Europe's Research and Development efforts in support of its PV industry

European Solar Technology Forum
From Research to Industrial Application
30 November 2017

This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration

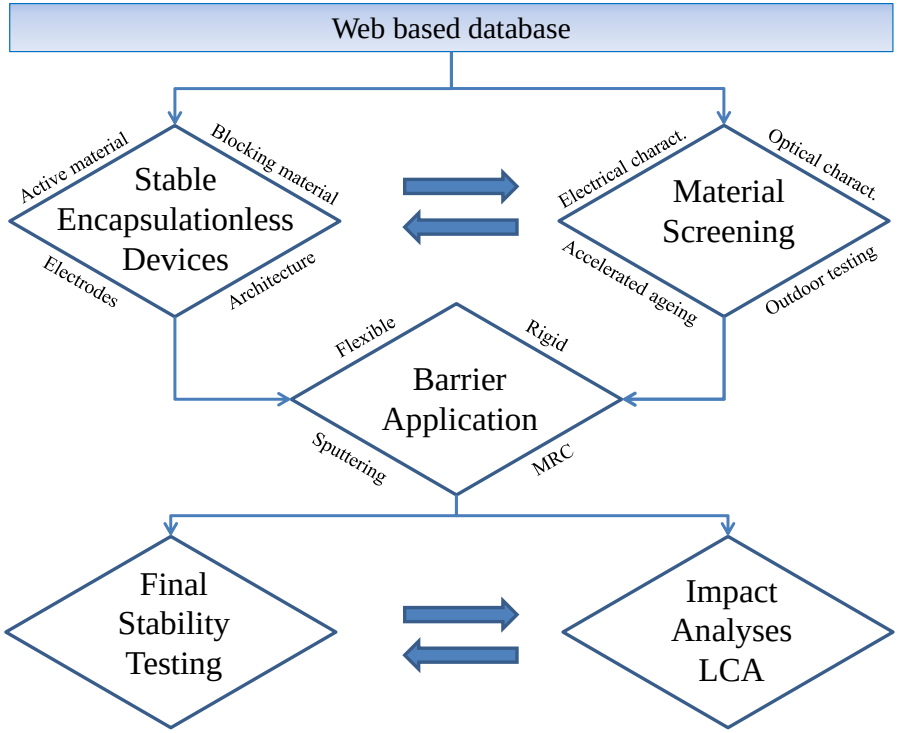
Reduction of cost via improvement of stability / WP10

Suren A. Gevorgyan, Technical University of Denmark

This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration

Objectives

- *To develop an "encapsulationless" organic or hybrid solar cell*
- *To build the methodology to screen materials and layers combinations for enhanced stability*
- *To use that innovation as platform for an encapsulated long-lived organic solar cell*

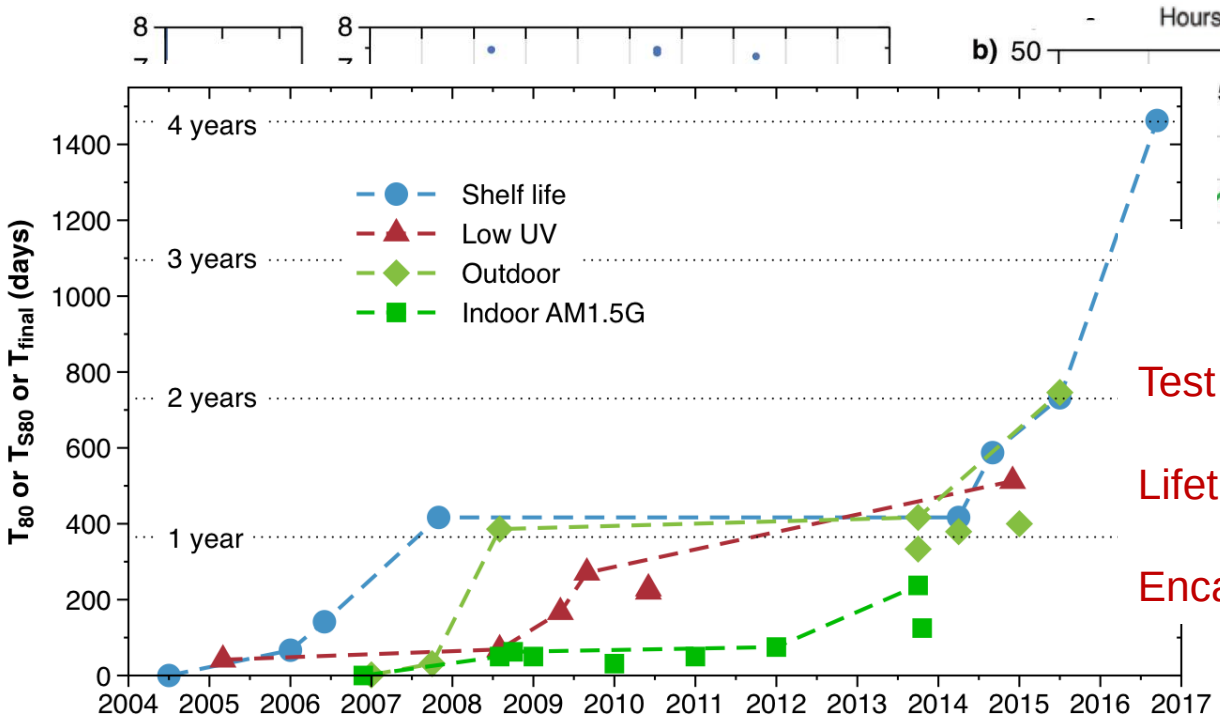


WP10 PARTNERS

Fraunhofer ISE	DE
ECN	NL
NPL	UK
Imperial College	UK
ENEA	IT
DTU	**DK**

E-infrastructure: lifetime database

Lifetime distribution



Challenges

Test conditions – ISOS guidelines

Lifetime marker – CHEETAH tool

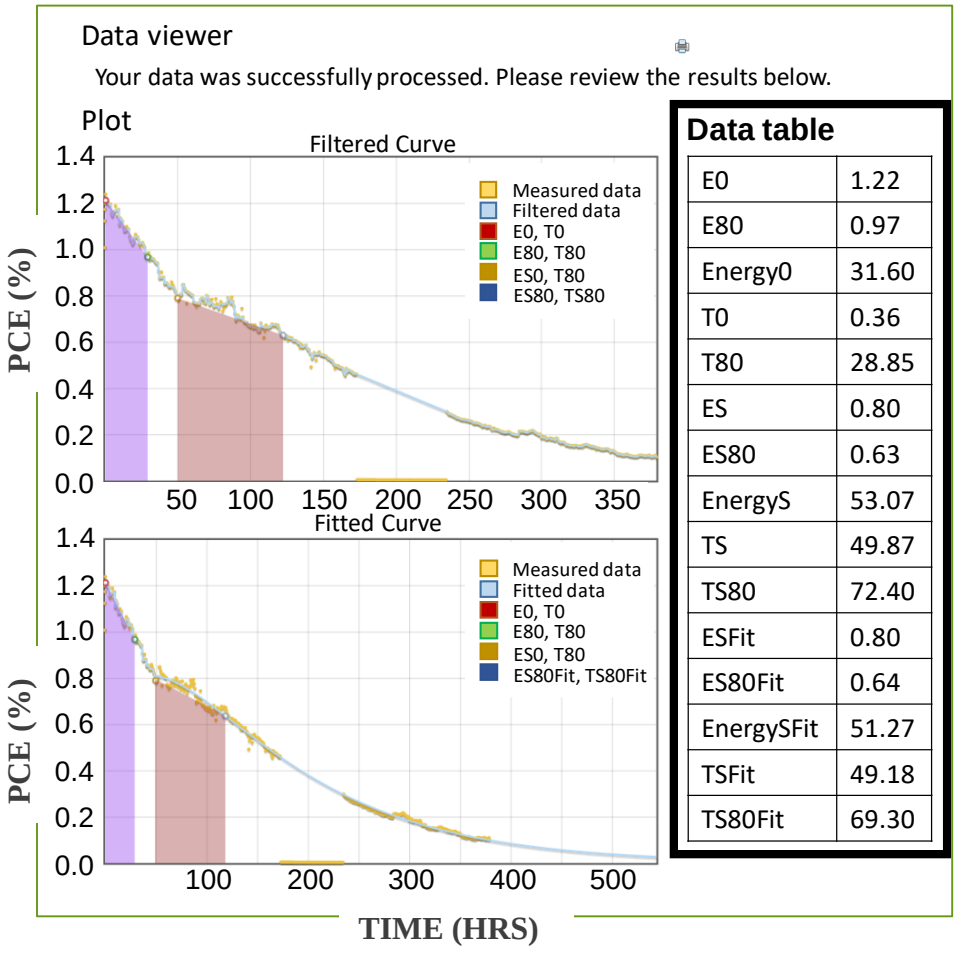
Encapsulation – ISOS-e

Gevorgyan et al., Adv. Energy Mater. **2015**, 1501208

Gevorgyan et al., Adv. Energy Mater. **2016**, *6*, 1600910

E-infrastructure: lifetime database

Lifetime calculation and prediction (Key exploitable result)



Data table

E0	1.22
E80	0.97
Energy0	31.60
T0	0.36
T80	28.85
ES	0.80
ES80	0.63
EnergyS	53.07
TS	49.87
TS80	72.40
ESFit	0.80
ES80Fit	0.64
EnergySFit	51.27
TSFit	49.18
TS80Fit	69.30

DOI:10.1002/smtd.201700285

Advanced characterization and metrics

Devices characterised in precisely-controlled environment – **Key Exploitation Result 10**

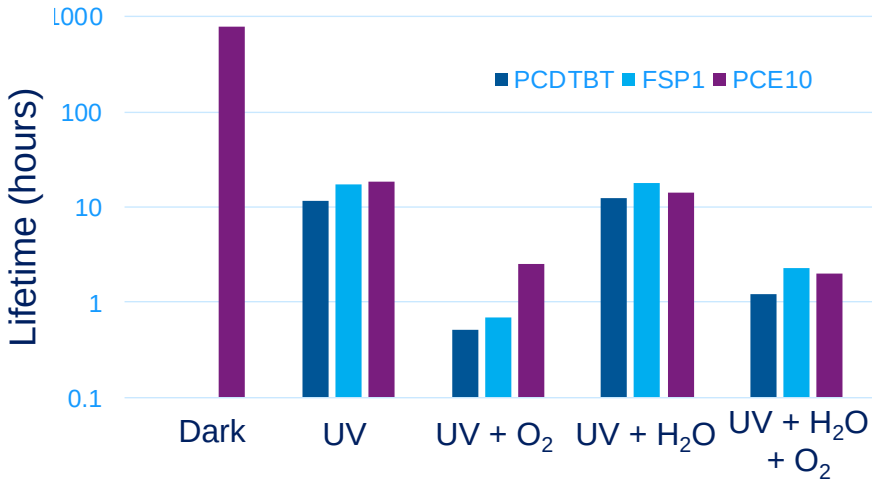
in situ characterisation suite:

- Electrical (I-V curve, impedance spectroscopy)
- Imaging
- Spectroscopy

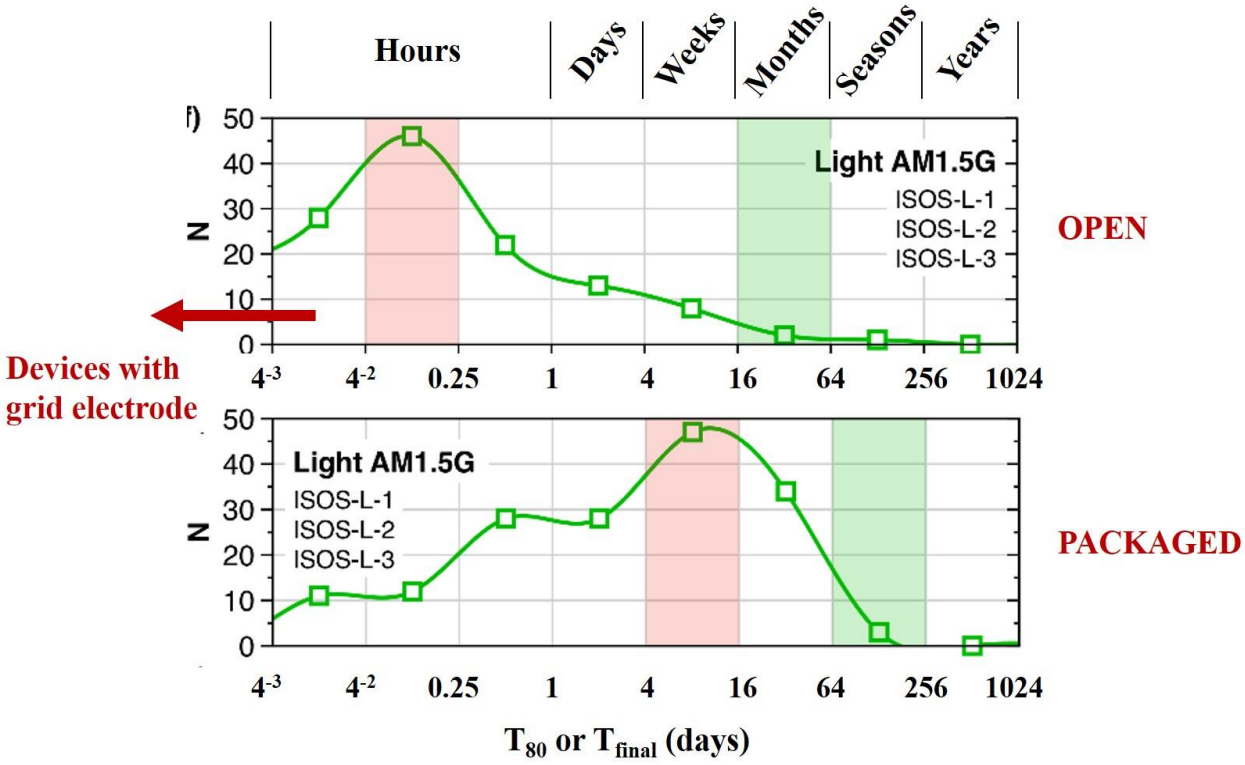
Data analysis protocol reduces >1,000,000 data points collected over ~3000 hours to a few key metrics

Results

- 7 materials characterised in 5 different environments
- Compared to encapsulated samples, lifetimes are highly reproducible
- Differences between materials were small compared to differences between conditions



Intrinsic versus extrinsic stability



Motivation: Improving intrinsic stability → Easing requirements for encapsulation → Reducing cost

Intrinsic

- Acceptors (NFA)
- Donors
- HTL

Extrinsic

- Adhesives
- Packaging improvement

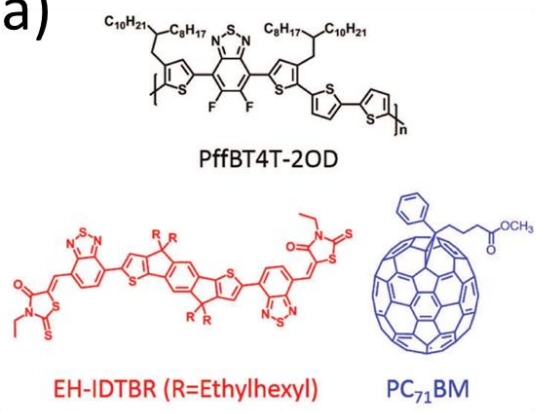
Alternative solutions

- Direct sputtering

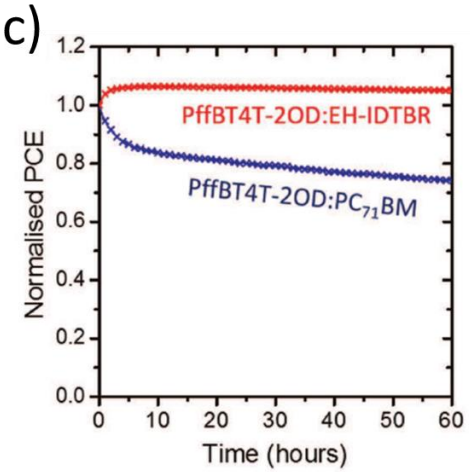
Intrinsic stability

Fullerene free devices

a)

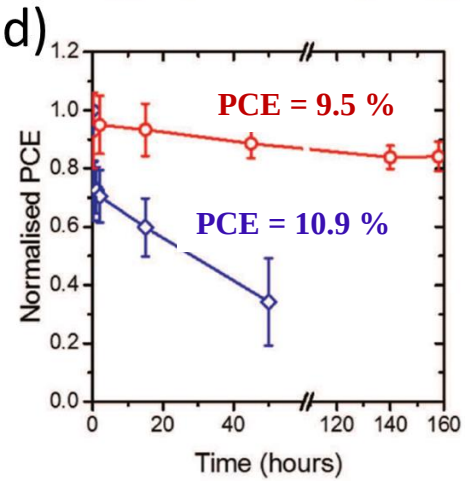


c)



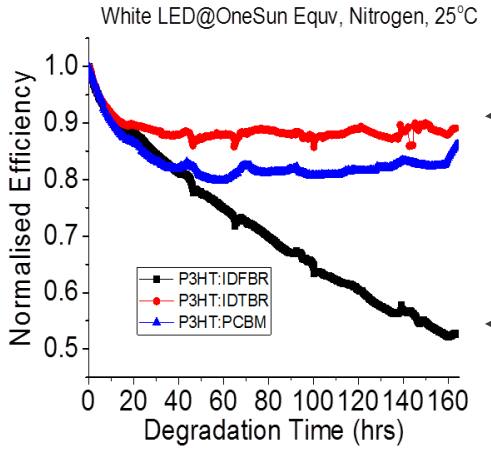
While LED, N_2, 50°C

d)

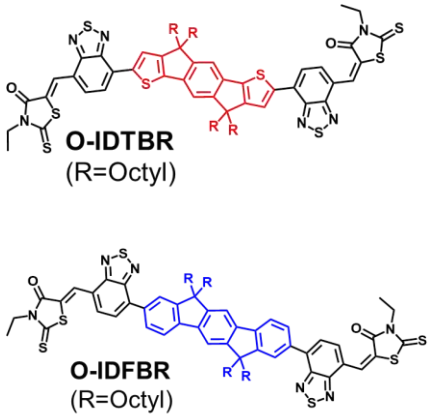


Dark 85°C under N_2

Adv. Mater. 2017, 29, 1701156



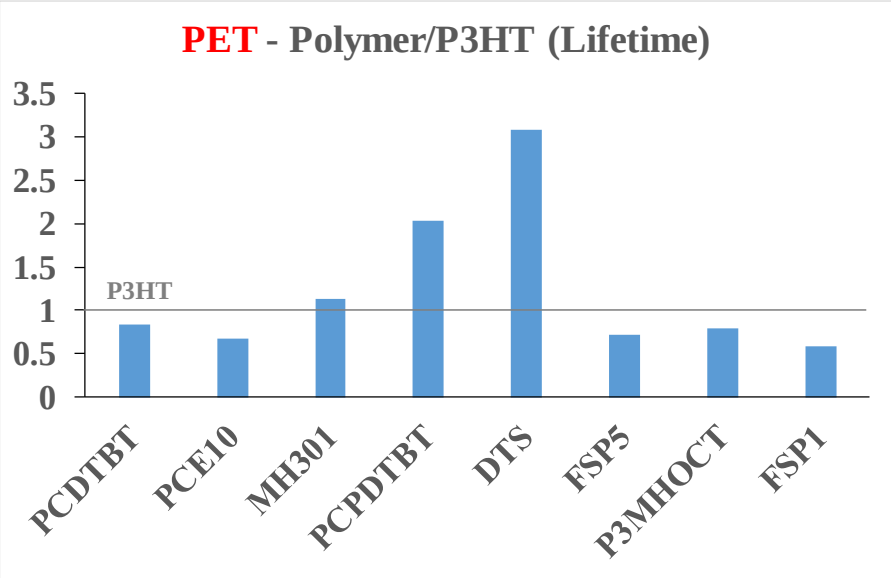
PCE = 3 - 4 %

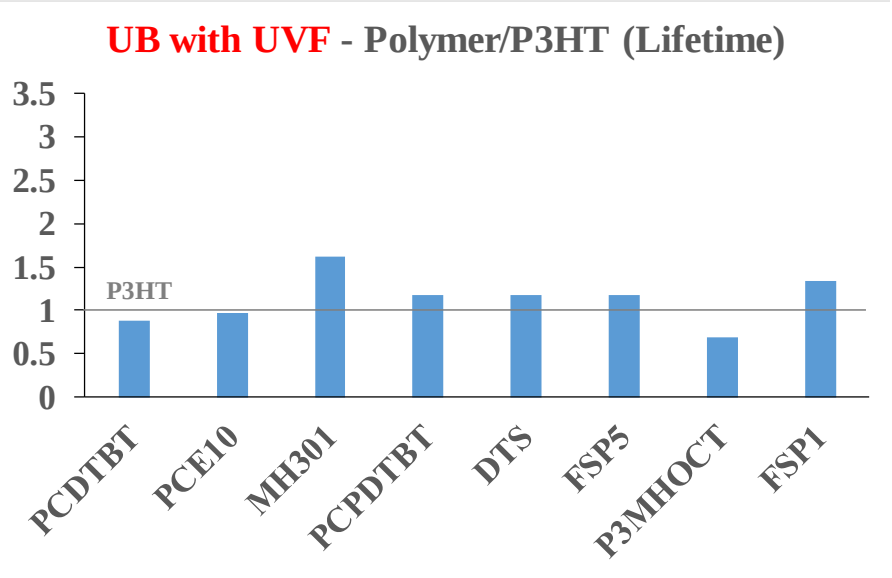


Intrinsic stability

Comparison of device stability for different polymers

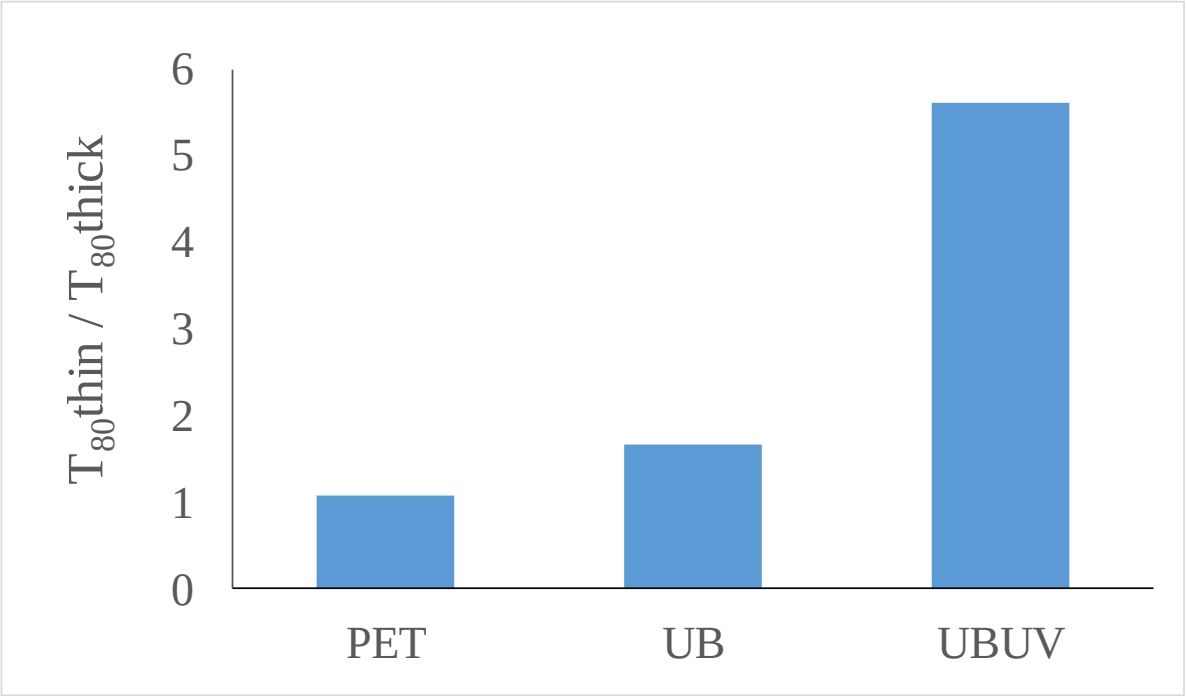
Indoor ISOS-L-2 light soaking tests of packaged devices





Intrinsic stability

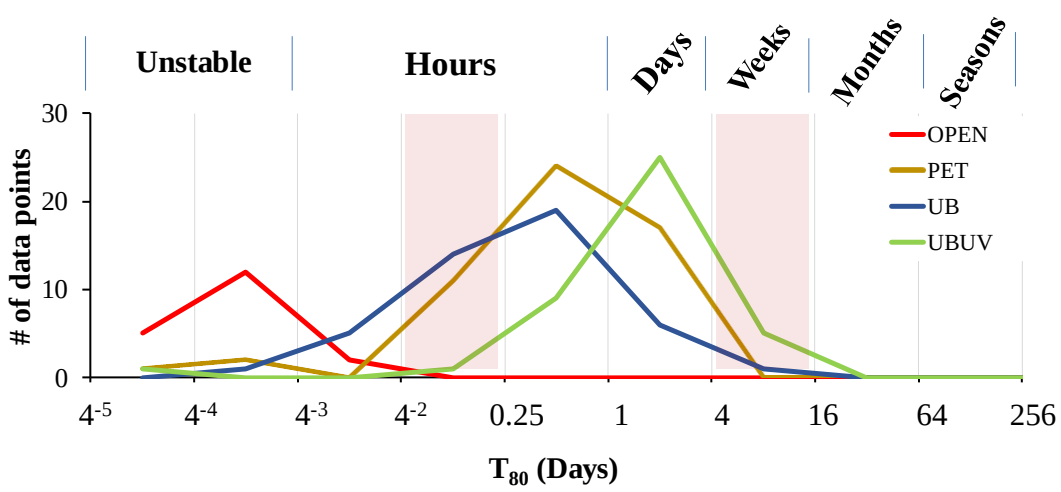
Hydrophilic HTLs reduce stability significantly (under ISOS-L-2 tests)

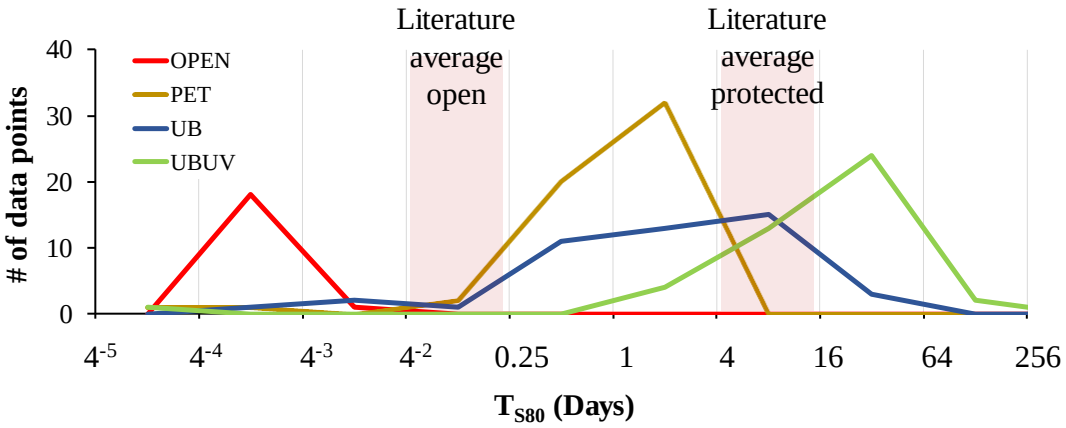


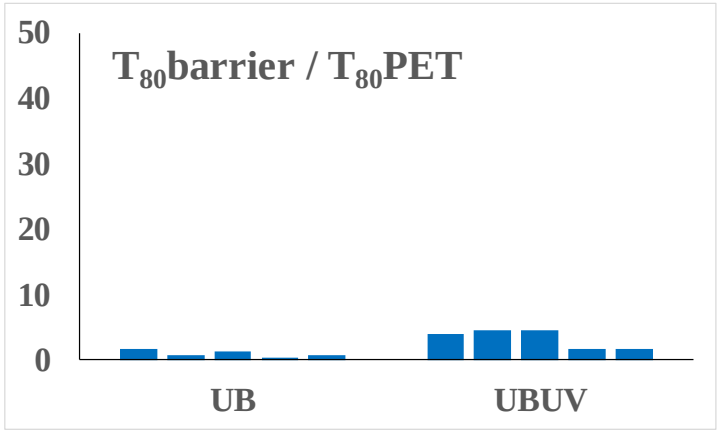
Lifetime ratio of samples with thick and thin PEDOT:PSS hole transport layers with different encapsulation

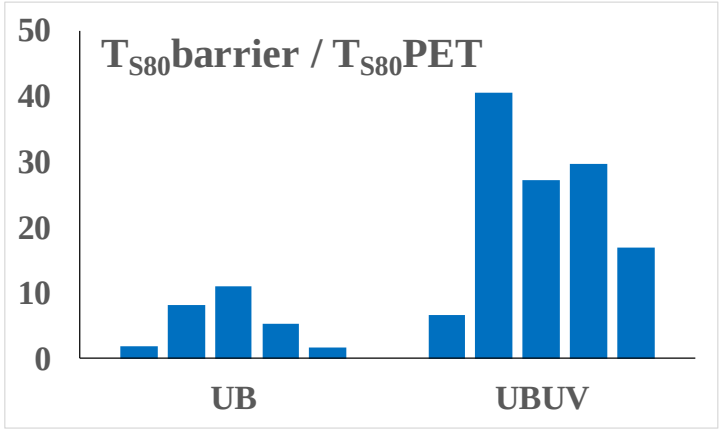
Intrinsic versus extrinsic stability

Comparison of device stability for different packaging (ISOS-L-2 tests)





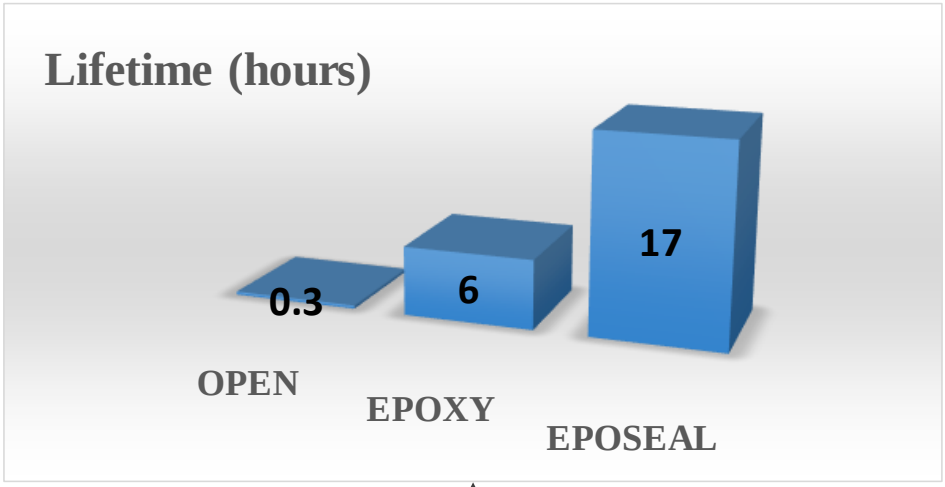




Extrinsic stability

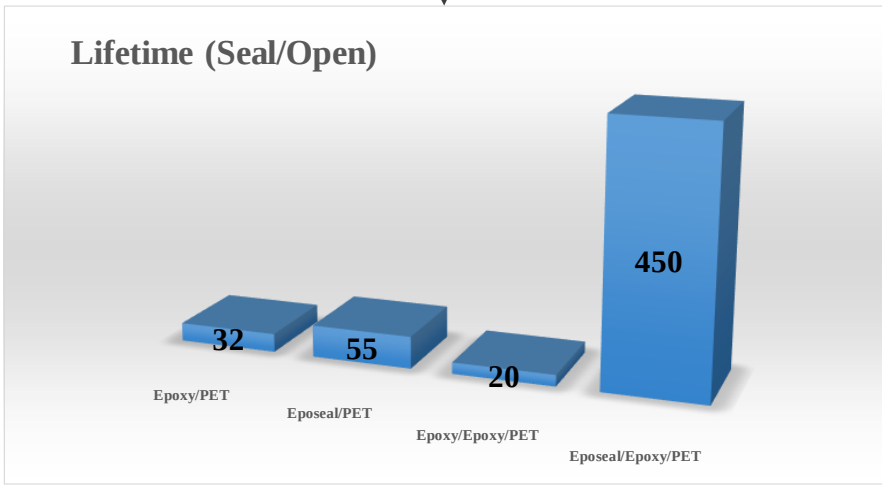
Packaging procedures: Adhesives

Mixing silica gel with epoxy



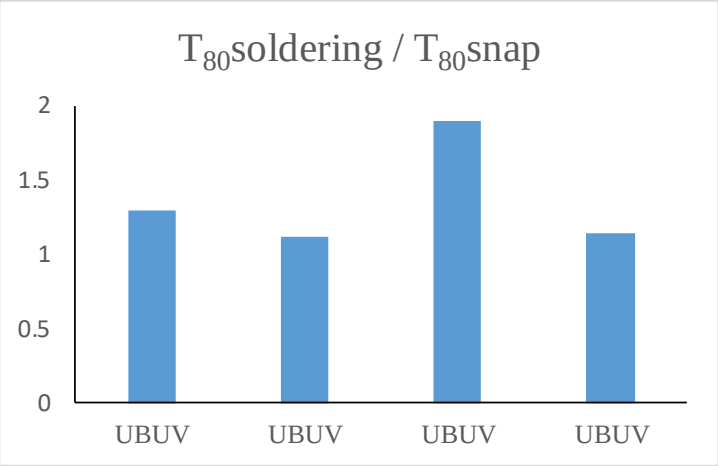
Stabilized lifetime of open devices with protective adhesive layer

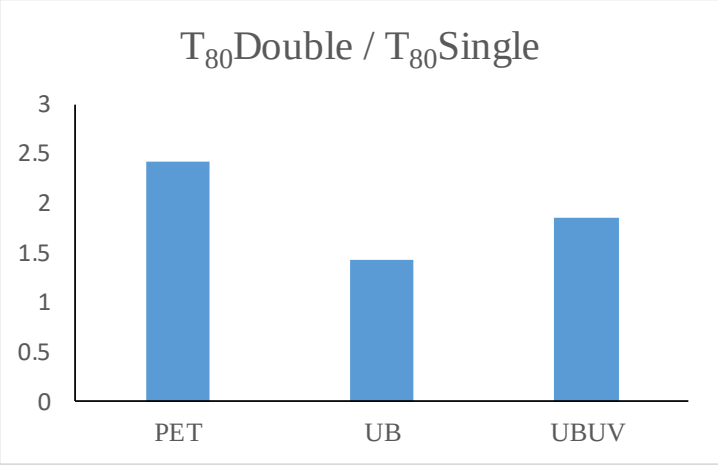
Ratio of lifetimes between sealed samples and open samples

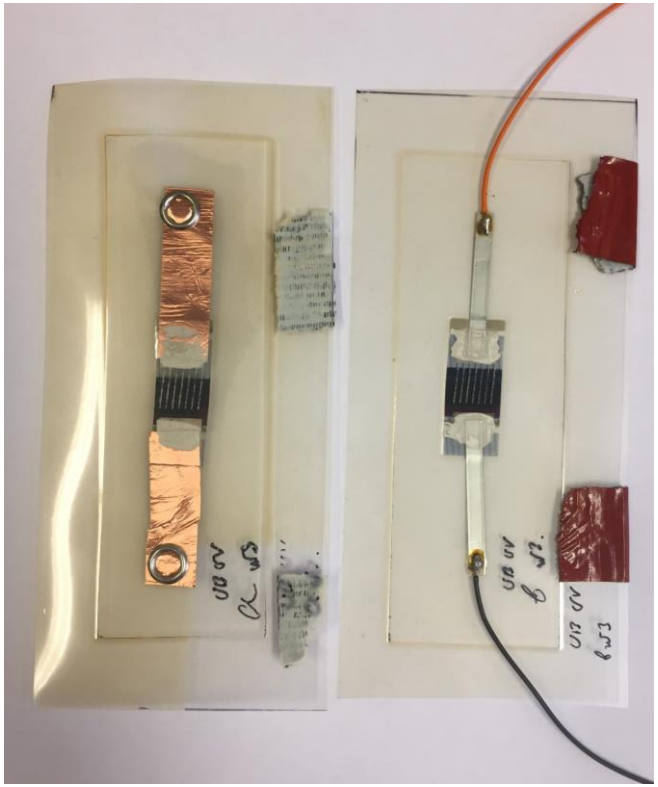


Extrinsic stability

Packaging procedures: Electrodes and edges

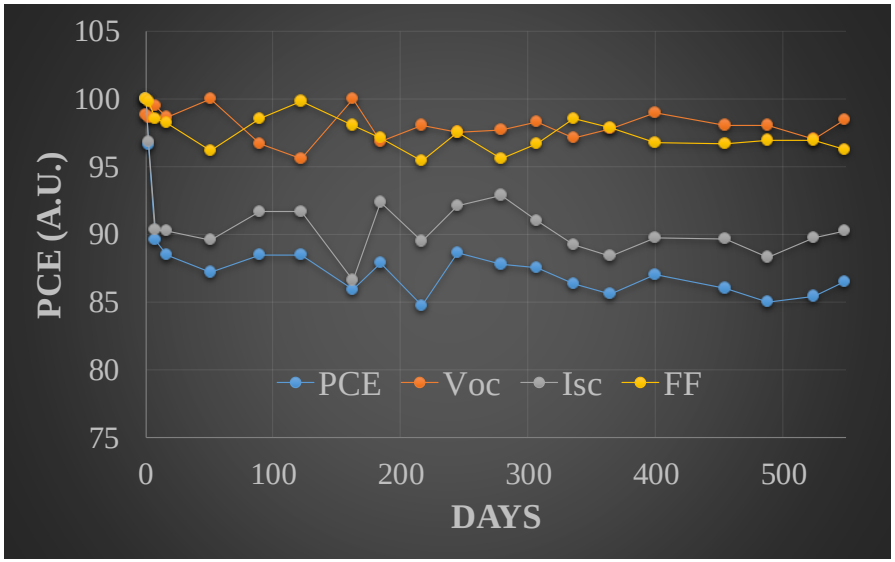


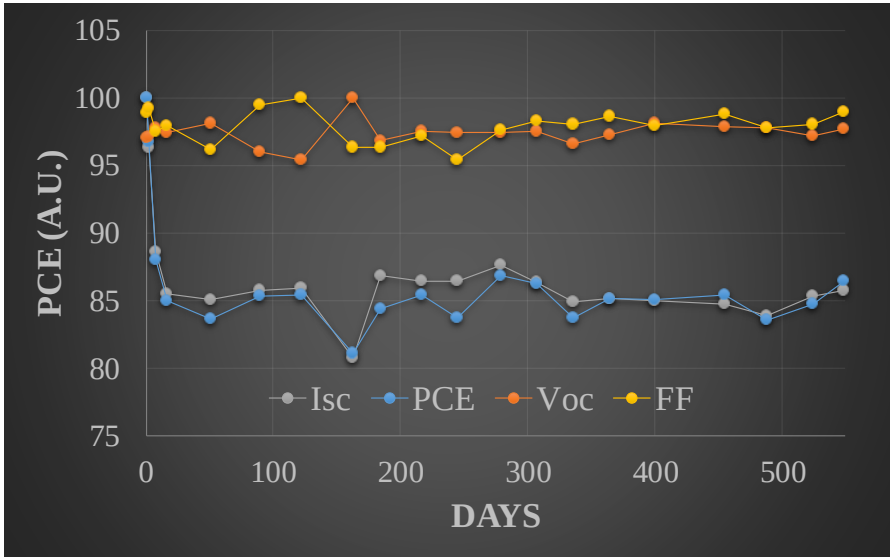




Extrinsic stability

13.000 hours (1.5 years) achieved





- Thin PEDOT:PSS
- Tin plated copper bus bars with soldering wires
- Edge sealing
- Device structure:

UBUV/Ag grid/PEDOT:PSS/ZnO/PCDTBT:PCBM/PEDOT:PSS/Ag grid/UBUV

Encapsulation protocols

Generally there is a large spread in lifetime data of identical encapsulated samples. Challenges are:

- Packaging outline
- Materials
- Electrodes
- Edges

ISOS-e pre-normative guidelines are being currently prepared

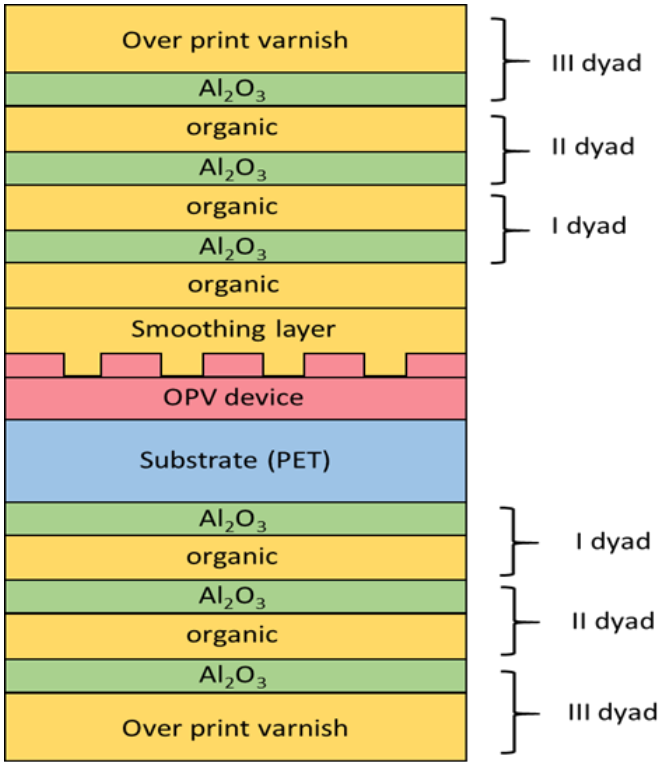
CHEETAH WP10 consortium and EERA are forming the core group

Total of 20 groups involved now

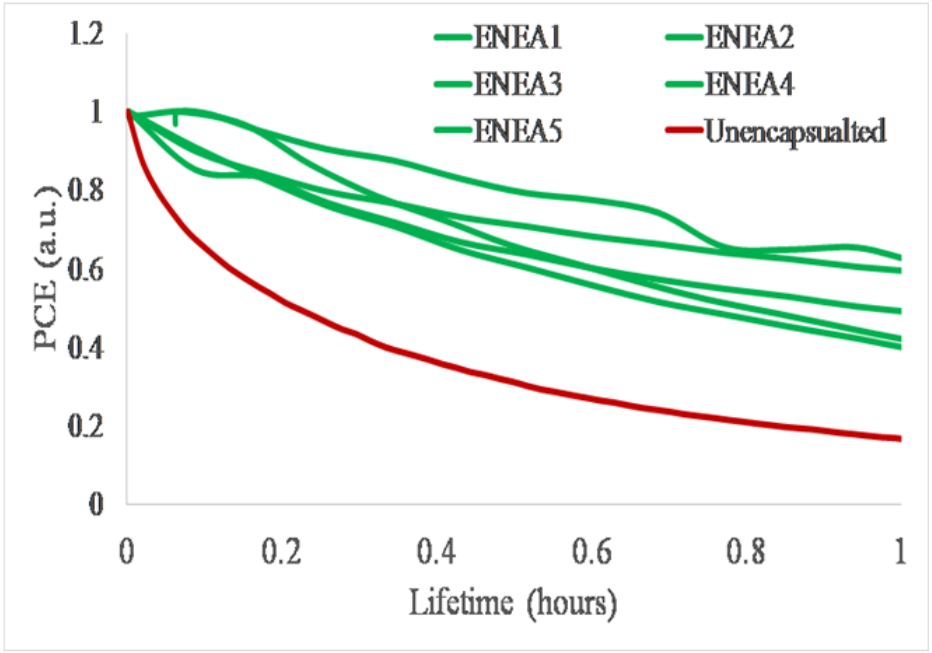
		ISOS-E-1 (Rigid)	ISOS-E-2 (Flexible)
Layout	Layout of encapsulation	•Size of rim •Edge cleaning	• Size of rim • Edge cleaning
Materials	Barrier material Adhesive	•Glass films •Most commonly used	•Most commonly used •Most commonly used
Terminals	Extension Connection	•Tin plated copper tape •Cr(5nm)/Au(l00nm) •Extension distance •Soldering wire •Silver epoxy glue	•Tin plated copper tape •Cr(5nm)/Au(l00nm) •Extension distance •Soldering wire • Silver epoxy glue
Sealing	Protection of terminals Edge sealing	•Weatherproof sealants •To be defined	•Weatherproof sealants •To be defined
Reporting	All parameters affecting stability	•To be defined	•To be defined

Direct deposition of barrier layers

ENEA – deposition of multilayer structure



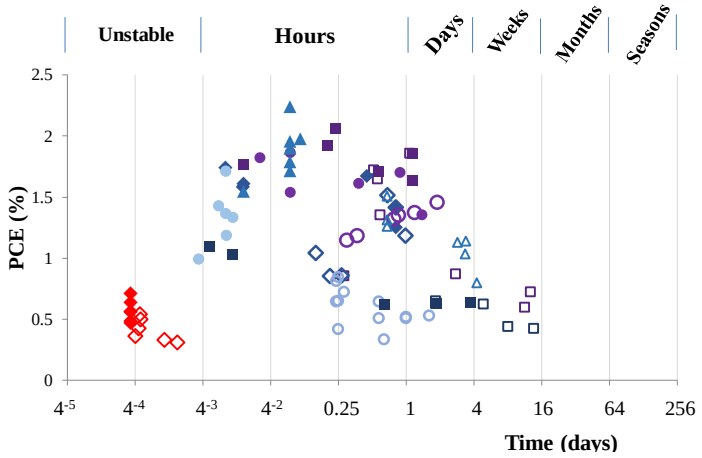
a)



b)

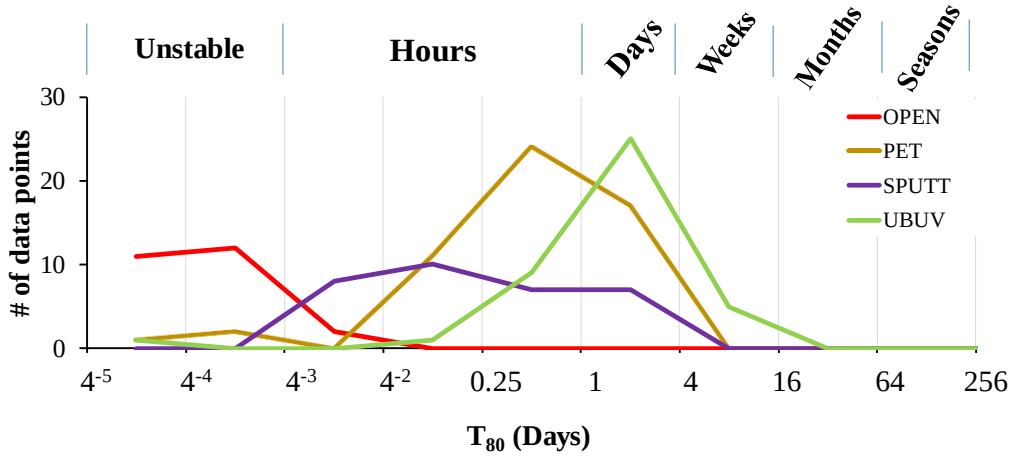
Direct deposition of barrier layers

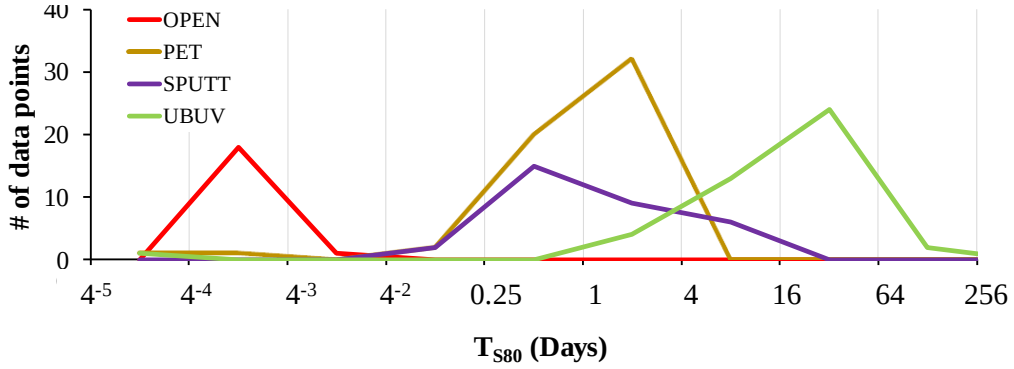
Juelich – Direct sputtering of Si_2N_2O



Efficiency versus lifetime for devices with sputtered protective layers with different thicknesses

- SiON/SiOx/SiON/SiOx/SiON
- SiON/SiOx/SiON/SiOx/SiON
- SiON 150 nm single layer
- SiON 150 nm single layer
- SiON 150 nm 5 layers a 30 nm
- SiON 150 nm 5 layers a 30 nm
- SiON 15 nm single layer
- SiON 15 nm single layer
- SiON 50 nm single layer
- SiON 50 nm single layer
- SiON 300 nm single layer
- SiON 300 nm single layer
- OPEN
- OPEN





Direct sputtering compared to foil packaging

Summary and Significance for Industry

- **e-Infrastructure** (online tools, databases, big data)

Proved to ease and accelerate material research, device optimization and data analyses. Pathway to **INDUSTRY 4.0**

- **Advanced innovative test chamber**

Proved to be highly efficient in distinguishing the weakest links in device stability: **Accelerates device lifetime optimization**

- **Improvement in intrinsic (moderate) and extrinsic (good) stability**

Hydrophilic materials reduction, adhesive enforcement, edge seal – **pathway to lifetime beyond several years**

- **Direct sputtering of barrier** (Si_2N_2O)

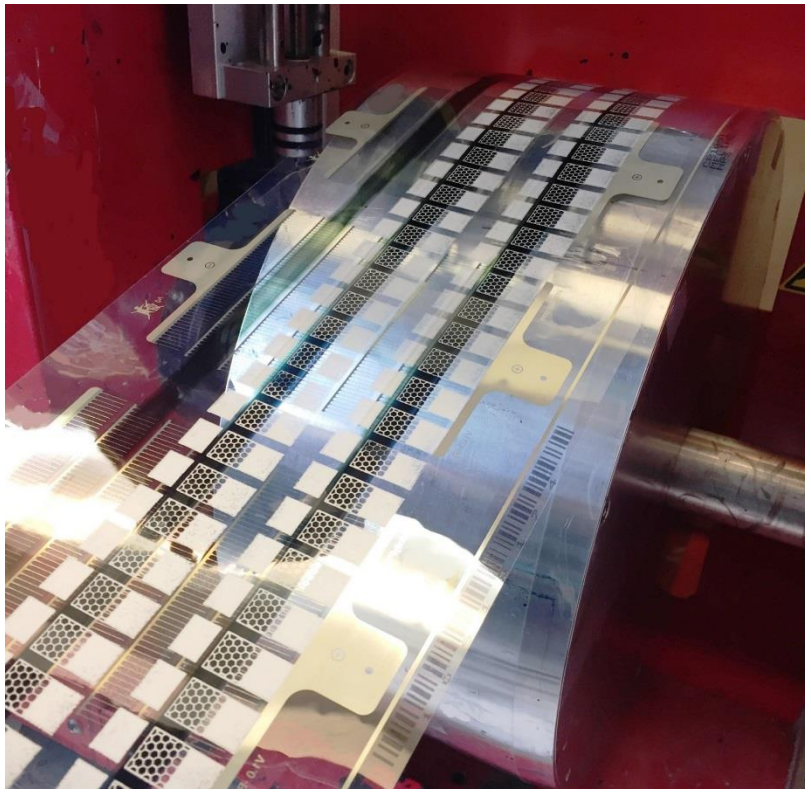
Simple thin layer overtook PET packaging. **Potential to boost device lifetime**, if cost efficiency is proven

- **ISOS-e pre-normative standards**

Essential for novel technologies, reliable testing, learning the right way. Right encapsulation especially is a key to **optimizing lifetime**

CHEETAH

Thank you!



This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration

Perovskites stability and up-scaling

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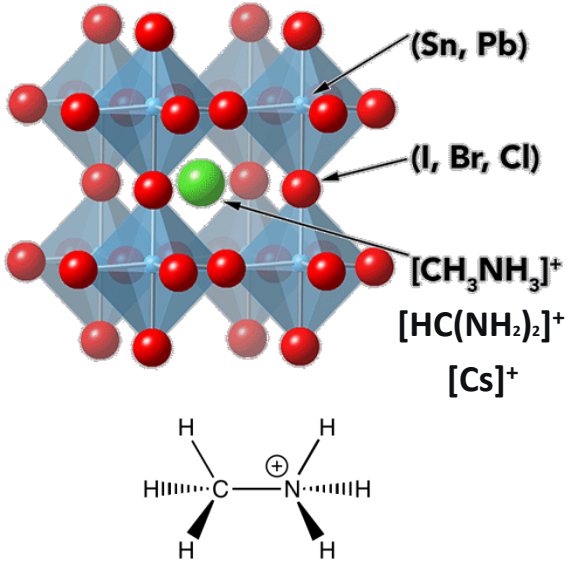
This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration

Perovskite and CHEETAH



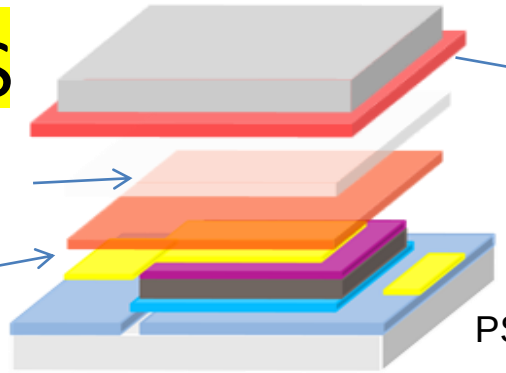
methylammonium ion

$CH_3NH_3^{(+)}$

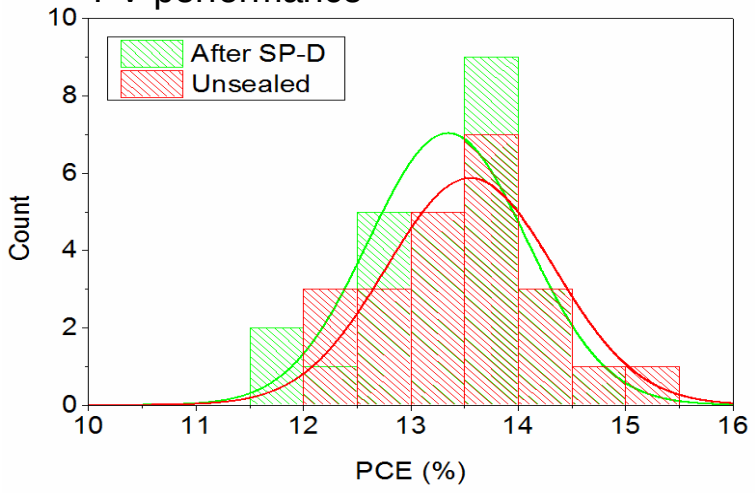
During the CHEETAH implementation and execution the Perovskite solar cells (PSCs) become one of the leading technology for solution process PV

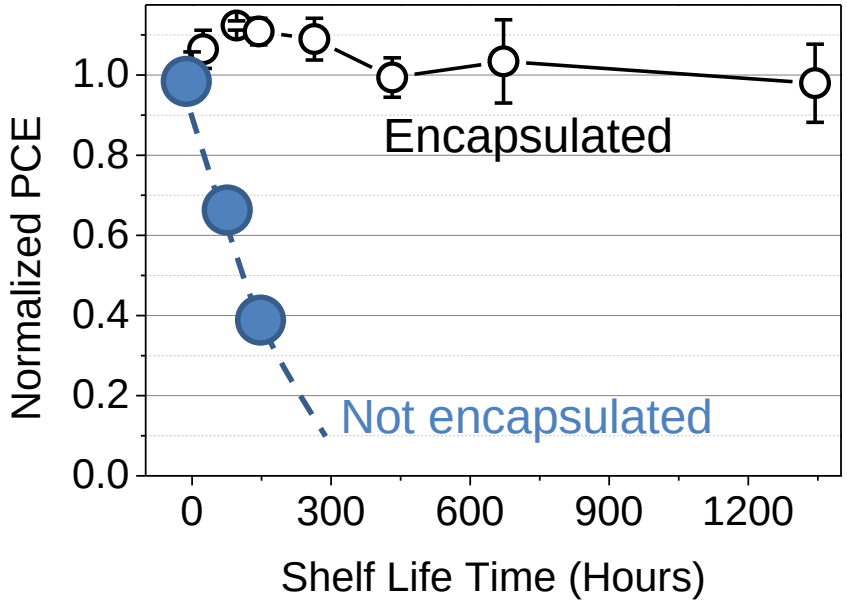
Encapsulation Strategy & Extrinsic Stability

SP-DES



No effect of the sealing on the initial PV performance





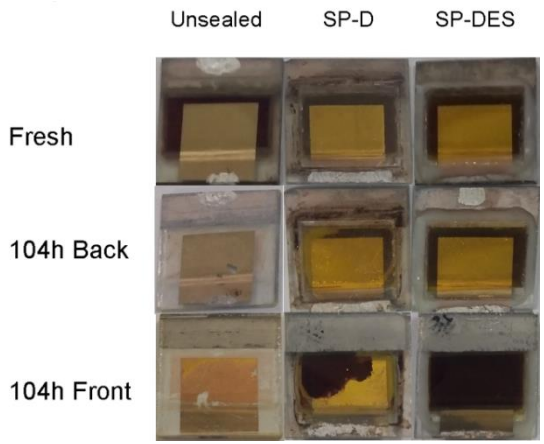
ISOS-D-1 Shelf life

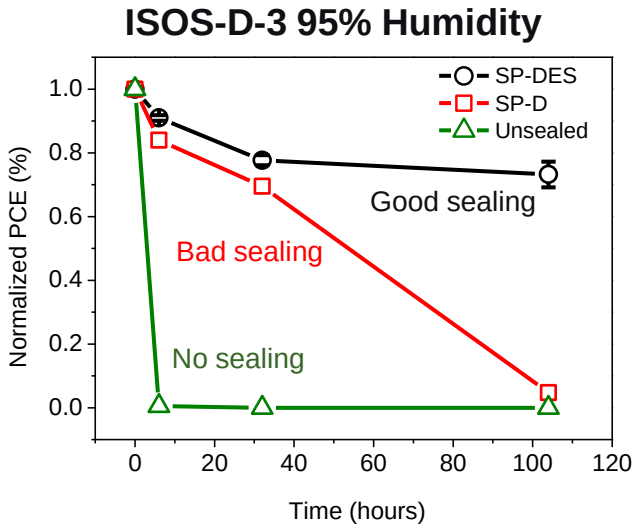
Results on Large area cells (1cm^2)

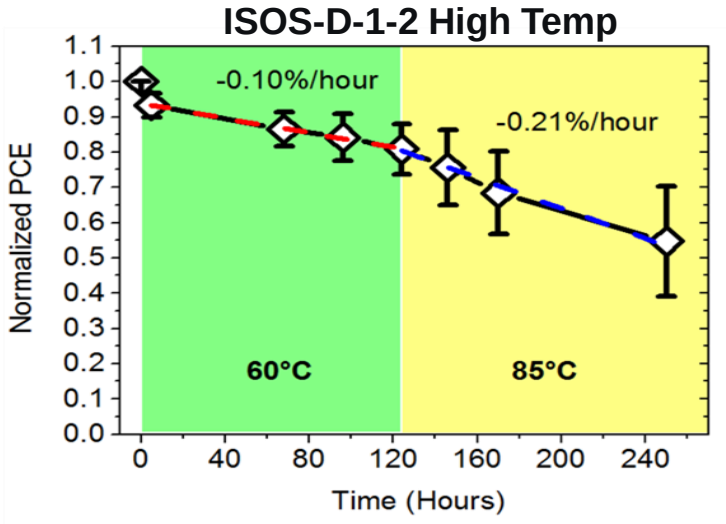
MAPI perovskite used

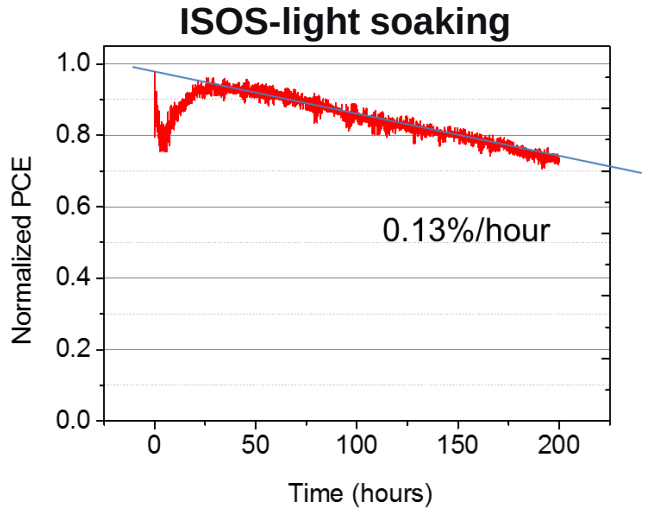
F. Matteocci et al. NanoEnergy (2016) DOI: 10.1016/j.nanoen.2016.09.041

Accelerated Life Time Tests





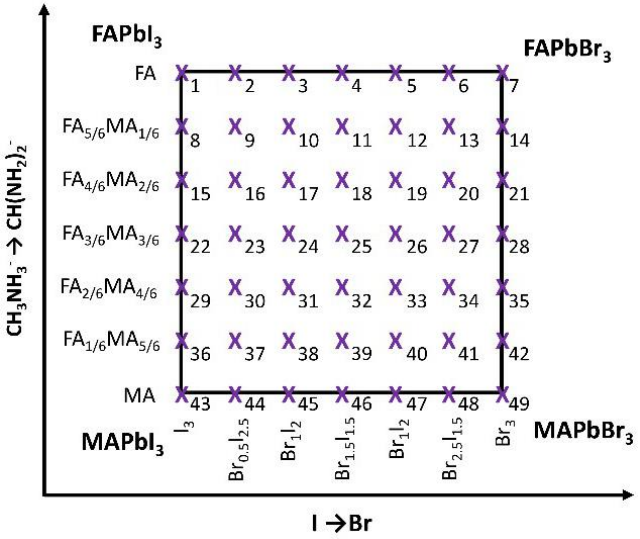




PSC with FTO/TiO_2/MAPI/SPIRO-OMeTAD/Au is not intrinsically stable

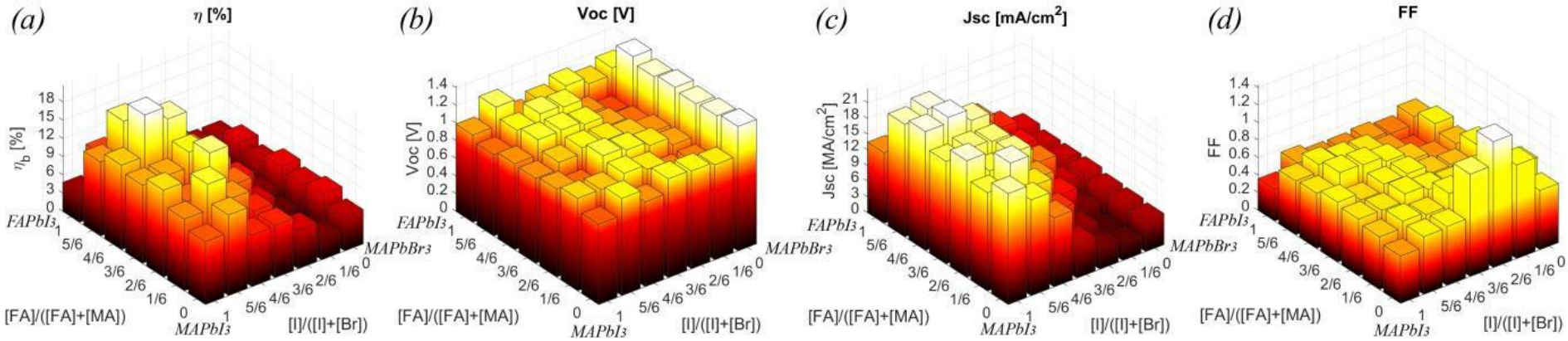
F. Matteocci et al. NanoEnergy (2016) DOI: 10.1016/j.nanoen.2016.09.041

Improving stability: Mixed Perovskites



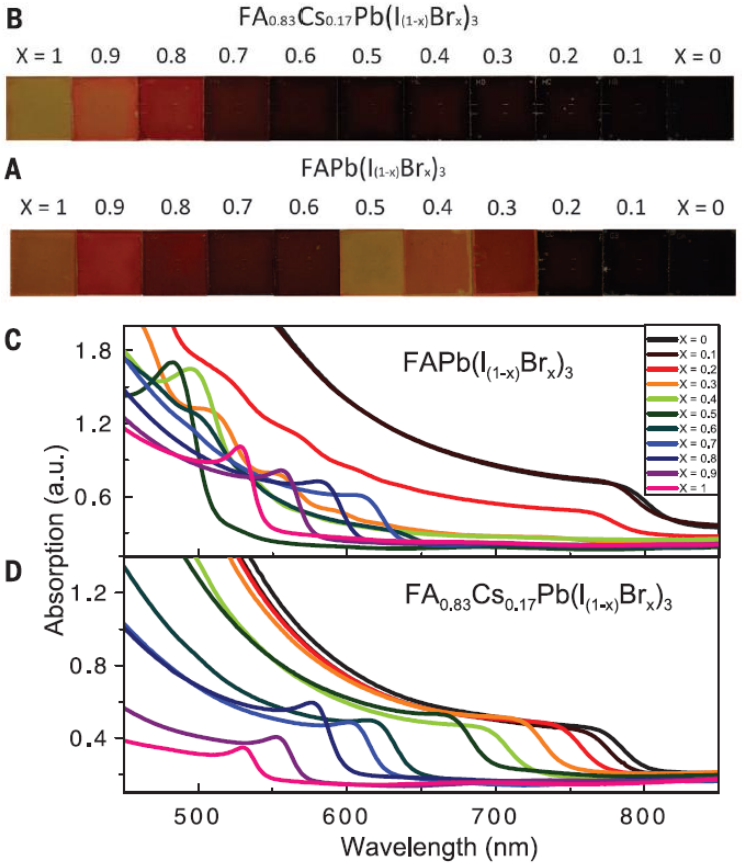
In general, increasing the perovskite complexity is motivated by the need to improve stability by adding more inorganic elements and increasing the entropy of mixing, which can stabilize ordinarily unstable materials

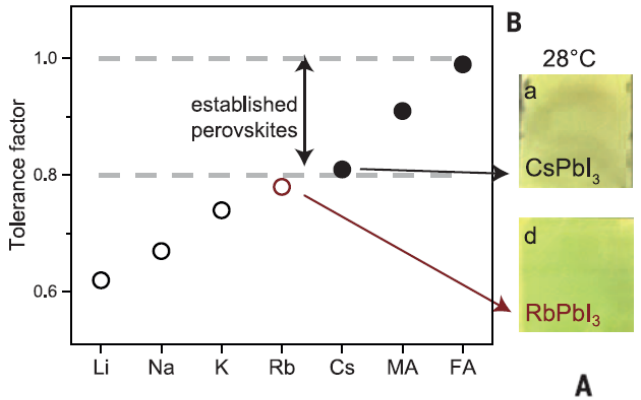
	η [%]						
Pb	I_3	$Br_{0.5}I_{2.5}$	Br_1I_2	$Br_{1.5}I_{1.5}$	Br_2I_1.	$Br_{2.5}I_{0.5}$	Br_3
FA	4.8	9.6	1.9	3.7	7.5	5.0	5.0
$FA_{5/6}MA_{1/6}$	12.1	17.4	14.7	11.4	5.8	3.3	6.5
$FA_{4/6}MA_{2/6}$	13.9	20.7	18.5	11.7	5.6	3.4	5.5
$FA_{3/6}MA_{3/6}$	12.8	12.9	15.3	11.9	7.9	3.9	7.1
$FA_{2/6}MA_{4/6}$	14.3	11.0	17.5	10.7	6.2	2.9	6.4
$FA_{1/6}MA_{5/6}$	11.8	16.0	12.2	8.7	3.5	2.3	7.1
MA	10.3	13.2	8.5	8.6	6.3	3.5	5.6



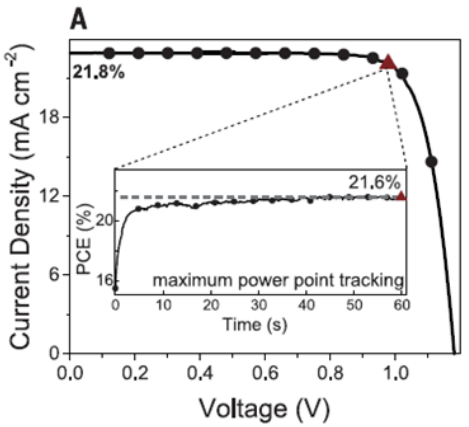
T. J. Jacobsson et al. Energy Environ. Sci., 2016,9, 1706-1724

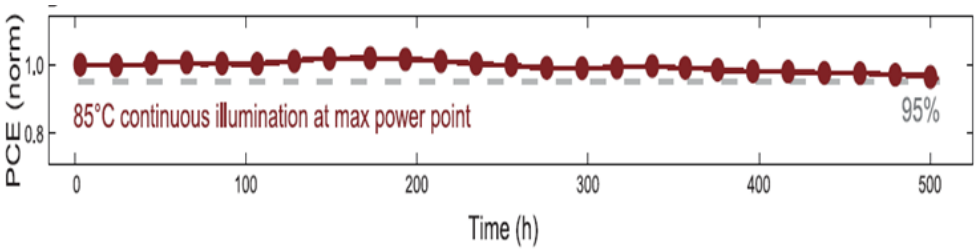
Mixed Perovskite: FA, Cs, Rb





RbCsMAFA

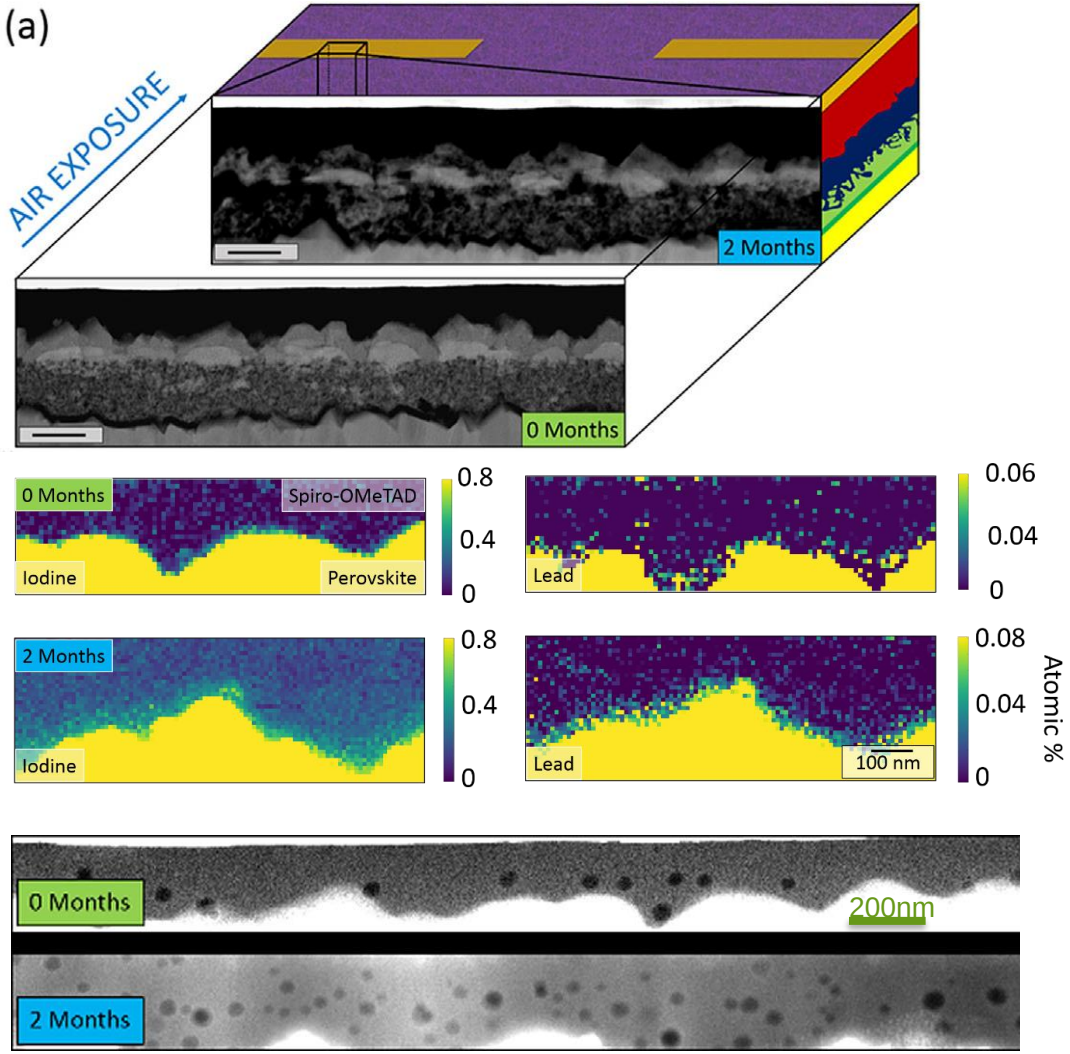




Cs/FA mixtures suppress halide segregation. The Cs/MA/FA-based solar cells are more reproducible and thermally stable than MA/FA mixtures

D. P. McMeekin et al. Science (2016) 351, 151; M. Saliba et al. Science (2016), 354, 206

What about air exposure ?



Sealing was removed and a TEM analyses performed on fresh and air aged cells

TEM signal decrease of about 15% of signal intensity perovskite capping and m-TiO2

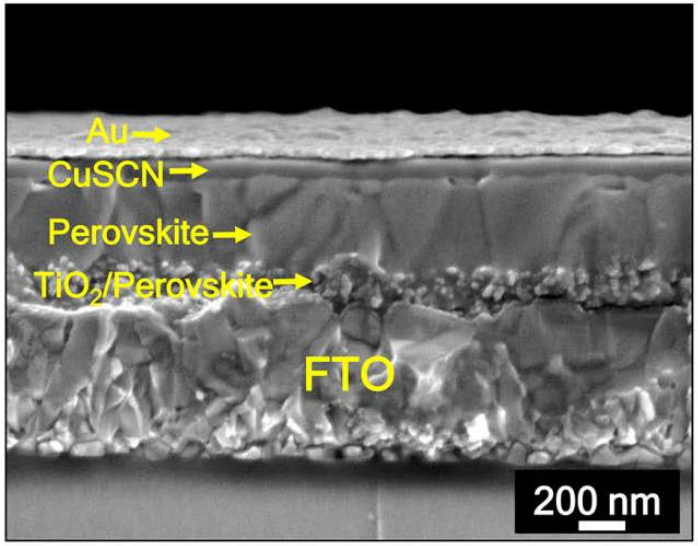
Iodine clearly diffuses in the HTL in the aged sample, whereas no migration of lead has been observed.

Bubble formation (40-50 nm).

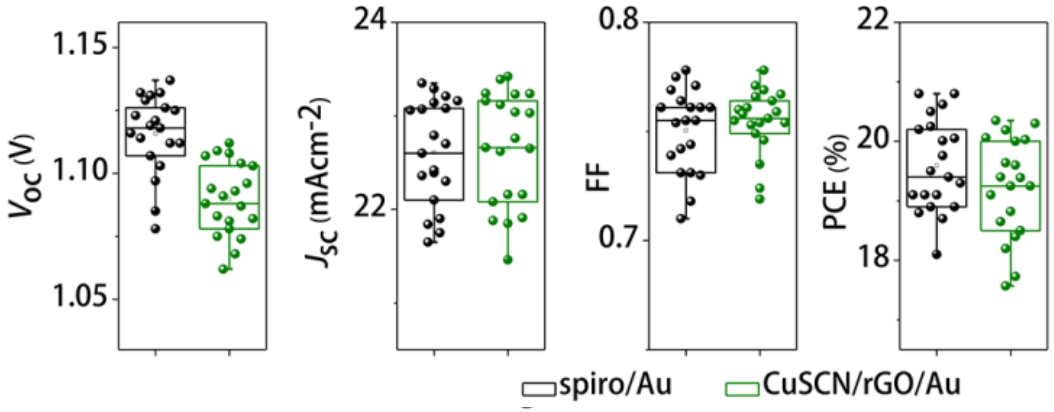
- **presence of dopants** in the HTL
- to the use of chlorobenzene

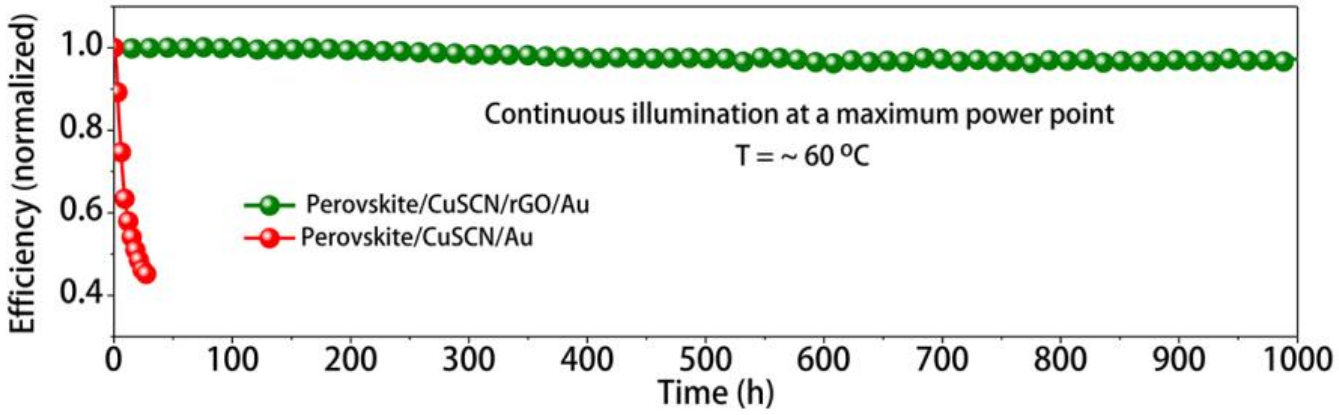
S. Cacovich et al ChemSuChem 2016 DOI: 10.1002/cssc.201600913

Mixed Perovskite + Inorganic HTL + Graphene



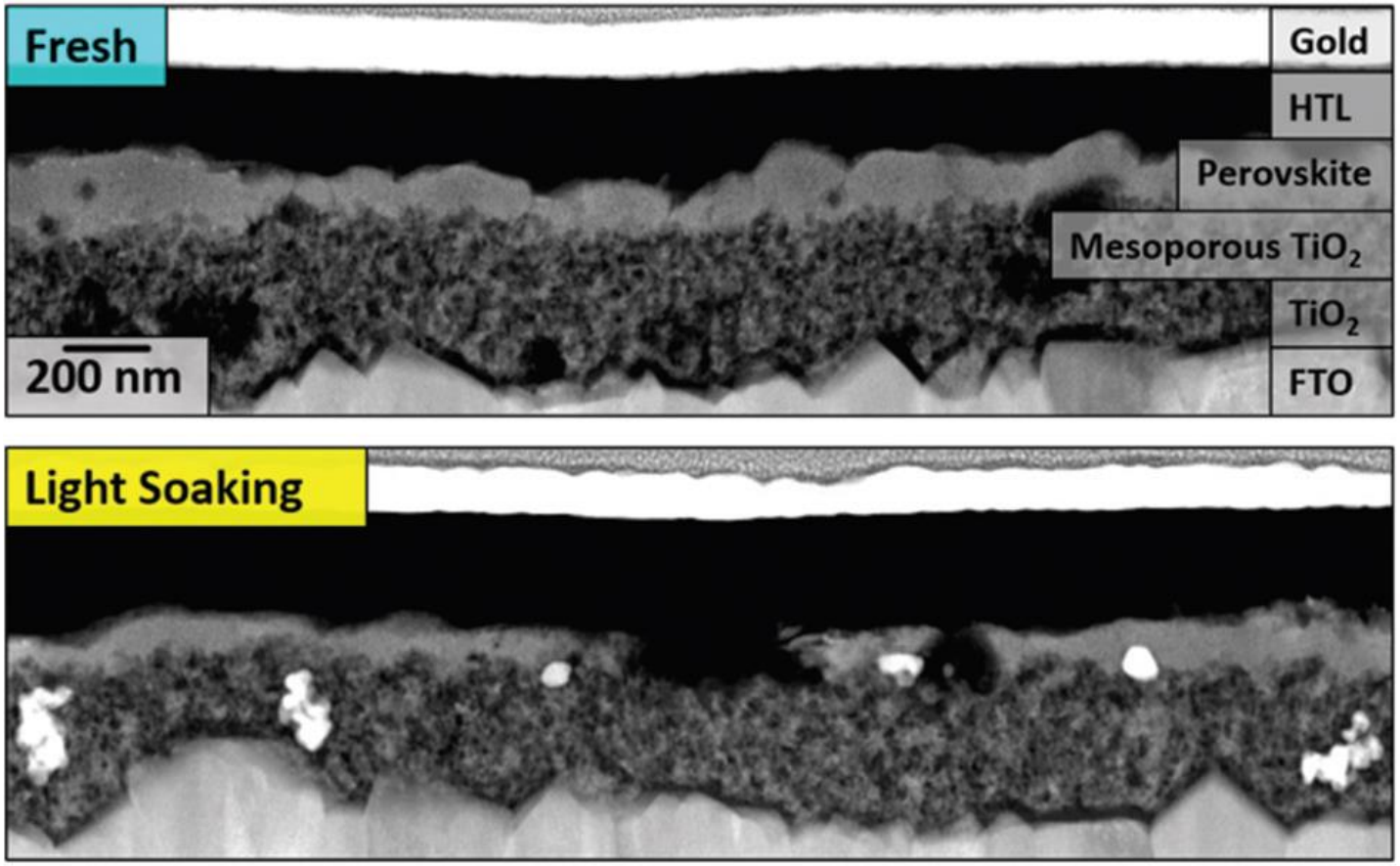
The inorganic CuSCN HTL reacts with Au contact. A thin layer of reduced Graphene Oxide (rGO) stabilize the system





A. Arora et al. Science 28 Sep 2017: DOI: 10.1126/science.aam5655

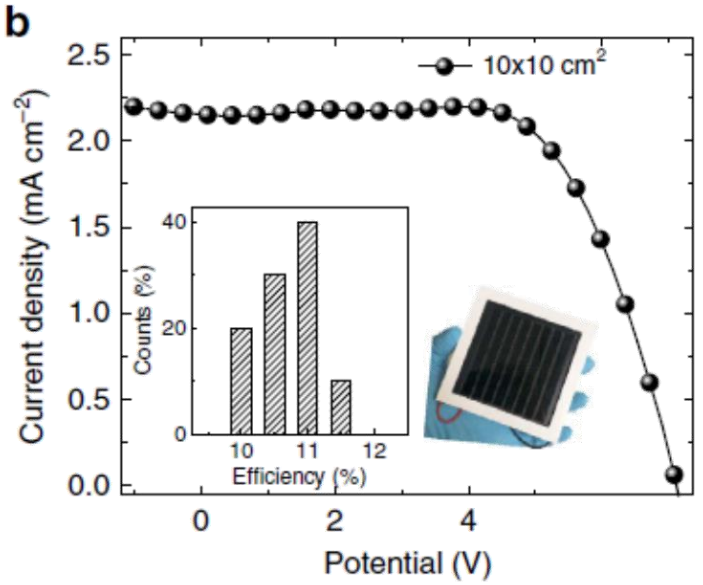
Gold Diffusion

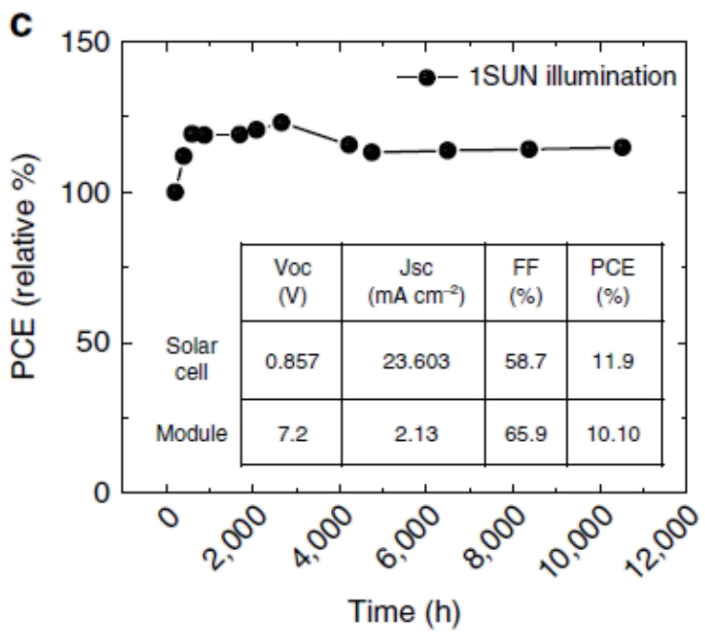


Light-soaking as well as temperature stress induce gold diffusion into the Perovskite

S. Cacovich et al. Nanoscale, 2017, 9, 4700–4706

Carbon based PSC





G. Grancini et al. Nature Communications, 8, 15684 (2017)

Scaling up: from perovskite cells to modules

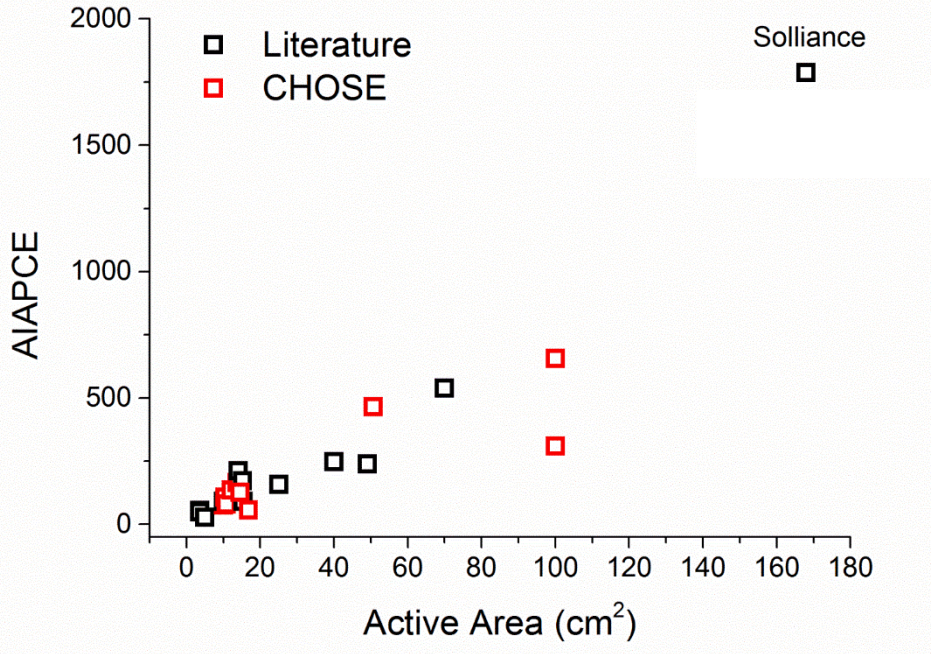
The progresses made in terms of efficiency and, with a minor extent, stability pushed the development of large area modules.

Since the demonstration of the first module (Matteocci et al. 2014) a well establish scaling-up activity is present in many research centers even if a coordinated action is missing (CHEETAH 2.0 ?)

We compare the different modules by defining the AIAPCE metric

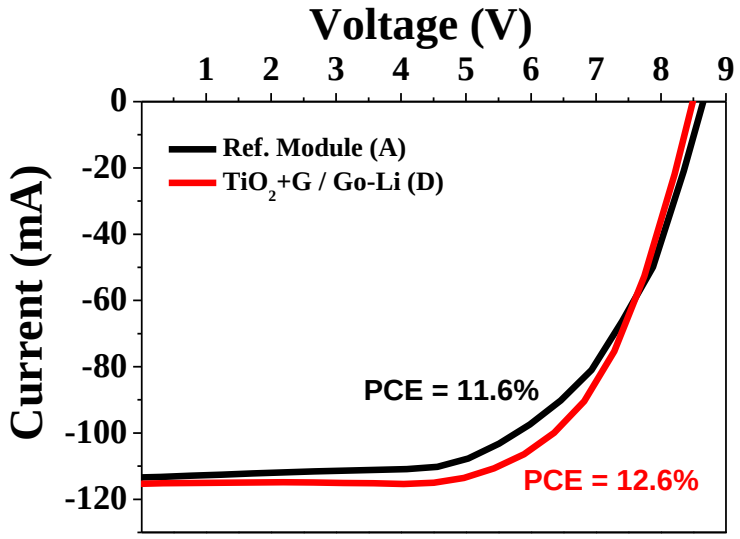
$AIAPCE = PCE_{APERTURE} \cdot \text{Active Area}$

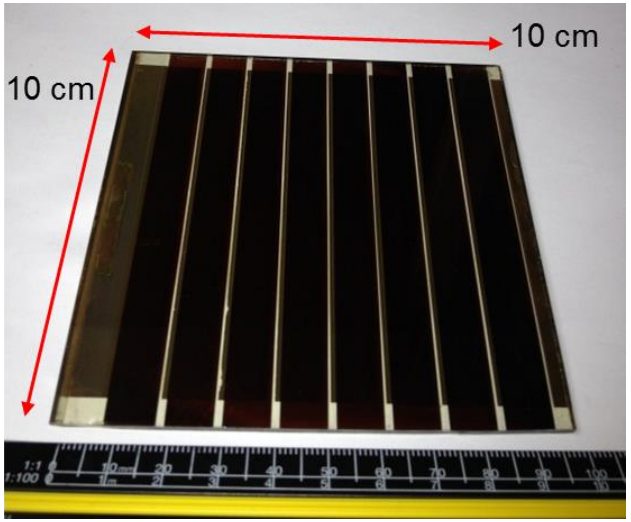
AIAPCE = Active Area Indexed Aperture PCE



Palma et al., IEEE Journal of Photovoltaics, 2017, 7 (6), 1674 - 1680

2D materials and Perovskites for modules



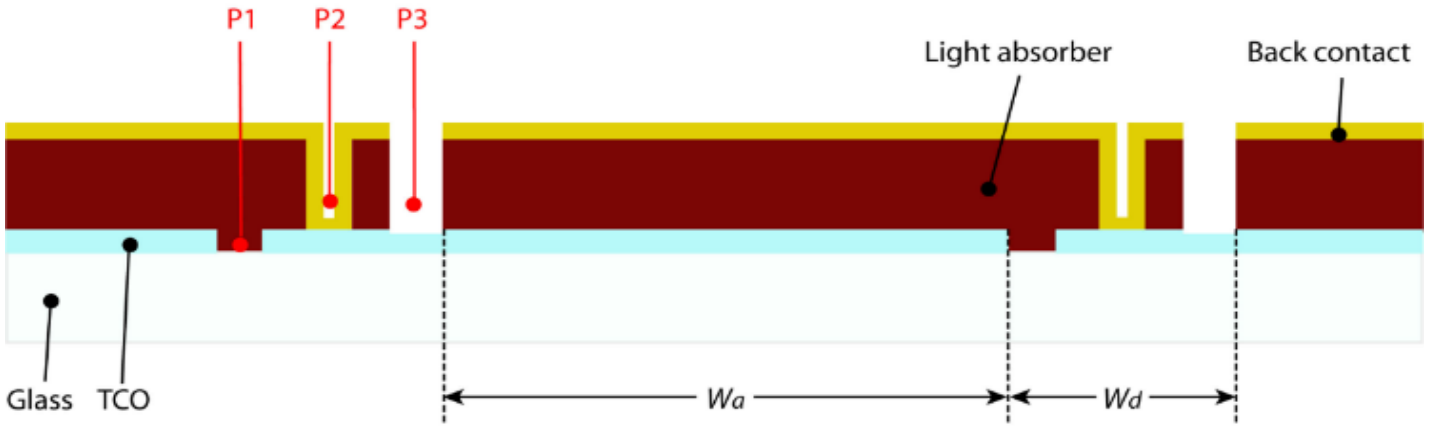


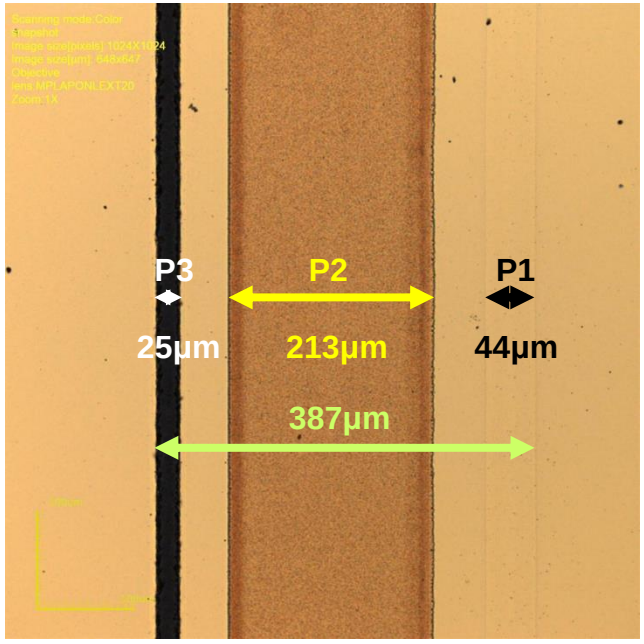
Module type	Electrical parameters				
	V_{OC} (V)	I (mA)	FF (%)	PCE(%)	ΔPCE(%)
Ref	8.72	-112.8	59.4	11.6	-
$mTiO_2$+G	8.23	-118.1	62.4	11.9	+3%
$mTiO_2$/GOLi	8.46	-121.6	61.4	12.5	+8%
$mTiO_2$+G/GOLi	8.6	-114.8	64.6	12.6	+9%

We exploited the Graphene Interface Engineering (GIE) to improve efficiency

A. Agresti et al. ACS Energy Lett., 2017, 2 (1), pp 279–287

Thin film standards for laser patterning





5 cells module
(on 5x5 cm substrate)
Active Area: 14,52 cm^2
Aperture Area: 15,28 cm^2

Aperture Ratio: 95%
PCE = 9.5%
Aperture PCE = 9.03%

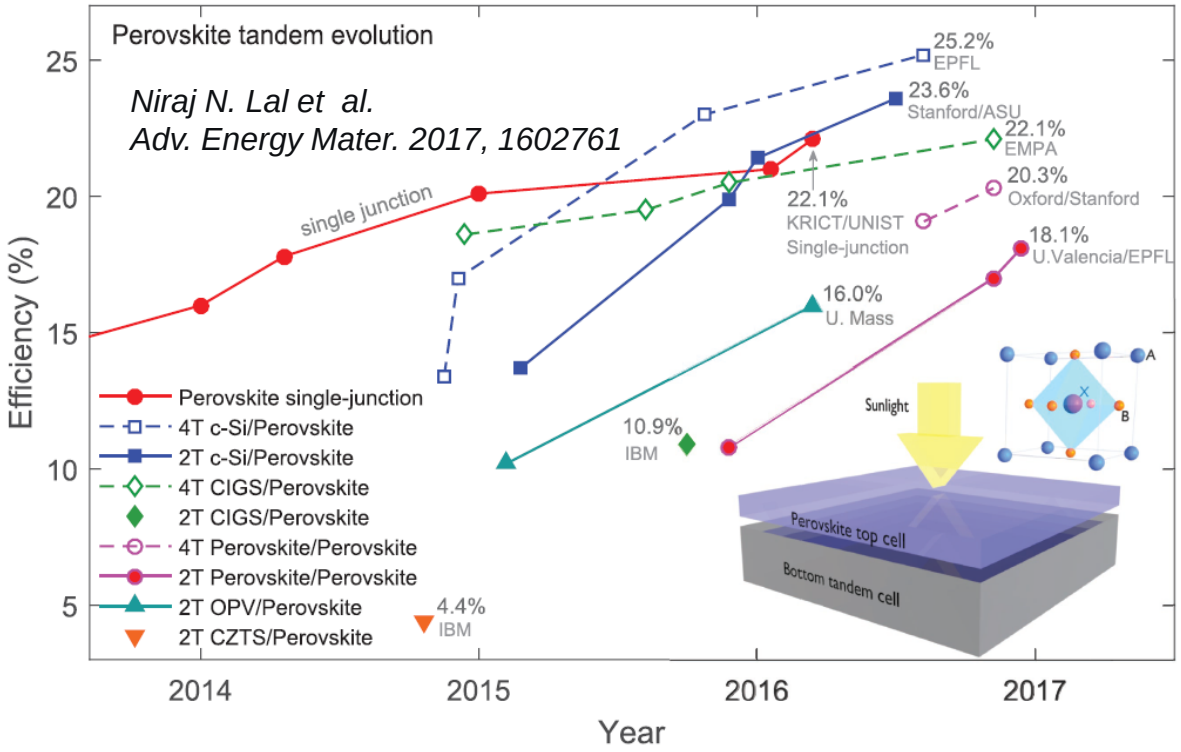
P1: $Nd:YVO_4$, λ=1064 nm, 15 ns pulsed laser

P2: $Nd:YVO_4$, λ=355 nm, 10 ps pulsed laser

P3: $Nd:YVO_4$, λ=355 nm, 10 ps pulsed laser

Palma et al., IEEE Journal of Photovoltaics, 2017, 7 (6), 1674 - 1680

Tandem:Perovskite/(Si, Perovskite, CIGS, OPV)



Based on the current state-of-the-art and the rapid recent progress, 30% Psk/Si is practically achievable for both the two- and four-terminal tandem configurations.

J. Werner et al *Adv. Mater. Interfaces* **2017**, 1700731

Simple modelling under modest assumptions suggests Psk/Psk tandem efficiencies above 30% are eminently achievable.

CHEETAH

Thank you!

Any questions for our experts?

This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration

Feedback from industry

Q1: What is the need of industry in terms of e-infrastructures?
Q2: Where research should focus in terms of intrinsic and extrinsic performance?
Q3: Are pre-normative guidelines for encapsulation useful (for industry)?
Q4: Is direct sputtering commercially viable technique?

Q5: Single junction module vs Perovskite/silicon tandem, where to go ?
Q6: Silicon/Perovskite or Perovskite/Perovskite ?
Q7: Is a Lead content PV such as perovskite technology acceptable ?
Q8: Solution process vs vacum deposition, is it still an open question ?
Q9: Perovskite shows very good performance for low light applications (indoor etc.). Is this an interesting application ? Which market ?
Q10: ALT stability is improving. Are field test required to introduce this new tecnology ? How long?

Feedback from the industry

- Do you think these CHEETAH innovations (will) matter?
- What do you think is important for short, medium and long term to further mature these innovations?
- What do you think is important for short, medium and long term for the industry to adopt these innovations?
- How could your company benefit from these innovations?
- Which markets do you want to address?
- What other innovations not investigated in Cheetah are important for the industry on short, medium and/or long term?