Monolithic Perovskite/Silicon-Heterojunction Tandem Solar Cells Processed at Low Temperature

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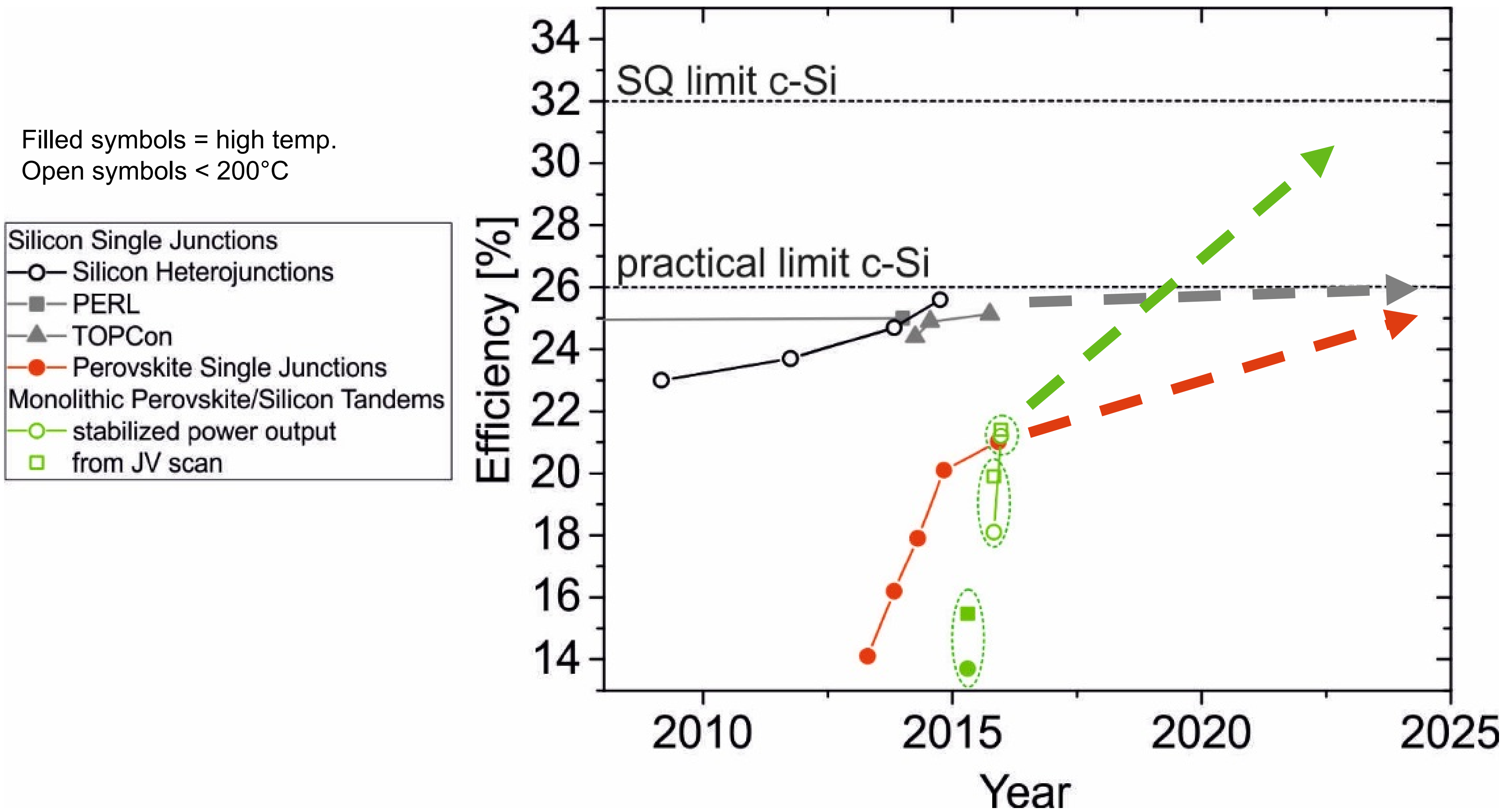
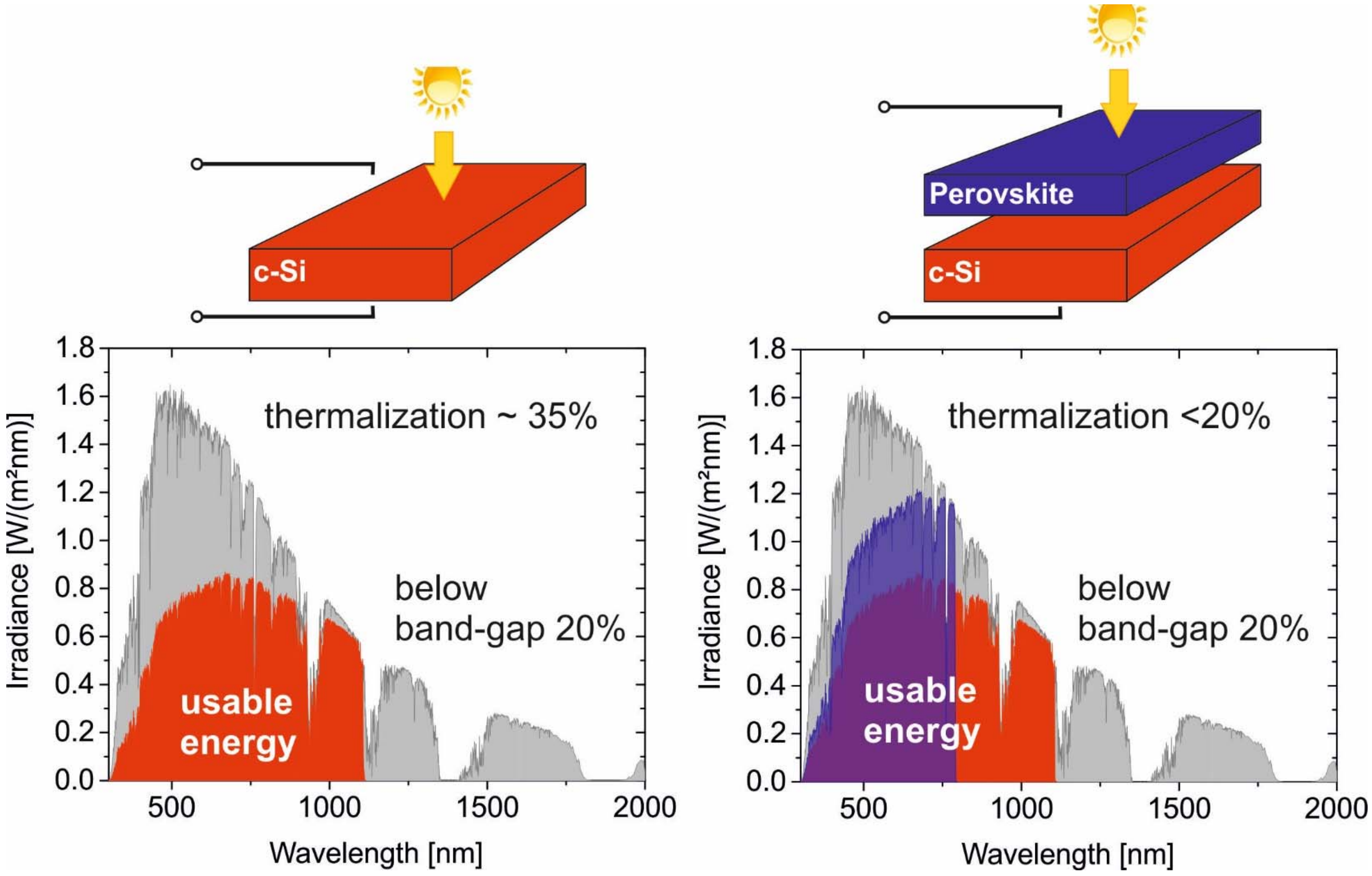
MOTIVATION - EFFICIENCY EVOLUTION



perovskite/silicon tandems have the potential to overcome the practical limit at reasonable "extra" costs

C-SI / PEROVSKITE TANDEM

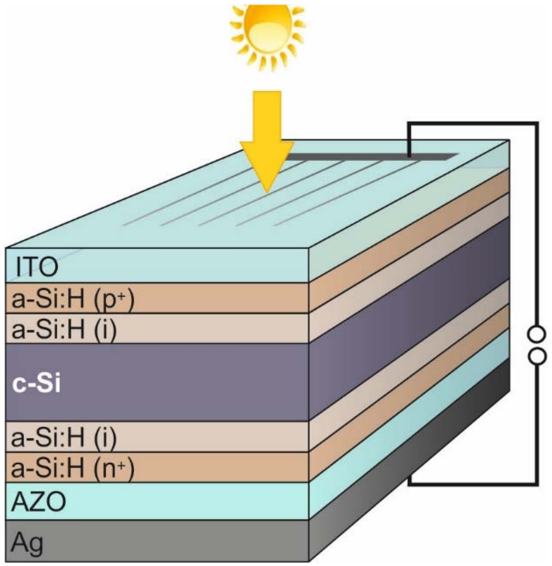


- high loss from thermalization
- high energy photons are absorbed by perovskite
  - converted at a high voltage
  - reduced losses from thermalization
- infrared photons are transmitted into c-Si
  - cover a wide spectral range of absorption

Image adopted from Jan Goldschmidt, Fraunhofer ISE

WHY A-SI:H/C-SI SILICON HETEROJUNCTIONS?

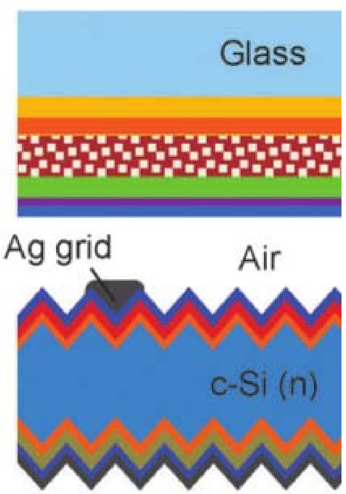
- highest certified efficiency of 25.6% (1)
- highest V_{oc} up to 750 mV (2)
- high voltages are maintained at reduced illumination levels (3)
- high EQE response in the long-wavelength region (4)
- parasitic absorption in a-Si:H layer not important in tandem
- increasing interest from industry
- restriction: not temperature stable above 200°C

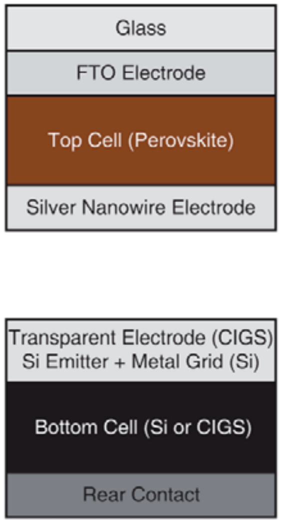


(1) Masuko, K.; Shigematsu, M.; Hashiguchi, T.; Fujishima, D.; Kai, M. et al., *Photovoltaics, IEEE Journal of* ***2014, 4, 1433.***
(2) Taguchi, M.; Yano, A.; Tohoda, S.; Matsuyama, K.; Nakamura, Y. et al., *Photovoltaics, IEEE Journal of* ***2014, 4, 96.***
(3) Filipič, M.; Löper, P.; Niesen, B.; De Wolf, S.; Krč, J.; Ballif, C.; Topič, M. *Optics Express* ***2015, 23, A263.***
(4) Holman, Z. C.; Descoeudres, A.; De Wolf, S.; Ballif, C. *Photovoltaics, IEEE Journal of* ***2013, 3, 1243.***

C-SI / PEROVSKITE TANDEMS LITERATURE

4 TERMINAL





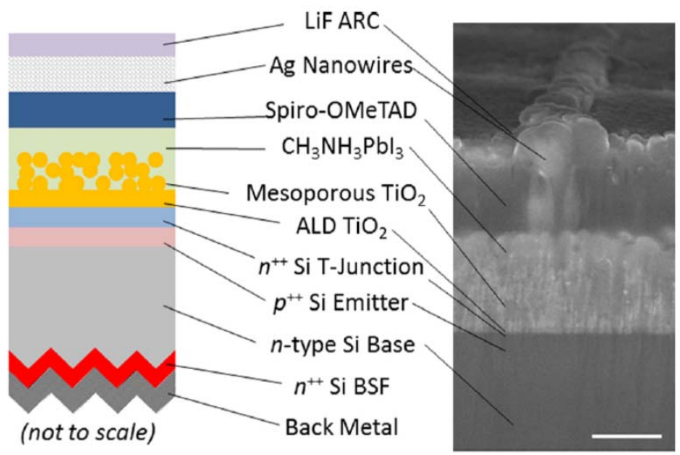
- Werner et al.
- *Sol. En. & Sol. Cells,* 2015.

- 18.2 % (22.8% stabilized)

- Bailie et al.
- Energy & Env. Sci, 2014.

- 17%

MONOLITHIC

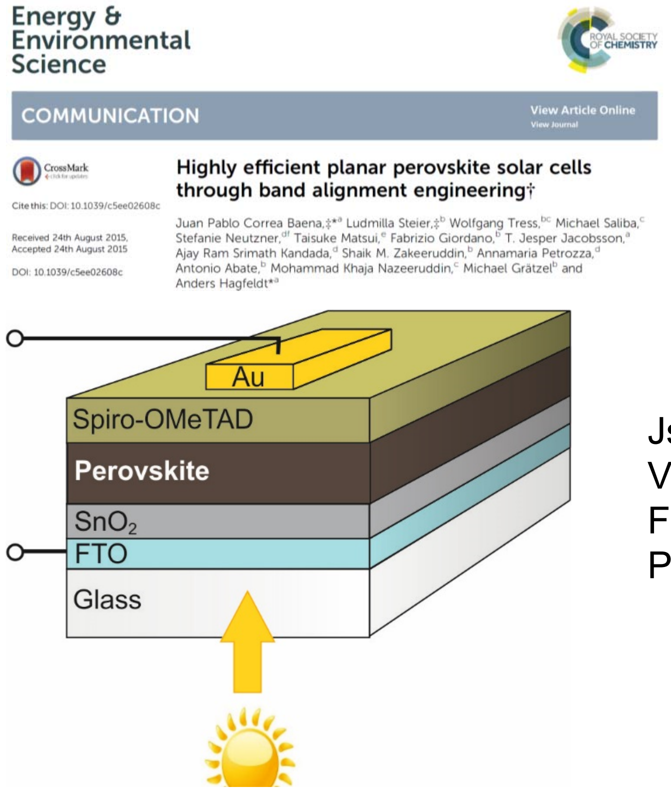


- Mailoa, Bailie et al.
- APL, 2015.

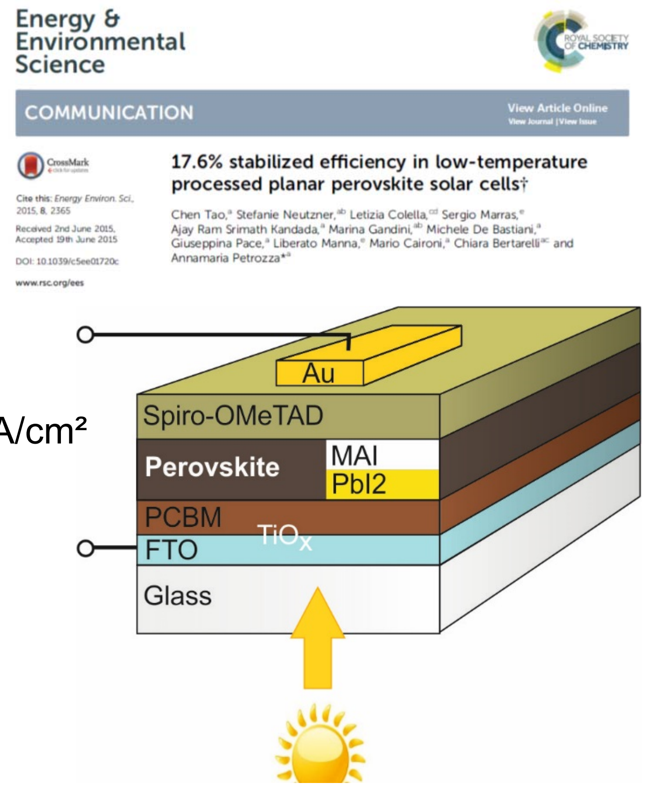
- 13.7% stabilized

⇨ The reported tandem designs use mesoporous TiO_2 sintered at 500°C. Temperatures above 200°C not feasible for silicon heterojunctions!

PLANAR PEROVSKITE CELLS AT LOW TEMP.



Jsc	21.3	21.0	mA/cm²
Voc	1.14	1.11	V
FF	74.0	76.6	%
PCE	18.4	17.9	%

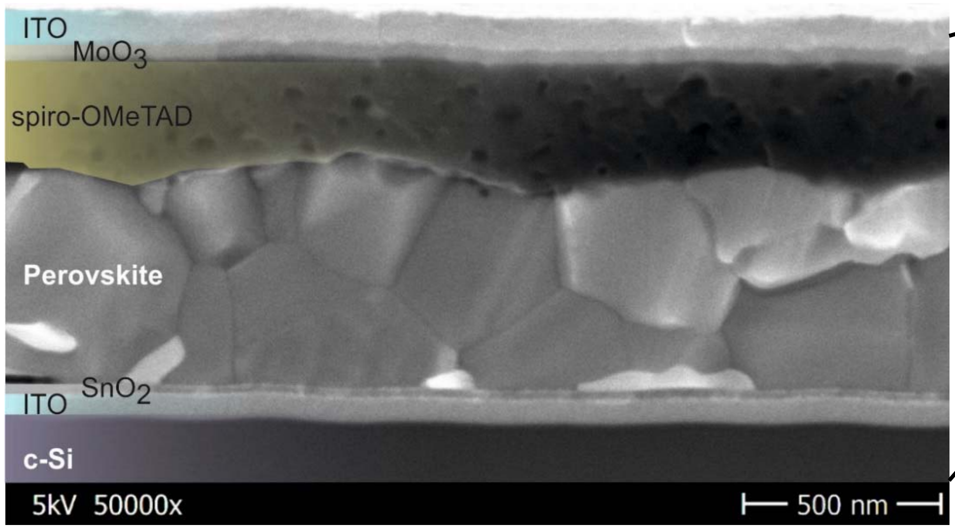


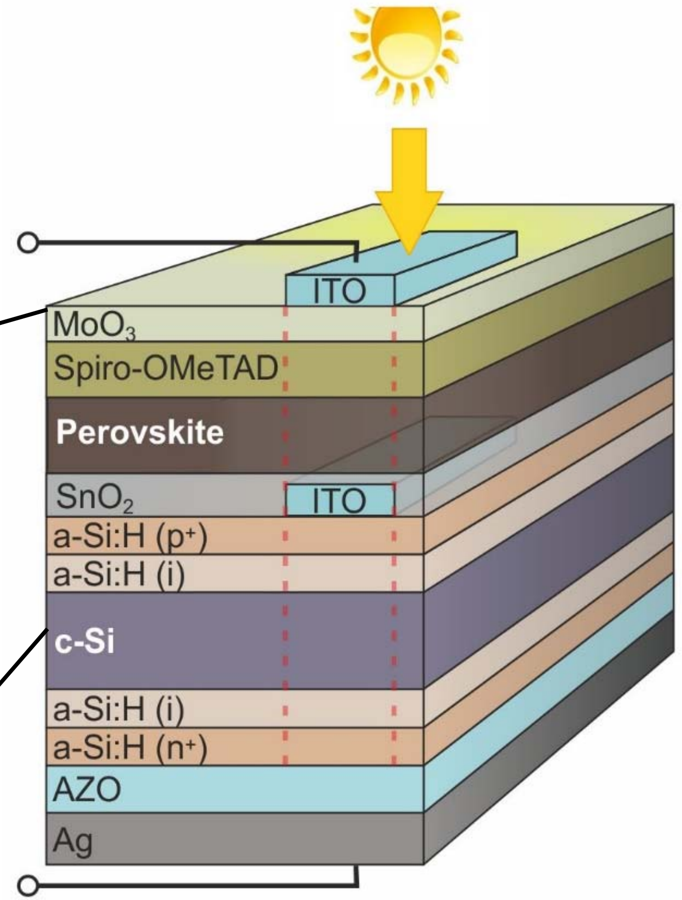
- developed by Baena and coworkers
- SnO_2 as electron selective contact
- one step spinning: FAI, PbI_2, MABr, $PbBr_2$
- >18% PCE stabilized w/o hysteresis

- developed by Tao and coworkers
- PCBM as electron selective contact
- evaporated PbI_2, spin coated MAI on top
- 17.6 % PCE stabilized w/o hysteresis

OUR MONOLITHIC C-SI / PEROVSKITE TANDEM DESIGN

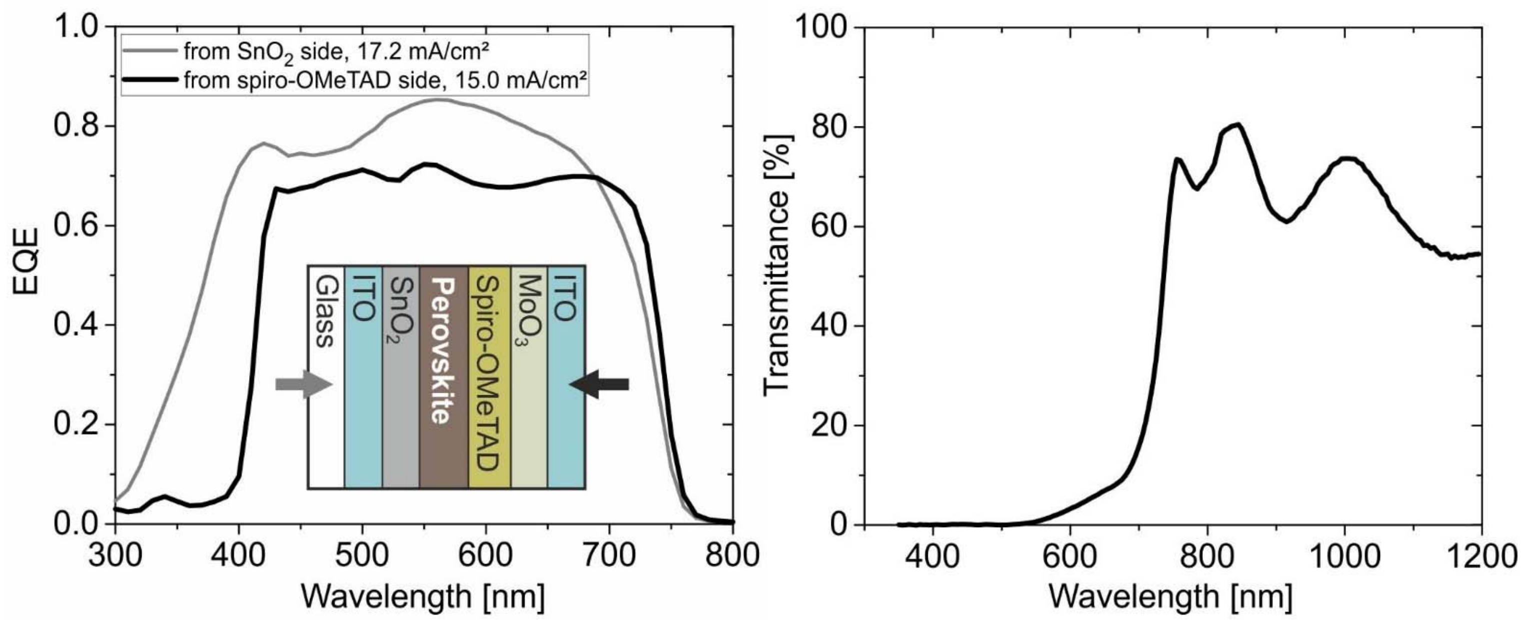
SEM cross section





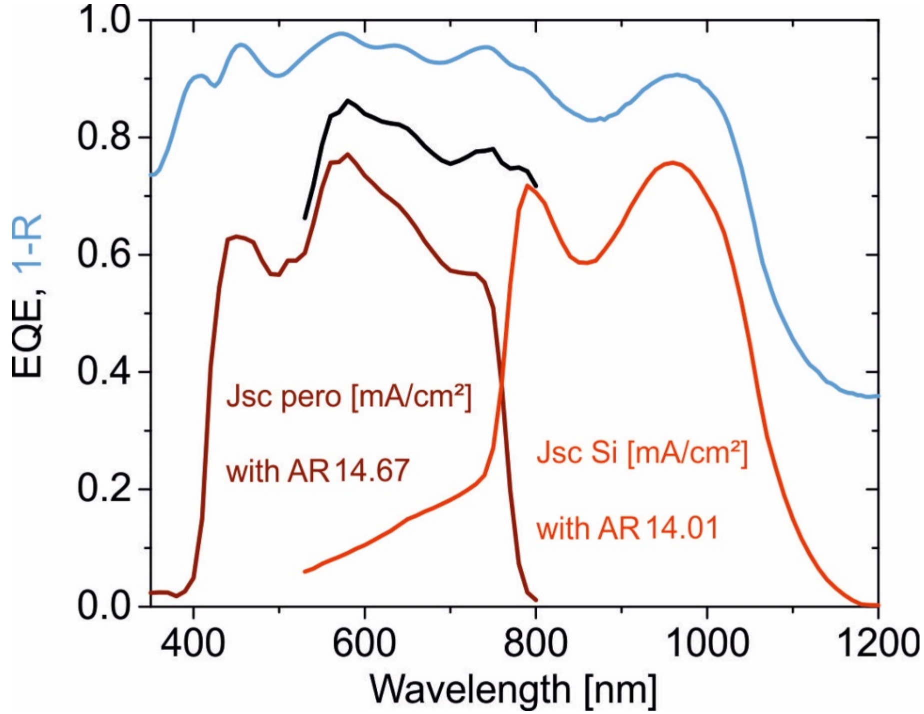
- flat Si heterojunction – no texture!
- ITO as recombination layer
- MoO_3 between spiro-OMeTAD and top ITO
- active area defined by ITO and aperture

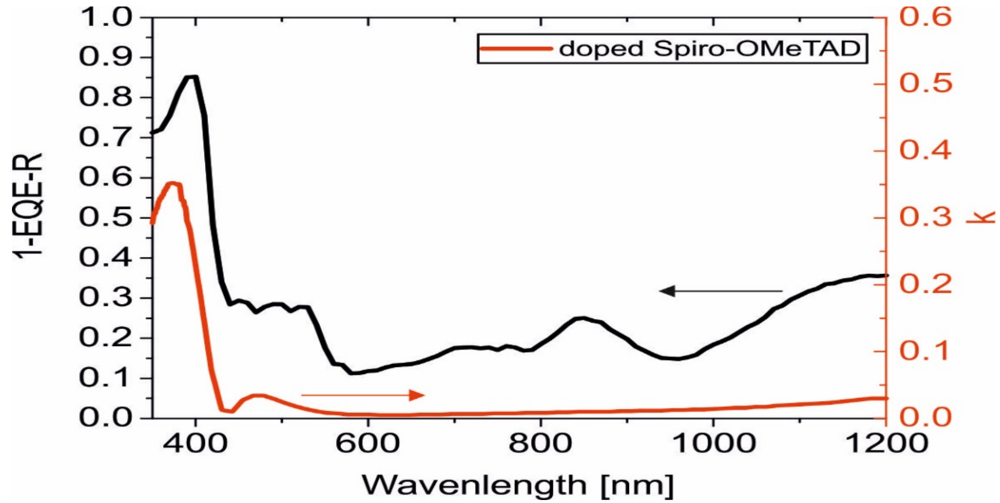
SEMITRANSPARENT PEROVSKITE DEVICE



- spiro-OMeTAD absorbs below 400 nm
- doped spiro-OMeTAD layers absorb also above 400 nm
- 2.2 mA/cm² less photocurrent when illuminated trough spiro-OMeTAD side
- gradual increase of transm. from 550 to 720 nm
- 70% average transm. between 750 and 1100 nm

C-SI / PEROVSKITE TANDEM EQE



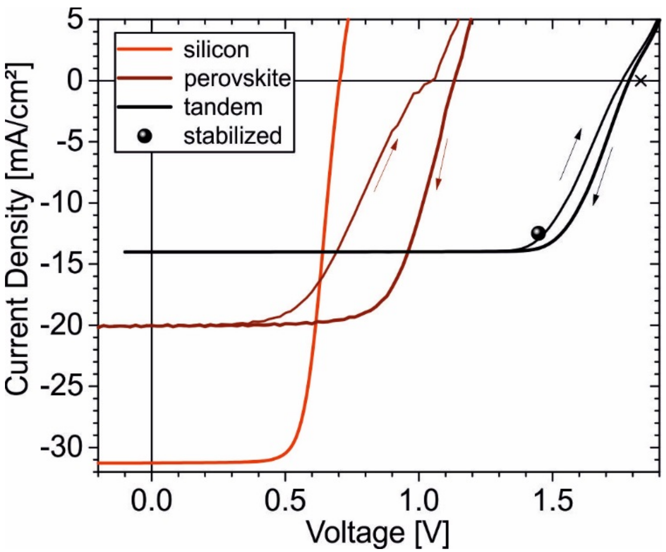


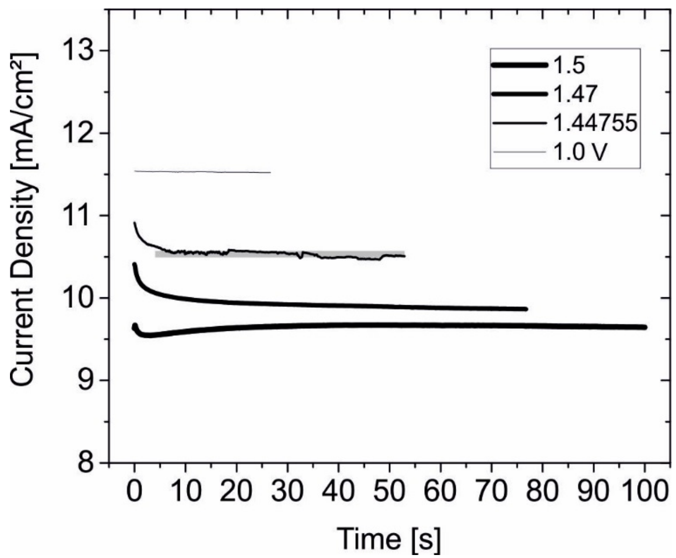
- high reflection in NIR
- silicon sub-cell limits photocurrent
- AR coating enhances Photocurrent

  both sub-cell generate 28.7 mA/cm²

- parasitic loss from spiro-OMeTAD

C-SI / PEROVSKITE TANDEM PERFORMANCE

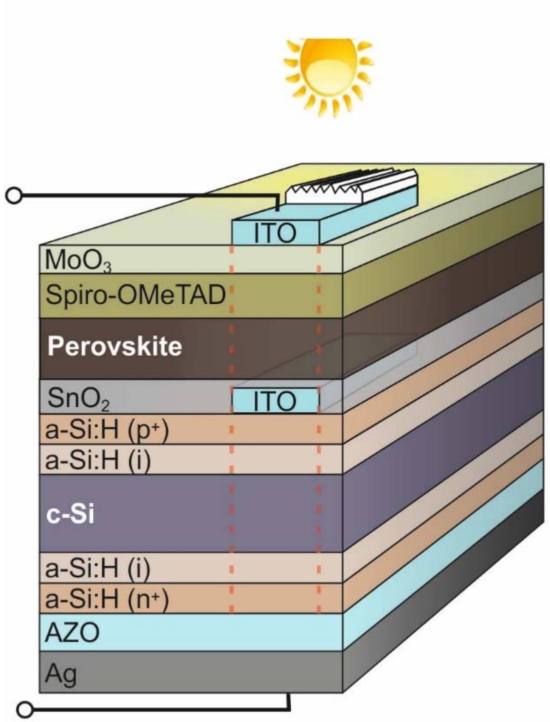


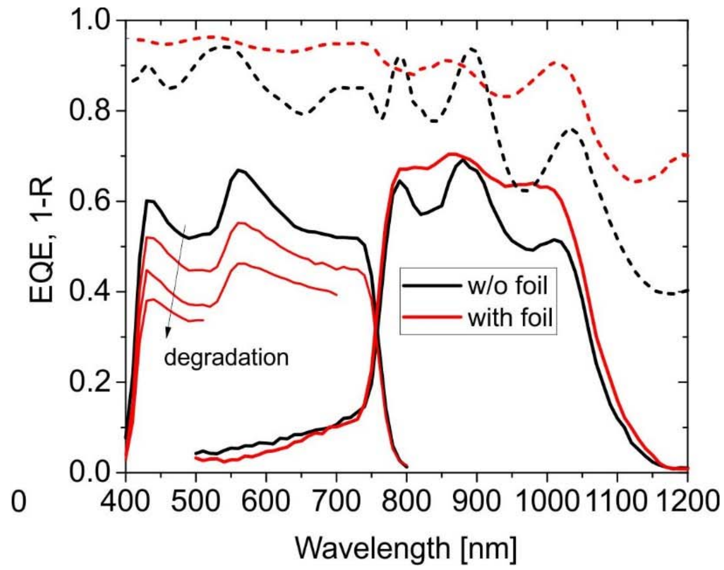


Device	J_{sc} [mA/cm²]	V_{oc} [mV]	FF [%]	PCE [%]
Perovskite reverse	20.1	1130	68.3	15.5
Perovskite forward	20.1	1048	49.3	10.4
Silicon	31.3	703	71.4	15.7
Tandem reverse	11.8	1785	79.5	16.8
Tandem forward	11.8	1759	77.3	16.1
Tandem reverse	14.0	1785	79.5	19.9
Tandem forward	14.0	1759	77.3	19.1
Tandem stabilized				18.1±0.1

- 18% monolithic tandem (stabilized at MPP)
- tandem V_{oc} close to sum of sub-cells
- high FFs approaching 80% in reverse scan
- silicon sub-cell limits photocurrent

FURTHER DEVICE OPTIMIZATION





- textured foil on front ITO is applied
- use matching liquid to couple foil on ITO
- reduces reflection losses
- increases the current in c-Si by 1.2 mA/cm²
- perovskite sub-cell degrades

Textured foil was provided by DSM, for details see Ulbricht et al., PROGRESS IN PHOTOVOLTAICS, 2013, 21, 1672

NEW RECORD

THE JOURNAL OF PHYSICAL CHEMISTRY Letters
Letter
pubs.acs.org/JPCL

Efficient Monolithic Perovskite/Silicon Tandem Solar Cell with Cell Area >1 cm²

Jérémie Werner,[*,†] Ching-Hsun Weng,[†] Arnaud Walter,[†] Luc Fesquet,[†] Johannes Peter Seif,[†] Stefaan De Wolf,[†] Bjoern Niesen,[*,†,‡] and Christophe Ballif[†,‡]

[†]Ecole Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT), Photovoltaics and Thin-Film Electronics Laboratory, Rue de la Maladière 71b, 2002 Neuchâtel, Switzerland
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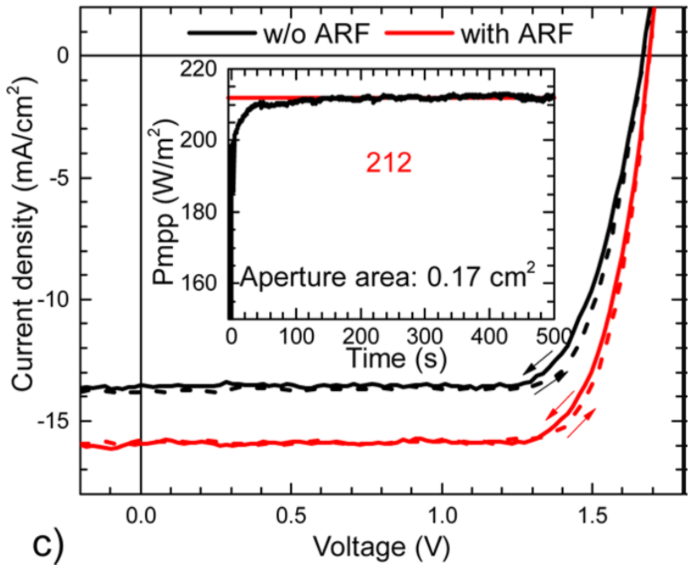
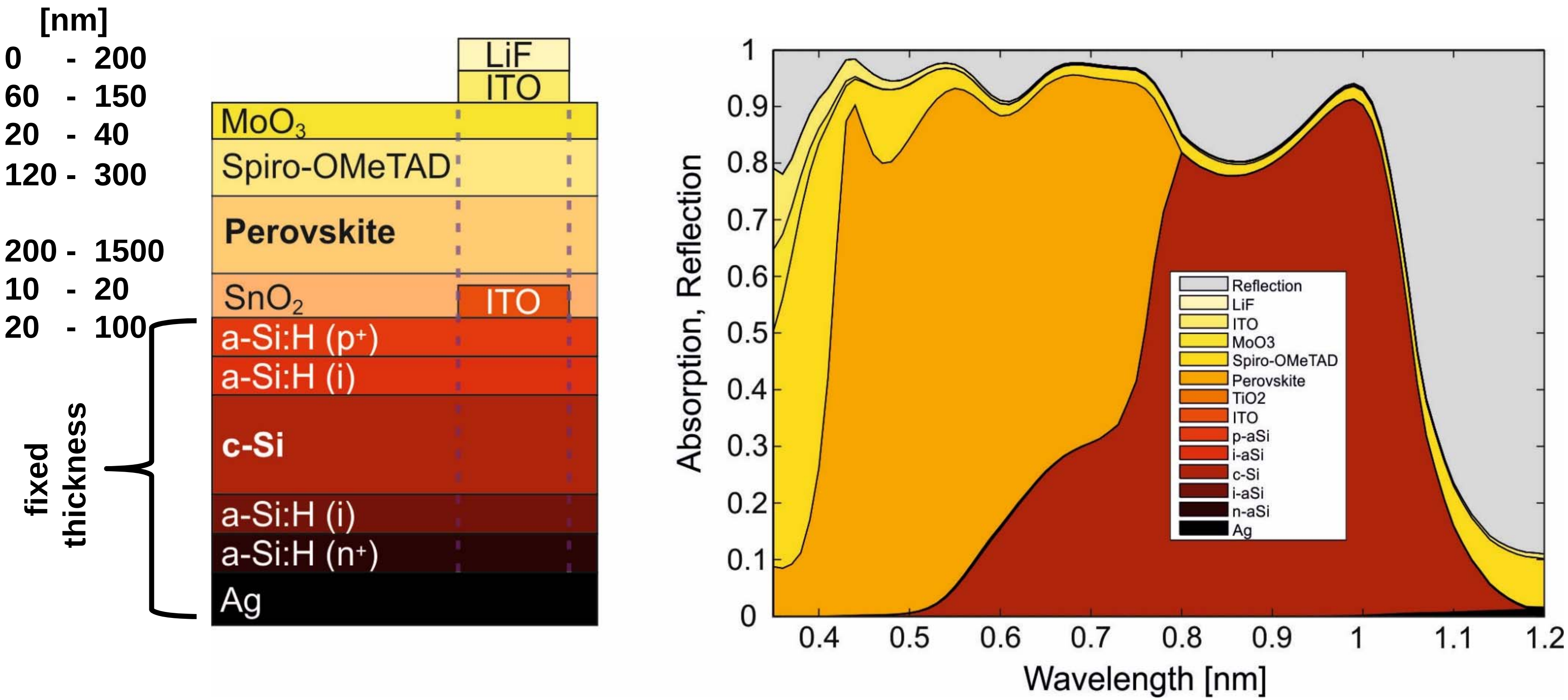


c)

- high currents due to AR foil
- 21.2% highest PCE at the moment
- higher than best perovskite single junction

FURTHER DEVICE OPTIMIZATION (SIMULATION)

- fixed a-Si:H and c-Si thickness
- tune thickness of top cell in experimental relevant range
- optimize minimum Jsc in ca. 10000 iterations
- repeat cycle to ensure to have not a local maximum



- thin middle ITO increases Jsc
- rather thin (below 300 nm) perovskite for current matching

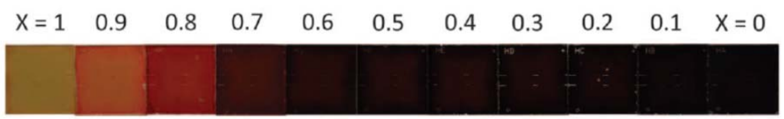
  energetically unfavorable

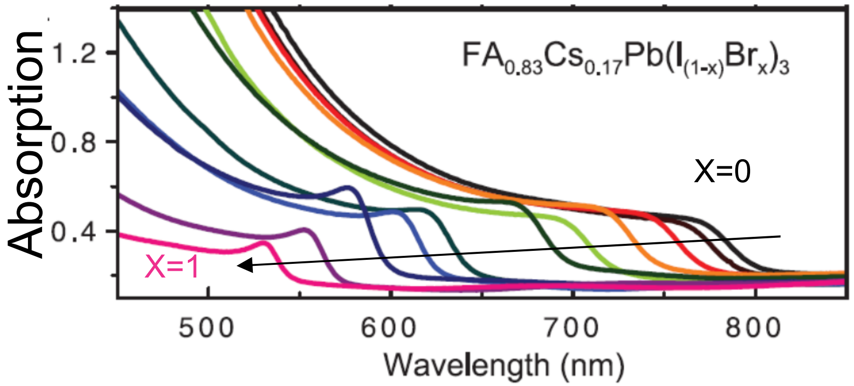
BAND-GAP OPTIMIZATION: CEASIUM!

SOLAR CELLS

A mixed-cation lead mixed-halide perovskite absorber for tandem solar cells

David P. McMeekin,[1] Golnaz Sadoughi,[1] Waqaas Rehman,[1] Giles E. Eperon,[1] Michael Saliba,[1] Maximilian T. Hörantner,[1] Amir Haghighirad,[1] Nobuya Sakai,[1] Lars Korte,[2] Bernd Rech,[2] Michael B. Johnston,[1] Laura M. Herz,[1] Henry J. Snaith[1*]





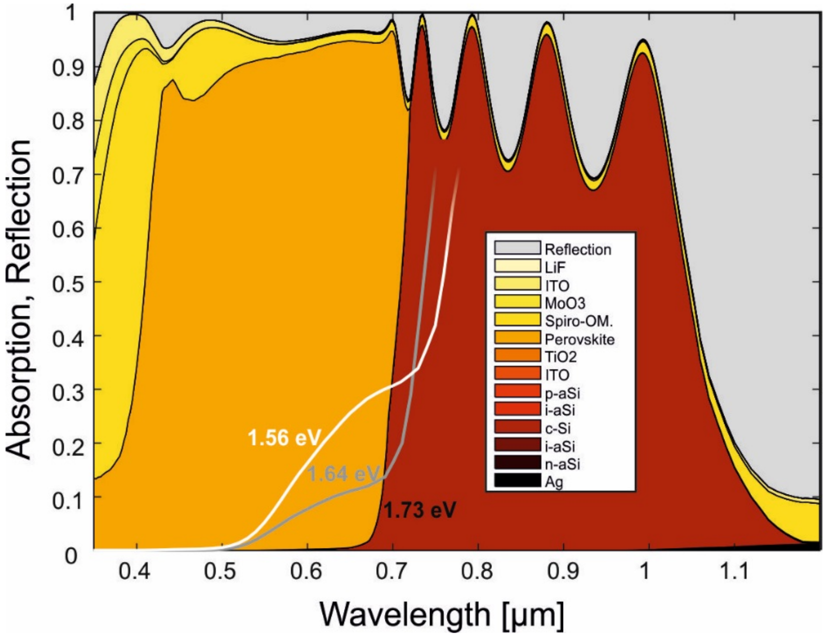
- photostable band-gap-tunable perovskite
- stabilized 19.8% 4-terminal perovskite/SHJ tandem

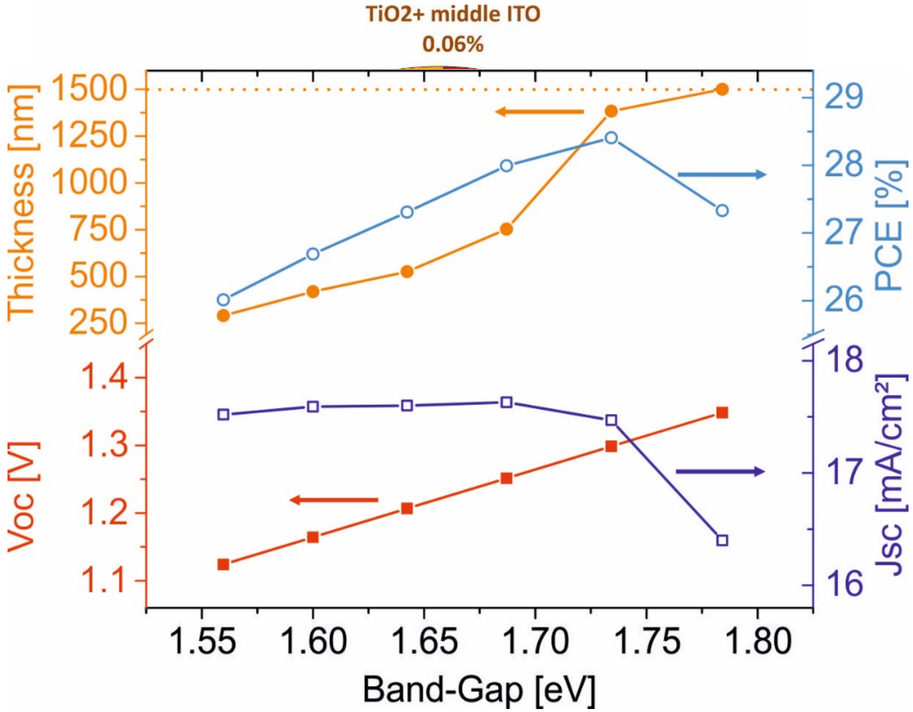
Adopt in simulation:

- fixed a-Si:H and c-Si thickness
- tune thickness of top cell in experimental relevant range for each band-gap
- optimize minimum Jsc in ca. 10000 iterations
- repeat cycle to ensure to have not a local maximum

OPTIMIZATION OF BAND-GAP (SIMULATION)

- increase the optical band-gap of perovskite
- enhance the Voc of the perovskite sub-cell accordingly





- 1.73 eV band-gap of perovskite and 1300 nm thickness
- Jsc = 17.4 mA/cm², Voc=1.30+0.71=2.01 V, FF=0.81 ⇒**PCE= 28.4%**

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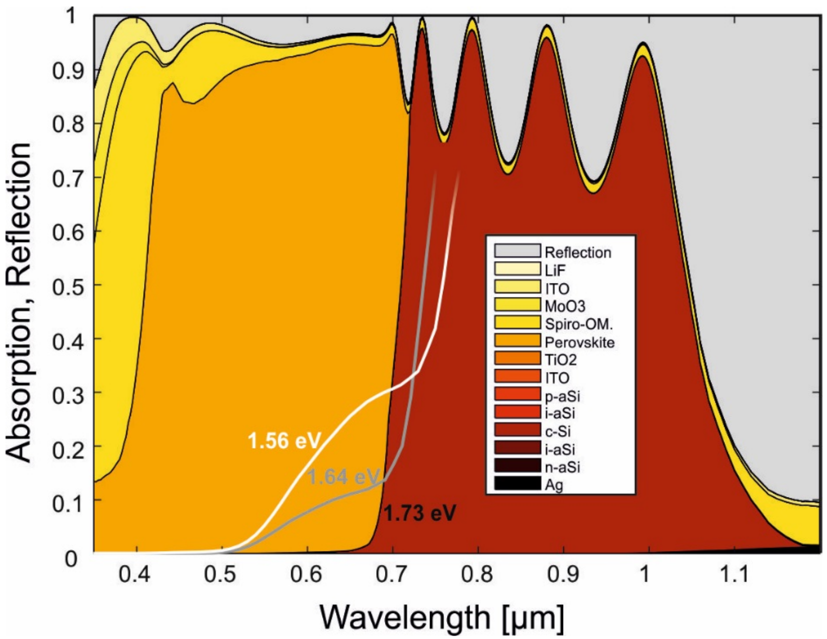

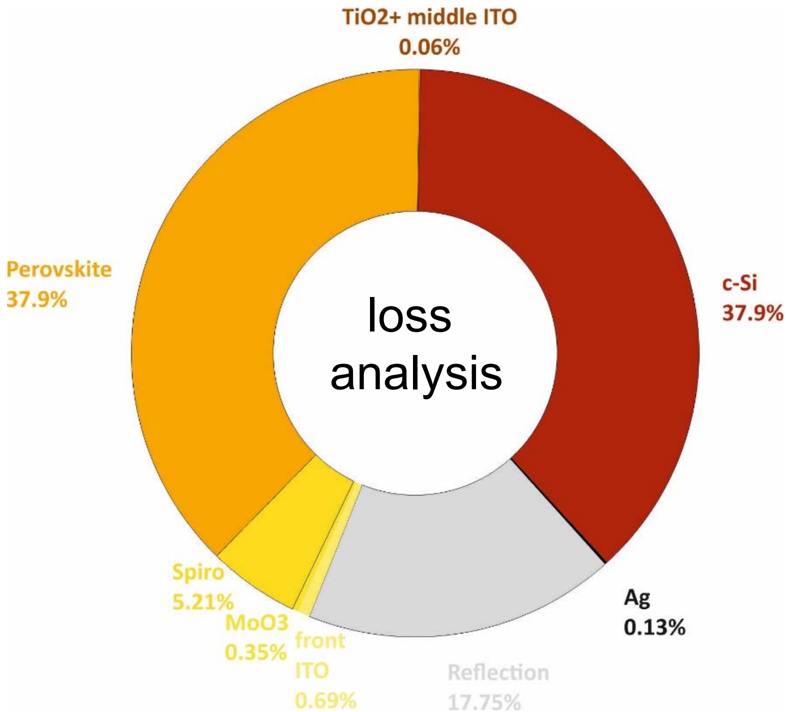

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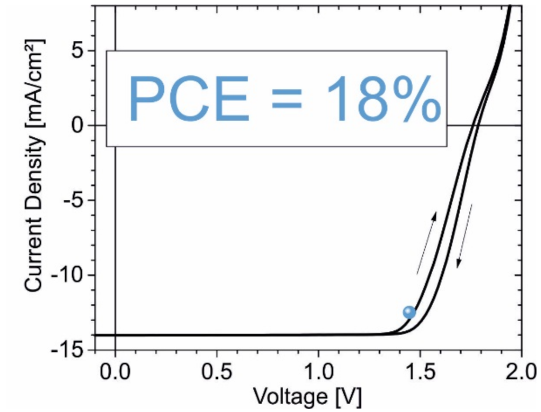
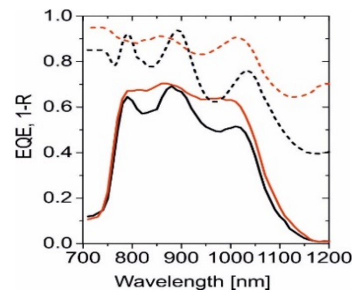
CONCLUSION

- first realization of monolithic perovskite / SHJ processed at low temp.
  - realized via ALD of SnO_2 and mixed perovskite (EPFL)
  - reverse scan: Jsc=14 mA/cm², Voc=1.78V, FF=79.5%, PCE=19.9%
  - stabilized power output 18.1%



- device design limited by optical losses
  - AR coating (100 nm LiF) significantly reduce optical losses
  - AR foil enhances EQE in silicon, but degrades perovskite



- strategy to overcome 30% with this tandem design:
  - enhance optical band-gap to ~1.7 eV and Voc to 1.3 eV – other selective contacts
  - enhance perovskite thickness to over 1 µm – other deposition techniques
  - implement effective light trapping – conformal growth on pyramids

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