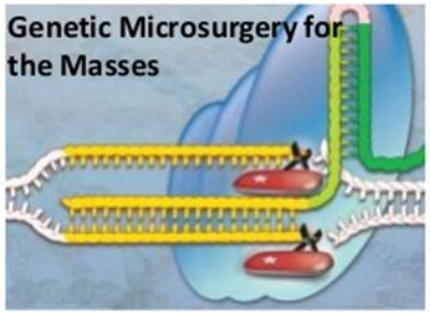
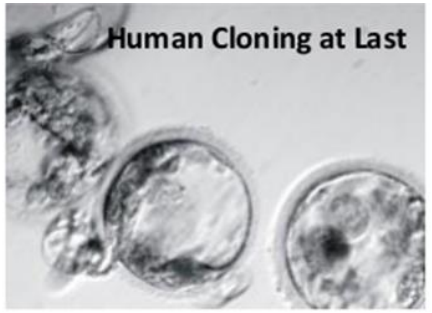
Next generation solar cells
Perovskites and tandems

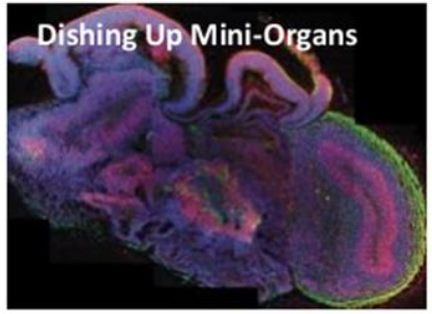
Tom Aernouts, 11 June 2020

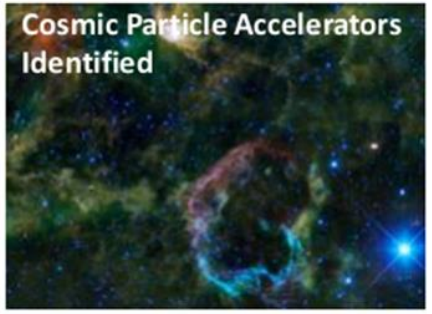
Perovskites for PV

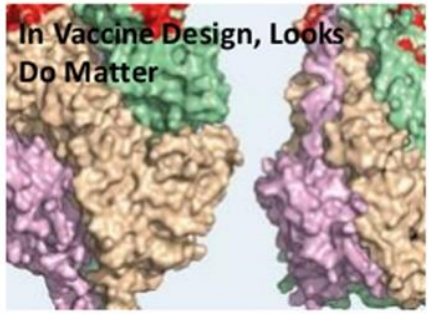
- Science's Top 10 breakthrough of 2013



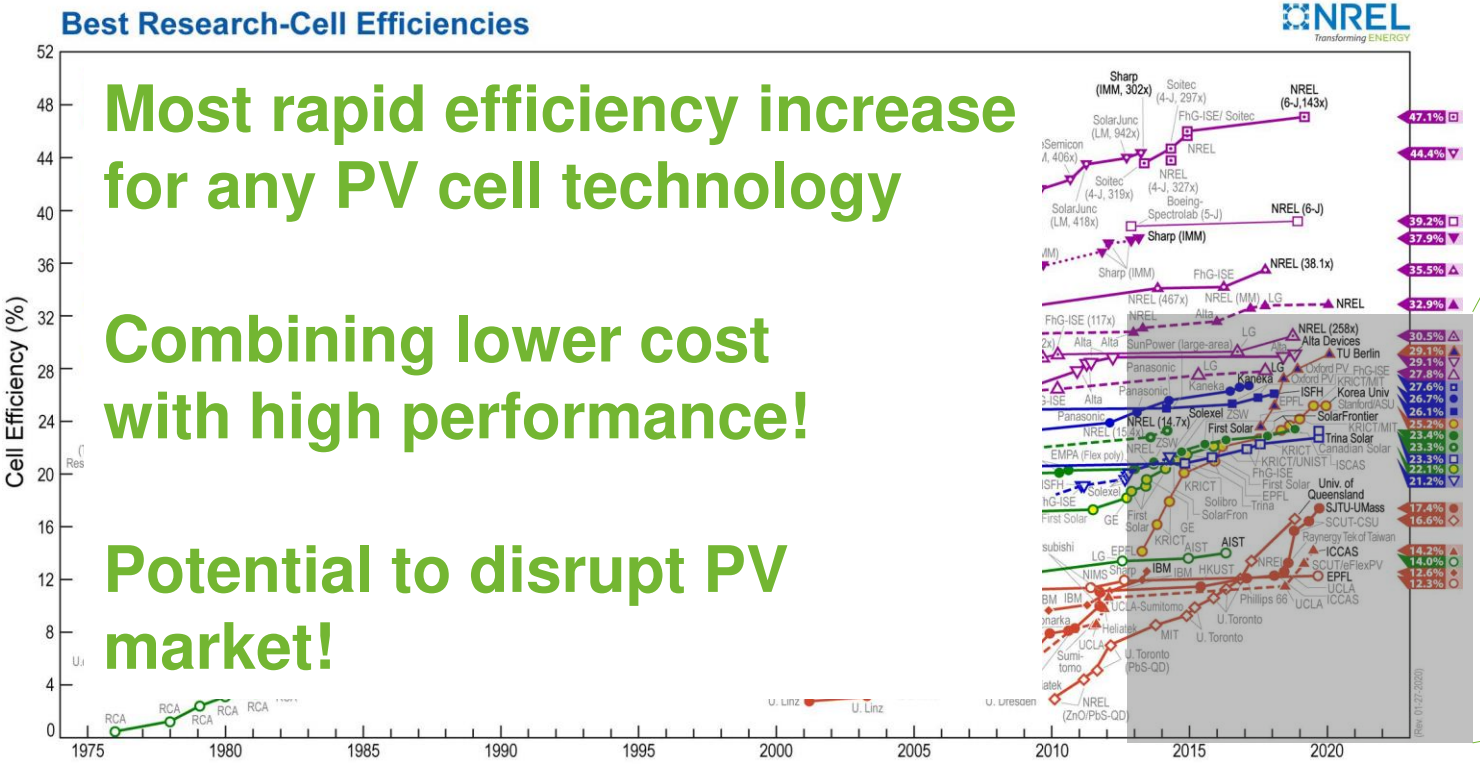








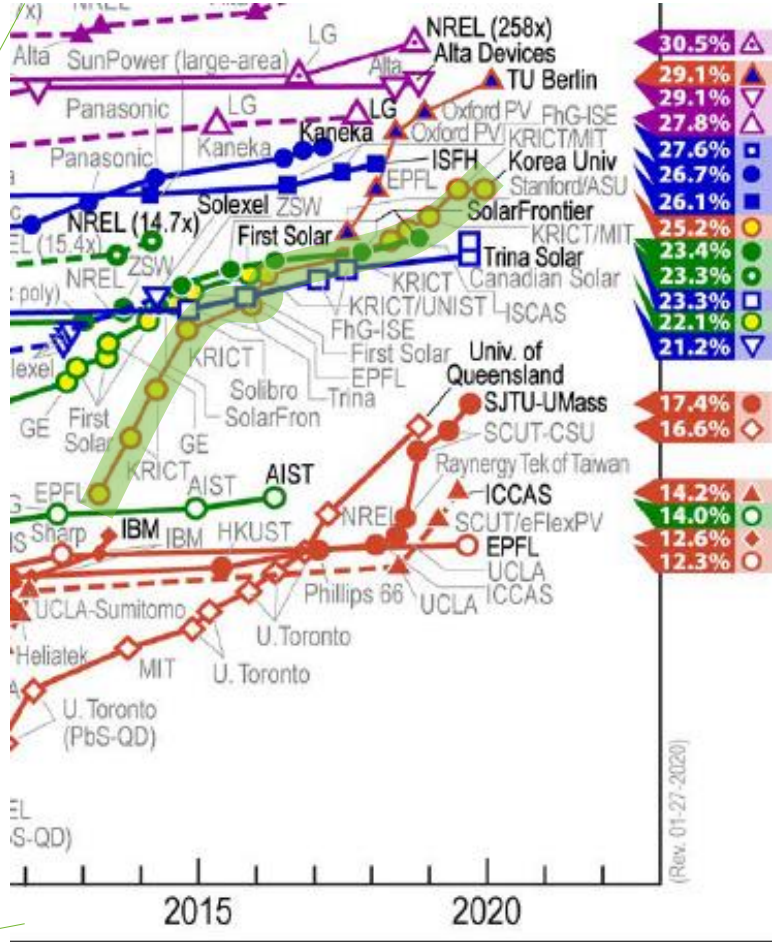
Perovskites for PV



Most rapid efficiency increase for any PV cell technology

Combining lower cost with high performance!

Potential to disrupt PV market!



This plot is courtesy of the National Renewable Energy Laboratory, Golden, CO.

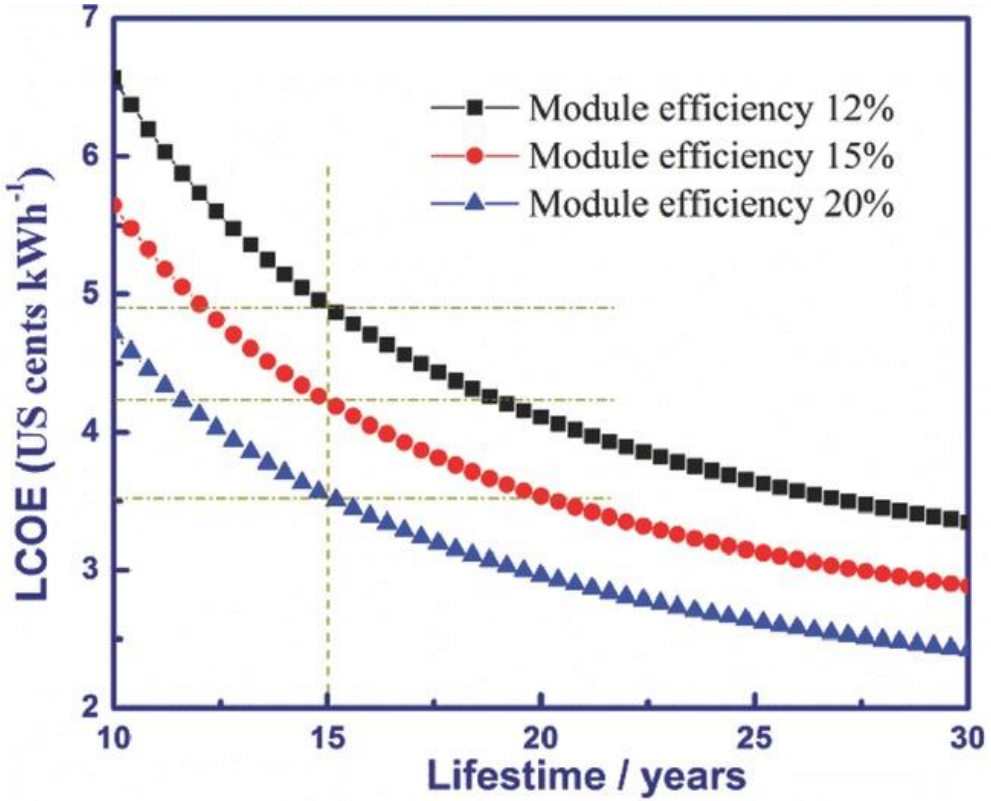
Best PSC cell efficiency = 25.2%
Small area (<1cm²)
Specific architecture

Emerging PV
- Dye-sensitized cells
- Perovskite cells
- Perovskite/Si tandem (monolithic)
- Organic cells (various types)
- Organic tandem cells
- Inorganic cells (CZTSSe)
- Quantum dot cells (various types)

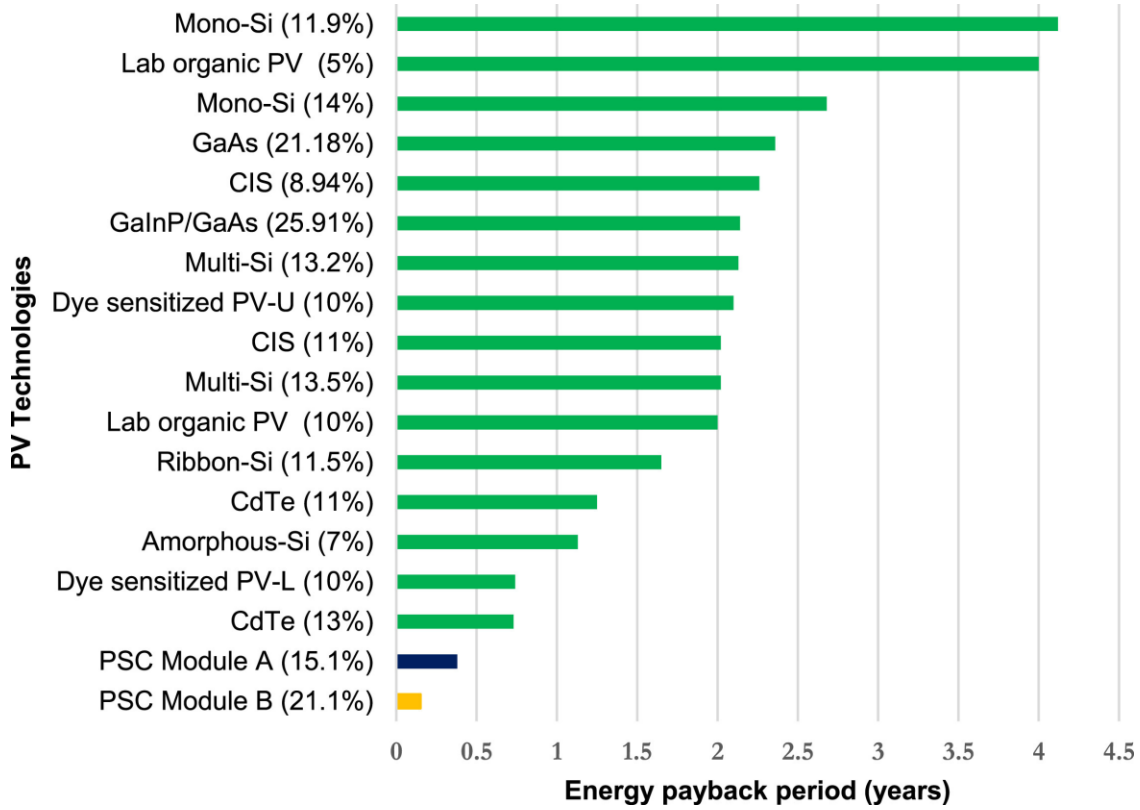
Thin-Film Technologies
- CIGS (concentrator)
- CIGS
- CdTe
- Amorphous Si:H (stabilized)

Energy Ville

Other promising perspectives



Advanced Science, Volume: 4, Issue: 1, First published: 15 September 2016, DOI: (10.1002/advs.201600269)

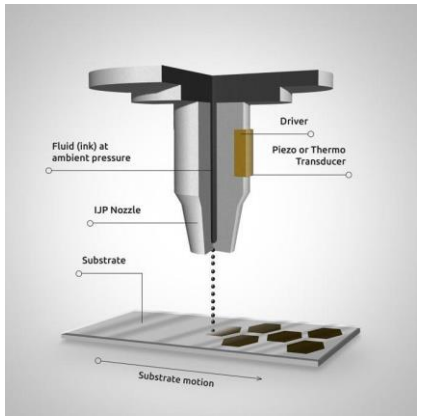


T.Ibn-Mohammed et al., Renewable and Sustainable Energy Reviews, Volume 80, December 2017, Pages 1321-1344;

Initiatives for commercialization started

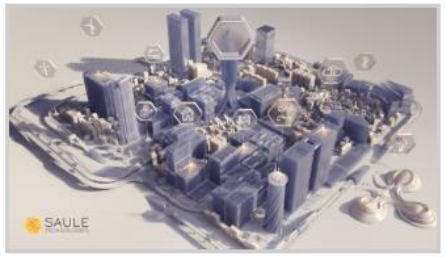
Example: Saule technologies

- Polish start-up, 2014
- Sheet-to-sheet inkjet printing on flex foil
- Prototype production line under construction
  - annual production capacity of 40,000 sqm
  - In 2020, increase the annual production capacity to 200,000 sqm
- Envisaging multiple applications



BIPV

Smart furniture



IoT

Roofing

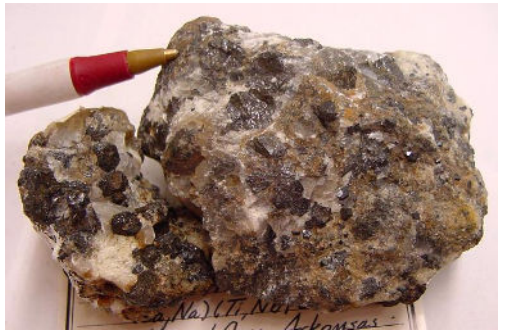
Transportation

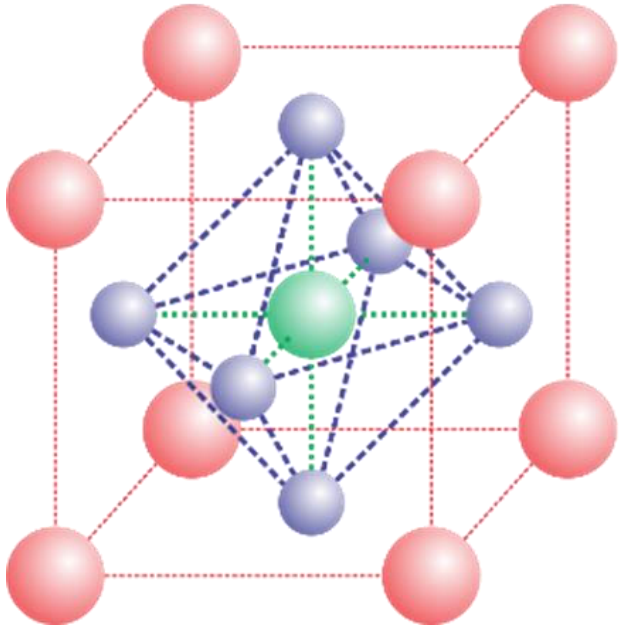
Space

Why not for sale yet?

Perovskites for PV

- ‘Perovskite’ describes a class of crystalline materials
  - Crystal structure similar to calcium titanate ($CaTiO_3$)
    - Named after mineralogist Lev Perovski
- For PV applications
  - Organic/Inorganic Metal Halide Perovskites





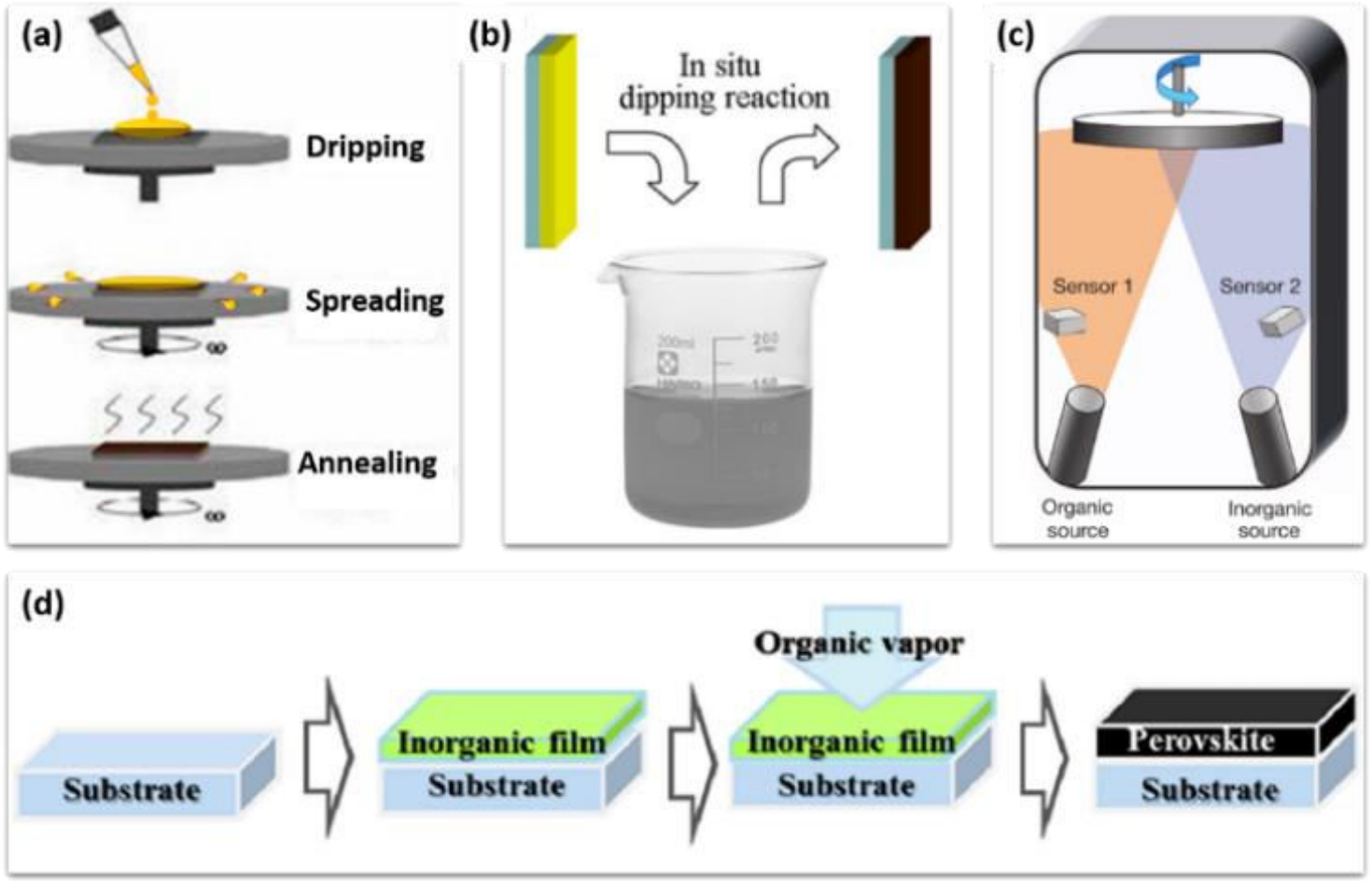
AMX_3

A — Cation = CH_3NH_3, $HC(NH_2)_2$, Cs, Rb

X — Anion (halogen) = I, Br, Cl

M — Metal cation = Pb, Sn, Ge

How to make Perovskite layers?

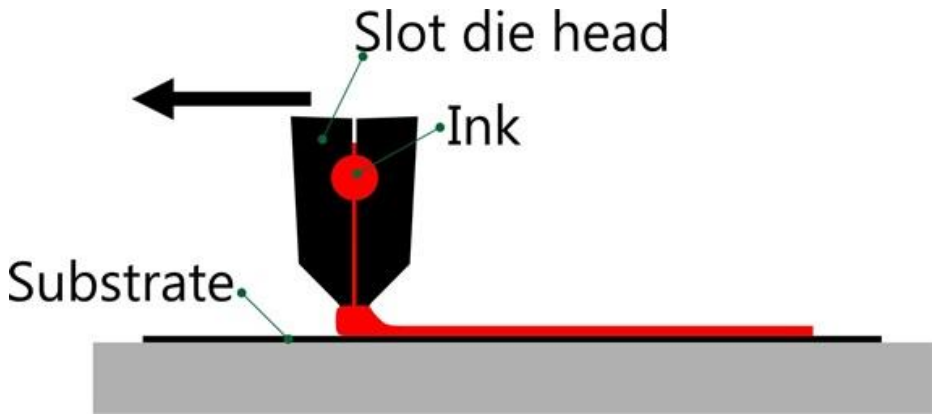


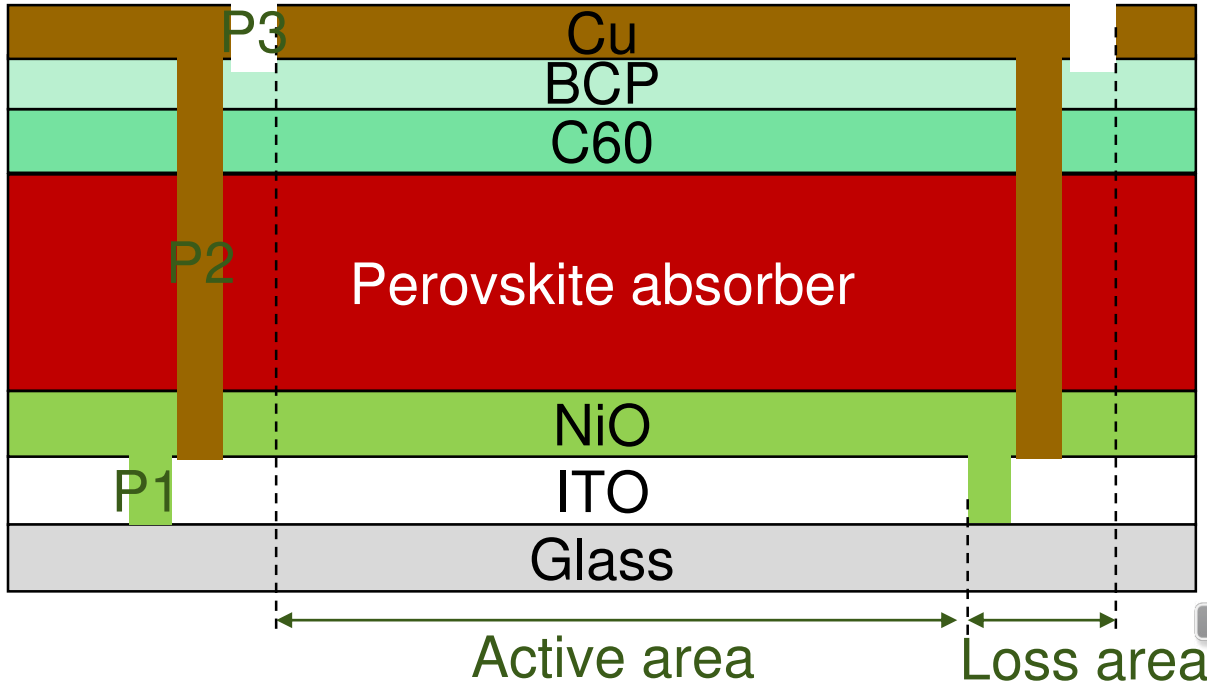
PbI_2 ($PbCl_2$) + CH_3NH_3I ⟶ $CH_3NH_3PbI_3$ ($CH_3NH_3PbI_xCl_{3-x}$)

Module process

- **Disconnect back contact**
  - P3 laser scribe
- **Back contact deposition**
  - sputter/evaporation
- **Back contact via**
  - P2 laser scribe
- **ETL deposition**
  - evaporation
- **Perovskite absorber deposition**
  - blade/slot die coating
- **HTL deposition**
  - sputter
- **Disconnect front contact**
  - P1 laser scribe
- **TCO deposition**
  - Sputter

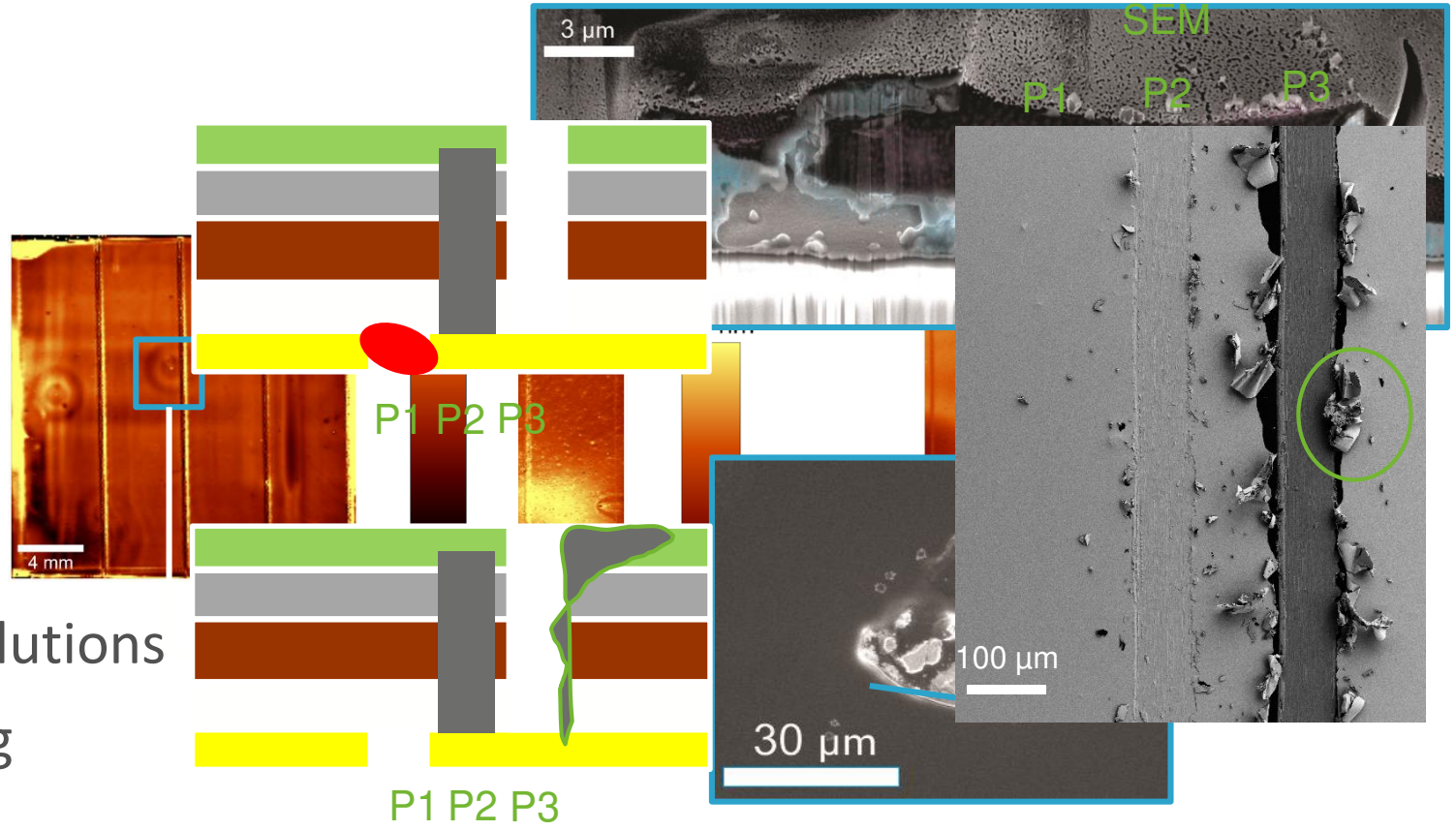
All steps in-house available



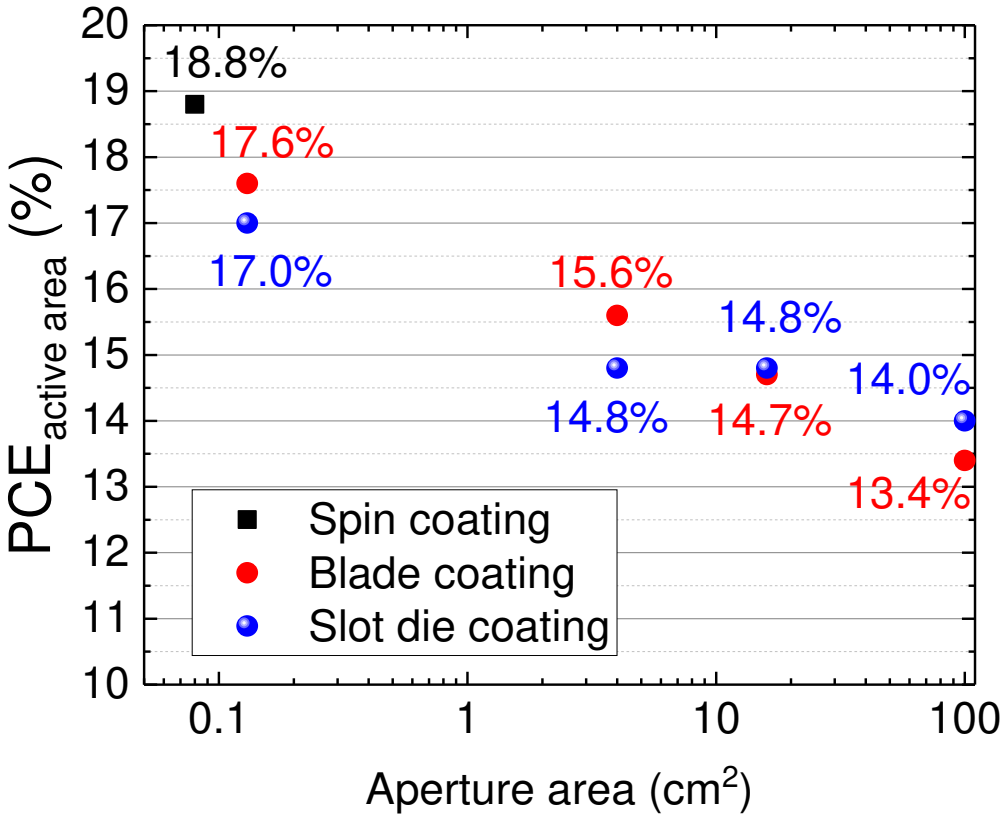


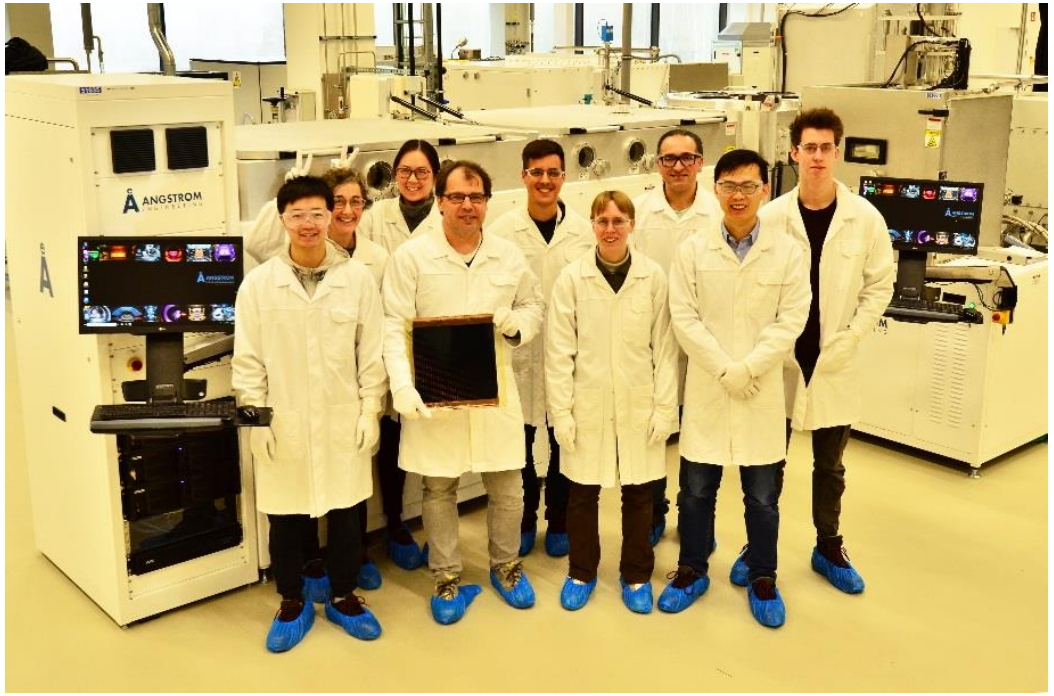
INHOMOGENEITY IN LAYERS

- Layer inhomogeneities identified with
  - EL, DLIT and µPL
  - SEM, EDX and FIB
- Caused by:
  - Deposition method
  - Crystallization method
  - Dust and particles from solutions
  - Interconnection patterning



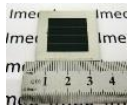
Perovskite research @ EV



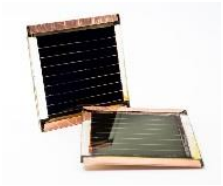


Perovskite (mini)modules

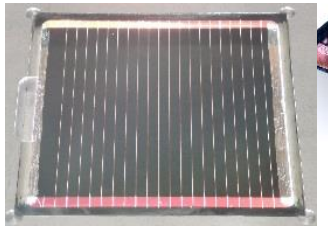
2x2 cm²



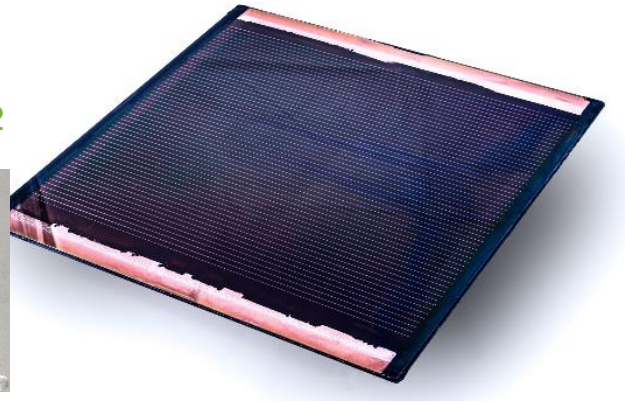
4x4 cm²



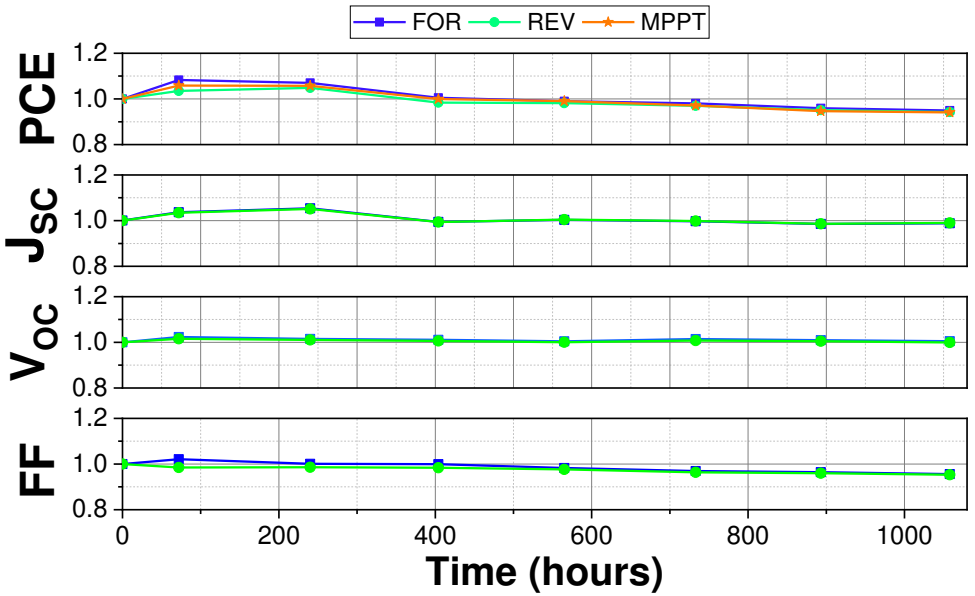
10x10 cm²



30x30 cm²



Stable perovskite module



Damp heat (85°C, 85 RH), 95% initial efficiency retained

Encapsulated perovskite module passed stability tests:

- Light soaking, >1000 h: in the first 100 hours performance increased then stabilized
- Damp heat (85°C, 85 RH), >1000 h: 95% retained.
- Thermal cycling (-40-85°C), 50 cycles: no efficiency loss

SOLLIANCE
10 YEARS OF SOLAR RESEARCH

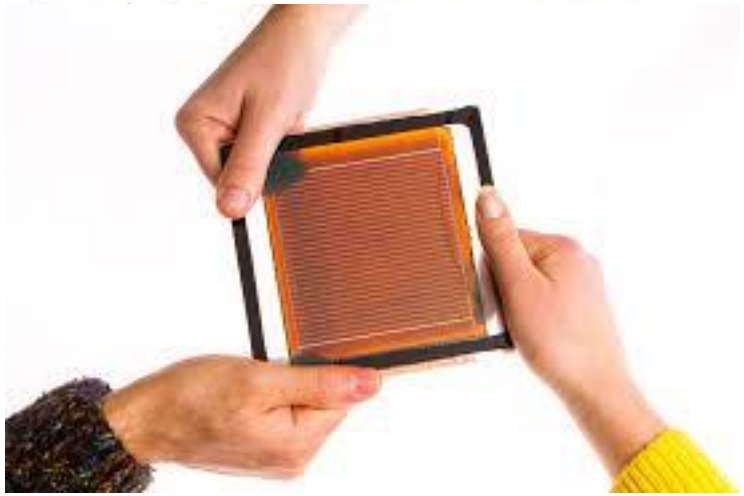
PRESS RELEASE

MAJOR MILESTONE TOWARDS THE COMMERCIALIZATION OF THIS NEW SOLAR TECHNOLOGY.

Scaled perovskite solar modules pass three critical stability tests.

Eindhoven (Netherlands), Genk (Belgium) January 23, 2020 – Solliance partners TNO, imec and the Eindhoven University of Technology, demonstrated encapsulated perovskite solar modules fabricated using industrial processes that withstand three established lifetime tests, i.e. the light soak test, the damp-heat test and the thermal cycling test. It is for the first time this milestone is passed with scaled perovskite solar modules prepared by research organizations.

Perovskite solar cells and modules, are nowadays widely acknowledged for their high efficiency values of up to 25.2% for the current latest record lab solar cell. Perovskite solar cells and modules combine high efficiency with low cost processability and are based on low cost and abundant materials. Furthermore, perovskite solar modules can be either rigid or flexible as well as opaque or semi-transparent. This allows a



TNO innovation for life imec TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

HREE CRITICAL STABILITY TESTS

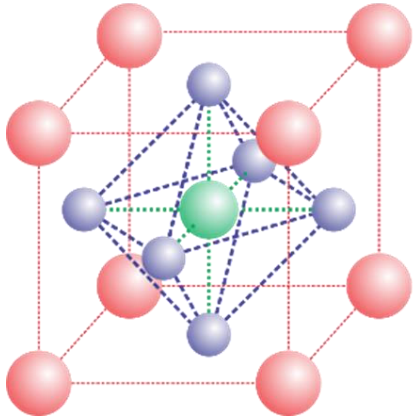
Energy Ville

Boosting performance

KU LEUVEN vito imec UHASSELT

Perovskites for PV

- **Impact of compositional variation**
  - Halide ratio → bandgap tuning



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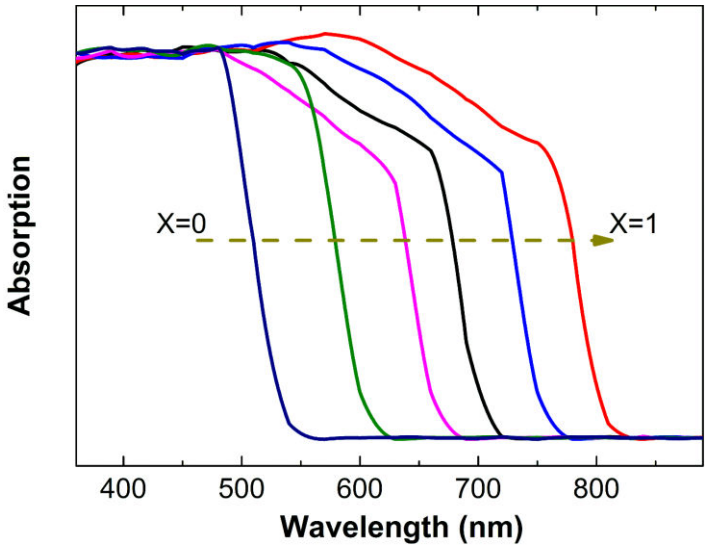
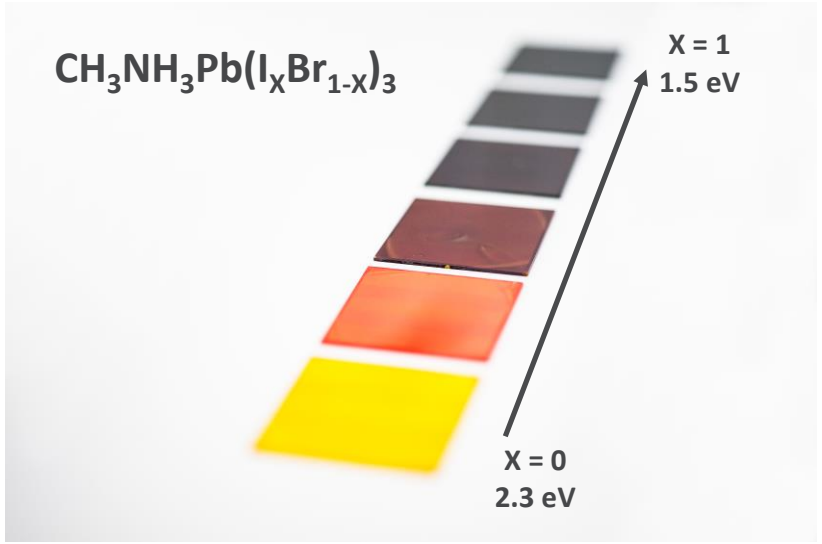
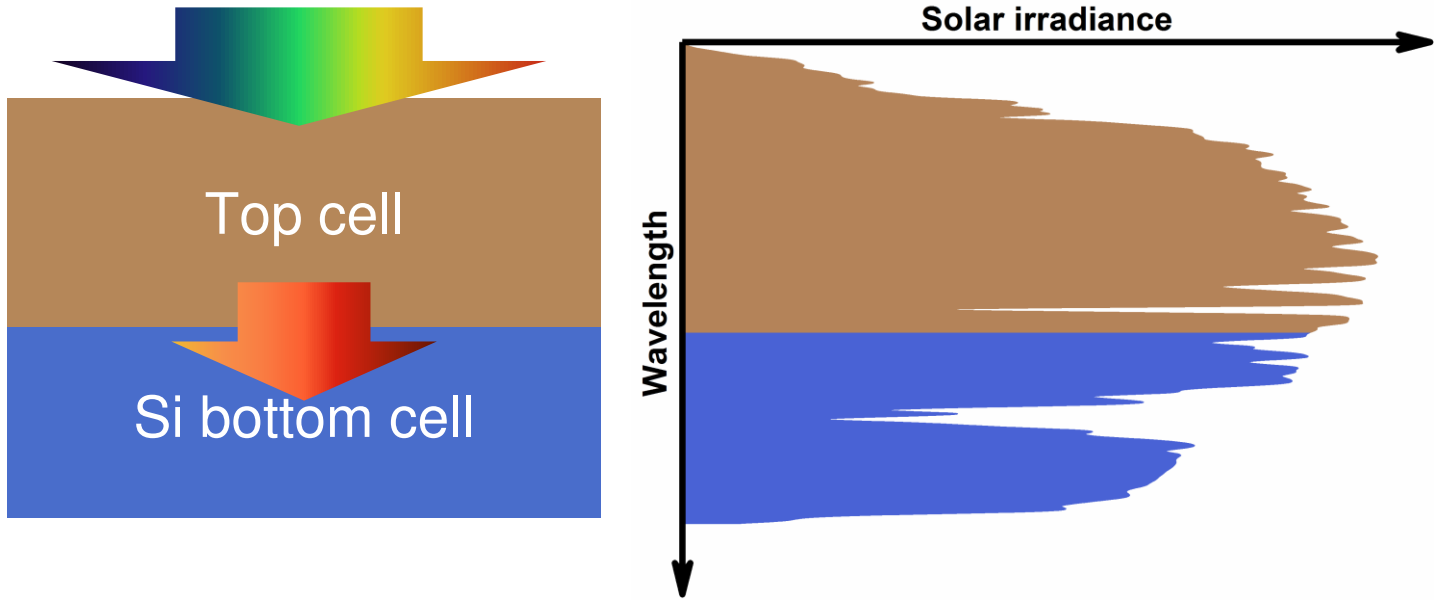




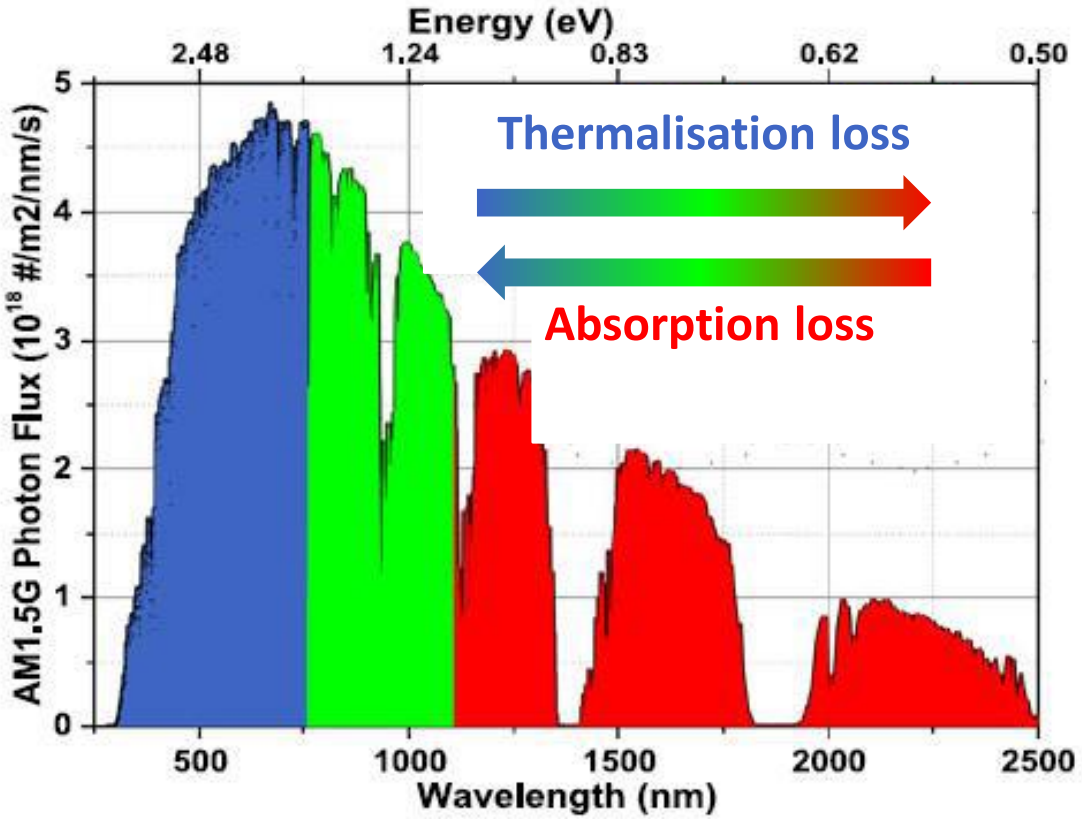
Tandem solar cells

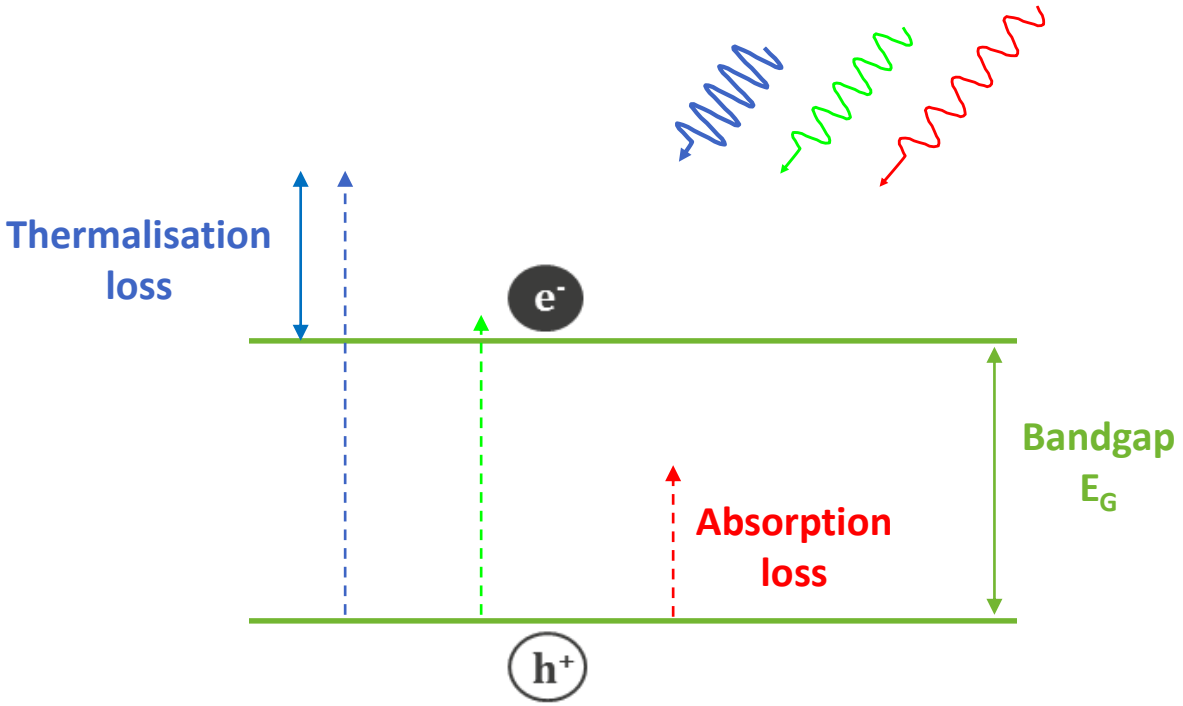
- Why?



More efficient usage of the solar spectrum of interest in a tandem fashion

Efficiency limited by bandgap

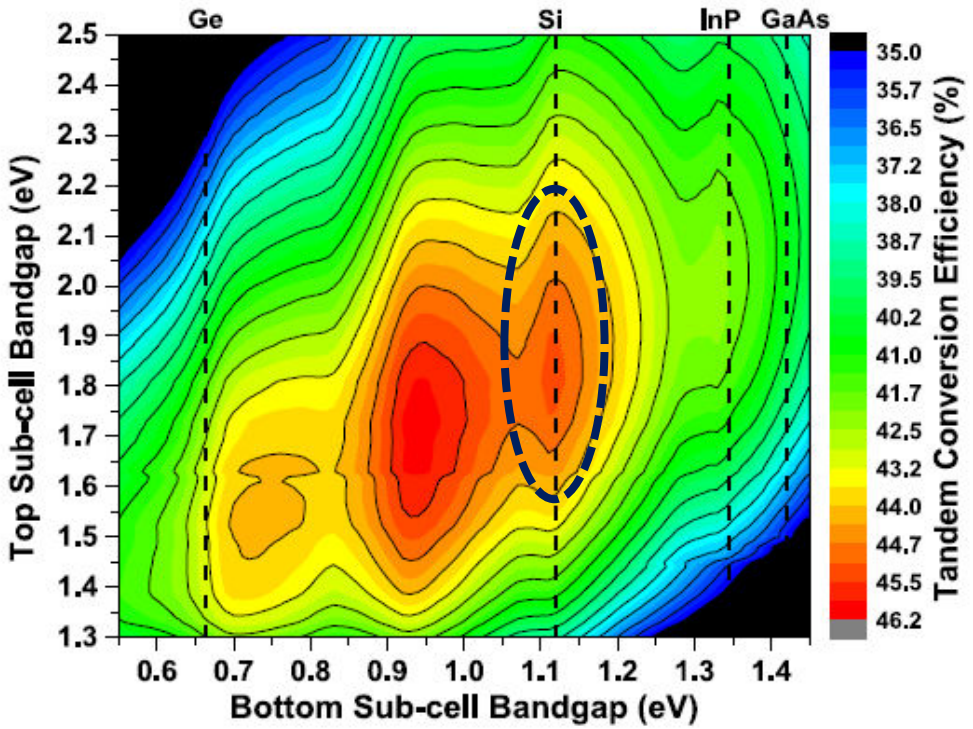




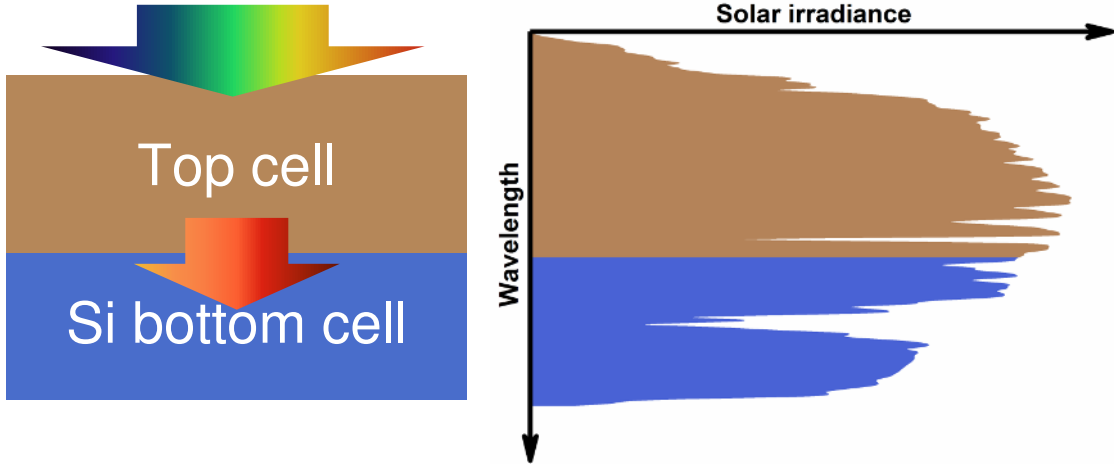
- Substantial thermalisation losses in single absorber solar cells

- Addition of wide-bandgap absorber on top can minimise these thermalisation losses

Choice of top cell

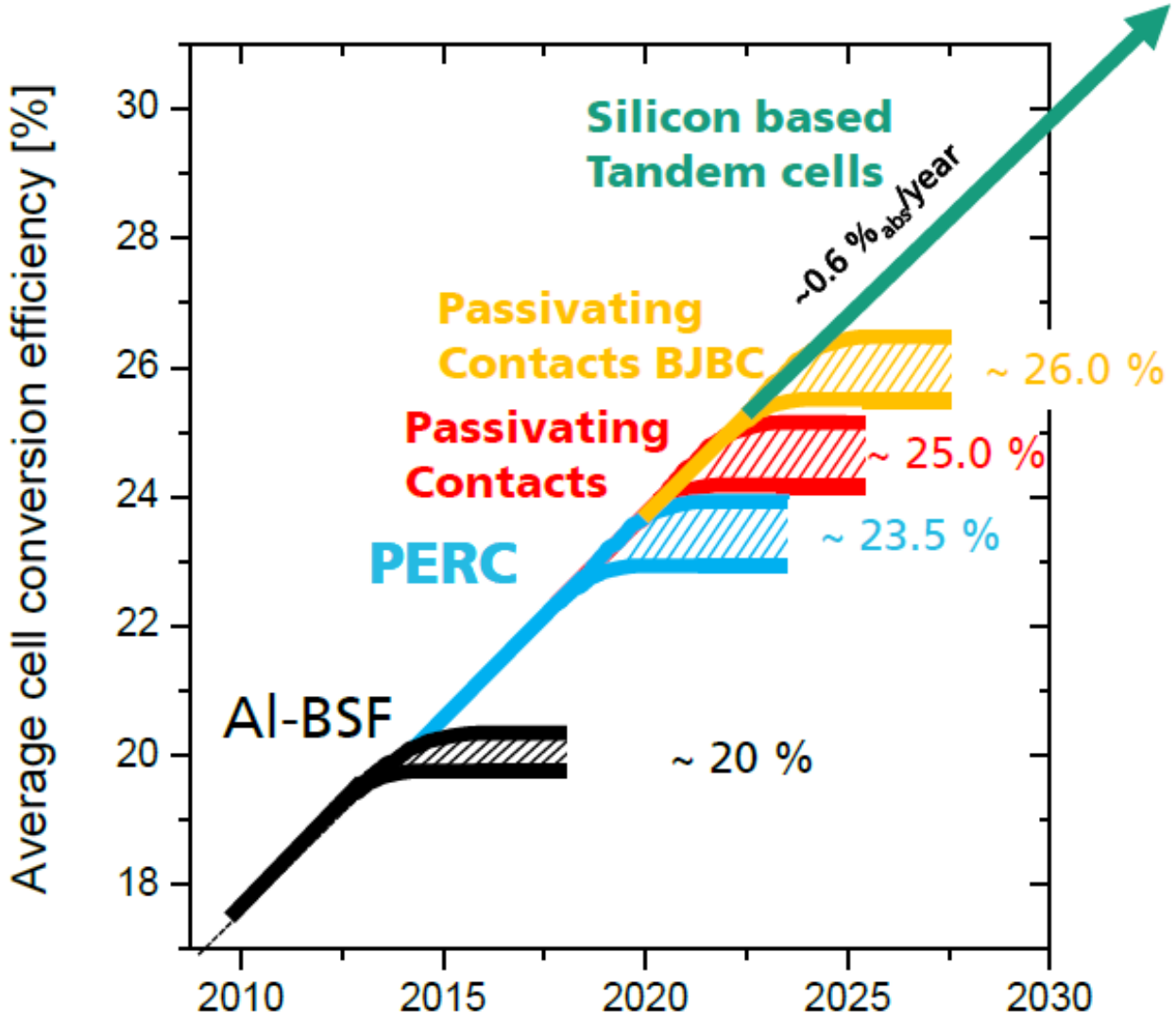


Almansouri et. al., IEEE J. Photovoltaics Vol. 5, 968 (2015)



- **Tandem efficiencies > 42% possible theoretically**
- **Need for a low cost, wide-bandgap top cell material**

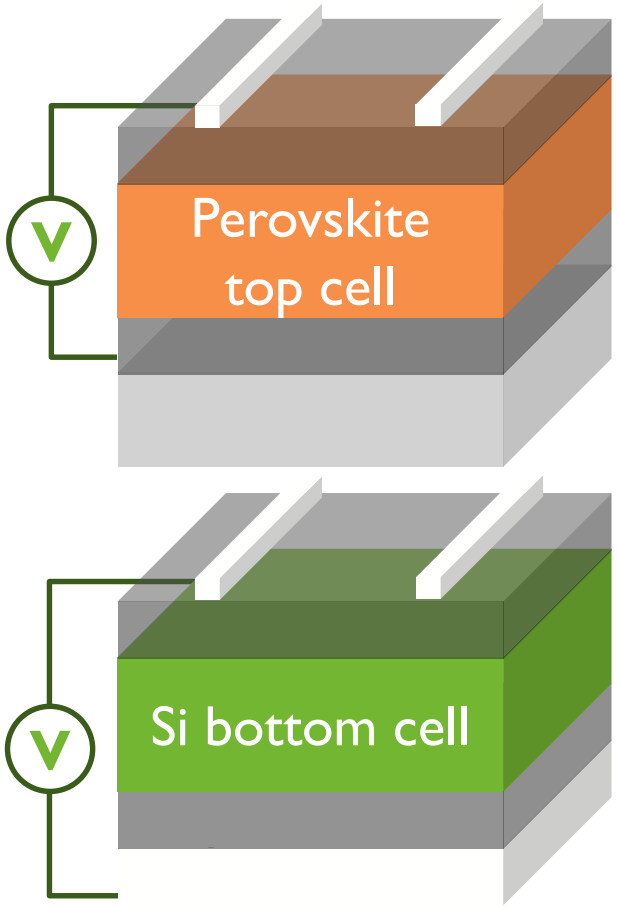
Tandem devices will ensure that silicon solar cell technology still has a long and bright future



Courtesy of M. Hermle, Fraunhofer ISE

Perovskite-Si Tandem solar cells

Four terminal (4T)



Independent fabrication and optimization of subcells

Easy assembly

Higher energy yield

≈ 22% more than 2T.

More exterior electronics.

More parasitic absorption.

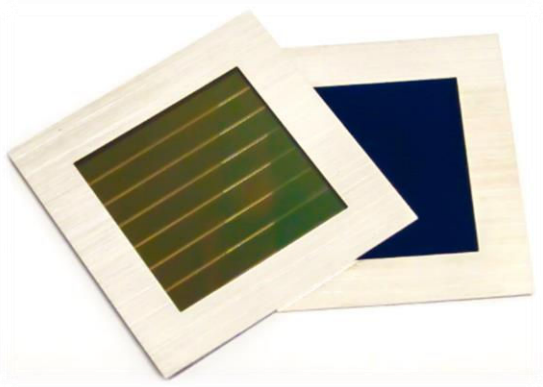
...

Perovskite - silicon 4T tandem solar cell and module

Cell-on-Cell
0.13 cm^2

$\eta_{\text{Four terminal}}$ 27.1%
(13.8% perovskite + 13.3% Si)

Module-on-Cell
4 cm^2



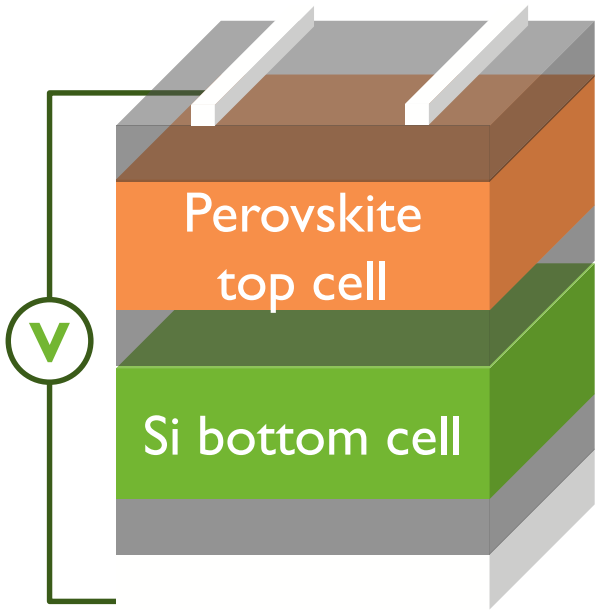
$\eta_{\text{Four terminal}}$ 25.3%

Imec IBC c-Si bottom cell alone: η = 23.0%

Press release: https://www.imec-int.com/en/articles/imec-beats-silicon-pv-with-27-1-percent-perovskite-silicon-tandem

Perovskite-Si Tandem solar cells

Two terminal (2T)



Less parasitic absorption.

Less exterior electronics.

Critical current matching.

...

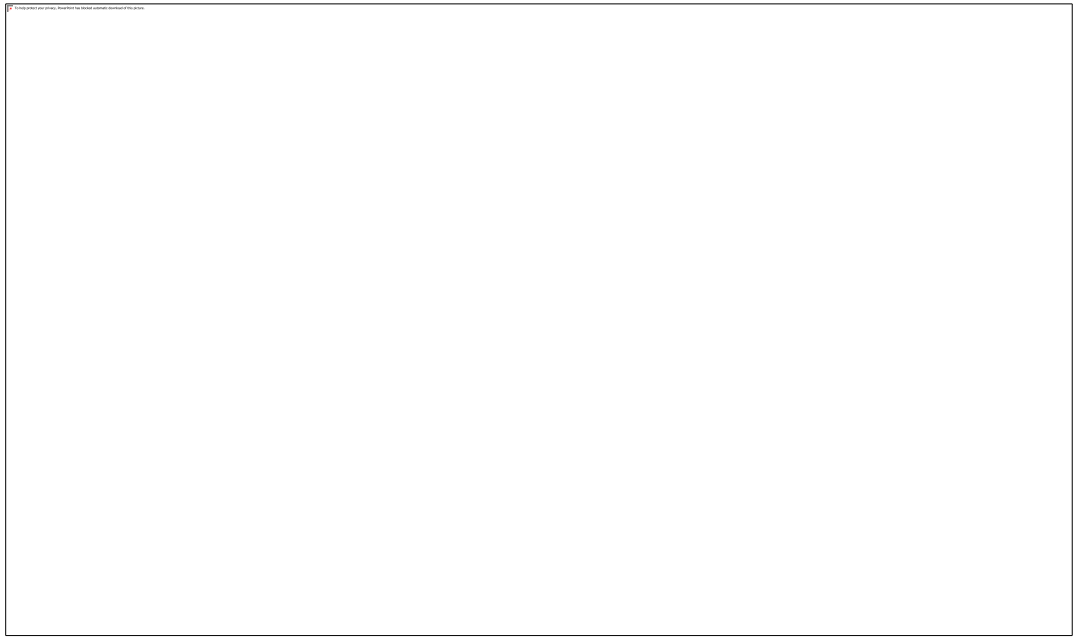
Conformal growth of perovskite on textured surfaces

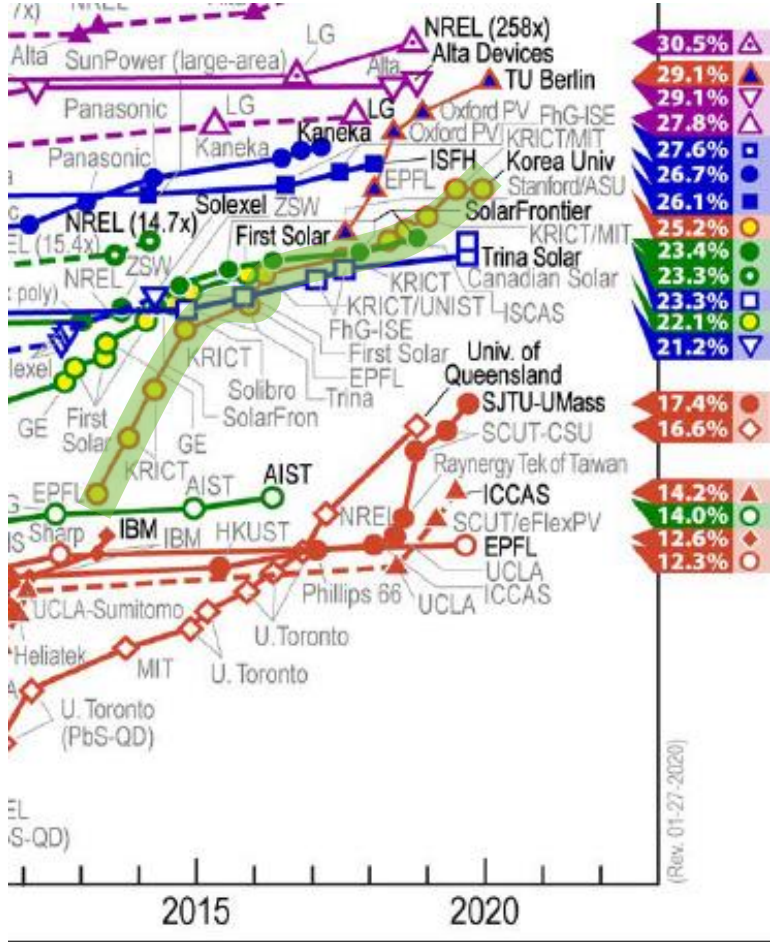
- Perovskite thickness < 0.5 micron
- Textures typically 3-5 micron

Two terminal tandem cell

Perovskite-Si 2T Tandem

Efficiency of perovskite silicon tandem solar cell of HZB yields 29.15 %





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Thin-Film Technologies
- CIGS (concentrator)
- CIGS
- CdTe
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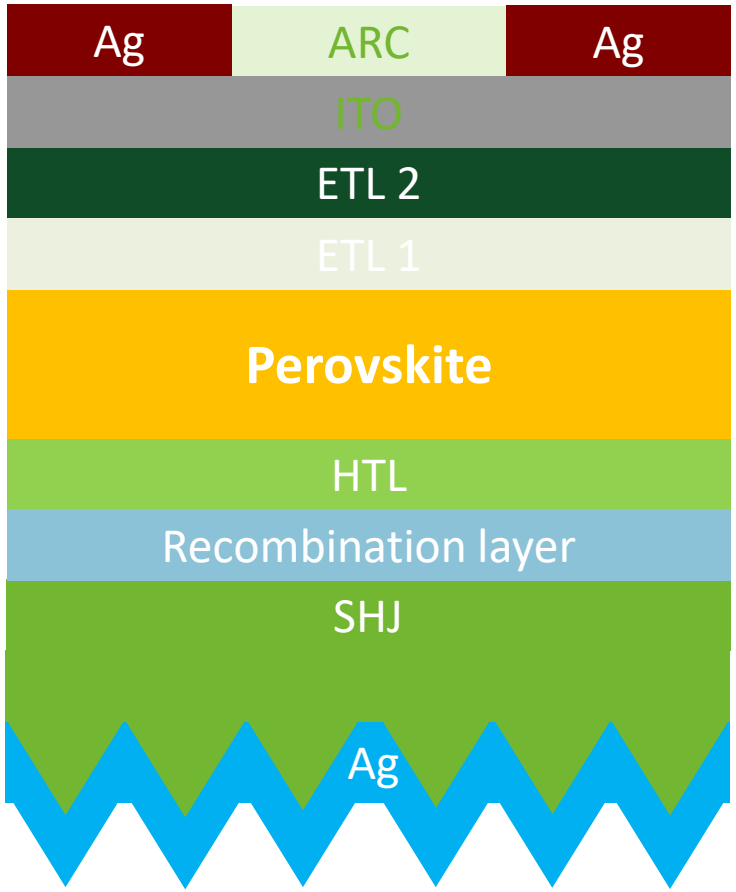
Getting tandems out of the lab

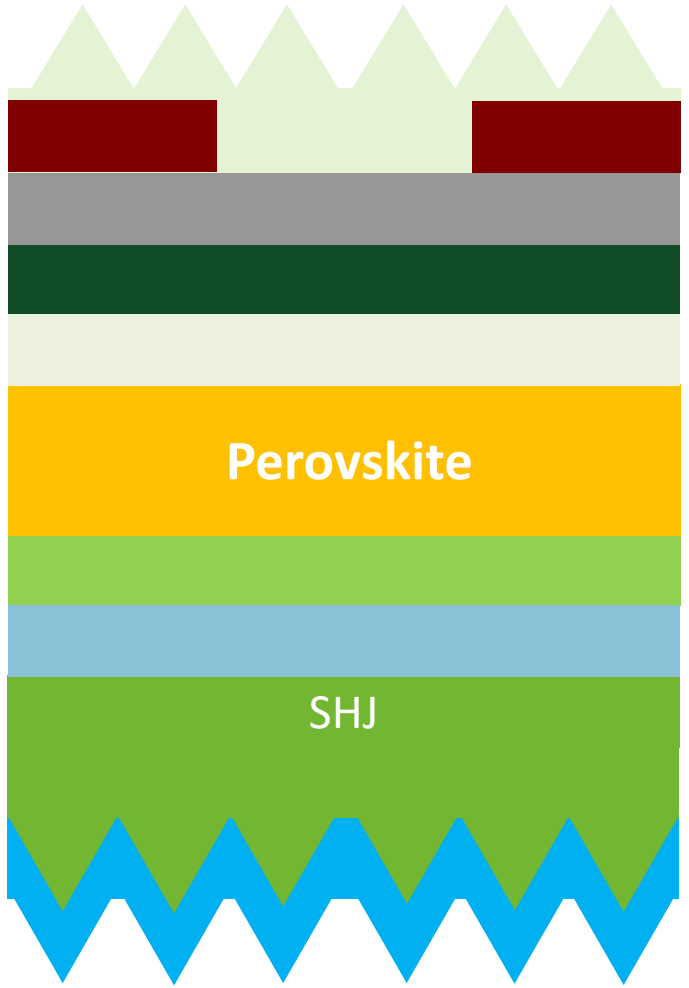
KU LEUVEN vito imec UHASSELT

Industrially relevant 2T PSC/cSi tandem

Industrial Si cell

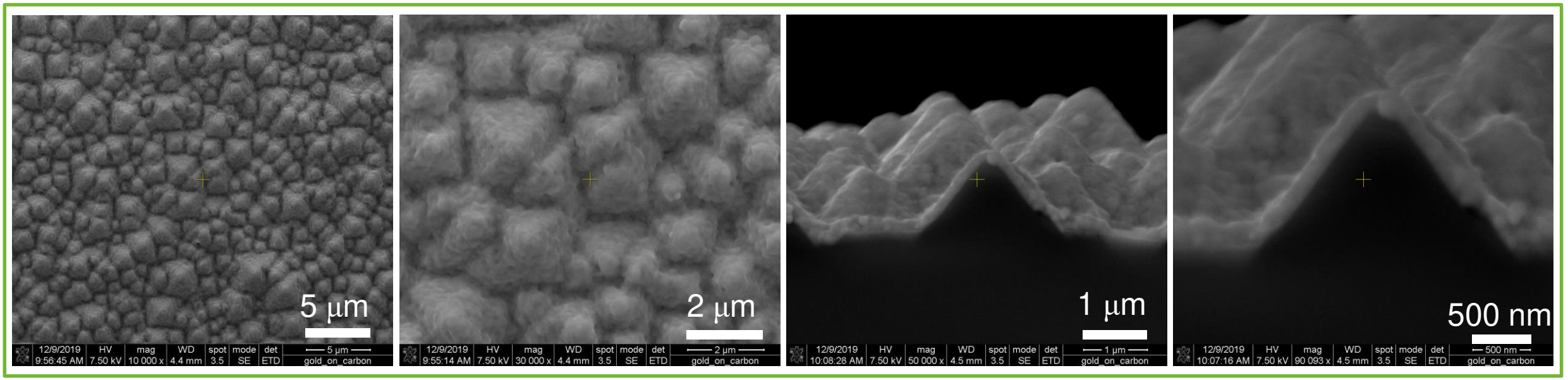


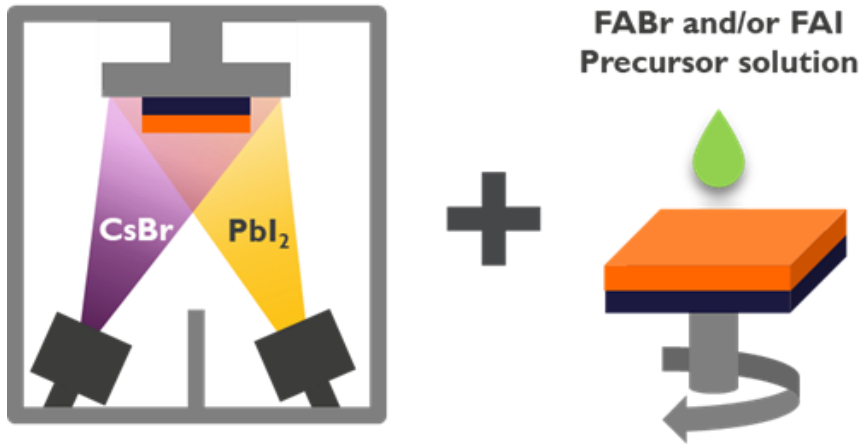
Frontside polished Si cell



Frontside polished Si cell
Textured front structure added

Perovskite conformal growth on random texture

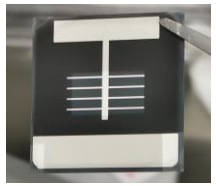




- Inorganic precursor first co-evaporated onto the texture
- followed by solution-processed organic precursor
- 150-200 nm conformal perovskite coating on random Si pyramids obtained.

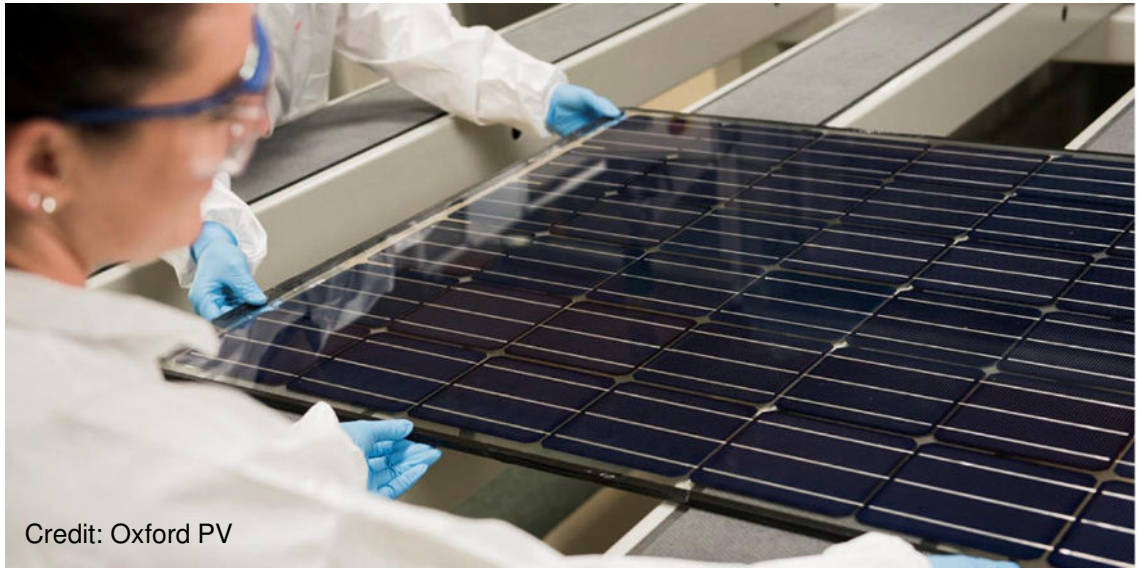
Large-area 2T Pk/Si tandems upscaling

- Ambition: Develop metallisation, interconnection and lamination for **large-area 2T Si/perovskite tandem cells**.

1 cm^2 cells 

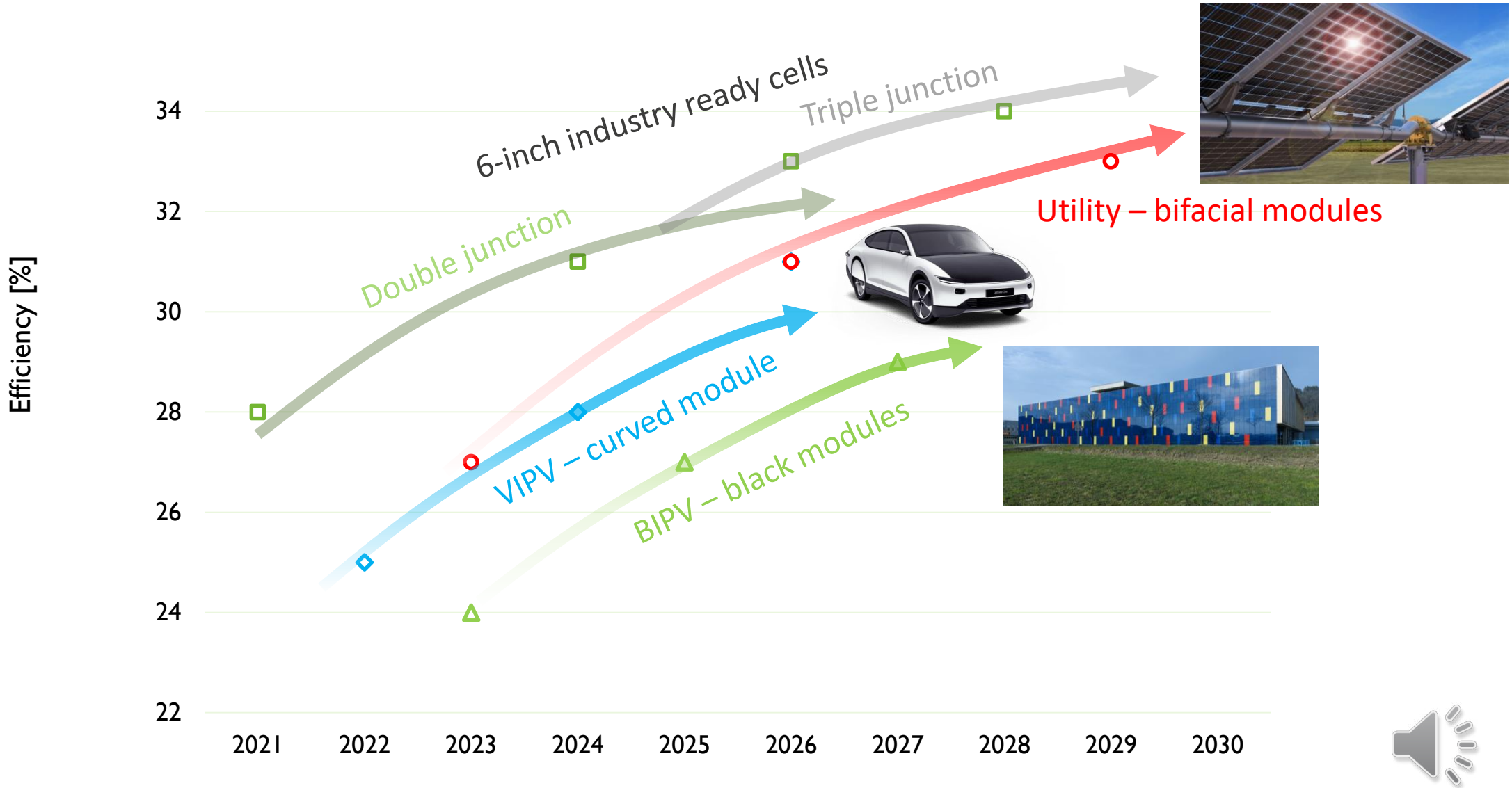
6-inch cells

Full-size module



Credit: Oxford PV

Application-driven roadmap for tandem and triple junction modules



Some more info

EPKI White Paper epki.eu

Thin Film PV PVThin.org

H2020 www.espresso-h2020.eu/

Thank you!
Questions?

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