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Roadmap CIGS towards 25% Efficiency

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CIGS Record Efficiency Development

Dynamic development since introduction of Alkali Post-Deposition Treatment (PDT)

Fig. 1: Evolution of record efficiencies highlighting a steeper increase since 2014; 2016–2019 projections based on current R&D projects.

Source: CIGS White Paper, cigs-pv.net
EU-Project Sharc25

„Super High Efficiency Cu(In,Ga)Se₂ Thin-Film Solar Cells Approaching 25%“

11 Partners
8 Countries
Coordinator: ZSW
ZSW Locations

**Stuttgart:**
Photovoltaics (with Solab), Energy Policy and Energy Carriers, Central Division, Finance, Human Resources and Legal

**Ulm:**
Electrochemical Energy Technologies Division, Main Building & eLaB

**Widderstall:** Solar Test Facility
New Building Autumn 2016

~ 2 km

Source: Google Maps
PV Thin-Film Modules: from Research to Production

- Cells
- Modules
- Production

CIGS on glass
Flexible substrates
Non-vacuum processes
ZSW High Efficiency Cu(In,Ga)Se$_2$ Cell Structure

Sketch of a high-efficiency CIGS solar cell

$\eta = 21.7\%$ certified achieved
Alkali Post-Deposition Treatment (PDT)

Findings:
- Thicker Cu-depleted surface layer
- Decreased ideality factor and reverse saturation current
- Longer minority carrier lifetimes, reduced recombination
- Higher density of charge carriers (fewer compensating defects) $\rightarrow$ higher $V_{oc}$
- Thinner CdS possible $\rightarrow$ higher $j_{SC}$
Improved Photocurrent in CIGS Record Cells

<table>
<thead>
<tr>
<th>Year</th>
<th>η (%)</th>
<th>$j_{sc}$ (mA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>20.8</td>
<td>34.8</td>
</tr>
<tr>
<td>2014</td>
<td>21.7</td>
<td>36.5</td>
</tr>
</tbody>
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Thinner CdS possible with PDT due to improved initial growth → Absorption losses reduced

External quantum efficiency (EQE):

GGI profile optimization:
Lower band gap minimum (1.13eV vs. 1.16eV) increases absorption at longer wavelengths

*certified by Fraunhofer ISE
PDT Allows Reduction of the CdS Thickness

- With PDT: initial CdS growth more uniform on all surfaces
- Film closure on all surfaces at an earlier stage of CdS deposition
- Minimum film thickness can be reduced
CdS/iZnO Buffer System: Loss Analysis

Loss due to absorption in i-ZnO

→ Exchange of i-ZnO with higher bandgap material
CdS Buffer System: Exchange of i-ZnO with (Zn,Mg)O

SEM image:
CdS/ZMO Buffer System: 22.0%\text{certified}

Three CdS/ZMO cells certified:

<table>
<thead>
<tr>
<th>$\eta$ (%)</th>
<th>$V_{OC}$ (mV)</th>
<th>$j_{SC}$ (mA/cm$^2$)</th>
<th>FF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.9</td>
<td>739</td>
<td>36.9</td>
<td>80.5</td>
</tr>
<tr>
<td>22.0</td>
<td>746</td>
<td>36.5</td>
<td>80.6</td>
</tr>
<tr>
<td>22.0</td>
<td>744</td>
<td>36.7</td>
<td>80.5</td>
</tr>
</tbody>
</table>

Improved Transmission in UV due to ZMO
Exchange of CdS/i-ZnO with Zn(O,S)/(Zn,Mg)O

- Cd-free buffer layer
- Reduced absorption due to higher bandgap of Zn(O,S)

21.0% certified achieved on CIGS with PDT
High-Rate Solution Deposition of Zn(O,S)

Standard Thiourea (TU)-based process:

• Limited growth rate

Direct comparison to CdS:
• equal maximum efficiencies
• lower average values

Hariskos et al., IEEE PVSC 2016
Thioacetamide (TAA)-based process:

- Faster decomposition of TAA
- Control of reaction kinetics by chelating ligands
- Relevant for industrial processes

→ Test of different chelating ligands with different concentration ratios

Hariskos et al., IEEE PVSC 2016
Tested Ligands:

- Citric acid ($H_3$Cit)
- Iminodiacetic acid ($H_2$IDA)
- Nitrilotriacetic acid ($H_3$NTA)
- Sodium salts of those:
  - $Na_3$Cit
  - $Na_2$IDA
  - $Na_3$NTA

- Deposition time strongly reduced
- Material consumption reduced
Solar cell performance:

Inline co-evaporated CIGS
• comparable results achieved with TAA-based processes (CdS references in the range of 15-17%)
• Highest efficiencies with Na₃NTA

Static high-efficiency CIGS with PDT
• Only few samples
• 19.1% achieved (with ARC) with H₃Cit
• Needs further optimization and adaption to PDT-modified CIGS surface

Hariskos et al., IEEE PVSC 2016
New World Record for CIGS Solar Cells: 22.6% certified

\[ \eta_{\text{cert.}} = 22.6\% \text{ with ARC} \]

\[ V_{\text{oc}} = 741 \text{ mV} \]

\[ FF = 80.6\% \]

\[ j_{\text{sc}} = 37.8 \text{ mA/cm}^2 \]
Towards 25% Efficiency

+1% by highly efficient CIGS absorber material
+2% by introducing novel concepts for surfaces and interfaces
+1% by advanced light management

Strategy ZSW:
- Stable high-efficiency cell line
- Good statistics for significance of trends
- Analytics on relevant samples

Topics:
- CIGS + Alkali-PDT
- Buffer-System
- Interface quality
- TCO
- Electrical and optical losses
Summary

- Dynamic development in efficiency since introduction of Alkali PDT
- Several optimizations for high efficiency cells with PDT
  - Thinner CdS, improved coverage
  - Exchange i-ZnO with (Zn,Mg)O for CdS buffered samples
- Method for high-rate solution-deposition of Zn(O,S)
- Very recent result:

  New world record for CIGS: 22.6% certified
Acknowledgments

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Thank you for your attention!