

Cost-efficient equipment for CIGS production

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ABSTRACT

Even in the competitive and turbulent present-day PV market, thin-film PV modules based on copper indium gallium selenide (CIGS) have good prospects for capturing a growing market share. Three important factors support the survival and growth of CIGS technology on the market: 1) proven lab results demonstrate considerable room for improvement of conversion efficiency; 2) the potential for cost reduction is high (reduced equipment CAPEX as well as reduced material and BOS costs); and 3) a high degree of freedom in the choice of substrate material and shape enables efficient application of the technology. These factors should be realized using more-generic or standardized CIGS production equipment to reach economy of scale. Examples of novel and improved strategies for cost-efficient thin-film deposition and absorber formation are presented in this paper. Within the framework of a new thin-film PV research alliance under the name Solliance, a CIGS demonstrator line has recently become available for accelerating R&D of cost-effective processes and equipment, and for demonstrating their capabilities in improving CIGS in terms of product performance and lifetime.

A new platform for CIGS equipment development

In 2010 and 2011 around 5% of the value creation of the total worldwide PV equipment market was realized by Dutch companies – not only by Netherlands-based OEMs, but also, for a substantial part in the form of custom-built systems and subassemblies, by Dutch industrial contractors along the equipment supply chain. In order to fully exploit the potential for thin-film PV production, a research alliance was founded in 2011 under the name Solliance, located in Eindhoven, and with financial support from the Dutch province of Noord Brabant. Although Solliance was founded as a collaboration between Dutch research partners ECN, TNO, the Holst Centre and Eindhoven University of Technology, the concept from the start was to create a regional cluster in Europe. So far, imec (Belgium) and Forschungszentrum Jülich (Germany) have joined the alliance, and further partnerships are under negotiation. An open research centre has been created in Eindhoven, where new equipment investments of Solliance are integrated with facilities that have been brought together by research partners and participating industrial stakeholders to form three thin-film research lines.

“To fully exploit the potential for thin-film PV production, a research alliance was founded in 2011 under the name Solliance.”

In December 2012 a reference demonstrator line for copper indium gallium selenide (CIGS) research was opened, and demonstrator lines for organic photovoltaic (OPV) technology and thin-film Si are currently under construction. Bridging the gap between fundamental research and industrial application is thus promoted by bringing together infrastructure and co-workers from research institutes, industry and universities. Further synergy is encouraged by centring these activities on the High Tech Campus (the former Philips Research campus) in Eindhoven, where over 100 companies and more than 8000 researchers are located, and where additional facilities for high-end equipment, thin-film processing and characterization are shared. The site is one of the three cornerstones of the Eindhoven-Leuven-Aachen triangle (ELAT region), and the Solliance partners are thus located on all three corners of this triangle. The mission of Solliance is to provide industrial equipment and process solutions for thin-film PV, to develop new cell concepts and to create smart integration concepts with optimized lifetimes.

Challenges in CIGS production

Thin-film solar modules based on CIGS are extremely promising. It is the only type of large-area produced thin-film PV that rivals the presently dominant wafer-based (multi)crystalline silicon modules in terms of efficiency. CIGS is therefore economically feasible for residential applications where limited roof area is available. In addition, as CIGS can be directly produced on a wide variety of substrate materials, including building

construction materials such as glass and steel, it has the potential to significantly reduce area-related balance of system (BOS) costs. Further, it shares the possibilities of other thin-film technologies (CdTe, OPV, a-Si) of achieving competitive production costs and potential for very high volume production, for example roll-to-roll (R2R) production on flexible substrates. And, finally, it is aesthetically attractive, as it can be produced with a wide range of forms and patterns, in combination with a homogeneous black appearance or an added colour. No other thin-film PV technology has been demonstrated in such a variety of forms and carrier materials as CIGS.

Although the full scope of this promise has yet to be proved by successful and economically sustainable production on a sufficiently large scale, CIGS modules produced by a number of manufacturers have already been on the market for a number of years. Most CIGS modules are currently produced on flat glass or brought to market with glass encapsulation. In 2010 a total CIGS volume of well over 200MW_p was produced by a number of companies with production capacities of the order of tens of megawatts. In 2012 Solar Frontier in Japan ramped up their CIGS production on a scale of many hundreds of megawatts, aiming at 1GW, and recently reported a profit-making financial quarter in the midst of PV overproduction turbulence. This shows that CIGS on rigid glass is in the running for utility- and rooftop-scale PV. At the same time, several companies have chosen to utilize the feasibility of CIGS on alternative and flexible substrates in order to address the market for integrated consumer devices and

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automotive applications. Flexible products without glass encapsulation have also been certified and introduced to the market.

Challenges and goals

Although the same general layer build-up is used by most CIGS producers, a wide variety of compositions (Ga,S and Se content, but also additives such as Na), composition gradients, morphologies and interlayers are employed. CIGS is a material with a very complicated phase diagram, and as a consequence the resulting properties are very dependent on the processing route that is followed to achieve a certain composition. Many recipes exist for the growth of these layers and which employ a wide variety of deposition methods. In the last decade between 40 and 80 industrial initiatives on CIGS production have been known, and almost every one of them employs a proprietary process, often requiring very specific, nonstandard equipment. Moreover, the work field of CIGS is currently hampered by a technology diversification, which hinders the achievement of a sufficient economy of scale.

This situation leads to the following challenges and roadmap goals:

- To reduce cost by choosing low-cost and rugged (controlled uniformity) high-yield processing routes, and by developing more-generic equipment solutions for these routes to obtain a better economy of scale.
- To improve quality by reducing the gap between laboratory efficiency records (20.3–20.4%) and those obtained in industrial practice (12–14%), while pushing the records further (23%) and improving lifetime.
- To improve fundamental understanding of material formation and properties, and most notably the role of interfaces

(grain and layer boundaries), which are less dependent on specific recipes and type of process.

- To identify important process and material parameters and to improve their control (e.g. explore the behaviour and control of impurities to achieve cost reduction by reducing purity-level requirements of source materials).

“The goal of the Solliance programme is low-cost mass production using improved material and process control.”

The goal of the Solliance programme is therefore low-cost mass production using improved material and process control, finally aiming at R2R production on flexible substrates. Innovations in R2R printing and curing, web handling and registration are accessible through collaborations with the OPV programme of Solliance. For the absorber layer, the focus of the Solliance CIGS programme is atmospheric, sequential CIGS formation – in other words the deposition of a CIG precursor layer, which is selenized and crystallized in a subsequent annealing step. A lot of emphasis is being placed on

- material and process development for the transparent conductor (TCO) and additional layer modifications for improved light management;
- replacement of the CdS layer by Cd-free and tuneable alternatives;
- barrier layers at the interface between device and substrate to enable more freedom of choice for (low-cost) substrates;

- flexible encapsulation for a longer lifetime.

As all these process steps are interdependent, it is necessary to develop individual process steps within the context of a complete demonstrator cell or module. Therefore, based on commonly known individual process steps, a research-scale line for the realization of reference CIGS demonstrators has been brought into operation. This reference line will be used for research and demonstration of innovations in individual alternative process steps.

To support these goals for material, process and equipment development, a substantial amount of work in the areas of cost of ownership modelling and accelerated lifetime testing is being undertaken.

Reference line using co-evaporation

As a reference for device, process and equipment innovations, a line of equipment has been built for the fabrication of complete CIGS demonstrator modules of dimensions up to $30 \times 30\text{cm}^2$. Glass substrates as well as framed sheets of foil can be handled. The standard process sequence is based on soda-lime glass substrates. After magnetron sputtering of molybdenum, a CIGS absorber layer is deposited by co-evaporation using a custom-designed system from 44Solar. A CdS buffer layer is added by chemical bath deposition with a Tenuis system from Singulus Stangl. Sputtering of an intrinsic ZnO film and an Al-doped ZnO transparent conductor complete the layer stack. Test samples are divided into individual test cells by mechanical scribing, while monolithically integrated module formation by ps-laser scribing is also available.

In collaboration with the University of Nantes (Prof. J. Kessler) a test cell efficiency

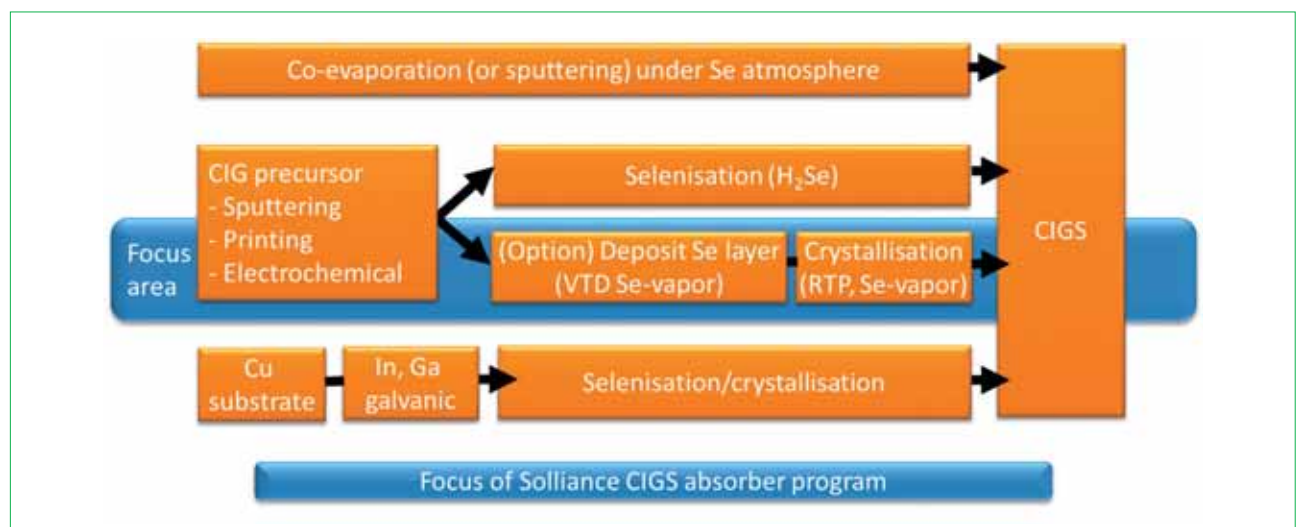


Figure 1. Schematic representation of different approaches for CIGS absorber formation. The focus of the Solliance CIGS programme is indicated in blue, i.e. elemental Se-based sequential CIGS formation by rapid thermal processing (RTP).

of 14.9% (aperture area) was achieved in the first six months after start-up of the line. For reference and research purposes, reproducible and homogeneous samples of sizes $5 \times 10\text{mm}^2$ up to $10 \times 10\text{cm}^2$ can be made available. Typical project activities are the evaluation of alternative substrates (special compositions, barriers, surface topologies), the demonstration of thinner co-evaporated absorber layers for testing new light-management concepts (nanotexturing and nanophotonics), and the performance evaluation of novel transparent conductors and back-end interconnection schemes. As a specific example, CdS replacement by fast atomic layer deposition (ALD) of Cd-free layers will be covered below, but first the CIGS absorber formation will be discussed.

CIGS absorber formation

Several approaches for forming the CIGS absorber are used by different groups of manufacturers and researchers, as shown schematically in Fig. 1. The first approach is to deposit all constituents directly in one process, either by simultaneous co-evaporation from typically four sources, or by (for example) sputtering CIG composite targets under a Se atmosphere.

A second approach is commonly referred to as 'sequential processing'. In this two-step process, a CIG precursor layer is deposited first, for which a number of dry or wet processes can be used; then, in the next step, Se (and/or S) is added and alloy formation and recrystallization are performed by thermal annealing. For this second approach, much development has taken place with regard to H_2Se -gas-based selenization. This typically takes place in batch processes, which deliver good uniformity and quality, but at the cost of long processing times requiring many oven systems in parallel. Moreover, H_2Se is less desirable owing to costly safety issues. A lot of research has therefore been recently devoted to reducing the process time and to switching to elemental Se-based processing. In order to prevent formation of undesired material phases, which can be irreversible and lead to phase separation, rapid thermal processing (RTP) is required.

Finally, a third approach has also been demonstrated, in which the substrate chosen is such that it provides one of the constituents of the absorber layer. Using copper substrates, subsequently coated with indium or indium/gallium alloys, fairly good quality absorbers are known to have been produced by sulphurization of this coated metal stack (by the former thin-film specialist Odersun).

On the basis of favourable cost of ownership analyses, the sequential-processing route has been chosen as the focus of absorber development in the Solliance programme.

“The sequential-processing route has been chosen as the focus of absorber development in the Solliance programme.”

Research line using sequential absorber formation

For the first step of sequential processing – the CIG precursor formation – several routes have been explored. In-house CIG precursor deposition by DC magnetron sputtering from Cu/Ga and In targets is available. Specific research activities in the in-line electrochemical deposition of CIG on specifically activated molybdenum-coated glass substrates, utilizing an in-line panel-plating line from MECO, are ongoing. Solution-processed or printed precursor layers have also been evaluated. In the rest of this paper, only the second step of the sequential process will be discussed, namely the Se-based atmospheric RTP processing of a CIG precursor layer.

High-throughput low-cost selenization

The results presented here were obtained using an R&D selenization tool from Smit Ovens (Fig. 2). The tool was developed using selenization mass-production technology while keeping the requirements of R&D in mind. The result is a versatile system with many capabilities and good repeatability, which enable an efficient development of a selenization process with direct scalability to a mass-production solution.

This novel CIGS-formation concept combines a number of process and equipment improvements that offer significant reductions in CAPEX and OPEX relative to state-of-the-art technology.

In contrast to many crystallization tools that are available worldwide, this is a non-vacuum tool in which the process is performed at atmospheric pressure while the reactive gas mixture is safely contained. Inert nitrogen is used as the carrier gas for elemental selenium transport. The purchase price of elemental selenium per unit mass is approximately a quarter of the price of the sole industrial alternative, hydrogen di-selenide (H_2Se). In addition to this inherent price difference, H_2Se has significantly higher safety costs, related to transport and handling of this hazardous gas. Successful examples of elemental Se-based processing, resulting in very competitive module efficiencies, have already been reported by other researchers [1].

Fig. 3 shows the cost of ownership calculations, which illustrate the impact of the higher H_2Se price per unit mass of selenium. Calculations are based on a 66MW production line with a cycle time of 60 seconds for a panel format of $1.60 \times 0.68\text{m}^2$. Comparison is made for three different in-line tools, all based on the Smit Ovens concept. First, an H_2Se process is assumed with no pre-deposited selenium in the precursor, followed by five minutes' soaking at 580°C . Second, an elemental selenium deposition process is performed by a vapour transport deposition (VTD) process on the precursor, followed by a crystallization process that incorporates an intermediate soaking step and a subsequent soaking step at 580°C for five minutes. Finally, there is an elemental selenium process with five minutes' soaking at 580°C without VTD or an intermediate soaking step.

It should be mentioned that currently competitive efficiencies are obtained by applying H_2Se in a batch oven. In this process the batch oven itself is heated up and cooled down in one very time-



Figure 2. The R&D selenization tool built by Smit Ovens to facilitate process development at Solliance. One-to-one translation of the set-up to a full-scale production line is possible.

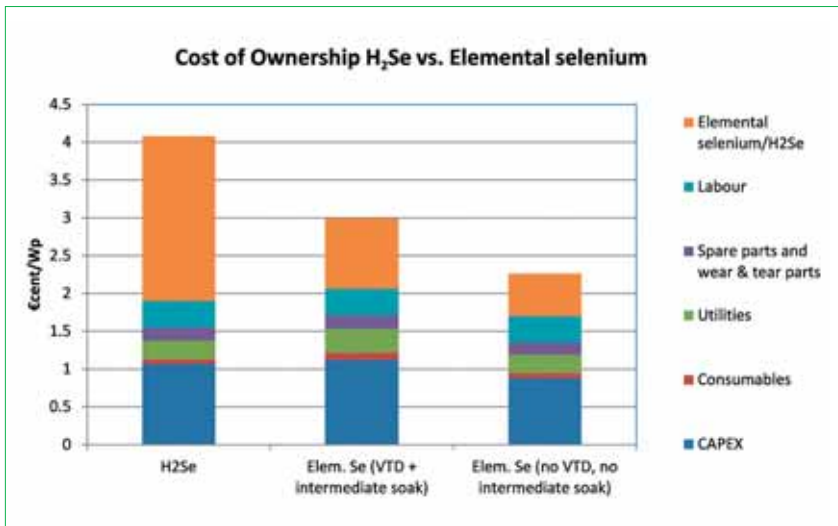


Figure 3. Cost of ownership calculations, illustrating that the choice of source material has a significant impact on the cost of CIGS absorber manufacturing.

consuming run in which a number of panels are crystallized. On the basis of certain calculations (not illustrated here) it could be concluded that batch processing is not a cost-competitive route for mass

production because of the high CAPEX and energy costs.

A typical process flow of the R&D selenization tool is as follows. First, an optional selenium layer can be deposited

on top of the CIG precursor in a cold VTD section. Second, CIGS crystallization takes place in an RTP oven section which allows a high flexibility in its thermal profile, created by the use of three independent RTP chambers. In particular, the flexibility in realizing high and homogeneous heating rates of the CIGS substrate is essential; it is known from research work of many companies and institutes around the world that this heating rate influences crystal growth dynamics and is an important parameter. Additional supplies of selenium at the various stages of the thermal profile are provided by three independent selenium sources. Selenium flux can thus be controlled independently of the product temperature, which is a unique feature of the technology concept. Further flexibility is offered by both fast- and slow-cooling possibilities, the absence of restrictions in the transport sequence between the various chambers, and the provision of special carriers for small-sized substrates or foils.

This flexibility gives effective and repeatable control of the process in order to efficiently develop the optimum

Tool features	Specification	Benefits
Multiple dimensions and types of substrate	Glass and foil	Flexibility for R&D
Freely programmable process		Flexibility in process development
Maximum substrate temperature	650°C	Processing capability, resulting in highest efficiencies
Fast and repeatable substrate heat-up rate	15°C/s	
Fast and repeatable substrate cool-down rate	3°C/s	
Control of partial vapour pressure	0–100%	
Uniform substrate temperatures	±2°C	Effective and repeatable processing, enabling efficient R&D
Uniform Se distribution/absorbance	±2%	
Data logging for substrate and tool		Enhanced analyses of R&D results
Industry-standard seals (vacuum)	< 10ppm O ₂	Low leakage rates, low O ₂ content
Substrate (un)loading via load lock		
Hot wall design		No reactor pollution, less cleaning, low cost
Electrical heaters (Se and S resistant)		Long lifetime, high uptime, low cost

Table 1. Features and specifications of the selenization equipment.

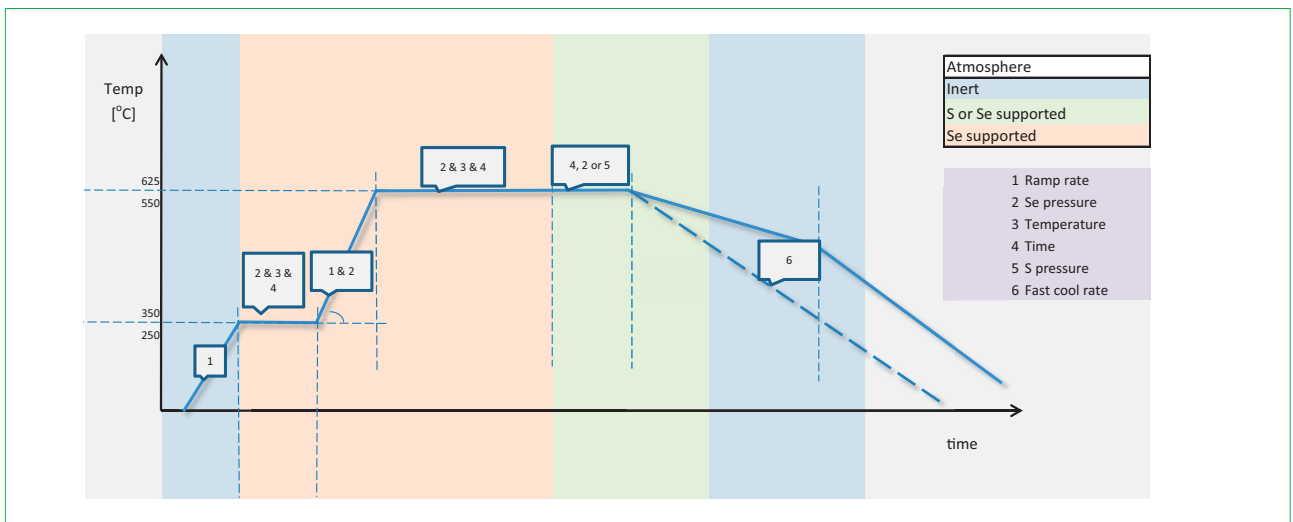


Figure 4. The available process variables of a two-step temperature profile with the R&D tool used.

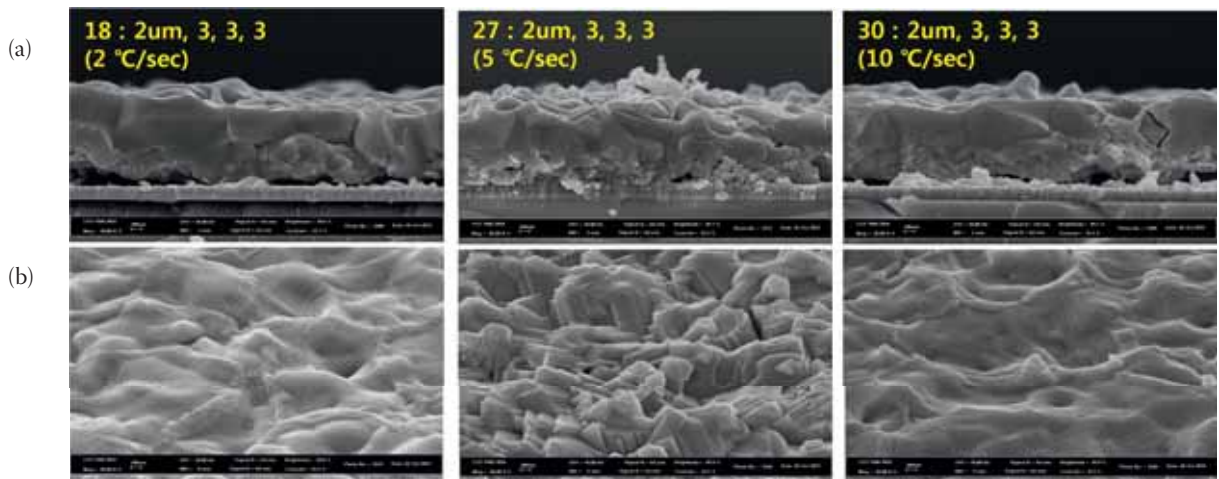


Figure 5. SEM images of absorber layers that have been made utilizing various heating rates with the $30 \times 30\text{cm}^2$ selenization tool: (a) cross section; (b) top view. (CIGS absorber thickness = $2\mu\text{m}$.)

process with the correct crystal composition, size and interfaces. More detailed specifications of the system are presented in Table 1.

A typical example of the temperature profile of a two-step selenization process performed with the research tool is given in Fig. 4; the freedom for modifying process temperature and pressure parameters is indicated. In this specific example an additional intermediate soak in a selenium atmosphere is used (first horizontal section on the graph).

A specific capability is the application of very fast heating rates while maintaining good temperature uniformity over the width of the substrate. For example, in a 50-second heating cycle in an 800°C chamber a substrate is heated with a ramp rate of $11^\circ\text{C}/\text{sec}$ to 600°C . During this fast heating stage a temperature spread of less than 12°C over the full $600 \times 300 \times 3.2\text{mm}^3$ substrate is realized. After this step the substrate is soaked in a 600°C chamber, and the temperature spread decreases to less than 4°C .

Scanning electron microscopy (SEM) images of CIGS layer samples produced from sputtered precursor layers, under various temperature ramp rates, are shown in Fig. 5. No intermediate soak was used. The impact of the heating rate on the morphology and density of the layers is clearly visible. The layer characteristics can be further investigated using other available analysis methods, such as XRD, XRF, EDX, SIMS, photoluminescence and profilometry.

Sulphurization steps can also be incorporated in the full-scale production machine. In this way, a very generic equipment solution is made possible for a wide variety of selenization and sulphurization processes, optimized for different types of precursor layer. By adapting the length of individual sections

of the machine to the required time intervals for each step, the throughput of the total process can be optimized further. A dedicated in situ XRD set-up has been designed to study crystal structure along the thermal trajectory, thereby further optimizing layer quality at reduced process times.

Spatial ALD for fast deposition

In the standard reference process, a CdS buffer layer is deposited after the formation of the CIGS absorber layer. It has been shown by numerous authors, and commercial producers too, that it is possible to replace this buffer layer by cadmium-free alternatives: examples are Zn(O)S and In_2S_3 , which in principle also offer the possibility of improved cell efficiency because their optical transmission is higher than that of a CdS window layer, thereby enabling more light to reach the absorber layer. The required thicknesses of these layers are of the order of tens of nanometres, and the layers are preferably deposited by 'soft' processes which do not generate interface damage.

Wet chemical processing and sputtering are already being applied, but logistic and (waste) cost aspects related to the

wet chemical method, and the inherent risk of interface damage using sputtering methods, give rise to continued interest in a third method that has been proved to yield very desirable results on a laboratory scale. This method is gas phase chemical deposition from volatile precursors by ALD. ALD is already a well-established technique in the microelectronics industry because of its high-quality characteristics, such as high conformality and film quality, and excellent thickness control down to Ångström level.

An emerging field of application of ALD is flexible electronics, including flexible displays, flexible organic light-emitting diodes (OLED) and flexible solar cells. ALD can be used as a production technique in the creation of, for example, transparent oxide (semi)conductors (e.g. ZnO), moisture barriers (e.g. Al_2O_3) and buffer layers for CIGS (e.g. Zn(O)S).

In all these applications, cost effectiveness and throughput are very important. However, conventional, time-sequenced ALD is inherently very slow, and merely upscaling the conventional method to accommodate large substrate sizes is costly. In order to achieve high throughput and cost reduction, there have been important developments in ALD,

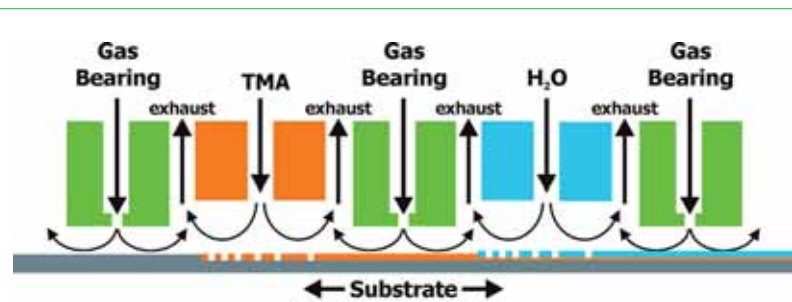


Figure 6. Principle of spatial ALD with separated gas flows for alumina deposition on flat rigid substrates.

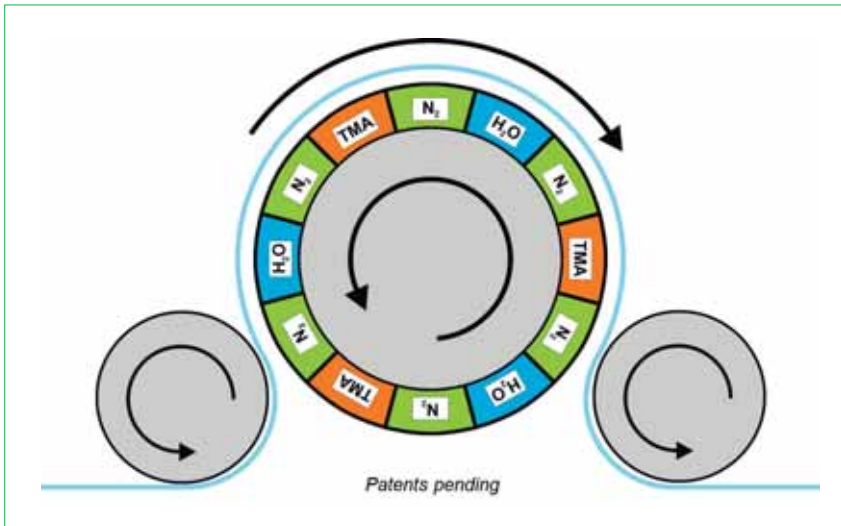


Figure 7. Principle of spatial ALD with separated gas flows for R2R application on flexible substrates.

one of which is 'spatial ALD'. Whereas for conventional ALD the precursors are dosed sequentially in time with purge steps in between, in spatial ALD the precursors are dosed simultaneously and continuously, but at different physical locations. The main advantage of spatially separating the half-reactions is that the purge steps between the precursor dosages, as required in conventional ALD, become obsolete. The result is dramatically increased deposition rates, limited by chemistry rather than pumping speed: reductions in processing time by an order of magnitude or higher have been demonstrated [2 and references therein,3,4].

In spatial ALD it is essential to have the precursors separated at all times, since cross reactions would lead to chemical vapour deposition (CVD) conditions. TNO has developed a spatial ALD concept based on gas bearing technology, in which the reactor is divided into separate zones, exposing the precursors one by one to a substrate that moves underneath the reactor. The reaction zones are surrounded by an inert gas flow that prevents the precursors from mixing. In this concept, the gas shields also act as gas bearings: this means that the reactor part is suspended with respect to the substrate, with a very small gap between, which can be as small as a few micrometres. The gas bearing function offers virtually frictionless movement between the reactor part and the substrate, and the small gap facilitates the gas separation function. Because of the separated precursors there is no parasitic deposition on the reactor parts. Deposition rates exceeding 1nm/s have been achieved for alumina from trimethyl aluminium (TMA) and water. Based on these principles, a mass-production tool for aluminium oxide passivation of crystalline silicon wafers has recently been brought to the PV market by start-up company Solaytec.

After the development of equipment solutions for spatial ALD on silicon wafers, an R2R concept was also developed and successfully demonstrated. Using spatial ALD on flexible substrates imposes additional boundary conditions on the process and equipment. First, because of the limited temperature stability of many polymer-based

substrates, deposition temperatures are required to be low (e.g. <math><120^{\circ}\text{C}</math>). Second, the deposition equipment has to be capable of handling and processing flexible substrates, either sheet to sheet or roll to roll, while maintaining the required gas separation.

An R2R spatial ALD tool that can continuously deposit alumina and other materials on flexible substrates, such as polyethylene terephthalate (PET) foil, has been realized. The spatial ALD concept using gas bearings, as described earlier, now involves a cylindrical shape instead of a flat one. The cylinder, or drum, contains a multitude of TMA and water half-reaction zones as illustrated in Fig. 7. These zones are separated and surrounded by nitrogen gas bearings. The foil to be coated is transported over the drum, where the gas bearing function ensures that the foil is not touching the drum. When moving the foil over the drum, ALD deposition takes place; the deposited layer thickness is determined by the number of half-reaction zones that the foil passes over. High deposition rates can be achieved by rotating the drum in the opposite direction to the foil motion. Total layer thickness is therefore determined by substrate speed as well as the frequency of drum rotation.



Figure 8. R2R tool for spatial ALD on 30cm-wide foils.

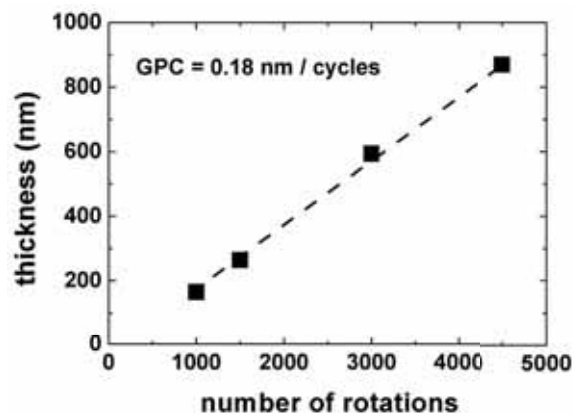


Figure 9. Deposited ZnO layer thickness as a function of the number of ALD cycles.

The main benefits arising from the R2R concept are that there is no mechanical contact between the deposition side of the foil and the reactor, and that there is a minimum of moving parts. This contactless operation, together with the low number of moving parts, minimizes particle generation, which can lead to a risk of, for example, pinholes in barrier layers. Furthermore, many types of substrate material can be used, as long as they have sufficient flexibility to be transported over a cylindrical drum.

“The main benefits arising from the R2R concept are that there is no mechanical contact between the deposition side of the foil and the reactor, and that there is a minimum of moving parts.”

Besides the contactless operation of the substrate-over-drum motion, the gas supplies to the rotating drum are also accomplished without any mechanical contact. Again, gas bearing technology in combination with gas separation is used to supply the bearing gases and precursors to the drum from both sides. Reaction products and excess precursors are also exhausted through these contactless gas feed-throughs. The configuration is such that the TMA precursor is supplied and exhausted on one side of the drum, while the water vapour is supplied and exhausted on the other side. In this way, the precursors stay separated until finally exhausted in the scrubber system outside of the reactor.

The R2R spatial ALD tool that is currently in operation has been used to deposit alumina layers of various thicknesses between 5 and 100nm on PET foil and other substrate materials (Fig. 8).

An equipment solution for spatial ALD on large-area rigid substrates (glass) has been designed, and a demonstrator tool will be available at the end of 2013. It will



Figure 10. Hybrid degradation set-up, allowing exposure to illumination, elevated temperature and humidity.

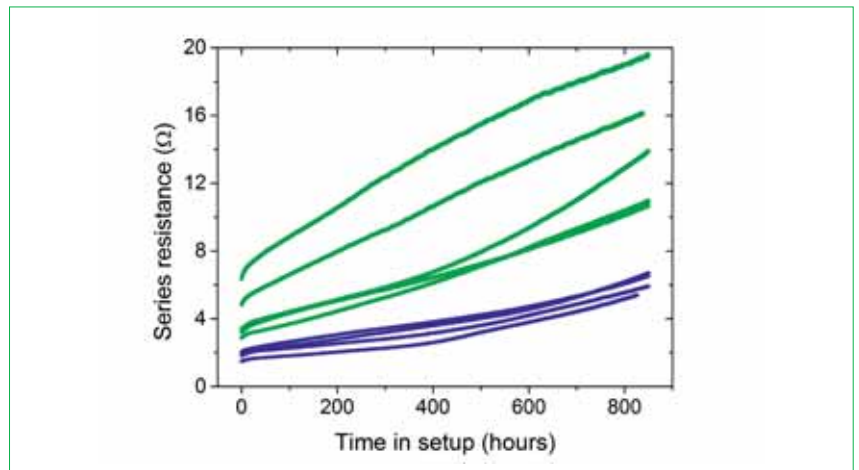


Figure 11. Series resistance as a function of time in the set-up of single CIGS (blue) and interconnected CIGS (green) samples. Operating conditions for the set-up are: 85°C temperature, 85% relative humidity and AM 1.5 illumination.

be evaluated for large-area application of buffer layers as well as for applying other functional layers in the CIGS system. Spatial ALD of ZnO has already been demonstrated on smaller samples using a set-up in which the substrate is rotating under two spatially separated gas inlets, thereby depositing one atomic layer per rotation cycle. The perfectly linear behaviour in Fig. 9 (taken from Illiberi et al. [5]) demonstrates true ALD. ZnO deposition rates of up to 1nm/s and above were demonstrated at temperatures of up to 250°C. At a precursor partial pressure of 4.5mbar, layers were obtained with higher than 90% optical transmission, resistivity around 4mΩcm, charge carrier density of $10^{19}/\text{cm}^3$, and charge mobility of $10\text{cm}^2/\text{Vs}$. Higher carrier densities ($7 \times 10^{19}/\text{cm}^3$) and charge mobilities ($30\text{cm}^2/\text{Vs}$) were also recorded. Doping with Al and In has been successfully demonstrated with this spatial ALD set-up, and a dedicated set-up for using H_2S will shortly be available for demonstration of fast ALD of Zn(O)S.

It is only briefly mentioned here that the high-rate, low-temperature CVD of high-quality transparent conductive oxides (TCOs) is also being developed in parallel. Atmospheric plasma-enhanced CVD, as well as low-pressure plasma-enhanced CVD, are currently under development for the deposition of doped ZnO in CIGS applications. This work, which has been reported elsewhere, completes the desired approach of a full line of atmospheric processes for the production of the CIGS cell layer stack (apart from the currently used molybdenum back electrode).

Quality evaluation: understanding degradation of CIGS

The electricity cost of PV is determined not only by production and installation costs, but also by module lifetime. Knowledge

of the degradation processes in CIGS cells and modules is therefore very important for identifying the lifetime-limiting factors which can be translated into process and device improvements. Processes, equipment and control are therefore developed at Solliance within the context of not only product quality but also product lifetime. Specific knowledge regarding this last aspect is obtained by both standard and advanced accelerated lifetime testing.

One example of advanced lifetime testing is the hybrid degradation set-up shown in Fig. 10. CIGS samples are exposed to AM 1.5 illumination, as well as to elevated temperature and humidity, thereby accelerating the degradation behaviour with three relevant environmental factors and allowing the in situ measurement of the I - V characteristics. This set-up is equipped with a data-processing system that allows on-line interpretation of the data and real-time monitoring of the degradation behaviour [6].

Fig. 11 shows an example of the development of a specific cell parameter – the series resistance – of both CIGS cells and mini-modules in the set-up as a function of time. All samples exhibit an increase in this resistance, probably caused by a decreasing conductivity of the zinc oxide. Furthermore, the mini-modules (green) show a much faster increase than the single cells (blue), which can be explained by degradation of the monolithic interconnection region. Similar information is obtained for the other cell parameters. By performing such real-time accelerated lifetime measurements on samples produced under controlled process variations, trends can be visualized and lifetime-limiting factors identified. The results are validated by comparison with field tests carried out by third parties, and model-based approaches (based on a validated background in accelerated lifetime modelling of consumer electronics) are used to gain a more basic understanding.

Summary

Solliance, a recently founded research alliance in the Eindhoven-Leuven-Aachen region, is a programme in which TNO, ECN, imec, the Holst Centre, Forschungszentrum Jülich and Eindhoven University of Technology collaborate on device, process and equipment development for the production of thin-film PV. In collaboration with industry, shared demonstrator lines and facilities for CIGS, OPV and thin-film Si are made available. Against this background, R&D in CIGS focuses on more-generic process and equipment development for low-cost, well-controlled, high-rate and high-yield production. To achieve this, Solliance has chosen to place particular emphasis on atmospheric processes and sequential CIGS absorber formation for H₂Se- and Cd-free production and R2R-compatible processing.

“Solliance has chosen to place particular emphasis on atmospheric processes and sequential CIGS absorber formation for H₂Se- and Cd-free production and R2R-compatible processing.”

To accelerate the development of economically competitive solutions, Solliance offers equipment manufacturers a platform where facilities can be shared not only for confidential technology assessments and demonstrations, but also for collaborative R&D. A CIGS demonstrator research line on 10 × 10cm² and 30 × 30cm² scales, based on co-evaporation, is made available. This can be used as a reference process for demonstrating and accelerating innovative concepts for more efficient production, for demonstration and testing of improved device architectures, and for fundamental research. This approach is illustrated by examples, including: atmospheric, H₂Se-free, in-line absorber formation by RTP; spatial ALD for the formation of Cd-free buffer layers; and in situ monitoring of accelerated lifetime testing.

Although not discussed in this paper, it should be mentioned that an important part of the Solliance CIGS programme is devoted to utilizing the participants' background experience in CIGS for the development of copper-zinc-tin-sulphide/selenide (CZTS)-based devices. New material and device concepts for CZTS are being explored in close collaboration with existing CIGS equipment manufacturers.

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Dr. Ando Kuypers has led the Solliance CIGS programme since 2011. He received his Ph.D. in plasma physics from FOM Institute AMOLF in Amsterdam.

From 1989 to 1992 Ando worked on thin-film process development at ASM International, and since 1993 he has managed projects and research groups in thin-film technology at TNO, with a focus on process development for PV applications.



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Maarten van der Vleuten is a CIGS process manager at Smit Ovens. In collaboration with customers over the past four years, his focus has been on process and equipment development for CIGS absorber formation. Maarten previously worked on optical storage applications (DVD, blu-ray) at Philips Electronics, and has a background in applied physics.



Wiro Zijlmans is the director of Smit Ovens. After acquiring the company in 2001, Wiro has successfully transferred its line of business from the display and glass industry to a focus on the development and supply of advanced thermal equipment for thin-film PV manufacturing. Close cooperation and personal involvement with R&D has led to intensive collaboration with PV research institutes in the Netherlands.

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