Innovation for optical, electrical and economic improvement of thin-film PV technology

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ABSTRACT
Innovation in the field of thin-film cells, in addition to economy of scale and the manufacturing learning curve, is an important element in keeping the price of this technology competitive. Most papers on these cells focus on their technology; however, the economic potential of the technology is also important. Of even greater significance, a realistic estimation of the potential, along with the associated costs, of advanced technology, is part of the equation for profitability. Two examples of technology – metallic grids and texturing – are given in this paper; the designs are discussed, and a brief economic analysis is presented for various scenarios of the technologies. Although the profitability of these technologies can be considerable, it is shown that one should be wary of basing decisions purely on potential and on ideal scenarios, and how the cost of a technology can turn a great prospect into a trade-off.

Introduction

The cost of PV has fallen dramatically over the past decade. At one time far more expensive than wind energy, its cost now matches, or is below, that of many renewable alternatives; important drivers are low-cost production facilities, economies of scale and, not least, innovation. The PV market mainly consists of Si wafer panels, for which large factories with standardized equipment are available. For thin-film, however, it is a different story: company-specific technology and mainly in-house-developed technology are typical. At this point in time, there is some economy of scale with multi-gigawatt production, but even so, the industrial learning curve for thin-film began about 20 years later than that for wafer-based production.

An advantage of thin-film technology is that it does not require energy-intensive purification of Si; moreover, a panel consisting of a few deposited layers is inherently more easily scalable. The latest buzz in thin film is the development of perovskite cells, which suggests that, at the cell level, 20% efficiency could be achieved in just a few years. In short, there are a few compelling assets and developments in the thin-film community that make it worthwhile to investigate the kind of technology that is needed in order to further improve the performance/cost ratio.

The heart of thin-film technology is the absorber material and its interfaces, and most academic research focuses on that part of the cell. However, there are also other components of a thin-film panel that are interesting: for example, with the front contact a trade-off exists between transparency and conductivity, and the contact is therefore not ideal in respect of either of these two properties. A good solution to this could be a combination of various materials; their design and application is the first topic of this paper. The second topic relevant to thin-film PV (such as CIGS and perovskites) is that Si-based technology involves texturing; whether or not texturing is a route to pursue in CIGS and perovskites, from both a technological and an economical perspective, needs to be investigated.

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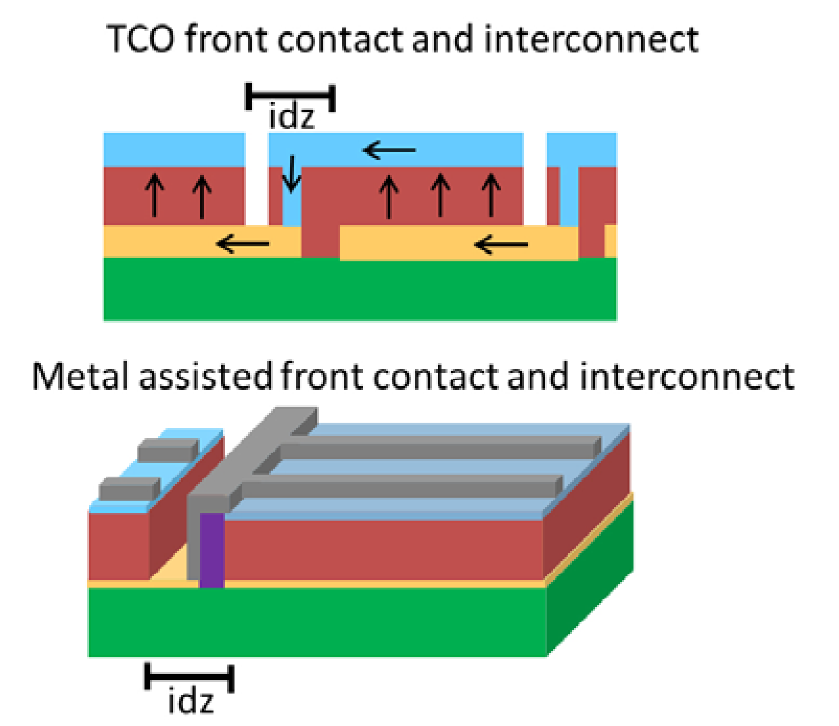

Figure 1. Front-contact and interconnection designs. The interconnection dead zone is represented by idz [1].

For both the above-mentioned topics, modelling has proved to be a valuable tool in determining the front-contact materials and in formulating the design of a pattern or texture. Moreover, in addition to design optimization, the ability to calculate the potential of a technology and the associated cost is essential in order to make smart decisions about innovation strategies. Design, technological and economic aspects will be addressed in this paper, along with a discussion of both the advantages and the limitations.

Multi material for the ultimate front contacts

Metallic grids and their sheet resistance

The front contact is an important part of the thin-film panel: its function is to be transparent to the light, so that the light can be absorbed by the absorber, while simultaneously serving as a current collector. Thin-film PV panels consist of parallel strips of cells; these are interconnected as shown in the schematic representation of a cross section of part of a thin-film PV panel in Fig. 1 (top). Each cell is connected to its neighbouring cells, and usually the front-contact material is also used as an interconnection material, indicated in blue in the figure. The entire width of the interconnection and cell separation area does not contribute to the efficiency, and for this reason is usually referred to as the *interconnection dead zone (idz).*

The arrows in Fig. 1 show the path of the electrons in the system: the electrons move through the front contact to the interconnection, and then through the back contact to the neighbouring cell. An alternative design of a metal-based interconnection is shown in Fig. 1 (bottom); this design also includes a metal-assisted front contact, the conductivity of which can be enhanced by adding the metal.

To what extent the conductivity can be enhanced by metallic grids has been investigated [2]. Fig. 2 shows a comparison between different front-contact options: 1) a transparent conductive oxide (TCO), which is the standard material currently in use; 2) a rectangular metallic mesh on top of a thin TCO layer; 3) a TCO/metal/TCO sandwich; 4) thin metal layers (thickness in the nm range); and 5) a rectangular metal grid. The plot shows the transmittance as a function of sheet resistance; clearly, a minimum sheet resistance at the highest possible transmittance is desirable.

For single materials, a reduction in sheet resistance has only a minor effect on the transmittance down to a transmittance threshold of 90%, below which there is a marked decrease in transmittance. This is visualized by the blue and green lines, which represent the trends for single materials of TCO and metal respectively [3].

As can be seen in Fig. 2, for the purpose of a transparent conductor a TCO is a better-performing material than a metal. A TCO/metal/TCO sandwich performs even better; this is because the reflection of the metal is reduced if it is sandwiched between other materials. However, a patterned metal on top of a TCO (TCO + grid in the figure) works even better still.

The different sheet resistances were obtained by using different rectangular grid designs of slightly different surface coverages. It can be seen that one can vary the sheet resistance of such a system by over an order of magnitude without incurring significant optical losses. More importantly, a patterned metal on top of a TCO outperforms the other materials.

The closed squares in Fig. 2 represent data for a square metallic grid on top of a TCO. However, in thin-film PV panels, a grid consisting of parallel metallic fingers (as depicted in Fig. 1) is more effective, since all the current needs to be transported in only one direction. The resistance of a metallic feature is

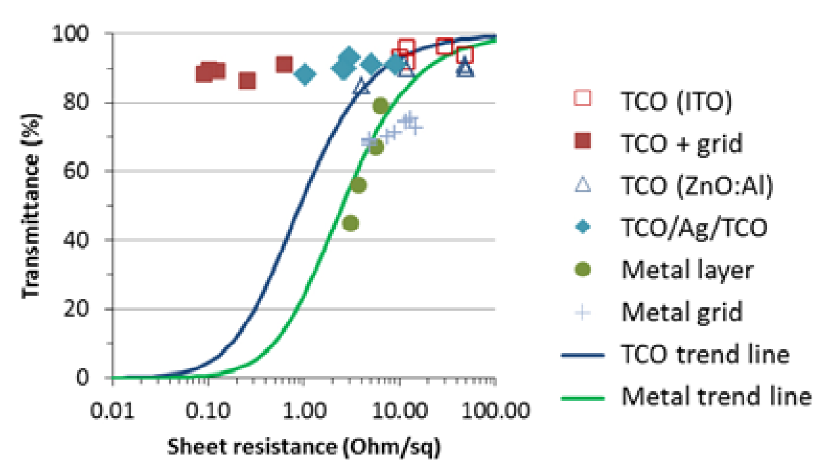

Figure 2. Comparison of various transparent conductors.

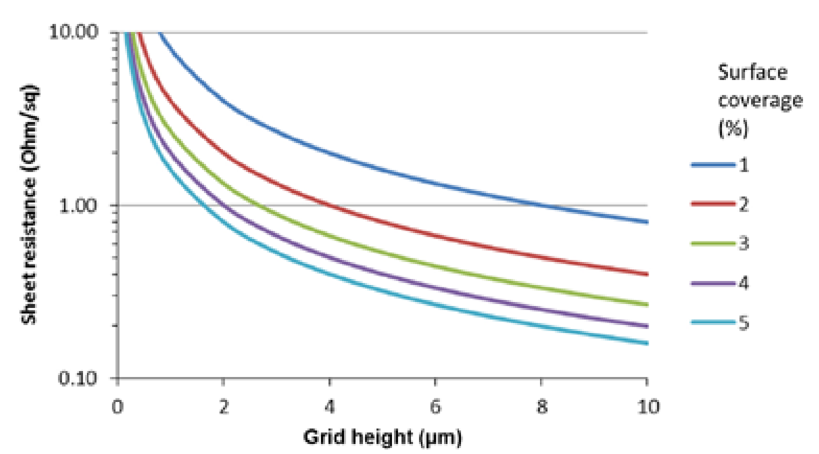

Figure 3. Overview of the sheet resistance of a linear wire grid as a function of grid height, for various surface coverages.

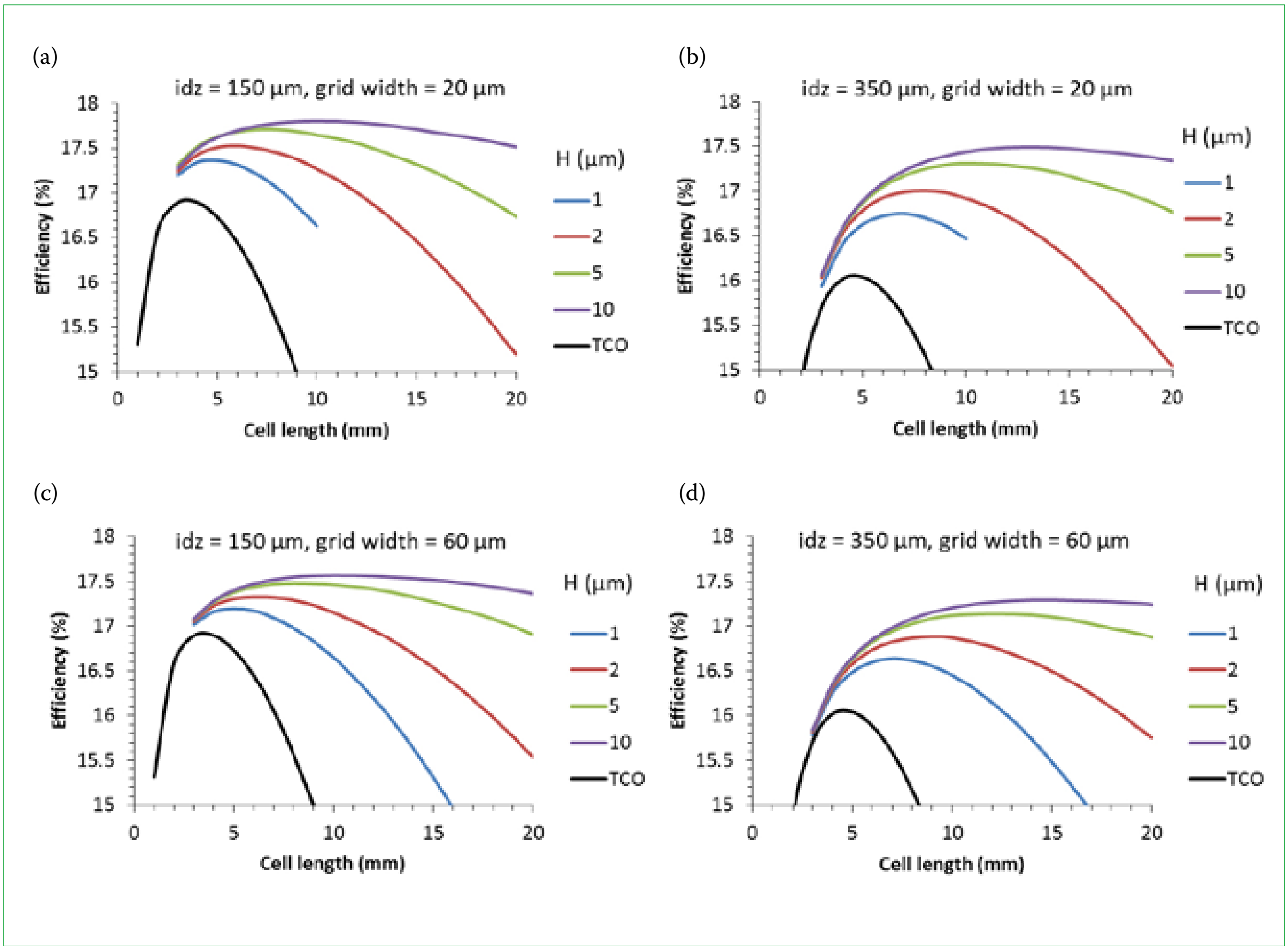

Figure 4. Panel efficiency as a function of cell length, showing the impacts of various grid finger heights (H), interconnection dead zones (idz) and grid finger widths [5].

given by the product of the resistivity and the surface area perpendicular to the direction of the current ($R = \rho \times A$). In the case of a finger grid, this surface area translates to the height and the surface coverage, the latter being a mathematically convenient expression for the number of fingers and the space between them. Fig. 3 shows an overview of the expected sheet resistance of such a metallic finger grid. A sheet resistance of around 1Ω/sq., which is only one-tenth of that of the front contact currently in use, seems feasible.

Application of grids to solar cells: design considerations

With the use of such material for the front contact as described above, the solar panel efficiency is expected to improve. Specific grid designs were developed in an optimization study [4], in which narrow lines of 20µm turned out to be a good choice, if a height/width ratio of 0.5 was assumed. However, in current state-of-the-art inkjet printing processes, such dimensions are not available. Calculations have therefore also been made with 60µm- and 100µm-wide grids [3] and an extensive range of finger heights [5], some details of which were presented in a previous issue of *Photovoltaics International* [6].

Besides grid design, the module design is also of importance: for instance, the optimal cell length depends on the idz. Fig. 4 shows the efficiency as a function of cell length for various heights of the grid. Clearly, a higher grid has more conductive material and therefore a lower resistance; this translates to a higher cell efficiency and also to a longer optimal cell.

In the very first study by TNO, the state-of-the-art width of the idz used in the industry was 500µm [3]. Not long ago, this width had decreased to 350µm, and 150µm is currently being reported by the industry as the next step. If the idz is reduced, the optimal cell length is also reduced. A lower fraction of surface area lost in the idz improves the optical performance; moreover, the optimal cell length shifts to a smaller value, because shorter cells will lead to reduced electrical losses in the front contact. It is important to check the benefit of grids for different idz cases, and to also consider all the effects associated with adding grids. For example, when the conductivity of the front contact is improved by adding a metallic grid (even with a small optical penalty), the optimal cell length is greater. All of these effects are summarized in Fig. 4.

As can be seen in all the graphs in Fig. 4, the application of a metallic grid improves the efficiency. The efficiency and the optimal cell length clearly increase with higher fingers, as the conductivity of the grid will increase. The current state of the art is effectively represented by Fig. 4(d). On the basis of a 19% small-cell efficiency covered with a commercial grade TCO of 10Ω/sq. and an idz of 350µm, the expected panel efficiency is about 16% with an optimized cell length of 4–5mm. A grid of 2µm in height would yield an improvement of just over $1\%_{abs.}$ for a 20µm-wide grid (Fig. 4(b)), and just under $1\%_{abs.}$ for a 60µm-wide grid (Fig. 4(d)).

A reduction in idz will yield a significant improvement in efficiency for the TCO-only sample, but a lesser one for the cells with a grid. The difference in magnitude between these two improvements mainly stems from the fact that cells with a grid are longer and the optical loss associated

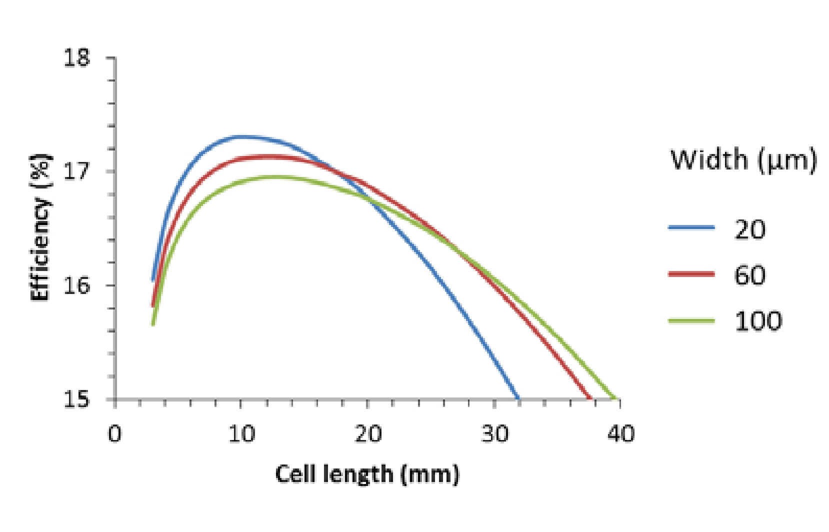

Figure 5. Efficiency as a function of cell length for various finger widths (grid height is 5µm).

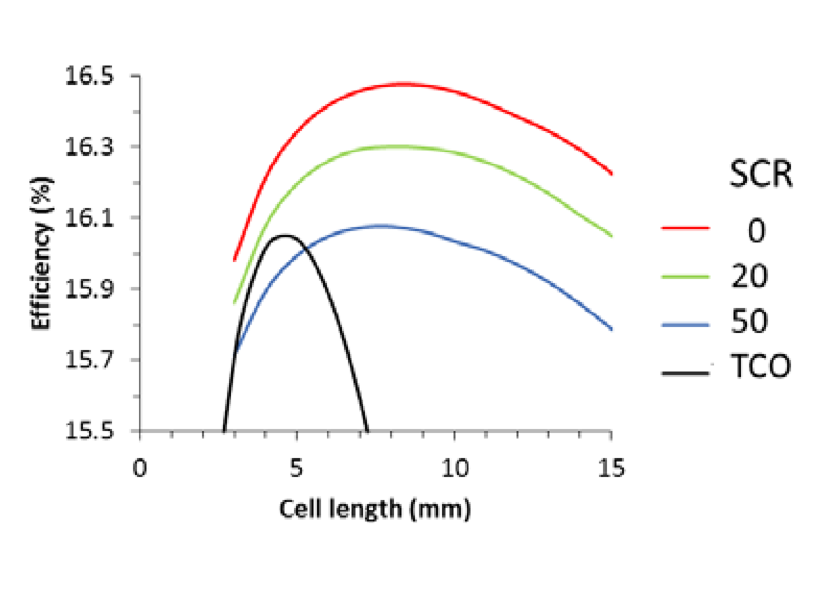

Figure 6. Efficiency as function of cell length, illustrating the impact of specific contact resistance (SCR, in mΩ·cm^2). The grid is 1µm high and 60µm wide in order to represent the current inkjet state of the art. An SCR of 0 represents no contact resistance, and 'TCO' indicates the cell without a grid and with no contact resistance [5].

with the idz is lower than for the shorter TCO-only cells. Nevertheless, the efficiency increase when passing from TCO-only to grid-assisted front contacts is still about 0.5%. This shows that it is important to co-optimize the panel design and the front contact, because the optimal configuration is a function of interdependent parameters.

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Fig. 5 shows another example, where the efficiencies calculated for various grid widths, while maintaining a height of 5µm, are compared. The values in this figure could serve as a reasonable benchmark and a technology decision aide, because a deposition technology that can achieve a grid width of 20µm will result in a higher efficiency than, for instance, printing technologies that can deliver 100µm. If a 0.1%$_{abs.}$ efficiency difference is estimated to have a value of around \$0.8/m^2 (see next section for details), then it is possible to determine how much added cost is allowed for a super-fine deposition technology, compared with a 'standard' 100µm line printer. Fig. 5 gives the answer: the difference in cost needs to be less than \$1.6/m^2, because otherwise there is no economic advantage in using the technology with the superior performance.

Not only do the configuration and technology play a role, but also the effect of suboptimal quality is an aspect that should be evaluated. For example, in the case of printing a metal on TCO, contact resistance might be present at the interface; this is represented by the specific contact resistance (SCR). A good specific contact resistance for metal printed on TCO is between 10 and 20mΩ·cm^2. Fig. 6 shows the calculated efficiencies of cells with a grid, plotted as a function of cell length for various contact resistances; the corresponding curve for a cell without a grid (and therefore no contact resistance) is also shown. The contact resistance reduces the benefit of the addition of the grid: however, it is estimated that the SCR will be less than 20mΩ·cm^2, and the impact could be minimized by dedicated ink development.

In short, although the potential for efficiency gain from grid-assisted front contacts is promising, there are a few boundary conditions, such as cell design and contact resistance, that have to be taken into account. A possible drawback of using a grid is the fact that an extra process is required. However, if a grid is used, the conductivity demands on the TCO are dramatically reduced; therefore, the TCO thickness can be much less, which results in not only increased transmittance of the TCO, but also reduced cost for TCO deposition in terms of materials and equipment. A careful cost–benefit calculation is necessary in order to determine the best options.

Technology options and cost–benefit balances

A new system was recently developed in which the cell separation and interconnection is made as a final step. In this case, the interconnection of choice would be a printed metal, as depicted in Fig. 1, which could seamlessly be combined with the metallic grid deposition [1]. In such an integrated separation/interconnection module, the positioning of the scribes would be much easier, and the expectation is that the idz could be reduced by switching to this type of system.

The economic values of several technological options were calculated and are compared in Fig. 7. The efficiency gain of adding a grid is around 0.5%$_{abs.}$, while the reduction in idz from 350µm to 150µm would yield a 0.8%$_{abs.}$ increase; the combination of the two adds 1%$_{abs.}$. These efficiencies are now translated into monetary values. It is assumed that the cost of making a solar panel is \$60/m^2 and that the total system is twice as expensive, at \$120/m^2. If this thin-film panel has an efficiency of a modest 15%, an additional 1%$_{abs.}$ in efficiency has a value of 1/15 × 120 = \$8/m^2, when just the costs mentioned above are taken into account. The ultimate value in terms of the value of electricity produced, however, is much higher: if a 1%$_{abs.}$ accounts for 10kWh/m^2 per year, which equates to around \$2/m^2 per year, then for a lifetime of 25 years that would add up to \$50!

The chart on the left in Fig. 7 shows the efficiency gain translated into \$/m^2. The middle chart shows the balance, which is the gain minus the associated cost of the grid deposition and change in manufacturing costs as a result of changes in cell length (number of scribes/m^2). In this middle chart, it is seen that reducing the idz contributes significantly to the balance, which is actually the profit. Adding a grid with an idz of 150µm yields a bonus in efficiency, but this effect is offset by the associated costs involved in the silver printing; such costs could be lower, however, once alternatives (such as copper-based inks) become available.

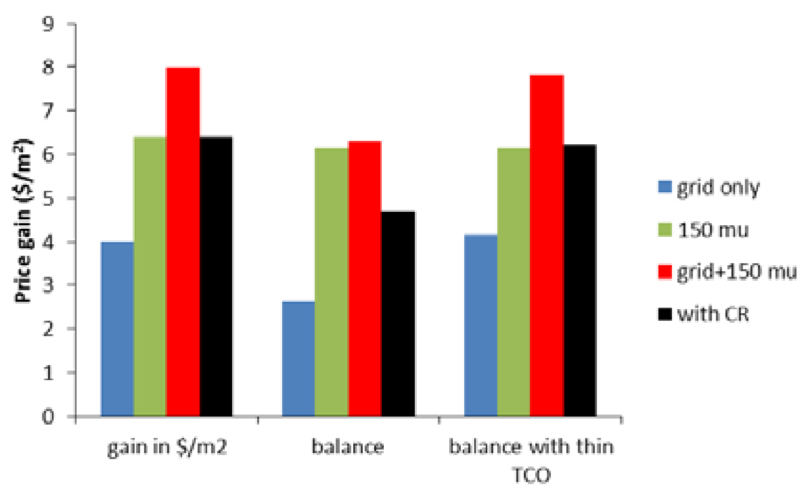

Figure 7. Gain, translated into \$/m^2, resulting from efficiency increases and cost–benefit balances of various technologies. The baseline is a cell with TCO-only and an idz of 350µm. In the legend, 'grid only' represents the addition of a grid, '150 mu' represents a TCO-only cell with an idz of 150µm, 'grid+ 150 mu' represents a combination of the two, and 'with CR' represents this same combination, but including the effect of contact resistance.

The set of data represented by the middle chart in Fig. 7 does not include the bonus of reduced manufacturing costs due to the thinner TCO; this is shown in the right chart. If reduced TCO costs are taken into account, the grid deposition in combination with 150µm, as shown by the red bar, seems an attractive option. Unfortunately, if the contact resistance is 20mΩ·cm^2, this cost benefit would be counteracted. Fig. 7 illustrates the advantage of putting benefit and gain–cost balance figures in \$/m^2 for various technological options next to each other; this can lead to the making of both technologically and economically viable decisions.

Texturing for black panels

Any light that is not captured by the absorber does not contribute to the solar panel operation. Maximizing the in-coupling of light has been a major topic for many decades. Thin-film PV offers the possibility of making layer

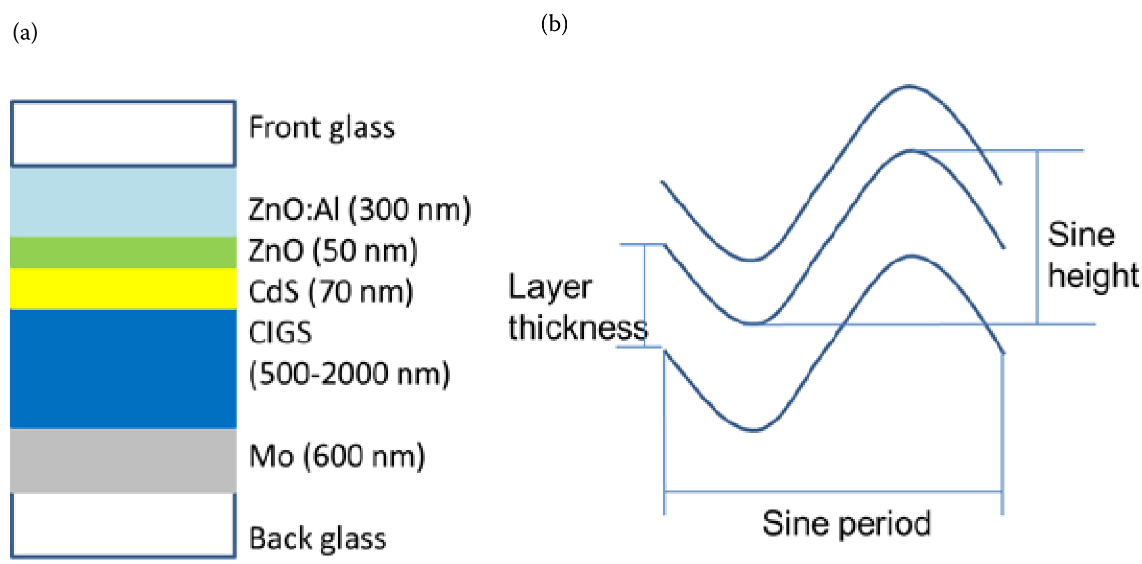

Figure 8. (a) Layer build-up of a CIGS cell. (b) An example of a texture as used in modelling.

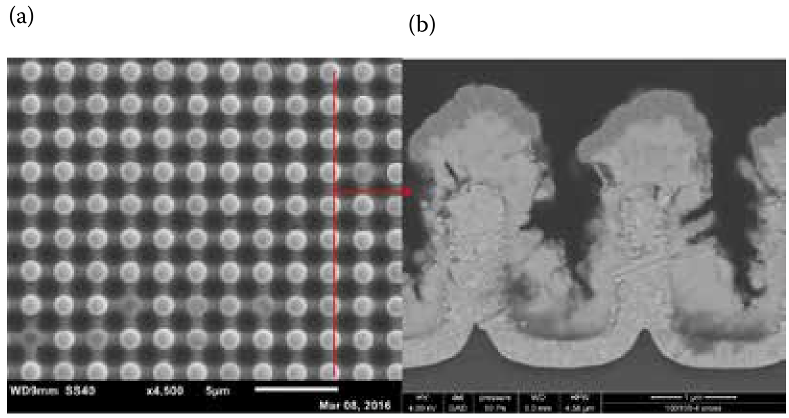

Figure 9. Scanning electron microscopy (SEM) images of textures: (a) top view of a texture with only a Mo layer; (b) cross section of a texture with a full cell stack.

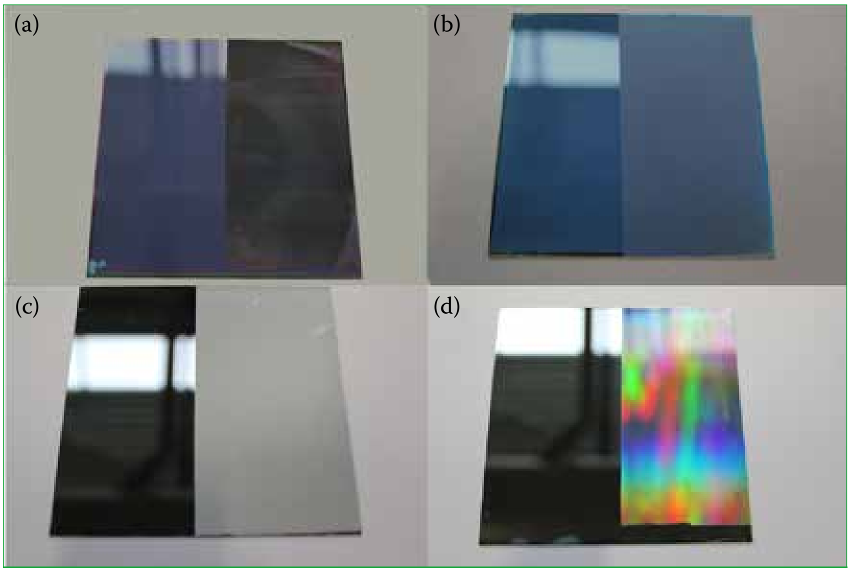

Figure 10. Examples of the optical effects caused by the choice of textures, with Mo+CIGS coatings on a texture (a,b), and a Mo coating (c,d): (a) high texture for 'black CIGS' appearance; (b) random texture for light-diffusing appearance; (c) random texture with strong light-scattering effect; (d) periodic texture with rainbow effect. The left-hand sides of the images are the smooth substrates, and the right-hand sides are textured. The whitish horizontal bar is a reflecting light source.

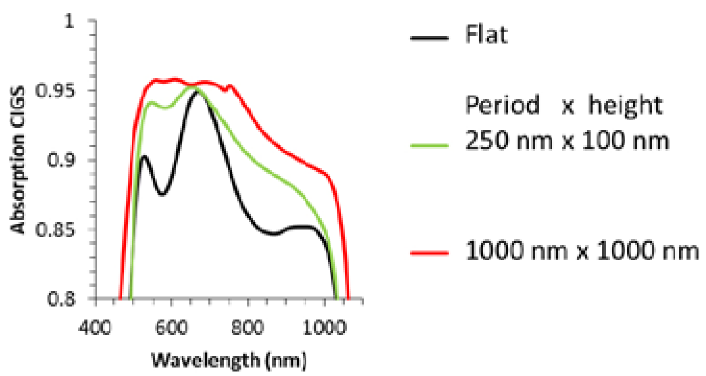

Figure 11. Examples of CIGS absorption spectra for different texture dimensions.

stacks on specifically designed textures; this has been developed especially for thin-film silicon, as it is an absolute necessity in this case because the Si layer needs to be thinner than optimal for light capturing.

For CIGS-based cells, however, much less has been done in terms of development in the texturing field. There has been some work on texturing the TCO, but it has only been very recently that the technology of texturing the substrate in order to enhance the performance of CIGS has surfaced as a point of interest. The main reason for this 'delay' is that CIGS layers can be made adequately thick so as to absorb most of the light. With the vision of thinner CIGS layers for cost reduction, work has been carried out on sub-500nm CIGS on textured substrates; however, the cell efficiencies achieved with such technology do not match the requirements of the industry at the moment. Nevertheless, it is worthwhile investigating the potential of back-contact texturing, because not only could it be useful for thinner layers, but it might also serve to eliminate internal reflections, i.e. create 'black' CIGS.

In air, the CIGS layer reflects more than 10%. Although this value is much less than that for Si (~30%), and the total stack in a CIGS solar cell is even less reflective, any gain in this domain directly translates to better performance. Back-contact texturing could therefore be a possible asset here, as well as for thick CIGS cells. In addition to random texturization, nano-imprint technology can be applied to create specific textures, and modelling can be used to determine the required functional texture dimensions. Fig. 8 shows a cross section of a CIGS cell layer stack and an example of a texture, in this case a sine texture. Periodic textures have a certain period and height, and even with just a simple sine shape, a large variety of textures can be obtained.

In addition to sine textures, another possibility is pillar-like textures, an example of which is shown in Fig. 9. When these pillars are coated by the solar cell materials, the vertical surfaces are coated too (almost). Fig. 9(b) shows a scanning electron microscopy (SEM) image of a cross section of a textured CIGS cell stack; the cross section is taken from the side of the pillars, indicated by the red line in Fig. 9(a). The imprint material (the dark layer on the bottom) therefore shows only a small texture at the location of the cross section, while the Mo (lowest bright material)

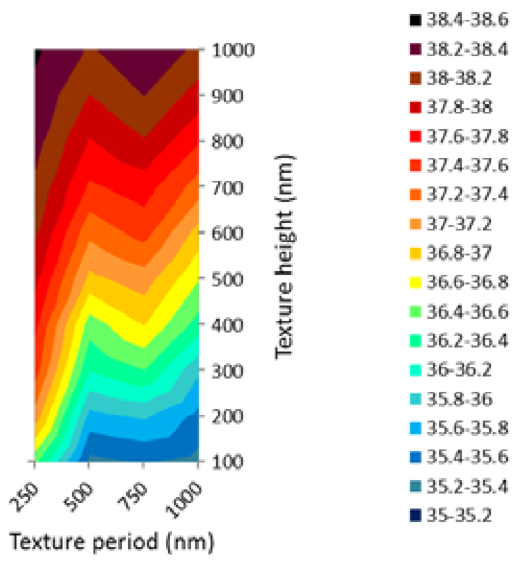

Figure 12. Area plot of modelled CIGS cell current density (mA/cm^2), represented by different colours, for various sine texture dimensions.

shows as a pillar in the image. Above and surrounding the Mo is the CIGS layer, and the slightly darker layer on top is the ZnO:Al. The CdS is located between the CIGS and the ZnO:Al layers, but is only visible on very close inspection of the image. The pillar texture results in a reduction in reflectance of more than 60%. Unfortunately, without substantial process development, the electrical performance of the cell with such an extreme texture does not match its optical performance. Nevertheless, this example shows that, from a deposition point of view, extreme textures are a possibility.

"An interesting aspect of periodic textures is that tuneable colours can be produced."

Once the processing and coating steps have been developed, reducing the reflection of the CIGS (stack) is just one option, as shown in Fig. 10. Note that the left side of each of the images in Fig. 10 shows the untextured sample, and the right side shows the textured portion. In Fig. 10(a) there is a reduction in reflection of about $3\%_{abs.}$ for the textured sample; this sample has the same texture as the samples shown in Fig. 9. Fig. 10(b) shows a CIGS on top of a random texture, and the reflected light has become totally diffuse because of the texture. CIGS itself has already a certain amount of texture, but perfectly smooth Mo layers too can be made completely light-diffusing by the use of a random texture, as seen in Fig. 10(c). An interesting aspect of periodic textures is that, when choosing the appropriate dimensions, tuneable colours can be produced; a rainbow appearance, as shown in Fig. 10(d), is the result of a Mo coating on top of such a period texture.

Modelling as a design tool

There is a wide range of exciting optical properties that can be achieved by texturization, and the most compelling benefit is the associated increase in efficiency. In order to determine the potential of such technology, modelling can be a powerful aid. Even more usefully, modelling can also calculate the expected benefit of texture dimensions and their impact on the optical behaviour of the solar cell stack. Fig. 11 shows the modelled absorption of CIGS in a CIGS cell stack for a flat layer stack and for two different sine texture dimensions. Depending on the dimensions, the absorption can be increased either in certain wavelength ranges or overall. From the resulting generated optical data, the current density can then be calculated. Fig. 12 shows a full mapping of the CIGS cell current density over a full range of texture periods and texture heights.

The modelling includes all the optical phenomena on the assumption that all the layers follow the texture perfectly. It can easily be seen that a higher texture is beneficial, but also that some periods are more effective than others. In particular, a period of 750nm can be a good choice, as it creates an increase in current at moderate height/period aspect ratios. A period of 250nm has the greatest impact, but the height/period aspect ratios required in order to obtain these effects are not practical in a manufacturing environment.

In summary, the modelling not only indicates the benefits but also provides a tool to rationalize certain design options. A comparison of the modelling results and the reflection measurements has been made. According to the model, a texture can increase the absorption of the CIGS layer, which is mainly caused by a reduction in the reflection, as shown by the measurement in Fig. 13; the measured value is expressed as 100 – reflection ($100 - R$) for comparison purposes. The differences between the modelled and measured values represents the parasitic absorption of the layers on top of the CIGS.

Cost–benefit balance

Efficiency gain is only part of the whole story, because the cost associated with it has to be taken into consideration. Fig. 14 shows that the potential gain in terms of efficiency is substantial (this figure is solely intended as an illustration of how important it is to take account of all factors). In an ideal case, the modelling suggests that the translated value of the efficiency gain could be greater than $\$10/m^2$. However, on the basis of experience, and of theoretical and practical insights, it is estimated that the realistic gain should be somewhere around $\$6/m^2$. The cost of light-management technology can vary widely, and here a rather expensive $\$4/m^2$ estimation is chosen in order to demonstrate that something that looks highly promising on paper could yield much less of a benefit when taking into account all the factors, and that the balance (i.e. gain minus cost) is only a fraction of the potential benefit. If the gain achieved by light-management technology is higher and the costs are lower, the balance will, of course, be much more favourable.

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No claims are being made here that

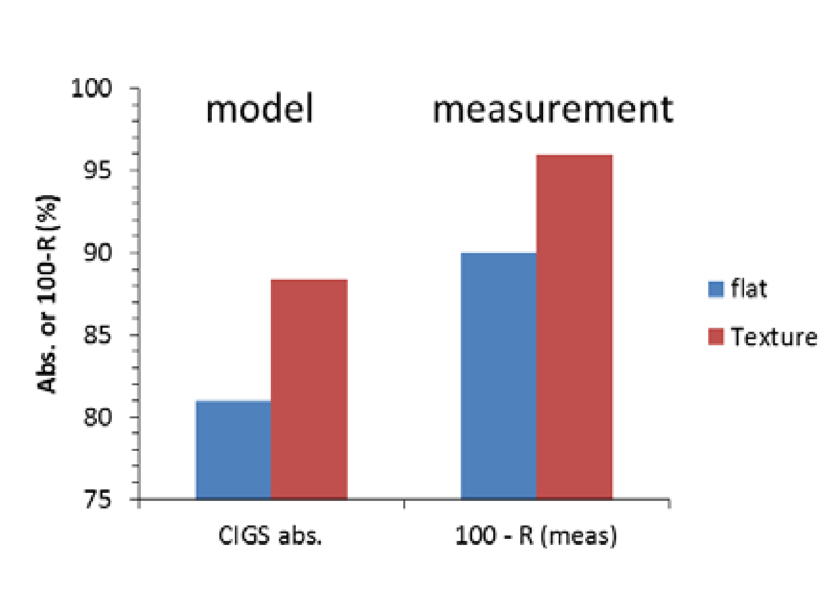

Figure 13. Modelled CIGS absorption for flat and texture surfaces of 1000nm × 1000nm, and optical measurements of flat and textured samples. The differences between modelled and measured values represent the optical losses of parasitic absorption in the ZnO:Al and CdS layers.

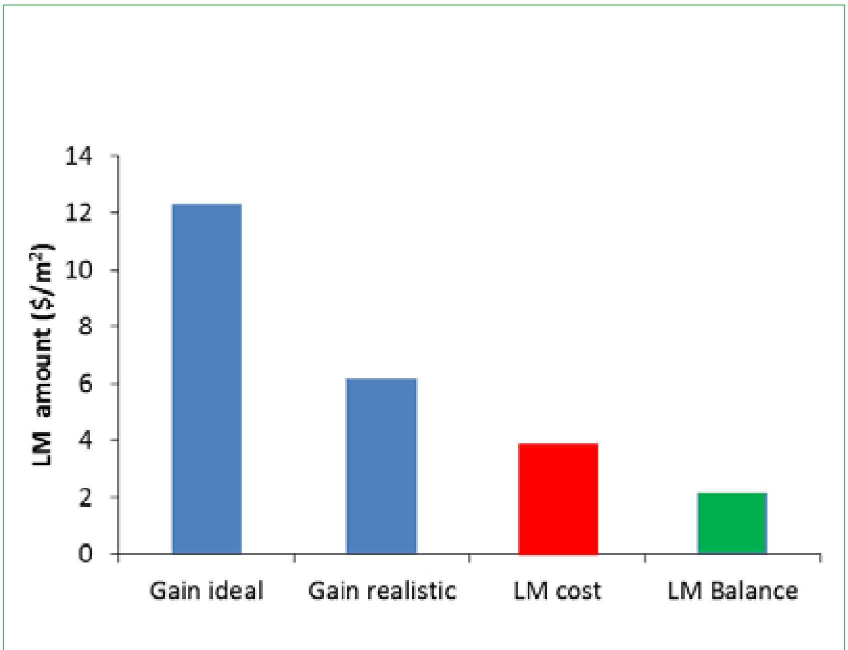

Figure 14. Calculated gain from using light-management (LM) technology for an ideal structure, along with the values for a more realistic scenario. Red signifies a very high estimation of the cost associated with LM technology, while green represents the balance, which equals gain minus cost.

nanotexturing and light management are not worthwhile: the intention is just to show that it is important to get the whole picture, and that both a good dose of realism as to the actual potential of the technology and a clear idea of the cost involved are indispensable. When the combination of all these important factors is considered, only then is it possible to make sensible decisions about innovation strategies.

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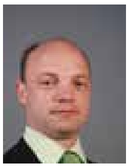
About the Authors



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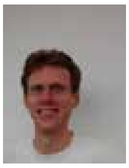

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