Routes to increasing efficiency and reducing the cost of thin-film solar panels

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ABSTRACT

Most development work in the laboratory is dedicated to efficiency enhancements at the cell level; improvements in efficiency can lead to higher cost-competitiveness of PV. However, the cost of panel manufacturing is an important aspect as well. For CIGS panels the deposition of the active layer is an important part of the cost, and decreasing the layer thickness can reduce costs. Moreover, cost of ownership calculations can determine how much benefit can be expected from thinner absorber layers from a cost perspective; clearly, a thinner absorber will result in reduced absorption. To avoid losses, modelling can be used to predict the efficiency and viable light management strategies. Other efficiency-enhancing technology is related to the fact that most thin-film solar panels are monolithically interconnected. The area loss involved in this type of interconnection, and the trade-off between conductivity and transmittance of the front contact, impose limits on the maximum efficiency. The impact of improving both of these aspects is demonstrated in this paper. A viable way to improve the front contact is by supplementing the front contact with a metallic pattern. The benefit and the impact of different configurations and dimensions of the cell and metallic pattern are presented.

Introduction

The pricing of PV panels is under tremendous pressure. Over the last two decades we have seen a decline in prices far exceeding any predictions; the lower prices have been accommodated by upscaling, cheaper processes and materials. Originally, thin-film solar technology yielded a lower efficiency than its high-end crystalline silicon counterparts. There has recently been a surge in record efficiencies at the laboratory level: an efficiency of 20% is now regarded as being achievable for different types of thin-film cells, with CIGS record efficiencies well above this figure. However, for CIGS in particular, there are numerous manufacturers that have gone bankrupt over the past few years, and the cost competitiveness of this technology needs to be looked into. A cost calculation can reveal the most important cost drivers and indicate which cost-cutting route is the most promising. In the past, indium has often been named as a cost driver, but detailed investigations show that the overall picture is more complex, as material cost is only a part of the total cost.

Because of the current low prices of PV panels, the panel cost contribution is often only half (or even less) of the total cost/kWh. The balance of system costs and maintenance costs have not seen such huge declines as those observed in the PV panel industry. The increase in the efficiency of a solar panel translates into a reduction in cost/Wp for the total system; therefore, the lower the share of the PV panel in the total cost/kWh, the more interesting it becomes to ramp up the efficiency. Major efforts at the laboratory cell level have been seen, along with their translation to industrial processes. Especially for CIGS, the manufacture of thin-film panels with a homogeneous composition and quality over the entire surface is challenging. Furthermore, improved in-coupling of the light is of interest, regardless of the PV technology.

Two other major areas in which innovation results in higher efficiency are better front contacts and reduced losses at the interconnections. Here too it is important to achieve a balance between optimum performance and minimum additional cost. Both cost calculations and innovations are presented, and the different routes to higher cost-competiveness are discussed.

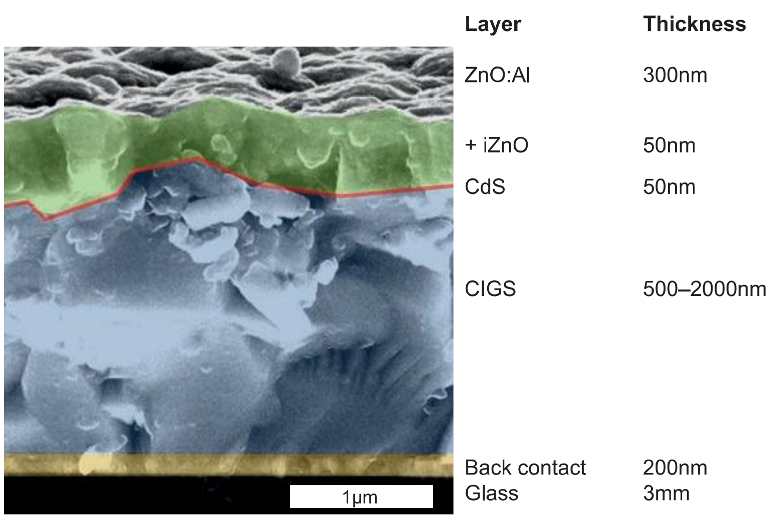

Figure 1. Scanning electron microscope (SEM) image of a CIGS cell stack.

Part I: Cost of CIGS panels

Cost breakdown and CIGS layer

The cost calculation is based on a CIGS material stack; a cross section of such a stack is shown in Fig. 1. The stack consists of sputtered Mo on top of glass, followed by a two-step CIGS deposition process (standard thickness of 2000nm), a chemical bath deposition for the CdS, and sputtered i-ZnO and ZnO:Al. The ZnO:Al is a transparent conductive oxide (TCO), which serves as a front contact [1] and as an interconnection in thin-film solar panels. In addition to the layers shown in the image, the cell is covered by an EVA layer and a top sheet of ultra-clear glass.

Figs. 2 and 3 show the breakdown of costs for a CIGS solar panel. In Fig. 2 it is seen that nearly half of the cost relates to materials, and around half of this is for glass and encapsulation material (see Fig. 3). The much-discussed price of indium is observed in the material cost, but represents only around 10% of this portion.

> "Because CIGS is the largest cost factor compared with the other layers, it can be considered an important cost driver."

In spite of the relatively low percentage contributed by indium to the total cost, the CIGS layer deposition represents about 32% of the total panel cost if a standard layer thickness of 2000nm is used. The related material cost is actually less than 25%. Because CIGS is the largest cost factor compared with the other layers, it can be considered an important cost driver. For this reason, it is interesting to investigate the impact of reducing the layer thickness on both the cost and the efficiency. The main question is whether a thinner CIGS layer will be effective as a cost-reduction strategy.

For this calculation, the layers surrounding the CIGS layer are kept constant. Furthermore, it is assumed that the equipment-related cost of the CIGS scale with the layer thickness to the power of 0.7. The total panel cost versus CIGS layer thickness is shown in Fig. 4. The cost of the total panel decreases if the CIGS layer becomes thinner: from the standard €59.39/m^2 for 2000nm CIGS, the cost falls 25%, to €44.10/m^2, for a very thin CIGS layer of 500nm. Such a significant drop justifies a more detailed investigation of the sensitivity of the overall price to changes in CIGS-related costs.

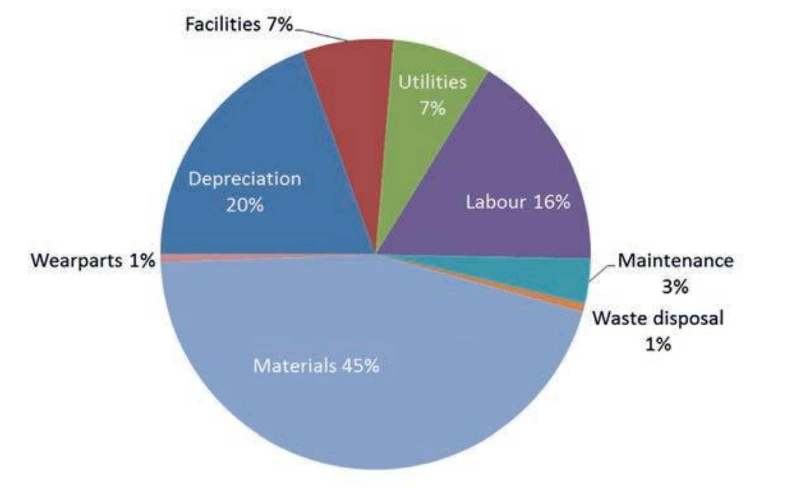

Figure 2. Cost structure of a CIGS panel with a CIGS layer thickness of 2000nm.

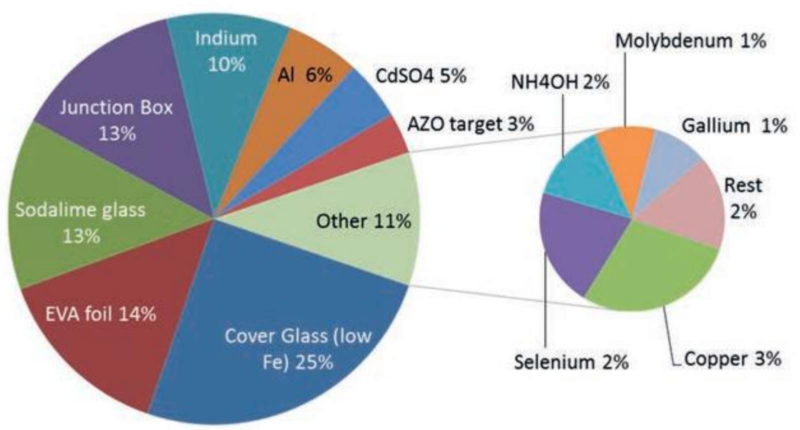

Figure 3. Breakdown of material costs for a CIGS solar panel.

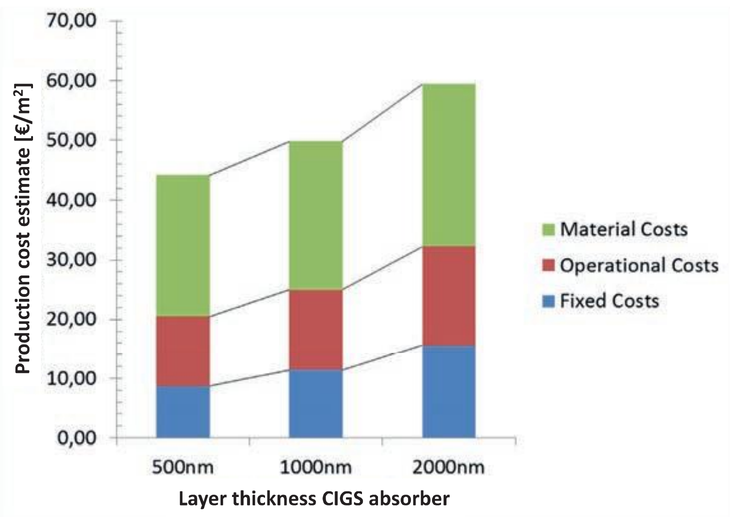

Figure 4. Cost breakdown of a CIGS panel with different CIGS layer thicknesses.

Thin Film

Price fluctuations of materials are often mentioned as a possible bottleneck in the case of CIGS. The impact of the material price on the total panel cost is deemed an important factor. For instance, copper zinc tin selenide (CZTS) cells are a topic of research because of the lower material prices. More specifically, indium prices have undergone dramatic rises and falls; in the past it has been suggested that this volatility might become an important bottleneck in view of potential shortages. To investigate this, the CIGS material price in the model for various CIGS layer thicknesses was changed, as shown in Fig. 5. In the case of standard 2000nm CIGS, a reduction in the materials price of CIGS elements to 10% of the current price will lead to a decrease in cost of about €4/m^2. If the prices of all the CIGS elements inflate to four times the current price, the cost will increase significantly. However, for thinner CIGS layers, the material cost component is much lower and has only a minor impact on the total production cost. Therefore, reduced layer thickness can result in the CIGS technology being less sensitive to material price fluctuations. It is also seen that the impact of a change in the layer thickness is much greater than a change in the material cost. This is because a change in layer thickness reduces both material and equipment costs, in contrast to the case where only the material cost is varied.

Decreasing the layer thickness comes with a penalty of reduced absorption, which translates to lower current density, resulting in decreased efficiency. Fig. 6 shows the current density as a function of the layer thickness, both by calculation and from the literature [2,3]. The impact of the layer thickness is most pronounced for very thin layers. A decrease in layer thickness from 2000nm to 1000nm has a relatively small effect on efficiency, but can be seen to have a significant effect on cost. Also noticeable is that the efficiency obtained from the experiments is lower than that predicted by the model; this can only in part be related to a lower fill factor or voltage. A thinner CIGS layer can also bring about an increased likelihood of recombination, an issue that is currently being investigated. In general, there will always be a trade-off between lower cost and lower output; however, if the lower output can be avoided, it will be a benefit for the thin-film CIGS case, and the potential of light management technology deserves a closer look.

It should be noted that the data in Fig. 6 are for flat CIGS layers. In other words, the light goes through the CIGS layer in a single pass, in a direction perpendicular to the surface; the path length is therefore equal to the layer thickness. This path length can be made longer by the use of light management technology; in the case of thin-film Si, it has been shown that light management technology can enhance the path length of the light in the solar cell dramatically and boost the current density by 25% [4].

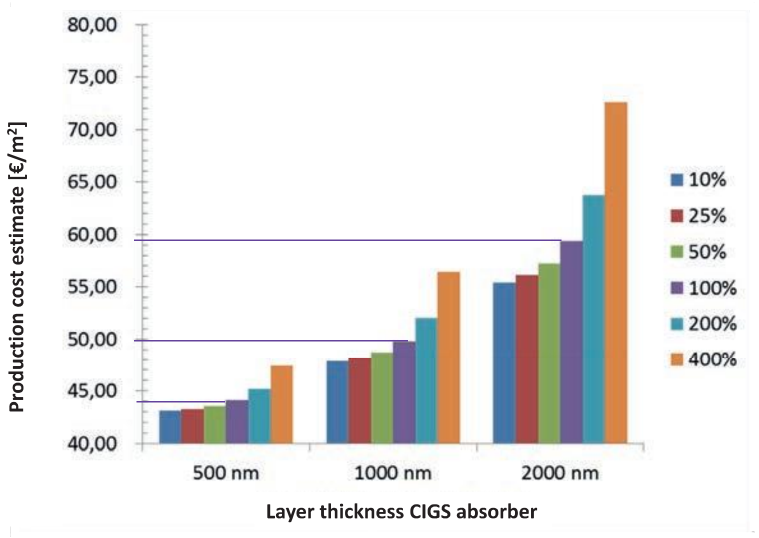

Figure 5. Panel cost as a function of CIGS material cost and layer thickness.

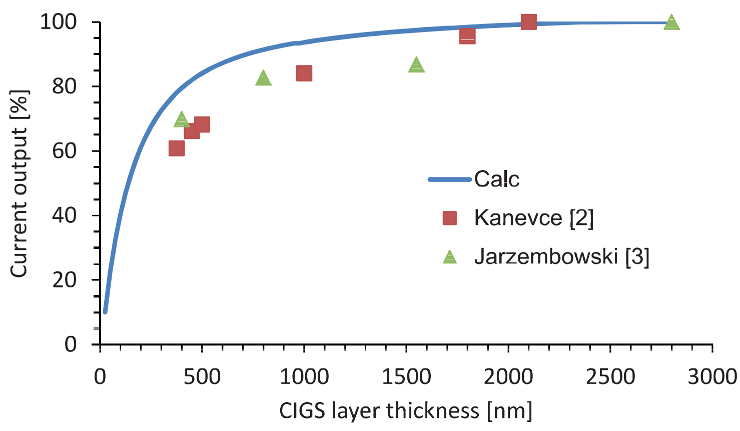

Figure 6. Cell current density as a function of CIGS layer thickness.

Light management

When there is insufficient absorption by the active layer, light management strategies to elongate the path length of the light are an asset. The best method depends on the required path length elongation and on the wavelength range which needs to be elongated. Most light management technology has been aimed at enhancing the performance of thin-film Si. For CIGS, research is still ongoing and there is relatively little information about this topic. Usually, if the CIGS layers are too thin, the light losses are mostly in the wavelength range above 800nm.

> "When there is insufficient absorption by the active layer, light management strategies to elongate the path length of the light are an asset."

Thin Film

Fig. 7 shows an example of a texture that has been used for thin-film Si and is now being applied to CIGS in research. It has been shown that a CIGS cell using such a texture exhibits an increase in current density. However, the texture influences not only the path length of the light, but also the crystal formation, the total surface (and interface) area, and so on. Therefore, for the moment, it is too early to make a statement on the exact optical benefits of the texture for the efficiency. Obviously, such technology would not be without cost: it is estimated that the additional expense would be in the range of €1–2/m^2. This light management technology is designed to compensate for the losses induced by the thinner absorber layer. Actually, it aims to enhance the efficiency compared with a flat design.

There are various ways to enhance the efficiency of thin-film solar cells, regardless of CIGS thickness; Part II of this paper discusses a number of technologies and demonstrates their value for thin-film PV, more specifically CIGS.

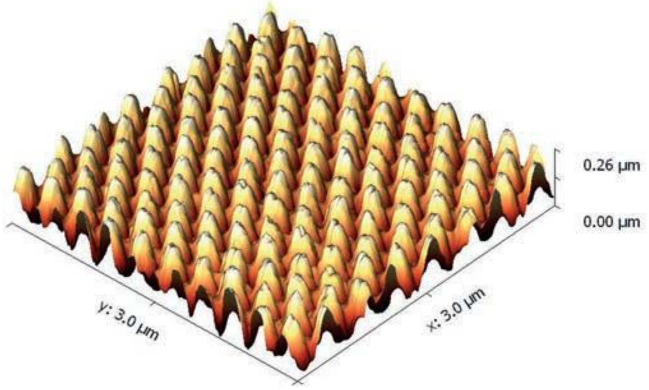

Figure 7. An example of a texture that might compensate for current density loss.

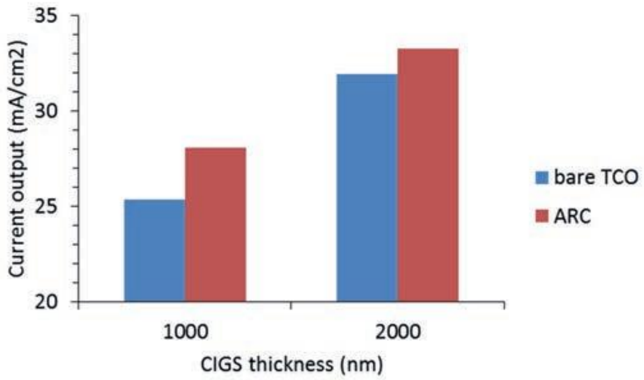

Figure 8. Efficiency increase when using an anti-reflection coating.

Part II: Efficiency enhancement

Anti-reflection coating

In a thin-film solar cell, part of the light is reflected; an anti-reflection coating (ARC) is a way of reducing these losses. Most development efforts focus on minimizing the reflection on the air–glass interface, which, for CIGS, is actually also the interface where most of the reflection losses occur. Because of the layer build-up of CIGS, the internal reflection is lower than experienced in thin-film silicon.

Fig. 7 is an example of a moth-eye texture, which was applied on top of a CIGS cell stack; the corresponding efficiency enhancement obtained from such a coating directly on the TCO is shown in Fig. 8 [5]. The reflection is reduced and the gain in current output is equivalent. Because a bare cell without encapsulation has a higher reflectance, the benefit is larger than would be expected from an encapsulated cell. Nevertheless, this work demonstrates that, even with laboratory cells, the expected gain is achieved. Work is presently under way to test the same technology on fully encapsulated cells [6].

Another example of an approach to texturing is shown in Fig. 9. This new 'light trapping' film technology from Royal DSM N.V. has the potential to improve the efficiency of CIGS modules. With the application of DSM's proprietary technology, it is expected that the efficiency of CIGS modules can be increased. Strengthening the light trapping will increase the output and reduce the $/Wp cost of the modules and therefore the cost of the energy produced.

The DSM technology consists of an outdoor-durable polymeric sheet that can be laminated to the (glass) cover of a PV module. The polymeric sheet features a smart-textured 3D structure, consisting of so-called 'corner cubes', which are tiny cubes pointing upwards. These cubes allow the light to enter the solar module, yet prevent the light from reflecting out of it. Effectively the light is trapped inside the module; as a result the module produces more energy. Depending on the type, location and age of the module, the additional energy can increase by approximately 6 to 12%. Light is also trapped effectively at low incident angles, which increases performance in morning and evening hours as well as under cloudy sky conditions. The technology is currently being evaluated in multiple geographies by a broad range of industrial partners. The film will be first brought to the market as a retrofit solution targeting large existing PV parks. The modules in these parks can reap greater benefits, as these older installations often suffer from higher reflective losses. In due course, the technology will also be applied to new systems.

Figure 9. Example of a multifunctional coating by DSM.

DSM is scaling up the manufacturing technology in preparation for a worldwide product launch and has joined the Solliance CIGS Research Program in order to explore and develop this potential. Solliance is an alliance of TNO, TU/e, Holst Centre, ECN, IMEC and Forschungszentrum Jülich for R&D in the field of thin-film photovoltaic solar energy in the ELAT-region (Eindhoven-Leuven-Aachen triangle).

Improvement of the front contact

The efficiency of thin-film solar panels is considerably lower than that obtained for record-efficiency cells. This efficiency gap is due in part to the larger surface area, which translates into higher demands on the front contact. The current panel configuration consists of stripes of cells approximately 5mm wide, which are interconnected in series, as shown schematically in Fig. 10(a); the current therefore travels a longer distance than in a small laboratory cell.

To meet the demands in a solar panel, the sheet resistance of the front contact is normally around 10Ω/sq.; this is a trade-off between sheet resistance and transmittance (about 5% more optical loss than with the TCO used in small cells) [7]. In addition, the fact that the panel consists of narrow stripes also induces an optical loss at the interconnection between the stripes, which is normally about 350μm wide; for an optimal cell width of 4mm, this loss amounts to 8.8%. Wider cell stripes would reduce these optical losses, but would also induce a higher electrical loss [8]. A higher sheet resistance of the TCO would give rise to a higher transmittance, but the electrical losses would severely limit the cell length [9].

The addition of metal fingers, as illustrated in Fig. 10(b), would enhance the conductivity of the front contact, which allows longer cells. To evaluate the benefit, the calculated efficiencies for cells with and without a finger grid are shown in Fig. 11; these calculations were based on a small cell efficiency of 15.5%. The boundary conditions used for the finger grid are a finger width of 20μm, a finger height of 1μm and copper bulk resistivity.

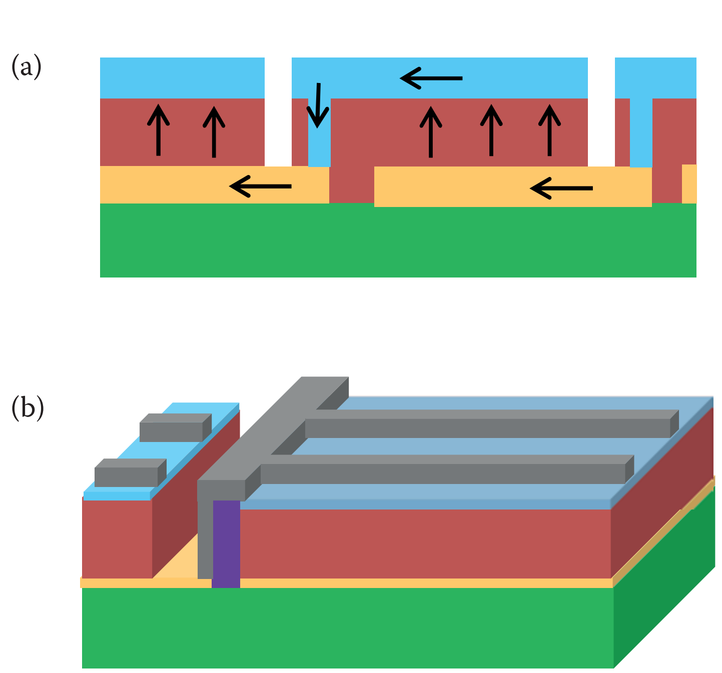

Figure 10. Schematic representation of (a) the classic method of interconnection and (b) a piece of solar panel with a finger grid [9].

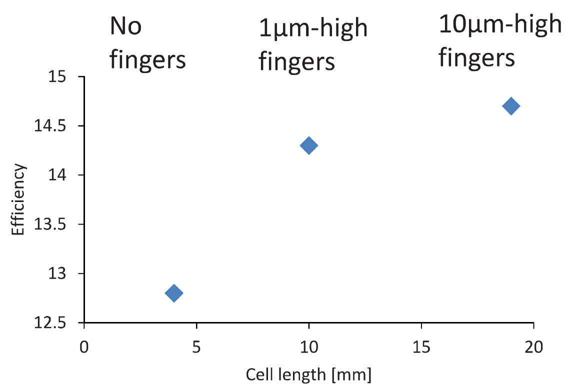

Figure 11. Solar panel efficiency for various front-contact materials; the fingers are combined with a 50Ω/sq. TCO.

> "The addition of metal fingers would enhance the conductivity of the front contact, which allows longer cells."

The optimal cell length is increased and the efficiency is higher too. Initial experimental verifications indicate that cell lengths of 10mm can be obtained with only a small loss in efficiency. These experimental data were based on a single-cell configuration, and no optical losses by interconnection were included. More elaborate modelling was performed in order to determine the best grid and cell configuration, and these results have been reported elsewhere [8,9].

In summary, the TCO sheet resistance and the finger dimensions have a distinct impact – the trends are shown in Fig. 12. In Fig. 12(a) it can be seen that, for a finger width of 20μm, a TCO of 100Ω/sq. is preferable and that increasing the height is beneficial. In practice, however, the 10μm-high fingers are less likely to be mass produced, but serve as an illustration to demonstrate the potential of this technology.

For grid fingers of width 60μm, the efficiency is slightly lower and there is less sensitivity to the TCO sheet resistance. The lower efficiency is due in part to the larger shadow of the fingers; obviously, this shadow is determined not only by the finger width, but also by the space between the fingers.

Fig. 12(b) shows the optimal finger spacing corresponding to the efficiencies shown in Fig. 12(a). A higher TCO sheet resistance requires a lower finger spacing, and wider fingers have a higher optimal spacing. This figure provides some general rules for the design of a finger grid for thin-film PV.

Optical losses from interconnection

As stated above, the interconnection area represents an optical loss. The interconnection is usually formed by three scribe lines and one interconnection area. The total width of this loss area can be minimized by placing the scribe lines as close as possible to each other. In a classic layout, where the isolation of the back contact is filled with the absorber material, some spacing is necessary between the isolation and the interconnection, because the absorber material is actually a semiconductor; this spacing should be at least 100µm [10]. However, if another material is used to fill this gap, the total area that is lost by this interconnection can be significantly reduced.

Fig. 13 shows the impact on the efficiency if the interconnection area is reduced. Two factors play a role here – the surface area losses are lower, but because of this, the optimal cell length is smaller, which in turn reduces the electrical losses. Therefore, a new optimum is found in the trade-off between TCO sheet resistance and cell length; here it is seen that the preferred TCO shifts from 10Ω/sq. to 20Ω/sq. and the optimal cell length decreases.

The cells with a finger grid are longer and therefore less sensitive to the interconnection area. Fig. 14 shows how things would work out if a finger grid were used together with a narrower interconnection area. In short, the maximum achievable efficiency with a finger grid of 20 × 10µm micron would increase to 14.9%, which is only 0.6% below the efficiency of a small laboratory cell.

"The cost of thin-film CIGS can be decreased significantly if the thickness of the CIGS layer is reduced by 50%."

Conclusions

The cost of thin-film CIGS can be decreased significantly if the thickness of the CIGS layer is reduced by 50%. Further reductions would probably require more extensive light management technologies; development in this direction is currently under way.

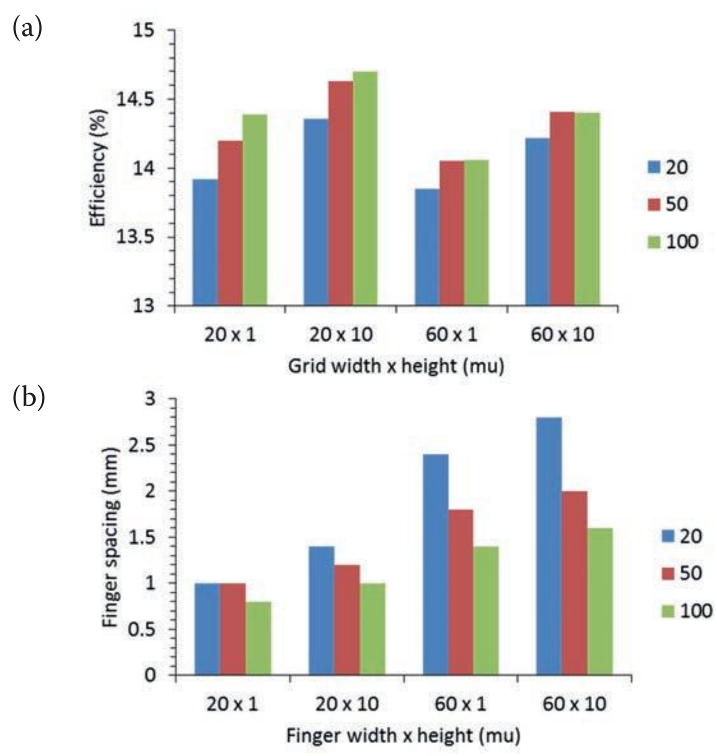

Figure 12. (a) Efficiency as a function of specific finger designs for three different TCO sheet resistances – 20Ω/sq. (blue), 50Ω/sq. (red) and 100Ω/sq. (green). (b) Corresponding optimal finger spacing.

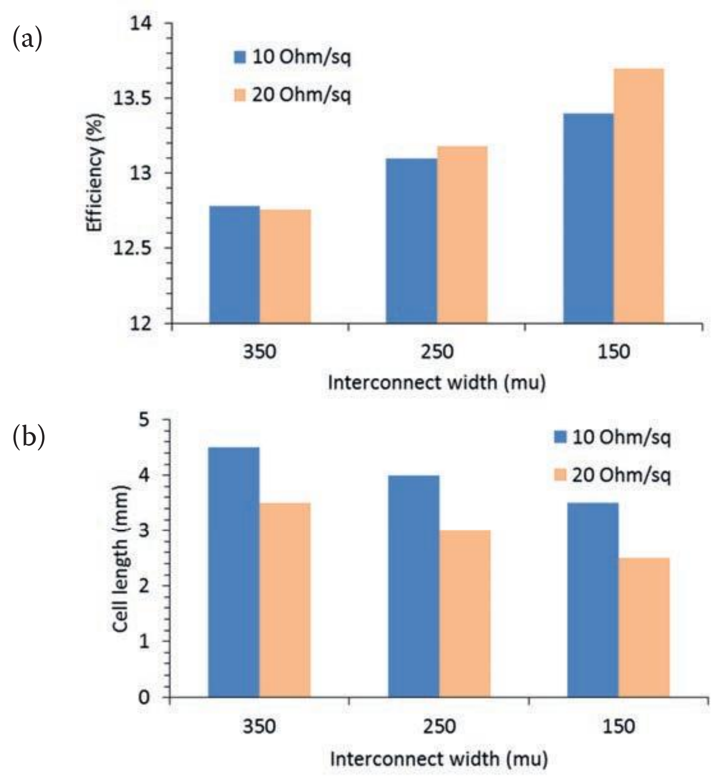

Figure 13. Impact of interconnection dead zone on efficiency and optimum cell length for two TCOs (10 and 20Ω/sq.).

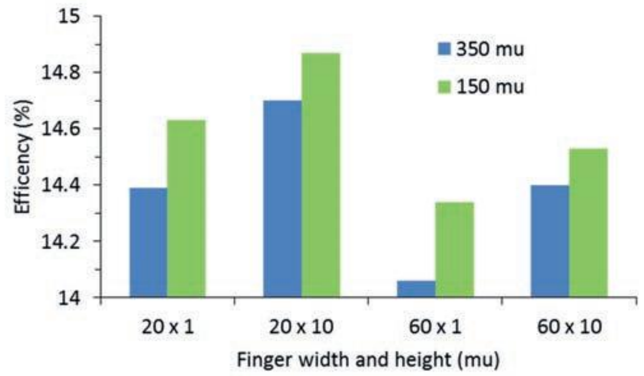

Figure 14. Impact of the interconnection dead zone on efficiency and optimum cell length for CIGS cells supplied with a metallic finger grid.

Increases in efficiency of solar panels can be achieved by improved light in-coupling, highly conductive front contacts and reduced interconnection area; the impact on efficiency has been presented here for various cases. Solliance is working on all these topics with the aim of making thin-film PV more competitive.

Acknowledgements

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Zeger Vroon received his Ph.D. from the University of Twente on the subject of ceramic membranes. In 1995 he started working at TNO; since 2008 his work has focused on reliability, light management and integration in solar cells. In 2009 he was appointed a coordinating lecturer at the Applied University Zuyd.

Pascal Buskens received his Ph.D. in chemistry from RWTH Aachen University in 2006, and is the author of 15 scientific publications and more than 25 conference proceeding papers, as well as being the inventor of 11 patents. Since 2011 he has been working at TNO, where he currently holds the position of principal scientist; he is also a research group leader at DWI – Leibniz Institute for Interactive Materials in Aachen, Germany. His work at TNO and DWI focuses on the development of optical materials and coatings.

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