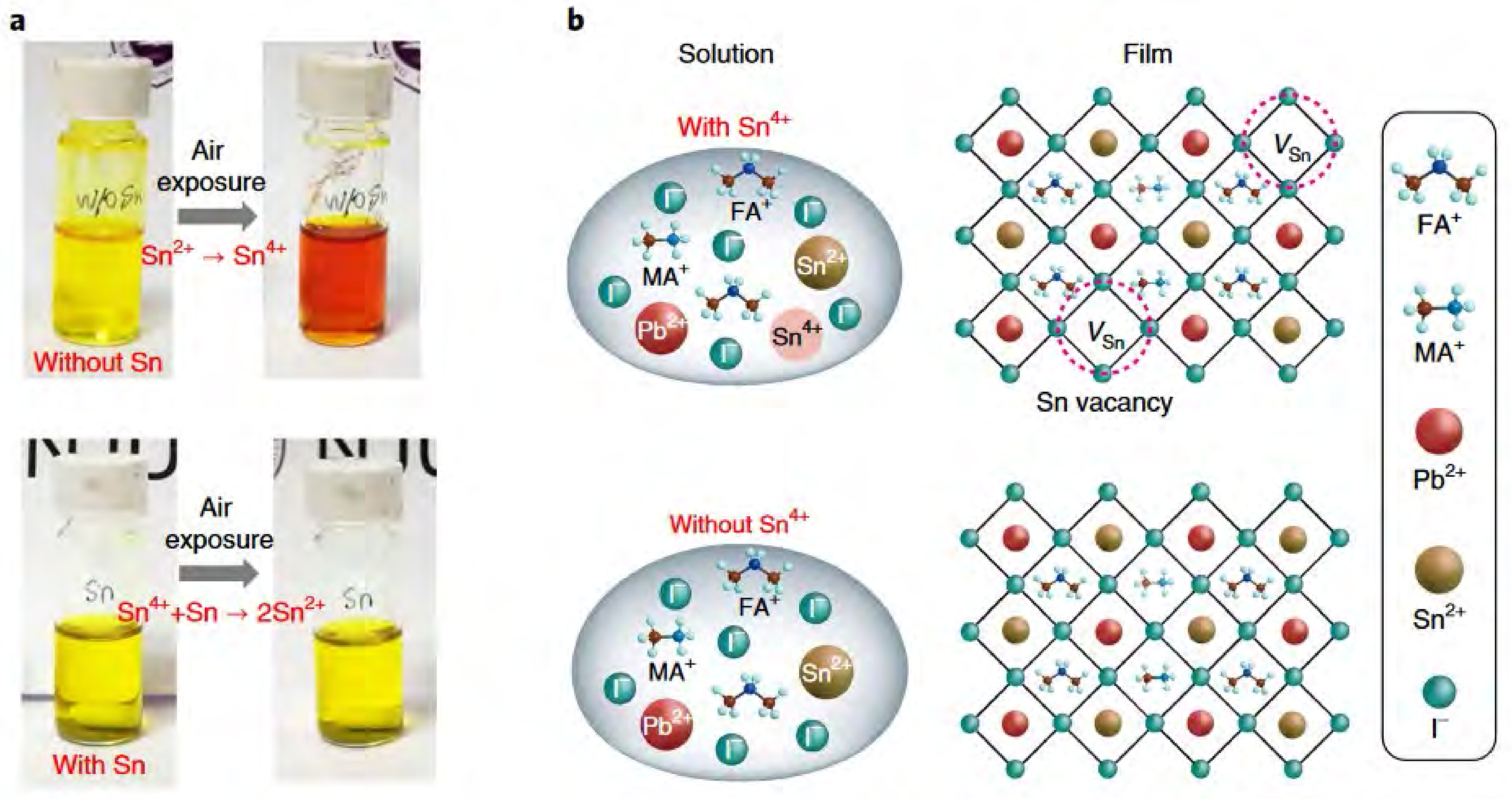
Narrow Bandgap Perovskite

Sargent, Tan et al. Nature 603, 73–78 (2022)

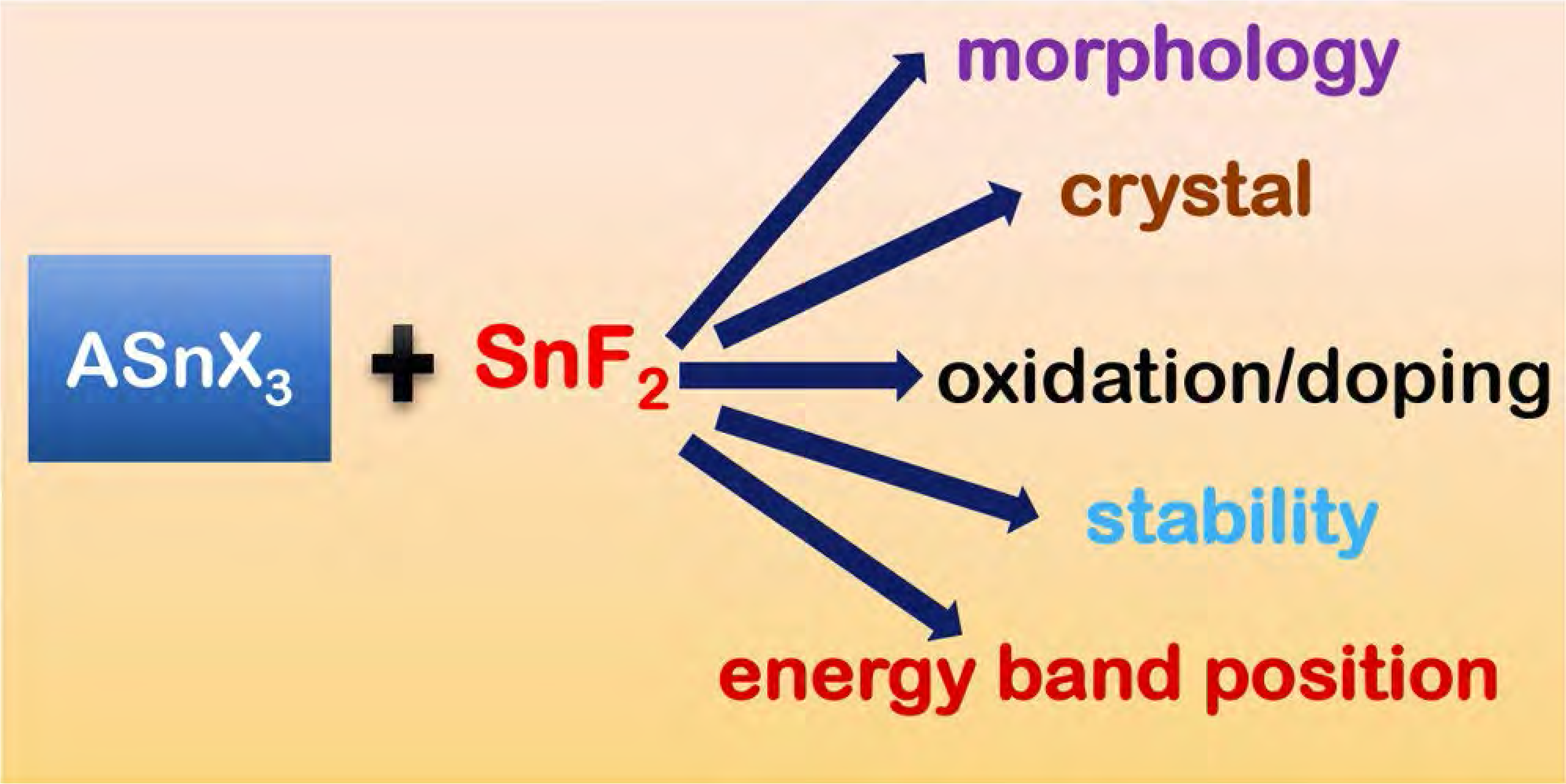




Narrow Bandgap Perovskite



Sargent, Tan, et at. Nat. Energy 4, 864–873 (2019)

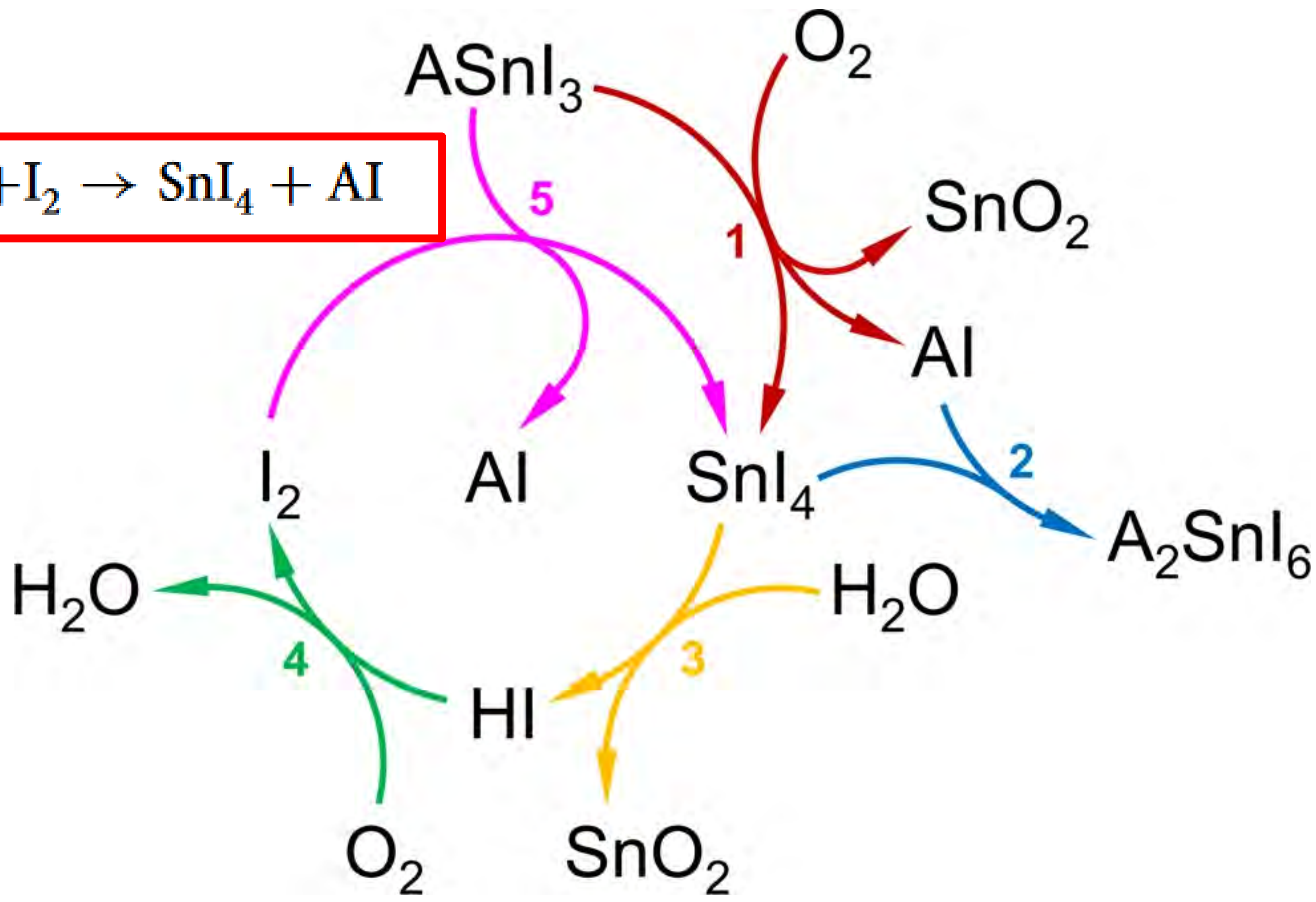


J. Phys. Chem. C 2018, 122, 25, 13926–13936

Narrow Bandgap Perovskite

Nat. Comms, ***12***, *2853 (2021)*

$$ASnI_3 + I_2 \rightarrow SnI_4 + AI$$



Article

nature

Perovskite–organic tandem solar cells with indium oxide interconnect

https://doi.org/10.1038/s41586-022-04455-0

Received: 9 December 2020

Accepted: 24 January 2022

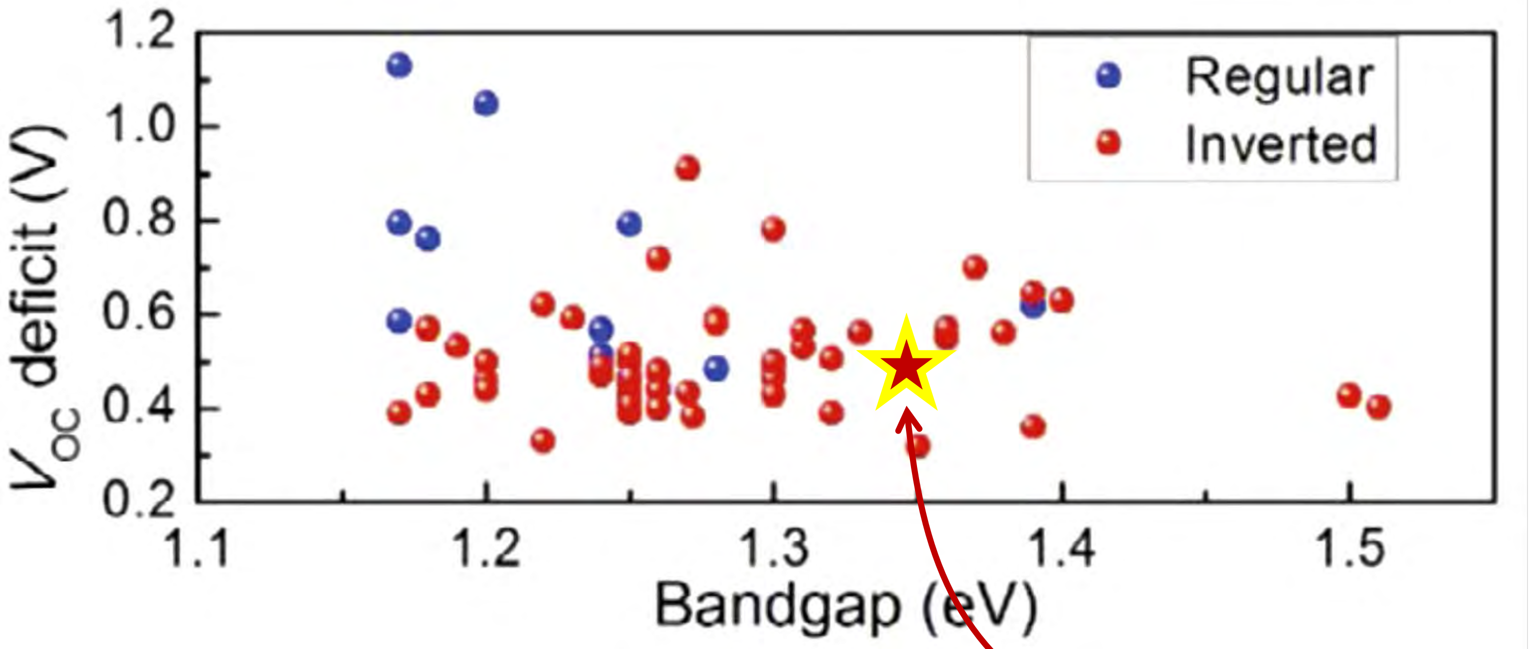
Check for updates

K. O. Brinkmann[1,2,8] ✉, T. Becker[1,2,8], F. Zimmermann[1,2], C. Kreusel[1,2], T. Gahlmann[1,2], M. Theisen[1,2], T. Haeger[1,2], S. Olthof[3], C. Tückmantel[1,2], M. Günster[1,2], T. Maschwitz[1,2], F. Göbelsmann[1,2], C. Koch[3], D. Hertel[3], P. Caprioglio[4], F. Peña-Camargo[4], L. Perdigón-Toro[4], A. Al-Ashouri[5], L. Merten[6], A. Hinderhofer[6], L. Gomell[7], S. Zhang[7], F. Schreiber[6], S. Albrecht[5], K. Meerholz[3], D. Neher[4], M. Stolterfoht[4] & T. Riedl[1,2] ✉

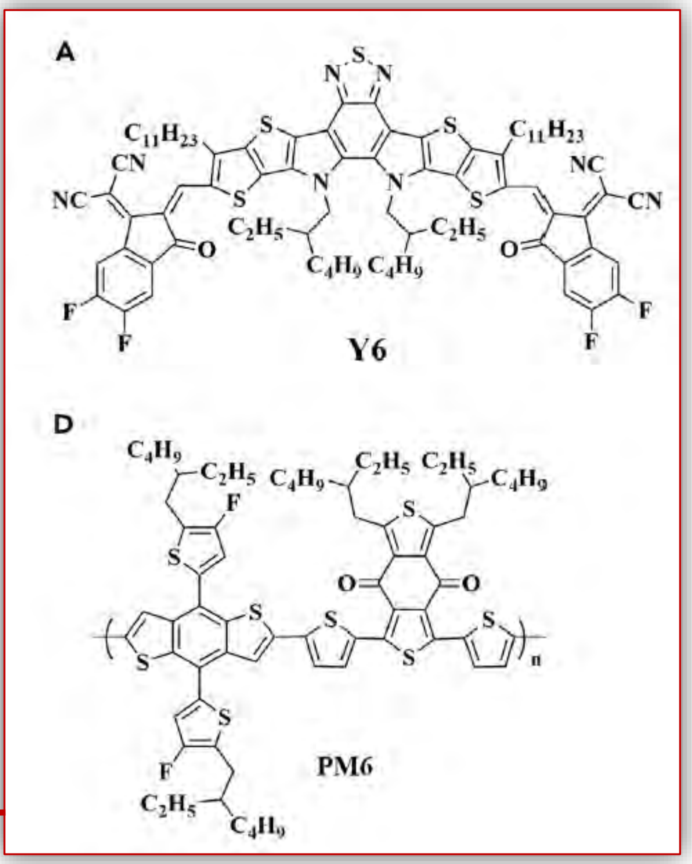
Brinkmann et al. Nature 604, 280 (2022)

Organic solar cell – low voltage loss

V_{OC} deficit of **narrow-gap perovskite** solar cells versus bandgap



Adv Funct Mater **2019** 29, 1808801

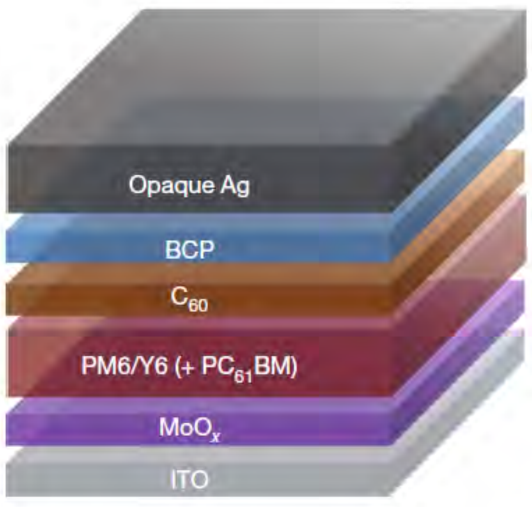


→ organic solar cells perform comparable to perovskite absorbers!

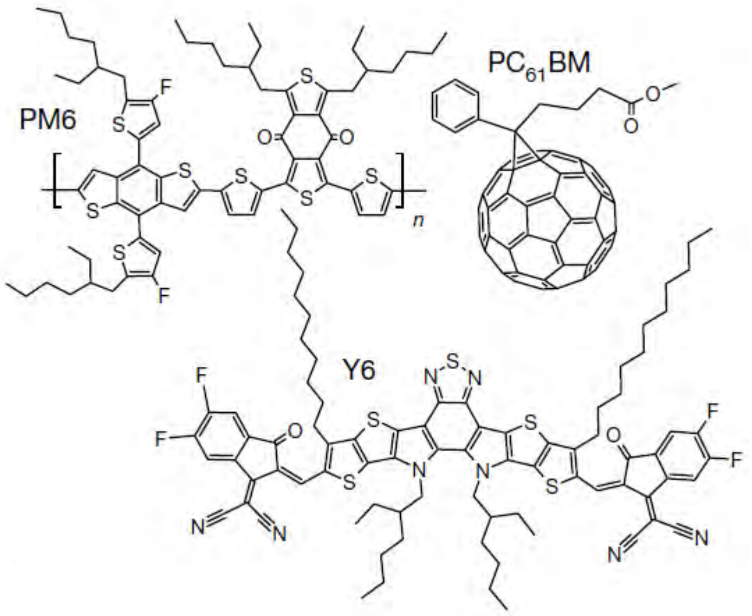
E_g = 1.33 eV
loss V_{oc} ≈ 0.5 V
high IQE approaching 100%

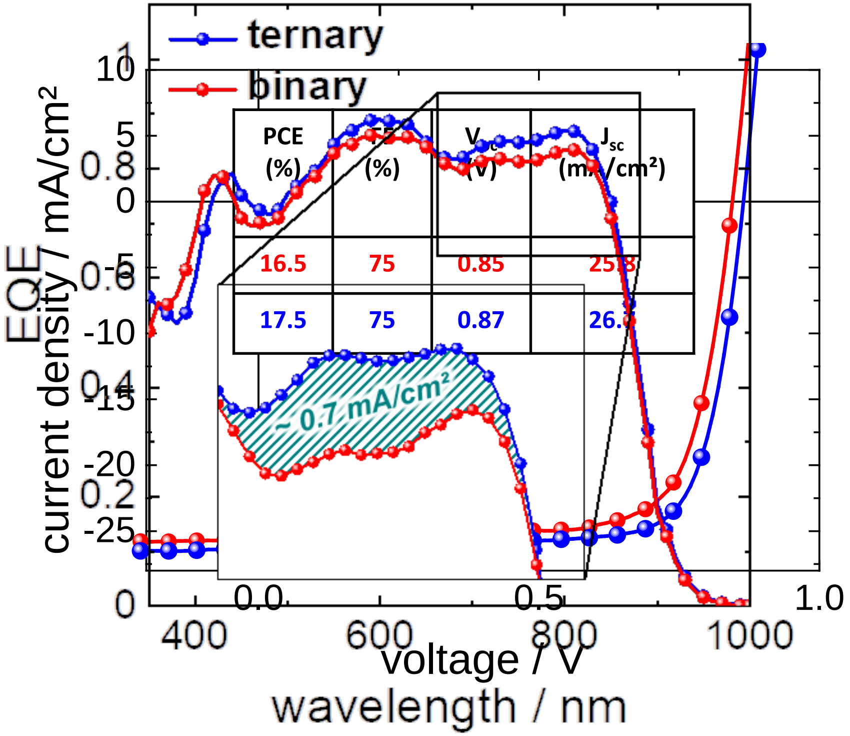
Joule **2019** 3, 1140
EES **2020**, 13, 635

Our OSCs based on PM6:Y6 (+$PC_{60}BM$)



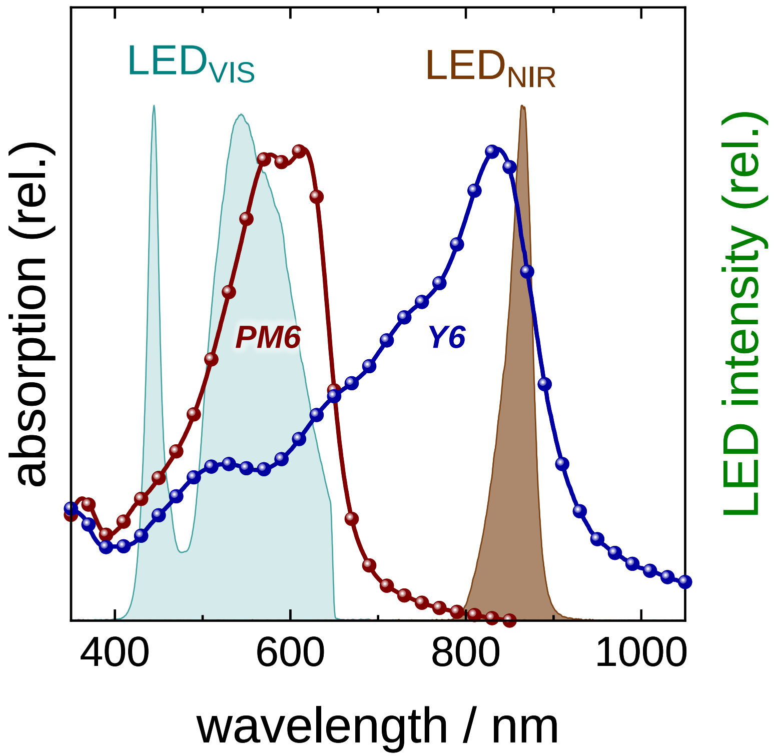
PM6:Y6 (1:1.2) in $CHCl_3$
+0.5% Cl-naphthalene



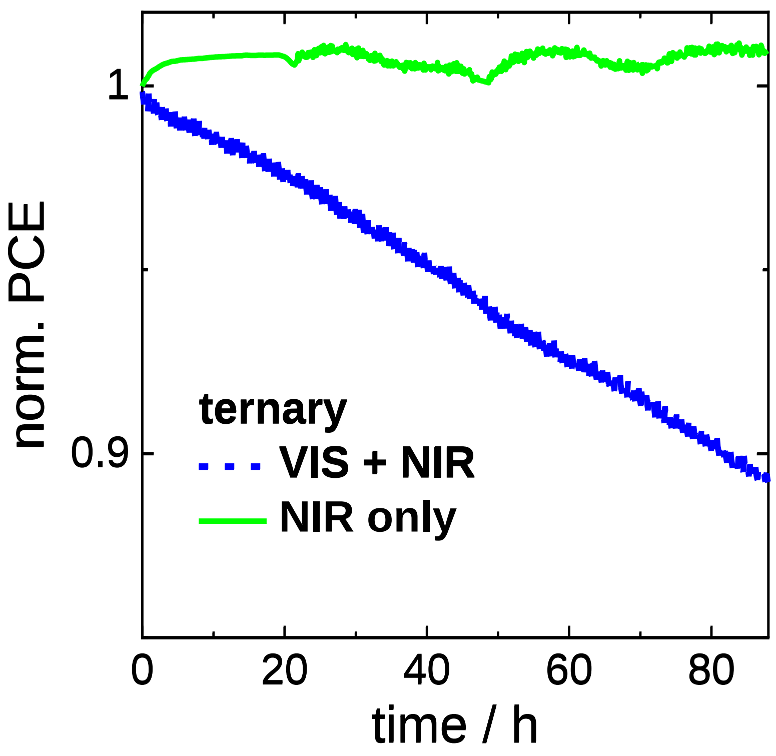


adding some fullerene $PC_{60}BM$ (20%) boosts efficiency to **17.5%** mainly due to **increased J_{sc}**

Operational stability



continuous MPP tracking in N2



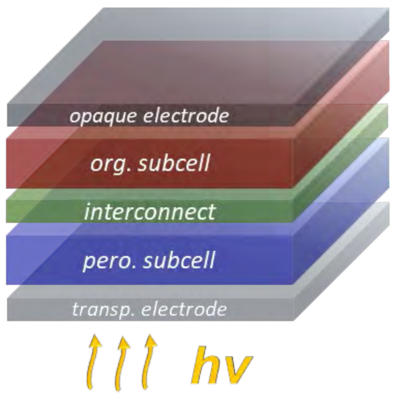
Brinkmann et al. Nature 604, 280 (2022)

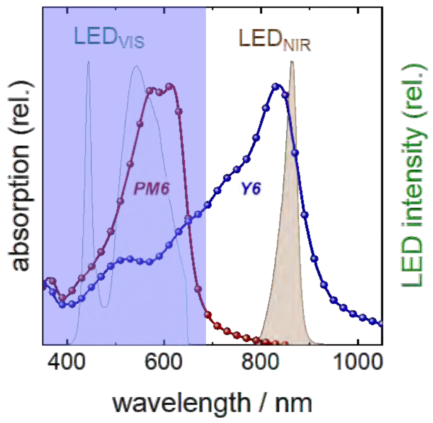
Operational stability of the organic cell

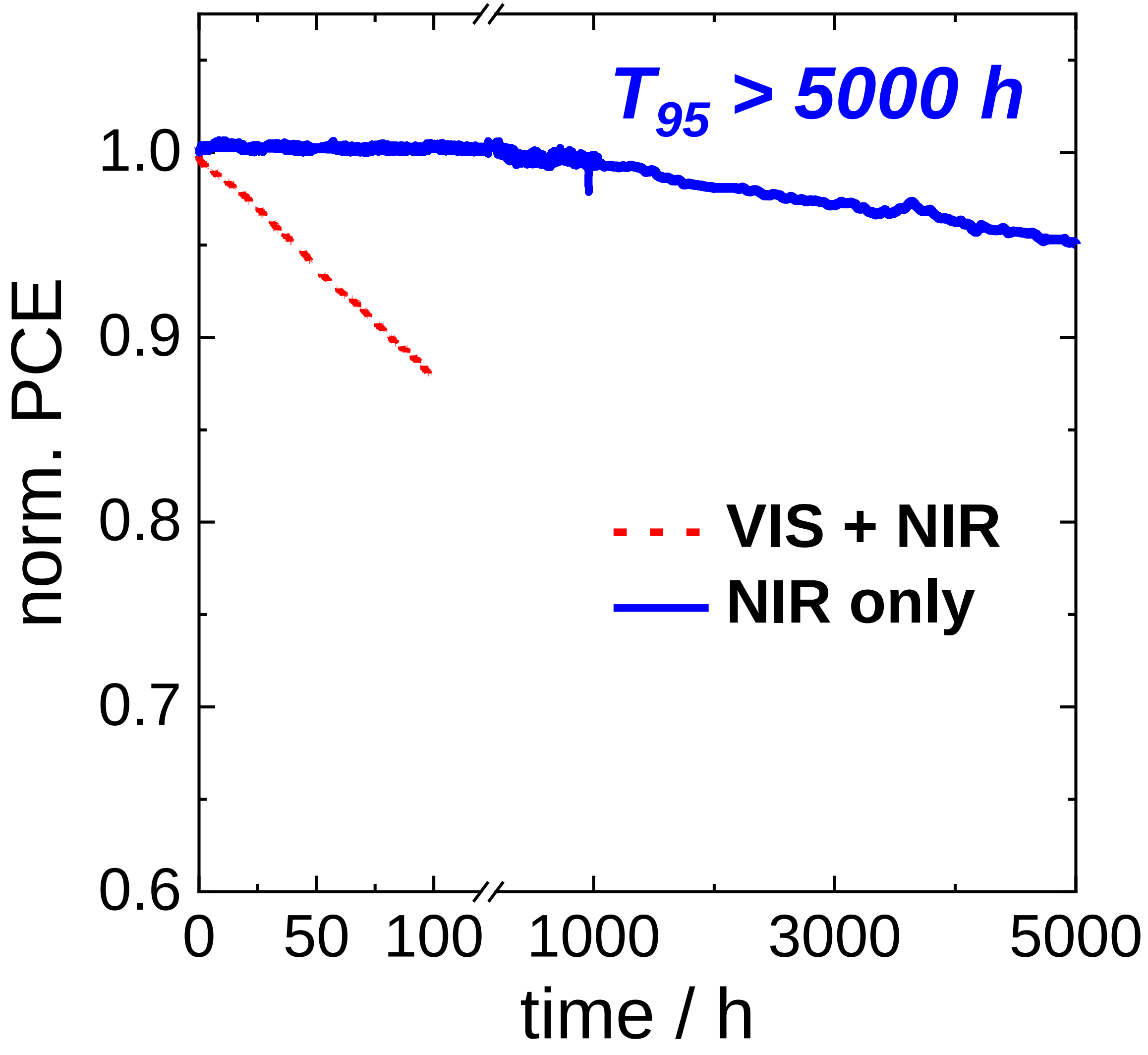
- **degradation linked to VIS illumination**
- **no degradation under NIR illumination**

→ **beneficial for tandems**

perovskite cell acts as low-pass filter



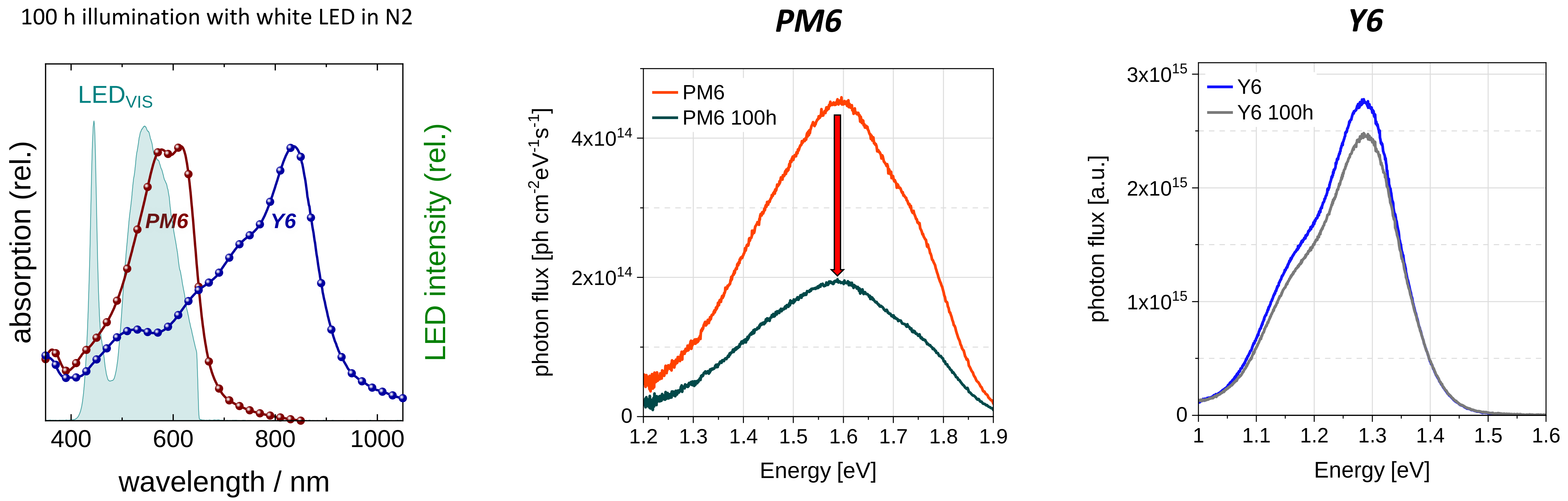




Brinkmann et al. Nature 604, 280 (2022)

Operational stability of the organic cell

100 h illumination with white LED in N2



→ **photo-degradation of PL-QY of donor polymer PM6**

→ **Y6 acceptor mostly unaffected**

L. Perdigón Toro and M. Stolterfoht, U Potsdam

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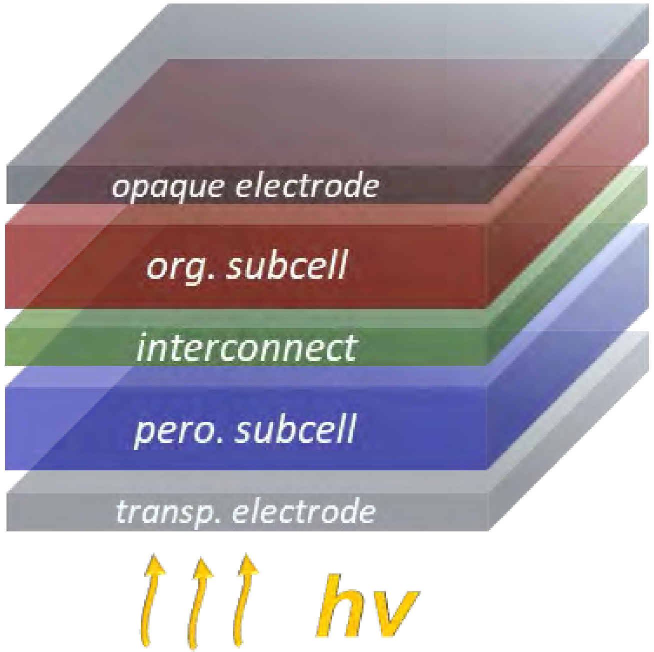
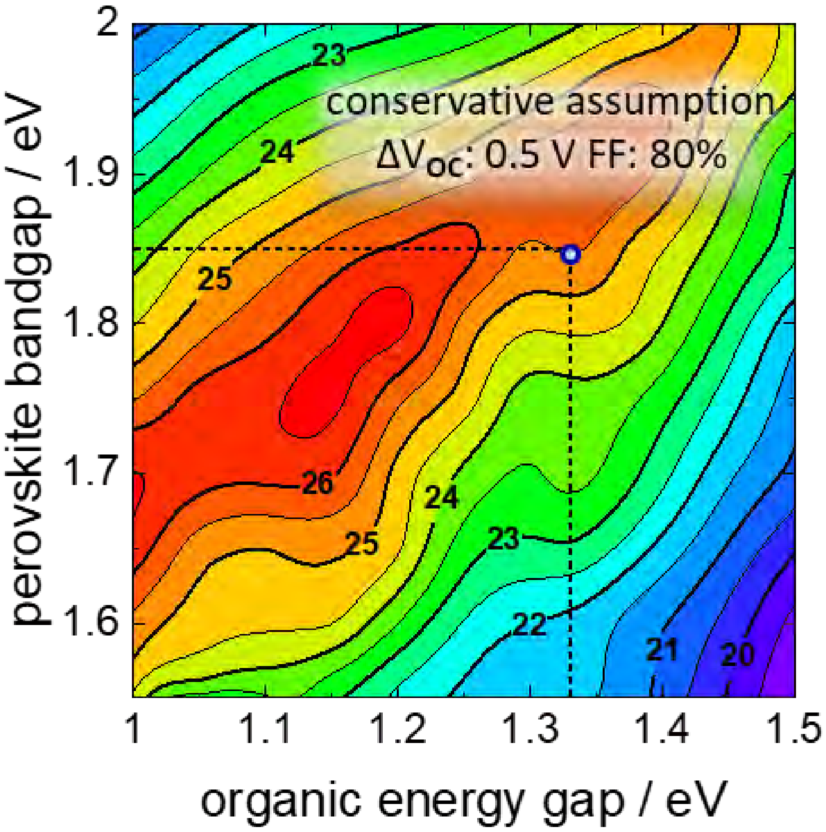
Perovskite/organic tandem semi-empirical simulation





25.5% estimated

With organic E_g = 1.33 eV, perovskite cell with min. $E_g \approx$ 1.85 eV required

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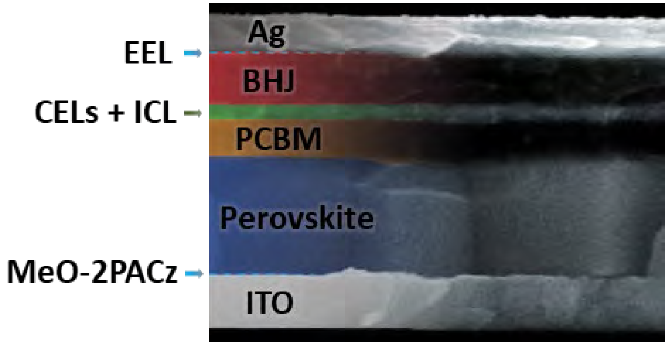
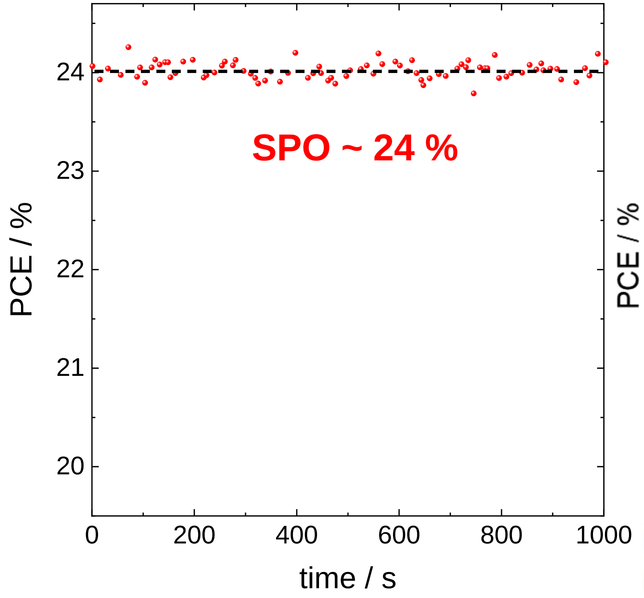
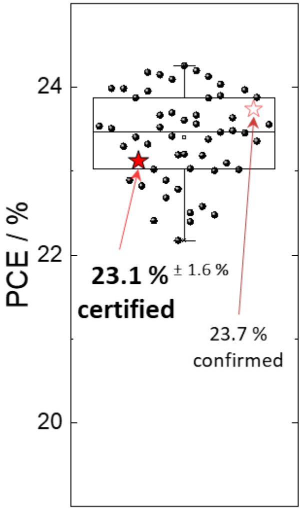
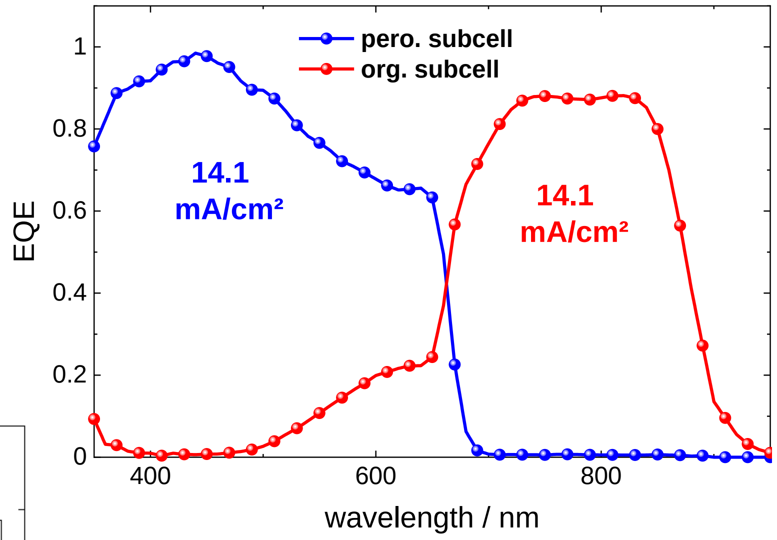
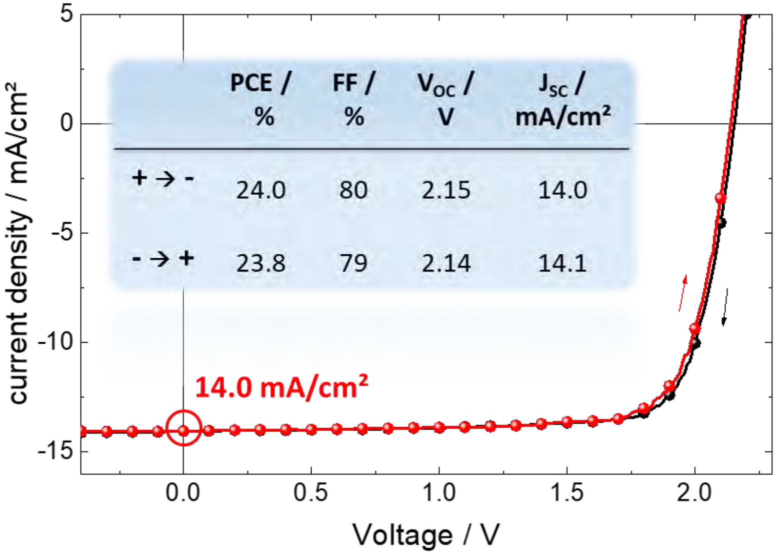
Perovskite/organic tandem











	PCE / %	FF / %	V_{oc} / V	J_{sc} / mA/cm²
+ → -	24.0	80	2.15	14.0
- → +	23.8	79	2.14	14.1

Fraunhofer ISE

CalLab PV Cells

high PCE = 24 % and high V_{oc} = 2.15 V

→ new world record for organic/perovskite tandem

→ highest efficiency with participation of an organic cell

Brinkmann et al. Nature 604, 280 (2022)

nature energy
Received: 9 May 2021; Accepted: 2 December 2021;
Published online: 20 January 2022
ARTICLES
https://doi.org/10.1038/s41560-021-00966-8

Check for updates

Monolithic perovskite/organic tandem solar cells with 23.6% efficiency enabled by reduced voltage losses and optimized interconnecting layer

Wei Chen[1,2,3,4,8], Yudong Zhu[2,5,8], Jingwei Xiu[2], Guocong Chen[2], Haoming Liang[3,4], Shunchang Liu[3,4], Hansong Xue[4], Erik Birgersson[4,6], Jian Wei Ho[4], Xinshun Qin[1], Jingyang Lin[1,7], Ruijie Ma[5], Tao Liu[5], Yanling He[1,7], Alan Man-Ching Ng[7], Xugang Guo[2], Zhubing He[2], He Yan[5], Aleksandra B. Djurišić[1] and Yi Hou[3,4]

RESEARCH ARTICLE
ADVANCED MATERIALS
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Constructing Monolithic Perovskite/Organic Tandem Solar Cell with Efficiency of 22.0% via Reduced Open-Circuit Voltage Loss and Broadened Absorption Spectra

Shucheng Qin, Chenxing Lu, Zhenrong Jia, Yiyang Wang, Siguang Li, Wenbin Lai, Pengju Shi, Rui Wang, Can Zhu, Jiaqi Du, Jinyuan Zhang, Lei Meng, and Yongfang Li**

RESEARCH ARTICLE
Adv. Funct. Mater. **2021**, 2109321
ADVANCED FUNCTIONAL MATERIALS
www.afm-journal.de

Surface Reconstruction for Stable Monolithic All-Inorganic Perovskite/Organic Tandem Solar Cells with over 21% Efficiency

21%

Weijie Chen, Dong Li, Xu Chen, Haiyang Chen, Shuo Liu, Haidi Yang, Xinqi Li, Yunxiu Shen, Xuemei Ou, Yang (Michael) Yang, Lin Jiang, Yaowen Li, and Yongfang Li*

Joule
Joule 4, 1594 (2020)
CellPress
Article

Efficient and Reproducible Monolithic Perovskite/Organic Tandem Solar Cells with Low-Loss Interconnecting Layers

20.6 %

Article
nature

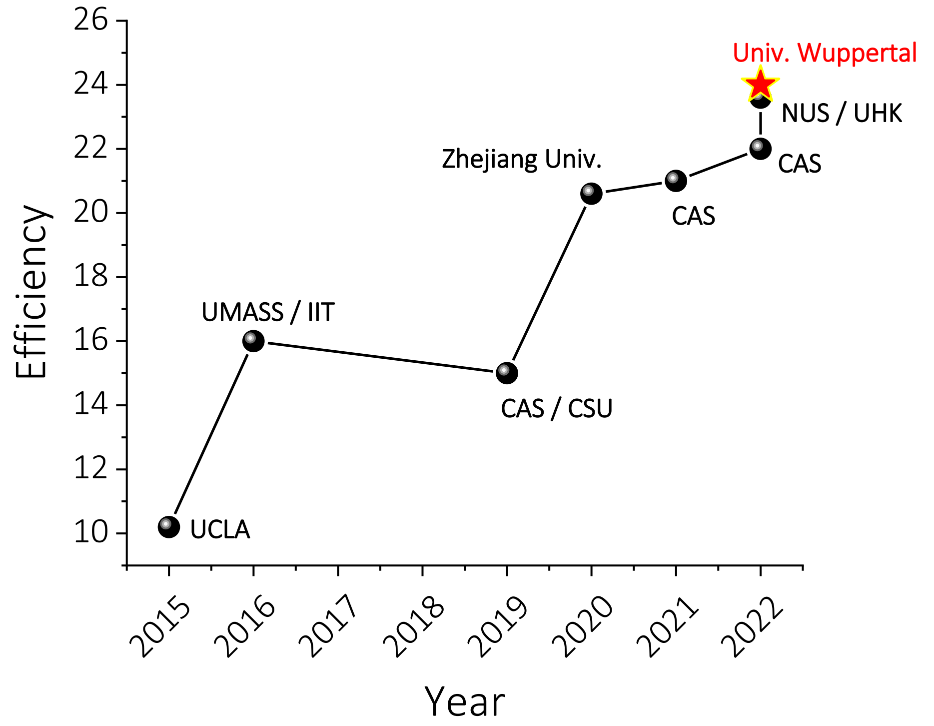
Perovskite–organic tandem solar cells with indium oxide interconnect

24 %

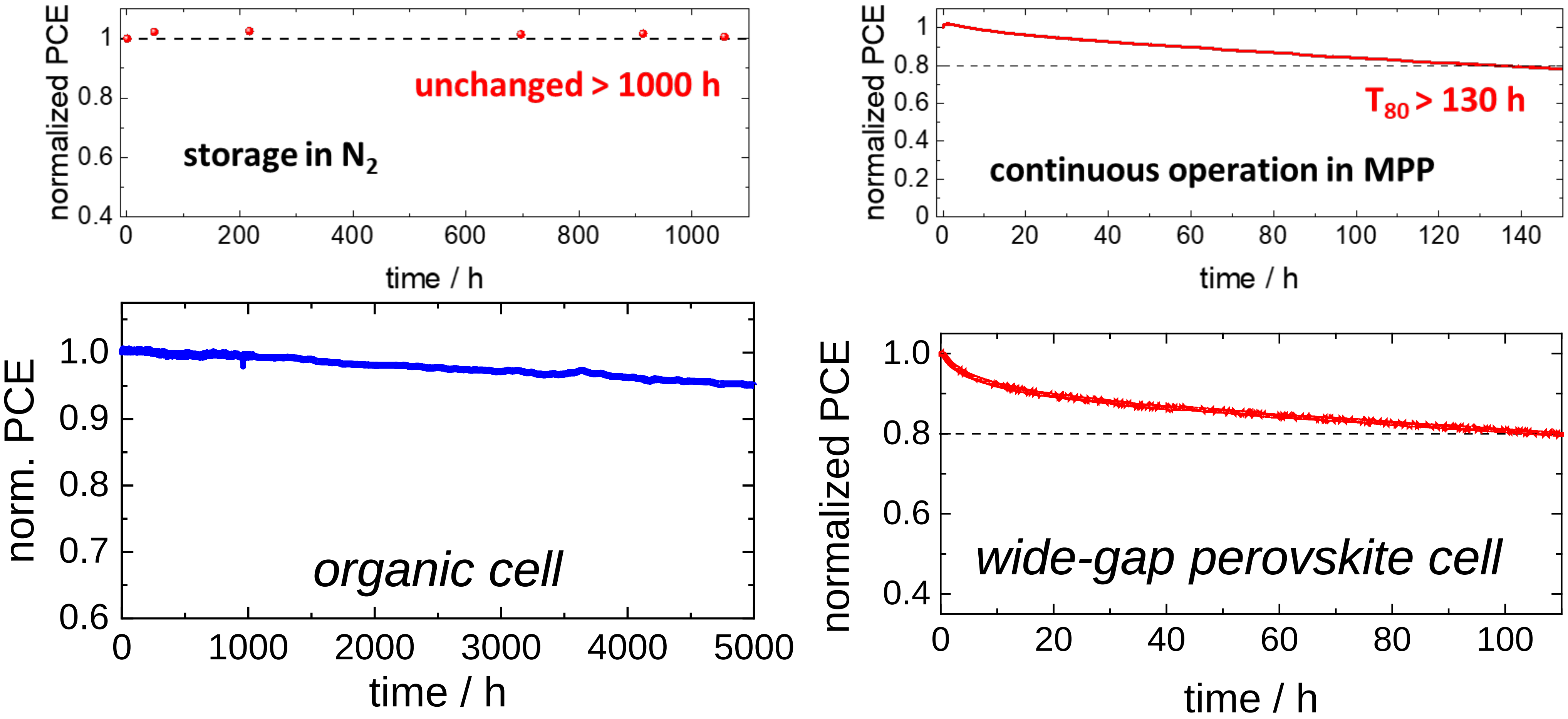
https://doi.org/10.1038/s41586-022-04455-0
Received: 9 December 2020
Accepted: 24 January 2022

Check for updates

K. O. Brinkmann[1,2,8], T. Becker[1,2,8], F. Zimmermann[1,2], C. Kreusel[1,2], T. Gahlmann[1,2], M. Theisen[1,2], T. Haeger[1,2], S. Olthof[3], C. Tückmantel[1,2], M. Günster[1,2], T. Maschwitz[1,2], F. Göbelsmann[1,2], C. Koch[3], D. Hertel[3], P. Caprioglio[4], F. Peña-Camargo[4], L. Perdigón-Toro[4], A. Al-Ashouri[5], L. Merten[6], A. Hinderhofer[6], L. Gomell[7], S. Zhang[7], F. Schreiber[6], S. Albrecht[5], K. Meerholz[3], D. Neher[4], M. Stolterfoht[4] & T. Riedl[1,2]



Stability of the tandem



Stability of the tandem limited by the wide-gap perovskite cell

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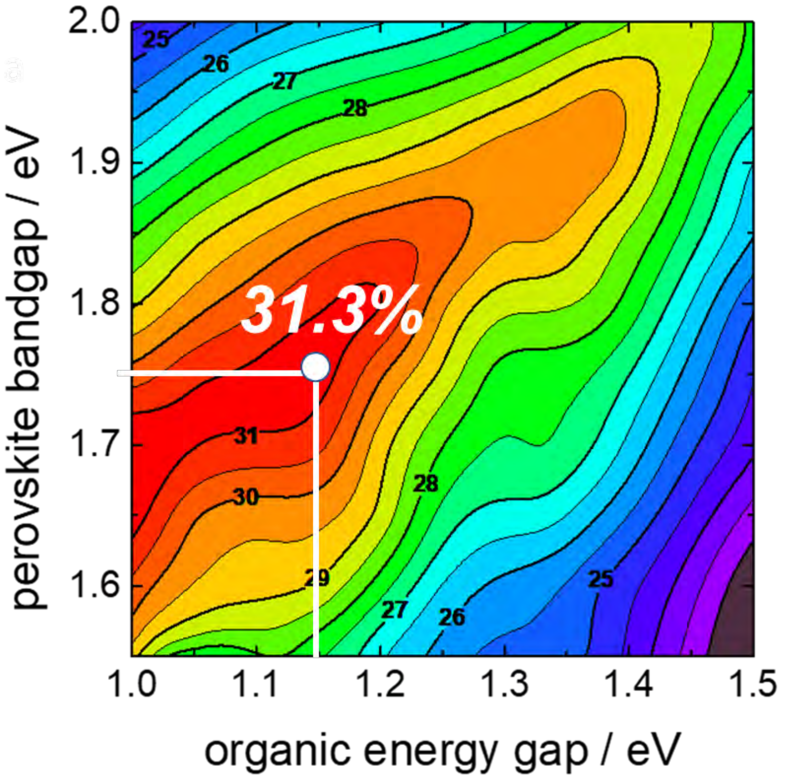
Where do we go from here?

FF = 85%; loss in V_{oc} = 0.4 V



Need organic cell with lower gap (1.15 eV) combined with 1.7-1.75 eV perovskite

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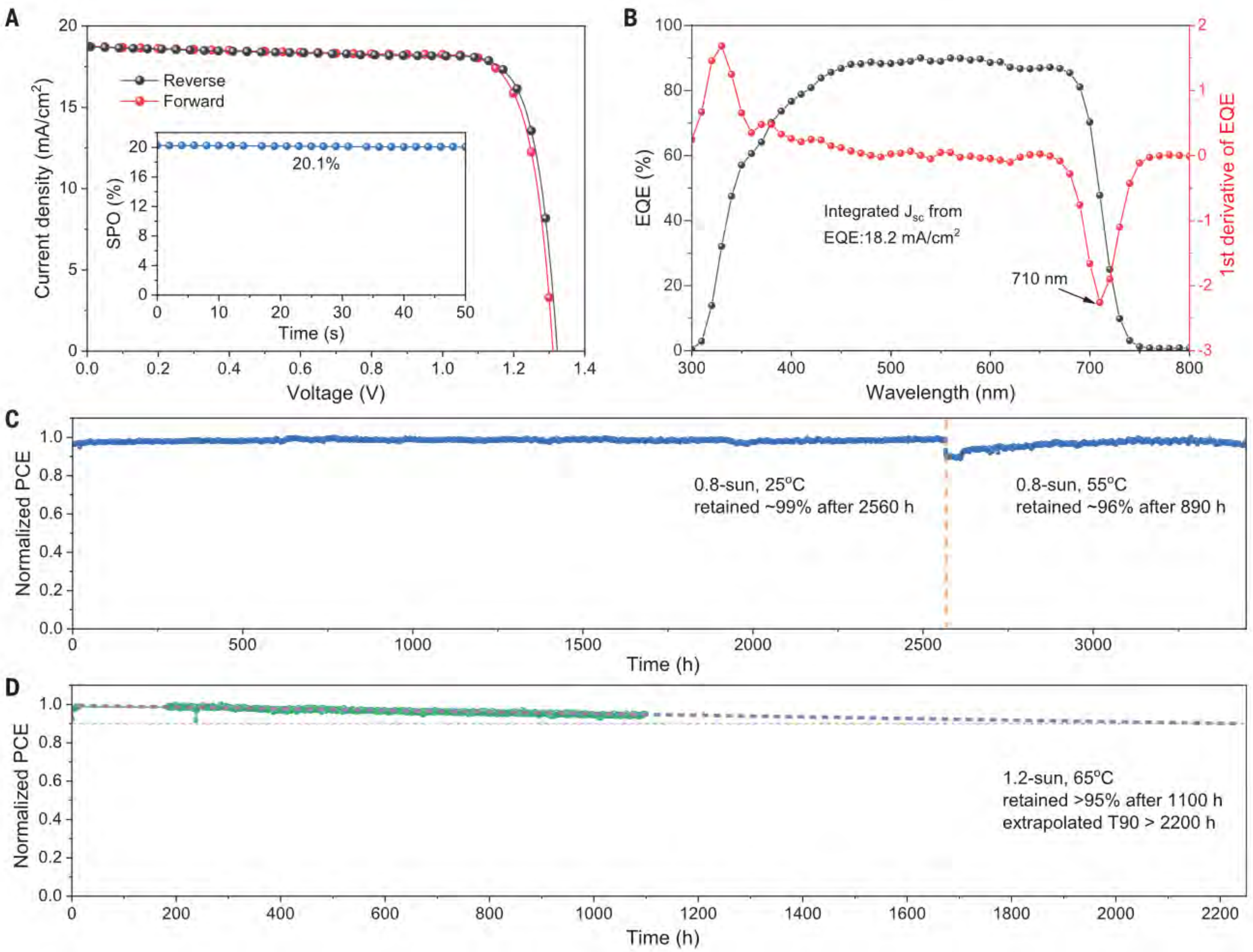
Jiang et al., Science 378, 1295–1300 (2022)



E_g = 1.75 eV

great MPP stability

MOLECULAR PHYSICS, 1970, VOL. 18, NO. 2, 145–164

The energy gap law for radiationless transitions in large molecules

by ROBERT ENGLMAN
Theoretical Solid State Physics Group,
Soreq Nuclear Research Centre, Yavne, Israel

and JOSHUA JORTNER
Department of Chemistry, Tel-Aviv University, Tel-Aviv, Israel

$$W = \frac{C^2\sqrt{(2\pi)}}{\hbar\sqrt{(\hbar\omega_M \Delta E)}} \exp\left(-\gamma \Delta E / \hbar\omega_M\right).$$

Rate for non-rad recombination W increases exponentially as the energy gap ΔE decreases

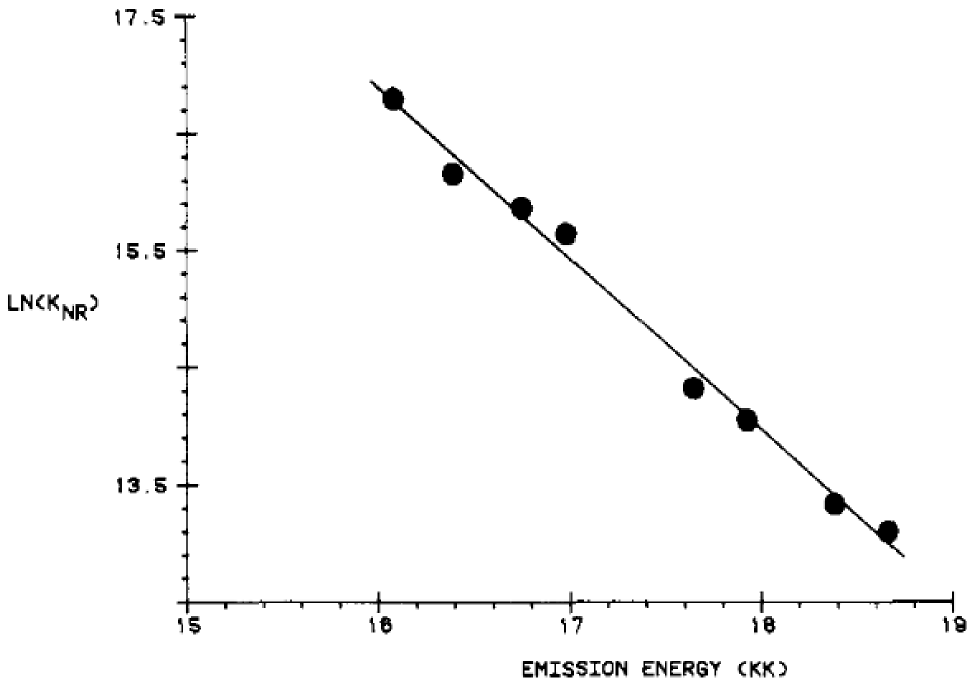
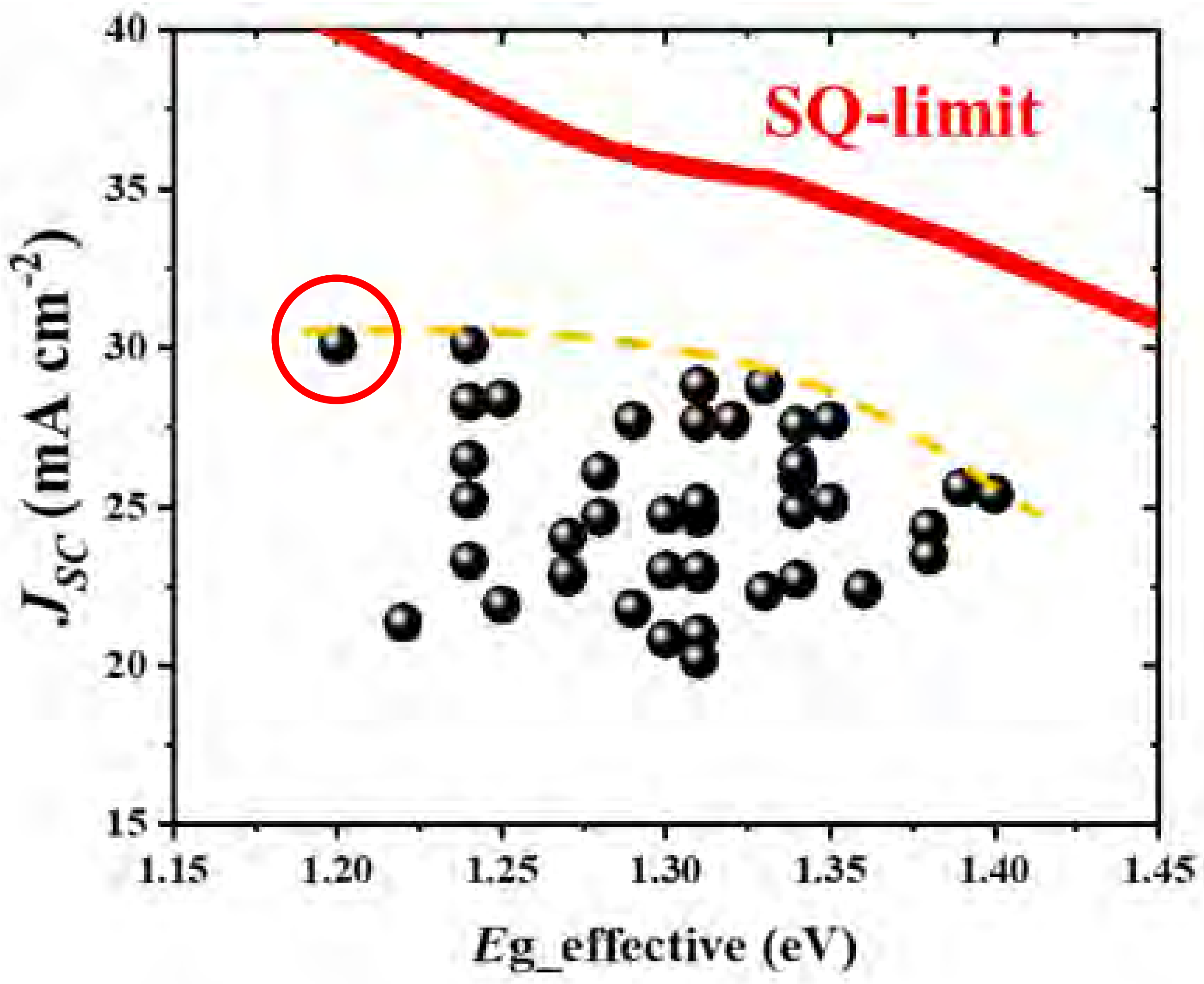
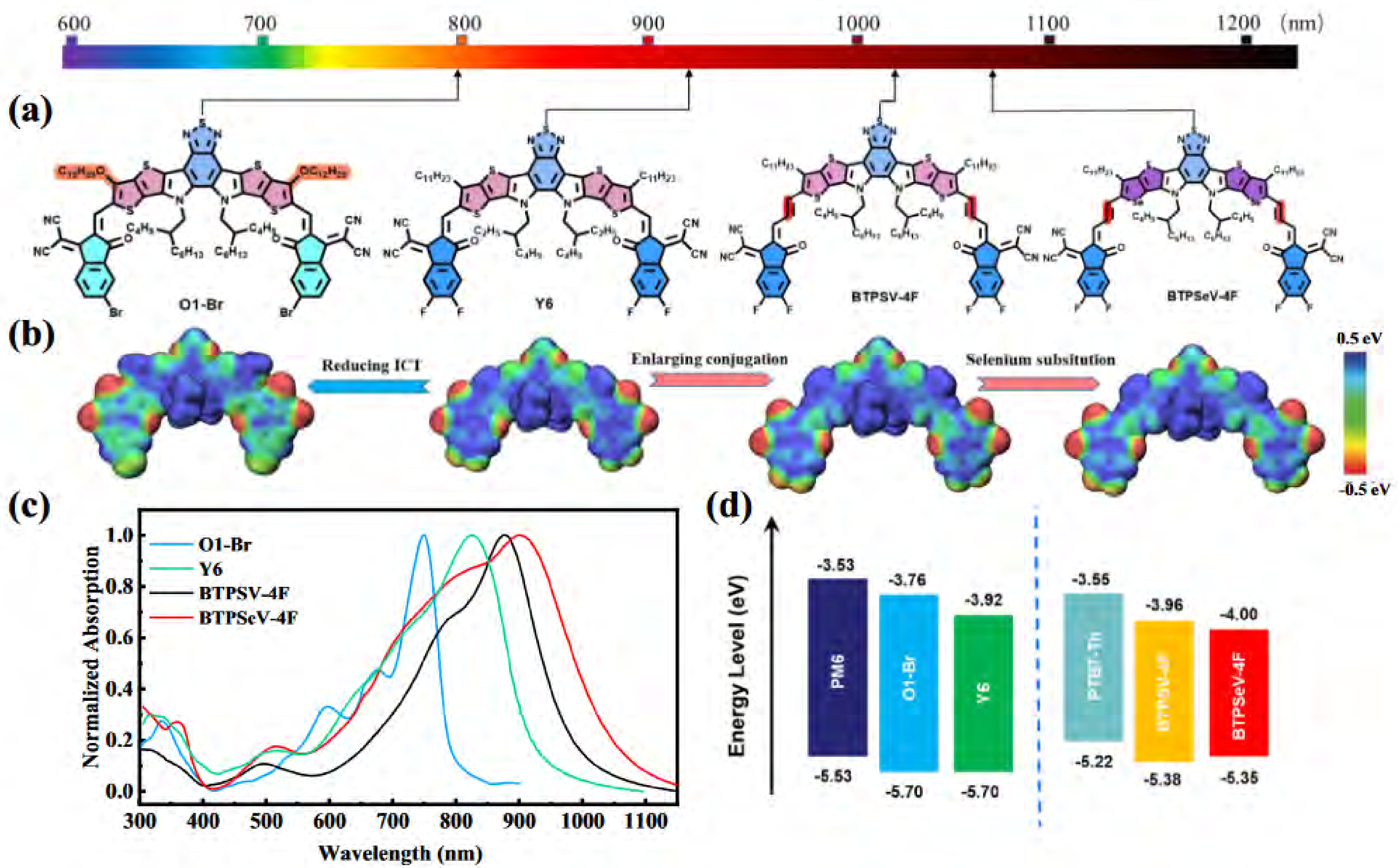


Figure 2. Plot of ln k_{nr} vs. E_{em} for the MLCT excited states of the series of complexes *fac*-[Re(bpy)(CO)$_3$L](PF$_6$) at 23 °C in methylene chloride solution.

The Journal of Physical Chemistry, 87, 6 (1983)



Nat. Rev. Mater. (in preparation)



$E_g = 1.2$ eV

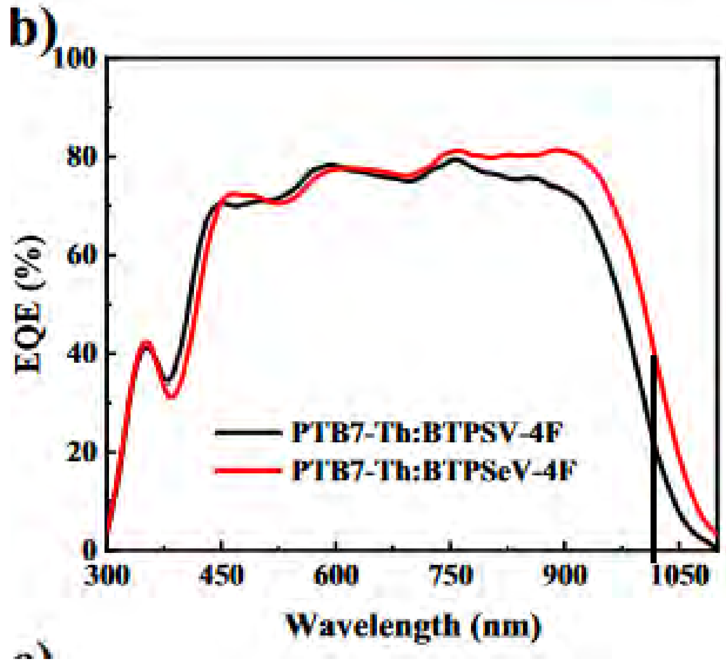


Table 1 | Photovoltaic parameters of the optimal single-junction OSCs based on PTB7-Th:BTPSV-4F and PTB7-Th:BTPSeV-4F, under the illumination of AM 1.5G, 100 mW cm^{-2}

Device	V_{oc} [V]	J_{sc} [mA·cm^{-2}]	J_{cal} from EQE [mA·cm^{-2}]	FF [%]	PCE [%]
PTB7-Th:BTPSV-4F	0.66 (0.66 ± 0.01)	28.4 (28.1 ± 0.3)	27.76	69.5 (69.2 ± 0.6)	13.0 (12.8 ± 0.2)[a]
PTB7-Th:BTPSeV-4F	0.66 (0.66 ± 0.01)	30.1 (29.8 ± 0.2)	29.30	71.4 (71.0 ± 0.4)	14.2 (13.9 ± 0.2)

[a]The average values and deviations are calculated from 10 independent devices.

Nature Communications 14, 1236 (2023)

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