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# Improving the efficiency of PV modules using glass with reflective strips

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## ABSTRACT

Conventional ribbons used for interconnecting solar cells in PV modules act like mirrors, causing a large proportion of incident light to be lost. Experimental results indicate that only around 5% of the perpendicular incident light on the connections can be reused; as a result, this area contributes very little, if at all, to the current generation. In order to reduce the mirroring effect, a new glass with reflective strips placed on top of the solar cell busbars has been tested. The use of white reflective strips with high reflectivity and good Lambertian behaviour is responsible for a theoretical increase in efficiency of $0.28\%_{abs.}$ in a standard PV module processed with three-busbar solar cells. Different PV mini-modules were fabricated in order to study the real effect of the glass with reflective strips. The experimental results showed that the average short-circuit current density increases by $1.2\%_{abs.}$ with this new glass, which equates to an increase in PV module efficiency of $0.23\%_{abs.}$, or a gain of 0.033% per cm$^2$ of connecting ribbon. In consequence, the glass with reflective strips helps to reduce cell-to-module losses. Moreover, and using the same effect, reflective strips can be placed on the glass, in the spaces between the solar cells in a PV module; this helps to improve the current density, mainly in glass–glass and bifacial modules. The study of this new type of PV module is currently under way, with the publication of results forthcoming. The technology is simple and inexpensive; it is compatible with polished and textured glasses, and supports glasses with anti-reflection coatings. In addition, no degradation has been found in PV modules after various tests carried out in a climate chamber. This reflective strip technology is therefore almost ready for use at the industrial level.


## Introduction

Reducing the costs associated with PV is an important contribution towards making this type of renewable energy more competitive. On account of the facts that over the last few years PV production capacity has exponentially increased, and that the industry has seen significant development in Asia, the price per watt of a PV module has currently reached a level of around $0.50/Wp [1]. Because of this low average price and the excellent efficiencies achieved, 93% of the actual PV industry was associated with silicon-wafer-based technology in 2015; around 96% of that percentage is attributable to double-side-contacted silicon solar cells. By 2026 this percentage is still expected to be very high (around 80%) [2].

There are two main reasons for this tendency: high efficiency and low price per watt. One way to reduce the latter is to increase the efficiency of the PV device. In this respect, the efficiency of a solar cell has increased more rapidly than that of a PV module; resistive and optical losses are the major reasons for this difference.

In recent years a lot of effort has been put into increasing the efficiency of PV devices; as a result, efficiencies of 19.8% have been achieved for multicrystalline silicon solar cells at the industrial level. For PV modules, however, the average industrial efficiency has been reduced to 17.1% [3]. Given this, the approaches to increasing PV module efficiency have focused on optical and electrical losses at the module level. Optical losses are mostly due to light absorption and/or reflection by the glass, the encapsulant and the metalized area of the solar cell. Electrical losses are mainly caused by series resistance in the string connectors; indeed, because of the interconnection between the cells, and on the basis of the above-mentioned achievable efficiencies, experimental studies have shown that the fill factor decreases by around $3\%_{abs.}$ for a PV module compared with that for a solar cell [4].

Many avenues of investigation are being pursued to reduce the loss in fill factor. One possibility is the use of solar cells with multiple busbars. This arrangement leads to a reduction in series resistance at both cell and module levels; moreover, the impact of grid damage (such as an accidental finger interruption in the metallization grid of the solar cell) is decreased. Another advantage of the use of a greater number of busbars is the reduction of the stresses associated with the ribbon-soldering step [5]. As a result, and according to the International Technology Roadmap for Photovoltaic (ITRPV 2016) [6], the industry will gravitate to the use of four (or even more) busbars in the near future. However, it must be borne in mind that any electrical improvement is partially negated by shading losses.

With standard PV glass, currently around 92% of the incident light is transmitted to the solar cells. The percentage can be improved by using textured glass and/or glass with an anti-reflection coating layer, resulting in around 96% of the incident light reaching the cells. A lot of effort has therefore been put into increasing the transmission of light in the glass; however, in glass design the light reflected by the solar cells is not considered. In particular, it is important to take into account the light reflected by the busbars. In today's industrial solar cells, around 3% of the total area is covered by the three busbars, which is even higher if more busbars are used.

When attempting to increase the efficiency, the optical utilization of the inactive areas of the solar cells and PV modules becomes an important issue. In particular, following encapsulation some of the light reflected by all the inner PV module surfaces can be reused. Taking into account the refractive indices of the encapsulant, the glass and the air, Snell's law shows that the critical angle for achieving total internal reflection of the light reflected by the inner PV module surfaces is 42°. For lower angles, most of the light will escape from the PV module and does not contribute to increasing the current photogenerated by the solar cells.

**"It is essential to increase the percentage of incident photons striking the solar cell ribbons and redirect them to the active area."**

In order to reduce the shading effects mentioned earlier, it is essential to increase the percentage of incident photons striking the solar cell ribbons and redirect them to the active area. One way to achieve this objective has been proposed by Hamann et al. [7], who proposed the use of white-painted ribbons. They reported an experimental improvement in efficiency of 0.20%$_{abs.}$ if the area covered by ribbons is 3.5%; this implies a 0.023%$_{abs.}$ increase in efficiency for each cm$^2$ of ribbon. However, because of the possibility of degradation and the reduction in optical properties during the soldering step of a solar cell series, white-painted ribbons have not yet gained (according to the authors' knowledge) the expected acceptance at the industrial level.

In this paper, another method for taking advantage of the ribbon area is presented; this method is based on the use of a new glass with reflective strips placed on top of the tabbing ribbons. The reflective strips are created with a white paint based on titanium oxide nanoparticles (NPs). These NPs are responsible for a high global reflectance, with a diffuse component close to the ideal Lambertian one. Calculations show a theoretical increase in PV module efficiency of 0.28%$_{abs.}$ if the area covered by ribbons is 2.9%. In this case, the improvement in efficiency per unit area of the ribbon is 0.040%/cm$^2$ as a result of the use of a glass with reflective strips.

Different PV mini-modules were fabricated in order to study the real effect of the glass with reflective strips. Three different glasses were used: 1) polished side facing the air, and textured side facing the cell; 2) textured side facing the air, and polished side facing the cell; and 3) both sides polished. In all cases, an improvement of 0.033%$_{abs.}$ per cm$^2$ of the tabbing ribbon was obtained experimentally, which implies a 0.23%$_{abs.}$ gain in efficiency for a standard PV module containing three-busbar solar cells. In consequence, the glass with reflective strips helps to reduce cell-to-module losses.

An interesting technology that is growing and expected to reach a 20% market share in 2026 is the bifacial solar cell concept [6]; here, the effect of the use of a glass with reflective strips will be even more notable. They can be placed on top of the busbars and in the spaces between solar cells, thus reducing the inactive areas of the PV module.

Reflective strips are compatible with any type of PV glass – polished or textured, and with anti-reflection coating layers. It is essential, however, that these strips remain stable in outdoor conditions. Different accelerated ageing methods have been studied for PV modules processed with glasses with reflective strips: no variation in module efficiency has been found compared with that for PV modules used as references.

There is also the possibility of using reflective strips on top of the interconnections between the solar cells in a series. Furthermore, and depending on the demand for architectonic integration, it is possible to use reflective strips of different colours.

## Optical behaviour of the metallization grid in a PV module

When trying to increase efficiency, the optical utilization of the inactive areas of solar cells and PV modules is vitally important; in particular, following encapsulation some of the light reflected by all the inner PV module surfaces can be reused. Taking into account the refractive indices of the encapsulant, the glass and the air, Snell's law shows that the critical angle for achieving a total internal reflection of the light reflected by the inner PV module surfaces is given by:

$$\theta = \arcsin\left[n_{air} / n_{glass\text{-}EVA}\right] \quad (1)$$

On the assumption that the glass and the encapsulant have a refractive index of 1.5, the internal reflectance angle $\theta$ at the glass–air interface must be greater than 42°. For smaller angles, most of the light will escape from the PV module and does not contribute to increasing the current photogenerated in the solar cells.

By considering the spacing of cells, and given a Lambertian reflector (ideal diffuse surface) embedded in EVA and glass, it can be shown that the maximum percentage of incident light that can be reused is 56% [8]. In this respect, it has been experimentally shown that the percentage varies from 43% to 52%, depending on the PV backsheet selected [9].

In standard industrial specifications, the area of the metallization grid of typical crystalline silicon solar cells occupies between 6 and 8% of the cell surface; this area has a low contribution to current generation because it is shaded by the metal. As shown in Fig. 1, shading losses can be reduced after encapsulation by the total internal reflection (RTI) from the metallization grid of a certain percentage of photons, which are redirected back to the cell.

Fig. 1 shows the case of a ray of light which falls perpendicular to the PV module. From the point of view of the optical properties of the metallization grid, the ribbons soldered to the busbars have a high specular component. As will be discussed later in this paper, it has been experimentally determined that less than 5% of the incident light is reused. This percentage is well below the theoretical limit of 56% mentioned previously, and implies only a 0.12% improvement in the short-circuit current of the solar cell.

A novel means of reducing the shadowing effect of the solar cell metallization grid is presented; the method is compatible with the vast majority of crystalline silicon solar cells, as well as with current industrial PV module fabrication processes. It is not necessary to impose restrictions on the ribbon selection and/or on the soldering step, both of which play an important part in reducing the series resistance of a PV module, and hence in increasing its efficiency. The method presented in this paper is based on the use of a glass with reflective strips placed on top of the solar cell metallization grid.

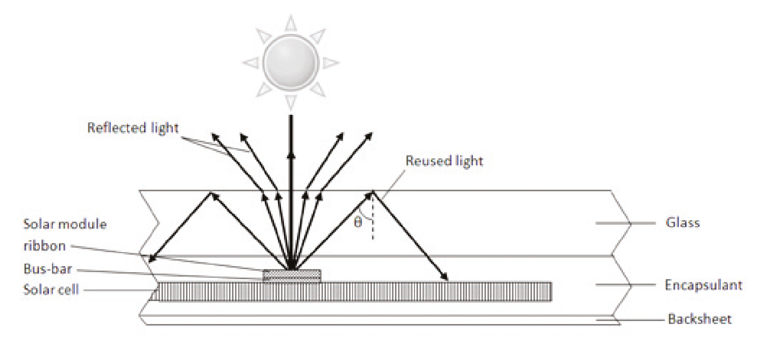


**Figure 1. Schema of the reflection of a ray of incident light striking a tabbing ribbon.**

> “The method is based on the use of a glass with reflective strips placed on top of the solar cell metallization grid.”



## Glass with reflective strips

To usefully exploit the light reflected from the solar cell ribbons, a glass with reflective strips was experimentally developed and tested in the laboratory at Valencia Nanophotonics Technology Center. As a result of the improvements obtained in performance, the glass with reflective strips has been patented.

The reflective strips are placed on the inner side of the glass, and on top of the solar cell metallization grid; a schema of a PV module with a reflective strip is shown in Fig. 2.

A white paint based on titanium dioxide pigments was used to define the reflective strip; as well as its high global reflectance, it efficiently scatters the light. As a result, a significant percentage of the incident photons can be reused by light trapping (Equation 1); these photons are subsequently absorbed by the solar cell active area.

The combination of high global reflectance and the short distance from the interconnection ribbon also allows an efficient use of a percentage of light transmitted through the reflective strip placed in the glass. In addition, as will be revealed below, the influence of the angle of incidence of the light is minimal.

The reflective strips discussed in this paper can be used to cover all the metallization grid of a solar cell, which includes the fingers and the busbars. Depending on the fabrication technology, two solar cells with the same number of busbars can have a different number of fingers. However, for a given number of busbars, the busbar positions on the solar cell surface are fixed; therefore in order to obtain a more general result, reflective strips placed only on top of the busbars have been studied.

## Optical characterization of the reflective strips

### Reflectance, transmittance and absorbance

Global reflectance and transmittance measurements of the reflective strips were obtained using a SpecWin Light CAS 140CT spectrophotometer and an Instruments Systems 150mm integrating sphere. Absorption was calculated from the equation:

$$\text{Absorption} = 1 - \text{Reflection} - \text{Transmission} \quad (2)$$

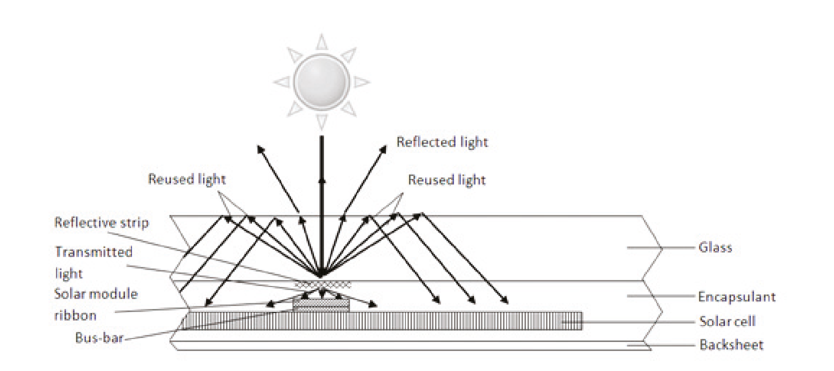


**Figure 2. Schema of the behaviour of a ray of incident light hitting a reflective strip.**

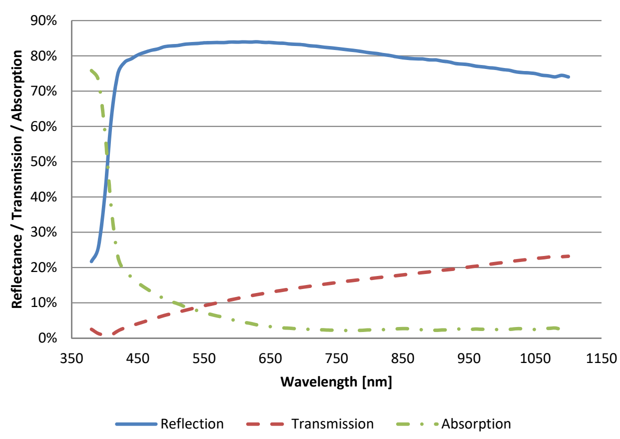


**Figure 3. Global reflection, transmission and absorption of the white paint used to define the reflective strips.**

Measurements as a function of wavelength are shown in Fig. 3. An average global reflectance of 79.3% and transmittance of 14.6% were determined for the reflective strips.

### Angular dependence of the reflected and transmitted light

According to Equation 1, and in order to estimate the percentage of the incident light on the reflective strip that can be sent to the active area of the solar cell, it is important to study the angular dependence of the reflected and transmitted light. To this end, and depending on the relevance of the specular component, a variation of $9\%_{abs.}$ for the reflected light that undergoes total internal reflection can be found in reflective layers with similar global reflectances [9].

An angular measurement set-up (Thorlabs optical components) was performed in order to determine the angular dependence of the light reflected by and transmitted through the reflective strip. Fig. 4 shows a schema of the set-up used.

To measure the angular dependence, both the laser and the sample were kept in fixed positions. The spectrometer was turned using a Thorlab’s NanoRotator 360° rotation stage and their APT precision motion controller. The angular measurement cannot be performed at angles between ±5° with respect to the laser position, because the laser beam and the spectrophotometer cannot be superimposed.

A 633nm red laser from JDS Uniphase was selected for this study. The reasons for this choice are its stable characteristics, the high reflectance of the white paint at 633nm, and the fact that the external quantum efficiency of a standard crystalline silicon solar cell reaches its maximum close to the laser emission wavelength.

For a quasi-normal incidence, Fig. 5 reveals the angular dependence of the reflected and transmitted light of the white paint used in the reflective strip. As a reference, the response of a standard metallic ribbon is also indicated (in green) in the figure.

According to Fig. 5, no specular peaks are visible in the case of the reflective strip. In addition, the reflected and transmitted light is markedly diffused. A different phenomenon is observed with a standard PV ribbon, for which the specular component is much greater

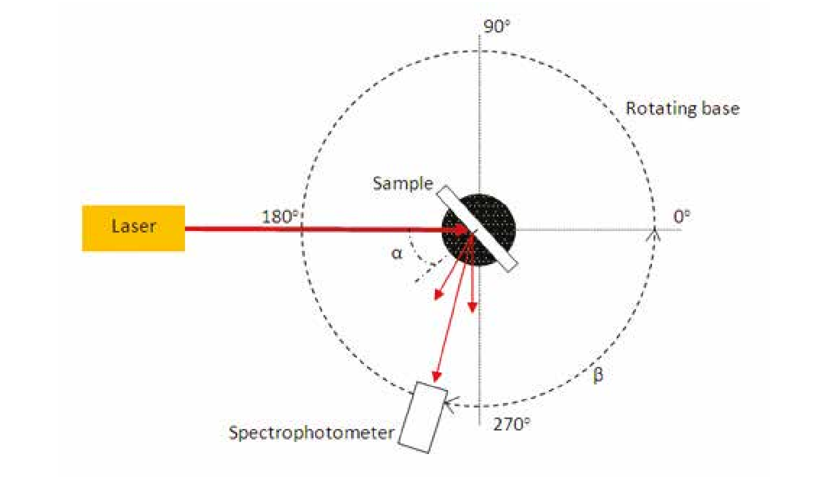


**Figure 4. The set-up used to measure the angular dependence of the backsheets. The laser is placed in a fixed position, where *α* is the angle between the laser beam and the perpendicular to the sample. The sample can be rotated through the range *α* = 0 to 90°, but is kept fixed while a measurement is being taken. *β* is an angle related to the position of the spectrophotometer, which can be rotated from 0 to 360°.**

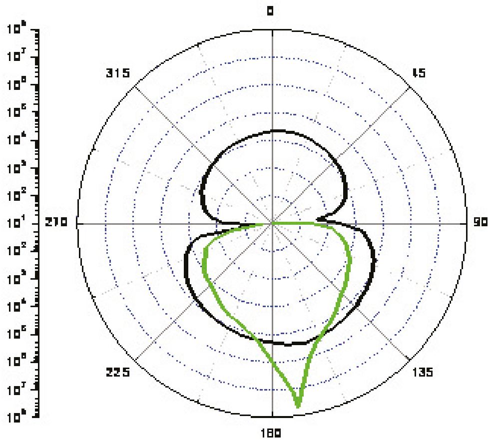


**Figure 5. Angular dependence of the light reflected by and transmitted through the reflective strip (black) compared with a standard PV ribbon (green). In this set-up, the light incidence takes place at 180°. In order to measure the specular component of the reflected light, the sample is rotated by an angle *α* = 5°. The reflectance response is located in the second and third quadrants, and the transmittance in the fourth and first quadrants.**

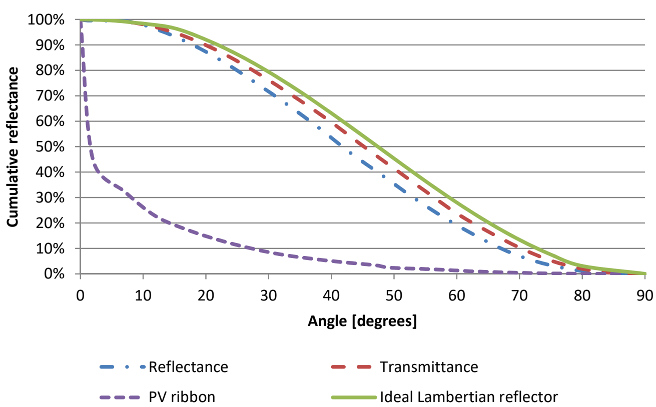


**Figure 6. Cumulative reflectance and transmittance of the reflective strip and a PV ribbon, for a quasi-normal light incidence.**

"No specular peaks are visible in the case of the reflective strip."

For a quasi-normal incidence of light ($\alpha$ = 5°), the cumulative reflectance was calculated by integrating the measured light over the solid angle of 2π; the results are shown in Fig. 6. A standard PV ribbon acts like a mirror; in this respect, as shown in Fig. 6, its specular component is important. On the other hand, and mainly in the case of transmitted light, the reflective strip has an angular dependence similar to that of an ideal Lambertian surface.

Depending on the position of the reflective strip in a PV module, and on the light reflected, the use of a significant fraction of the light transmitted through the module is possible; a greater percentage of the light directed towards the metallization grid can therefore be utilized. Bearing in mind that total internal reflection at the glass–air interface takes place for angles of incidence greater than 42°, for a standard PV ribbon the percentage of the reflected light that can be reused is close to 5%. In contrast, the percentage values achieved for the reflected and transmitted light that can be reused in the case of a reflective strip are around 50% and 55% respectively. It is therefore expected that improvements to the current of a PV module can be made because of the better utilization of the light directed towards the solar cell metallization grid and module interconnections.

## Dependence of the reflectance and transmittance on the angle of incidence of the light

The following characterization step consists of studying the optical response of a standard PV ribbon and a reflective strip as a function of the angle of incidence of the light. Three angles were selected: $\alpha$ = 5°, 30° and 60±2° (low- to high-gloss regions). Figs. 7 and 8 summarize the results; according to Fig. 7, a standard PV ribbon has a significant specular component, which increases slightly with the angle of incidence.

As regards the reflective strip, the percentage of reflected light increases as the angle of incidence increases, which is consistent with the Fresnel equations [10]. This behaviour is mainly due to a reduction in the transmitted light through the reflective strip. No specular peaks are observed, and a significant

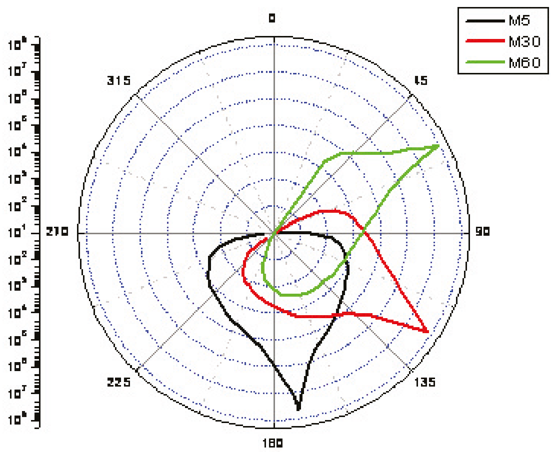


**Figure 7. Angular dependence of the light reflected by a standard PV ribbon, for three different angles of incidence.**

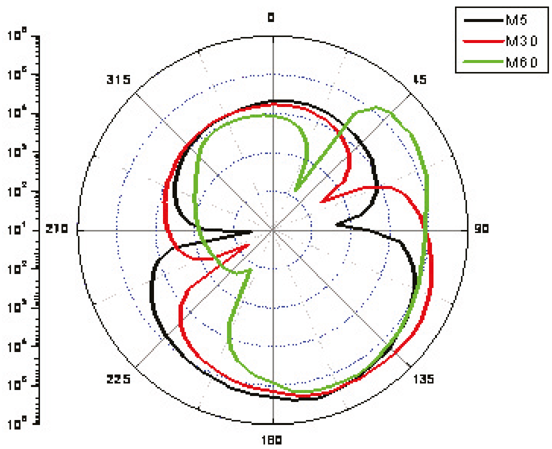


**Figure 8. Angular dependence of the light reflected by and transmitted through a reflective strip, for three different angles of incidence.**

diffused component is present in all cases. The reflective strip therefore acts like an ideal Lambertian surface.

## Effective optical surface area calculation

With the previous characterization measurements in mind, and neglecting multiple internal reflections, the optically active surface area ($S_{opt}$) of a PV ribbon was defined. This surface area can be deduced from the metallization grid area and can be added to the active area of the solar cells. As shown in Equation 3, $S_{opt}$ depends on the ribbon's global reflectance and transmittance, and on the angular response to the light:

$$S_{opt} = [(G_R \times R_{lr}) + (G_T \times T_{lr})] \times S_{ribbon} \quad (3)$$

where $G_R$ is the global reflectance of the ribbon, $R_{lr}$ is the reflected light due to total internal reflection at the glass–air interface and which can be reused, $G_T$ is the global transmittance of the ribbon, $T_{lr}$ is the transmitted light that can be reused, and $S_{ribbon}$ is the PV ribbon surface area. In an ideal case, where the global reflectance and the reflected light of an inactive area of the PV module that can be reused is 100%, the entire surface would be active.

In the case of a standard PV ribbon, the average global reflectance is close to 85%, the reflected light due to the total internal reflection at the glass–air interface and which can be reused is 5%, and the global transmittance is 0%. Because of this, only 4.3% of a standard PV ribbon surface is optically active.

In comparison, for a reflective strip placed on top of a PV ribbon, the average global reflectance is 79.3%, the reflected light due to the total internal reflection at the glass–air interface and which can be reused is 50%, the global transmittance is 14.6%, and the percentage of the transmitted light that can be reused is 55%. In this case, around 47.7% of the PV ribbon surface is optically active on account of the effect of the reflective strip. The metallic surface area that is optically active thanks to this effect is increased by a factor of more than 10, because of the use of reflective strips; this equates to a short-circuit current gain of 1.35% for a standard PV module fabricated with three-busbar solar cells. This improvement becomes more significant with an increase in the number of busbars and/or their surface area.

"Around 47.7% of the PV ribbon surface is optically active on account of the effect of the reflective strip."

## Experimental results

### Electrical parameters

Three-busbar high-efficiency 156×156×0.18mm multicrystalline silicon solar cells with similar electrical parameters were used to study the effect of the reflective strips on the short-circuit current and efficiency of PV mini-modules. Each glass had two different configurations on two independent solar cells: one of them had reflective strips, and the other was used as a reference. The same low-iron PV glass, encapsulant and backsheet were utilized in each case.

Three mini-modules were fabricated with each type of glass (polished side facing the air, and textured side facing the cell; textured side facing the air, and polished side facing the cell; and both sides polished).

The electrical characterization of the mini-modules was carried out under standard test conditions using a class A solar simulator from Abet Technologies. A black mask with a separation of 2±0.3mm between the solar cell and the mask edges was utilized. The incident light was perpendicular to the PV mini-modules, and at least three measurements were taken in each case.

Fig. 9 shows a reference module with a standard PV glass, and a test module with the same glass, but with reflective strips painted on its inner side. According to Fig. 9, there is a pronounced difference between the PV modules in terms of the light reflected by the connecting ribbons. In the standard module, the connecting ribbons have a high specular reflection, as mentioned previously. As a result, the light is reflected away from the camera, and they have a dark appearance. On the other hand, in the case of the module with a glass incorporating reflective

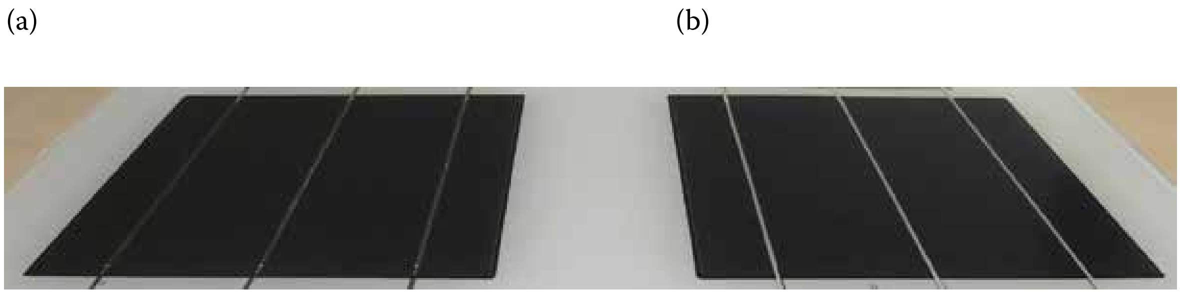


**Figure 9. (a) Standard PV module. (b) PV module with a glass incorporating reflective strips.**



strips, a large percentage of the light directed towards the connecting ribbons is reflected back to the camera. This effect highlights the different reflection behaviours of the two mini-modules.

The short-circuit current of the PV modules processed with a glass incorporating reflective strips showed an average improvement of 1.2±0.2%$_{abs.}$, which is close to the theoretical value of 1.35%. This short-circuit current improvement implies a reduction in cell-to-module efficiency losses of 0.23%$_{abs.}$ due to optical effects alone. If the surface of the busbars in the solar cells used in this study is taken into account, the improvement in efficiency is 0.03%$_{abs.}$ per each cm$^2$ of busbar. For three-busbar solar cells, according to the theoretical results a variation in efficiency of 0.28%$_{abs.}$ (0.04%$_{abs.}$/cm$^2$) is achievable.

## Degradation

In general, different methods of accelerated ageing have traditionally been used on PV modules, for example the UV exposure, thermal-cycling and damp-heat tests, as well as the highly accelerated stress test (HAST). The application of simultaneous multiple stresses – such as temperature, humidity and UV radiation – is also common. In this study, two degradation tests were investigated: damp heat (IEC 61215) and thermal cycling (TC200) [11]:

- Damp-heat test: a module is subjected to 1,000 hours at 85°C/85% RH in accordance with IEC 61215, which corresponds to 20 years' outdoor exposure. For this study, however, the duration of the test was extended to 1,200 hours.
- Thermal cycling test: performed for 200 cycles (TC 200), this test aims to simulate the thermal stresses on materials as a result of extreme changes in temperature (between −40°C and +85°C).

In this study, one mini-module with a glass having both faces polished was used as a reference, while another mini-module with the same glass but incorporating reflective strips was investigated. An Espec Global N environmental chamber was used to perform the degradation. Special attention was paid to the variation in short-circuit current, with the initial short-circuit current of the standard PV module taken as the reference. Figs. 10 and 11 show the degradation results, as well as the standard deviations.

No adhesion problems between the reflective strips and the glass were observed. Moreover, no important variations were discovered between the initial short-circuit current density and the value after both degradation processes. In this respect, the resulting

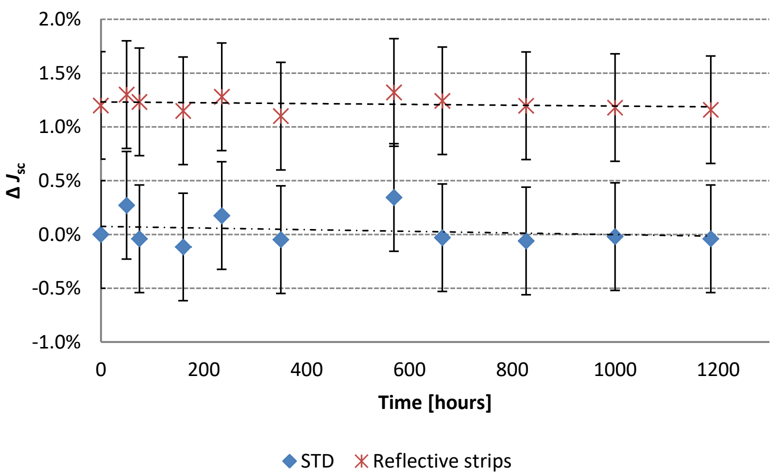


**Figure 10. Short-circuit current density variations during the damp-heat test.**

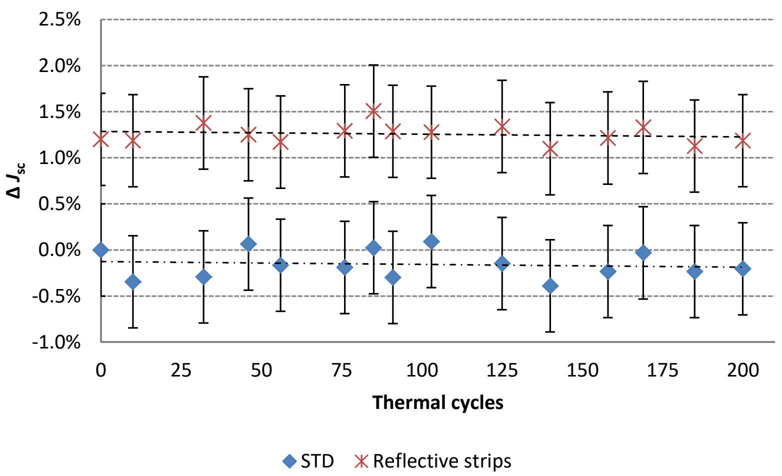


**Figure 11. Short-circuit current density variations during the thermal-cycling test.**

trends for the reference module and for the module with reflective strips were similar, leading to the conclusion that neither case demonstrated any appreciable degradation.

## Conclusions

A new glass with reflective strips has been presented, which aims to reduce cell-to-module losses and to improve the efficiency of standard PV modules. The technique allows the use of the otherwise inactive area of the solar cells. The reflective strips are placed on the inner side of the glass, as well as on top of the solar cell metallization grid. The benefit of these strips has been demonstrated by studying their effect on the connecting ribbons.

Because of the high specular reflection of a standard PV ribbon, only around 5% of the incident light falling on it is utilized for increasing the current of the solar cells. With the use of a glass incorporating reflective strips, this percentage is increased by a factor of 10, an improvement that is due to the high global reflectance and the Lambertian response of the said strips. In addition, their transmitted light is highly diffused, and so some of that light can be reused.

With a normal light incidence, a theoretical short-circuit current improvement of 1.35% was obtained for a PV module processed from solar cells with three busbars, which equates to an improvement in efficiency of 0.28%$_{abs.}$ Experimentally, average improvements of 1.20% in the short-circuit current, and 0.23%$_{abs.}$ in the efficiency, of different PV mini-modules were obtained. These values imply a theoretical gain of 0.04%$_{abs.}$, and an experimental gain of 0.03%$_{abs.}$, per cm$^2$ of tabbing ribbon. Owing to the Lambertian behaviour of the strips, this improvement is expected to be almost constant for any angle of incidence of light.

If the reduction in the shading effect is taken into account, a new solar cell metallization grid can be designed to reduce the series resistance losses. In this respect, the glass with reflective strips favours the use of a large number of busbars.

Glass incorporating reflective strips can be integrated in the vast majority of PV modules fabricated with crystalline silicon solar cells – in other words, in modules constituting more than 90% of the current market. Given the presence of metallization grids on both of the main surfaces, bifacial solar cells would benefit even more from the use of reflective strips on the glass. Moreover, reflective strips can be placed in the spaces between solar cells, which helps to reduce the inactive areas of this type of PV module.

"Because there are no technical obstacles, and no incompatibility issues with existing industrial fabrication procedures, reflective strip technology is almost ready for implementation at the industrial level."

The reflective strip approach is simple and inexpensive; it is compatible with polished and textured glasses, and supports glasses with anti-reflection coatings. In addition, no degradation was found in PV modules after various stress tests carried out in a climate chamber. The method offers the possibility of independently optimizing each PV module fabrication process in general, and the soldering interconnection step in particular. Moreover, the use of this novel glass does not require any additional fabrication processes. Because there are no technical obstacles, and no incompatibility issues with existing industrial fabrication procedures, reflective strip technology is almost ready for implementation at the industrial level.

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