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 2017
The Bell labs 1954
Gerald Pearson, Darryl Chapin, and Calvin Fuller testing their silicon solar cell.
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
PAST
From Space to Earth

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


PRESENT
Average Price for PV Rooftop Systems in Germany

Data: BSW-Solar. Graph: PSE 2018

System costs strongly area-related → Further increase of cell efficiency
PRESENT
Large-area Record Cells on n-type Silicon

- Interdigitated back contact back junction solar cells
- Excellent contact passivation (a-Si/c-Si heterojunction, passivated contacts)
- Sanyo\(^1\) (da=143.7 cm\(^2\)) 25.6\%(V\(_{\text{oc}}\) = 740 mV)
- SunPower\(^2\) (ta=153.5 cm\(^2\)) 25.2\%\(^3\) (V\(_{\text{oc}}\) = 737 mV)
- 2016: Kaneka (da=180.4 cm\(^2\)) 26.6\%\(^3\) (V\(_{\text{oc}}\) = 744 mV)

\(^1\) Masuko et al., IEEE PVSC (2014)
\(^2\) Smith et al., IEEE PVSC (2014)
\(^3\) Yoshikawa et al., Nature Energy (2017)

PRESENT
Record Cells on Crystalline Silicon

- Large-area (Sunpower, Sanyo/Panasonic, Kaneka)
- Sophisticated cell architecture
- Excellent material quality needed

© Stefan Glunz, Fraunhofer ISE 2018
THE Working Horse
Screen-printed Al-BSF solar cell on p-type silicon

- Still the main technology of the PV technology (70 to 80% of the market)
- Efficiencies up to 19% (multi-Si) or 20% (mono-Si)
- Incremental improvements (better pastes, surface passivation)
  → It is hard to beat the main stream!

Process

The Next Industrial Cell Generation
Partial Rear Contact Cells (PRC or PERC)

- The successor of Al-BSF cells:
  Partial Rear Contact (PRC) cells also known as PERC (25 years after its invention!)
The Next Industrial Cell Generation
Switching from Al-BSF to PRC (PERC)

- Al-alloyed back surface field (Al-BSF) solar cells have dominated the industry for decades
- Partial rear contact cells (PRC) like PERC/PERL are introduced in production

\[ \eta = 19\% - 20\% \]

\[ \eta = 20\% - 21.5\% \]


The Next Industrial Cell Generation
Industrial process for PERC cells

- Two additional process steps
  - Dielectric passivation
  - Local contact opening (LCO)
The Next Industrial Cell Generation

Partial Rear Contact Cells (PRC or PERC)

- The successor of Al-BSF cells: Partial Rear Contact (PRC) cells also known as PERC (25 years after its invention!)

- Record cell results:
  - p-type mono-Si:
    - 22.1% (Trina)
    - 22.0% (Solar World)
    - >23% (Jolywood)
  - p-type multi-Si:
    - 21.25% (Trina)
    - 22% (Jinko Solar)

P. Verlinden, WCPEC, Kyoto, 2014

PERC Modules

Bifacial p-type PERL Solar Cells

- Starting point: PERC-process
- Fingers on front and back side
- Bifacial power conversion

Dullweber et al. PIP 2015

SolarWorld BiSun technology
Module Technology
No More Busbars

- Cell has only fingers and no busbars
- Interconnection with solder-coated wires
- Lower reflection losses
- Improved aesthetics

Meyer&Burger Smart Wire  LG Neon module

Bridging the Gap
State-of-the-Art Silicon Solar Cell: Cost Analysis

- Allowed costs for same levelized costs of electricity (LCOE) as a function of cell efficiency

M. Hermle et al., 29th EUPVSC 2014.
Bridging the Gap
State-of-the-Art Silicon Solar Cell: Cost Analysis

- Allowed costs for same levelized costs of electricity (LCOE) as a function of cell efficiency
- Bridging the gap:
  - Higher efficiency
  - Reasonable complexity

**PRESENT**
PERC – Restrictions

- PERC cells have high efficiency potential
- **But:** Strongly two-dimensional cell structure (contact distance = 5 cell thickness)
  - Trade-off in cell design: \( V_{oc} \) vs. FF
  - Influence of base resistivity
  - Additional patterning step required
Bridging the Gap
n-Type PRC – Restrictions

\[ J_{0,\text{met}} > J_{0,\text{pass}} \]

- local contact
- \( n^{++} \) – base \( p^+ \)

\[ J_{0,\text{met}} = J_{0,\text{pass}} \]

- passivating contact

Bridging the Gap
Hybrid TOPCon Cell

- 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

\[ J_{0,\text{met}} = J_{0,\text{pass}} \]

- passivating contact
TOPCon (Tunnel Oxide Passivated Contact)  
Combining a-Si Hetero and poly-Si/Tunnel Oxide Approach

- Higher band gap  
  - Very good selectivity
- Better thermal stability

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

© Fraunhofer ISE, S. Glunz 2018

© Stefan Glunz, Fraunhofer ISE 2018
TOPCon (Tunnel Oxide Passivating Contact)  
A New Rear Contact

![Diagram showing Si Thin Film, SiOx, c-Si, 1.1nm, 1.2nm, 5 nm](image)

F. Feldmann et al., SOLMAT (2014)

---

High-Efficiency Solar Cells  
Cells with Top/Rear Contacts

<table>
<thead>
<tr>
<th>Material</th>
<th>Area [cm²]</th>
<th>V_{oc} [mV]</th>
<th>J_{sc} [mA/cm²]</th>
<th>FF</th>
<th>η [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNSW/ PERL¹</td>
<td>p-type 400 μm</td>
<td>4 (da)</td>
<td>706</td>
<td>42.7</td>
<td>82.8</td>
</tr>
<tr>
<td>Kaneka/ HJT²</td>
<td>n-type 200 μm</td>
<td>152 (ap)</td>
<td>737</td>
<td>40.8</td>
<td>83.5</td>
</tr>
</tbody>
</table>

¹Zhao et al., Progr. Photovolt. (1999)  
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### Cells with Top/Rear Contacts

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</tr>
<tr>
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<td>152(ap)</td>
<td>737</td>
<td>40.8</td>
<td>83.5</td>
<td>25.1</td>
</tr>
<tr>
<td>ISE / TOPCon&lt;sup&gt;1&lt;/sup&gt;</td>
<td>4 (da)</td>
<td>719</td>
<td>41.5</td>
<td>83.4</td>
<td>24.9*</td>
</tr>
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</table>

*ISE CalLab Measurement

**TOPCon**: $J_{0,\text{rear}} \approx 3-5 \text{ fA/cm}^2$

---

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### Cells with Top/Rear Contacts

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*ISE CalLab Measurement

**TOPCon**: $J_{0,\text{rear}} \approx 3-5 \text{ fA/cm}^2$

---

**Note**: The table above lists the material, area, open-circuit voltage ($V_{oc}$), short-circuit current ($J_{sc}$), fill factor (FF), and efficiency ($\eta$) for different high-efficiency solar cells with top/rear contacts. The top/rear contacts configuration is crucial for achieving high efficiencies. The values are measured in a controlled laboratory environment, indicated by the *ISE CalLab Measurement* note.
### High-Efficiency Solar Cells

#### Cells with Top/Rear Contacts

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<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNSW/ PERL</td>
<td>$p$-type mono-Si</td>
<td>4 (da)</td>
<td>706</td>
<td>42.7</td>
<td>82.8</td>
</tr>
<tr>
<td>Kaneka/ HJT</td>
<td>$n$-type mono-Si</td>
<td>152(ap)</td>
<td>737</td>
<td>40.8</td>
<td>83.5</td>
</tr>
<tr>
<td>ISE / TOPCon1</td>
<td>$n$-type mono-Si</td>
<td>4 (da)</td>
<td>725</td>
<td>42.5</td>
<td>83.3</td>
</tr>
</tbody>
</table>

*ISE CalLab Measurement

**TOPCon: $J_{0,rear} \approx 3-5$ fA/cm²**

---

**Richter et al., SOLMAT (2017)**
## High-Efficiency Solar Cells

### Cells with Top/Rear Contacts

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<tr>
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<th>Area</th>
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</tr>
</thead>
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<td>25.0</td>
</tr>
<tr>
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<td>n-type mono-Si 152(ap)</td>
<td>737</td>
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<td><strong>25.7</strong>&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
<tr>
<td>ISE/ TOPCon&lt;sup&gt;1&lt;/sup&gt;</td>
<td>n-type multi-Si 4</td>
<td>674</td>
<td>41.1</td>
<td>80.5</td>
<td><strong>22.3</strong>&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>*</sup>ISE CalLab Measurement

<sup>1</sup>Benick et al., *IEEE JPV* (2017)

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### Record Efficiencies

**Best Research-Cell Efficiencies**

![Record Efficiencies Graph](image)

October 2017
Record Efficiencies

Best Research-Cell Efficiencies

- Mono-Si heterojunction
- Mono-Si homojunction
- Perovskite (not stabilized)
- CIGS
- Multi-Si
- CdTe

What is the limit?
Detailed Balance

- Shockley und Queisser, 1961
- Detailed balance between sun and solar cell
- Assumption: Solar cell emits photons via radiative recombination
What is the limit?
Maximum Efficiency as a Function of Bandgap

- Max. Efficiency ~ 33%
- High thermalisation for low bandgaps
- High transmission for high bandgaps
- Silicon and GaAs are close to the optimum
- But: Record values of GaAs are closer to the limit.
- Is III/V-R&D better than silicon-R&D?

What is the Limit?
Other Recombination Channels

- Assumption:
  Ideal solar cell: only radiative recombination
  (Shockley and Queisser, J. Appl. Phys. 1961)

  Radiative recombination in an indirect semiconductor

  Radiative recombination has a low probability

  Radiative recombination in an indirect semiconductor

  Radiative recombination has a low probability
What is the limit?
Auger-Recombination

- In silicon solar cells Auger-recombination is the limiting intrinsic loss mechanism.

Shockley, Queisser (1961) = 33% (AM1.5)

- Theoretical efficiency limit for silicon (taking actual Auger model\(^1\) into account) = 29.4%\(^2\)


What is the Limit?
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 = 25.6%\(^2\)
- Corresponds to 87% of theoretical efficiency limit
- (GaAs = 87% ☺)

FUTURE
Beyond the Shockley-Queisser-Limit

- Shockley, Queisser (1961): Efficiency limit of solar cell made of one material = 33%
- Theoretical efficiency for silicon (Auger limit) = 29.4%\(^1\)
- Light management
  - Up-conversion
  - Beam splitting
- Tandem cells with silicon as bottom cell
  - Perovskite top cell
  - Silicon quantum dots
  - III/V top cell

\(^1\)Richter, Hermle, Glunz et al., IEEE J. Photovolt. 2013
\(^2\)Masuko et al., IEEE-PVSC (2014)
Beyond the Limit
Magic Antireflection Coatings (AAA-Coating®)

- Silicon Solar Cells with AAA-Coating®
  (amazingly active antireflection coating)

Silicon Solar Cell

- Theoretical limit for $E_g,\text{Si}$: 33% (29.4% considering Auger recombination)
- World record for silicon solar cells: 26.7%
Beyond the Limit
Multijunction Solar Cells

- Tandem cells with Si bottom cell
  - III/V on Si
  - Silicon quantum dots
  - Perovskites
→ “Silicon Solar Cell 2.0”

Beyond the Limit
III-V on Silicon Tandem Solar Cells
Beyond the Limit
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
GaInP pn-junction
GaAs pn-junction
Si bottom cell

III-V substrate lift-off and recycling
Bonding to new substrate
Beyond the Limit
Silicon-based Multijunction Cells

GaInP pn-junction
GaAs pn-junction
Si bottom cell

Processing of solar cell contacts and ARC

5-10 μm

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

HRTEM-image of Si/GaAs interface
4 nm thick amorphous layer
Beyond the Limit
2-terminal GaInP/AlGaAs//Si

- Very good current matching: Each cell around 12 mA/cm²
- Efficient utilization of spectrum

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%

Brand new result = 33.3%

R. Cariou et al., Fraunhofer ISE
IEEE Journal of Photovoltaics 2017
R. Cariou et al., Fraunhofer ISE
Nature Energy 2018
Wafer-Bonded 2-Terminal GaInP/AlGaAs//Si Tandem TOPCon with Nanostructured Diffraction Grating

<table>
<thead>
<tr>
<th>$V_{oc}$ [V]</th>
<th>$J_{sc}$ [mA/cm²]</th>
<th>FF [%]</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Gen 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.127</td>
<td>12.7</td>
<td>83.8</td>
<td>33.3</td>
</tr>
</tbody>
</table>


Beyond the Limit
III-V on Silicon Tandem Solar Cells

- 1.9 μm of III-V material on Si sufficient to realize η = 33.3% solar cell by wafer bonding
- η = 19.7% efficiency reached for GaInP/GaAs/Si triple-junction by direct growth
- Both values included in PIP Efficiency tables 2018
Beyond the Limit
2-terminal GaInP/AlGaAs//Si > 29.4% @ 1-Sun AM1.5g

- Efficient utilization of spectrum
- Very good current matching
- Efficiency = 33.3 > 29.4%
- Beyond the Auger limit for crystalline silicon solar cells

R. Cariou et al., Fraunhofer ISE
Nature Energy 2018

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.
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New fascinating concepts for an old technology: Crystalline silicon solar cells 2.0
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