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Review Article

Thin-Film Solar Cells Based on the Polycrystalline Compound Semiconductors CIS and CdTe

Michael Powalla[1] and Dieter Bonnet[2]

[1] *Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW), Industriest 6, 70565 Stuttgart, Germany*
[2] *SOLARPACT, Breslauer Ring 9a, 61381 Friedrichsdorf, Germany*

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Thin-film photovoltaic modules based on Cu-In-Ga-Se-S (CIS) and CdTe are already being produced with high-quality and solar conversion efficiencies of around 10%, with values up to 14% expected in the near future. The integrated interconnection of single cells into large-area modules of $0.6 \times 1.2\ m^2$ enables low-cost mass production, so that thin-film modules will soon be able to compete with conventional silicon-wafer-based modules. This contribution provides an overview of the basic technologies for CdTe and CIS modules, the research and development (R&D) issues, production technology and capacities, the module performance in long-term outdoor testing, and their use in installations.

1. INTRODUCTION

A high potential for cost reduction is expected for the production of thin-film photovoltaic modules as compared to conventional silicon-wafer-based methods [1]. Regardless of the material, all thin-film techniques have advantages because of their low active material consumption and costs, the monolithic integration of cells, and independence from shortages in solar-grade silicon supplies. Thin-film module production involves fewer processing steps than silicon, and allows a higher degree of automation. Industrially produced modules attain efficiencies between 8 and 12% on the square-meter scale with individual modules exceeding 50 W_p (watts peak), and expected long-term stability over more than 20 years—all requirements to successfully gain long-term acceptance in the power market.

Thin-film PV is also especially suited to meet particular product needs, such as flexibility or utilizing an already present surface, like the product's housing or a façade, as the substrate. Furthermore, most thin-film PV producers use glass substrates and can profit from the experience and commercial equipment available from the glass-coating industry, as well as from their know-how in glass applications such as building façades. In the future, a flexible substrate will enable the production of lightweight, flexible modules by using the cost-efficient roll-to-roll method.

In this article, we will describe and compare the basic principles of CIS and CdTe solar cells and modules. We will include an overview of the potentials of these technologies and of the R&D issues under investigation. Afterwards, we will describe how the large-area mass production of CIS and CdTe solar modules is realized in real factories and present an overview of the current production activities worldwide.

2. BASIC PRINCIPLES

Both CdTe and CIS employ a stack of functional thin-film layers to create an efficient photovoltaic heterojunction. A window/absorber design localizes the greater part of the charge carrier generation and separation within the absorber layer, avoiding excessive recombination within the window layer or at the interface between these layers. In this construction, the window layer has a higher band gap in order to transmit the sunlight to the absorber layer and a high level of doping in order to minimize the resistive losses and provide an electrical contact. Since the crucial processes of charge carrier generation and separation take place within the absorber layer, this material largely defines the characteristics of the solar cell and traditionally lends its name to the technology—CdTe for cadmium telluride and CIS for the range of chalcopyrite compounds $Cu(In, Ga)(S, Se)_2$. Figure 1 illustrates the basic cell design for both heterojunctions.

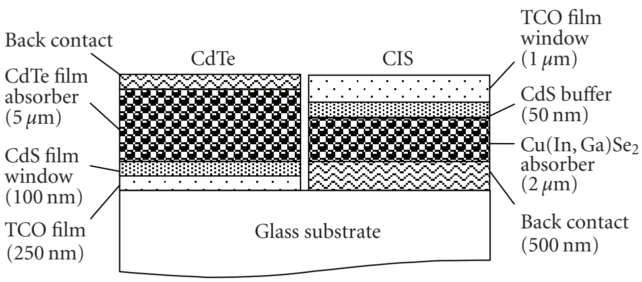


Figure 1: Layer sequence for polycrystalline thin-film CdTe and CIS solar cells.

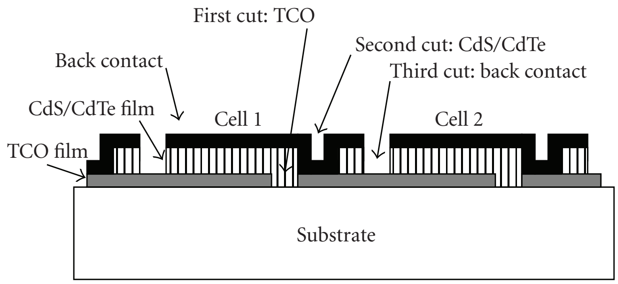


Figure 2: Monolithic interconnection illustrated for CdTe modules.

CdTe solar cells are processed on the front glass, so the first layer is a transparent conductive oxide (TCO) for the front contact. It is followed by the CdS window layer and the CdTe absorber layer. A back contact completes the device. The chemically very stable CdS and CdTe compounds are relatively easy to deposit stoichiometrically within a wide processing range from 400°C up to 600°C. Typically, the close-spaced sublimation method is used to deposit the semiconducting films [2]. A slight natural nonstoichiometry produces the desired p-doping of CdTe and n-doping of CdS, respectively. After deposition, the CdS-CdTe junction must be "activated" to achieve high photovoltaic efficiencies. The process involves annealing at temperatures between 400 and 500°C in the presence of Cl-containing species, generally $CdCl_2$ [3]. Efficiencies exceeding 16% have been achieved with laboratory cells [4].

The layer sequence for CIS solar cells is also illustrated in Figure 1. CIS cells are processed from back to front, so the Mo back contact does not need to be optically transparent. The CIS absorber film follows. CIS can either be deposited directly, for example, by thermal coevaporation of the elements, or indirectly by first depositing more simple precursor layers which then react in a subsequent processing step to form the compound semiconductor [5]. The CIS materials system is more complex than CdTe and has higher demands on the process control systems. However, it also offers more freedom for optimization, for example, by integrating gradients [6]. CIS solar cells typically employ an extremely thin CdS film deposited in a chemical bath followed by a sputtered intrinsic ZnO film and the transparent conductive ZnO : Al window layer, also deposited by sputtering. CIS devices have achieved the highest efficiencies of all thin-film solar cells, at values approaching 20% [7].

Table 1: Overview of current status of CIS and CdTe solar cells and modules.

Type	CIS	CdTe
Laboratory best (cell)	19.5% [7]	16.5% [4]
Large-area best (module)	13% [8]	11% [9]
Production average (module)	11.5% [10]	9% [11]

A major advantage of thin-film photovoltaic module processing lies in the monolithic series interconnection of cells to form modules with higher voltages. Whereas silicon wafer-based solar cells are connected by welding conductors onto both sides of the wafers, thin-film cells are flexibly defined and interconnected through simple patterning steps integrated into the processing line. The techniques are similar for both CdTe and CIS technologies. Three scribes between deposition steps accomplish the cell definition, separation, and series interconnection. The optimum cell width is defined by the amount of active area lost to scribing, the series resistance, and the desired output module voltage. The TCO properties can also be integrated into the optimization. Figure 2 illustrates the monolithic interconnection for CdTe modules. The first and third cuts separate the cells at the front and back contacts, respectively. The second cut enables the back contact of cell 1 to connect with the front contact of cell 2. The monolithic interconnection of CIS modules occurs in the same manner, just in the reverse processing sequence (the first cut separates the back contact and the third cut separates the front contact).

In the final processing steps, the contact leads are attached to the first and last cells and the modules are hermetically sealed against environmental effects by encapsulation with a lamination foil and a second glass plate. Frames and contact boxes complete the commercial modules.

An overview of the current state-of-the-art is given in Table 1. The minimum efficiencies required for profitable systems can be achieved with both systems. The large-area modules for both systems are about 6 percent points less efficient than the best laboratory cells, a good indication that module performance will continue to improve in the future. The efficiencies achieved with the CIS technology are generally 2 to 3 percent points higher than for CdTe. However, since it is the cost per watt peak which will define the commercial success of the modules, the more simple processing of CdTe can lead to lower production costs and a competitive product. Both technologies must of course compete with conventional silicon-based modules.

3. RESEARCH AND DEVELOPMENT TOPICS

Both the CdTe and CIS technologies have the potential to compete with traditional Si-wafer-based photovoltaic modules in the commercial market. While CdTe has a higher potential for cost reduction due to its simple processing, CIS has the potential to achieve higher efficiencies, thereby lowering the price per watt of generated power. Each material system has its specific issues requiring R&D efforts.

Two major issues for the CdTe technology are the activation step and the back contact to CdTe. The activation step leads to interdiffusion at the CdS/CdTe interface, thereby reducing the defect density and improving the morphology [12]. However, its effects are still being investigated. Research results could enable further optimization or even elimination of the activation step. The low p-type doping and relatively high energy gap of CdTe complicates the contacting. A practical solution consists of generating a highly doped back-surface layer in the semiconductor through which charge carriers can pass via the tunneling effect. The current technique involves generating a highly doped accumulation layer on the CdTe surface by chemical etching, followed by depositing a p-type narrow-band-gap chemically inert semiconductor or semimetal buffer layer and the metal contact [13].

The CIS technology would also benefit from further integration of the processing steps. One issue is the need to break vacuum for the wet-chemical CdS buffer deposition before reentering vacuum for the window deposition steps. Modifications to replace or even eliminate the buffer layer are therefore being explored [14]. Although CdS, too, can be thermally evaporated, thicker films are required for complete coverage and the process is less robust than the wet-chemical deposition. Since photons absorbed in the buffer layer do not contribute to the current generation, thicker films represent a source of loss. Absorption in the buffer layer also motivates the search for an alternative material with a higher band gap.

Significant efforts are also under way for the production of CIS solar modules on flexible substrates [15]. Changing the substrate is not trivial: it may introduce undesirable impurities in the absorber, sodium, which diffuses from the soda lime glass in the standard process and which improves the absorber film quality by increasing its charge carrier density [16], may not be present, the allowed processing temperatures may not be sufficient for high film quality, and additional films may become necessary, such as an insulating layer for the monolithic interconnection on conductive substrates.

Moreover, the long-term goal to significantly increase the CIS cell efficiency to more than 20% will only be achievable through a better fundamental understanding of CIS [17, 18]. The CIS technology has a high potential for improvement, with efficiencies of up to 25% for cells and 18% for modules believed possible. All inhomogeneities, metastabilities, doping mechanisms, and so forth, must be better understood. The wide range of compositions possible in the Cu-In-Ga-Se-S system complicates the collection and comparison of scientific data. Fundamental research is needed both on reference systems, like high-quality laboratory absorber films, and on industrially produced absorber layers. New techniques like measuring electron-beam-induced currents in the junction configuration, micro-photoluminescence, and micro-Raman spectroscopy are opening the doors for understanding the recombination mechanism [19] in real devices and for exploring the role of inhomogeneities.

Furthermore, both technologies are exploring alternative methods of material synthesis, like electrodeposition, spraying, and screen printing, because of their potential for reducing production costs and materials consumption. Several production parameters like deposition rates and other modifications undergo continuous optimization for improved throughput and yield.

4. STANDARD MODULE PROCESSING

For the industrial production of thin-film modules, high-throughput in-line coating systems are required for each processing step as well as automated mechanisms to transfer the glass panes from each step to the next one. Figure 3 illustrates a module processing line like the one used for CdTe module production. The numbers relate to Table 2 which describes the processing steps for both CIS and CdTe modules. The production begins with cleaning the substrate glass (1) in a washer. Step (2) is the sputter deposition of either the Mo back contact for CIS or the TCO front contact for CdTe. The initial film is patterned with a laser in step (3). Steps (4), (5), and (6) involve the junction deposition and formation. For CIS the absorber layer of $Cu(In, Ga)Se_2$ is first deposited, for example, by thermal coevaporation of the elements. The CdS buffer layer follows in a chemical bath deposition step after which the i-ZnO film is sputtered. Three separate deposition systems are required, one for each film. For CdTe, a single plant with different processing zones can cover the deposition by close-spaced sublimation of CdS and CdTe and the junction activation step. Step (7) is the second patterning step, usually a mechanical scribe. Step (8) is the contact deposition, the front-side TCO for CIS which consists of a doped ZnO deposited by sputtering. For CdTe modules, a chemical etch precedes contact deposition for improved current flow. A final mechanical patterning step (9) completes the separation of the individual cells. The edge insulation step involves removing all films in the boundary region around the module for perfect electric insulation from the environment after encapsulation. The contact bands between the first and last cells are applied in step (10) before the module is laminated with a clean cover glass in step (11). The modules are framed—if required—and contact bands are connected to the contact box in step (12). Step (13) is the final characterization of the module and its classification by quality.

There is currently a "boom" in the construction of thin-film solar module production plants. Eight new CIS factories recently started production, or will do so in the near future. Several of these plants are located in Germany and a few are in USA and Japan. Table 3 presents an (incomplete) list of current manufacturers of compound thin-film photovoltaic modules and their status. The number of players and their capacities are steadily increasing.

In addition to these companies, which are in mass production or very close to it, several "newcomers" are entering the field. In the CIS family, new companies located mainly in USA (e.g., Miasole, Daystar, Ascent Solar) and Germany (e.g., Odersun, Solarion, CIS Solartechnik) are focusing on flexible cells and modules. Some companies are developing new vacuum-free deposition methods based on small particles or electrodeposition (e.g., Nanosolar, ISET, IRDEP). New commercial activities with CdTe modules have been announced by Arendi (based on the technology developed at Parma University, Italy), Primestart Solar (based on

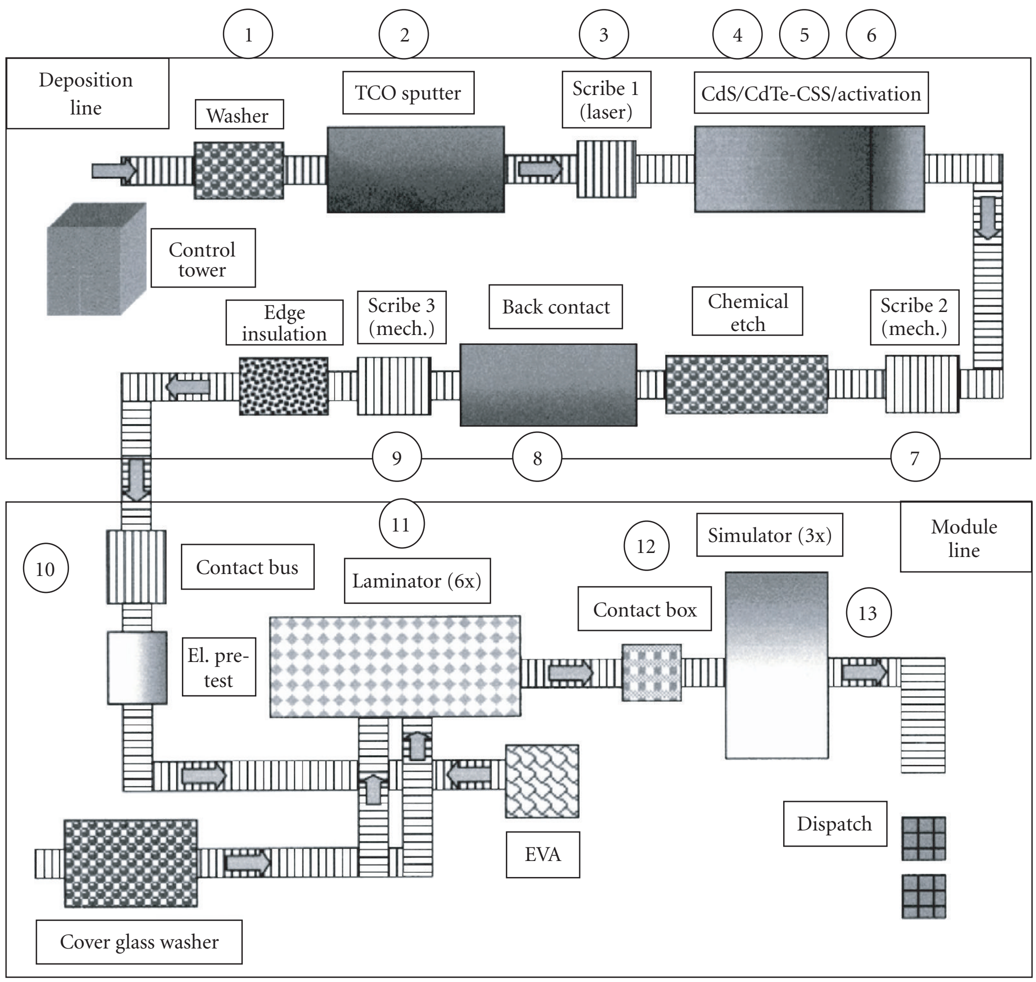


FIGURE 3: Schematic of commercial production line for CdTe thin-film solar modules.

the technology developed at NREL, USA and Applied Thin Films, Inc.), and AVA Technology (based on the know-how developed at Colorado State University, USA).

5. POWER GENERATORS AND OUTDOOR TESTING

Long-term outdoor testing is especially important for a new PV technology to prove itself in the existing market. The consumer expects high performance for a period of 20 years or more in order to justify the investment. Provided that the modules are properly encapsulated, neither fundamental considerations of the materials chemistry, nor accelerated and real outdoor testing indicate that long-term stability issues will be of concern for either CdTe or CIS modules. Due to the strong ionicity of the CdTe and CIS semiconductor compounds, the energy of the chemical bonds between the constituting elements is quite high, leading to an extremely high chemical and thermal stability and reducing the risk of performance degradation over time. Furthermore, the energy of any photon in the solar spectrum is lower than the binding energies so that the compounds will not degrade as a result of solar irradiation.

Extended outdoor testing of CdTe and CIS modules proves their stability. Figure 4 presents real data measured for CIS and CdTe modules, measured within a window around 1000 W/cm^2 and corrected with a power factor and the temperature coefficient to reflect standard testing conditions (25°C and 1000 W/m^2). Graph (a) illustrates the performance of a CIS module in terms of efficiency, with data missing for the winter months when the irradiation did not approach 1000 W/cm^2 required for significant testing or when snow covered the modules [21]. Graph (b) illustrates the corresponding performance for CdTe modules in terms of the peak power [22].

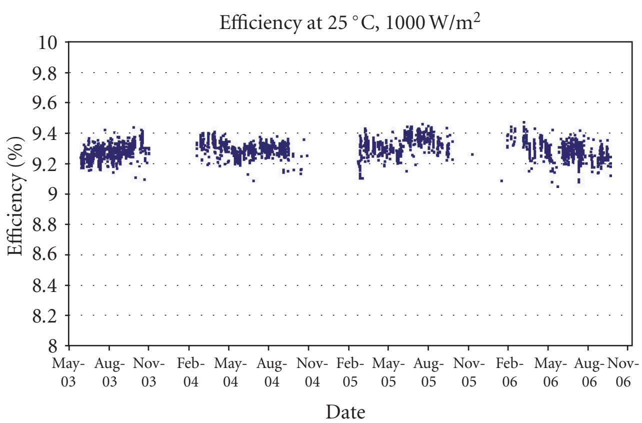
Besides testing at outdoor sites, thin-film modules have also proven themselves in large-scale installations. Architects are especially interested in the uniform black appearance of thin-film PV modules which they can use as functional design elements in building façades. As an example, Figure 5 presents an attractive integration of over 1000 CIS modules into the façade of the grain silo “Schapfenmühle” near Ulm, Germany. Several other projects have been realized with both CdTe and CIS modules and are successful ambassadors to present these technologies to the consumers.

Table 2: Processing steps for the production of CIS and CdTe thin-film solar modules.

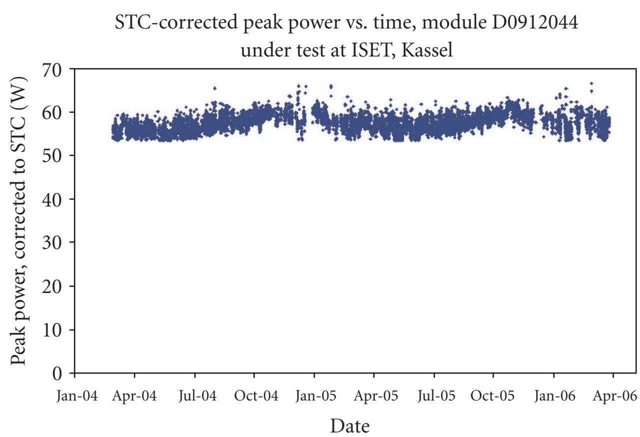
Step no.	CIS	CdTe
1	Cleaning of glass substrate	Cleaning of glass superstrate
2	Deposition of back contact (Mo)	Deposition of front contact (SnO_2, etc.)
3	Scribing of back contact	Scribing of front contact
4	Deposition of p-CIS film	Deposition of n-CdS film
5	Deposition of n-CdS film	Deposition of p-CdTe film
6	Deposition of i-ZnO film	"Activation"
7	Scribing of semiconductor film	Scribing of semiconductor film
8	Deposition of front contact	Deposition of back contact
9	Scribing of front contact	Scribing of back contact
10	Attachment of contact-bus structure	Attachment of contact-bus structure
11	Lamination with front glass plate	Lamination with back glass plate
12	Contact box attachment	Contact box attachment
13	Measurement, classification	Measurement, classification

Table 3: Some manufacturers of thin-film photovoltaic markets and their current status.

Manufacturer	Capacity in MW_P/a	Substrate (m × m)	Efficiency max./mean	Market
CIS				
Johanna Solar, Germany	30 (2008)	0.5 × 1.2	–/9.4% [20]	no
Würth Solar, Germany	14.8 (2007)	0.6 × 1.2	< 13%/11.7%	yes
Global Solar, USA	4.2 (2006)	metal foil 1 ft wide	10%/8%	yes
Showa Shell, Japan	20 (2007)	0.6 × 1.2	14.2%/11.8%	yes
Honda Soltec Co. Ltd., Japan	27 (2007/2008)	0.8 × 1.3(0.2 × 0.2)	13%/10%	no
Sulfur Cell, Germany	5 (2007/2008)	0.65 × 1.25	8.2%/∼7%	yes
AVANCIS, Germany	20 (from 2008)	0.6 × 1.2	13.1%/12.2%	no
Solibro GmbH (Q-Cells), Germany	25–30 (2009)	0.6 × 1.2	—	no
CdTe				
ANTEC Solar Energy AG Germany	7	0.6 × 1.2	7%/6%	yes
First Solar, USA, Germany, and Malaysia	175 (2007/2008)	0.6 × 1.2	11%/9%	yes



(a)



(b)

Figure 4: Long-term outdoor testing of thin-film modules, data adjusted to standard testing conditions of 25°C and 1000 W/m². Graph (a) shows the efficiency of a CIS module over a period of three years and half. Graph (b) shows the peak power of a CdTe module over more than two years.

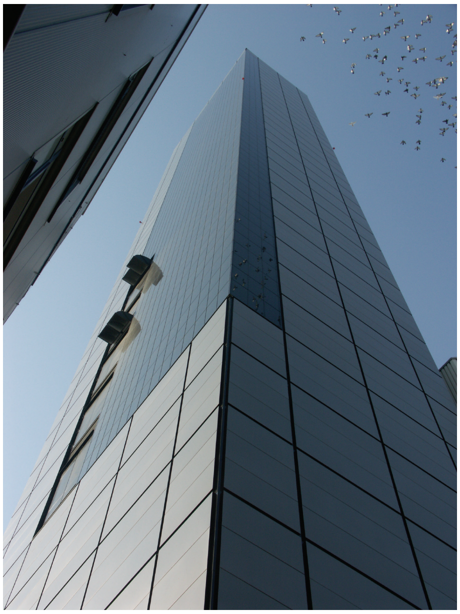


Figure 5: Grain silo "Schapfenmühle" on the outskirts of Ulm, Germany. Integrated into the façade are 1306 CIS modules from the Würth Solar pilot plant with a nominal installed power of 98 kW_p.

6. CONCLUSION AND OUTLOOK

Photovoltaic modules based on the thin-film compound semiconductors CdTe and CIS are successfully being mass produced on a large scale (100 000 per annum or more) and are commercially available for PV installations. Profitable mass-production will be achieved at capacities of 1 mio. square meters of module surface area per year. Presently, the German feed-in law helps industry to achieve this goal faster. Thin-film CIS and CdTe modules of 14% efficiency can be expected within 5 to 7 years. Besides their excellent long-term performance efficiency and expected lower costs, thin-film photovoltaic modules are attractive to architects and consumers due to their very homogeneous appearance, leading to harmonious and visually pleasing installations.

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