MANUFACTURING OF LARGE-AREA CUINS$_2$ SOLAR MODULES
– FROM PILOT TO MASS PRODUCTION

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Sulfurcell’s history: Passion for CIS since 1991

1991 – 2001  Hahn-Meitner-Institut Berlin takes lead in thin-film technology based on Copper-Indium-Sulfide (CIS)
April 2003  Launch of HMI spin-off Sulfurcell (EUR 16m financing closed)
July 2004  Plant begins operation
July 2005  Scale-up of CIS technology completed (5 x 5 $\Rightarrow$ 125 x 65 cm²), prototype presented to public
Dec 2005  Market entry

2005 – 2008  Continuous improvement of key performance indicators up to a run rate of 2.5 MW/a / 80 % yield
Jul 2008  75 MW expansion started (EUR 85m of equity raised)
Nov 2009  First CIS modules from 75 MW line
Sulfurcell’s 75 MW production facility CIS-Line

Dimension
- 16,000 m² production
- 3,000 m² offices

BIPV
- 700 facade-integrated CIS modules
- PV test field + 300 kW PV power plant on roof

05 10 09  Pilot plant Berlin Adlershof

21 April 09
Sulfurcell serves the market with high-quality products with a focus on building integrated photovoltaics (BIPV)

**SULFURCELL’S PRODUCT PORTFOLIO**

**Framed modules**
- Max. mechanical load (4800 kPa/m²)
- Applicable as cladding element

**Frameless modules**
- Optimized for minimum costs
- Excellent self-cleaning

**Modules for roof integration**
- Aesthetic excellence
- Replacing roof tile (rainproof)

**QUALITY**
All products passed accelerated life-time tests (IEC 61646) and are certified by German TÜV

**CONTRACTED WHOLESALER**

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![Sulfurcell Logo]
Sulfurcell’s technology roadmap towards high-efficiencies and lowest costs

GOAL
- Grid-parity, manufacturing costs lower than 0.7 €/W.

STRATEGY
- Specialisation on technologies based on CIS/CIGSe
  - Technology evolution
    → Driven by Sulfurcell’s technology team (50 engineers and PhDs in engineering, R&D and product development)
    → Continuous improvement of production technology
    → Mid-term projects targeting on advanced processes (Keeping 80%, improving 20%)
      → Test of new methods/materials within the CIS/CIGSe family
      → Modification of Indium-to-Gallium and Sulfur-to-Selenium ratio
    → Deep cooperation with Helmholtz-Zentrum Berlin (HMI) and other research groups
  - Orientation towards manufacturing
    → Fast transfer of innovations into production
      → Test & optimisation of new techniques in pilot production environment parallel to production
    → Focus on fast, highly-productive processes

INNOVATION FOCUS
- Material modifications
- New methods
- Moly
- Patterning
- Copper, Indium
- Sulfur
- Chemistry
- Patterning
- Zincoxide
- Patterning
- Finishing

EFFICIENCY GOALS
- 0%
- 5%
- 10%
- 15%
- 2005 2010 2015
Sulfurcell’s Technology

**Formation of CuInS<sub>2</sub>**

**Needs**
- Deposit of copper, indium and sulfur
- Compound copper, indium and sulfur (activated at 500 °C)
- Build polycrystalline layer

**Sulfurcell’s approach**
- Sputtering of copper and indium (precursor) → to avoid high-temperature processes for metal deposition → to achieve reasonable machine costs
- Rapid thermal annealing of copper and indium under sulfur atmosphere → to benefit from high reactivity of sulfur → to achieve short cycle-time
- Use Cu-rich precursor (Cu:In > 1) → to benefit from copper accelerating growth and enhancing crystal quality

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**Sequential absorber preparation**

Glass
Sputtering
Molybdenum
Sputtering
Copper / Indium
Chemical Processing...
Sputtering
Zinkoxid
Laser scribing
Scribing
Scribing
Heating, Sulfurization
CIS
Edge
Decoating
Sodalime Glass
Wiring
& Testing
Laminating
Framing & Junction box
Solar module
Sulfurcell’s technology

Sulfurcell has a lean production process involving five deposition steps.

**Sulfurcell’s production process**

1. Sodalime Glass
2. Sputtering Molybdenum
3. Glass
4. Laser scribing
5. Sputtering Copper / Indium
6. Heating, Sulfurization CIS
7. Chemical Processing
8. Sputtering Zinkoxid
9. Scribing
10. Scribing
11. Framing & Junction box
12. Laminating
13. Wiring & Testing
14. Edge Decoating
15. Solar module
16. Solar module

Sequential absorber preparation
Learning curves of key performance indicators

Key performance indicators

- start of 24/7 operation in Oct 07
- run rate since Jul 08 of 2.5 MW/a
- yield stabilized in Q1/08 at 80%
- continuous improvement of module power

Yield
Modules OUT / Glass IN

<table>
<thead>
<tr>
<th>Year</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>22%</td>
<td>40%</td>
<td>50%</td>
<td>80%</td>
<td>80%</td>
</tr>
</tbody>
</table>

Average Efficiency
Aperture Area: 1.20 m x 0.60 m

<table>
<thead>
<tr>
<th>Year</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>5.8%</td>
<td>7.2%</td>
<td>7.4%</td>
<td>7.7%</td>
<td>7.9%</td>
</tr>
</tbody>
</table>
CIS module development

R&D top four in 2008/2009:
• production-line stability issues
• bulk absorber properties
• CIS/CdS/ZnO interface issues
• active area / patterning

Module power development
• best CIS modules reach 9% active area efficiencies.
• average quarterly module power reached 60Wp (=8.2%) in Q4/09
• narrowed power distribution down to a FWHM of only 2.2 W
CIGS technology integration

Integration of Gallium

Incorporation of Gallium has been shown to be a successful way in increasing the efficiency of small area laboratory cells

<table>
<thead>
<tr>
<th></th>
<th>Eg [eV]</th>
<th>Eff [%]</th>
<th>Voc [mV/cell]</th>
<th>FF [%]</th>
<th>Jsc [mA/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIS</td>
<td>1.5</td>
<td>11.4</td>
<td>730</td>
<td>71.7</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ga-free reference</td>
</tr>
<tr>
<td>CIGS</td>
<td>1.56</td>
<td>13.0</td>
<td>864</td>
<td>64.0</td>
<td>23.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>active area, w AR</td>
</tr>
<tr>
<td>CIGS</td>
<td>1.60</td>
<td>12.7</td>
<td>885</td>
<td>71</td>
<td>20.2</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>active area, w/o AR</td>
</tr>
<tr>
<td>CIGS</td>
<td>1.60</td>
<td>12.0</td>
<td>865</td>
<td>69</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>total area, w AR, NREL certified</td>
</tr>
<tr>
<td>CIGS</td>
<td>1.65</td>
<td>11.5</td>
<td>890</td>
<td>64</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>active area, w AR</td>
</tr>
</tbody>
</table>

E_g derived from external quantum efficiency measurements

Source: Reiner Klenk, Helmoltz-Zentrum Berlin für Materialien und Energie
CIGS technology integration

Integration of Gallium

- Sodalime Glass
- Sputtering Molybdenum
- Glass
- Laser scribing

Sequential absorber preparation

- Heating, Sulfurization CIGS
- Chemical Processing

- Sputtering Zinkoxid
- Scribing

- Framing & Junction box
- Laminating
- Wiring & Testing
- Edge Decoating

Solar module
Sulfurcell's Gallium-technology

**Status of Gallium project**

- Steady increase in module power since start of process development on large area
- Latest results 3W better than standard Ga-free process

![Graph showing power/module [W] over time for CIGS best of process and Ga-free (ave)]
Sulfurcell’s Gallium-technology

**Current project status**

- Process will be ready for production in June
- Best modules show 67W module power

Comparison of small area reference cells

<table>
<thead>
<tr>
<th>technology</th>
<th>CIS</th>
<th>CIGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>process</td>
<td>lab</td>
<td>prod</td>
</tr>
<tr>
<td>lab</td>
<td>lab</td>
<td>prod</td>
</tr>
<tr>
<td>area [sqcm]</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Eff [%]</td>
<td>11.4[1]</td>
<td>10.4</td>
</tr>
<tr>
<td>Voc [mV/cell]</td>
<td>730</td>
<td>700</td>
</tr>
<tr>
<td>FF [%]</td>
<td>71.7</td>
<td>71</td>
</tr>
<tr>
<td>Jsc [mA/cm²]</td>
<td>21.8</td>
<td>21</td>
</tr>
</tbody>
</table>

Comparison of Ga to Ga-free module

Higher voltage per module due to Gallium incorporation
Sulfurcell’s Gallium-technology shows very low temperature coefficient

**Comparison of T-coefficient of various PV technologies**

**Very low temperature coefficient**

- Observation of lowest temperature coefficient of all PV technologies besides amorphous
- Low temperature coefficient promises high performance on a kWh per kW basis in warm-weather regions (e.g. 8 % more than poly-Si at 65 °C)

<table>
<thead>
<tr>
<th>Type</th>
<th>Power loss in % per °C</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly-Si</td>
<td>-0,44</td>
<td>Solon AG</td>
</tr>
<tr>
<td>CIGSe</td>
<td>-0,36</td>
<td>Würth Solar</td>
</tr>
<tr>
<td>CIS</td>
<td>-0,28</td>
<td>Sulfurcell</td>
</tr>
<tr>
<td>CdTe</td>
<td>-0,25</td>
<td>FirstSolar</td>
</tr>
<tr>
<td>CIGS</td>
<td>&lt; -0,24</td>
<td>Sulfurcell</td>
</tr>
</tbody>
</table>
Continuous quality control – a daily in-house

**Accelerated life-time test – Sulfurcell resources**
- Damp heat test
- Dry heat test
- UV test
- Mechanical load and deformation test
- Light-soaking test

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

**Extended in-house testing program at Sulfurcell:**
- 3000 h damp heat
- 30 cycles humidity freeze
- damp heat under bias,
- mechanical load under torsion

**Extended testing program in coop. with externals:**
- 500ppm NH3-atmosphere according to DIN50916:1985,
- Salt-mist corrosion test according to IEC61701:1995
- Hail impact test
Product stability

Encapsulatio of CuInS$_2$ modules

- Improvement of encapsulation has led 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.

The graph shows the power/initial power (%) against damp heat storage time (h), with data points indicating a high level of stability over extended periods.
CIS outdoor performance experience

- stable and reliable performance over 3 years of outdoor experience.
- energy yield of c-Si and CIS comparable.
- CIS does not show any light-induced degradation effects.
- Outdoor results have been confirmed by numerical simulations using the PV-Sol software

Comparison of outdoor performance of c-Si, a-Si and CIS

(location of 3 x 1 kWp pv installation: Berlin, Germany)
CIS outdoor performance experience

Comparison of c-Si and CIS in hot climates

Numerical simulations using the PV-Sol software confirm our outdoor results:

Simulated specific energy yield [kWh/kWp a] of a CuInS$_2$ PV system and a c-Si system.

<table>
<thead>
<tr>
<th>Location</th>
<th>CuInS$_2$</th>
<th>c-Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berlin, Germany</td>
<td>925</td>
<td>891</td>
</tr>
<tr>
<td>Rome, Italy</td>
<td>1478</td>
<td>1396</td>
</tr>
<tr>
<td>Madrid, Spain</td>
<td>1492</td>
<td>1401</td>
</tr>
<tr>
<td>Cairo, Egypt</td>
<td>1772</td>
<td>1652</td>
</tr>
</tbody>
</table>

Temperature coeff. for CuInS$_2$: 0.28% / K
Temperature coeff. for c-Si: 0.48% / K

Systems are installed on the same site in Rizoma near Trikala, Greece.
Summary

TECHNOLOGY

● Application of proprietary CIS-based technology.
● Long-years track record in industrial application of CIS: Sulfurcell modules shipped and sold, 2.5 MW/a manufacturing rate.
● 220 staff with 30 in-house CIS-specialists. Alliance with Europe’s leading research institute on thin-film PV (Helmholtz Centre Berlin).
● 75MW line has been installed in 2009, will reach stage one capacity of 35MW in mid 2010

PRODUCTS

● Sulfurcell products are designed and equipped for building integration.
● The high quality standard is certified by TÜV Rheinland (IEC 61646).