SILICON SOLAR CELLS – CURRENT PRODUCTION AND FUTURE CONCEPTS

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Solar Energy Systems ISE

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BESSY II Foresight Workshop on
Energy Materials Research

Berlin

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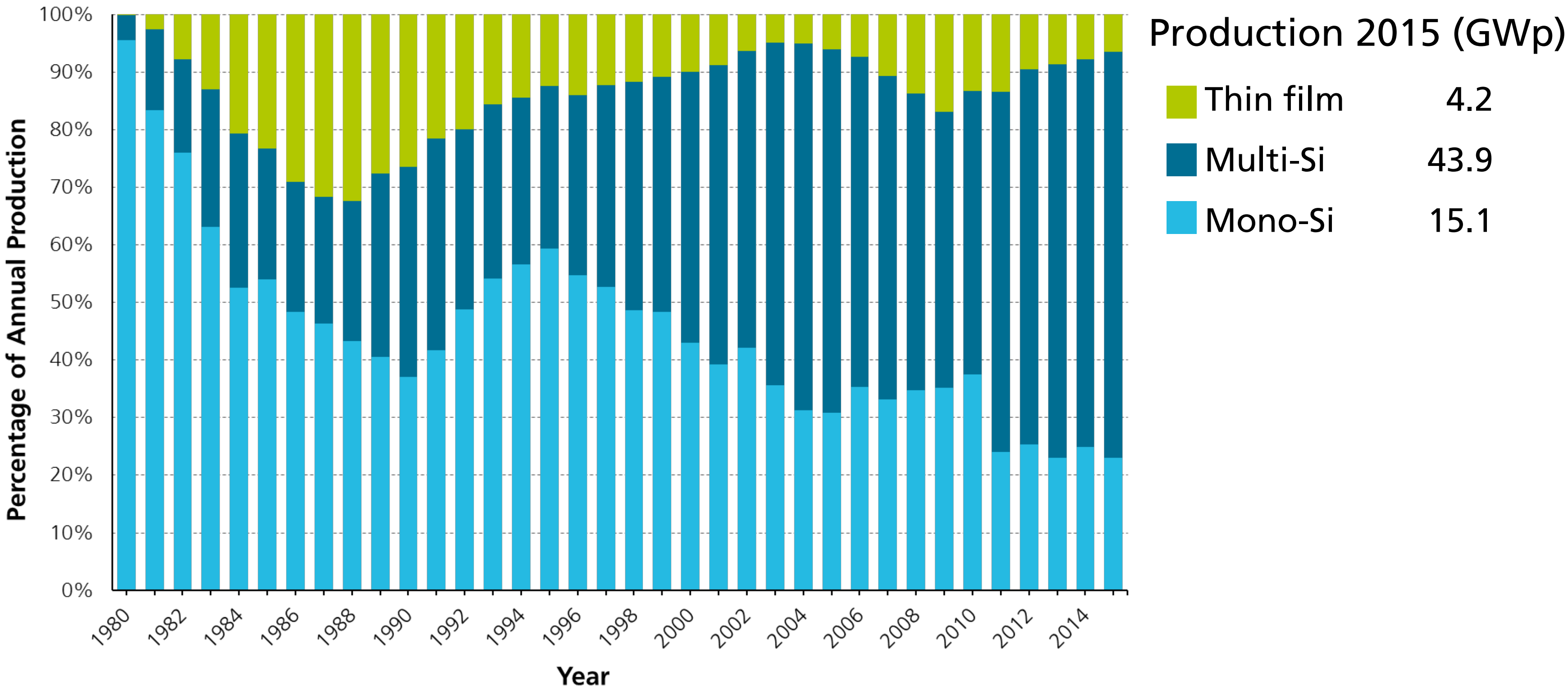
PV Module Production Development by Technology

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

- PAST
  - The early days in the Bell labs
  - Increasing efficiencies and the battle between materials
- PRESENT
  - Current production of silicon solar cells
  - Surviving in the days of overcapacity
  - New cell types
- FUTURE
  - A new generation of silicon solar cells

PAST
The Bell Labs 1954

Cross section of the first cell:

- Arsenic-doped n-type base
- Boron-diffused emitter
- Back contact structure

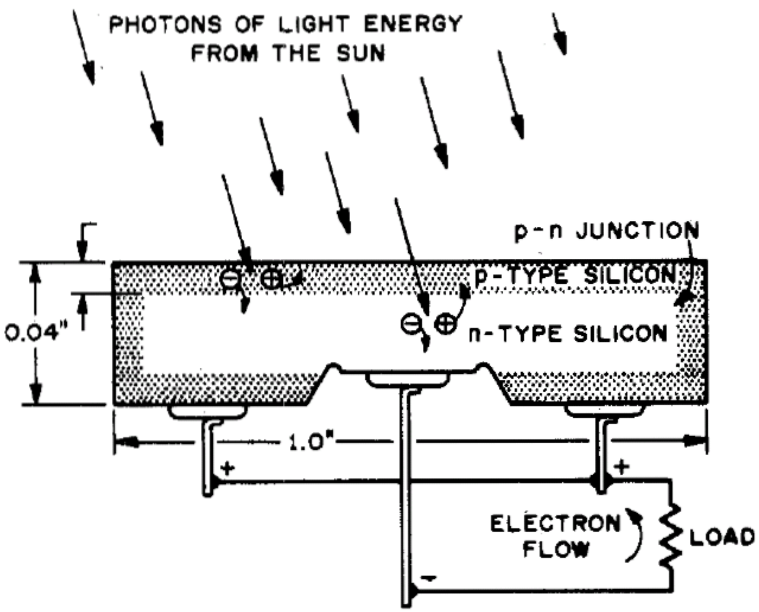


Fig. 2. Schematic of early silicon solar cell [8].

The first publication in Journal of Applied Physics:

A New Silicon *p-n* Junction Photocell for Converting Solar Radiation into Electrical Power

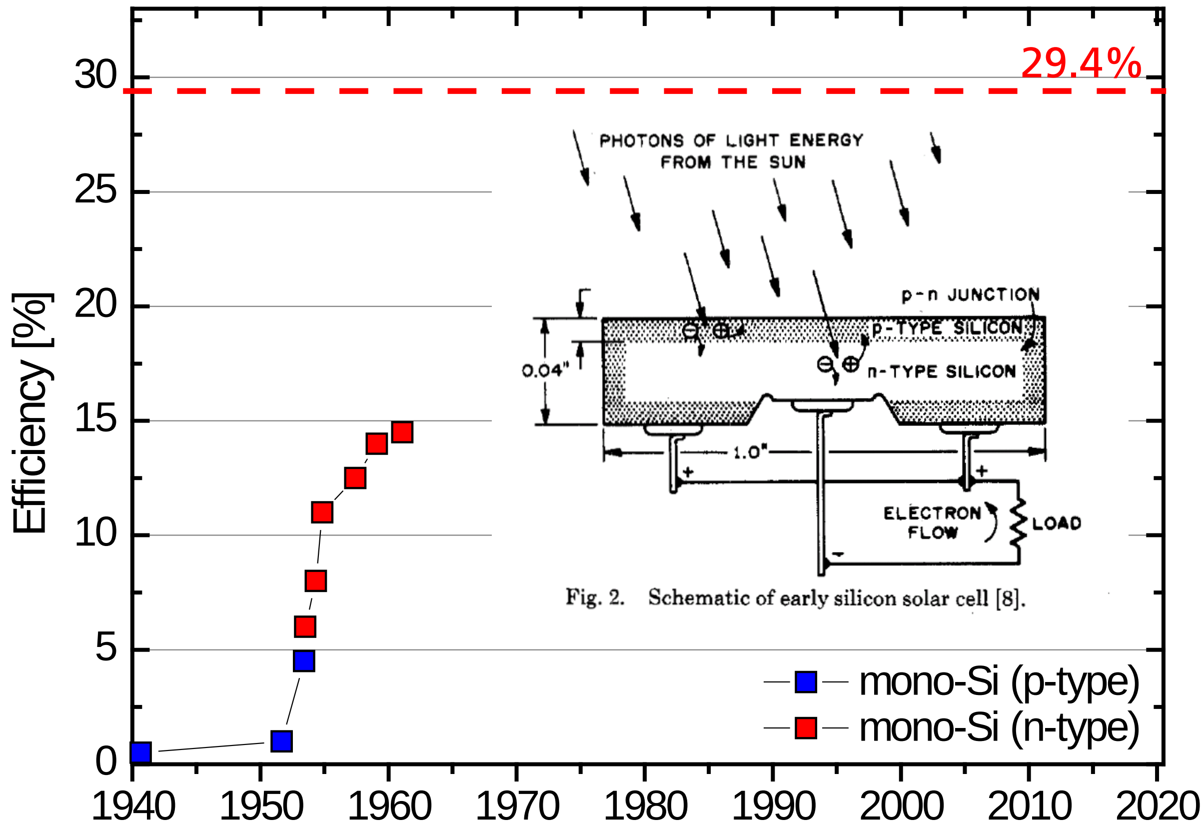
D. M. Chapin, C. S. Fuller, and G. L. Pearson
Bell Telephone Laboratories, Inc., Murray Hill, New Jersey

(Received January 11, 1954)

THE direct conversion of solar radiation into electrical power by means of a photocell appears more promising as a result of recent work on silicon *p-n* junctions. Because the radiant energy is used without first being converted to heat, the theoretical efficiency is high.

PAST
The Beginning

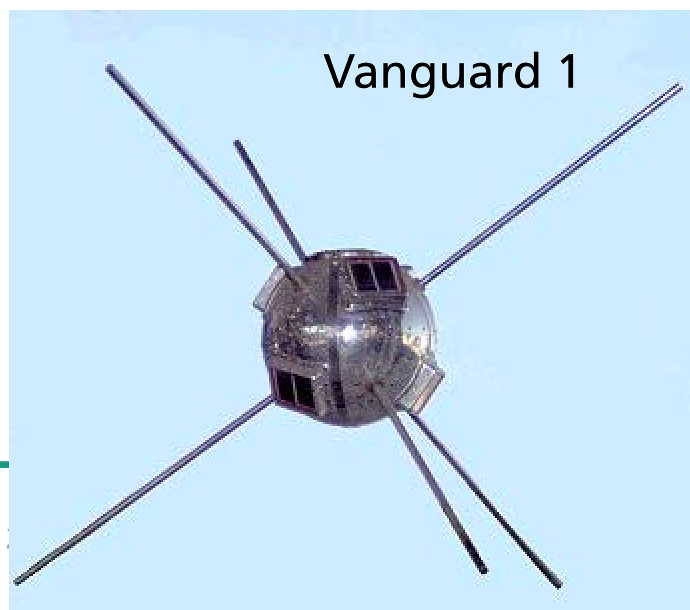
- Strong increase of efficiency in the 1950s
- n-type silicon dominates as base material



PAST
The First Application → Space

- 1957 Sputnik (USSR)
- 1958 Explorer 1 (USA)
- 1958 Vanguard
  First solar-powered
  satellite

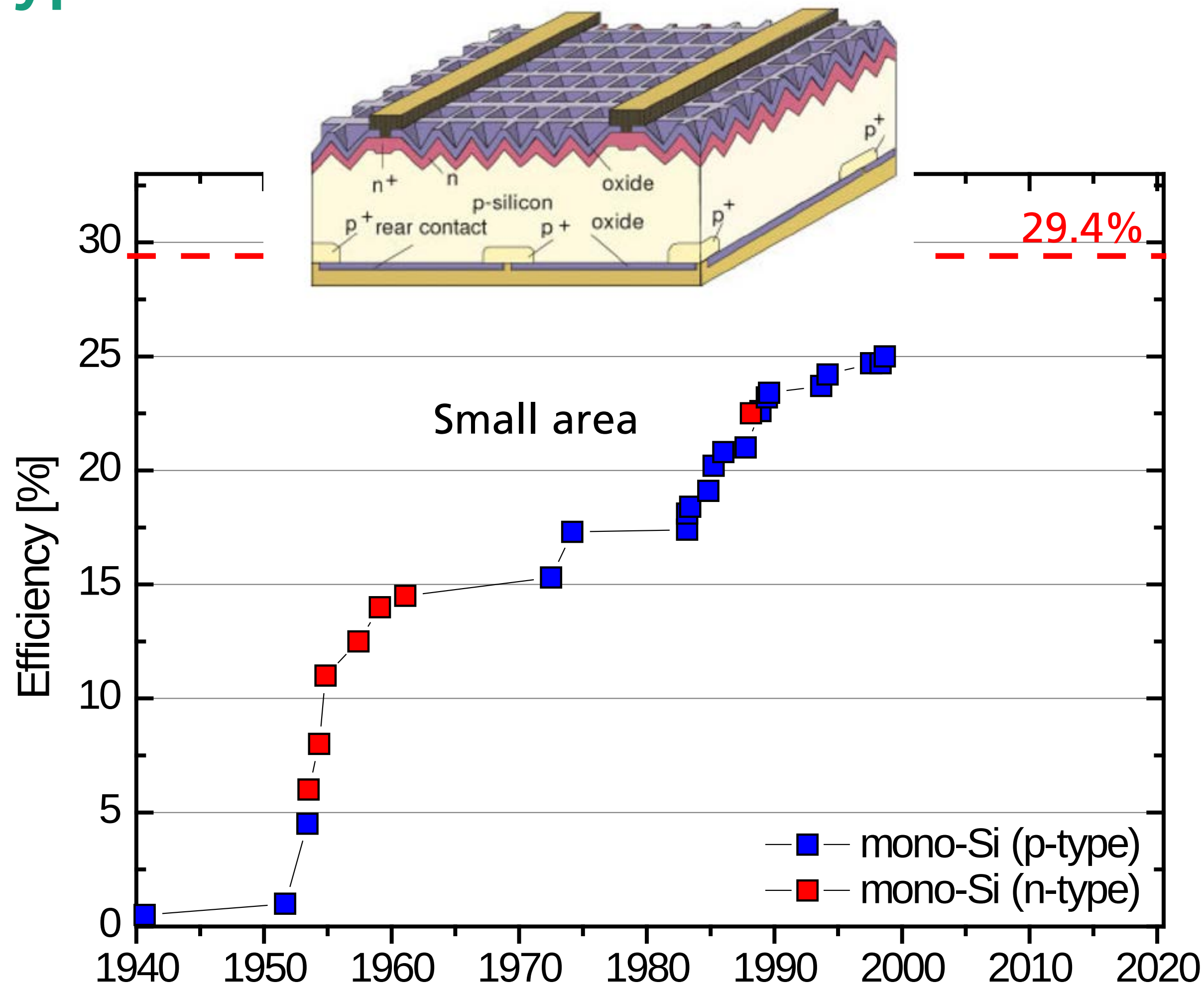
Sputnik 1



Vanguard 1

PAST
From n-type to p-type

- Switch to p-type silicon due to higher radiation stability for space applications
- Reduction of recombination losses
- Model for current industrial cell generation



PAST

From Space to Earth
Niche Markets

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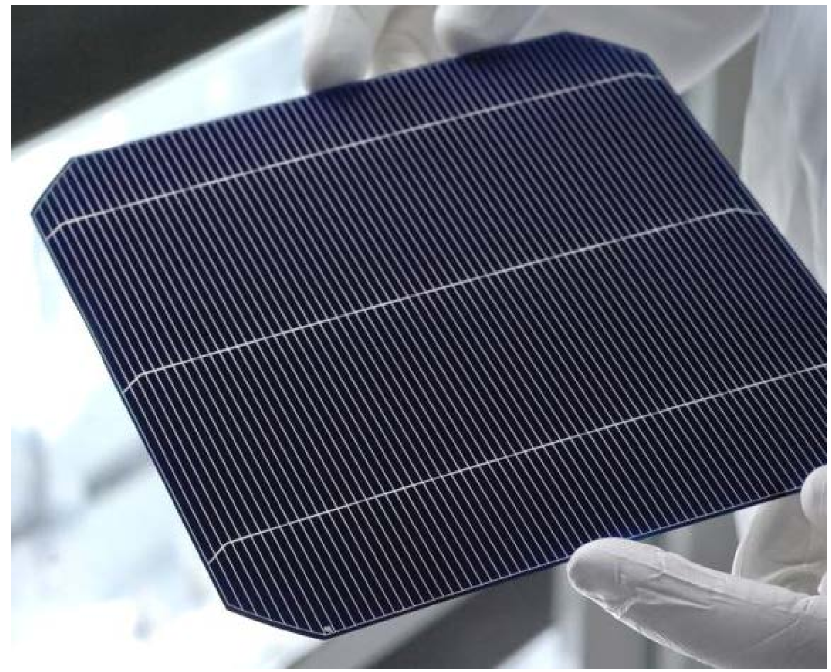
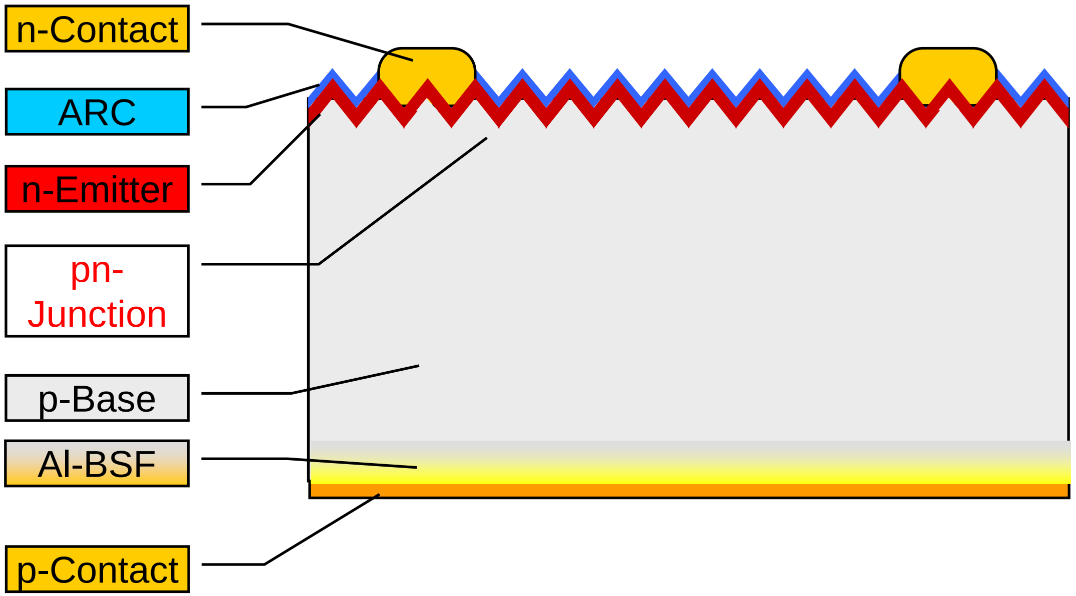
PRESENT
Grid-connected Mass Market



PRESENT
Screen-printed Al-BSF solar cell on p-type silicon

- Still the main technology of the PV technology (> 60 % of the market)
- Efficiency up to 20 %



Process

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PRESENT

The main driver of PV technology → the working horse

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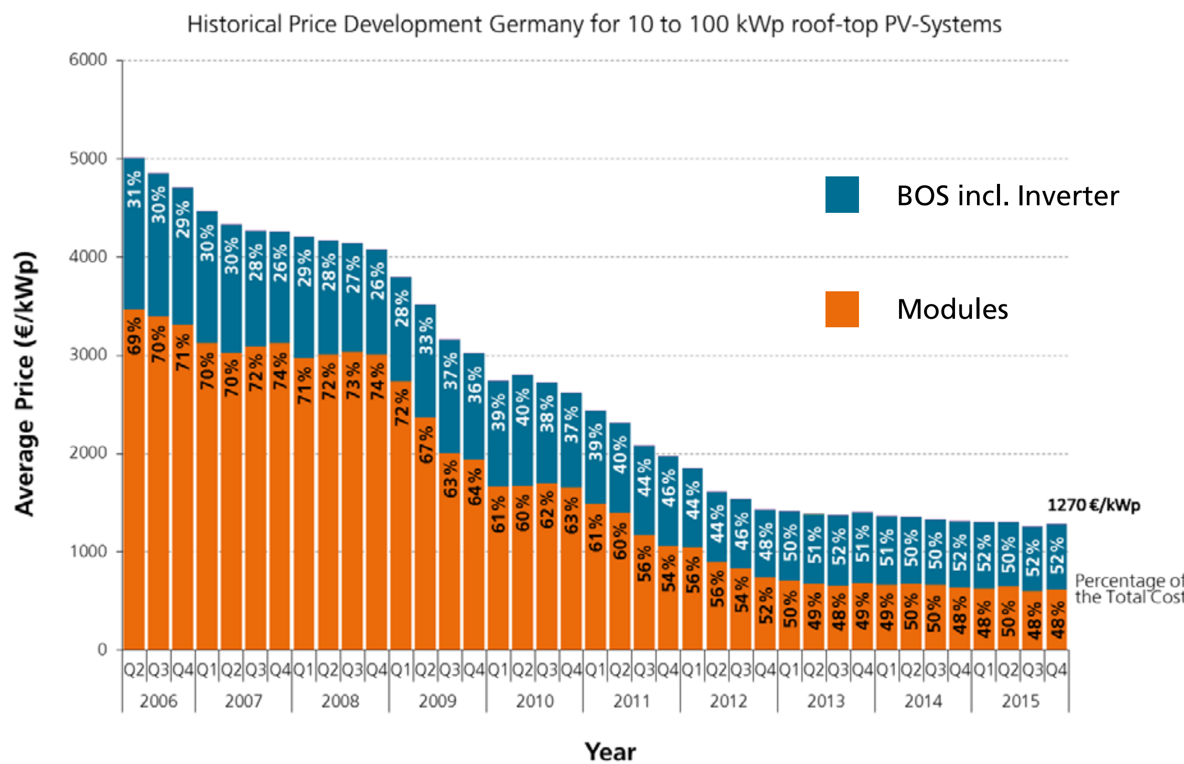
Present

Average Price for PV Rooftop Systems in Germany

- Share of Balance of System costs (**BOS**) increases from 31 % in 2006 to now about **52 %**
- Large fraction of system cost scale with the **solar cell efficiency**



→ **High efficient solar cells reduces your system cost**

Data: BSW-Solar. Graph: PSE AG 2016

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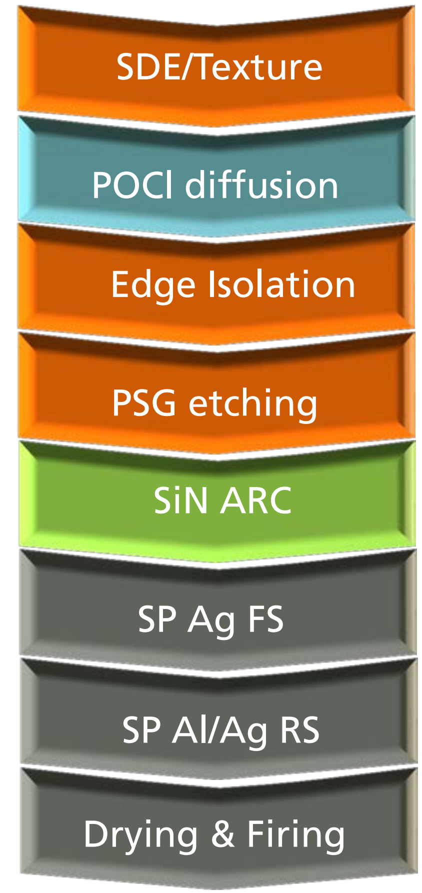
Why Going to High Efficiencies?
Levelized Cost of Electricity (LCOE)

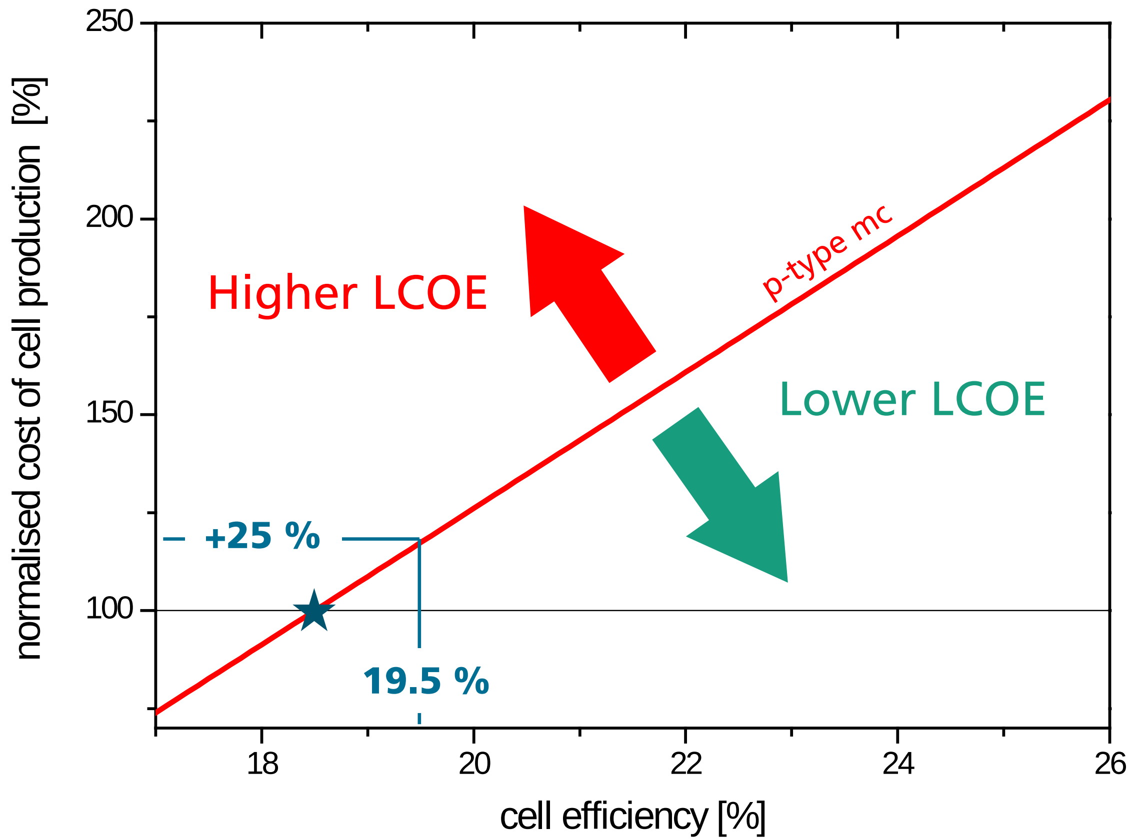
- What really matters are the Levelized Cost of Electricity (LCOE)
- To rate new solar cell concepts, they have to be compared with the LCOE of the **p-type mc Al-BSF cell**
- Reference system:
  - p-type mc Al-BSF cell
    (> 60 % of total PV production)
  - Cell efficiency 18.5 %
  - 900 kWh/kWp, 25 years



LCOE<10 €ct/kWh

Why Going to High Efficiencies?
Efficiency versus Cost

- Calculation of additional costs in cell production to get the same LCOE with simplified model: **Allowable system costs (except inverter) scale with efficiency**
- Rule of thumb:
  - 1 % gain in η
  - ~ + 25 % cell processing costs



More detailed model: S.Nold et al. , EUPVSEC 2012

PRESENT
Price trend for Silicon Wafer: mc versus Cz Silicon

- Price difference between Mono and Multi strongly increased in 2016
- CoO for cell production of Al-BSF cells less than 45 $ct/cell
- Efficiency difference can currently not compensate the cost difference in wafer

Wafer	01/16 [$]	10/16 [$]
156 mm Multi Solar Wafer	0.89	0.52
156 mm Mono Solar Wafer	0.9	0.65
Difference	**0.01**	**0.13**

www.pvinsights.com

PRESENT

Price trend for Silicon Modules

- Strong decrease in module price the last 10 month
- Overcappacity lead to a strong price reduction

Origin of Module	€ / Wp	Trend since January 2016
Germany	0.53	-10,17 %
Japan, Korea	0.63	-4,55 %
China	0.51	-8,93 %
South Asia , Taiwan	0.47	-2,08 %

Challenges for the future

- Higher efficiencies
- No significant increase of production costs
- Scale

www.pvxchange.com

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Large-area Record Cells on n-type Silicon

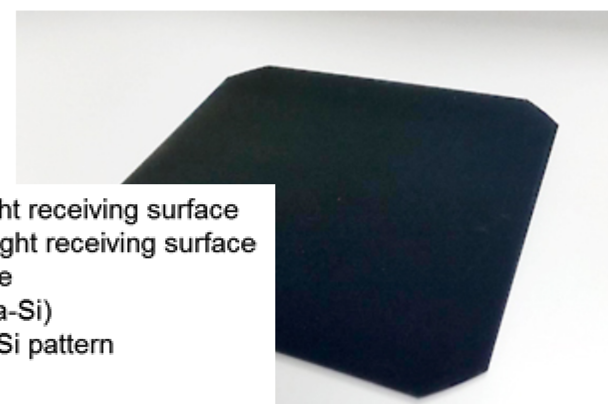
- Kaneka shows efficiency **breakthrough** for silicon solar cells
- **26.33 % n-type IBC solar cell**

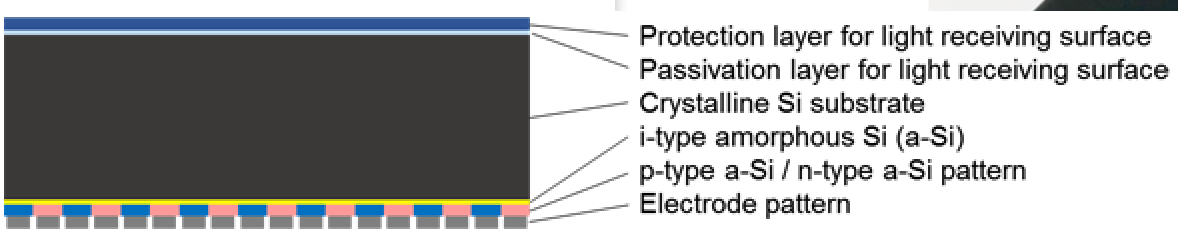
News Release

World's Highest Conversion Efficiency of 26.33% Achieved in a Crystalline Silicon Solar Cell
—A World First in a Practical Cell Size—

September 14,2016
New Energy and Industrial Technology Development Organization (NEDO)
Kaneka Corporation

Kaneka Corporation has achieved in a NEDO project the world's highest conversion efficiency of 26.33% in a practical size (180 cm^2) crystalline silicon solar cell.
This record-breaking result will advance technical development of crystalline silicon solar cells and contribute significantly to reducing the cost of power generation through use of high-efficiency solar cells.





http://www.nedo.go.jp/english/news/AA5en_100109.html

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The Return of *n*-type Silicon

- Large-area record cells are all n Type IBC solar cells (Kaneka,Sunpower, Sanyo/Panasonic)
- Extremely high lifetimes needed (>> 1 ms)
- The return of *n*-type silicon ?

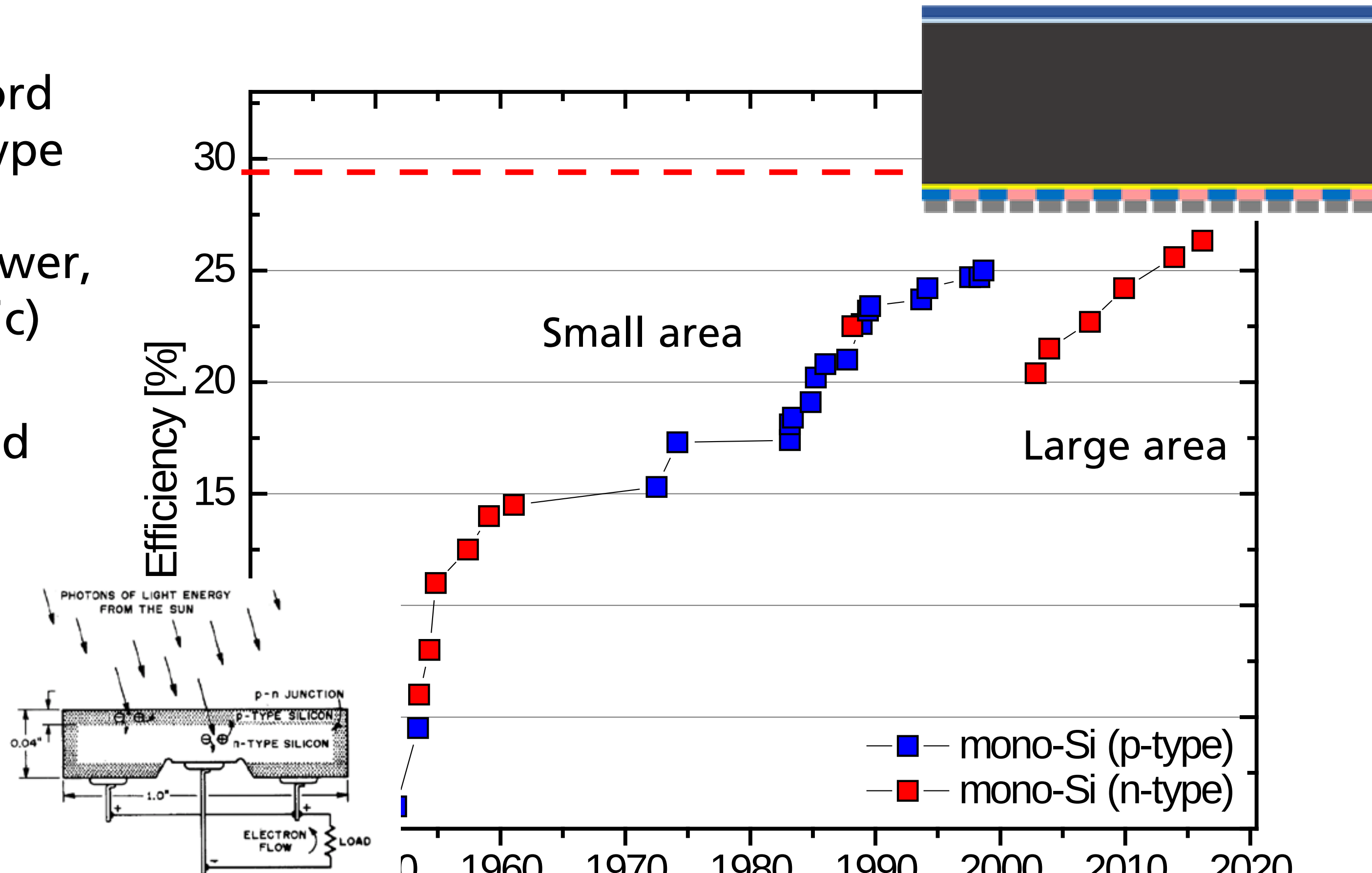

Fig. 2. Schematic of early silicon solar cell [8].

PRESENT
n-type BJ-BC cell with Passivated Contacts
→ the racehorse

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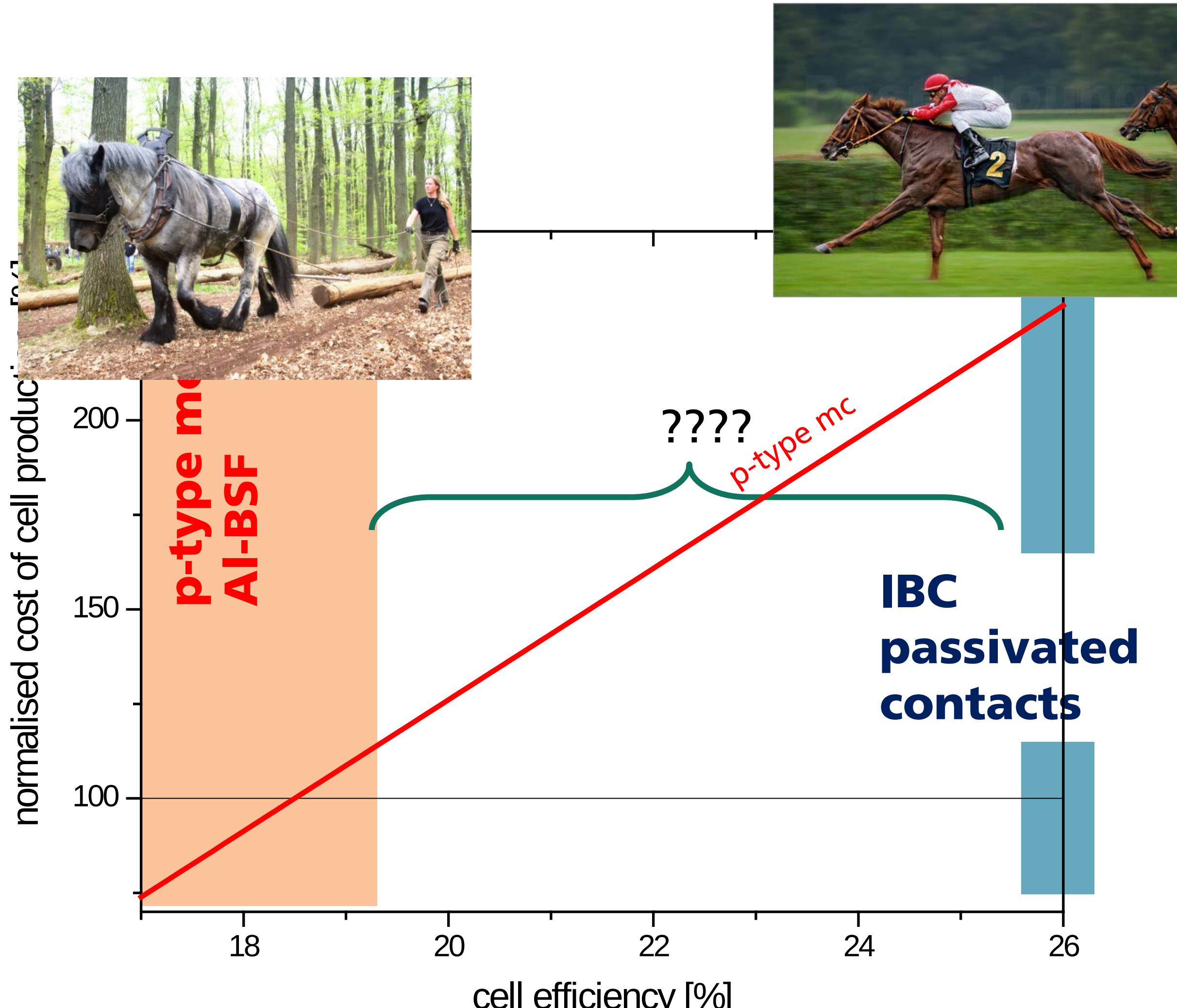
Bridging the Gap

- Can such cell realized without a significant increase of production costs ?
- Which technologies will go into the gap ?
- Bridging the gap:
  - Higher efficiency
  - Reasonable complexity



M. Hermle et. al., *29th EUPVSC 2014.*

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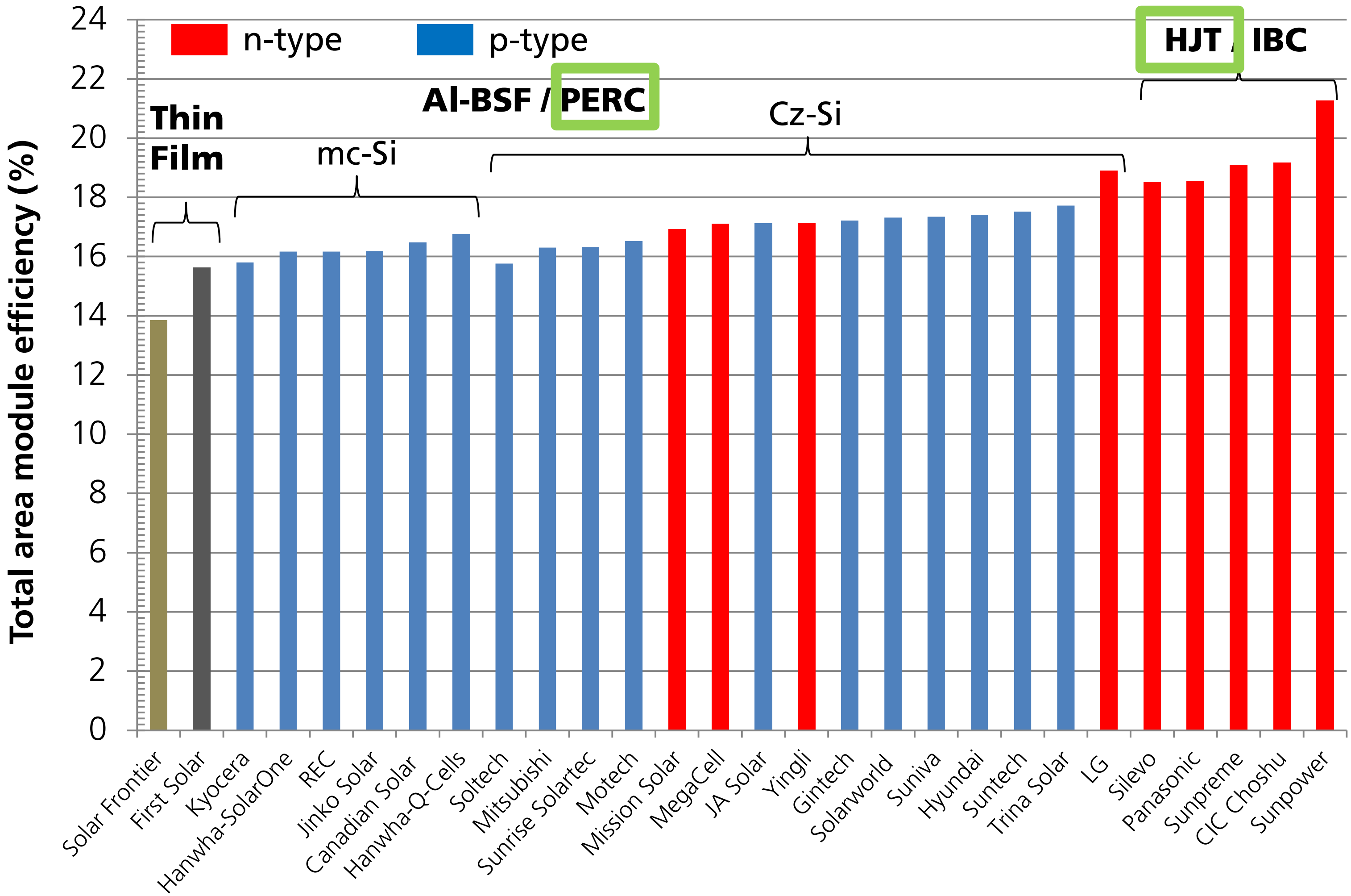
Current Efficiencies of Selected Commercial PV Modules

Sorted by Bulk Material, Cell Concept and Efficiency



Note: Exemplary overview without claim to completeness; Selection is primarily based on modules with highest efficiency of their class and proprietary cell concepts produced by vertically integrated PV cell and module manufacturers; Graph: Jochen Rentsch, Fraunhofer ISE. Source: Company product data sheets. Last update: Nov. 2015.

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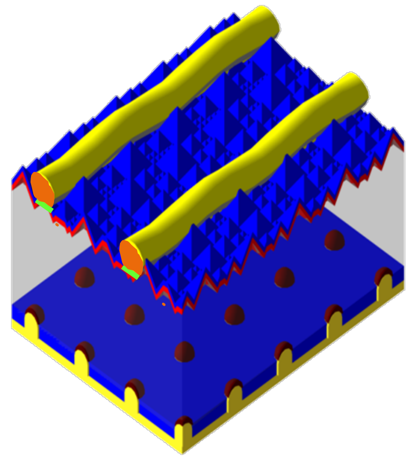
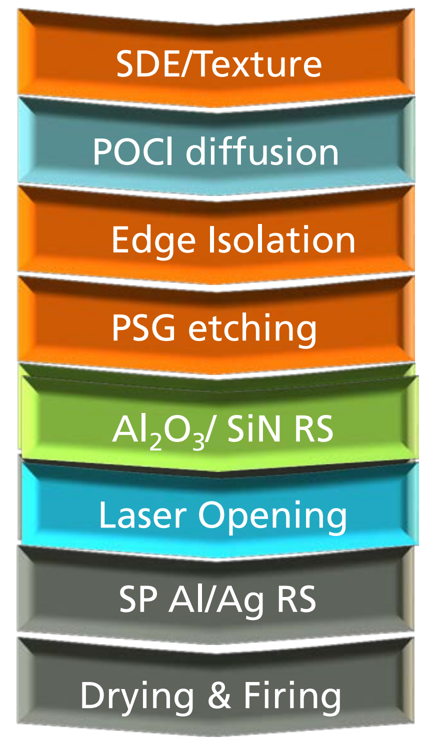
The Next Industrial Cell Generation: PRC Cells

- Replacement of the full area Al-BSF with **partial rear contacts (PRC)**
- Two additional process steps
  - Dielectric passivation
  - Local contact opening (LCO) or Laser fired contact (LFC)
- **Advantage:**
  - Excising lines can be upgraded
  - Can be used for **mc** und **Cz** silicon





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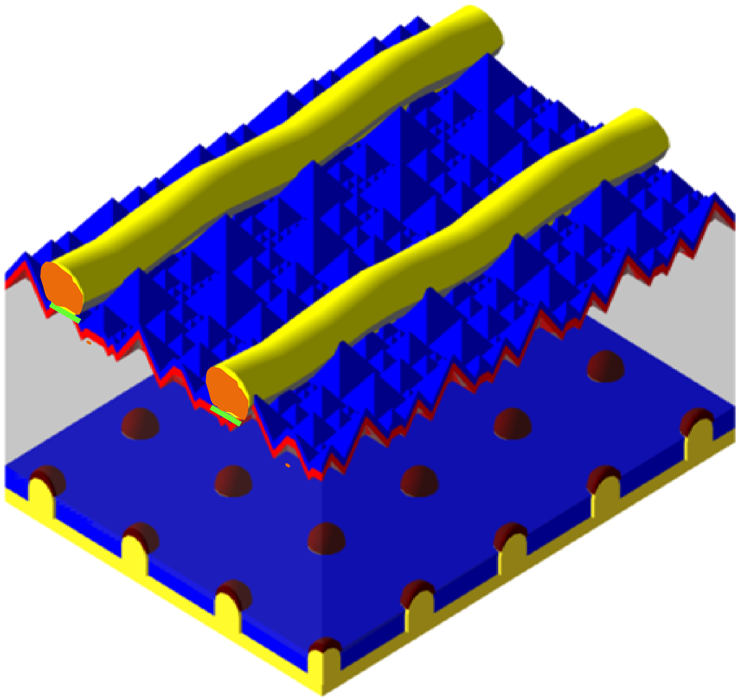
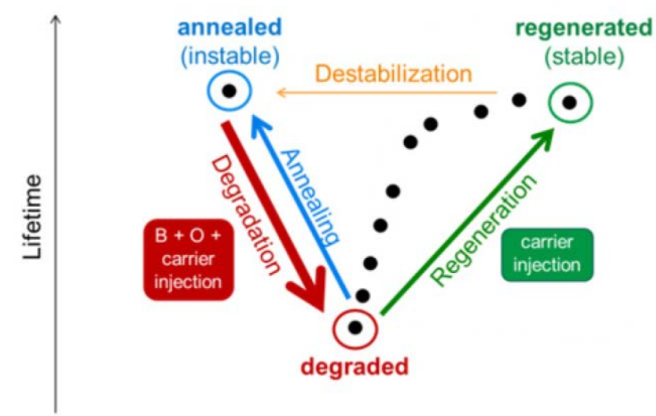
The Next Industrial Cell Generation: PRC Cells

- PERC is currently replacing the Al-BSF cells (25 years after its invention!)
- Record industrial results:
  - p-type mono-Si:
    22.1% (Trina)
    22.0% (Solar World)
  - p-type multi-Si
    21.25% (Trina)



PRESENT
The Next Industrial Cell Generation: PRC Cells

- Degradation mechanism limiting industrial efficiency
- Cz-Silicon: Boron Oxygen defect limits liftime
  - Regeneration can be used to recover the material[2]
- mc-Silicon: Light and elevated Temperature Induced Degradation (LeTID) [1]

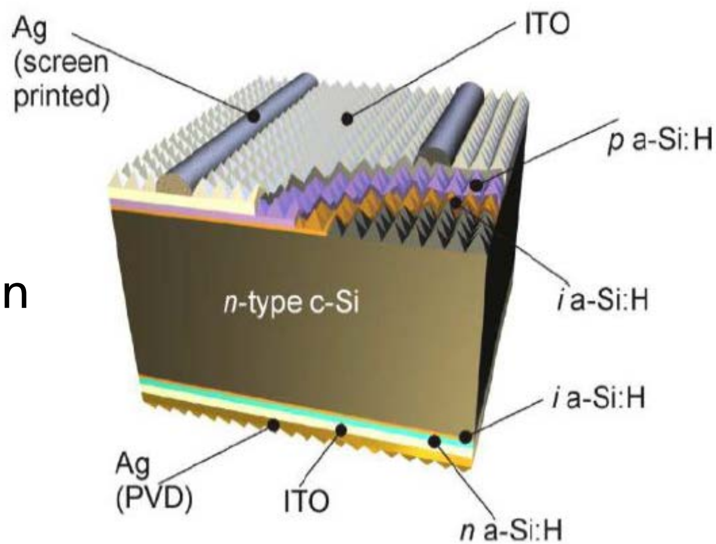


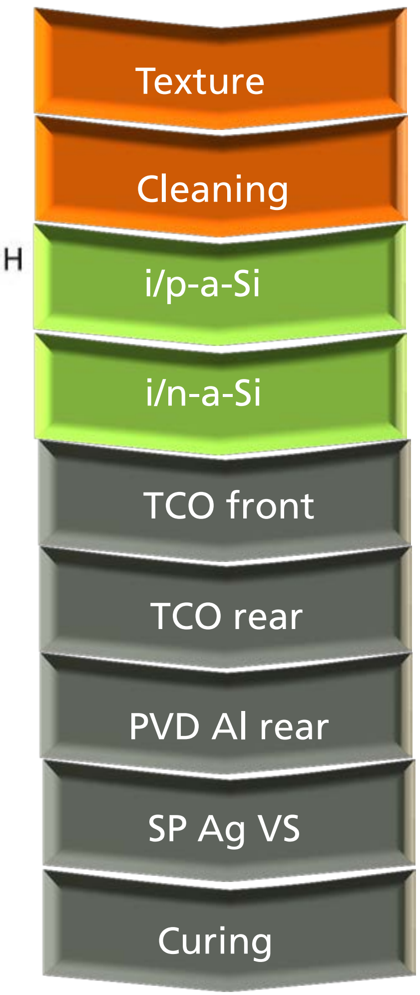
[1]S.Kersten et al. Solar Energy Materials and Solar Cells Volume 142, Pages 83–86

[2]S. Wilking et al EU-PVSEC 2014

PRESENT
The Next Industrial Cell Generation: Heterojunction

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





from: D.Bätzner Silicon PV 2014

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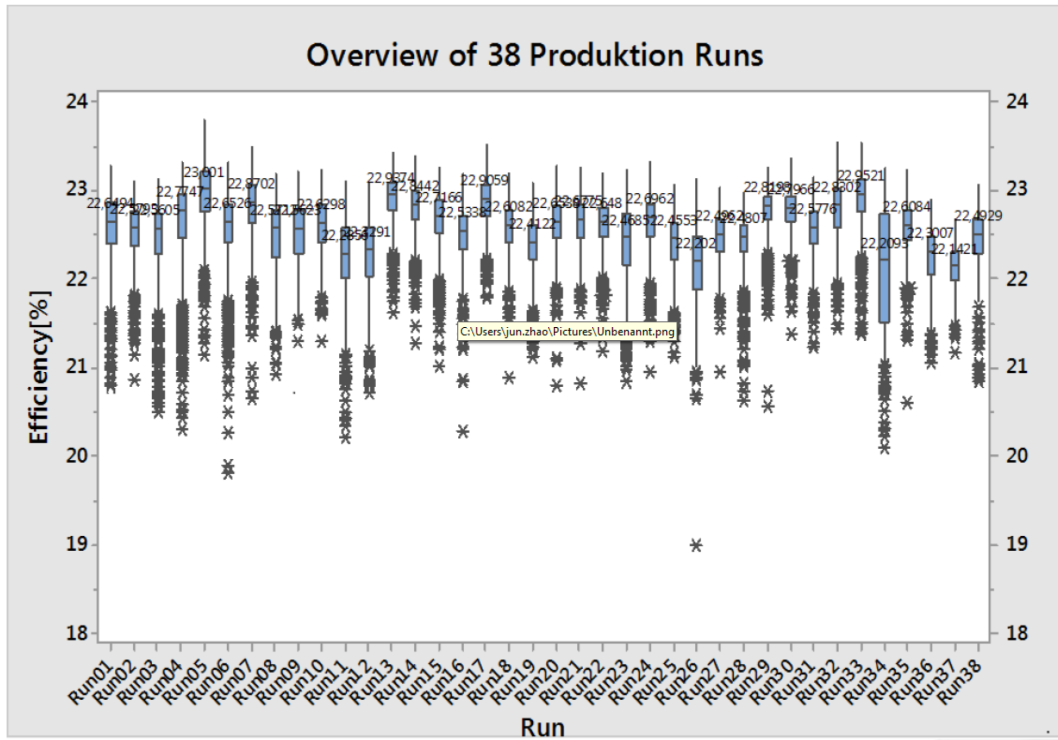
The Next Industrial Cell Generation: Heterojunction?

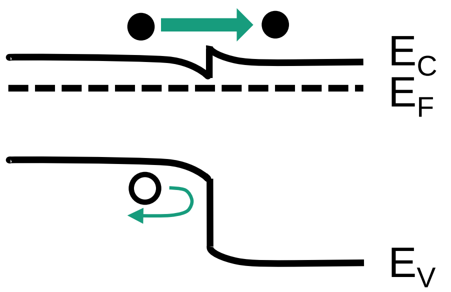
- Record efficiency for both side contacted HJ Solar cells 25.1 % from Kaneka
- Pilot line results form MEYER BURGER

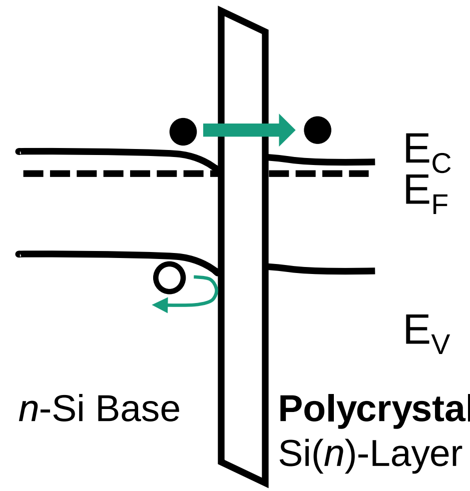
MEYER BURGER



from: T. Söderström, Metalliszation Workshop 2016

PRESENT
Alternative passivated contacts





- a-Si(*i*)/a-Si(*n*) Hetero
- Excellent selectivity
- Low thermal stability

- Tunnel oxide/Polysilicon
- Excellent selectivity
- Better thermal stability

F. Lindholm et al, IEEE Electron Device Letters, (1985)

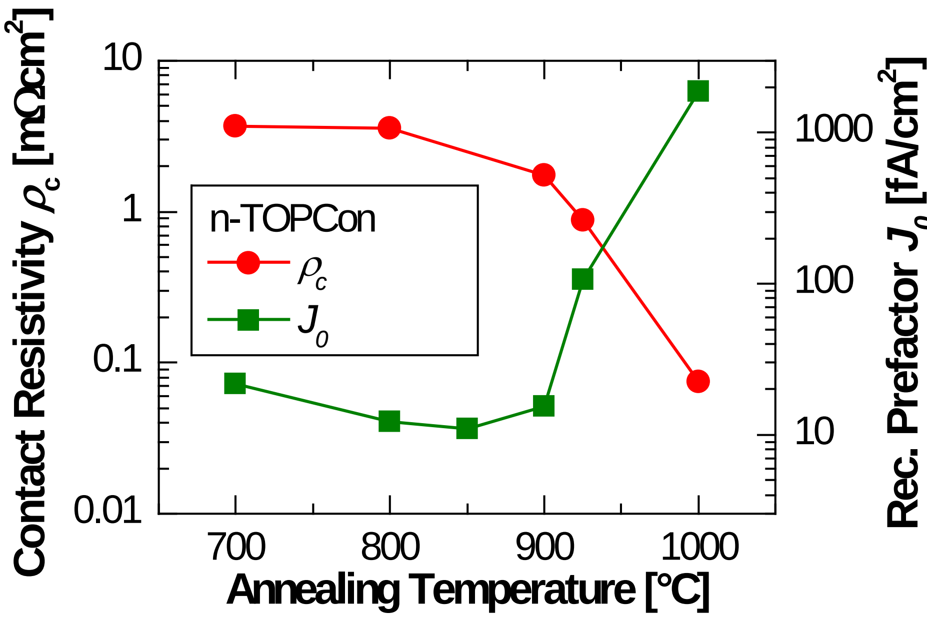
J. Y. Gan and R. M. Swanson, 22nd IEEE PVSC, (1990).

Post et al., *IEEE TED* (1992)

PRESENT
Alternative passivated contacts

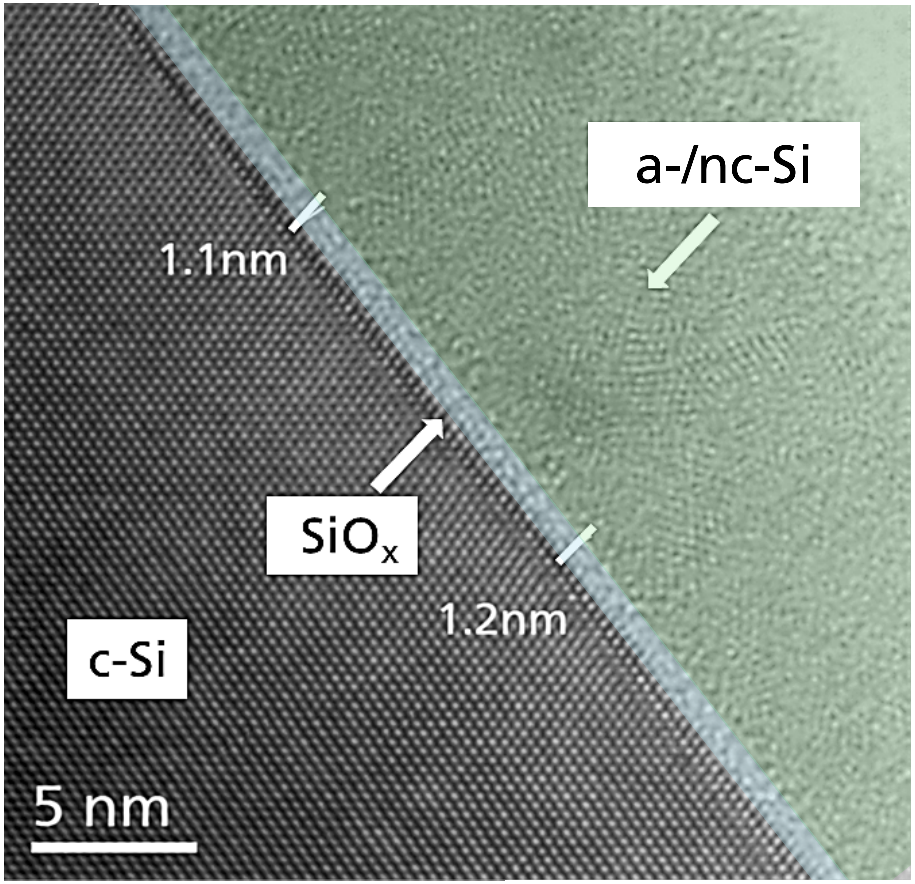
TOPCon process

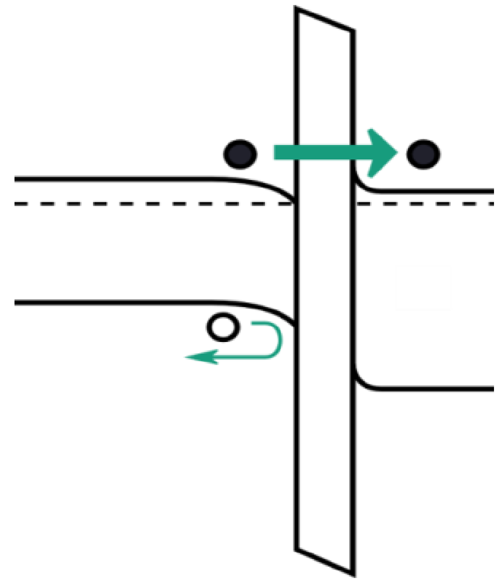
- Tunnel oxide
  (wet chemical or UV/O_3 growth)
  → Interface passivation
- PECVD deposition (single side) of doped amorphous Si layer
  → Carrier selectivity
- Furnace Anneal + H-passivation
  → Change of layer crystallinity (band gap)



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)

PRESENT
Alternative passivated contacts





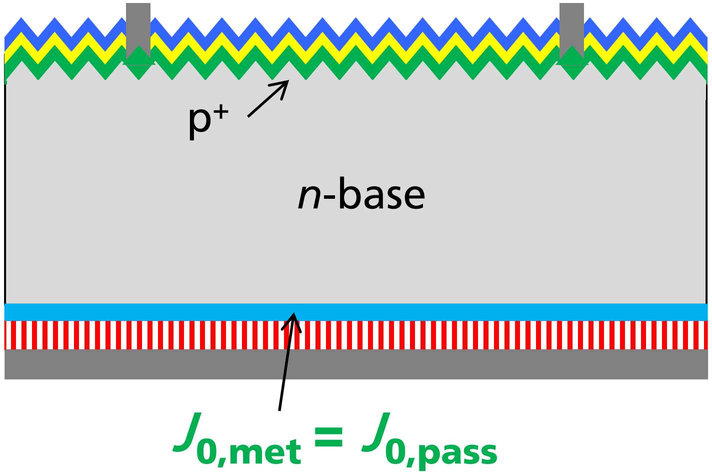
F. Feldmann et al., *SOLMAT 120* (2014)

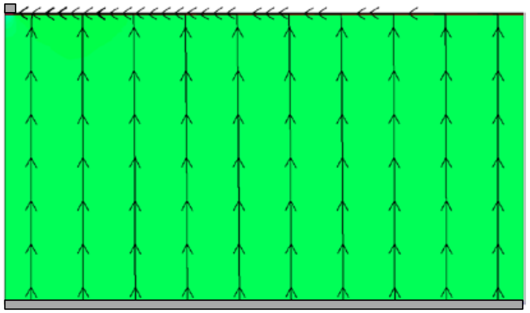
U. Römer, et al. IEEE Journal of Photovoltaics (2015)

D. Yan Solar Energy Materials and Solar Cells (2015)

n-Type Hybrid TOPCon Cell – Reducing the Complexity

- n-type hybrid cell with boron emitter at the front and a passivated rear side offers
  1. transparent front side
  2. less influence of base resistivity
  3. no patterning of the rear side





passivated contact

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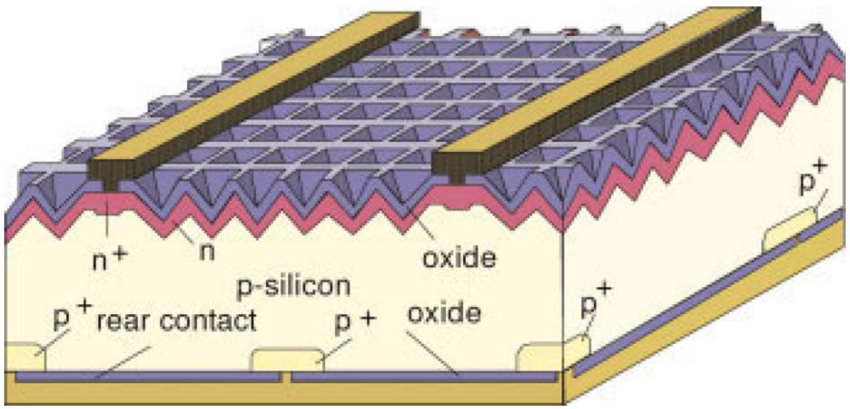
High-Efficiency Solar Cells

Record Cells with Top/Rear Contacts

	Material	V_{oc} [mV]	J_{sc} [mA/cm^2]	*FF* [%]	η [%]
UNSW/PERL[1]	*p*-type 400 µm	706	42.7	82.8	25.0[1]



[1] 4 cm^2 (da), Zhao et al., *Progr. Photovolt. 7* (1999)

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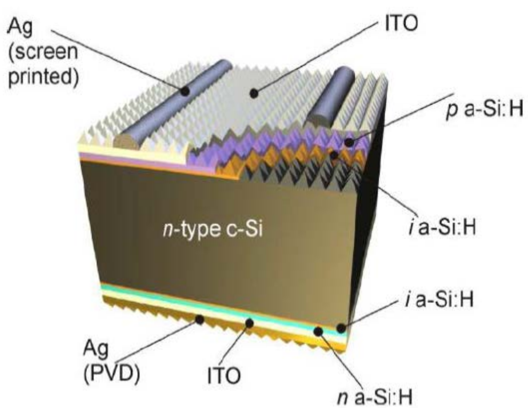

[1] 4 cm^2 (da), Zhao et al., *Progr. Photovolt. 7* (1999)
[2] 151,88 cm^2 (ap), *Yamamoto K,* et al., 25th *PVSC* (2015)

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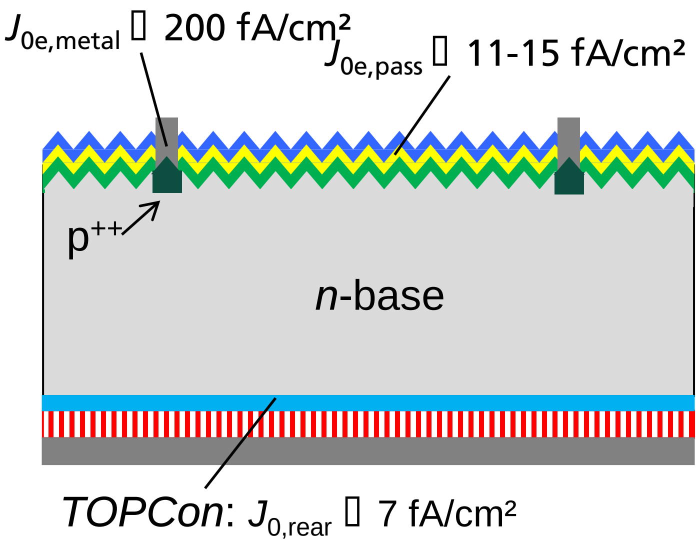
ISE / TOPCon[3]	*n*-type 200 µm	718	42.5	82.8	**25.3**



[1] 4 cm² (da), Zhao et al., *Progr. Photovolt. 7* (1999)
[2] 151,88 cm2 (ap), Yamamoto K, et al., 25th PVSEC (2015)
[3] 4 cm² (da), Richter A. et al., 26th PVSEC (2016)

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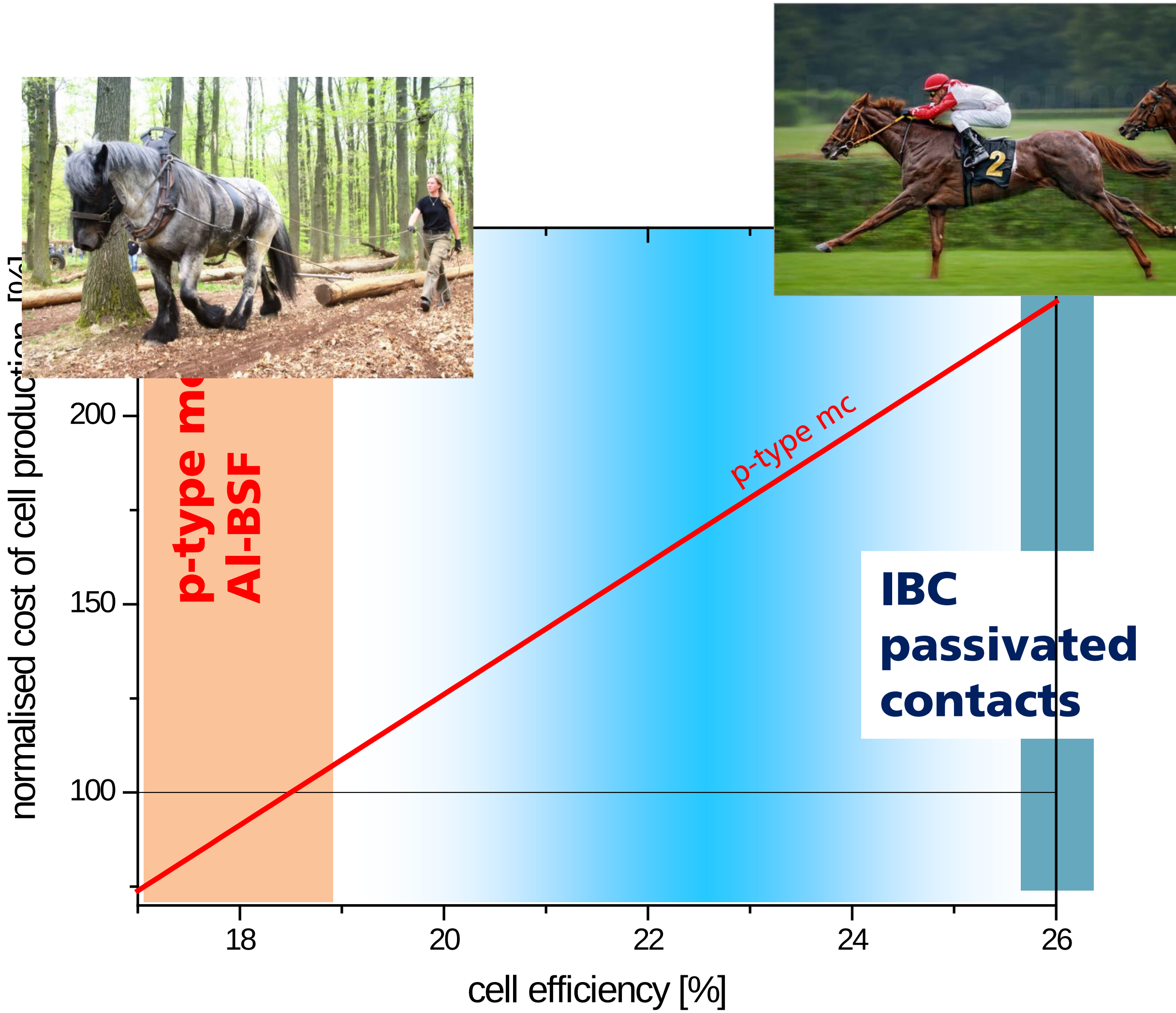
PRESENT
Bridging the Gap

- Both side cells will further dominate the market
- PERC cells will replace the Al-BSF cells
- **Cells with passivated contacts can come into the gap**
- They can have
  - Higher efficiency
  - with reasonable complexity



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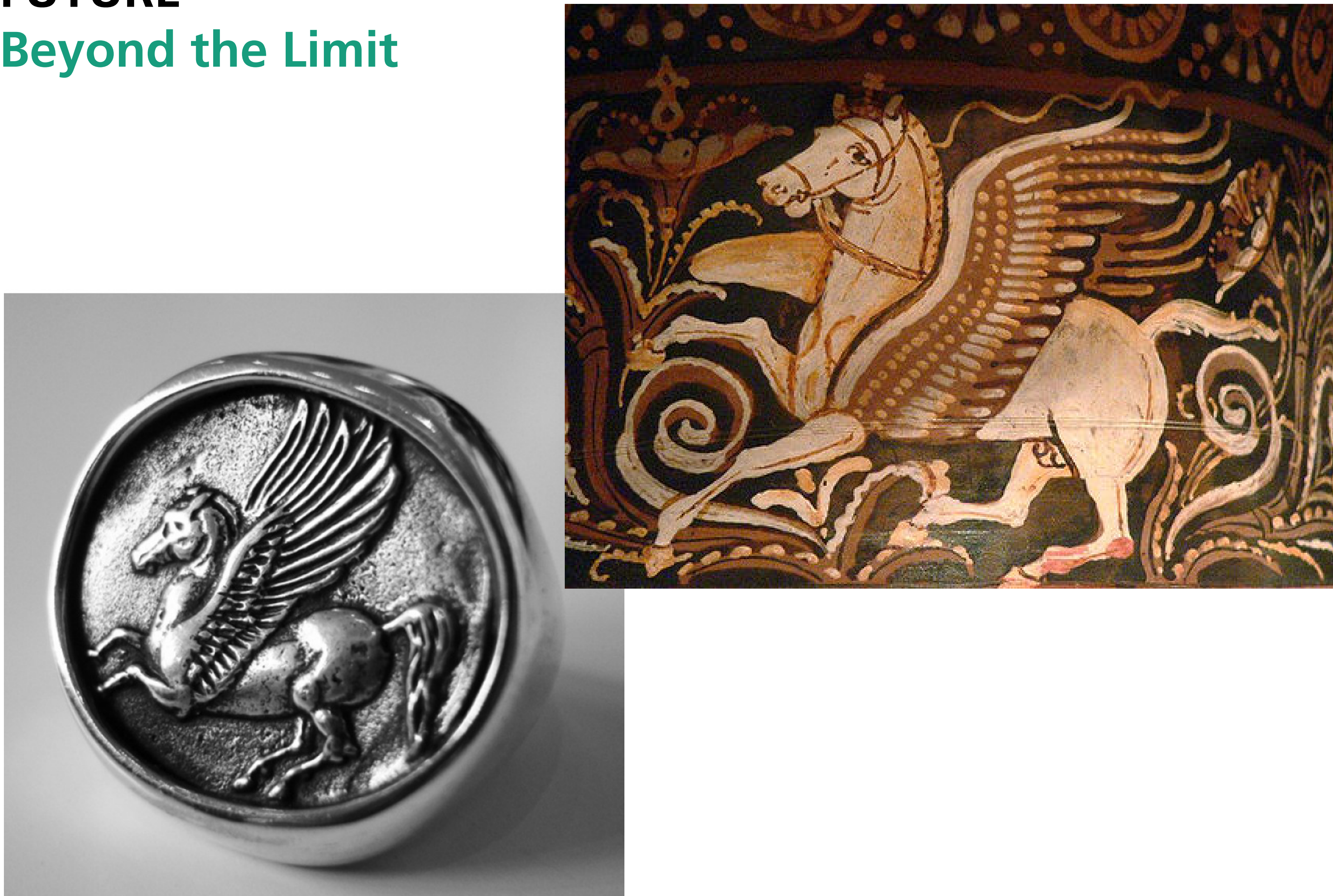
FUTURE
Beyond the Limit



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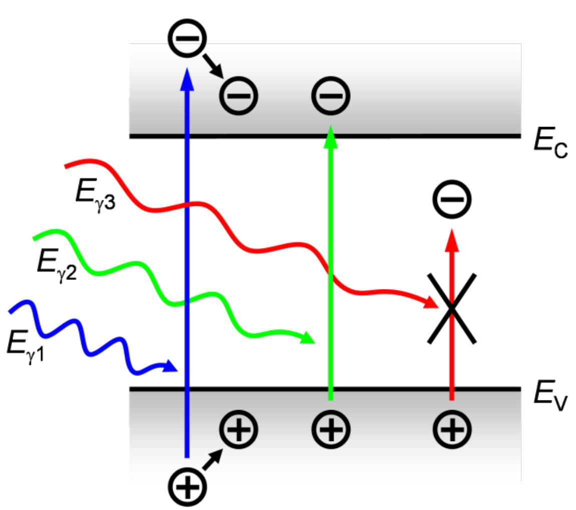
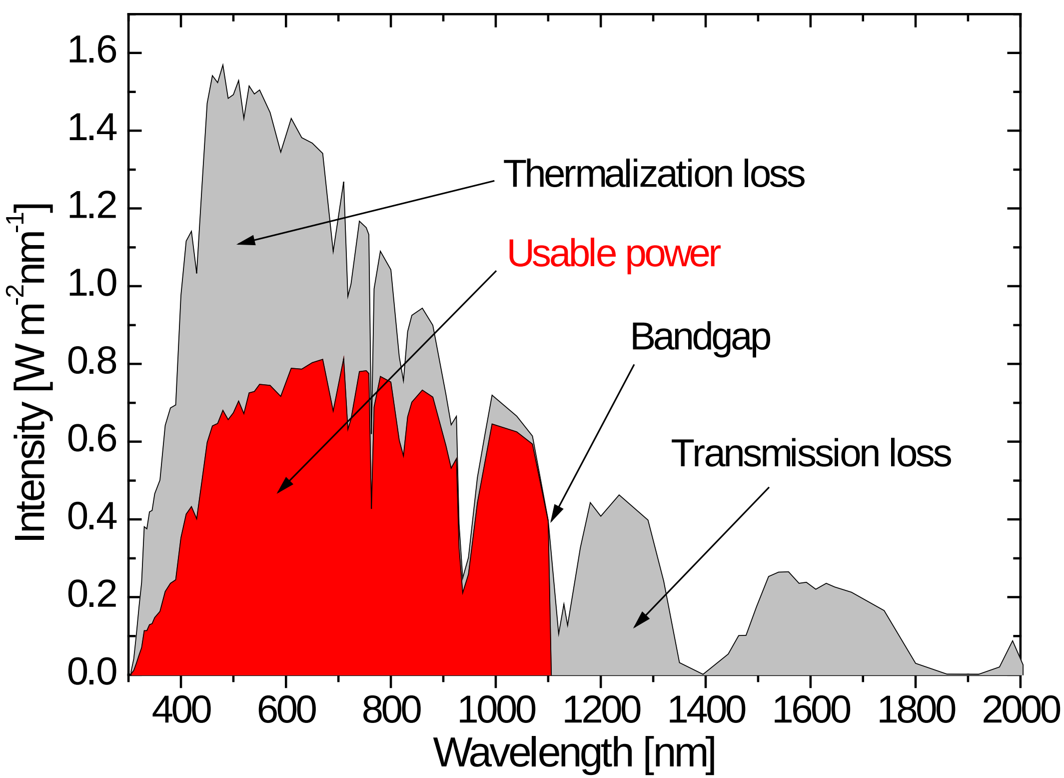
FUTURE
What is the Limit of Silicon Solar Cells

- Shockley, Queisser (1961)
  Limit for Si 33% (AM1.5)
- Limitations by thermalization and transmission





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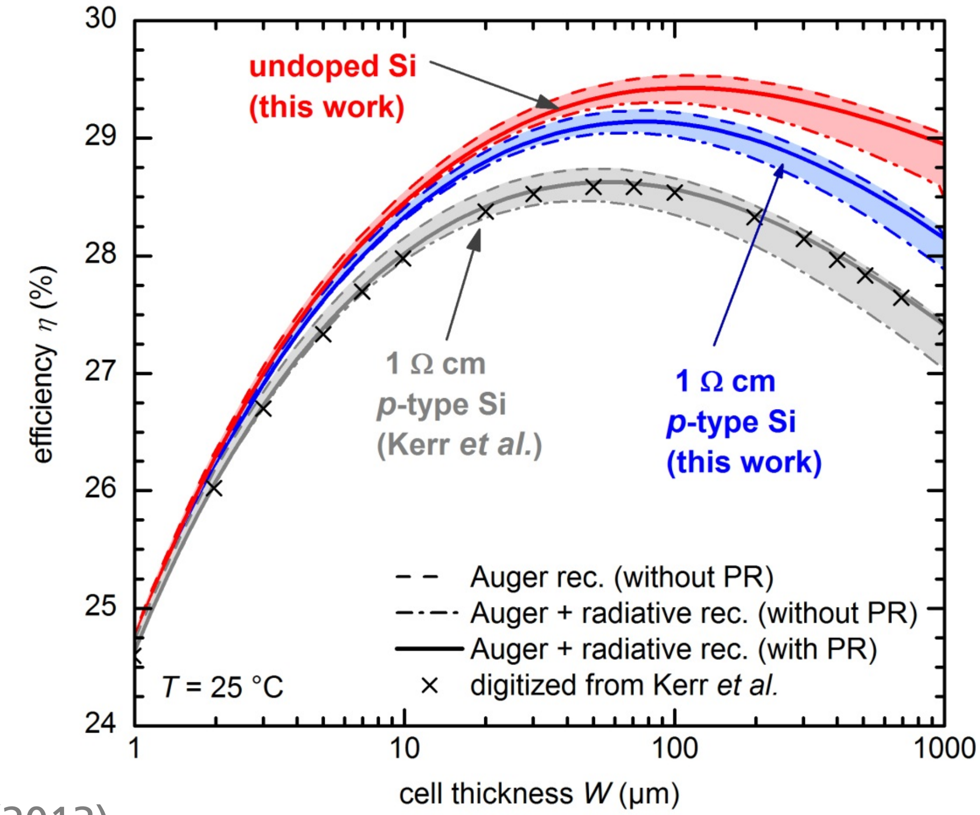
FUTURE
Taking Auger Recombination into Account

- Shockley, Queisser (1961) = 33% (AM1.5)
- Theoretical efficiency limit for silicon (incl. Auger) = 29.4%[1]
- Best silicon solar cells = 26.33%
- Corresponds to 88% of theoretical efficiency limit



[1]Richter, Glunz *et al., Phys. Rev. B 86* (2013)

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

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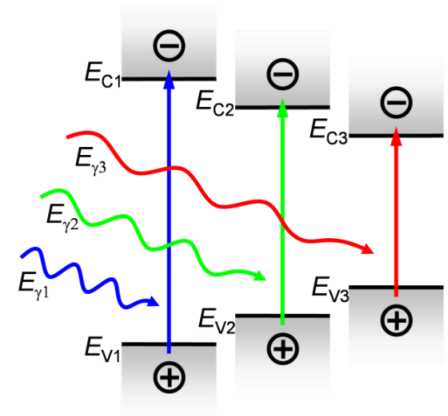
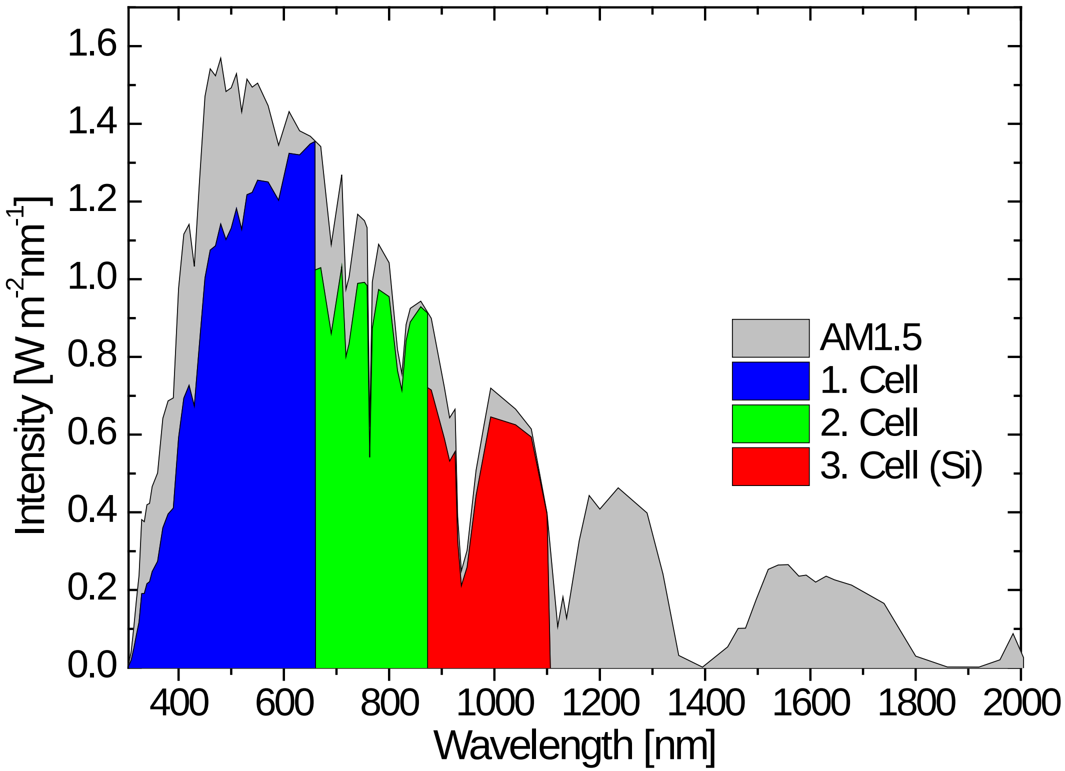
FUTURE
Beyond the Shockley-Queisser-Limit

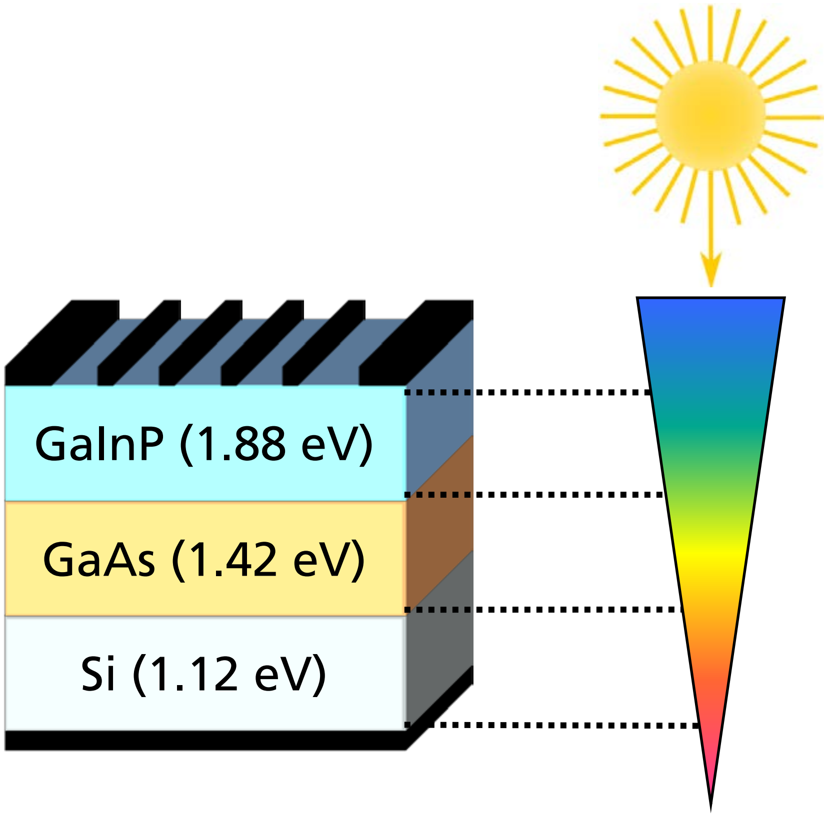


- Light management
  - Up-conversion
  - Down-conversion
- Tandem cells with silicon as bottom cell
  - Perovskite top cell
  - III/V top cell

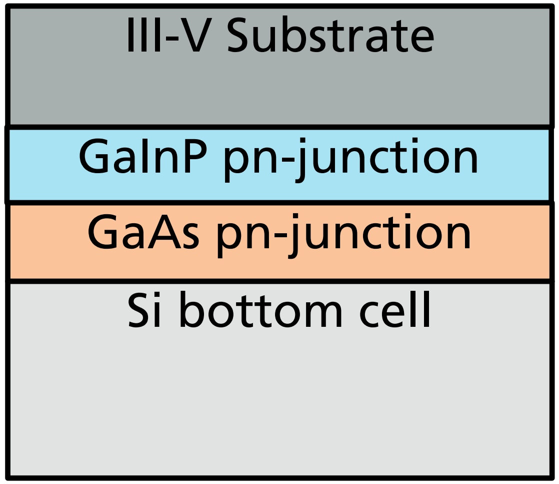


FUTURE
Silicon-based Multijunction Cells

- Top cells with high bandgap to utilize blue and visible light
- c-Si bottom cells for IR light
- Deposition by direct epitaxial growth or wafer bonding



Beyond the Limit
Silicon-based Multijunction Cells



III-V substrate lift-off and recycling

Bonding to new substrate

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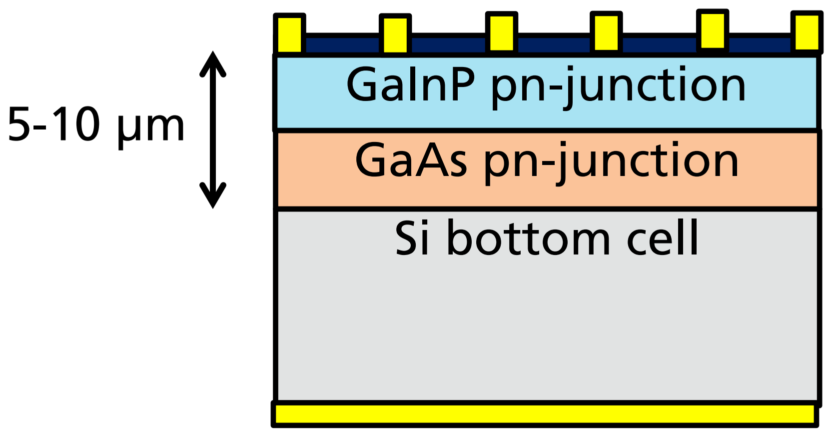
Beyond the Limit
Silicon-based Multijunction Cells

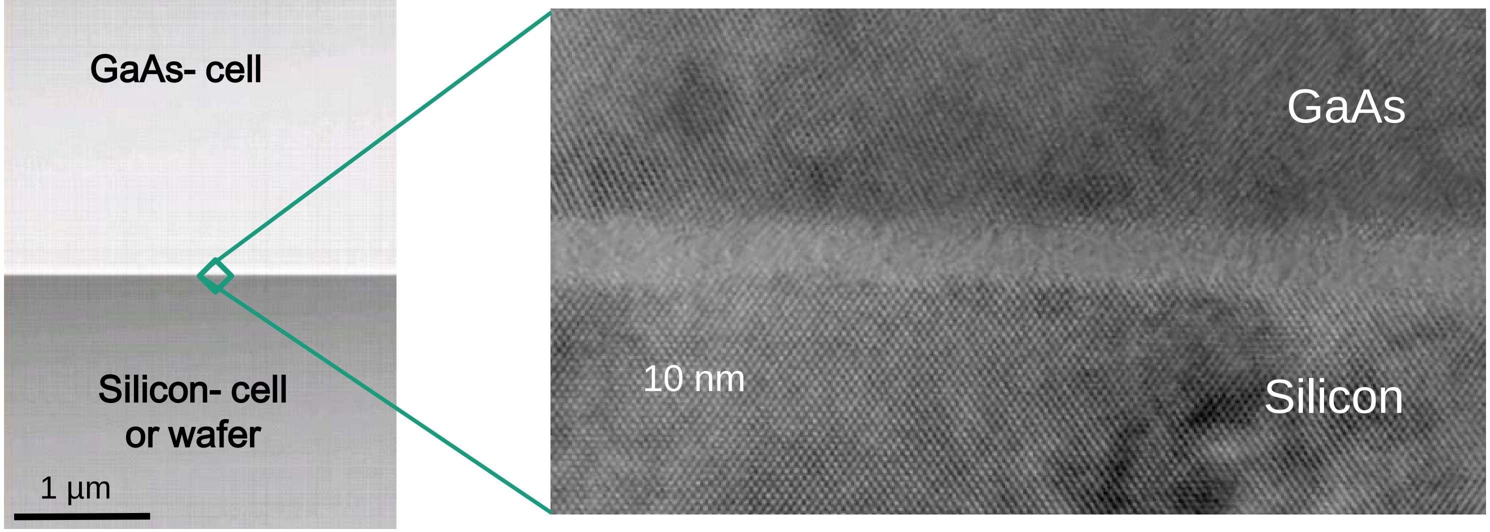


Processing of solar cell contacts and ARC

Beyond the Limit
2-terminal GaInP/AlGaAs//Si

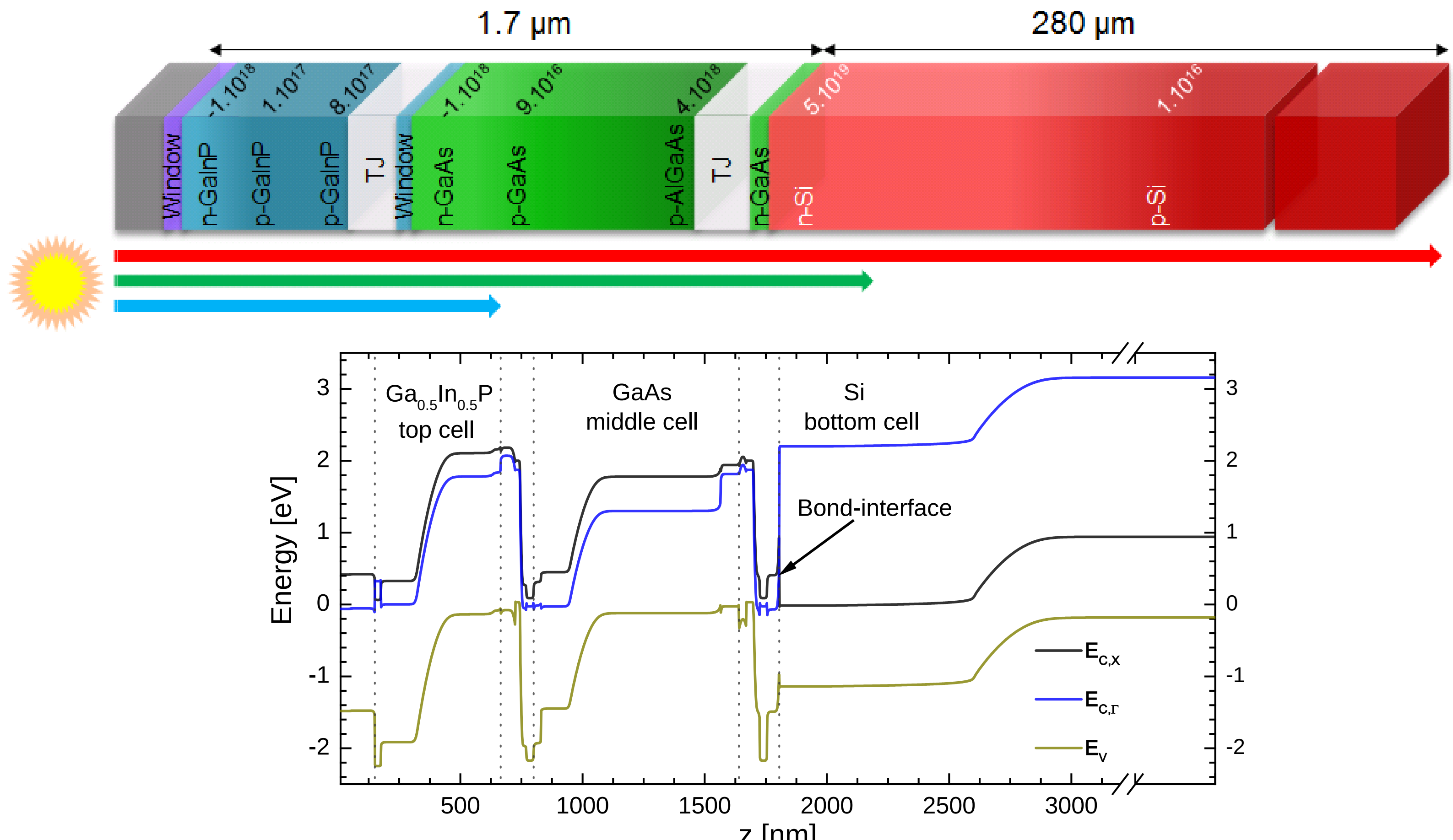
HRTEM-image of Si/GaAs interface

→ 4 nm thick amorphous layer



High Resolution TEM Image, Bright Field, Zone Axis Si, Universität Kiel, Group Prof. Dr. Jäger, 2011

Beyond the Limit
2-terminal GaInP/AlGaAs//Si



Schockley Queisser efficiency limit of 47.3 % (AM1.5g)

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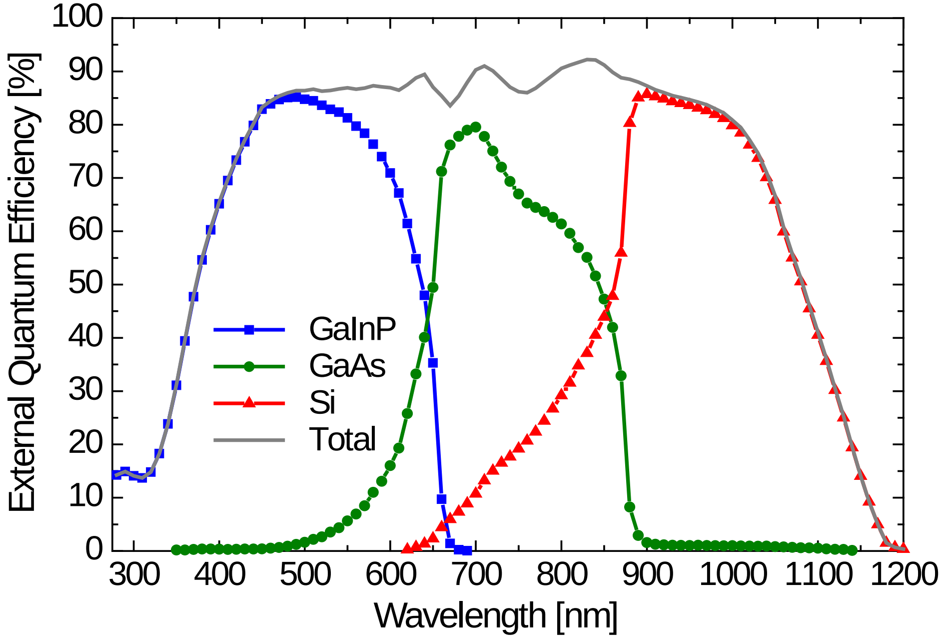
Beyond the Limit
2-terminal GaInP/AlGaAs//Si

- Efficient utilization of spectrum
- Very good current matching



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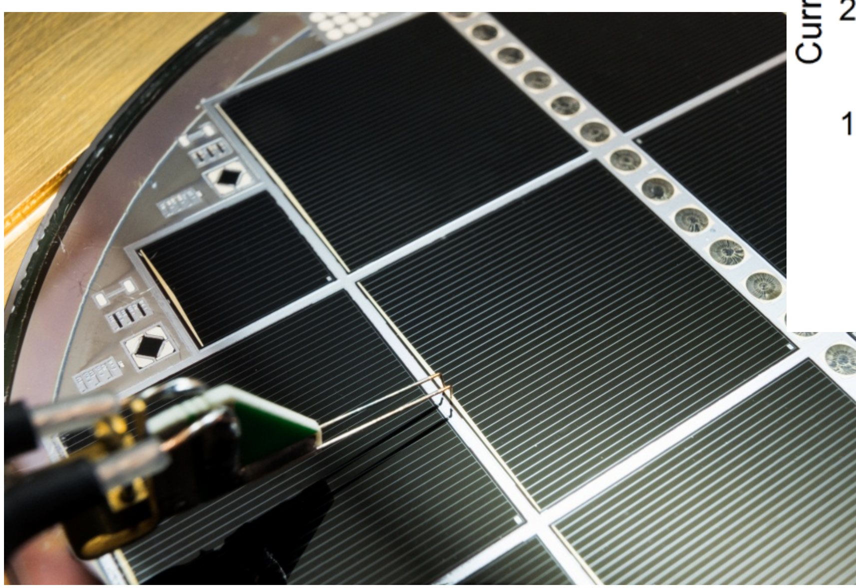
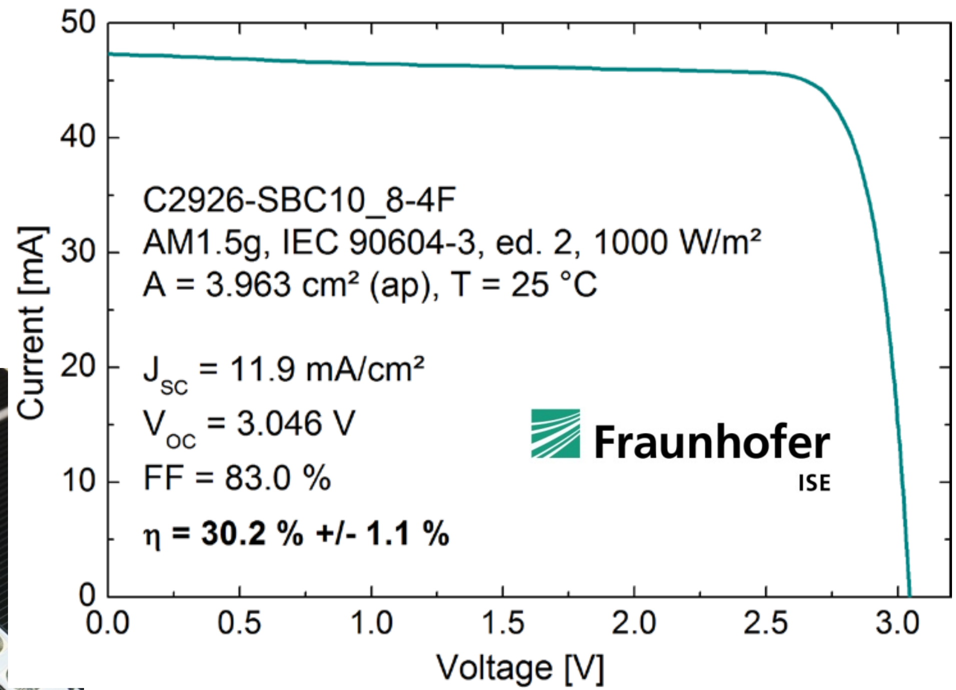
Beyond the Limit

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

- Efficient utilization of spectrum
- Very good current matching
- Efficiency = 30.2 > 29.4%

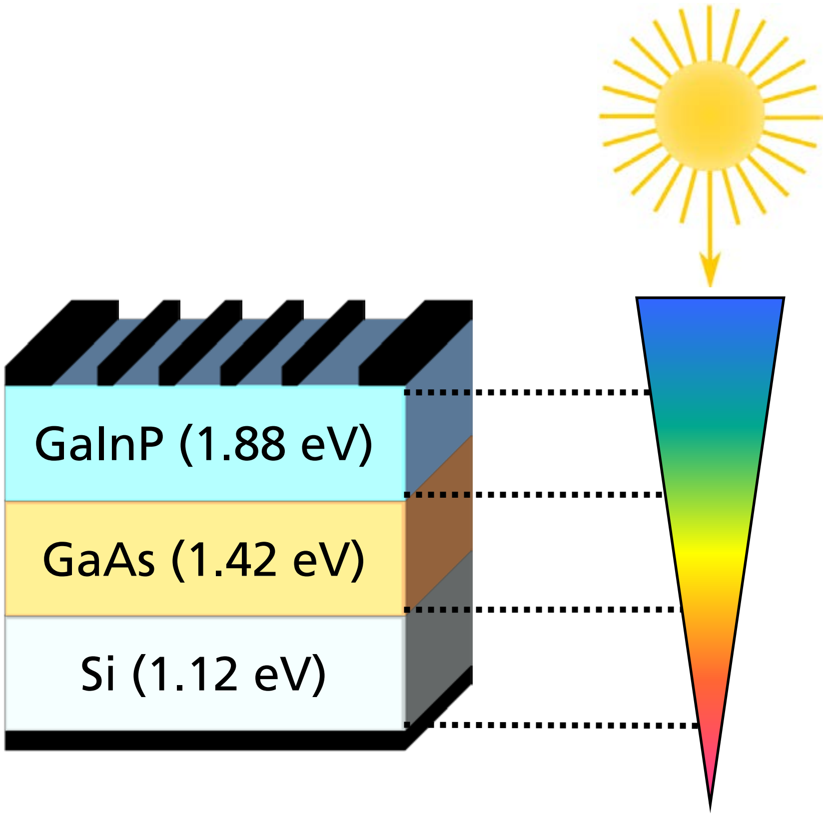




https://www.ise.fraunhofer.de/de/presse-und-medien/presseinformationen/presseinformationen-2016/30-2-prozent-2013-neuer-rekordwert-fuer-siliciumbasierte-mehrfachsolarzelle

Conclusion

- Photovoltaics is a significant player in the energy market.
- Prices are already very low. 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.
- New fascinating concepts for an old technology: Crystalline silicon solar cells **2.0**



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