Perovskite Silicon Tandem Cells

Reliable, efficient and cost effective

Daniel Kirk

11th October 2016

Oxford PV

UK Centre focused on commercializing perovskite solar cell technology

December 2010 Oxford University spinout

>GBP30M equity raised to date

Combining the talents of 30+ Oxford PV scientists and engineers with Prof Henry Snaith's academic research team of 20 scientists

Chemistry/formulations laboratory

- Chemical preparation and characterisation
- Kg scale formulations capacity

Fabrication

- ISO class 7 clean room
- Research scale monolithic tandem cells
- Currently commissioning demonstration line

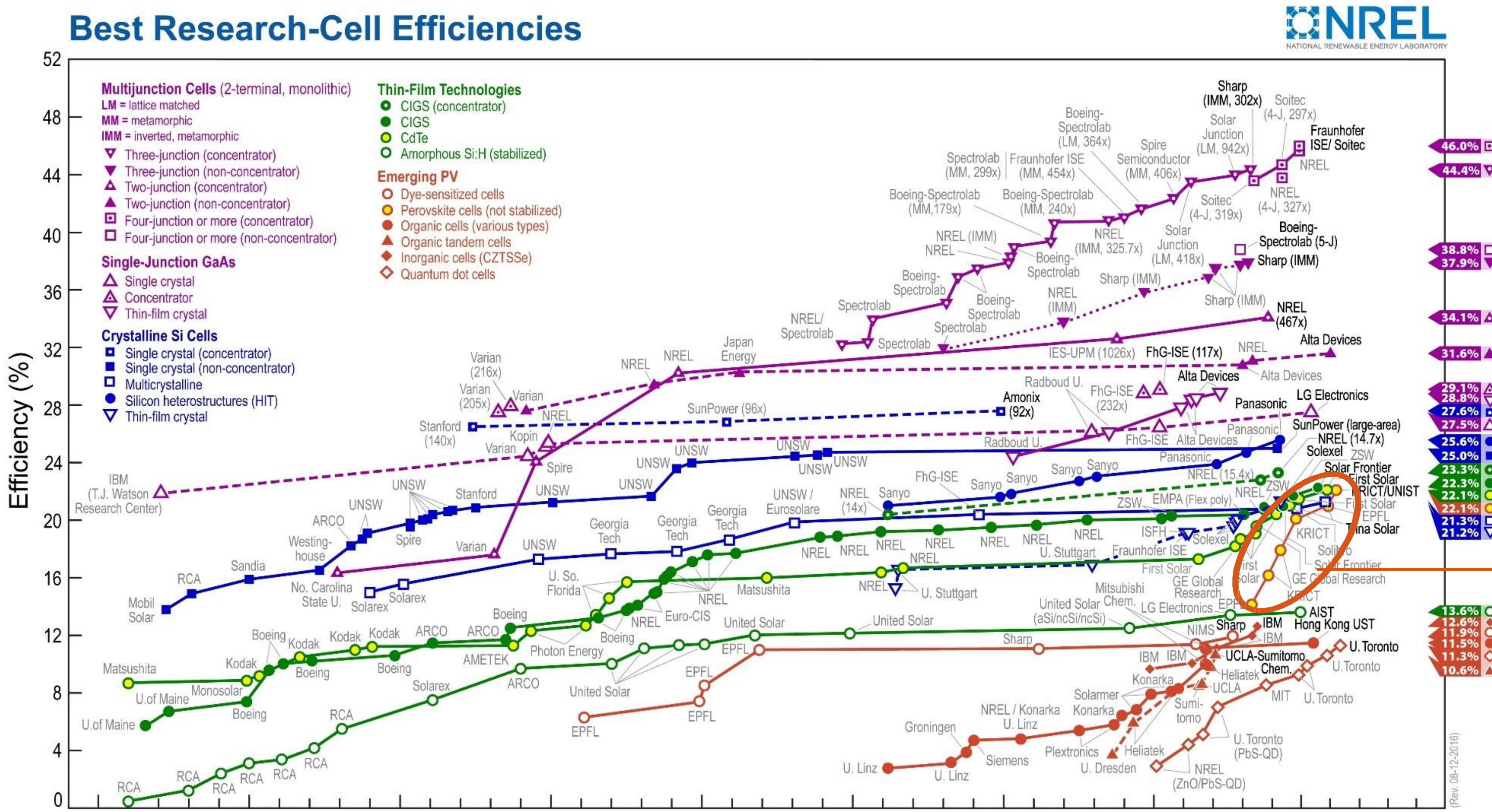
Test and reliability laboratory

- Climatic testing to IEC 61646

Perovskite solar cells

Perovskite is the fastest improving technology in PV history

0 – 22% in 3 years

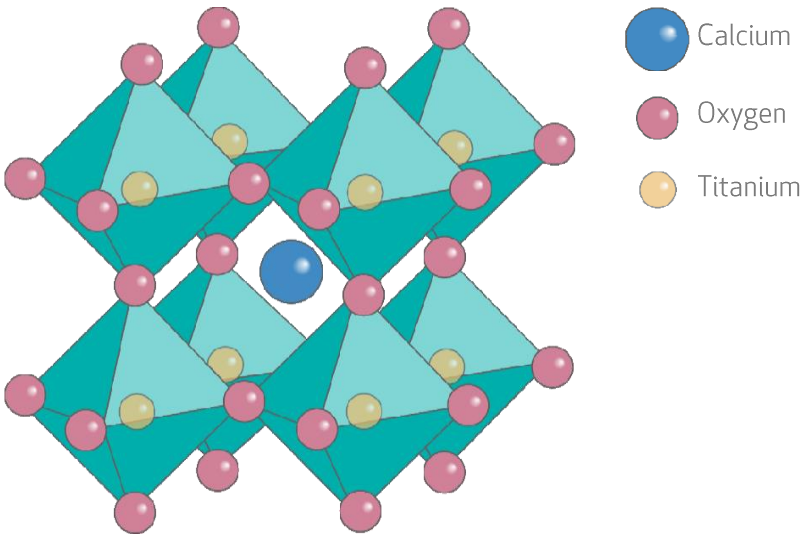


That's perovskite

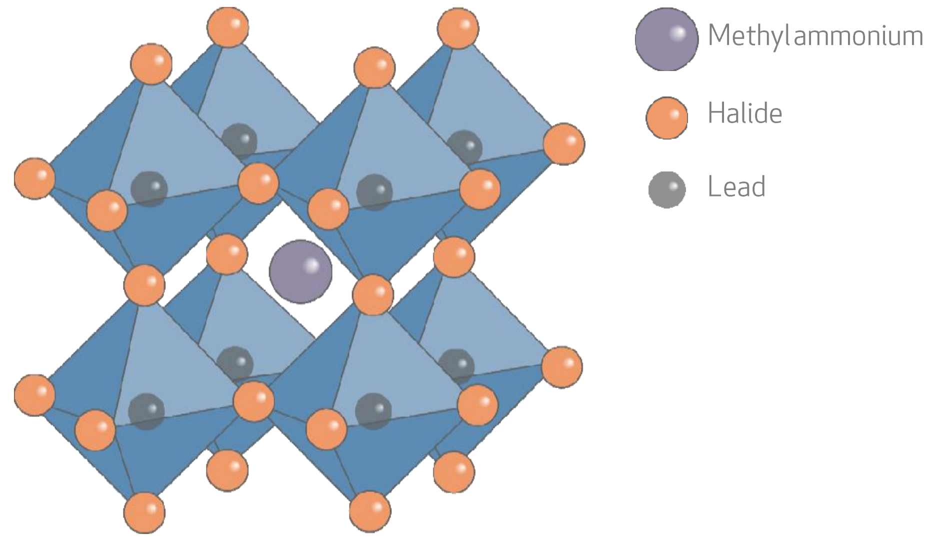
OXFORD PV

What is a perovskite?

The mineral perovskite



Typical perovskite solar absorber



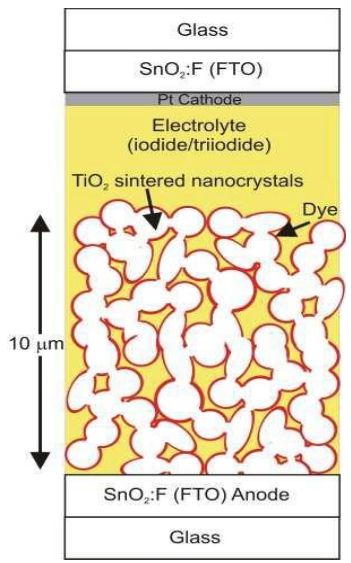
Miyasaka *et al.* JACS 2009, 131, 6050-6051
Park *et al. Nanoscale*, 2011,**3**, 4088-4093

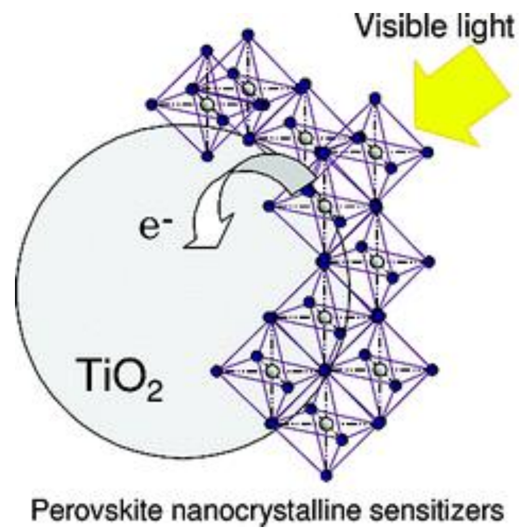
First published perovskite PV cells

Organometal Halide Perovskites as Visible-Light Sensitizers for Photovoltaic Cells

Akihiro Kojima,[†] Kenjiro Teshima,[‡] Yasuo Shirai,[§] and Tsutomu Miyasaka[*,†,‡,∥]

J. AM. CHEM. SOC. 2009, *131*, 6050–6051





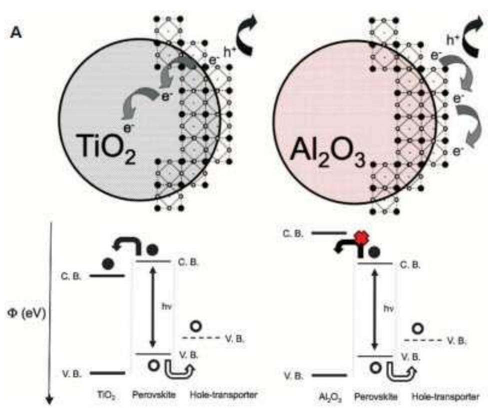
Miyasaka ***et al.*** **JACS** 2009, 131, 6050-6051
Park ***et al. Nanoscale***, 2011,**3**, 4088-4093

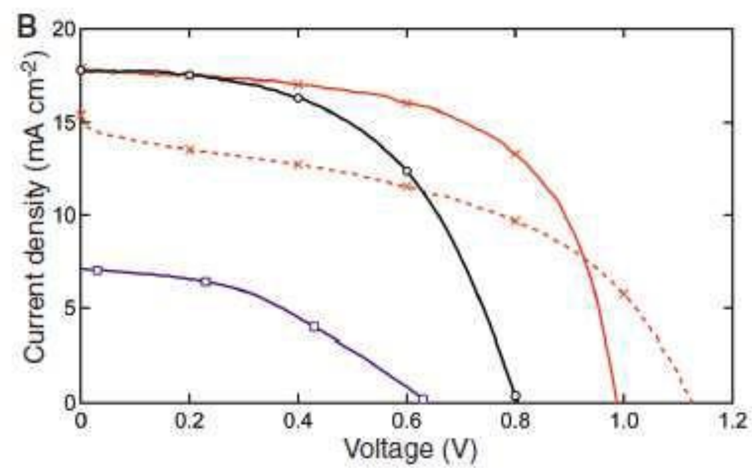
The paper in *Science* that prompted all the fuss

Efficient Hybrid Solar Cells Based on Meso-Superstructured Organometal Halide Perovskites

Michael M. Lee,[1] Joël Teuscher,[1] Tsutomu Miyasaka,[2] Takurou N. Murakami,[2,3] Henry J. Snaith[1]*

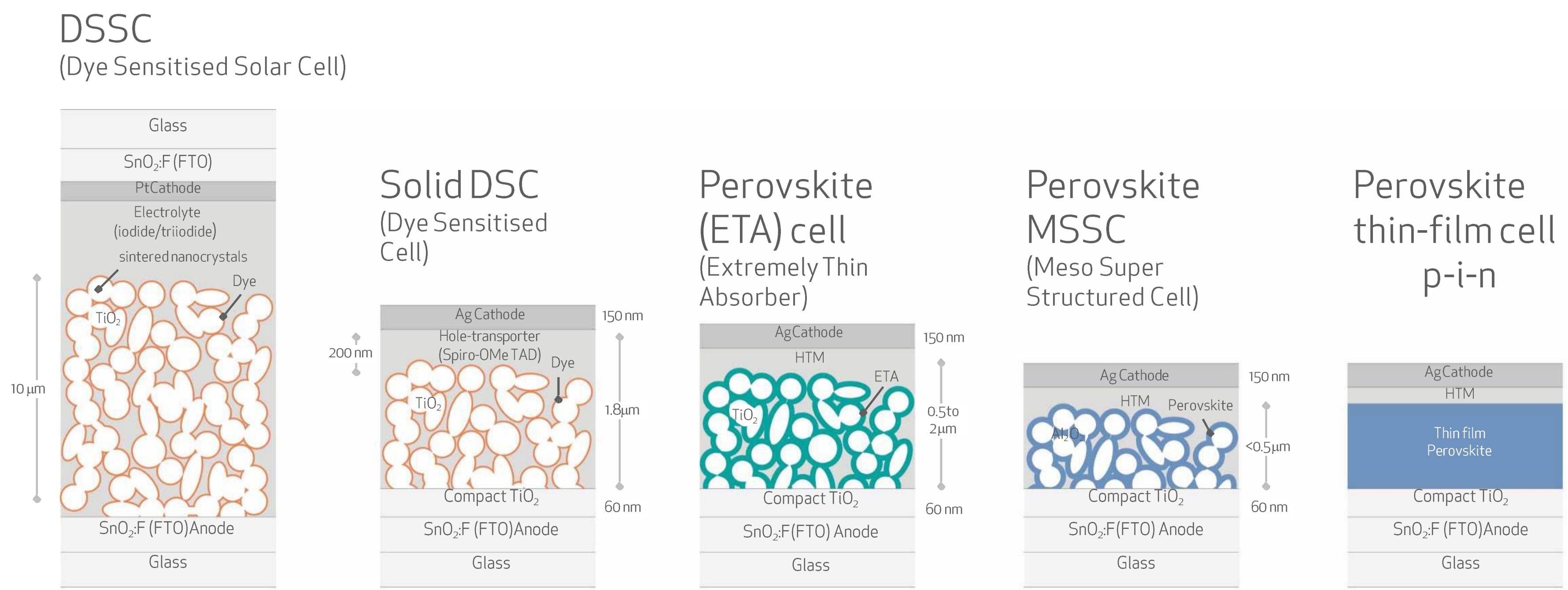
SCIENCE VOL 338 2 NOVEMBER 2012 643





Evolution to revolution

No longer a dye-sensitised cell



2011
5% efficiency
500 °C process
UV instability

2014
17% efficiency
150 °C process
UV stable

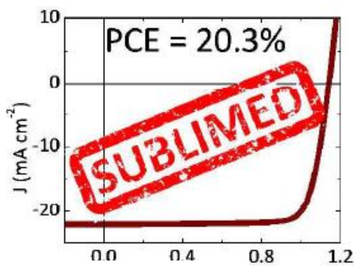
State-of-the-art and target perovskite efficiencies

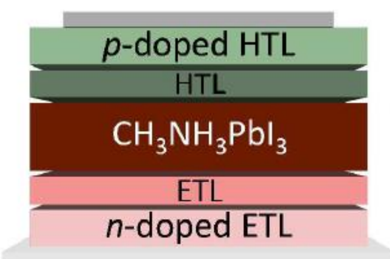
A number of competing high efficiency architectures and processing options

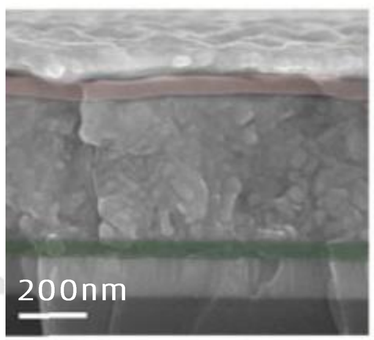
Vacuum deposition - Bolink

Energy & Environmental Science
View Article Online

Efficient vacuum deposited p-i-n and n-i-p perovskite solar cells employing doped charge transport layers





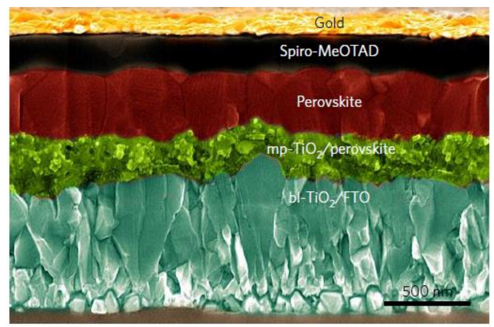


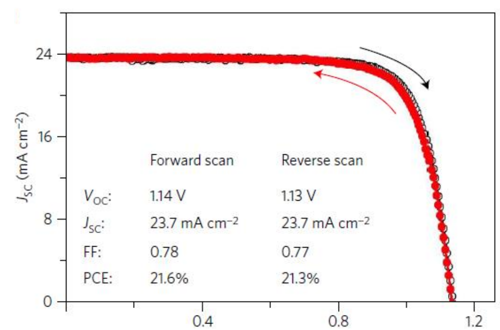
Solution deposition - Graetzel

nature energy
ARTICLES
PUBLISHED: 19 SEPTEMBER 2016 | ARTICLE NUMBER: 16142 | DOI: 10.1038/NENERGY.2016.142

Polymer-templated nucleation and crystal growth of perovskite films for solar cells with efficiency greater than 21%

21%



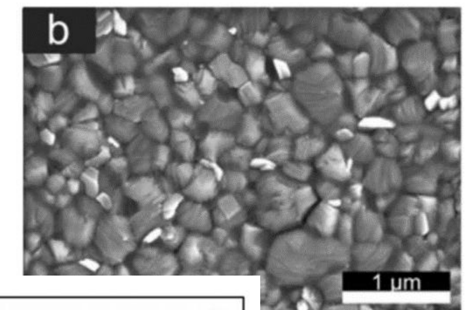


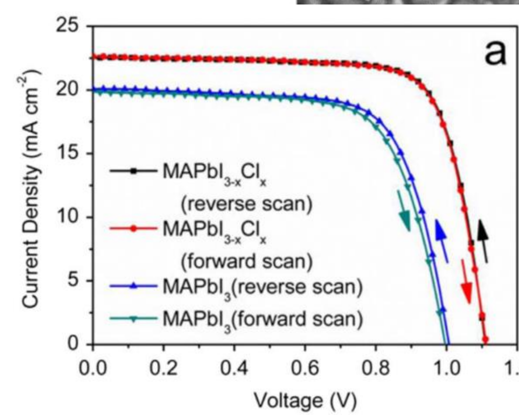
p-i-n 'inverted' – Liu & Bian

Contents lists available at ScienceDirect
Nano Energy
journal homepage: www.elsevier.com/locate/nanoen
ELSEVIER

A 19.0% efficiency achieved in CuO_x-based inverted $CH_3NH_3PbI_{3-x}Cl_x$ solar cells by an effective Cl doping method

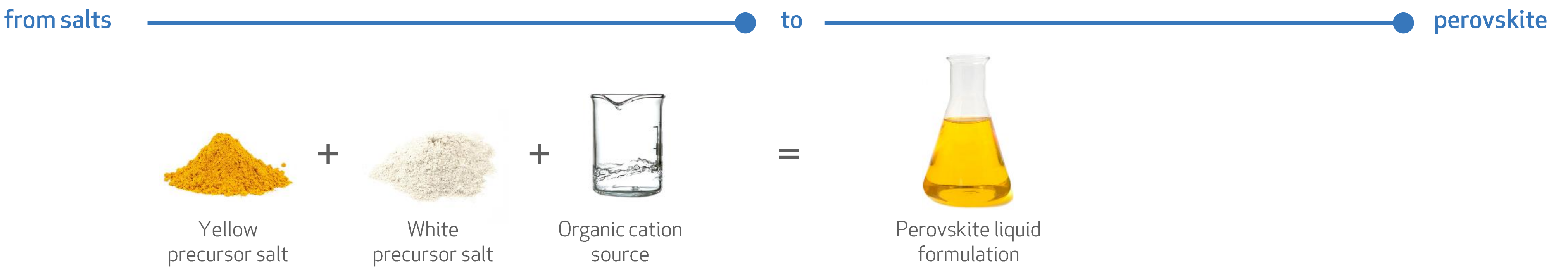
19%

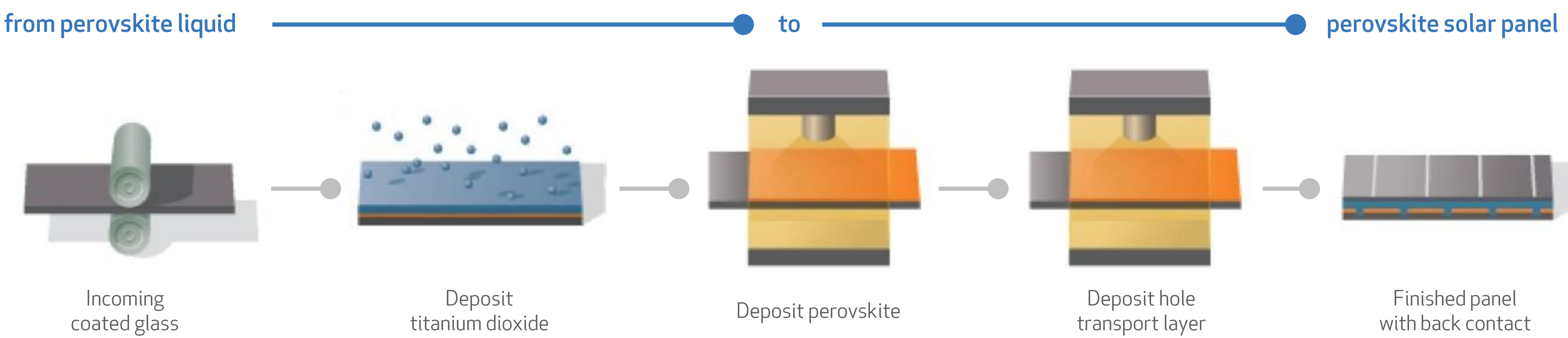




Production of perovskite cell

Simpler, lower cost, lower energy payback, reduced environmental impact, low LCOE





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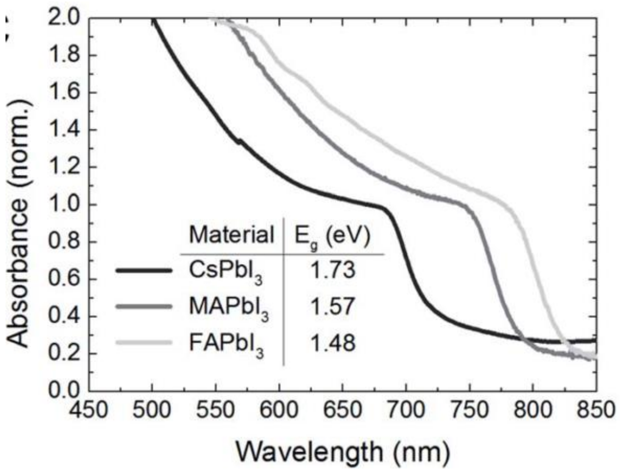
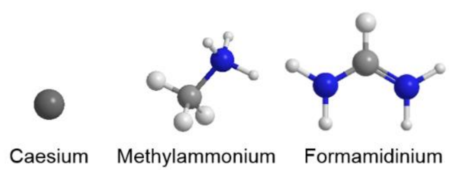
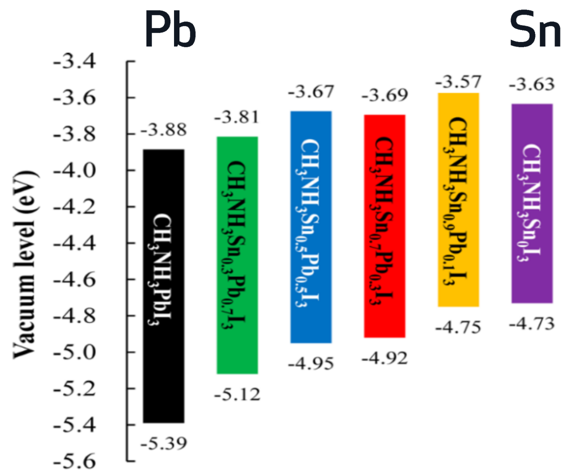
Band gap tunable by composition ABX3

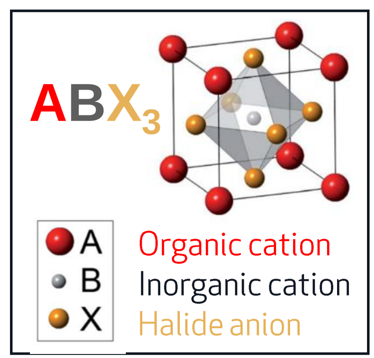
A cation substitution



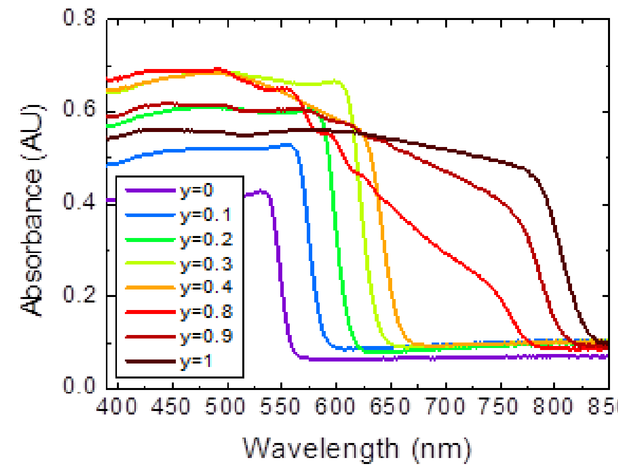


B: Metal substitution





X: Halide substitution



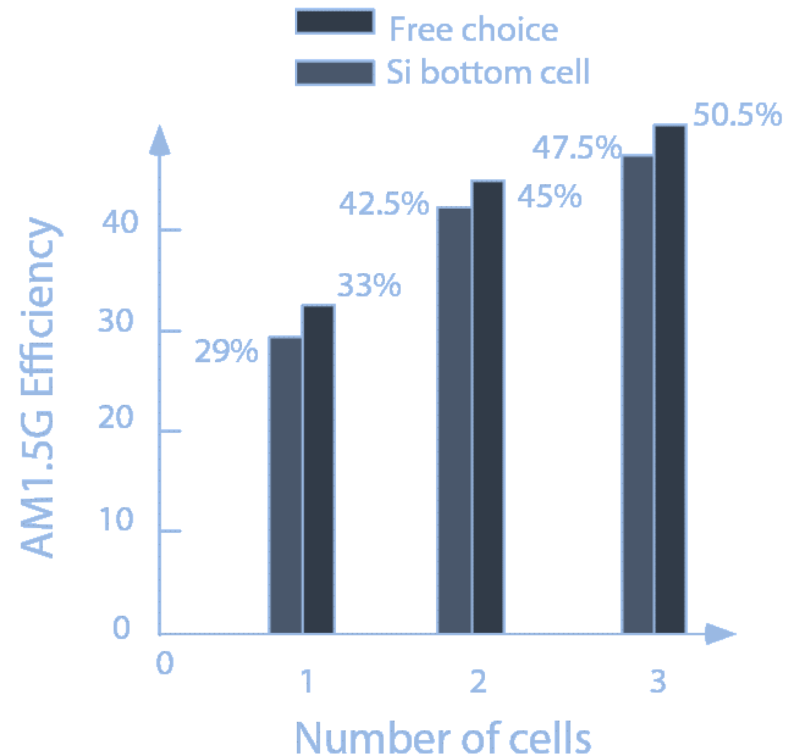
2.23 eV 1.48 eV

Br_3 I_3

Tandems

The Tandem: A group of two people or machines working together

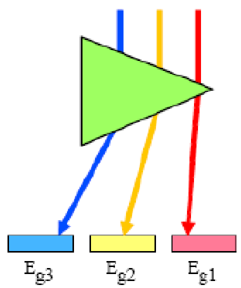
SQ limit of 42.5% for a silicon – 1.7eV two-junction cell



Two cells in one…

Possible tandem integration schemes

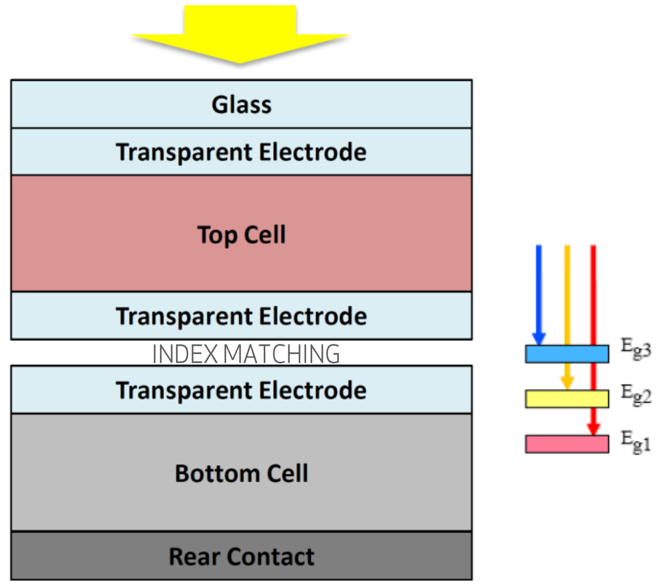
NO INTEGRATION



Spectral splitting of incident illumination

- Demonstration vehicle
- Not an obvious product

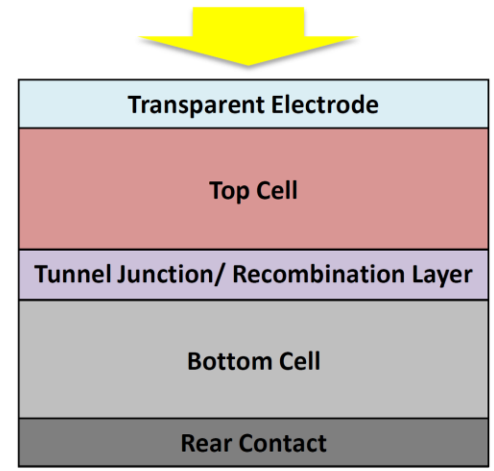
MECHANICAL STACK



4-terminal (mechanical stacking)

- Development time is probably shorter
- Optical loss of extra electrode layers
- More electrical components required

MONOLITHIC STACK



2-terminal (monolithic)

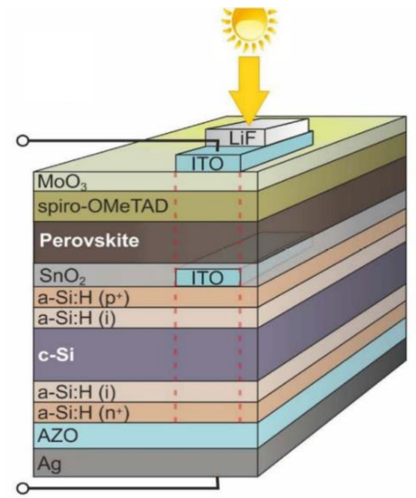
- Module fabrication easier
- Standard electrical connections
- Tunnel junction and current matching required

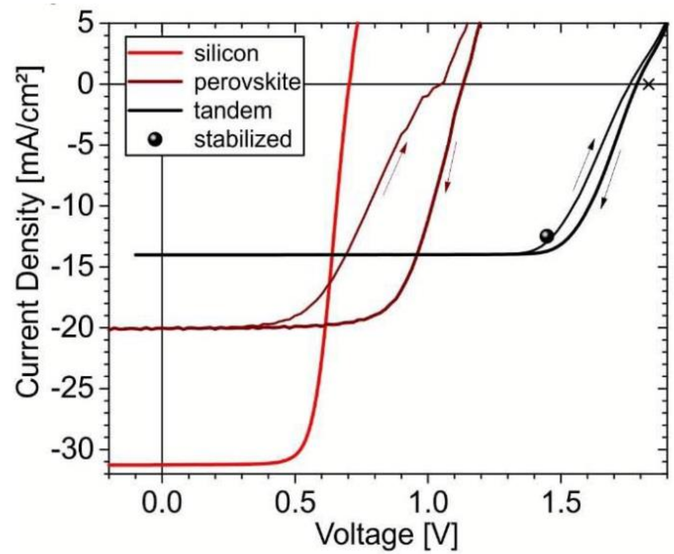
Predicted max efficiency is similar between both architectures

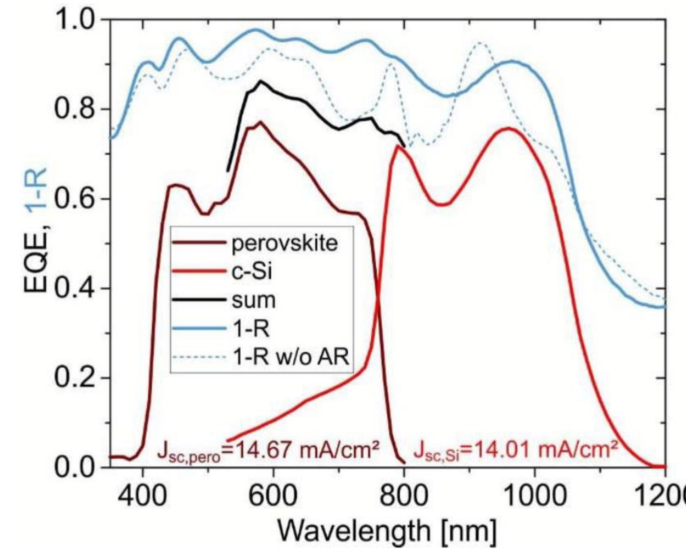
Monolithic 2-terminal silicon – perovskite PV cell

1.6eV perovskite absorber (1.13V single-junction V_{OC})

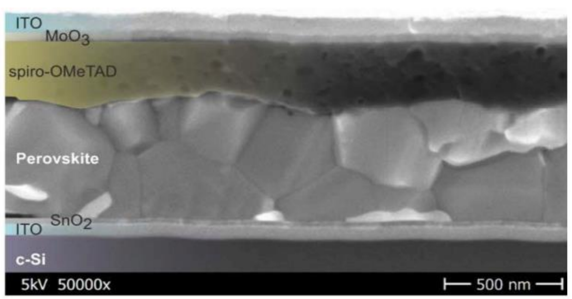
2-terminal schematic







Perovskite sub-cell

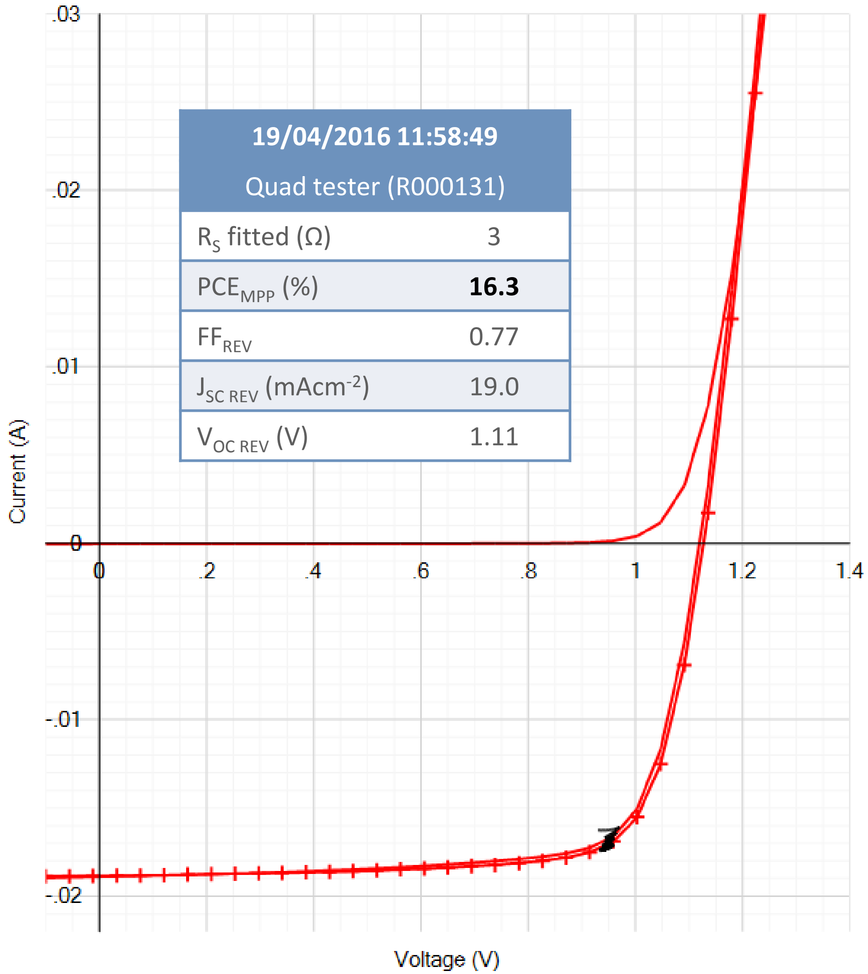


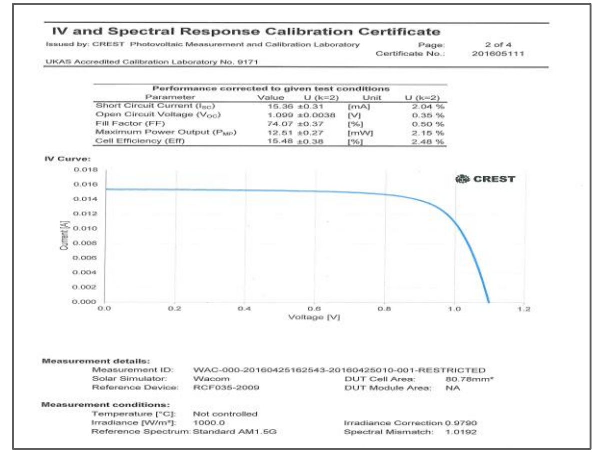
- Helmholtz centre (Berlin) and EPFL collaboration*
- Reported cell efficiency has reached 18.1%
- Optical optimisation (light coupling and IR parasitic loss) predict beyond 25%

*Albrecht et al. **EES 2015**, DOI: 10.1039/C5EE02965A

First prerequisite is good perforing wide bandgap perovskite

16.3% Single junction 1.7 eV perovskite – 1cm2





IV and Spectral Response Calibration Certificate

Issued by: CREST Photovoltaic Measurement and Calibration Laboratory — Page: 2 of 4 — Certificate No.: 201605111

UKAS Accredited Calibration Laboratory No. 9171

Performance corrected to given test conditions

Parameter	Value	U (k=2)	Unit	U (k=2)
Short Circuit Current (I_{SC})	15.36	±0.31	[mA]	2.04 %
Open Circuit Voltage (V_{OC})	1.099	±0.0038	[V]	0.35 %
Fill Factor (FF)	74.07	±0.37	[%]	0.50 %
Maximum Power Output (P_{MP})	12.51	±0.27	[mW]	2.15 %
Cell Efficiency (Eff)	15.48	±0.38	[%]	2.48 %

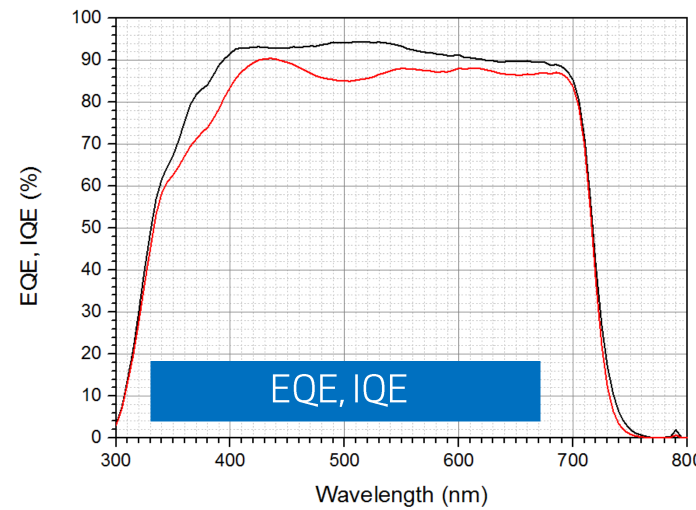
IV Curve:

Measurement details:

Measurement ID: WAC-000-20160425162543-20160425010-001-RESTRICTED
Solar Simulator: Wacom — DUT Cell Area: 80.78mm²
Reference Device: RCF035-2009 — DUT Module Area: NA

Measurement conditions:

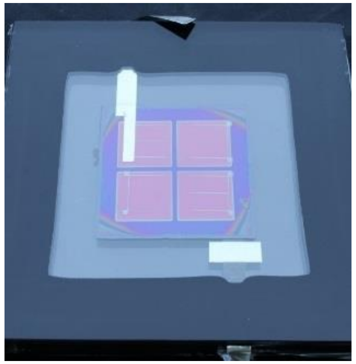
Temperature [°C]: Not controlled
Irradiance [W/m²]: 1000.0 — Irradiance Correction 0.9790
Reference Spectrum: Standard AM1.5G — Spectral Mismatch: 1.0192

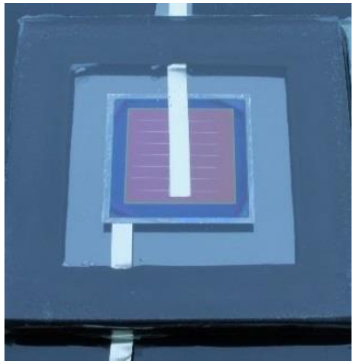


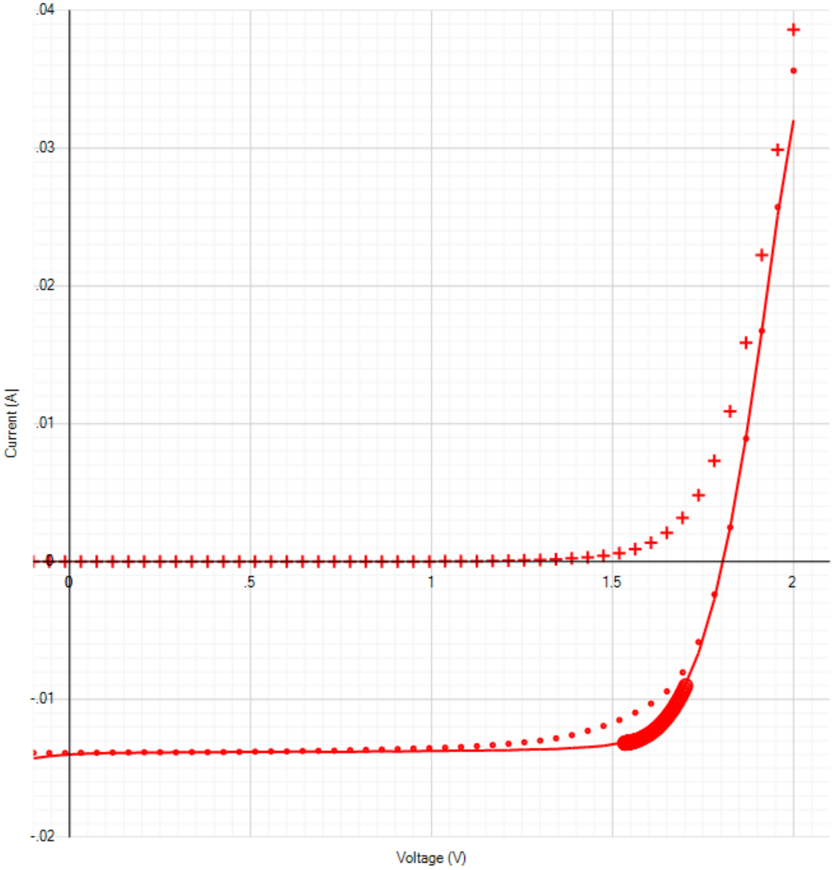
Monolithic (two-terminal) silicon perovskite tandem cells

Cells fabricated on heterojunction Si cells

	~1cm²	~4cm²
Efficiency (IV curve)	22.0%	21.4%
Isc	14.4mA	64.6 mA
Jsc	15.3mAcm^{-2}	16.5 mAcm^{-2}
Voc	1.80V	1.73V
Fill Factor	0.80	0.753
MPP efficiency	**22.0%**	**21.6%**



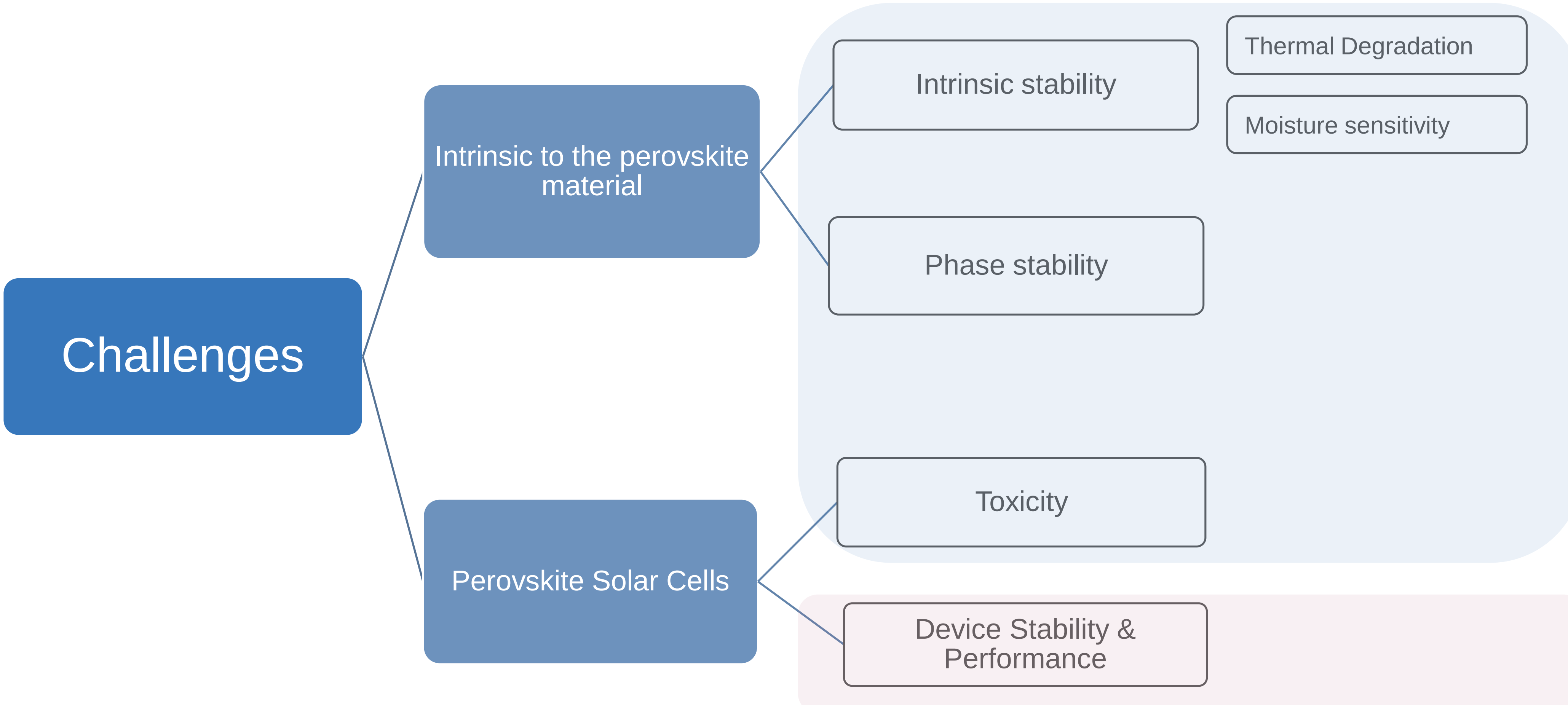




OXFORD PV

Commercial challenges

Challenges



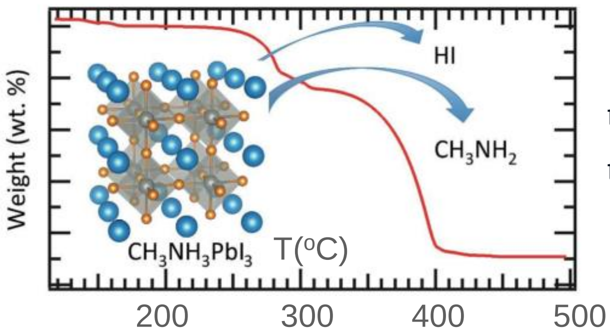
Challenges
Intrinsic to the perovskite material
Perovskite Solar Cells
Intrinsic stability
Thermal Degradation
Moisture sensitivity
Phase stability
Toxicity
Device Stability & Performance

Intrinsic perovskite stability

Estimated 90% of the published literature on PSC use the formulation **$MAPbI_3$** for the absorber layer.

This material presents the following features

Thermal degradation observed under 80-100°C stressing



thermal loss of the organic salt

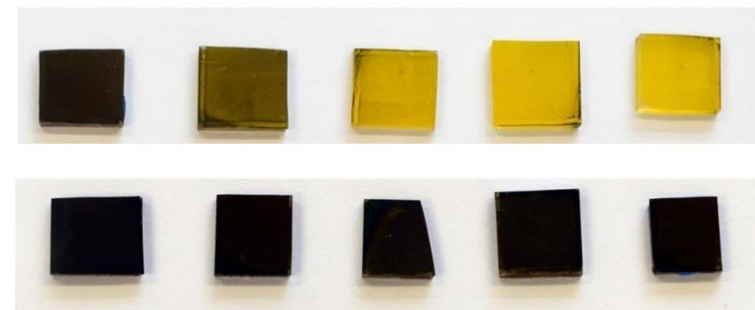
Degradation accelerated by exposure to ambient air

80°C

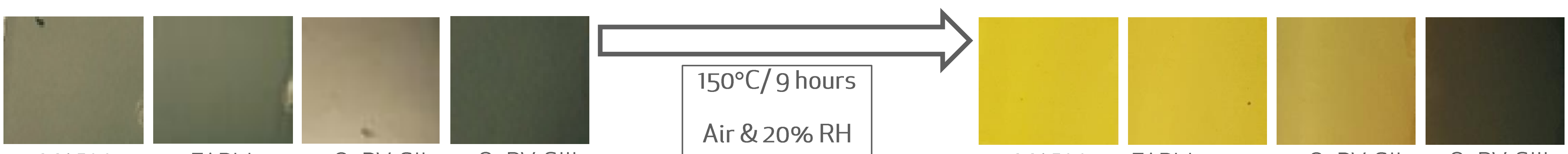
0 h | 24 h | 48 h | 72 h | 96 h

Exposed film

Thin-film encapsulated



By *tuning the A B and X stoichiometry* (ABX_3) of the perovskite, OxPV has developed a perovskite with improved thermal stability



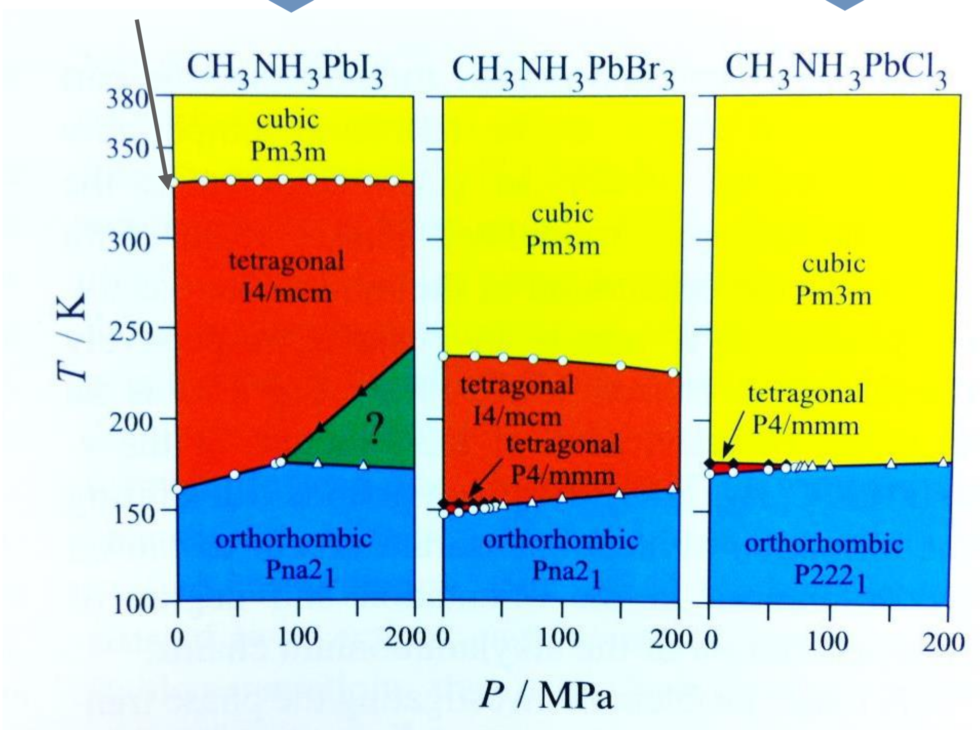
$MAPbI_3$ | $FAPbI_3$ | OxPV-SII | OxPV-SIII → $MAPbI_3$ | $FAPbI_3$ | OxPV-SII | OxPV-SIII

Improved phase stability

Covers entire operating range of PV panels

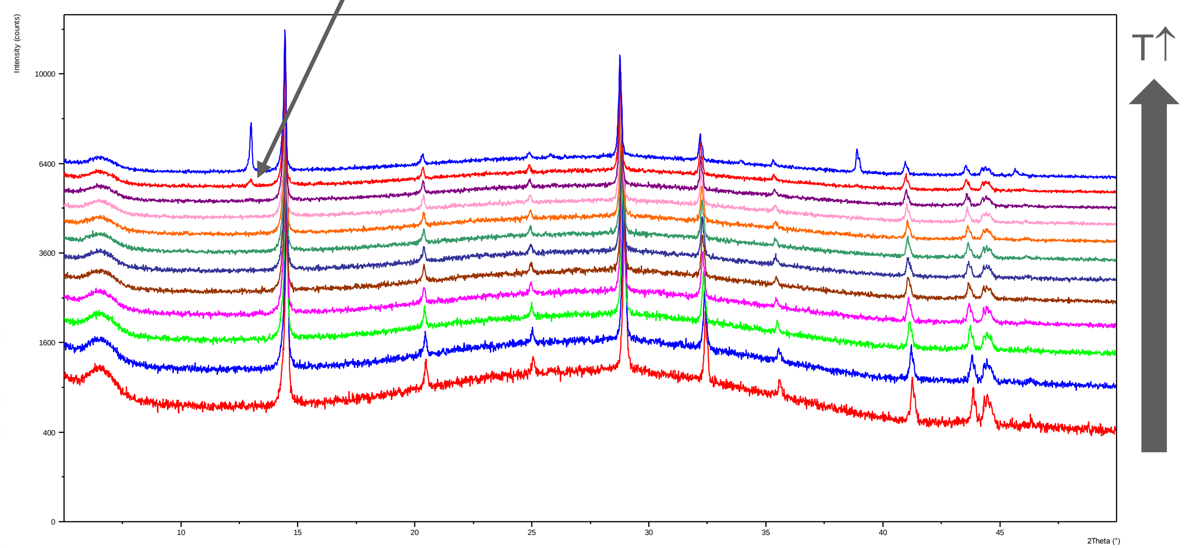
60°C

MAPbX$_3$



OxPV-SIII

No phase transition by XRD between 0 and 200C

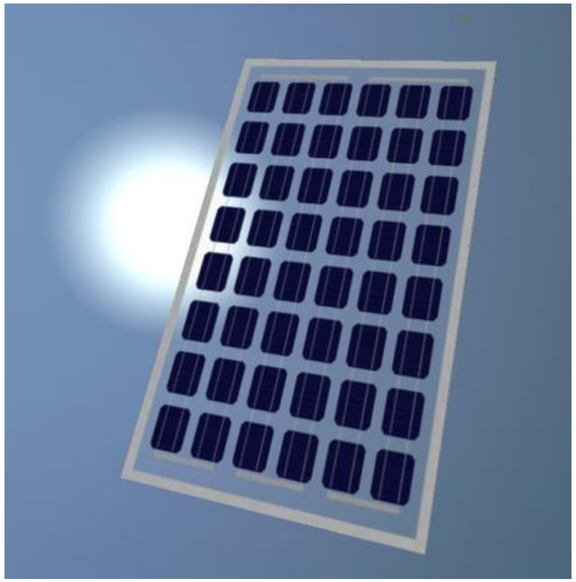


N. Onoda-Yamamuro et al. *J. Phys. Chem. Solids,* 1992, 53, 277
Roger H. Mitchell, Perovskites: Modern and ancient, 2002, Almaz Press Inc.

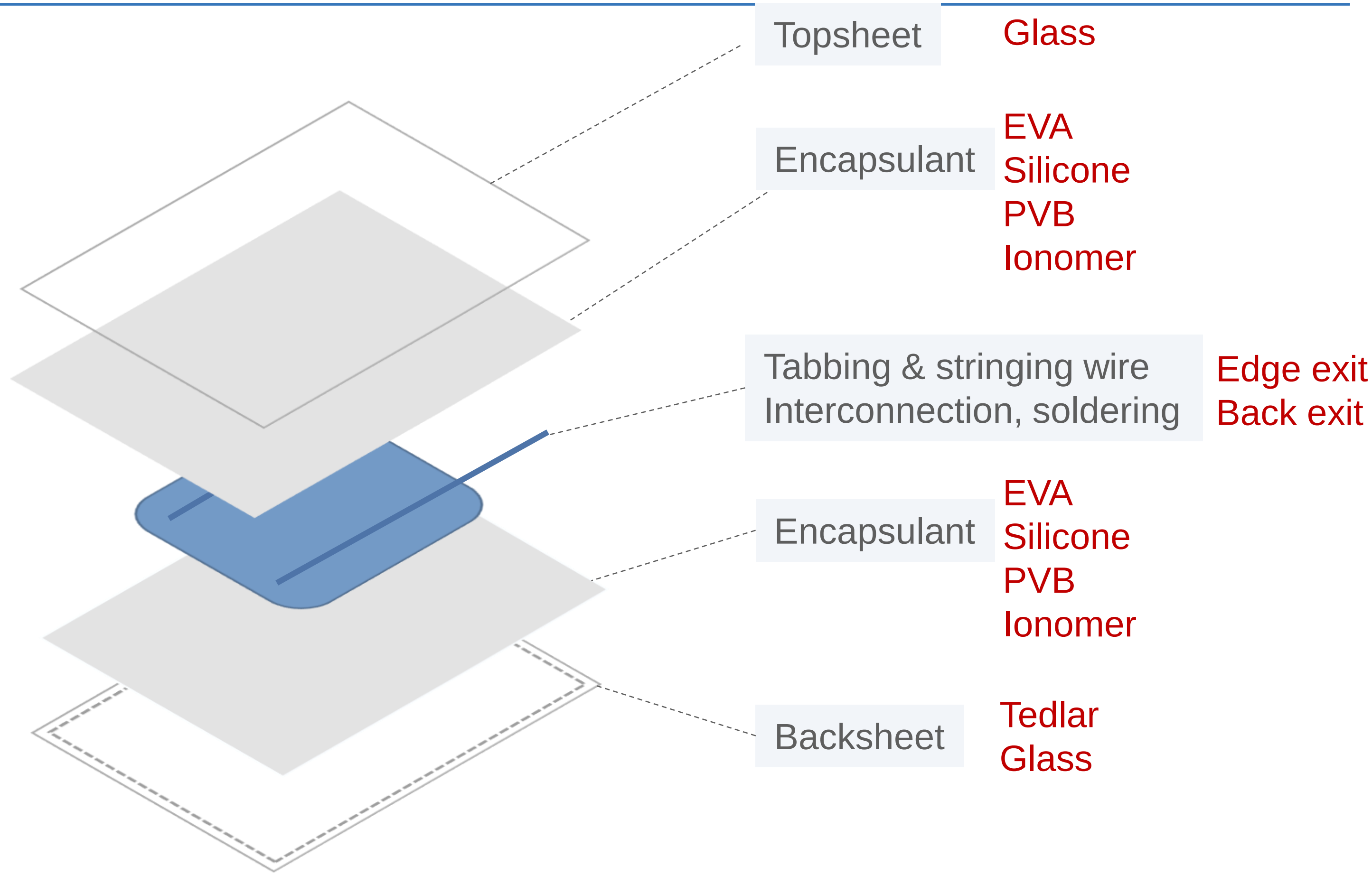
Device Stability

Module assembly - encapsulation

Perovskite tandem cells use industry standard encapsulation processes



- Encapsulate to protect from external environment
- Improve lifetime of devices



Tandem encapsulation

85°C-85%RH stressing

Encapsulated

- Scalable encapsulation process compatible with standard module assembly process

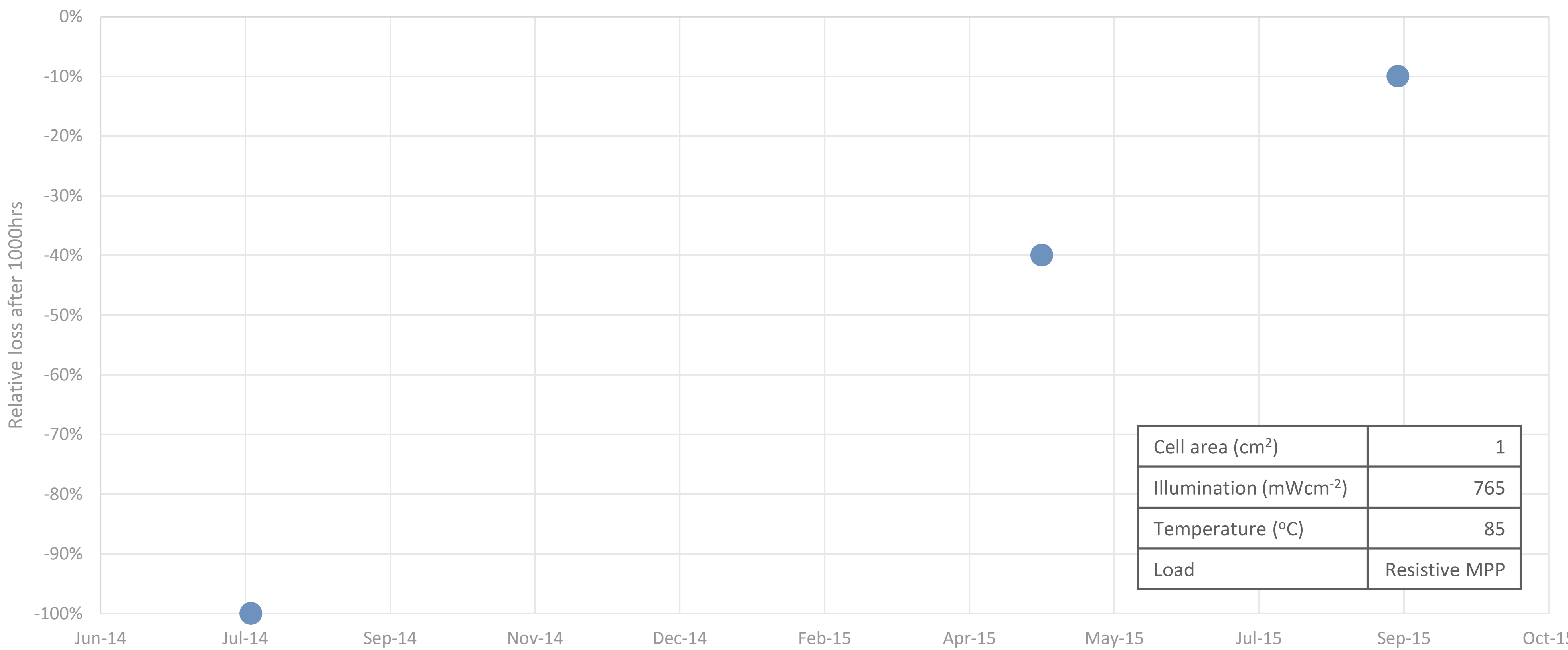
Perovskite stability requirements

Target stability performance for cells based upon IEC61646

Perovskite Targets		
Test	Details	Performance
Light Soaking	60°C illuminated under MPP loading	<10% drop in 1000 hrs
Thermal cycle	-40 to +85°C	<10% loss in 200 cycles
Damp heat	85°C, 85% rh	<10% drop in 1000 hrs

Perovskite operational cell stability historic progress

Light Soak 1000h stability for 1cm² glass-glass laminated single junction cells – 85C



Cell area (cm^2)	1
Illumination ($mWcm^{-2}$)	765
Temperature (°C)	85
Load	Resistive MPP

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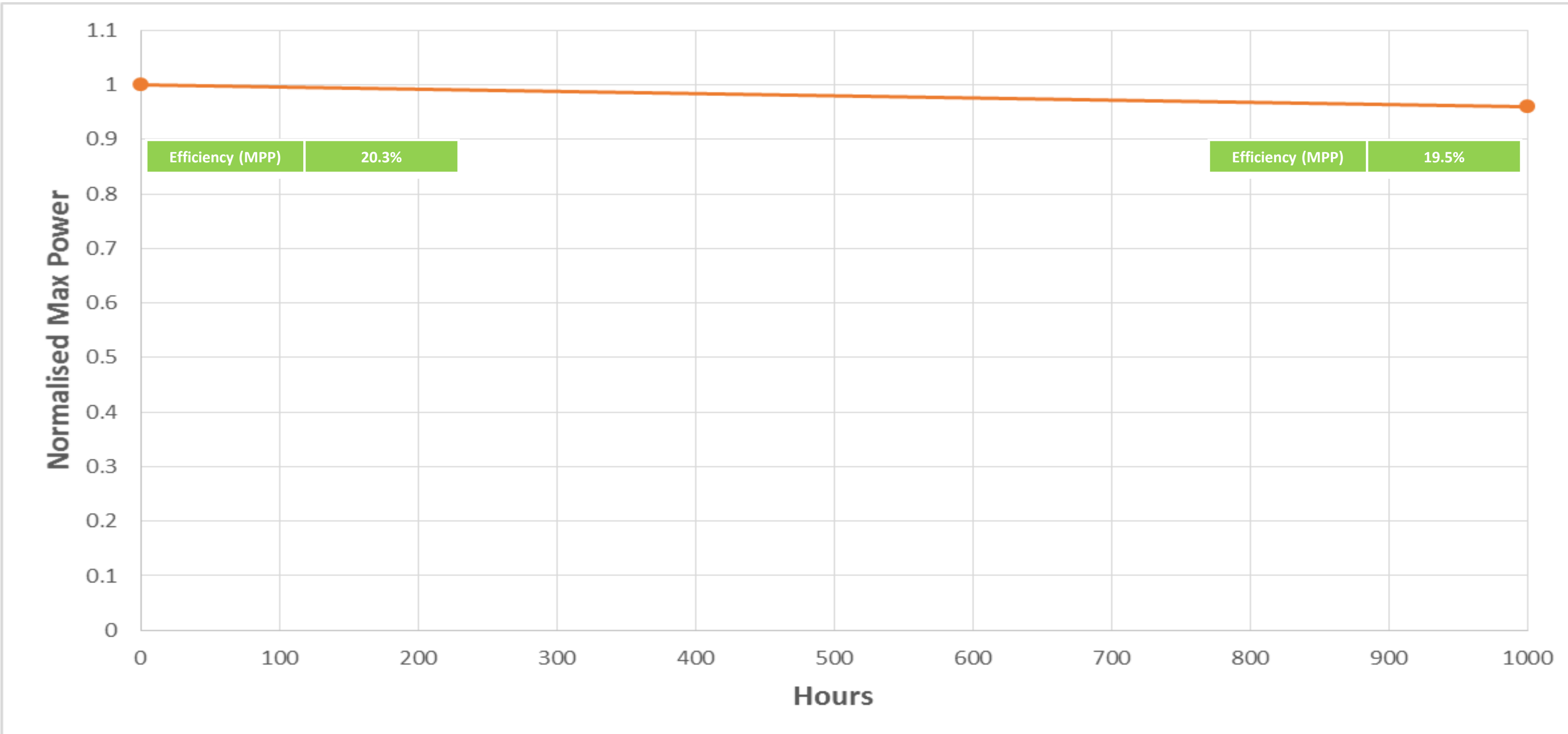
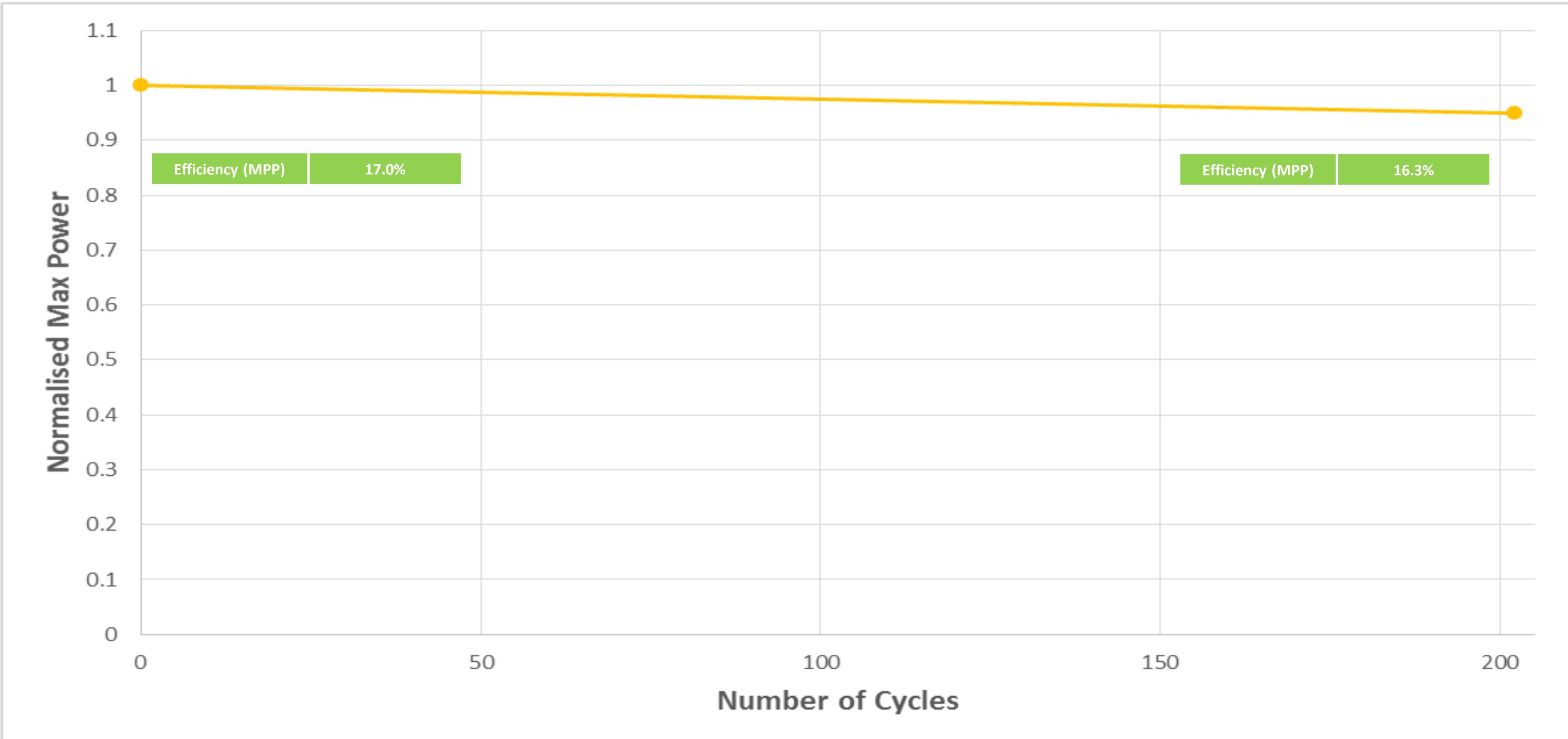
Reliability testing: tandem cells light soak

1000 hours (60°C light soak) with <5% drop achieved



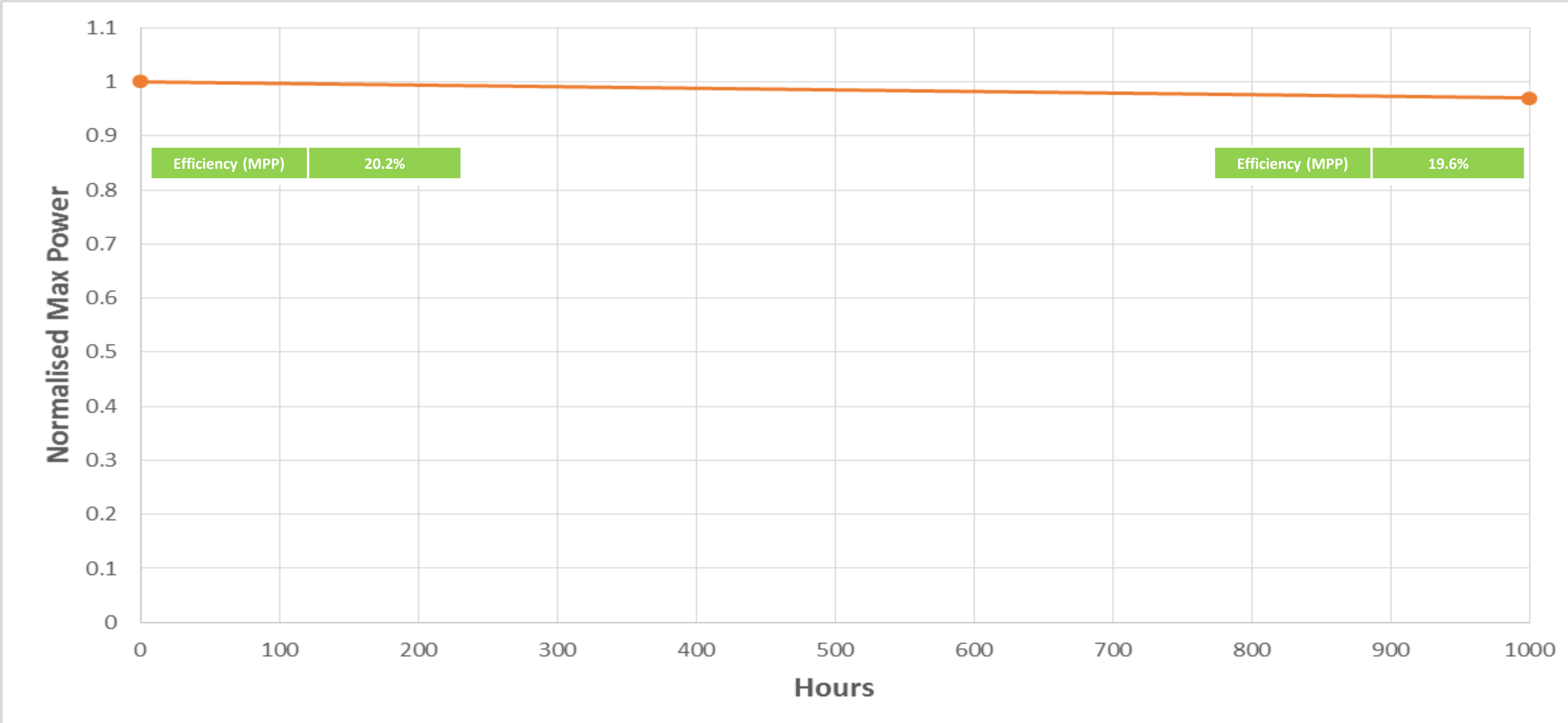
Reliability testing: tandem cell temperature cycling

200 cycles (-40ºC to +85ºC) with < 5% drop achieved



Reliability testing: tandem cells damp heat

1000 hours (85%RH/85^{o}C) with <4% drop achieved



Sustainability

Lead content in perspective

Toxicity

Expected lifetime (years)	∞	∞	∞	3-4	10-25

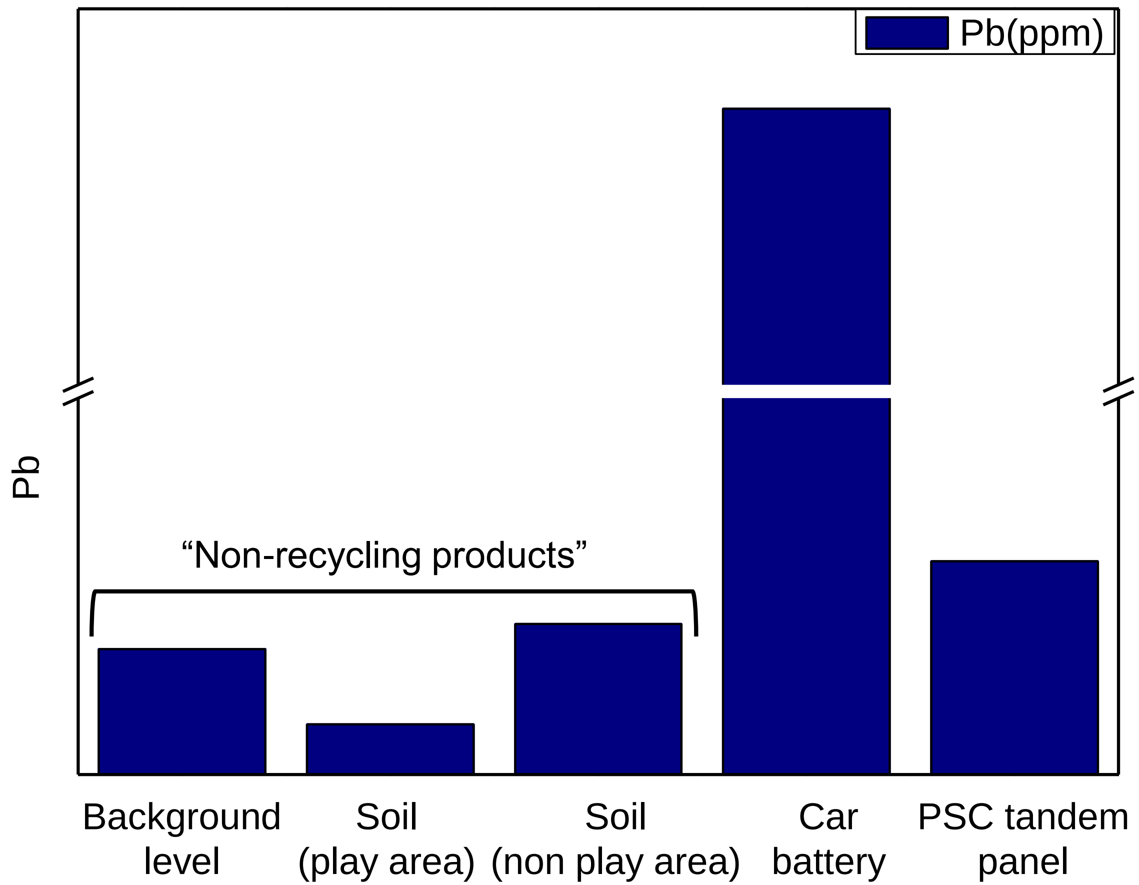
0.8 grams /m2

Energy payback

2 months

Contrast

8 g (average) of Pb in solder for PV panels



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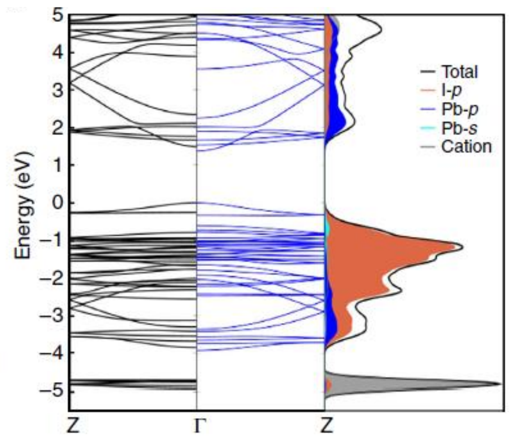
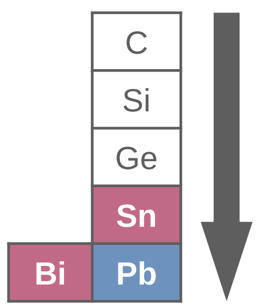
Lead replacement and/or reduction

No Pb-free perovskites have matched Pb-containing for performance

VB: Halide *p* states + Lead empty *s* states
CB: Lead *p* states

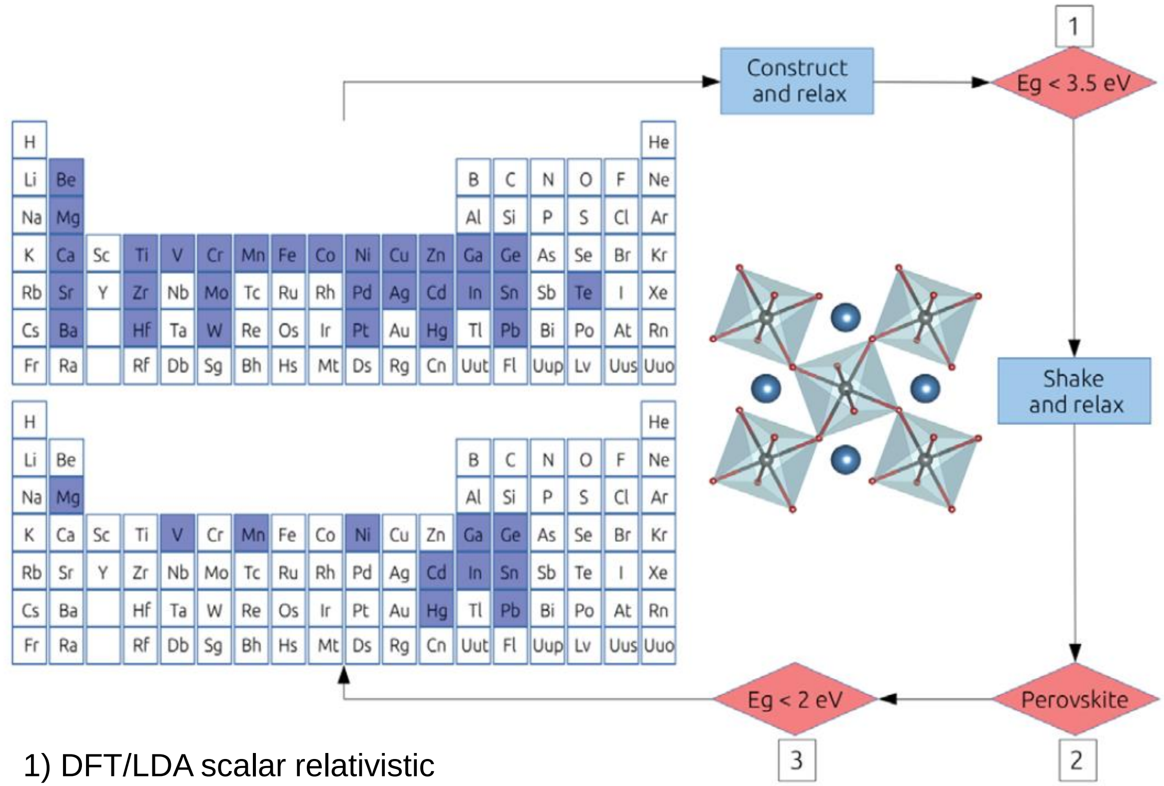




Ionic character

Electro neutrality?

Homovalent Lead substitutions



1) DFT/LDA scalar relativistic
2) Fully relativistic band gap

OXFORD PV

Filip *et al.* Nature. Com. (2014)
T. Baikie et al. J. Mater. Chem. A. (2013)
Filip *et al.* J. Phys. Chem. C. (2015)

Economic benefits of silicon perovskite tandem PV technology

External verification of cost added

Modeled 100MW PV fab perovskite tandem upgrade

For 100MW of existing capacity upgraded to perovskite:

	Volume production setup	Pilot production setup
Capital expenditure	$16.5m	$25.5m
Added production cost per cell:		
Materials	$0.11	$0.11
Equipment amortisation (inc. depreciation, labour & overhead)	$0.11	$0.15
Total	$0.22	$0.26

Assumptions:

- 7-year asset life
- 80% materials utilisation
- 90% equipment utilisation

- Calculated using “Factory Commander” model from Wright, Williams & Kelly - www.wwk.com
- Industry-standard software, widely used by semiconductor and PV manufacturing companies

Reduced cost per watt

Efficiency benefit outweighs extra cost

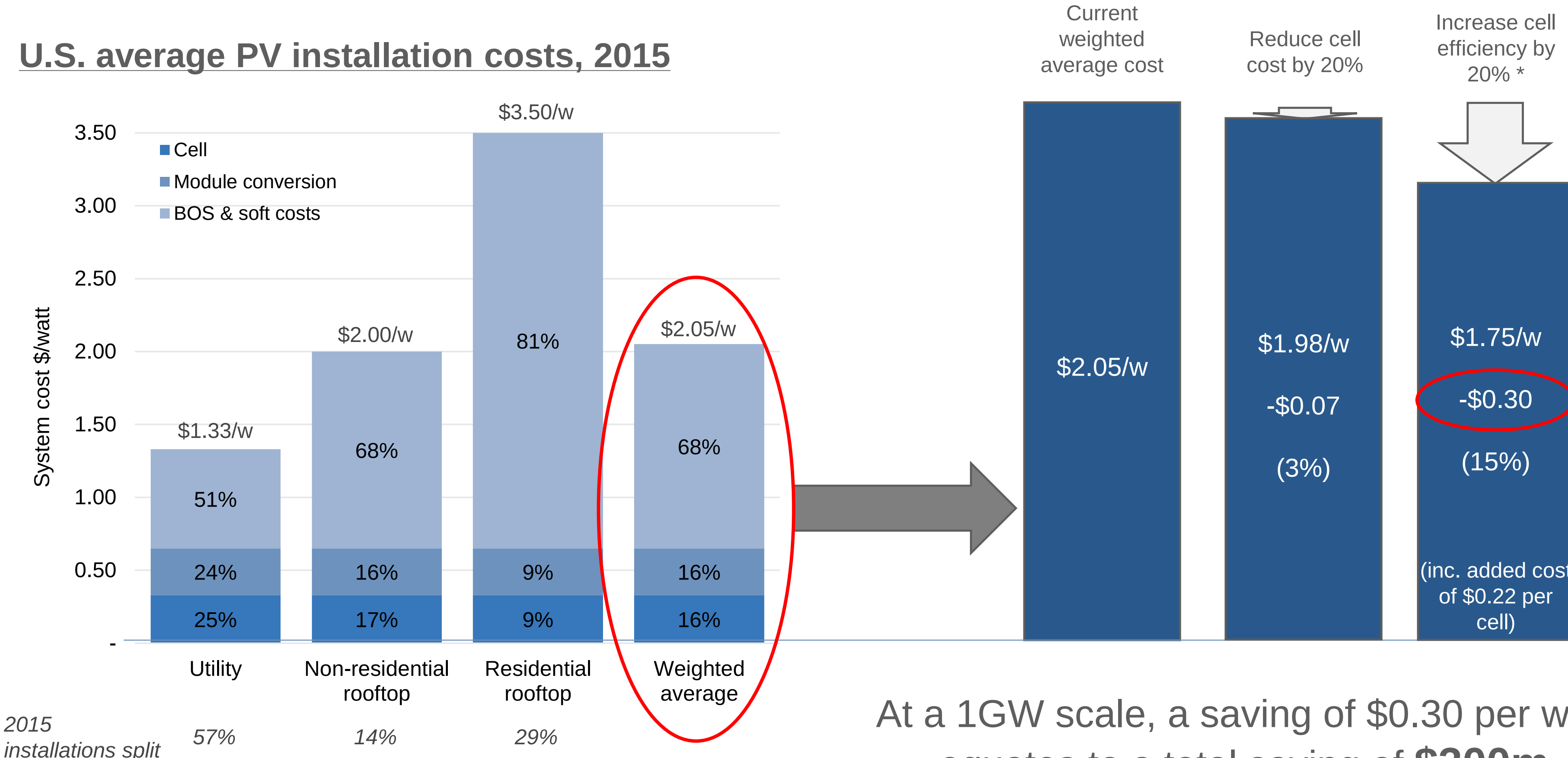
		Base cell		Upgraded cell
Cell output	*Watts*	4.5	+20% cell efficiency	5.4
Cost per watt	$/W	**0.33***		**0.32**
		4.5 x $0.33		$1.71 ÷ 5.4
Total cost of 1 cell	$	1.49		1.71
				$1.49 + $0.22
			Extra production cost to upgrade cell	0.22**

** U.S. average 2015, source: GTM Research*

***verified in a 3rd party manufacturing cost model*

OXFORD PV

Efficiency improvements offer the potential for significant savings on PV installations



At a 1GW scale, a saving of $0.30 per watt equates to a total saving of **$300m**

Data: GTM Research

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Summary

- Perovskites are a potentially revolutionary new PV material
- They are uniquely suited to tandem cell applications with silicon
- They have demonstrated excellent performance via many different material and cell designs
- Using standard encapsulation materials, perovskite-silicon tandems can meet IEC61646 requirements
- The business case for perovskite silicon tandems is clear

The end