Scaling up issues of CIGS solar cells

M. Powalla, B. Dimmler

Zentrum für Sonnenenergie- und Wasserstoff-Forschung (ZSW), Baden-Württemberg, Hefbrahlstraße 21c, D-70565 Stuttgart, Germany

Würth Solar GmbH & Co. KG, Ludwigshügler Straße 100, D-71672 Marbach am Neckar, Germany

Abstract

Thin film solar modules based on Cu(In,Ga)Se₂ (CIGS) have a very high potential to reduce production costs for photovoltaic modules. The challenge is to combine the large area issues with high throughput and yield with the high quality of the device. ZSW has developed in-line processes for almost all process steps for glass/glass modules and reaches a 12.7% efficiency level with high yield for 30×30 cm CIGS modules. A 30×30 cm Cd-free module with nearly 10% efficiency is realised after a short time of development. The modules are very stable in the damp/heat test. These results qualify the process to start the next scaling up step. Würth Solar GmbH & Co. KG, a joint venture of ZSW, Würth group, and EnBW AG, was founded to commercialise CIGS technology and PV products. A cost estimation will be given, which considers the sensitivity of the relevant input parameters. With medium risk assumptions the manufacturing costs of CIGS modules for a 60 MWp/a capacity are about 0.6 Euro/Wp. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Cu(In,Ga)Se₂; Photovoltaic modules; Scaling up; In-line processes; Cost estimation

1. Introduction

In thin film photovoltaics the development of large area semiconducting thin films is a big challenge [1]. For competitiveness in the PV power market a considerable reduction of manufacturing costs together with conversion efficiencies well above 10% are required. High material quality on large areas has to be achieved with high throughput in order to meet the cost targets.

Thin film technology has the potential to provide high production capacity at reduced material and energy consumption in the fabrication process. Monolithic modules allow high flexibility with respect to electrical output and module geometry.

Modules on the basis of Cu(In,Ga)Se₂ (CIGS) are produced in pilot and production lines, which have started operation or are under construction. Substantial progress has been made during the last few years with respect to efficiency on the laboratory scale.

CIGS solar cells with an area smaller than 1 cm² have been fabricated by several groups with efficiencies over 15% and with an actual maximum of 18.8% total area efficiency [2,3]. The best results ever reported have been achieved by thermal co-evaporation of the elements for deposition of CIGS. The up-scaling strategies and production lines of e.g. Siemens [4] are based on sequential CIGS processes, which normally contain sulphur in the absorber material.

During the last years a line for the development and small scale fabrication of 30×30 cm CIGS modules has been constructed at ZSW and has after a short time shown the proof-of-concept on a high level of quality. The CIGS process is based on one step co-evaporation and nearly all process steps are done in-line. It is planned to build up a production with 10 MWp/year capacity. To minimise the risk of investment a pilot production of 1.2 MWp/year capacity is now started and will come in operation in the end of 1999 at Würth Solar in Marbach am Neckar near Stuttgart, Germany.

The technologies described in this paper are the basis for flat glass/glass modules fabricated for the terrestrial PV market up to a size of 120×60 cm.

This paper deals with the up-scaling issues of the whole CIGS module from the raw float glass plate to the encapsulated module. The focus is on homogeneity over large area, the throughput and the yield of the process and nevertheless the quality and the stability of the modules. We make also some remarks about the production costs and the sensitivity of some important parameters.

2. Experimental

The deposition processes were initially developed at the
Institute of Physical Electronics (IPE, University of Stuttgart) and they have led to the very high quality, which is based on the one-step thermal co-evaporation of the CIGS film (approaching 17% on the small area cell level) [5]. The results have been the basis for the work at ZSW, targeted to apply, transfer and bring the processes to an industrial scale.

Soda-lime sheet glass with a thickness of 1–3 mm is used as mechanical support for the thin films. The glass is cut to 30x30 cm or smaller and the edges are ground. At ZSW alternative substrates are tested but not described in this paper. The glass sheets are cleaned in a commercial batch system with cleaning agents. Process check is by visual inspection.

A molybdenum back contact is deposited by DC magnetron sputtering. The Mo thickness and film resistance is measured as a standard process control. The preparation conditions for Mo in combination with the Na containing glass have significant influence on cell performance [6]. For monolithic integration the back contact is patterned by Nd:YAG laser scribing. The separation is checked by measurements of the resistance between the stripes. For our process on soda-lime sheet float glass no diffusion barrier and no Na precursor are necessary. One-step co-evaporation of the elements is applied for the deposition of the absorber layer. The composition and the thickness of the CIGS film is controlled with atomic absorption spectroscopy (AAS) [7] and X-ray fluorescence (XRF) [8]. For the formation of the heterojunction a thin buffer layer of CdS is prepared by chemical bath deposition (CBD) technique. Alternatively other compounds like In(OH)₅S, and others are applied to realise a completely Cd-free device [9]. Al-doped ZnO has been found to be the most suitable material for the n-type transparent electrode. ZnO is fabricated in a two-layer process (i-ZnO and Al-doped ZnO) by magnetron sputtering from oxide targets (RF for i-ZnO and DC for Al:ZnO). Results of reactive sputtering of ZnO from a metal target are promising. Further details of the ZnO process can be found in [10]. Thickness and resistivity are checked as a process control. The semiconductor patterning (second and third patterning step) is done by mechanical scribing. The modules are finished by bonding electrical contacts and standard EVA/glass encapsulation. Module design is given in [11]. We measure the I/V performance of the modules under standard conditions before and after the encapsulation. All vacuum deposition processes (Mo back contact, CIGS absorber and ZnO window) are realised in a one-step mode in in-line high vacuum systems. The deposition systems are shown schematically in Fig. 1.

The coating processes are done either by DC magnetron sputtering with linear cathodes for back and front contact or, in the case of CIGS, by linear evaporation sources for the single elements, which are developed at ZSW.

3. Results

3.1. Solar cell and module performance

The resulting uniformity (film thickness, composition and properties) is excellent [11]. Cycle time is optimised by the in-line approach and is only limited by the film formation time. By integration of suitable in-line and on-line process and quality control systems, reproducibility and hence process yield is optimised. A precise quality control and end point detection is essential to give long term stable deposition of high quality CIGS films. For the other process steps reproducibility is high and process windows are large.

Process optimisation with respect to film and module quality, deposition time and reproducibility has been the focus of the work after installation of all process and characterisation equipment. The best cell and module results are summarised in Table 1.

The best result of an integrated mini-module is a 13.9% aperture area efficiency fabricated in 1996 in partnership with IPE. The best small area reference cell fabricated in the large area systems gave a total area efficiency of 16.1% (0.5 cm² with AR coating, active area efficiency 17.2%). With the 30x30 cm modules a maximum efficiency of 11.5% was achieved in 1998. Due to process optimisation the maximum efficiency could be improved to 12.7% in 1999 (both measured at ISE/FhG Freiburg). The performance of the unencapsulated module is given in Fig. 2.

A very large module was built of 15 single 30x30 cm modules laminated on one piece of cover glass for demonstration of a high voltage AC-module with innovative integration of a transformer less inverter. This resulted in a high

Fig. 1. Schematic view of in-line large area deposition systems either for thermal evaporation for CIGS or sputtering for Mo or ZnO as fast and economic processes for CIGS modules.
voltage module \( (V_{oc} = 550 \text{ V}, V_{MPP} = 440 \text{ V}) \) with output power of 125 W. The area utilisation is not optimised as the efficiencies of all 30 × 30 cm submodules were measured as 11.1% on average. Substitution of CdS still in use as standard buffer layer by a completely Cd-free material is an actual topic at ZSW [9]. A 30 × 30 cm Cd-free module with an efficiency of 9.7% was realised after a short time of development. This gives hope that we can substitute the Cd-containing buffer also on the module level without losing quality.

### 3.2. Process statistics

At ZSW standard process conditions have been defined and the whole process line was run on several consecutive days. First manufacturing statistics are shown in Figs. 3 and 4. A large number of 30 × 30 cm glass substrates has been treated in a batch up to the finished module.

A few glass sheets were sorted out before Mo deposition because of handling mistakes (broken or finger prints). During Mo deposition the main failure resulted from transport problems from our sputtering system. But at last the deposition is very stable, as to be seen from the thickness and \( R_{sq} \) logging shown in Fig. 3 (Mo). In order to see the influence of Mo thickness the samples numbers 1344 to 1346 have been intentionally prepared with about half of the thickness. Obviously this does not change the efficiency systematically. Including these surely avoidable failures the yield of substrate preparation including Mo deposition is about 82%.

The main failures occurring in CIGS absorber deposition processes are some operator mistakes in entering setpoints for process automation and some software induced transport problems. In two cases the cooling water from laboratory infrastructure caused some problems, but in the second half none of these avoidable mistakes occurred ending in very good statistics for samples with numbers above 1320. The yield of this process is 92%, which is very good because of the not inherent failures.

For the ZnO deposition process the most important quality control parameters are shown in Fig. 3 (Al:ZnO). Transmission and \( R_{sq} \) are controlled by the system and are very constant. The decrease of thickness is due to changes of sputtering condition in the erosion tracks. No major failure occurred. During encapsulation and module finish some failure occurred, due to the manual handling and operating at ZSW. Some sheets are broken during handling for sandblasting or encapsulation. In some cases the module performance suffers from problems of adhesion and conducting of the busbars. Due to these problems the efficiency values are given before encapsulation.

In the process steps patterning and CBD no remarkable failure occurred, which is why the yield is nearly 100%.

The overall process yield and an efficiency distribution are summarised in Fig. 4. The yield is 62% but the failures are very simple due to the process steps which are not yet automated and optimised at the ZSW line. The medium efficiency is about 11.3%. If these simple failures could be avoided the overall yield could be well above 90%.

### 3.3. Stability

Reliability during the lifetime of the module is a very important feature. Outdoor and accelerated lifetime tests

---

### Table 1

<table>
<thead>
<tr>
<th>Aperture area (cm²)</th>
<th>Number of cells</th>
<th>Efficiency (%)</th>
<th>Output power (W)</th>
<th>Year of production</th>
<th>Labour</th>
</tr>
</thead>
<tbody>
<tr>
<td>91</td>
<td>15</td>
<td>13.9</td>
<td>1.3</td>
<td>1996</td>
<td>IPE/ZSW&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>60</td>
<td>12</td>
<td>12.7</td>
<td>0.8</td>
<td>1997</td>
<td>ZSW&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
<td>16.1</td>
<td>0.008</td>
<td>1997</td>
<td>ZSW&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>718</td>
<td>41</td>
<td>11.5</td>
<td>8.2</td>
<td>1998</td>
<td>ZSW&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>717</td>
<td>41</td>
<td>9.7</td>
<td>7</td>
<td>1998</td>
<td>ZSW(Cd-free)</td>
</tr>
<tr>
<td>14200&lt;sup&gt;d&lt;/sup&gt;</td>
<td>15 × 60</td>
<td>8.8</td>
<td>125</td>
<td>1998</td>
<td>ZSW&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>731</td>
<td>53</td>
<td>12.7</td>
<td>9.3</td>
<td>1999</td>
<td>ZSW&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Measured at ISE/FhG Freiburg.

<sup>b</sup> Measured under standard AM 1.5 and 1000 W/cm², 25°C.

<sup>d</sup> Module composed of 15 single 30x30 cm modules with a medium efficiency of 11.1% with an open circuit voltage of 550 V, equipped with an AC-high voltage converter without transformer.

<sup>c</sup> Measured under standardised sun.

---

Fig. 2. Performance of the best 30×30 cm unencapsulated module with 53 interconnected single cells.
are therefore performed to give input for optimisation of the technologies. The modules of the first generation show a slight decrease in outdoor performance. But all modules produced with further optimised processes show stable outdoor behaviour without any additional framing, which is shown in Fig. 5.

Accelerated lifetime testing of modules with EVA/glass encapsulation has shown that the module performance is susceptible to water vapour. The main reason found was the increasing electrical resistance of the ZnO and the corrosion of the Mo especially in the interconnection region as an effect of humidity ingress. Furthermore the heterojunction is affected. Investigations are on the way to avoid negative influence of water vapour. Preparation conditions as well as encapsulation techniques have been varied and modified. The resistance of frameless CIGS modules against high

![Graphs showing process statistics for Mo, CIGS, and ZnO processes with efficiency from 50 consecutively produced 30x30 cm modules.](image)

**Fig. 3.** Process statistics for the Mo, CIGS and ZnO process and efficiency from 50 consecutively produced 30x30 cm modules.

![Bar chart showing number of modules (unencaps.) and number of samples](image)

**Fig. 4.** Process yield and statistics of consecutively processed 30x30 cm modules.
humidity and high temperature could be improved to withstand the standard damp heat test (85°C and 85% relative humidity for 1000 h) within the accepted tolerances (maximum 5% degradation) according to IEC1646. Fig. 6 shows the damp heat behaviour of two modules fabricated under varied process conditions and modified encapsulation techniques. Even for 1500 h the degradation is less than 5% for certain fabrication conditions. The thermal cycle and the mechanical test is already done and the humidity freeze test is almost passed (according to IEC1646).

4. Commercialisation

According to ZSW’s long term strategy on scaling-up CIGS technology the first step is successfully done. The technologies for large area CIGS modules with the construction of a fabrication line are developed and 30×30 cm modules with efficiencies above 12% are realised. The next step to increase module size to 60×120 cm and proof-of-concept for high yield and short cycle time is already started at ZSW. Planning of the building of a pilot line has been started in parallel. This scenario is shown in Fig. 7.

A new company (Würt Solar) was founded as a joint venture of ZSW together with Würt group and the energy provider EnBW, all placed in Baden-Württemberg, the southwest state of Germany. Würt Solar will be placed in the city of Marbach am Neckar near Stuttgart. ZSW is responsible for the technology, whereas Würt brings in their world-wide market experience and most of the capital. It is planned to set up the pilot line within one year with the goal to start operation at the end of 1999. The final production capacity of that pilot line will be in the range of 1–1.2 MWp/a with total capital cost of about 15 Million Euro. After approval of the manufacturing technology the capacity will be raised to around 10 MWp/a as fast as possible.

The commercialisation of the CIS technology will be supported by the close collaboration with IPE and ZSW concerning further development and optimisation of material science and process technology and the direct link with the ZSW crew to support the start-up of the pilot line. A direct and long term support of the commercial activity at Würt Solar by ZSW’s advanced CIS module technology will help the commercialisation of CIS-technology to be successful.

5. Economical and ecological aspects

In an European study on Multi-Mega-Watt Upscaling of PV Technologies (APAS/MUSIC.FM [12]) it was a clear conclusion for thin films that it should be possible for the three most important materials a-Si (Phototronics/ASE), CIGS (ZSW) and CdTe (BP-Solar) to fabricate modules on costs far below 1 Euro/Wp at a production capacity of 60 MWp/a. In comparison costs for crystalline silicon are not expected to fall below 1 Euro/Wp even at production levels of 500 MWp/a except with the EFG process used by ASE Americas. Another conclusion of this study was that high quality, i.e. high efficiency and large volume, fabrication is essential for market penetration.

All thin film technologies end up more or less at the same
cost level of approximately 0.6 Euro/Wp. Nevertheless the risk to gain assumed efficiency levels in production are assessed. According to the study, as already mentioned above, CIGS is expected to reach the highest quality level with lowest risk among all thin film materials.

A calculation on the basis of concrete assumptions for production parameters, labour, equipment and material costs was done at ZSW in detail. Some of the main parameters of influence are summarised in the second column (base case) of Table 2 for the 10 MWp/a case. All these assumptions are based on ZSW’s experience and on actual circumstances. A sensitivity analysis performed for the most important parameters to show the influence of changes in conditions, prices and product performance is given in in Table 2.

In this analysis labour and equipment cost as well as the indium prices are shown on a relative unit basis to show their influence on the resulting module cost. Efficiency is influencing linearly whereas yield and up-time are less affecting. Among the input materials indium is seen to be the most critical point as the indium price has changed by a factor of 3 during the last decade. Nevertheless the influence on module cost is low. The cost share of substrate and encapsulation materials is higher and it is expected that further innovations in supporting and sealing materials can further decrease fabrication costs of CIGS modules. Respective developments are under way at IPE and ZSW but far from manufacturing maturity.

The issue of material resources for large volume CIGS production is assessed to be not critical even for indium. This is supported by a internal ZSW study and by works of the University of Utrecht [13,14] and Brookhaven National Laboratories [15].

Health and safety aspects during module production and 20–30 years usage as an energy source are of great importance for market acceptance and under national and international regulations. These have been investigated by European and German programs with participation of IPE and ZSW. In conclusion it can be said that the production of CIGS modules applying ZSW’s technologies are in no respect critical for the environment and human beings. More details can be found elsewhere [13,16–18]. Nevertheless ZSW and Würth Solar are developing recycling concepts in order to reuse valuable raw materials and to minimise environmental pollution.

6. Conclusion

Thin film PV modules in general have very high potential to overcome the high cost level of conventional crystalline silicon technology. CIGS in particular has the highest efficiency potential among all thin film technologies. After the fundamental R&D work at IPE, University of Stuttgart and the baseline CIGS module development at ZSW on a module area of 30×30 cm the first step towards commercial production will be done within 1999 in a pilot line. In this phase the module area will be increased to 60×120 cm. At ZSW a production like continuous fabrication of 30×30 cm CIGS module was done. A maximum efficiency of 12.7% and medium efficiency of 11.3% with a narrow distribution was measured. If simple failures are avoided a process yield above 90% could be reached. After focusing on the development and verification of manufacturing parameters a pilot production capacity of 1.2 MWp/a will be installed in 1999. This capacity will be increased to at least 10 MWp/a as fast as possible. For these purposes Würth Solar was founded as a joint venture of the Würth group, the energy supplying company EnBW and the ZSW to realise these plans for commercialisation of CIGS technology and PV products. Cost estimations and a feasibility study of ZSW show that it should be possible to produce CIGS PV modules well below the common market price for the Si wafer technology even at capacity of about 10 MWp/a.

Acknowledgements

The authors thank the CIS team at ZSW. The work of ZSW was partially supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF) under contracts 0329585B and 0329585C, the Stiftung Energieforschung Baden-Württemberg the Ministry
of Economy of the state of Baden-Württemberg and by the
European Commission under contract JOR3-CT97-0149.

References


Ehmann, E.D. Dunlop (Eds.), Proc. 2nd World Conf. of Photovoltaic
Communities, 1998, p. 381.


1994, p. 935.


1994 IEEE 1st World Conf. on Photovoltaic Energy Conv., Hawaii,

Ossenbrink, P. Helm, H. Ehmann, E.D. Dunlop (Eds.), Proc. 2nd
World Conf. of Photovoltaic Sol. Energy Conv., Office for Official


de Reyeff, H. Kiess, P. Helen (Eds.), Proc. 11th Eur. Photovoltaic Sol.

Steinberger, P.D. Moskowitz, Proc. 1994 IEEE 1st World Conf. On Photo-


3621, 1990.

[18] V.M. Fthenakis, P.D. Moskowitz, Prog. Photovoltaics Res. Ap-