CIS THIN-FILM SOLAR MODULES – AN EXAMPLE OF REMARKABLE PROGRESS IN PV

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ABSTRACT: The thin-film solar module technology based on $Cu(In,Ga)Se_2$ is truly on the brink of mass production as the Würth Solar factory prepares to expand to a 15 MW per annum capacity. This contribution summarises the results of the work of Würth Solar and ZSW during 2004 with some retrospection of the time before, outlines the strategy of further growth in the expanding PV market, gives an impression of the product spectrum, and shows examples of successful installations. These include roof-integrated modules, large-area façade examples, semi-transparent glazing, and retrofit installation on existing buildings, special module designs and sizes adapted to and integrated in grid independent products and the standard sized module of 60 cm x 120 cm area. The annual production capacity of Würth Solar increased up to 1.3 MW_p in 2004 with an average efficiency between 11 and 11.5 % over 0.72 m^2 and around 85 % yield in the production. These encouraging results enabled the decision to construct a multi-megawatt plant. Technology developments of the second and third generations are discussed including technical optimisations, alternative materials, and flexible substrates.
Keywords: Manufacturing and Processing, $Cu(InGa)Se_2$, PV Materials

1 INTRODUCTION

Thin-film solar modules based on the chalcopyrite compound $Cu(In,Ga)Se_2$ (CIS) are the main actors in an exemplary success story about the progress of a new technology from a university research topic to a multi-megawatt production plant.

Fundamental materials research and process development began at the Institute for Physical Electronics at the University of Stuttgart in 1975. In 1993 the Centre for Solar Energy and Hydrogen Research (ZSW) took up the challenge to upscale the promising CIS technology and to develop the basic technology required for large-area in-line production and monolithic module integration [i]. A full technical line for producing modules on the 30 cm × 30 cm scale was constructed in the ZSW laboratory, achieving module efficiencies around 12 % by 1999. The results from the experimental line, together with those from cost studies, were promising enough that, in 1999, the Würth Solar GmbH & Co. KG was founded as a joint venture between the Adolf Würth GmbH & Co. KG, the utilities company Energy Baden-Württemberg (until 2004), and the ZSW for the mass production and commercialisation of CIS solar modules [ii].

The pilot production at Würth Solar has since progressed steadily, operating continuously to achieve maximum capacity. So far, the best modules on the standard size of 60 cm x 120 cm achieved 85 W_P, which corresponds to 13 % aperture-area efficiency. By 2004, the average module efficiency from the pilot line was between 11 and 11.5 % with an overall process yield exceeding 80 %. At the same time, the number of modules produced more than doubled each year until the plant reached its maximum capacity of about 20,000 pieces a year, corresponding to ca 1.3 MW_p/a in 2004. Würth Solar's success led to the recent decision to construct a 15 MW CIS module plant in the near future.

The CIS module technology is still a young technology with room for new developments and potential for further improvement. The ZSW supports the Würth Solar development by assisting with scientific and technical questions as well as with specific developments like designing the components for the new 120-cm deposition width plants. Major research topics at the ZSW for future CIS generations include Cd-free buffer layers, flexible modules, and CIS modules for space applications. Some aspects of these topics are briefly addressed in the next sections. Specific details can be found in the other ZSW contributions in these proceedings [iii,iv,v].

This contribution presents results from the Würth Solar pilot production line, including yield, efficiencies, piece numbers, and outdoor testing. Especially the trends over the few years of operation are impressing and promise continued success in the future. We then continue to describe some results from current research and development activities. These activities will pave the way for the next generations of CIS technology.

2 CURRENT AND FUTURE TECHNOLOGY GENERATIONS

CIS production has already had a great start. To be competitive, however, the CIS technology must continue to develop. Short- and mid-term improvements will include mainly optimisations working with the existing equipment, with the goal of reducing production costs while increasing yield and product quality. Later, more far-reaching developments will include flexible, lightweight modules for space applications or mobile terrestrial purposes.

2.1 Production at Würth Solar: the first generation

The current generation of CIS technology is approaching its prime - the pilot production at Würth Solar has progressed steadily, successfully achieving continuous operation and producing at its full capacity of 1.3 MW_p /a. A total of ca 16,000 modules were produced in 2004 and 22,000 are planned for 2005. The overall process yield of the pilot line, as described in the following section, could be increased and stabilised at high values well above 80%.

2.1.1 Production yield at the Würth Solar pilot plant

Assuming a high and stable efficiency and a narrow distribution process, the most important parameters for low-cost production are yield and throughput. We define the yield as the percentage of raw glass panes which are successfully processed into solar modules that meet specifications. Each process is controlled automatically by on-line measures or, at the least, visual inspection by the operators to meet an acceptable quality. The final assessment is the IV characterisation of each completed module at the sun simulator. The yield therefore includes all process steps starting from the incoming glass plates up to the finished module ready for delivery.

Figure 1 demonstrates the yield for standard modules averaged over each quarter-year period starting from mid-2001 until the first quarter of 2005. Earlier periods are excluded because the numbers of pieces were too low for representative statistics. The required module efficiency for a module to be included in the yield was originally 8 %. Starting from around 20 to 30 % or even lower, a clear improvement in the yield can be observed. At the end of 2003 (Q4/03), the production yield passed 80 %. Starting in 2004 (Q1/04), the pass value for the module efficiency was increased to 10 %, reflecting the achieved improvements in the average module efficiency. Despite the more stringent criteria, the yield remained above 80 % since and generally lies closer to 85 %. The data shown here excludes experimental runs used for development purposes.

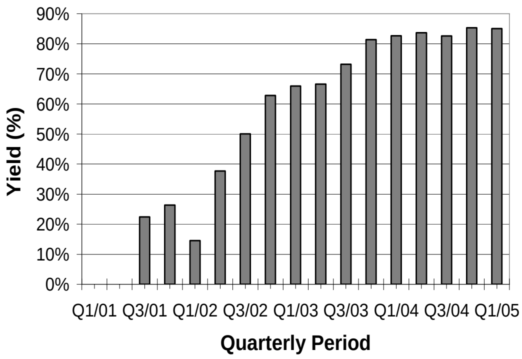

Figure 1: Yield for standard modules from the Würth Solar pilot production line for the quarterly periods indicated. The pass value for module efficiency was increased from 8 % to 10 % at the beginning of 2004. Experimental runs are excluded from the data.

2.1.2 Module efficiencies from the production line

The average module efficiency for standard 60 cm x 120 cm modules from the Würth Solar pilot line has been improving steadily, as indicated in Figure 2. All efficiency values presented here are related to the aperture area, including series interconnects and contact areas, in order to more easily compare different module designs. After an initial, short, optimisation phase, the first modules were fabricated in January 2001 and measured at efficiencies already exceeding 8 %. The average module efficiencies have since increased to between 9 and 10 % in 2002, to between 10 and 11 % in 2003, and to between 11.0 and 11.5 % in 2004. Maximum values of 13 % have already been realised, corresponding to about 85 W_p for the standard module at STC (standard testing conditions: 1000 W/m^2 AM 1.5 irradiance and 25 °C).

It must be pointed out that these efficiency increases were realised while simultaneously increasing production volumes from some 100 in 2001 up to about 20,000 pieces per year, which is the maximum capacity of the existing production line. The production volume more than doubled each year, as indicated in Figure 3.

Assuming a realistic learning curve, at least 12.5 % average module efficiency is expected within the next two years using the existing equipment and processes. Laboratory-tested modifications in the CIGS process and further optimisation of the Mo and ZnO contact layers, together with minimisation of patterning losses, indicate realistic improvements of up to 14 % or even above 15 % for mass-produced CIS within the next decade.

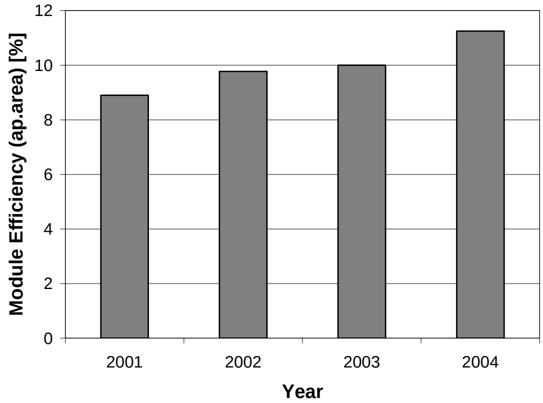

Figure 2: Development of module efficiency over the years of production at the Würth Solar plant in Marbach a. N. (Germany).

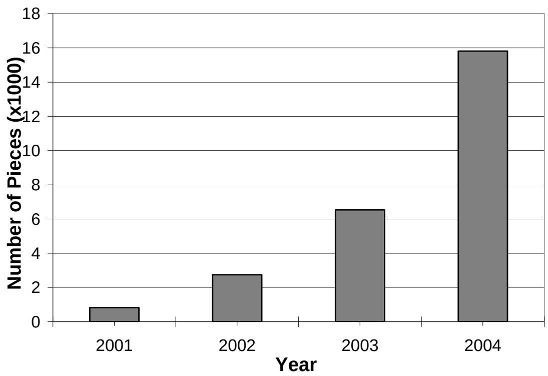

Figure 3: The number of pieces produced in the Würth Solar CIS solar module pilot production line has more than doubled each year.

2.1.3 Outdoor testing

Besides being characterised under realistic outdoor conditions, we also regularly subject a number of modules to long-term outdoor testing at the ZSW test field in Widderstall in the South of Germany. Outdoor testing is important to confirm the stability and real-life performance of the modules.

Figure 4 illustrates the module power of a representative CIS module from Würth Solar, measured when the irradiance was 800 W/m^2 over a period of nearly two years. This irradiance level was chosen instead of the more-common 1000 W/m^2 used in standard testing procedures because the higher value is rarely available during the winter months at the testing site at about 48 ° latitude north. Despite the lower irradiance value, data is missing occasionally during the winter months when irradiance levels remained below 800 W/m^2.

The data in Figure 4 is also presented in a temperature-corrected form, since PV modules will lose voltage at higher temperatures. The lighter symbols represent the true measured data and the darker symbols indicate data corrected to a temperature of 25 °C. After a first light-induced power enhancement the module exhibits very stable performance near 65 W, corresponding to 81 W at STC with total irradiance of 1000 W/m^2, over the two-year period. For more information about the outdoor performance of CIGS modules see ref. [vi].

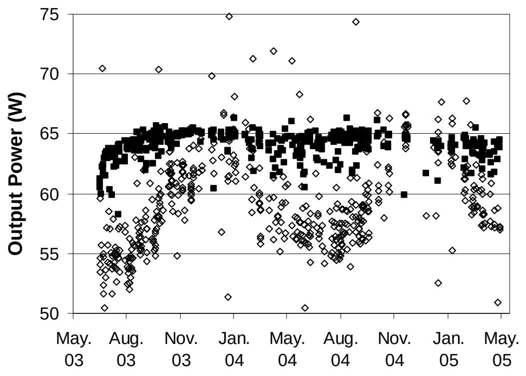

Figure 4: Output power during outdoor testing under 800 W. The open symbols represent the measured data whereas the solid symbols are temperature-corrected to 25 °C.

Furthermore, the CIS solar modules from Würth Solar received the EN61646 certification from the TÜV-Rheinland in 2004. Information on the testing procedure can be found at the TÜV-Rheinland website www.de.tuv.com. The most critical testing procedures for CIS modules are the thermal cycling tests (50 and 200 cycles at -40 °C to +85 °C) and the damp heat test (1000 h at 85 °C and 85 % relative humidity), whereby the degradation sustained due to the test should be less than 5 %.

2.2 Development: the second generation

This section covers a selection of second-generation developments, referring to near-term improvements and optimisations within the potential of the existing production line. Some optimisations are along the lines of trimming down material costs by reducing waste and through bulk purchasing. Others, like the new 120-cm deposition width plants are designed to increase throughput. The improved coordination of processing steps pays out in throughput and yield. Adjustments to the baseline processes are also included here: Efficiency increases are expected through the implementation of modifications to the deposition process for the CIS absorber layer, and the buffer layer can be replaced with a Cd-free alternative.

2.2.1 CIS plant with 120-cm deposition width

As a result of the piloting phase at Würth Solar, it became clear that one of the major bottlenecks for low-cost production of CIS modules is the cycle time for high-quality CIS films. Therefore, Würth Solar decided to enhance and qualify equipment for a deposition width of 120 cm, twice the initial 60 cm. Doubling the coating width of the in-line CIS deposition plant effectively doubles the throughput. Figure 5 demonstrates the uniformity in composition and thickness of a CIS film deposited in a 120-cm plant from the very first optimisation runs. These first results are very encouraging. Small cells cut from modules coated in the 120-cm plant demonstrate the very good homogeneity of the deposition. Their parameters are included in Figure 5.

From the first optimisation runs of the 120-cm plant, first batches with 250 to 270 modules were produced. The mean value increased from 67 W_p to 72 W_p with process optimisation. It also demonstrates the long-term stability of the process, even for the first runs, and also the necessity for further improvement. The work at the moment is focussing on narrowing the distribution, enhancing the efficiency and avoiding out-of-specs modules.

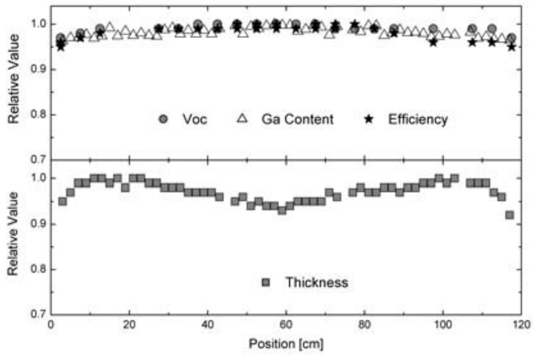

Figure 5: Relative uniformity of film thickness and composition across the long length of the substrate for a film coated in the 120-cm plant.

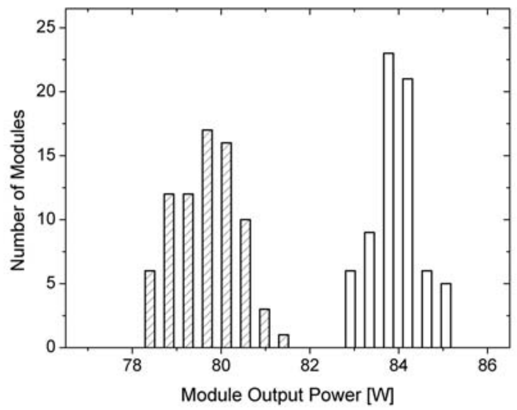

Figure 6: Comparison of a series of standard modules (69 cells) with a series of modified modules with smaller cells connected in parallel (2x67 cells) over a centre tap.

2.2.2 Modified cell integration

A further technical improvement involves modifying the cell integration. The module output power could be increased by 4 W in this manner. The fill factor increases thereby from an average of 69.4 % to 73.5 %. The best module with the modified configuration delivered slightly over 85 W, corresponding to 13.2 % efficiency.

Figure 6 illustrates the improvement in module performance by comparing a series of standard modules with a series of modified modules. The modified modules demonstrate both higher performance and a more narrow distribution.

2.2.3 Cd-free

Another second-generation goal is to eliminate Cd from the device structure. It is currently present as CdS in the buffer layer at the heterojunction between the absorber and the window layers. The same low-cost wet chemical bath method (CBD) can be applied for the deposition of a ZnOS buffer layer. This Cd-free material has shown promising results which are comparable with the performance of CdS-buffered cells and modules: 14.8 % for 0.5 cm^2 laboratory cells and 11.1 % for 30 x 30 cm^2 modules [vii]. Other authors demonstrated 18.5 % for this material combination [viii]. Devices with the CBD ZnOS, however, exhibit a light-soaking behaviour which must be addressed to ensure long-term stability.

Although the atomic layer deposition (ALD) method is considered too slow for industrial production, it enables the growth of very well-defined films under controlled conditions. Based on published work from the University of Uppsala, this advantage of the ALD method was used to investigate a possible correlation between the composition of the ZnOS film and the metastable behaviour of the produced modules. The group at the University of Uppsala could produce small cells with efficiencies up to 16 % using the ALD ZnOS buffer layer [ix]. Based on this work, we deposited ZnOS using ALD on 30 x 30 cm^2 CIS-coated substrates. Very promising results with efficiencies up to 12.7% for 30 x 30 cm^2 modules were produced with a S/Zn atomic ratio of roughly 0.3. Figure 7 illustrates the stability with regard to time and illumination of modules with the ALD and the CBD ZnOS buffer layers. The device with the ALD layer is clearly stable while the CBD device suffers from degradation which can be regained by illumination. The ZnOS compound is therefore proven suitable as a buffer layer for CIS modules and the task ahead lies in adjusting the low-cost CBD deposition method to produce optimised, stable ZnOS films.

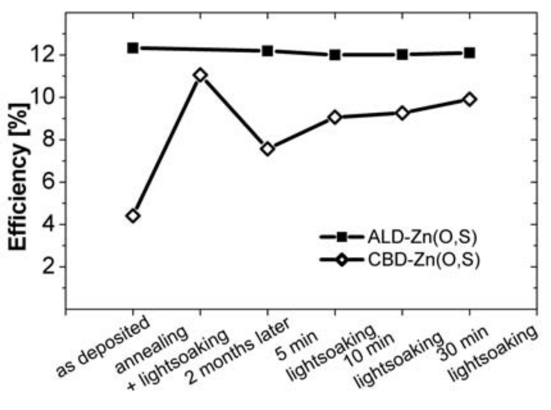

Figure 7: Stability behaviour of modules (30 cm x 30 cm) with ZnOS buffer layers deposited by CBD or ALD. The device with an ALD film is very stable whereas the CBD buffer is linked to a metastable light-soaking effect.

2.3 Third generation

The developments belonging to the third generation of CIS technology require more far-reaching changes to the current baseline. We are pursuing two third-generation subjects which have some overlapping interests: flexible CIS solar modules, and CIS modules for space applications. Whereas the long-term goal for flexible modules is to allow cheap mass production with roll-to-roll techniques, space applications have strict requirements on efficiency, weight, and stability. The CIS technology is, however, particularly interesting for the space industry due to its high power-to-mass ratio, especially when using thin substrates, and due to its radiation hardness [x]. The most promising flexible substrates are currently polyimide and titanium.

When using polyimide substrates, the process temperatures must remain under 400°C, less than ideal for high-quality absorber deposition. Various techniques have been explored for introducing sodium into the absorber which normally diffuses from the glass substrate during the high-temperature CIS deposition process [xi]. Using the Na precursor method, cells up to 11.2 % (0.5 cm^2) and monolithically integrated modules up to 7.5 % on 10 x 10 cm^2 and 5.2 % on 20 x 30 cm^2 could be produced [xii,iv]. Photolithography techniques were applied for the module patterning steps [xiii].

Depositing modules on a metallic, electrically conducting substrate complicates their monolithic integration: they require an insulating film between the substrate and the device layers. The results for monolithically integrated modules on Ti foil are still relatively modest. Using a SiO_x barrier film results of 6.8 % on 7 x 8 cm^2 and 3.8 % on 20 x 30 cm^2 have been achieved [xiv]. Best overall results so far are achieved on large single cells which can be connected with a shingling technique. Using titanium foil, an average efficiency of 11.4 % (AM 1.5) was already achieved in the small-series production of large single cells, with a best efficiency of 13.8 % (Voc: 647 mV, FF: 72.3 %, jsc: 29.5 mA/cm^2) [iii]. An example is shown in Figure 8. For the latest developments in these fields we kindly refer you to the contributions [iii] and [iv] also presented at this conference.

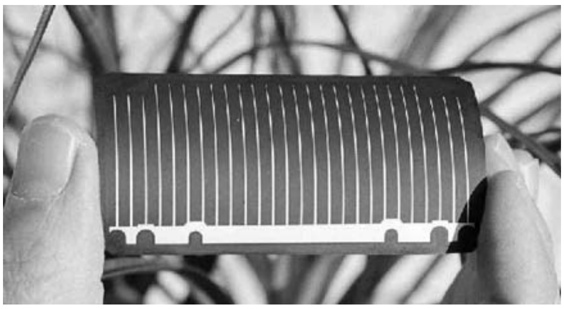

Figure 8: 4 x 8 cm^2 CIS solar cell on 25 µm Ti foil.

3 INSTALLATIONS

The CIS solar modules are particularly interesting for architectural applications as their uniform black appearance is exceptionally aesthetic. Figure 9 presents a more recent installation at the Schapfenmühle grain silo on the outskirts of Ulm in Germany. 1,306 Würth Solar modules are integrated into the façade, representing an installed nominal power of 98 kW_p producing 70,000 kWh/a. The modules are installed at heights up to 102 m. The architects chose to install CIS PV modules from Würth Solar due to their excellent combination of performance and appearance. Würth Solar's website www.wuerth-solar.com offers further examples and details of CIS modules providing both form and function as well as electricity in architectural applications.

Figure 9: Schapfenmühle grain silo on the outskirts of Ulm, Germany. Integrated into the façade are 1,306 CIS modules from the Würth Solar pilot plant with a nominal installed power of 98 kW_p.

4 FUTURE PLANS FOR MASS PRODUCTION

Recently, Prof. Dr. h.c. Reinhold Würth, Chairman of the Advisory Board of the Würth Group, announced the construction of a new production facility for CIS photovoltaic modules with an investment volume of around 55 million Euro. Construction of the new plant is expected to begin already this year (2005) and the company management anticipates the availability of its planned annual capacity of 15 MW from 2007 onwards. A total of 120 persons will be employed at the 15 MW CIS factory.

Würth Solar is part of the Würth Elektronik Group and was founded in 1999. The pilot factory was successful in transferring the innovative technology for producing CIS photovoltaic modules from the technical scale to industrial dimensions. The research results from its partner ZSW (Centre for Solar Energy and Hydrogen Research, Baden-Württemberg) helped Würth Solar achieve a significant lead in production technology and meet all of the goals that were defined for the pilot factory before approval of large-scale series production: the overall process yield exceeds 80% and the module efficiency 11%. After five years of development activity, investments in the range of 20 million Euro, and a lot of hard work, Würth Solar can now announce that the company has met all of these goals and is moving on with the next step: the mass production of CIS solar modules.

5 CONCLUSIONS

The combined efforts of the ZSW and Würth Solar enabled the progress of the CIS solar module technology from laboratory research to a successful industrial pilot production. All of the goals could be met, indicating further success for CIS in industrial mass production. Würth Solar's decision to construct a multi-megawatt CIS module plant is truly a milestone in the history of CIS technology.

Beyond the achievements in standard CIS module technology, development work for the next generations of CIS continue primarily at the ZSW. Highlights presented here include new developments in Cd-free buffer layers and progress with flexible modules on titanium or polyimide foil substrates. Advances of a more technological nature include the development of 120-cm wide CIS deposition plants and the application of the centre tap technology for enhanced module performance.

6 ACKNOWLEDGEMENTS

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