HySPRINT
Helmholtz Innovation Lab

HZB Helmholtz Zentrum Berlin

Towards Efficient Perovskite/Silicon Tandem Solar Cells

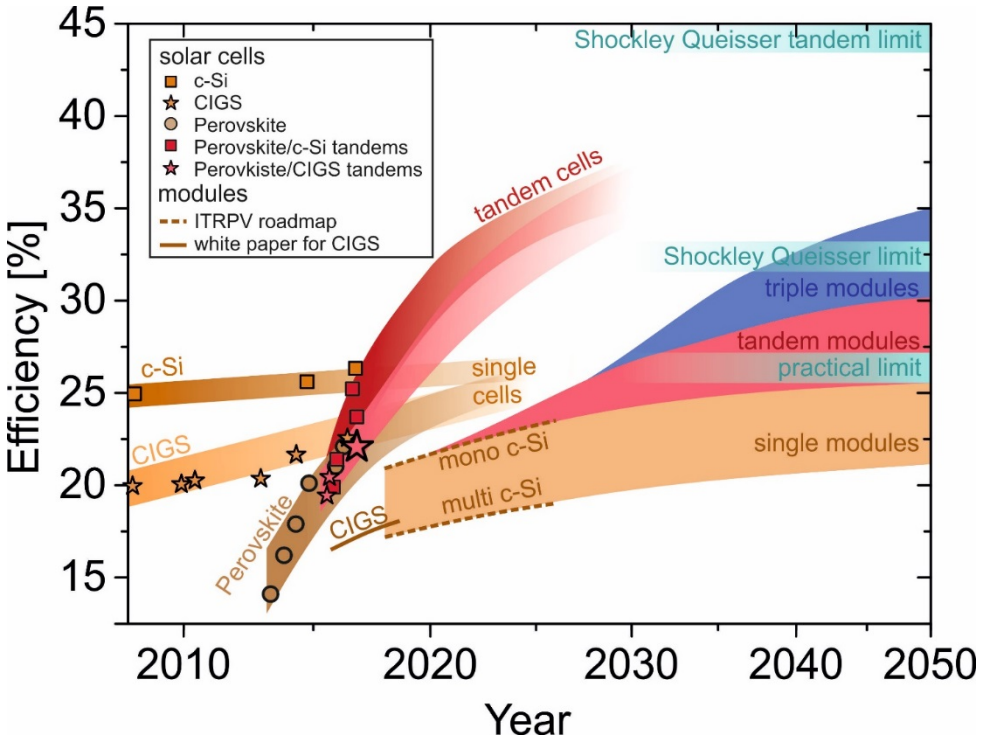
First HySPRINT Industry Day

Steve Albrecht … and many others

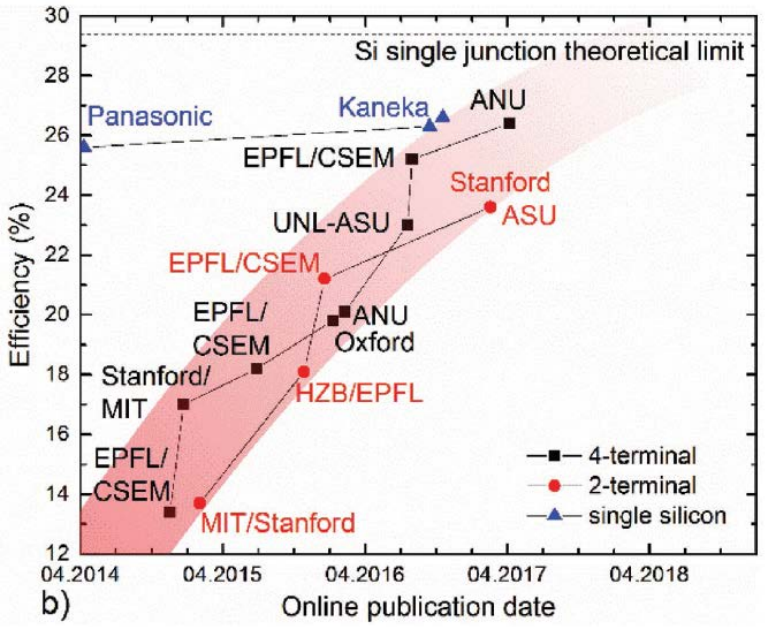
Friday the 13th, October 2017, Helmholtz-Zentrum Berlin

Motivation - Efficiency Evolution

S. Albrecht and B. Rech,
NATURE ENERGY 2, 16196, 2017



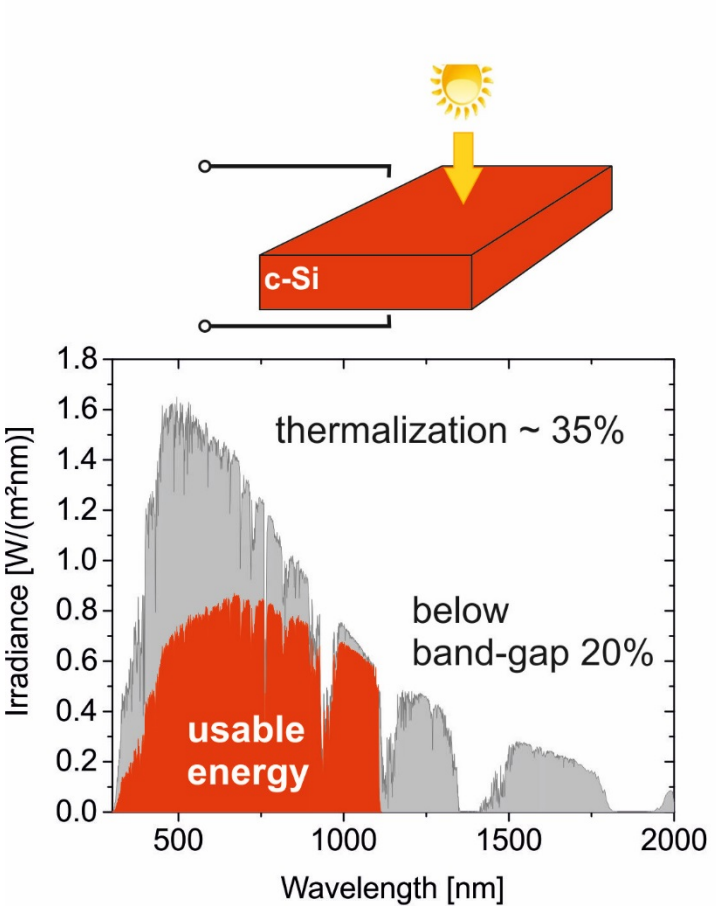
J. Werner et al., Adv. Mater. Interf., 2017



- Single junctions will be limited to ~27%
- Perovskite based tandems are on the way to outperform Si- cells
- To develop more efficient modules:

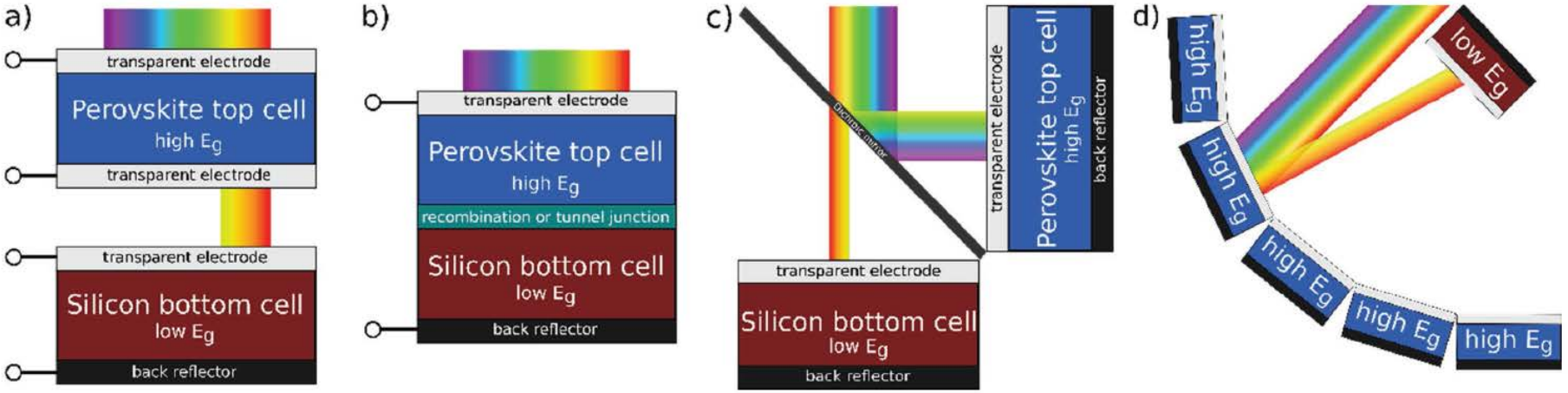
  Tandem and triple junction technology important in next decades

C-Si / Perovskite tandem



- high loss from thermalization

Different Tandem Architectures



4-terminal

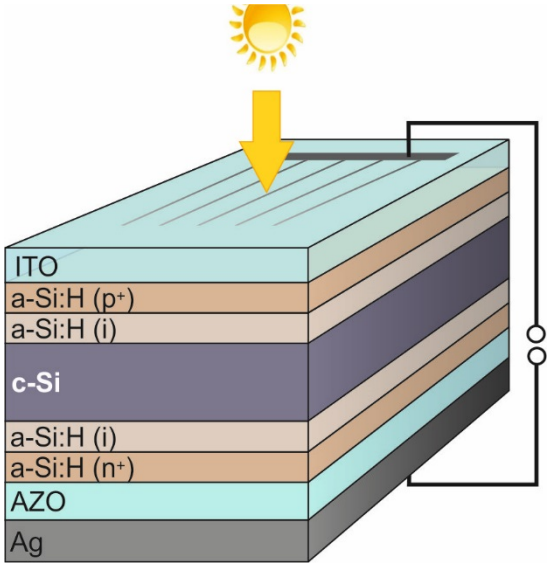
2-terminal monolithic

4-terminal spectral splitting

4-terminal reflective

Why a-si:H/c-Si Silicon heterojunctions?

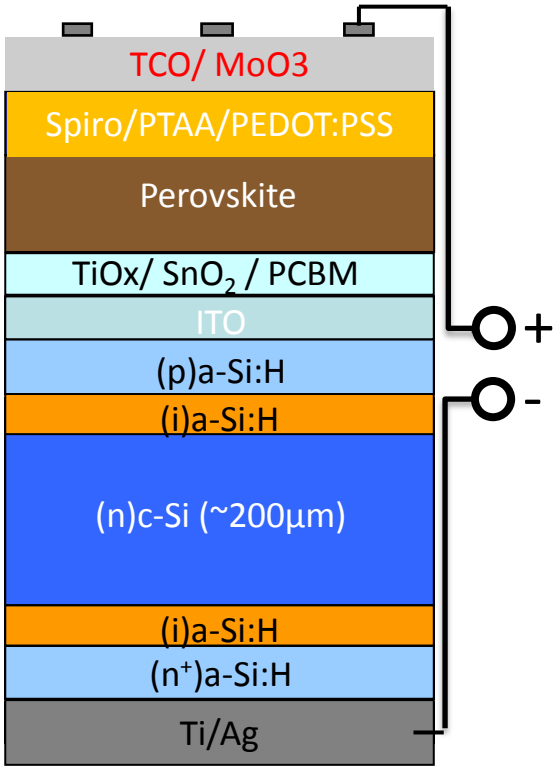
- highest certified efficiency of 26.6% (1)
- highest V_{oc} up to 750 mV (2)
- high voltages are maintained at reduced illumination levels (3)
- high EQE response in the long-wavelength region (4)
- parasitic absorption in a-Si:H layer not important in tandem
- increasing interest from industry
- Fully covered ITO front contact
- restriction: not temperature stable above 200°C



(1) Yoshikawa, K.; Kawasaki, H.; Yoshida, W.; Irie, T. et al., *Nature Energy* ***2017, 2, 17032***.
(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.***

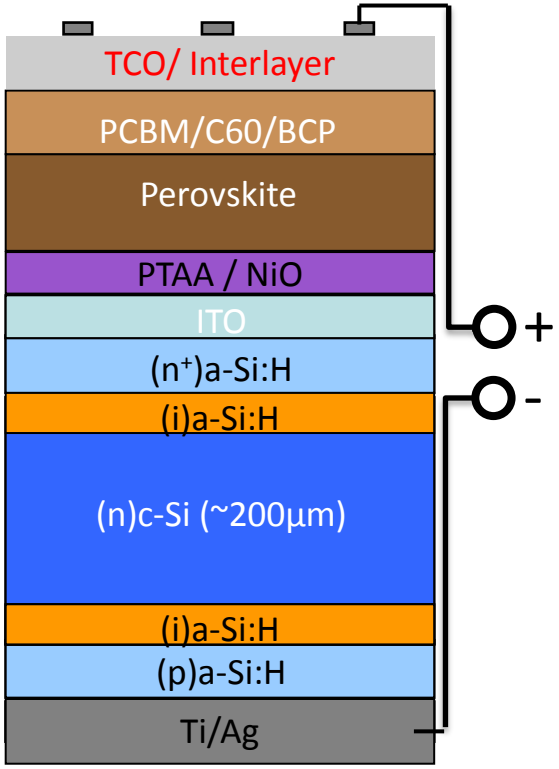
Different device design enable flexibility

„normal“



a-Si/ c-Si heterojunction
front emitter,
normal Perovskite

„inverted“



a-Si/ c-Si heterojunction
rear emitter,
inverted Perovskite

Low Temperature Electron Contact

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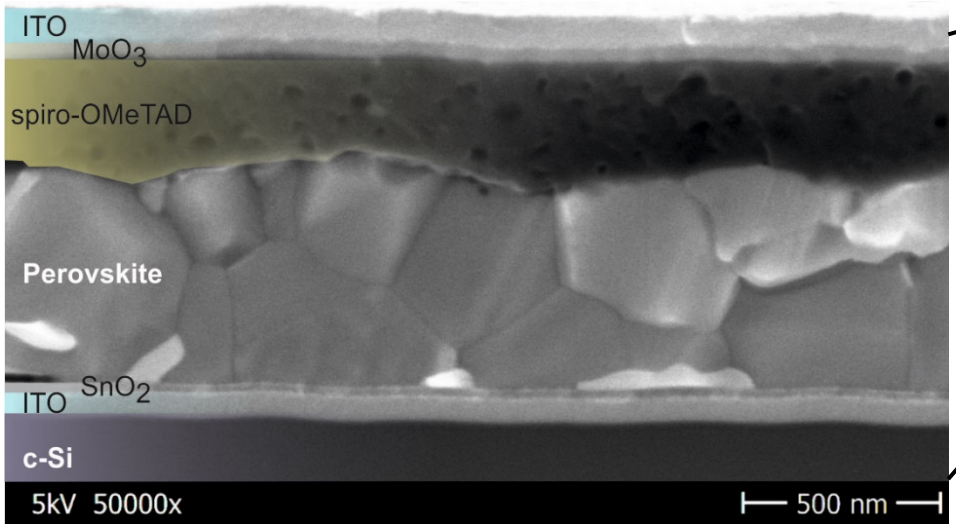
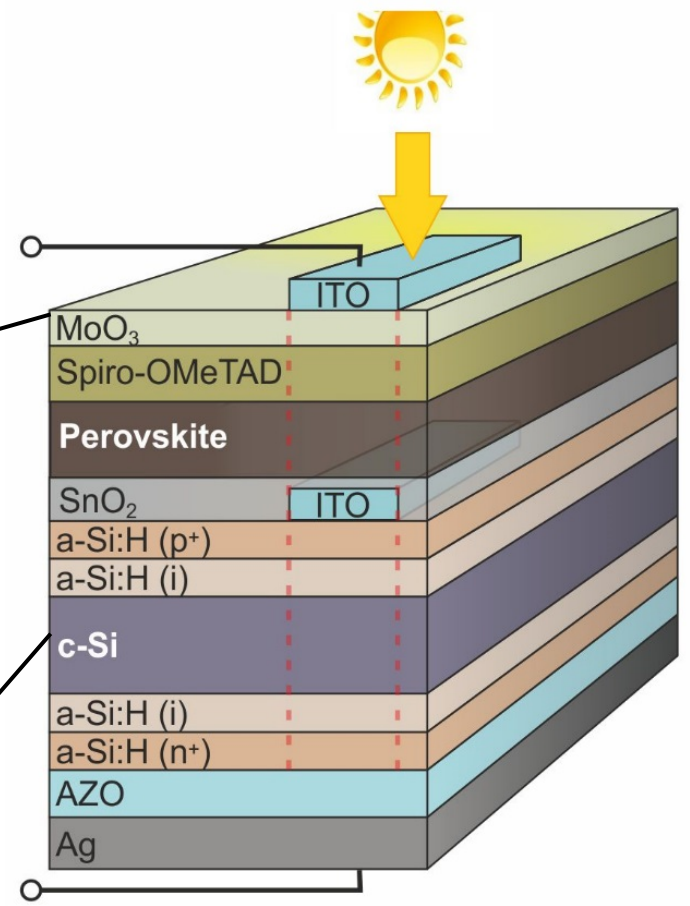
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

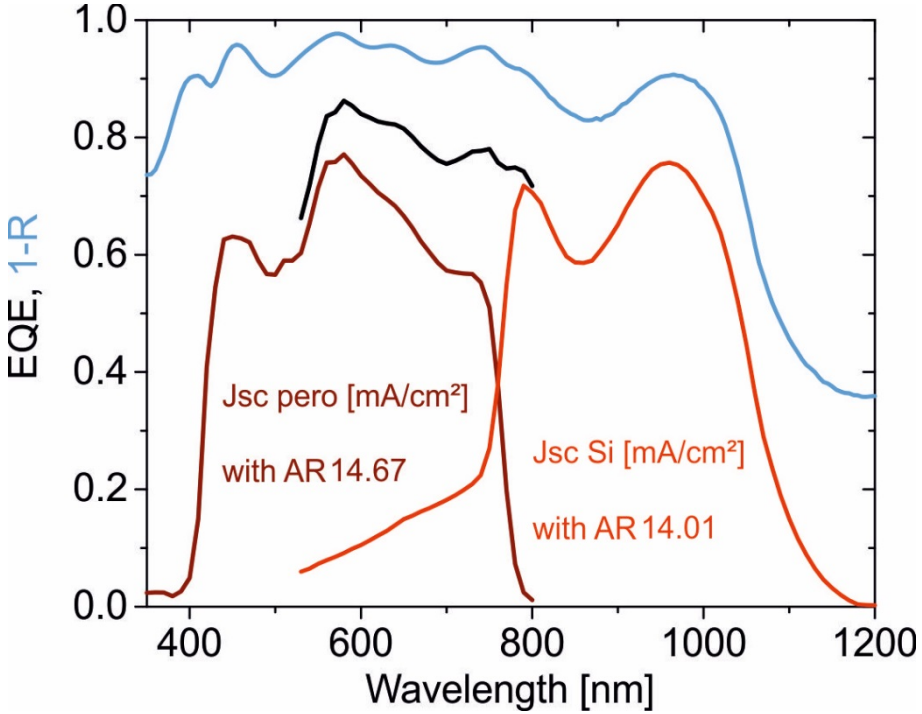
SEM cross section

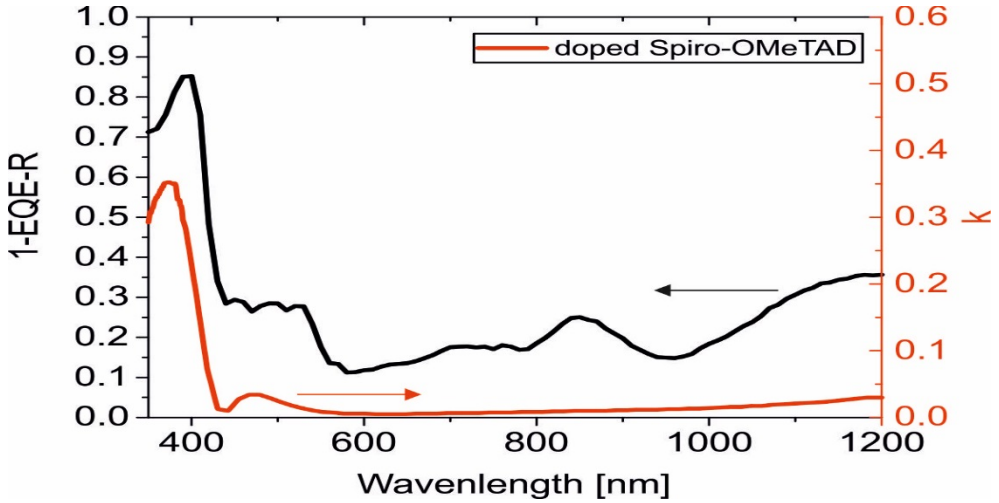




- flat Si heterojunction – no texture!
- ITO as recombination layer
- MoO_3 between spiro-OMeTAD and top ITO
- active area defined by ITO and aperture

c-Si / Perovskite Tandem EQE

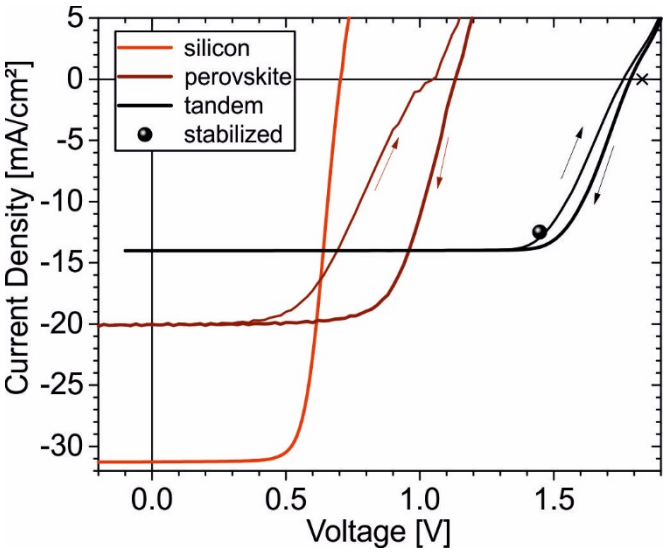


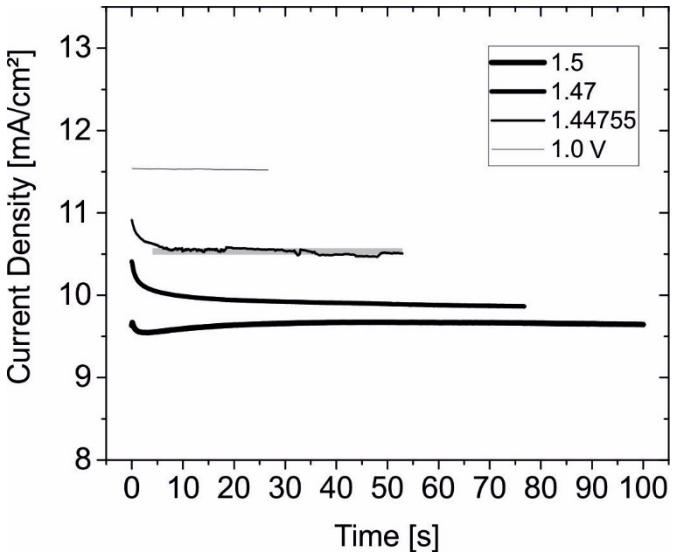


- high reflection in NIR
- silicon sub-cell limits photocurrent
- AR coating enhances Photocurrent
  both sub-cell generate 28.7 mA/cm²
- parasitic loss from spiro-OMeTAD

Albrecht, S.; Saliba, M. et al., Energy & Environmental Science 2016, 9 (1), 81-88.

c-Si / Perovskite Tandem Performance



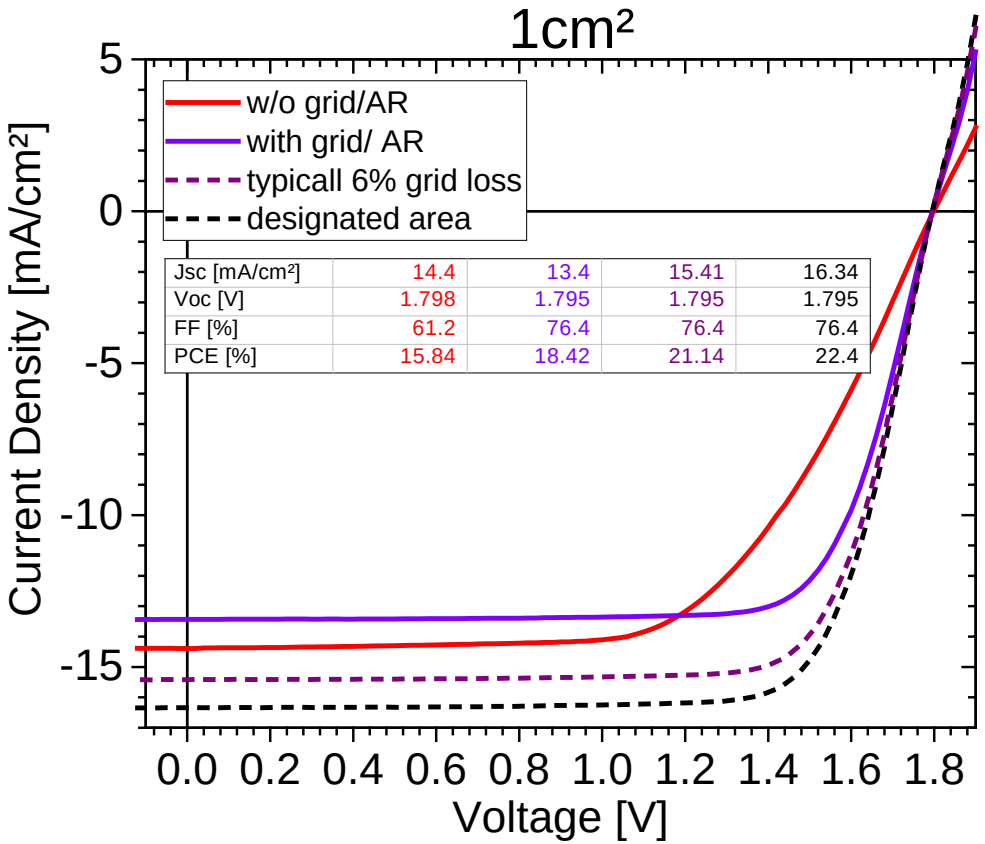


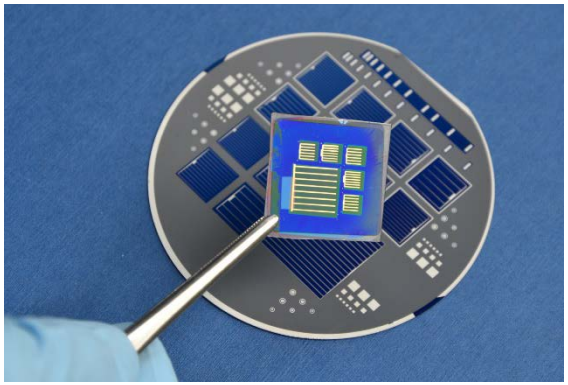
Device	J_{sc} [mA/cm²]	V_{oc} [mV]	FF [%]	PCE [%]
Perovskite reverse	20.1	1130	68.3	15.5

- 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

Albrecht, S.; Saliba, M. et al., Energy & Environmental Science 2016, 9 (1), 81-88.

„Larger“ Area Tandem Cell





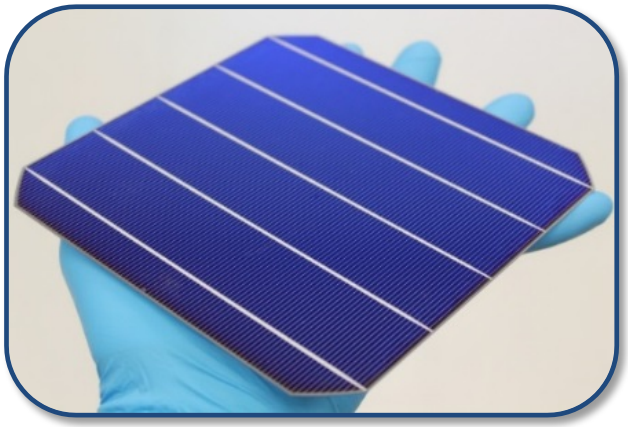
- Bigger active area 1cm² cell size
- w/o metal grid - reduced FF
- Used metal grid gives 18% shading
- 6% shading results in approx. 21%

Albrecht S. et al., unpublished results

Silicon Heterojunction Baseline at PVcomB

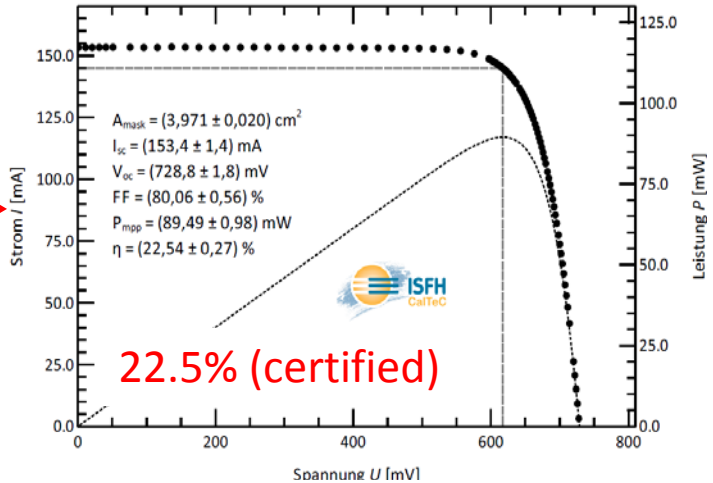
PVcomB
Competence Centre Thin-Film- and Nanotechnology for Photovoltaics Berlin

4 cm² solar cells on 5-inch Cz-Si wafer



239 cm² solar cell on 6-inch Cz-Si

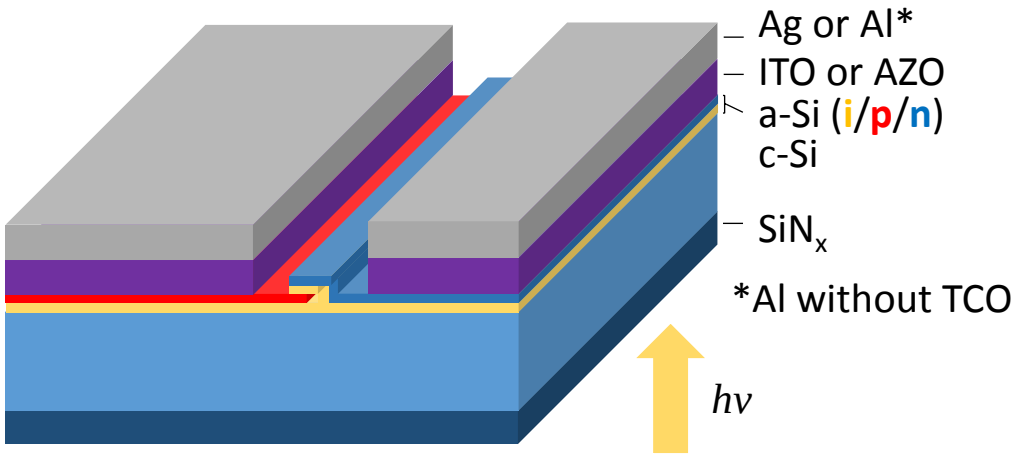
Cell area (cm²)		values	η (%)	V_{oc} (mV)	j_{sc} (mA/cm²)	FF (%)
4 (da)	busbars less	median	**22.3**	728	38.3	79.8
		best	**22.6**	730	38.2	81.0
239 (t)	5 busbars	best	**20.6**	722	36.0	79.3

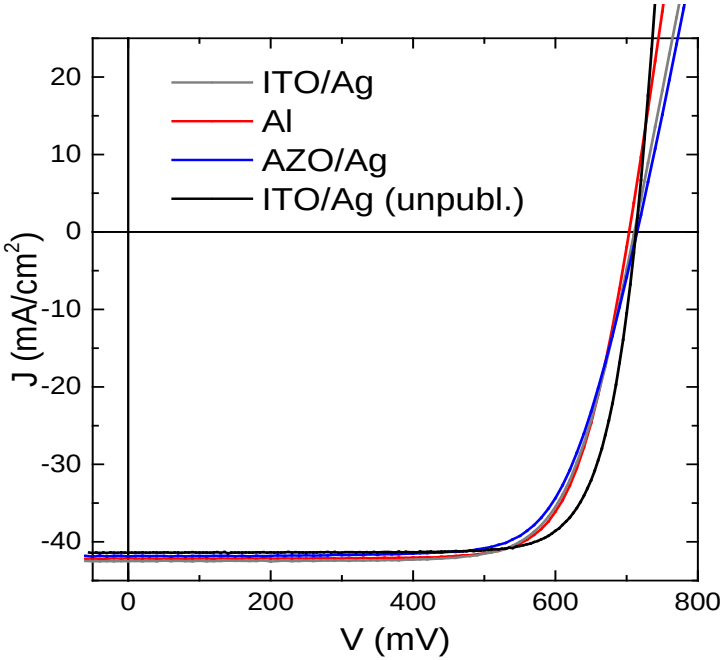


L. Mazzarella et al., 44th IEEE PVSC, Washington 2017, submitted to J-PV

A. Morales-Viches et al., 33rd EUPVSEC, Amsterdam 2017 (2.AV.3.3)

IBC-SHJ with Photolithography





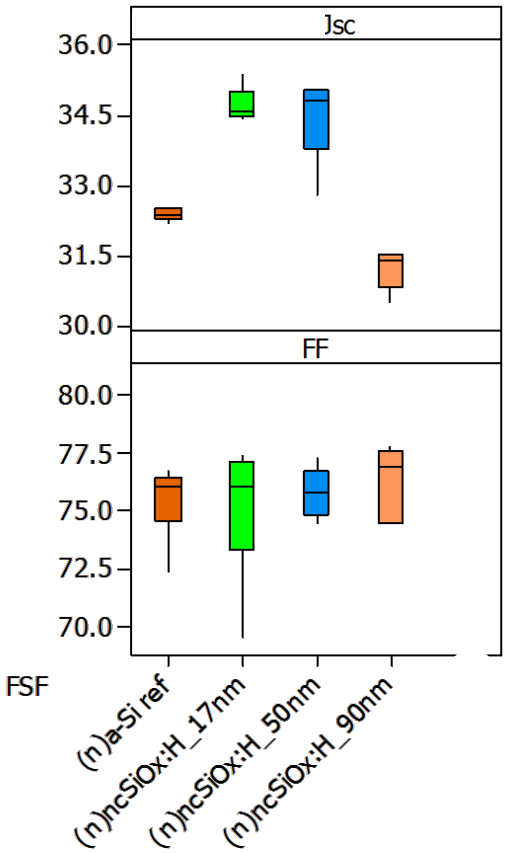
- Further tests Al vs. ITO/Ag
- Small cell size (1 cm²) limits V_{OC}
- Improved FF due to optimised a-Si:H layers

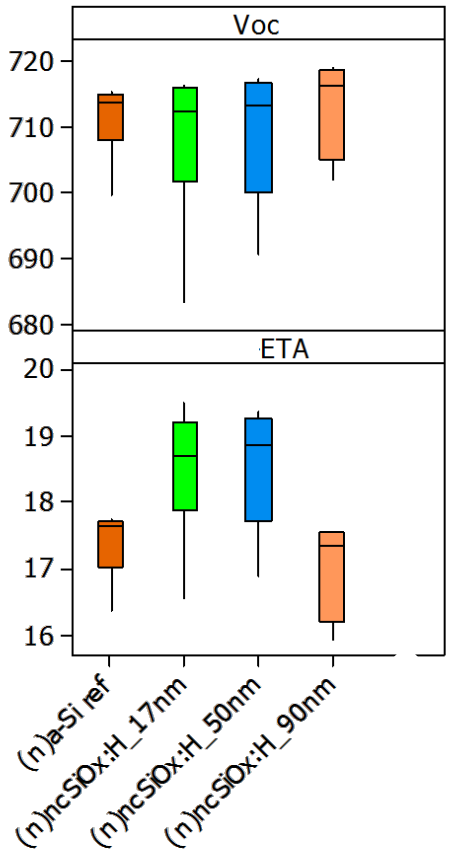
Metallization	V_{oc} (mV)	J_{sc} (mA/cm²)	FF (%)	η (%)
ITO / Ag	711	41.5	73.1	21.6
Al	703	41.6	75.2	22.0
AZO1 / Ag	715	41.9	72.2	21.6
ITO / Ag (unpubl.)	713	41.4	**78.5**	**23.2**

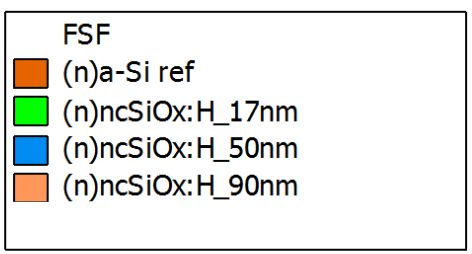
*Stang C., Korte L. et al., Solar RRL **1** (2017) 1700021*
Stang C., Korte L. et al., to be published

Planar Silicon Heterojunction Developement

PVcomB



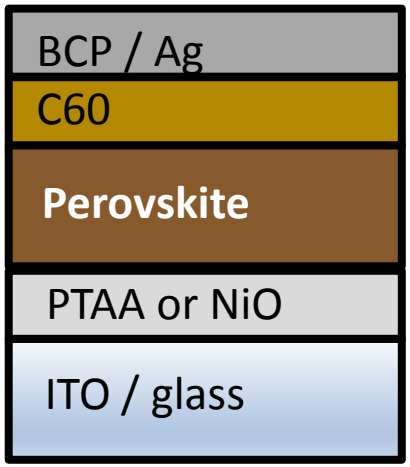


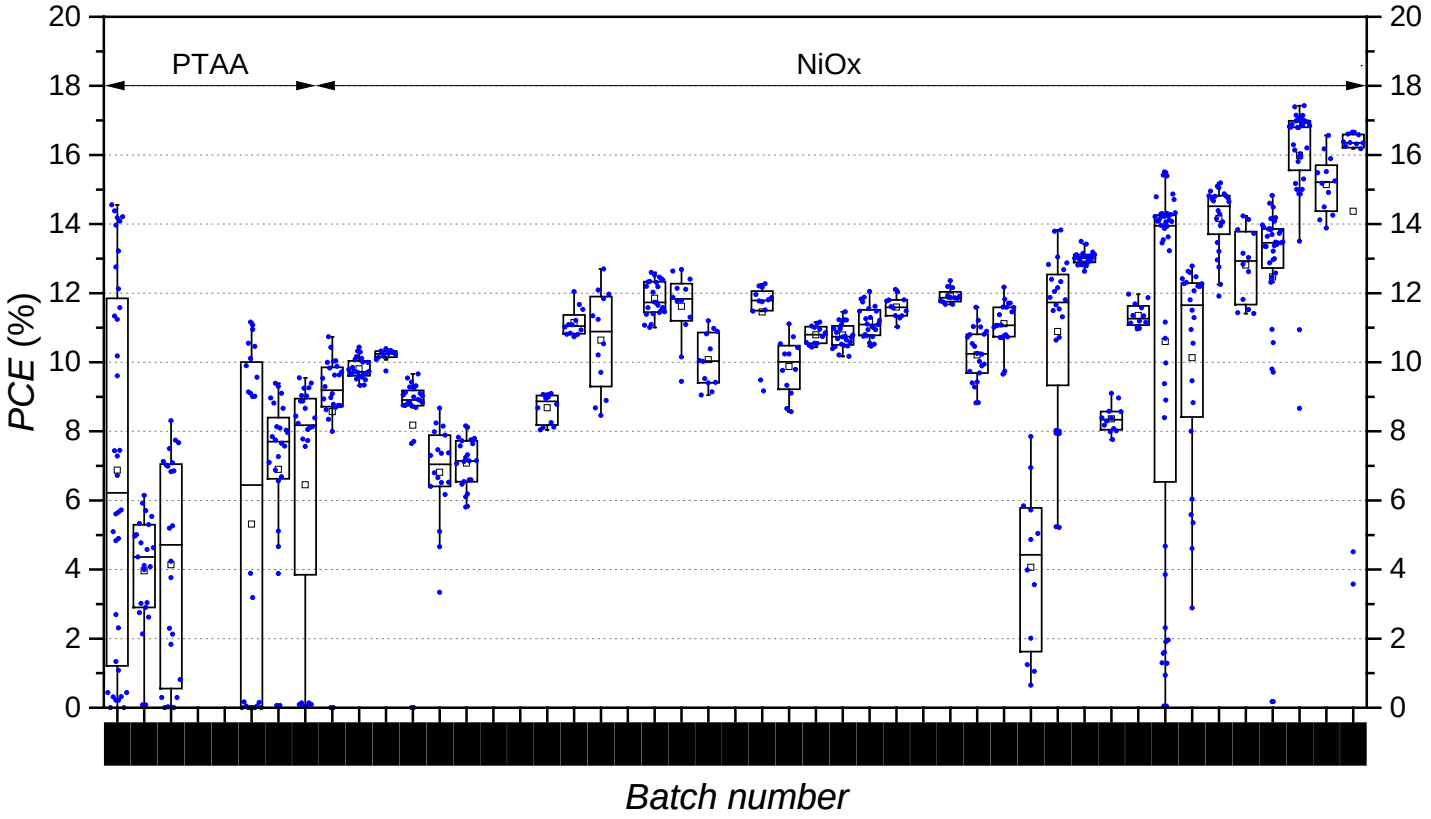


- Optical enhancement of front surface field (FSF) to gain higher photocurrent
- Potential of FF optimization
  - **20.5% to 21% efficiency possible**

Mazarella L., Stannowski B. et al., unpublished results

Planar Perovskite Solar Cells: Efficiency Evolution

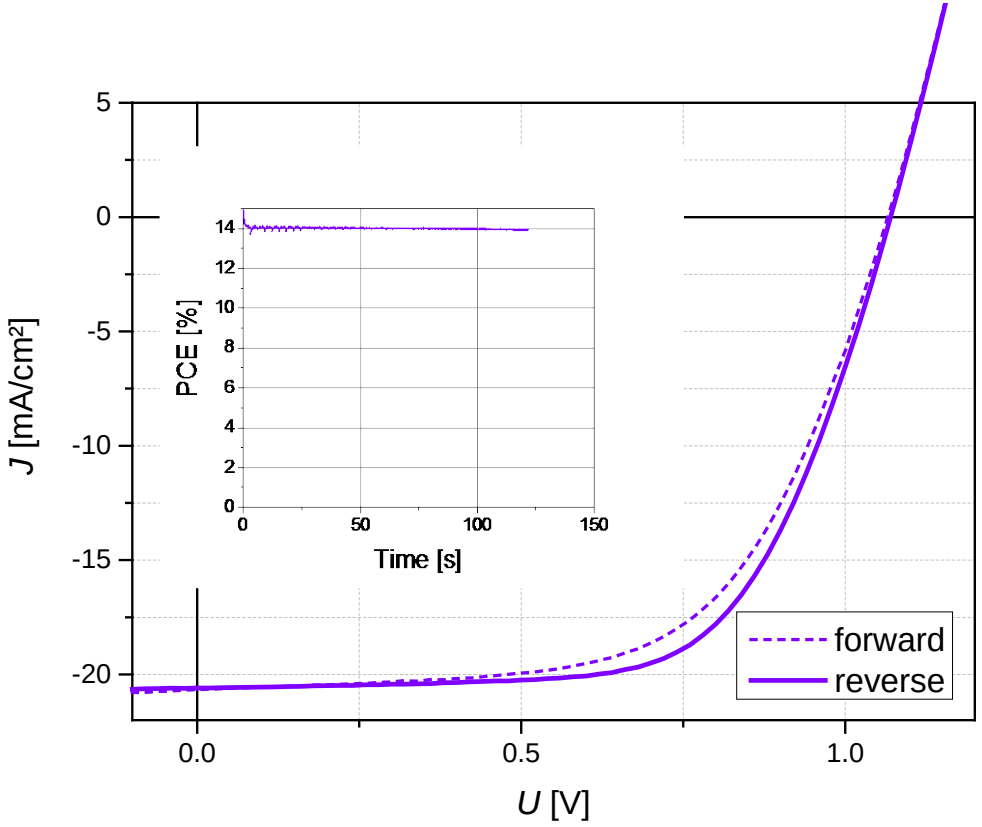


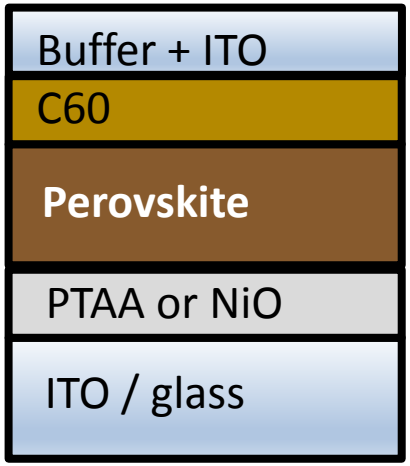


- Over 2000 solar cells from over one year
- Steadily increasing efficiency by more control of process and contact layers
  - **Now: High reproducibility on the 18% level**

Braunger S., et al., unpublished results

Semitransparent Perovskite Solar Cells

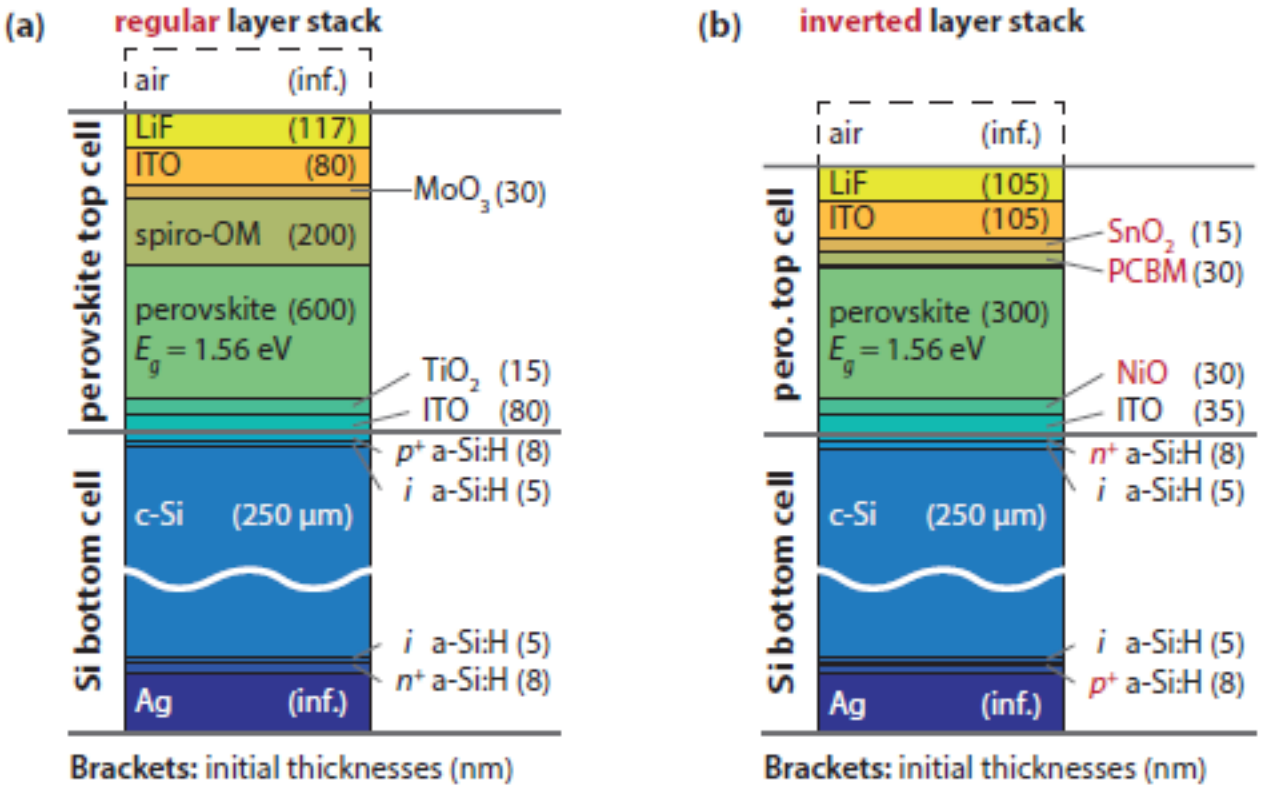




- Different buffer layers tested
- TCO sputter deposition optimized

  - **14% semi-transparent perovskite solar cell**

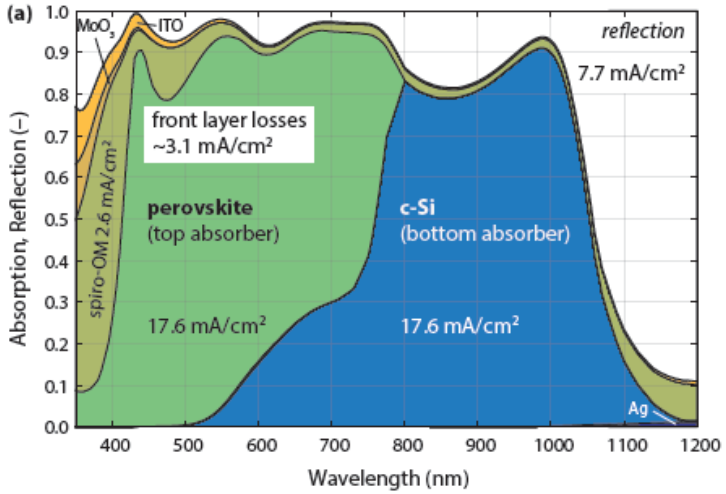
Comparison of Tandem Designs (Simulation)

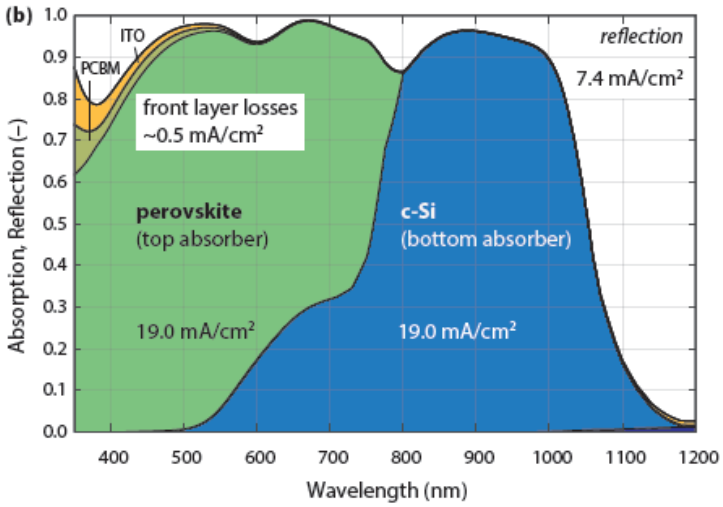


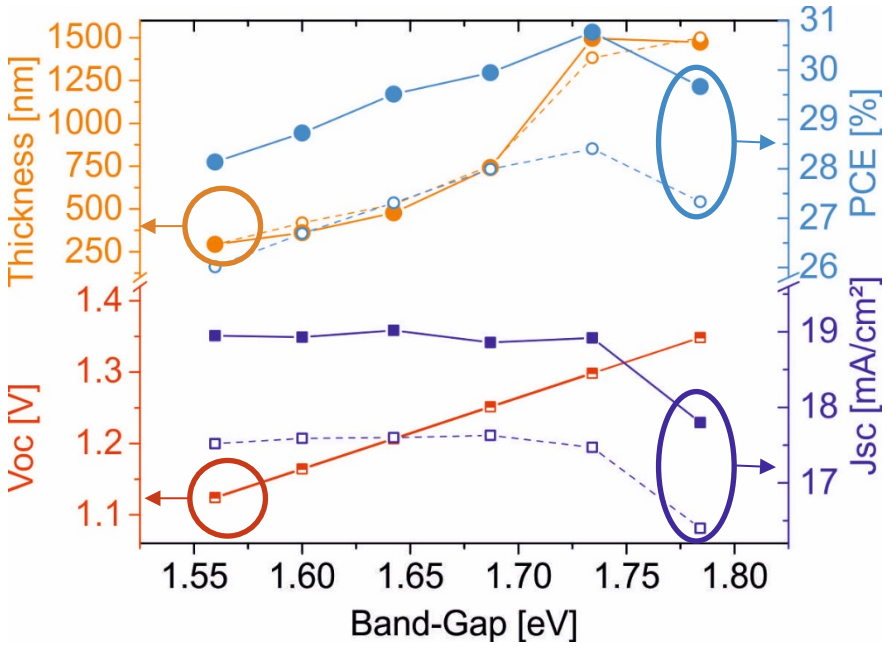
- Compare regular in inverted tandem designs
- Use realistic layer and thickness combinations
- Simulate the optimized thicknesses for current matching

Jäger K., Albrecht S., et al., Optics Express 2017, 25 (12), A473-A482.

Comparison of Tandem Designs (Simulation)





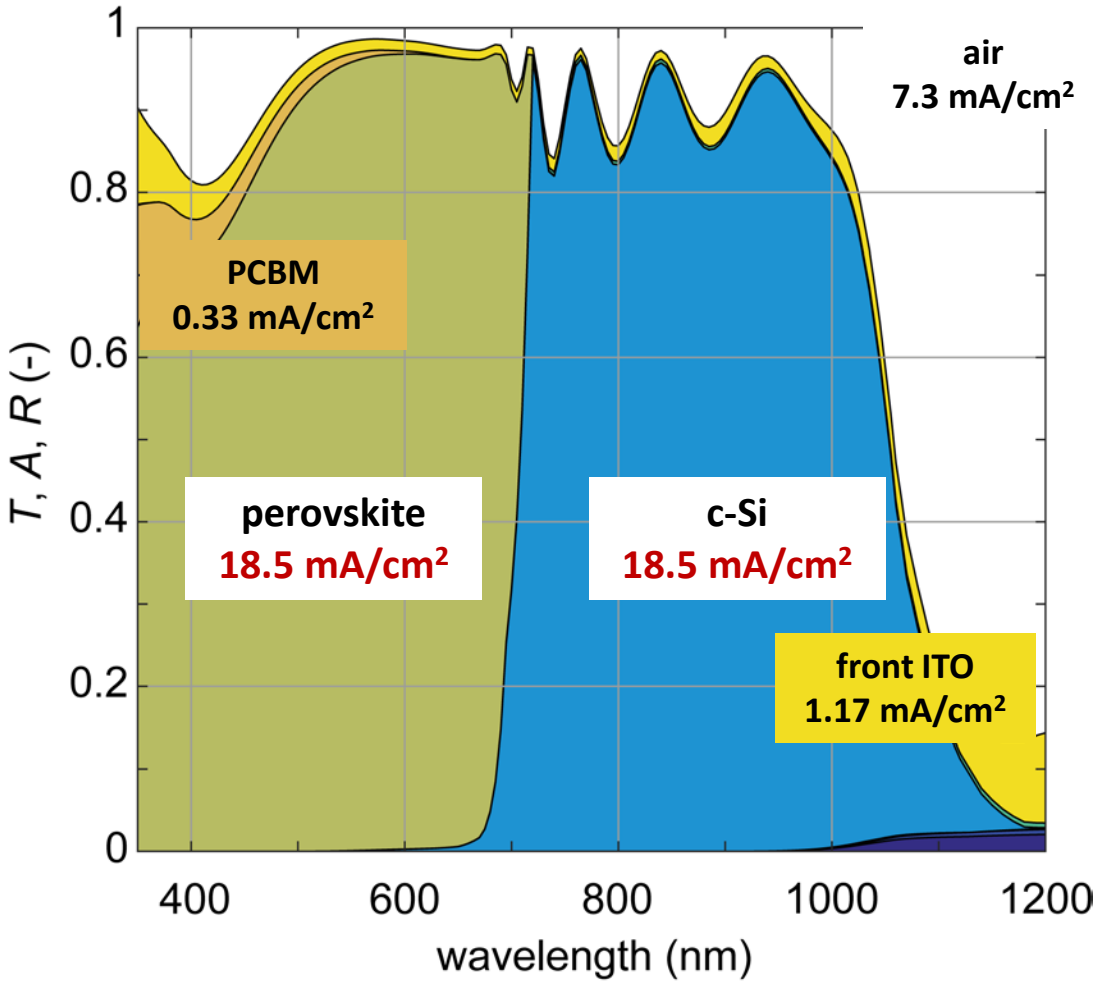


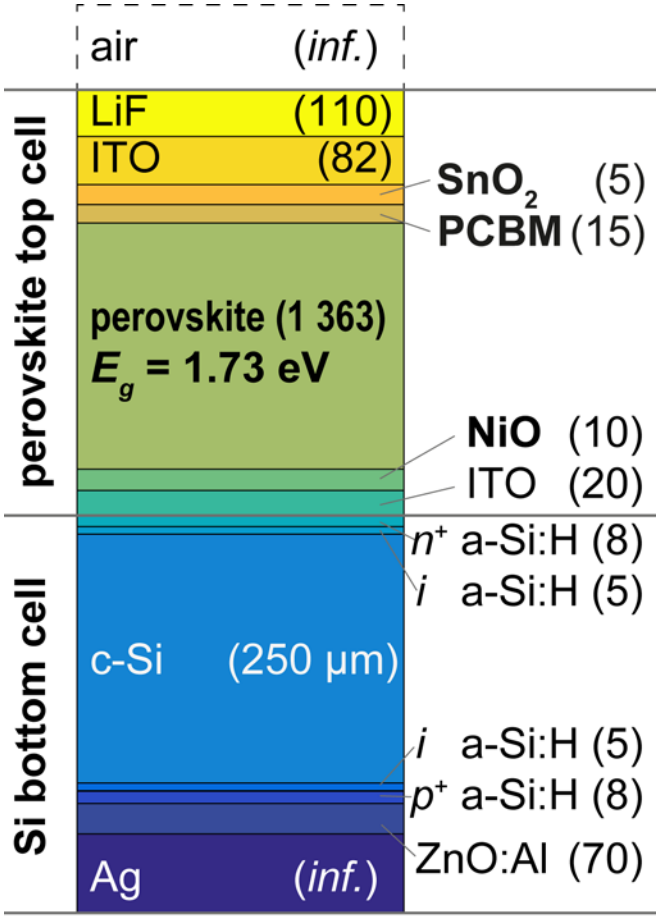
- Thinner, more transparent top contact in inverted cells
- Alter perovskite band-gap for current matching use optimized thicknesses
- Higher efficiency potential >30 % for inverted design
- No light trapping implemented so far

Jäger K., Albrecht S., et al., Optics Express 2017, 25 (12), A473-A482.

Simulation with optimized Perovskite Band-Gap

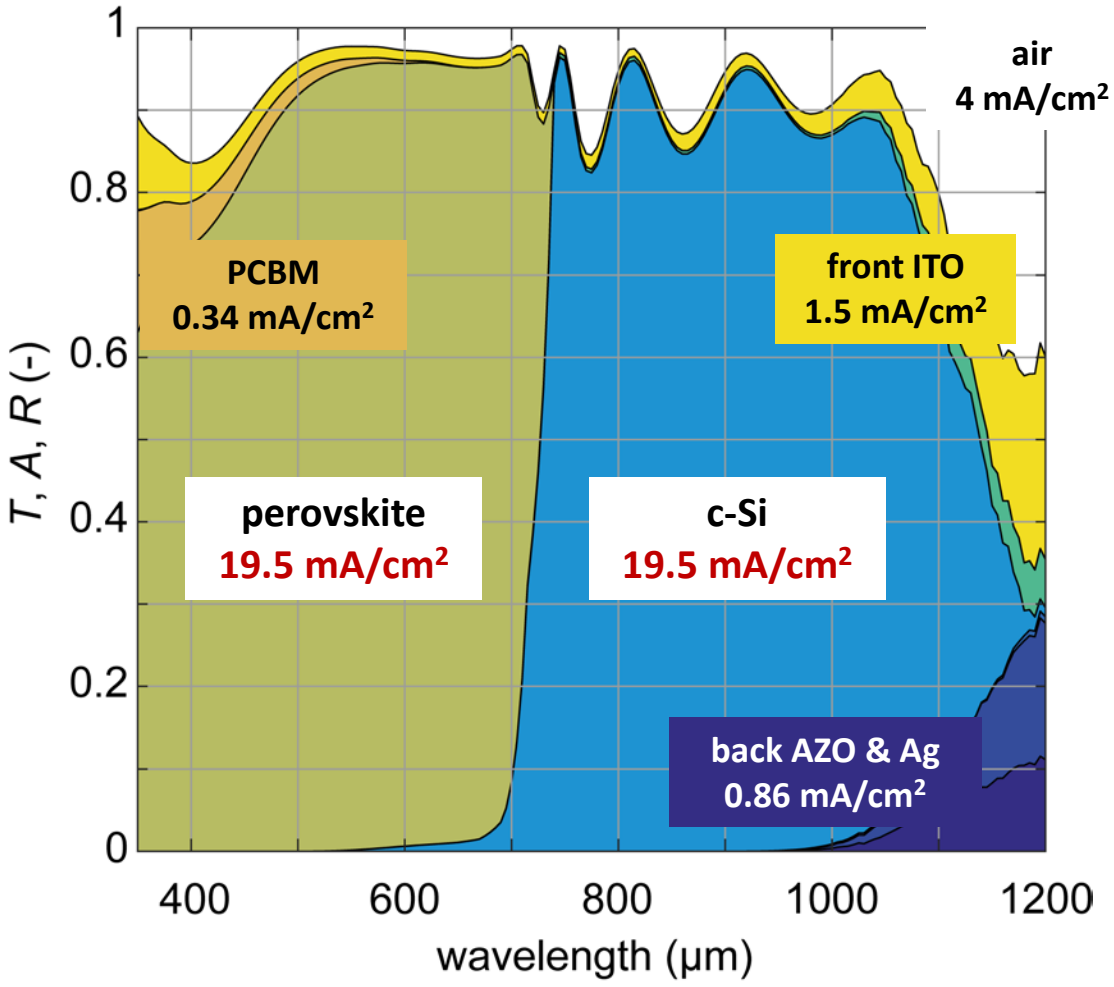
- Sharp transmission onset by thick perovskite layer

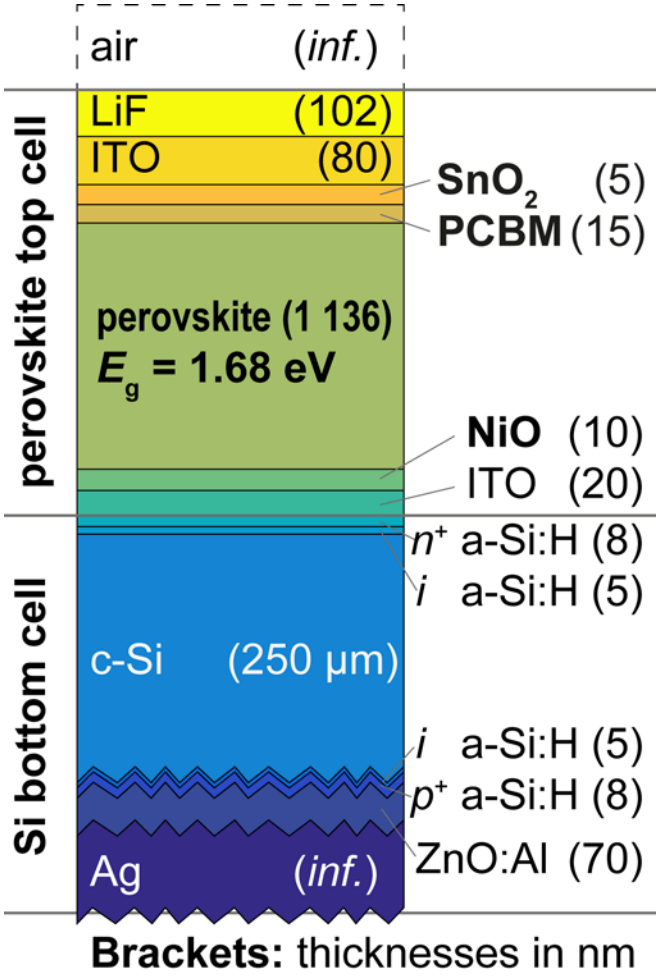




Simulation with Back-Side Texture

- Absorption gain mostly in NIR regime due to back-side texture

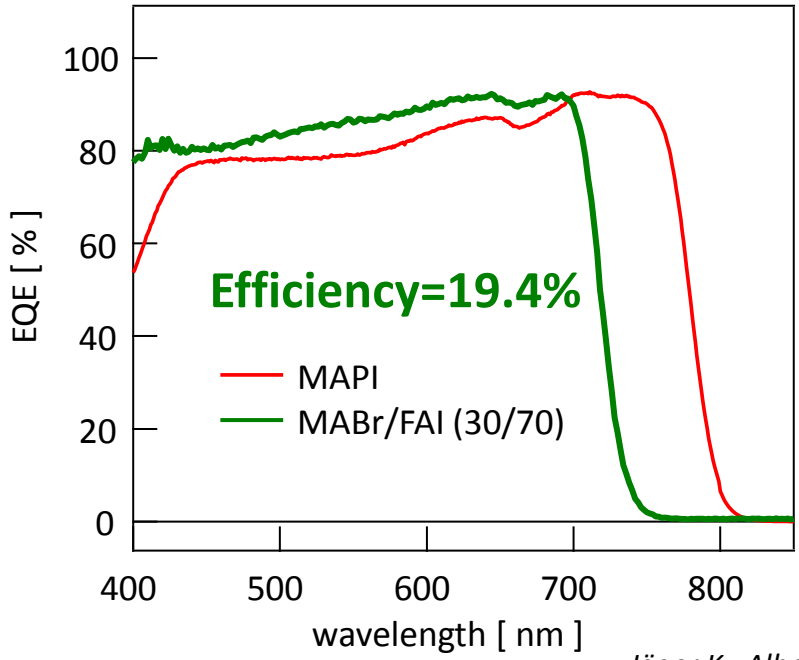




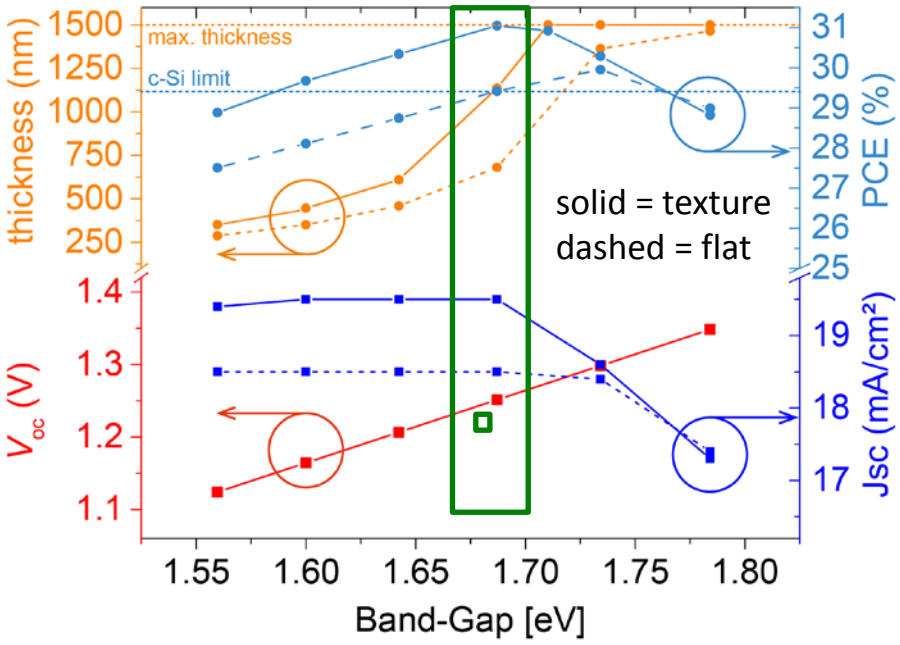
Is the Tandem-optimized Perovksite yet available ?

- Graduate school on perovskite materials
- More than 10 PhD, most of them graduating in 2018
- Key expertise on perovskite solar cells

Perovskite single junction



Tandem simulation

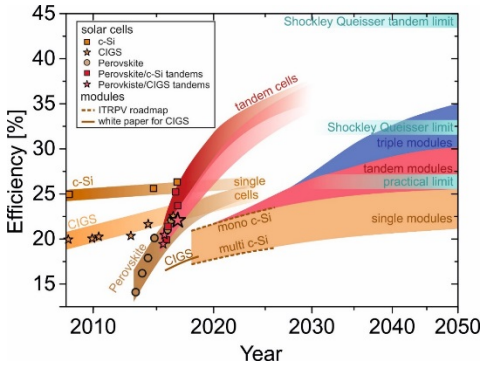


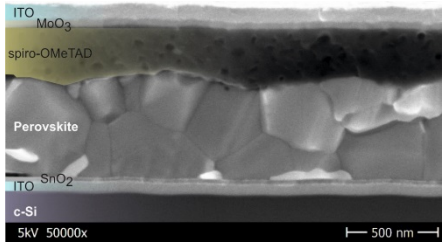
Jäger K., Albrecht S., et al., presented at EUPVSEC 2017.

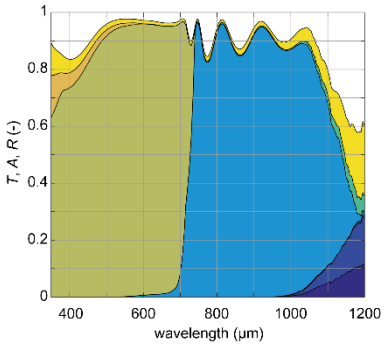
Wolff C.M., Neher D. et al., presented at PSCO 2017.

Summary

- Perovskite/Silicon Tandem cells are promising for highly efficient solar modules at reasonable costs
- HZB+EPFL demonstrated first Perovskite /SHJ Tandem with 19.9% Efficiency
- HZB focusses on high efficiency SHJ solar cells from 4 cm² to 6” wafer
- Within HySPRINT highly efficient opaque and semitransparent perovskite single junctions are developed
- Optical simulations help to establish guidelines to overcome 30% efficiency with perovskite/silicon tandem solar cells







Thank you
for your
attention!