Manufacturing of Large-Area Cu(In,Ga)Se$_2$ Solar Modules
Fast Ramp Up to More than 12% Module Efficiency in Mass Production – Road Map to 14%

A. Neisser et. al., Soltecture, Berlin, Germany
Sulfurcell is now Soltecture

- Solar
- Technology
- Architecture
Soltecture: Passion for CIS since 1991 and more than 200 years of combined CIS experience

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991–2001</td>
<td>Helmholtz-Center Berlin (HZB) takes lead in thin-film technology based on CIGS</td>
</tr>
<tr>
<td>2001</td>
<td>Founding of Sulfurcell Solartechnik GmbH</td>
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<tr>
<td>2004</td>
<td>Pilot production facility ready for production</td>
</tr>
<tr>
<td>Dec 2005</td>
<td>Market entry</td>
</tr>
<tr>
<td>Apr 2010</td>
<td>35 MW facility ready for production</td>
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</tbody>
</table>

More than 200 years of combined CIS experience in Soltecture’s staff of 50 highly qualified engineers
Latest result: Incorporation of Gallium into Soltectures sequential technology

Glass
Sputtering Molybdenenum

Glass
Laser scribing

2-step absorber preparation

Sputtering Copper/Indium/Gallium

Heating, Sulfurization CIGS

Chemical Processing

Sputtering Zinkoxid

Scribing

Scribing

Framing & Junction box
Laminating
Wiring & Testing
Edge Decoating

Solar module

Wiring & Testing

Laminating

Framing & Junction box

Solar module
Soltecture’s has successfully qualified an improved Gen1 process enhancing module power from 60 W to 70 W in average.
Incorporation of Gallium

- Soltecture has introduced Gallium in its sequential technology, hereby increasing module power to more than 70W in production
- Best modules reach 10.0% aperture area efficiency
- Highest value for selenium free large area module

PV parameters of Cu(In,Ga)S\textsubscript{2} champion module

<table>
<thead>
<tr>
<th>Pmp</th>
<th>eta</th>
<th>Voc</th>
<th>Isc</th>
<th>ff</th>
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</thead>
<tbody>
<tr>
<td>74.6 W</td>
<td>10.0 %</td>
<td>60.1 V</td>
<td>1.76 A</td>
<td>70.5 %</td>
</tr>
<tr>
<td>732mV/cell</td>
<td>19.4mA/cm\textsubscript{2}</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Aperture area: 1.215 x 0.615m\textsuperscript{2}
Soltecure’s efficiency roadmap continues the company’s historic achievements

Champion efficiencies: Milestones and roadmap
Module aperture area: 1.215 x 0.615 m²

- **CIGSe (GEN2)**
  - Selenium-based CIS
  - Laboratory proven potential: 20.0%
  - Milestone: 13.0%

- **CIGS (GEN1)**
  - Sulfur-based CIS
  - Laboratory proven potential: 12.7%
  - Milestone: 10.0%
Soltecture’s technology platform for CIGS & CIGSe: Modules with premium performance and top efficiency

**GEN1**
- CIGS = Cu(In, Ga)S$_2$
- 2-step process: Sputtering + Annealing
- Capacity: 20 MW
- Average efficiency: 8%  
  **Champion efficiency: 10.0 %**
  Technology roadmap to 10%
  ↓
  High-quality modules with excellent heat tolerance

**GEN2**
- CIGSe = Cu(In, Ga)Se$_2$
- 1-step process: Coevaporation
- Capacity: 15 MW
- Average efficiency: 11%  
  **Champion efficiency: 13.1 %**
  Technology roadmap to >14%
  ↓
  Premium modules with very high efficiency

Manufacturing process in Sulfurcell’s Berlin production

All efficiency numbers related to aperture area of full-sized modules of 1.25 m x 0.65 m.
Sulfurcell’s manufacturing process for CIGSe PV modules (Gen2)

1-step absorber preparation

Glass
Sputtering Molybdenum
Glass
Laser scribing
Evaporation CIGSe
Chemical Processing
Scribing
Sputtering Zinkoxid
Framing & Junction box
Laminating
Wiring & Testing
Edge Decoating
Solar module

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The coevaporation technology

**Technique**
- Simultaneous evaporation of the elements Copper, Indium, Gallium and Selenium
  ⇒ Formation of CIGSe on glass substrates passing the evaporation sources
- Optimisation of film composition by adjusting evaporation rates and temperature

**Features of the machine design**
- Material usage rate as high as for sputtering (> 40%)
- Stable operation over several days (no drift, no glass breakage, total yield > 80%)
- Excellent homogeneity of film composition: Cu:(In+Ga): ± 2.5%
- Excellent CIGSe quality: 15% efficiency of solar cells cut out of full-scale modules
- High productivity (4 min cycle-time, roadmap to < 2 min)

*Molybdenum-coated glass (1.25 x 0.65 m²)*
## Project Plan for Introduction of GEN 2 technology fulfilled

**Objectives:**
- Process definition
- Product qualification
- Pilot production
- Production & Sales (Continuous Improvement)

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<thead>
<tr>
<th>Apr 10</th>
<th>Aug 10</th>
<th>Oct 10</th>
<th>Jan 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process definition</td>
<td>Product qualification</td>
<td>Pilot production</td>
<td>Production &amp; Sales</td>
</tr>
</tbody>
</table>

### Targets
- **Module efficiency >10%**
- **Industrial feasibility**
  - Cycle-time 5 min
  - No glass damage
  - Reproducibility
  - Good adhesion
- **Product design**
- **Production:**
  - Multi-day runs
  - Accelerated lifetime tests
- **Uptime > 50%**
- **Yield > 70%**
- **Output: > 2,000 per month**
- **Outdoor-testing**
- **Shipping to pilot customers**
Rapid learning curve demonstrates good process understanding and control

Evolution of module power

> 80W (>10.7%) after 4 month of process development

Continuous steady progress towards 100W (13.4%)
CIGSe composition optimisation

**Topic:**
Dependence of module power on elemental ratios Cu/(Ga+In) & Ga/(Ga+In)

**Solution:**
Optimisation of source parameters to define optimum setpoints for CIGSe runs:
- Precise source control and stability allow straightforward optimisation
- Setpoints for Cu/(Ga+In) & Ga/(Ga+In) defined

Soltecture technology allows for very tight control of layer composition – key for further performance improvements
CIGSe-coater (Gen2) achieves excellent uniformity of +/- 2% across individual substrates

Results: Homogeneity of metal ratios along substrate length (measured by XRF)

Uniformity across substrate +/- 2%
Good uniformity in composition leads to good uniformity in electrical performance

**Homogeneity of metal ratios along substrate length**

- measured by XRF
- Uniformity across substrate +/- 2%
- Very homogeneous electroluminescence image of large area modules
**Best module from Soltecture production line**

generates $98\,\text{W} = 13.1\,\%\,$ app. area efficiency

**PV data of best module**

- taken from Soltecture production line
- aperture area $= 0.75\,\text{m}^2$
- number of cells $= 123$

- 12.6 % externally confirmed (different module)

<table>
<thead>
<tr>
<th>$P_{mp}$</th>
<th>$\eta$</th>
<th>$V_{oc}$</th>
<th>$I_{sc}$</th>
<th>$ff$</th>
</tr>
</thead>
<tbody>
<tr>
<td>98.2 W</td>
<td>13.14 %</td>
<td>72.8V</td>
<td>1.89 A</td>
<td>71.3 %</td>
</tr>
</tbody>
</table>

$592\,\text{mV/cell}$ | $31.3\,\text{mA/cm}^2$
CIGSe-coater (Gen2) achieves excellent long term stability of coating conditions

Composition of CIGSe layers on 125 cm x 65 cm sized substrates during 36 h of continuous operation run (measured by XRF) → Excellent substrate to substrate uniformity – key to successful scale up
Soltecture’s gen2 process has proven excellent process stability and narrow power distribution

POWER DISTRIBUTION OF 2.100 SEQUENTIALLY PROCESSED MODULES (FEB 11)

Scatter diagram

Histogram

90 W = 12% aperture area efficiency
= 11% total area efficiency
Yield level of 80% proven
40% scrap reduction in less than one year

Evolution of Yield during ramp up of first coevaporation tool
First pass yield > 80%
Minimizing absorber related yield issues will lead to > 95%

Current Yield analysis sorted by production line section

- Total first pass yield > 80% level
- Electrical yield higher than 97%
- Back end yield constantly in the 97-98% range
- Front end yield P2/ZnO/P3: half of rejects due to CIGSe absorber issues
- By minimizing the number of rejects at coevaporation tool alone yield will improve by 7%
- By minimizing all other absorber related detractors, yield will improve to >95% level

<table>
<thead>
<tr>
<th>Section</th>
<th>Yield</th>
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</thead>
<tbody>
<tr>
<td>Front End w/o CIGSe</td>
<td>95%</td>
</tr>
<tr>
<td>CIGSe</td>
<td>93%</td>
</tr>
<tr>
<td>IV out of spec</td>
<td>98%</td>
</tr>
<tr>
<td>Back End</td>
<td>97%</td>
</tr>
<tr>
<td>Total</td>
<td>84%</td>
</tr>
</tbody>
</table>
Lessons learned during ramp up

Conclusions

– Ramp up of our new absorber technology to > 10% modules in less than 20 weeks
– Ramp up of yield to more than 80% in less than a year
– due to high synergy effects between Gen01 and Gen02 technology

– Production stability and quality assurance in CIS manufacturing require:
  ● CIS related expertise of the manufacturer’s technology team
  ● Production experience with CIS-based technology
  ● Scientific support
  ● Industrial knowledge

  → there is no turn key CIS technology yet, Soltecture and it’s team combines more the 200 person
  years of CIS experience and more than 5 years in continuous production → prerequisite for fast ramp
  up
PRODUCT QUALIFICATION
All relevant IEC test can be performed in soltecture’s in-house module test center

**Accelerated life-time test**
- Damp heat test
- Dry heat test
- Thermal cycling test
- Humidity-Freeze test
- UV irradiation
- Mechanical load and deformation test
- Light-soaking test

**Thin-film analysis**
- Electrical and optical analysis (a.o. Raman, PL)
- Microscopic analysis of layer structure (SEM)
- Homogeneity analysis
- X-ray analysis (XRF)

**System test**
- Monitoring of PV-test systems
- Qualification of inverters and mounting systems

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**Damp heat test**

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**Deformation test**
### Product qualification and certification

**SCG-GEN2-HV-F (CIGSe) product**

<table>
<thead>
<tr>
<th>Test</th>
<th>Internal pass criteria</th>
<th>External pass criteria acc. IEC61646 / IEC61730</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical load</td>
<td>$P_{\text{MPP}} &gt; 95%$ after MLT 10 modules</td>
<td>✔️ $P_{\text{MPP}} &gt; 90%$ after final lightsoaking 2 modules</td>
</tr>
<tr>
<td>Humidity freeze test</td>
<td>$P_{\text{MPP}} &gt; 95%$ after 40 cycles 10 modules</td>
<td>✔️ $P_{\text{MPP}} &gt; 90%$ after final lightsoaking 2 modules</td>
</tr>
<tr>
<td>Damp heat test</td>
<td>$P_{\text{MPP}} &gt; 95%$ after 2000h 10 modules</td>
<td>✔️ $P_{\text{MPP}} &gt; 90%$ after final lightsoaking 2 modules</td>
</tr>
<tr>
<td>UV preconditioning</td>
<td>$P_{\text{MPP}} &gt; 95%$ after UV test 2 modules</td>
<td>✔️ $P_{\text{MPP}} &gt; 90%$ after final lightsoaking 2 modules</td>
</tr>
<tr>
<td>Reverse current overload test</td>
<td>$P_{\text{MPP}} &gt; 95%$ after test according to EN50380 5 modules</td>
<td>✔️ $P_{\text{MPP}} &gt; 95%$ after test according to EN50380 1 module</td>
</tr>
<tr>
<td>Hot-spot test</td>
<td>no evidence of major visual defects insulation resistance &gt;50MΩ 5 modules</td>
<td>✔️ no evidence of major visual defects insulation resistance &gt;50MΩ 1 module</td>
</tr>
</tbody>
</table>

→ **SCG-GEN2-HV-F modules are qualified according to IEC61646 and IEC61730 and passed the internal higher requirements**

→ **confirmation by TÜV Rheinland received in June 2011**
Damp heat stability of Soltecture modules exceeds the IEC standard by three times

Encapsulation of CuInS2 modules

- Improvement of encapsulation has lead to an outstanding damp heat stability of Sulfurcell’s products
- Today damp heat stability exceeds the IEC standard by three times
- Sulfurcell products have passed the IEC61646 certification procedure at TÜV Rheinland
IEC 61646 received after less than a year of process and product development

- Total module size: 1.25 m x 0.65 m
  (aperture area: 1.215 m x 0.615 m)
Soltecture’s unique flatroof solution

**Fast and easy installation**
- Module carries its mounting system
  - Plug and Play, tool-free installation
- No roof penetration
- No or very low requirements for additional loads

**Applicable on large commercial roof-tops**
- System weight and wind load at least 30% lower than for standard solutions on the market
- Unique solution for building with very low load tolerance

**High energy yield**
- On-roof power density comparable to c-Si solutions due to 10° slope allowing low distance between modules lines
- Very low output reduction by flat installation due to excellent performance under low insolation angles

**Dependence of the power output on the insolation angle**

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### Outlook / Road Mapping

#### Losses and Improvement Areas

<table>
<thead>
<tr>
<th>Loss</th>
<th>Improvement Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale up losses</td>
<td>Improvement of uniformity and temporal fluctuations</td>
</tr>
<tr>
<td>CIGSe</td>
<td>Reduction of defect density of absorber</td>
</tr>
<tr>
<td>CIGSe/CdS</td>
<td>Heterojunction / Contact layers</td>
</tr>
<tr>
<td>Scale up losses</td>
<td>Improved module design</td>
</tr>
<tr>
<td>CIGSe/CdS</td>
<td>Alternative buffer layer</td>
</tr>
<tr>
<td>CIGSe</td>
<td>High-temperature CIGSe coating</td>
</tr>
</tbody>
</table>

- **Module Power**
  - 100W = 12.3%
  - 110W = 13.5%
  - 125W = 15.4%

**Graph Details**

- **X-axis**: Time
- **Y-axis**: Module Power
- **Data Points**:
  - 100W at 12.3% efficiency
  - 110W at 13.5% efficiency
  - 125W at 15.4% efficiency
The company has introduced a new one-step deposition process for high efficiency Cu(In,Ga)Se2 absorber layers based on coevaporation.

Ramp up of our new absorber technology took place in less than one year to 12.0% module efficiency, yield levels > 80% and including external certification.

Technology road map to >15% module efficiency defined and in progress.

→ Coevaporation is very well compatible with mass production.
Acknowledgement


Cooperation partners:

and others
Thank you for your attention