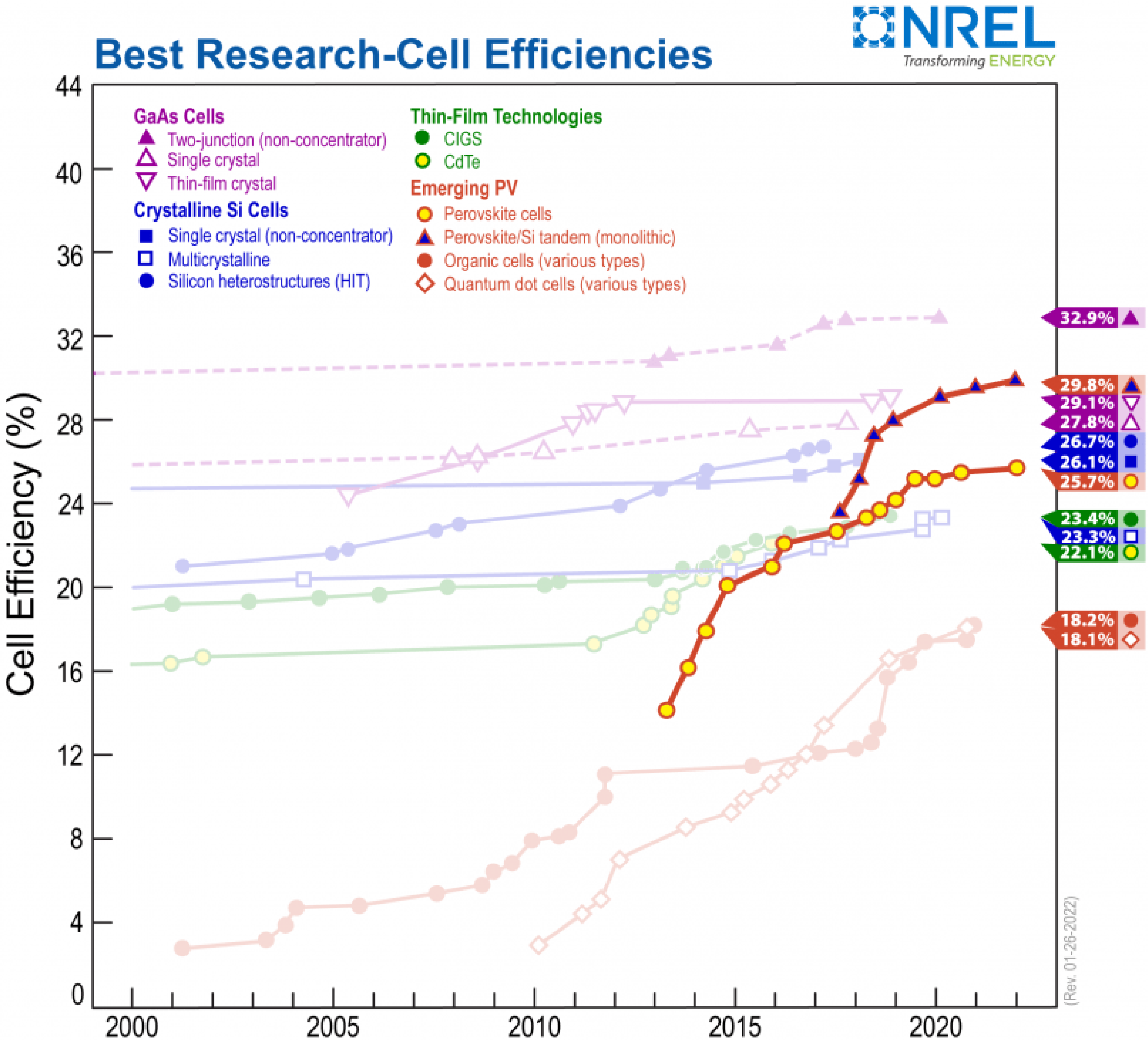
2.3A Hybrid solar cells - Perovskites

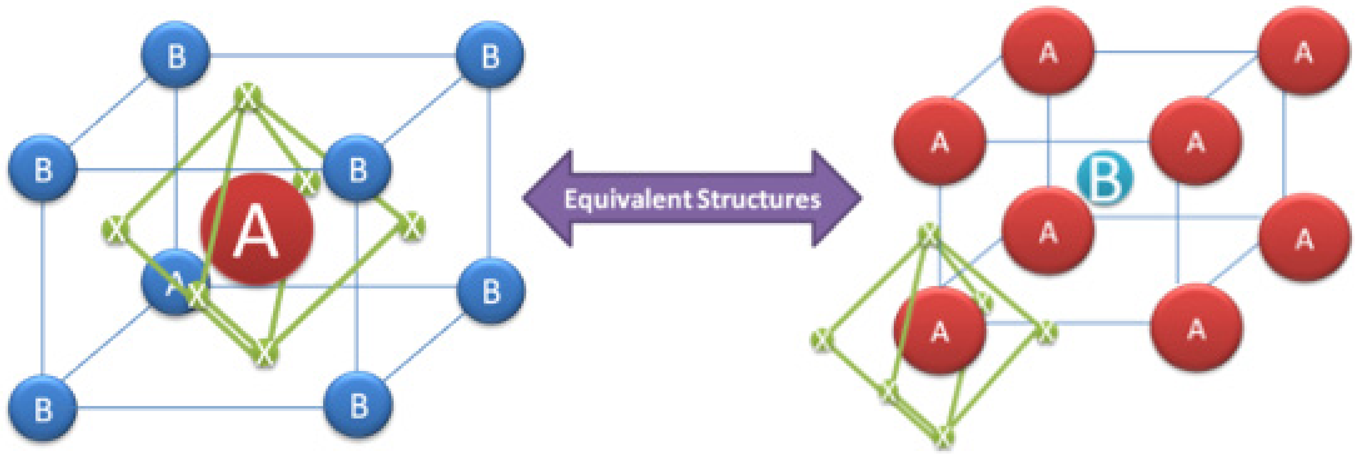
Learning goals

- What are Perovskite solar cells?
- Architectures? How are they made?
- Why are they so good?
- Strategies towards high efficiency cells
- Challenges towards industrialization
    - Up-scaling
    - Stability


NREL
Transforming ENERGY
Best Research-Cell Efficiencies
GaAs Cells
Two-junction (non-concentrator)
Single crystal
Thin-film crystal
Crystalline Si Cells
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-Film Technologies
CIGS
CdTe
Emerging PV
Perovskite cells
Perovskite/Si tandem (monolithic)
Organic cells (various types)
Quantum dot cells (various types)
Cell Efficiency (%)
44
40
36
32
28
24
20
16
12
8
4
0
2000
2005
2010
2015
2020
32.9%
29.8%
29.1%
27.8%
26.7%
26.1%
25.7%
23.4%
23.3%
22.1%
18.2%
18.1%
(Rev. 01-26-2022)

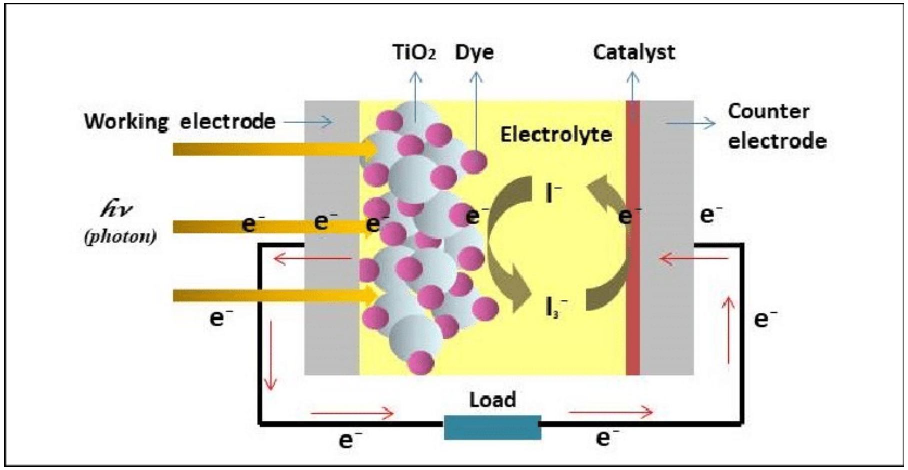
Perovskite

- The original ***perovskite*** (the mineral) is composed of calcium, titanium and oxygen in the form $CaTiO_3$.
- Today: any crystal structure of the form ABX_3



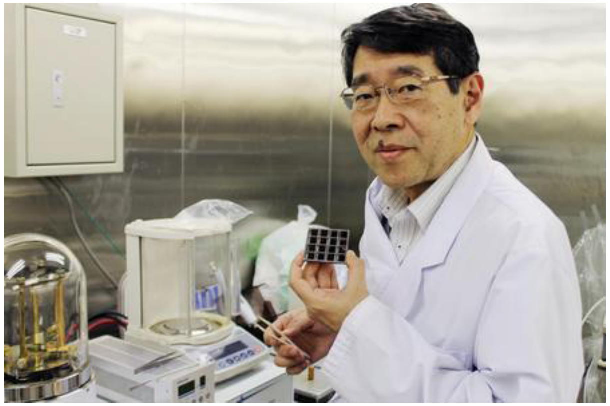
- Typically:
  - A = An organic cation – methylammonium ($CH_3NH_3^+$) or formamidinium ($NH_2CHNH_2^+$)
  - B = A big inorganic cation – usually lead(II) (Pb_2^+)
  - X_3= A slightly smaller halogen anion – usually chloride (Cl^-) or iodide (I^-)

Where it all started



Dye sensitized solar cells

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



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

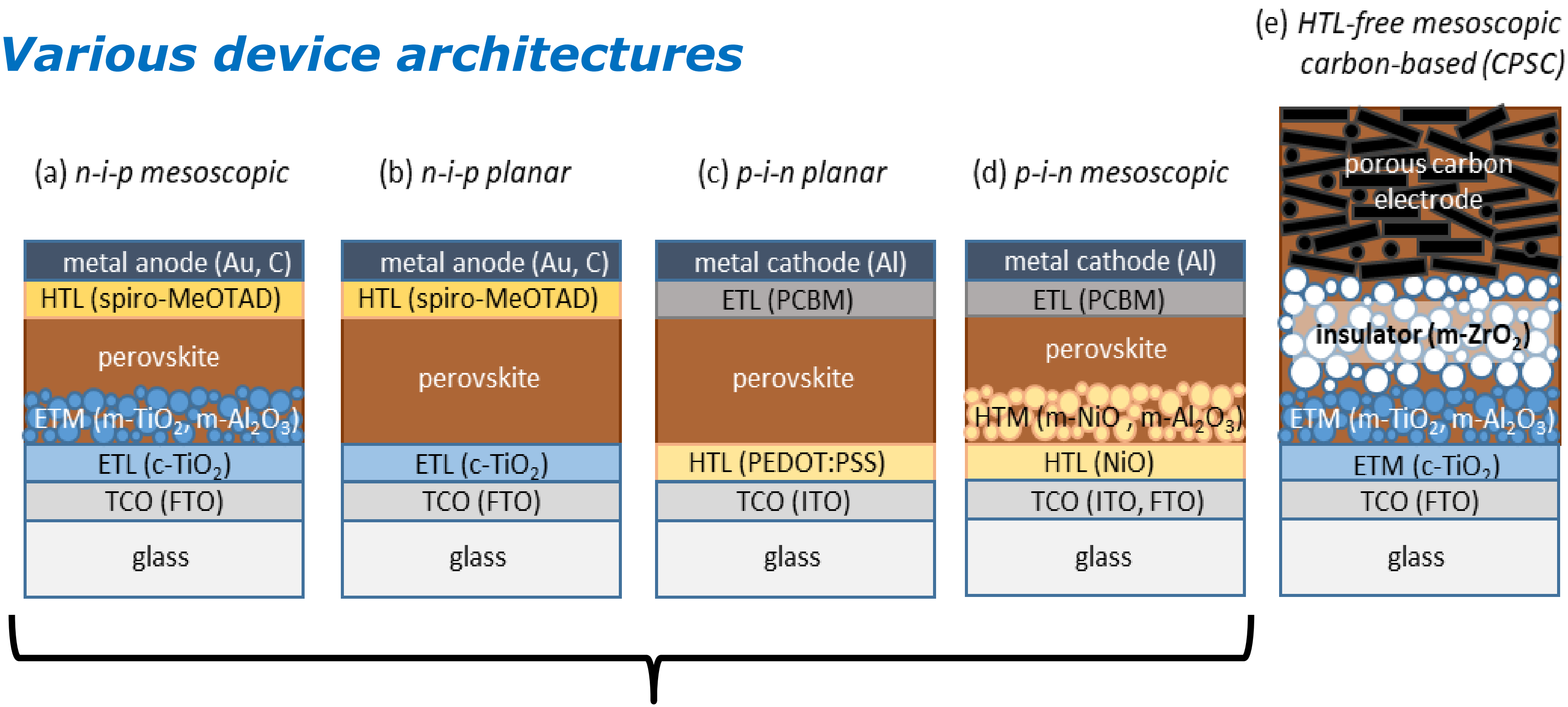
$MAPbI_3$ were first used as sensitizers in liquid electrolyte mesoporous cells

2009	Park (Korea)	4% to 6%
2012	M. Grätzel, S. I. Seok and H. Snaith	10-11% (solid-state perovskite)
2016	M. Grätzel group	21.1%

Elumalai et.al Energies (2016)

H. D. Pham et al., Energy Environ. Sci., 12, 1177 (2019)

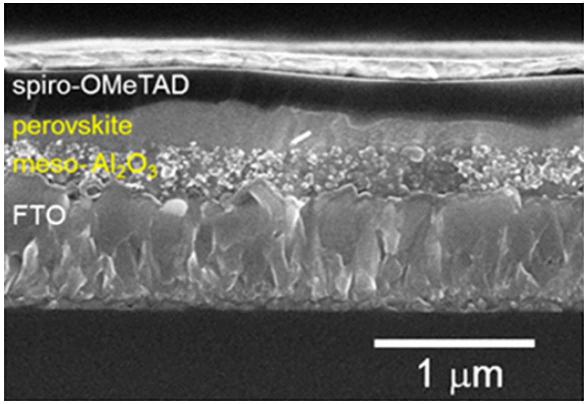
Various device architectures

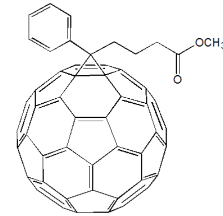


- All architectures showed high efficiences
- Planar: higher charge mobilities and slower trap-mediated recombination
- Mesoscopic: less interfacial recombination at ITO electrode

Examples of typical cell architectures

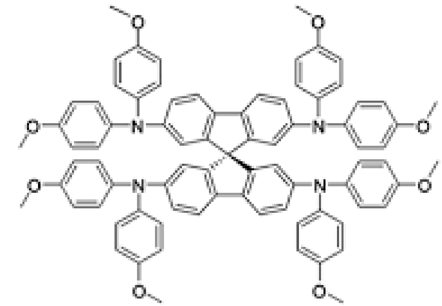
«mesoscopic n-i-p (Al_2O_3)»

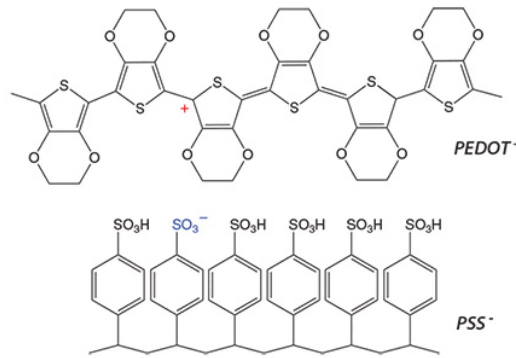




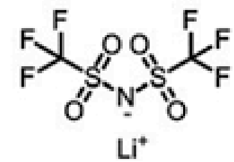
PCBM

Spiro-MeOTAD





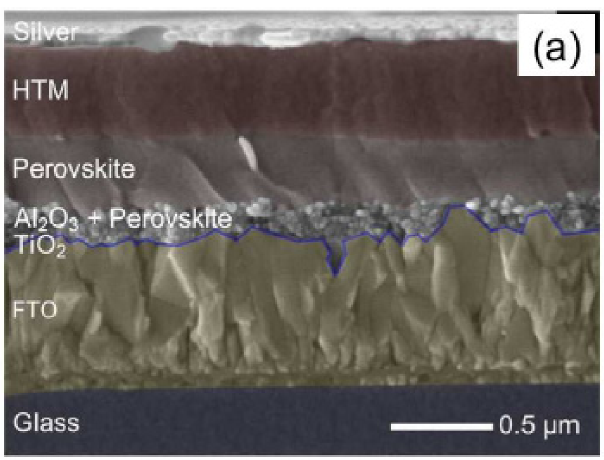
Li-TFSI

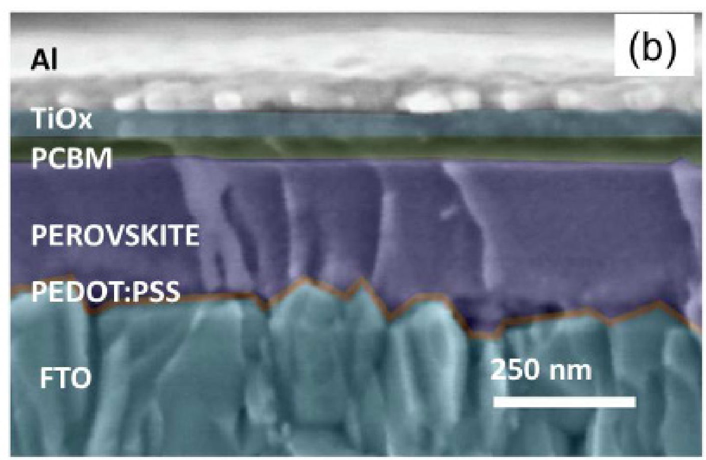


PEDOT:PSS

«mesoscopic n-i-p (TiO_2)»

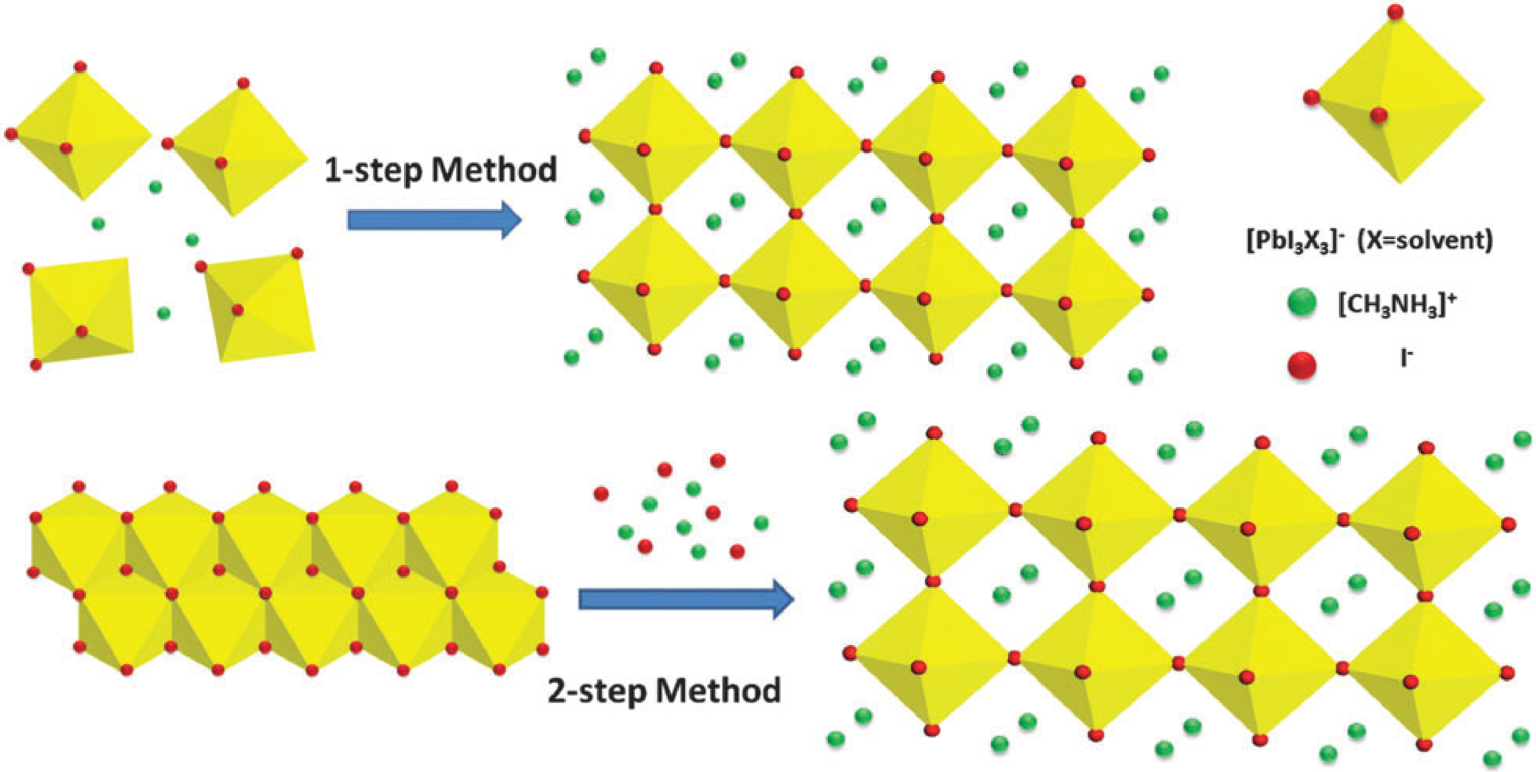
«planar p-i-n»





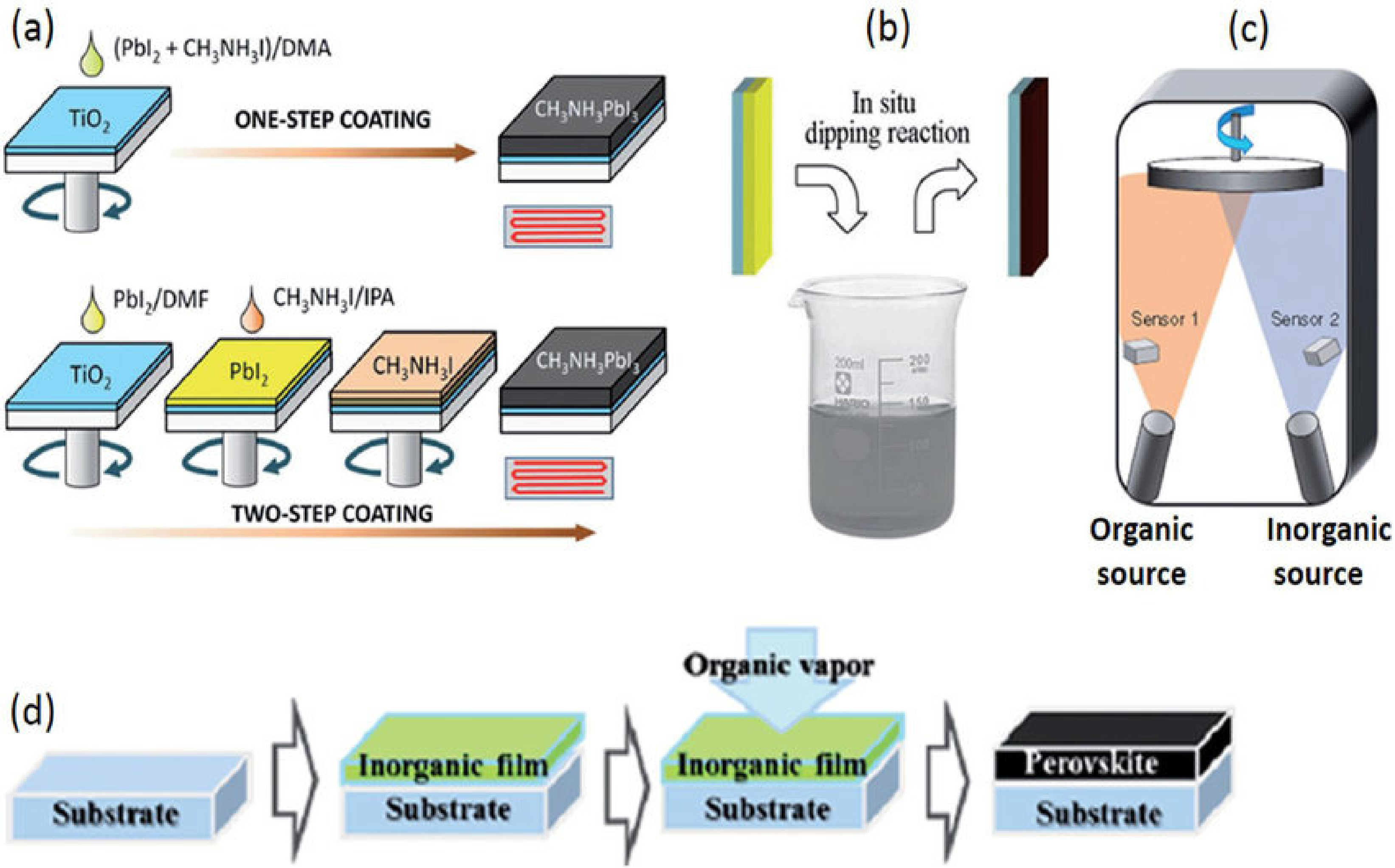
Ball et al., Energy & Environmental Science, 2013, 6, 1739-1743
P. Docampo et al., Nature Communications, 2013, 4

One-step and two-step solution growth method of perovskite films



Y. Zhao, *Chem. Soc. Rev.*, 2016, 45, 655--689

Growth methods of perovskite films



Journal of Photochemistry and Photobiology C: Photochemistry Reviews 35 (2018) 1–24

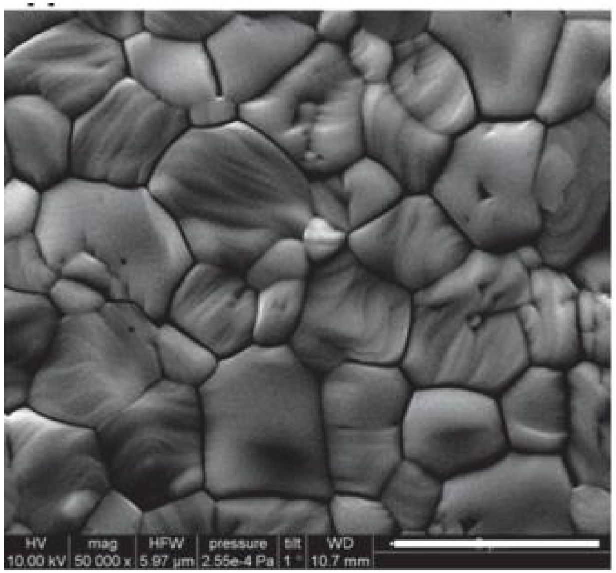
Why do perovskite solar cells work so well?

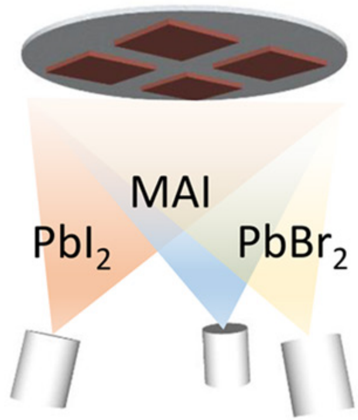
- Good crystallinity, large grains (few defects, reduced grain boundary scattering)
- High absorption coefficient (direct bandgap semiconductor)
- Low exciton binding energy (thermal generation of charge carriers)
- Long carrier diffusion length

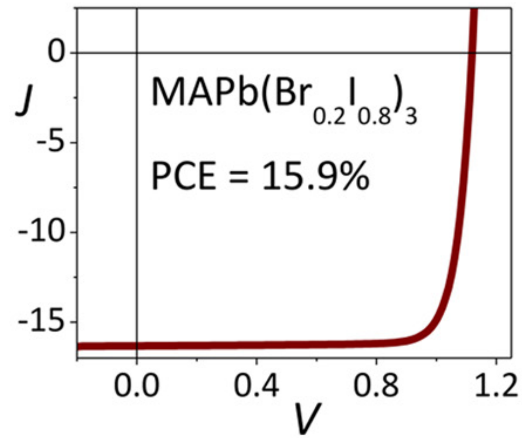
Good crystallinity and large grains

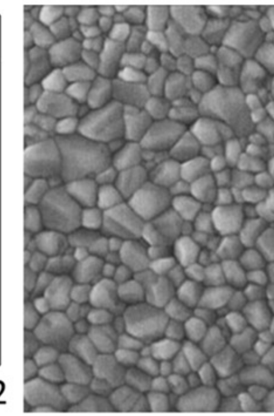
Solution-processed

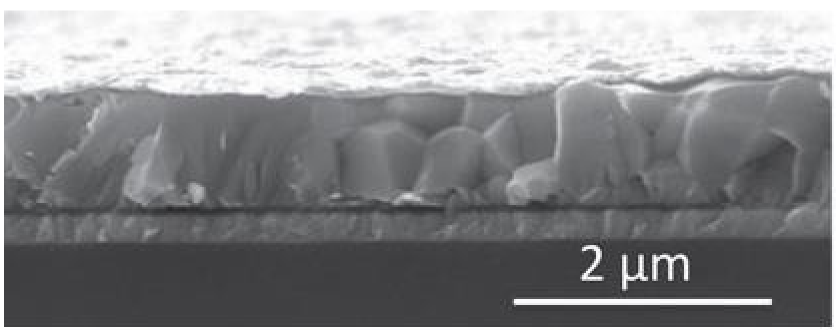
Vaccum-processed







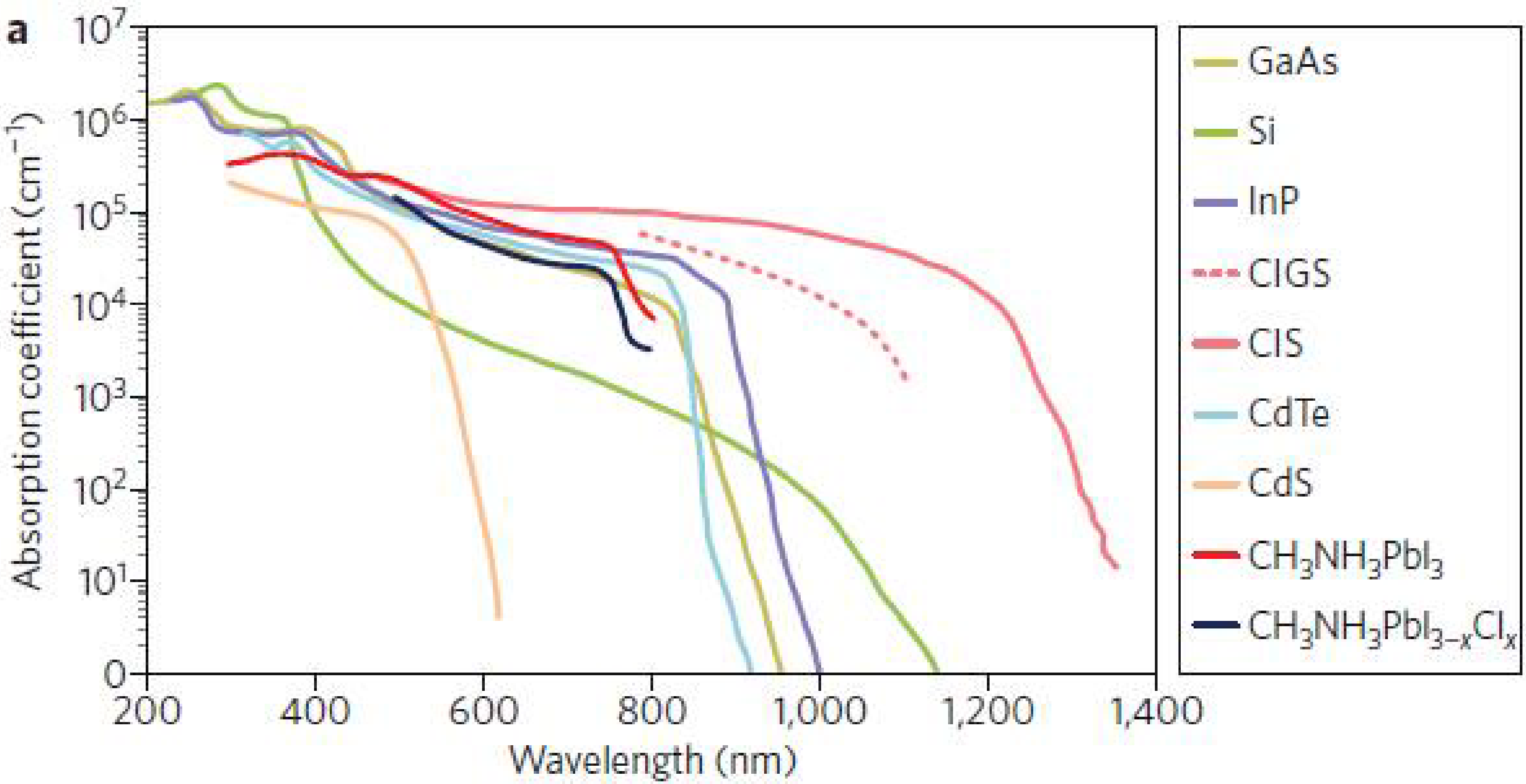




- Good crystallinity gives rise to low defects concentration within perovskite
- Large grain size significantly reduces grain boundary scattering of carriers

Snaith et al, *Nature* **501**, 395 (2013)
J. Huang et al., Adv. Mater. 2014
Longo and Bolink et.al. ACS Energy Letters (2018)

Rather high optical absorption coefficient



- Only 300-400 nm thick films are sufficient to absorb most of the visible solar spectrum

Low exciton binding energy

Table 1 Exciton binding energies E_b of the 3-D $CH_3NH_3PbI_3$ and $CH_3NH_3PbI_{3-x}Cl_x$ perovskites and selected low-dimension perovskites

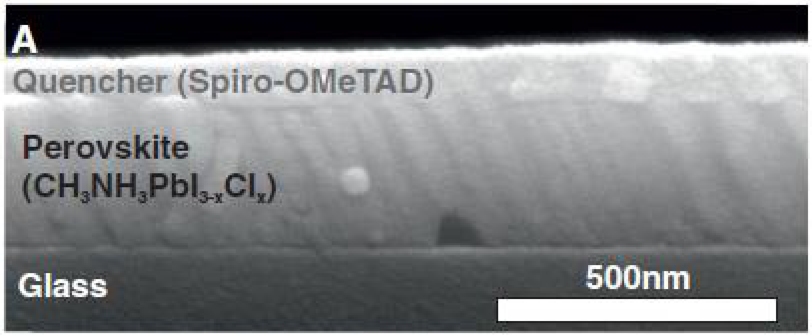
Compound	Dimensionality	E_b (meV)	Method
$CH_3NH_3PbI_3$	3D	30	Optical absorption[7]
		37	Magneto-absorption[67]
		45	Temperature dependent PL[69]
		50	Magneto-absorption[68]
		19 ± 3	Temperature dependent PL[45]
$CH_3NH_3PbBr_3$	3D	76	Magneto-absorption[68]
		150	Optical absorption[7]
$CH_3NH_3PbI_{3-x}Cl_x$	3D	98	Temperature dependent PL[72]
$(C_9H_{19}NH_3)_2PbI_4$	2D	≥330	Temperature dependent PL[69]
$(NH_2C(I){=}NH_2)_3PbI_5$	1D	≥410	Optical absorption[7]
$(CH_3NH_3)_4PbI_6\cdot 2H_2O$	0D	545	Optical absorption[7]

- Binding energy ranging from 19-50 meV, comparable thermal energy at with room temperature

~ 25 meV

T.C Sum et al., *Energy Environ. Sci.* **7**, 2518 (2014)

Long carrier diffusion length

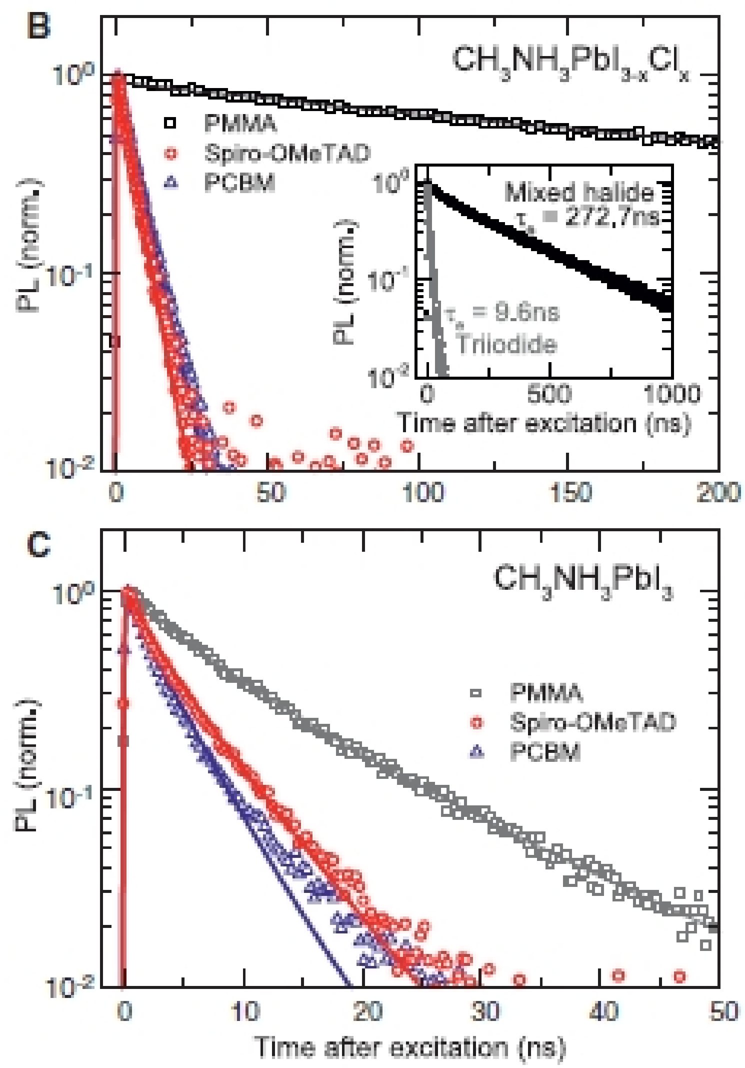


Perovskite	Species	L_D (nm)
$CH_3NH_3PbI_{3-x}Cl_x$	Electrons	1069 ± 204
	Holes	1213 ± 243
$CH_3NH_3PbI_3$	Electrons	129 ± 41
	Holes	105 ± 32

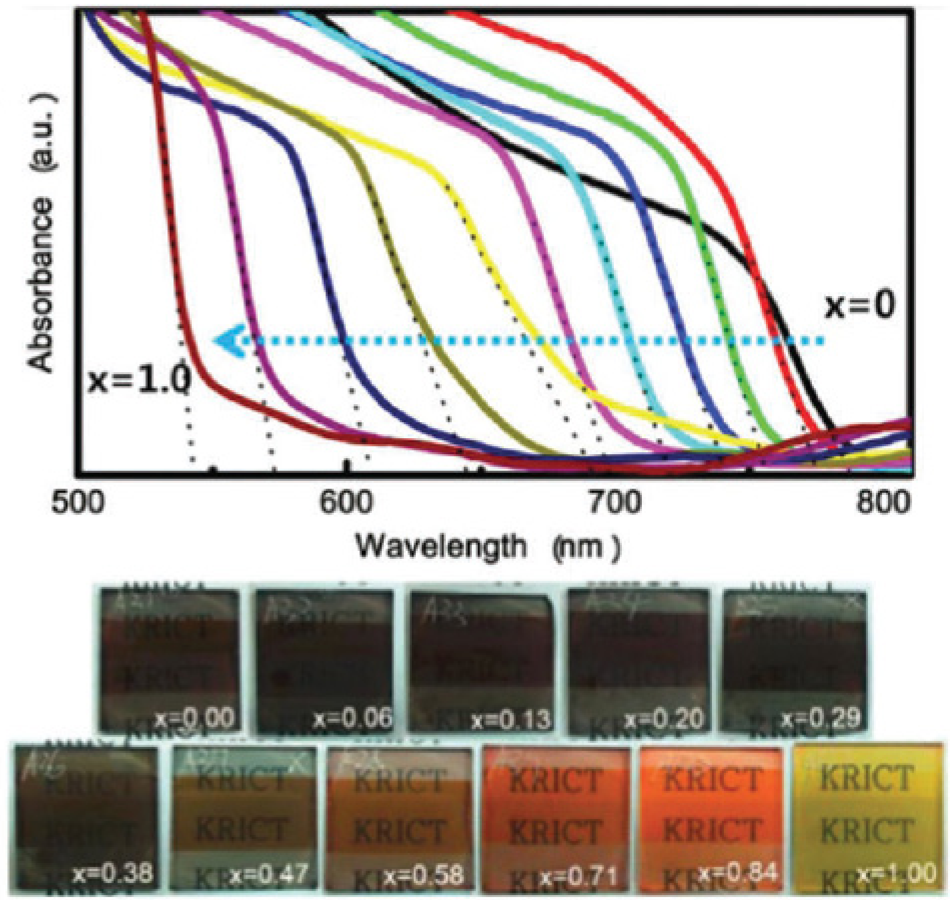
- Long carrier lifetime: ~300 ns
- Carrier diffusion length >1 mm for $CH_3NH_3PbI_3$:Cl

Snaith et al, Science 342, 341(2013)

Time-resolved photoluminescence



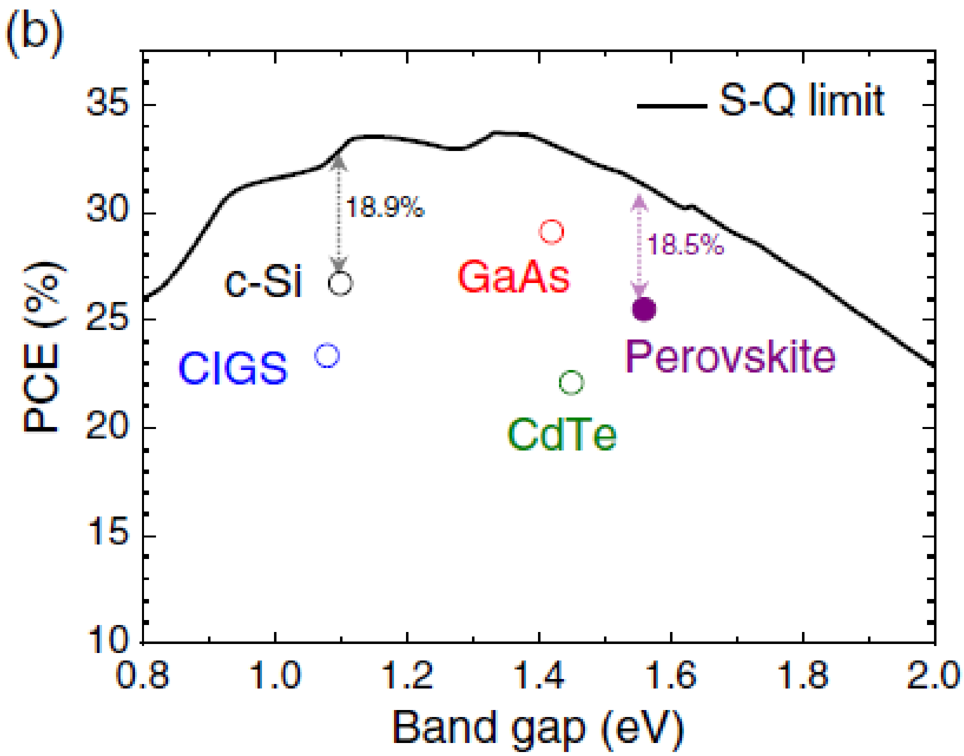
Bandgap engineering of $MAPb(I_{1-x}Br_x)_3$ perovskites



J. H. Noh, S. H. Im, J. H. Heo, T. N. Mandal and S. I. Seok, Nano Lett., 2013, 13, 1764–1769.

Efficiency improvement

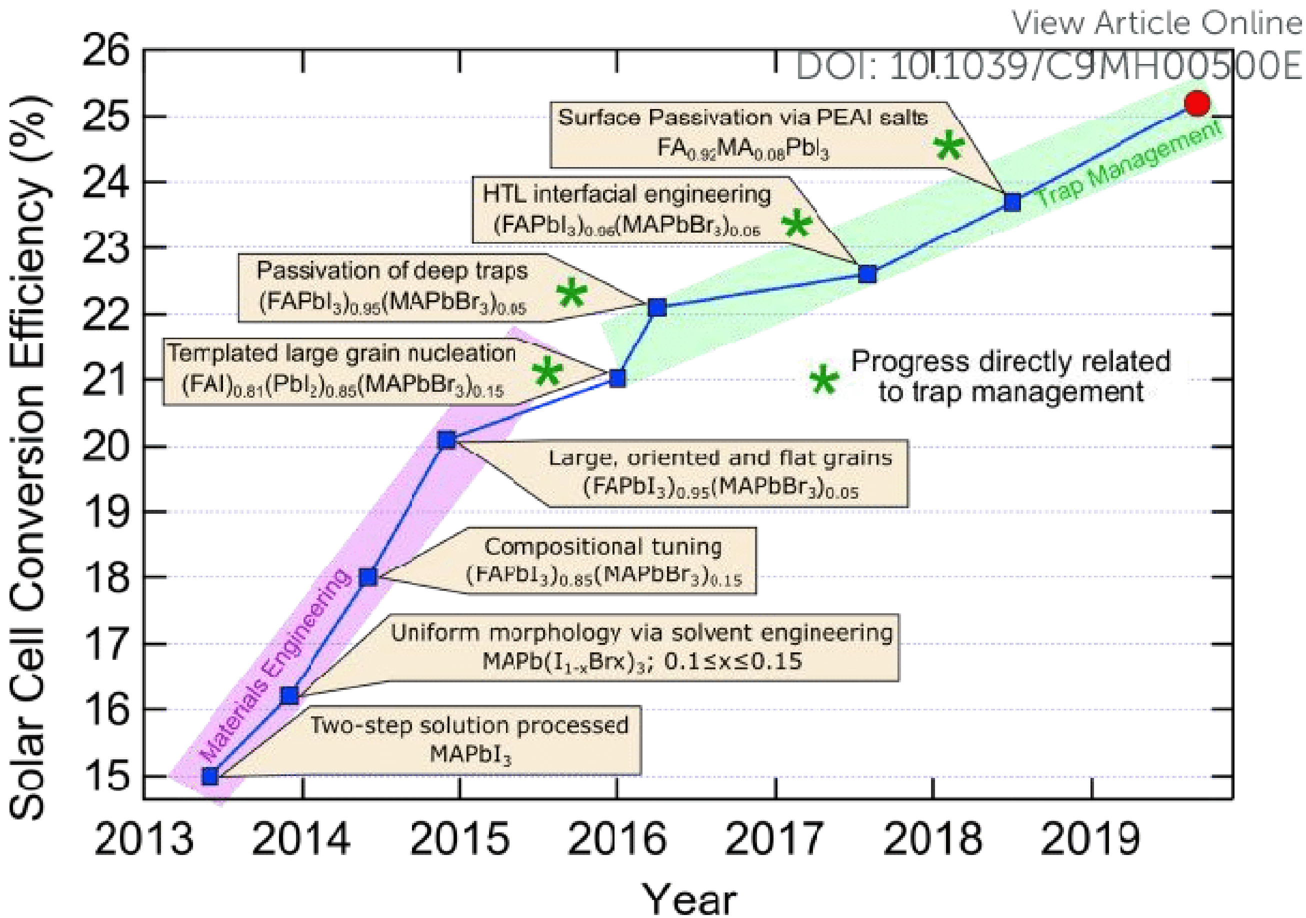
- How much better can we get?



- Typical cell size 5 cm^2; efficiency measurement on 0.1 cm^2

Sol. RRL 2022, 6, 2100455

Efficiency improvement



- Typical cell size 5 cm^2; efficiency measurement on 0.1 cm^2

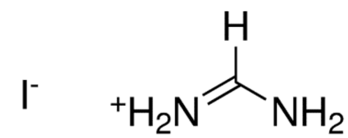
H. Jin, E. Debroye, M. Keshavarz, I. Scheblykin, M. B. Roeffaers, J. Hofkens and J. Steele, Mater. Horiz., 2019, DOI:10.1039/C9MH00500E.

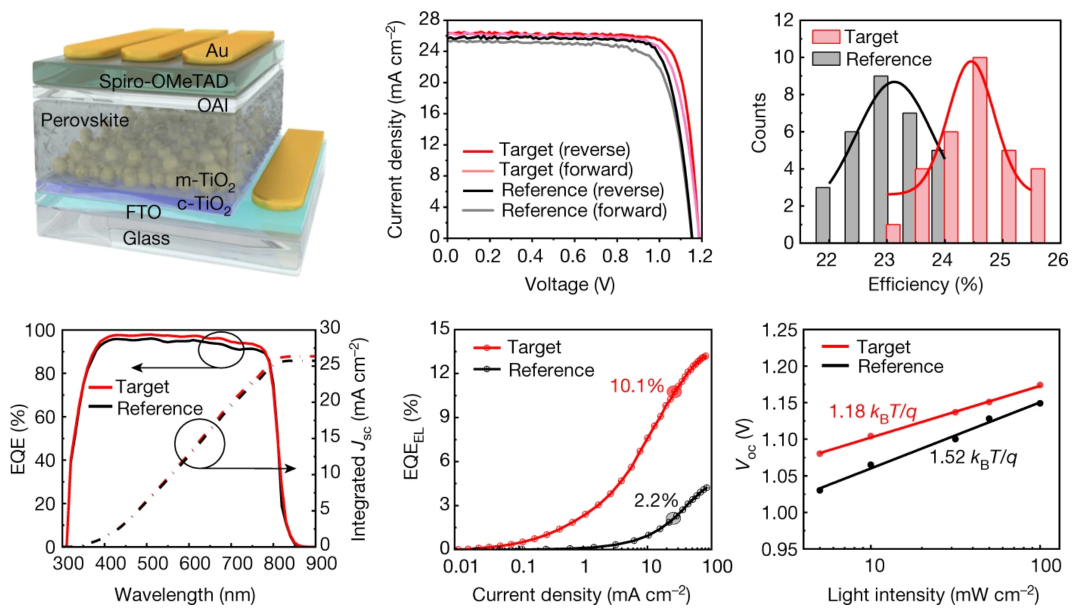
Efficiency improvement – generic strategies

- Antisolvents for control of crystallization
- Compositional engineering for improved optical and electrical properties
- Additives for defect passivation

Recent 25.6% record solar cells – reaching the efficiency of Silicon

- The perovskite semiconductor is composed of $FAPbI_3$, where FA is formamidinium.





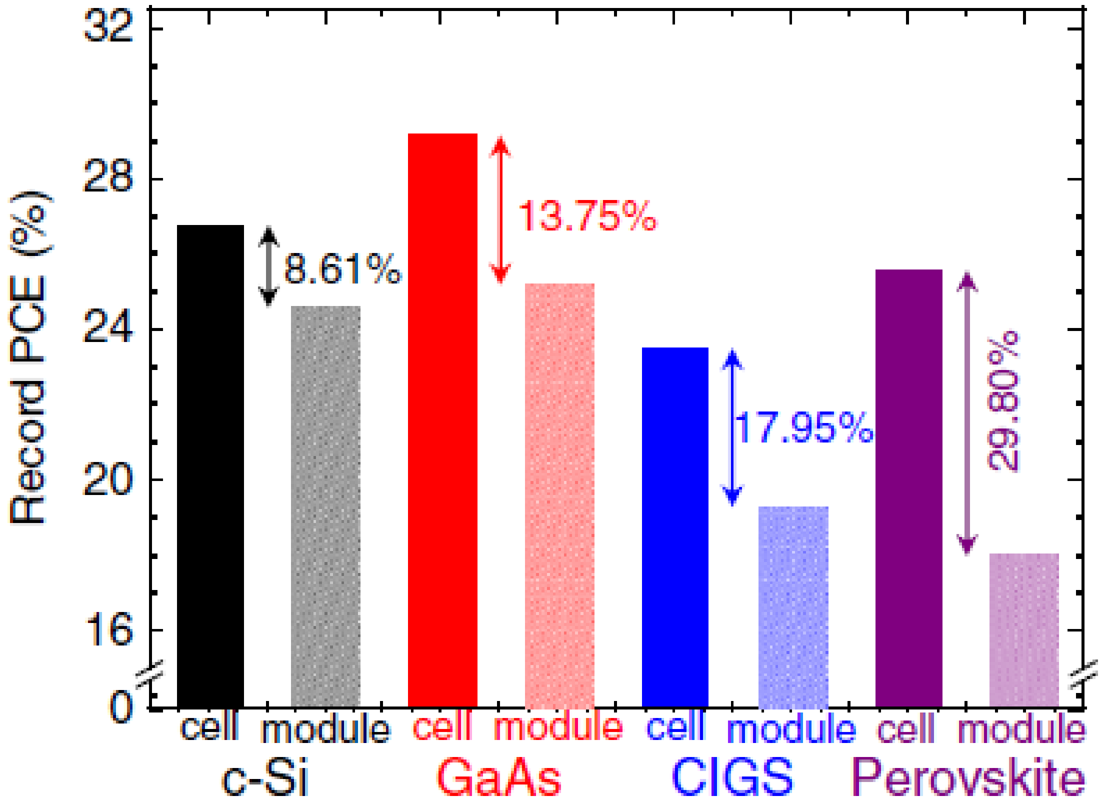
- The novelty of this work is to introduce pseudo-halide anion formate (HCOO−) to suppress anion-vacancy defects that are present at grain boundaries and at the surface of the perovskite films and to augment the crystallinity of the films

Jeong et al., Nature, 2021, 593, 381–385

Challenges

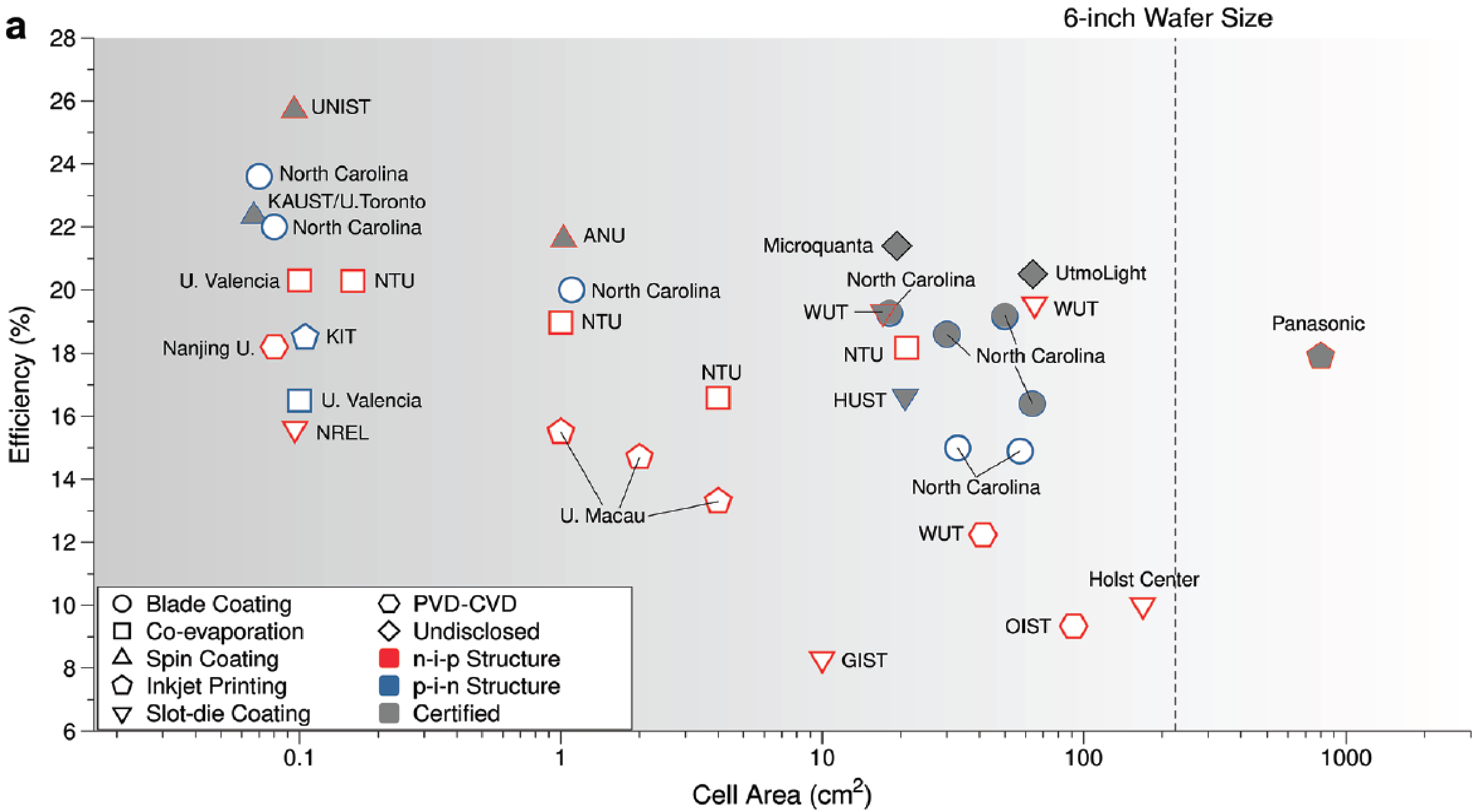
- Up-scaling
- Stability
- Lead

Efficiency loss in modules



Sol. RRL 2022, 6, 2100455

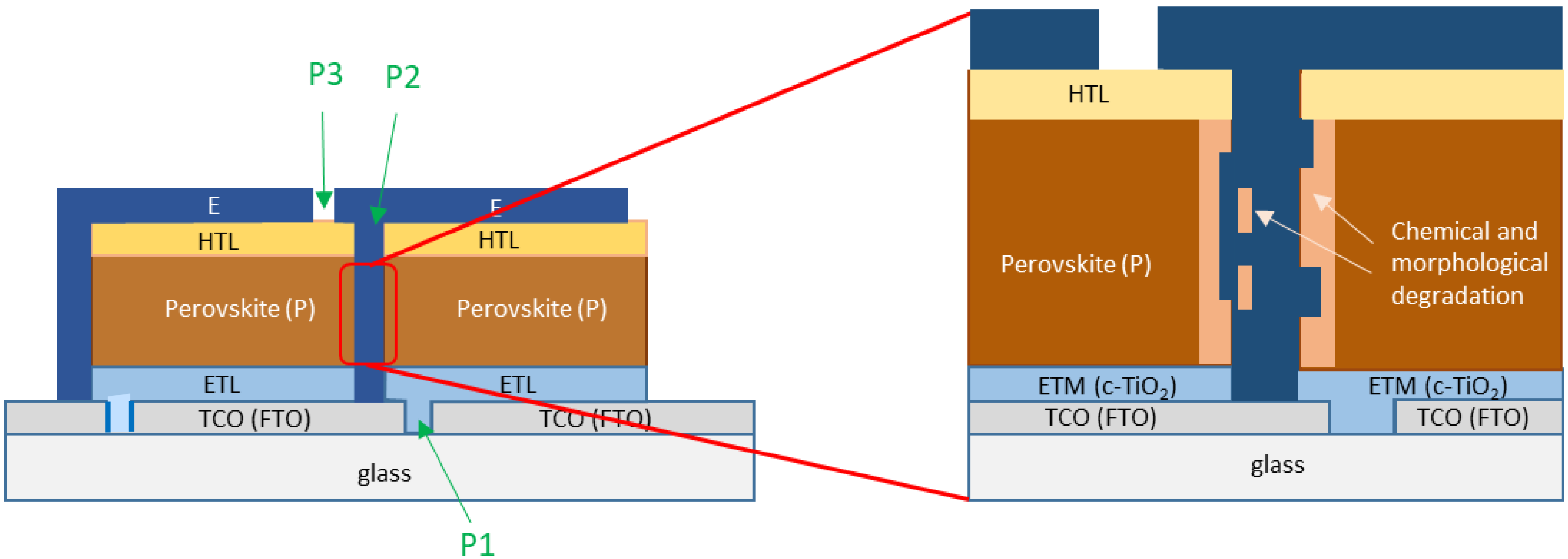
Towards industrialization – different approaches



Adv. Mater. 2022, 2106540

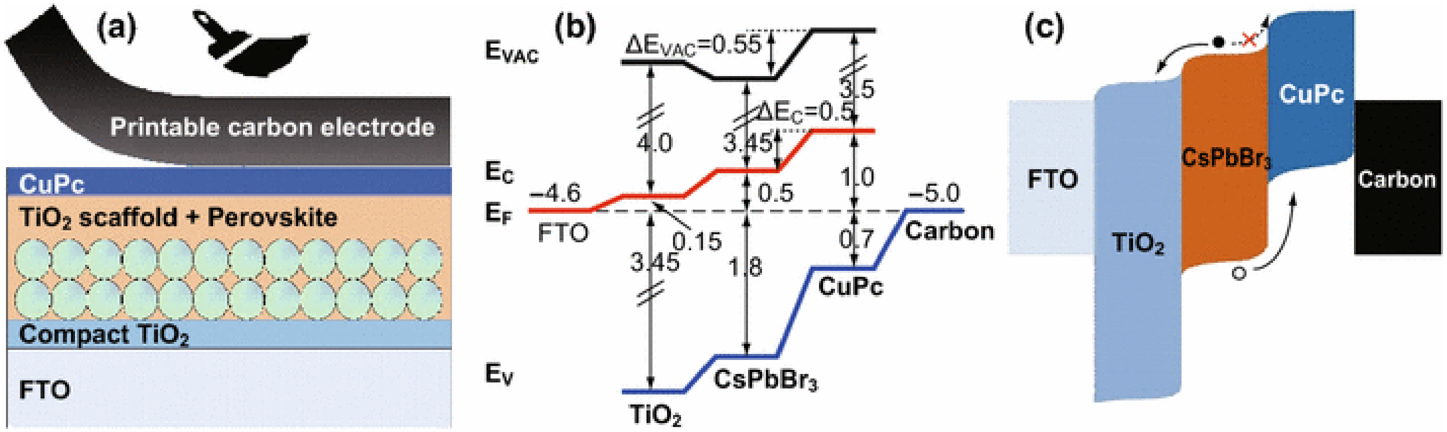
The challenge of series interconnect

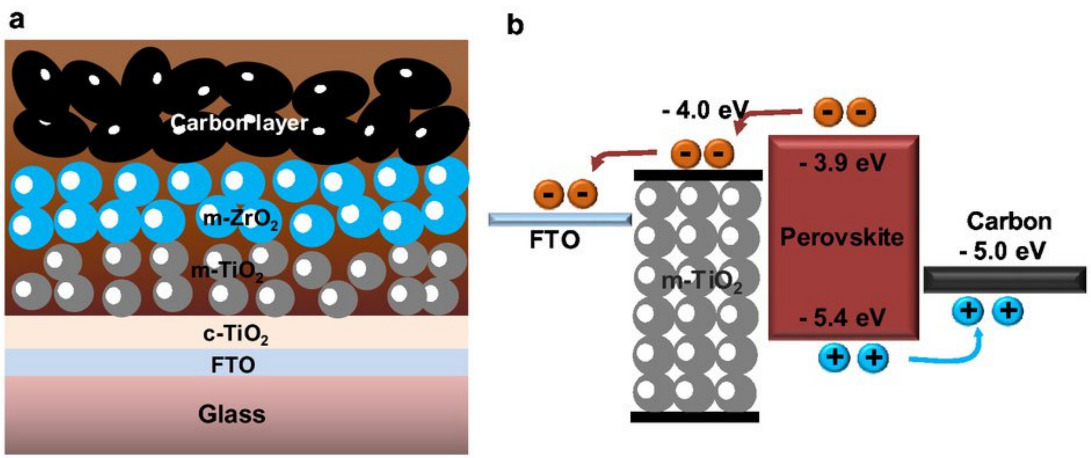
- Laser or mechanical scribing
  - Structural deterioration
  - Chemical degradation



J. Werner et al.,Energy & Environmental Science 2020, *13* (10), 3393-3403

Carbon based perovskite solar cells



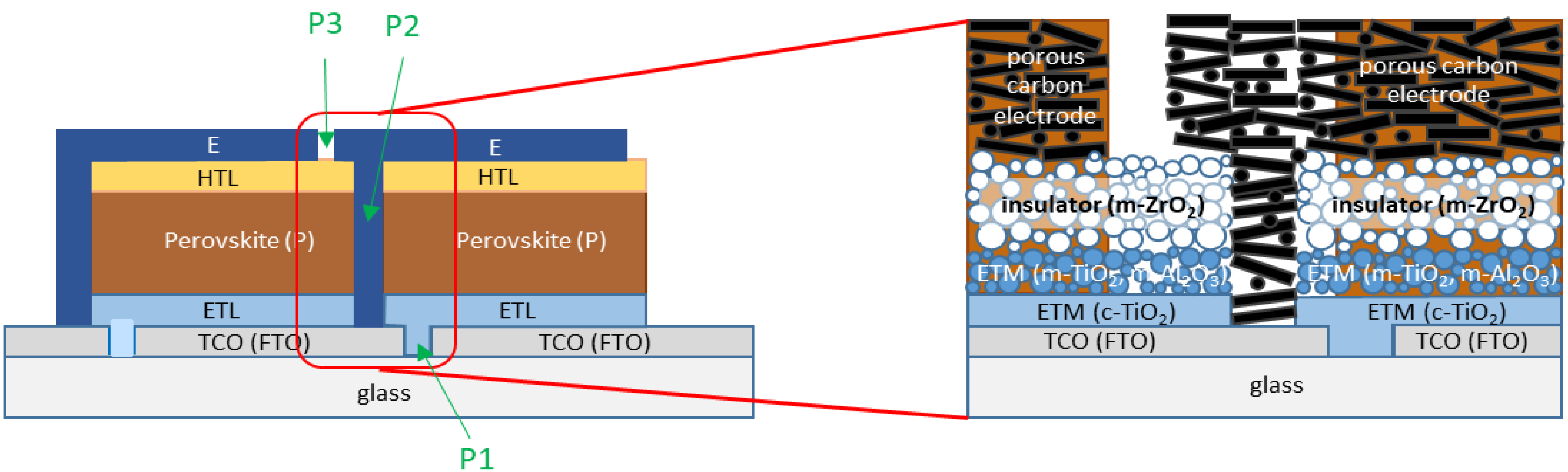


- Good air stability
- High efficiency ~ 13.83 %
- Completely printable

Liu et.al. Nano-Micro Letters (2018)
Duan SPIE (2018)

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



Stability issues of perovskite solar cells

Perovskite solar cells have demonstrated **competitive power conversion efficiencies (PCE)** with potential for higher performance, but their stability is limited compared to leading photovoltaic (PV) technologies. Perovskites can **decompose** when they **react with moisture and oxygen** or when they spend **extended time exposed to light, heat, or applied voltage**. To increase stability, researchers are studying degradation in both the perovskite material itself and the surrounding device layers. Improved cell durability is critical for the development of commercial perovskite solar products

https://www.nature.com/articles/s41586-021-03406-5

Stability issues of perovskite solar cells

- Volatility / 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 $\longrightarrow PbI_2$
- Mixed 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
- UV light irradiation
- Reverse bias instability

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

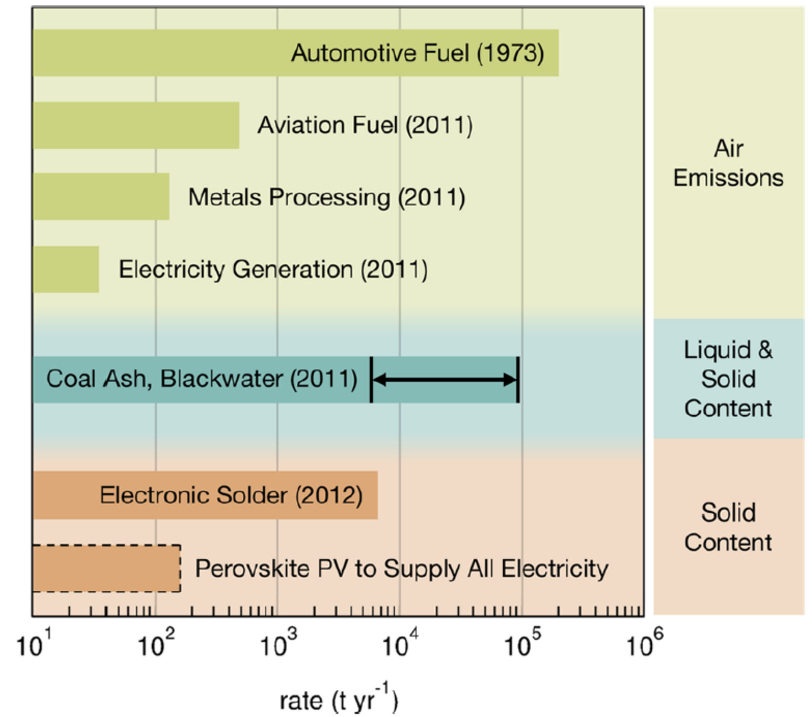
Light source	UV filter	Reported	Intensity (Suns)	T (°C)	Atmosphere	Encap-sulation	Cell structure	Initial PCE (%)	Time (h)	Ref.
Sulfur plasma	-	'Triple A class' sulfur plasma lamp, Plasma-I AS 1300 Light Engine (http://www.plasma-i.com/plasma-i-products.htm).	0.77	30 °C	Ambient Air 10%–20% RH	No	ITO/SnO_2 $(FA_{0.76}MA_{0.15}Cs_{0.09})_{0.97}Pb(I_{0.89}Br_{0.11})_{2.97}$ 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-AVA)$_x$(MA)$_{1-x}$$PbI_3$/Carbon	11.9	10,000	133
	No	Newport solar simulator (model 91192) giving light with AM 1.5 G spectral distribution	1		Ambient air, unspecified	No	FTO/c-TiO_2/mp-TiO_2/ZrO_2 (5-AVA)$_x$(MA)$_{1-x}$$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-AVA)$_x$(MA)$_{1-x}$$PbI_3$/mcarbon	12.9	1056	72

RT, room temperature; RH, relative humidity

T. Huang et al., J. Phys. Chem. C, https://doi.org/10.1021/acs.jpcc.1c05841
M. Khenkin et al., 2020, Nature Energy, VOL 5, 35–49

Environmental issues

- Lead salts are water soluble
- Toxicity of lead salts is of high concern. Intake of lead by the human body affects the liver, kidney and nervous tissues leading to various forms of intoxication
- Lead has a relatively short half-life in the latter soft tissues, but is eventually deposited in the skeleton where it fixates as lead phosphate.
- Health issues with lead are known since Roman times

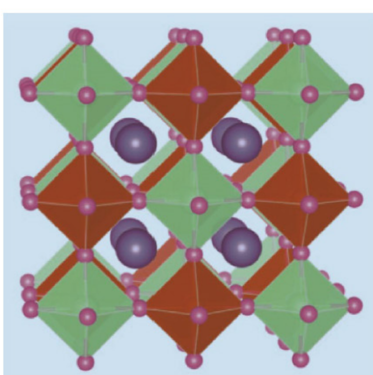


D. Fabini et al., J. Phys. Chem. Lett. 2015, 6, 3546−3548
B. Hailegnaw et al., J. Phys. Chem. Lett. 2015, 6, 1543−1547
A. Babayigit, A. Ethirajan, M. Muller, B. Conings, Nature Materials 2016, *15*, 247.

Possible remedies

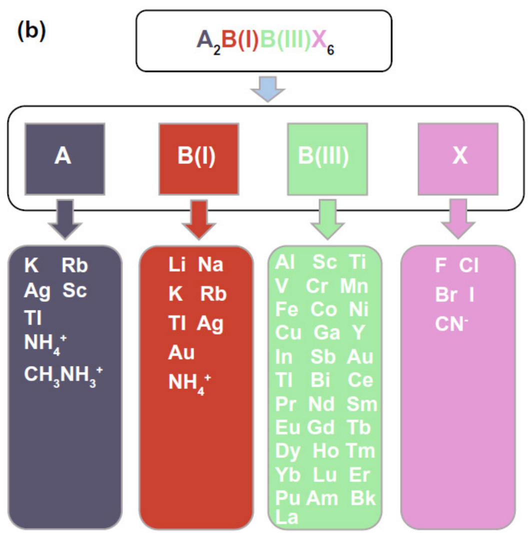
$FASnI_3$ (CDTA)	ITO/PEDOT:PSS/$FASnI_3$/C_{60}/BCP/Ag	21.83	0.64	0.74	10.32	Solution process
$FASnI_3$ (THDH)	ITO/PEDOT:PSS/$FASnI_3$/PCBM/BCP/Ag	22.12	0.54	0.71	8.48	Spin coating
$CsSnI_3$ ($SnCl_2$)	ITO/$CsSnI_3$/$PC_{61}BM$/C_{60}/Ag	9.89	0.50	0.68	3.56	Spin coating
$CsSnIBr_2$ (HPA)	FTO/c-TiO_2/m-TiO_2/Al_2O_3/$CsSnIBr_2$/Carbon	17.40	0.31	0.57	3.20	Spin coating
$FA_{0.8}Cs_{0.2}SnI_3$	ITO/PEDOT:PSS/$FA_{0.8}Cs_{0.2}SnI_3$/PCBM/Bis-C_{60}/Ag	16.05	0.24	0.36	1.38	Spin coating
$CsSnI_3$ (SnI_2)	ITO/CuI/$CsSnI_3$/C_{60}/BCP/Al	8.50	0.47	0.54	2.13	Solution process
$FA_{0.75}MA_{0.25}SnI_3$ (SnF_2)	ITO/PEDOT:PSS/$FA_{0.75}MA_{0.25}SnI_3$/C_{60}/BCP/Ag	21.20	0.61	0.63	8.12	Spin coating
$FA_{0.75}MA_{0.25}SnI_{2.75}Br_{0.25}$ (SnF_2 + MACl)	ITO/PEDOT:PSS/$FA_{0.75}MA_{0.25}SnI_{2.75}Br_{0.25}$/$C_{60}$/BCP/Ag	22.30	0.52	0.70	8.07	Secondary crystallization growth process
$CsSnBr_3$ (SnF_2)	FTO/c-TiO_2/m-TiO_2/$CsSnBr_3$/Spiro-OMeTAD/Au	9.00	0.41	0.58	2.10	Spin coating
$CsSnBr_3$ (SnF_2)	ITO/MoO_3/$CsSnBr_3$/C_{60}/BCP/Ag	2.40	0.40	0.55	0.55	Vapor deposition
$FASnI_2Br$	ITO/PEDOT:PSS/$FASnI_2Br$/ C_{60}/Ca/Al	6.82	0.47	0.54	1.72	Low-temperature processed
(BEA)$FA_2Sn_3I_{10}$	ITO/PEDOT:PSS/(BEA)$FA_2Sn_3I_{10}$/PCBM/Ag	18.85	0.62	0.55	6.43	liquid phase crystallization method
$(FA_{0.9}EA_{0.1})_{0.98}EDA_{0.01}SnI_3$	FTO/PEDOT:PSS/GeI_2 doped Sn-perovskite/C_{60}/BCP/Ag/Au	20.32	0.84	0.78	13.24	Spin coating

(a)



3D $A_2B(I)B(III)X_6$ Halide Double Perovskites

(b)



- But: Sn is also toxic.

-> Explore «double perovskites»

$Cs_3Bi_2I_9$ (PCE of a few %)

M. Wang et al., Nano-Micro Lett. (2021) 13, 62
B. W. Park et al, 2015, Adv. Mater, 27, 43
J. Li et al., Nano Energy 2021, 80, 105526

Towards industrialization – different strategies

OXFORD PV™
The Perovskite Company

MEYER BURGER

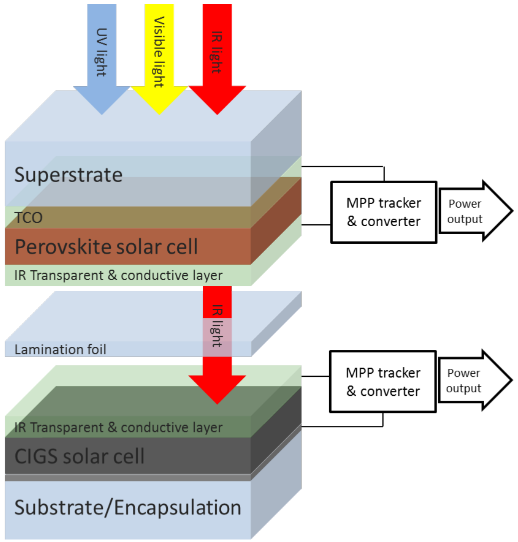
Oxford PV ***perovskite Si tandem solar cell*** achieves 28% efficiency

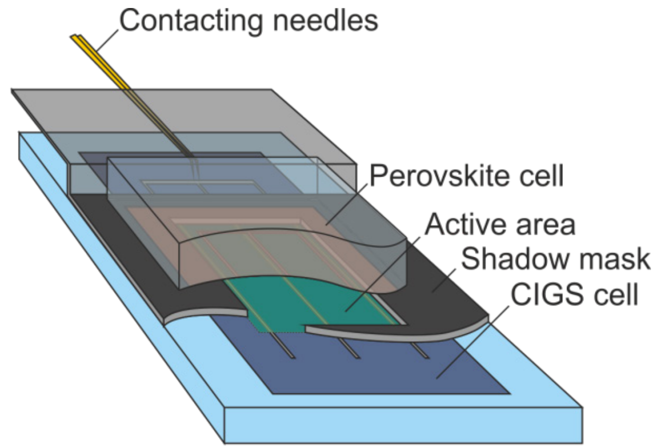
Sauletechnologies:
fully printed (Inkjet)

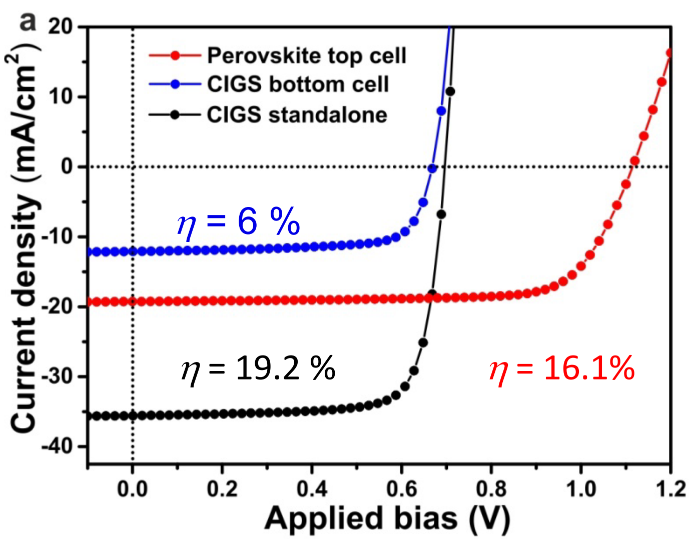
SOLARONIX

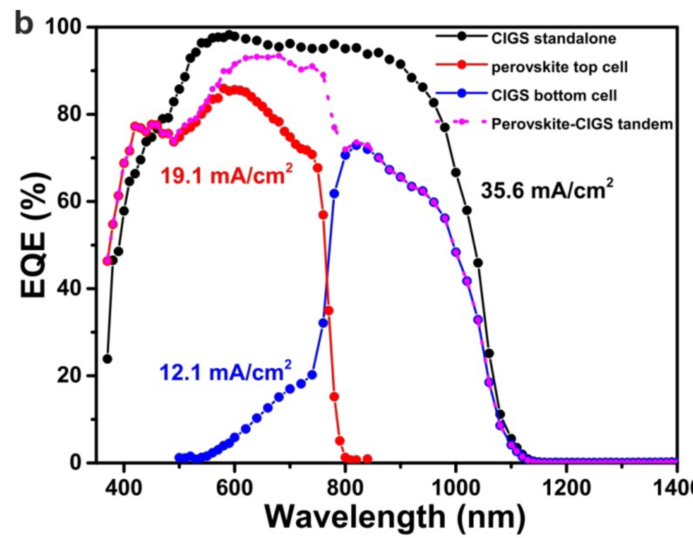
Solaronix
fully printed carbon based hole conductor free

22.1% 4-terminal perovskite/CIGS tandem cells



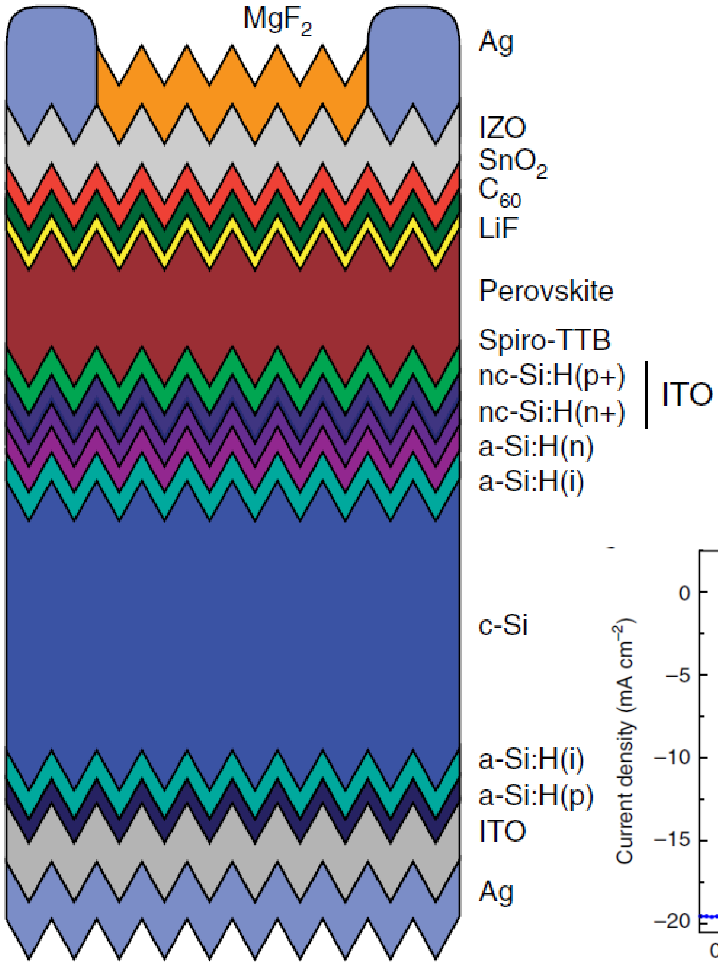


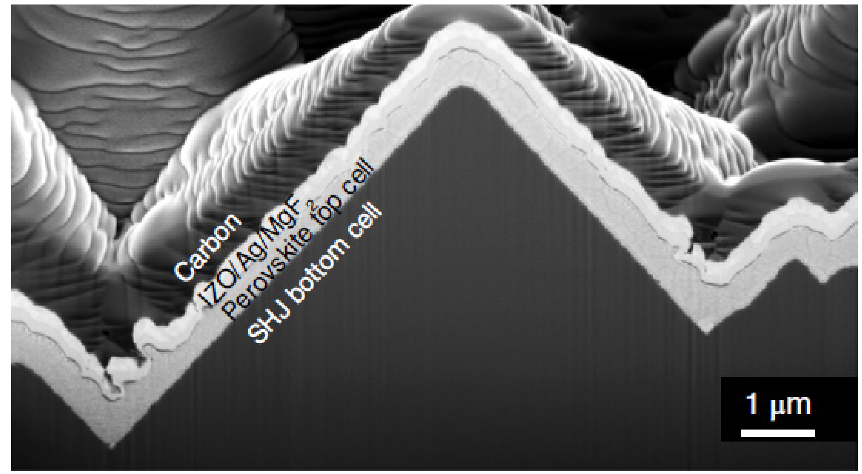


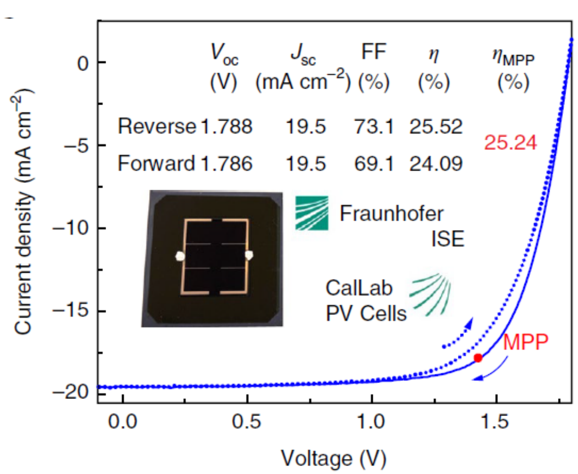


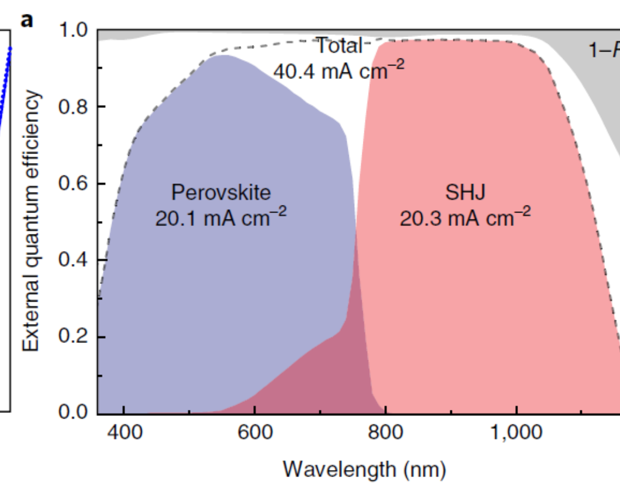
F. Fu, S. Buecheler, A.N. Tiwari et al., *Nature Energy,* 2, 16190 (2016)

25.2% 4-terminal perovskite/Si tandem solar cells



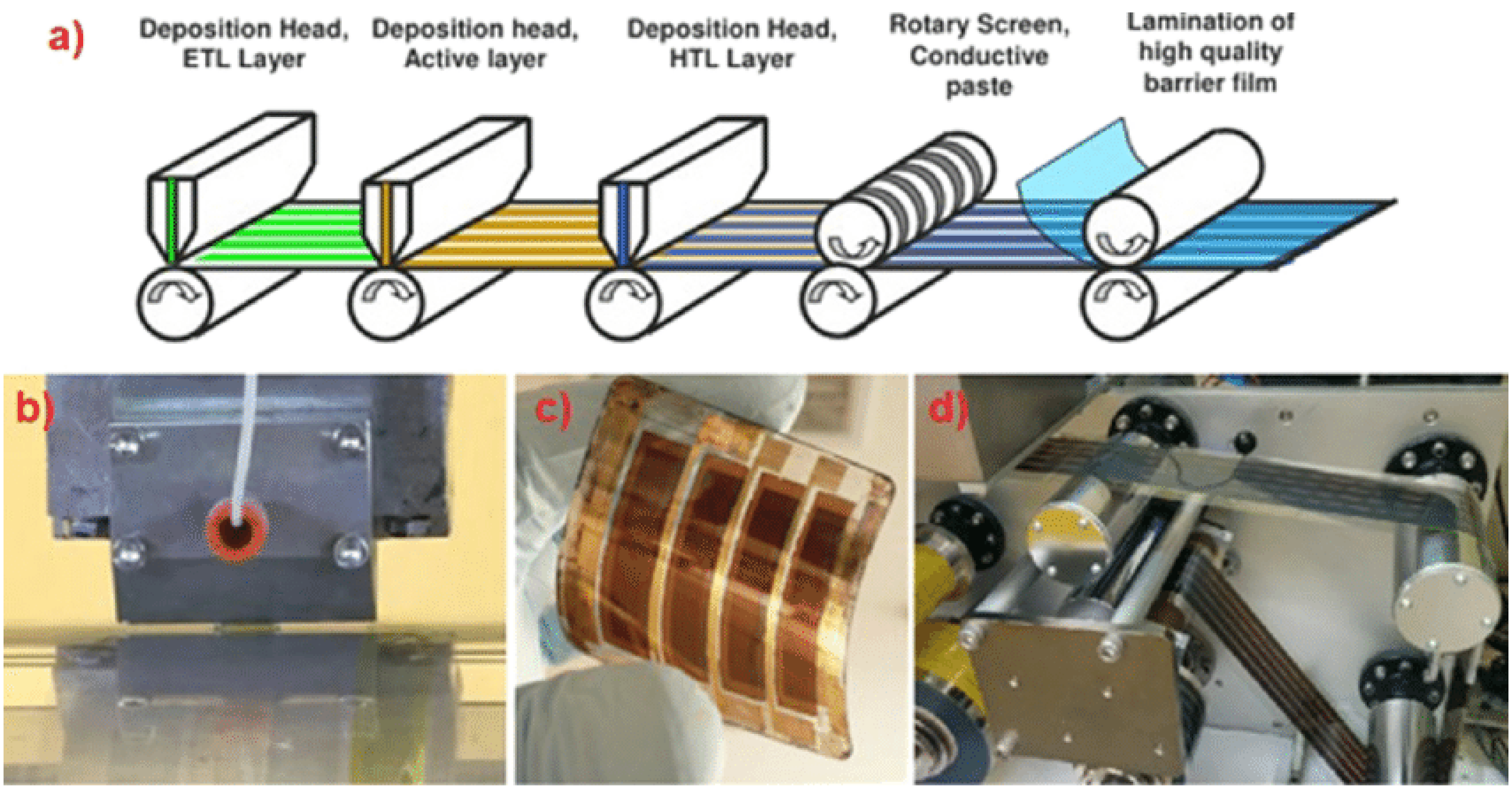






Sahli and Werner et al., *Nat. Mat.*, 2018, 1 (2), pp 474–480

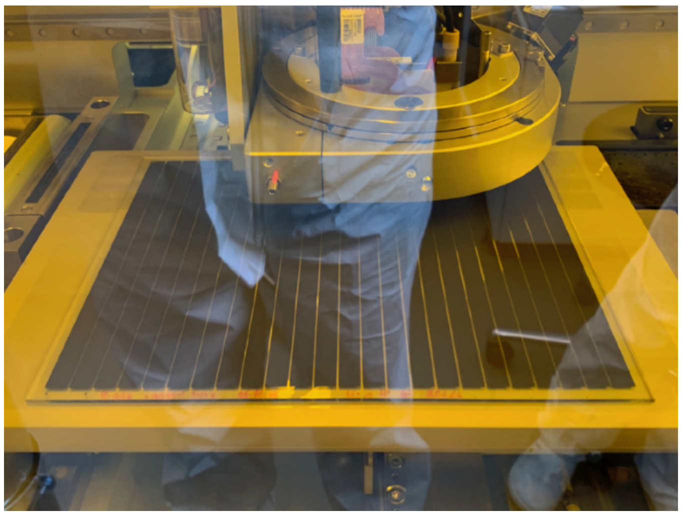
Fully printed Perovskite solar cells

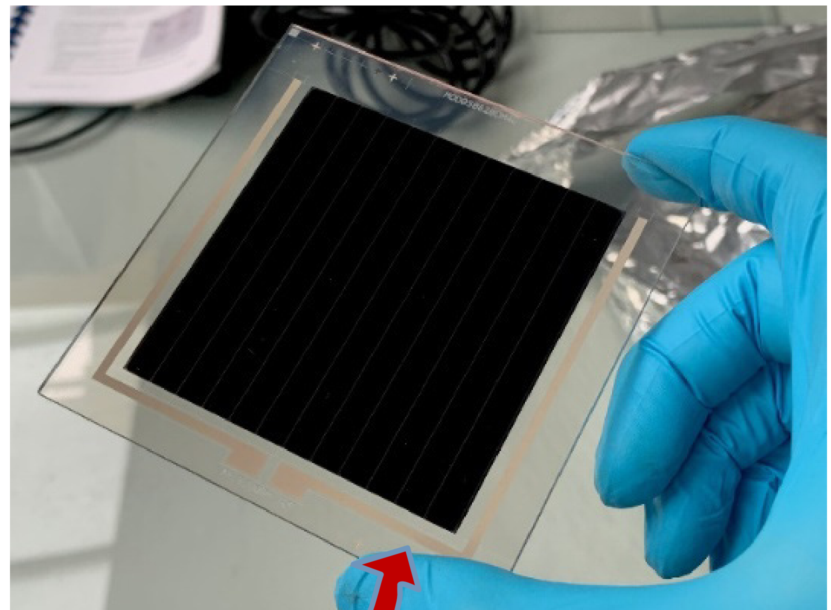


Research Update: Large-area deposition, coating, printing, and processing techniques for the upscaling of perovskite solar cell technology, Stefano Razza, Sergio Castro-Hermosa, Aldo Di Carlo, and Thomas M. Brown , APL Mater. 4, 091508 (2016)

Uniqueness of the mesoscopic PSC architecture

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



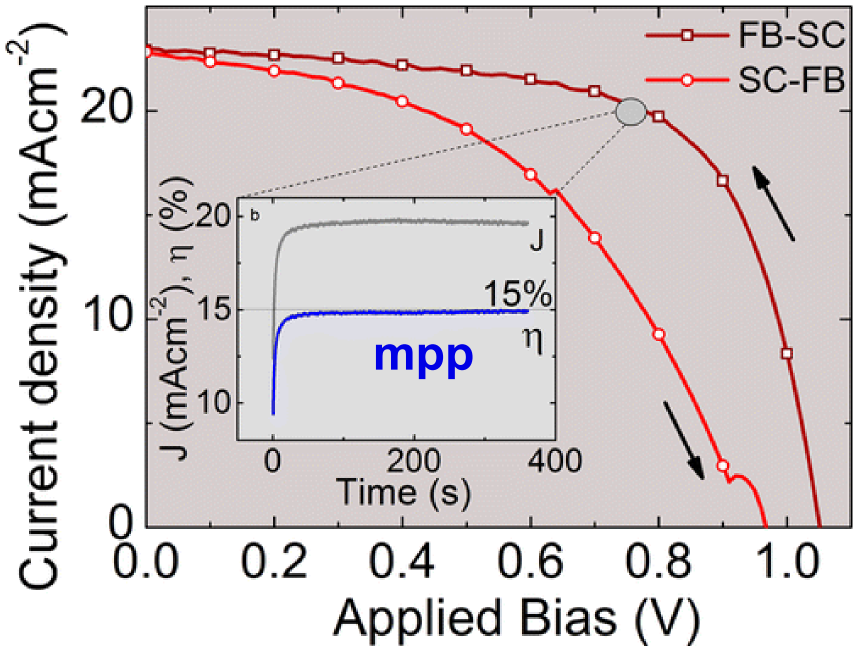


Both have a PCE of 13 %

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

How to measure the perovskite solar cells

- Mask your solar cells properly
- Calibrate your light source
- The best way to evaluate the perovskite solar cell is to present the steady state maximum power output over time



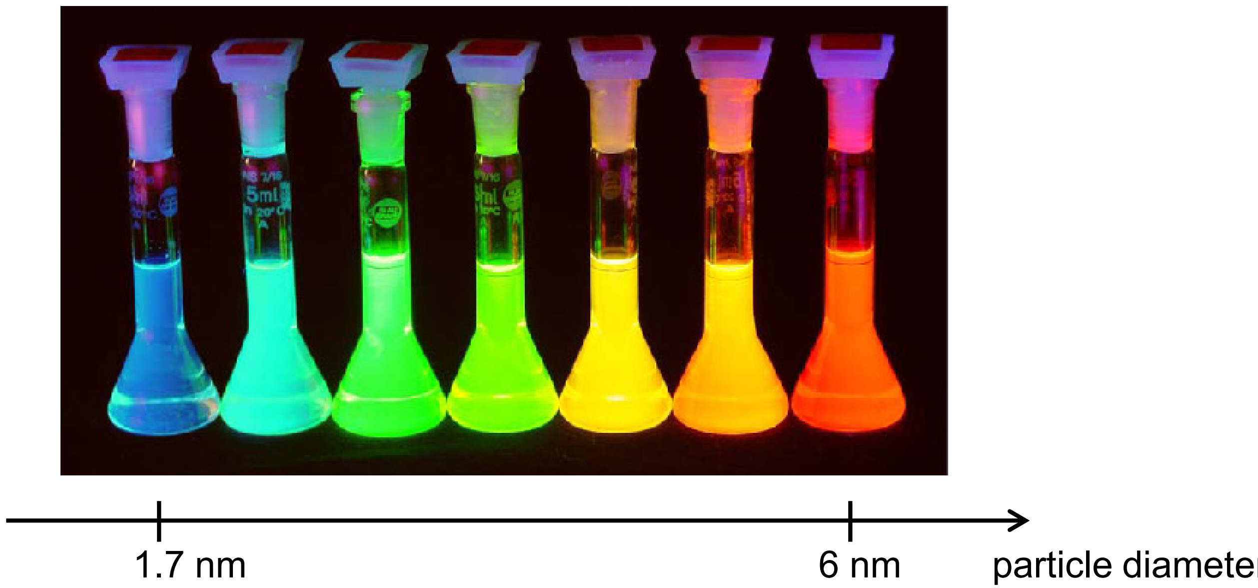
Certify the cell by accredited standard labs or company

- National Renewable Energy Laboratory (NREL, USA)
- National Institute of Advanced Industrial Science and Technology (AIST, Japan)
- Fraunhofer Institute for Solar Energy Systems (ISE, Germany)
- Newport, USA

Learning outcome

- What are Perovskite solar cells?
  - *Based on $MAPbI_3$ perovskite*
- Architectures? How are they made?
  - *Mesoscopic and planar; solution processing or evaporation*
- Why are they so good?
  - *High absorption, low exciton binding energy, long charge carrier diffusion*
- Strategies for efficiency improvement
  - Crystallization, materials, defect passivation
- Challenges towards industrialization
  - *Upscaling, stability, lead*
- , Opportunities
  - *Tandem in combination with Silicon; Carbon based hole conductor free, fully printed*

2.3B Hybrid solar cells - Quantum dot

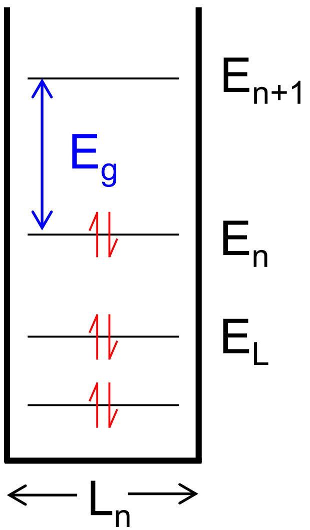


Nanoproperties: change in properties of due to its physical size. The image shows CdSe-CdS core-shell nanoparticles with various diameters.

E. Roduner, *Size matters: why nanomaterials are different* , Chem. Soc. Rev., 2006,35, 583–592

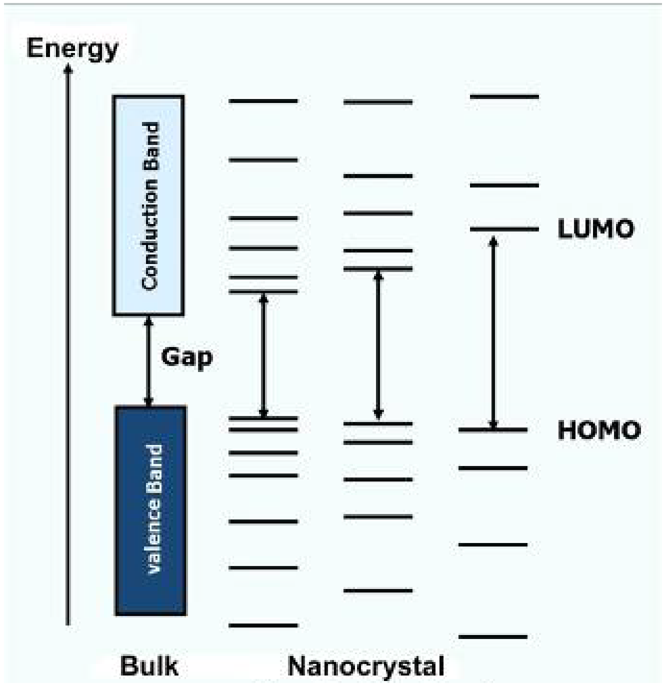
Quantum Confinement Effect

Particle in a box model



$$E_n = \frac{n^2 h^2}{8 m_e {L_n}^2}$$

where, $L_n \approx n \cdot L_0$
(for large enough box length)



$$n_1 > n_2 > n_3$$

$$Band\ gap\ (E_g) = E_{n+1} - E_n$$

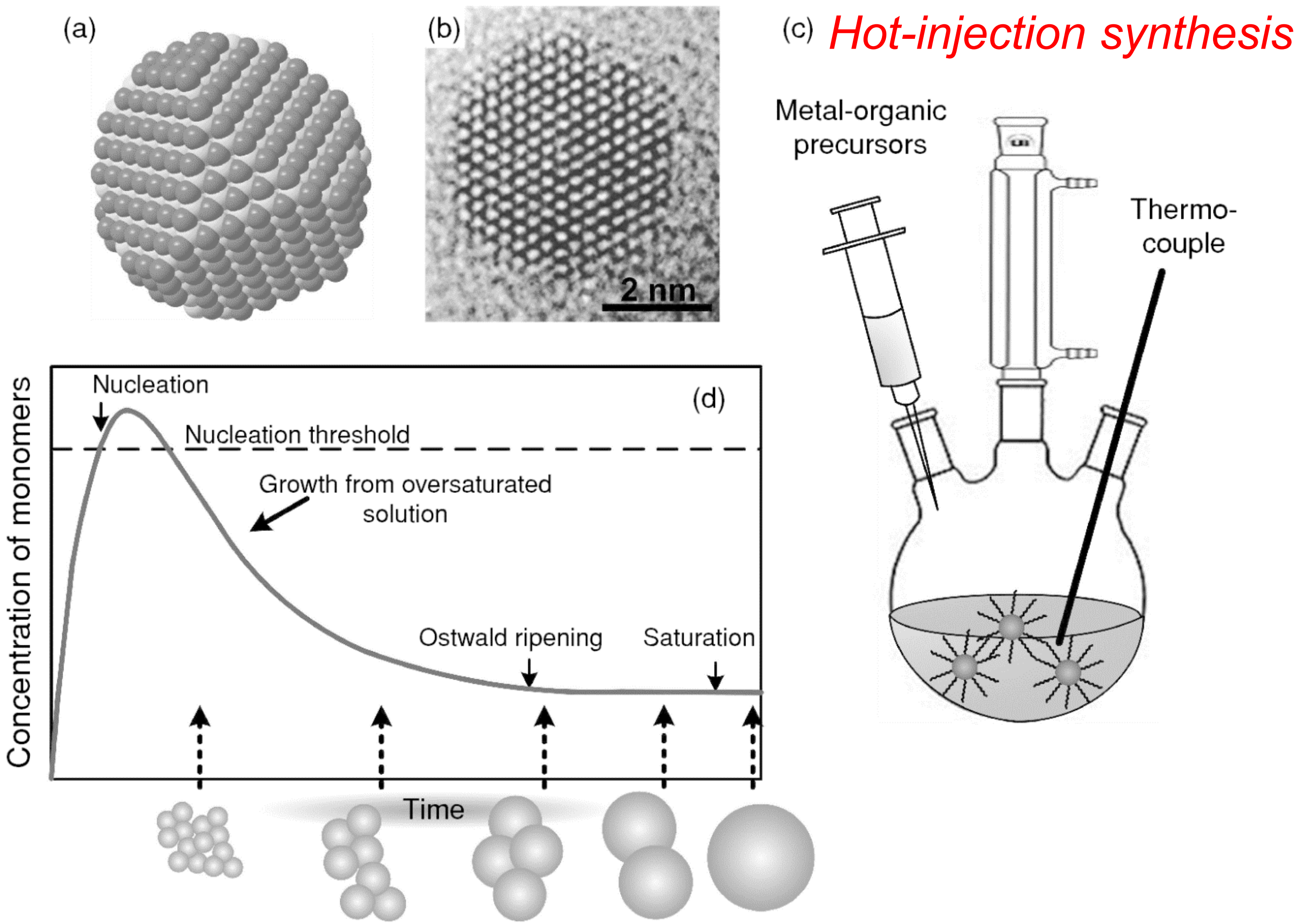
$$= \frac{(n+1)^2 h^2}{8 m_e {L_n}^2} - \frac{n^2 h^2}{8 m_e {L_n}^2} = \frac{h^2}{8 m_e {L_n}^2}((n+1)^2 - n^2)$$

$$= \frac{h^2}{8 m_e (n.L_0)^2}\ (2n + 1)$$

$$E_g = \frac{h^2}{8 m_e (L_0)^2}\ (\frac{2}{n} + \frac{1}{n^2})$$

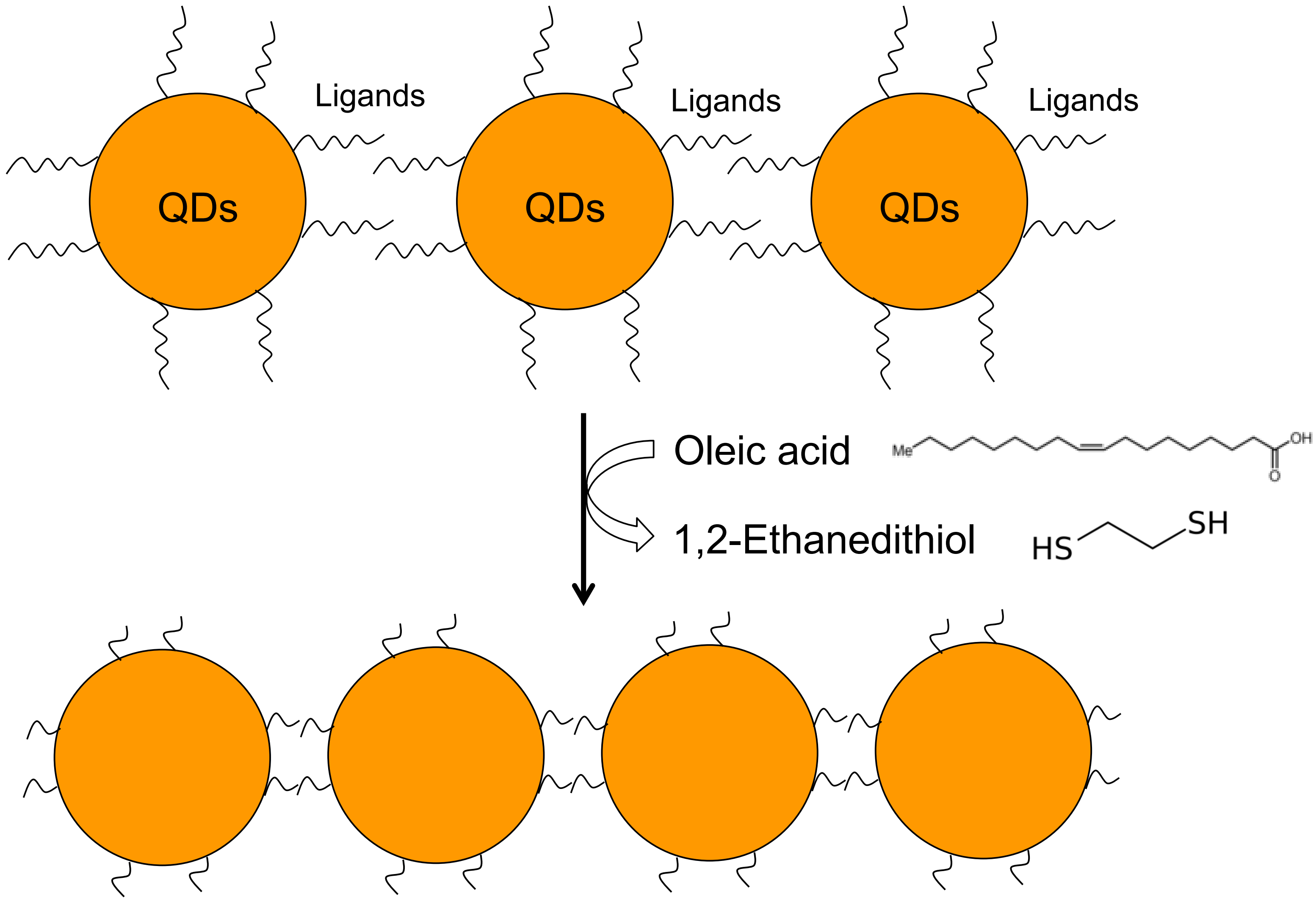
$$E_g \propto \frac{1}{n}$$

Thermodynamics and Kinetics in QDs Synthesis



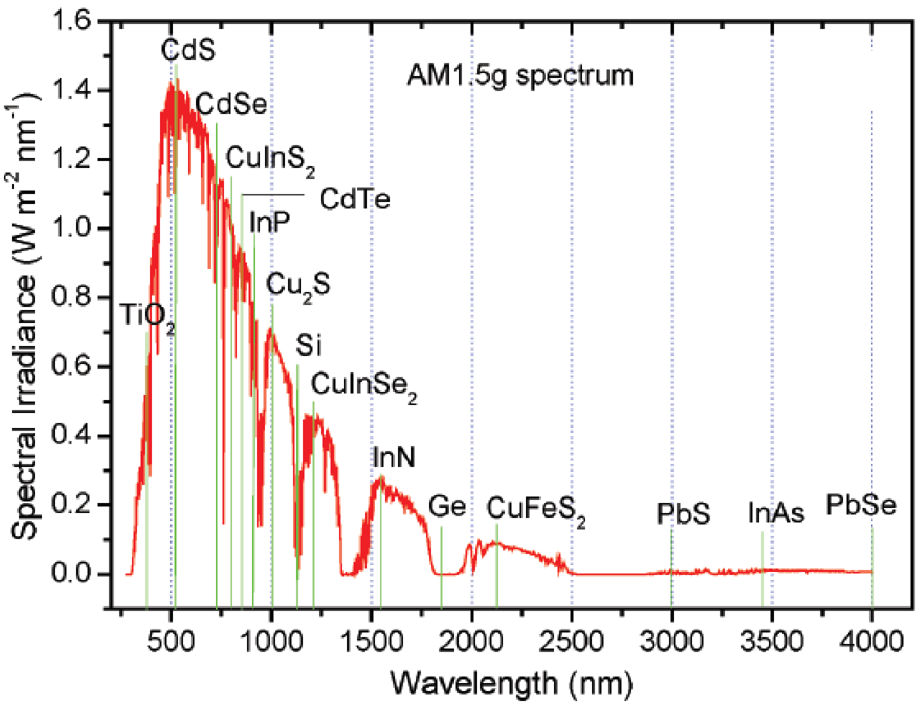
Bodnarchuk, M., & Kovalenko, M. (2013). *Colloidal Quantum Dot Optoelectronics and Photovoltaics* (pp. 1-29). Cambridge University Press.

Ligand Exchange

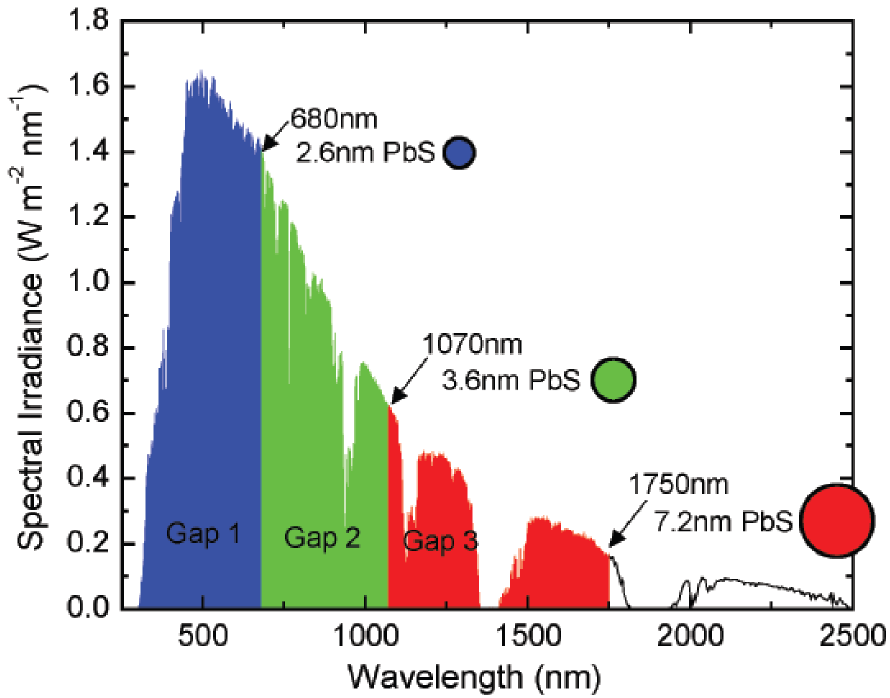


Band gap tunability in QDs

Changing the material of nanocrystals

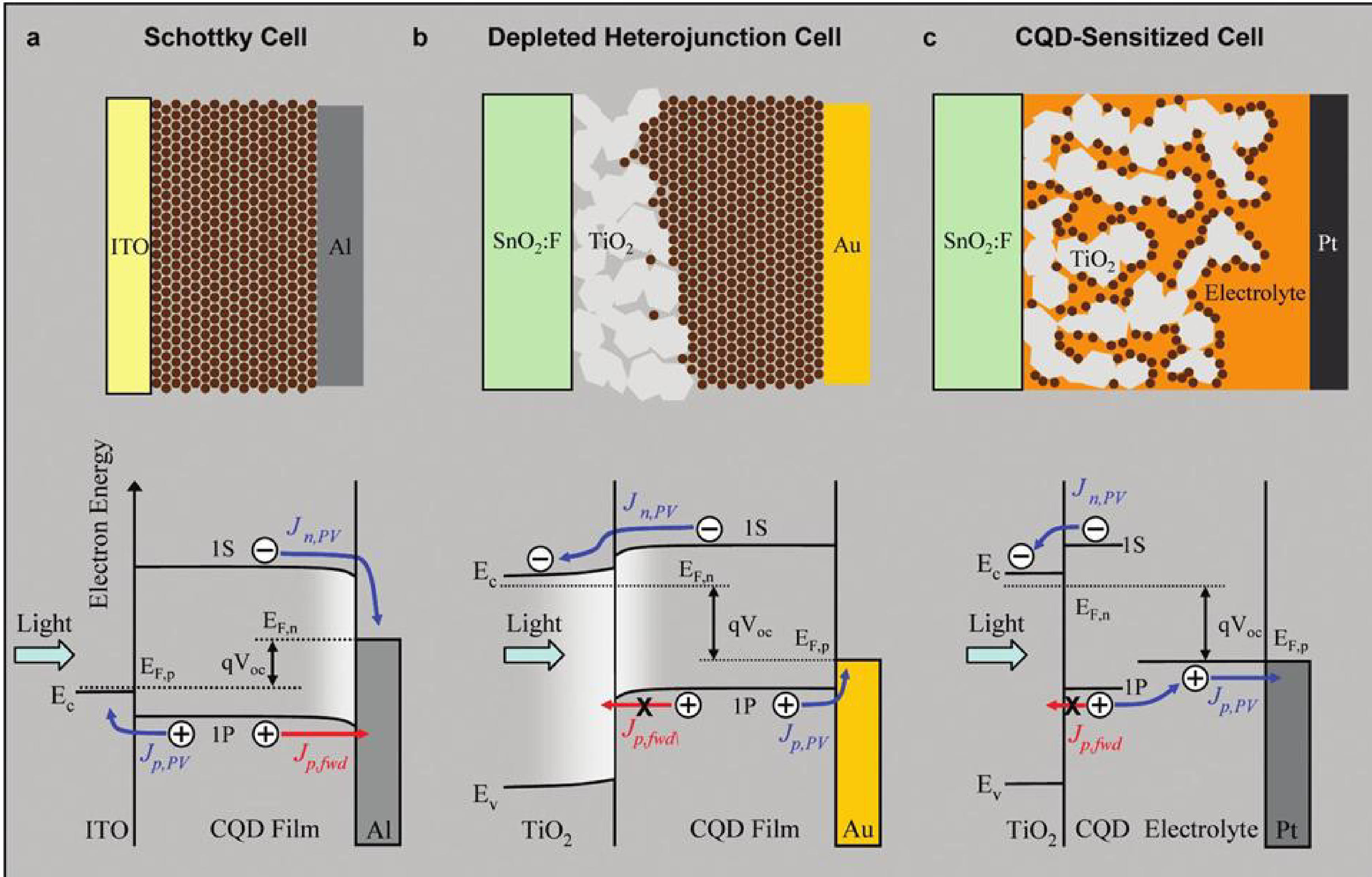


Changing the radius of nanocrystals - quantum confinement effect



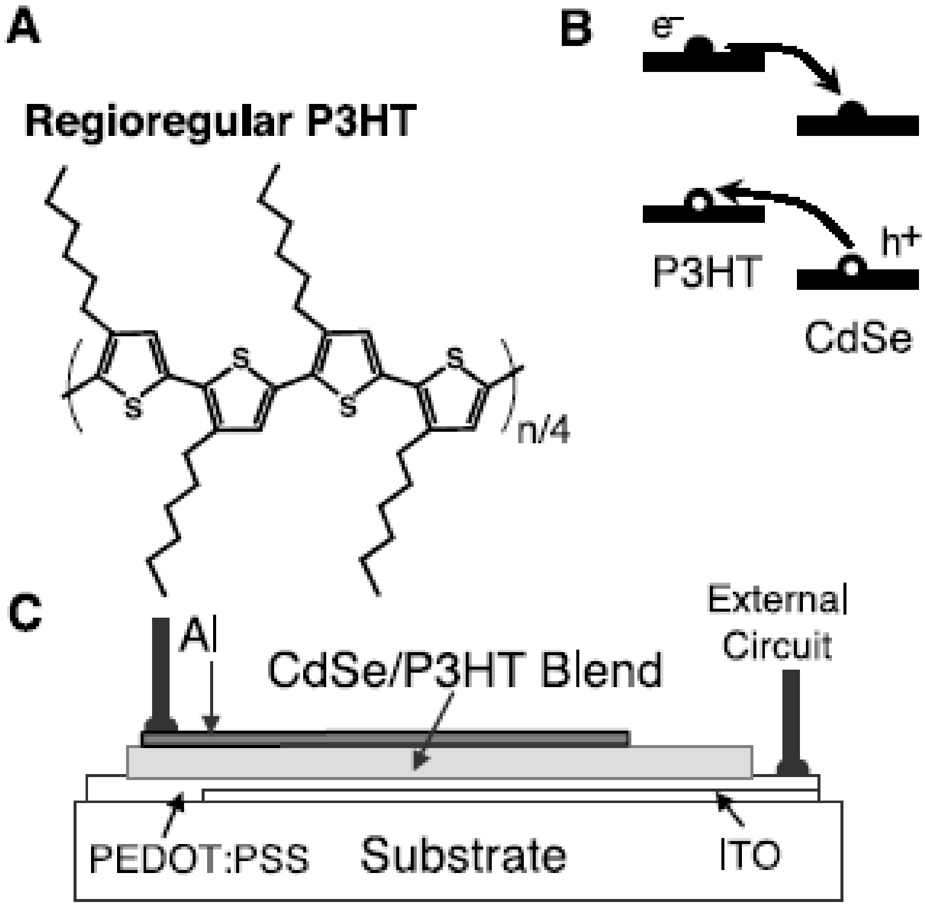
→ J. Tang, E.H. Sargent, *Adv. Mater.* **13**, 12 (2011)

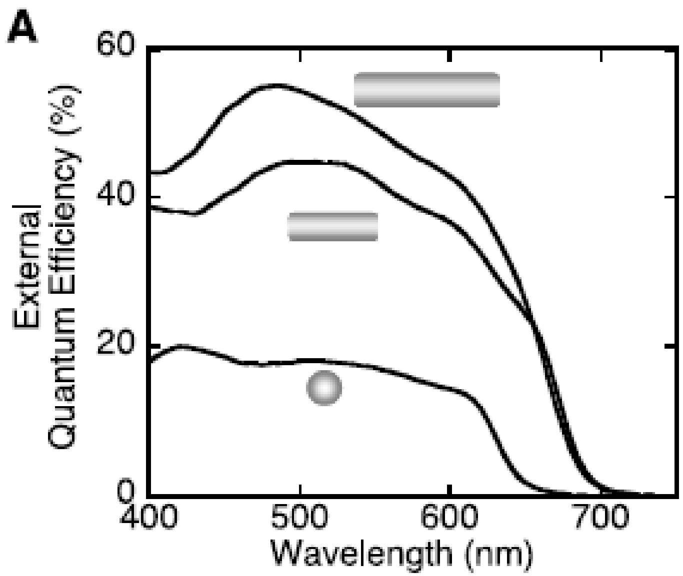
Design of „real“ QD solar cells



Uni Toronto, Sargent`s group web-site, 2012

Hybrid QD-polymer cells





Efficiency is higher for nanorods due to better charge transport (1.7%)

W. U. Huynh *et al.*, Science **295**, 2425 (2002)

Perovskite Quantum Dot Solar Cells

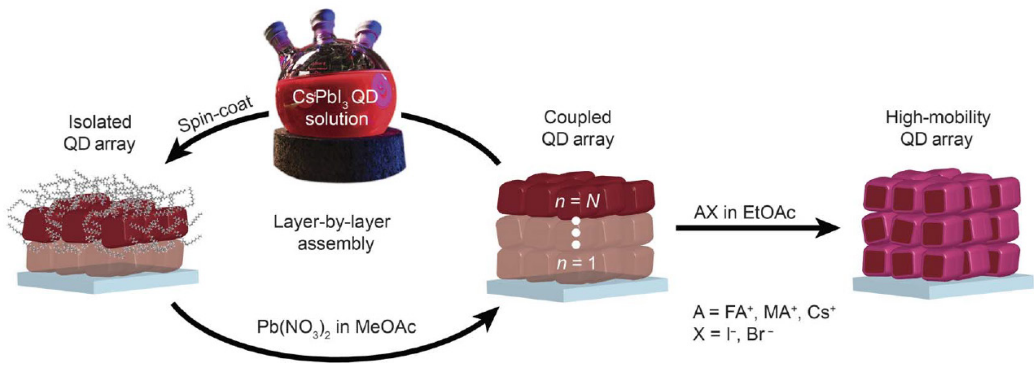
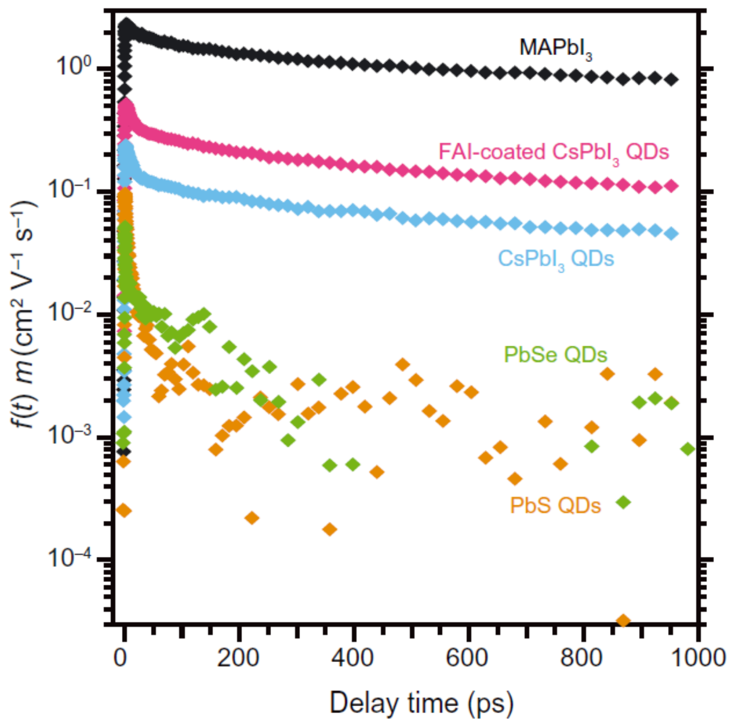
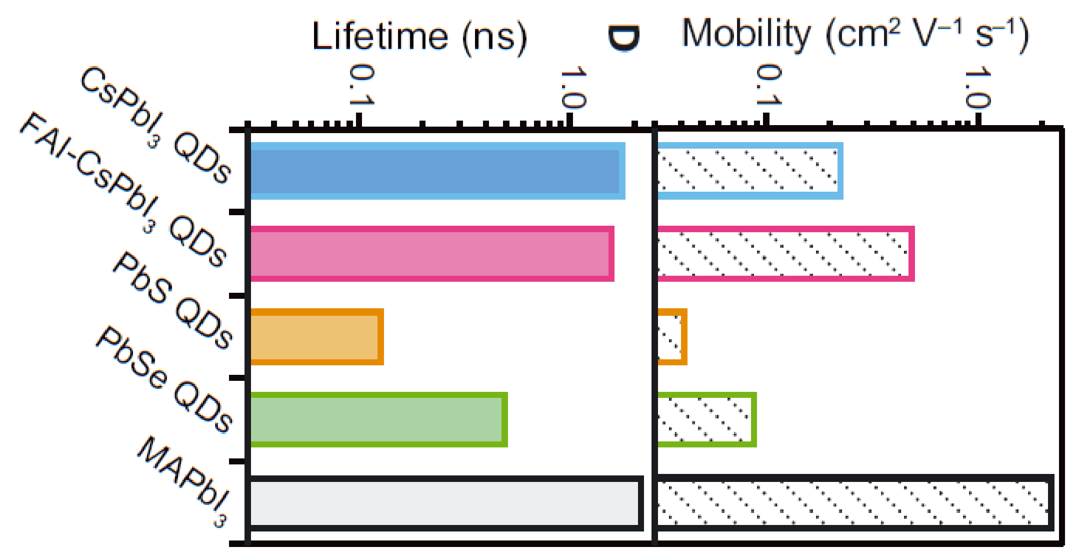


Table 1. Effect of AX salts on PV parameters extracted from *J-V* scans.

AX salt posttreatment	V_{OC} (V)	J_{SC} (mA cm^{-2})	FF	PCE (%)
FAI (EtOAc)	1.20	14.37	0.78	13.4
FABr (EtOAc)	1.22	12.70	0.81	12.6
MAI (EtOAc)	1.20	13.39	0.79	12.6
MABr (EtOAc)	1.21	11.27	0.82	11.2
CsI (EtOAc)	1.20	10.64	0.81	10.3
Neat EtOAc	1.17	9.22	0.78	8.5





Sanehira et al., Sci. Adv. (2017) 3

Upcoming Materials

- Transition metal dichalcogenides or 2D materials
- Perovskite quantum dot solar cells
- 2D perovskites
- Hybrid Perovskite QDs on Silicon cells
- and more….