Exploring Innovative Processes and Materials for High Efficiency CIGS Modules

OUTLINE

- About AVANCIS
- High Efficiency Technology
- Wide Bandgap Absorber
- Innovative RTP Tool
- Buffer Development
- Conclusions
About AVANCIS

COMPANY FACTS

- German Manufacturer of CIGS thin-film modules
- **More than 25 years CIGS knowledge** as PV Pioneer (Arco Solar, Siemens)
- Founded in 2006 as JV of Shell and Saint-Gobain
- Since 2014, part of CNBM group (China National Building Materials)
- ~ 300 employees in Torgau and Munich
- Production capacity (p.a.): 100 MW Germany / 100 MW South Korea
- Full vertical integration: Glass in – modules out
- **R&D core competence** in driving efficiency world record
- Own **pilot-line** for ongoing efficiency improvements
- **Technology centre** for scale-up and customized modules

→ „Engineered and Made in Germany“
GLOBAL ACTIVITIES – EURASIAN LOCATIONS

AVANCIS

Munich, DE
(R&D)

Torgau, DE
(HQ, R&D, P)

Bengbu, CN
(P)

Jiangyi, CN
(P)

Ochang, KR
(P)

AVANCIS

AVANCIS

CNBM

CNBM

CNBM

AVANCIS

About AVANCIS

established (200 MW)

planned (3000 MW)

Author: R. Lechner

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About AVANCIS

TECHNOLOGY TRANSFER TO CHINA

- Ground Breaking on Sep 25, 2015
- First 300 MW production unit with AVANCIS CIGS technology; to be opened in 2017
- Total planned output 1.5 GW
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THE 2 KEY ELEMENTS OF AVANCIS CIGS TECHNOLOGY

1. **Element**: Low Cost Large Area Sputtering

2. **Element**: Rapid Thermal Processing (RTP)
### AVANCIS' Cd-FREE BASELINE MANUFACTURING SEQUENCE

<table>
<thead>
<tr>
<th>Pattern 1</th>
<th>Cu-Ga-In-Se:Na</th>
<th>CIGSSe</th>
<th>buffer + i-ZnO</th>
<th>Pattern 2</th>
<th>ZnO</th>
<th>Pattern 3</th>
<th>Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>Coating</td>
<td>Heating</td>
<td>Coating</td>
<td>ps Laser</td>
<td>Coating</td>
<td>Scribing</td>
<td>Laminate</td>
</tr>
</tbody>
</table>

- **Substrate:** Sodalime float glass w/ higher strain point / SiN / Mo1 / Se-barrier / Mo2
- **Precursor Deposition (low temp.):** Stacked Elemental Layer (SEL)
  - Cu-In-Ga:Na by magnetron sputtering
  - Se by thermal evaporation
- **Absorber formation by rapid thermal processing (RTP) in sulfur containing gas**
- **PVD-InₓSᵧ:Na buffer + i-ZnO**
- **ZnO:Al by magnetron sputtering**
- **Contacts by ultrasonic welding**
- **Anti-reflective (AR) coated front glass**
- **Standard module size of 65x160cm² in production and 30x30cm² in R&D**
AVANCIS' Track Record of Certified Champion Efficiencies

30x30cm² EXTERNALLY CERTIFIED CHAMPION EFFICIENCIES

AVANCIS' 30x30cm² Certified Champion Module Efficiencies

- CdS buffer
- InₓSᵧ:Na buffer

17.93% (Fh-ISE)
AVANCIS' Track Record of Certified Champion Efficiencies

Comparison of champion modules

### LATEST 2016 EXTERNALLY CERTIFIED CHAMPION MODULE

<table>
<thead>
<tr>
<th></th>
<th>$\eta_{ap}$ (%)</th>
<th>Jsc (mA/cm²)</th>
<th>Voc (mV)</th>
<th>FF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014 Champ (NREL)</td>
<td>16.6</td>
<td>38.5</td>
<td>621</td>
<td>69.4</td>
</tr>
<tr>
<td>2016 Champ (ISE)</td>
<td>17.9</td>
<td>39.7</td>
<td>627</td>
<td>72.2</td>
</tr>
<tr>
<td>Improvement</td>
<td>+7.8%</td>
<td>+3.1%</td>
<td>+1%</td>
<td>+4%</td>
</tr>
</tbody>
</table>

Key improvements 2016:
- Optimized cell width and dead area
- Improved TCO layer

EUPVSEC 2016 3BO.8.2

STC measurement under natural sunlight according to IEC 60904-1 / IEC 60891

- Major improvements on FF and Jsc

Key improvements 2016:
- Optimized cell width and dead area
- Improved TCO layer

$P = 11.16 \text{ W}$
$A_{ap} = 622.3 \text{ cm}^2$
$\eta_{ap} = 17.93\%$
- About AVANCIS
- High Efficiency Technology
- **Wide Bandgap Absorber**
- Innovative RTP Tool
- Buffer Development
- Conclusions
BANDGAP INCREASE – S & GA

- Increase **Ga-content in precursor** +0%, +24%, +44%, +52%
- Same RTP leads to systematic change in depth distribution of Ga and S in the absorber
- Typical double S-gradient: surface and back interface widening of $E_{\text{gap}}$
- Increased bulk S-content, reduced S-content at the back contact, comparable total S-content
BANDGAP PROFILE

- Systematic increase of minimum bandgap with increasing Ga content
  - $V_{oc}$ increase expected
  - $j_{sc}$ decrease expected
- Systematic shift in the minimum bandgap position towards pn-junction
BANDGAP INCREASE

- $V_{oc}$ increase as expected, up to +10.2%
- $j_{sc}$ decrease as expected, up to -6.7%
- Net overall gain in efficiency
- Side-effect: improvement of temperature coefficient

**V_{oc}** increase

**j_{sc}** decrease
TEMPERATURE COEFFICIENT

- Increased $V_{oc}$ leads to reduction of temperature coefficient
- About AVANCIS
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- Large Bandgap Absorber
- Innovative R&D RTP Clustertool
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Clustertool

**Process line RTP#1 and RTP#2:**
- Innovative heating concepts
- In situ metrology

**Transport module:**
- Substrate/Carrier Handling in inert atmosphere
- Automated loading

**Process line RTP#3:**
- High throughput
- Innovative heating concepts

**CIS-Clustertool**
- Proof of concept tool for future mass production
- In-line selenization equipment

**Se-Evaporator for deposition**
PROMINENT FEATURES AND SCOPE OF PERFORMANCE

- **Double throughput** within RTP section compared to production sites
- At least 30% **energy saving with innovative heating concepts** at RTP
- **Enhanced power density**, higher temperature stability, and prolonged lifetime of the IR heaters
- Modular functionality of the heaters allows **superior homogeneity** of the IR radiation reaching the substrate / suitable up to jumbo glass size
- Four different RTP concepts and various processing methods aim for **significant CAPEX and OPEX reduction**

**Significant reduction in €/W_p**
**CAPEX, OPEX, POWER**

**Future Fab concepts**
DESIGN PHASE: FEM AND CFD ISSUES

- **Substrate strain simulation after RTP/Cooling**
- **Temperature distribution aiming < 1°C**
- **Design optimization of a large area heating element**
- **Investigate impact of shieldings and various thermal insulating materials on energy consumption**
- **Gas flow optimization with CFD**
ENERGY SAVINGS WITH INNOVATIVE HEATING CONCEPTS

Temperature/Power vs. Heating Concept

-54%  -59%  -62%

Infrared (IR) heating elements with high efficient reflector

Innovative large area (LA) heaters and highly efficient thermal insulation

Time (sec)  0  100  200  300  400  500  600  700  800  900  1000  1100  1200  1300  1400  1500  1600  1700  1800  1900

Temp. IR (°C)  Temp. LA (°C)  IR-Power (%)  LA-Power (%)

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TUNABLE 2D TEMPERATURE HOMOGENEITY

Tuning Capabilities: Temperature Line Profiles ROI 002

Temperature Deviation (°C)

Substrate Position (cm)

ROI 001
ROI 002

R00160  R00162  R00177  R00179  R00180
**IMPACT OF TEMPERATURE HOMOGENEITY**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard IR</th>
<th>Innovative IR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temp. Substrate: Average Center Stdev</strong></td>
<td>( T_{\text{ref}} ) ( T_{\text{ref}} +19 \text{ K} ) ( 15,3 \text{ K} )</td>
<td>( T_{\text{ref}} + 16 \text{ K} ) ( T_{\text{ref}} + 11 \text{ K} ) ( 6,2 \text{ K} )</td>
</tr>
<tr>
<td>S+Se Stdev (%) @ ROI001</td>
<td>1,0 %</td>
<td>0,4 %</td>
</tr>
<tr>
<td>( E_1 ) “surface sulfur content“ Stdev (%) @ ROI001</td>
<td>0,8 %</td>
<td>0,2 %</td>
</tr>
<tr>
<td>( E_{\text{gap}} ) Stdev (%) @ ROI001</td>
<td>0,5 %</td>
<td>0,1 %</td>
</tr>
<tr>
<td><strong>Eta relative (%)</strong></td>
<td>100 %</td>
<td>109 %</td>
</tr>
<tr>
<td>FF / ( V_{\text{oc}} ) / ( j_{\text{sc}} ) rel. (%)</td>
<td>100 % / 100 % / 100 %</td>
<td>109 % / 98 % / 102 %</td>
</tr>
</tbody>
</table>
IMPACT OF TEMPERATURE HOMOGENEITY

Boxplot von Eta; Uoc; Jsc; FF (normalized)

- Eta: +9 %
- Uoc: +9 %
- Jsc: +9 %
- FF: +9 %

IR-Config
- Standard
- Innovative
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ADVANCED CD-FREE BUFFER

- **Approach 1**
  - Wide bandgap buffer In$_x$S$_y$:Na in combination with a Zn$_{0.85}$Mg$_{0.15}$O i-layer
  - **Efficiency improvement**
  - **Cost reduction**

- **Approach 2**
  - All-sputtered buffer and TCO stack Zn(O,S) / ZnO:Al
  - **Simplification of the device stack**
  - **Simplified CIS manufacturing sequence**
  - **Simplified fab design**
  - **Cost reduction**
WIDE BANDGAP BUFFER $\text{In}_x\text{S}_y:Na$

- Increase of Na-content in the buffer layer $\text{In}_x\text{S}_y:Na$ increases the buffer bandgap.
- Consequently, gain in $j_{sc}$ is observed, $V_{oc}$ decreases.
- $+4\%$ gain in $\eta_{rel}$ gain for ZMO vs. optimized i-ZnO.
- Benefit in $\text{FF}_{rel}$ mainly driven by reduced $j_0$.
- Hypothesis: a mismatch at buffer / i-layer interface is responsible for FF decrease.
- Additional contribution of $R_{ser}$. 

Conventional
$\text{In}_x\text{S}_y:Na$/i-ZnO bilayer CIS stack
$\rightarrow$
New
$\text{In}_x\text{S}_y:Na/\text{Zn}_{0.85}\text{Mg}_{0.15}\text{O}$ bilayer CIS stack
ALL-SPUTTERED BUFFER AND TCO STACK

• Thermally evaporated In$_x$S$_y$:Na buffer layer and RF-sputtered i-ZnO layer are replaced by a single RF-sputtered ZnO$_{1-x}$S$_x$ buffer layer.
• simple and low-cost approach
• sputtering from ceramic target
• nominal composition of [ZnS] / ([ZnS]+[ZnO]) = 0.25.
• Zn(O,S) shows typical benefit in $j_{sc}$ +1.9% relative
• yet inferior recombination characteristics: Voc/FF-loss
• Zn(O,S)-buffered device stack lacks -3.2% relative in module efficiency.
• Still room for improvement
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CONCLUSIONS

- Demonstration of new record module 17.9%
- Tuning of Ga-content leads to wide bandgap absorbers for improved efficiency and $T_k$ performance
- Innovative RTP tool for future fab concepts & further absorber improvements
- Innovative sputter-deposited Zn(O,S) buffer seems promising for industrialization
- Process R&D paves the way for the AVANCIS CNBM technology roadmap – towards 3 GW production capacity worldwide
THANK YOU FOR YOUR ATTENTION

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http://www.innovationsallianz-photovoltaik.de/main/cis-clustertool/

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