Sunday

Stable and Scalable Perovskite Solar Cells

Sjoerd Veenstra

November 7th, 2018
Bussum

SOLAR RESEARCH
SOLLIANCE
led by imec, ECN and TNO

Thermal instability $MAPbI_3$

3. Conclusion

In conclusion, we have investigated the thermal stability of $MAPbI_3$ perovskite layers in different environmental conditions from a morphological, electronic and chemical point of view. The final verdict is that this type of perovskite is not intrinsically stable while heating to temperatures comparable to the higher range of operational temperatures in full sunlight (85 °C). The unit cell of the perovskite breaks down not only due to humidity but also due to thermal instability of its constituents (which are partially volatile species), thereby confirming the soft matter character of this new class of light absorbers.

UHASSELT
KNOWLEDGE IN ACTION

B. Conings, Adv. En. Mater. (2015) 5, 1500477

Materials Views
www.MaterialsViews.com
ADVANCED ENERGY MATERIALS
www.advenergymat.de
FULL PAPER

Intrinsic Thermal Instability of Methylammonium Lead Trihalide Perovskite

Bert Conings, Jeroen Drijkoningen, Nicolas Gauquelin, Aslihan Babayigit, Jan D'Haen, Lien D'Olieslaeger, Anitha Ethirajan, Jo Verbeeck, Jean Manca, Edoardo Mosconi, Filippo De Angelis, and Hans-Gerd Boyen**

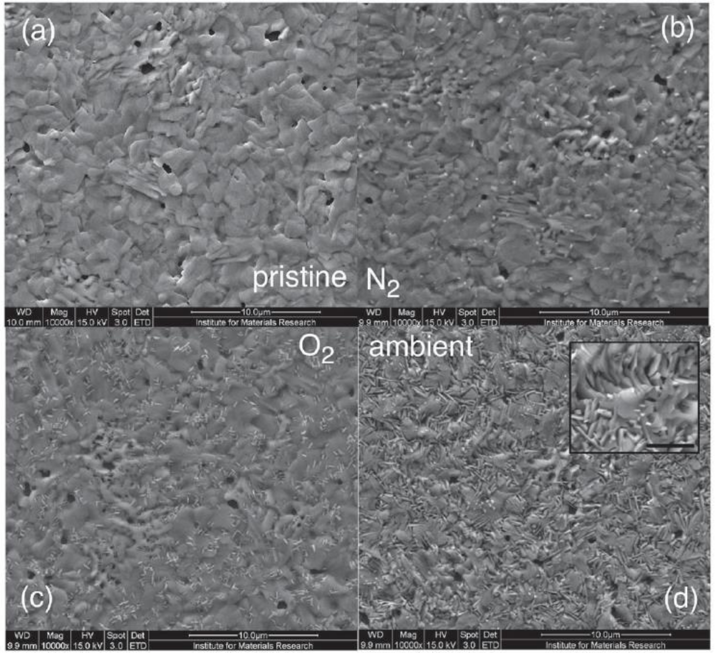
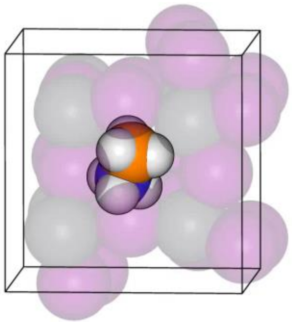
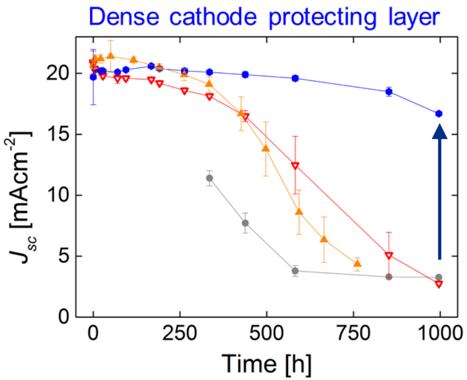


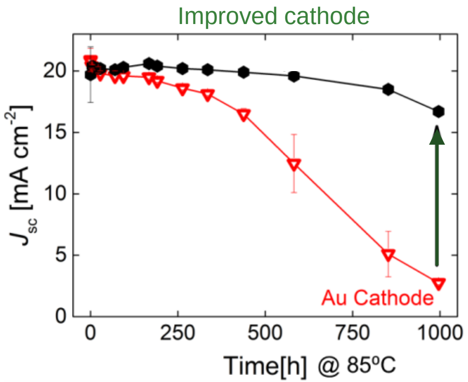
Figure 2. Scanning electron microscopy images of ITO/TiO_2/perovskite samples that were degraded in different atmospheres for 24 h at 85 °C.

Thermal stability of perovskite solar cells (baseline 1)

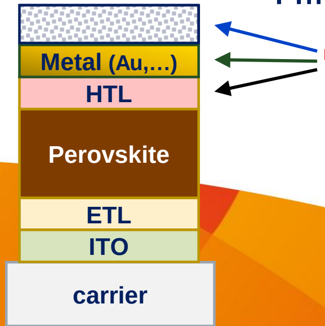
- **Temperature stability**

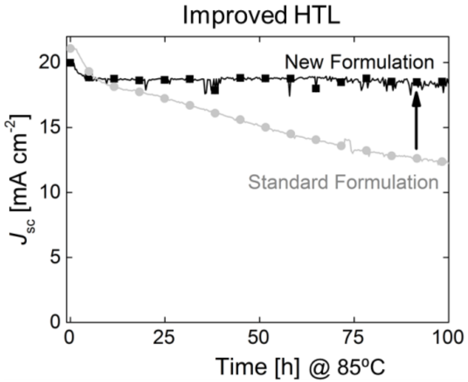






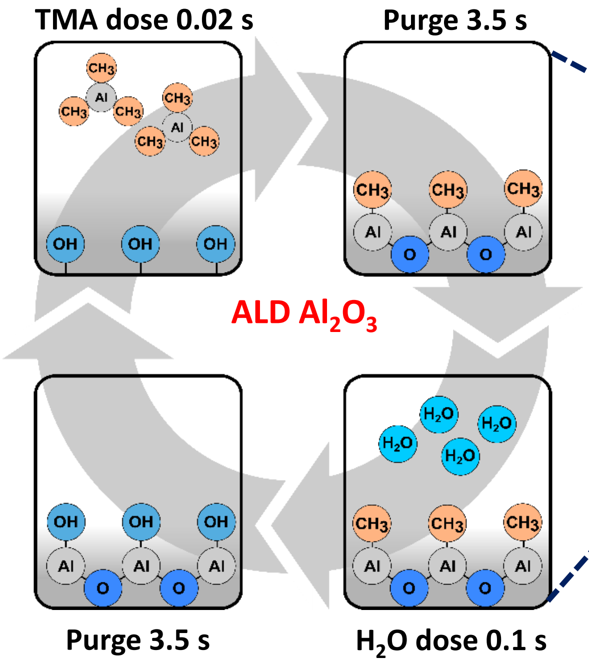
- **Introducing improvements:**
  - Hinder escape of small MethylAmmonium cation:
    - Dense inorganic (inter)layers

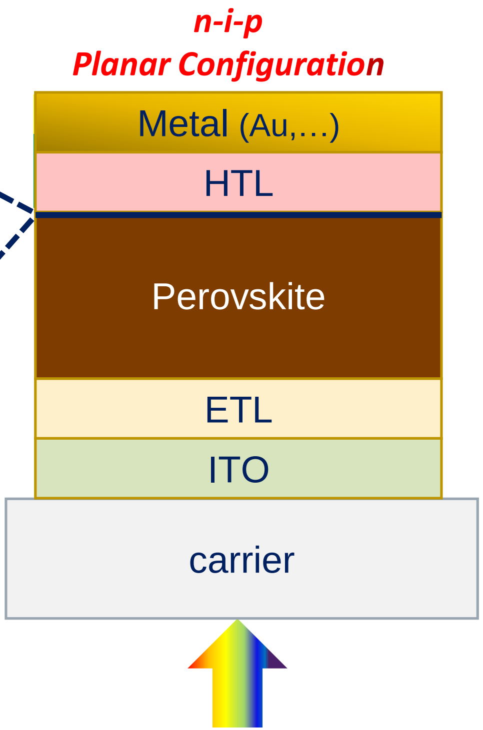




Insert conformal ALD Al_2O_3 layer between perovskite and HTL

Baseline V1.0 - opaque version

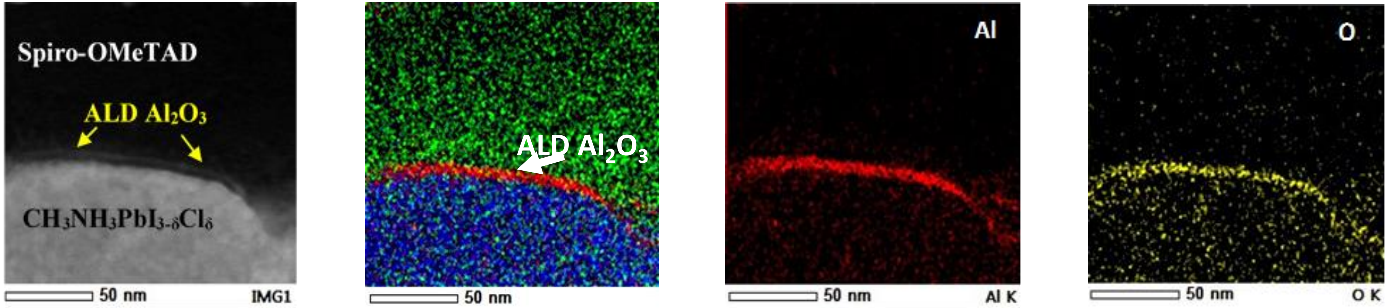


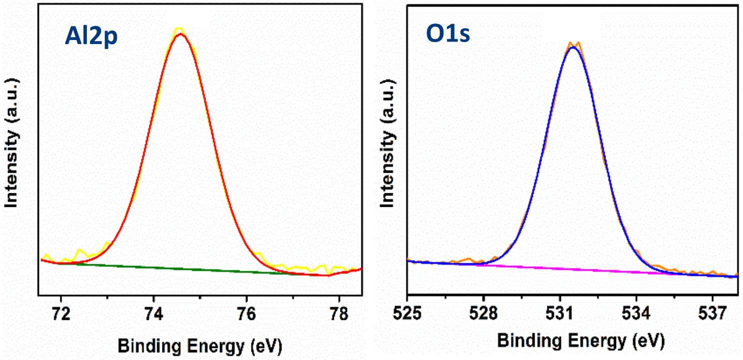


Dingemans *et al.*, *J. Vac. Sci. Tech. A*, 2012, **30**, 040802.
Langereis *et al.*, *Appl. Phys. Lett.*, 2006, **89**, 081915.

Does ALD Al_2O_3 grow on perovskite?

TEM and XPS Studies



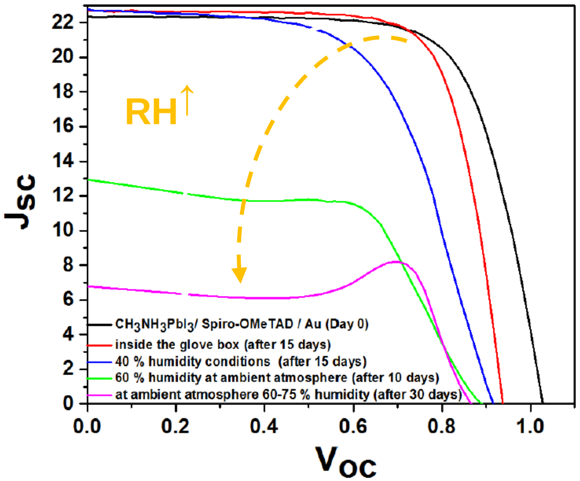


1. D. Koushik *et al.*, *Energy Environ. Sci.*, 2017, **10**, 91.
2. D. Koushik *et al.*, *Adv. Mater. Inter.*, 2017, 1700043.

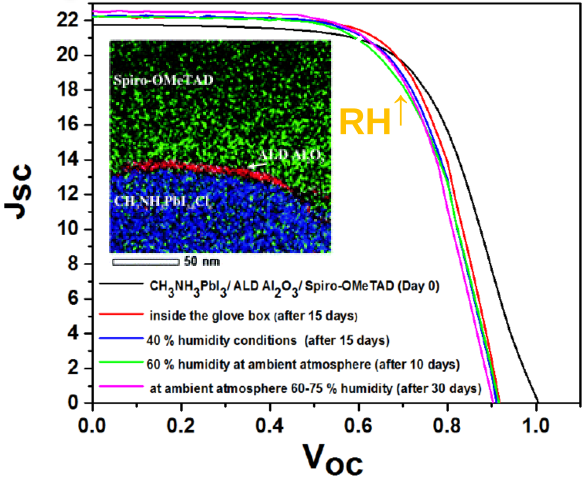
Al_2O_3 grown on perovskite

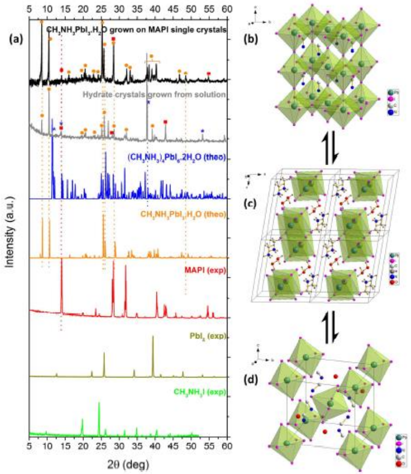
- Humidity stability

Baseline V1.0, no Al_2O_3



Additional **ALD** Al_2O_3 on PER



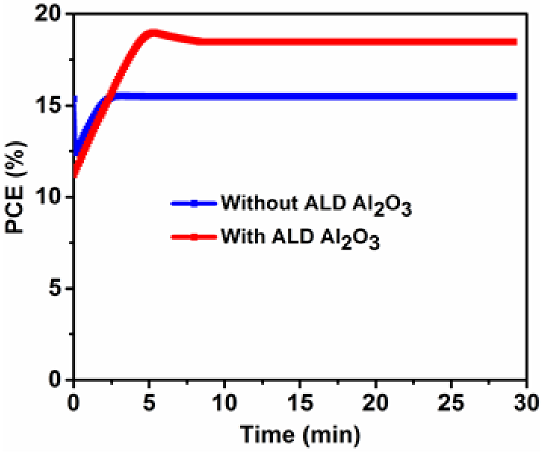


➢ Almost no device deterioration by increased exposure to humidity

1. D. Koushik *et al.*, *Energy Environ. Sci.*, 2017, **10**, 91.
2. D. Koushik *et al.*, *Adv. Mater. Inter.*, 2017, 1700043
3. A. Leguy et al., *Chem. Mater.*, 2015, **27**, 3397
4. H. Wei *et al.*, Phys. Chem. Chem. Phys., 2015, **17**, 4937

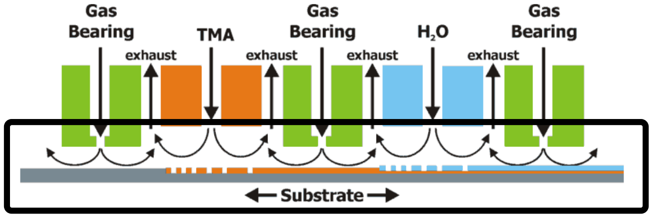
Al_2O_3 grown on perovskite – efficiency and scale up

ALD Al_2O_3 (PCE↑)

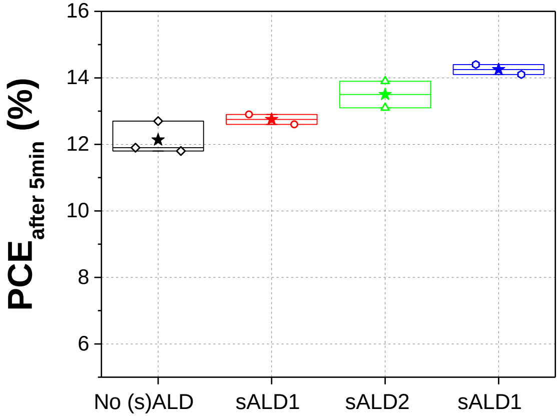


sALD
Lab scale

sALD
S2S scale

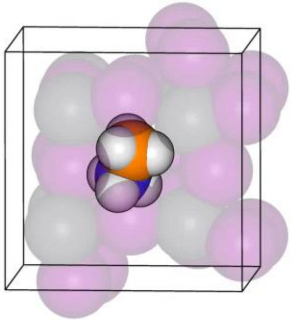


spatial ALD Al_2O_3 (PCE↑)

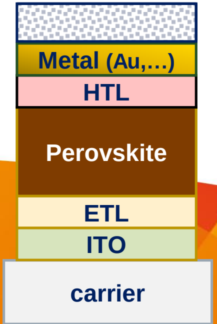


Thermal stability of perovskite solar cells

- **Temperature stability**



- **Introducing improvements:**
  - Hinder escape of small MA cation:
    - Dense (inter)layer
  - Larger cation/Smaller anion:
    - Formamidinium/Bromide



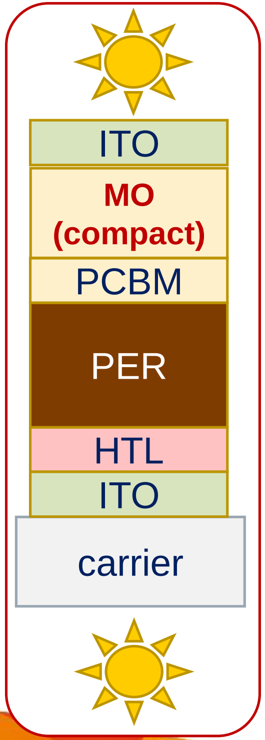
- **Baseline V2.0:**
  - Planar and low temperature → R2R compatible
  - Introducing Formamidinium & Bromide
    - Two step process
    - **$FA_{1-x}MA_xPbI_{3-x}Br_x$**
    - More stable and …
  - **Glass**: 15 → 17 → **19%**
  - **PET**: **16,5%**
  - **In depth study on low T plasma assisted ALD SnO_2 deposition for PSCs**

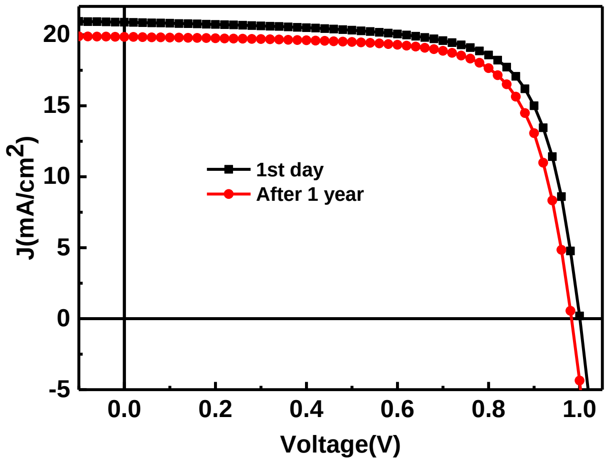
    Y. Kuang et al., *ACS Appl. Mater. & Interf.* (2018) **10** 30367
  - Thermal stability limited by top (p) contact
  - Need for stable / scalable / low cost top contact → baseline 3

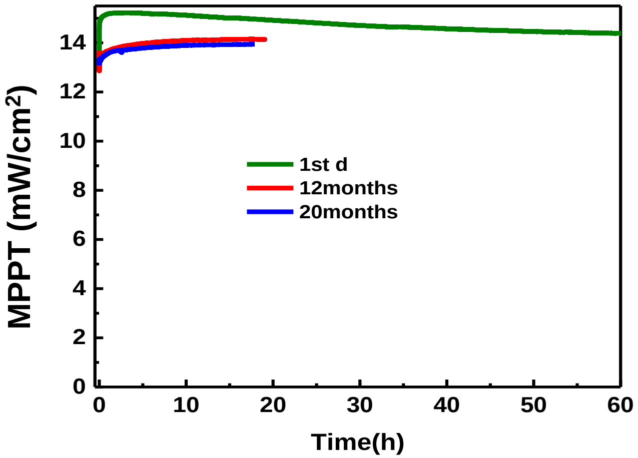
Y. Kuang et al., *ACS Appl. Mater. & interf.* (2018) 10 30367
Courtesy Jarvist Moore Frost, https://www.youtube.com/watch?v=Rr2DDiYUoNA

SOLLIANCE

Shelf life







- 95% of initial stabilized power output after **15 000 hr. shelf life** aging (N_2, RT, unencapsulated)

Thermal Stability

- Devices encapsulated
- Thermal stress at 85 °C in N_2 (similar results obtained in air)

➢ s-ALD layer drastically improves the thermal stability both with Al and ITO electrodes

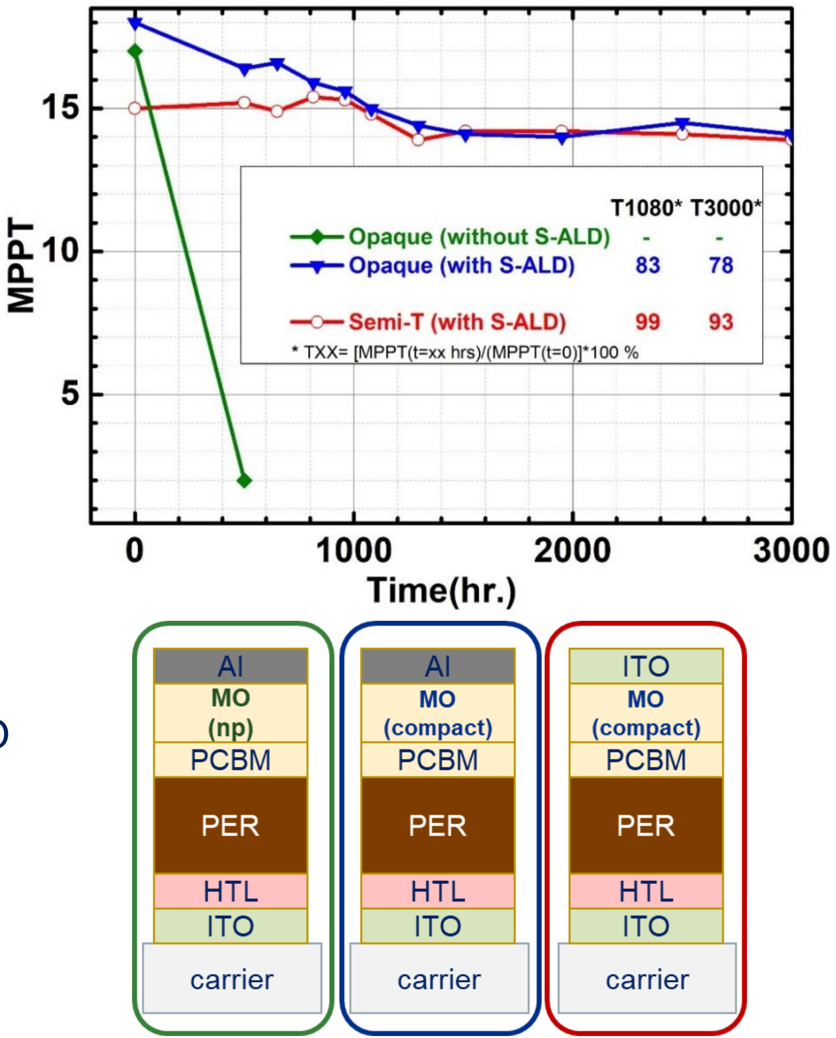
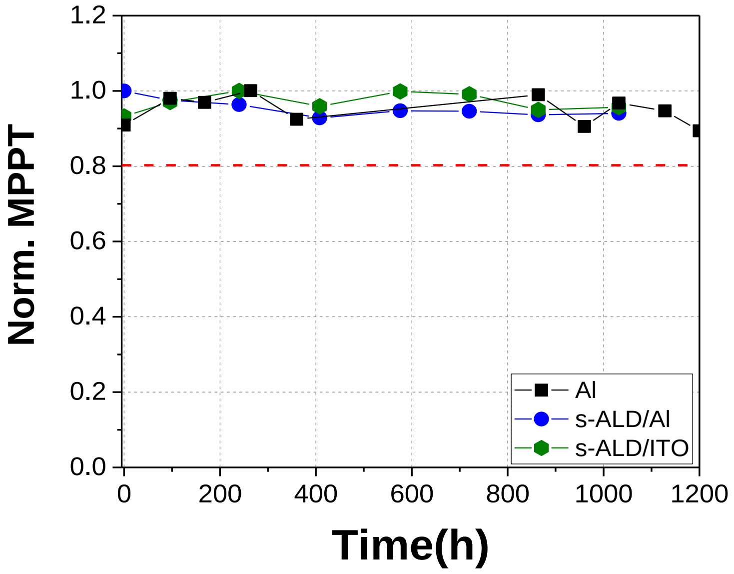


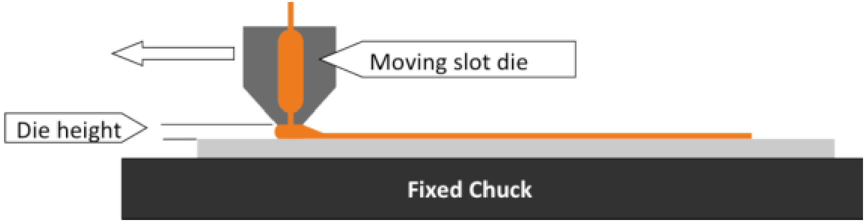
Photo Stability

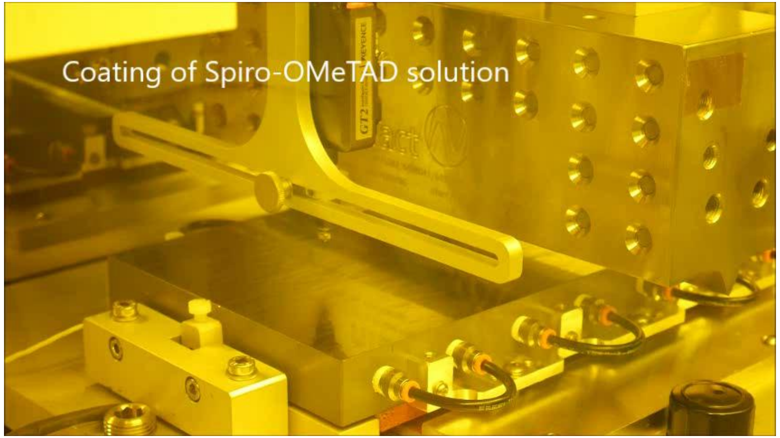


- 90% of initial stabilized power output after 1000 hr. MPPT in continuous operational condition (air, 40 °C, at Voc, encapsulated, for opaque and semi-transparent devices)

M. Najafi, V. Zardetto et al. *Sol. RRL* 2018, 1800147

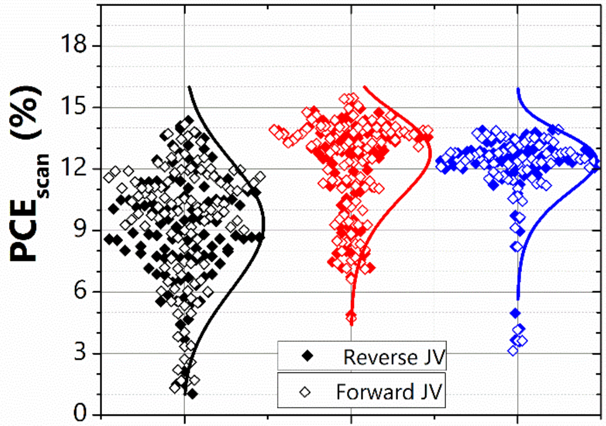
Scale up of baseline V3.0
Slot die coating (SD) of perovskite layer

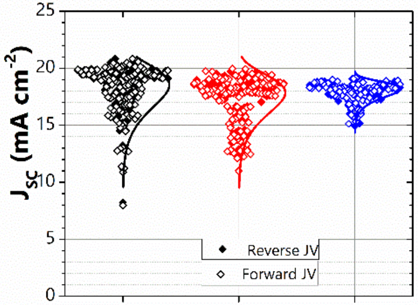


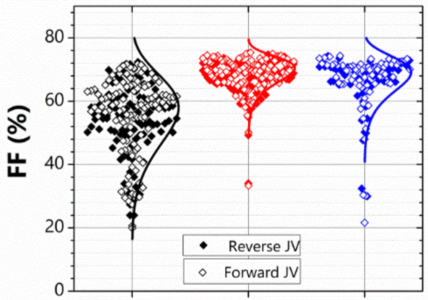


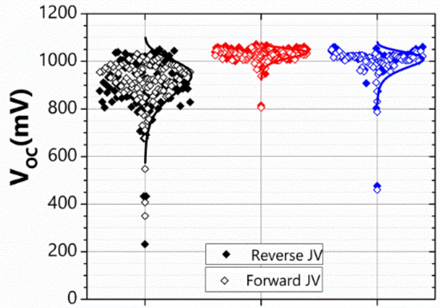
PIN Structure Upscaling: different stack

- **Different stack tested so far:**
  - **4x SD + metal**
  - **3x SD + sALD + metal**
  - **3x SD + sALD + TCO**
- **Advantage of sALD**
  - **Improve yield and PCE**
  - **Enable sputtering of TCO**
    - **Semitransparent and bifacial solar cell**





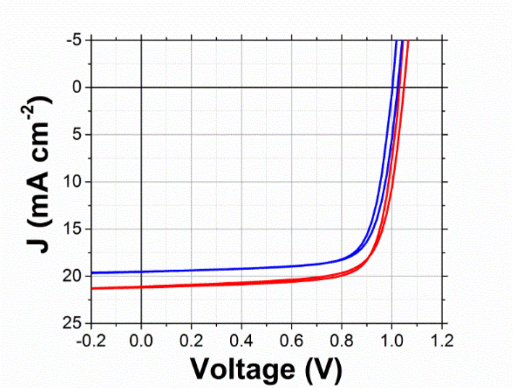


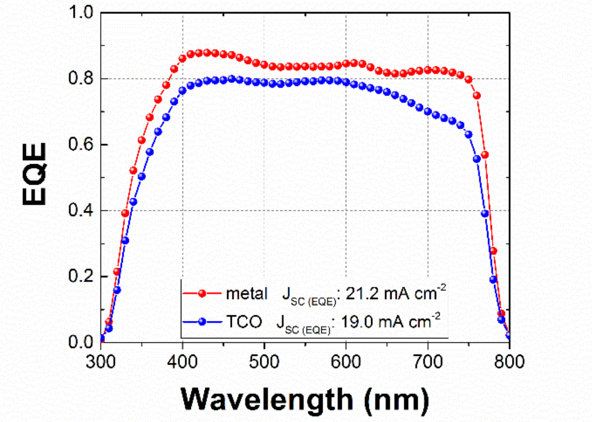


High PCE upscaled cell

- **Confirmed with EQE and MPPT**
  - **Up to 17% for sALD + METAL**
  - **Up to 15.2% for sALD + TCO**

	METAL		TCO	
scan	REV	FORW	REV	FORW
PCE (%)	16.4	16.6	15.1	14.9
J_{SC} (mAcm^{-2})	21.1	21.2	19.5	19.5
V_{OC} (mV)	1050	1030	1020	1000
FF (%)	74.4	76.2	75.3	76.0
MPPT (%)	17.0		15.2	

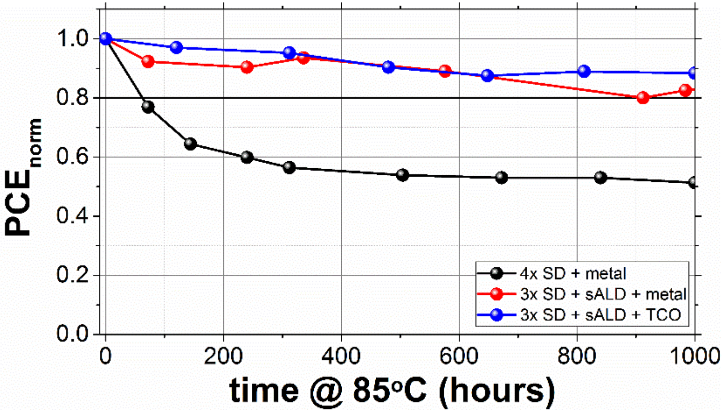




SOLLIANCE

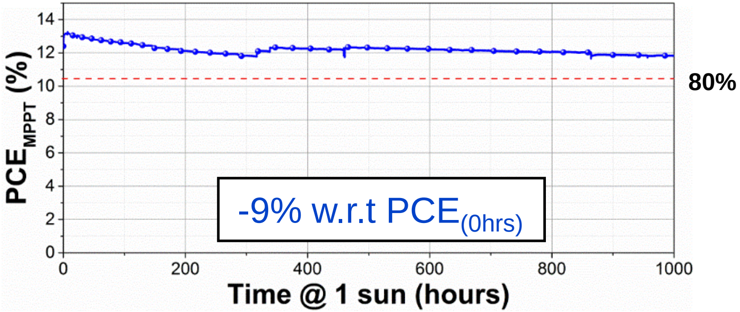
Light and Thermal Stability in N_2 environment

- **85ºC Thermal stress in N_2 (no encapsulation)**
  - sALD layer is crucial for stability
    - **LT_{80} ≈ 100 h**
    - **LT_{80} ≈ 1000 h**
    - **LT_{80} > 1000 h**



- **Light soaking in N_2 (with MPPT)**
  - **Tested only for sALD + TCO**
    - **LT_{80} >> 1000 h**
- **Encapsulated PSC* <u>pass both tests in air</u>**

* (SC + sALD)

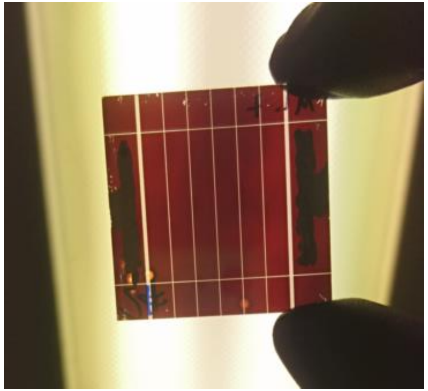


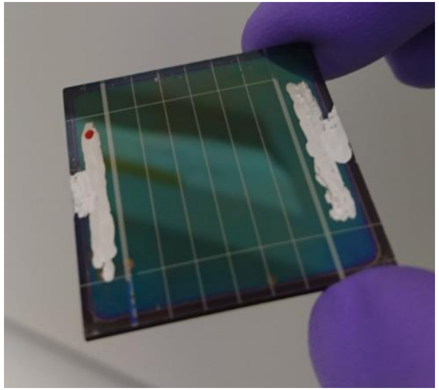
Towards large area stable modules

- **$16x\ 4\ cm^2$ minimodules processed on 6 inch**
  - PCE_{MPPT} of 13.6% on aperture area
  - PCE_{MPPT} of 14.7% on active area (GFF 92.6%)
  - Bifaciality factor 0.9 (without ARC)

Scan	Backward*	Forward*
V_{oc} (V)	6.33	6.36
J_{sc} (mA/cm^2)	19.0	19.0
FF	0.705	0.710
PCE	14.2%	14.3%
MPPT	**13.6**	

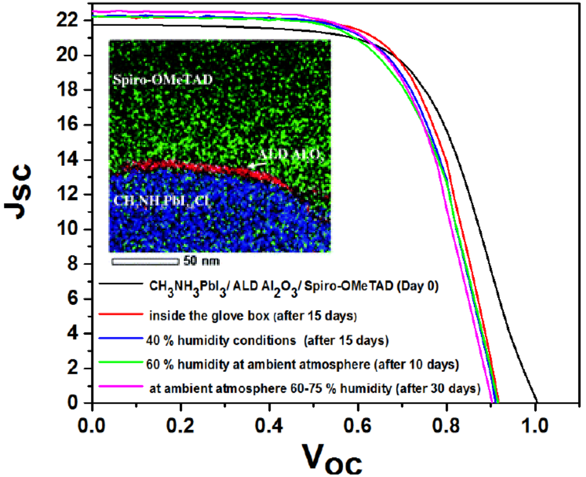
*Data on aperture area

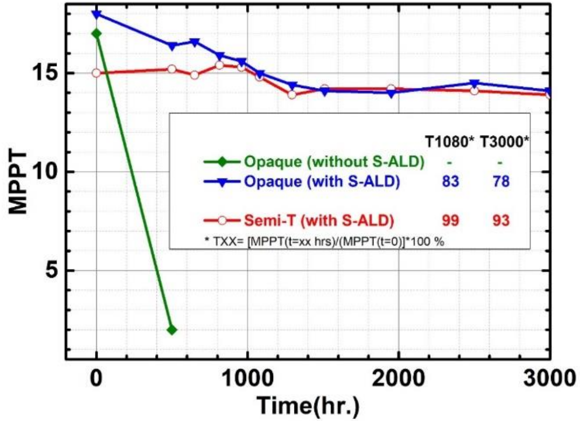




Conclusions

- ALD Al_2O_3 layers improve the efficiency *and* humidity stability of perovskitsolar cells with n-i-p configuration
- ALD deposited (or compact) MO layers enable semi-transparent perovskite solar cells apparently free of sputter damage
- ALD deposited (or compact) MO layers enable high thermal stability
- The developed stack (baseline V3.0) is stable and scalable: Devices have been prepared on 6 inch by a combination of slot die and sALD processes.

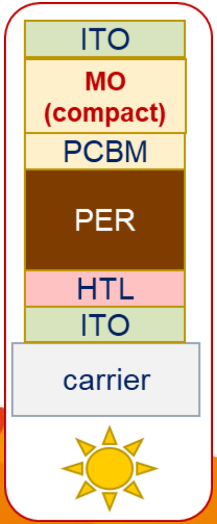


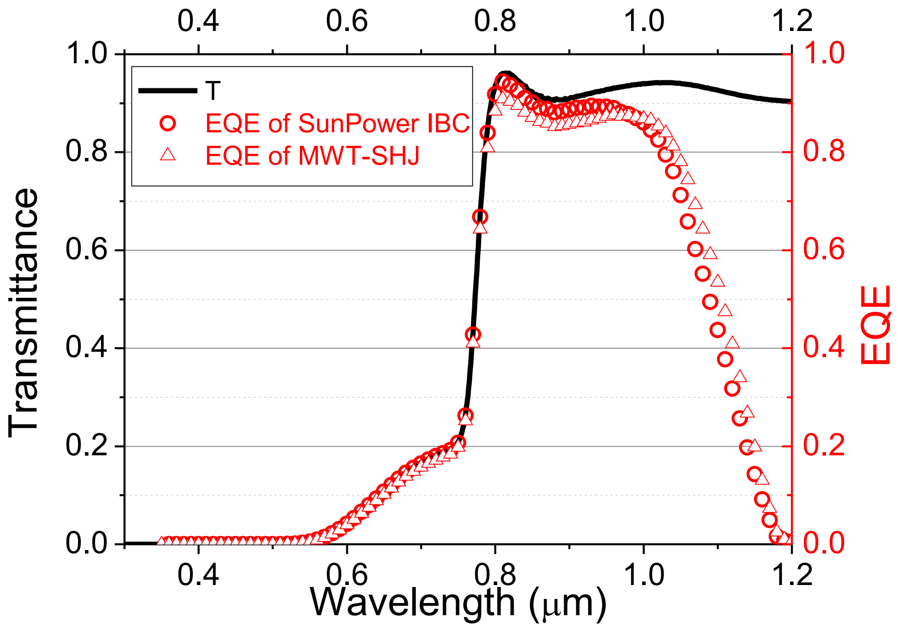


SOLLIANCE

High transmittance of ST-PSC

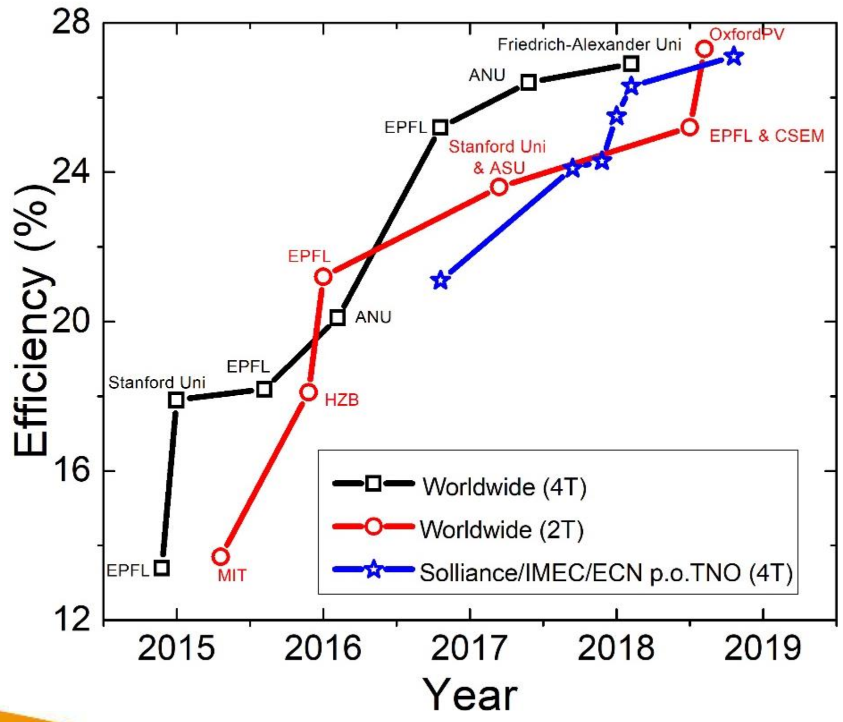
- **ITO improvement and light management**
- **Record NIR transmittance of average 93%**
- **EQE of SunPower IBC peaks at 94%**
- **MWT-SHJ has higher IR response in EQE**





D. Zhang et al. SOLMAT (2018) **188** 1–5

Fast progress in perovskite/c-Si tandem cells



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K. Bush et al, Nature Energy, 2, 2017,17009.
T. Duong et al, Adv. Energy Mater. 2017, 1700228.
J. Werner et al, Adv. Mater. Interfaces 2018, 5, 1700731.
J. Werner et al, ACS Energy Letters, 2016,1, 474.
https://www.imec-int.com/en/articles/imec-beats-silicon-pv-with-27-1-percent-perovskite-silicon-tandem

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Thank you for your attention!

www.solliance.eu
sjoerd.veenstra@solliance.eu