Photovoltaics: An overview of current and future solar cell technologies

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The world is slowly moving towards a sustainable energy future

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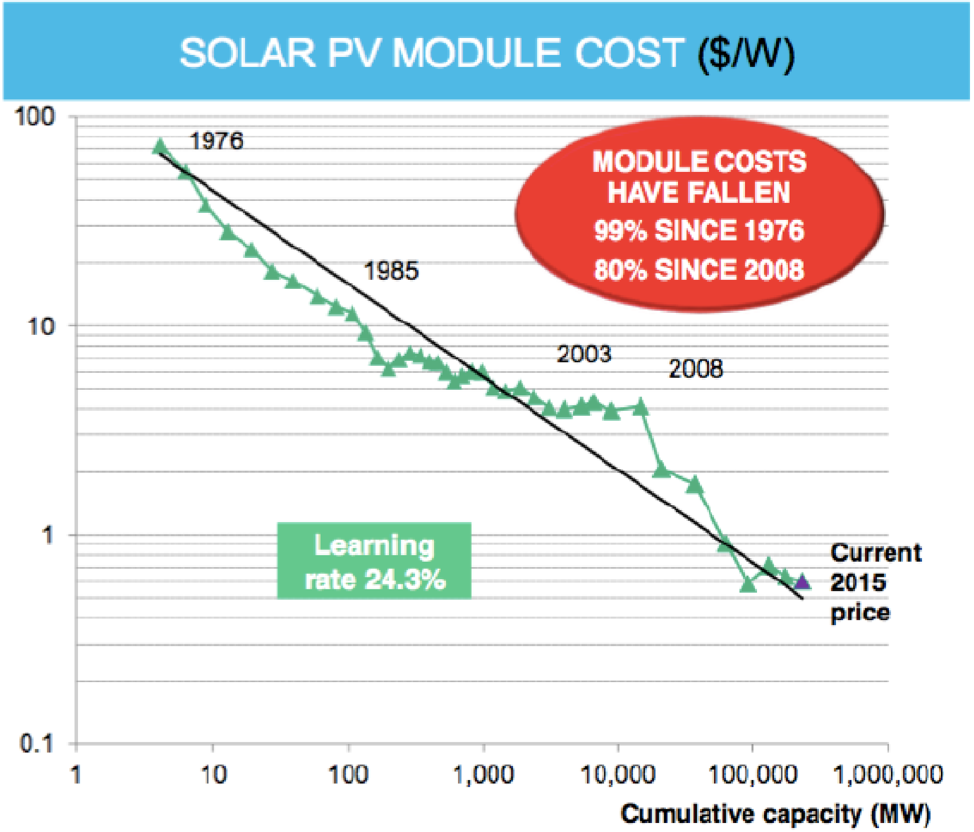
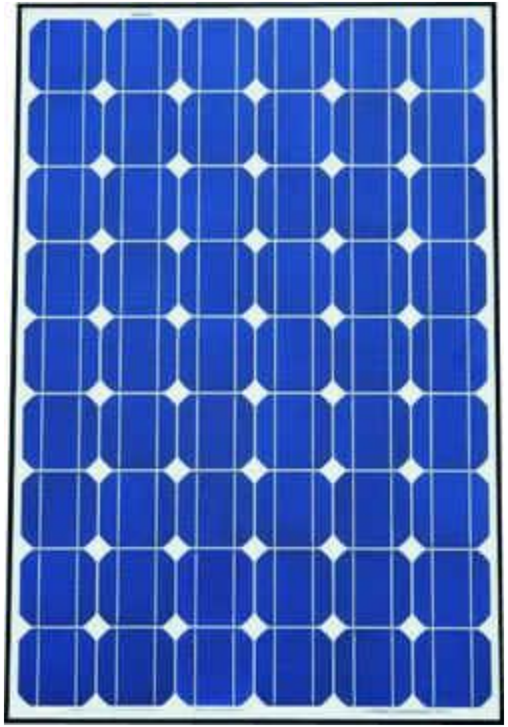
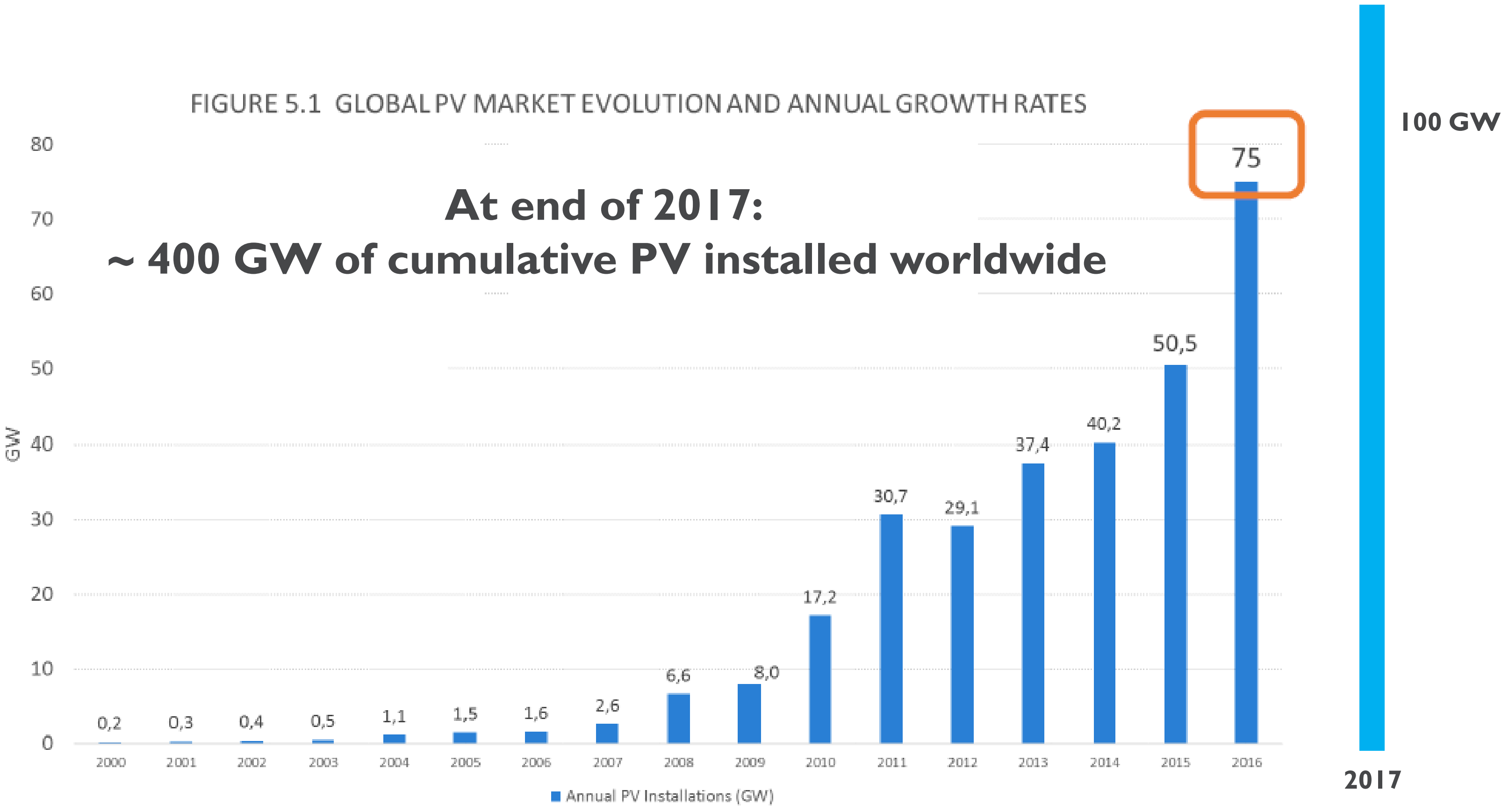
This transition is driven by large cost reductions of renewable energy





Note: Prices are in real (2015) USD. 'Current price' is $0.61/W Source: Bloomberg New Energy Finance, Maycock

In 2016 around 75 GW of photovoltaic modules were installed worldwide



PV Market Alliance 2017

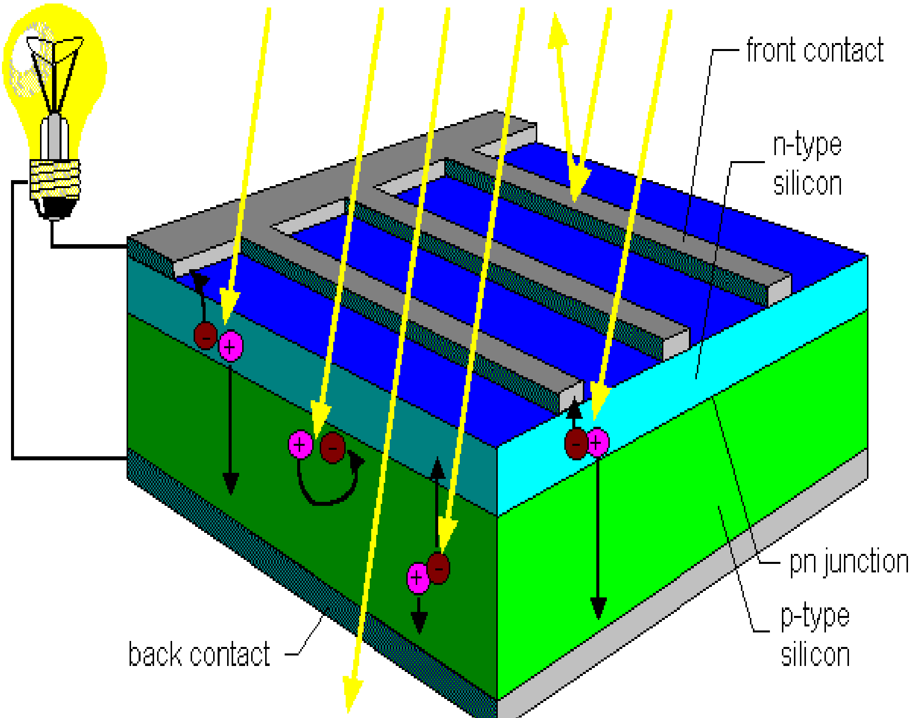
Research in PV is driven by the reduction of cost/kWh

$$\text{Levelized cost of electricity} = \frac{\text{Investment cost} + \text{Maintenance cost}}{\text{Years of operation} \times \text{Annual energy output}} + \text{Cost for energy storage (balancing)}$$

- Further reduction of the PV LCOE is possible via:
  - Reduction of cost (further scaling, standardization)
  - **Increasing performance**
  - **Increasing lifetime**
  - **Increasing energy yield**

Photovoltaic solar cells are semiconductor p-n diodes working under illumination

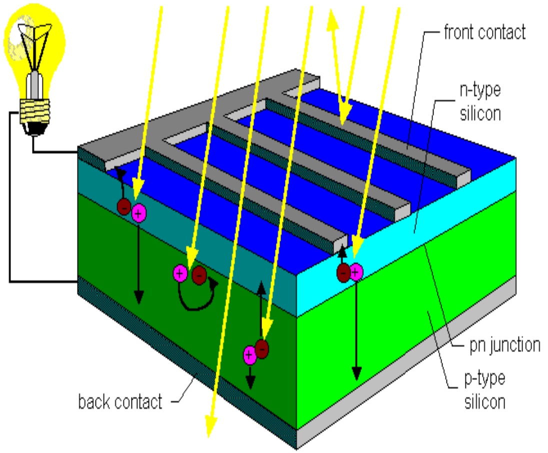
Energy conversion efficiency = P cell / P incoming light



Solar cell = Diode under illumination

Photovoltaic solar cells are semiconductor p-n diodes optimized to absorb as much light as possible and collect as much current as possible

- Absorption of light:
  - Absorption coefficient
  - Reflection, transmission
- Separation of excess carriers = make them move in a different direction
  - Junctions
  - Electrical field in depletion layer
  - Diffusion length (minority carrier lifetime, diffusion constant, mobility) or drift length (minority carrier lifetime, electrical field, mobility)
- Transport
  - Resistance of the base and emitter
  - Contact resistance



Solar cell = Diode under illumination

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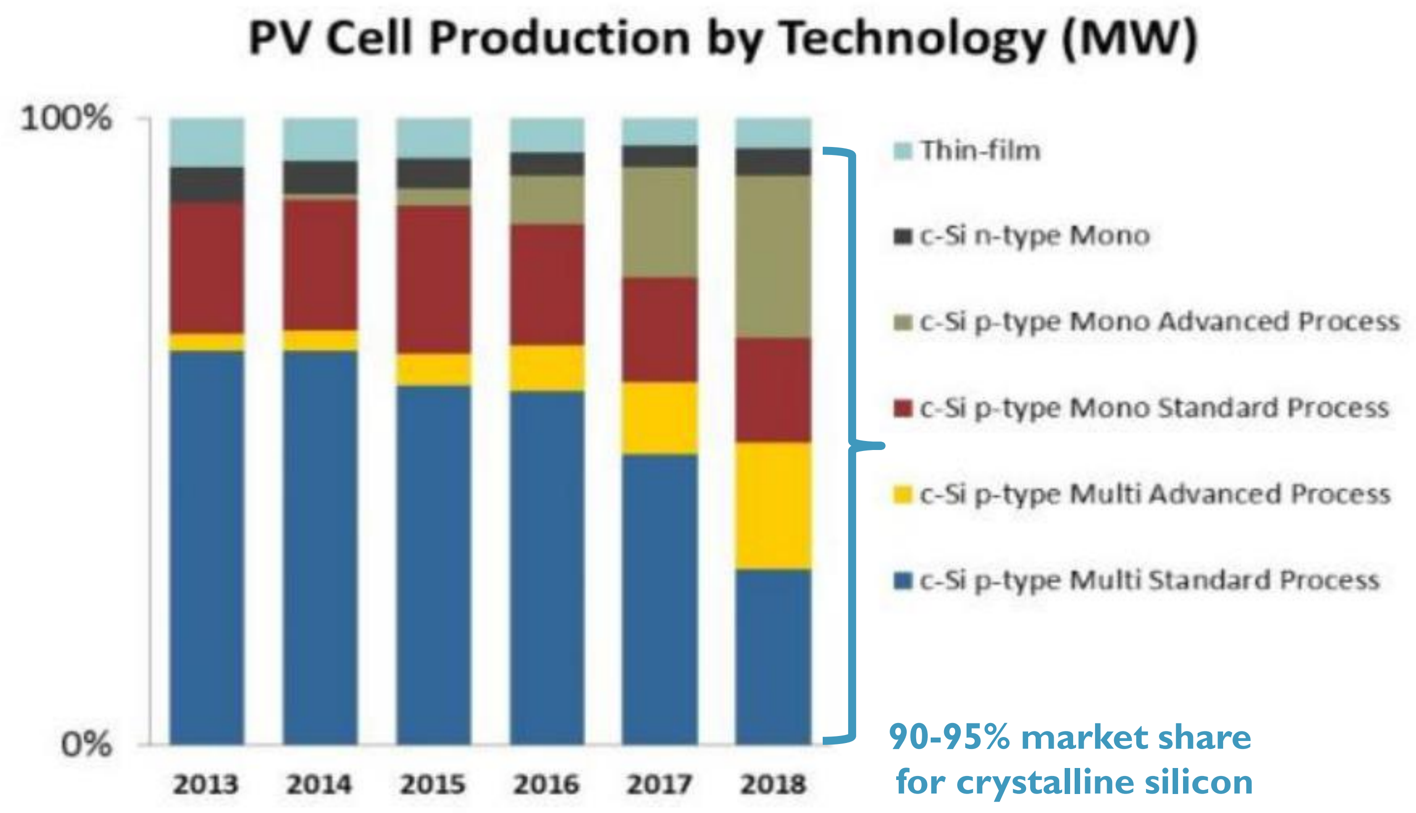
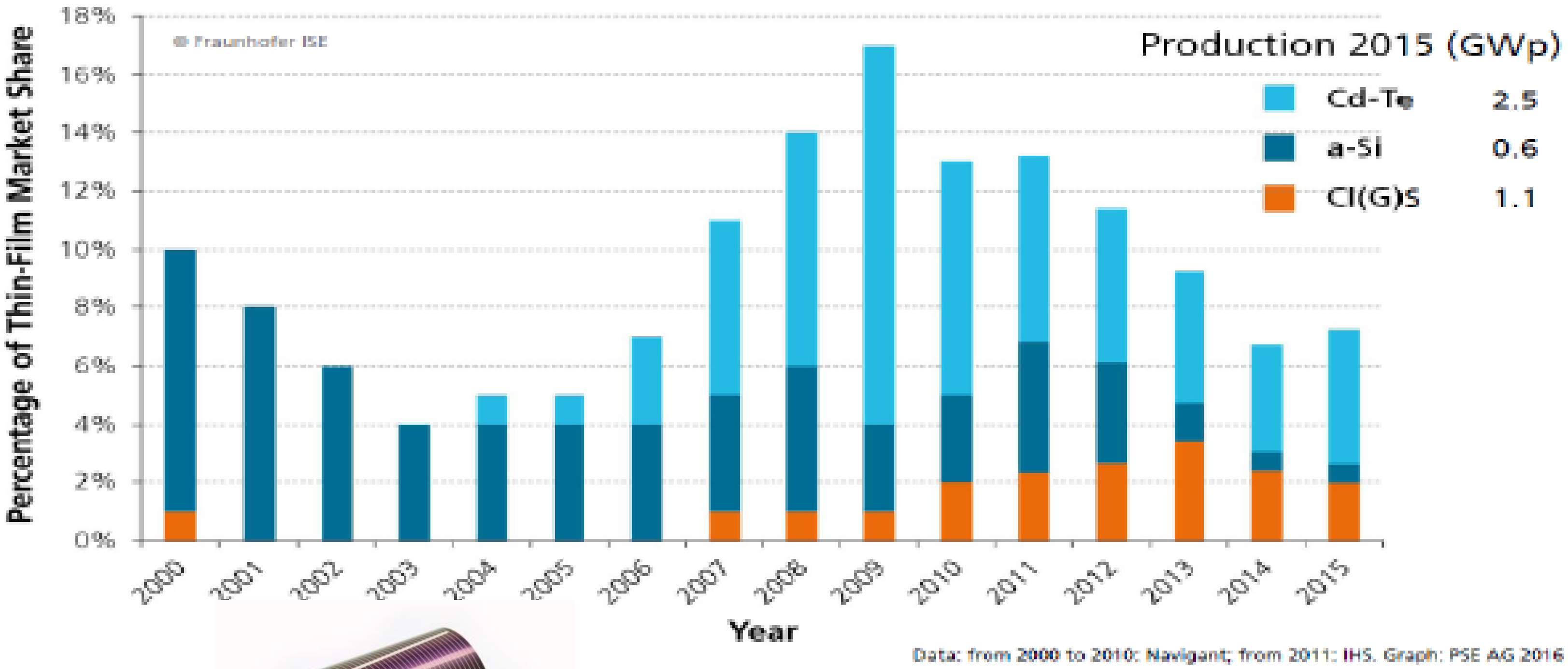
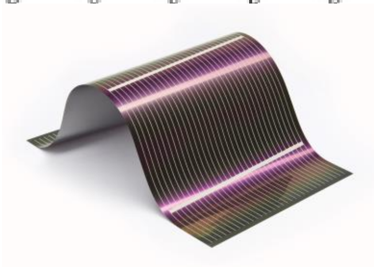
Crystalline-silicon technology is dominating the PV market



90-95% market share for crystalline silicon

The small share of thin-film PV is based on CdTe and CIGS technology

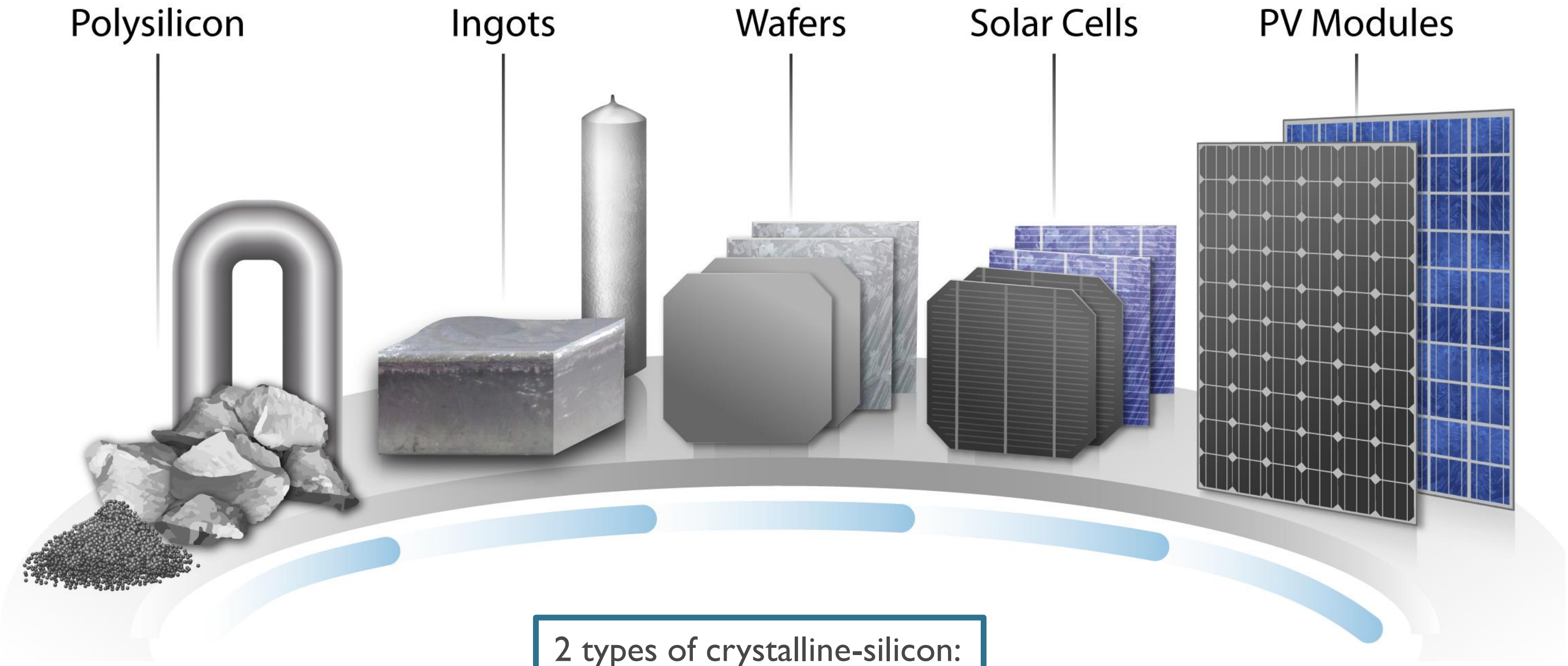




Outline

- Crystalline-Silicon Photovoltaics
- Inorganic Thin-Film Photovoltaics
- Perovskite Photovoltaics
- Tandem Photovoltaics

The value chain of crystalline silicon photovoltaics



2 types of crystalline-silicon:
- Monocrystalline
- Multicrystalline

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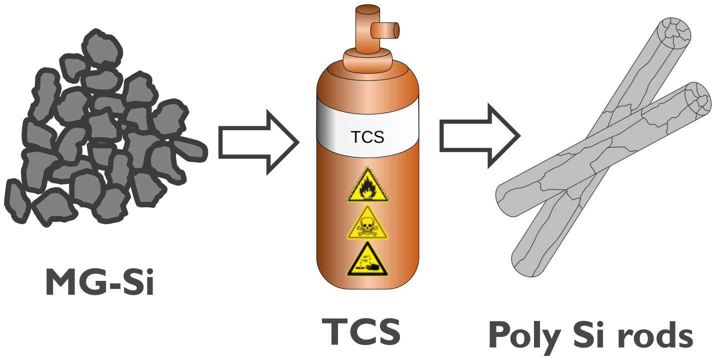
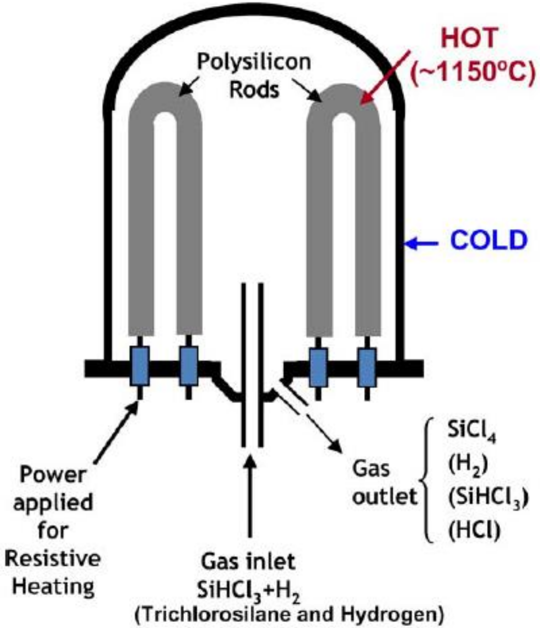
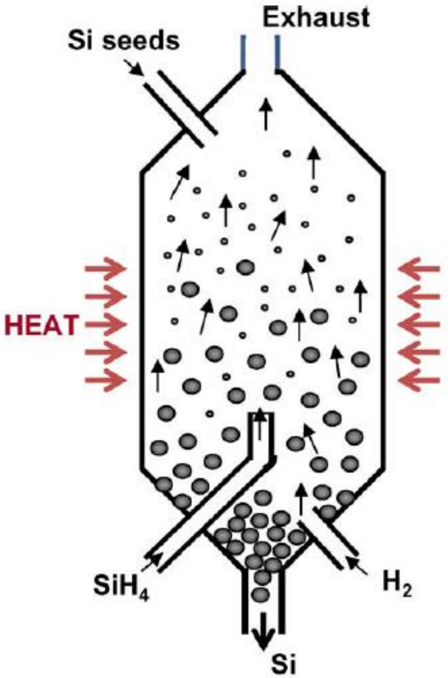
Crystalline-silicon wafer formation

From metallurgical grade silicon to electronic-grade polysilicon





Siemens Reactor



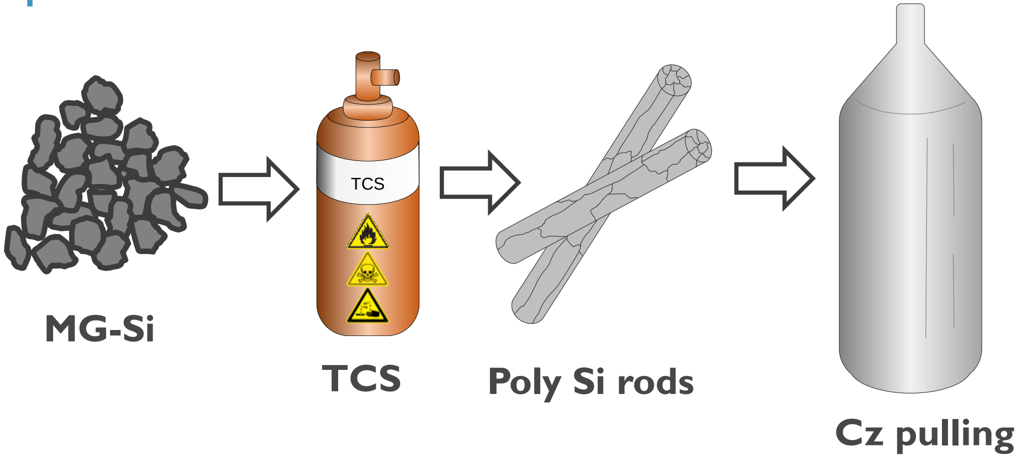
Fluidized Bed Reactor

90-120 kWh/kg of poly Si

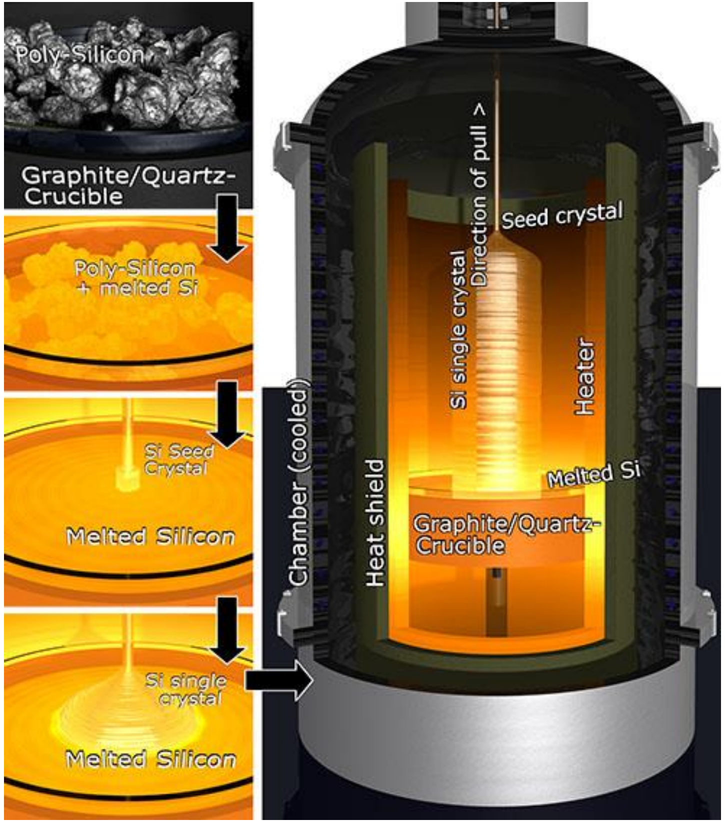
12-20 kWh/kg of poly Si

Fisher et al., Proceedings of the IEEE, pp. 1454-1474 (2012)

The polysilicon is molten in large furnaces and Czochralski ingots are pulled from the melt

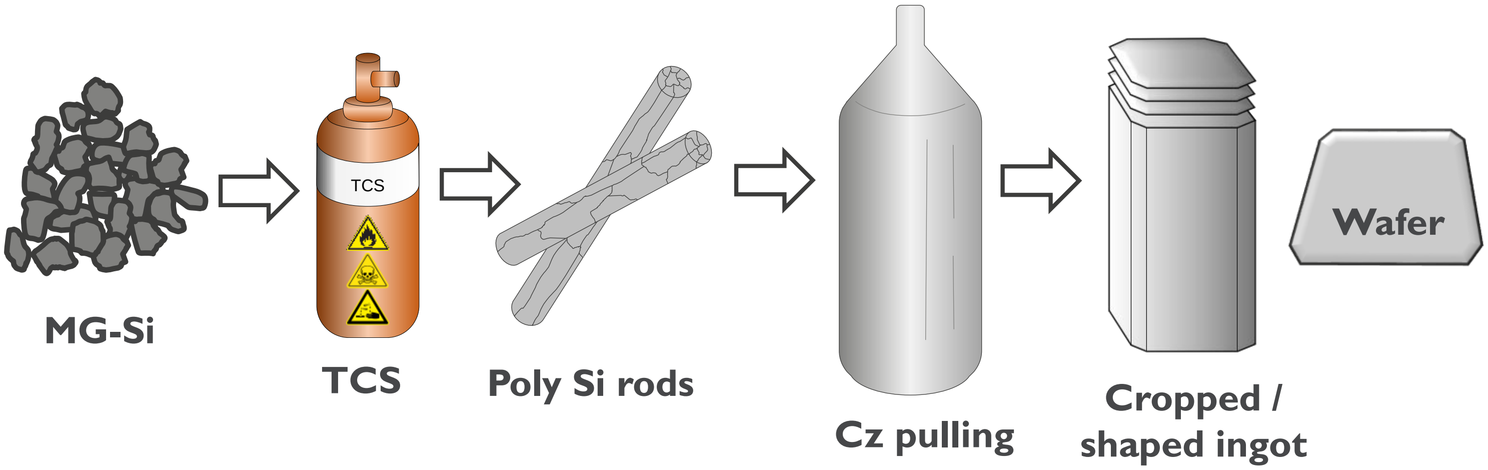


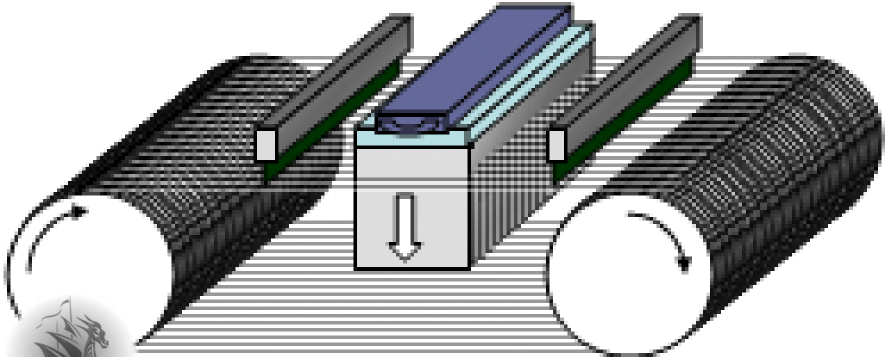
Silflex, Inc., www.silflex.com



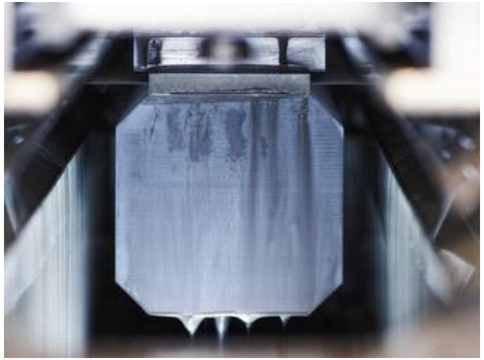
Microchemicals GmbH, www.microchemicals.com

Individual silicon wafers are formed by wire-sawing the ingots

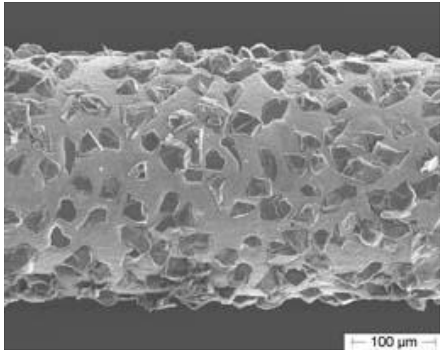




Wafer slicing process
Source: Osaka Fuji Corp., www.ofic.co.jp

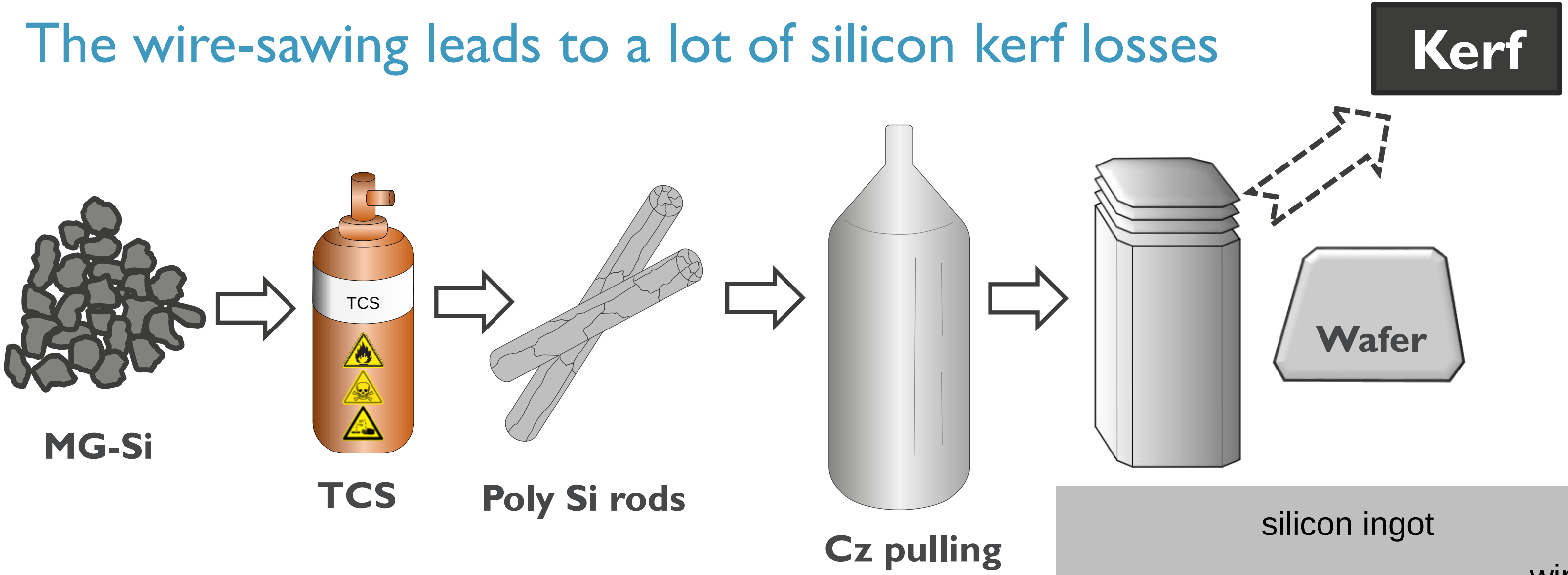


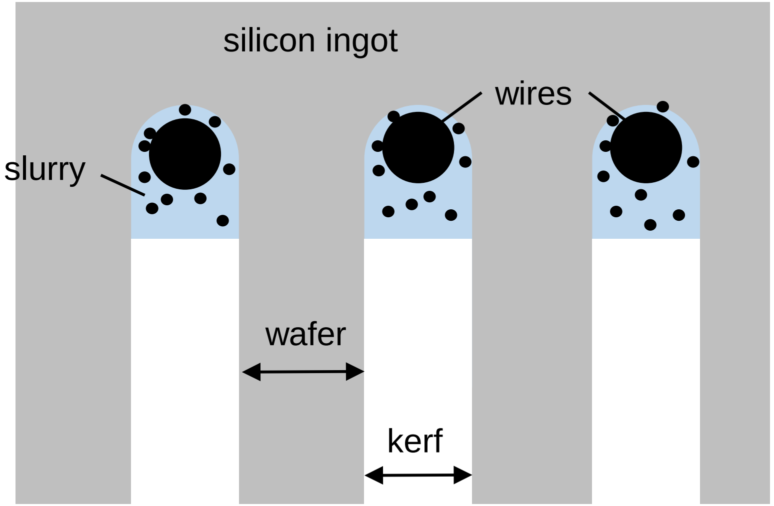
Meyer Burger's diamond saw system
Source: Cleantechnica.com



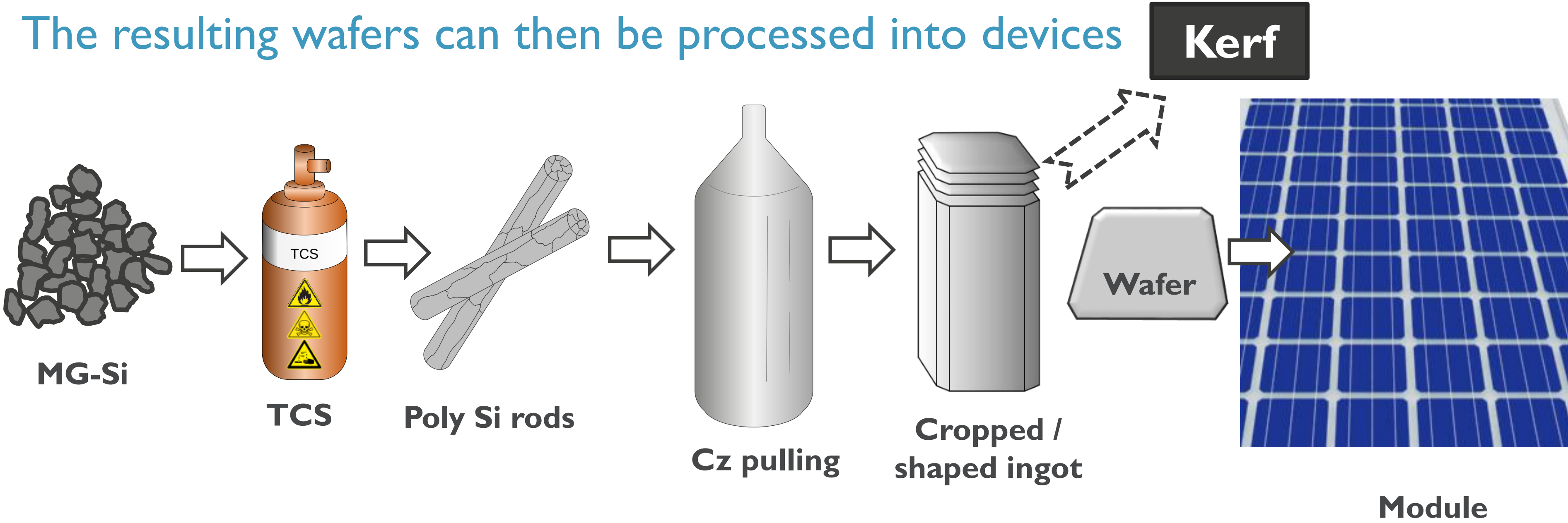
SEM of diamond-coated wire
Source: www.ceramicindustry.com

The wire-sawing leads to a lot of silicon kerf losses





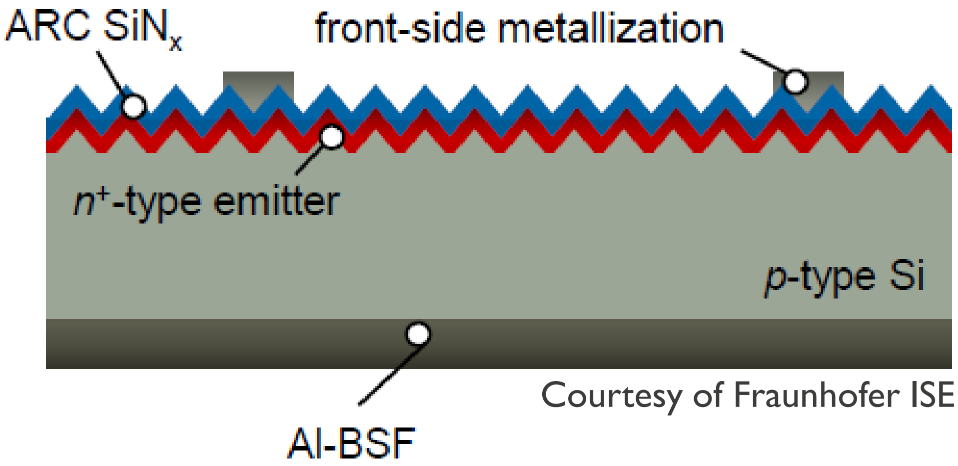
The resulting wafers can then be processed into devices



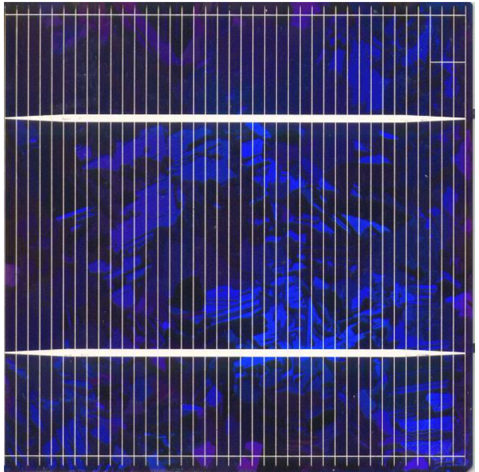
Conventional Si wafer production process involves many energy-intensive and expensive processes (Siemens process, Cz process, kerf loss during wafering,...)

Crystalline-silicon solar cell processing

The Al-Back Surface Field (Al-BSF) cell is the industrial standard today

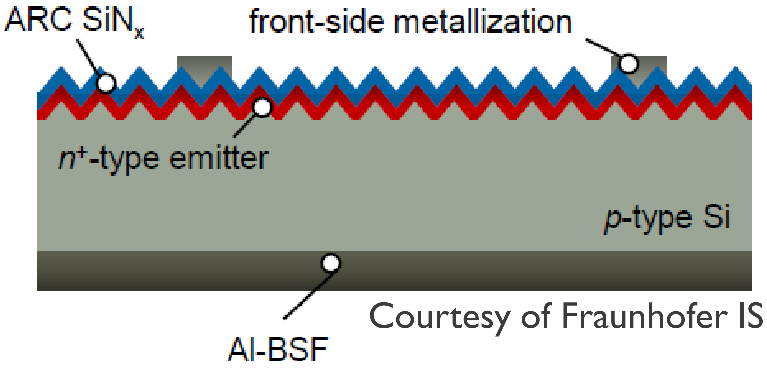


Courtesy of Fraunhofer ISE



- Individual wafer (mono or multi)
- Saw damage removal + texturing
- $POCl_3$ Diffusion
- Parasitic Junction Removal
- PECVD SiNx:H ARC layer
- Screen Printed Metallisation
- Co-firing

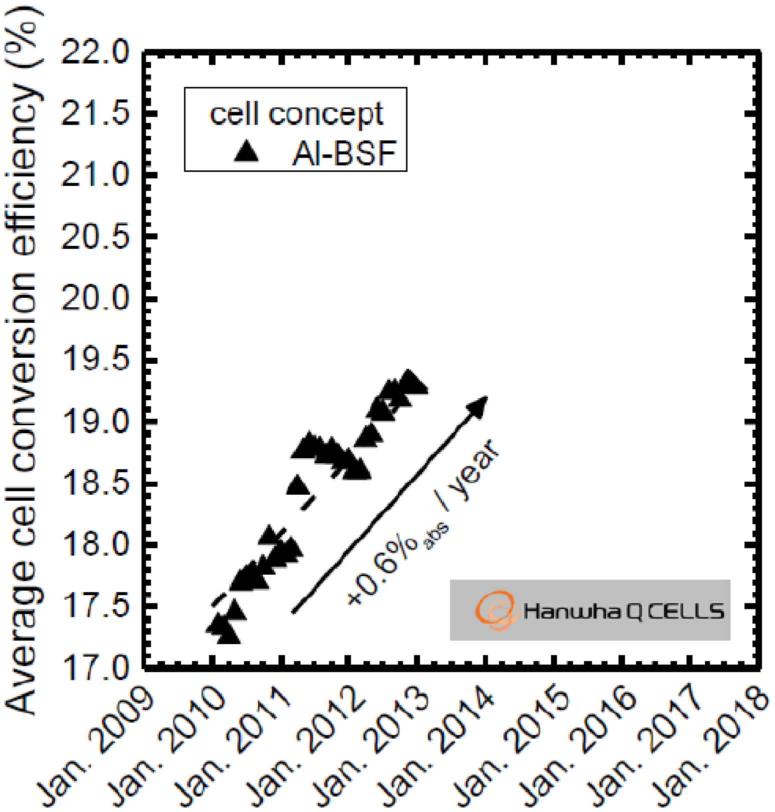
The efficiency of industrial Al-BSF solar cells has been improved substantially over the years



Courtesy of Fraunhofer ISE

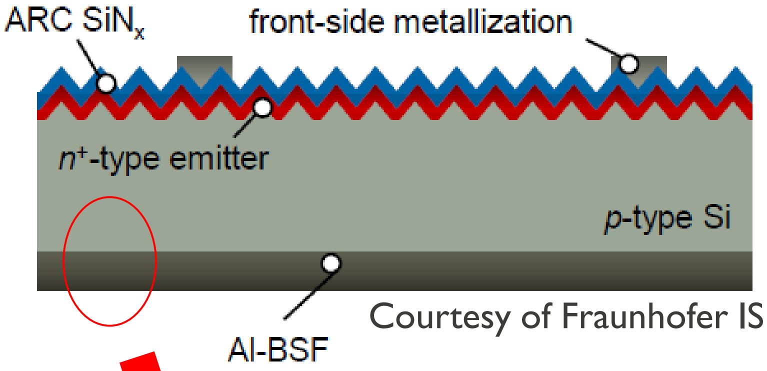
Average efficiency in production:

Multi ~ 16-18 %, Mono ~ 17-20 %



Fabian Fertig et al "***Mass Production of p-Type Cz Silicon Solar Cells …*** "
7th Silicon PV, Freiburg, Germany, April 3, 2017

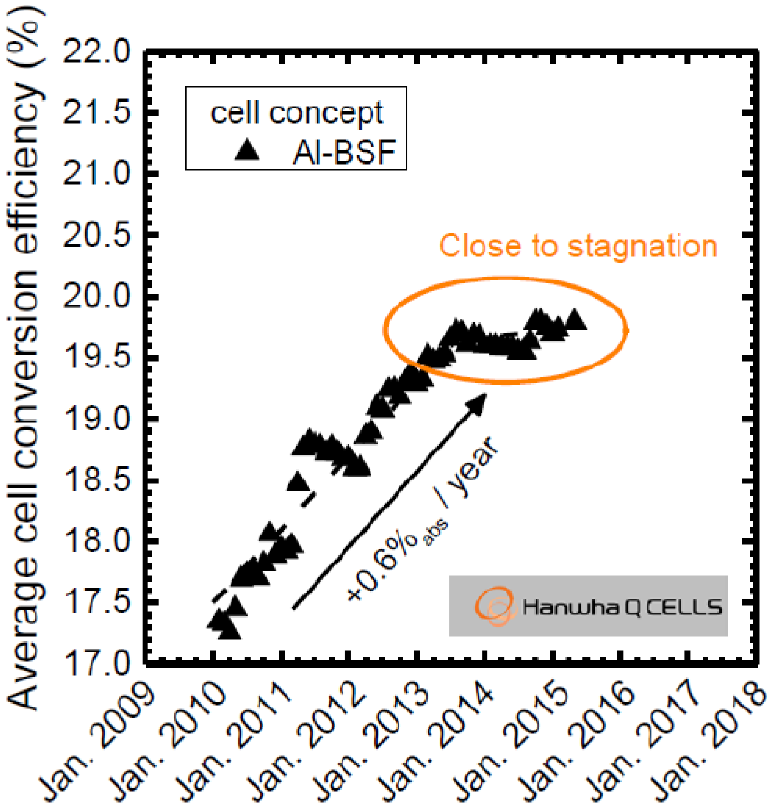
The efficiency of industrial Al-BSF solar cells is limited due to the full-area metallized rear side



Courtesy of Fraunhofer ISE

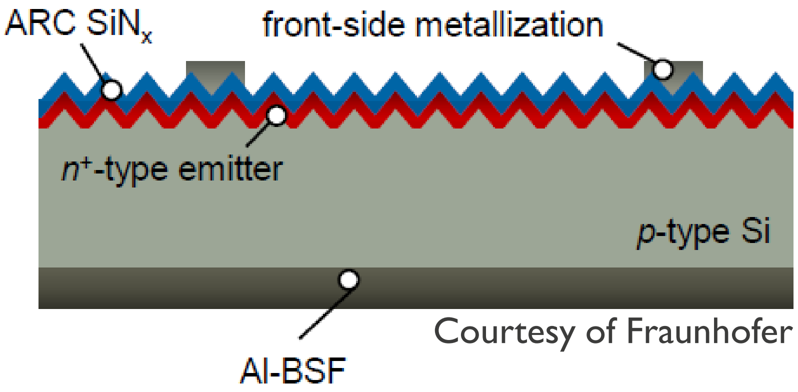
The whole rear silicon surface is in direct contact with Aluminium

This leads to high recombination losses at the rear of the device



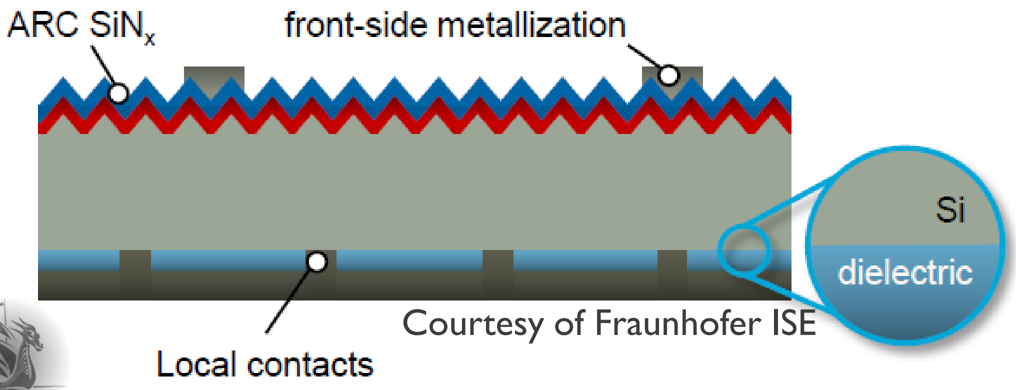
Fabian Fertig et al "***Mass Production of p-Type Cz Silicon Solar Cells …*** "
7th Silicon PV, Freiburg, Germany, April 3, 2017

The PV industry is currently making the switch from Al-BSF to PERC-like solar cells



Courtesy of Fraunhofer ISE

“Standard cell”
Al-BSF



Courtesy of Fraunhofer ISE

“PERC cell”
Passivated rear contact

Two extra steps:

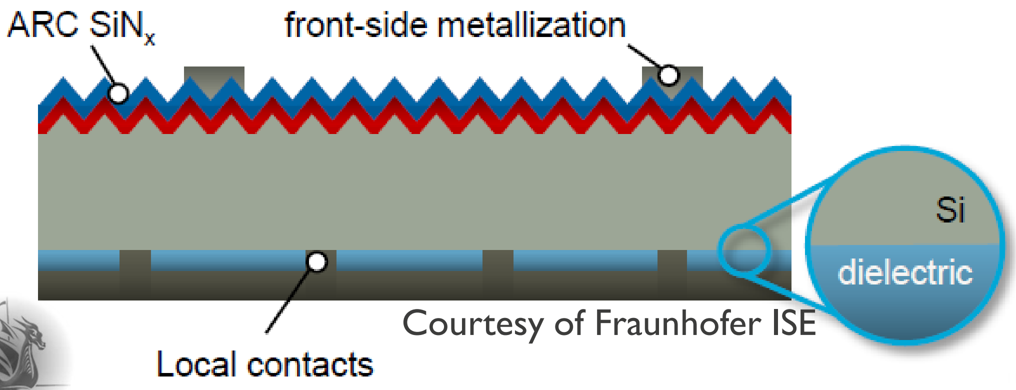
- Dielectric passivation on rear
- Local contact opening on rear

The switch to PERC cells allows the industry to continue to increase the cell efficiency year by year

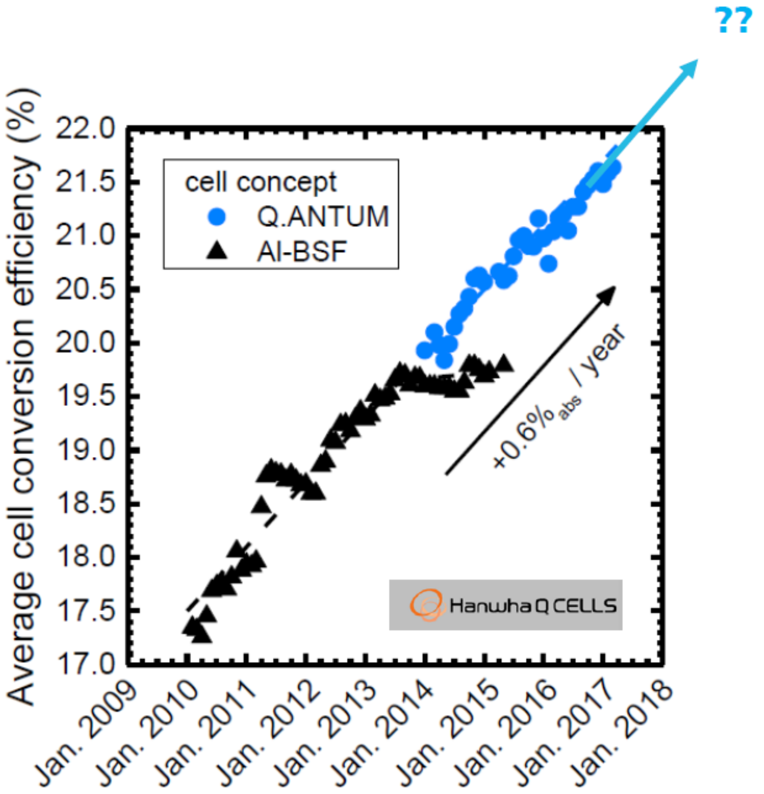
Q.ANTUM = PERC cell of Hanwha Q Cells

Still 0.6 %abs /year increase

How far can we go like this?

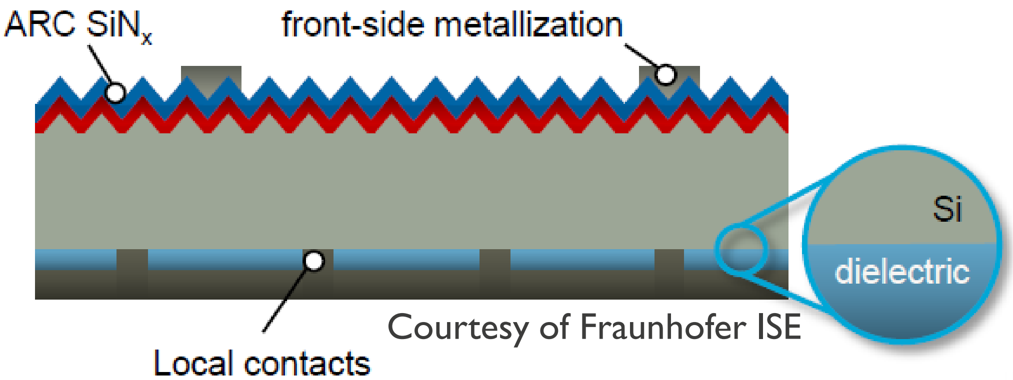


Courtesy of Fraunhofer ISE

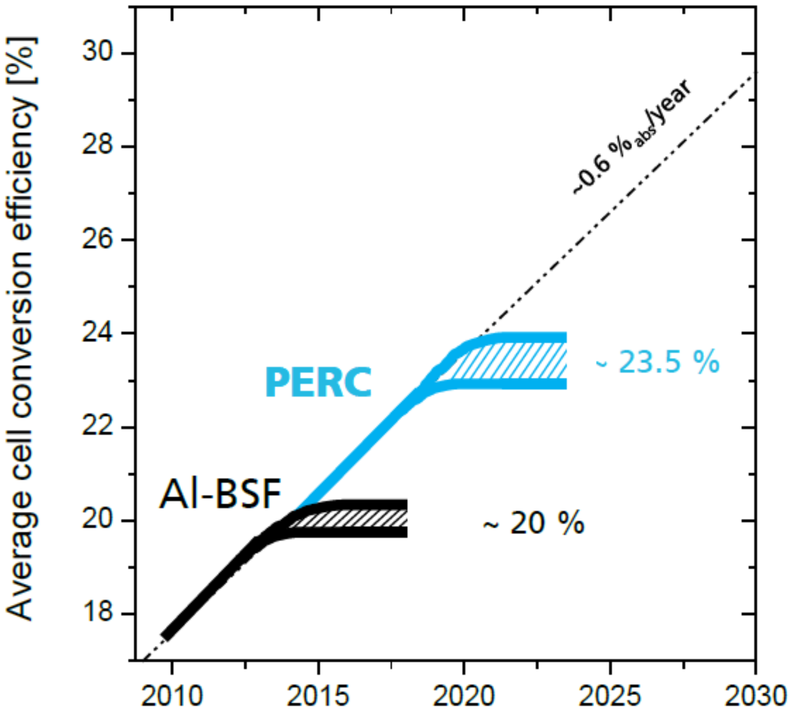


Fabian Fertig et al "*Mass Production of p-Type Cz Silicon Solar Cells …* "
7th Silicon PV, Freiburg, Germany, April 3, 2017

The efficiency of PERC cells is limited by contact recombination



Courtesy of Fraunhofer ISE



Further improvements possible by using passivating contacts, using to n-type silicon wafers and going to back-contact solar cells.

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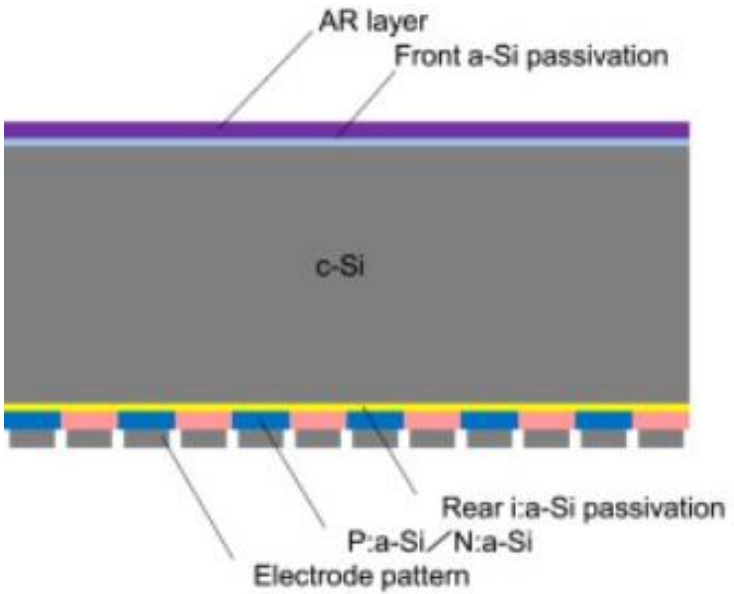
The world record silicon solar cell efficiency was obtained with a heterojunction back-contact device



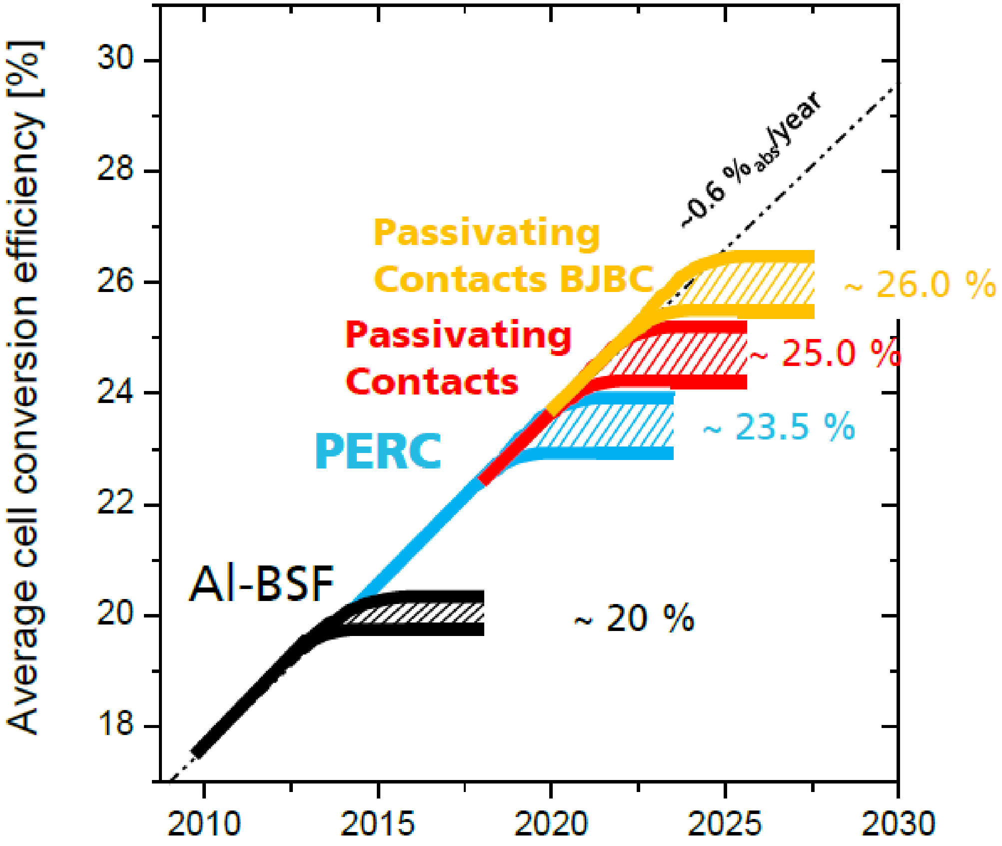
Courtesy of Kaneka

- n-type crystalline silicon absorber
- emitter and BSF regions at rear made by a-Si:H
- all contacts at rear side
- less shadowing losses on front
- more complicated processing required

World record efficiency obtained with this cell structure for crystalline silicon:

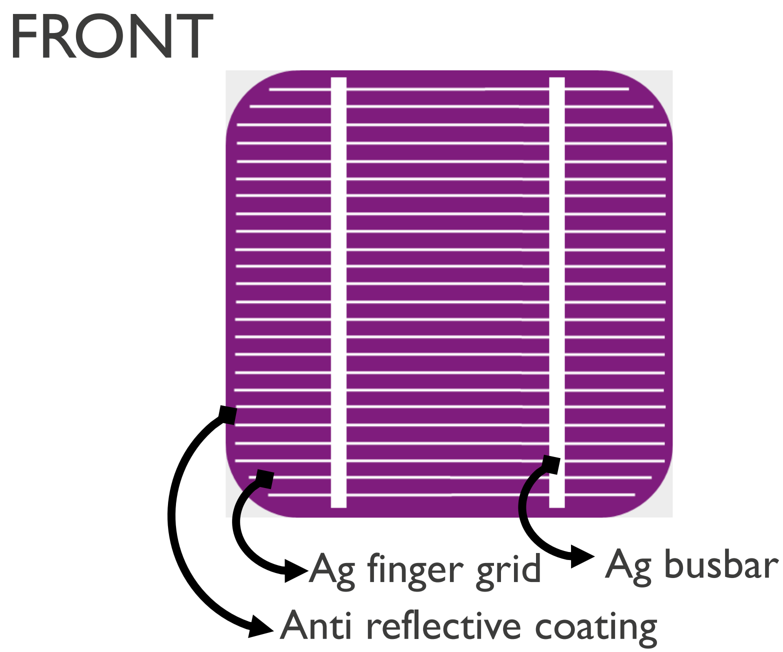
Best cell	**J_{sc} [mA/cm²]**	**V_{oc} [mV]**	**FF [%]**	**Eta [%]**
Kaneka – 180 cm²	42.5	740	84.7	26.6

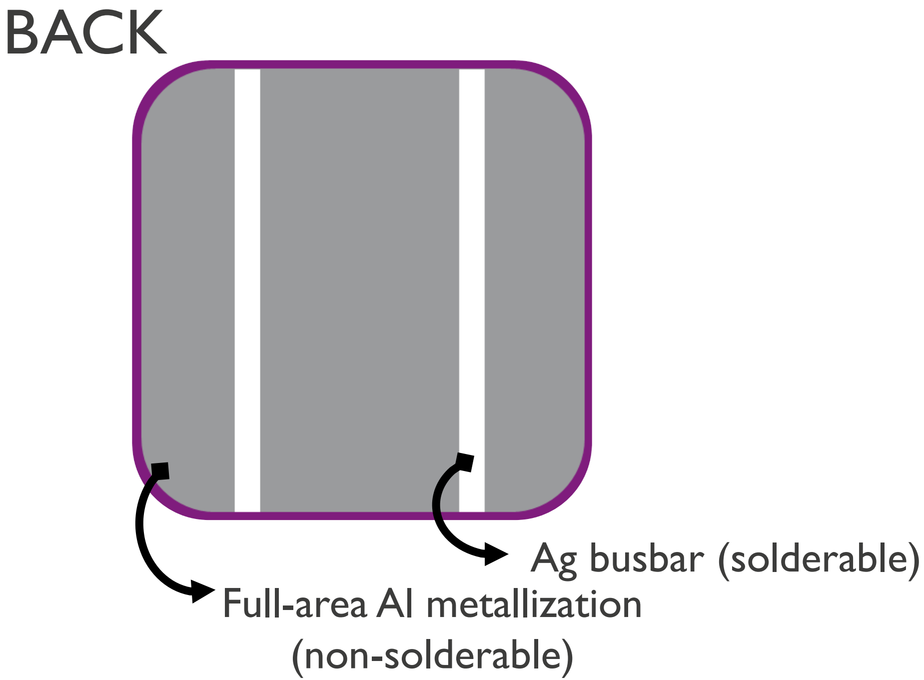
A crystalline silicon solar cell structure roadmap



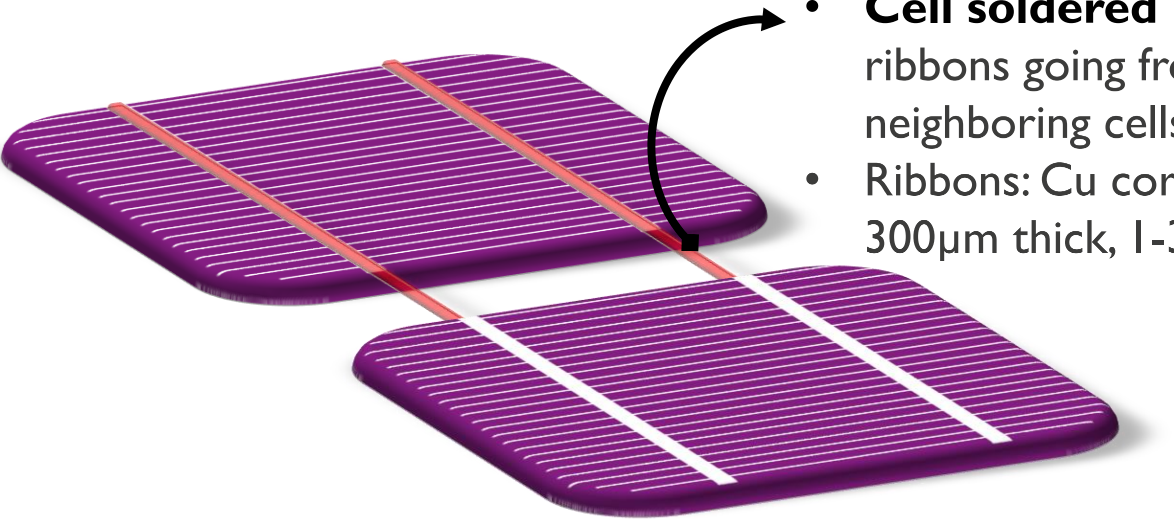
Crystalline-silicon module processing

Standard cells for standard modules



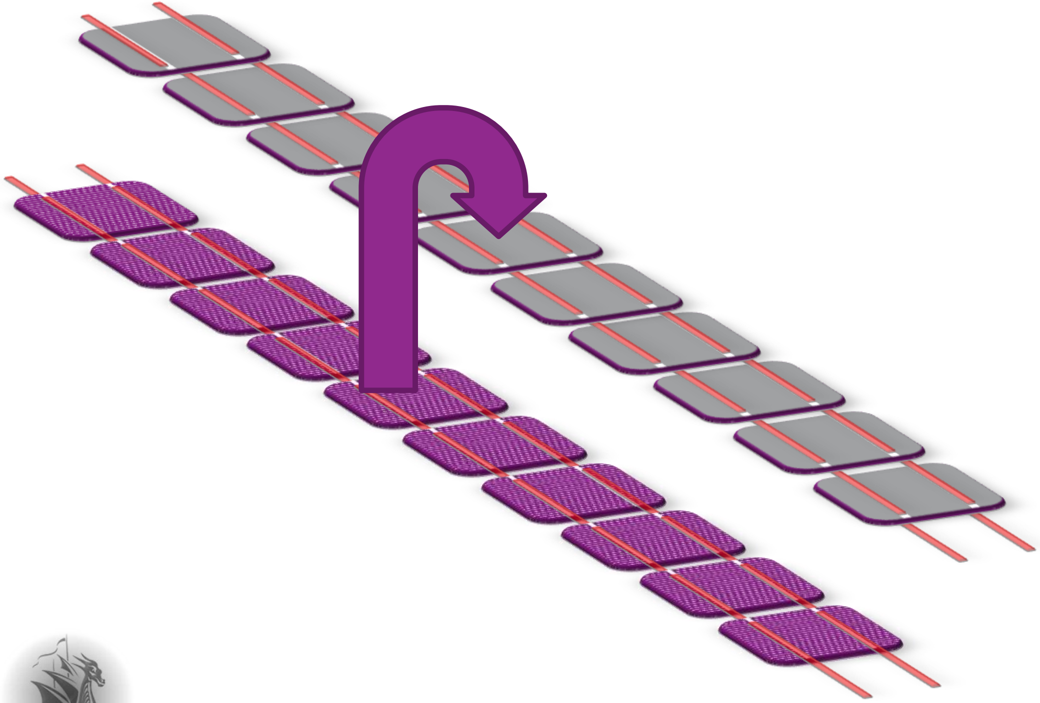


Cell interconnection

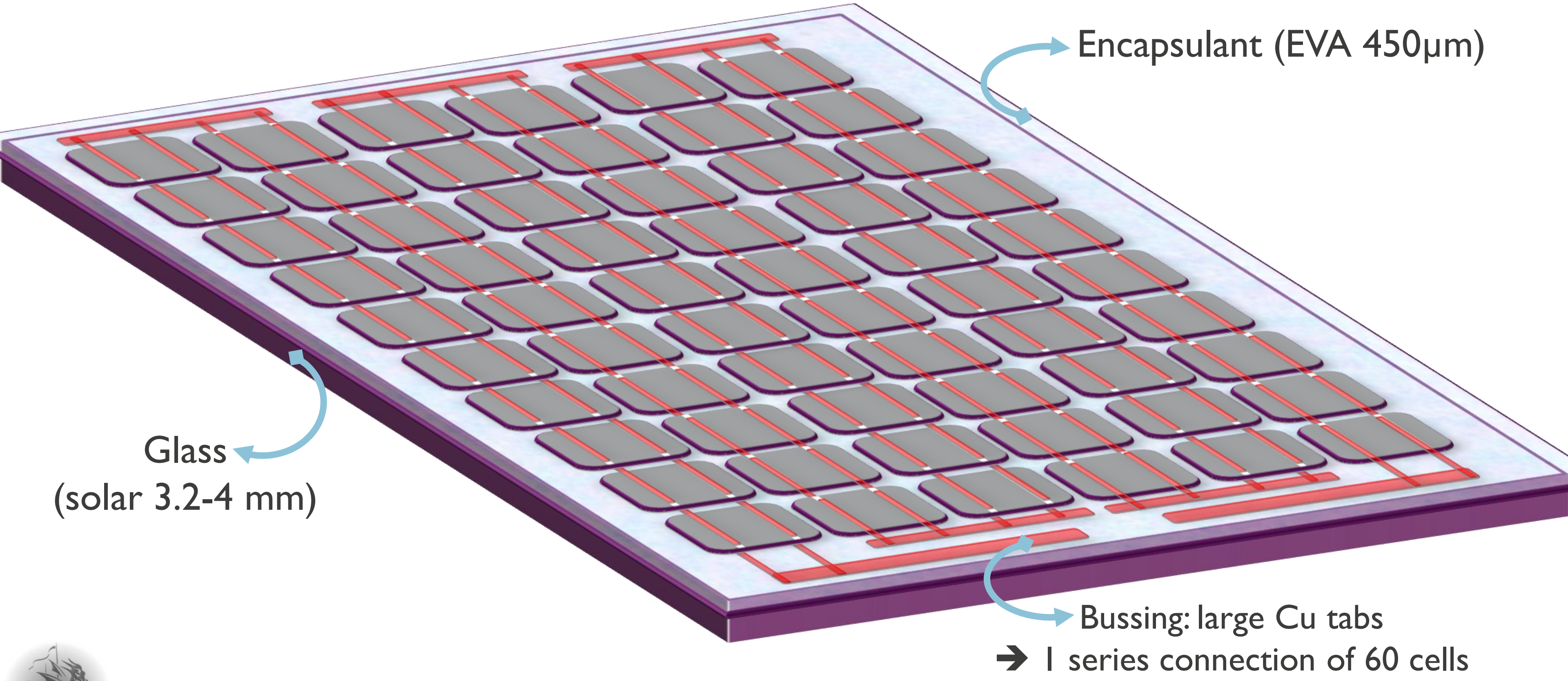


- **Cell soldered in series connection** using ribbons going from the front to back of neighboring cells
- Ribbons: Cu core with Sn Pb(Ag) coating with 100-300μm thick, 1-3mm wide

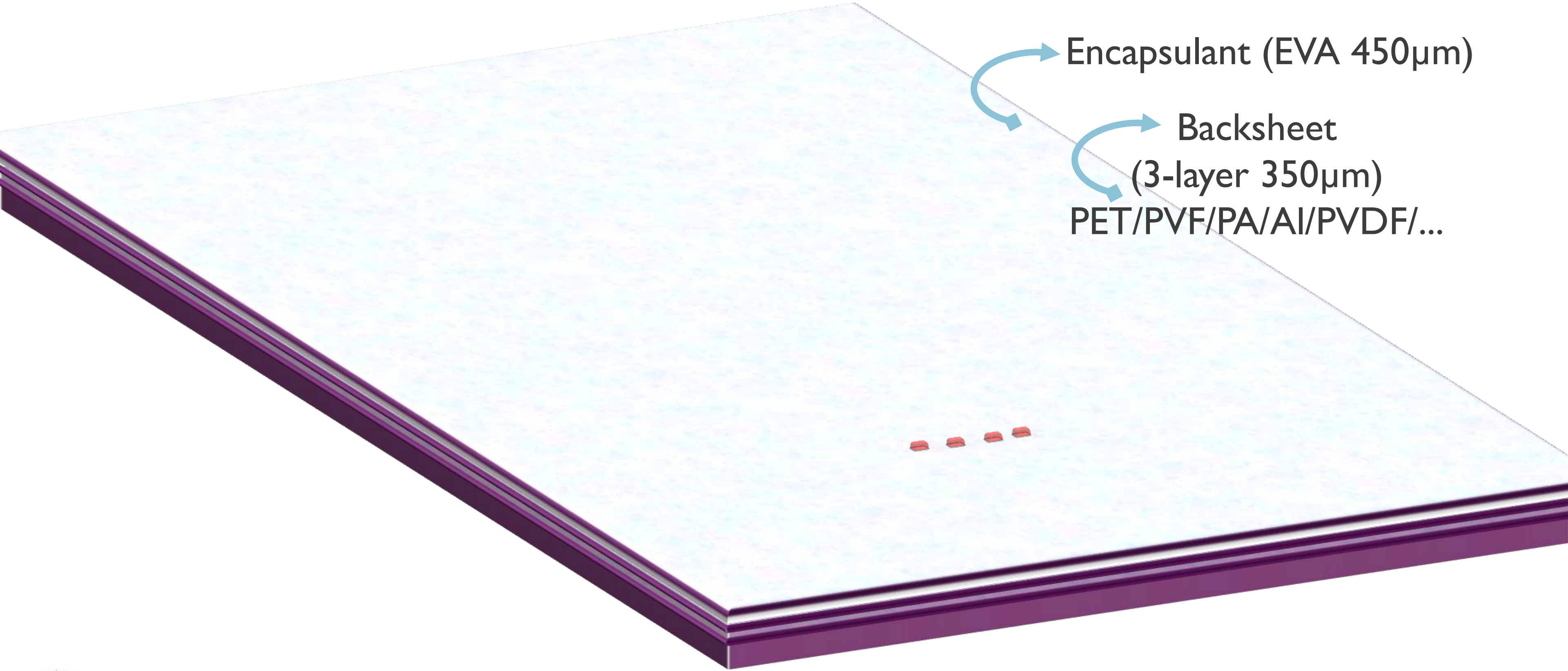
Soldering (tabbing) into strings (stringing)



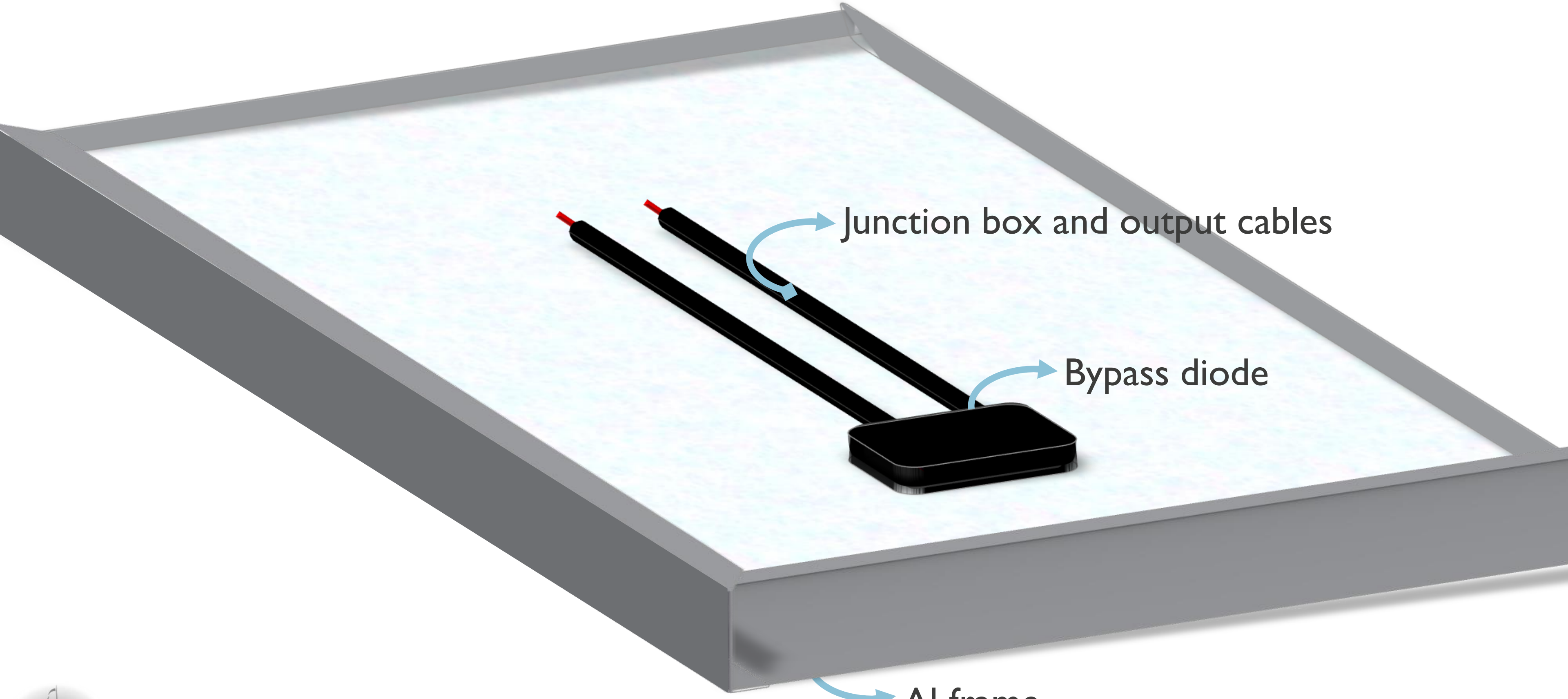
Layup of strings and bussing



Layup for lamination

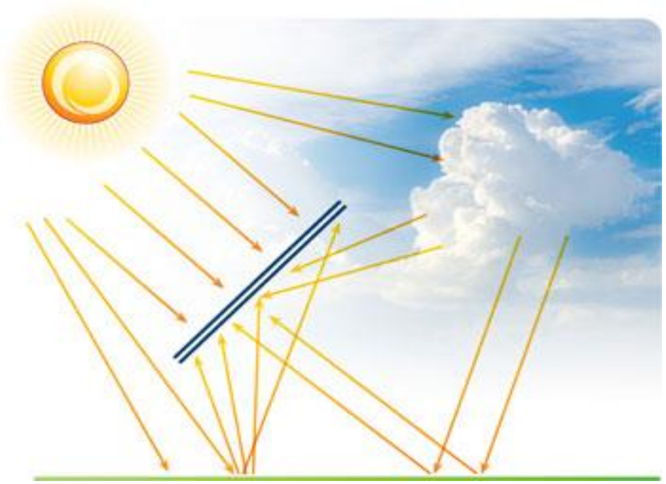


Framing and junction box connection



Main ways to further improve energy conversion efficiencies and reduce LCOE of crystalline-silicon modules

- Modifying the cell structure for higher cell efficiencies
  - PERC cells
  - Cells with passivated contacts
  - IBC cells
  - …
- Reducing material cost
  - Thinner wafers
  - Less use of Silver
  - Reduction of module material cost
  - …
- Increasing energy yield
  - Bifacial cells (albedo effect)
  - …



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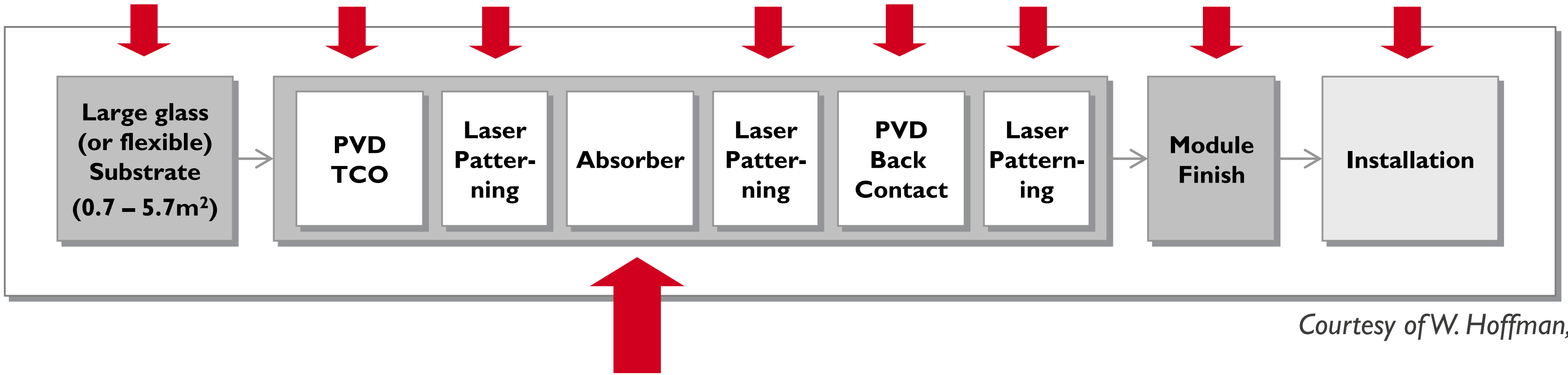
Outline

- Crystalline-Silicon Photovoltaics
- Inorganic Thin-Film Photovoltaics
- Perovskite Photovoltaics
- Tandem Photovoltaics

The value chain of inorganic thin-film photovoltaics

Same/similar process steps with same/similar cost / m²



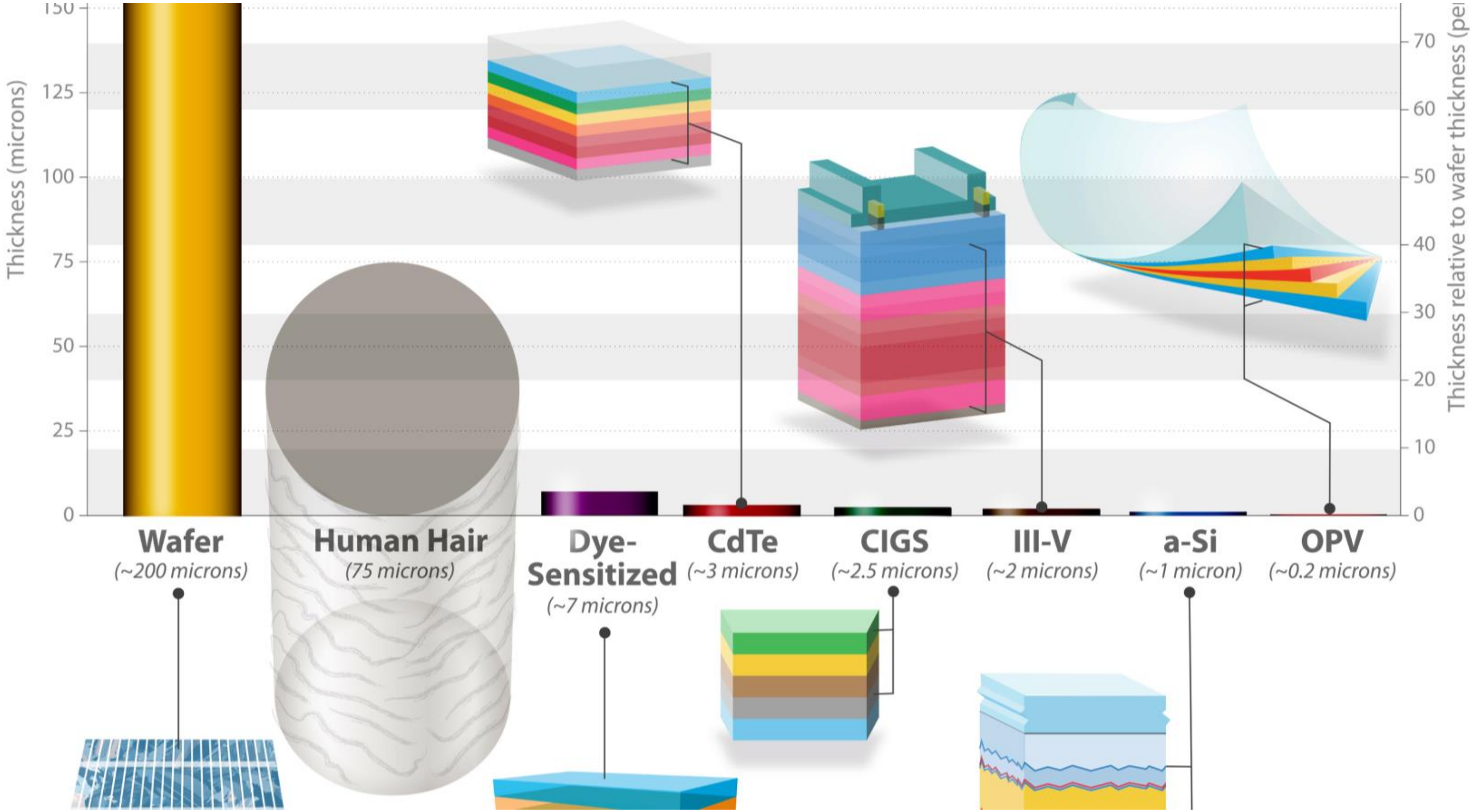
Courtesy of W. Hoffman, ASE

Main absorber types in production:

- (Thin-film Silicon)
- CdTe
- CIGS (CuInGaSe)

Different processes and material cost for absorber formation

Thin-film photovoltaics typically uses very thin absorber layers and can be made flexible and light-weight



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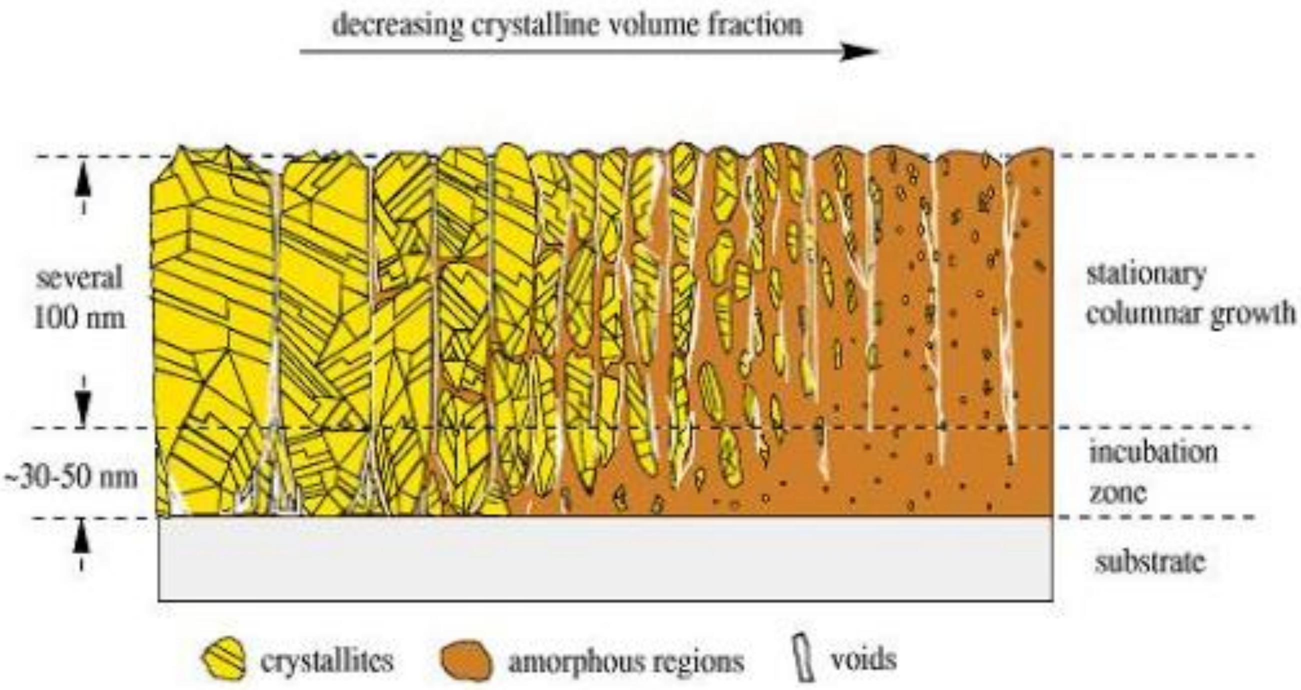
State-of-the-art thin-film silicon solar cells

Based on amorphous silicon (1.6-1.8 eV) and microcrystalline silicon (1.1 eV) grown by PECVD



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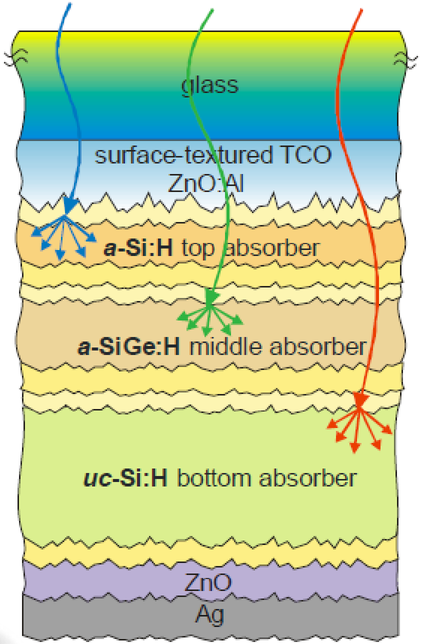
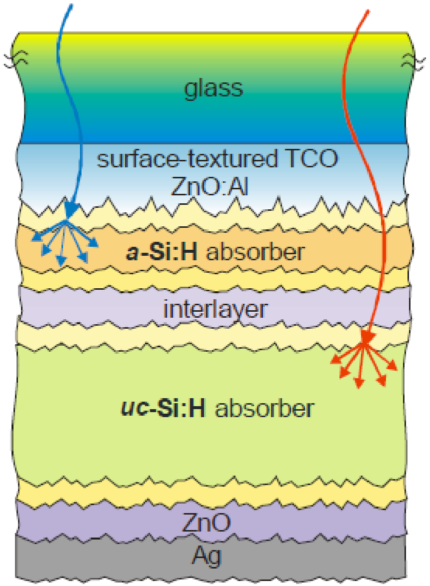
State-of-the-art thin-film silicon solar cells

triple-junction
e.g. a-Si:H/a-SiGe:H/
uc-Si:H



14.0% (AIST)

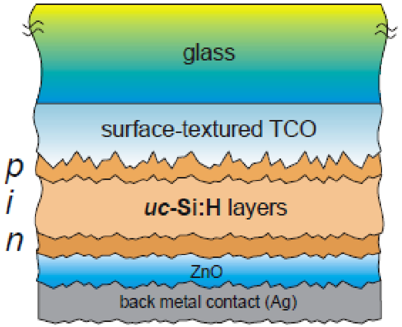
double-junction
micromorph
a-Si:H/uc-Si:H



12.7% (AIST)

Efficiency of TF-Si cells too limited
+ Staebler-Wronski effect:
a-Si degrades under light soaking

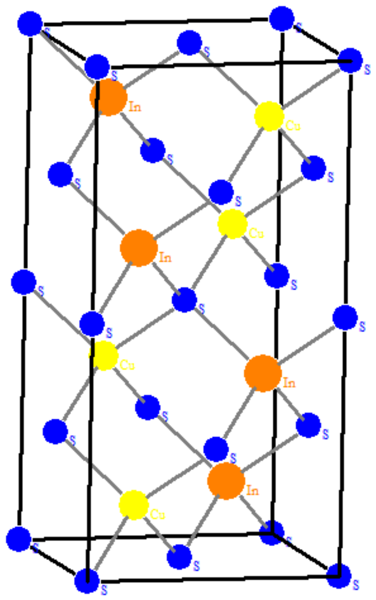
single-junction
amorphous (a-Si:H)
microcrystalline (uc-Si:H)



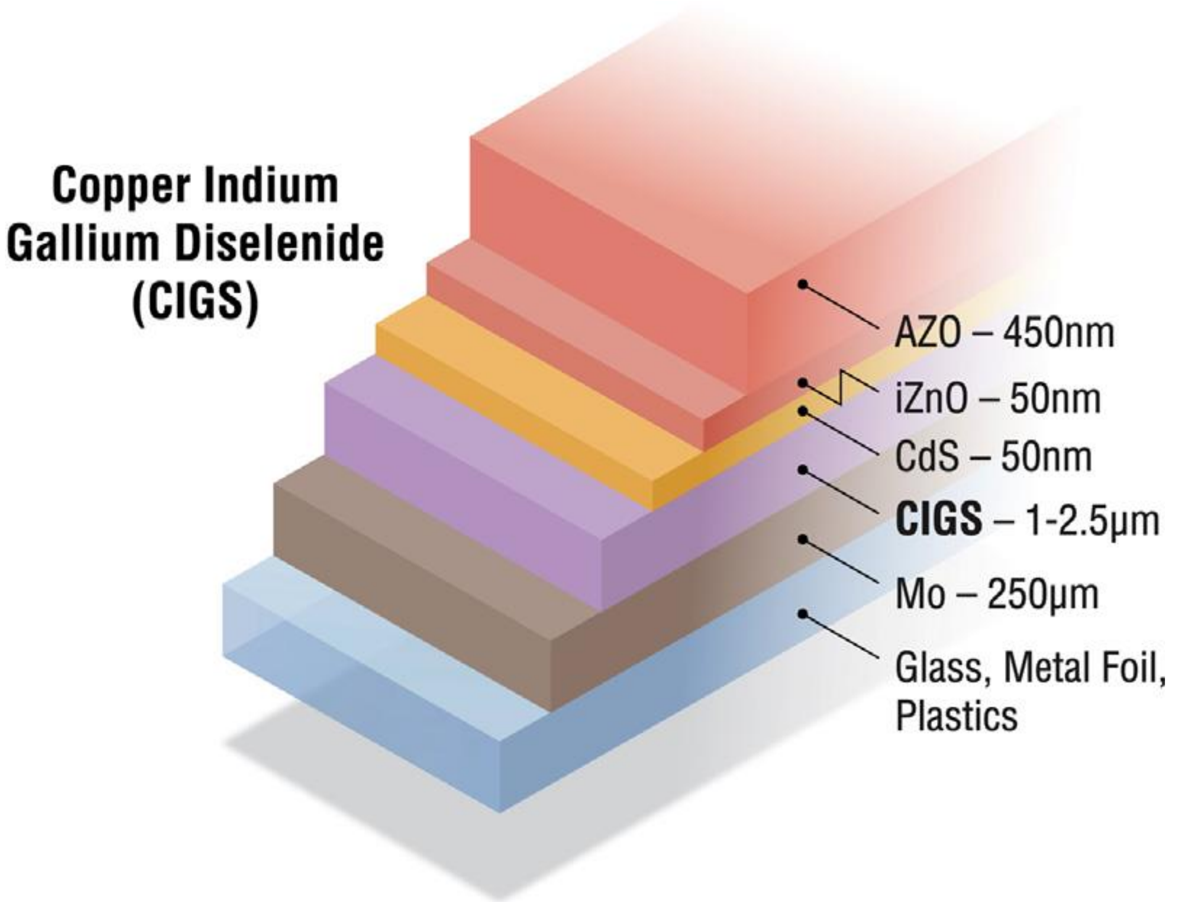
a-Si: 10.2% (AIST)
u-Si: 11.9% (AIST)

Courtesy of M. Zeman, TU Delft

State-of-the-art CIGS solar cells

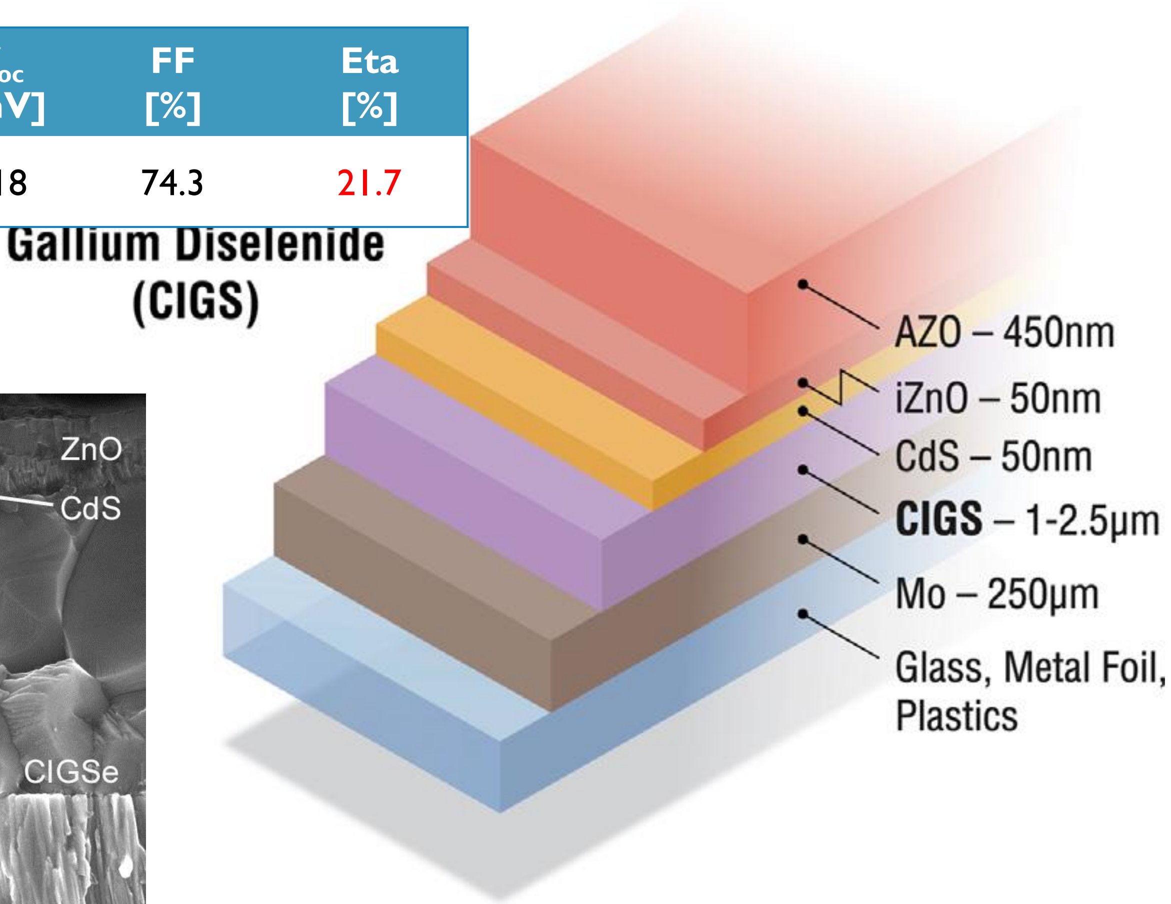


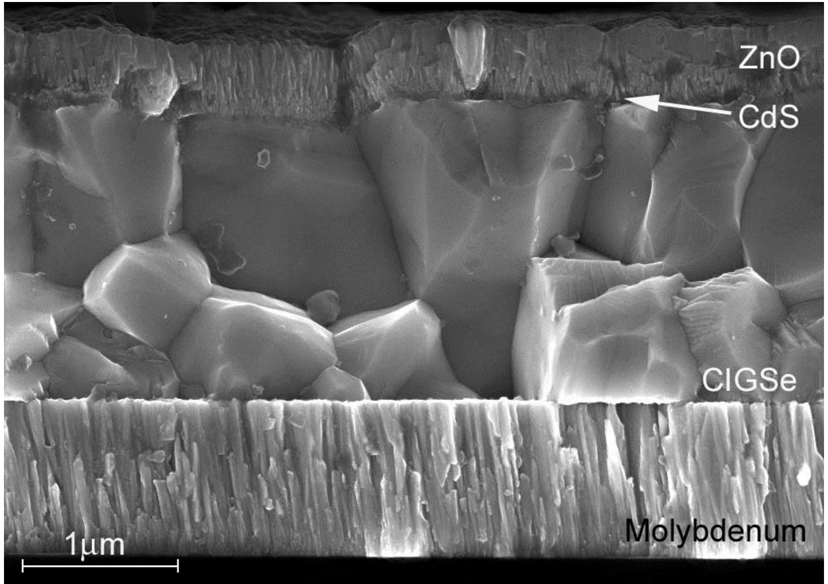
$CuIn_xGa_{(1-x)}Se_2$
Chalcopyrite
crystal structure



State-of-the-art CIGS solar cells

Best cell	J_{sc} [mA/cm²]	V_{oc} [mV]	FF [%]	Eta [%]
Solar Frontier – 1 cm^2	40.7	718	74.3	21.7





Main challenges in CIGS solar cell research

- Further increase of efficiency: Alkali post-deposition treatment, composition grading in absorber layer, surface passivation, ...
- Cd-free buffer layers
- Closing the gap between lab efficiencies and industrial large-area efficiencies
- Thinner absorber layers and introduction of light trapping
- The Indium issue: In is scarce and contributes a few % to module cost currently

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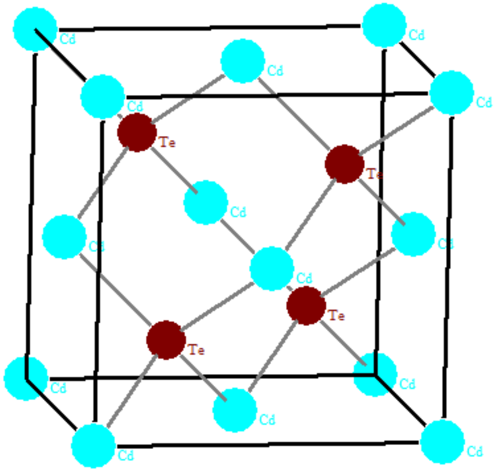
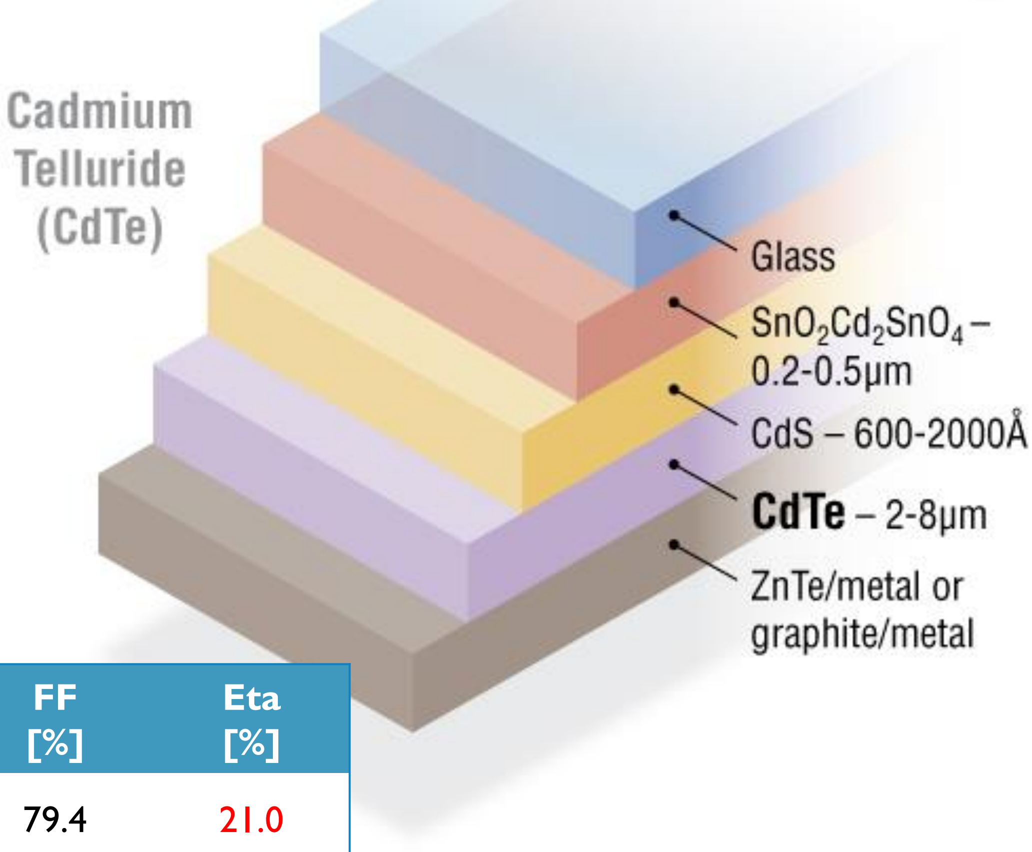
State-of-the-art CdTe solar cells



Zinc blende
crystal structure



Best cell	J_{sc} [mA/cm²]	V_{oc} [mV]	FF [%]	Eta [%]
First Solar – 1 cm²	30.3	876	79.4	21.0

Main challenges in CdTe solar cell research

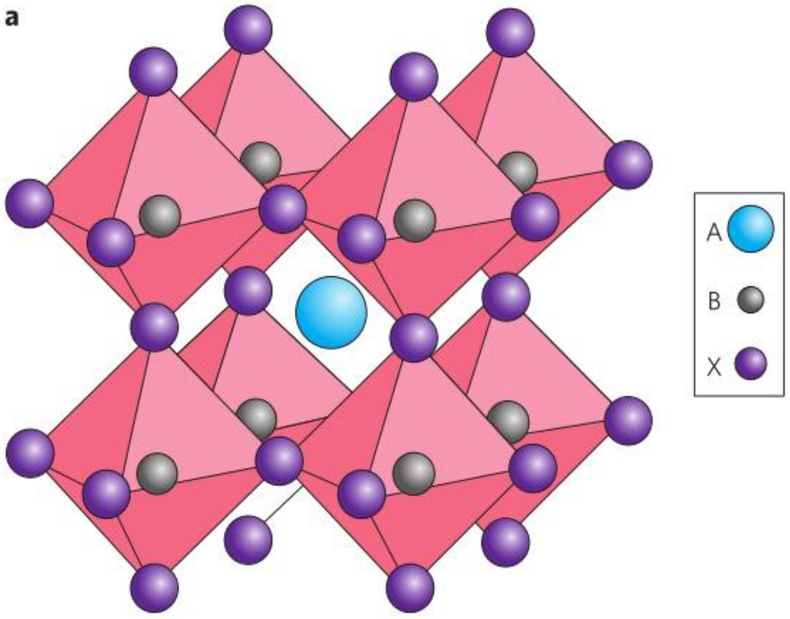
- Proving that CdTe modules are not dangerous for health and environment and can be recycled (Cd is very toxic)
- Reduce back-interface recombination to ~ 1000 cm/s
- Increase doping density to 10^{16} while maintaining lifetime ~ 10ns
- Optimize absorber thickness
- Optimize the concentration and profile of Se
- Increase module lifetime

Outline

- Crystalline-Silicon Photovoltaics
- Inorganic Thin-Film Photovoltaics
- Perovskite Photovoltaics
- Tandem Photovoltaics

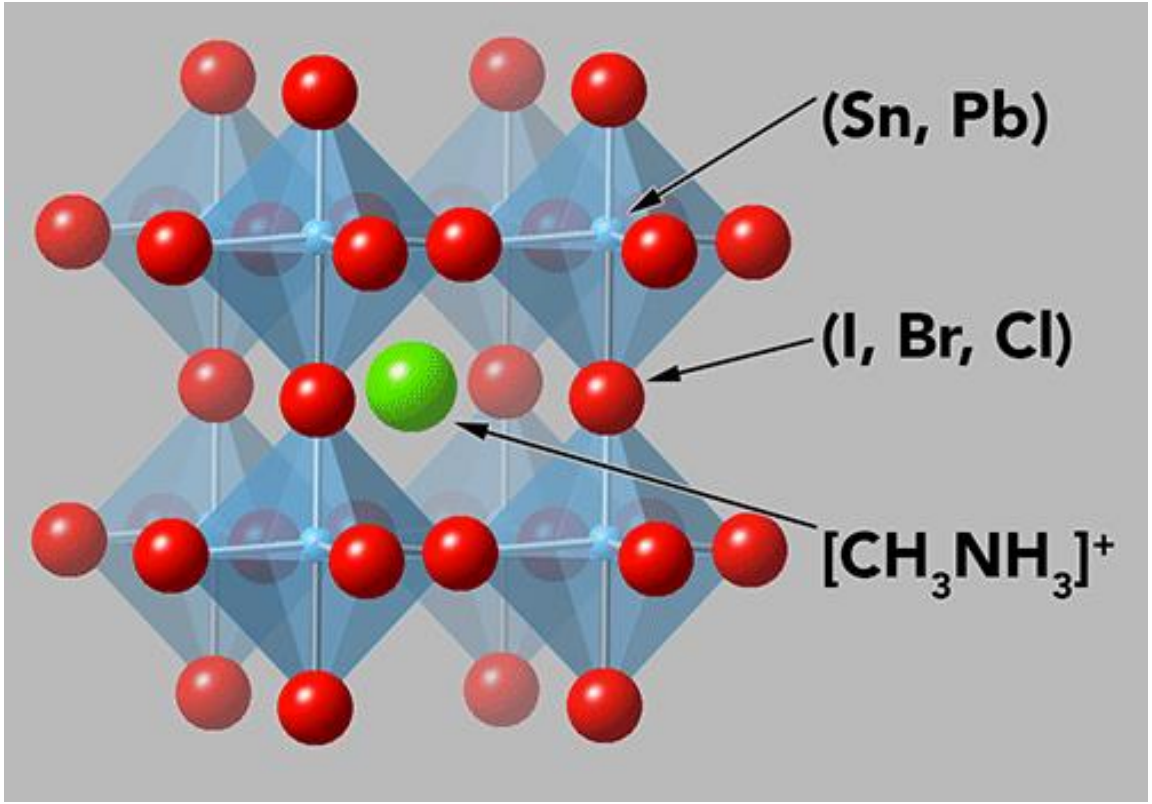
Perovskites in general

- Materials with same structure as the mineral $CaTiO_3$
- Named after Lev Perovski
- Crystal structure: ABX_3
  - A = large cation
  - B = small cation
  - X = anion
- Wide variety of characteristics:
  - Superconducting
  - Insulating or conducting
  - Semiconducting
  - Thermoelectric
  - Piezoelectric
  - Magnetic



Perovskite solar cells: a new kid on the block

- Inorganic-organic perovskites for PV: **A B X_3**
- where A = organic ammonium cation, B= Pb, Sn and X=Cl, Br, I
  - Most common is methylammonium lead iodide: CH_3NH_3 Pb I_3
  - Bandgap is typically 1.5-1.6 eV (tunable)
  - Solution processed or vapour deposited (inexpensive)



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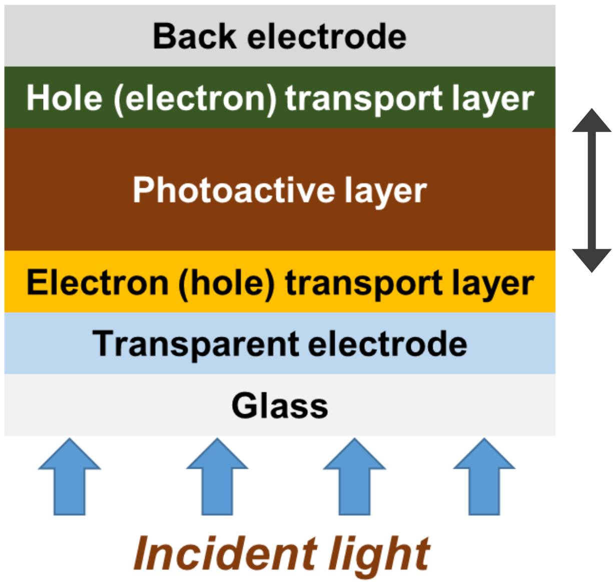
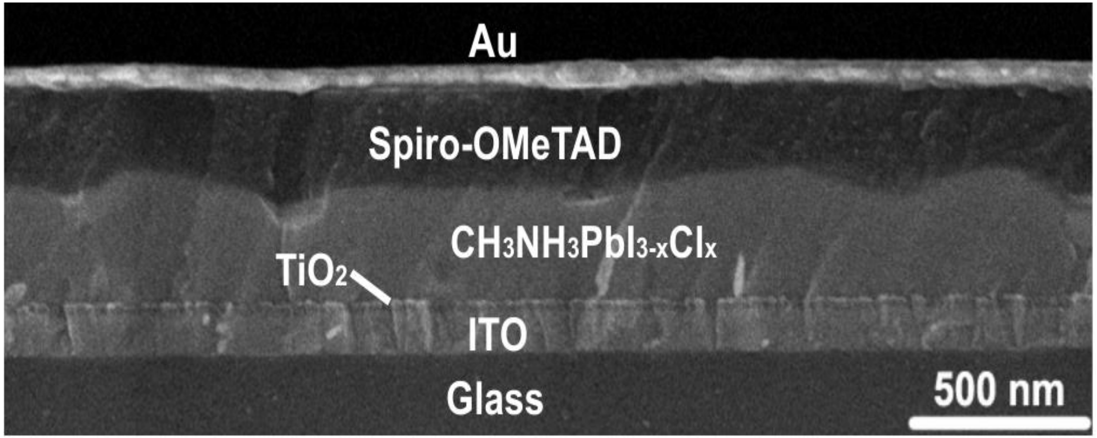
Perovskite solar cells have a p-i-n device architecture

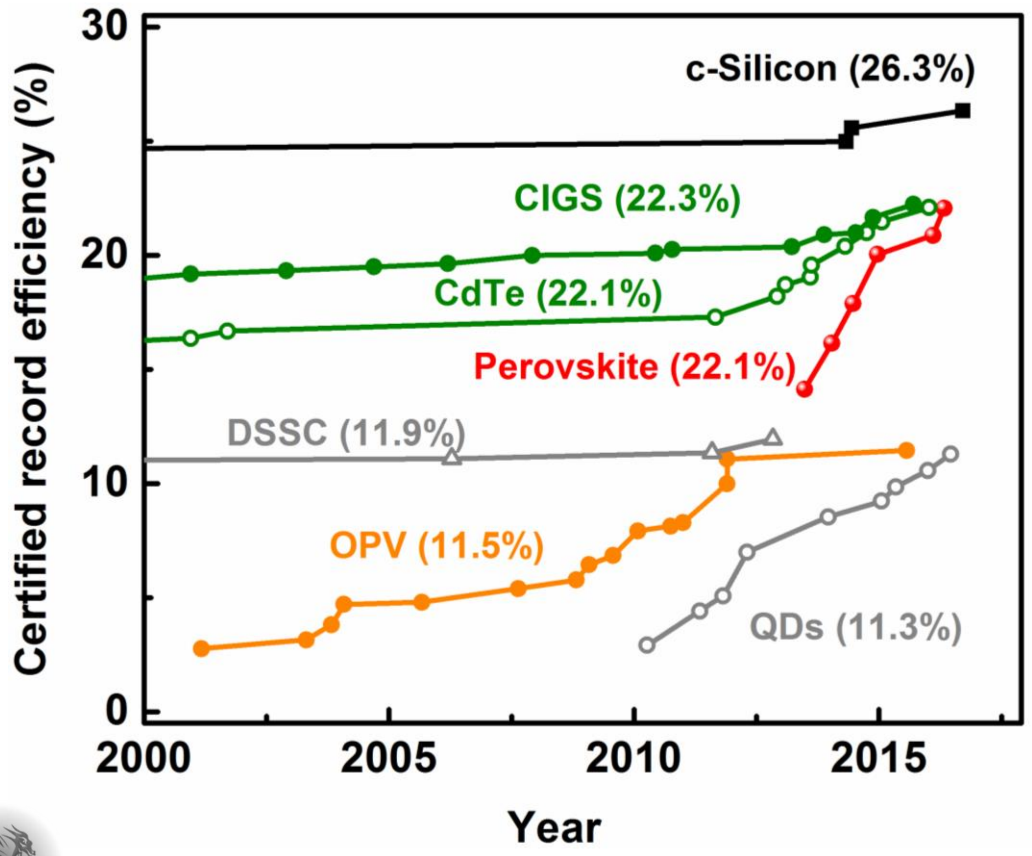


Thickness		*Diffusion length*
d ~ 0.3μm	<	l_{diff} > 0.3 μm

Strong, direct absorber
+
Effective carrier transport



Very fast progress in perovskite cell efficiency has been made in recent years



Remaining challenges:
Increase efficiency further
Stability (long life-time)!
Upscaling

Science's Top 10 breakthrough of 2013

Ocean Cross Group

Outline

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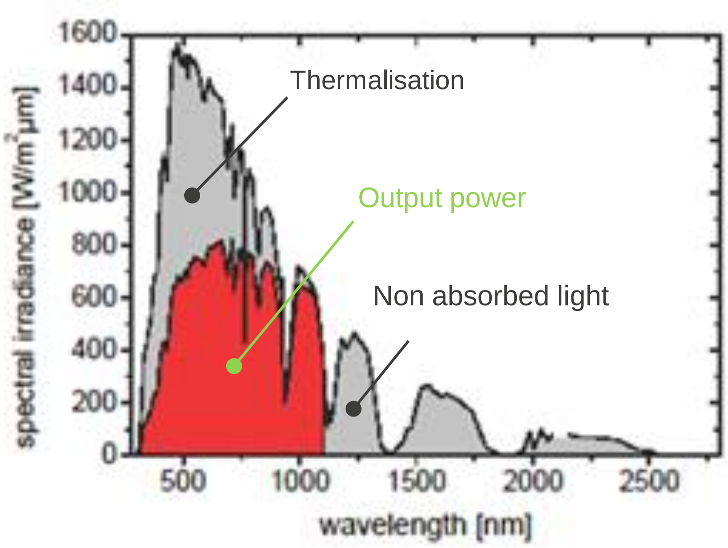
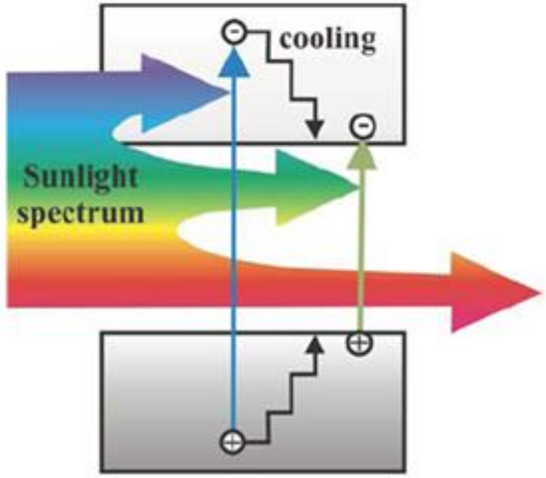
The theoretical efficiency limit of a single junction silicon solar cell is 29.4%

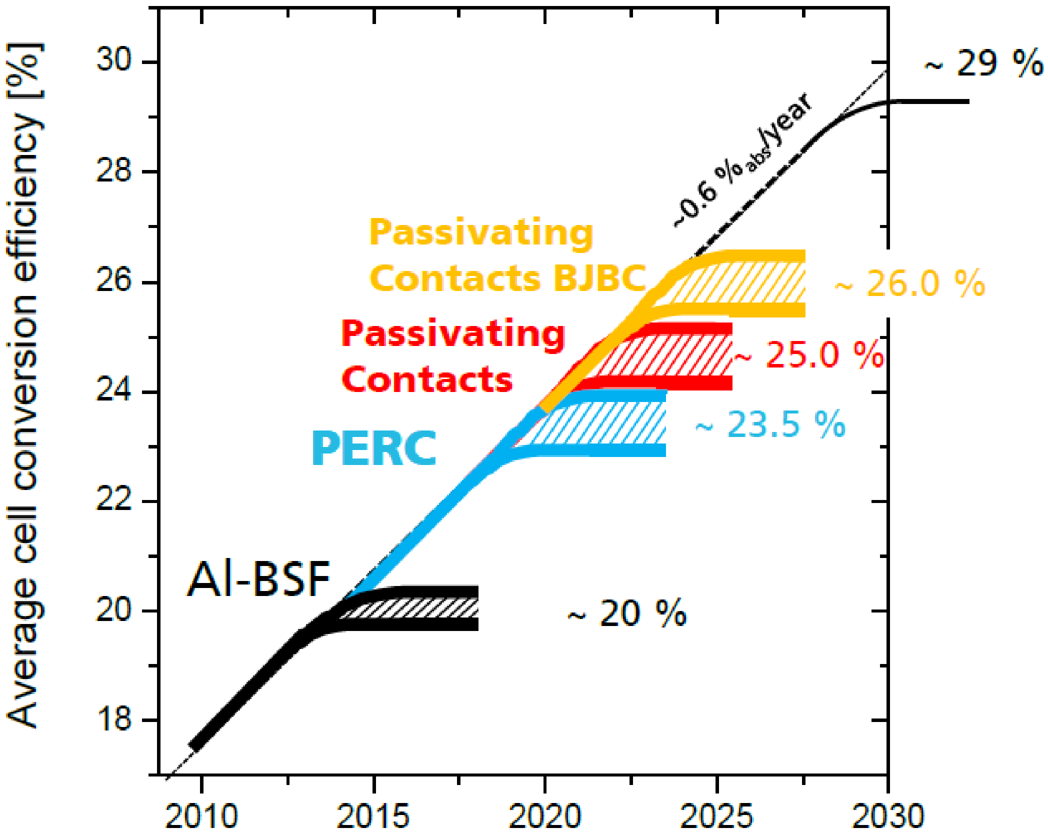
Auger limit of single-junction silicon solar cell is 29.4%

Limitations by thermalization and transmission



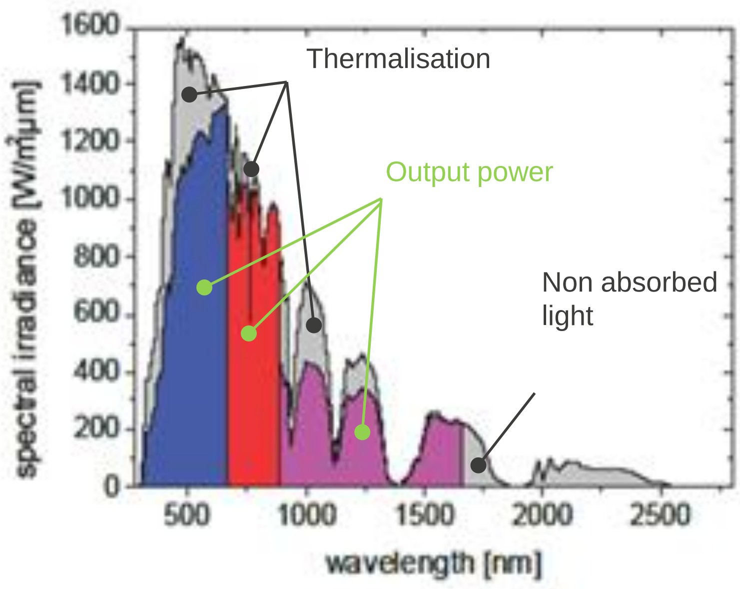


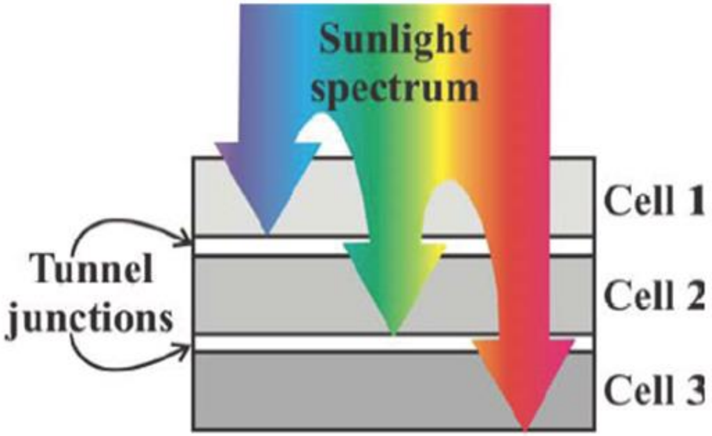
Will this limit mean the end of silicon solar cell technology?



Crystalline-silicon based multi-junctions will allow to push efficiencies above 30%

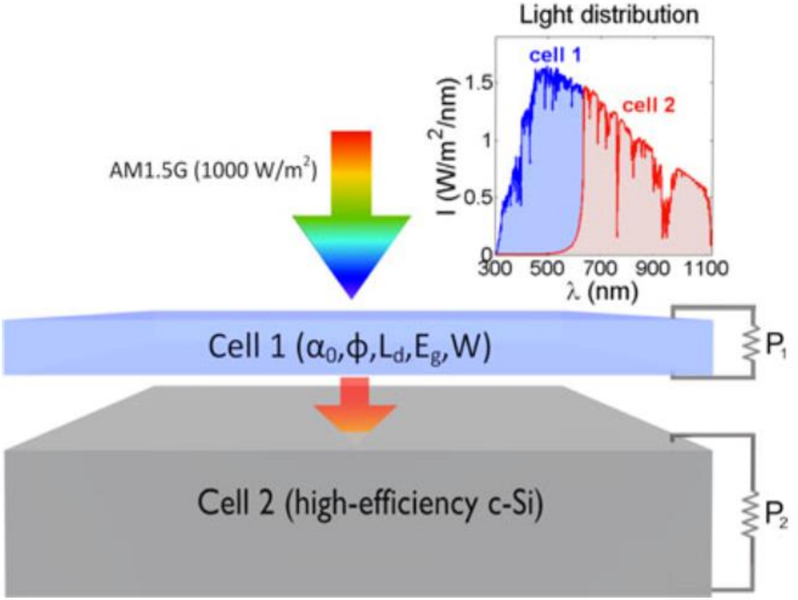
Multi-junction cell concept:

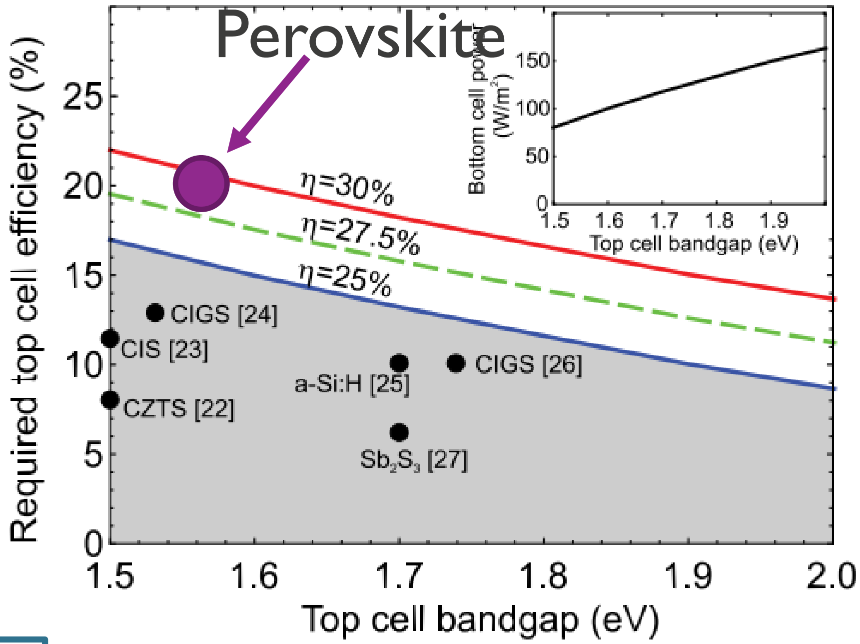




Note: multi-junction with two cells is called tandem

Crystalline-silicon based tandem devices





Needed: thin-film top cell with high bandgap, high efficiency, and minimal sub-bandgap absorption

Perovskite solar cells with tunable bandgap seem suited for tandems

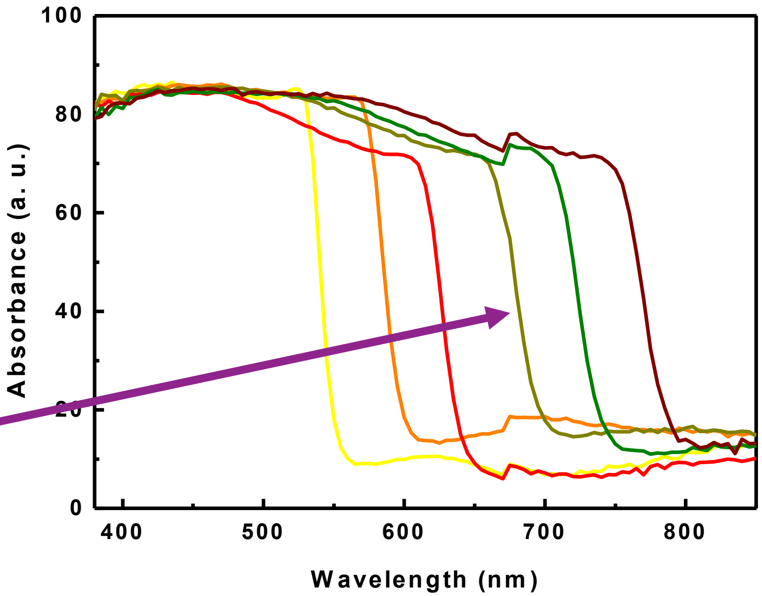
$CH_3NH_3Pb(Br_yI_{1-y})_xCl_{3-x}$

Br content	100%	80%	60%	40%	20%	0%

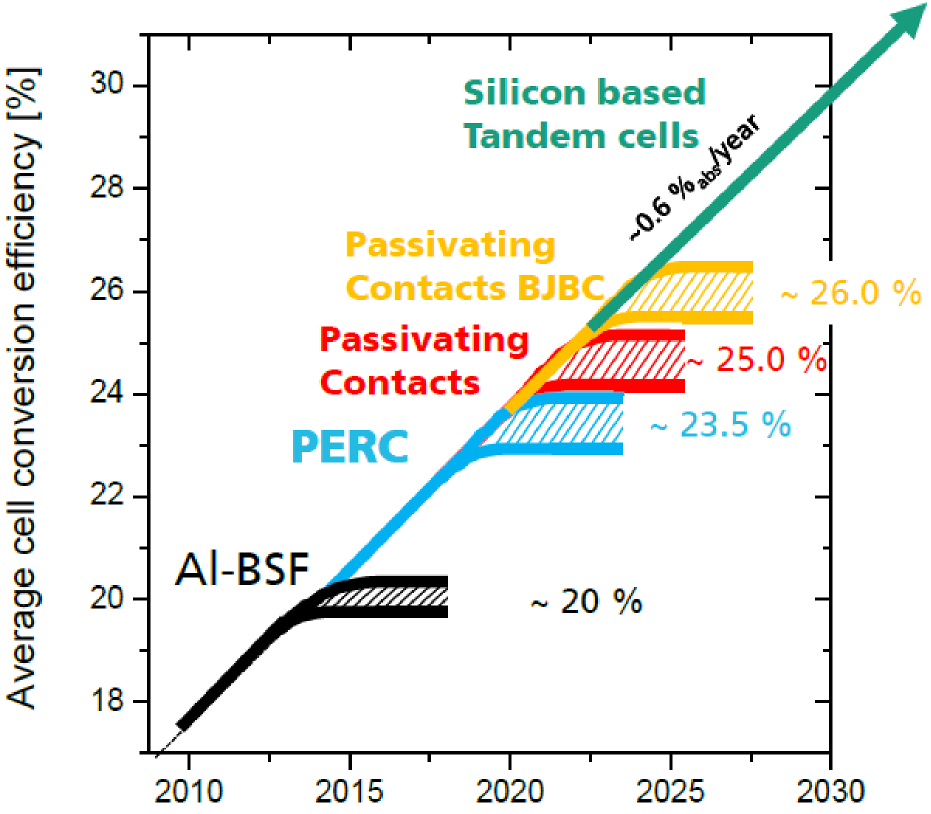
Limited sub-bandgap absorption

40% Br:

- $E_g = 1.77$ eV



Silicon-based tandem devices will ensure that silicon solar cell technology still has a long and bright future



Conclusions

Conclusions

- Single-junction crystalline Si is getting closer to its ultimate practical efficiency of ~ 27%
- TF-PV technologies (e.g. CIGS, CdTe) are rapidly increasing in efficiency
- Perovskites are a very interesting new material with very high potential for PV
- Crystalline-silicon based tandem devices will be the way forward to efficiencies above 30% at low cost

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Jutta Trube, Managing Director
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Int’l Technology Roadmap for Photovoltaics (ITRPV) 8th ed.

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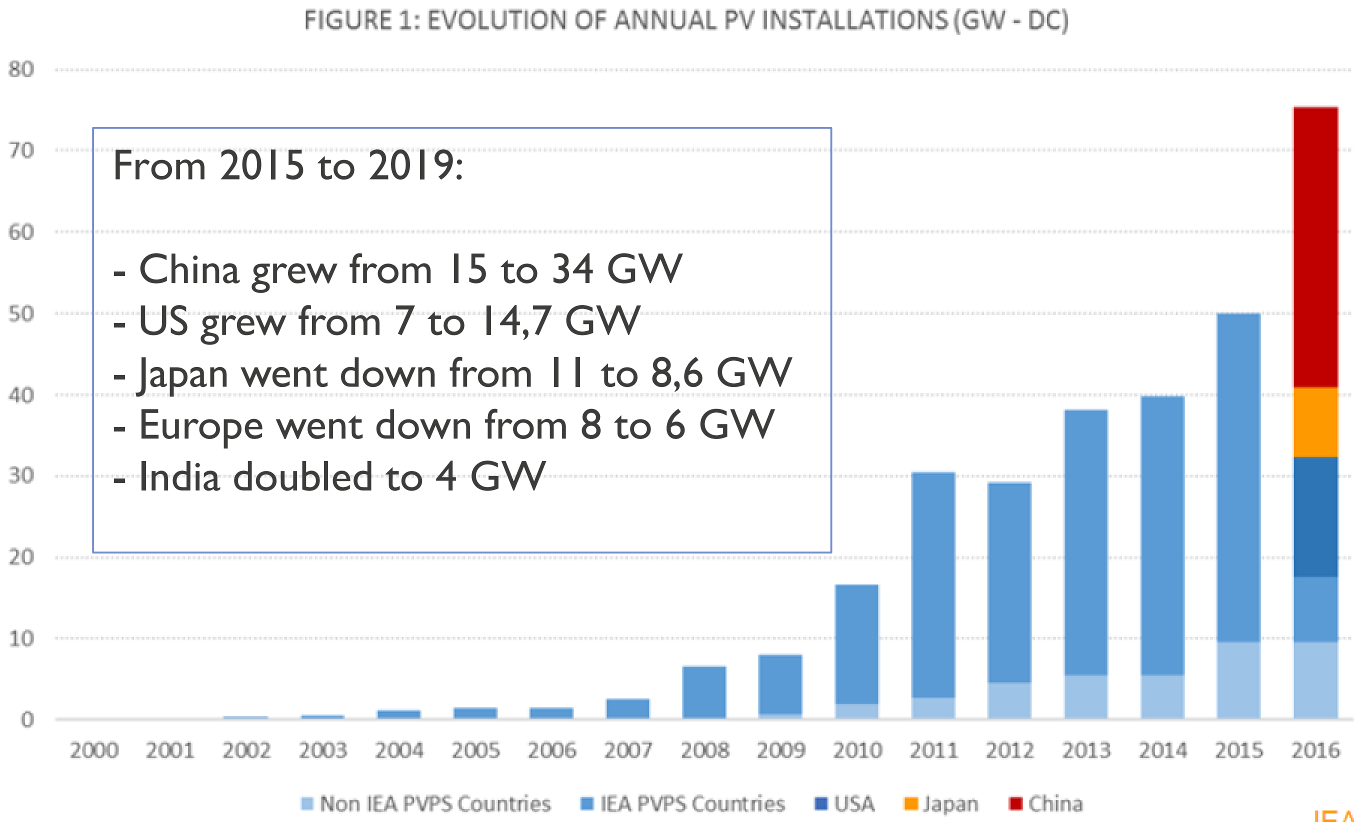
China and USA are the largest PV markets

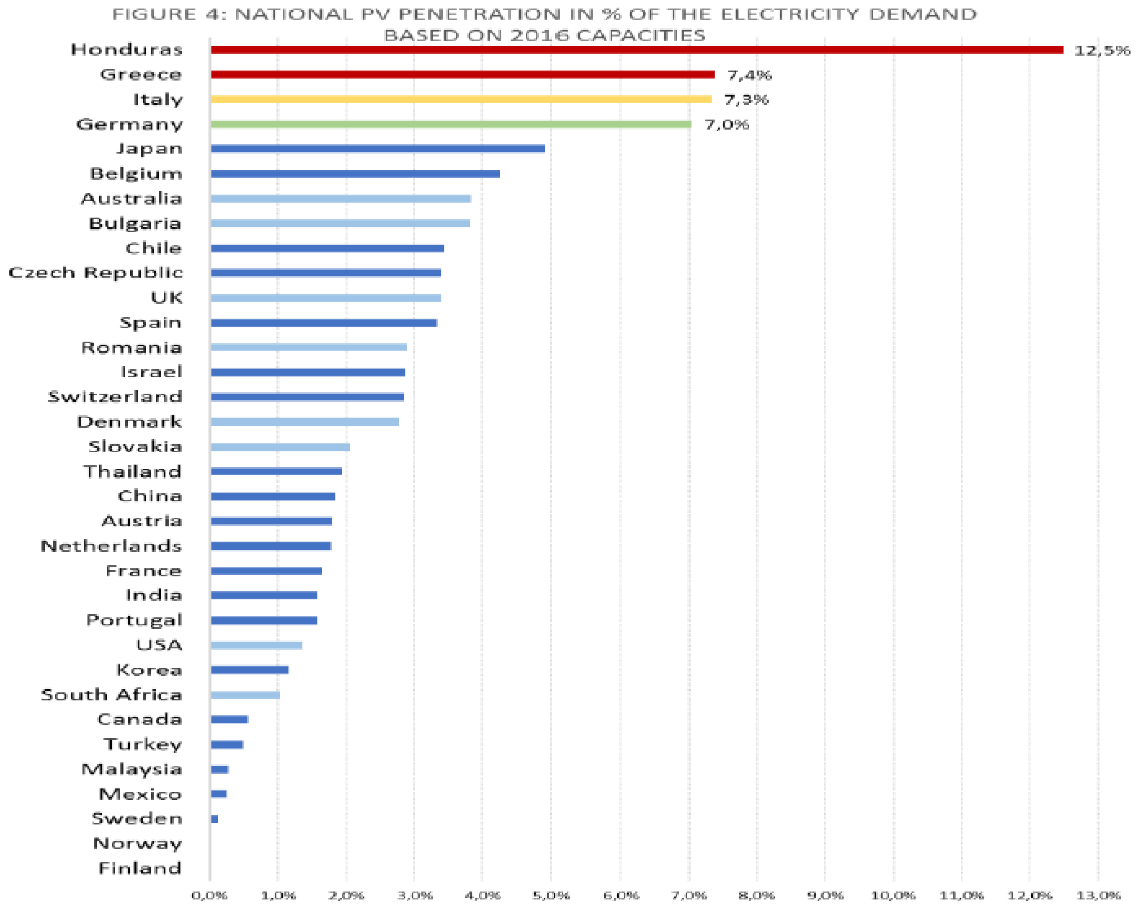


From 2015 to 2019:

- China grew from 15 to 34 GW
- US grew from 7 to 14,7 GW
- Japan went down from 11 to 8,6 GW
- Europe went down from 8 to 6 GW
- India doubled to 4 GW

IEA-PVPS 2017

In many countries PV provides already more than 3% of the electricity demand



IEA-PVPS 2017

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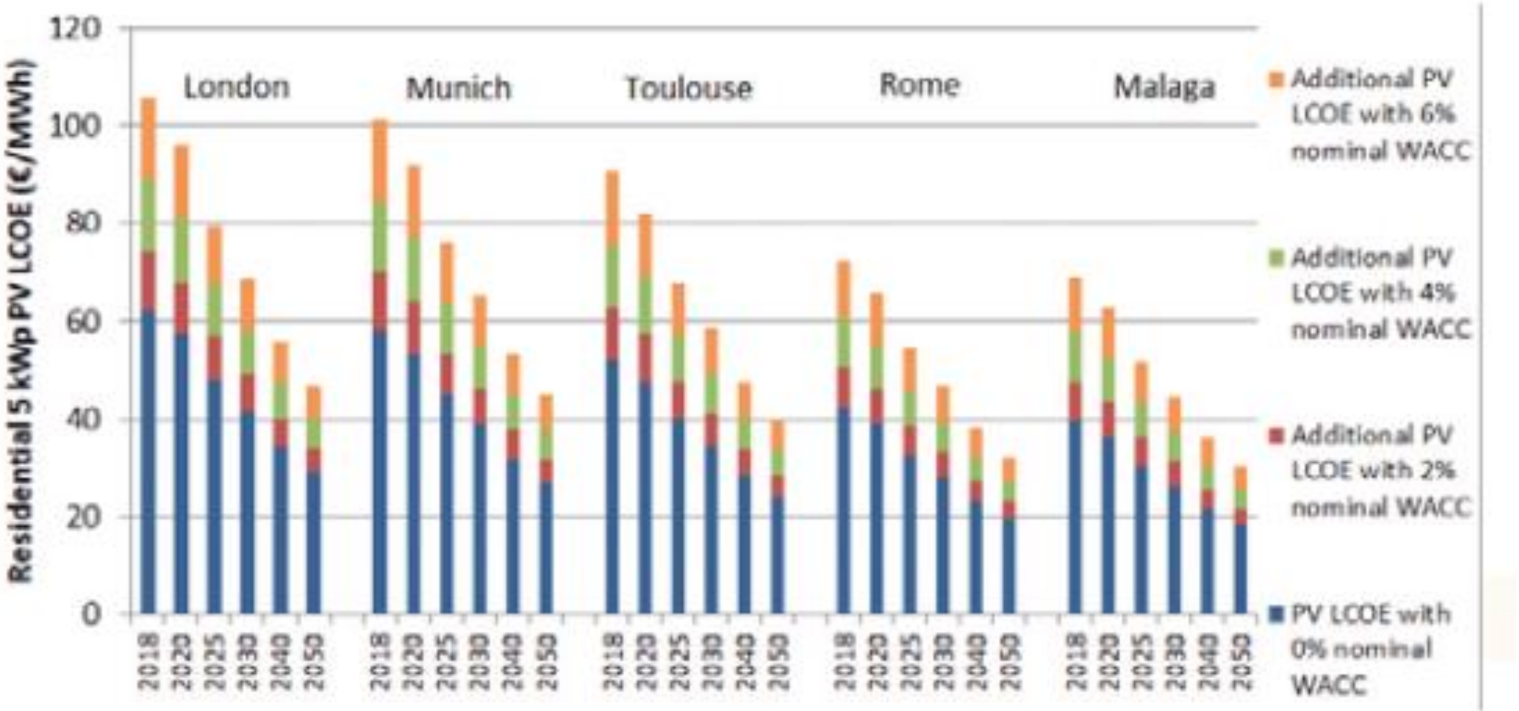
The levelized cost of PV electricity is dependent on location and on (local) economical factors

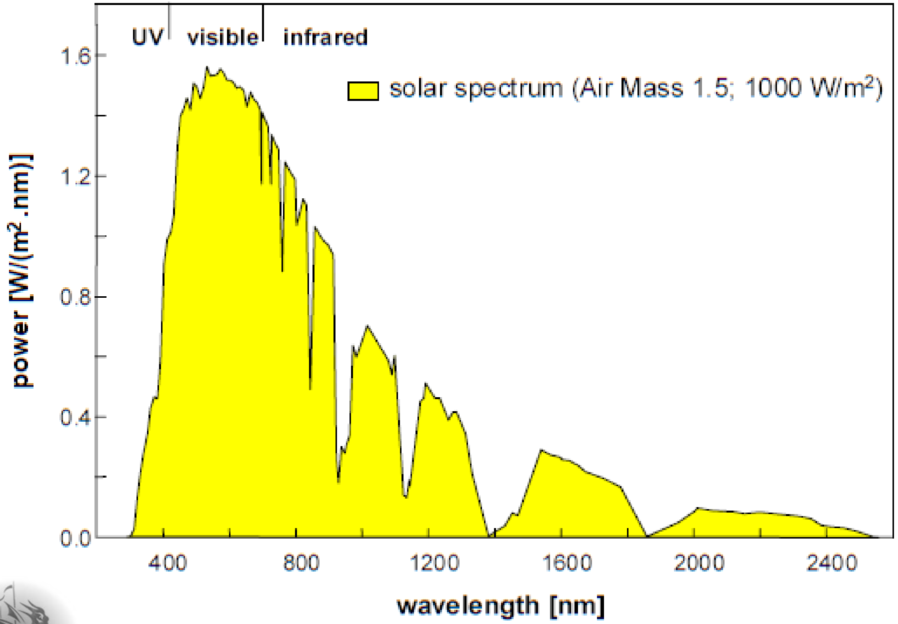


Source = European Technology & Innovation Platform

The energy conversion efficiency of solar cells is measured and compared under standard conditions

Energy conversion efficiency = P cell / P incoming light

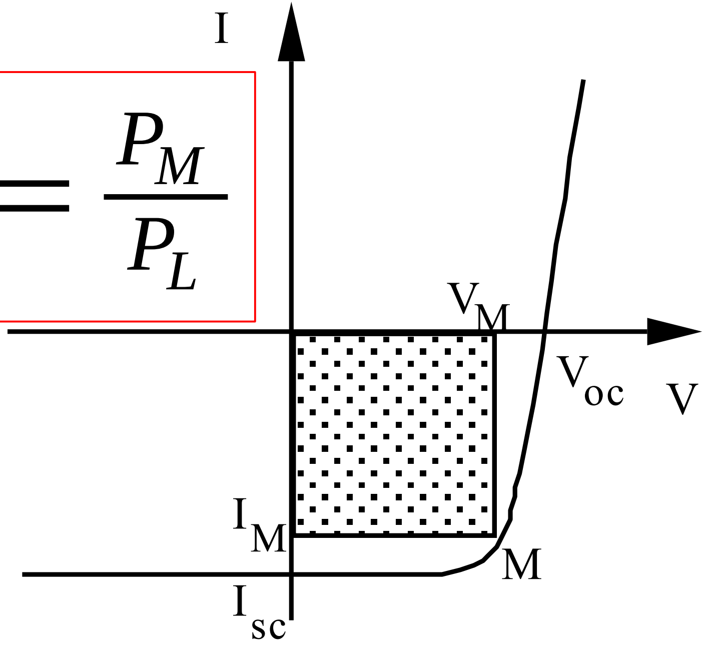
Solar spectrum



Courtesy John Schermer, RUN, NL

I-V curve of solar cell under illumination

$$\eta = \frac{P_M}{P_L}$$



I_{sc} = short circuit current
V_{oc} = open circuit voltage
M = maximum powerpoint