Perovskite/Silicon Tandem Solar Cells and Modules

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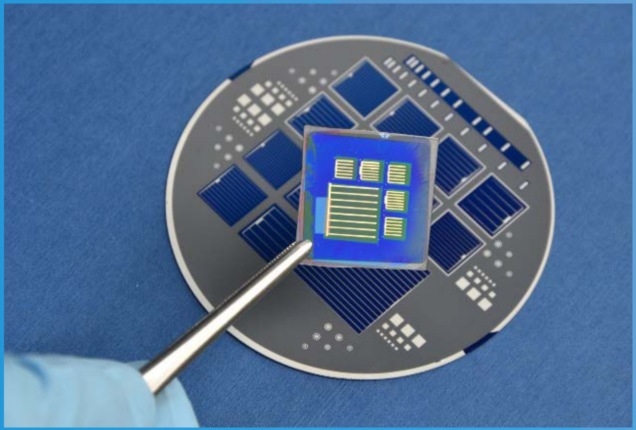

Many thanks to my colleagues at HZB, cooperation partners and within the FVEE the discussions in the Framework of the ESYS project , University of Ljubljana, colleagues from EPFL and University of Oxford

2017 EU-US Frontiers of Engineering Symposium, Davis, CA, US, November 16 th, 2017

The Global Challenge

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Noah´s ark 2050

(artist´s impression, courtesy of Lisa, Emilia and David)

Outline

- **PV today and tomorrow**

  from a niche technology to pillar of energy supply

- **Wafer based and thin film crystalline silicon**

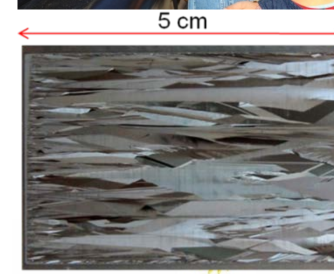
  The working horse of PV

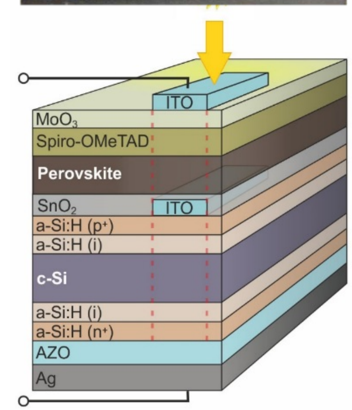
  c-Si on glass – an example from research

- **High efficiency perovskite solar cells**

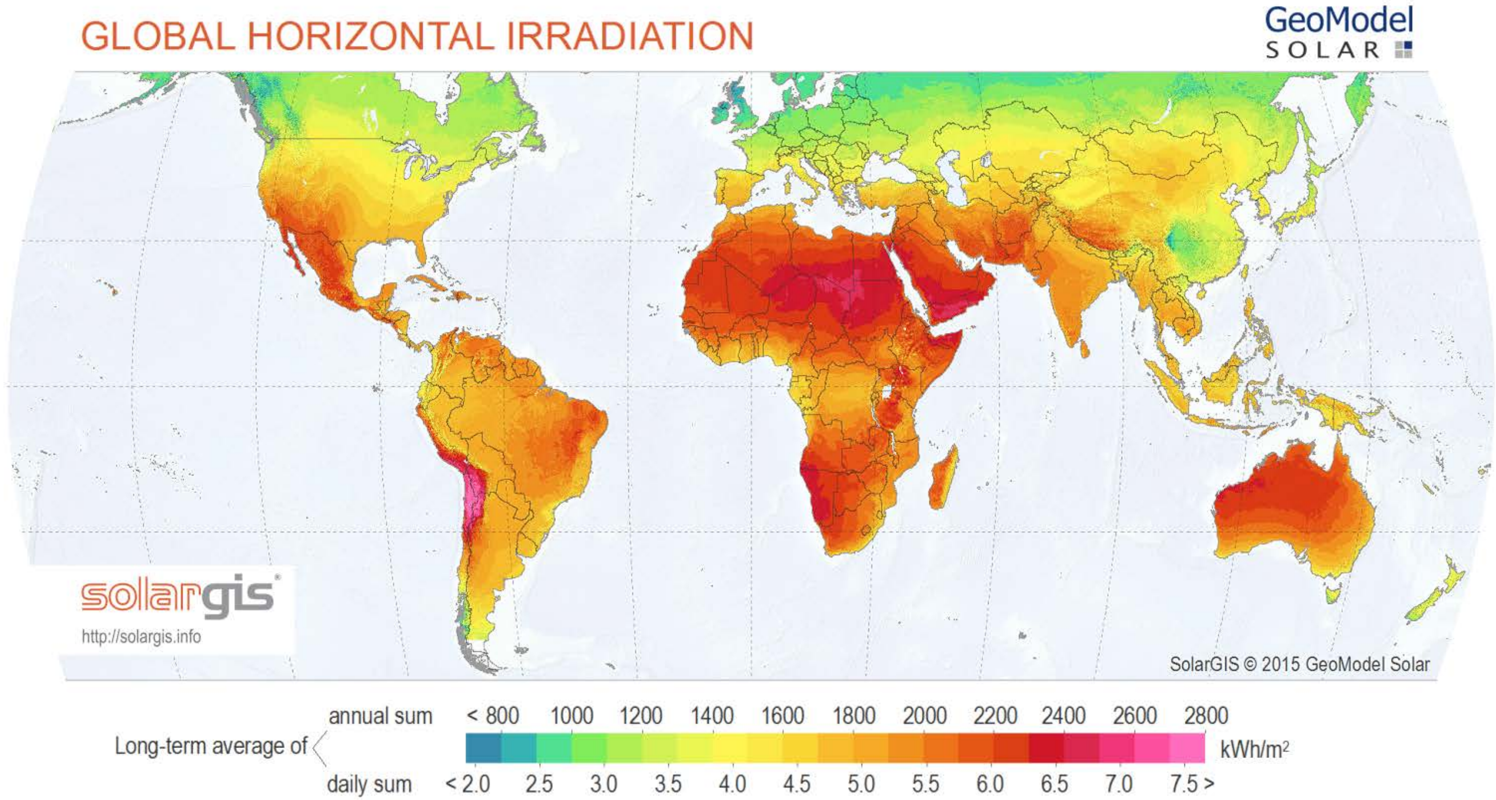
  perfect partner for c-Si in tandem solar cells

- **Conclusion**



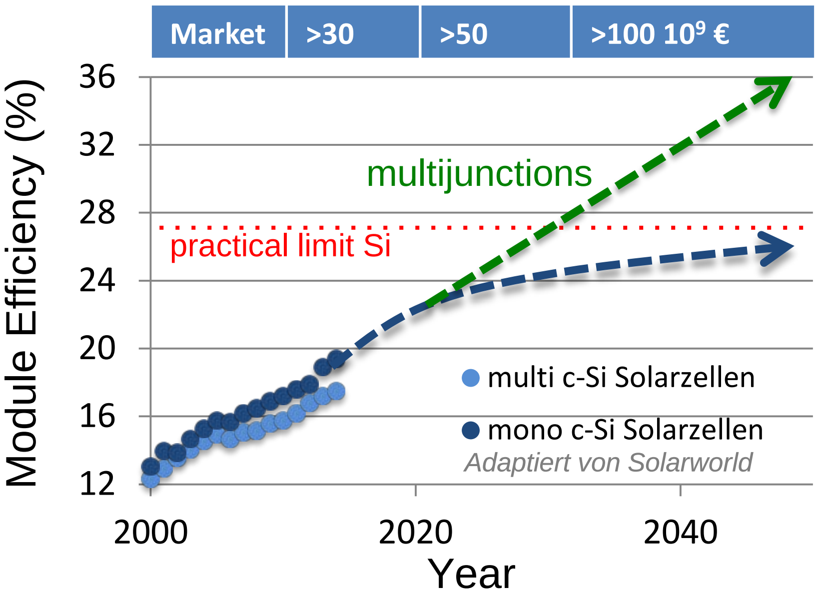


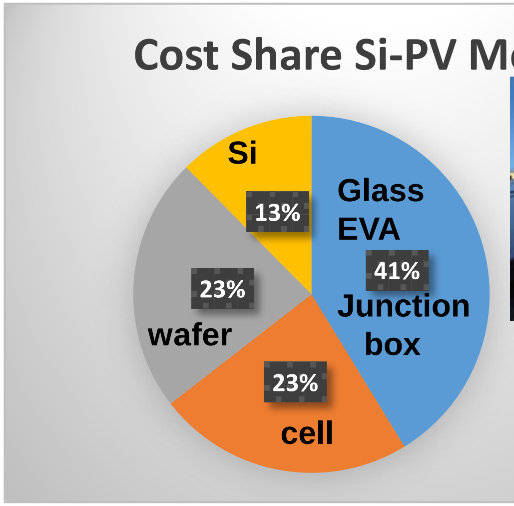
Prospects of PV



- Vast global potential
- Dramatic cost reductions (international bids down to 3 $cent/kWh)
- Further strong cost reduction expected
- PV is still a new comer in the energy sector
- To impact/fight climate change huge growth of PV over decades required
- Improved and new technologies are needed – see VDMA PV roadmap

Perspectives by New Technologies





Data: ITRPV/VDMA 2016

Overcome limitations in efficiency

Reduce Energy and Materials consumption

- New concepts for c-Si
- Thin film solar cells
- On the horizon: highly efficient low cost multijunctions

Progress in PV devices & power electronics will provide **low cost electricitity** @ optimum working conditions for chemical processes!

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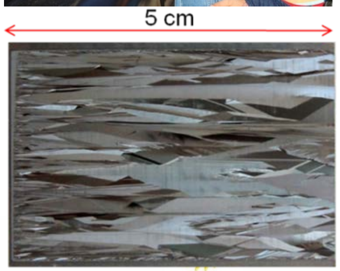
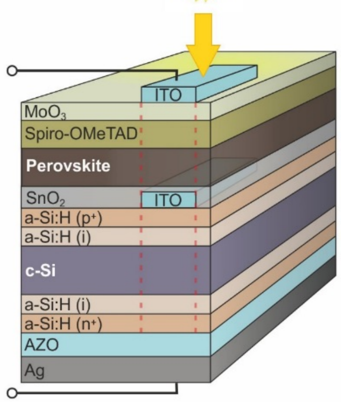
  The working horse of PV
  c-Si on glass – an example from research
- **Low cost – high efficiency mulitjunction solar cells**
  prospects and challenges of perovskite solar cells





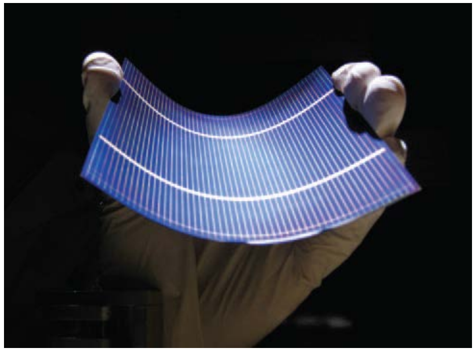
Wafer Based Crystalline Silicon

50 years manufacturing experience

- monocrystalline
- multicrystalline

Bricks of multicrystalline silicon produced via the Vertical Gradient Freeze method at SIMTEC.

Source: SIMTEC/ FHG ISE



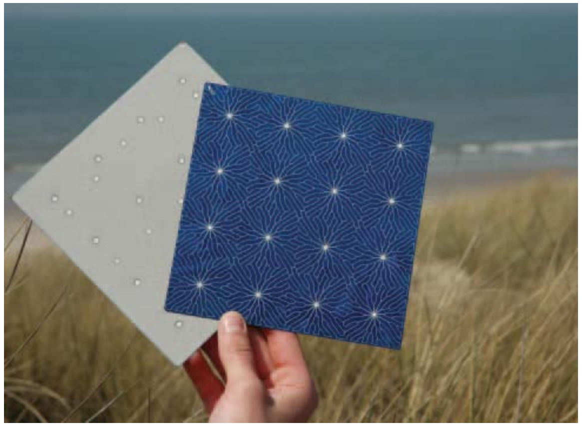
Laboratory cell efficiency:

- 23% various approaches

(world record lab cell: 26.6 %)

Commercial Module Efficiencies:

- 16 - 20%



source: ECN

Silicon Heterojunction Baseline

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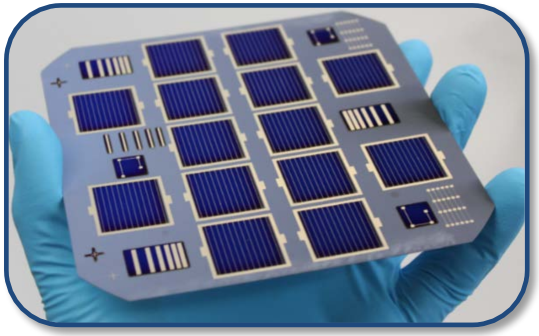
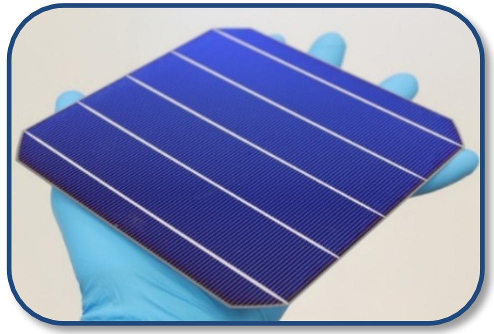
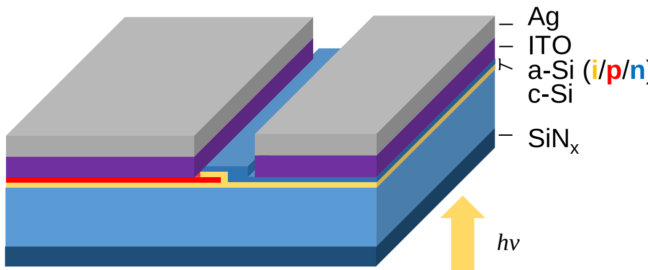
4 cm² solar cells
on 5-inch Cz-Si wafer



239 cm² solar cell
on 6-inch Cz-Si



IBC solar cell
with photolithography



Cell area (cm^2)		values	*η* (%)	V_{OC} (mV)	j_{SC} (mA/cm^2)	*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

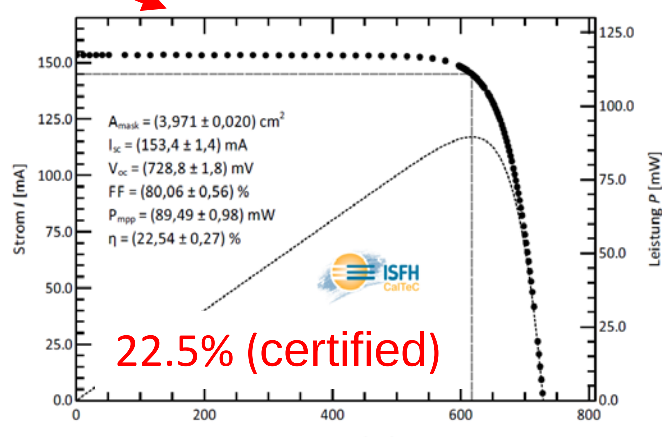
L. Mazzarella et al., 44th IEEE PVSC, Washington 2017, submitted to J-PV

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

Cell area (cm^2)	*η* (%)	V_{OC} (mV)	j_{SC} (mA/cm^2)	*FF* (%)
1 (da)	**23.2**	713	41.4	78.5

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

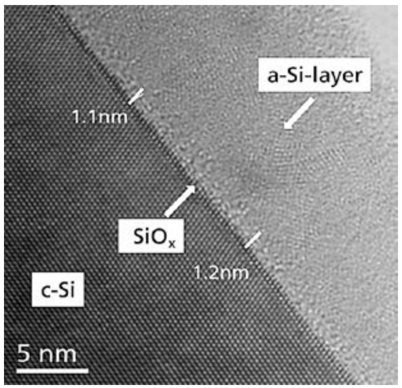
Stang C., Korte L. et al., to be published



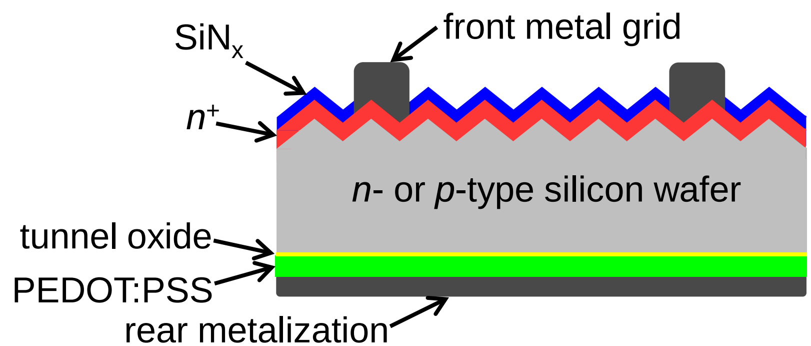
PVcomB
Competence Centre Thin-Film- and
Nanotechnology for Photovoltaics Berlin

New Materials for c-Si: Perfect Interfaces, Novel Heterojunctions

World record: 26,6 % a-Si:H/c-Si heterojunction back contact cell
Yoshikawa et al, Nature Energy 2, 17032 (2017)



25.8% for Topcon concept
Team around S. Glunz
Presented at FVEE conference



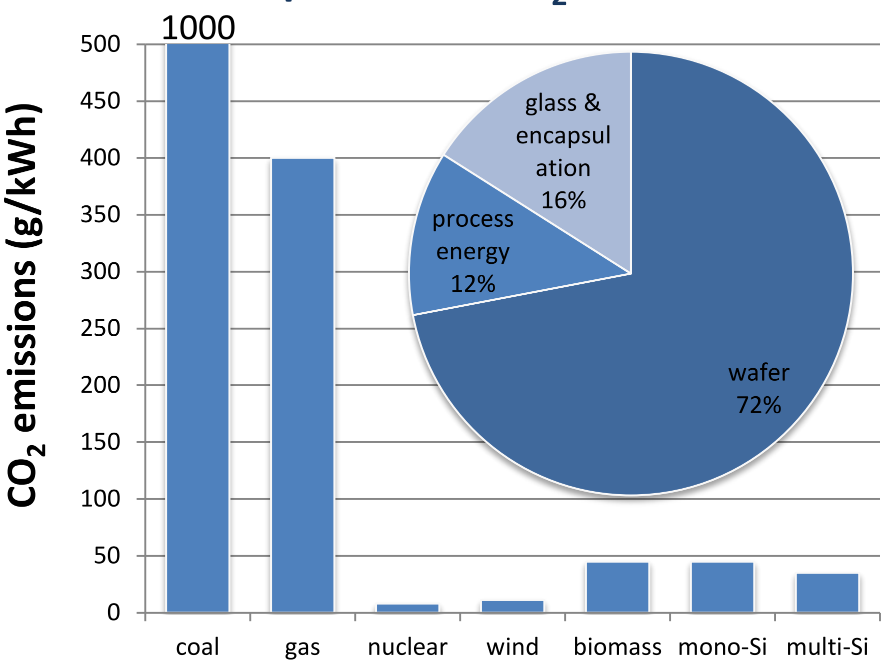
20,2% with organic emitter
J. Schmid et al. ISFH
presented at EU-PVSEC 2016

Beyond classical doping:
carrier selective contacts
MoOx, WOx, TiOx, organic semiconductors...

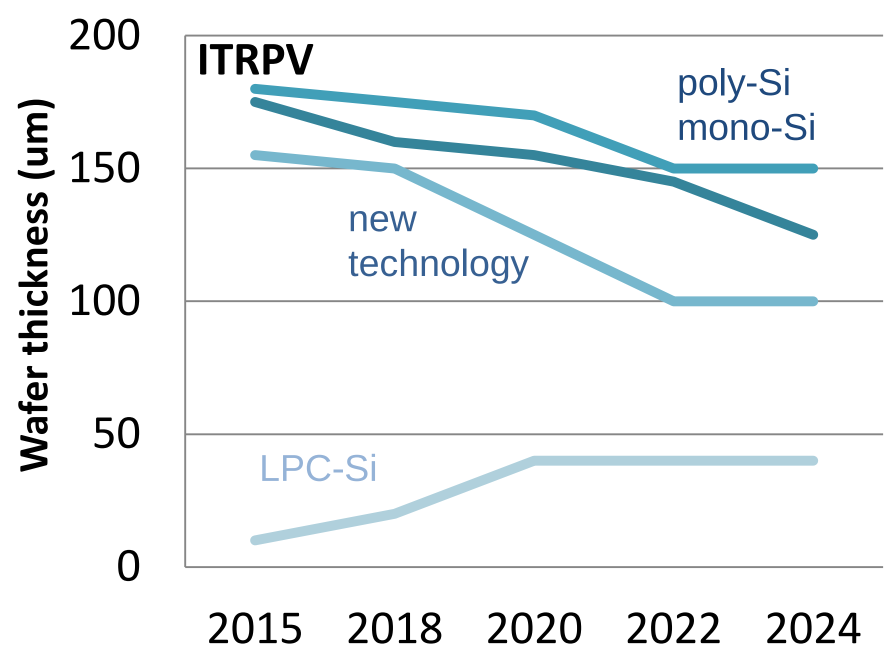
Efficient silicon solar cells with dopant-free asymmetric heterocontacts
J. Bullock et al. Nature Energy 1
15031 (2016)

Challenges in Silicon PV Technology

Comparison of CO_2 emissions



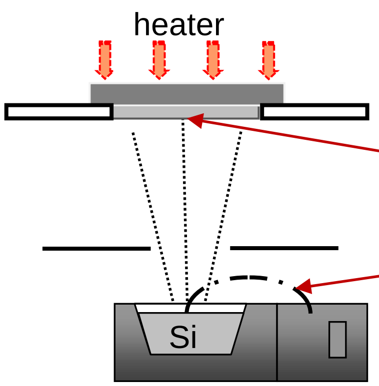
Predicted trend for wafer thickness



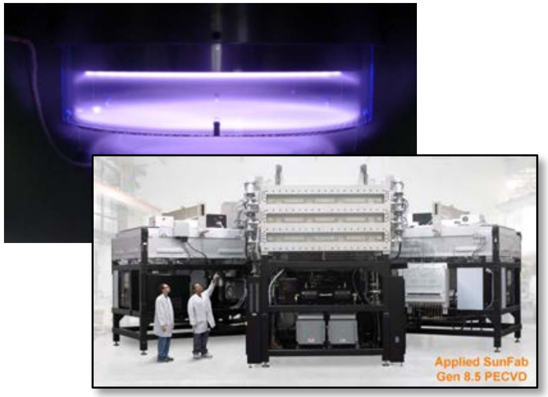
- Reduction in CO_2 emissions necessary
- No technology available to cut wafers << 100 mm
- LPC-Si as bottom up approach

Precursor Deposition & Crystallisation

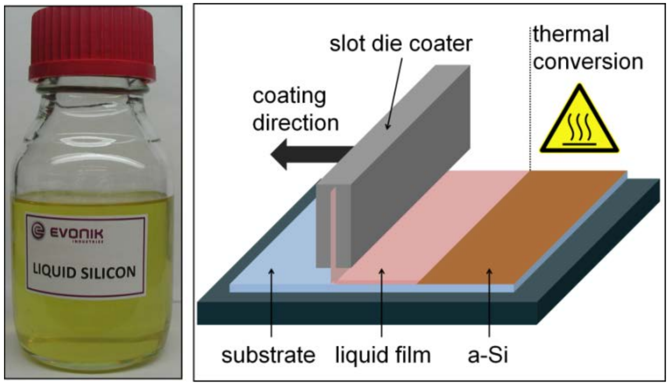
high rate evaporation (PVD)



PECVD

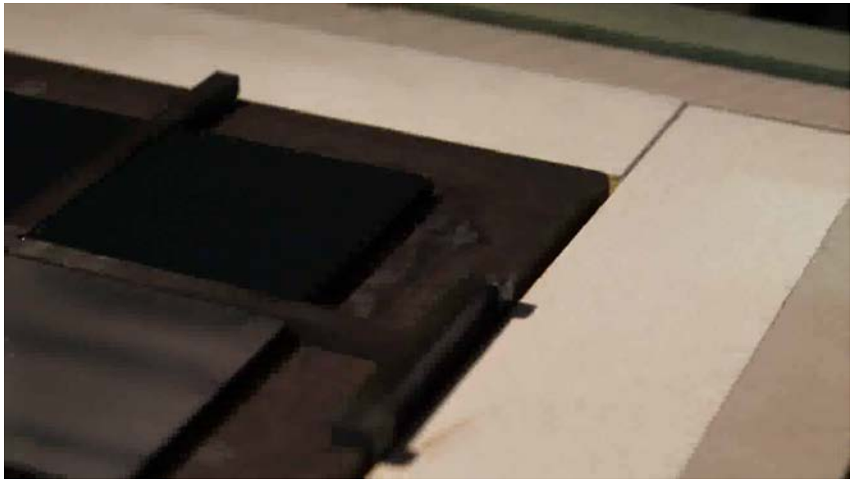


liquid silicon



T. Sontheimer et al.
Adv. Materials Interfaces, (2014)
proof of principle

and subsequent crystallization



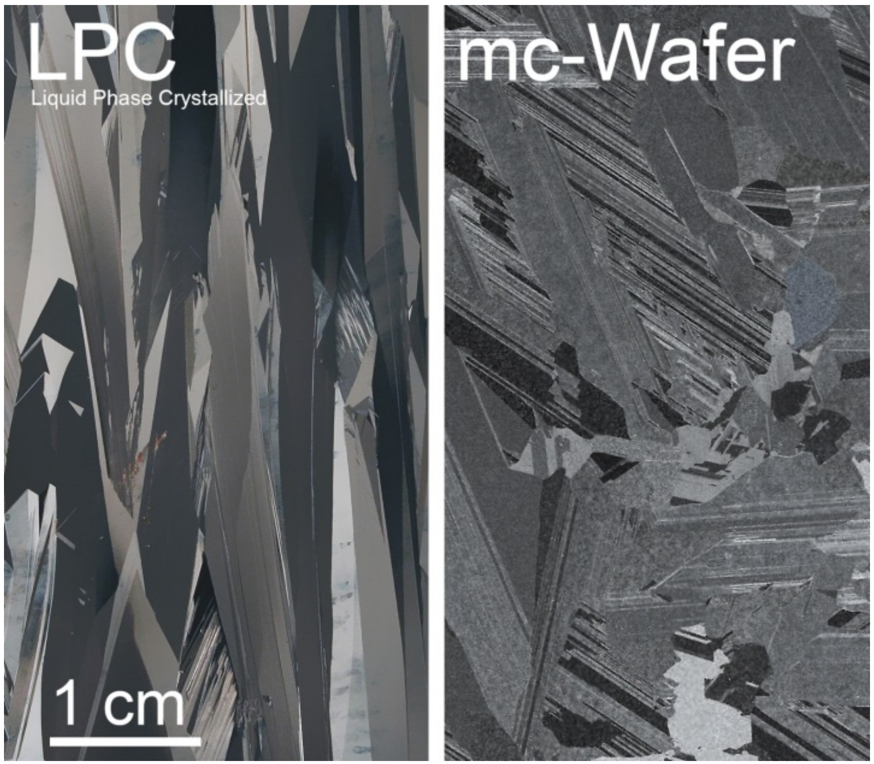
D. Amkreutz et al. *Prog. Photovolt. Res. Appl.* 19, 937 (2011)

J. Dore et al., IEEE Journal of Photovoltaics 4, 33 (2014)

Liquid Phase Crystallized (LPC) Silicon

HZB Helmholtz Zentrum Berlin

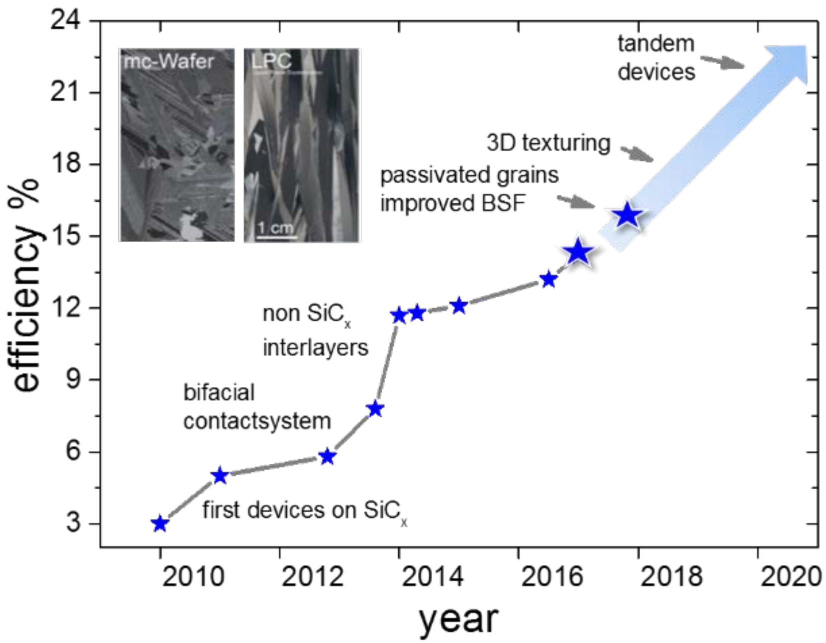
General Properties



- Wafer equivalent morphology
- Low oxygen concentration ($10^{18}cm^{-3}$)
- Low carbon concentration ($10^{17}cm^{-3}$)
- High carrier mobilitiy
- Glass:silicon bond
- Fast & scaleable process

J. Haschke, D. Amkreutz, B. R., Japanese Journal of Applied Physics 55, 2016

Thin Film Si on Glass by Liquid Phase Crystallization



Process energy	Wafer Si 120 µm	c-Si on glass 20 µm
Σ (MJ/m²)	**134**	**37**

- Material Quality approaching multi c-Si
- 16 % efficiency on very small areas
- „Between" wafer & thin film technology

Thin Si remains an important challenge for reduction of costs/energy demand

P. Sonntag et al., Sci. Rep. 2017

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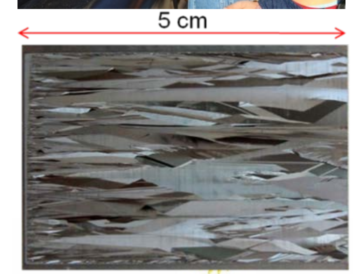

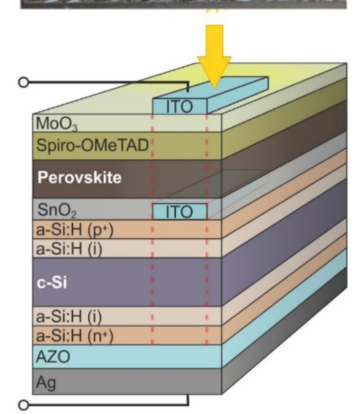

Perovskite the "Hype Material"

http://www.med.upenn.edu/chbr/documents/tr_scientific_minds_online_final.pdf

New Devices and Materials

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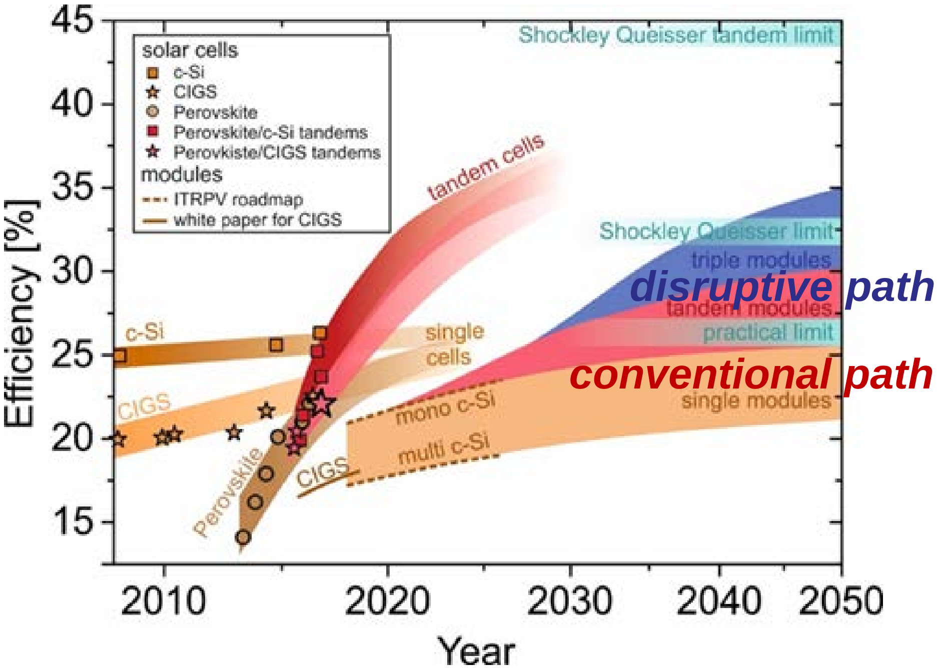

S. Albrecht & B. Rech, Nat. Energy 2017

- **Multi-junction PV (tandem/triple)** can provide efficiencies surpassing todays limits.
- New material class of metal-halide **perovskites** provides a **unique opportunity**

Applications beyond PV: conversion of solar energy into chemicals, Lasers, LEDs and other optoelectronic devices

Perovskite Based Solar Cells

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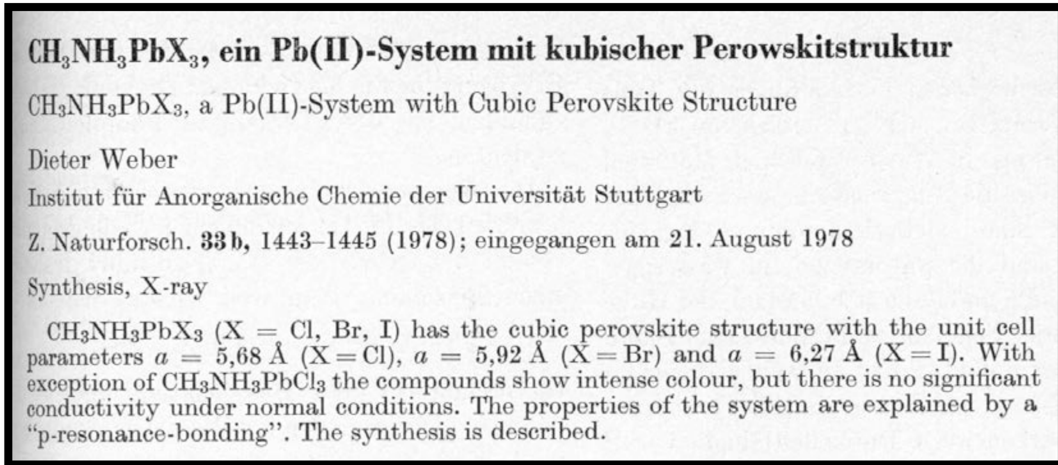


CH₃NH₃PbX₃, ein Pb(II)-System mit kubischer Perowskitstruktur

$CH_3NH_3PbX_3$, a Pb(II)-System with Cubic Perovskite Structure

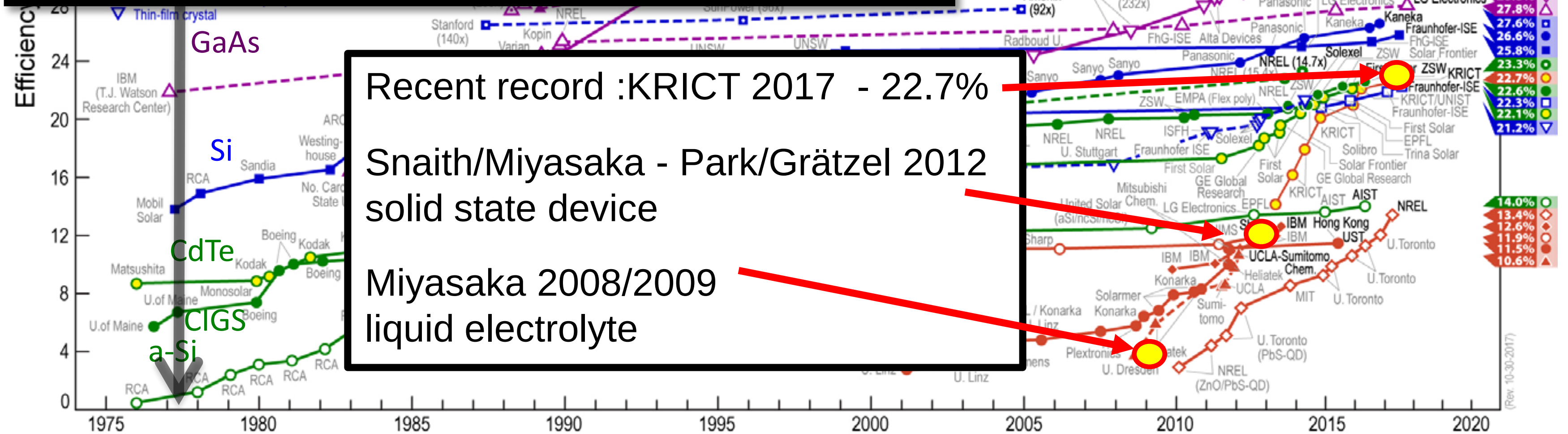
Dieter Weber

Institut für Anorganische Chemie der Universität Stuttgart

Z. Naturforsch. **33b**, 1443–1445 (1978); eingegangen am 21. August 1978

Synthesis, X-ray

$CH_3NH_3PbX_3$ (X = Cl, Br, I) has the cubic perovskite structure with the unit cell parameters a = 5,68 Å (X = Cl), a = 5,92 Å (X = Br) and a = 6,27 Å (X = I). With exception of $CH_3NH_3PbCl_3$ the compounds show intense colour, but there is no significant conductivity under normal conditions. The properties of the system are explained by a "p-resonance-bonding". The synthesis is described.



http://www.nrel.gov/ncpv/images/efficiency_chart.jpg Version 10-30-2017

Metal-organic perovskites showed that there are **surprising** options for **new materials**!

Opportunities & Challenges

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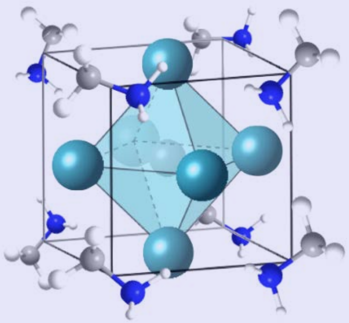


Structure

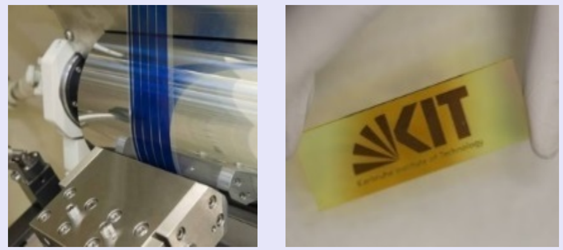
ABX_3

A = org./ inorg.

B = Pb, Sn

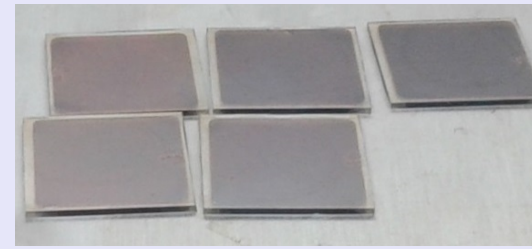
X = Br, I

Coating & Printing



Coutesy of KIT, Uli Paetzold et al.

Perovskite films



- ✓ **Chemical tunability**
- ✓ **Low T , solution processing**
- ✓ **Excellent semiconductor**

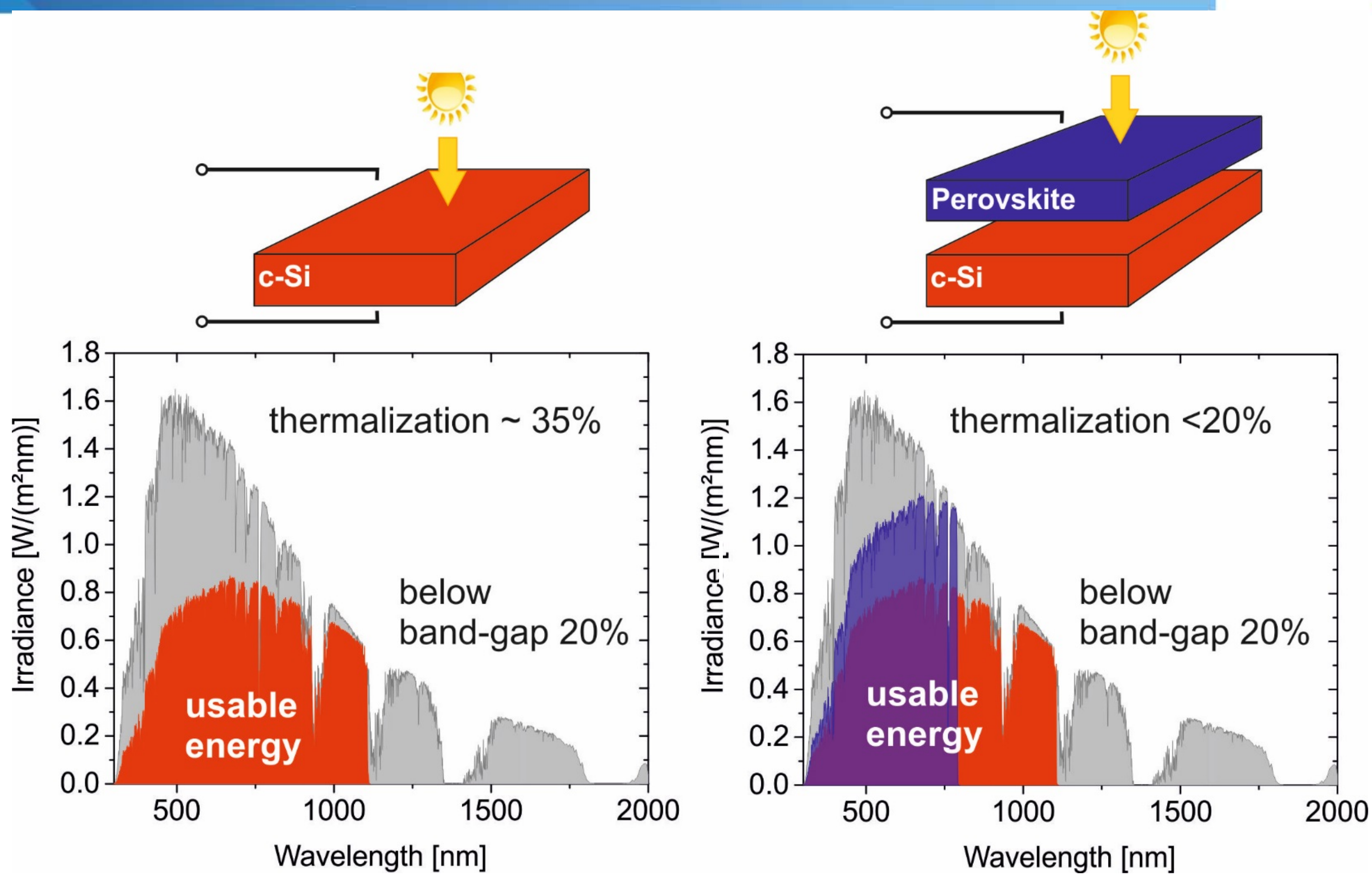
New Material Class → **Facile Processing** → **Innovative Devices**

- × **Best performance Pb**
- × **Interface control**
- × **Stability is critical**

Most progress by emperical approach!

More knowledge driven development possible?

c-Si / Perovskite Tandem Cells

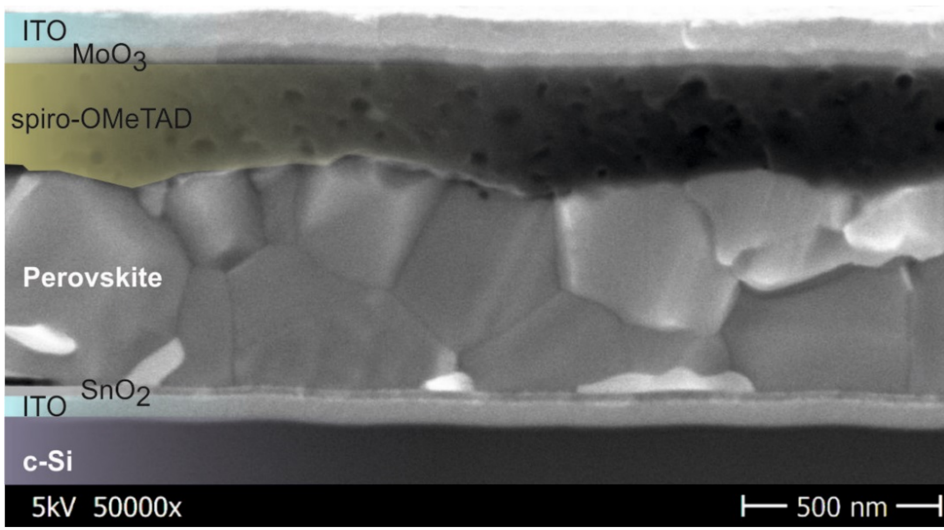


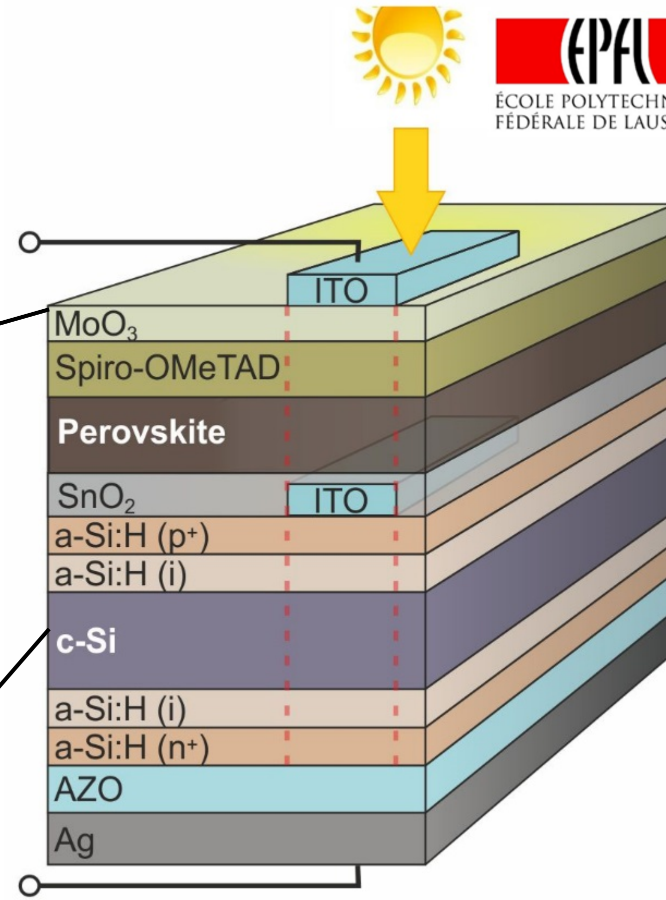
- High loss from thermalization
- High energy photons are absorbed by perovskite
  - converted at a high voltage
  - reduced losses from thermalization
- Infrared photons are transmitted into c-Si
  - cover a wide spectral range of absorption

Figure from Jan Goldschmidt, Fraunhofer ISE

Monolithic c-Si/Perovskite Tandem Cell

SEM cross section





Efficiency: 19.9 %

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

S. Albrecht et al., Energy & Environmental Science 2016

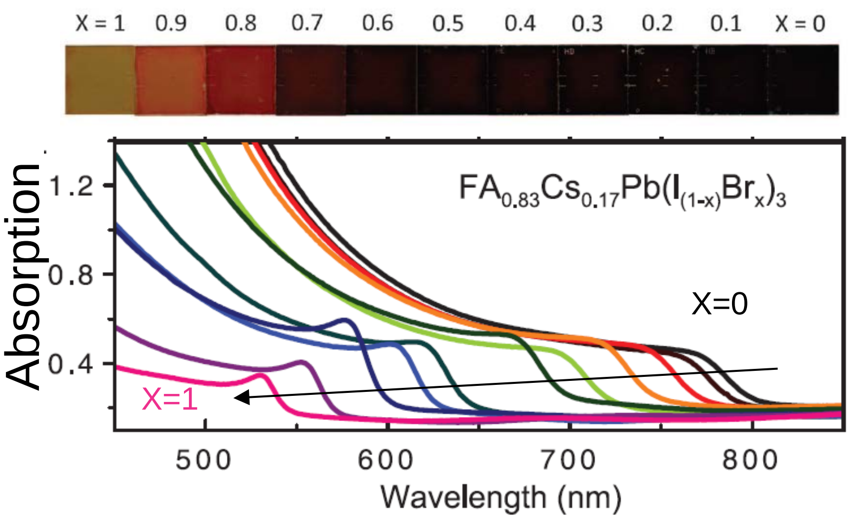
Band-Gap Optimization: Cesium!

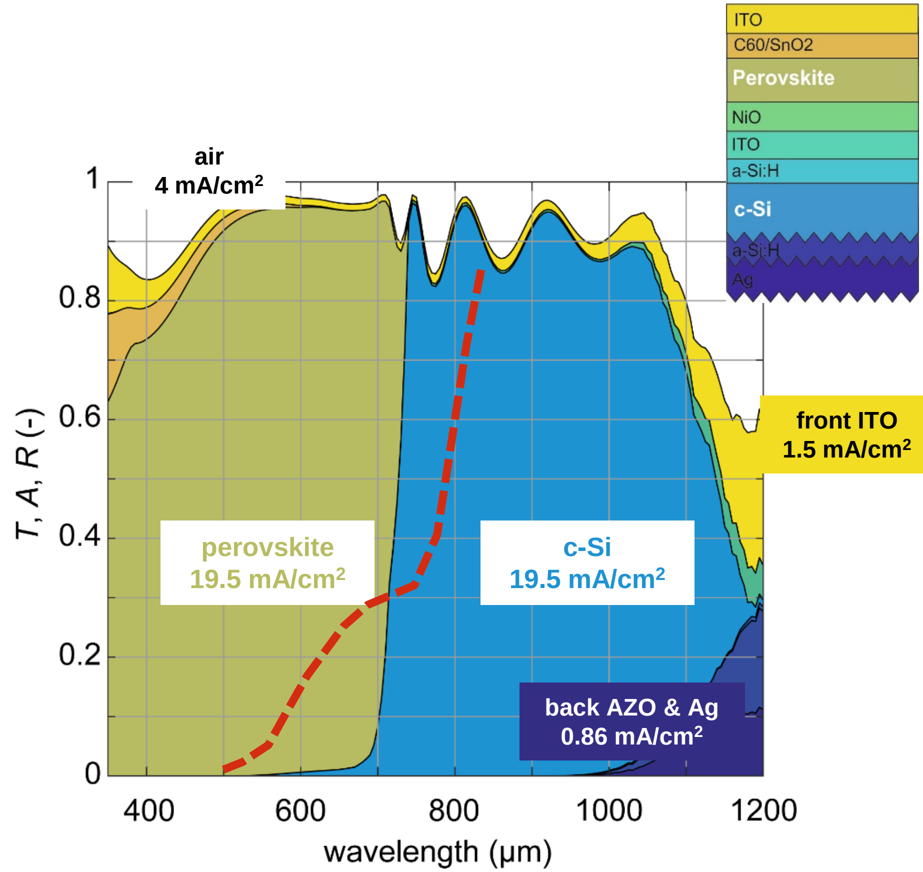
HZB Helmholtz Zentrum Berlin

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 for tandem cells

- Optimized architecture, light trapping
- Optimized Perovskite band-gap of 1.68 eV
- Potential for over 30% efficiency

Science 2016

Jäger, Rech, Albrecht et al., EUPVSEC 2017

Perovskite Solar Cells for Space

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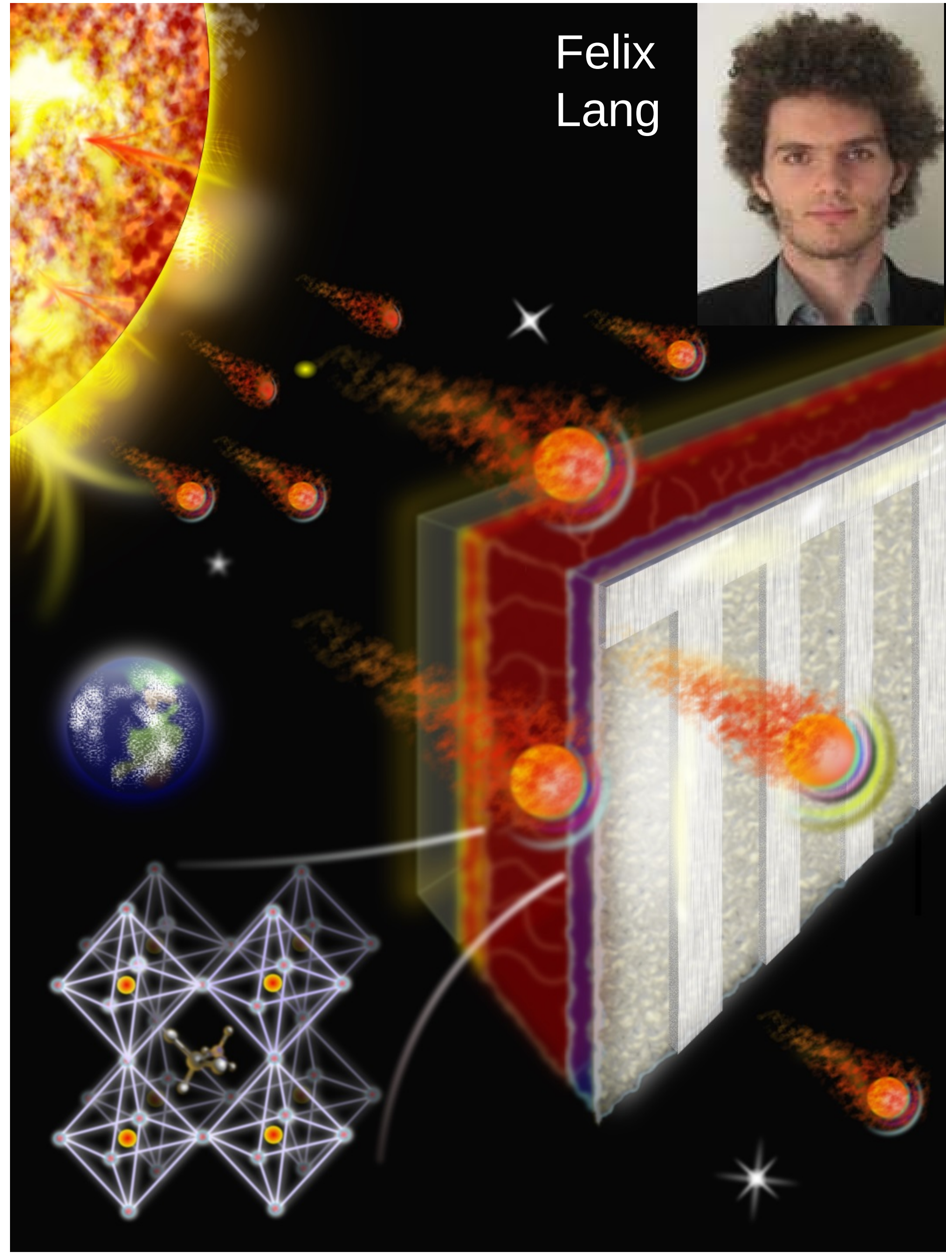
Irradiated perovskite solar cells with high energy (68MeV) protons

- Perovskite solar cells are <u>radiation hard</u>
- Self-Healing of induced defects after Irradiation

in cooperation with University Salerno

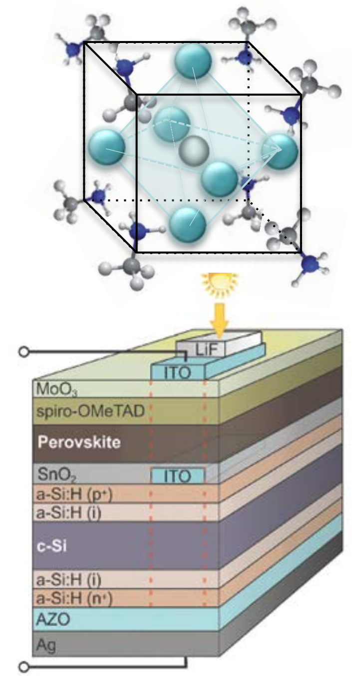
ADVANCED MATERIALS

[1] F. Lang, et al., Adv. Mater. **28**, (2016)



Challenges

- Long-lifetime, stable, including Pb-free alternatives
- Scalable low-cost processes for efficient devices
- Multi-junction solar cells & modules (*Si/Pero*, *CIGS/Pero*, *Pero/Pero*)
- Sustainability, environmental impact & implementation into energy system



Research approach along **entire value chain** (materials → system integration) covering **complete development cycle**

Conclusions & Statements

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PV has emerged from a niche technology to a global industry

Wafer baser crystalline silicon PV dominates the market but is intrinsically limited in efficiency as a single junction technology.

- Energy demand for Si wafer production is high – go thin!
- Multi-junction-technology

The development of new PV technologies relies on breakthroughs in **material science, processing and device integration**.

- Efficiency potential of novel hybrid materials has to be transferred into stable efficiency
- Prerequisite: Scalability of processes and equipment

Cheap & efficient & stable & environmentally benign is a must!