SILICON SOLAR CELLS – CURRENT PRODUCTION AND FUTURE CONCEPTS

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PV Manufacturing in Europe

Brussels

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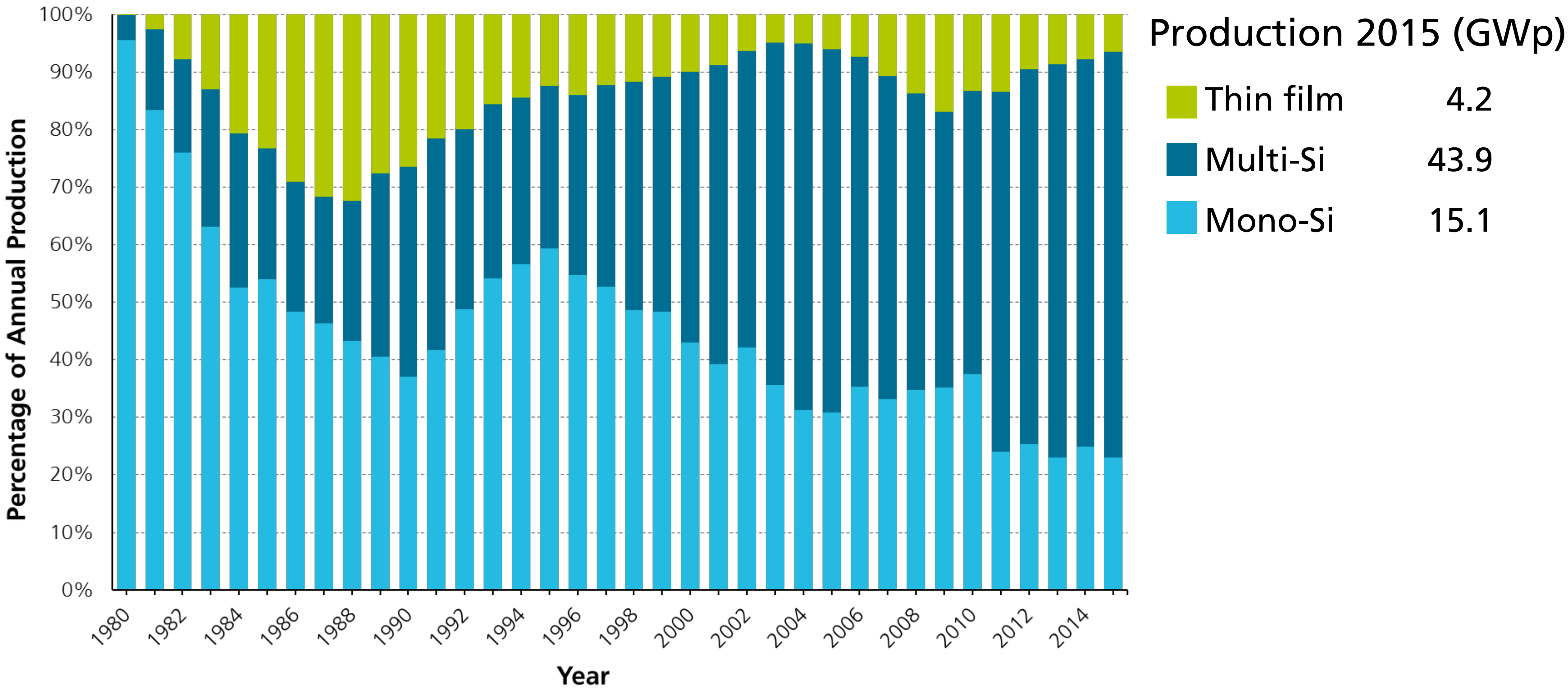
PV Module Production Development by Technology

It is still silicon …



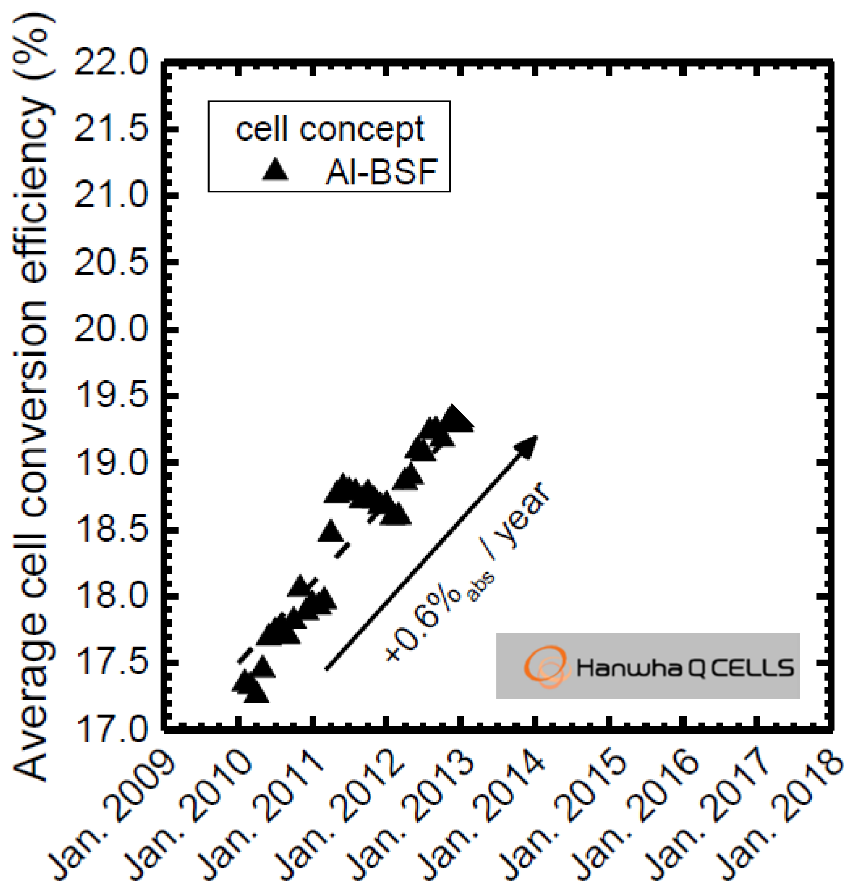
Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion from cell production). Graph: PSE AG 2016

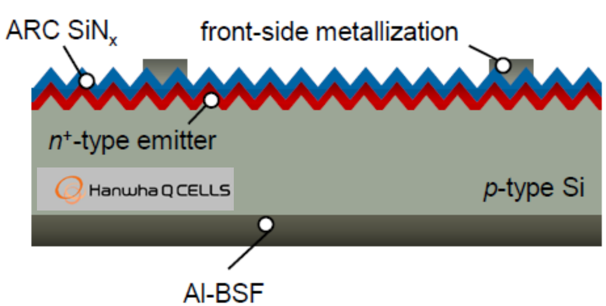
SILICON SOLAR CELLS – CURRENT PRODUCTION AND FUTURE CONCEPTS

- PRESENT
  - Current production of silicon solar cells
  - Evolution of cell efficiency → The pathway to highest efficiencies
- FUTURE
  - Overcoming the limits of silicon
  - A new generation of silicon solar cells

Present
Screen-printed Al-BSF Solar Cell on p-Type Silicon

- Production data from Hanwha QCELLS





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

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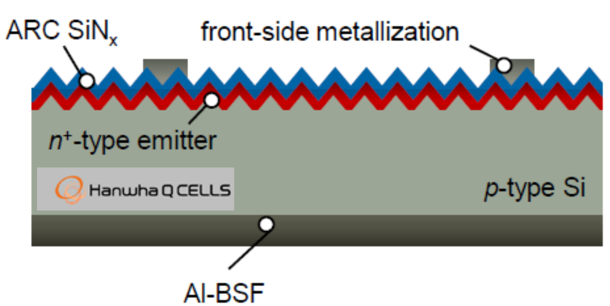
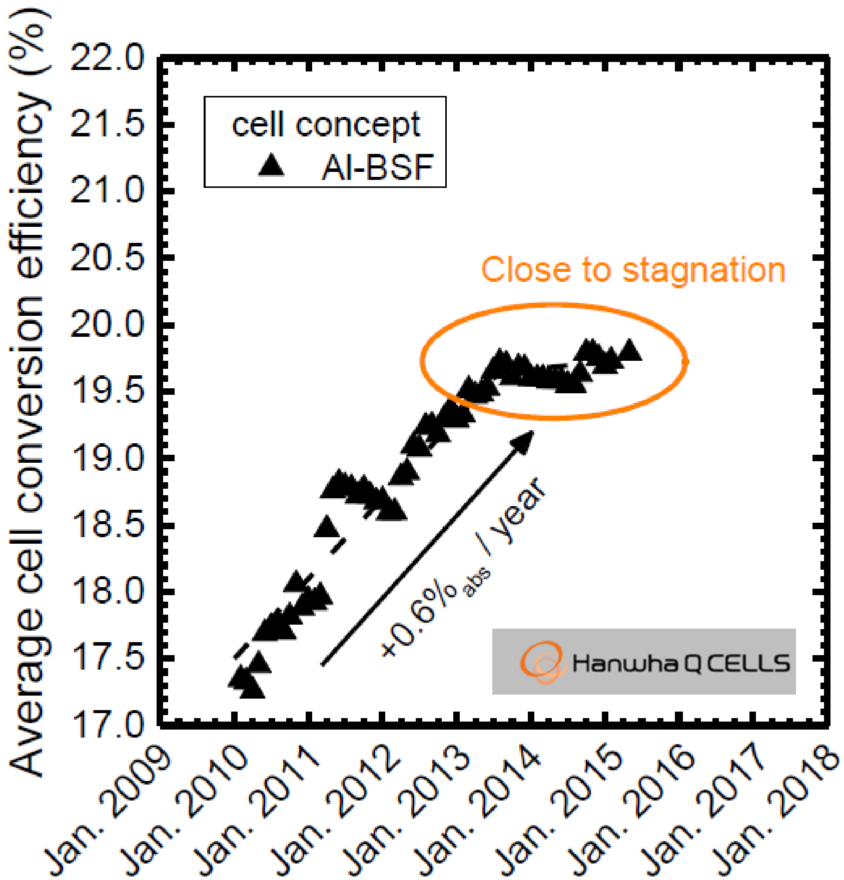
Present
Screen-printed Al-BSF Solar Cell on p-Type Silicon

- Production data from Hanwha QCELLS
- Efficiency limitation due to full area Al-BSF rear side
- What is the next step?
  - Make it cheaper?
  - Make it better?





Fabian Fertig et al "***Mass Production of p-Type Cz Silicon Solar Cells …*** "
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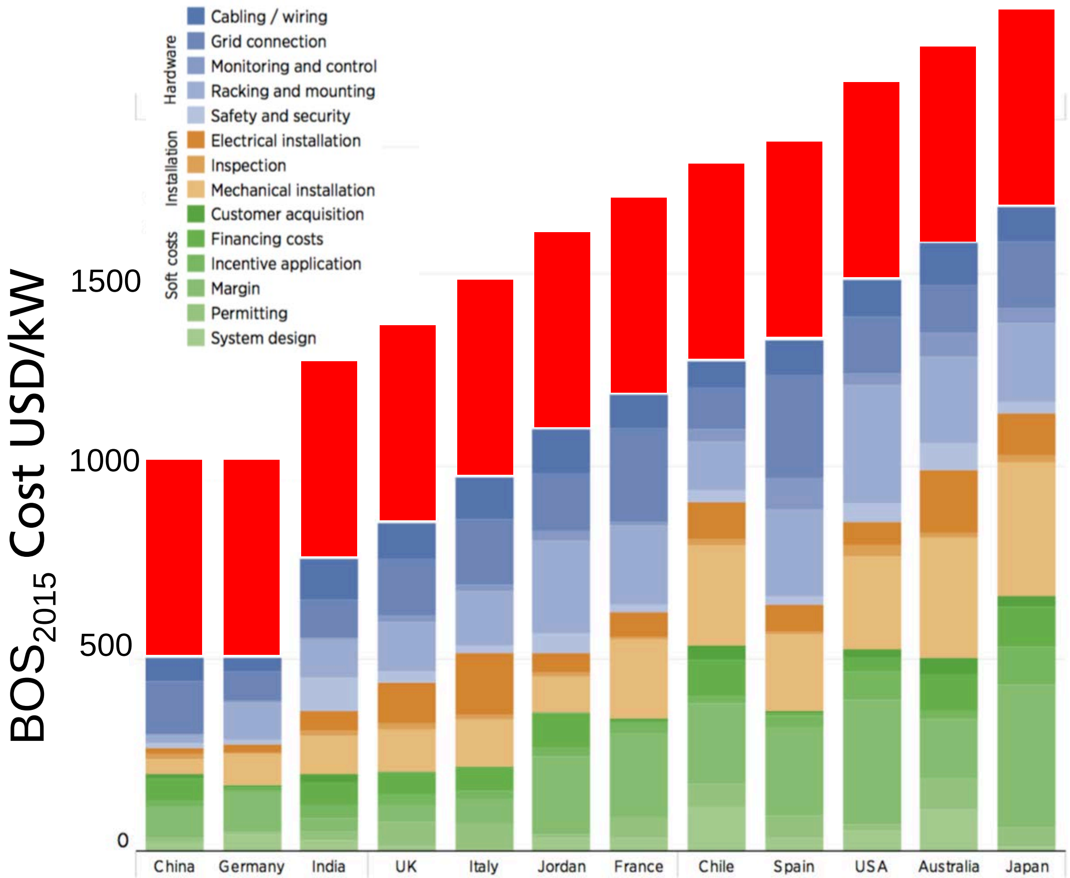
Present

System Cost: BOS and Module Costs

- Different BOS for different Countries
- Current Module price < 0.5 $/W
- Module price only a small fraction of system cost in most countries



→ **Highly efficient solar cells reduces System Cost and the LCOE**

IRENA (2016), The Power to Change: Solar and Wind Cost Reduction Potential to 2025

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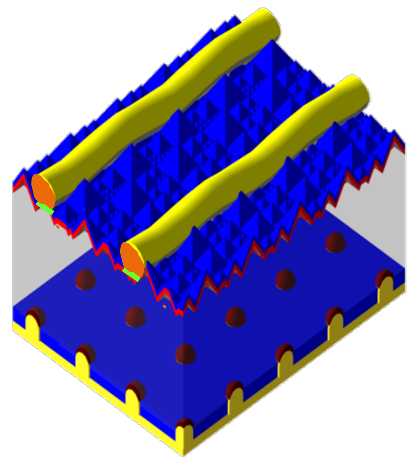
Present

From Al-BSF to PERC

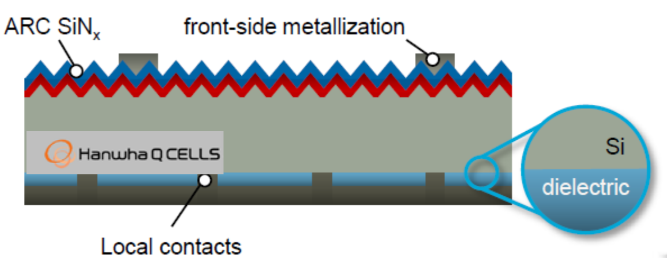
- Replacement of the full area Al-BSF with **a partial rear contact (PRC)**
- Two additional process steps
  - Dielectric passivation
  - Local contact opening (LCO) or Laser fired contact (LFC)

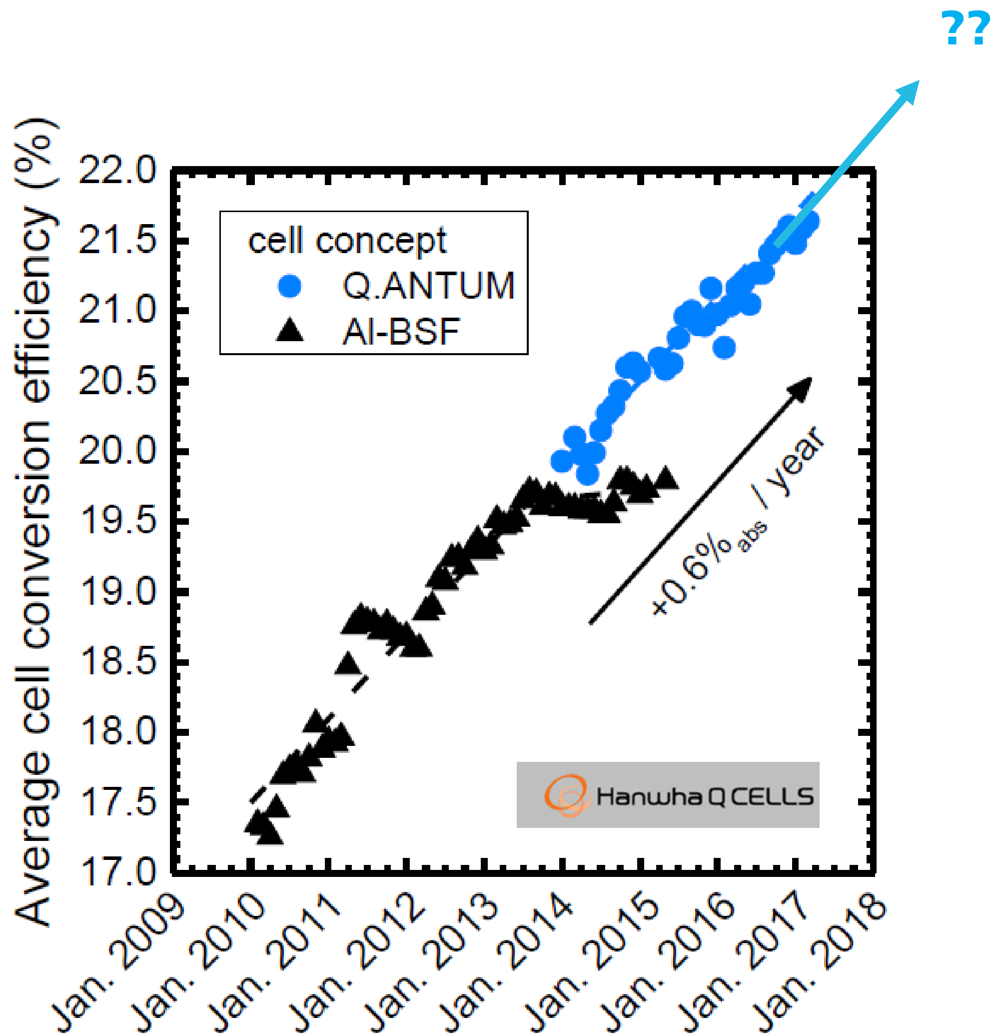


- SDE/Texture
- POCl diffusion
- Edge Isolation
- PSG etching
- SiN ARC
- Al_2O_3/ SiN RS
- Laser Opening
- SP Ag FS
- SP Al/Ag RS
- Drying & Firing

Present
From Al-BSF to PERC

- Q.ANTUM production data from Hanwha QCELLS
- Still 0.6 $\%_{abs}$/year efficiency improvement
- How far can we go?





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

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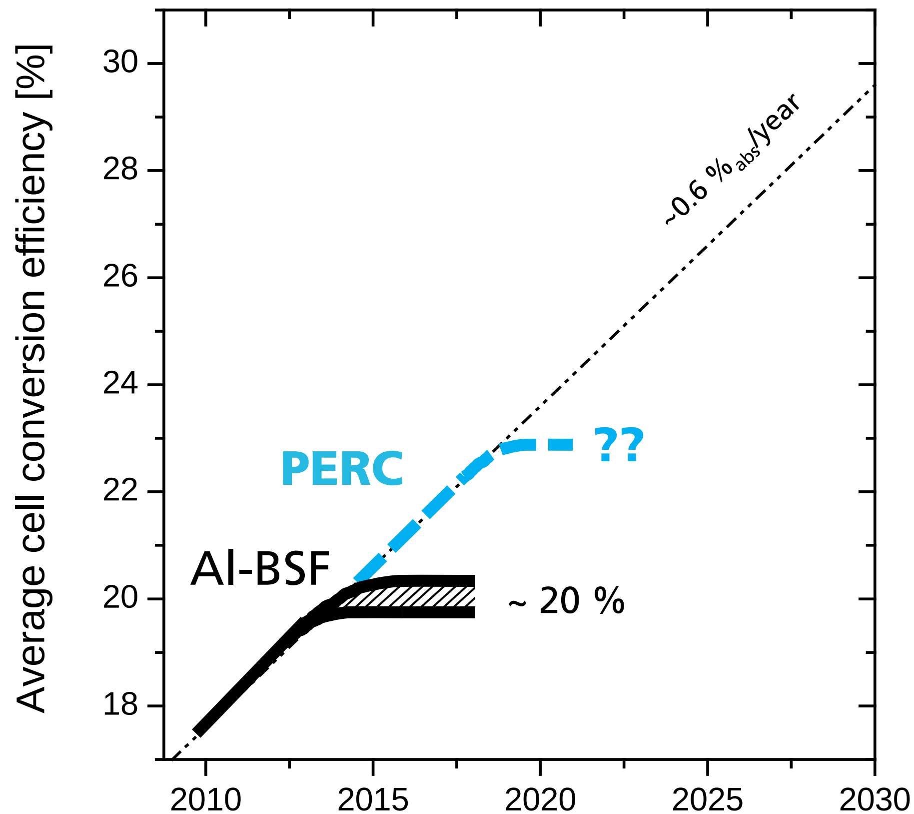
From Present to Future
Silicon Solar Cell Production: What is the Efficiency Limit?

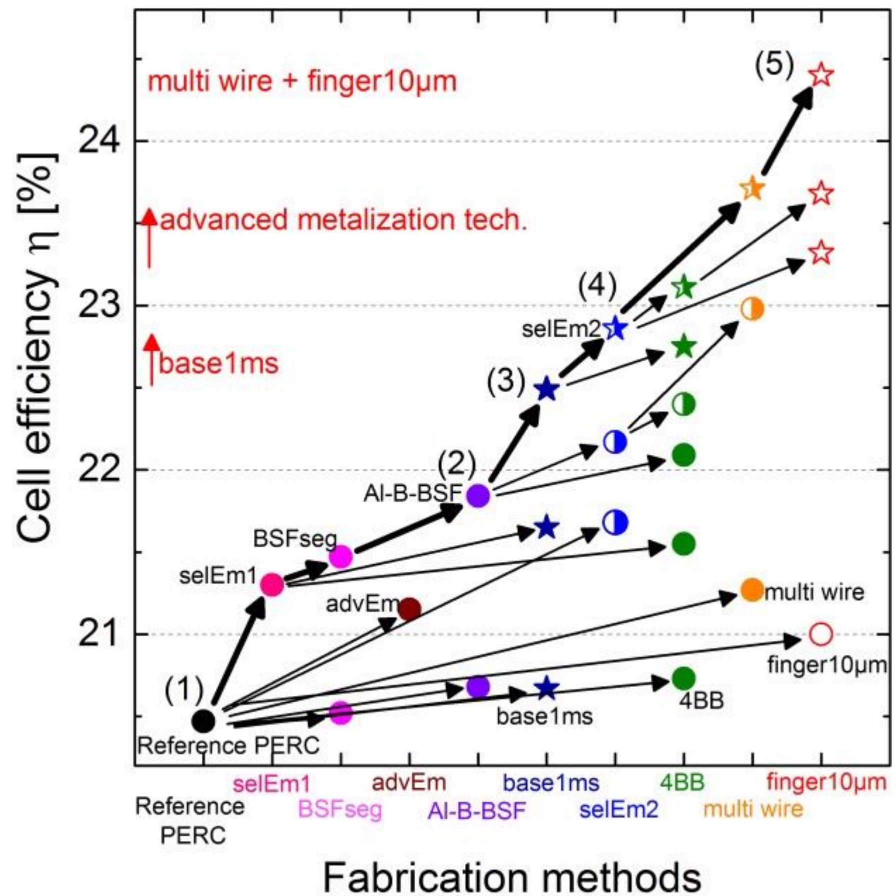
- Assuming constant ***"learning curve"***
  → efficiency improvement ~0.6 %$_{abs}$/year

- What limits the cell efficiency and which technologies are needed in the future ?



From Present to Future
PERC – What is the Limit

- Continuous increasing is possible by
  - Improving base lifetime > 1 ms
  - Smaller fingers and smaller selective emitter regions
  - Multi-wire Module



B.Min et al , *INCREMENTAL EFFICIENCY IMPROVEMENTS…,* 31st EUPVSC 2015, Hamburg

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From Present to Future
PERC – What is the Limit

- Continuous increasing is possible by
  - Improving base lifetime > 1 ms → No material degradation, cleaner processes/environment
  - Smaller fingers and smaller selective emitter regions → Higher alignment accuracy, increased metallization costs (e.g. screens)
  - Multi-wire Module → Higher CTM losses, higher module manufacturing costs

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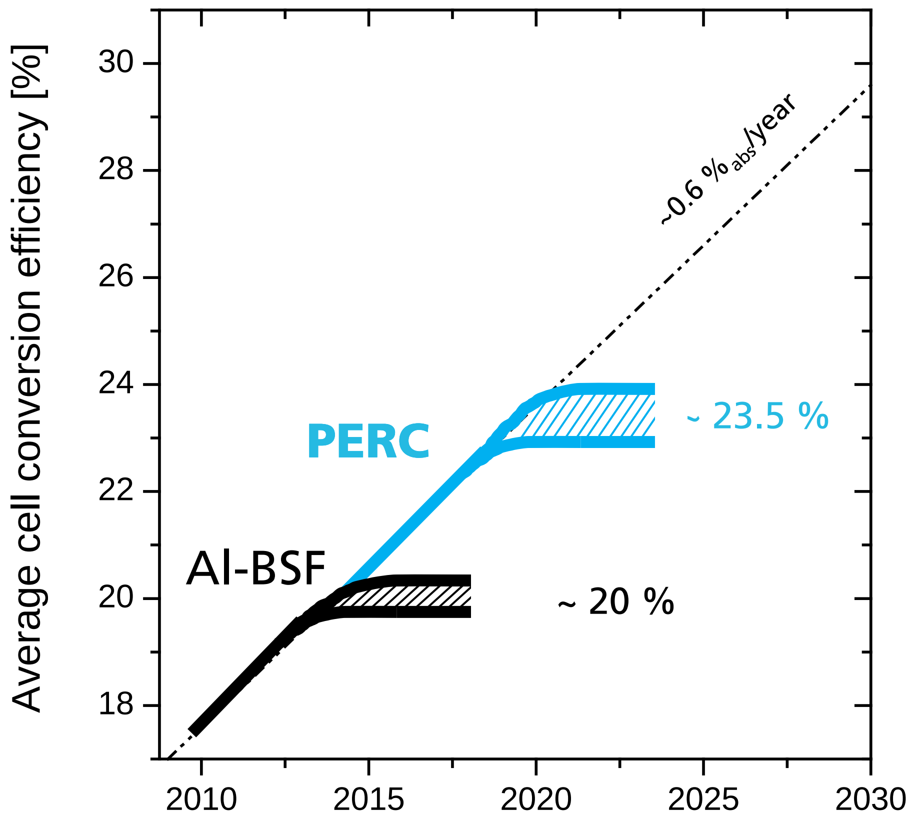
From Present to Future
PERC – What is the Limit

- Physical Limitations
  - Contact recombination and lateral current flow

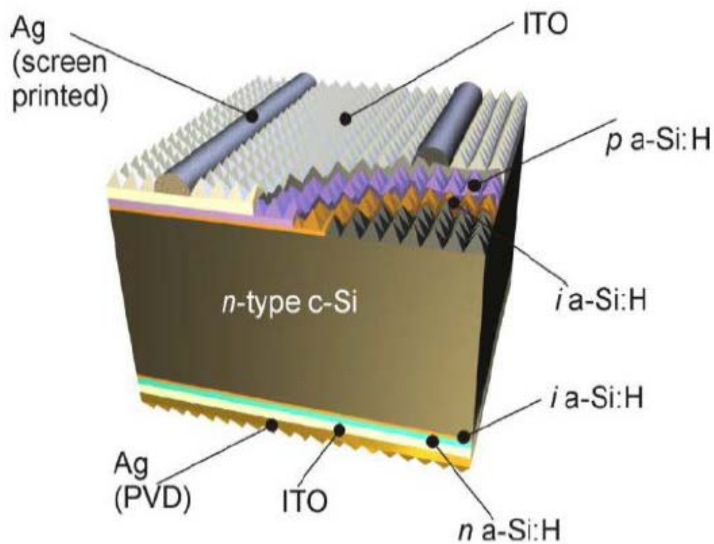
→ Passivating Contacts



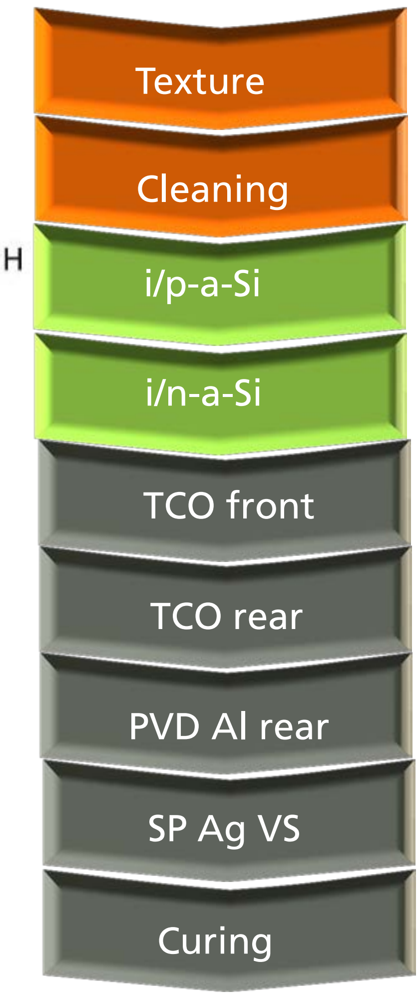
From Present to Future
Heterojunction Solar Cells

- Lean process flow
- Highly efficient carrier selective contacts
- High V_{oc} and low T_k

- Parasitic absorption
- Metallization temperature is limited



from: D.Bätzner Silicon PV 2014



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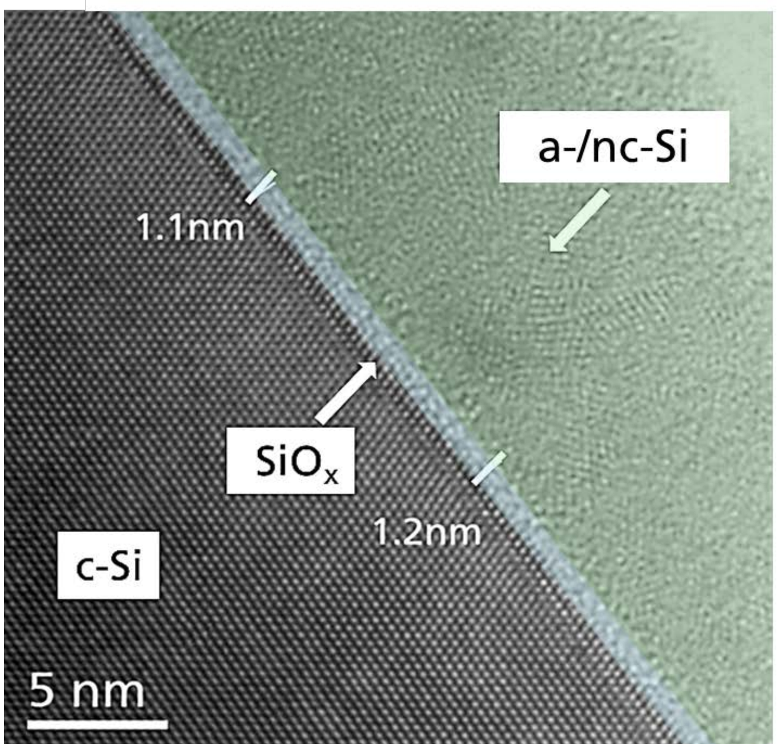
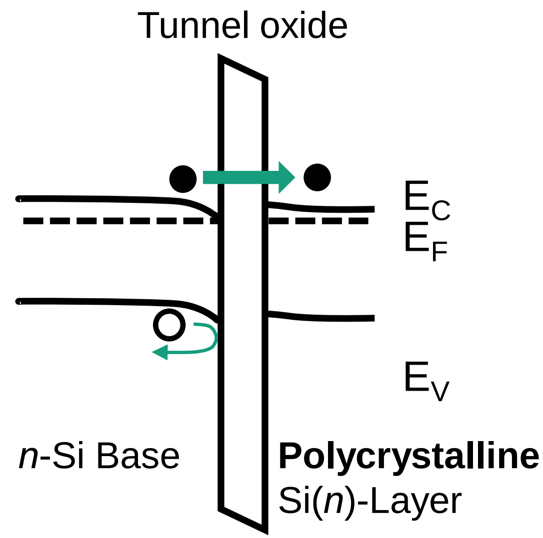
From Present to Future
Passivating Contacts with Oxide and Polysilicon

TOPCon Stucture



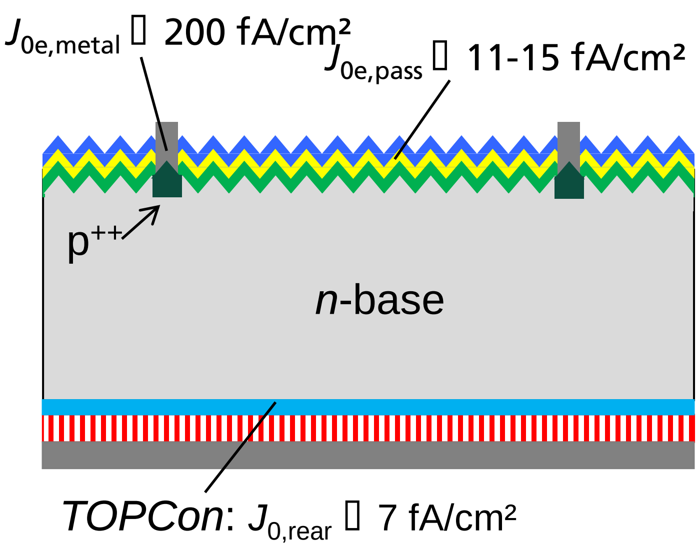


Post, IEEE Transactions on Electron Devices (1992)
F. Feldmann et al., *SOLMAT 120* (2014)
U. Römer, et al. IEEE Journal of Photovoltaics (2015)
D. Yan Solar Energy Materials and Solar Cells (2015)

From Present to Future

TOPCon Record Cells with Top/Rear Contacts

Material	Area	V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]	η [%]
n-type Mono	4 cm² (da)	725	42.5	83.3	**25.7***



➔ World record efficiency of **25.7%** for both side contacted solar cells

A.Richter ***Silicon Solar Cells with Passivating Rear Contacts***
7th Silicon PV, Freiburg, Germany, April 3, 2017

* confirmed by Fraunhofer ISE Callab

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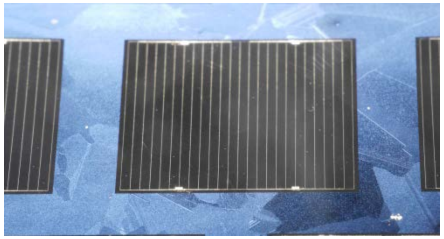
From Present to Future
TOPCon Record Cells with Top/Rear Contacts

Material	Area	V_{oc} [mV]	J_{sc} [mA/cm²]	*FF* [%]	η [%]
n-type Mono	4 cm² (da)	725	42.5	83.3	**25.7***
n-type Multi	4 cm² (ap)	673	40.8	79.7	**21.9***



Photograph of the *n*-type HP mc solar cell

→ World record efficiency of **21.9%** for a mc silicon solar cell

J. Benick *High-efficiency multicrystalline n-type silicon solar cells* 7th Silicon PV, Freiburg, Germany, April 3, 2017

* confirmed by Fraunhofer ISE Callab

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From Present to Future
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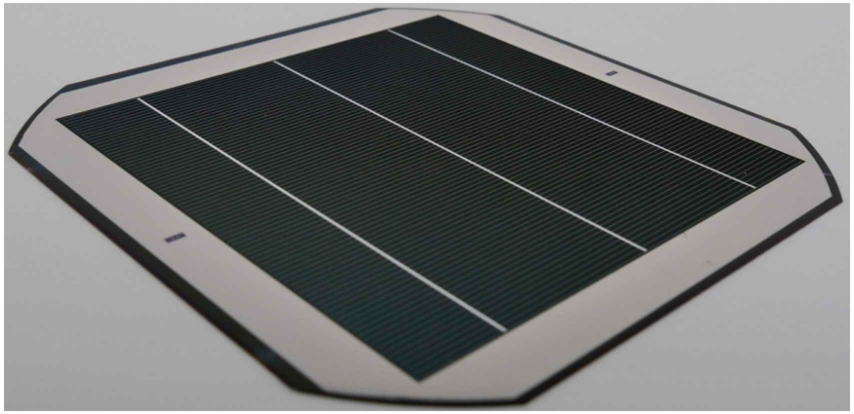
Material	Area	V_{oc} [mV]	J_{sc} [mA/cm²]	*FF* [%]	η [%]
n-type Mono	4 cm² (da)	725	42.5	83.3	**25.7***
n-type Multi	4 cm² (ap)	673	40.8	79.7	**21.9***
n-type Mono	100 cm² (ap)	713	41.4	83.1	**24.5***



→ Process scalable on lager area

F.Feldmann, **Evaluation of TOPCon technology on large area solar cells** EUPVSEC, Amsterdam, 2017

* confirmed by Fraunhofer ISE Callab

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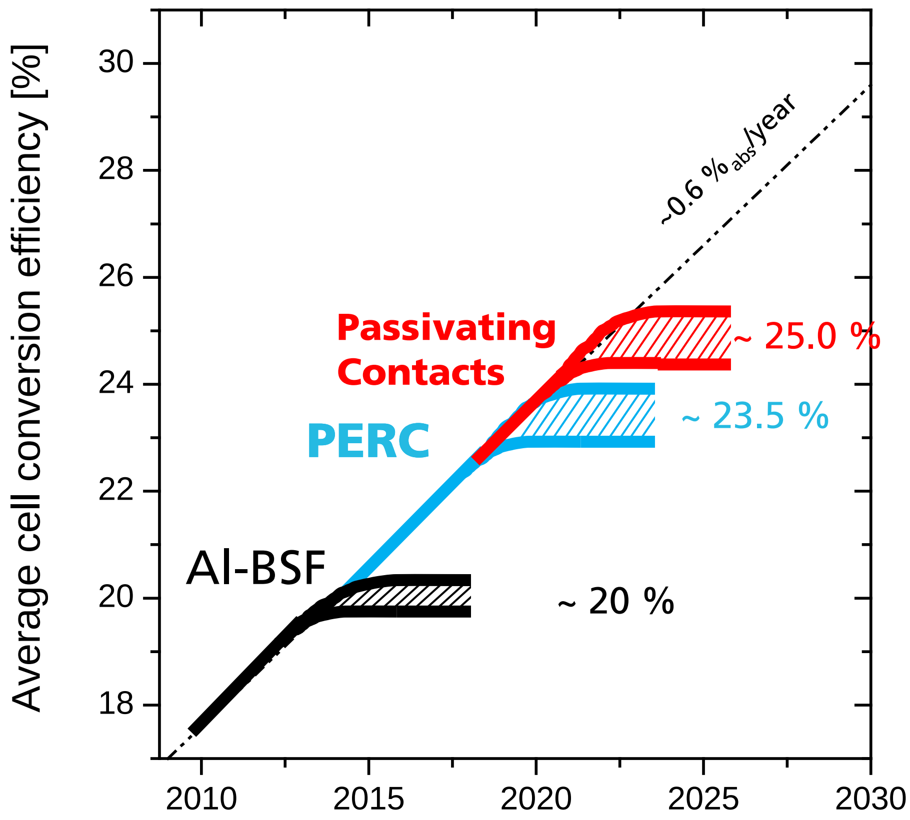
From Present to Future
Passivating Contacts – What is the limit

- Physical Limitations
  - Intrinsic Auger recombination, parasitic absorption and transport losses

→ Back Junction Back Contact



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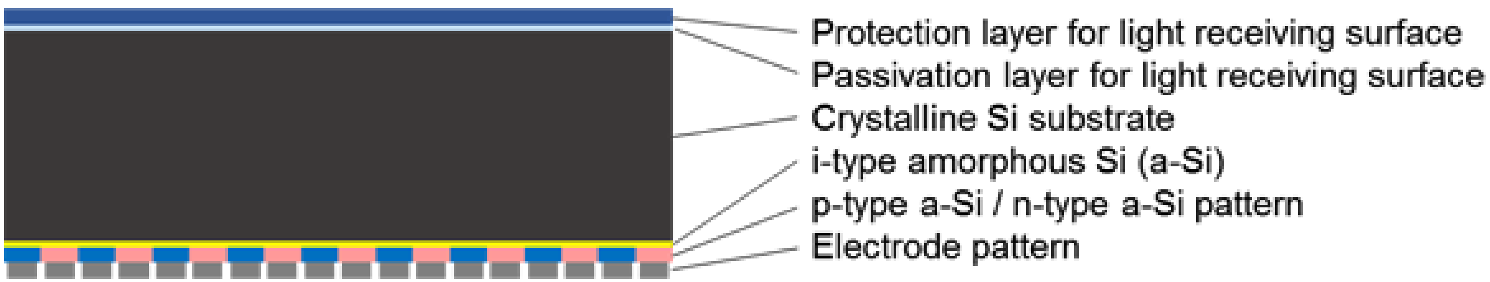
From Present to Future
Back Junction Back Contact with Passivating Contacts



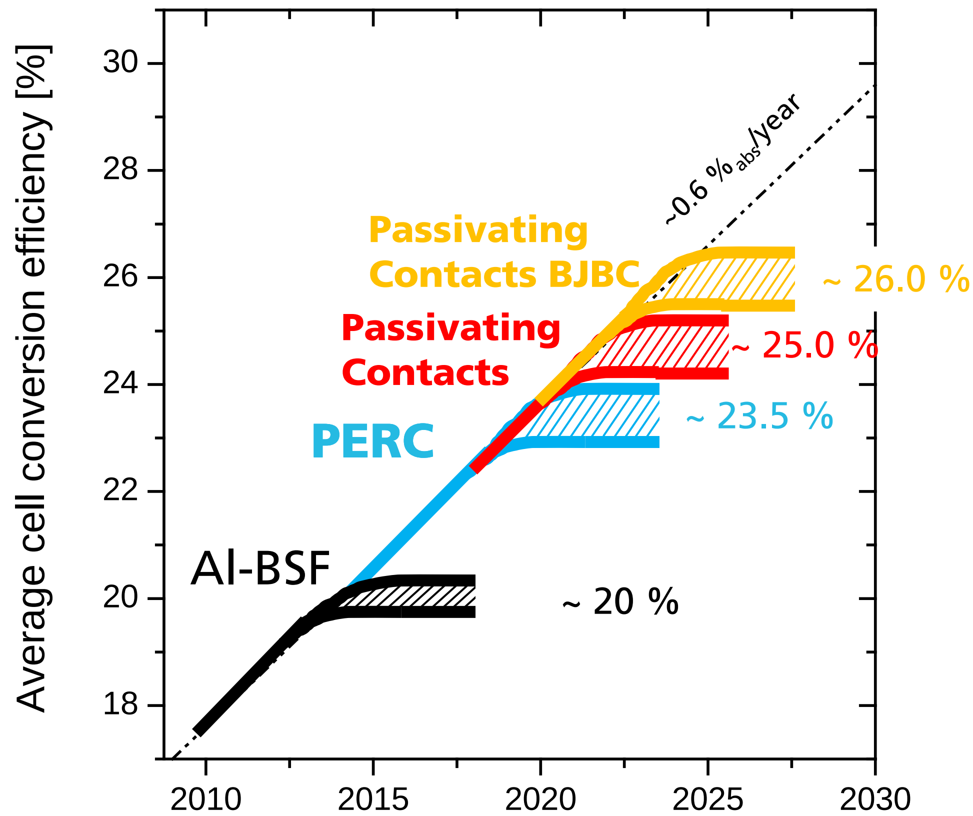
- ➔ Kaneka (Heterojunction) 26.6 % (180 cm^2 ,da)*
- ➔ Sunpower (Passivating contacts) 25.2 % (153 cm^2 ,ta)

* NATURE ENERGY 2, 17032 (2017) | DOI: 10.1038/nenergy.2017.32

From Present to Future
Back Junction Back Contact with Passivating Contacts

- Physical Limitations
  - Intrinsic Auger recombination, imperfect light trapping and transport losses

→ **And now ?**



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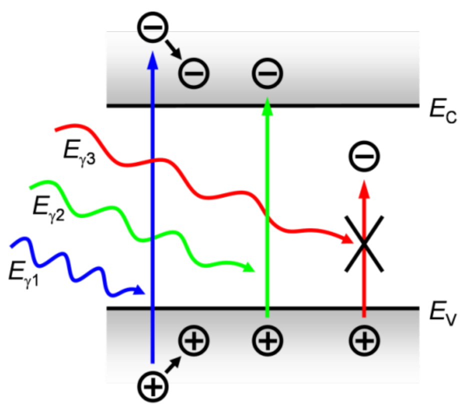
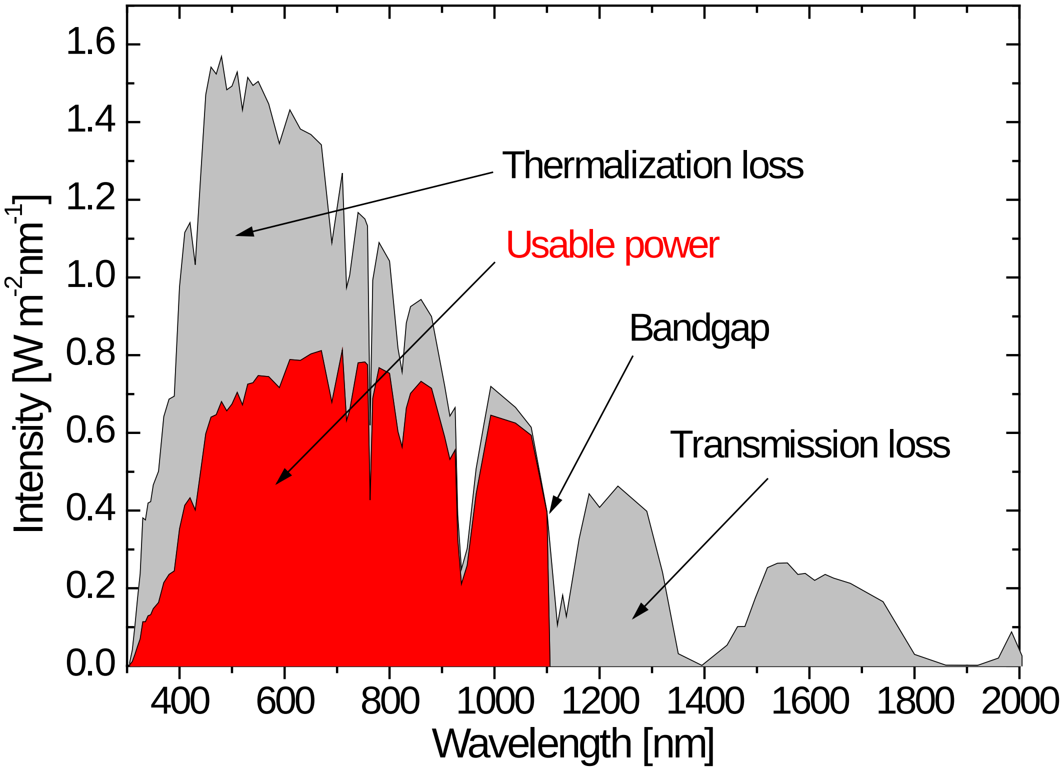
Future
What is the Limit of Silicon Solar Cells

- Shockley, Queisser (1961) Limit for Si 33% (AM1.5)
- Limitations by thermalization and transmission
- **Auger Limit 29.4 %[1]**





[1]Richter, Hermle, Glunz, *IEEE J. Photovolt.* (2013)

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Future
What is the Limit of Silicon Solar Cells

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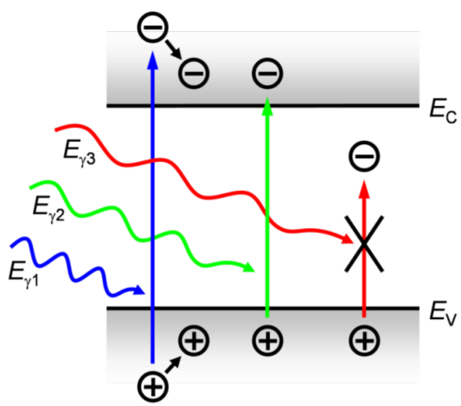
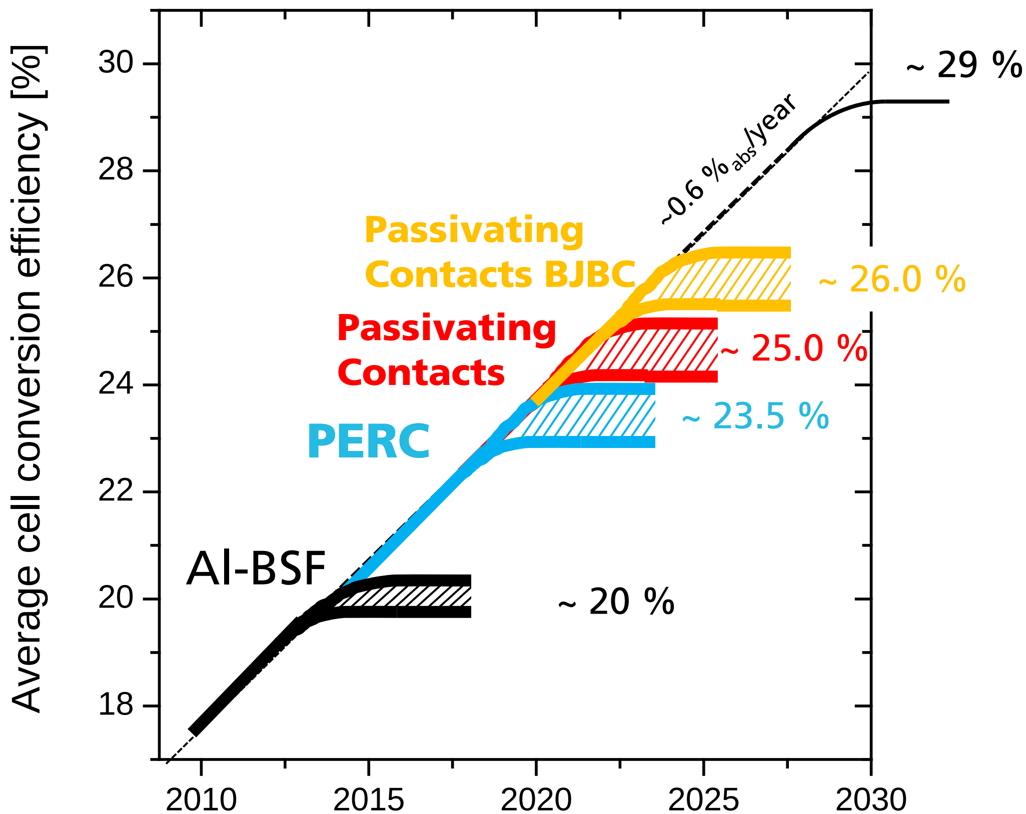
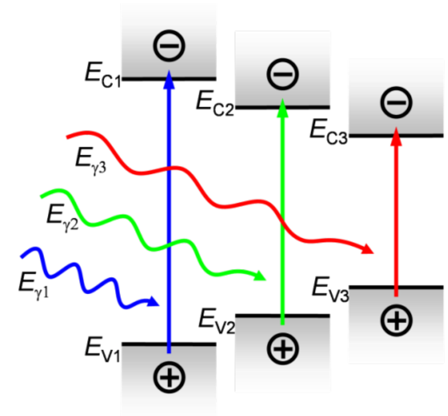




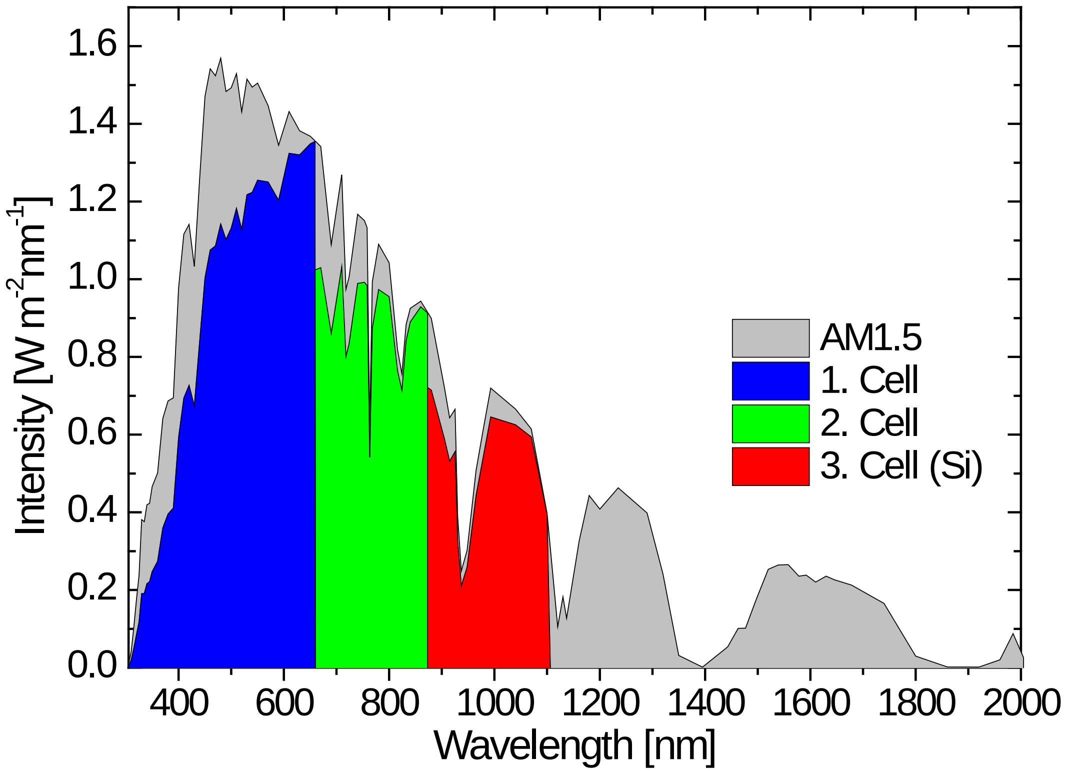
→ End of Silicon Solar Cell Technologies?

[1]Richter, Hermle, Glunz, *IEEE J. Photovolt.* (2013)

Future
Beyond the Single Junction-Limit



- Light management
  - Up-conversion
  - Down-conversion
- Tandem cells with silicon as bottom cell
  - Perovskite top cell
  - III/V top cell



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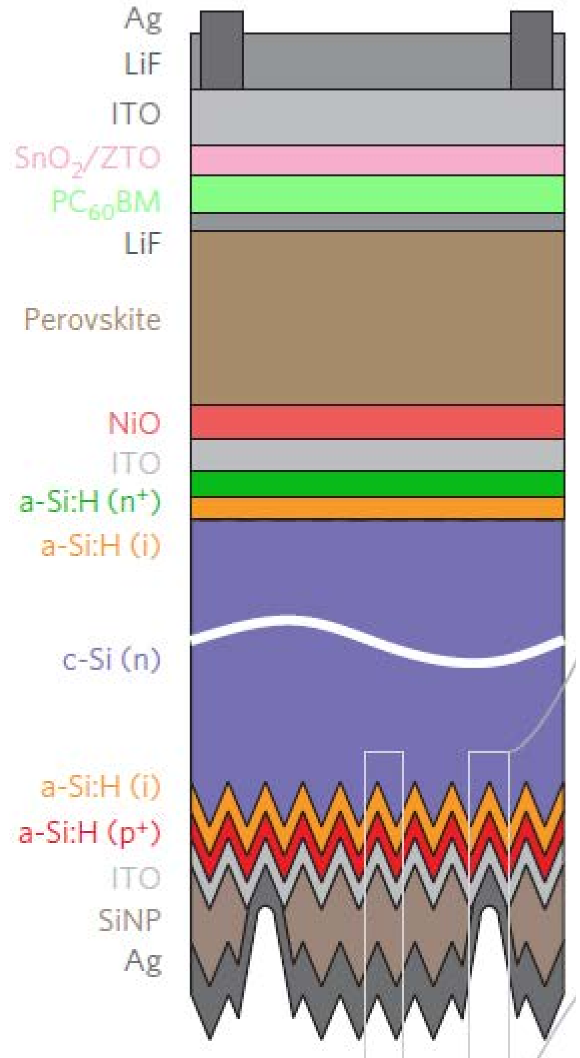
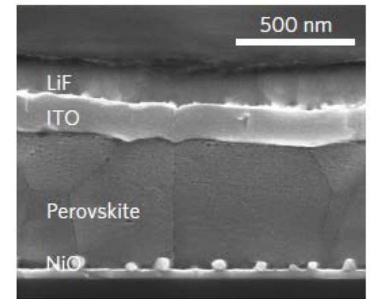
Future
Perovskite / Silicon Tandem

- Perovskite has a wide, tunable bandgap appropriate for a top cell
- Solution processability allows potentially cheap processes
- 23.6 %[1] achieved so far for monolithic 2 terminal devices





[1]*K. Bush et al. Nature Energy* **2**, Article number: 17009 (2017)doi:10.1038/nenergy.2017.9

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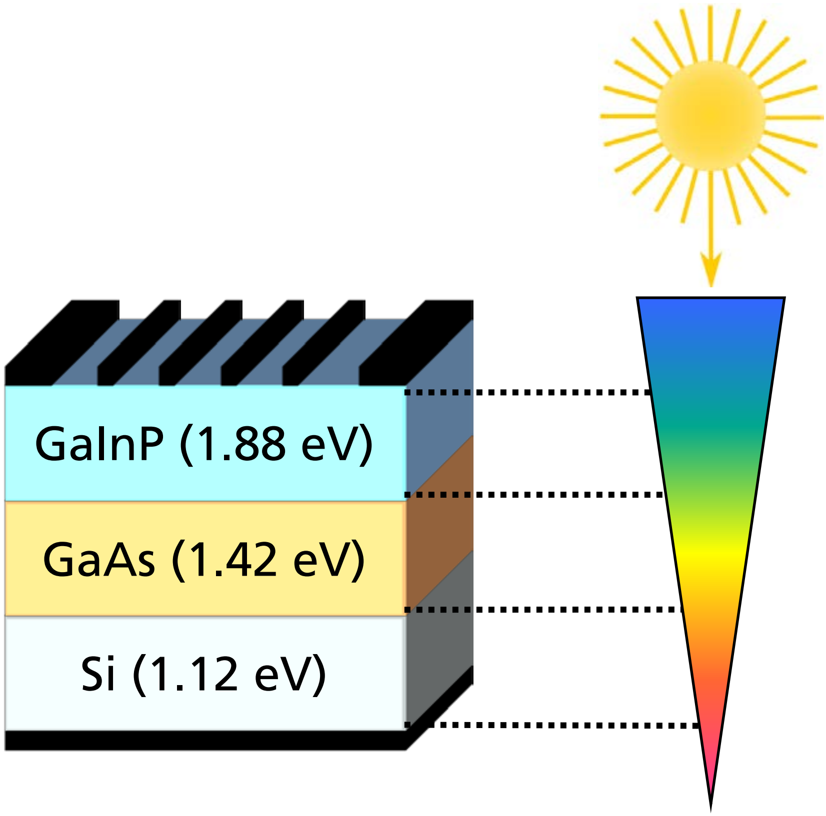
Future
III/V / Silicon Tandem

- III/V solar cells have already shown excellent efficiencies
- Deposition by direct epitaxial growth or wafer bonding



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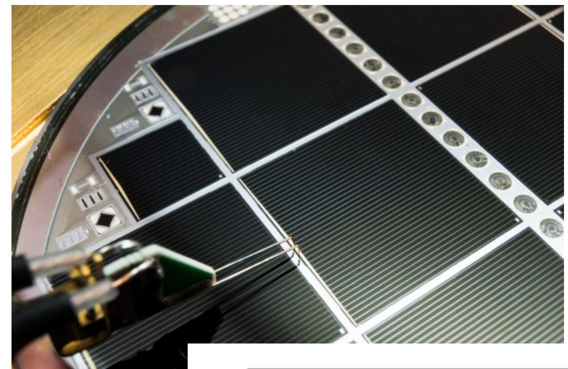
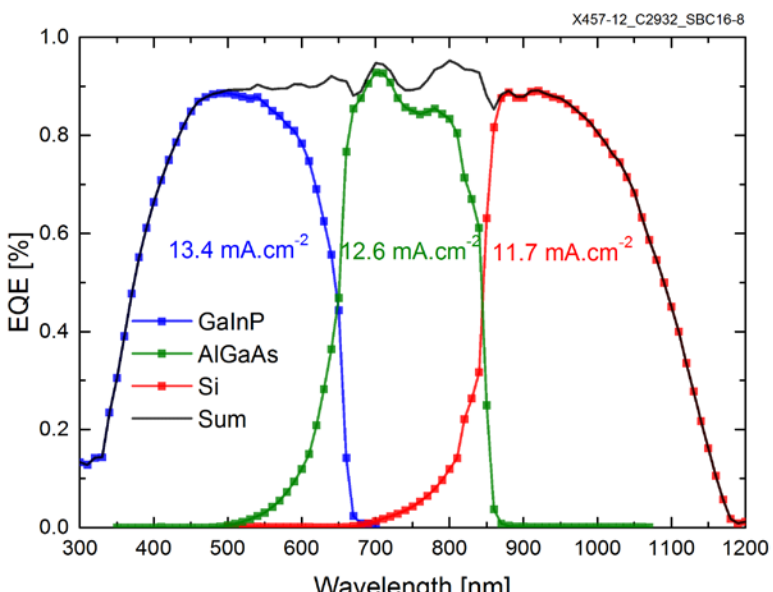
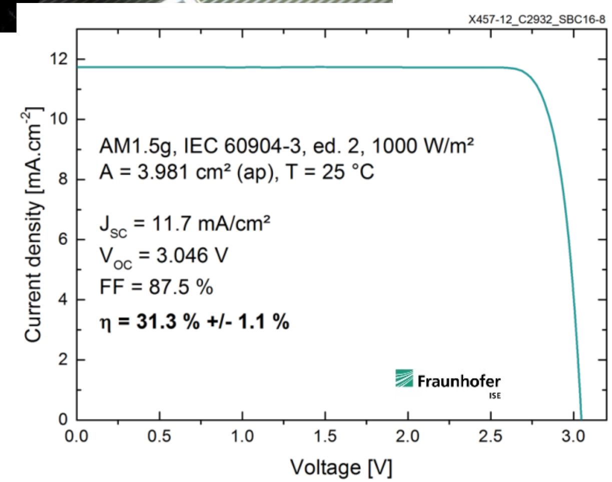
Beyond the Limit
2-terminal GaInP/AlGaAs//Si >30% @1-Sun AM1.5g

- Efficient utilization of spectrum
- Efficiency = 31.3%
- Near term potential above 35 %







R.Cariou et al **Monolithic III-V//Si Tandem Solar Cells with Efficiency > 30% Enabled by Wafer-Bonding** 7th Silicon PV, Freiburg, Germany, April 3, 2017

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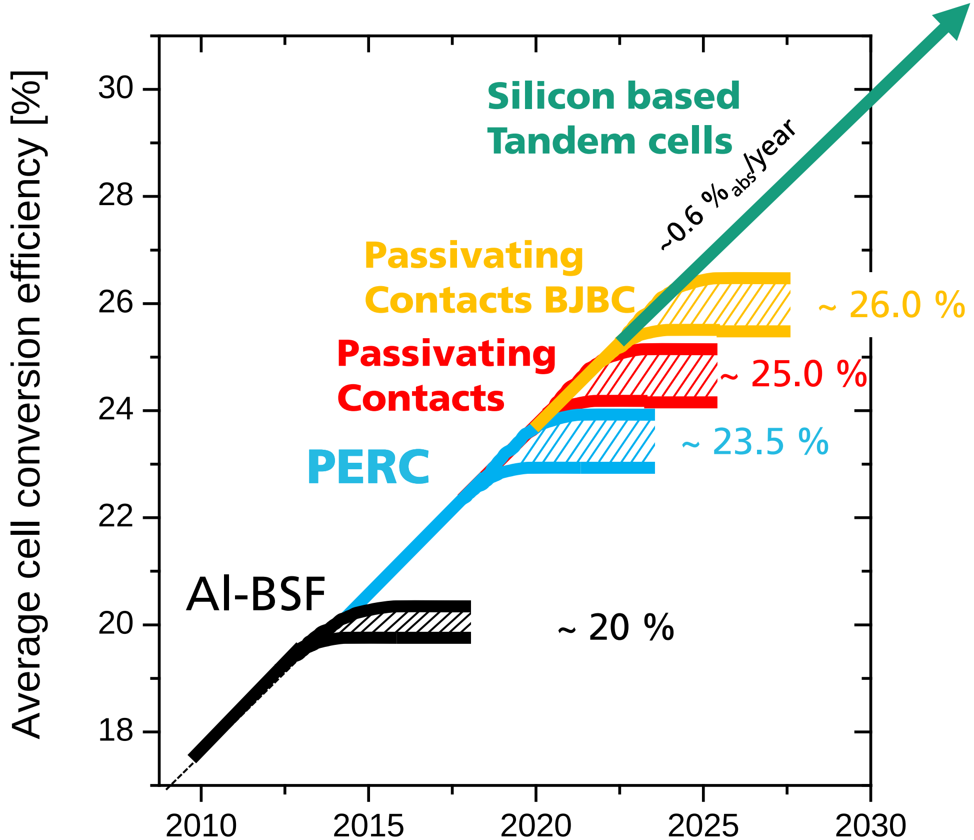
Beyond the Limit
Silicon Based Tandem Cells

→ **Silicon Solar Cell Technology has still a bright future**

→ **R&D is very important to stay on the efficiency "learning curve"**



Conclusion

- Silicon is it the working horse of Photovoltaic

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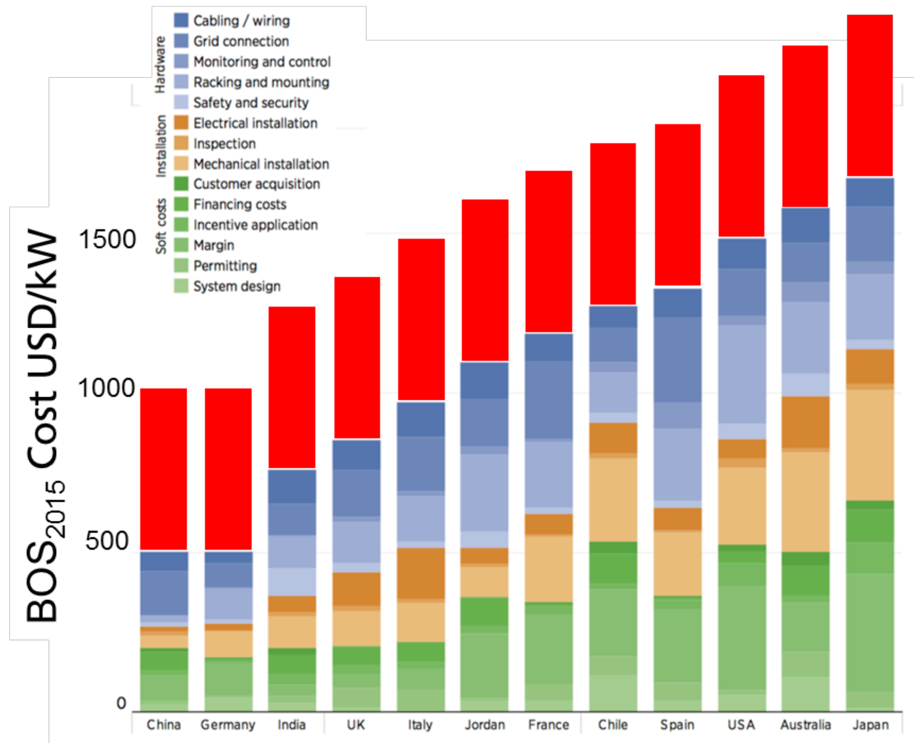
Conclusion

- Silicon is it the working horse of Photovoltaic
- Conversion efficiency is the key to further bring down the levelized costs of electricity and to survive competition.



Conclusion

- Silicon is it the working horse of Photovoltaic
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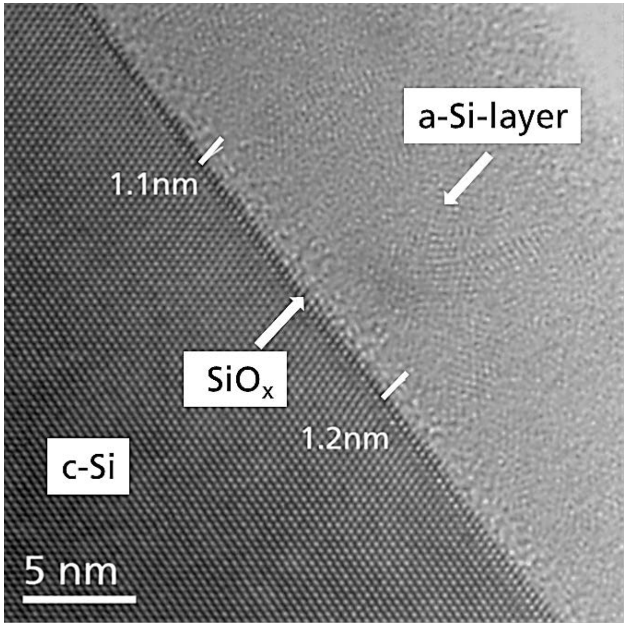
- New cell structures with high industrial potential are available



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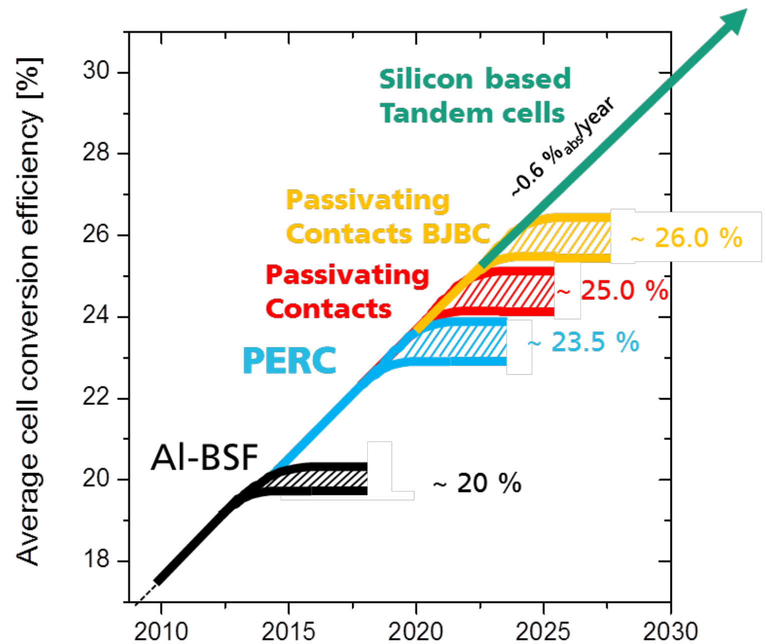
Conclusion

- Silicon is it the working horse of Photovoltaic
- Conversion efficiency is the key to further bring down the levelized costs of electricity and to survive competition.
- New cell structures with high industrial potential are available
- New fascinating concepts for an old technology: Crystalline silicon solar cells **2.0**



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   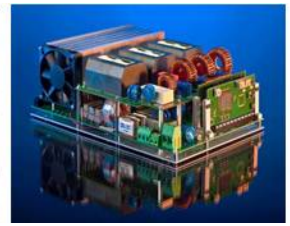 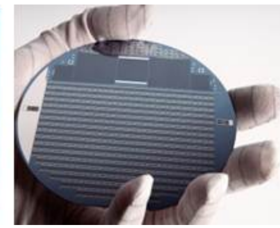 

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