

THIN FILM SOLAR CELLS: AN OVERVIEW

- **Why thin film technology for photovoltaic energy production?.....2**
 - *The different thin film technologies*
 - *Market share of thin film technologies*
 - *The record efficiencies of thin film technologies*
 - *Quantity of needed active material*
 - *The manufacturing*
- **Thin film solar cells based on CdTe.....9**
 - *Cadmium telluride*
 - *Environmental, health and safety issues of CdTe solar cells*
 - *Manufacturing of CdTe solar cells*
 - *CdTe manufacturers*
- **Thin film solar cells based on chalcopyrite.....17**
 - *CIGS*
 - *Manufacturing of CIGS solar cells*
 - *CIGS manufacturers*
 - *Long term stability*
- **Thin film solar cells based on silicon.....24**
 - *Crystalline Silicon on Glass*
 - *Manufacturing of CSG solar cells*
 - *Long term stability*
- **Thin film solar cells based on amorphous silicon.....32**
 - *Single junction amorphous silicon solar cell*
 - *Multijunction amorphous silicon solar cells*
 - *Long term stability*
- **A selected overview of commercially available thin-film modules.36**
- **References.....38**

THIN FILM SOLAR CELLS: AN OVERVIEW

Ben Minnaert

Why thin film technology for photovoltaic energy production?

The competitiveness of a photovoltaic module is largely determined by the cost per unit power output. Thin film solar cells have the potential for low cost production and are gradually entering the market. They have certain advantages in manufacturing compared to traditional silicon photovoltaic cells [AVAN1]:

- Lower consumption of materials.
- Independence from shortages of silicon supplies.
- Fewer processing steps.
- Simplified materials handling.
- Process lends itself to automation.
- Integrated, monolithic circuit design; no assembly of individual solar cells into final products.

The different thin film technologies

Different thin film photovoltaic technologies have been studied and developed for terrestrial applications. Those with the greatest potential to significantly reduce manufacturing costs are already commercially available. These are:

- amorphous silicon (a-Si)
- cadmium telluride (CdTe)
- copper indium gallium diselenide / sulfide (CIGS)
- thin film silicon (Si-film)

Market share of thin film technologies

Today's world wide PV market is dominated by the crystalline silicon technology, about 94 % (status 2005, see figure 1). The remainder is based on thin film solar cell technologies and consists mainly of 5 % based on thin film amorphous Si solar cells and 1 % CdTe (CIGS and thin film silicon, although yet commercially available, take up (for now) a negligible part of the market). Most enterprises favour the crystalline technology because of former problems with thin film a-Si technology caused by high failure rates as well as degradation of efficiency.

It is estimated that by 2010, the production capacity for thin-film PV technologies worldwide will be more than 3700 MW, as depicted in table 1. The table is divided into various regions of the world. The United States is estimated at 1127 MW, Japan at 1312 MW, Europe at 793 MW and Asia at 472 MW for thin-film PV production capacity [ULLAL].

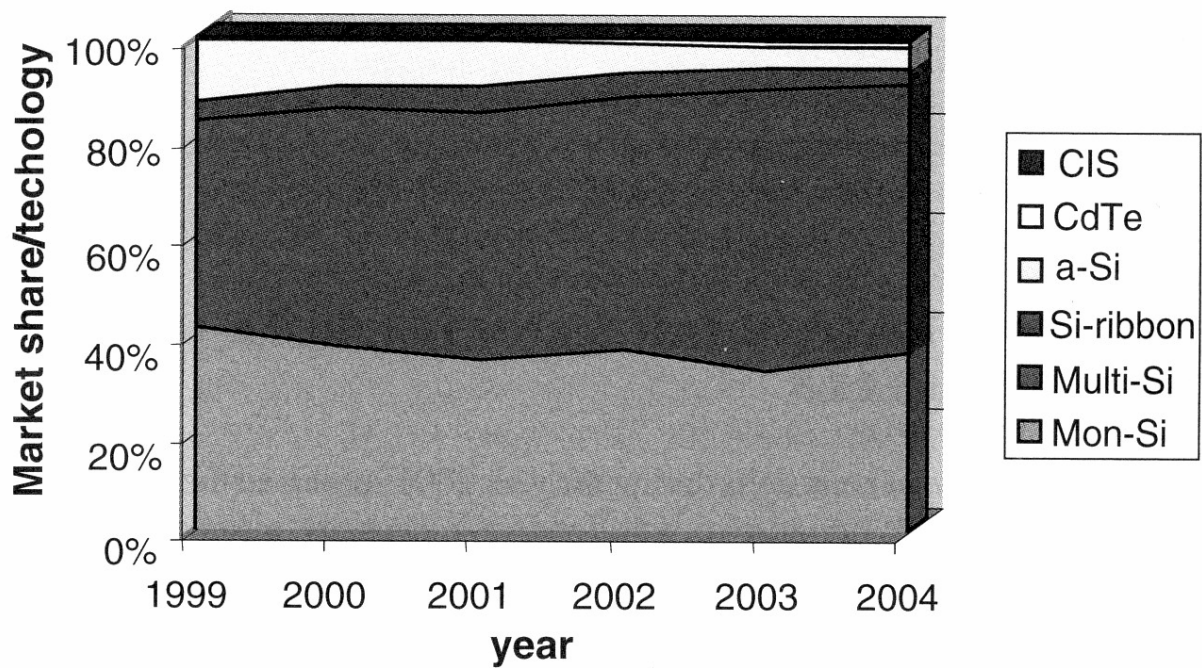


Figure 1: Market share evolution taken by the different solar cell technologies [POORT].

	Group	Material	Present (MW)	Additional (MW)	Total (MW)	Group	Material	Present (MW)	Additional (MW)	Total (MW)	Totals	Grand Total	
USA	First Solar	CdTe	90	—	90	Nanosolar	CIS	—	430	430	1127	3704	
	Uni-Solar	a-Si	60	240	300	AVA Solar	CdTe	3	20	3			
	MiaSole	CIS	5	50	55	Nano PV	a-Si	—	4	4			
	Global Solar	CIS	3	60	63	OptiSolar	a-Si	—	40	40			
	EPV	a-Si	2	25	27	Primestar Solar	CdTe	—	20	20			
	Daystar Technologies	CIS	1	10	11	SoloPower	CIS	—	20	20			
	Power Film	a-Si	1	10	11	ISET	CIS	—	3	3			
	Ascent Solar	CIS	2	25	27	MWVOE Solar	a-Si	—	3	3			
					Heliovolt	CIS	—	20	20				
JAPAN	Kaneka	a-Si	20	50	70	MH1	a-Si	14	56	70	1312		
	Showa Shell	CIS	20	60	80	Kanto Sanyo	a-Si	7	—	7			
	Sharp	a-Si	15	1000	1015	Honda	CIS	3	27	30			
	Fuji	a-Si	15	25	40								
EUROPE	First Solar	CdTe	120	100	120	AMI	a-Si	—	160	160	793		
	CSG Solar	Thin-Si	10	19	29	Johanna Solar Tech	CIS	—	30	30			
	Würth Solar	CIS	3	15	18	Brilliant	a-Si	—	25	25			
	Antec Solar	CdTe	10	—	10	Solisbro	CIS	—	30	30			
	Schoff Solar	a-Si	3	27	30	Global Solar	CIS	—	30	30			
	ICP Solar Tech	a-Si	3	—	3	Helio Grid	a-Si	—	60	60			
	Solar Cells	a-Si	1	—	1	SunFilm	a-Si	—	60	60			
	Free Energy	a-Si	1	—	1	T. J. Solar	a-Si	—	40	40			
	Solar Plus	a-Si	—	5	5	Signet Solar	a-Si	—	20	20			
	Sulfur Cells	CIS	5	—	5	Clyxco	CdTe	—	25	25			
	Aleo Solar	CIS	—	30	30	Avancis	CIS	—	20	20			
Ersol	a-Si	—	40	40	Odersun	CIS	—	5	5				
					Scheuten Solar	CIS	—	10	10				
ASIA	First Solar	CdTe	—	220	220	GET	a-Si	—	40	40	472		
	Bangkok Solar	a-Si	7	—	7	Nanowin Tech	a-Si	—	35	35			
	Sinonar	a-Si	3	—	3	Mosen Baer	a-Si	—	20	20			
	T. J. Solar Cell	a-Si	2	—	2	Solar Morph	a-Si	—	20	20			
	Soltech	a-Si	15	—	15	Topray Solar	a-Si	20	—	20			
	Suntech Power	a-Si	—	50	50	CMC	a-Si	—	40	40			

Table 1: Thin film PV capacity in MW (2007-2010) [ULLAL]

Crystalline silicon PV systems presently have an energy payback time of 1.5 - 2 years for South-European locations and 2.7 – 3.5 years for Middle-European locations. The energy payback time for thin film technologies is already lower than the mature Si-PV technology, i.e. 1-1.5 years for South-European locations [ALSEM].

The record efficiencies of thin film technologies

To compare the output of the different photovoltaic technologies, we show in table 2 the record lab efficiencies for cells and modules of different technologies (situation first half of 2008). Please note that these are record lab efficiencies and not commercially guaranteed efficiencies. The progress of the efficiencies in the last 15 years is plotted in figure 2.

Technology	Cell efficiency (%)	Module efficiency (%)	Reference cell / module
Crystalline Si	24.7 ± 0.5	22.7 ± 0.6	[ZHAO1] / [ZHAO2]
Multi crystalline Si	20.3 ± 0.5	15.3 ± 0.4	[SCHUL] / [KING]
CIGS	19.9 ± 0.6	13.4 ± 0.7	[REPIN] / [TANAK]
CdTe	16.5 ± 0.5	10.7 ± 0.5	[WU] / [CUNNI]
Thin film Si	10.4 ± 0.3	8.2 ± 0.2	[KEEVE] / [BASO3]
Amorphous Si	9.5 ± 0.3 (*1)	10.4 ± 0.5 (*2)	[MEIER] / [YANG]

Table 2: Confirmed terrestrial record cell and module efficiencies measured under the global AM 1.5 spectrum (1000 W/m²) at 25 °C.

(*1) stabilised at 800h, global AM 1.5 spectrum (1000 W/m²) at a cell temperature of 50 °C.

(*2) triple junction tandem cell a-Si/a-SiGe/a-SiGe, light soaked for 1000 h global AM 1.5 spectrum (1000 W/m²) at 50°C.

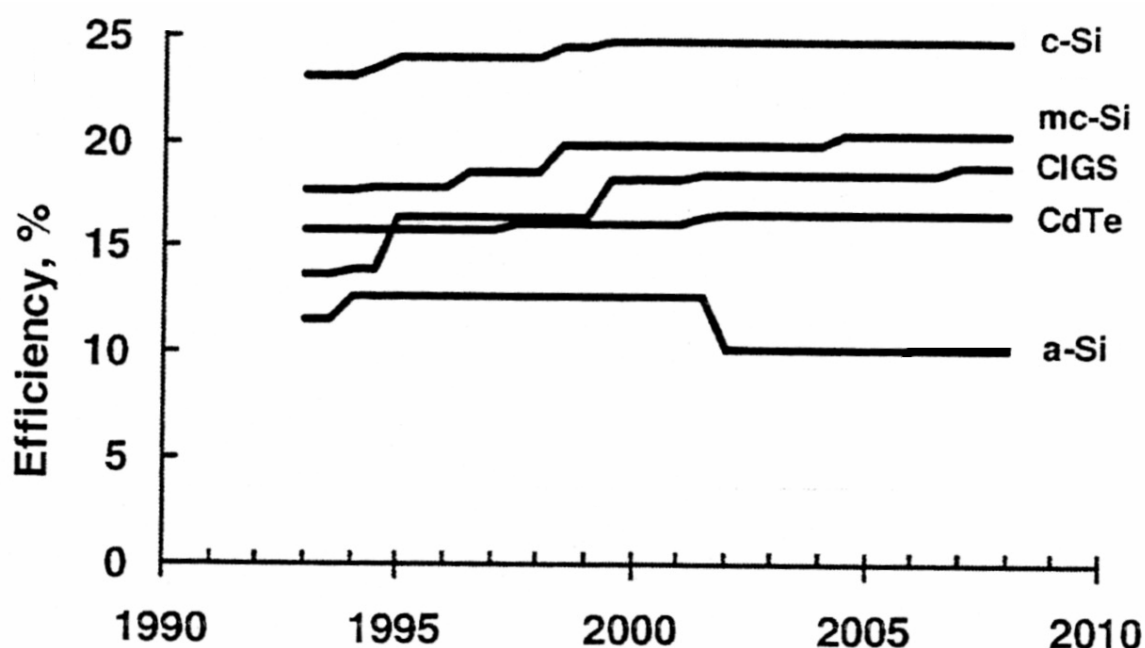


Figure 2: Fifteen years of progress: confirmed cell efficiencies for crystalline Si (c-Si), multi crystalline Si (m-Si), CIGS, CdTe and amorphous silicon (a-Si) [GREE1].

The apparent decrease in performance of the a-Si category arises from a change to reporting stabilised values.

Quantity of needed active material

A classical crystalline solar cell uses an absorber silicon layer of 200 to 300 μm thick. Per kWp of Si-solar cells produced, 10 to 15 kg silicon is needed [AVAN1]. Although silicon is widely abundant on the earth, the manufacturing of Si-solar cells requires raw material of high purity. Semiconductor Si is very expensive. There even is a shortage of silicon because of the growth of the photovoltaic industry. Manufacturers are forced to use lesser grades of silicon, including off-spec virgin, re-melt from wafer manufacturers, and other silicon scrap. The quality of this material varies considerably. Supply shortages, quality issues and the steadily increasing price of silicon have seriously impacted traditional solar cell manufacture.

In contrast with the 200 to 300 μm thick active layer in classical silicon cells, thin film cells only require an active layer of a few μm to a few tenths of a μm .

The manufacturing

Obviously, the complexity of the manufacturing of the solar modules strongly influences cost. Traditional crystalline silicon must be handled in several different forms, complicating manufacturing logistics. First the silicon raw material must be melted at very high temperature and grown into a silicon ingot (or ribbon). The ingot must be shaped and sawn into individual wafers for cell processing. After testing, individual cells must be sorted and wired together and assembled into the photovoltaic circuit. Lastly, the circuit must be carefully placed and positioned in the laminate assembly prior to lamination and final module assembly [AVAN1].

As shown in figure 3, the complete process involves more than twenty separate steps to prepare and process ingots, wafers, cells and circuit assemblies before a module is complete.

In contrast, thin film manufacturing simplifies materials handling. Assembly of the circuit from individual cells is eliminated. Separate processing and handling of ingots, wafers and cells are replaced by the direct fabrication of the final circuit on a single large substrate, usually a glass sheet. All processing is done on these large substrates. Thin film photovoltaic circuits require deposition of three layers: a base electrode layer, a semiconductor layer and a transparent conductor window layer (figure 4). A stack of functional thin-film layers is used 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 CISG for the range of chalcopyrite compounds $\text{Cu}(\text{In}, \text{Ga})(\text{S}, \text{Se})_2$ [POWAL].

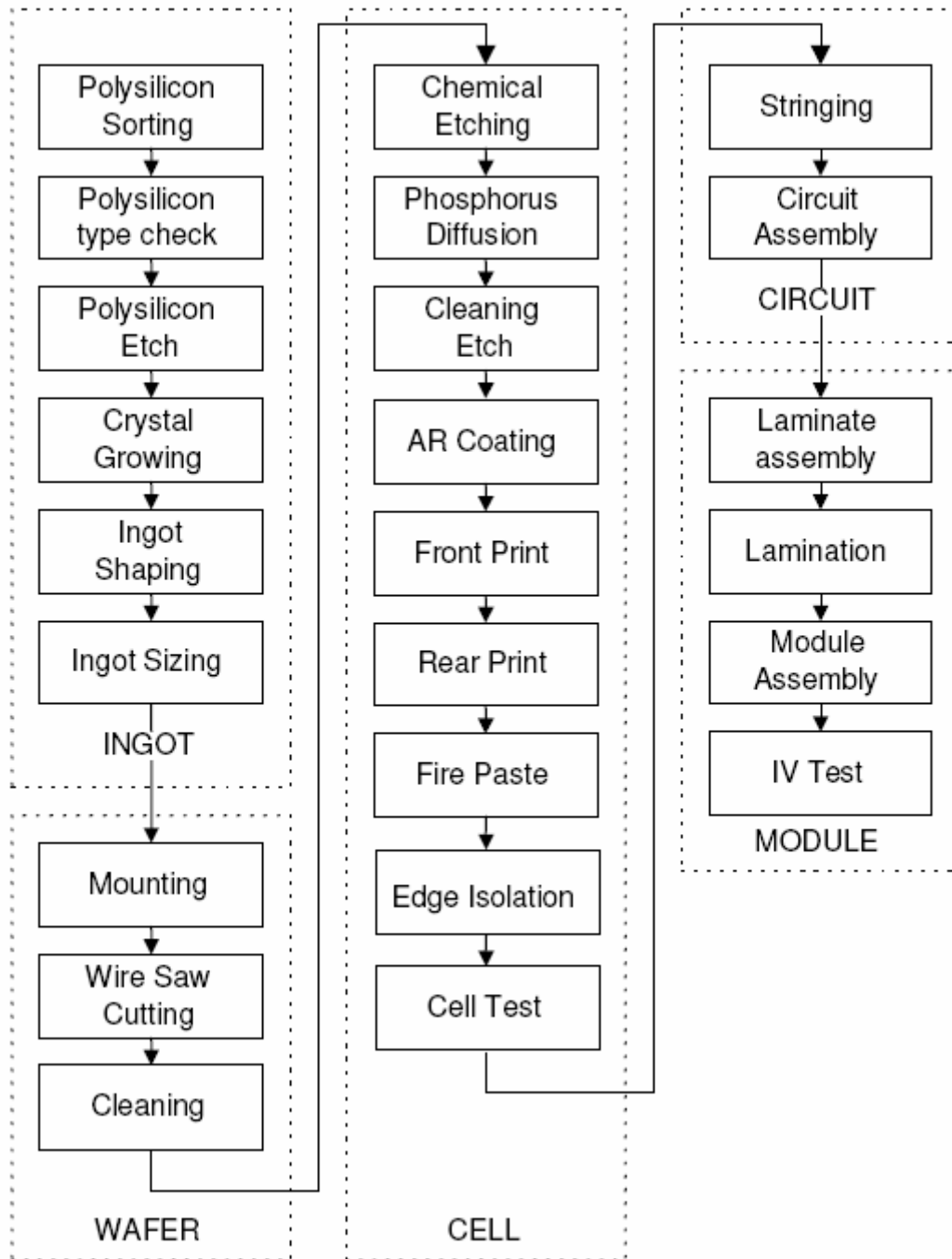


Figure 3: Process sequence for manufacturing crystalline silicon modules [AVAN1].

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 waferbased 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. Three patterning steps, one after each of the three layers, create the integrated series connection from cell to cell on the circuit (displayed in magnified crosssection in figure 5). 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 properties of the transparent conductive oxide (TCO) can also be integrated into the optimization. [POWAL].

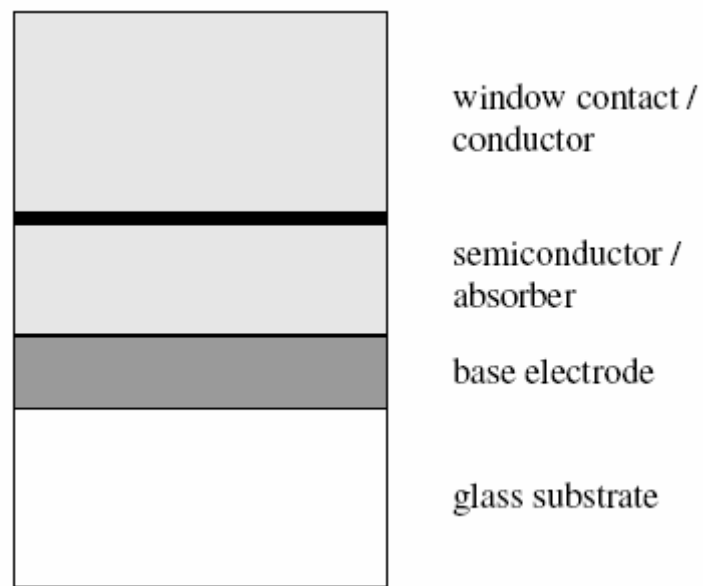


Figure 4: Common elements of most thin film photovoltaic cells [AVAN2].

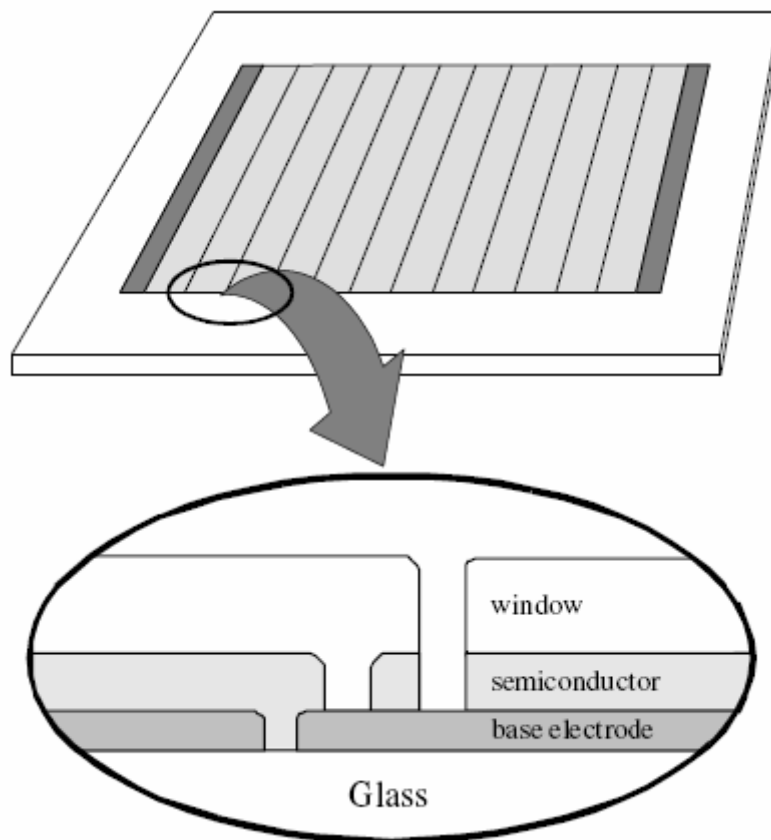


Figure 5: Common patterning structure of most thin film photovoltaic circuits.

Thin film photovoltaic technologies use similar encapsulation schemes to construct modules, including lamination of a cover glass to the circuit substrate, a frame, and a junction box or other electrical connection. About half of the total module cost - material, labor, and overhead - originates in the encapsulation scheme. These costs are for the most part independent of the thin film technology itself. A typical module encapsulation scheme is illustrated in figure 6.

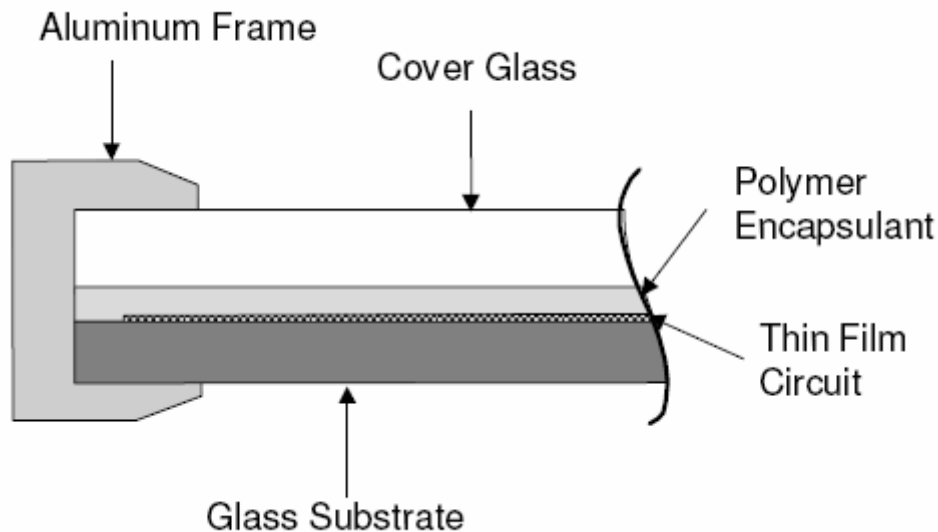


Figure 6: Common structural elements of most thin film modules.

As shown in figure 7, thin film module production requires only half as many process steps as crystalline silicon with simplified materials handling.

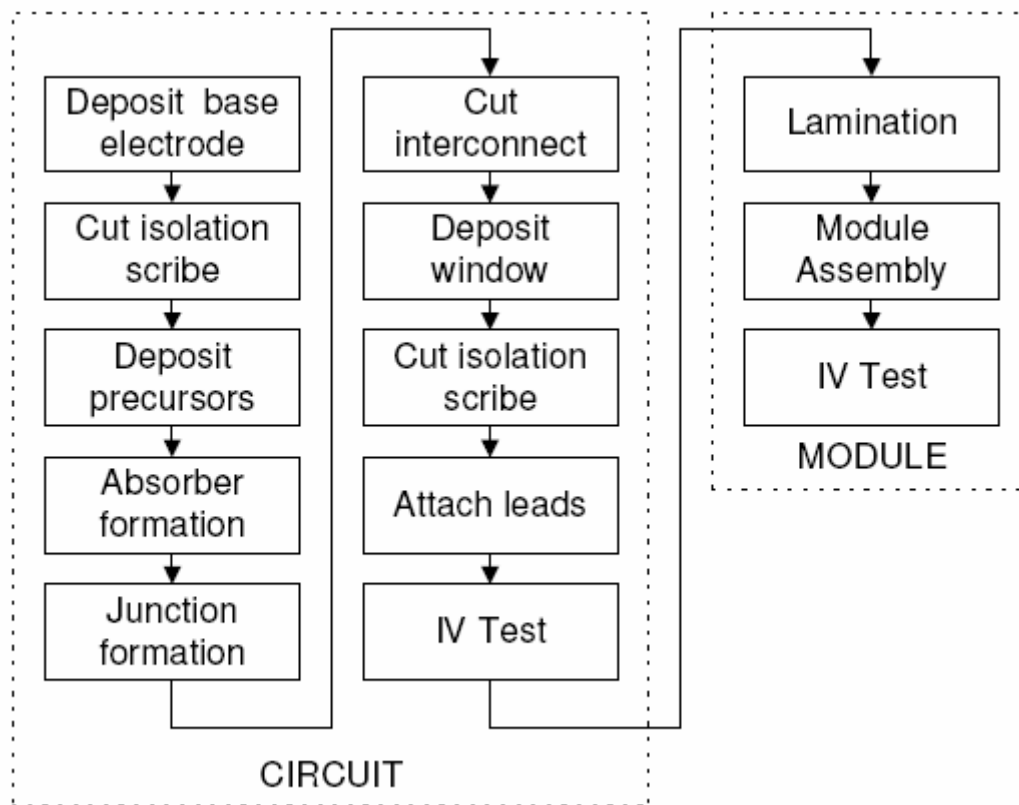


Figure 7: Process sequence for manufacturing thin film modules [AVAN1].

Thin film solar cells based on CdTe

Cadmium telluride

Cadmium telluride is a material that is particularly well suited for thin film photovoltaics. It has a direct bandgap of 1.45 eV, which is well within the optimum range of 1.2 eV to 1.5 eV for maximum photovoltaic energy conversion. Because of the high optical absorption coefficient (higher than a-Si, much higher than crystalline Si), only a few micrometers of CdTe is sufficient to absorb all the incident light, thus minimising material costs. As a consequence, a minority carrier diffusion length of the order of one μm can do the job. Also, nature has been benevolent to CdTe (and other II-IV materials e.g. Cu(In,Ga)Se_2), since the grain boundaries in the polycrystalline layers are not very electrically active, even without technological passivation steps [BURGE].

Cadmium telluride is the only stable Cd-Te compound in the Cd-Te phase diagram, and it melts congruently. This advantageous property allows deposition of near stoichiometric CdTe films of device quality with a multitude of deposition technologies. On the other hand, CdTe does not lend itself to tailoring of the bandgap profile in the device, as can be done with CIGS and a-Si. The high energies of the Cd-Te and the Cd-S bond, the extremely low solubility of CdTe and CdS compounds in water and the low vapour pressure of these compounds are advantages from the environmental point of view [BURGE].

Other material properties are less advantageous. Being a binary compound, the occurrence of native defects renders a precise control of the doping density difficult. This is a fortiori the case for ternary and quaternary compounds such as CIGS and amorphous materials. The interactions between these native defects and foreign elements can trigger self compensation reactions, and this renders impurity doping of CdTe difficult. These effects are more pronounced in CdTe than in e.g. CIGS [BURGE].

Environmental, health and safety issues of CdTe solar cells

As CdTe photovoltaics reached commercialization, questions were raised about potential cadmium emissions from CdTe PV modules. Some have attacked the CdTe PV technology as unavoidably polluting the environment, and made comparisons of hypothetical emissions from PV modules to cadmium emissions from coal-fired power plants. We give a short overview of the issues pertinent to these questions and further explore the potential of environmental, health, and safety risks during production, use, and decommissioning of CdTe PV modules [FTHEN].

Note: cadmium can also -in low amounts- be present in CIGS solar cells, but one can also produce good CIGS cells without Cd.

Toxicology of CdTe

Elemental cadmium, which forms CdTe when reacted with tellurium, is a lung carcinogen, and long-term exposures can cause detrimental effects on kidney and bone. The primary route of exposure to Cd in industrial settings is inhalation. Inhalation of cadmium-containing fumes can result initially in metal fume fever but may progress to chemical pneumonitis, pulmonary

edema, and death. CdTe is a more stable and less soluble compound than Cd and, therefore, is much less toxic than Cd.

Cd Mining

Cadmium is produced primarily as a by-product of zinc production. Because Zn is produced in large quantities, substantial quantities of cadmium are generated as a by-product, no matter how much Cd is used in PV, and can either be put to beneficial uses or discharged into the environment. When the market does not absorb the Cd generated by metal smelters/refiners, it is cemented and buried, stored for future use, or disposed of to landfills as hazardous waste. Arguably, encapsulating cadmium as CdTe in PV modules presents a safer use than its current uses and is much preferred to disposing it off [FTHEN].

More than half of the Cd is used in rechargeable batteries, the rest is applied in pigments, plastic stabilizers, plating, soldering, etc. A GW/year scale CdTe PV production would take up about 1 % of the Cd consumption only [BURGE]. Related to NiCd batteries, a CdTe PV module uses Cd about 2500 times more efficiently in producing electricity. A 1 kW CdTe PV system contains as little cadmium as seven size-C NiCd batteries [FTHEN].

CdTe PV Manufacture

In CdTe PV production facilities, workers may be exposed to Cd compounds through the air they breathe and by ingestion from hand-to-mouth contact. These are real risks and continuing vigilance is required. However, current industrial practice suggests that these risks can be managed and controlled successfully [FTHEN]. The health and environmental aspects of CdTe PV production are well documented by the leading production companies First Solar [BOHLA] and Antec [BONN1]. Handling and processing potentially hazardous materials is not an uncommon industrial activity at all. As with all other industrial activities, CdTe PV is subject to safety laws and regulations. Careful design of the plant and tight control of the production equipment, permanent monitoring of the workers environment and possibly medical monitoring of the personnel are key points. Though not legally required for the exposure levels occurring in the plant, First Solar has carried out medical monitoring of the personnel [BOHLA], and all blood and urine Cd levels measured were way below the threshold concern levels. It appears to be technically and economically possible to design and operate a factory with zero cadmium emissions [BONN2] [BURGE].

CdTe PV Use

No emissions of any kind can be generated when using PV modules under normal conditions. Any comparisons made with cadmium emissions from coal fired power plants are erroneous, because they compare potential accidental emissions from PV systems to routine (unavoidable) emissions from modern coal-fired plants. In reality, PV, when it replaces coal-burning for electricity generation, will prevent Cd emissions in addition to preventing large quantities of CO₂, SO₂, NO_x and particulate emissions [FTHEN].

The main perceived risks during the active lifetime of a solar panel are leaching out of broken modules and fire hazards. First results are that in typical residential fires, where a temperature of 800 – 1000 °C is reached, no Cd compound is released, due to the low vapour pressure of CdTe and CdS at these temperatures. These compounds are encapsulated in the molten glass instead [MOSKO]. Leaching of hazardous materials from crushed CdTe and CIGS modules

was also investigated [STEIN], however, the concentrations measured in all scenarios were below the limit or tolerable concentrations [BURGE].

CdTe PV Decommissioning

The only environmental issue is what to do with the modules about 30 years later, if they are no longer useful. The cadmium telluride is encapsulated between sheets of glass and, according to current laws, passes the leaching criteria for nonhazardous waste. However, disposal of such modules in landfills is not a scenario that is promoted by any PV actor. Instead, recycling schemes have been set up for used PV modules, including broken modules or fragments from manufacturing. These schemes include scraping, crushing, melting and regeneration of materials that will reenter in the production lines [BONN2] [BURGE]. Recycling will completely resolve any environmental concerns. The recycling already happens, e.g. the company First Solar focuses very strongly on the environment friendly decommissioning of their CdTe modules.

CdTe PV Life Cycle

Based on a life cycle study performed [ALSEM], the life-cycle cadmium emissions of CdTe-based PV systems have been compared with those of other module types and also with other energy technologies. According to this study the cadmium emissions of CdTe PV- technology are among the lowest, and even lower than those of silicon PV-technology. This result which at first sight may seem counter-intuitive, is caused by the cadmium emissions in electricity production plants that are fuelled by coal or oil. In other words because the direct cadmium emissions in the CdTe module production are very low, it is actually the electricity input for module production – and the related indirect cadmium emissions – which determines the total life-cycle emission for a PV system. This highlights of course the importance of reducing energy input for silicon module production.

In conclusion, the environmental risks from CdTe PV are minimal. Every energy source or product may present some environmental, health, and safety hazards, and those of CdTe are by no means barriers to scaling-up the technology.

However...

Governmental regulation

There can be a difference between the real environmental risks from cadmium and the governmental regulation concerning this hazardous material, thus hampering the production of Cd containing solar cells.

The use of cadmium in various products is coming under increasingly stringent governmental regulation. Future regulation in this area could impact the manufacture and sale of cadmium-containing solar modules and could require to make unforeseen environmental expenditures or limit the ability to sell and distribute solar cells with Cd. For example, the European Union Directive 2002/96/EC on Waste Electrical and Electronic Equipment, or the “WEEE Directive”, requires manufacturers of certain electrical and electronic equipment to be financially responsible for the collection, recycling, treatment and disposal of specified products sold in the European Union. In addition, European Union Directive 2002/95/EC on the Restriction of the Use of Hazardous Substances in electrical and electronic equipment, or

the “RoHS Directive”, restricts the use of certain hazardous substances, including cadmium, in specified products. Other parts of the world are considering adopting similar legislation. Currently, photovoltaic solar modules in general are not subject to the WEEE or RoHS Directives; however, these directives allow for future amendments subjecting additional products to their requirements and the scope, applicability and the products included in the WEEE and RoHS Directives are currently being considered and may change [FIRST]. According to the European legislation, it is at this time allowed to use cadmium in CdTe and CIGS solar cells. However, the conversion from European directives to national regulations can lead to stricter rules. For example, in the Netherlands, the cadmium order of 1999 forbids the use of cadmium in solar cells, due to a different interpretation of the definition of surface treatments. This resulted in the situation that solar cells with cadmium were allowed to be produced in the Netherlands, but only when they were intended for export. Further, cadmium containing solar cells, legally produced in the European Union, could not be imported into the Netherlands [WENTI].

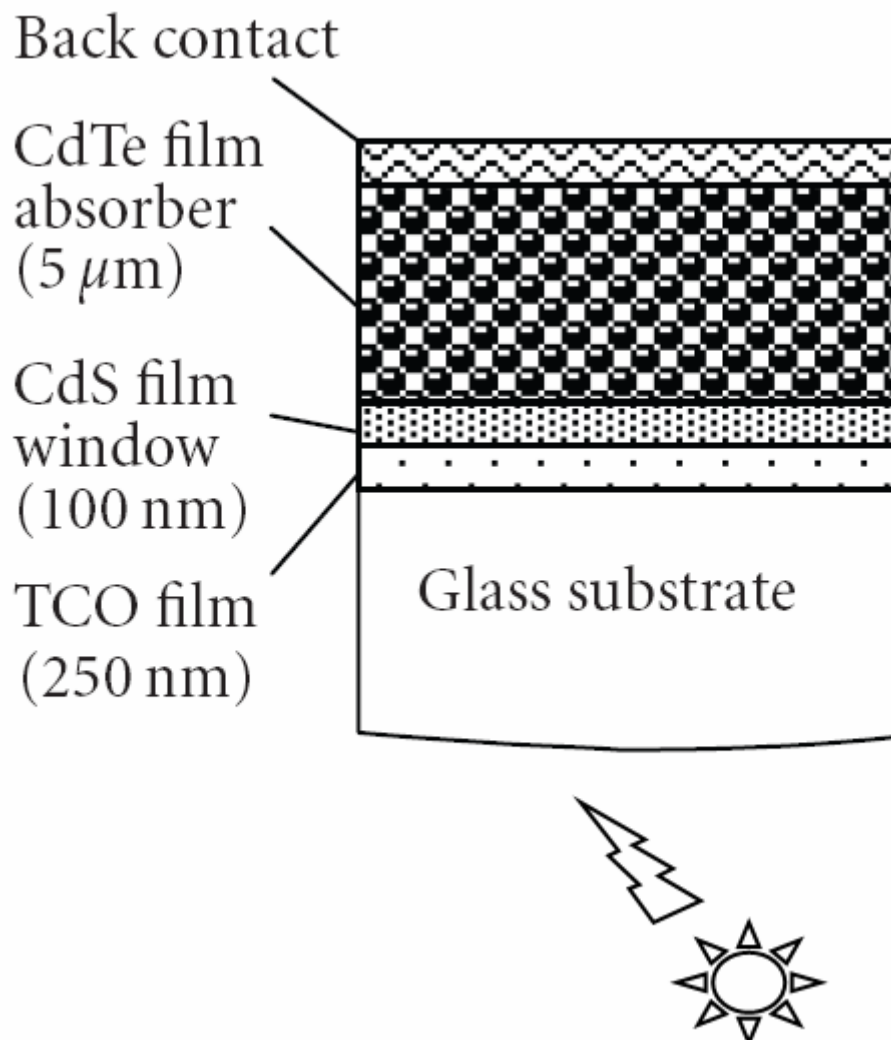


Figure 8: Layer sequence for CdTe solar cells [POWAL]

Manufacturing of CdTe solar cells

CdTe solar cells are processed on the front glass, so the first layer is a TCO for the front contact. It is followed by the CdS window layer and the CdTe absorber layer. A back contact completes the device. A schematic cross-sectional view of the device is shown in figure 8.

Today's two leading CdTe PV manufacturers, Antec and First Solar, use a sublimation technique for the deposition of the CdTe absorber. Antec uses close spaced sublimation (CSS) to deposit about 0.1 – 0.2 μm of CdS and about 5 – 10 μm of CdTe sequentially [BONN2]. In the CSS technique, the source and the substrate are placed at a short distance of each other (1 mm to a few cm, depending on the size) in a rough vacuum (0.1 to 1 Pa). The source and the substrate are heated to a high temperature (in the 500 °C range), the source being at a slightly higher temperature than the substrate. The high deposition temperatures used in this method results in CdTe layers free from secondary elemental phases method, and the production of dense, faceted grains. As a source, one can use the CdTe compound in the form of a pressed tablet, or in granulate or powder form. A stoichiometric mixture of Cd and Te powder can also be used. The driving force for the deposition is the source to substrate temperature difference, and the surface energy at the substrate, which can depend on the substrate composition, crystallography and morphology [BURGE].

After deposition, the CdS-CdTe junction must be “activated” to achieve high photovoltaic efficiencies. The process involves annealing at temperatures between 400 °C and 500 °C in the presence of Cl-containing species, generally CdCl_2 [POWAL].

In parallel with the development of CSS (“close spaced sublimation”) based devices other methods have been used to produce CdS/CdTe solar cells [BURGE]. These include:

- spray pyrolysis by Golden Photon. This company ceased the production because of lack of cell stability.
- electrodeposition by BP Solar. They reached an advanced technical status with their electrodeposited CdTe modules, illustrated by a large area panel with efficiency exceeding 10 %. A 10 MWp plant was set up in Fairfield, California, but the activity was stopped in 2002.
- screen printing by Matsushita Battery in Japan. They have produced screen printed and sintered CdTe solar cells for the indoor market, e.g. for Panasonic calculators. Although the technical status was well developed, the activity as stopped in 2002.

The highest efficiency CdTe-based solar cell produced to date is that made by Wu and coworkers at NREL [WU]. This device was produced by depositing layers in the sequence Cd_2SnO_4 , Zn_2SnO_4 , CdS, CdTe and finally the back contact. The improvement is due to the Cd_2SnO_4 layer being both more transmissive and more conductive than $\text{SnO}_2\text{:F}$, increasing the amount of light reaching the interface and lowering lateral resistance losses. The inclusion of a Zn_2SnO_4 layer between the Cd_2SnO_4 layer and the CdS buffer layer was introduced to improve V_{OC} and FF.

This type of structure has advantages when the technology is scaled up in that the Cd_2SnO_4 , Zn_2SnO_4 and CdS can be sputtered in argon at room temperature from hot pressed targets, speeding up throughput by eliminating warm up and cool down times for the substrates and sources. The CdTe is deposited using CSS at 570-625 °C and the samples were then heat treated in CdCl_2 vapour at 40-420 °C for 15 min. It is mainly during the CdTe deposition that the Cd_2SnO_4 , Zn_2SnO_4 and CdS layers are recrystallised and interdiffusion promoted at the

interfaces of the materials. It is expected that the commercial CdTe cell manufacturers i.e. Antec and First Solar will incorporate the stannate layers into their production processes over the next few years [MILES].

An essential advantage of thin film solar cells is, as already mentioned (figure 3), the possibility of automated series connection of cells in a module. All layers are deposited at the full module size. After deposition, the TCO layer(s) are patterned by laser or mechanical scribing over the entire width of the substrate. The cuts have to be as narrow as possible (100 μm range) and leave no TCO material which could shunt the structure; their mutual spacing follows from an optimization design and is of the order of 5 – 10 mm. After deposition of the CdS and the CdTe layer and the activation treatment, a second scribe is given which leaves the TCO layer. This is possible because the TCO layer is usually much harder and adherent than the semiconductor layers. In this second cut, the metallization layer(s) form an interconnection between the left hand and the right hand cell. A third scribe then isolates the back contacts of the two cells from each other. This integrated series connection technology can be automated to handle a full 60 x 120 cm^2 module at high throughput (e.g. 2 minutes) [BURGE].

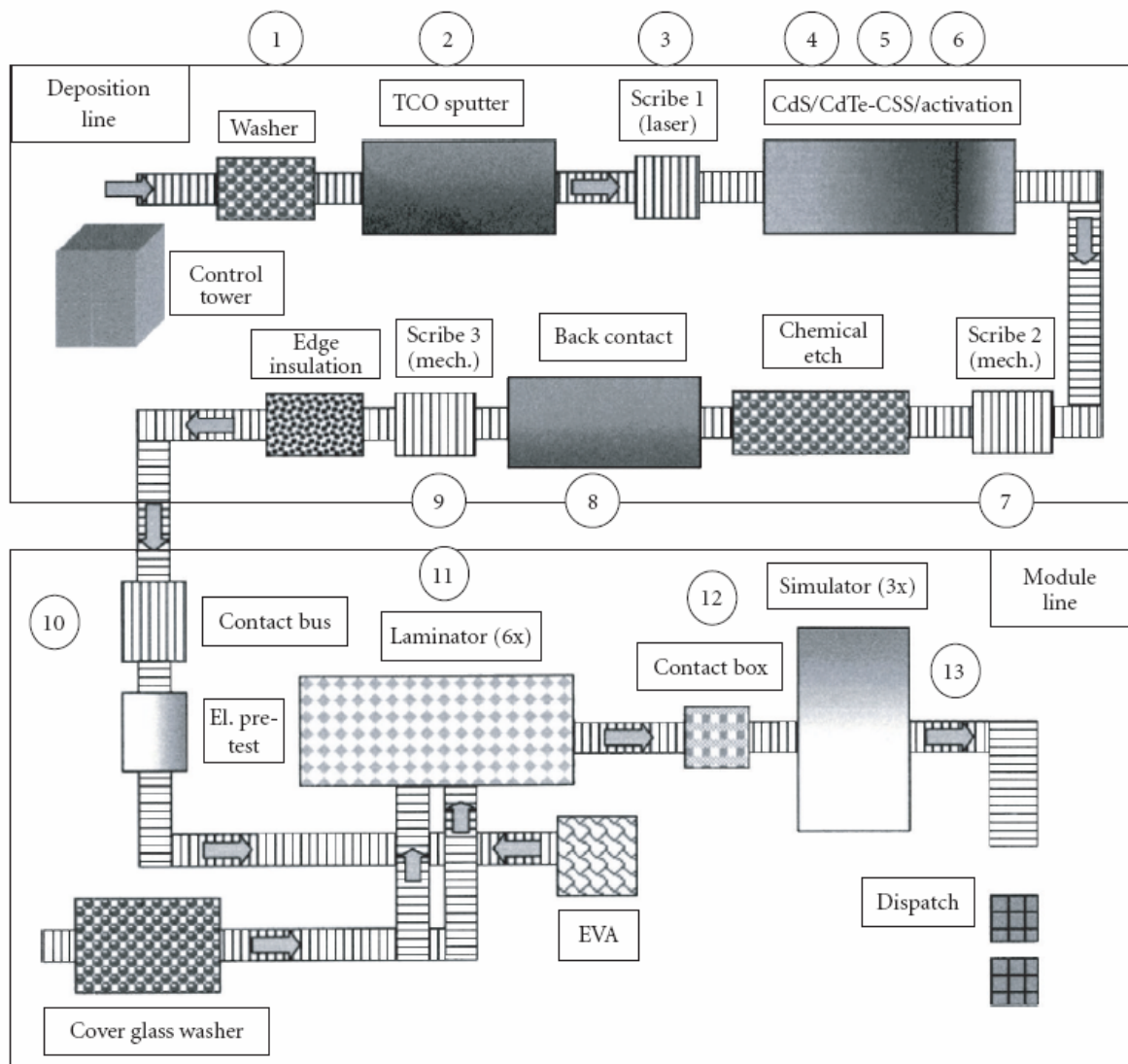


Figure 9: Schematic of commercial production line for CdTe thin-film solar modules [POWAL].

An overview of the CdTe photovoltaic module industrial production line is given (figure 9). 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. The production begins with cleaning the substrate glass (1) in a washer. Step (2) is the sputter deposition of the TCO front contact. The initial film is patterned with a laser in step (3). Steps (4), (5), and (6) involve the junction deposition and formation. 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; 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 [POWAL].

The long-term stability of CdTe modules is discussed further, together with the durability of CIGS.



Figure 10: CdTe module production at Antec.

CdTe manufacturers

Today's two leading CdTe PV manufacturers are Antec (Germany) and First Solar (U.S.A.). Antec went bankrupt in 2002, but it made a fresh start as Antec Solar Energy GmbH and focuses now only on the production site. In the Antec plant, the TCO is applied by sputtering, and the CdS and CdTe are deposited by CSS. These steps, together with the activation of CdTe, the contact treatment, the sputter deposition of the contact buffer and contact metal, and the laser scribing for the series connection, are integrated in one production line. The size of the panels is 60 x 120 cm², the throughput is 2 minutes per module. This gives a production capacity of 100 000 m²/year, corresponding to 8 MWp/year. In a second production line, the glass plates are encapsulated and sealed to finished modules. The actual production costs

below 2 \$/Wp, and the energy payback time is less than one year under central European insolation conditions [BURGE].



Figure 11: Antec's thin-film manufacturing plant in Arnstadt, Germany

First Solar uses the same module size. The CdS and CdTe layer are deposited with high rate vapor transport deposition (HRVTD), where the vapors of subliming CdS or CdTe are brought over the substrate plates (this is a variant of the CSS technique) [BURGE]. This company is the world leader in CdTe PV technology development and global sales. They have an installed capacity of 90 MW in Perrysburg, Ohio for the manufacture of thin-film CdTe power modules, shown in figure 11. They have also recently started a new facility in Germany with an installed manufacturing capacity of 120 MW [ULLAL].



Figure 11: First Solar's 90-MW thin-film manufacturing plant in the USA [ULLAL].

They are also installing an additional 240 MW manufacturing capacity in Malaysia to be completed in 2009. Thus, the total global target for First Solar is about 450 MW by 2009 making it one of the leading PV companies in the world.

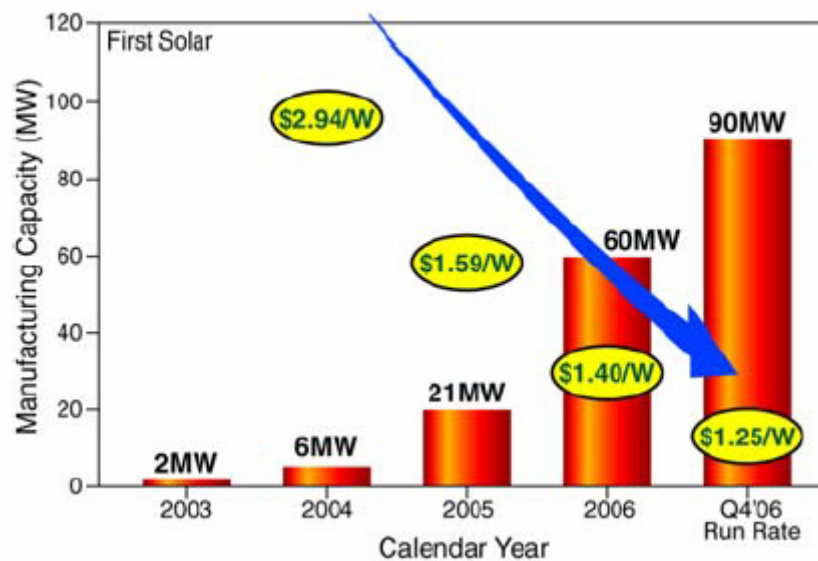


Figure 12: Thin-Film CdTe manufacturing capacity and cost reduction of First Solar versus calendar year [ULLAL].

Figure 12 shows First Solar's manufacturing cost for thin-film CdTe PV modules. As economies-of-scale have been realized, the manufacturing cost has dropped substantially from \$ 2.94/W (6 MW) in 2004 to \$ 1.25/W (90 MW) at 2007. The target manufacturing cost is expected to be \$ 0.70/W due to improvements in productivity, module efficiency, and yield by 2012, thus making it potentially price competitive with grid-parity electricity [ULLAL].

Thin film solar cells based on chalcopyrite

CIGS

Chalcopyrite based solar modules combine advantages of thin film technology with the efficiency and stability of conventional crystalline silicon cells. It is therefore believed that chalcopyrite based modules can take up a large part of the photovoltaic market growth once true mass production is started [KLENK]. Chalcopyrites are compounds based on the use of elements from groups I, III and VI of the periodic table and include copper indium diselenide (CuInSe_2), copper gallium indium diselenide ($\text{CuGa}_{1-x}\text{In}_x\text{Se}_2$) and copper indium disulphide (CuInS_2). One refers to these cells as CI(G)S solar cells. As with amorphous silicon and cadmium telluride these materials have direct energy bandgaps and high optical absorption coefficients for photons with energies greater than the energy bandgap making it possible for a few microns of absorber layer material to absorb most of the incident light [MILES].

As mentioned already, thin film technologies make very efficient use of raw materials. While 0.5-1 kg/m² of semiconductor grade silicon are required for a conventional module, the material consumption per square meter for the active films of a CIGS module is given as: 7-20 g molybdenum, 1.5-4 g copper, 3-9 g indium, 7-20 g selenium and 1-3 g zinc (depending on

the exact module structure and yield. This implies that the total material input is comparable to the material used for just the grid metallization of silicon modules [KLENK].

Nevertheless, it has been argued that indium is the bottleneck concerning the abundance of raw materials. In 2003 it was used mainly for coating (65 %), solders and alloys (15 %) and electrical components (10 %). Indium based coatings are used in the production of flat panel displays where indium tin oxide (ITO) is used as a transparent contact. The annual world production of indium, mainly from zinc ores, is in the order of 300 tons, which translates into chalcopyrite modules with approximately 15 GWp/year in total. On the other hand, indium is about three times more abundant in the Earth's crust than silver, the latter having an annual production of 20 000 tons and a reserve base of 570 000 tons. These numbers imply that the availability of indium is not likely to be an ultimate limiting factor. Moreover, it has already been shown that even thinner active films in a chalcopyrite module are feasible. The flat panel industry may replace ITO by the cheaper ZnO in future and indium recycling should contribute to higher availability and lower market prices. Indium free absorbers are under development. Within the last three decades, the prices of indium have been varying over a wide range from below 100 \$/kg to more than 500 \$/kg. However, even the latter price would imply that indium is responsible for only approximately 2 % of the module manufacturing costs.[KLENK]. Nevertheless, some workers are trying to replace the In and Ga (which is also not that abundant) with Zn and Sn to produce $\text{Cu}_2\text{ZnSnS}_2$ solar cells [MILES].

In contrast to amorphous silicon based cells, chalcopyrite devices do not show any degradation under illumination. Outdoor testing indicates that achievable product lifetimes may be comparable to those of conventional photovoltaic modules. The low cost potential is roughly comparable of that of other thin film technologies, and is rooted in the use of inexpensive substrates, effective use of raw materials, high throughput, and large area deposition at low temperatures as well as monolithic interconnection. The energy payback time is obviously an important parameter when considering how far photovoltaics can contribute to the energy supply. The much lower thermal budget of thin film preparation (lower process temperatures as well as short process times) leads to a significant benefit [KLENK].

There is a considerable flexibility concerning the choice of components of a CIGS module as well as concerning the preparation methods. It is therefore possible to design products with an optimum efficiency/cost trade-off for various applications, with power demands ranging from mW to MW and with illumination intensity ranging from indoor, low level to high level under concentration. Chalcopyrite cells can be grown on rigid as well as flexible substrates. They perform well in challenging environments because they are mechanically robust, can operate in a wide temperature range, and can tolerate high radiation levels [KLENK].

To summarize, the attractive advantages of CIGS photovoltaic modules are: [KLENK]

- High efficiency
- Stability
- Low cost
- Effective use of raw materials
- Short energy payback time
- Adaptable to various applications
- Large supporting research and development community.

Manufacturing of CIGS solar cells

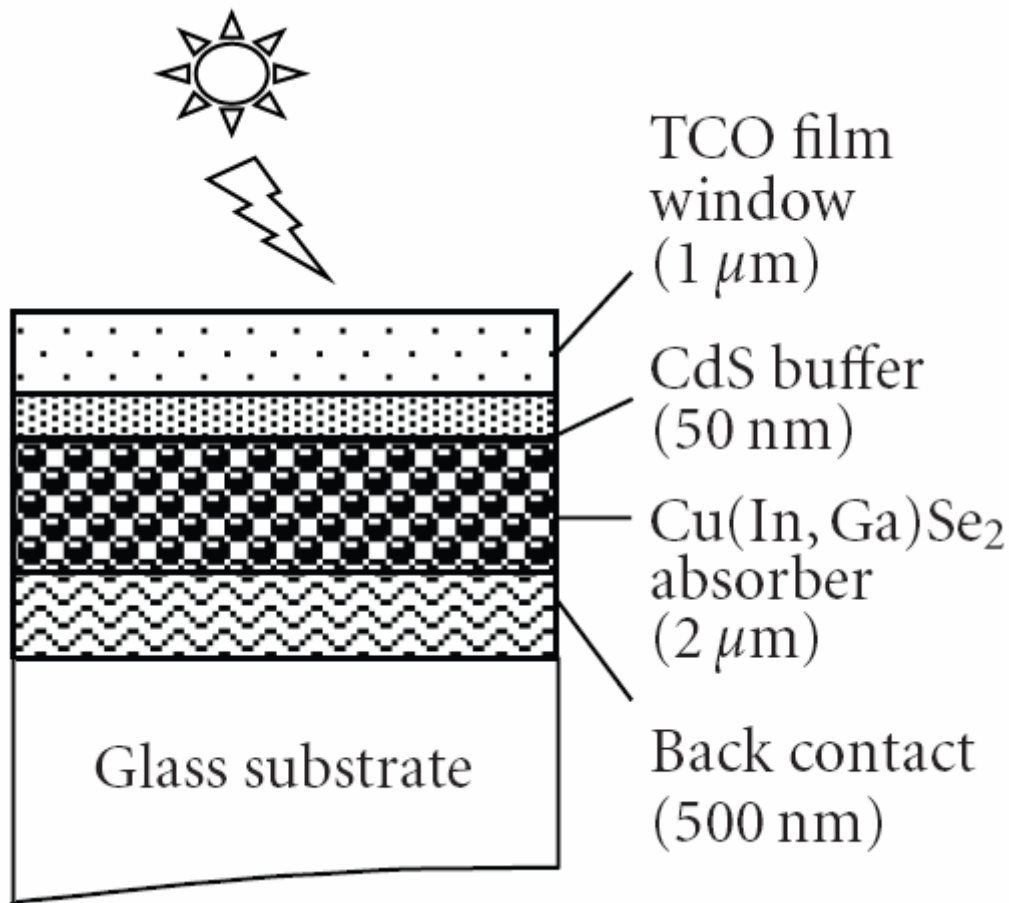


Figure 13: Layer sequence for CIGS solar cells [POWAL]

The layer sequence for CIGS solar cells is illustrated in figure 13. CIGS cells are processed from back to front, so the molybdenum (Mo) back contact does not need to be optically transparent. The Mo is coated by sputtering. The CIGS absorber film follows. CIGS 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. The CIGS 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. CIGS solar cells typically employ an extremely thin CdS film deposited in a chemical bath. CIGS solar cells without the toxic Cd can however already be successfully produced (good candidates for Cd-replacement are ZnSe, ZnIn₂Se₄ and MgZnO [MILES]). Finally, a sputtered intrinsic ZnO film and the transparent conductive ZnO:Al window layer are also deposited by sputtering. As already mentioned, CIGS devices have achieved the highest efficiencies of all thin-film solar cells [POWAL].

The monolithic interconnection of CIS modules occurs in the same manner as with CdTe, just in the reverse processing sequence (the first cut separates the back contact and the third cut separates the front contact), see figure 3. 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 [POWAL].

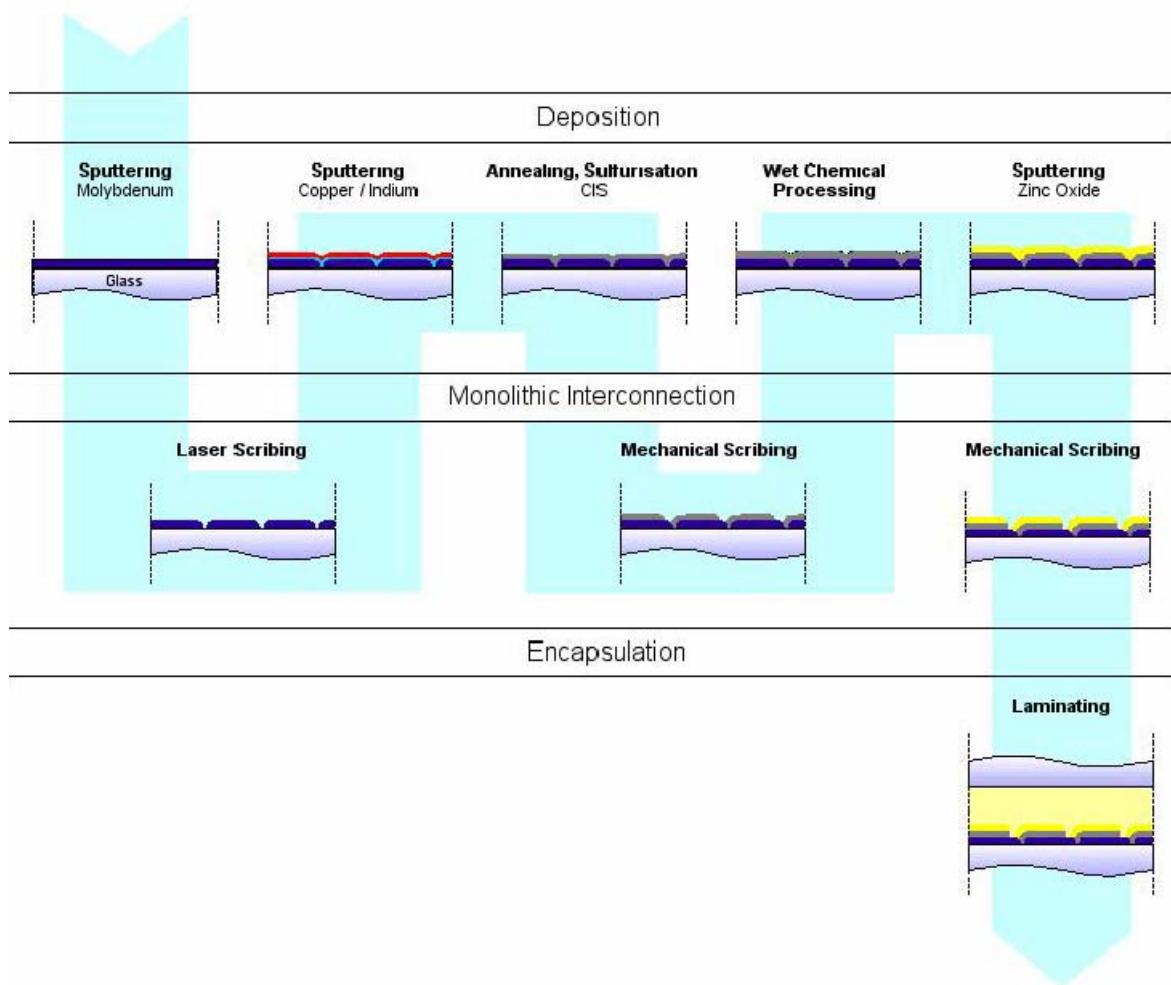


Figure 14: The production process of CIS modules at Sulfurcell

For the industrial production of thin-film CIGS 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. The overview of the module processing is similar to that of CdTe of Figure 9 and 14. The production begins with cleaning the substrate glass (1) in a washer. Step (2) is the sputter deposition the Mo back contact. The initial film is patterned with a laser in step (3). Steps (4), (5), and (6) involve the junction deposition and formation. 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. Step (7) is the second patterning step, usually a mechanical scribe. Step (8) is the contact deposition, the front-side TCO which consists of a doped ZnO deposited by sputtering. 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 [POWAL].

CIGS manufacturers

Worldwide, five companies are presently **offering** commercial thin-film PV CIGS products:

Company	Capacity (MWp/year)	Substrate (m x m)	Efficiency max./mean
Honda Soltec, Japan	27	0.8 x 1.3	13 % / 10 %
Showa Shell, Japan	20	0.6 x 1.2	14 % / 12 %
Würth Solar, Germany	15	0.6 x 1.2	13 % / 12%
Sulfurcell, Germany	5	0.65 x 1.25	8 % / 7 %
Global Solar, USA	4	metal foil 1 ft wide	10 % / 8 %

Table 3: Commercially available CIGS solar modules [POWAL].

There is currently a “boom” in the construction of thin-film solar module production plants. Worldwide, about 34 companies are actively **developing** thin-film CIGS PV technologies. These companies are using about ten different deposition methods for growing the thin CIGS absorber layers, as is shown for some in Table 4. The absorber layer for commercial products uses either co-evaporation or the two-stage process such as the deposition of the precursors by sputtering followed by selenization. All companies use Mo as the back contact deposited by sputtering, and the majority use ZnO as the front contact deposited either by sputtering or chemical vapor deposition [ULLAL].

Company	Substrate	Back Contact	Process	Front Contact
Shell Solar	Glass	Mo	Sputter/Selenization	ZnO
Global Solar	Steel	Mo	Coevaporation	ITO
Miasole	Glass	Mo	Sputter	ZnO
Würth Solar	Glass	Mo	Coevaporation	ZnO
Avancis	Glass	Mo	Sputter / RTP	ZnO
Daystar Tech	Glass	Mo	Sputter	ZnO
EPV	Glass	Mo	Sputter/Evaporation	ZnO
Ascent Solar	Polymer	Mo	Coevaporation	ZnO
ISET	Glass/Flex	Mo	Ink/Selenization	ZnO
Nanosolar	Flexible	Mo	Print / RTP	ZnO
Heliovolt	Glass/Flex	Mo	FASST	ZnO
SoloPower	Steel	Mo	ED / RTP	ZnO

Table 4: Thin Film CIGS Technology [ULLAL].

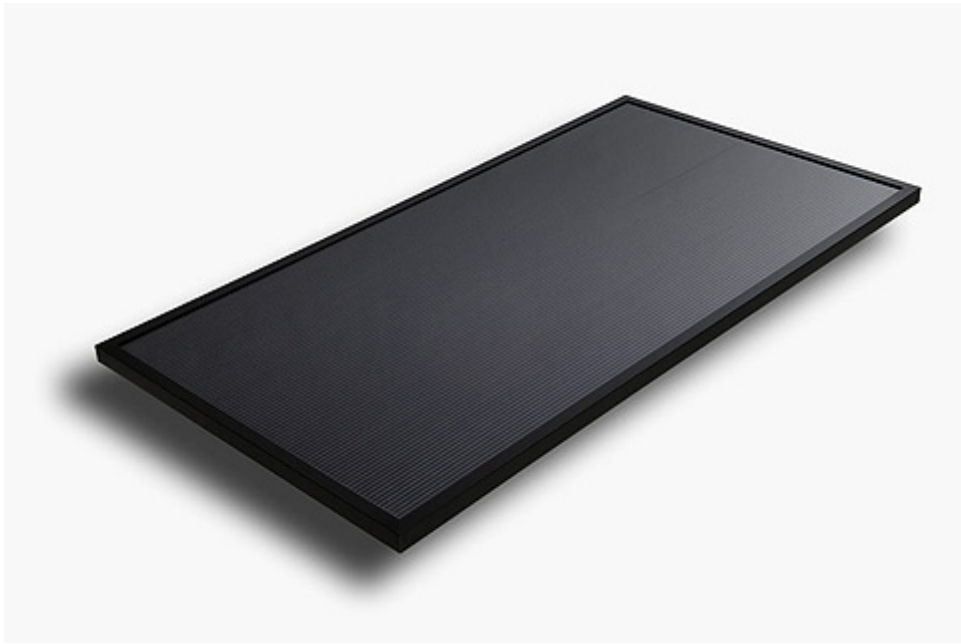


Figure 15: The CIG module of Sulfurcel.



Figure 16: Würth Solar's thin-film manufacturing plant in Schwäbisch Hall, Germany.

Long term stability

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 [POWAL].

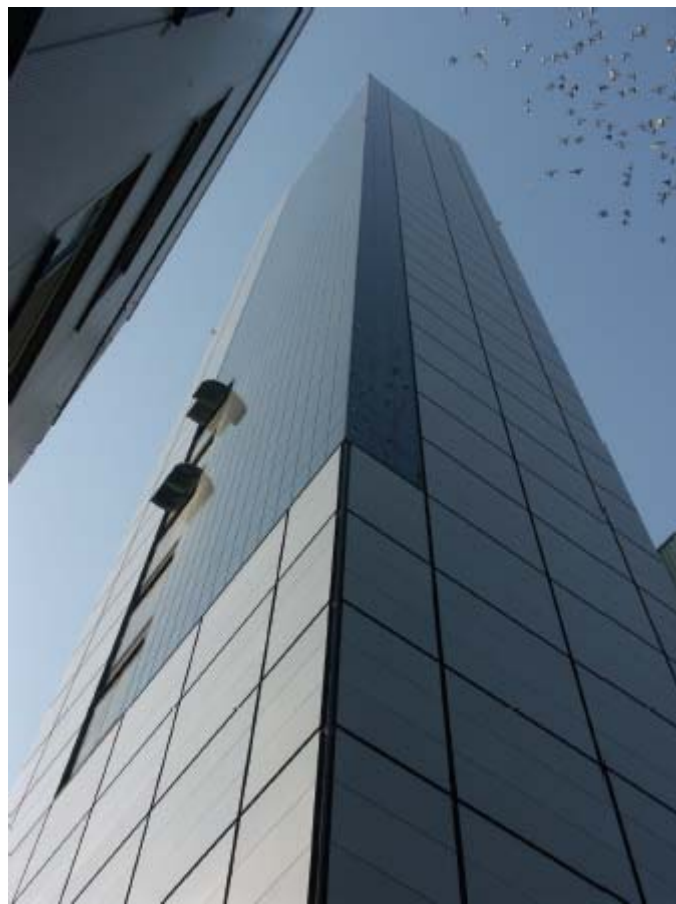


Figure 17: Grain silo “Schapfenmühle” on the outskirts of Ulm, Germany. Integrated into the façade are 1306 CIGS modules from the Würth Solar pilot plant with a nominal installed power of 98 kWp.

Extended outdoor testing of CdTe and CIS modules proves their stability. 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 17 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 [POWAL].

Thin film solar cells based on silicon

Crystalline Silicon on Glass

Today's terrestrial PV market is dominated by crystalline silicon wafers. However, due to its material intensiveness, it appears unlikely that wafer-based technology will ever reach cost levels (€/W) required for a widespread application of PV [ABERL]. The solution to this problem might be polycrystalline silicon thin film solar cells on supporting materials. Per watt of output power, such devices require as little as 1 % or less of Si compared to today's wafer-based technology. Glass is a particularly promising supporting material as it is cheap, transparent, electrically insulating (simplifying cell interconnection), long-term stable, readily available and already a standard component in today's PV modules. The drawback with glass sheets is their limited thermal stability, excluding the use of lengthy high-temperature ($> 650^{\circ}\text{C}$) processing steps during solar cell fabrication.



Figure 18: A 287 kW IBC Solar Installation of CSG-80 modules in Eurishofen, Germany [KEEVE].

Crystalline silicon on glass (CSG) is a thin-film polycrystalline silicon PV technology with an inherently low manufacturing cost that requires less than $2\text{ }\mu\text{m}$ of silicon thickness. Thin-film polysilicon does not contain any amorphous tissue, or only a very small amount (well below 1%). Initially developed in Australia by Pacific Solar (1995-2004), the technology has since been commercialised by CSG Solar AG (founded in June 2004). After an initial period of technology demonstration, a combination of private investment and government support was secured in December 2004 to build a factory in Germany to manufacture CSG modules. The factory is located in the state of Saxony-Anhalt near Thalheim and started with a rated annual capacity of 10 MW. The first functional modules were produced in this plant in April 2006. The entire output of this plant for the first year and 80 % of the output through 2010 had been

sold in advance. [BASO1]. At present, ‘CSG-80’ modules with a glass / SiN / Si / resin / Al / EVA / TPE structure (75-90 W, 7.2 % efficiency, 1.38 m²) are commercially available as CSG with a annual capacity of 20 MW [KEEVE]. The manufacturing cost is close to 120 € / m².

CSG technology uses the relatively simple device structure shown in figure 19. It consists of a textured borosilicate glass superstrate, silicon nitride anti-reflection layer, a thin layer of poly-Si (~1.4 μm thick) with ‘grooves’ separating adjacent cells, a white reflective insulating resin layer patterned to produce n-type ‘crater’ and p-type ‘dimple’ contacts, and Al metallisation patterned to connect adjacent cells in series. Good light trapping is provided by the combination of textured glass and rear reflector. Adequate lateral conductance is provided by the heavily doped n⁺ and p⁺ poly-Si layers so there is no need for any TCO layers [KEEVE].

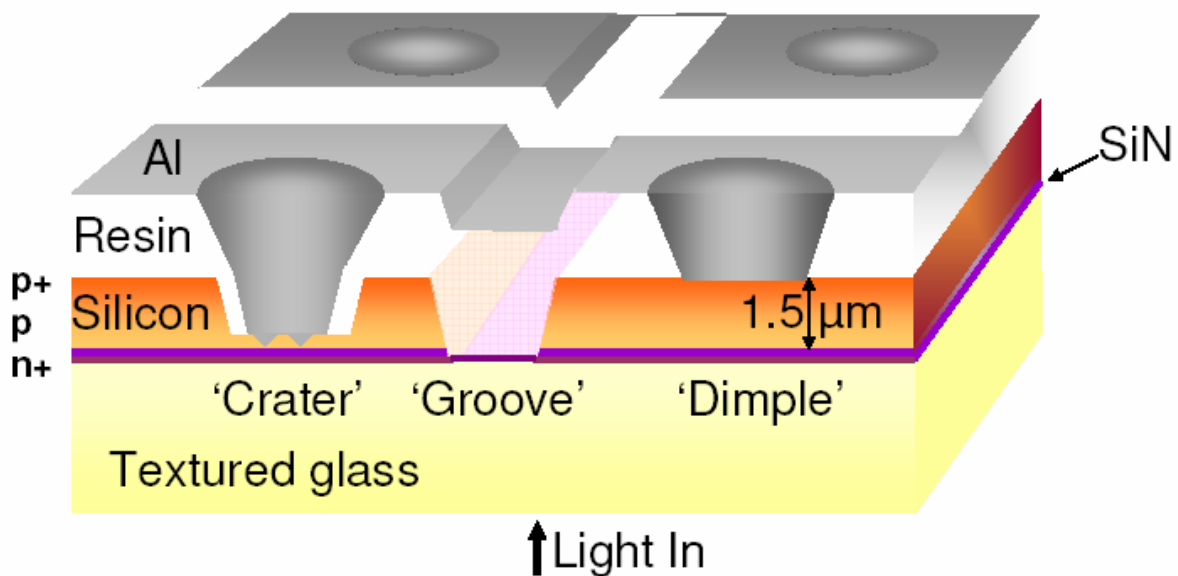
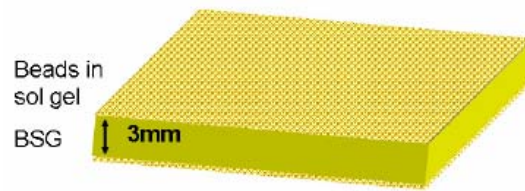
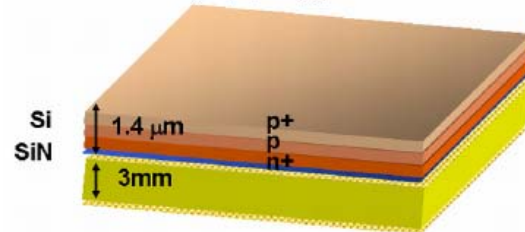


Figure 19: Schematic cross section of an CSG module.

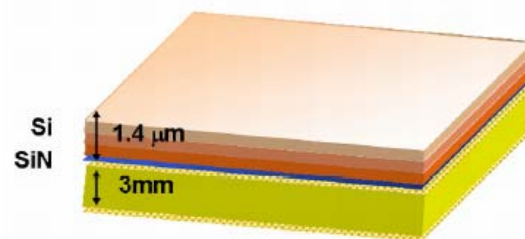
There is very limited data on reliability and durability of thin-film polysilicon modules because the technology is so new. The expectation is that, based on the fully crystalline nature of the active layer and the absence of a degradation prone TCO, very little degradation will occur. The scarce experimental data available, indeed, give very positive indications [BEAUC].



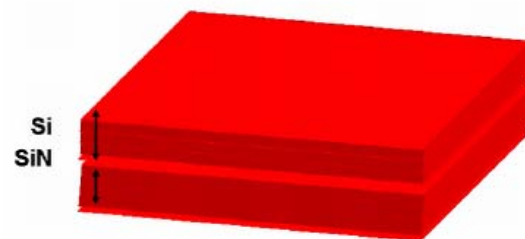
**Texture Coat Both Glass Surfaces
(Dipping)**



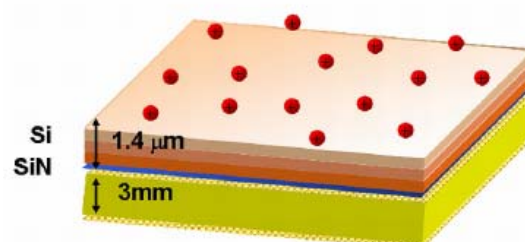
**Deposit Amorphous Silicon Film
(PECVD)**



Crystallise Si



Anneal Defects



Hydrogen Passivation

Figure 20: Process sequence for CSG [SCHN2].

Manufacturing of CSG solar cells

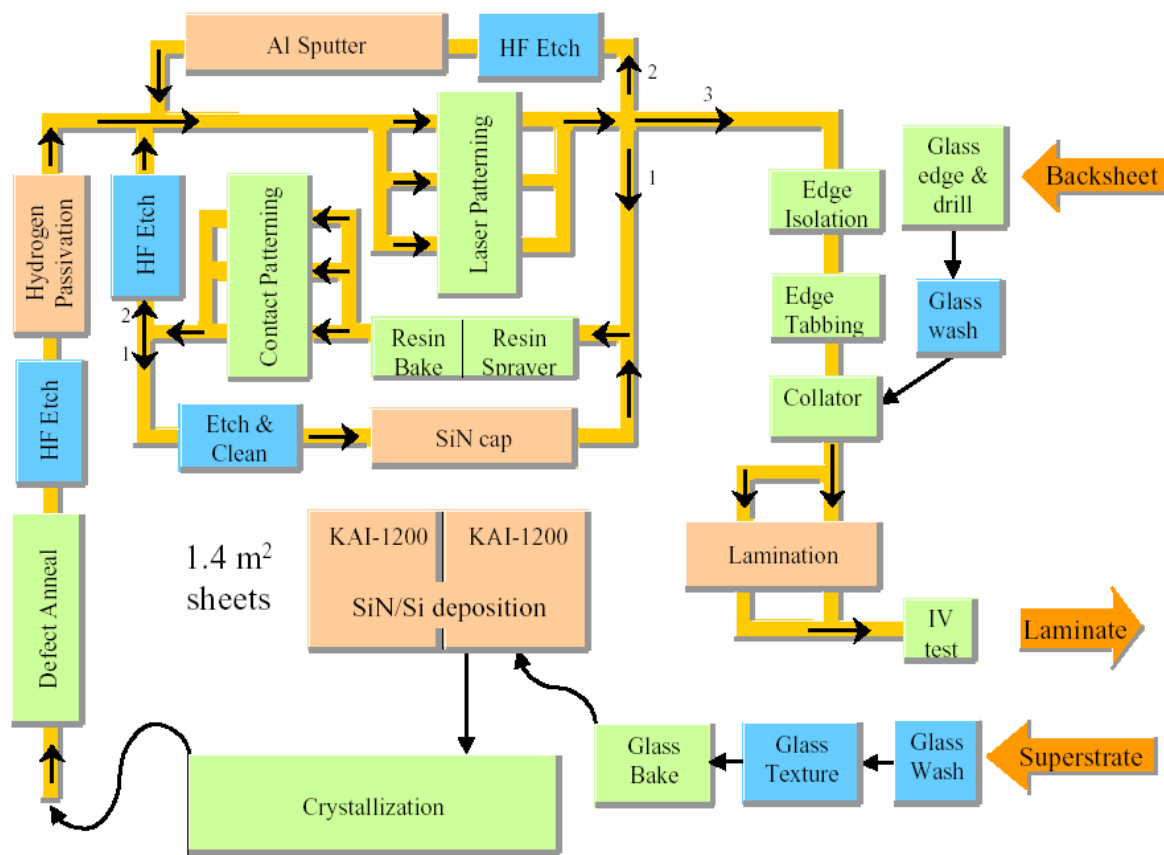


Figure 21: Factory flow of CSG modules in CSG Solar, Thalheim, Germany.

1) Glass preparation

The manufacturing sequence used to produce CSG modules involves many PV industry firsts, starting with the glass superstrate material, which is borosilicate glass (BSG). BSG differs from the soda-lime glass used in most PV modules primarily because it has a much lower thermal expansion coefficient. This makes it well suited for the high temperatures used in CSG manufacturing, and also makes the modules more durable. BSG plate glass is produced in limited quantities at present and represents about one-third of the total materials cost for a completed CSG module. Figure 22 shows the factory's glass washer. Because much of the glass as-delivered has a rubbery residue on the surface, a wash cycle with detergents is done. Because of this wash cycle, the glass surface is so clean that it can hold a substantial electric charge. A corona discharge bar is used at the exit of the glass washer to remove this charge [BASO1].



Figure 22: The Vitrododi glass washer.

An important issue to obtain high efficiency devices is light confinement because the layers are thin and the material is not an efficient light absorber. A major component of any light trapping scheme is to ensure oblique coupling of the light into the active layer. The traditional methods used for crystalline silicon, namely, etching in dedicated alkaline or acidic solutions to texture the surface, cannot be used because they are not adapted to polysilicon materials and consume too much Si. Texturing of the glass prior to active layer formation has been successfully applied in the CSG Solar plant by coating with an oxide film containing half-micron silica beads. [BEAUC]. These beads are suspended in a liquid bath and the glass is dipped vertically into the bath. The solution is mostly ethanol, hence the all-metal housing. The coating dries as the glass is withdrawn, but a subsequent belt bake is used to drive out any remaining water. The bead coating of pure silica is present on both surfaces and on the edges. This prevents the glass from sticking to its supports in subsequent high-temperature processing [BASO1].

2) Silicon preparation

The textured glass is coated with layers of amorphous silicon nitride (anti-reflection coating) and amorphous silicon in a PECVD deposition reactor. This system was developed for the flat-panel display industry. The use of this commercially available equipment makes it possible to process large area glass sheets ($1.10 \times 1.25 \text{ m}^2$) without incurring the very high cost and delay of developing specialized equipment for this purpose [BASO1].

Each of the two PECVD deposition machines processes 20 sheets of glass in a batch, with a cycle time of 120 minutes for one batch. Initially, these 20 sheets are loaded together into the input load lock. Half of the sheets are transferred as a group into one stack of ten deposition chambers. The other half are transferred as a group into a second stack of ten deposition chambers. This parallel processing improves throughput for a given investment in equipment. Nevertheless, this deposition system costs nearly as much as the rest of the factory's processing equipment combined. Thanks to years of experience in the flat-panel display industry, this equipment has proven to be reliable despite its complexity. The silicon as-

deposited is amorphous. Solid-phase crystallization is performed at 600°C in eight batch ovens. [BASO1]. The higher the temperature, the faster full crystallization will be reached, but the smaller the grains will be. If the temperature is too low, full crystallization is not reached within a reasonable time. The compromise temperature is 600°C [BEAUC].

Each oven holds a stack of 40 – 60 panels. Although crystallisation is a slow process, only a few ovens are needed because so many sheets can be loaded together. A typical load of 40 sheets requires an oven cycle of 20 hours, giving a throughput of 16 panels per hour [BASO2] [BASO1].

The crystallisation step produces a polycrystalline silicon material having an average grain size of about 1 μm . The silicon as-crystallized contains many crystallographic defects. These are annealed in a furnace shown in figure 23 by heating the glass briefly to over 900°C [BASO1].



Figure 23: Tecnofimes roller furnace

Like all polycrystalline Si materials, CSG requires hydrogen passivation to maximize performance. The amount of hydrogen required is much greater than for cast-ingot silicon. The equipment developed for this step was especially developed at CSG Solar. It accomplishes the required intense exposure to atomic hydrogen at temperatures above 600°C using an in-line process for high throughput [BASO1].

3) Device fabrication

Device fabrication utilizes a novel sequence that starts with a pulsed infrared laser to slice the silicon layer into a series of discrete adjacent cells. In CSG-1 this process is done on the same laser system used to pattern the metal interconnect layer, to be described subsequently. A white resin layer is then applied using the roller coater. The resin layer is patterned using the industrial ink-jet printer. The first pass through the ink-jet printer creates openings in the resin where contact is to be made to the n+ layer. To reach the buried n+ layer, a patented silicon

etch process is used to remove some of the silicon from within these openings, using the in-line tool shown in figure 24.



Figure 24: Schmid chemical etching.

The panel is then exposed to a solvent vapor that causes the resin to reflow just enough to protect the walls of the etched ‘craters’. A second pass through the ink-jet creates openings in the resin where contact is to be made to the surface p+ layer. Another etch is used to remove damaged silicon from the surface within these ‘dimple’ openings, then a thin layer of aluminum is sputtered onto the surface. The metal contacts the n+ and p+ layers at the contact openings, but is otherwise isolated from the silicon by the resin layer. The pulsed infrared laser is used to remove the metal in an intricate pattern that separates the n+ and p+ contacts within each cell while connecting all of the p+ contacts in one cell to the n+ contacts in the adjacent cell (figure 25). This step obtains high throughput despite the complexity of the pattern by using scanned pattern-projection optics while the panel is moving below. Bead blasting removes all layers from the perimeter of the module to ensure safe operation up to 1000 volts [BASO1].

4) Module assembly

Lead-free tabs are ultrasonically soldered along the two edges of the module and a polymer backsheet is laminated using the three-panel laminator. A junction box is attached and an aluminum frame fitted. The modules use only a single sheet of 3-mm glass, so they are quite lightweight for their size (13 kg for 1.4 m²), but it is necessary to include an extra aluminum cross-beam on the back of the module to provide sufficient strength against wind loads. For installations where heavy snow loads are expected (5.4 kPa), two such cross-beams are used. A flash test gives the illuminated I-V curve at four light intensities and allows each panel to be classified into performance bins with 5-watt increments. The completed modules from a given performance bin are then packaged for delivery to customers [BASO1].

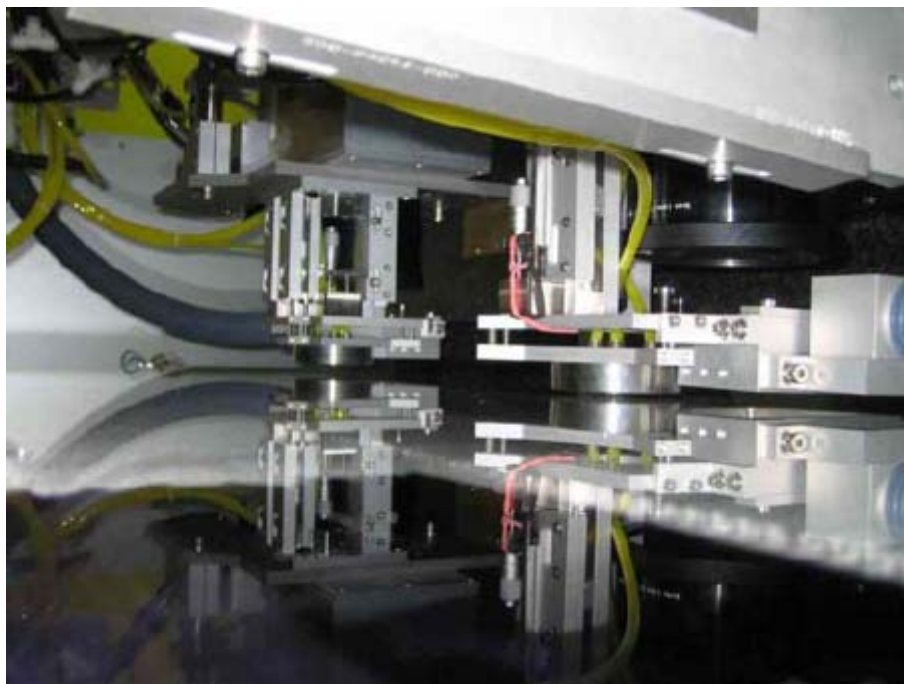


Figure 25: Exitech four-head scanning laser

Long term stability

Wafer-based silicon modules generally degrade by 1–3 % relative in output during the first few hours of light exposure and then more gradually, about 0.3–0.6 % per year relative over their operating life [GREE2]. Different mechanisms may be responsible for these effects in different modules, but possible causes are the degradation of the cell, its coatings, solder joints or interconnects, or degradation of the ethylene vinylacetate (EVA) encapsulant including its delamination or even degradation of the glass cover. As opposed to this well-documented experience, no comparable degradation has been observed in CSG modules subject to outdoor exposure. There are good reasons to expect this result, since none of the degradation modes mentioned above might be expected. The boron–oxygen defects likely to cause cell degradation on light exposure are present in insignificant numbers, the cell coating is high quality silicon nitride, there is no EVA in the light path between the cell and sun, and a higher quality glass cover is used. Because the CSG technology is new, only a few years of outdoor testing has been done, so it still has to prove its durability in the long term.

The evidence for stability is however reinforced by the fact that no degradation is observed in CSG modules after exposure to the equivalent of 25 years of UV radiation, while conventional wafer-based modules degrade by at least 5–10% after such exposure. Even more impressive has been the performance under accelerated temperature-cycle, humidity-freeze and damp heat testing. In durability tests based on the IEC61646 standard qualification test for thin-film modules [GREE2], the CSG modules performs better than two commercial CIGS modules and two commercial standard crystalline silicon wafer-based modules.

Thin film solar cells based on amorphous silicon

Single junction amorphous silicon solar cell

Amorphous Si is usually deposited using the plasma-enhanced chemical vapour deposition (PECVD) technique, and the gas silane (SiH_4) is mostly used as precursor. As a result of decomposition, surface adsorption and surface reactions, a network of Si atoms is formed on the substrate, mostly glass or a metal foil. The deposition temperature ranges typically between 180 °C and 280 °C. As a result of the deposition mechanism, amorphous silicon contains a large concentration of hydrogen atoms (10%). Hydrogen is, in fact, crucial for the material's electronic properties, while unhydrogenated amorphous Si is of no use for devices. Therefore, the material one usually refers to using the words “amorphous silicon” is in fact hydrogenated amorphous silicon (a-Si:H). The absorption coefficient in a-Si is much higher than that in crystalline Si, and, therefore, a much lower thickness is required to achieve the same absorption. However, the bandgap is also larger, 1.7 to 1.9 eV. Therefore, a large part of the infrared light cannot be absorbed in amorphous Si. Alloys can be deposited by adding germanium (to form a-SiGe:H) or carbon (to form a-SiC:H) precursors to the gas flow, so that the bandgap can be tuned to some extent [BEAUC].

The first amorphous Si solar cell was made in 1976 [CARLS]. Although the efficiency at the time was below 3%, it generated enormous interest and started a large research effort worldwide. Fast progress was reached in the end of the seventies and the beginning of the eighties, and, for some time, it looked like the days of crystalline Si would soon be over and that amorphous Si was going to conquer the whole PV scene. However, an important problem with amorphous Si was also identified. The new material turned out to suffer from degradation upon exposure to sunlight. This phenomenon, called the Staebler-Wronski effect, causes a large increase in defect density and thus a decrease in efficiency [BEAUC].

The optimal thickness of the silicon layer is around 300 nm. This low thickness is a clear advantage for manufacturing, as one of the most significant costs in amorphous silicon modules is the deposition cost. The drawback is that efficiencies are usually quite low and difficult to increase. It also explains why light trapping is an important topic in amorphous Si solar cell research, even though the material features high absorption coefficients [BEAUC].

Most types of amorphous silicon solar cells are in superstrate configuration, which means that the light enters the solar cell through the supporting substrate. This configuration requires a highly transparent substrate material and the presence of a transparent conductive oxide between the substrate and the active layer. These cells are also called “p-i-n” solar cells, referring to the sequence in which the different layers are deposited. The other option is to make a-Si:H cells in substrate configuration (“n-i-p” solar cells), which enables the use of a wider range of substrate materials. After deposition of the different layers, the cells have to be isolated and interconnected with each other. Typically this is done using a combination of laser scribing and blanket deposition (transparent conductive oxide, the amorphous Si layers, and metal - combined or not with TCO - for the rear contact) in a monolithic module concept (figure 3) [BEAUC].

Over the years, many companies have been created to produce single junction a-Si:H modules. Generally, the modules are based on the monolithic concept shown (figure 3), and have an efficiency ranging from 5 to 7 %. Although many of these companies stopped, a number of them have survived and grown over the years. One of the problems encountered

when producing amorphous silicon modules is the lack of reliable deposition equipment, with good uniformity, high up-time, and not requiring only moderate maintenance. This is because the deposition systems used are often specifically developed, sometime in-house, and have been produced only in small volumes. This situation has recently completely changed. Large companies that were so far involved in equipment manufacturing for LCD displays have entered the photovoltaic business. Their PECVD systems for amorphous Si deposition for displays are excellent platforms to develop equipment for amorphous silicon solar modules. Indeed, most of the issues concerning uniformity, cleaning, reliability, and so forth have already been solved, and they can concentrate on reaching the required material quality and production speed for solar cells. These companies are Unaxis (now Oerlikon Solar) and Applied Materials. They have hired experts in amorphous and microcrystalline deposition for solar cells, and are working to offer complete processes to the clients purchasing their systems. They are presently rapidly introducing their deposition systems into the photovoltaic market, or even complete production lines revolving around the deposition systems. In the last years, there have been many announcements of new large scale production lines based on such systems (e.g., Brilliant 234, Ersol thin-film, and Moser Baer), which should come on-line within two years. Although all new players have plans to move to multijunction solar cells at some point, they start with single junction amorphous modules, for which it is easier to reach the short-term cost targets. However, it is generally recognized that this technology can only be an intermediate step towards a technology with higher-efficiency potential [BEAUC].

The temperature coefficient of amorphous silicon solar cells is lower (in absolute value) than that of a crystalline Si. As a result, the modules do not lose so much in performance (relatively) when heated up. Moreover, amorphous Si modules have a good sensitivity to blue light, which is more present in diffuse illumination. Finally, the module efficiency under very low illumination is quite well maintained in contrast to standard crystalline Si modules, for which the performance collapses. As a result, the relative performance of single junction amorphous Si modules, expressed in kWh/kWp per year, which takes into account all the different conditions under which a PV module has to operate in a year, tends to be rather good for a-Si modules, better than that of conventional crystalline Si modules. The long-term stability of amorphous Si modules is not necessarily granted. The producers have to pay special attention to the design of the modules, particularly to the type of transparent conductive oxide and to the encapsulation selected [BEAUC].

Multijunction amorphous silicon solar cells

Because of the possibility of bandgap tuning (see above) and because of the too low efficiency of a single junction, amorphous silicon cells are often fabricated in a multijunction structure. Multijunction thin-film silicon solar cells consist in stacking two (tandem) or even three (triple) junction structures on top of each other, the different subcells being connected in series. This concept has the potential to increase device performance well beyond that of single junction devices, particularly when the materials are selected so as to better exploit the solar spectrum. Indeed, if a high bandgap material is used for the top cell, less thermalization losses will occur as a result of absorption of high energy photons. The longer wavelength photons, which are not absorbed in the top cell, get absorbed in the bottom cell which consists of a lower bandgap material. The fraction of unused photons from the spectrum is lower for tandem cells as the cut-off wavelength is given by the optical bandgap of the lowest bandgap material.

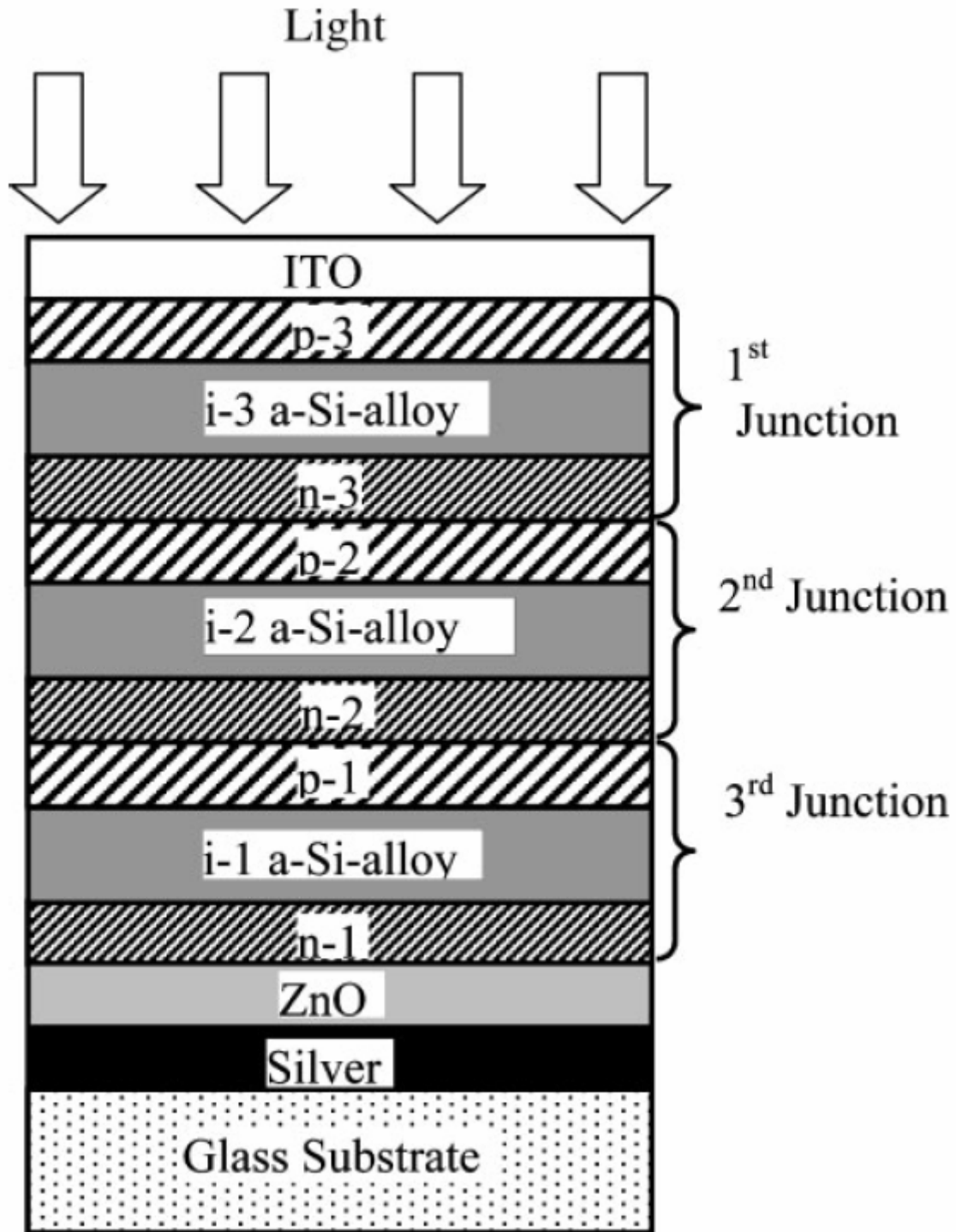


Figure 26: Typical structure for an a-Si triple-junction device. The silver layer is used as metal reflector. The ITO and ZnO layer are respectively the front and back contact. The i-1, i-2 and i-3 a-Si alloys can e.g. be respectively $\mu\text{c-Si:H}$, a-SiGe:H and a-Si:H (i.e. from lowest to highest bandgap).

In figure 26, a triple junction solar cell in substrate configuration is depicted with an amorphous Si top cell, an amorphous SiGe middle cell, and a microcrystalline Si bottom cell. Because the p-layer always has to be on the side where light enters the cell, the subcells are all of the nip type. There is a large freedom concerning the substrate because it needs neither to

be transparent nor to act as a front cover. A popular choice is a stainless steel foil, which is inexpensive and flexible, and which withstands, relatively, high temperatures. A drawback is that it is conductive and is, therefore, ill-suited for a monolithic module concept. The substrate is usually covered by a metal layer with high reflection, such as a silver layer. The United Solar Company (UniSolar), one of the major thin-film solar cells companies, is well known for its triple junction cells. Until recently, the middle and bottom cells were based on a-SiGe:H with two different Ge concentrations, but they have introduced new structures like the one in figure 26, and even with microcrystalline Si in both the middle and bottom cells [BEAUC]. For a list of a-Si manufacturers and their production capacity, we refer to table 1.

Long term stability

The degradation of single junction a-Si:H devices are $\sim 25\%$ and the degradation of multijunction devices is between 12%-18%. Figure 27 shows the degradation of a triple junction device from Uni-Solar which stabilizes at 88% of its initial efficiency [ARYA]. Amorphous silicon panels have functioned well in outdoor testing and applications. Long-term outdoor reliability is a function of the “back-end” processes, such as, tabbing, lamination, wiring and junction termination. These “back-end processes” are different for the two technology configurations. In the superstrate configuration, generally, the solar cells are interconnected to form the module by monolithic laser or mechanical scribing during various stages of the solar panel production. The solar panel is then laminated with EVA (Ethyl Vinyl Acetate) or a similar material and another piece of glass or TAP (Tedlar Aluminum Polymer). In the substrate configuration, the solar cells slabs are tabbed and laminated with EVA and Tefzel or glass. In both configurations, junction boxes and frames can be added [ARYA].

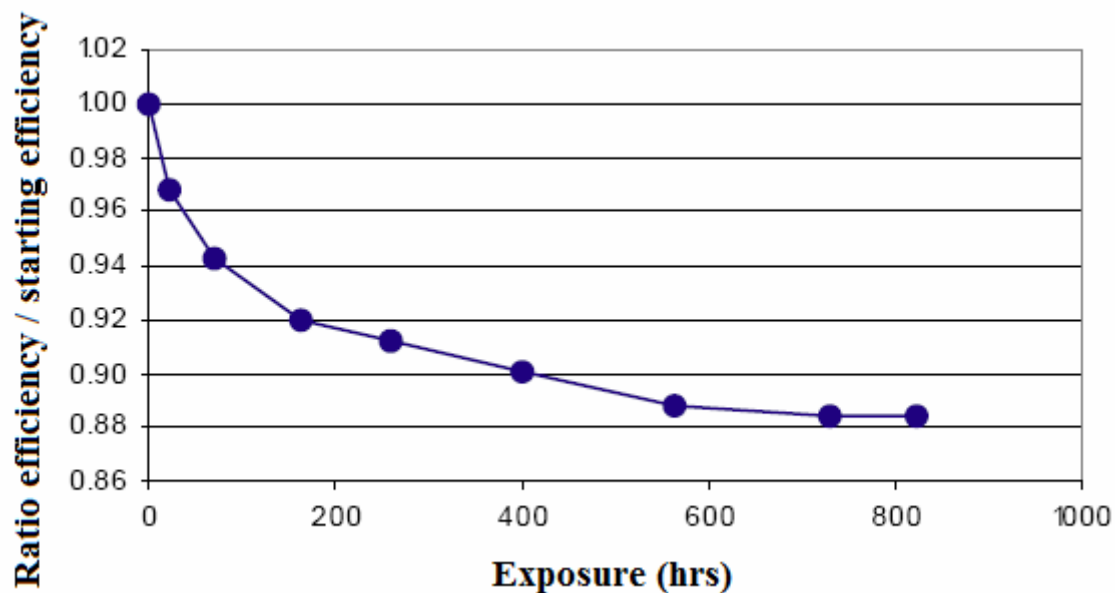


Figure 27: Long-term light soaking of a Uni-Solar triple junction module under one sun illumination at 50 °C.

The outdoor reliability of modules is largely a function of the efficacy of the encapsulation and the packaging system in keeping moisture out of the active solar cells. Moisture ingress, contact reliability under thermal cycling and humidity-freeze cycling are the main

modes of failure. Many organizations have developed packaging schemes that pass the testing requirements for 20 year outdoor applications [ARYA].



Fig. 28: a-Si solar cells from Kaneka

A selected overview of commercially available thin-film modules

Table 5 finally gives the characteristics of some commercially available thin-film modules.

Cell type	Manufacturer	Website	Module	Length (mm)	Width (mm)	Thickness (mm)	Weight (kg)	Efficiency (%) (*)	Power (W)	Tolerance (%)	Vmp (V)	Imp (A)	Voc (V)	Isc (A)	80%-output warranty (years)
CSG	CSG Solar AG	www.csgsolar.com	CSG-80	1253	1103	41	14.5	5.8	80		59	1.4	83	1.6	25
CdTe	Antec Solar	www.antec-solar.de	ATF-43	1200	600	20	16	6.0	43	10	53	0.81	81	1.07	20
CdTe	Antec Solar	www.antec-solar.de	ATF-50	1200	600	20	16	6.9	50	10	56	0.89	85	1.11	20
CdTe	First Solar	www.firstsolar.com	FS CTS-265	1200	600	6.8	12	9.0	65	5	63.7	1.02	87	1.17	25
CdTe	First Solar	www.firstsolar.com	FS CTS-267	1200	600	6.8	12	9.4	67.5	5	64.6	1.05	87	1.18	25
CdTe	First Solar	www.firstsolar.com	FS CTS-270	1200	600	6.8	12	9.7	70	5	67.1	1.04	89	1.19	25
CdTe	First Solar	www.firstsolar.com	FS CTS-272	1200	600	6.8	12	10.1	72.5	5	67.9	1.07	90	1.19	25
CdTe	First Solar	www.firstsolar.com	FS CTS-275	1200	600	6.8	12	10.4	75	5	69	1.08			25
ClGS	Würth Solar	www.wuerth-solar.de	WSK0001	305	205	31	1.3	8.8	5.5	10	16.5	0.33	22	0.35	20
ClGS	Würth Solar	www.wuerth-solar.de	WSK0039	405	305	31	2.4	9.7	12	10	16.5	0.73	22	0.78	20
ClGS	Würth Solar	www.wuerth-solar.de	WSK0019	605	405	31	4.5	9.4	23	10	16.5	1.4	22	1.5	20
ClGS	Würth Solar	www.wuerth-solar.de	WSK0020	605	605	31	6.5	9.6	35	10	16.5	2.12	22	2.29	20
ClGS	Würth Solar	www.wuerth-solar.de	WSK0021	905	605	35	9.7	10.0	55	10	16.5	3.33	22	3.56	20
ClGS	Würth Solar	www.wuerth-solar.de	WSG0039 E075	1205	605	35	12.7	10.3	75	10	35	2.15	44.5	2.36	20
ClGS	Würth Solar	www.wuerth-solar.de	WSG0035 E075	1205	605	35	12.7	10.3	75	10	16.5	4.42	22	5.01	20
ClGS	Würth Solar	www.wuerth-solar.de	WSG0025 E080	1205	605	35	12.7	11.0	80	10	120	0.67	160	0.72	20
ClGS	Global Solar	www.globalsolar.com	PN 33005-O	454	228.5	21	1.3	5.8	6	15	15.8	0.38	23	0.45	10
ClGS	Global Solar	www.globalsolar.com	PN 33010-O	454	416	21	2	6.4	12	15	15.8	0.76	23	0.9	10
ClGS	Global Solar	www.globalsolar.com	PN 33030-O	635	620	34.5	5	7.6	30	15	17.5	1.7	25	2.2	25
ClGS	Global Solar	www.globalsolar.com	PN 33060-O	1180	635	34.5	9	8.0	60	15	17.5	3.5	25	4.5	25
ClGS	Sulfurcell	www.sulfurcell.de	SCG50-HV-F	1258	658	30	14.6	6.0	50	5	37.5	1.35	50	1.65	20
ClGS	Sulfurcell	www.sulfurcell.de	SCG55-HV-F	1258	658	30	14.6	6.6	55	5	39.2	1.4	51	1.7	20
ClGS	Sulfurcell	www.sulfurcell.de	SCG60-HF-F	1258	658	30	14.6	7.2	60	5	41	1.48	52.5	1.7	20
a-Si	TopraySolar	www.topraysolar.com	Dual-junction	1253	643	38	14.7	5.0	40	5	46	0.87	61	1	20
a-Si	Mitsubishi	www.mhi.co.jp	MA100T2 single junction	1414	1114	35	21	6.3	100		108	0.93	141	1.17	20
a-Si	Kaneka	www.pv.kaneka.co.jp	G-EA060	990	960	40	13.7	6.3	60		67	0.9	91.8	1.19	25
a-Si	Kaneka	www.pv.kaneka.co.jp	T-EC120	1919	990	46	27.5	6.3	120		67	1.8	91.8	2.38	25
a-Si	Uni-Solar	www.uni-solar.com	PVL-68 -triple junction	2849	394	16	3.9	6.1	68	5	16.5	4.1	23.1	5.1	20
a-Si	Uni-Solar	www.uni-solar.com	PVL-124 -triple junction	5007	394	16	7	6.3	124	5	30	4.1	42	5.1	20
a-Si	Uni-Solar	www.uni-solar.com	PVL-136 -triple junction	5486	394	16	7.7	6.3	136	5	33	4.1	46.2	5.1	20

Table 5: A selected overview of commercially available thin-film modules. (*) The area of the whole module was taken into account for the calculation of the efficiency.

References

- [ABERL] “Progress with Polycrystalline Silicon Thin-Film Solar Cells on Glass at UNSW”, A.G. Aberle, *Journal of Crystal Growth* 287, 2006, 386-390.
- [ALSEM] “Environmental Impacts of PV Electricity Generation – a Critical Comparison of Energy Supply Options”, E.A. Alsema, M.J. de Wild-Scholten, V.M.Fthenakis, 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, 4-8 September 2006.
- [ARYA] “Technology and Market Challenges to Mainstream Thin-Film Photovoltaic Modules and Applications”, R.R. Arya, Conference NREL 2004.
- [AVAN1] “Why Thin Film Technology for Photovoltaics?”, AVANCIS GmbH & Co. KG (www.avancis.de).
- [AVAN2] “Why is CIS the Best Thin Film Photovoltaic Technology?”, AVANCIS GmbH & Co. KG (www.avancis.de).
- [BASO1] “CSG-1: Manufacturing a New Polycrystalline Silicon PV Technology”, P.A. Basore, 4th World Conference on Photovoltaic Energy Conversion, Waikoloa, Hawaii, 9 May 2006.
- [BASO2] “CSG-2: Expanding the Production of a New Polycrystalline Silicon PV Technology”, P.A. Basore, 21st European Photovoltaics Solar Energy Conference, Dresden, Germany, 4-8 Sept. 2006.
- [BASO3] “Pilot Production of Thin-Film Crystalline Silicon on Glass Module, P.A. Basore, Conf. Record, 29th IEEE Photovoltaic Specialists Conference, New Orleans, May 2002, 49-52.
- [BOHLA] “First Solar’s CdTe module Manufacturing Experience; Environmental, Health and Safety Results”, J. Bohland, K. Smigielski, Proc. 28th IEEE Photovoltaic Specialists Conference, Anchorage, AL, September 2000, 575-578.
- [BONN1] “Manufacturing of CdTe Solar Cells, D. Bonnet, M. Harr, Proc. 2nd World Conference on Photovoltaic Energy Conversion, Vienna, Austria, July 1998, 397-402.
- [BONN2] “Cadmium Telluride Solar Cells”, D. Bonnet, *Clean Electricity from Photovoltaics*, (ed. M. Archer, R. Hill), Imperial College Press, London, 2001.
- [BURGE] Thin Film Solar Cells: Fabrication, Characterization and Applications, (ed. J. Poortmans, V. Arkhipov), “Chapter 7: Cadmium Telluride Thin Film Solar Cells: Characterization, Fabrication and Modeling”, M. Burgelman, (John Wiley, Chichester, England) 277-314.
- [CARLS] “Amorphous silicon solar cell”, D.E. Carlson, C.R. Wronski, *Applied Physics Letters*, vol. 28, no 11, 1976, 671-673,.

- [CUNNI] “Large area Apollo Module Performance and Reliability” ,D. Cnningham, K. Davies, L. Grammond, E. Mopas, N. O’Connor, M. Rubcich, M. Sadeghi, D. Skinner, T. Trymbly, Conf. Record, 28th IEEE Photovoltaic Specialists Conference, Alaska, September 2000, 13-18.
- [FIRST] Prospectus of “First Solar Inc.”, form 424B4, 13 August 2007, p. 17.
- [FTHEN] “CdTe PV: Real and Perceived EHS Risks”, V. Fthenakis, K. Zweibel, Proc. Of the Nat. Center for Photovoltaics and Solar Program Review Meeting, Denver, Colorado, 24-26 March 2003.
- [GREE1] “Solar Cell Efficiency Tables (Version 31)”, M.A. Green, K. Emery, Y. Hishikawa, W. Warta, Prog. Photovoltaics: Res. Appl.16, 2008, 61-67.
- [GREE2] “Crystalline Silicon on Glass (CSG) Thin-Film Solar Cell Modules”, M.A. Green, P.A. Basore, N. Chang, D. Clugston, R. Egan, R. Evans, D. Hogg, S. Jarnason, M. Keevers, P. Lasswell, J.O’Sullivan, U. Schubert, A. Turner, S.R. Wenham, T. Young, Solar Energy 77, 2004, 857–863.
- [KEEVE] “10 % Efficient CSG Minimodules”, M.J. Keevers, T.L. Young, U. Schubert, M.A. Green, 22nd European Photovoltaic Solar Energy Conference (PVSEC), Milan, Italy, 3-7 Sept. 2007.
- [KING] “World’s First 15 % Efficiency Multicrystalline Silicon Modules”, D.L. King, W.K. Schubert, T.D. Hund, Conf. Record, 1st World Conference on Photovoltaic Energy Conversion, Hawaii, December 1994, 1660-1662.
- [KLENK] Thin Film Solar Cells: Fabrication, Characterization and Applications, (ed. J. Poortmans, V. Arkhipov), “Chapter 6: Chalcopyrite Based Solar Cells”, R. Klenk, M.C. Lux-Steiner, (John Wiley, Chichester, England) 237-275.
- [MEIER] “Potential of Amorphous and Microcrystalline Silicon Solar Cells”, J. Meier, J. Sitznagel, U. Kroll, C. Bucher, S. Fay, T. Moriarty, A. Shah, Thin Solid Films 451-452, 2004, 518-524.
- [MILES] “Photovoltaic Solar Cells: An Overview of State-of-the-art Cell Development and Environmental Issues”, R.W. Miles, K.M. Hynes, I. Forbes, Progress in Crystal Growth and Characterization of Materials, 51, 2005, 1-42.
- [MOSKO] “Toxic Materials Released from Photovoltaic Modules during Fires; Health Risks”, P. Moskowitz, V. Fthenakis, Solar Cells, 29, 1990, 63-71.
- [POORT] Thin Film Solar Cells: Fabrication, Characterization and Applications, (ed. J. Poortmans, V. Arkhipov), “Preface” (John Wiley, Chichester, England).
- [POWAL] “Thin-Film Solar Cells Based on the Polycrystalline Compound Semiconductors CIS and CdTe”, M. Powalla, D. Bonnet, Adv. In OptoElectronics, Vol. 2007, 97545.

- [SCHN1] “Industrial Solid Phase Crystallisation of Silicon”, J. Schneider, R. Evans, 21st European Photovoltaics Solar Energy Conference, Dresden, Germany, 4-8 Sept. 2006.
- [SCHN2] “Crystallisation Analysis of Thin Silicon’-Project (CATS)”, J. Schneider, S. Christiansen, C. Genzel, , 22nd European Photovoltaic Solar Energy Conference (PVSEC), Milan, Italy, 3-7 Sept. 2007.
- [SCHUL] “Multicrystalline Silicon Solar Cells exceeding 20 % Efficiency”, O. Schultz, S.W. Glunz, G.P. Willeke, Progress in Photovoltaics: Research and Applications 12, 2004, 553-558.
- [STEIN] “Health, Safety and Environmental Risks from the Operation of CdTe and CIS Thin-Film Modules”, H. Steinberger, Prog. Photovolt. Res. Appl. 6, 1998, 99-103.
- [TANAK] “Improvement of V_{oc} upward of 600 mV/cell with CIGS-based Absorber prepared by Selenization/Sulfurization”, Y. Tanaka, . Akema, T. Morishita, D. Okumura, K. Kushiya, Conf. Proceedings, 17th EC Photovoltaic Solar Energy Conference, Munich, October 2001, 989-994.
- [ULLAL] “Thin-Film CIGS and CdTe Photovoltaic Technologies: Cemmercialization, Critical Issues, and Applications”, H.S. Ullal, B. von Roedern, 22nd European Photovoltaic Solar Energy Conference (PVSEC), Milan, Italy, 3-7 Sept. 2007.
- [WENTI] “Regelgeving ten aanzien van cadmium in zonnepanelen. Interpretatie en consequenties van Nederlandse en Europese regelgeving voor toepassing van cadmium in zonnepanelen en gebruik van zulke zonnepanelen”, C.H.M. Wentink, J.A.M. van Roosmalen, C.J.J. Tool, M.J. de Wild – Scholten, M.C.C. Lafleur, Energy research Centre of the Netherlands (ECN), July 2001.
- [WU] “16.5 %-efficient CdS/CdTe Polycrystalline Thin-Film Solar Cell”, X. Wu, J.C. Keane, R.G. Dhere, C. DeHart, A. Duda, T.A. Gessert, S. Asher, D.H. Levi, P. Sheldon, Conf. Proceedings 17th European Photovoltaic Solar Energy Conference, Munich, 22-26 October 2001, 995-1000.
- [YANG] “Progress in Triple-Junction Amorphous Silicon-based Alloy Solar Cells and Modules using Hydrogen Dilution, J. Yang, A. Banerjee, T. Glatfelter, K. Hoffman, X. Xu, S. Guha, Conf. Record, 1st World Conference on Photovoltaic Energy Conversion, Hawaii, December 1994, 380-385.
- [ZHAO1] “19.8 % Efficient Honeycomb Textured Multicrystalline and 24.4 % Monocrystalline Silicon Solar Cells”, J. Zhao, A. Wang, M.A. Green, F.N. Ferrazza, Applied Physics Letters 73, 1998, 1991-1993.
- [ZHAO2] “20 000 PERL Silicon Cells for the 1996 World Solar Challenge Solar Car Race”, J. Zhao, A. Wang, F. Yun, G. Zhang, D.M. Roche, S.R. Wenham, M.A. Green, Progress in Photovoltaics 5, 1997, 269-276.