OPTIMISATION OF CELL INTERCONNECTORS FOR PV MODULE PERFORMANCE ENHANCEMENT

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ABSTRACT : In commercial crystalline silicon PV modules usually two parallel metallic strings are used to collect the current from the grid and interconnect the individual cells. Typically, the cross section of these cell interconnectors is rectangular, they are approx. 100 µm high and about 2-3 mm wide, resulting in a 4-6% shadow loss. The basic idea of this paper is to use structured cell interconnectors to increase the short circuit current by taking advantage from multiple internal reflections inside the module compound. A structure on top of the interconnectors has to be designed in a way that light being incident on the interconnectors is reflected under an angle suitable for total internal reflection at the glass/air boundary. A new structuring type called TRITOP has been experimentally and theoretically investigated to check whether a significant enhancement of PV module performance is achievable. An increase of 2-3% relative in module efficiency seems to be cost-effectively transferable to PV module production soon.
Keywords: PV Module - 1: Module Manufacturing - 2: Evaluation - 3

1 INTRODUCTION

PV module prices are usually related to a specific peak power, though a high efficiency can be important in special occasions of limited available area. PV modules made by encapsulation of crystalline silicon solar cells show a total area efficiency, which is typically 10-20 % below active area cell efficiencies. This is mainly due to electrical losses and rising non-active area percentage outweighting the encapsulation gain from refractive index matching of module short circuit current optimized cells. Electrical losses can be minimized using cell matching [1] and low resistance interconnection. Non-active area percentage can be reduced by high packing factors, small frame and shadow area. On the other hand one can use non-active areas for 'zero-depth' concentration by multiple internal reflections. This effect has been addressed for cell interspaces already in the 70s [2], where the increase of short circuit current with decreasing packing factors was studied. It also has an impact on photovoltaic irradiance sensors with low packing factors (such as the first ESTI sensors), since the angular response can be significantly different when compared to pyranometers or standard modules as has been shown in our laboratory. The use of multiple internal reflections can be further increased using special surface structuring. This can be applied either to the front glass, cell interspaces or shadowing metal surfaces, i.e. grid and cell interconnectors.

An improved cell interconnector can be designed from an optimisation of four competing issues related to cost and performance of PV modules:

- optical losses
- electrical losses
- production cost and yield
- long-term stability

In this paper we will focus on an optimisation from the optical and electrical loss point of view, but we will also discuss the relevance of the last two issues for the proposed interconnector type.

2 BASIC IDEA AND APPROACH

The basic idea how to take advantage from multiple internal reflection is sketched in Figure 1. The low total reflection angle of the glass/air boundary can be employed by the use of structured cell interconnectors. A ray being incident on the metallic surface of an interconnector is reflected. On a regular flat surface most of the light will leave the module compound. In the case of a structured interconnector the probability of light trapping due to total reflection at the glass/air boundary can be very high.

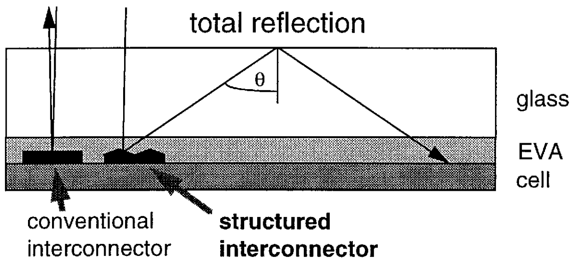

Figure 1 : Schematic sketch of the advantage of structured in comparison with conventional (smooth) interconnectors. For the angle θ being above 42° total internal reflection is achieved.

Furthermore the structure can be optimized very effectively, since the angle between the ray and the module normal after penetration of the air/glass boundary is limited to 45°. For a typical application (latitude tilt angle, south directed) more than 70% of the yearly irradiation is incident with this angle being within 5 and 30° [3]. For two reasons grooves on the top of the cell interconnectors (TRITOP shape, TRIangular structure on TOP) have been favoured from first considerations.

- The structure should be producible at low cost.
- Multiple grooves enable to keep the cross section to base width ratio of the interconnector high. This is indispensable to realize gains in order not to increase electrical losses by increasing the interconnector resistance, when considering both optical and electrical losses.

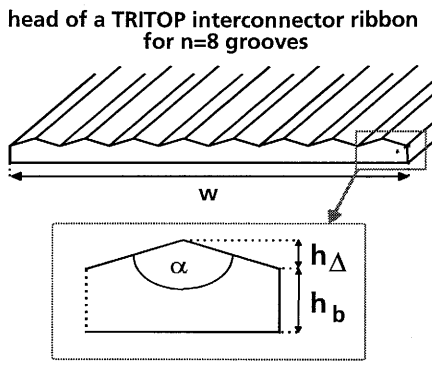

Figure 2 shows a sketch of the TRITOP structure and the relevant parameters.

3 EXPERIMENTAL

In order to study the impact of TRITOP type interconnectors on PV-module performance, four test „modules" of 20x30cm^2 size were constructed: Five metallic strings of 5mm width were encapsulated within two glass plates for each module. The interconnector to total surface area ratio κ was chosen to be κ=12.5%, much higher than usual, aiming to reduce measurement uncertainties. The modules only differed in the structure on top of the metallic strings. One had a conventional smooth, one a micro-rough surface and two of them were TRITOP-like, with α=135° and n=2. Two identical „modules" have been used to get information about the reproducibility and reliability of the encapsulation process.

The following two types of measurements have been performed with these test „modules": An integrating sphere was used to measure the hemispherical reflectance of an incoming beam on top of the different module types. The reflectance was measured in dependence of the incidence angle in the range from 10-80° (since the measurement device used is limited to this range for reliable data) parallel to the strings. The results are shown in figure 3.

The TRITOP shaped interconnectors show the lowest reflectance followed by the micro-rough and the smooth one, showing the highest reflectance. The results for the two (identical) TRITOP structures are almost identical.

In order to be able to assess the gain for other interconnector to total surface area ratios than κ=12.5%, the reflectance of the micro-rough and TRITOP interconnectors as compared to the smooth interconnector, has to be normalized to the interconnector area. Therefore we define the normalized reduction N_R as:

$$N_R = \frac{R_n - R_s}{\kappa} \qquad (1)$$

where R_n and R_s are the reflectances of the modules with normal and structured interconnectors respectively. The product of N_R and κ can be used as an estimation of the relative gain in efficiency for any cell independent from κ, as long as κ is sufficiently small, since one has to keep in mind that N_R is only approximately independent of κ (as can be seen easily by considering the limit $\kappa \rightarrow 1$).

The straight lines in figure 3 show ray tracing simulations of the reflectance. To simulate the micro-rough structure a model for diffuse reflecting surfaces by Phong [4] has been used. All other surfaces have been assumed to show specular reflection. Within the framework of this approximation the simulations fit the data well. Even more accurate calculations could be performed by taking diffuse reflectivity into account for the smooth and structured surfaces as well, but this is not the aim of this paper. At the time being we take these results as a proof of concept for the simulations of „real" modules to be discussed in the next section.

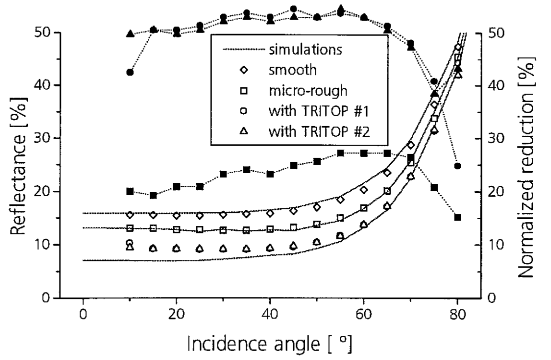

Figure 3 shows the result from the direct-hemispherical reflectance measurement (hollow symbols, left axes) together with the simulated data (lines). The solid symbols show the reduction of the reflectance of the micro-rough and TRITOP interconnectors compared to the smooth and normalized to the interconnector area (right axes).

Apart from the reflection measurements also short-circuit currents of a silicon solar cell being optically coupled to the different test modules have been measured at Standard Testing Conditions (STC) using the Fraunhofer ISE calibration laboratory pulsed sun simulator [5]. The results of the measurements are shown in figure 4. Again these values were normalized to the interconnector area.

As a result from these test module experiments, we can state that an increase of approx. 50% per unit interconnector area in short circuit current has been proven for the TRITOP, when compared to the smooth (conventional) structure. The micro-rough structure has shown a gain of approx. 10% per unit interconnector area. For the TRITOP structure the results show a high degree of reproducibility

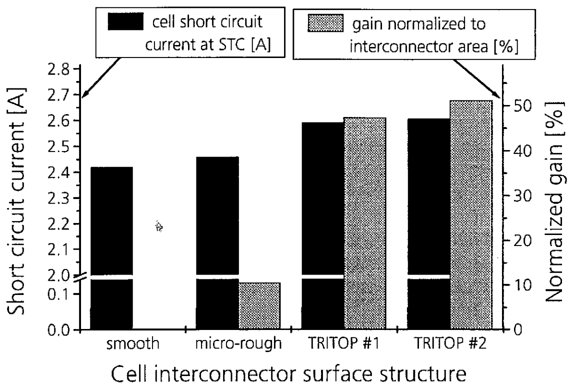

Figure 4 shows the short circuit current of one cell being optically coupled to the four different modules (left axes). The gain in short circuit current when compared to the smooth (conventional) surface is also normalized to the interconnector area (right axes).

for both the encapsulation process and the two different measurement techniques. For the micro-rough structure the difference in the normalized data can be attributed to the diffuse reflection. A non-ideal angle of reflection from the metallic surface leads to higher absorption within the module compound.

4 SIMULATION

In this section we want to discuss the results of ray tracing calculations predicting the possible enhancement of module performance by TRITOP type interconnectors for „real PV-modules". Therefore the simulated module is assumed to consist of 3mm glass, 0.5mm EVA and a 0.4 mm thick silicon solar cell (coated with 64nm TiO_x) having a back-contact reflectivity of 80%. The interconnectors are w=2mm wide and h=0.1mm high, having n=8 triangles with apex angle α on the top (the hight of the base and the triangles h_b and h_Δ can be determined out of n, α, w and h by $h=h_\Delta+h_b$, compare figure 2). The spacing between them was set to 50mm resulting in an interconnector to total surface area ratio of κ=4%. In principle a finite size and number of cells and different packing factors could be included in the model as well, however we neglect these effects for the sake of clearness and simplicity. Furthermore we neglect boundary effects and regard the module as infinitely extended. In order to describe the incoming beam in spherical coordinates, we want to introduce the convention, that a zenith angle of θ=0° indicates perpendicular incidence on the module surface, and an angle of φ=90° describes incidence in the plane being parallel to the interconnectors and the module normal.

The numerical calculations were performed with the 3D-ray tracer RAYN developed at Fraunhofer ISE and described elsewhere [6]. Calculations were carried out for wavelengths from 300nm to 1200nm in steps of 10nm. Figure 5 shows the absorptance of the module with the wavelength dependent absorptance values being weighted with the AM1.5-spectrum, for different angles of incidence θ perpendicular to the interconnectors (i.e. φ=0 in spherical coordinates according to our convention) as a function of the apex angle α of the TRITOP structure. The angle of α =180° refers to conventional interconnectors. At θ=0 a broad maximum can be detected for the apex angle α between 120° and 140°, which decreases and shifts to smaller angles α with growing θ. From the displayed absorption data the normalized enhancement N_E (defined analogous as for the reflection) can be deduced. The maximum values of $N_E(\alpha)$ for the shown curves, lie in the range from 1 to 0.65. The value of 1, which means that all the light being incident on the interconnector is directed towards and absorbed by the cell, is actually reached for an incidence angle of 10°. Even values greater than 1 are possible theoretically if one thinks of the enhancement of the absorption by light trapping of otherwise weakly absorbed longwave radiation.

For a given distribution of angular dependent irradiation an optimum angle α_{max} can be found which maximizes the mean absorption. That means that the efficiency at RRC (Realistic Reporting Conditions), as defined in [7], can be optimized for applications with different angular distributions of the irradiance .

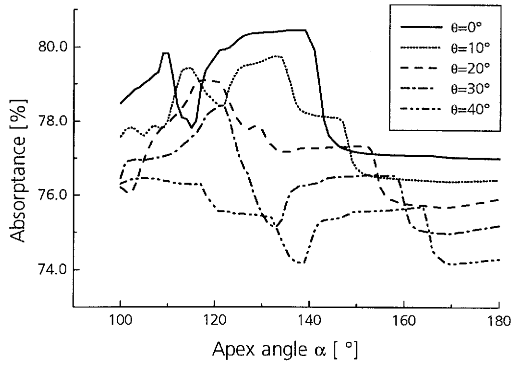

Figure 5 shows the absorption in the solar cell as a function of the apex angle α of the TRITOP structure for different incidence angles θ and a fixed azimuth angle φ=0° (i.e. perpendicular to the interconnectors).

In order to illustrate this connection, we calculated the annual energy yield E_{ann} [kWh/m²year] using given angular dependent irradiation distributions $H_{ann}(\theta)$ [kWh/°m²year] for a latitude tilted (48° declination, south-directed) module and a PV-facade (90° declination, south-directed) in Freiburg respectively. These azimuthal-symmetric irradiation distributions (i.e. independent of φ) have been published in [3] before. The calculations were performed using a „typical" crystalline silicon internal spectral response s_{int} and the spectral irradiance according to AM1.5 using the following estimate :

$$E_{ann} \cong c_{ic}\,\eta_{RRC}\,H_{ann}\,, \tag{2}$$

$$\text{with}\quad H_{ann}(\theta)=H_{rel}(\theta)H_{ann}\quad,\text{ and} \tag{3}$$

$$c_{ic}=\frac{\int_0^\infty E_{AM1.5}(\lambda)s_{int}(\lambda)\int_0^{\frac{\pi}{2}}A_\alpha(\lambda,\theta)H_{rel}(\theta)d\theta d\lambda}{\int_0^\infty E_{AM1.5}(\lambda)s_{int}(\lambda)\int_0^{\frac{\pi}{2}}A_{180^\circ}(\lambda,\theta)H_{rel}(\theta)d\theta d\lambda} \tag{4}$$

where c_{ic} denotes the interconnector gain factor, $A_\alpha(\lambda,\theta)$ denotes the absorptance, $H_{rel}(\theta)$ denotes the relative angular distribution of the yearly irradiation and H_{ann} the total yearly irradiation. For smooth interconnectors c_{ic} is identical to 1, which also yields a definition for the efficiency under realistic reporting conditions η_{RRC} ([7]). The relative deviation of c_{ic} from 1 can be denoted as the gain of a structured interconnector, when compared to a conventional one. Actually this gain is a gain in short circuit current and it is an approximation of equation (2), that this increase in short circuit current will transfer to an identical gain in efficiency and consequently in energy yield.

Using the mean values (averaged over φ∈[0,2π]) of $A_\alpha(\theta,\lambda)$ and $H_{rel}(\theta)$ in (4), instead of taking the full dependence on θ and φ into account, introduces a further (azimuthal) approximation, since the geometry under consideration has definitely no azimuthal-symmetry (i.e. the differences in the angular dependence of the absoption are significant for perpendicular (φ=0°) and parallel (φ=90°) incidence). More accurate simulations, taking into account the dependence of the absorption as well as the dependence of the irradiation distribution on both spherical angles are in preparation. The results for the azimuthal approximation are displayed in figure 6. The maximum gain (in comparison to a conventional interconnector) is attained for an apex angle of about 120° for both installation types.

For an interconnector to total area ratio of κ=4% a gain in yearly energy yield of 2% is possible under realistic operating conditions. This corresponds to a relative gain of 50% per interconnector area. However this is only the lower limit of the possible gain. If one takes into consideration, that the absorption for parallel incidence (φ=90°) is only slightly dependent on θ and mainly looks like the curve displayed in figure 5 for θ=0°, it seems likely that even higher gains will result for the complete angular dependence being taken into account.

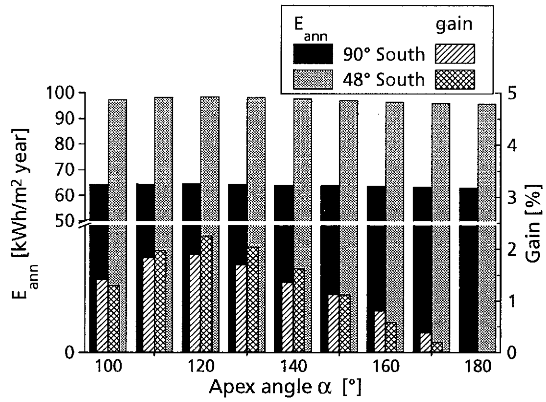

Figure 6 shows the calculated annual energy yield E_{ann} (left axis) for two inclinations in Freiburg (η_{RRC}=10%) and the resulting gain (right axes) in dependence of the apex angle α.

5 DISCUSSION

The criteria mentioned in the introduction have been analysed to assess the feasibility of structured cell interconnectors :

5.1 TRITOP shape

If the cross section, the specific resistance and the contact area of the solder points stay constant there should be no influence on electrical losses, when using a TRITOP shaped cell interconnector. Consequently the remaining issues are whether the greater maximum height yields problems during lamination and whether the shape does influence solderability. Due to the shallow angle structure the high deformability of the EVA and the high heat conductivity of the metal we do not expect any impact on producibility. Also the conditions for long term stability shouldn't be altered effectively, if a sufficient stress relief loop is used. The TRITOP shape could be formed e.g. during rolling of the metalic ribbon used as the basic interconnector material and seems to be easily transferable to module production.

5.2 Other concepts

There are some other possible approaches to take advantage of different from normal cell interconnector concepts which should be shortly discussed :

5.2.1 Overall triangular shaped cell interconnectors

Form the optical point of view it seems ideal to use multiple highly and directly reflecting cell interconnectors with a triangular shape and an apex angle of about 90°. This type would result in a high percentage of rays being incident on the interconnector surface to be reflected on the cell surface. This concept has been successfully addressed for the cell grid in [8]. But for cell interconnectors there are several counterparts when looking at the producibility :

- soldering of a triangular shaped interconnector with a high aspect ratio is a difficult task
- retaining the overall cross section to keep the series resistance low, has further negative consequences, since either the EVA thickness, the number of cell interconnectors and soldering points or the series resistance have to be increased significantly

Consequently an overall triangular shape does not seem to be reasonable.

5.2.2 A highly diffuse reflective cell interconnector

Another approach would be to keep the regular shape of the cell interconnector, but to use a micro-rough-structure providing a high diffusivity and a high intensity of the reflected light. We have seen, that this type can also increase the cell short circuit current after encapsulation. Due to low structuring costs a higher rentability when compared to the TRITOP structure might be achieved.

6 CONCLUSIONS

An increase of 2-3% relative in module efficiency seems to be cost-effectively achievable soon using cell interconnectors with a TRITOP-like shape. The used measurement and simulation instruments have proven to be a useful tool to determine the optical properties of different cell interconnectors.

ACKNOWLEDGEMENT

This work was supported by the European Community and the German BMBF under contract no. JOR3-CT-96-0095 and contract no. 0328650F respectively. The authors would also like to thank J. Schumacher for his help with the 3D-ray tracing program RAYN.

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