CdTe thin-film modules: basic developments, optimizing performance and considerations in module design

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ABSTRACT

A growing number of thin-film photovoltaic module producers are either trying to keep up with the current cost leader or aiming to differentiate on product design. Calyxo is dedicated to both keeping the pace in the US$0.50/Wp race and introducing new product generations, therefore delivering more value to the customer. We have tried to improve the methodology and approaches for knowledge building in the individual process steps, by learning the relevant interactions between them, as well as ramping volume and lowering manufacturing cost in the first production line. Developing and building the deposition equipment suited to the high process temperatures of approximately 1000°C at atmospheric pressure took some time, but the technology itself now enables Calyxo to benefit from significant cost savings both on capital investment and operational cost – compared to some well-known vacuum deposition methods. Besides the continuous decrease in manufacturing costs, even early on in building the manufacturing capacity, the ability to design the product itself according to the needs of the customers proved itself to be a decisive factor in ensuring competitiveness. This paper aims to give an insight into some of the basic design features of a new product generation and how the so-called new CX3 product will generate more watts by improved performance: delivering better customer value by decreased voltage to save on BOS costs and ensuring further increased field durability through an optimized package design.

Introduction

There are numerous accounts on the details of transferring scientific results to production and ramping up thin-film PV manufacturing lines. This paper will add to these considerations the notion of a holistic approach to PV module design criteria, covering aspects from manufacturing to special package consideration, and how it will affect the process of transfer and eventual ramp-up of a new technology. The process used by Calyxo will serve as an example.

Established in 2005 and based on a technology invented by SolarFields (Perrysburg USA), Calyxo has since developed a unique deposition method for thin-film CdTe solar cells known as atmospheric pressure physical vapour deposition (APPVD). This sets forward certain specific boundary conditions for the process steps to complete a solar module, as the knowledge regarding the individual process steps – as well as the relevant intermediary interactions – needed to be developed while also ramping up production.

This study will report on this unique deposition method and give an account of some of the major aspects of thin-film solar module process development. The specifics of package and device design will be discussed in some detail. One particular focus will be on the fact that our CdTe modules are manufactured using the so-called superstrate technique, giving rise to advantages in solar module design. An account is given of common features of thin-film PV developments

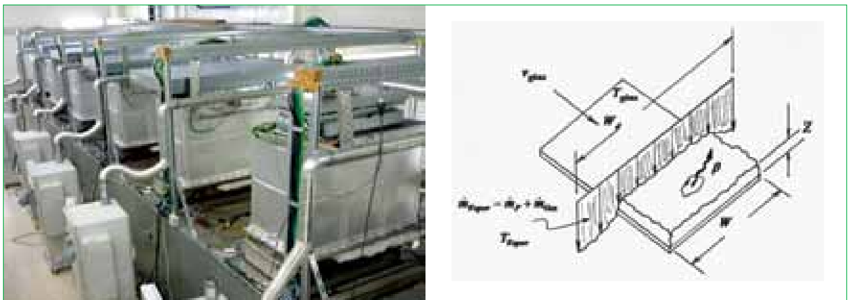

Illustration by Kenneth R. Kormanyos.

Figure 1. Evaporation and powder feed units at an APPVD furnace. The left-hand picture was taken during ramp-up of the furnace. The right-hand schematic illustrates the principle of APPVD film formation.

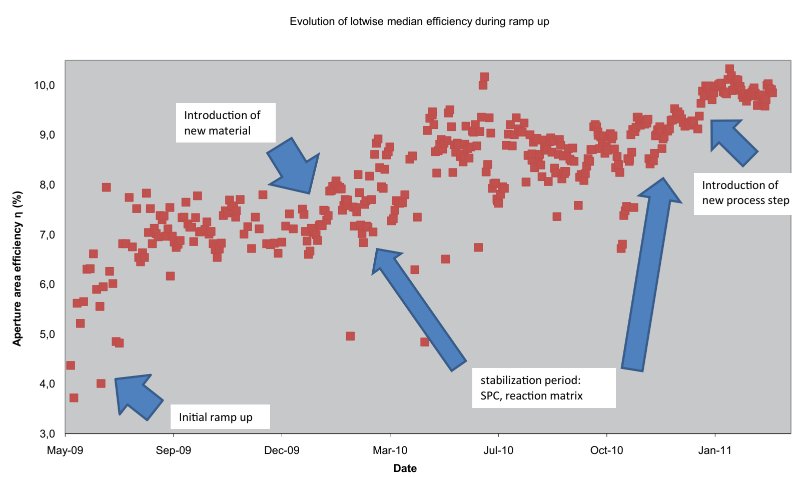

Figure 2. Evolution of lotwise efficiencies during ramp-up of a CdTe production process. Each lot is 1,000 modules strong. The arrows mark the parts of the ramp-up that are discussed in detail in the text.

and some of the specifics of the CdTe technology employed are highlighted.

APPVD process for CdTe semiconductor deposition

With any thin-film deposition process there are numerous competing approaches to successfully deposit CdS/CdTe films for solar applications. These include sputtering [1], close-space-sublimation (CSS) [2], vacuum-transport-deposition [3] or APPVD [4], to name but a few. Among those, the APPVD approach has received some attention because of its potentially intrinsic low costs for initial expenditure as well as high material utilization rates [6], although it is deemed difficult to both establish a reliable process and transfer into mass production [7].

Atmospheric processes differ from the more widely used thin-film vacuum technologies in a number of respects. The mean free path of particles hitting any surface is substantially shorter than with vacuum technologies. While this is challenging because it may lead to nucleation in the deposition – which in turn may lead to dust formation in the deposited films in case of the solid-gaseous two-phase system – there is also the incentive that potentially dynamic deposition rates exceed those of comparable vacuum technologies. These two processes compete in any atmospheric thin-film processes. It is necessary to design process and machinery in such a way that the balance of film formation on the substrate is favourable for thin-film nucleation. The parameters to be controlled to this end are temperature, gas flow and mixture.

Since the dynamic deposition rate is the parameter that determines the rate at which a work piece can be transported through a given set of machinery, it eventually lowers the limits of expenditure necessary for a thin-film deposition apparatus. Therefore, Calyxo has always chosen the atmospheric process as the core process for CdS/CdTe deposition [4].

Fig. 1 shows a purpose-built APPVD furnace for commercial manufacturing of CdS/CdTe semiconductor thin films. The furnace shown in Fig. 1 features six vaporizer stations which can either be run in parallel to achieve a high throughput or run alternately to achieve a maximum MTBM (mean-time-between-maintenance) for the APPVD furnace as a whole. This way, a maximum MTBM of 1,200h with dynamic deposition rates of the order of 1μm/s has been demonstrated in full-scale production. The deposition rate is realized by a very small effective area of deposition. This is illustrated by the schematic drawing on the right-hand side of Fig. 1. As a positive by-effect, any parasitic effects due to process-substrate-deposition reactor interactions are also minimized, since the necessary temperatures for deposition are achieved in the deposition zone only.

The following section will discuss some of the basic considerations that determine this optimization process.

Ramping up a novel thin-film production line

While thin-film processes have been known and explored for a long time [5] and have found widespread application in such diverse industries from car-making to nanoelectronics, the challenge of transferring thin-film technologies from lab to pilot scale and then to full production still remains. Most of this challenge originates in the fact that the task of transferring opens a multi-parameter space in all terms, from process limitations to manufacturing requirements. Hence, it is obviously beyond the scope of a technical paper to give a detailed account of the transfer process and every detail that needs to be considered. Nevertheless, it is worthwhile to note that common features can apply to any transfer process. There is much to be learned for future upgrading steps or introduction of new and potentially disruptive technologies by looking at the broader picture and analysis of the basic motivation for major developments.

Fig. 2 shows the median efficiencies of distinct production lots during the ramp-up phase. The data on the production result

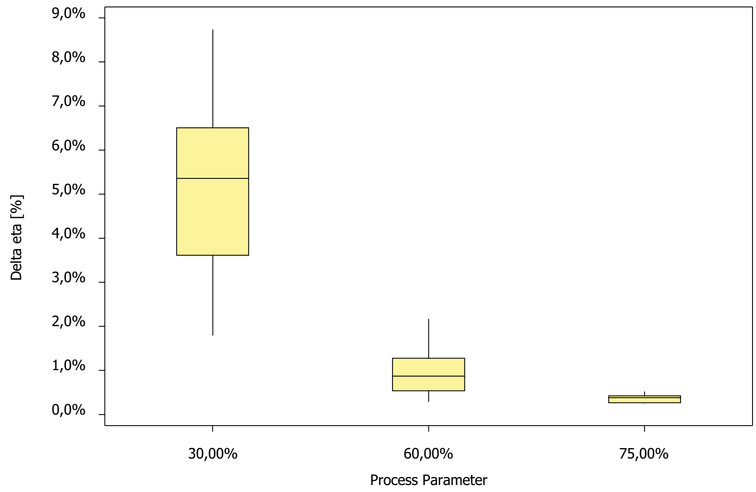

Figure 3. Example for reduction of variability of a production process by adjusting specific process parameters.

stretches over a significant period of time (and thus hundreds of thousands of modules), representing a good portion of a ramp-up scenario. From the data in Fig. 2 it may be concluded that ramping up a novel production of thin-film modules is characterized by several distinct phases if the major output variable, module efficiency, is taken as a measure. Initially, improvements in efficiency are easy to achieve. These improvements are mainly the result of replacing manual production steps by industrial machinery. Not only do the process parameters set forth on the lab scale need to be transferred, but also the geometric dimensions and interaction are altered. The machinery introduced also ensures that the variation is reduced, and parameters may be controlled far more effectively, thus increasing the efficiency as well. Therefore faults and errors (e.g. miscalculated transfer ratios of process parameters) are obvious, found quickly and tend to contribute significantly.

> "These improvements are mainly the result of replacing manual production steps by industrial machinery."

Still, it can be seen clearly in Fig. 2 that variation in efficiency remains comparatively large throughout this period.

The second event noted in Fig. 2 is the introduction of a new raw material into the production process. While in earlier experiments the positive effect was clearly identified, it is almost invisible because of the large fluctuation of net output at that time. This example is to illustrate one of the most imminent dangers during ramp up; a major analytical effort was necessary to stick with the introduction since at first glance the experimental result did not show itself in production volume. This is quite often the case on introducing new process steps and/or materials, and this is a pitfall that needs to be safely avoided. To avoid this, some 2,500 data sets from 13 individual process steps were continuously monitored. Included were machine parameters, process settings, film properties and module readings. From the sheer number of data sets monitored, it is clear that a great understanding of the underlying technical and physical processes is necessary to separate the parameters from having major second-order effects. It is impossible to discuss the influence of every single data set or process step, so the effect of tuning specific process parameters will be discussed with one example. It is shown that both optimizing maximum efficiency of the devices produced, as well as reducing noise, is achievable.

It is shown in Fig. 2 that the next step is mainly characterized by reducing the variation of the efficiencies of the modules produced. A reduction of noise can be achieved through a variety of measures. These include, among others:

- Introduction of an SPC-based production system, preferably based on an automated MES system.
- In-line control systems with short and frequent feed-back loops. These feed-

	CX1 design	CX3 design
V_{max} Inverter	600V	600V
V_{oc} Module	90V	60V
Max No. of modules in string	6	10

Table 1. Sample calculation of maximum string length in a solar array.

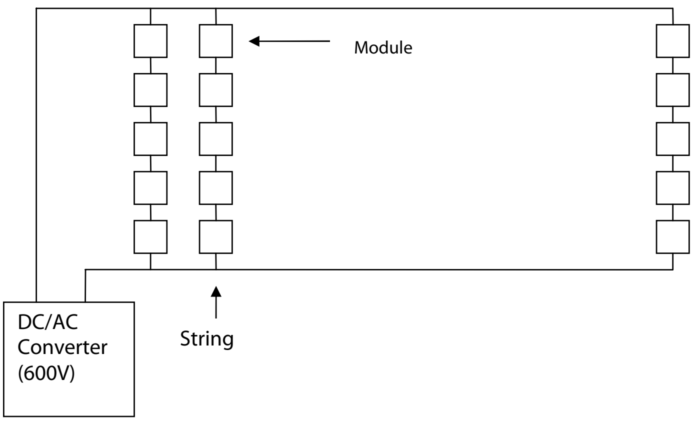

Figure 4. Schematic drawing of a PV array.

Figure 5. Schematic drawing of the monolithic serial connection of individual cells in a thin-film module.

back loops may be automated, but in a ramp-up situation it is more important to establish the right correlations first.

- Specialized reactions matrices to deal with deviations anytime, anyplace.
- Reduced noise in the individual process steps.

As obvious as the last point may be, it is often overlooked. Fig. 3 gives an example of the improvement of a specific process step. One specific process parameter was investigated. At one particular point it was noted that fluctuation was at a high level. In the experiment represented in Fig. 3, the setting of this process parameter in the production flow was adjusted during ramp-up. Results were compared to the maximum efficiency of the champion cell of the basic process as established in small-scale experiments before ramp-up. It can be seen from Fig. 3 that at a low level the overall result is low, but the noise is high. By adjusting the process parameter, both the overall result as well as the noise were improved considerably.

Having introduced this package of measures as well as having improved the performance of the major processing steps in thin-film solar module production, the efficiency of the modules produced was significantly stabilized – as can be seen in Fig. 2. The next step noted was the introduction of a new process step. While at an experimental level this new process step should have yielded lower impact than the introduction of the new raw material introduced earlier, the effect was more clear cut.

Thus it may be concluded that for optimum performance, stabilization of the line output – both in terms of volume and efficiency of the solar modules produced – needs to take first priority in any ramp-up or major redevelopment project.

Thin-film PV module design

Upon designing a photovoltaic system there are numerous considerations to be taken into account. Among them is the fact that the maximum DC voltage for today´s inverters is between 600–1000V. This limit is due to technical and safety considerations of an inverter with the American UL 1703 (flat-plate PV modules and panels) setting the limit of installations at or on buildings to 600V DC. The maximum DC voltage of the inverter in turn determines the maximum number of PV modules to be put serially in a string. The maximum number of modules can easily be determined if the V_{oc} (open circuit voltage) of the PV module is known. A sample calculation is shown in Table 1.

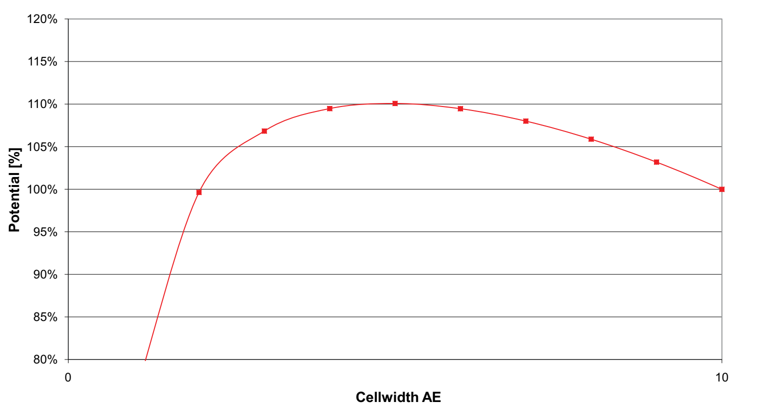

Figure 6. Schematic drawing showing the optimum width of a cell in a thin-film module.

It can be seen from the calculation in Table 1 that the maximum length of a string roughly follows the open circuit voltage of a PV module: the lower the module's V_{oc}, the larger the number of modules in a string. This way, connecting the modules to an array (see Fig. 4) is much simpler and requires less material (including cables, protecting diodes and auxiliary facilities), thus reducing the BOS costs of a PV power station by as much as 4%. Since eventually the BOS costs are the main factors in determining the price of PV electricity, there is a drive in the market towards lower module voltages.

"By adjusting the cell width, the efficiency of the thin-film module is also optimized."

With thin-film PV modules there is another incentive driving the development for modules with a lower V_{oc}. Thin-film modules are usually monolithic serial connections of individual cells (see Fig. 4). Thus, the structuring of individual cells into the thin-film design is, for the majority of thin-film technologies, the easiest (and in some cases the only) way of adjusting the open circuit voltage of the module.

It comes as a welcome additional benefit that by adjusting the cell width, the efficiency of the thin-film module is also optimized. The width of the individual cells is a compromise; it both minimizes the losses due to serial resistance in connecting the individual cells and minimizes the area between cells and the area of the module. These areas are consumed by the scribes themselves – which do not contribute to power generation, hence the term 'dead area'. The wider each cell, the lower these losses. On the other hand, the wider the cells, the more current is generated in each cell leading to increased serial losses due to:

$$P = R \times I^2 \quad (1)$$

The current in a cell is given by

$$I = j \times l \times z \quad (2)$$

where j is the current density (essentially determined by the specific number of carriers generated by the photoeffect), l the width of the cell given by the modules outer dimensions in one direction and z is the width of the cells given by scribe distances as shown in Fig. 5. From these

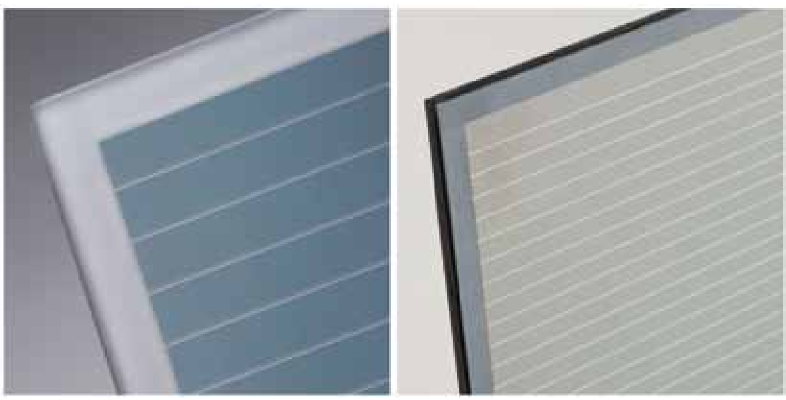

Figure 7. Picture of a CX1 module (left-hand picture) in comparison to a CX3 module (right-hand side) featuring optimized cell widths and improved package design. Details discussed in the text.

basic considerations it can be calculated that for a given set of materials (TCO, n-p diode, back contact) there is a specific optimum width of a cell in a thin-film solar module, as can be seen in Fig. 6.

Fig. 6 gives a representative calculation for one particular thin-film set. The maximum is rather broad, so for minor deviations of the cell width, negligible losses are expected. It has to be pointed out that for a different set of PV cell materials the maximum efficiency is yielded at different cell width. Since making the cells smaller implies the use of more advanced technologies, in positioning and referencing the scribes and materials included in the PV cell, they are also subject to manufacturing variability. It is common to choose a design cell width larger than the optimum width.

> "Package design in PV technology is not yet considered as part of the technology roadmap."

A comparison between a conventional thin-film module and a thin-film module with optimized cell width is shown in Fig. 7. The overall appearance of the module with optimized cell width is much more uniform. This aspect is further underlined by the use of an all-black sealing material. The comparison in Fig. 7 is an example for a specifically designed package. Being a comparatively new industry, package design in PV technology is not yet considered part of the technology roadmap. In the last paragraph we will point out some aspects whereby this largely uncharted territory can be exploited with CdTe thin-film modules.

On the whole, thin-film PV modules are distinguished by the order in which the individual layers are deposited. With substrate technology, the back contact is deposited as the first layer, followed by the semiconductors and the front contact, respectively. The advantage of this approach is that the substrate material is to be chosen either to account for processing needs or to comply with PV modules' system specifications. The range of substrate materials currently employed covers plastics as well as thin metal foils for large-area roll-to-roll deposition. With substrate technology, the final processing step is the encapsulation of the thin-film solar cell material, so the encapsulating material has to be applied to the 'sunny side' of the module. Therefore, careful choice of the encapsulation material and its durability upon UV exposure, for example, is imperative.

In contrast, with the so-called superstratetechnology, the first layer to be deposited is the transparent front contact followed by the semiconductor layers and the back contact. CdS/CdTe thin-film modules are usually deposited using superstrate technology. This is done primarily for historic reasons (most of the CdTe module manufacturers have deep roots in the glass manufacturing industry), and partially due to issues with high temperature properties of the back-contact metals that are being employed. With superstrate technology, attention has to be paid to the choice of glass substrate. This approach allows use of established inexpensive deposition technologies employed in large volumes by the glass manufacturing industry. In addition, there are several other advantages. The encapsulation material is not exposed to UV radiation, so the major property prone to degradation with currently used materials like EVA is of minor importance. The encapsulation design can be done placing the focus on diffusion barrier properties, appearance or matching expansion coefficients. Also, the overall efficiency of the module is enhanced since there is one layer less facing towards the sun, reducing the overall optical transmission [8].

The newly designed package CX3 shown in Fig. 7 is an example of this approach. Here, the encapsulation is designed for maximum durability leading to long-life modules.

Summary and conclusion

In this article we have given an overview of considerations in designing modern thin-film PV modules together with their respective manufacturing technology. We have pointed out that from the offset all aspects of module design, from electrical to mechanical to optical specifications, need to be taken into account. We have demonstrated this with the example of ramping a novel CdS/CdTe thin-film production with a novel deposition technology combined with new approaches in module and package design. The manufacturing process needs to be effective and fast, while at the same time ensuring high utilization rates of the equipment. Ramping up a thin-film line follows distinct patterns which need to be accounted for in the ramp up plan. From the start, all specifications for the PV module need to be laid out in order to put forward the specifications for the production systems. This way, high efficiency, long-term stability, economically attractive and optically pleasing modules are produced. The success of this approach is shown with the CX3 module, presented to create customer value in the US\$0.5/W_p race.

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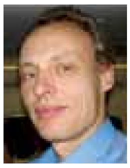
About the Authors



Dr. Hubert-Joachim Frenck studied physics at the University of Münster. Under Prof. Kassing at Kassel he concluded his Ph.D. on "Molecular engineering in PE-MOCVD thin film deposition" in 1988. In 1999 he joined Ikarus Solar and worked at Viessmann SA from 2005 until 2007, when he joined Q-Cells, being responsible for the vacuum division of the process development department there. In November 2009 he was appointed head of production at Calyxo where he is also responsible for semiconductor process improvement.

Frank Becker studied electrical engineering at the University of Saarland, where he specialized in semiconductor and sensor technology. In 1997 he became manager of the Siemens Fiber Optics Group in Japan and the business unit manager of the Fiber optics, USA in 1999. He joined the start-up company Mergeoptics in 2002, followed by Q-Cells in 2007 as department head of the metallization group. Since 2008 Frank Becker has been head of development in the technical management team at Calyxo.

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