Empa
Materials Science and Technology

Printed and Custom Design Perovskite Solar Cells

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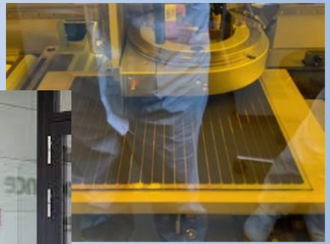
PV at Empa

PV at Empa

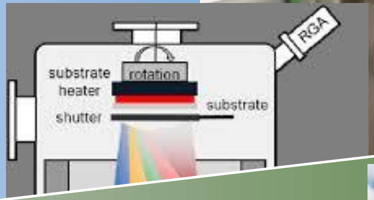
Materials for thin film PV

Perovskites

Processes for fabrication



Inkjet



Implementation of PV

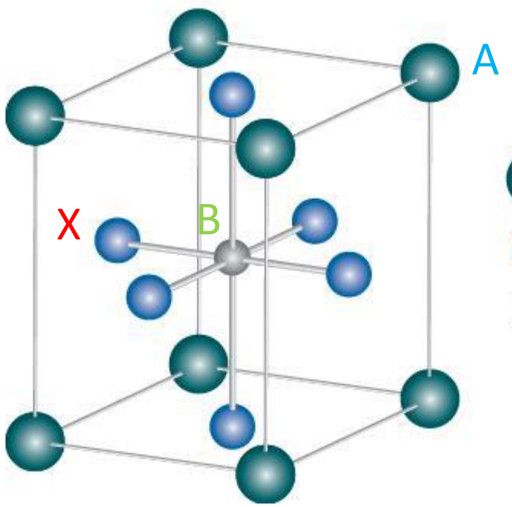
Perovskite demonstrator

Silicon

Flexible CIGS

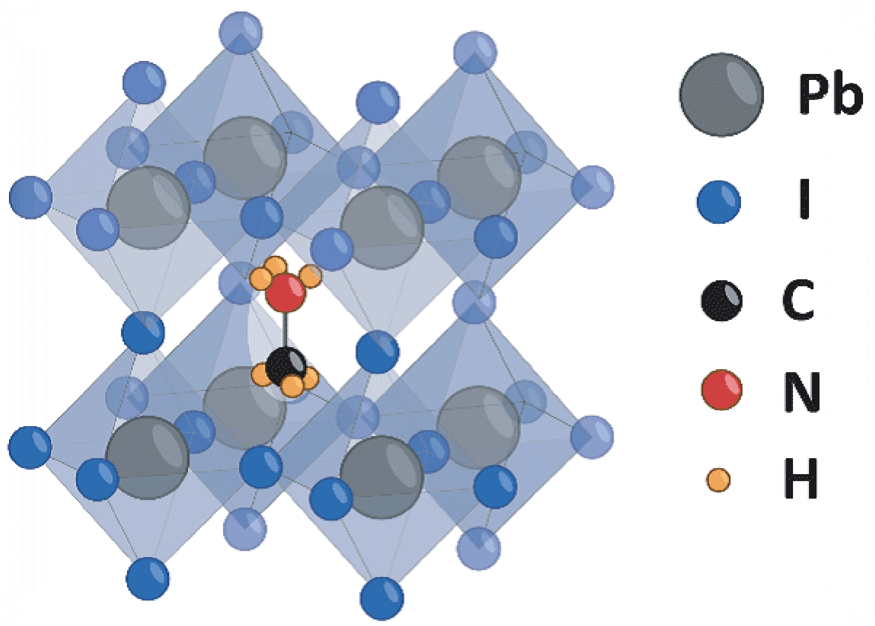
Perovskite thin film photovoltaic technology

$CH_3NH_3PbX_3$ ($MAPbI_3$)



BAX_3: A and 'B' are two cations of very different sizes, and X is an anion that bonds to both.

(or)

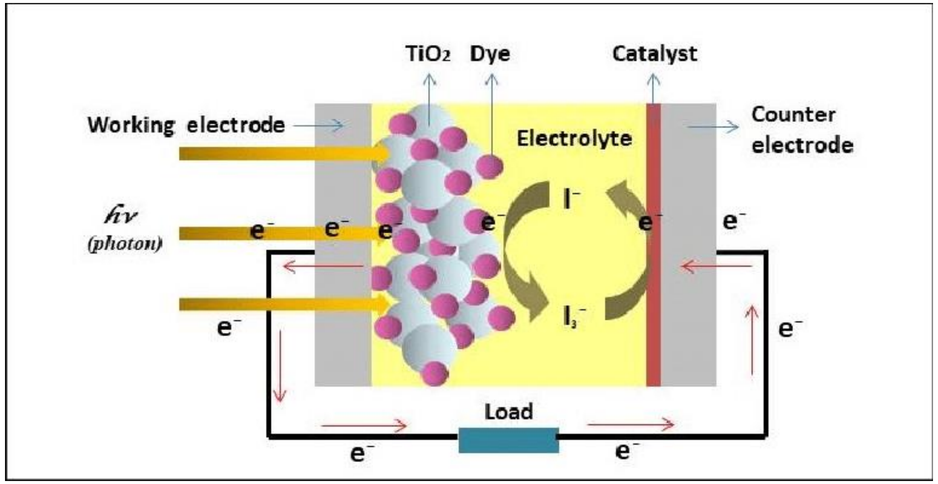


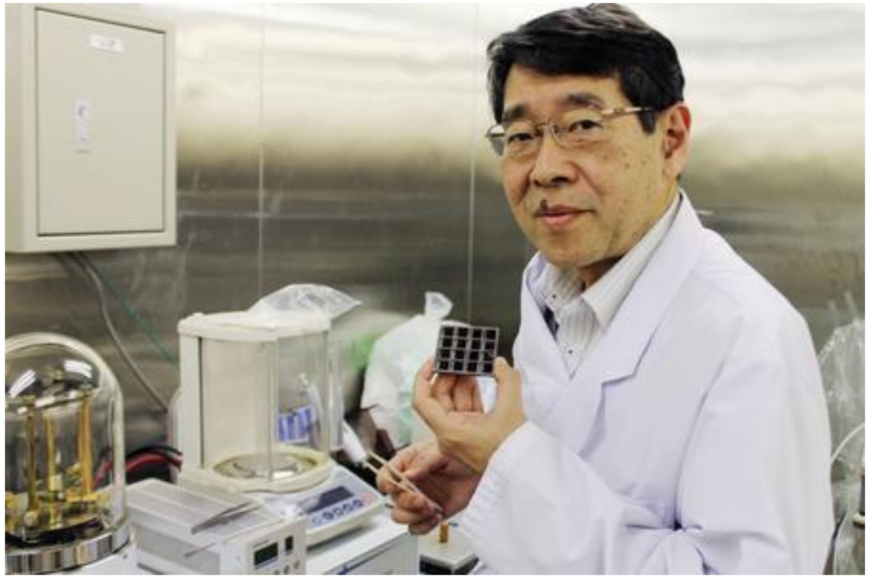
Goldschmidt tolerance factor $t = (R_A + R_X)/\sqrt{2(R_B + R_X)}$

For 0.8 < t < 1.0, a stable perovskite structure is predicted at room temperature

T. Huang et al., 2021https://doi.org/10.1021/acs.jpcc.1c05841

Where it all started





T. Miyasaka, J. Am. Chem. Soc., 2009, 131, 6050–6051

Dye sensitized solar cells

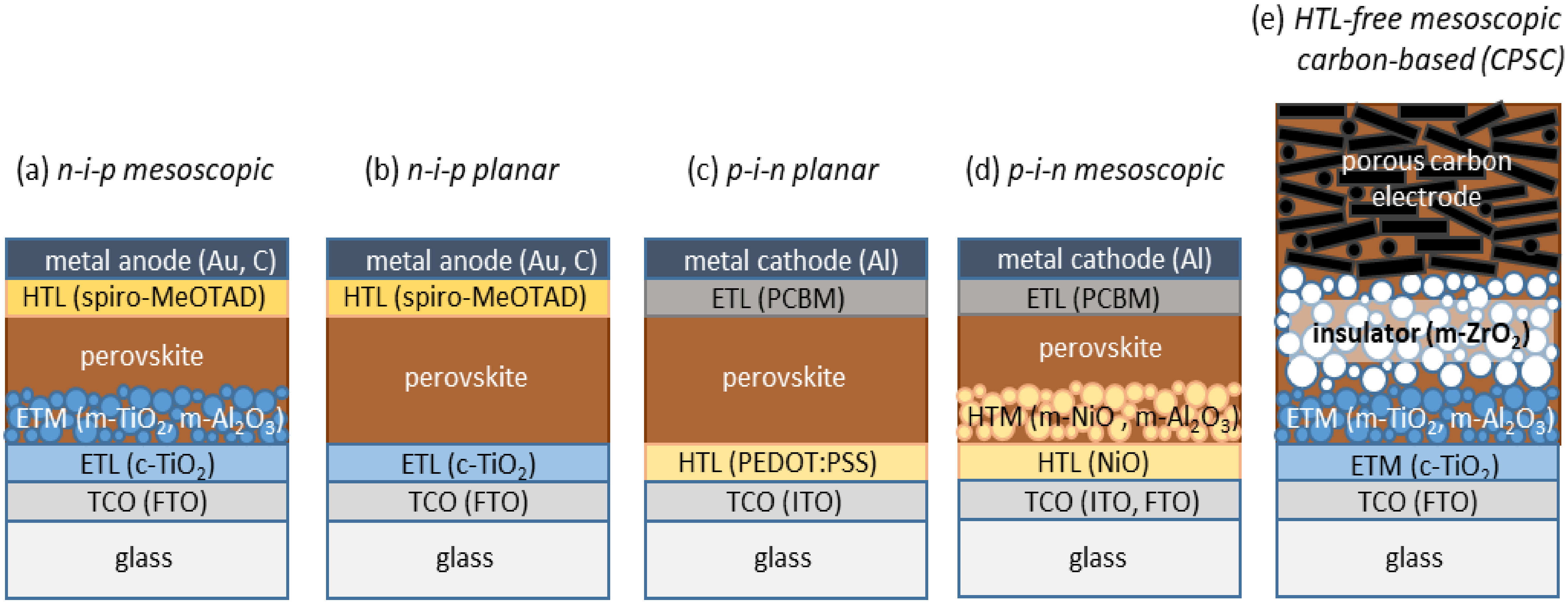
- This principle works with dyes adsorbed on TiO_2
- It also works with quantum dots as sensitizers, e.g. CdS or Perovskite

$MAPbI_3$ were first used as sensitizers in liquid electrolyte mesoporous cells

2009	Park (Korea)	4% to 6%
2012	M. Grätzel, S. I. Seok and H. Snaith	10-11%
2016	M. Grätzel group	21.1%
2019	Park (KRIKT)	25.2%
2021	Grätzel, KIER, UNIST, UU	25.6 %

Elumalai et.al Energies (2016)
H. D. Pham et al., Energy Environ. Sci., 12, 1177 (2019)
Jeong et al., Nature, 593, 381–385 (2021)

Various device architectures



Stability issues of perovskite solar cells

Material stability of the photoactive layer

- Volatility and acidic nature of MA^+ ($CH_3NH_3^+$)

  $CH_3NH_3PbI_3 \xrightarrow{\Delta} PbI_2 + CH_3NH_2 + HI$

- Water uptake, $MA_4PbI_6 \cdot 2H_2O$ hydrate phases $\longrightarrow$ PbI_2

- Crystalline phase instability cations FA (too large), Cs^+ (too small), MA (unstable)

- Halide segregation of mixed Br and I anions (mixed anions are good for tuning the bandgap tandem solar cells)

- Interface stability, grain boundary passivation

- Electric field induced degradation

- Damage by UV light irradiation

T. Huang et al., J. Phys. Chem. C, 125, 19088 (2021)

Table 4 | Conditions of stability analysis of selected PSCs analyzed under continuous illumination for over 1000 h. Only cells losing less than 15% of initial PCE are included

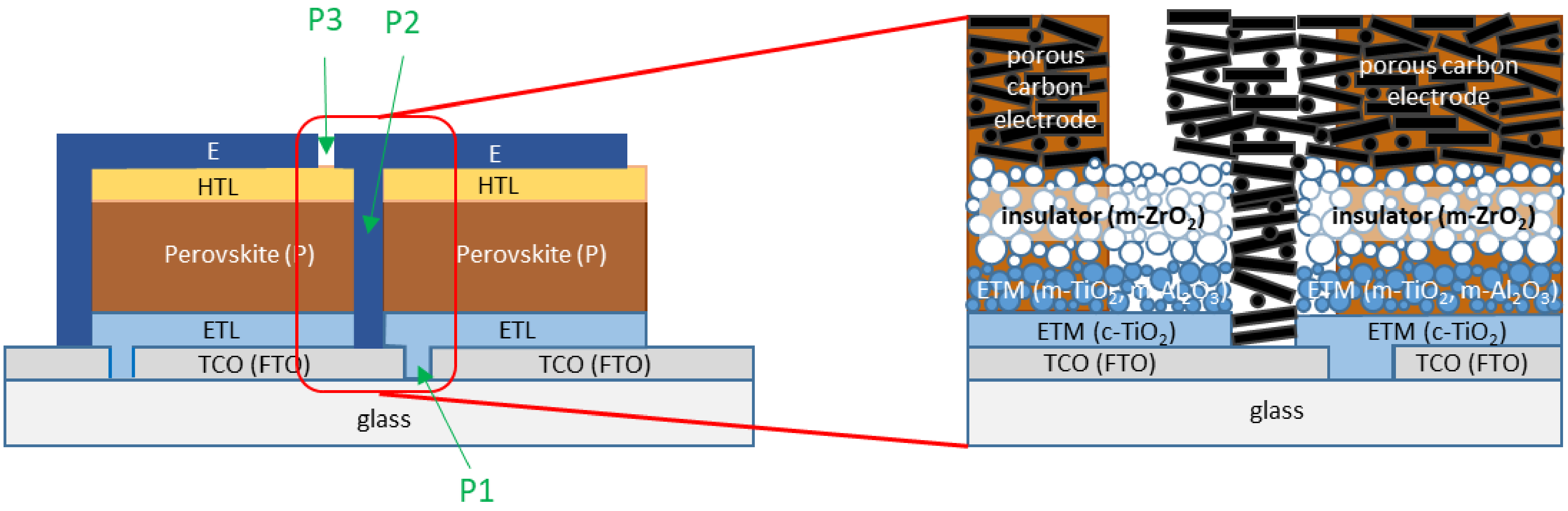
Light source	UV filter	Reported	Intensity (Suns)	T (°C)	Atmosphere	Encap-sulation	Cell structure	Initial PCE (%)	Time (h)	Ref.
Sulfur plasma	-	'Triple A class' sulfur plasma lamp, Plasma-I AS 1300 Light Engine (http://www.plasma-i.com/plasma-i-products.htm).	0.77	30 °C	Ambient Air 10%–20% RH	No	ITO/SnO_2 ($(FA_{0.76}MA_{0.15}Cs_{0.09})_{0.97}Pb(I_{0.89}Br_{0.11})_{2.97}$ EH44/MoOx/Al	16.6	1500	[49]
	-	Sulfur plasma lamp from LG (6000 K blackbody).	1	35 °C	Ambient Air 40% RH	No	ITO/NiO/LiF $Cs_{0.17}FA_{0.83}Pb(I_{0.83}Br_{0.17})_3$ LiF/$PC_{60}BM/SnO_2/ZnSnO_2$/ITO/LiF/Ag	14.5	1000	[148]
White LED	-	White LED illumination	1	RT	N_2 filled chamber	No	ITO/SnO_2/PCBM:PMMA/ $Rb_{0.05}Cs_{0.1}FAPbI_3$ PMMA/ Spiro-OMeTAD/Au	20.4	1000	[149]
	-	White light LED array	1	55–60 °C	Ar filled chamber	No	FTO/c-TiO_2/mp-TiO_2/$(FAI)_{0.9}Cs_{0.1}(PbI_2)_{1.05}$: 3-(5-mercapto-1H-tetrazol-1-yl)benzenaminium iodide/Spiro-OMeTAD/Au	20.9	1000	[150]
	-	White LED (XLamp CXA2011 1300 K CCT)	1	RT	N_2 filled chamber	No	ITO/C_{60}-SAM $FA_{0.83}MA_{0.17}Pb_{1.1}Br_{0.5}I_{2.8}$ PDCBT/Ta-WO_x/Au	21.2	1050	[151]
	-	Array of white LEDs was powered by a constant current	1	60 °C	N_2 filled chamber	No	FTO/c-TiO_2/mp-TiO_2 $CsFAMAPbI_{3-x}Br_x$ CuSCN/r-GO/Au	20.4	1000	[131]
	-	White LED lamp	1	55 °C	N_2 filled chamber	No	FTO/c-TiO_2/mp-TiO_2/ $(FAI)_{0.81}(PbI_2)_{0.85}(MABr)_{0.15}(PbBr_2)_{0.15}$/ doped with N-(4-bromophenyl)-thiourea Spiro-OMeTAD/Au	21.5	1500	[152]
	-	White LED lamp	1	RT	N_2 filled chamber	No	FTO/c-TiO_2/mp-TiO_2/ $MAPbI_3$/PTAA/Au	16.4	1000	[21]
Metal halide or xenon-plasma lamp	No	Light-soaking chamber, K3600-MH300, McScience Inc.	1	RT	N_2 filled chamber	Yes	FTO/La-$BaSnO_3$/$MAPbI_3$/ NiO/FTO/glass	21.2	1000	[66]
	Yes	Class AAA solar sim. from Newport equip. with a 1000 W Xenon lamp. AAA class simulator using a plasma lamp with a spectrum that exactly superimposes to the standard.	1	55 °C	Ar filled chamber or encapsulated	Yes	FTO/c-TiO_2/mp-TiO_2/ $ZrO_2(5\text{-}AVA)_x(MA)_{1-x}PbI_3$/Carbon	11.9	10,000	[133]
	No	Newport solar simulator (model 91192) giving light with AM 1.5 G spectral distribution	1		Ambient air, unspecified	No	FTO/c-TiO_2/mp-TiO_2/ZrO_2 $(5\text{-}AVA)_x(MA)_{1-x}PbI_3$/Carbon	10	1008	[153]
	No	Atlas SUNTEST XLS+ (1,700 W air-cooled xenon lamp) light-soaking chamber under simulated full-spectrum AM1.5 sunlight.	0.76	70–75 °C	Ambient air 40%–50% RH	Yes	FTO/NiO/$(FA_{0.83}MA_{0.17})_{0.95}Cs_{0.05}Pb(I_{0.9}Br_{0.1})_3$ + $BMIMBF_4$/ PCBM/Cr(Cr_2O_3)/Au	~19	1885	[154]
Solar simulator with unspecified light source	Yes	'Solar cell light resistance test system (Model BIR- 50, Bunkoh-Keiki Co., LTD) equipped with a Class AAA solar simulator'	1	45–50 °C		Yes	FTO/NiMg(Li)O/$MAPbI_3$/ PCBM/Ti(Nb)Ox/Ag	18.3	1000	[155]
	Yes	'Sun Simulator Sumitomo Heavy Industries Advanced Machinery'	1	35 °C	N_2	Yes	ITO/ BDPSO/$MAPbI_3$/ C_{60}/BCP/Ag	17.2	1300	[156]
	Not specified	'AM.1.5 G solar simulator'	1			Yes	FTO/PEDOT:PSS/$(BA)_2(MA)_3Pb_4I_{13}$/ PCBM/Al	12.5	2250	[157]
	No	'AM 1.5 G illumination'			Air 38% RH		PET/Gr/TiO_2/PCBM $MAPbI_3$/ Spiro-OMeTAD:cross-stacking carbon nanotube/All Carbon Electrode	11.9	1014	[158]
Outdoor	No		Variable	Variable up to 45 °C		Yes	FTO/c-TiO_2/mp-TiO_2/ZrO_2/ $(5\text{-}AVA)_x(MA)_{1-x}PbI_3$/mcarbon	12.9	1056	[72]

RT, room temperature; RH, relative humidity

M. Khenkin et al., Nature Energy, 5, 35–49 (2020)

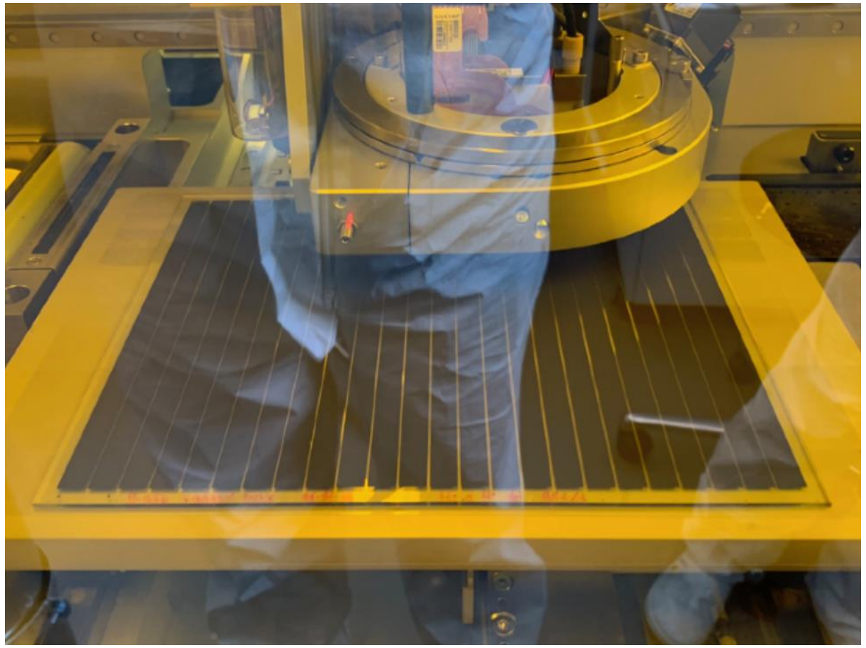
Uniqueness of the mesoscopic PSC architecture

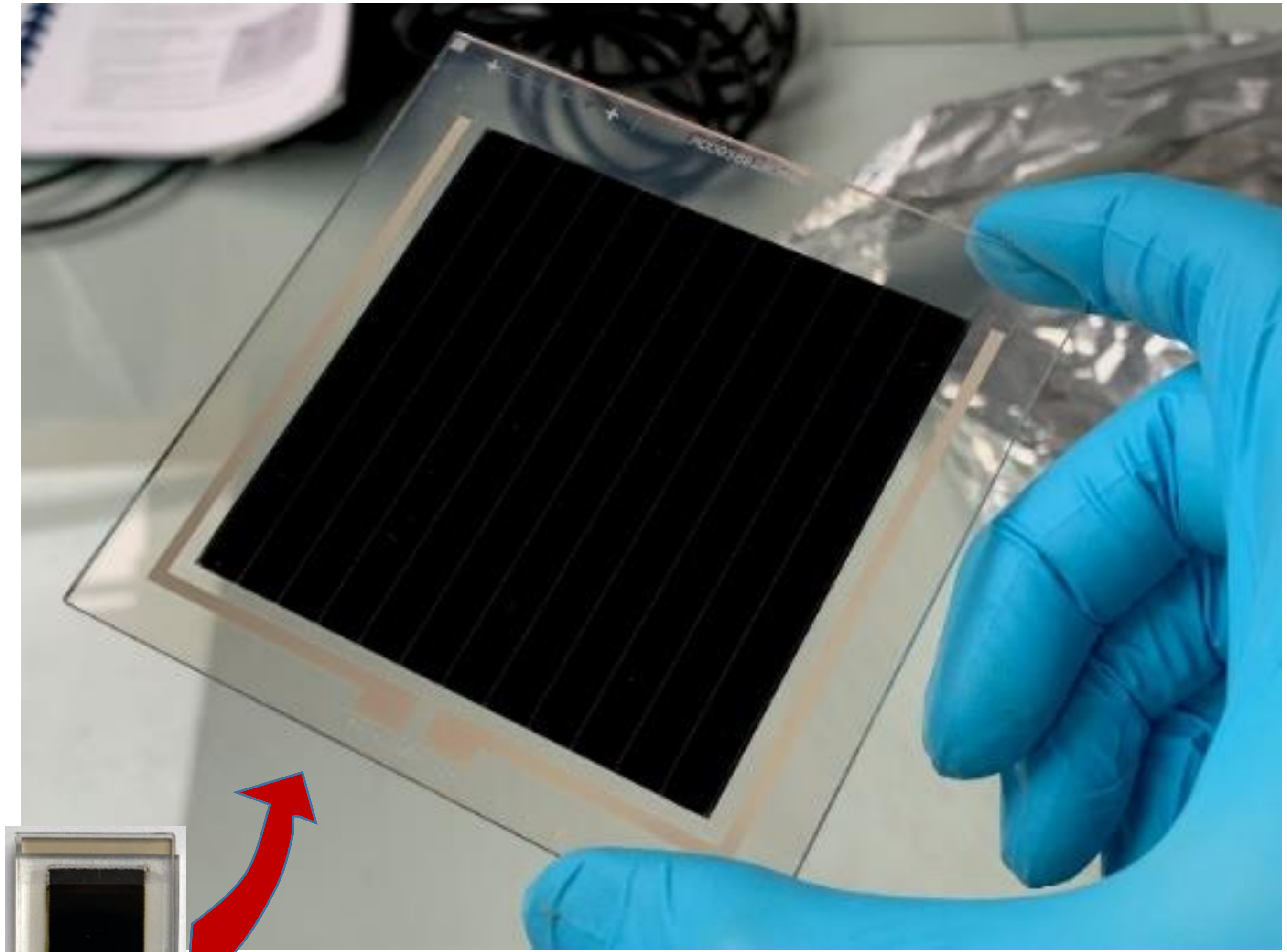
- Crystal growth uniform over the full surface using inkjet
- Robust thick structure is less sensitive to surface defects
- Cell interconnect does not create interfacial defects since the active material is added after the scribing step



Scale-up challenge

Inkjet infiltration of the perovskite precursor. Slot-die coating of porous scaffold.





A. Verma et al, J.Mater.Chem.C, 2020,8,6124
A. Verma et al, Materials Advances, 2020, DOI: 10.1039/d0ma00077a

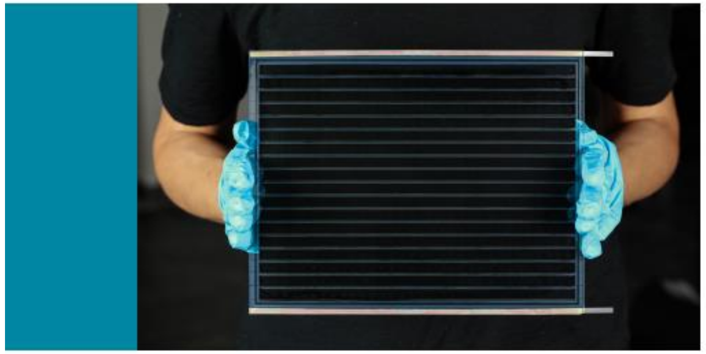
Both have a PCE of 13 %

Industrialization of Perovskite PV technology

Empa Akademie

WORKSHOP

Industrialization of Perovskite Thin Film Photovoltaic Technology



Virtual via Zoom
Thursday, December 16, 2021
from 13:00 to 16:00 CET

SWISS PHOTONICS

Empa Akademie

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PROGRAM

13:00 **Opening**
Prof. F. Nüesch, Empa, Dübendorf (CH)

13:15 **Stable Perovskite Module on the Way for Mass Production**
Dr. B. Yan, Microquanta Semiconductor, Hangzhou (CN)

13:30 **Printable Mesoscopic Perovskite Solar Cells**
Prof. H. Han, Huazhong University of Science and Technology (HUST), Wuhan (CN)

13:45 **100 MW Production Capacity of Perovskite Solar Modules**
Prof. B. Fan, GCL Nano Technology, Suzhou (CN)

14:00 **Efficient Structures and Processes for Upscaling of Perovskite Modules and Tandems**
Dr. T. Aernouts, R&D manager Thin-Film PV, imec, partner in EnergyVille & Solliance, Eindhoven (NL)

14:15 Coffee break – Poster session

14:45 **Pilot Production and Market Entrance**
Dr. D. Forgács, Saule Technologies, Warsaw (PL)

15:00 **A Radically Simpler Way to Manufacture Thin-Film Solar Panels, On the Scale-Up to Meet Future Photovoltaic Goals**
Dr. T. Meyer, Solaronix SA, Aubonne (CH)

15:08 **Digitally Printed Custom Design Solar Cells**
Dr. A. Verma, PEROVSKIA SA, Aubonne (CH)

15:15 **Is Perovskite PV Prepared for TW Solar?**
Dr. C. Case, Oxford PV, Oxford (UK)

15:30 **Swift Solar – Perovskite Tandem PV with New Form Factors**
Dr. T. Leijtens, Swift Solar, Colorado (US)

15:45 **Perspectives on Market Application for Perovskite Solar Cells**
Mr. D. Travesso, FIR Capital, Nova Lima (BRA)

16:00 **Short conclusions**
Prof. F. Nüesch, Empa, Dübendorf (CH)

SOLARONIX

Perovskia

Acknowledgements

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Prof. C. Ballif
Prof. Md. K. Nazeeruddin

Universities of Applied Science
Prof. Dr. Beat Ruhstaller - ZHAW
Dr. Roman Rudel - SUPSI

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