3G rule for attending in person lectures at KIT:

Karlsruher Institut für Technologie

- ***geimpft* – vaccinated**
- ***genesen* – recovered**
- ***getestet* – tested**

KIT
Karlsruher Institut für Technologie

"Solar Energy" WS 2021/2022

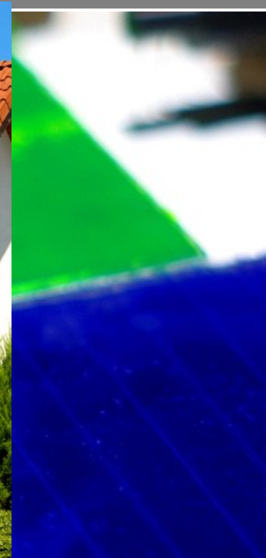
Lecture 17: Multijunction Solar Cells

Tenure-Track-Prof. Dr. Ulrich W. Paetzold

Institute of Microstructure Technology (IMT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen

Light Technology Institute (LTI), Engesserstrasse 13, Building 30.34, 76131 Karlsruhe

KIT Focus Optics & Photonics



Parts of the material used here have been kindly provided by Prof. T. Kirchartz, and Dr. D. Cheyns.

Evaluation Feedback

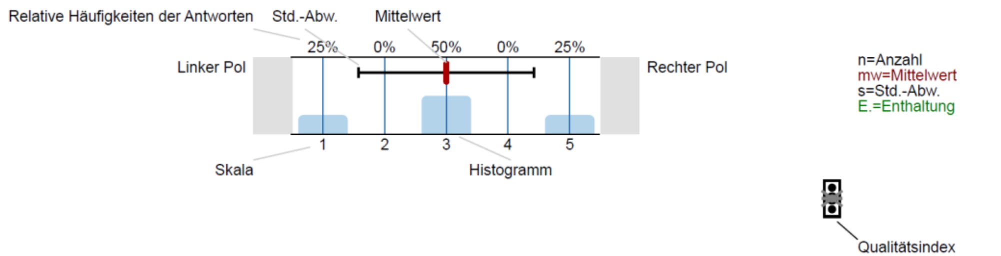
Auswertungsbericht Lehrveranstaltungsevaluation an die Lehrenden

Sehr geehrter Herr Prof. Dr. Paetzold,

mit diesem Schreiben erhalten Sie die Ergebnisse der automatisierten Auswertung Ihrer Lehrveranstaltung „Solar Energy“.

Ihre Lehrveranstaltung „Solar Energy“ hat den Lehrqualitätsindex

LQI = 100.



Der Mittelwert liegt unterhalb der Qualitätsrichtlinie.

Der Mittelwert liegt im Toleranzbereich der Qualitätsrichtlinie.

Der Mittelwert liegt innerhalb der Qualitätsrichtlinie.

=> Let us go through some details!

Unfortunately, no excursion

Karlsruher Institut für Technologie

Instead we will provide a selection fo educative videos!

"A Brief History of Photovoltaics: Yesterday, Today and Tomorrow"

Charlie Gay
Director, Solar Energy Technologies Office
Office of Energy Efficiency and Renewable Energy (EERE)
U.S. Department of Energy (DOE)

https://www.youtube.com/watch?v=C5KfGxTZRpw

https://www.youtube.com/watch?v=3I1JhyOahIw

Examination

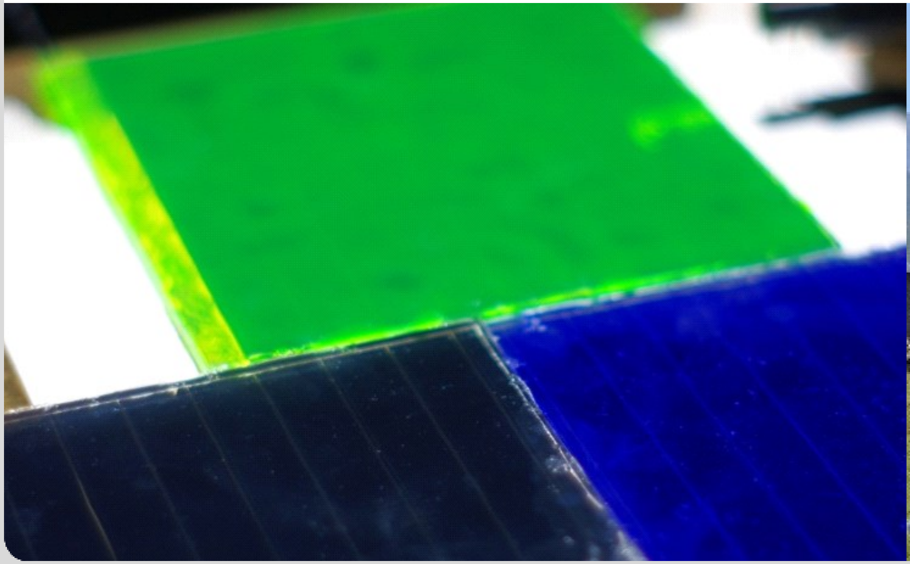
- **Date:** 08.03.2022, 15:00-17:00,
- **Room:** Audimax 30.95 (arrive 15 min early!)
  [back up: Fasanengarten-Hörsaal 50.35]
- **Please note the following for the Exam:**
  - Allowed aids:
    - Calculator (**No phones or similar, no programmable calculators**)
    - **No extra sheet of paper** (A4, two-sided)
  - You are only allowed to use the sheets of paper which are provided from the university. If necessary, we will give you more sheets of paper.
  - Please write on every sheet your name and matriculation number, since sheets without both will not be taken into account.
  - Please do not use lead pencils or red pens for your solutions.
  - Please put your student ID in front of you during the exam so that we can check it.
  - Duration of the exam: 120 min.
  - Post-exam review: to be specified.

"Solar Energy" WS 2020/2021

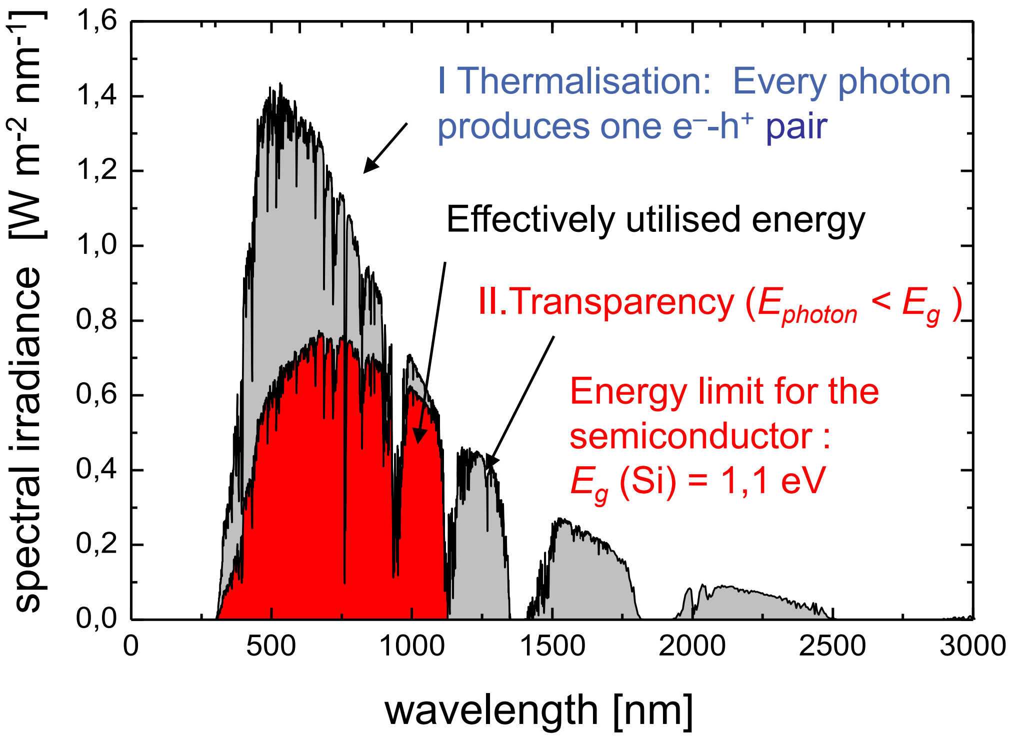
Lecture 17: Multijunction Solar Cells

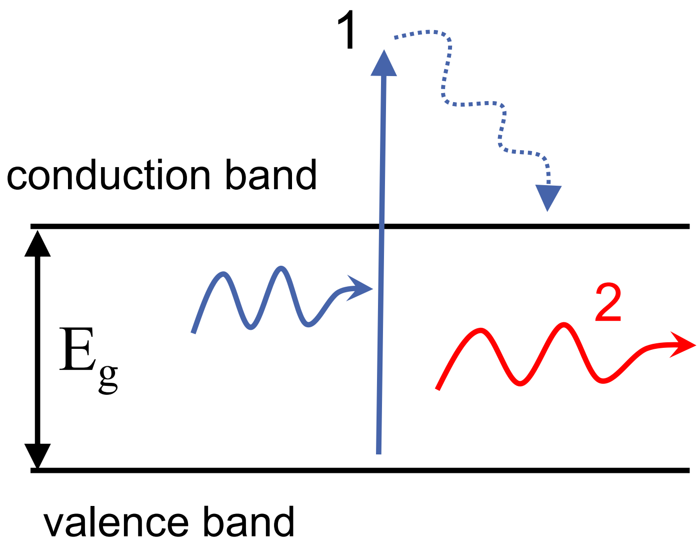
Dr. Ulrich W. Paetzold
Institute of Microstructure Technology (IMT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen
Light Technology Institute (LTI), Engesserstrasse 13, Building 30.34, 76131 Karlsruhe

KIT Focus Optics & Photonics



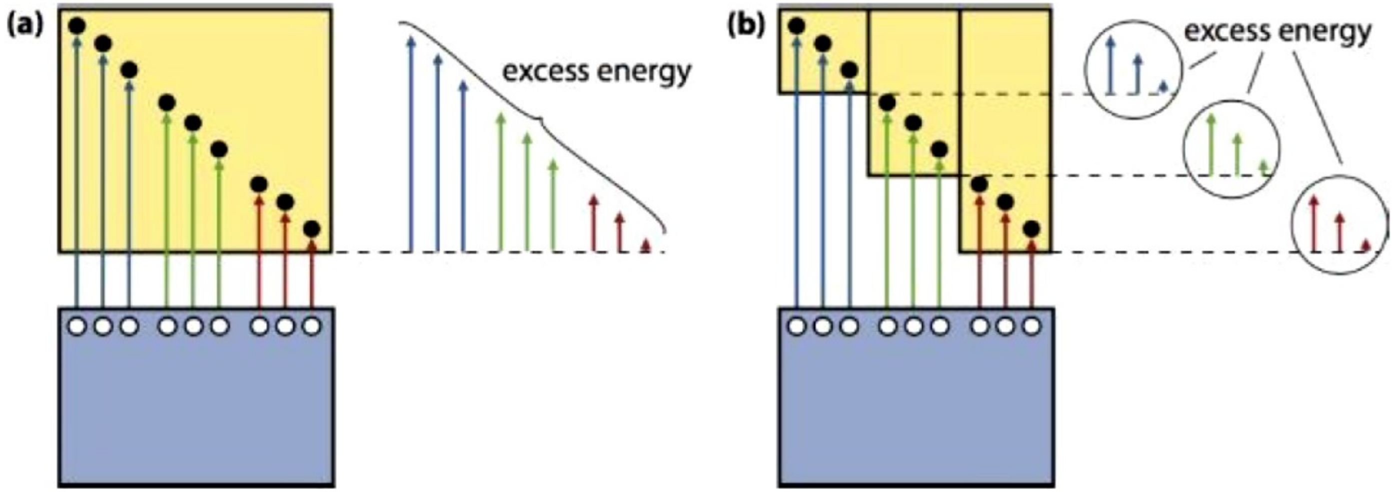
Intrinsic Optical Losses in Single-Junction Solar Cells





Multijunction Solar Cells

In multi-junction cells, several cell materials with different bandgaps are combined in order to maximize the amount of the sunlight that can be converted into electricity. **Transmission and thermalization losses are reduced.**



- Assuming an infinite number of solar cells with gradually increasing bandgaps the max. efficiency according to the detailed balance limit (theory behind the SQ limit) is around 86%!!!

Source: textbook

Multijunction Solar Cells

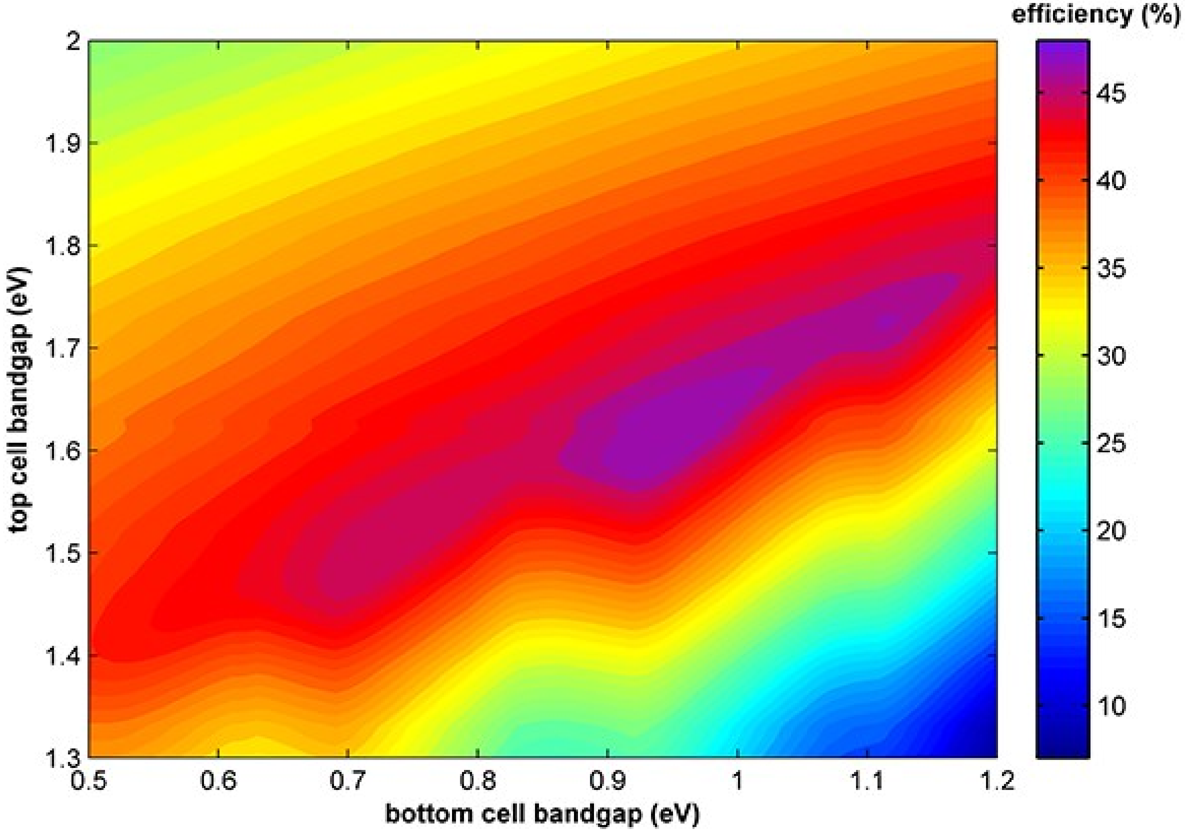
No. of Cells	Description	Optimal Bandgaps (eV)						Effic %
		E1	E2	E3	E4	E5	E6	
1	Diffuse	1.31						31.0
	Direct	1.11						40.8
2	Diffuse, series connected	0.97	1.70					42.5
	Diffuse, unconstrained	0.98	1.87					42.9
	Direct, series connected	0.77	1.55					55.5
	Direct, unconstrained	0.77	1.70					55.9
3	Diffuse, series connected	0.82	1.30	1.95				48.6
	Diffuse, unconstrained	0.82	1.44	2.26				49.3
	Direct, series connected	0.61	1.15	1.82				63.2
	Direct, unconstrained	0.62	1.26	2.10				63.8
4	Diffuse, series connected	0.72	1.10	1.53	2.14			52.5
	Diffuse, unconstrained	0.72	1.21	1.77	2.55			53.3
	Direct, series connected	0.51	0.94	1.39	2.02			67.9
	Direct, unconstrained	0.52	1.03	1.61	2.41			68.8
5	Diffuse, series connected	0.66	0.97	1.30	1.70	2.29		55.1
	Diffuse, unconstrained	0.66	1.07	1.50	2.03	2.79		56.0
	Direct, series connected	0.44	0.81	1.16	1.58	2.18		71.1
	Direct, unconstrained	0.45	0.88	1.34	1.88	2.66		72.0
6	Diffuse, series connected	0.61	0.89	1.16	1.46	1.84	2.41	57.0
	Diffuse, unconstrained	0.61	0.96	1.33	1.74	2.26	3.00	58.0
	Direct, series connected	0.38	0.71	1.01	1.33	1.72	2.31	73.4
	Direct, unconstrained	0.40	0.78	1.17	1.60	2.12	2.87	74.4
∞	Diffuse (unconstrained, series connected, 2-terminal)							68.2
	Direct (unconstrained, series connected, 2-terminal)							86.8

- Multijunction solar cells can achieve efficiencies up to 86.8% for an infinite number of cells!
- With decreasing number of subcells, the max. achievable efficiency drops.
- Even for tandem solar cells (= multijunction solar cell with 2 sub cells), the max. achievable is >42% (an increase of more than 10% compared to junction solar ceklls)

Source: *Martin Green, "Third Generation Photovoltaics: Advanced Solar Energy Conversion", Springer 2003*

Ideal bandgaps for tandem solar cell

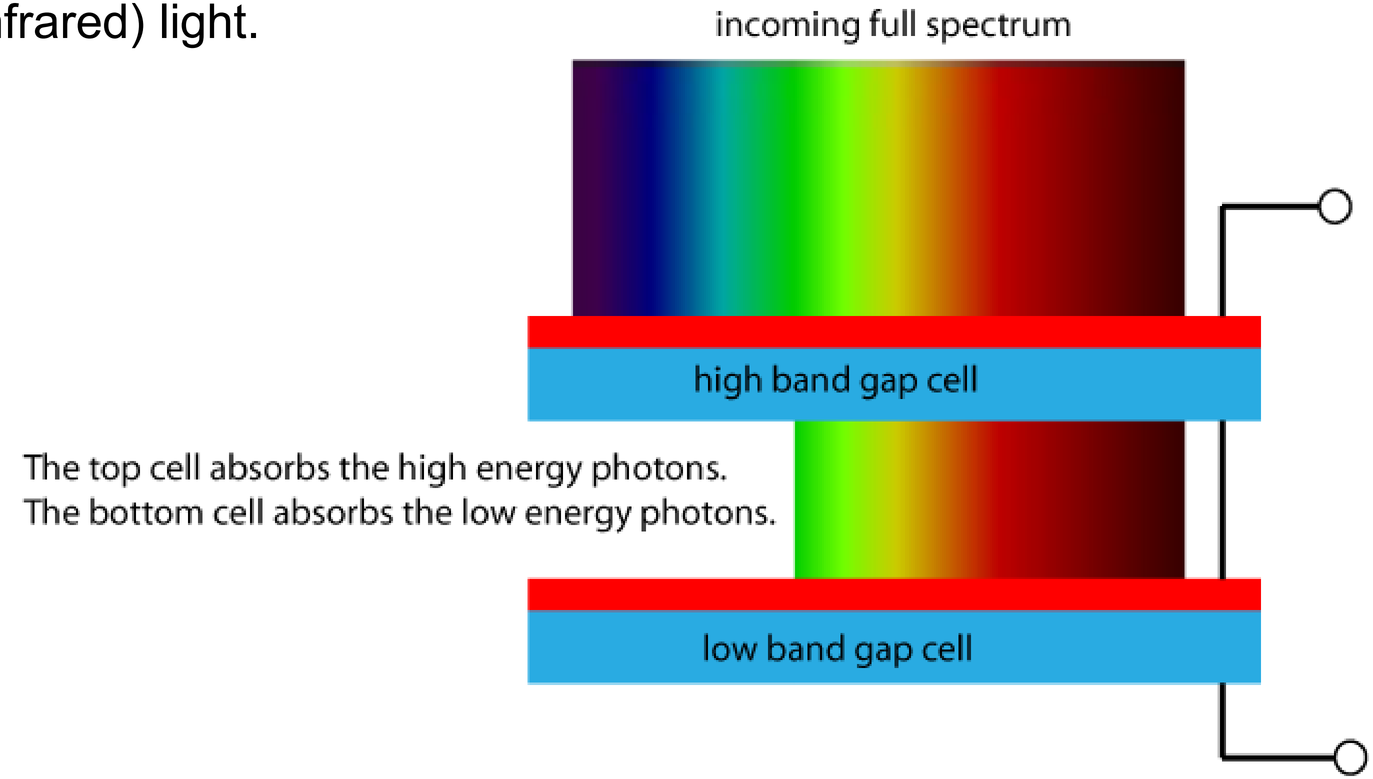
The maximum efficiency for a monolithic tandem solar cell under the AM1.5G spectrum and without concentration is 47 %. At the peak efficiency the top cell has a bandgap of 1.63 eV and the bottom cell has a bandgap of 0.96 eV.



Source: adapted from http://pveducation.org/pvcdrom/solar-cell-operation/tandem-cells

Multijunction Solar Cells

To realize multijunction solar cells, two or more cells are stacked onto each other. The top cell has the highest bandgap and will absorb and convert the short wavelength (blue) light. Light with wavelengths longer than the bandgap wavelength can traverse the top cell and be absorbed in the cells with lower bandgaps below. The bottom cell has the lowest bandgap and absorbs the long wavelength (red and near-infrared) light.

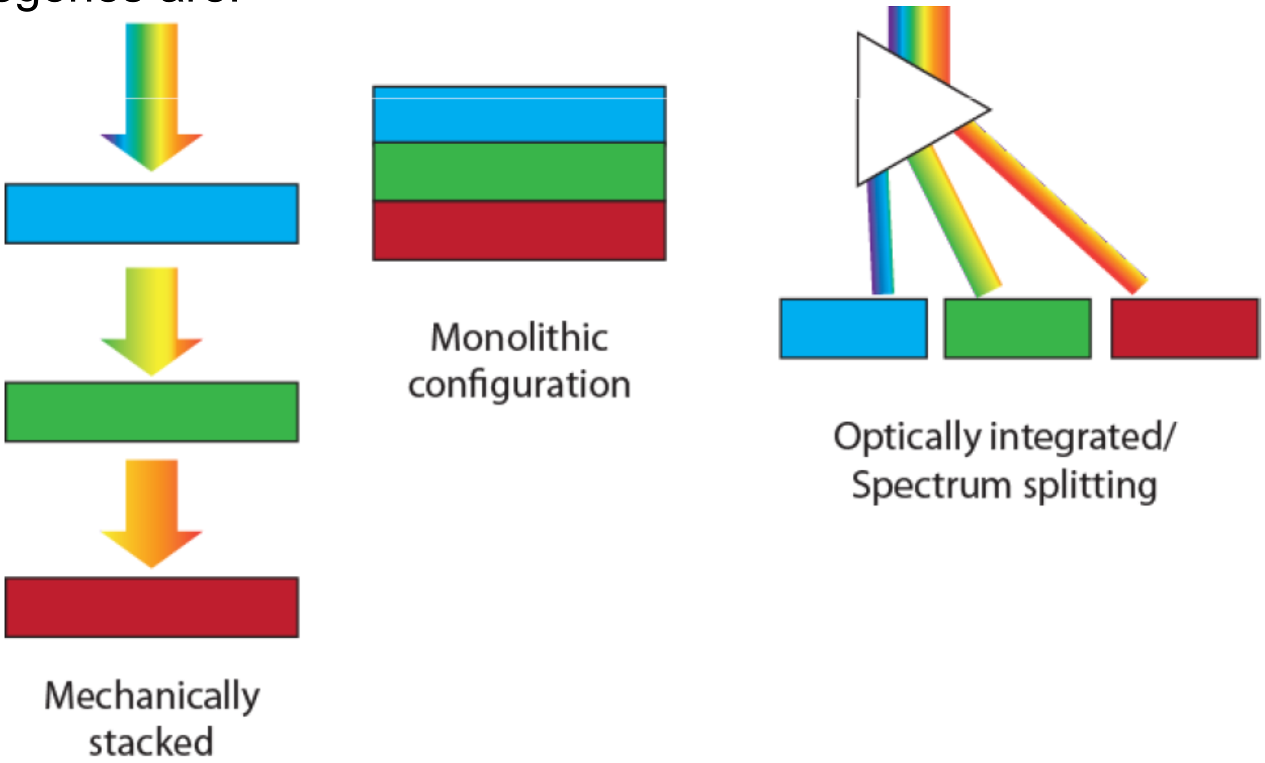


Source: adapted from http://pveducation.org/pvcdrom/solar-cell-operation/tandem-cells

Multijunction Solar Cells

In principle, multijunction solar cells can be designed in many different ways.

The main categories are:

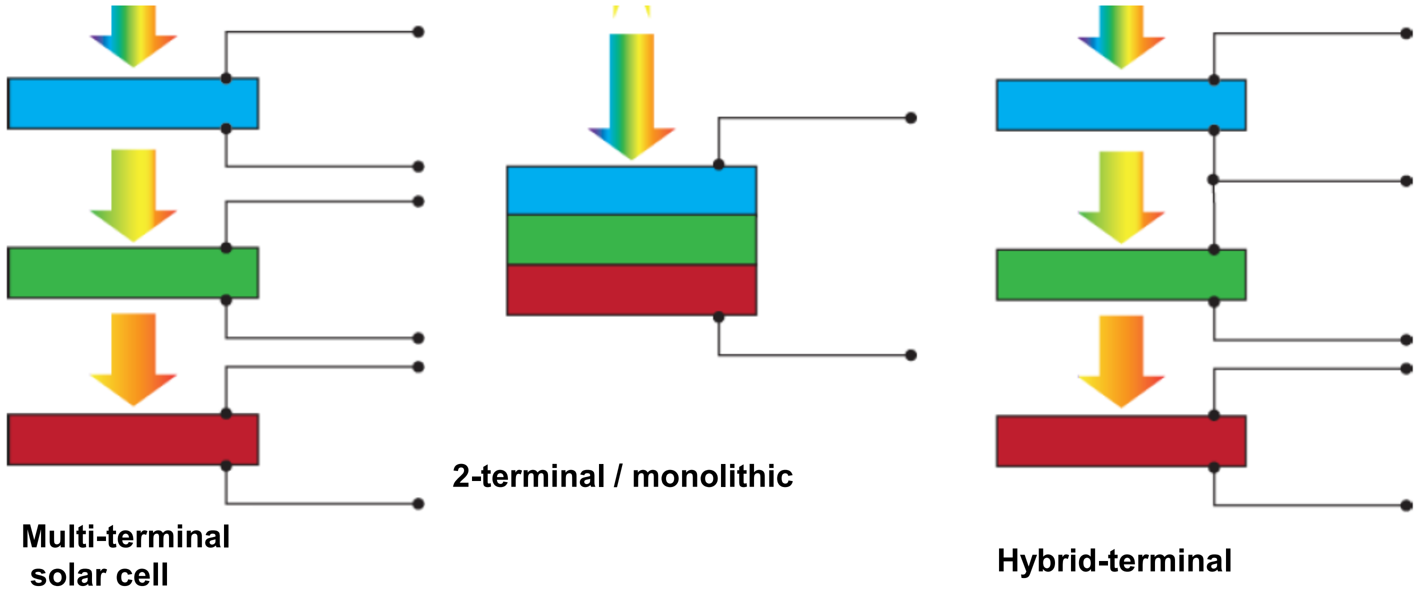


However, the category of “optically integrated/spectrum splitting” is less practical from an application point of view.

Source: *Christiana Honsberg, ASU, “Tandem Solar Cells”*

Multijunction Solar Cells

Interconnection schemes:



- Electrical interconnection impacts the theoretical efficiency (small effect), optimum materials, and device design
- Monolithic, series connected devices are most common, but series connected requires current matching and places substantial constraints on tandem efficiency by limiting the materials that can be used.

Source: Christiana Honsberg, ASU, "Tandem Solar Cells"

Examples of Multijuntion Solar Cells

In the following, we will discuss prominent example of tandem solar cells:

- III/V Monolithic Multijunction Solar Cells
- Tandem Thin-Film Silicon Solar Cells
- Organic Tandem Solar Cells
- Perovskite-Based Tandem Solar Cells
  - Perovskite/Si tandem solar cells
  - Perovskite/CIGS tandem solar cells
  - Perovskite/perovskite tandem solar cells

III/V Monolithic Multijunction Solar Cells

Karlsruher Institut für Technologie

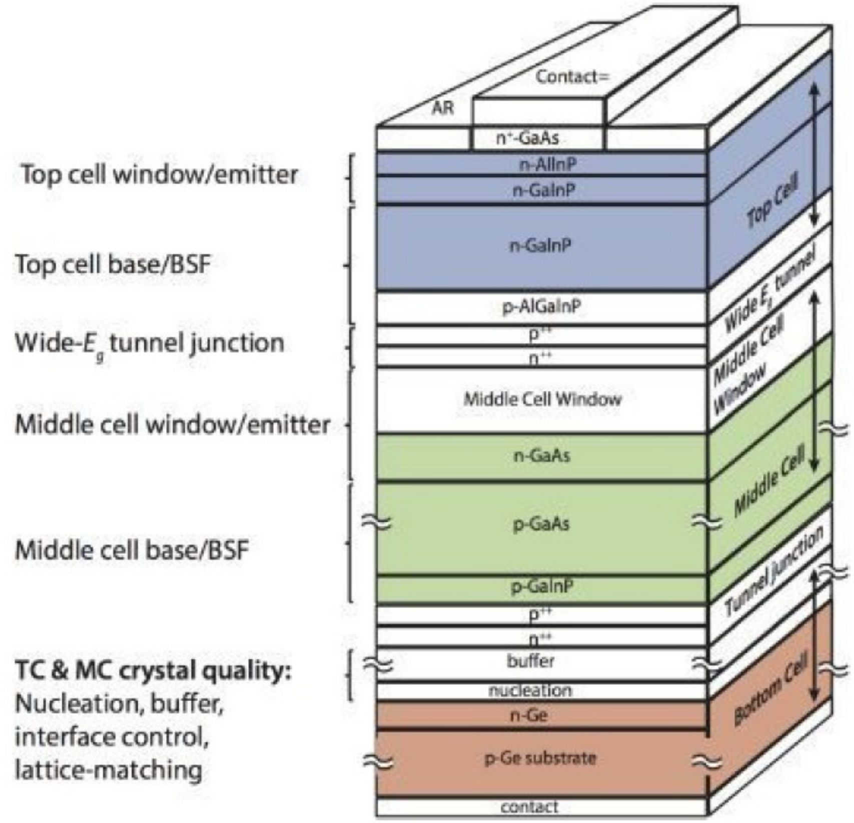
Typical monolithic III-V triple junction cell:

As substrate, a germanium (Ge) wafer is used. From this wafer, the *bottom cell* is created.

Germanium has a bandgap of 0.67eV.

The *middle cell* is based on GaAs with a gap of about 1.4 eV.

The *top cell* is based on GaInP with a bandgap in the order of 1.86 eV.

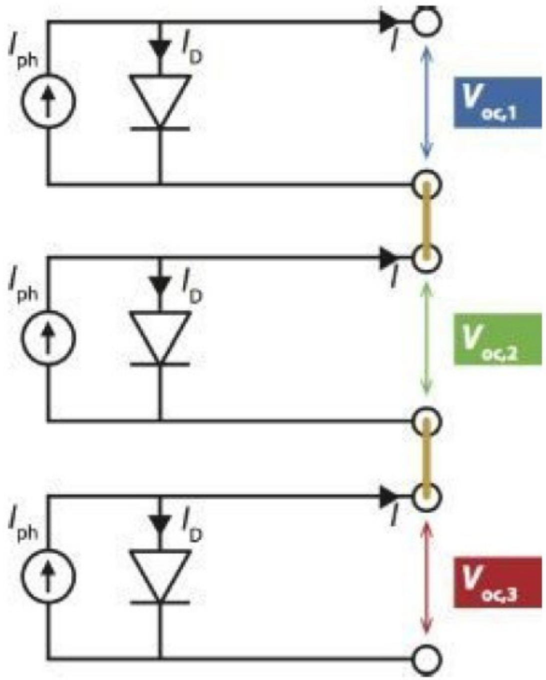


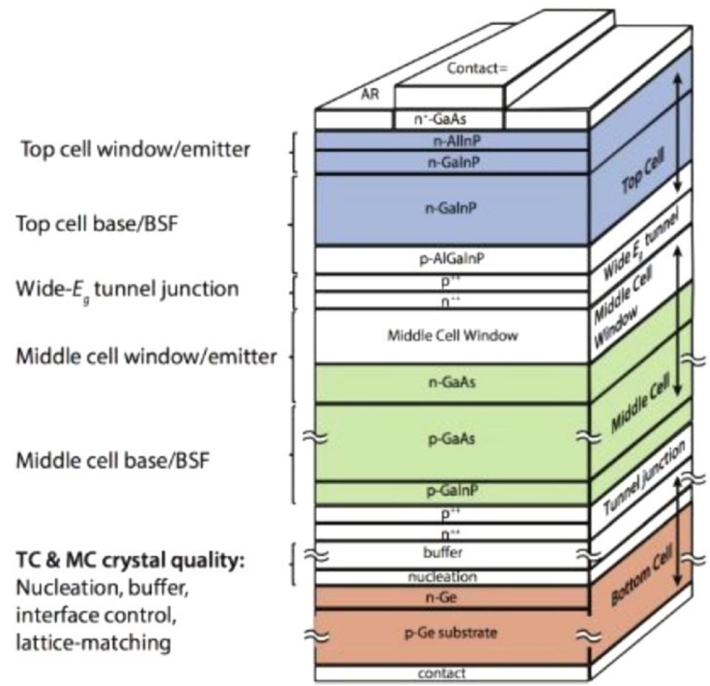
Source: textbook

III/V Monolithic Multijunction Solar Cells

Karlsruher Institut für Technologie

Equivalent Circuit of a monolithic triple junction cell:





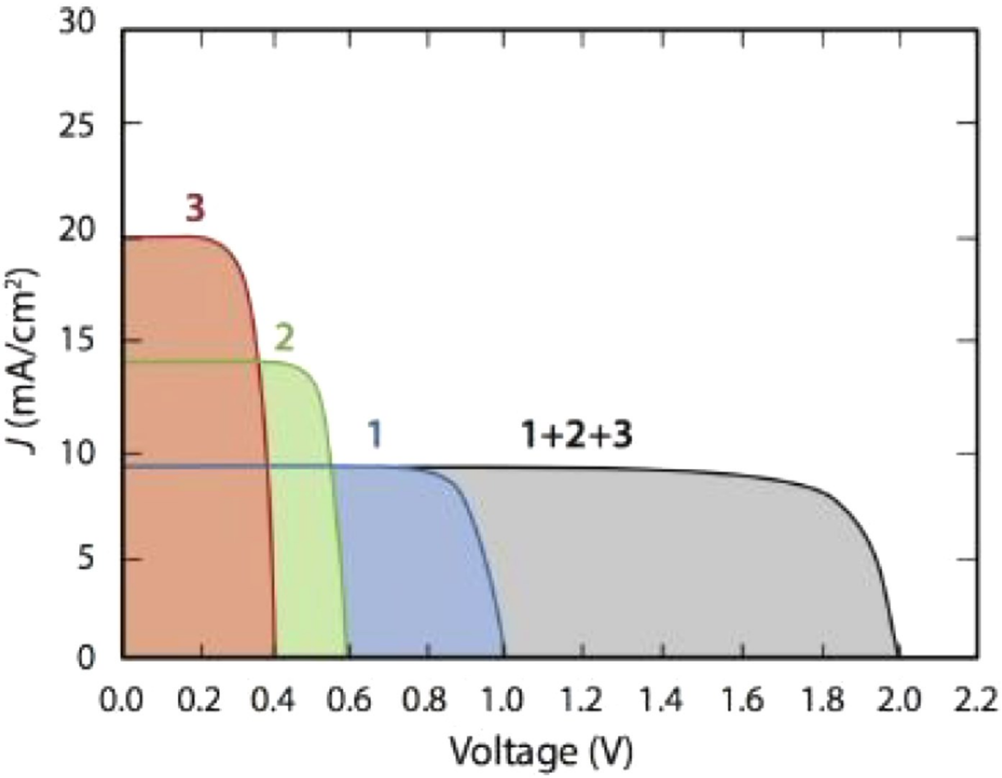
Every *p-n* junction in the multi-junction cell can be represented by the circuit of a single-junction cell. As the three junctions are stacked onto each other, they are connected to each other *in series*.

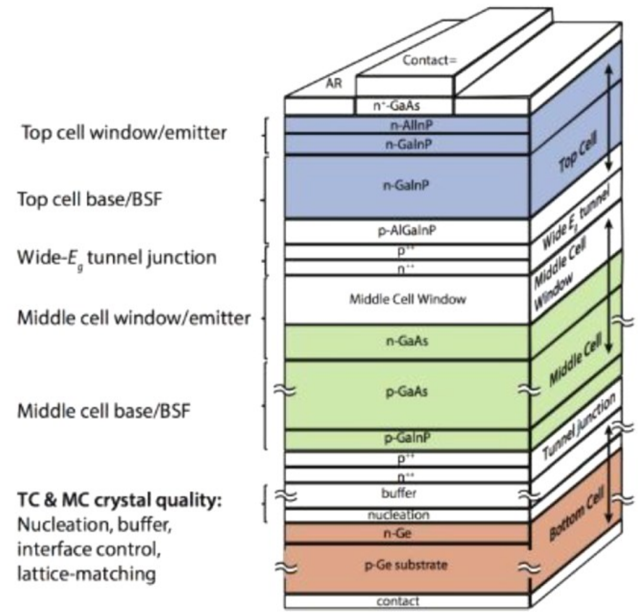
Source: textbook

III/V Monolithic Multijunction Solar Cells

Karlsruher Institut für Technologie

IV-Characteristic of a monolithic triple junction cell:





Series connection:

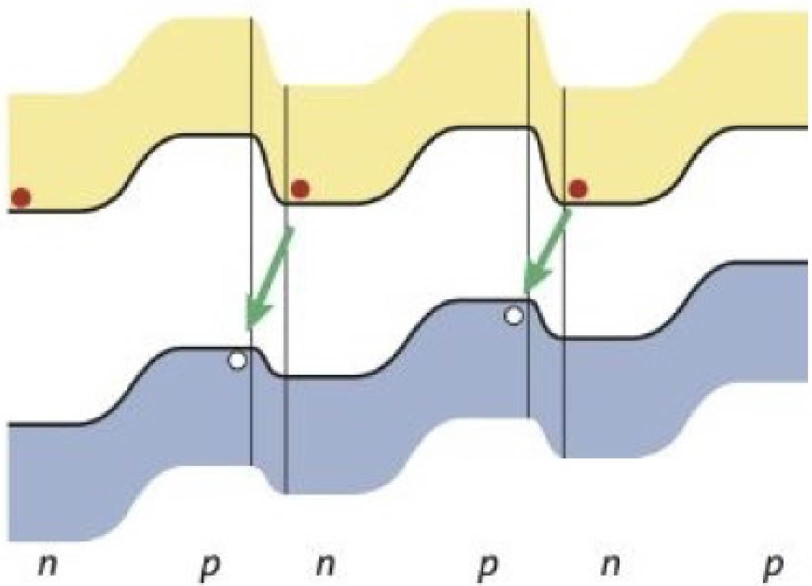
- V_{OC} is the sum of the V_{OC} of each sub
- J_{SC} is limited by the sub cell with the lowest J_{SC}

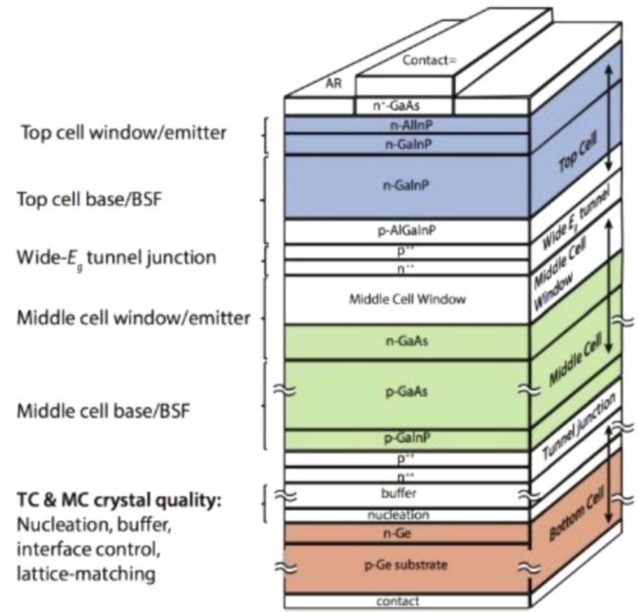
Source: textbook

III/V Monolithic Multijunction Solar Cells

Karlsruher Institut für Technologie

Band diagram of a monolithic triple junction cell:





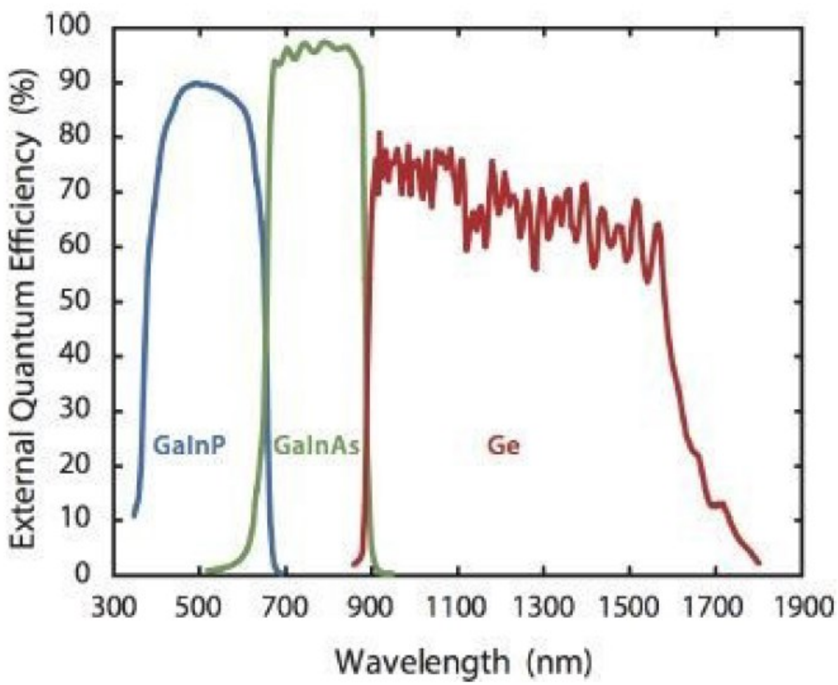
- To prevent the creation of such reverse junctions, *tunnel junctions* are included.
- Tunnel junctions align the VB at one side with the CB at the other junction side.
- Tunnel junctions high bandgap to prevent parasitic absorption losses.
- Tunnel junctions are very thin and have an extremely narrow depletion zone. = >Slopes of the valence and conduction bands are so steep that the electrons from the *n*-layer can tunnel through the small barrier to the *p*-layer, where they recombine with the holes.

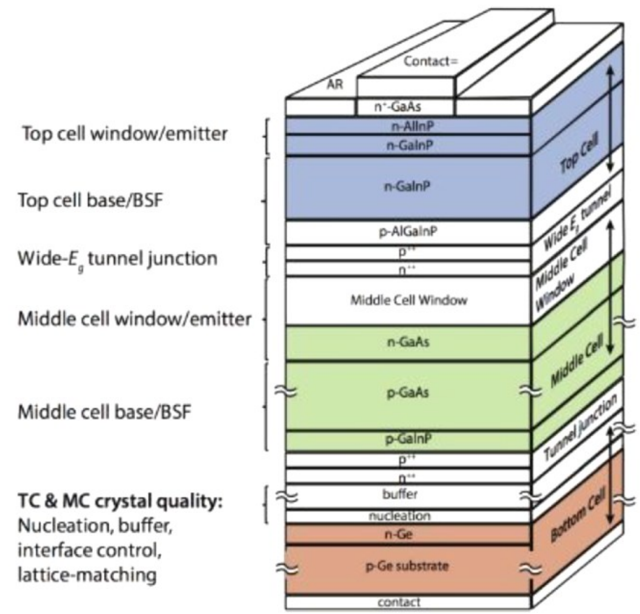
Source: textbook

III/V Monolithic Multijunction Solar Cells

Karlsruher Institut für Technologie

EQE of the subcells of a typical III-V triple-junction cel:





- Spectral utilization of all curves approaches the shape of block functions.
- These block shapes are possible because the III-V materials have very sharp bandgap edges and high absorption coefficients.
- The spectral utilization can be even increased further by moving to multi-junction solar cells consisting of 4-6 junctions.

Source: textbook

III/V Monolithic Multijunction Solar Cells

Karlsruher Institut für Technologie

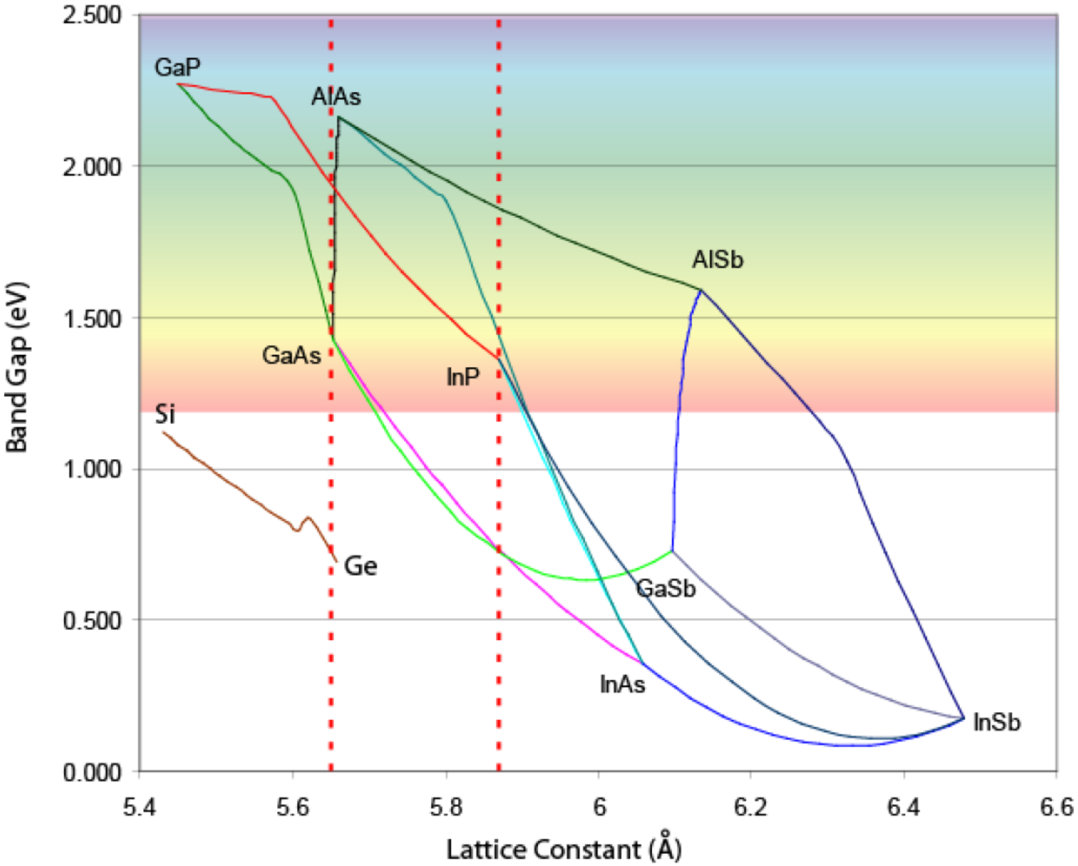
Epitaxy of high quality III-V semiconductor materials:

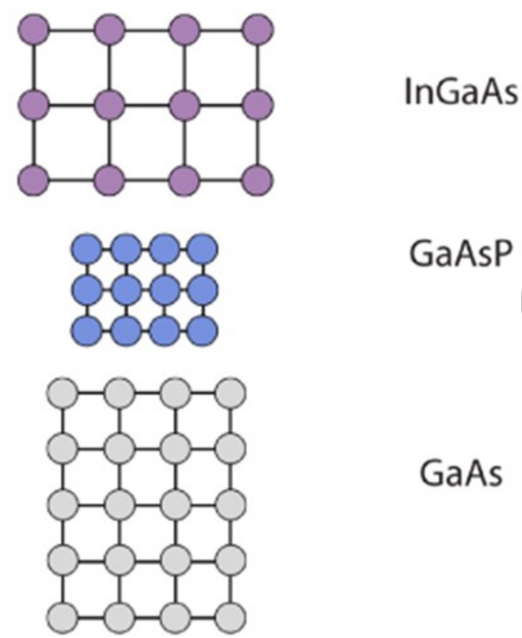
- Crystalline overlayers are deposited on a crystalline substrate, such that they adopt the crystal lattice structure of the substrate.
- The *precursor* atoms from which the layers are grown are provided by various elemental sources.
- For example, if GaAs is deposited with epitaxy, Ga and As atoms are directed to a growth surface under ultra high vacuum conditions.
- As the layer-by-layer growth process is very slow, it allows the deposition of compact materials without any vacancy defects.
- Typically, III-V semiconductor layers are deposited by using *metal organic chemical vapour deposition* (MOCVD).

Source: textbook

III/V Monolithic Multijunction Solar Cells

Epitaxy of high quality III-V semiconductor materials: A big challenge is that the lattice constants of the various materials are different





=> This problem can be solved by *lattice matching*: gradually varying the stoichiometry.

Source: *Christiana Honsberg, ASU, "Tandem Solar Cells"*

III/V Monolithic Multijunction Solar Cells

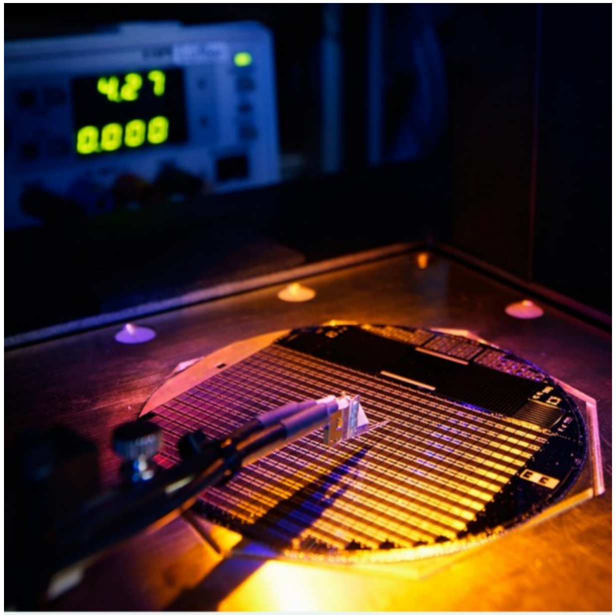
Karlsruher Institut für Technologie

Record III-V multijunction solar cells

Record 6-junction solar cell with power conversion efficiency up to **47.1% at a concentration of 144 suns** AM1.5D.

Same solar cell architecture also set a new world record for one-sun efficiency of **39.2% under the AM1.5G spectrum**.

NREL
Transforming ENERGY



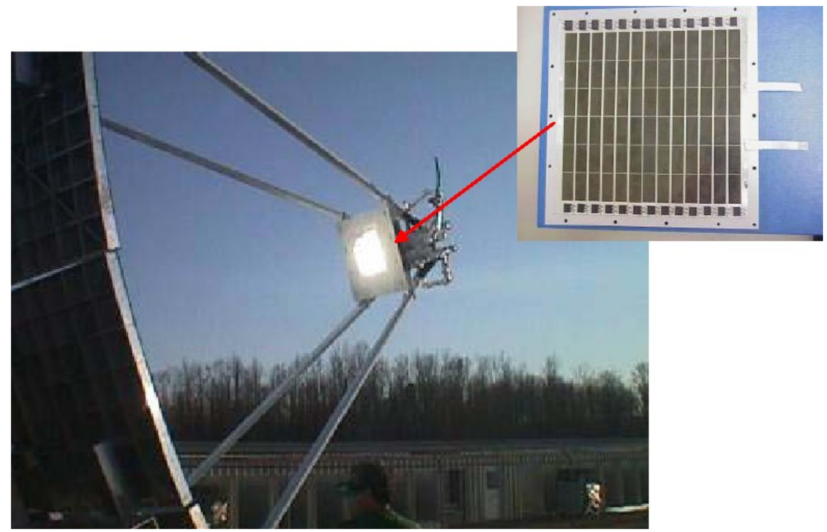
New record solar cell on a 100 mm wafer yielding approximately 500 concentrator solar cell devices.

Source: Christiana Honsberg, ASU, "Tandem Solar Cells"

III/V Monolithic Multijunction Solar Cells

Current applications: The III-V PV technology is very expensive. Hence, such cells are mainly used for space applications and in concentrator technology, where high performance is more important than the cost.

Source: Azur Space Solar Powe



Source: *Christiana Honsberg,*

Source: textbook

III/V Monolithic Multijunction Solar Cells

Summary:

Advantage: Very high-efficiency (nearly 50%)

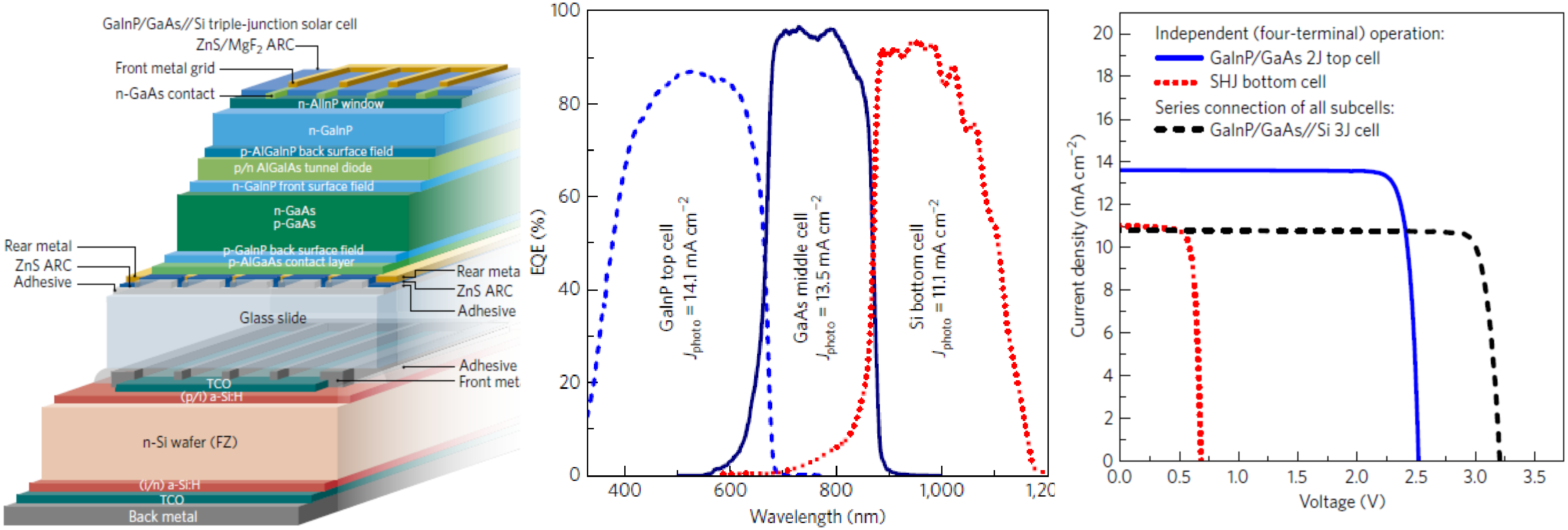
Disadvantages

- Solar cells connected in series
  $\Rightarrow$ current matching problem with varying spectrum
- Best suited for non-varying sunlight $\Rightarrow$ space
- Price... also best suited for space or vehicle integrated photovoltaics

Source: textbook

III/V - Si Tandem Solar Cells

Si-based tandem cells with top cells made out of III–V semiconductors that exhibit efficiencies of up to 32.8% for two junctions and 35.9% for threejunctions.



Source: S. Essig etal. Nature Energy 2 17144 (2017)

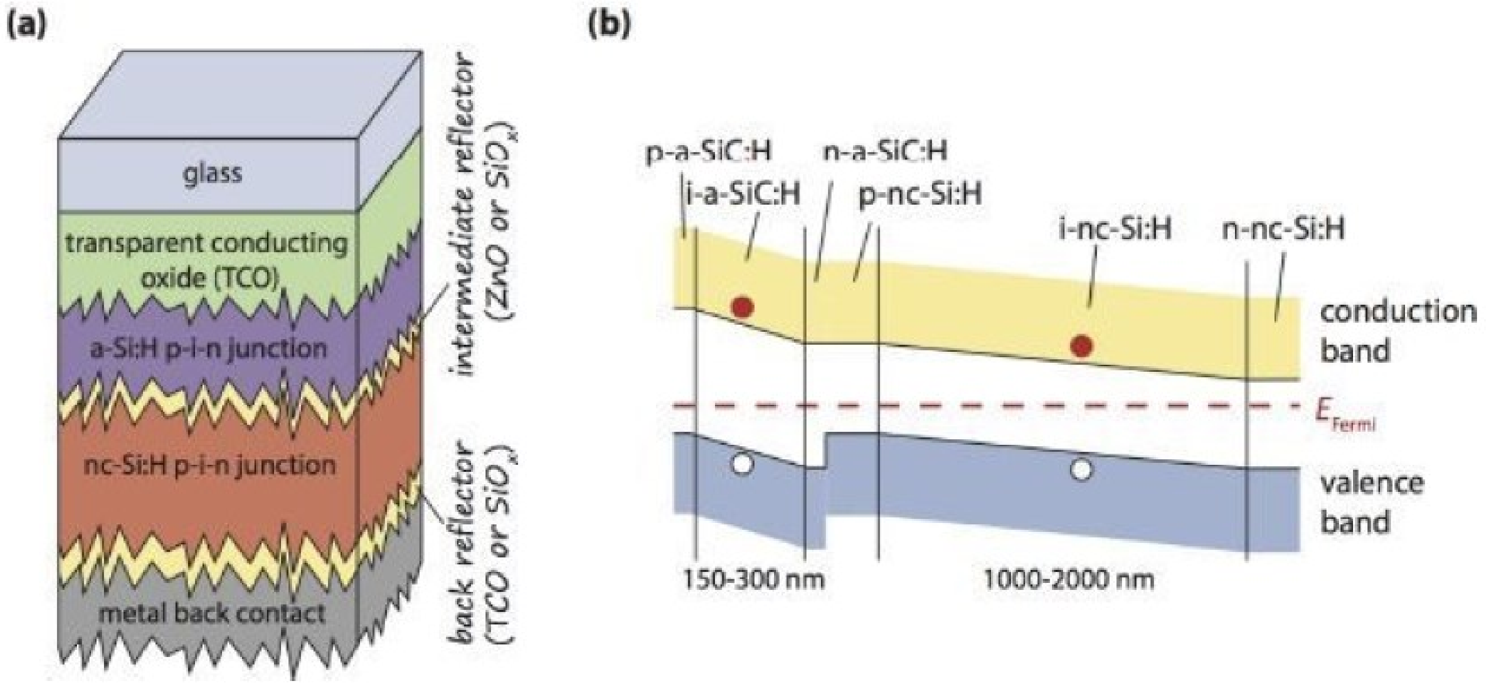
Examples of Multijuntion Solar Cells

In the following, we will discuss prominent example of tandem solar cells:

- III/V Monolithic Multijunction Solar Cells
- **Tandem Thin-Film Silicon Solar Cells**
- Organic Tandem Solar Cells
- Perovskite-Based Tandem Solar Cells
  - Perovskite/Si tandem solar cells
  - Perovskite/CIGS tandem solar cells
  - Perovskite/perovskite tandem solar cells

Thin-film Si Tandem Solar Cells

- Thin-film silicon tandem cells, an a-Si:H top cell is stacked onto an nc-Si:H bottom cell.
- To achieve current matching, the top cell is much thinner than the bottom cell.
- The reported record efficiency of a-Si:H/nc-Si:H tandem cells is 12.3% and for a-Si:H/nc-Si:H/nc-Si:H it is 13.4% [77].

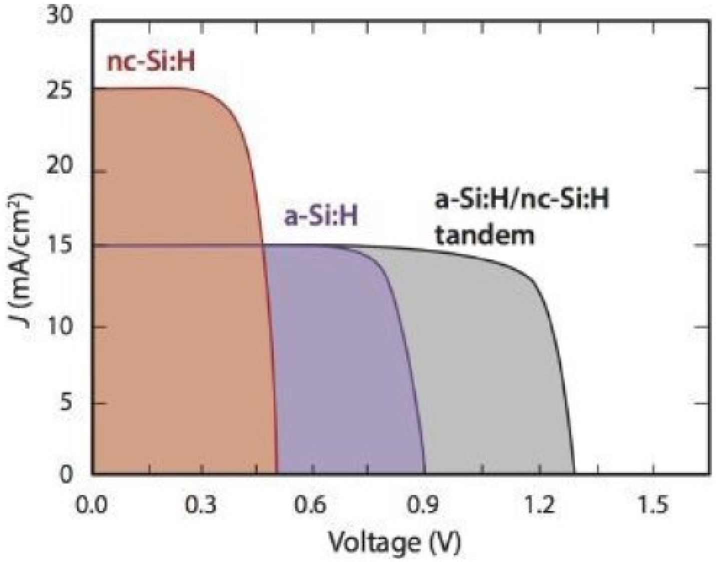


Source: textbook

Thin-film Si Tandem Solar Cells

- *J-V characteristic* of single junction a-Si:H and nc-Si:H solar cell compared to tandem device.

- High bandgap a-Si:H:
  V_{OC} of ~0.9 V, J_{SC} of ~15mA cm^{-2}
- Low bandgap nc-Si:H:
  V_{OC} of ~0.5 V, J_{SC} of ~25mA cm^{-2}
- The total tandem current is the minimum current of the sub cells
- The V_{OC} approximately adds up.

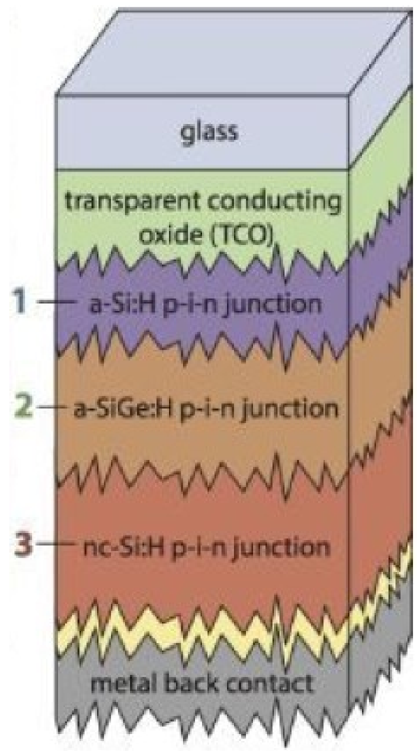


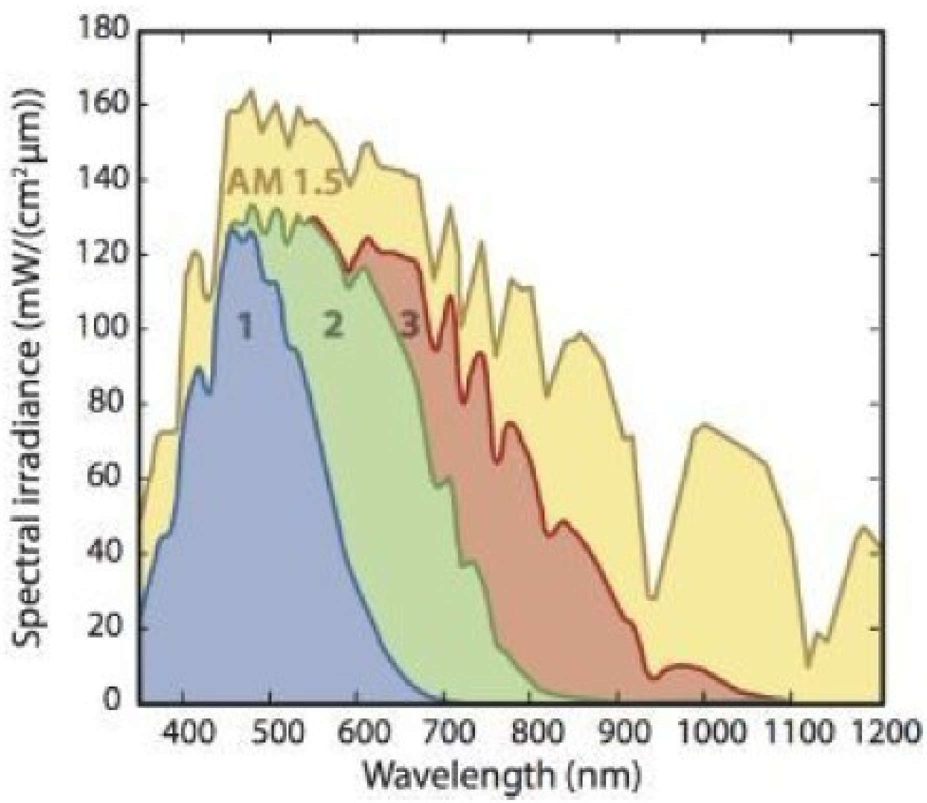
- The current record tandem cell has an efficiency of 12.3% and was manufactured by the Japanese company *Kaneka*.
- **Note, given the low efficiency this technology has no relevant market share anymore.**

Source: textbook

Thin-film Si Triple Junction Solar Cells

- Structure and typical spectral utilization (EQE·AM1.5) of a triple-junction thin film solar cell.





Source: textbook

Examples of Multijuntion Solar Cells

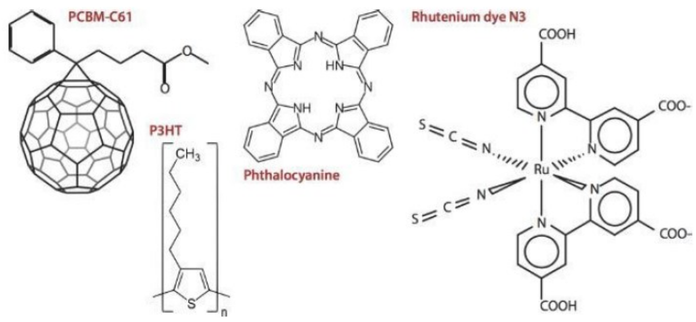
In the following, we will discuss prominent example of tandem solar cells:

- III/V Monolithic Multijunction Solar Cells
- Tandem Thin-Film Silicon Solar Cells
- **Organic Tandem Solar Cells**
- Perovskite-Based Tandem Solar Cells
  - Perovskite/Si tandem solar cells
  - Perovskite/CIGS tandem solar cells
  - Perovskite/perovskite tandem solar cells

Organic tandem solar cells

- With PCEs approaching 15%, single-junction OPV cells continue to advance in efficiency, but still lack behind thin film photovoltaic technologies based on inorganic and hybrid semiconductors.
- A major challenge is the short diffusion/drift length, limiting the maximum thickness of the absorber layers.

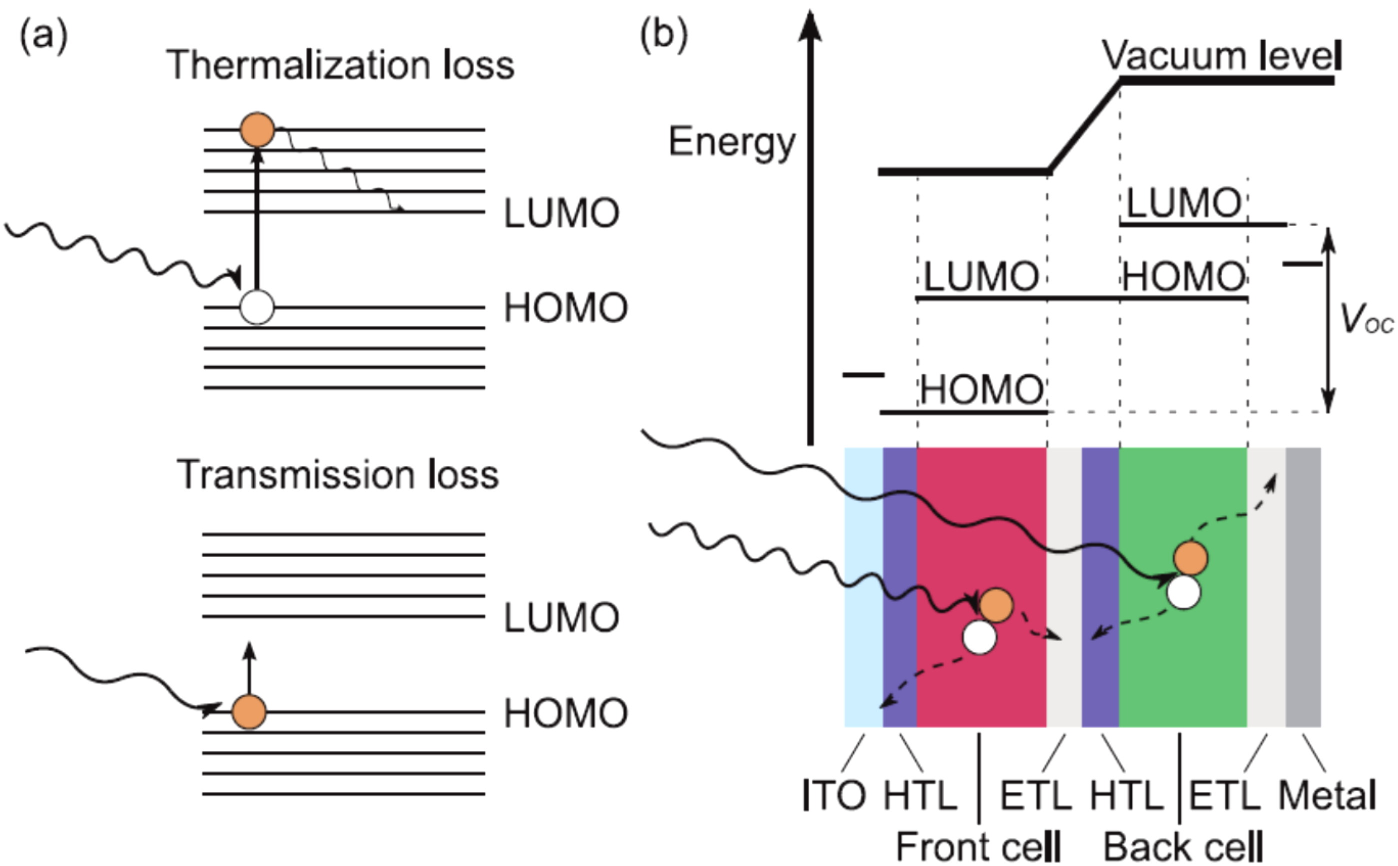
=> Incident sunlight is harvested incomplete
in a single junction organic solar cell.



Source: textbook

Organic tandem solar cells

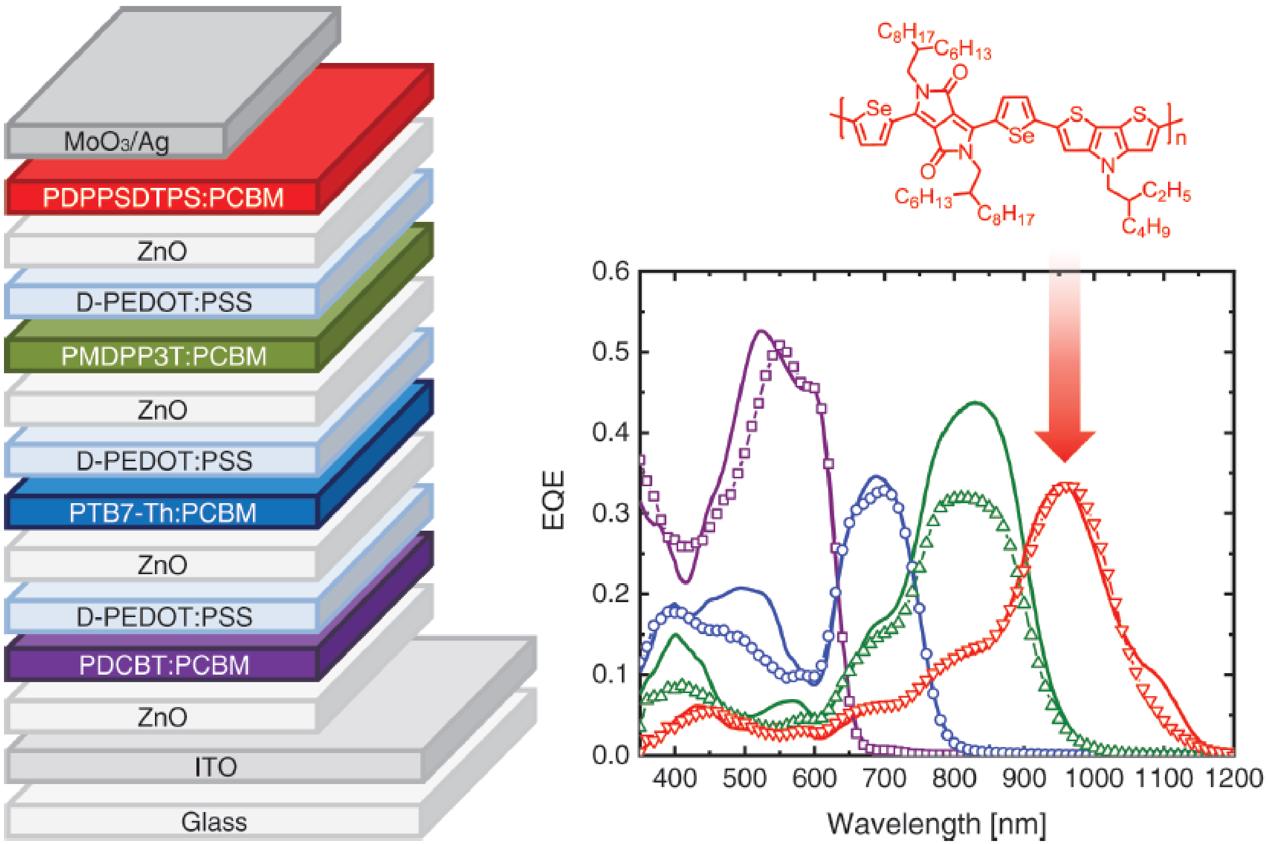
- Thermalization losses in a tandem solar cells
- Functional layers and energy levels in an organic tandem solar cell



Source: D. Di Carlo Rasi and R. A. J. Janssen Adv. Mater. 31 1806499 (2019)

Organic tandem solar cells

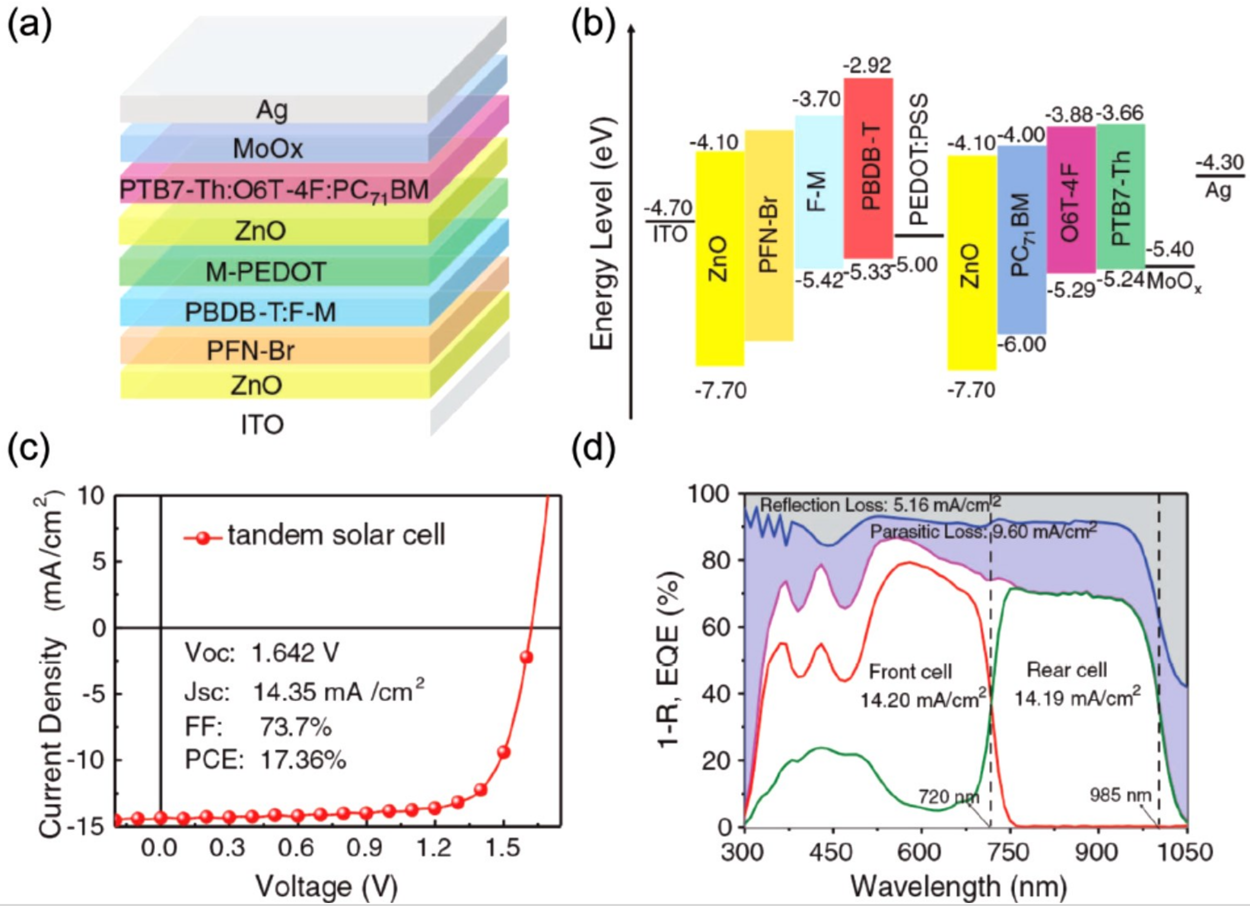
- Quadruple-junction polymer solar cell with four complementary absorber layers and chemical structure of PDPPSDTPS



Source: D. Di Carlo Rasi and R. A. J. Janssen Adv. Mater. 31 1806499 (2019)

Organic tandem solar cells

- Record efficiency (17.4%) tandem organic solar cell. a) Device stack. b) Energy level diagram. c) *J*–*V* characteristic and device metrics. d) EQE of the subcells measured under relevant light and voltage bias conditions.



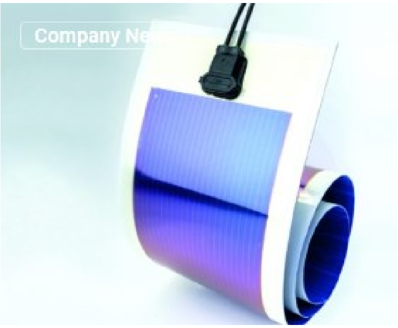
Source: D. Di Carlo Rasi and R. A. J. Janssen Adv. Mater. 31 1806499 (2019)

Organic tandem solar cells

KIT
Karlsruher Institut für Technologie

- Commercialization of organic tandem solar cells

Roll-to-roll fabrication

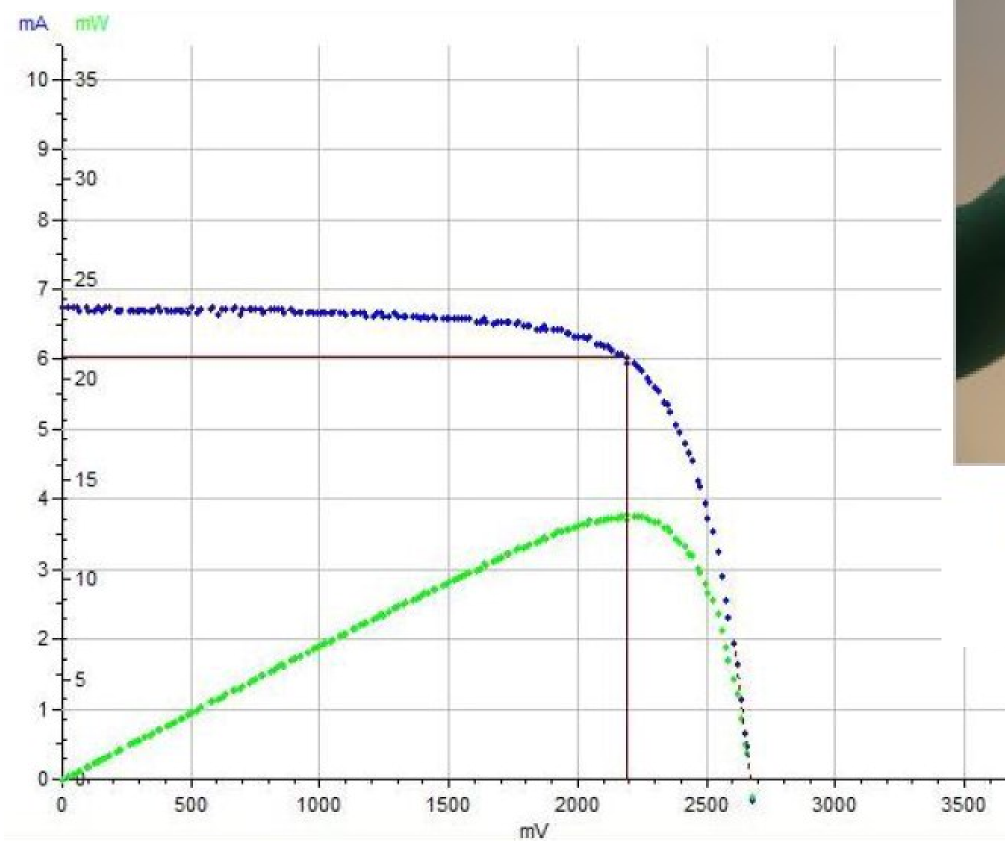


Heliatek®
Say hello to solar. Wherever you are

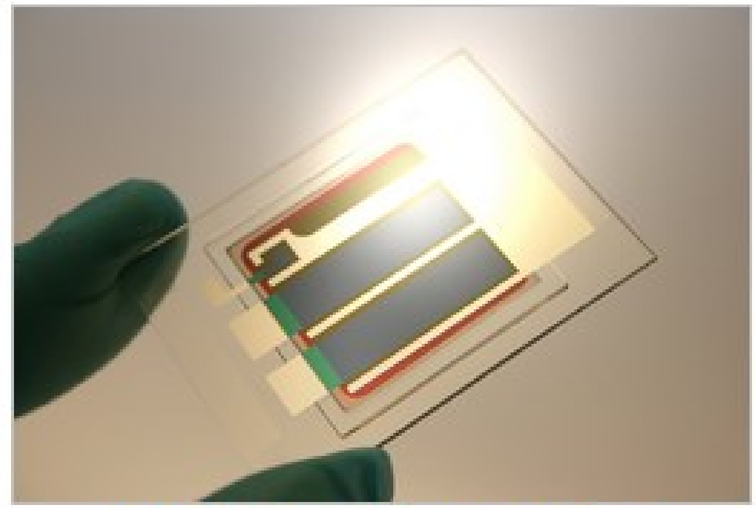
Flexible & light weight

Organic tandem solar cells

- Commercialization of organic tandem solar cells



Rser = 35.700 Ω
Rsht = 34215.76 Ω



Heliatek world record cells with 12.0% efficiency on an active area of 1.1 cm². © Heliatek GmbH

Heliatek®
Say hello to solar. Wherever you are

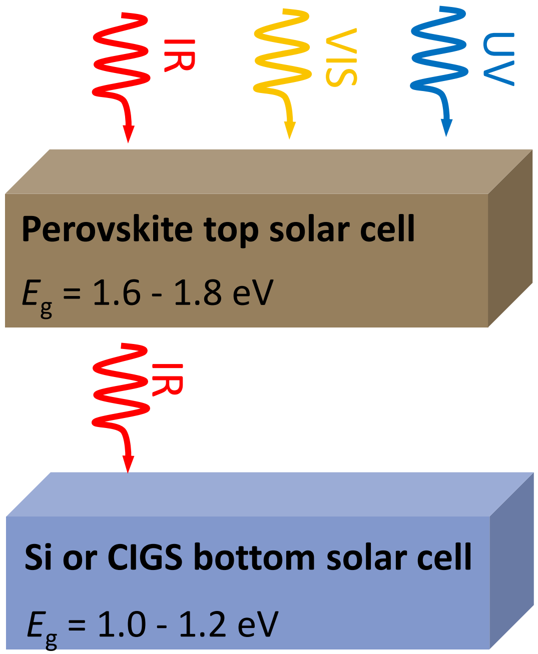
Source: K. Walzer, Heliatek

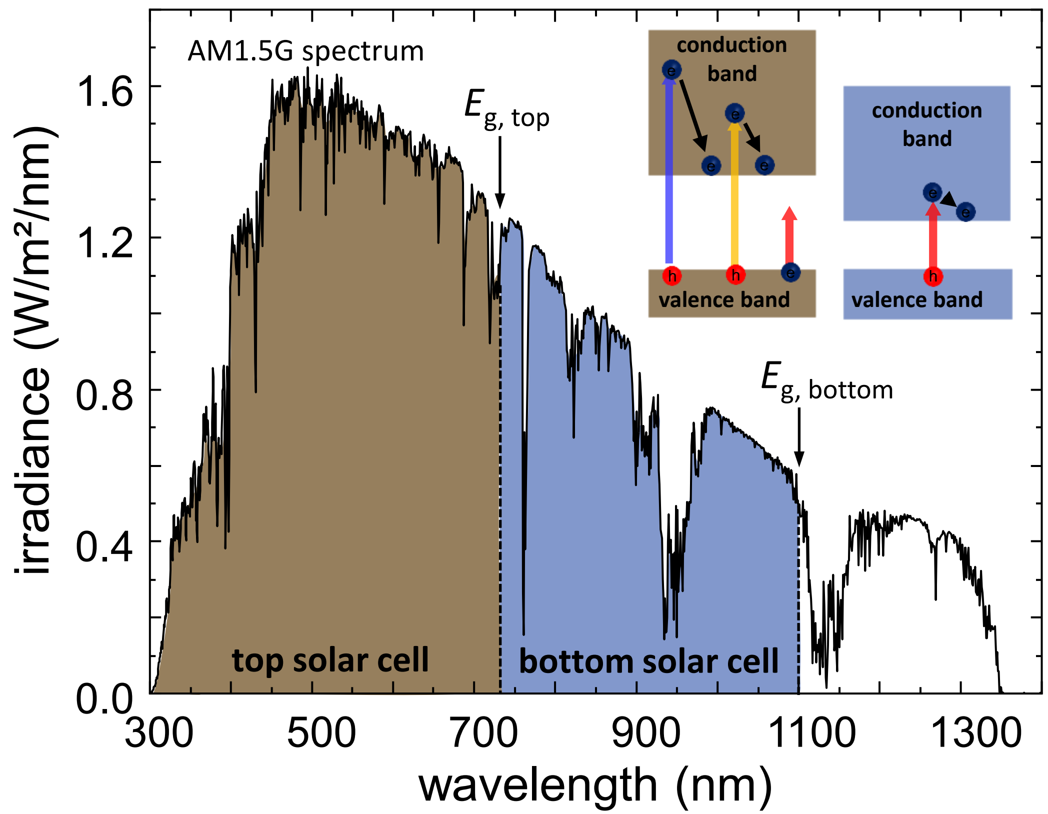
Examples of Multijuntion Solar Cells

In the following, we will discuss prominent example of tandem solar cells:

- III/V Monolithic Multijunction Solar Cells
- Tandem Thin-Film Silicon Solar Cells
- Organic Tandem Solar Cells
- **Perovskite-Based Tandem Solar Cells**
  - Perovskite/Si tandem solar cells
  - Perovskite/CIGS tandem solar cells
  - Perovskite/perovskite tandem solar cells

Perovskite-Based Tandem Photovoltaics

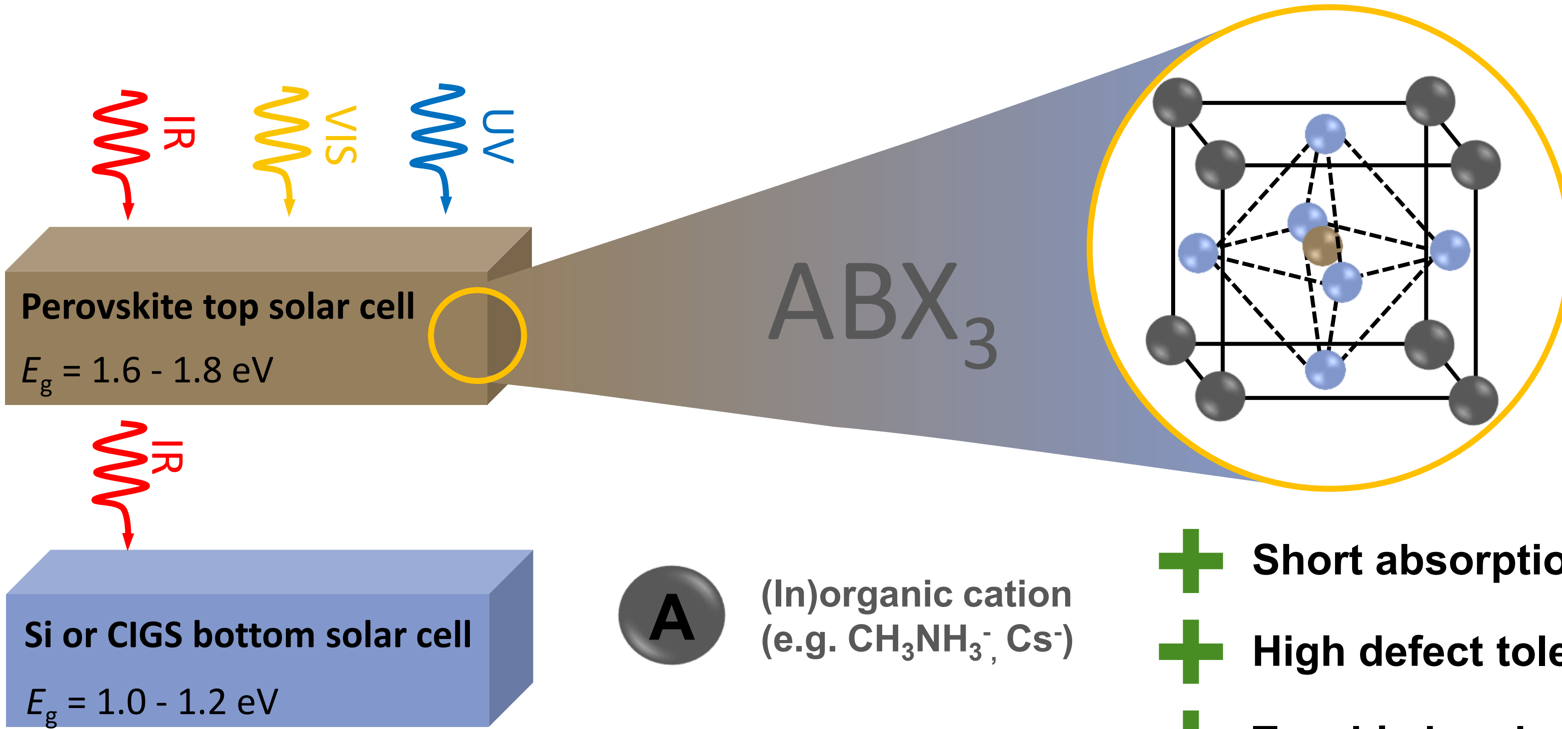




Tandem photovoltaics reduces intrinsic thermalization losses, thereby enabling much higher power conversion efficiencies (theoretical limit ~ 46%).

Source: Paetzold/KIT

Metal Halide Perovskite Semiconductors



A (In)organic cation (e.g. $CH_3NH_3^-$, Cs^-)

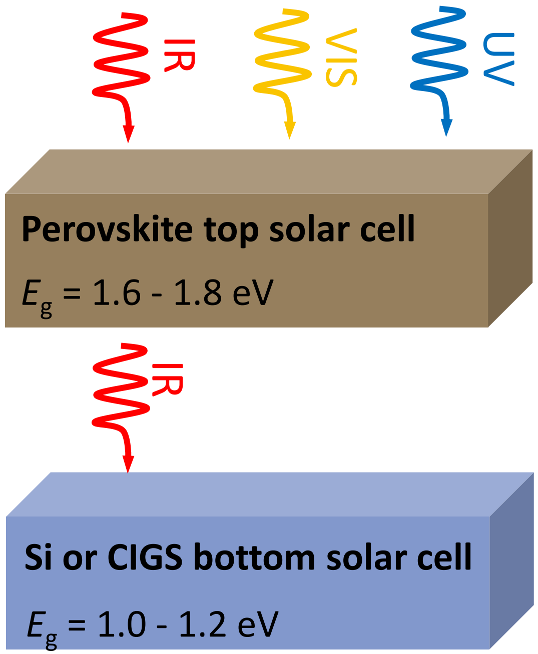
B Inorganic cation (e.g. Pb^-, Sn^-)

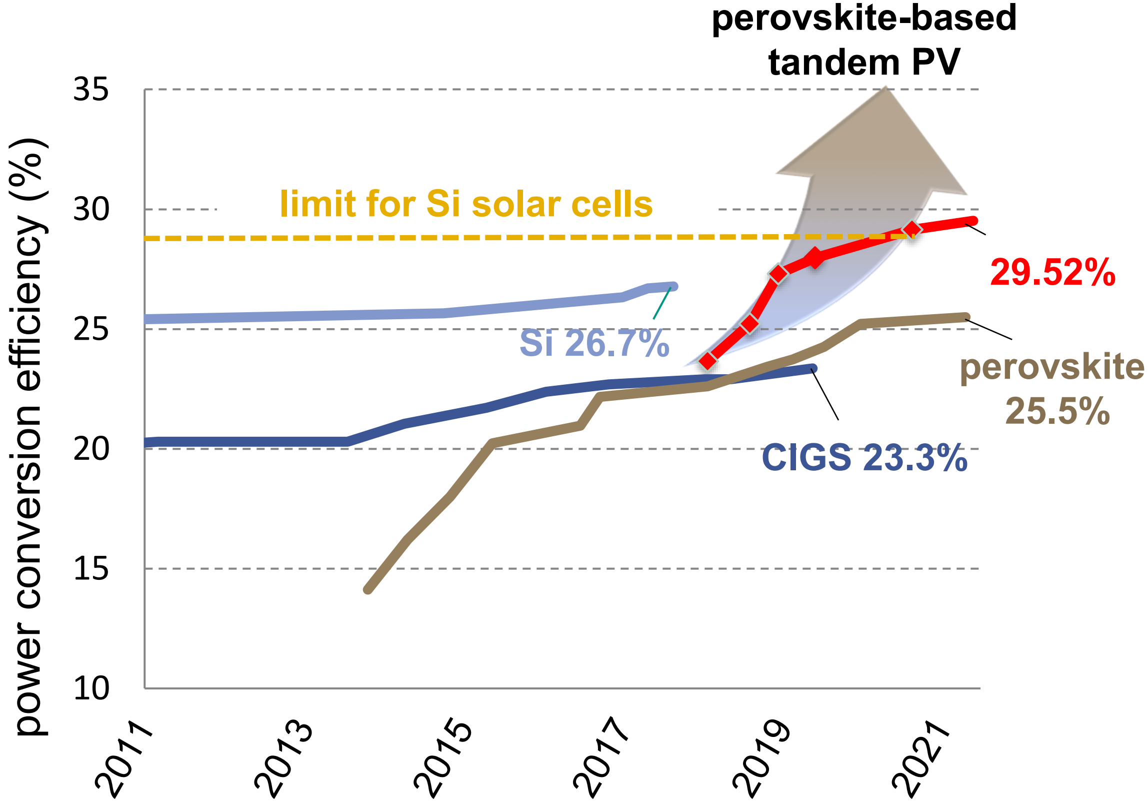
X Anion (e.g. I^+, Br^+)

- \+ **Short absorption length**
- \+ **High defect tolerance**
- \+ **Tunable bandgap**
- \+ **Solution processable**
- − **Toxicity**
- − **Stability**

Source: Paetzold/KIT

Perovskite-Based Tandem Photovoltaics



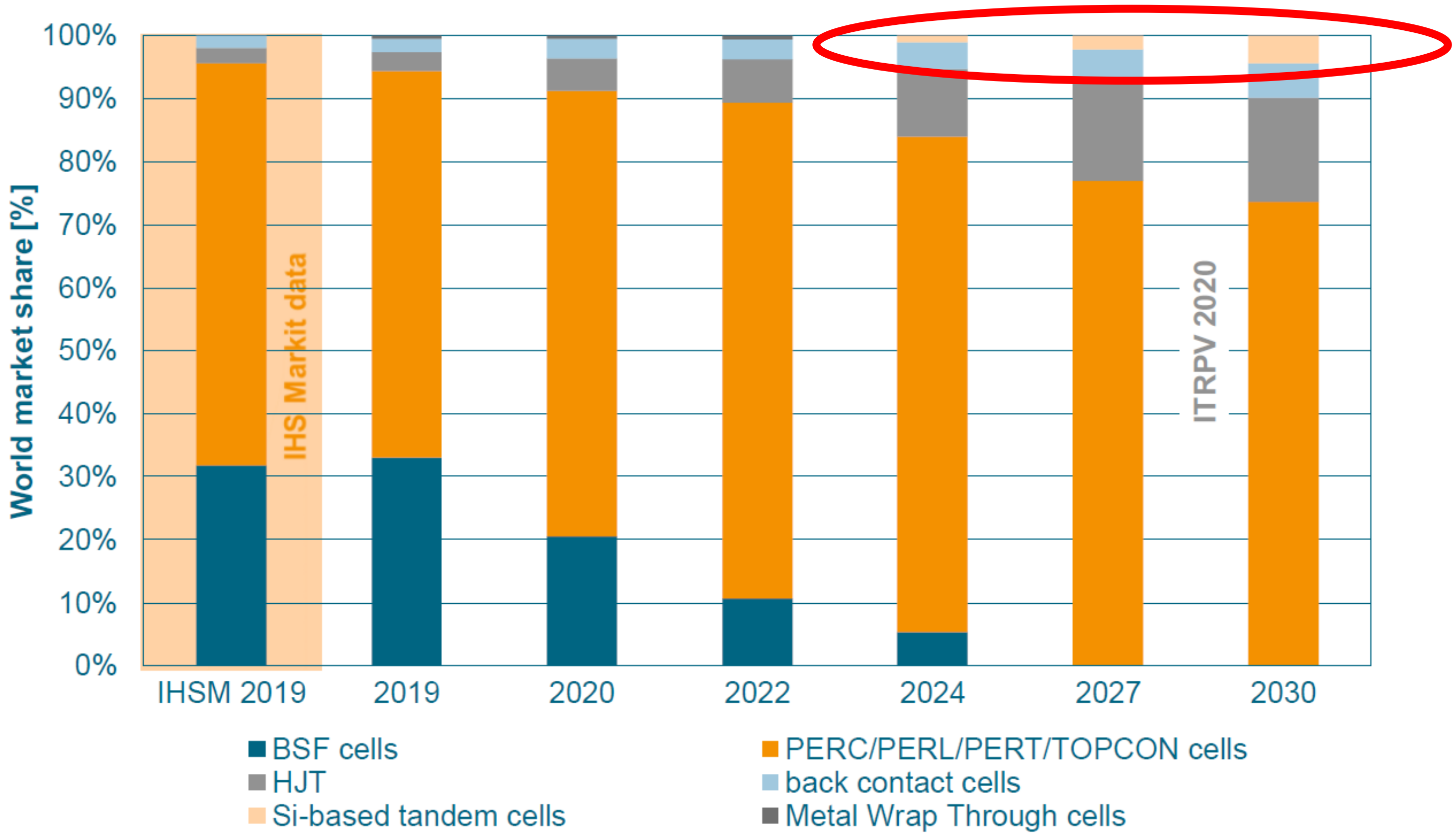


NREL/Best Research-Cell Efficiency Chart (Dec 2019)

For the first time in the history of PV, a low-cost and high E_g material is available that opens a window of opportunity to boost the efficiency of Si solar cells > 33%.

Source: Paetzold/KIT

Tandem PV in the *International Technology Roadmap for PV (ITRPV 2020)*

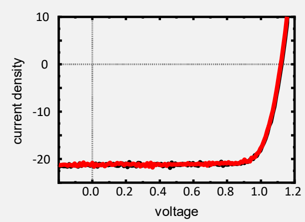
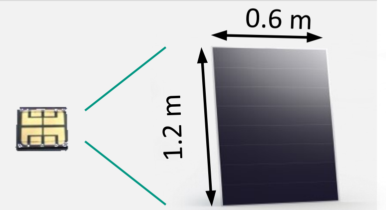
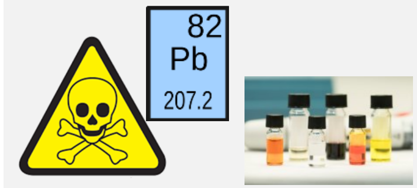


- „c-Si-based tandem PV are expected to appear in mass production from 2024“
- Perovskite/c-Si tandem PV a prominent option!

Research Strategy

Karlsruher Institut für Technologie

Grand Challenges of Perovskite-Based Tandem Photovoltaics

high efficiencies	large areas	stability	toxicity ?
			
~28% ⇒ >33%	**~1 cm² ⇒ >1 m²**	**~1000 h ⇒ >25 years**	• **Pb-free** • **non-toxic solvents**

<u>Our mission:</u> Advance the **stability** and **scalability** of perovskite-based tandem photovoltaics and increase the **power conversion efficiency above 33%**.

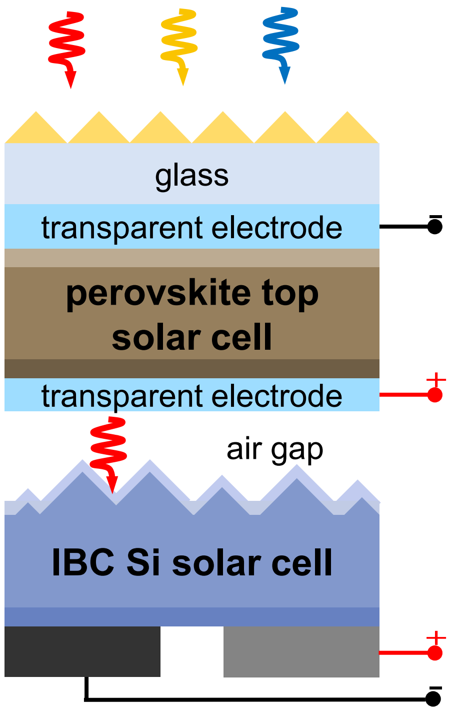
- *Paetzold research group (AOPV)*
  [6 postdocs, 11 doctoral students]

- *Perovskite PV Taskforce at KIT*
  [cross-university collaboration with critical mass]

Source: Paetzold/KIT

Perovskite/Si Tandem Solar Cells

Perovskite top solar cell with 2D/3D heterostructure combined with IBC Si solar cell.



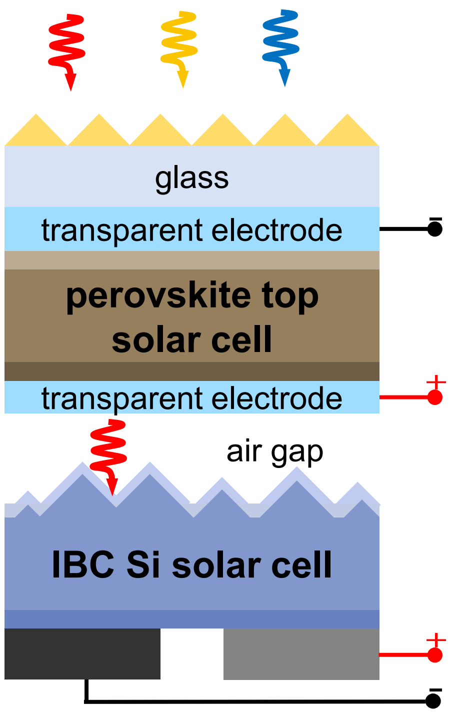
Engineering the device architecture:

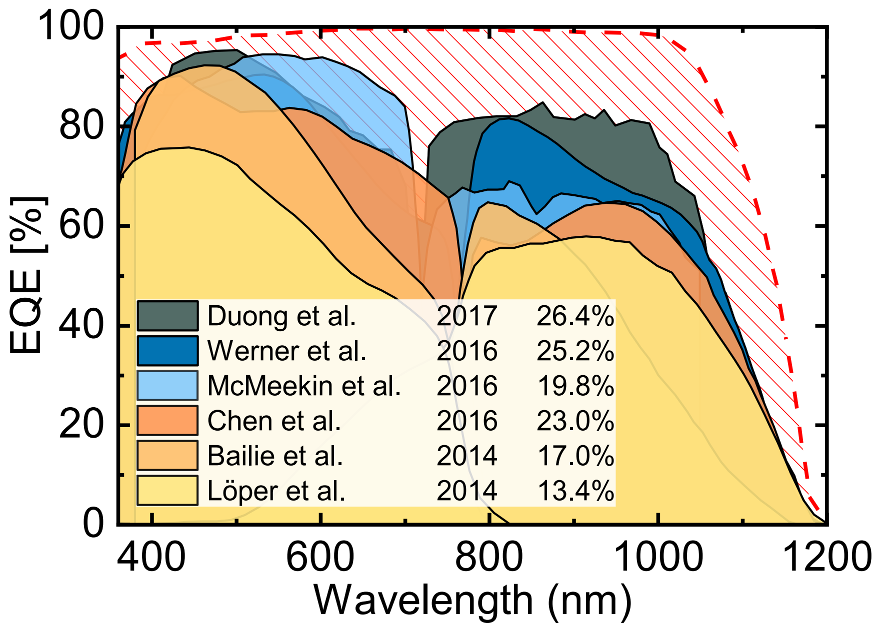
- Semitransparent perovskite top solar cell
- Light management concepts
- Interconnection schemes
- Solar module integration

Source: Paetzold/KIT

Light Management: A Key Concept for High-Efficiency Perovskite-Based Tandem PV

Historical evolution of the external quantum efficiency (EQE) of laboratory scale 4-terminal perovskite/c-Si tandem solar cells.





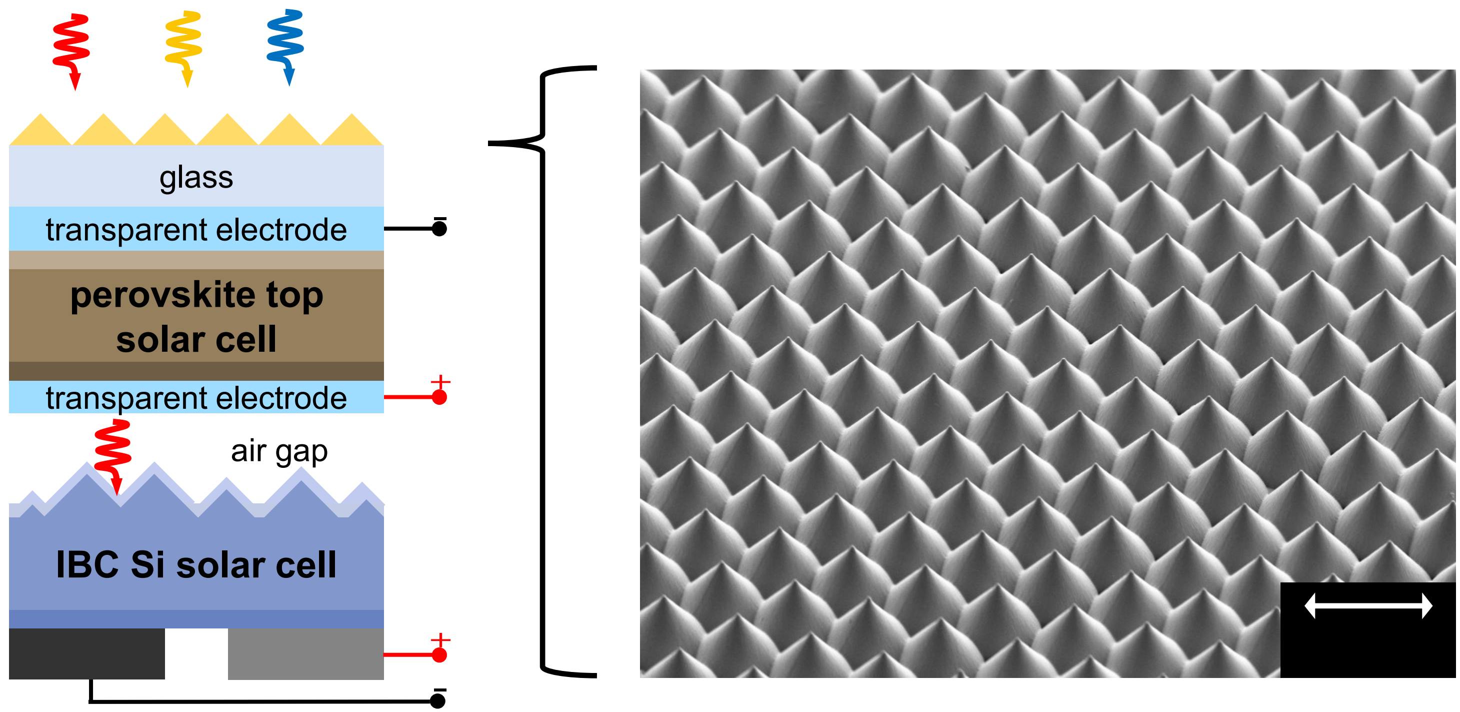
D. A. Jacobs et al., *J. Phys. Chem. Lett.* **10**(11), 3159–3170, 2019.

Source: Paetzold/KIT

Light Management: Micrometer-Scale Textures for Improved Light Harvesting

Karlsruher Institut für Technologie

Multi-functional textures reduce reflection losses.



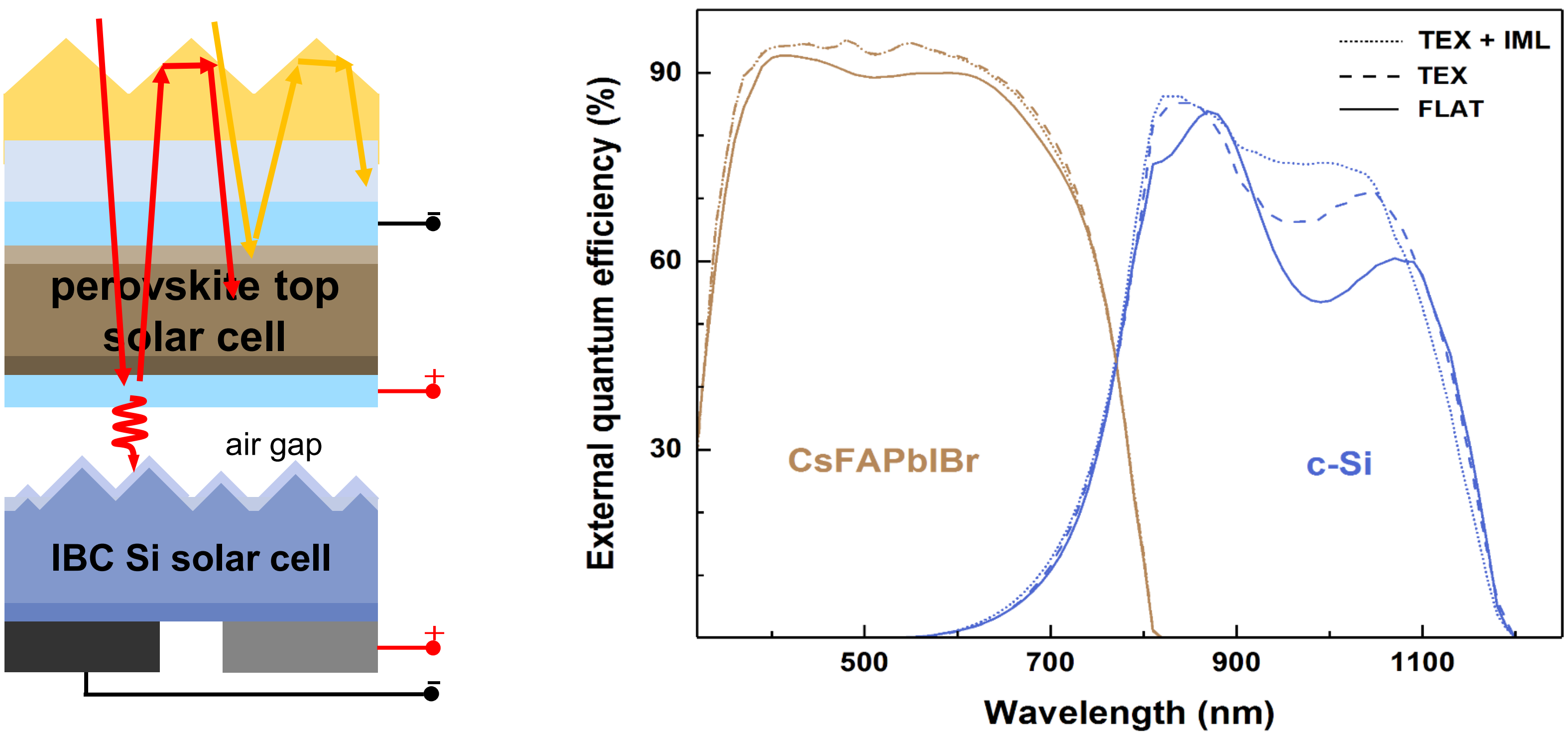
M. Jaysankar et al., *Energy & Environmental Science*, **11**(6) 1489-1498 (2018).

S. Dottermusch et al., *Progress in Photovoltaics,*

Source: Paetzold/KIT

Light Management: Micrometer-Scale Textures for Improved Light Harvesting

Improved light harvesting enhanced external quantum efficiency.

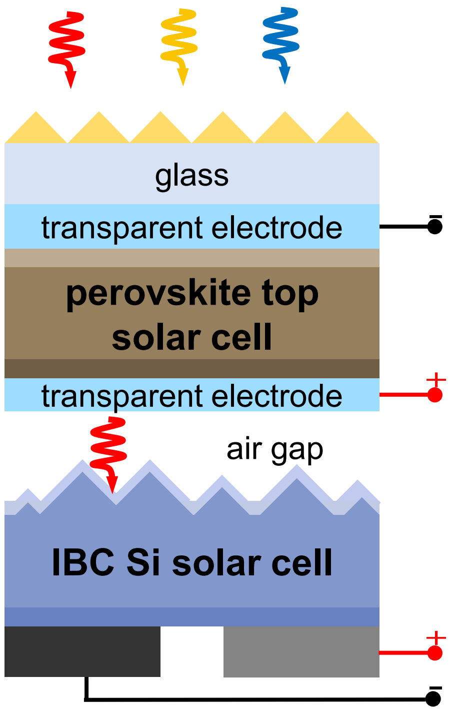


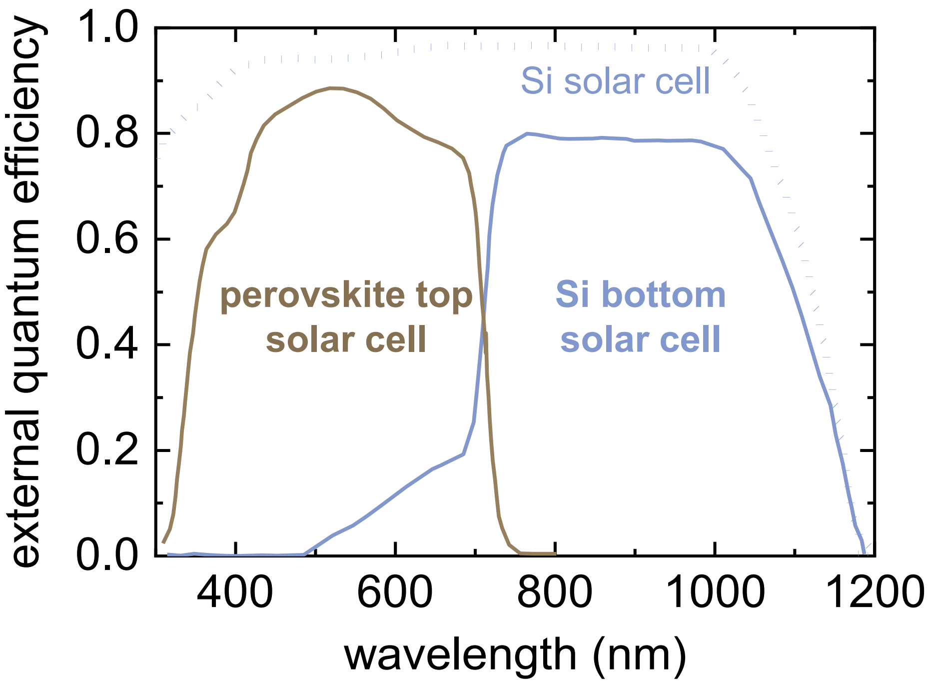
Improved power conversion efficiency by 1-2% absolute.

M. Jaysankar et al., *Energy & Environmental Science*, **11**(6) 1489-1498 (2018).

Perovskite/Si Tandem Solar Cells

Perovskite top solar cell combined with IBC Si solar cell in 4-terminal device.

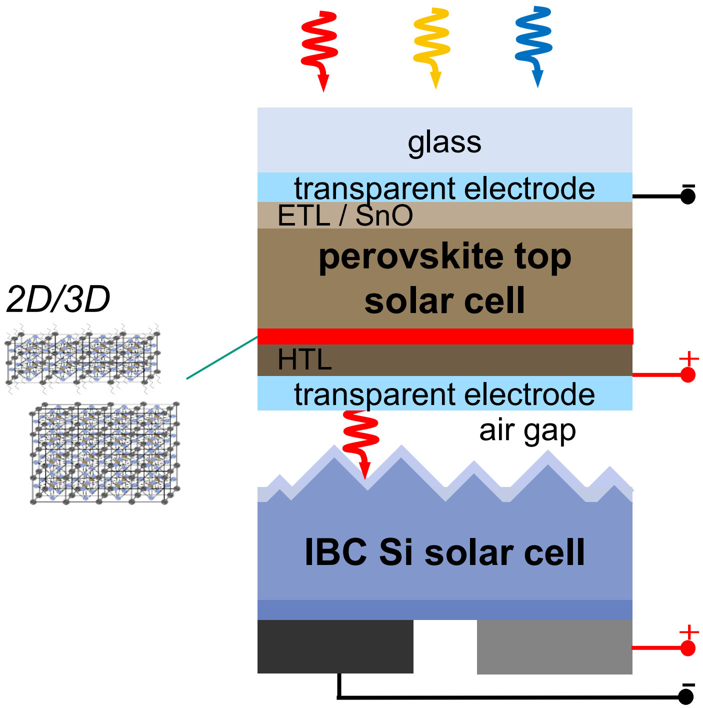




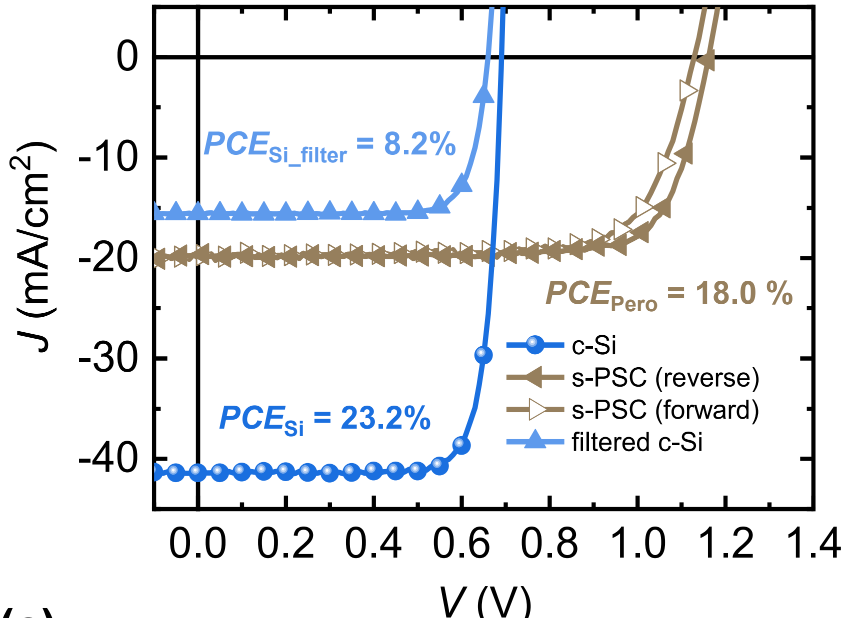
T. Doung et al. accepted in Advanced Energy Materials 2020.

Source: Paetzold/KIT

4T Perovskite/Si Tandem Solar Cells



(a)



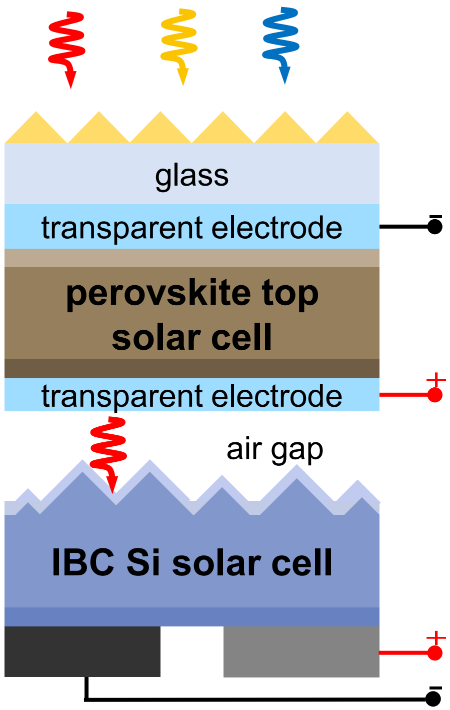
(c)

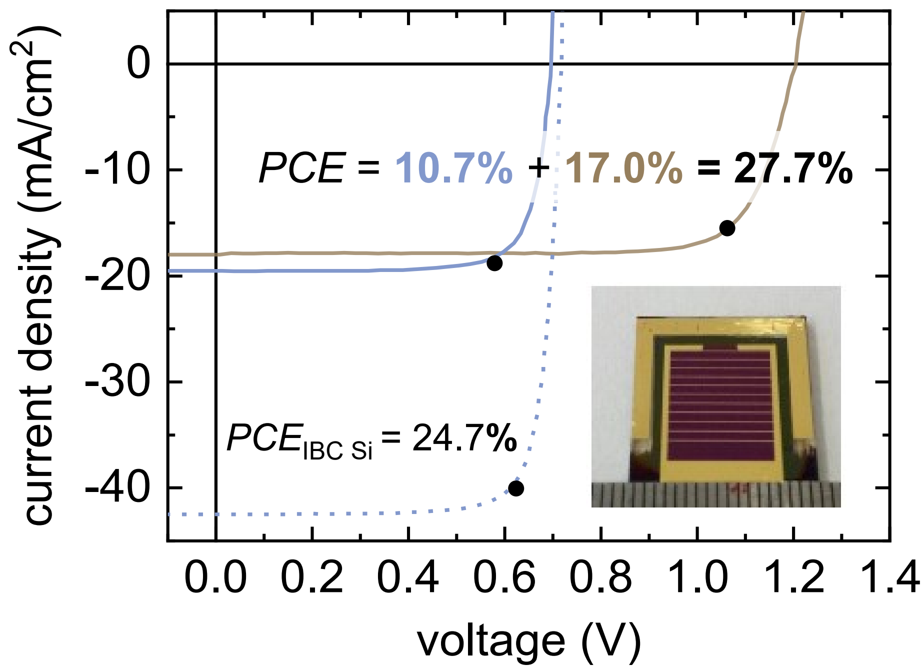
- *$SPCE_{5min}$ = 25.7% and PCE_{IV} = 26.2% for perovskite/c-Si tandem solar cells.*
- *Significant improvement potential: (1) light management, (2) perovskite top cell.*

S. Gharibzadeh, I. M. Hossain et al., *Advanced Functional Materials* **30**(19) 1909919 (2020)

Perovskite/Si Tandem Solar Cells

Perovskite top solar cell combined with IBC Si solar cell in 4-terminal device.





- Power conversion efficiency (*PCE*) of 27.7% exceeds record of single junction Si solar cells (26.7%).

T. Doung et al. – *under review.*

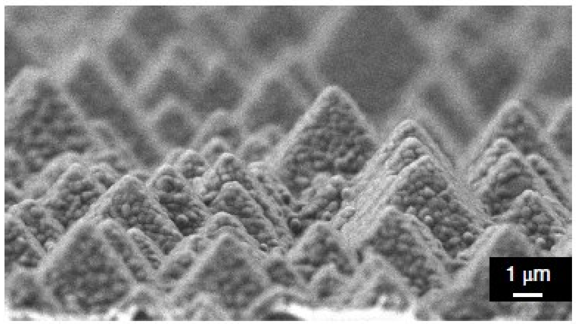
Source: Paetzold/KIT

Monolithic Perovskite/Si Tandem Solar Cells

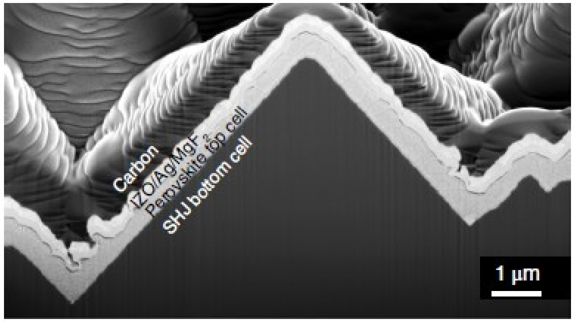
Karlsruher Institut für Technologie

Key challenge: Process high efficiency perovskite thin film solar cell (thickness ~ 1um) on textured So bottom solar cell (texture ~ 5um).

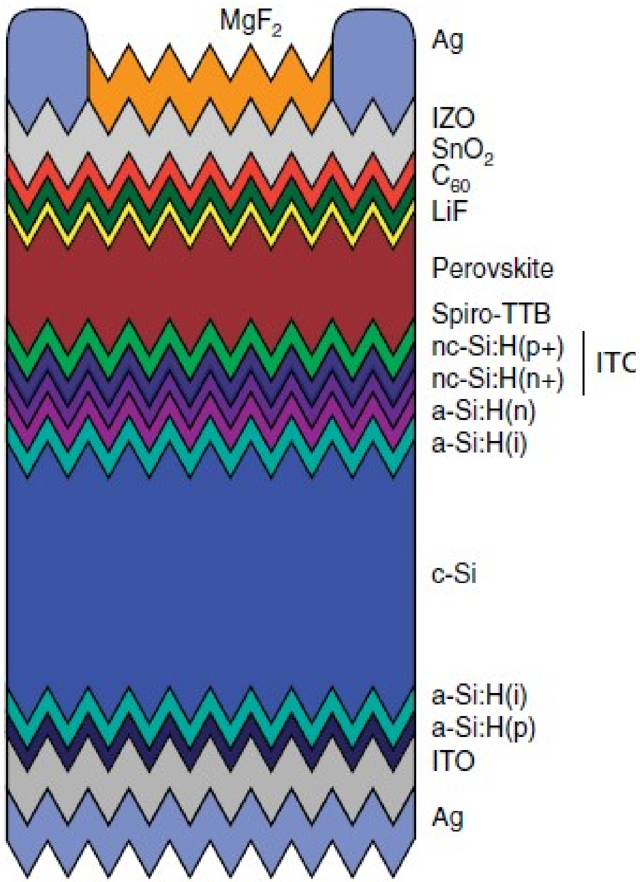
d



e



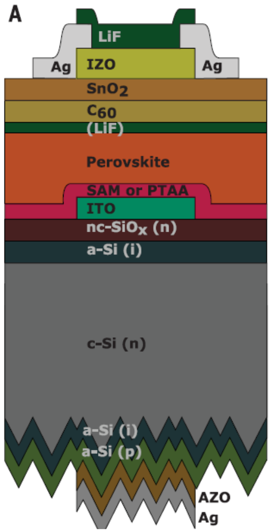
a

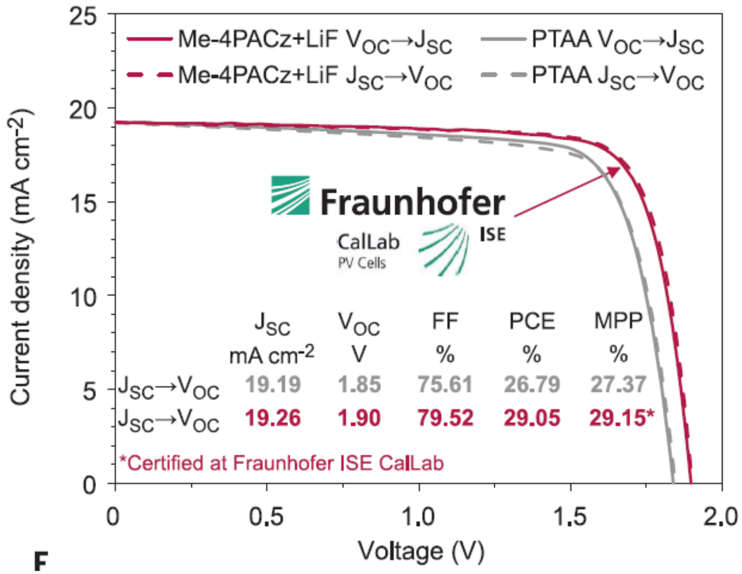


Source: F. Sahli et al. Nature Materials 17 820-826 (2018)

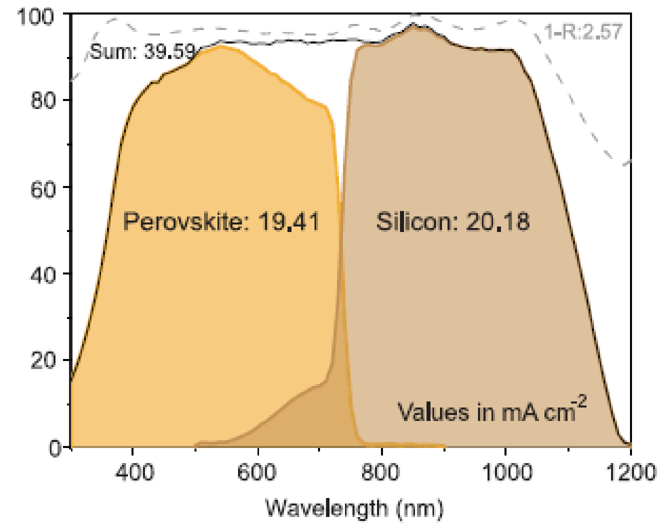
Monolithic Perovskite/Si Tandem Solar Cells

A



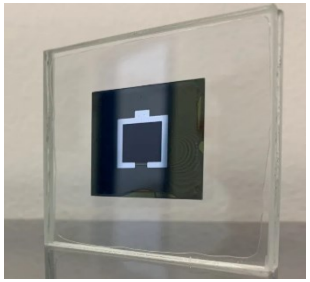


F



Monolithic perovskite/silicon tandem solar cell with >29% efficiency by enhanced hole extraction.

Jan 2020

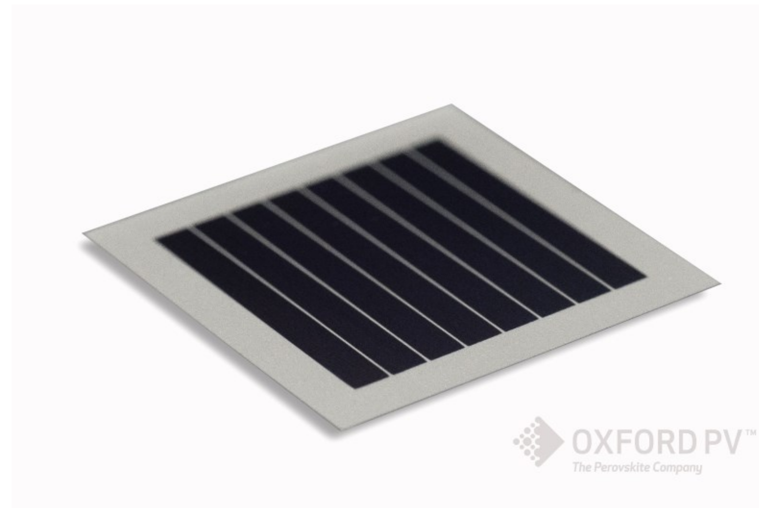


Source: Amran Al-Ashouri et al. Science (2020)

28% Record Perovskite/Si Tandem Solar Cell

Karlsruher Institut für Technologie

OXFORD PV™
The Perovskite Company



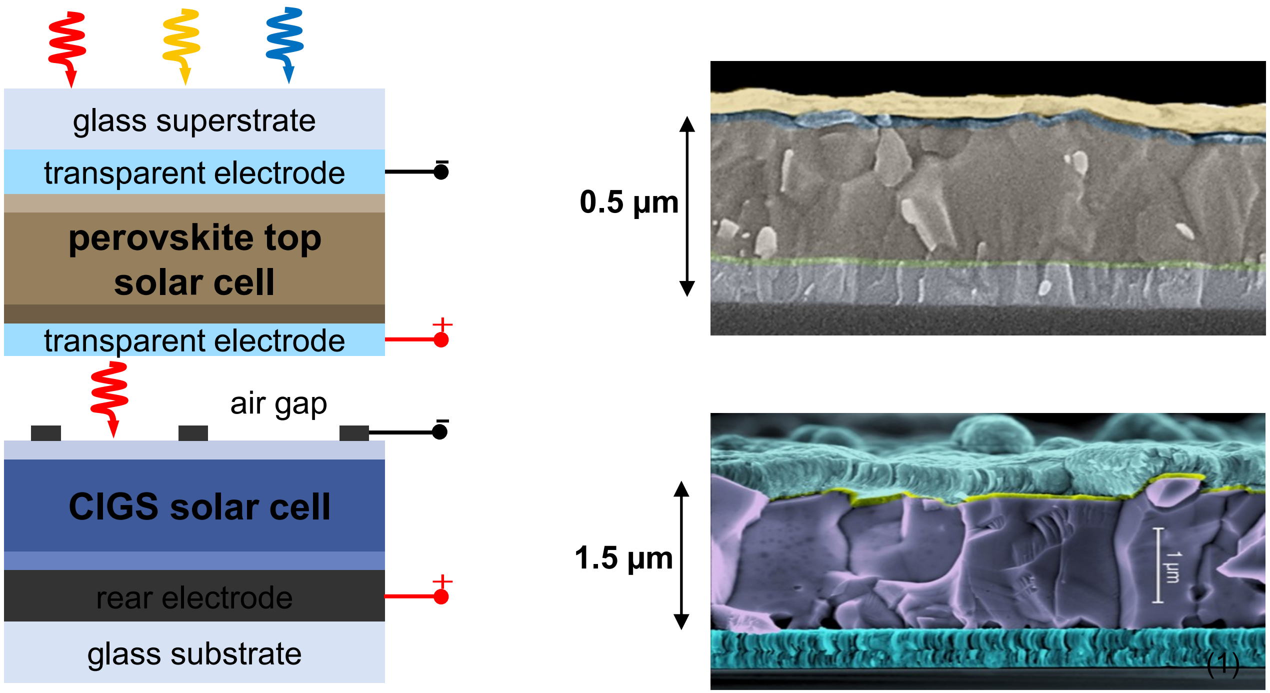
Oxford PV's 1 cm² perovskite-silicon tandem solar cell has achieved a 29.52% conversion efficiency, certified by the National Renewable Energy Laboratory.

Nov 2020

Source: https://www.oxfordpv.com/news/oxford-pv-perovskite-solar-cell-achieves-28-efficiency

All-Thin-Film Perovskite/CIGS Tandem PV

Combining two thin-film photovoltaic technologies.



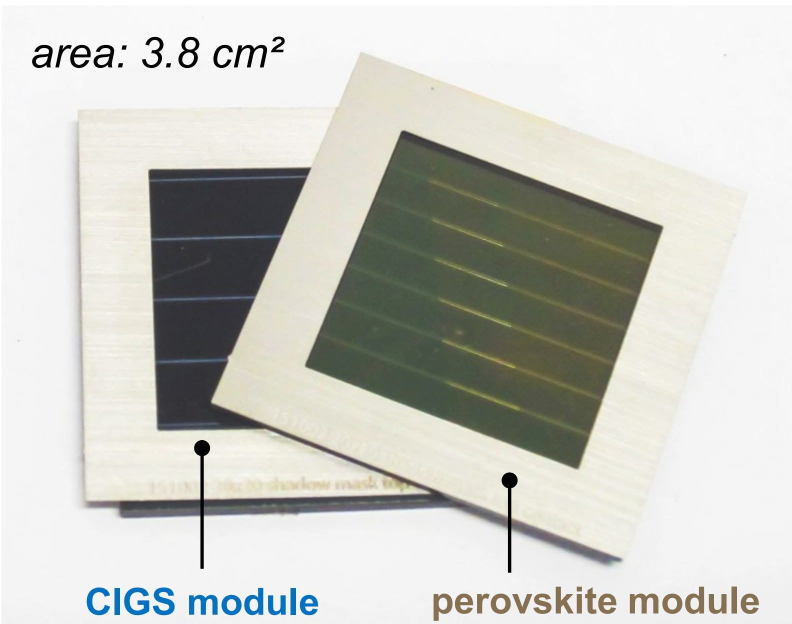
+ High efficiency **+** Flexible & light-weight **+** Sub- & superstrate

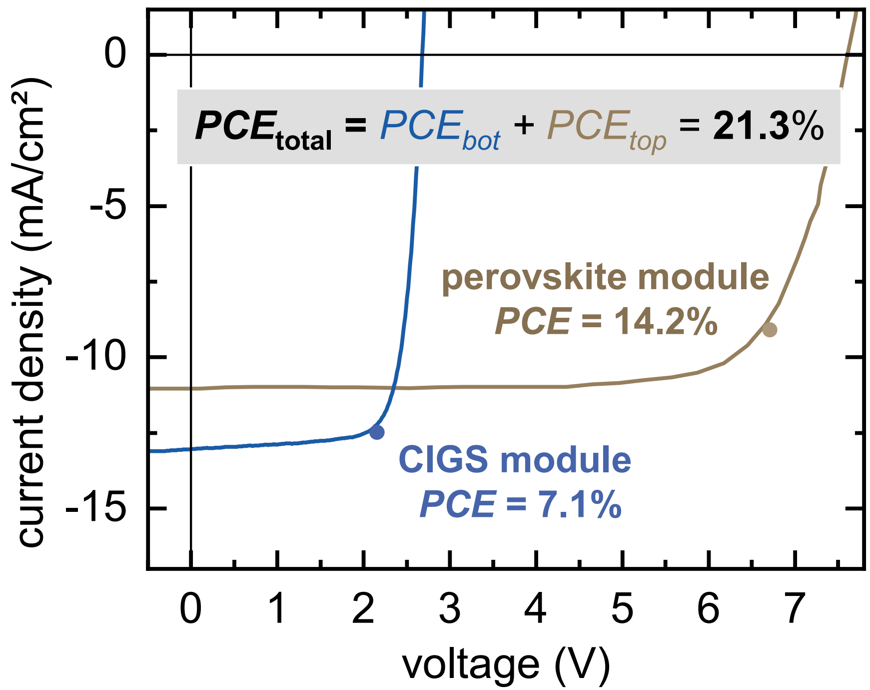
Source: ZSW Annual report 2018

Source: Paetzold/KIT

All-Thin-Film Perovskite/CIGS Tandem PV

Combining two thin-film photovoltaic technologies.





- Power conversion efficiency (*PCE*) of perovskite/CIGS solar module of up to 21.3% exceeds efficiency of the individual solar modules!

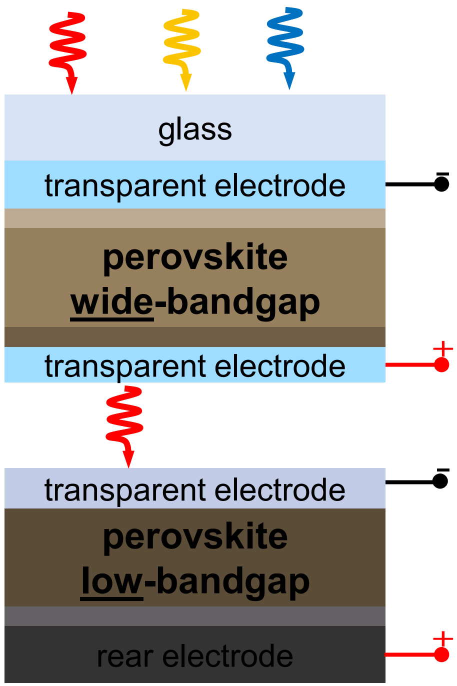
U. W. Paetzold et al., *Journal of Materials Chemistry* **A5** (20), 9897-9906 (2017).

M. Jaysankar et al., *Progress in Photovoltaics* **27** (8), 733-738 (2019).

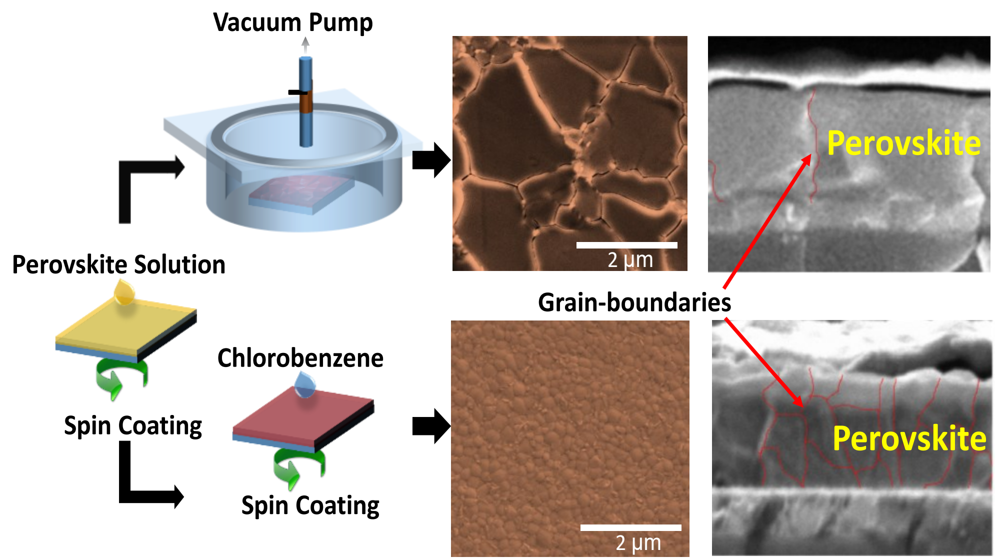
Source: Paetzold/KIT

All-Perovskite Tandem PV

Development of low-bandgap perovskite solar cells ($FA_{0.8}MA_{0.2}Sn_{0.5}Pb_{0.5}I_3$).



Low-bandgap perovskite thin-films



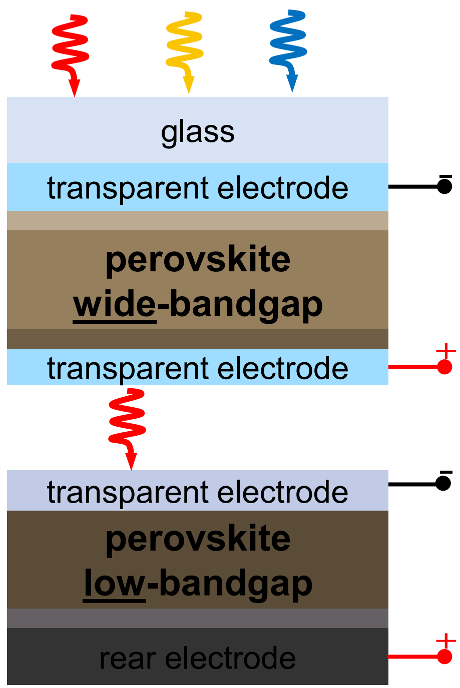
- Vacuum-assisted growth of perovskite thin-films yields large crystal grains.

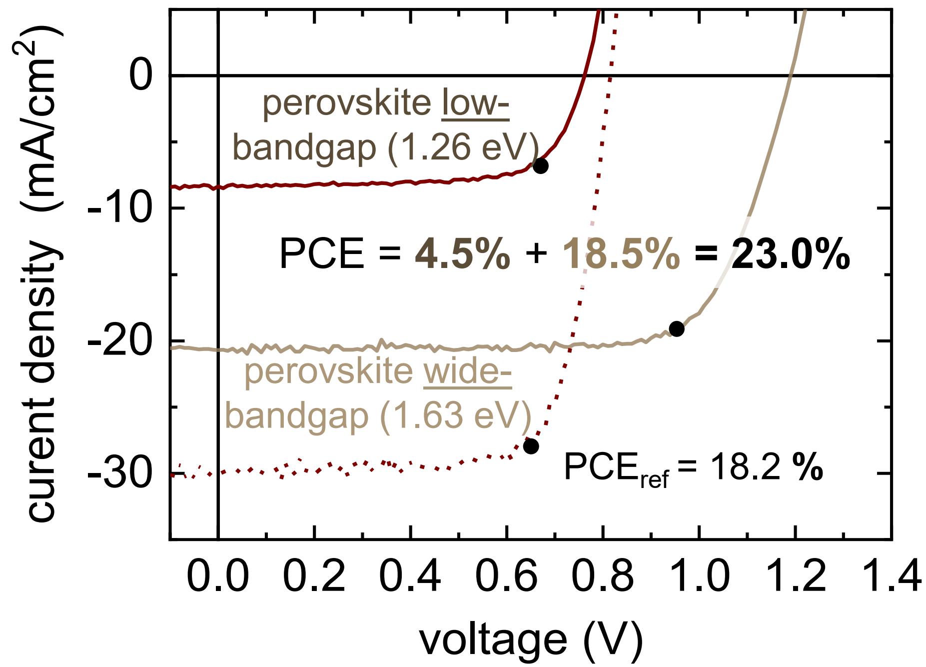
B. N. Abdollahi et al., *Advanced Energy Materials* – accepted (Nov 2019).

Source: Paetzold/KIT

All-Perovskite Tandem PV

Development of low-bandgap perovskite solar cells ($FA_{0.8}MA_{0.2}Sn_{0.5}Pb_{0.5}I_3$).





- Research still in its infancy, but very encouraging first results.
- Stability of low-bandgap perovskite semiconductors remains a key challenge.

B. N. Abdollahi et al., *Advanced Energy Materials* – accepted (Nov 2019).

Quick Test

- What are the fundamental losses are reduced in a tandem solar cell architecture? How?
- Explain the difference between a monolithic tandem solar cell and a multi-terminal tandem solar cell.
- What is the maximum efficiency for an infinite number of junctions? For two junctions? Compare to the SQ limit of a single junction solar cell.
- What is the optimal bandgap (range) for a wide bandgap top solar cell in combination with a low bandgap Si solar cell.
- Which solar cell needs to face the sun in a tandem solar cell: (i) the wide bandgap solar cell or (ii) the low bandgap solar cell? Why?
- What are the targeted applications for III/V-multijunction solar cells? Why?